Photon beam properties at the European XFEL (December 2010 revision)

E.A. Schneidmiller, M.V. Yurkov

Deutsches Elektronen-Synchrotron (DESY), Hamburg, Germany

Abstract

A new set of baseline parameters of the electron beam and undulator for the European XFEL project has been defined recently. Changes refer to the electron beam emittance, charge, operation at different electron energies, and change of undulator period. According to the present concept, it is planned to vary charge from 20 pC to 1 nC allowing control of the FWHM radiation pulse duration. Operation at different electron energies of 17.5 GeV, 14 GeV, and 10.5 GeV will allow extension of the wavelength range to longer wavelengths. Electron bunches with different charges possess different properties. These features have an inmpact on photon beam properties which should be taken into account at the design stage optical beamlines and instruments and planning user experiments. In this note we present an overview of the radiation properties generated by SASE FEL radiators driven by electron beam with revised baseline parameters.

Contents

DESY 11-152 *September 2011*

1 Introduction

Recent success of the Linac Coherent Light Source (LCLS) demonstrated feasibility for reliable production, compression, and acceleration of electron beams with small emittance. Currently LCLS provides different modes of operation with different charges (20 pC to 250 pC), different peak currents (1.x kA to 3.x kA) and wide wavelength range (0.12 nm to 2.2 nm) [1]. Conceptual Design Report of LCLS considered two possible options of the LCLS operation: baseline with bunch charge of 1 nC and low charge option with bunch charge of 250 pC [2]. An option with 1 nC bunch charge was based on rather conservative value of the normalized emittance of 1.2 mm-mrad assuming some set of possible physical effects and technical imperfections leading to emittance degradation. Optimistic analysis of the low charge option predicted much smaller value of the emittance of about 0.4 mm-mrad. In practice small charge option has been realized experimentally [1].

Similar level of concerns of possible problems of physical and of technical nature has been accepted in the European XFEL project as well: baseline option assumed operation with the bunch charge of 1 nC and value of the normalized emittance 1.4 mm-mrad [3]. It has been planned to operate XFEL ate the energy of 17.5 GeV and cover wavelength range from 0.1 nm to 1.6 nm. However, recent trends and experimental results provided the base for revision of the baseline parameters. First we refer to successful operation of FLASH free electron laser which serves as a prototype of the European XFEL. In particular, thorough analysis of the radiation properties generated by FLASH gave an indication on a small value of the slice emittance of about 1 mm-mrad [4]. Recent results of the Photo Injector Test Facility in Zeuthen (PITZ) demonstrated the possibility to generate electron beams with smaller charge and emittance [5, 6]. Computer modelling of the beam formation system at the European XFEL also indicate on the possibility to preserve electron beam quality during acceleration and compression [7, 8]. These trends have been analyzed thoroughly. First iteration on expected electron beam parameters has been issued in April, 2010 [9]. It has been based on extensive start-to-end simulations with proceeding application of safety margin based on possible physical effects and problems of technical nature which are beyond physical models implemented in start-to-end simulations. Relevant simulations of SASE FEL performance has been performed in two directions. The first one was a set of start-to-end simulations for specific working points [10]. A comprehensive overview of the whole parameter space has been performed in [11] using generic set of electron beam parameters derived from start-to-end simulations [9].

The work on more detailed analysis of the electron beam properties has been continued further on [12], and the next iteration on the new baseline parameters of the electron beam have been fixed in December 2010 [14]. In parallel there was also revision of the undulator parameters based on user's requirements. It has been decided that SASE1 and SASE2 undulators will have period of 4 cm, and SASE3 undulator will have period 6.8 cm [13].

Parameter space of the baseline parameters has been significantly extended in terms of the bunch charge and electron energy. As a result, different modes of FEL operation become possible with essentially different properties of the radiation. Table 1 presents comparison of parameters of hard x-ray FELs before and after revision. Averaged characteristics are calculated for the same pulse pattern in both cases. We see that transition from TDR 2006 baseline parameters to new baseline parameters of 2010 results in visible improvement of all characteristics of the radiation. The matter of importance here is degree of transverse coherence which reaches ultimate values with new baseline parameters. Variation of the bunch charge will allow to control radiation pulse duration in wide limits.

In this paper we present an overview of radiation properties of SASE FEL radiators driven by electron beam with new baseline parameters. Summary of photon beam properties is compiled in tables 2 - 7. An overview of such a wide parameter space was impossible without making use of fitting formulae based on application of similarity techniques to the results of extended numerical simulations [15–18]. To make an overview be consistent, we present here basic set of fitting formulae describing operation of an optimized SASE FEL. In the general case FEL process is simulated with time-dependent FEL simulation code FAST [19]. Properties of the radiation are presented in three ways. The first one are properties of the radiation of SASE FELs operating in the saturation regime. These tables contain complete set of parameters. Another way for presentation of the results are contour plots for the properties on the plane of bunch charge and radiation wavelength. These plots allow visual guiding of the main dependencies. Saturation regime of the SASE FEL operation is an important operating point, but not the only one which can be used in the experiments. For instance, knowledge of the properties of the radiation for SASE FEL operating in the linear regime are of importance for designing photon diagnostics hardware. Also, operation of the SASE FEL in the deep nonlinear regime with enhanced power can be of interest for some user's applications. We illustrate general features of the SASE process for several operating points. Complete data set of time-dependent simulations of the radiation pulse will available in the data base of the photon beam properties which we organize together with the experts from the European XFEL.

We included basic definitions of the radiation parameters in the text. For those readers interested in extended knowledge we provide relevant references.

Table 1
Comparative table of the properties of the radiation from SASE1 as of TDR 2006 and December 2010 revision (electron energy 17.5 GeV, wavelength 0.1 nm)

	Units	SASE1 2006	SASE1 (2010)		
Bunch charge	nC	1	1	0.25	0.02
Pulse energy	mJ	1.3	1.80	.697	.635E-01
Peak power	GW	11.7	16.8	30.0	37.8
Average power	W	35.2	48.7	18.8	1.71
FWHM spot size	μm	53.8	42.7	34.2	27.3
FWHM angular divergence	μrad	1.22	1.35	1.60	2.00
Coherence time	fs	0.29	.201	.164	.135
FWHM spectrum width, $\Delta\omega/\omega$	%	.081	.117	.144	.175
Degree of transverse coherence	#	.62	.820	.950	.960
FWHM pulse duration	fs	110	107.	23.2	1.68
Degeneracy parameter	#	.106E+10	.139E+10	.235E+10	.246E+10
Number oh photons per pulse	#	.656E+12	.907E+12	.351E+12	.319E+11
Average flux of photons	ph/sec	.177E+17	.245E+17	.947E+16	.862E+15
Peak brilliance*	#	.179E+34	.237E+34	.399E+34	.417E+34
Average brilliance*	#	.540E+25	.685E+25	.250E+25	.189E+24
Saturation length	m	131.	100.	70.6	57.6

*Units of photons/sec/mm^2/rad^2/0.1% bandwidth.

**Averaged characteristics are calculated for 27000 pulses per second.

Table 2
Photon beam properties of SASE1 (SASE2) at the European XFEL
December 2010 revision
Electron energy 17.5 GeV

	Units						
Bunch charge	nC	.02	0.25	1	.02	0.25	1
Radiation wavelength	nm		.500E-01			.150	
Photon energy	keV		24.8			8.27	
Pulse energy	mJ	.320E-01	.302	.863	.809E-01	.994	3.04
Peak power	GW	19.0	13.0	8.05	48.1	42.8	28.4
Average power	W	.863	8.16	23.3	2.18	26.8	82.1
FWHM spot size	μ	25.1	36.3	55.2	28.6	36.0	43.0
FWHM angular divergence	μrad	1.09	.857	.660	2.83	2.28	1.91
Coherence time	fs	.991E-01	.128	.199	.173	.203	.256
FWHM spectrum width, dw/w	%	.119	.918E-01	.592E-01	.205	.174	.138
Degree of transverse coherence	#	.942	.711	.419	.960	.960	.941
FWHM FWHM radiation pulse duration	fs	1.68	23.2	107.	1.68	23.2	107.
Number of longitudinal modes	#	16	181	538	9	114	418
Fluctuations of the pulse energy	%	8.33	2.48	1.44	11.1	3.12	1.63
Degeneracy parameter	#	.447E+09	.299E+09	.169E+09	.602E+10	.630E+10	.516E+10
Number oh photons per pulse	#	.804E+10	.761E+11	.217E+12	.610E+11	.750E+12	.229E+13
Average flux of photons	ph/sec	.217E+15	.205E+16	.586E+16	.165E+16	.202E+17	.620E+17
Peak brilliance*	#	.606E+34	.405E+34	.229E+34	.302E+34	.316E+34	.259E+34
Average brilliance*	#	.275E+24	.254E+25	.663E+25	.137E+24	.199E+25	.751E+25
Saturation length	m	84.2	126.	199.	49.5	58.5	74.0

*Units of photons/sec/mm^2/rad^2/0.1% bandwidth.

**Averaged characteristics are calculated for 27000 pulses per second.

Table 3
Photon beam properties of SASE1 (SASE2) at the European XFEL
December 2010 revision
Electron energy 14 GeV

	Units						
Bunch charge	nC	.02	0.25	1	.02	0.25	1
Radiation wavelength	nm		.800E-01			.250	
Photon energy	keV		15.5			4.96	
Pulse energy	mJ	354E-01	.347	.991	.782E-01	1.04	3.59
Peak power	GW	1.1	14.9	9.24	46.5	44.7	33.5
Average power	W	955	9.37	26.8	2.11	28.0	97.0
FWHM spot size	μ	8.5	34.9	53.5	32.6	41.2	49.2
FWHM angular divergence	μrad	.54	1.31	1.00	4.11	3.32	2.79
Coherence time	fs	131	.148	.228	.246	.282	.341
FWHM spectrum width, dw/w	%	144	.127	.828E-01	.239	.209	.173
Degree of transverse coherence	#	958	.835	.569	.960	.960	.958
FWHM FWHM radiation pulse duration	fs	.68	23.2	107.	1.68	23.2	107.
Number of longitudinal modes	#	12	156	470	6	82	314
Fluctuations of the pulse energy	%	9.62	2.67	1.54	13.6	3.68	1.88
Degeneracy parameter	#	.106E+10	.744E+09	.482E+09	.138E+11	.152E+11	.137E+11
Number oh photons per pulse	#	.142E+11	.140E+12	.399E+12	.983E+11	.131E+13	.452E+13
Average flux of photons	ph/sec	.384E+15	.377E+16	.108E+17	.265E+16	.353E+17	.122E+18
Peak brilliance*	#	.351E+34	.246E+34	.160E+34	.150E+34	.165E+34	.149E+34
Average brilliance*	#	.159E+24	.155E+25	.462E+25	.681E+23	.104E+25	.432E+25
Saturation length	m	69.7	91.4	142.	42.6	48.9	59.3

*Units of photons/sec/mm^2/rad^2/0.1% bandwidth.

**Averaged characteristics are calculated for 27000 pulses per second.

Table 4
Photon beam properties of SASE1 (SASE2) at the European XFEL
December 2010 revision
Electron energy 10.5 GeV

	Units						
Bunch charge	nC	.02	0.25	1	.02	0.25	1
Radiation wavelength	nm		0.1			0.45	
Photon energy	keV		12.4			0.276	
Pulse energy	mJ	228E-01	.264	.754	.701E-01	.992	3.70
Peak power	GW	3.6	11.4	7.03	41.7	42.7	34.5
Average power	W	616	7.13	20.4	1.89	26.8	99.8
FWHM spot size	μ	2.3	38.3	58.7	38.4	48.5	58.0
FWHM angular divergence	μrad	.70	1.52	1.17	6.26	5.06	4.26
Coherence time	fs	174	.191	.294	.376	.419	.494
FWHM spectrum width, dw/w	%	135	.124	.801E-01	.282	.253	.215
Degree of transverse coherence	#	957	.806	.528	.960	.960	.960
FWHM FWHM radiation pulse duration	fs	.68	23.2	107.	1.68	23.2	107.
Number of longitudinal modes	#	9	121	364	4	55	217
Fluctuations of the pulse energy	%	11.1	3.03	1.75	16.7	4.49	2.26
Degeneracy parameter	#	.114E+10	.879E+09	.550E+09	.341E+11	.389E+11	.370E+11
Number oh photons per pulse	#	.115E+11	.133E+12	.379E+12	.159E+12	.225E+13	.837E+13
Average flux of photons	ph/sec	.310E+15	.359E+16	.102E+17	.428E+16	.606E+17	.226E+18
Peak brilliance*	#	.194E+34	.149E+34	.933E+33	.634E+33	.724E+33	.689E+33
Average brilliance*	#	.878E+23	.935E+24	.270E+25	.288E+23	.454E+24	.199E+25
Saturation length	m	74.7	94.9	149.	36.3	40.7	48.1

*Units of photons/sec/mm^2/rad^2/0.1% bandwidth.
**Averaged characteristics are calculated for 27000 pulses per second.

Table 5
Photon beam properties of SASE3 at the European XFEL
December 2010 revision
Electron energy 17.5 GeV

	Units						
Bunch charge	nC	.02	0.25	1	.02	0.25	1
Radiation wavelength	nm		0.15			1.6	
Photon energy	keV		8.27			0.775	
Pulse energy	mJ	.902E-01	1.01	2.69	.203	2.89	11.8
Peak power	GW	53.7	43.4	25.1	121.	124.	110.
Average power	W	2.43	27.2	72.7	5.49	78.0	320.
FWHM spot size	μ	30.4	38.5	48.5	38.3	49.3	59.9
FWHM angular divergence	μrad	2.60	2.11	1.56	17.0	14.7	12.8
Coherence time	fs	.150	.181	.210	.850	.936	1.06
FWHM spectrum width, dw/w	%	.236	.195	.168	.444	.403	.356
Degree of transverse coherence	#	.960	.960	.941	.960	.960	.960
FWHM FWHM radiation pulse duration	fs	1.68	23.2	107.	1.68	23.2	107.
Number of longitudinal modes	#	11	128	509	1	24	01
Fluctuations of the pulse energy	%	10.1	2.95	1.48	33.3	6.80	3.32
Degeneracy parameter	#	.582E+10	.568E+10	.375E+10	.795E+12	.899E+12	.903E+12
Number oh photons per pulse	#	.680E+11	.760E+12	.203E+13	.164E+13	.233E+14	.952E+14
Average flux of photons	ph/sec	.184E+16	.205E+17	.549E+17	.442E+17	.628E+18	.257E+19
Peak brilliance*	#	.293E+34	.286E+34	.189E+34	.329E+33	.372E+33	.374E+33
Average brilliance*	#	.133E+24	.179E+25	.546E+25	.149E+23	.234E+24	.108E+25
Saturation length	m	72.8	88.3	119.	39.7	43.9	49.8

*Units of photons/sec/mm^2/rad^2/0.1% bandwidth.
**Averaged characteristics are calculated for 27000 pulses per second.

Table 6
Photon beam properties of SASE3 at the European XFEL
December 2010 revision
Electron energy 14 GeV

	Units						
Bunch charge	nC	.02	0.25	1	.02	0.25	1
Radiation wavelength	nm		0.2			2.5	
Photon energy	keV		6.2			0.5	
Pulse energy	mJ	.790E-01	.938	2.55	.185	2.66	11.0
Peak power	GW	47.0	40.3	23.8	110.	115.	102.
Average power	W	2.13	25.3	68.9	5.00	71.9	297.
FWHM spot size	μ	33.9	42.9	50.0	43.2	55.7	67.7
FWHM angular divergence	μrad	3.12	2.54	1.98	23.1	20.0	17.5
Coherence time	fs	.184	.218	.241	1.17	1.28	1.45
FWHM spectrum width, dw/w	%	.256	.216	.195	.502	.459	.407
Degree of transverse coherence	#	.960	.960	.949	.960	.960	.960
FWHM FWHM radiation pulse duration	fs	1.68	23.2	107.	1.68	23.2	107.
Number of longitudinal modes	#	9	106	444	1	18	74
Fluctuations of the pulse energy	%	11.1	3.24	1.58	33.3	7.86	3.87
Degeneracy parameter	#	.837E+10	.850E+10	.548E+10	.156E+13	.178E+13	.179E+13
Number oh photons per pulse	#	.794E+11	.943E+12	.257E+13	.233E+13	.335E+14	.138E+15
Average flux of photons	ph/sec	.215E+16	.255E+17	.694E+17	.629E+17	.904E+18	.373E+19
Peak brilliance*	#	.178E+34	.180E+34	.116E+34	.170E+33	.193E+33	.194E+33
Average brilliance*	#	.805E+23	.113E+25	.336E+25	.770E+22	.121E+24	.563E+24
Saturation length	m	67.4	80.1	103.	35.3	38.7	43.7

*Units of photons/sec/mm^2/rad^2/0.1% bandwidth.

**Averaged characteristics are calculated for 27000 pulses per second.

Table 7
Photon beam properties of SASE3 at the European XFEL
December 2010 revision
Electron energy 10.5 GeV

	Units						
Bunch charge	nC	.02	0.25	1	.02	0.25	1
Radiation wavelength	nm		0.2			5	
Photon energy	keV		6.2			0.25	
Pulse energy	mJ	.491E-01	.563	1.56	.168	2.45	10.2
Peak power	GW	29.2	24.2	14.6	99.9	105.	94.9
Average power	W	1.32	15.2	42.2	4.53	66.1	275.
FWHM spot size	μ	37.5	47.3	60.4	51.0	65.9	80.1
FWHM angular divergence	μrad	2.87	2.32	1.80	37.1	32.6	28.7
Coherence time	fs	.203	.241	.292	1.97	2.13	2.38
FWHM spectrum width, dw/w	%	.232	.196	.162	.599	.554	.496
Degree of transverse coherence	#	.960	.958	.890	.960	.960	.960
FWHM FWHM radiation pulse duration	fs	1.68	23.2	107.	1.68	23.2	107.
Number of longitudinal modes	#	8	96	367	3	10	45
Fluctuations of the pulse energy	%	11.8	3.40	1.74	33	10.5	4.97
Degeneracy parameter	#	.573E+10	.563E+10	.381E+10	.474E+13	.541E+13	.545E+13
Number oh photons per pulse	#	.494E+11	.567E+12	.157E+13	.422E+13	.615E+14	.256E+15
Average flux of photons	ph/sec	.133E+16	.153E+17	.425E+17	.114E+18	.166E+19	.691E+19
Peak brilliance*	#	.121E+34	.119E+34	.808E+33	.644E+32	.733E+32	.739E+32
Average brilliance*	#	.551E+23	.749E+24	.234E+25	.292E+22	.460E+23	.214E+24
Saturation length	m	74.2	88.5	125.	29.7	32.3	36.2

*Units of photons/sec/mm^2/rad^2/0.1% bandwidth.

**Averaged characteristics are calculated for 27000 pulses per second.

2 Definition of the radiation characteristics

Due to start-up of the amplification from the shot noise in the electron beam Self-Amplified Spontaneous Emission Free Electron Laser (SASE FEL) produces random fields $\tilde{E}$ in time and space. Integration of the power density $I = |\tilde{E}|^2$ over transverse cross section of the photon beam gives us instantaneous radiation power, $P \propto \int I \,\mathrm{d}\,\vec{r}_{\perp}$. Integration of the radiation power along the pulse gives us the radiation pulse energy. Partial longitudinal coherence is formed due to slippage effect, and partial transverse coherence is formed due to diffraction effects. We describe radiation fields generated by a SASE FEL in terms of statistical optics [20, 21]. Longitudinal and transverse coherence are described in terms of correlation functions. The first order time correlation function, $g_1(t,t')$, is defined as:

$$g_1(\vec{r}, t-t') = \frac{\langle \tilde{E}(\vec{r},t)\tilde{E}^*(\vec{r},t')\rangle}{\left[\langle|\ \tilde{E}(\vec{r},t)\ |^2\rangle\langle|\ \tilde{E}(\vec{r},t')\ |^2\rangle\right]^{1/2}} \ . \qquad (1)$$

For a stationary random process the time correlation functions are dependent on only one variable, $\tau = t - t'$. The coherence time is defined as [20, 21]:

$$\tau_{\mathrm{c}} = \int\limits_{-\infty}^{\infty} |g_1(\tau)|^2 \,\mathrm{d}\,\tau \ . \qquad (2)$$

The transverse coherence properties of the radiation are described in terms of the transverse correlation functions. The first-order transverse correlation function is defined as

$$\gamma_1(\vec{r}_{\perp}, \vec{r'}_{\perp}, z, t) = \frac{\langle \tilde{E}(\vec{r}_{\perp}, z, t)\tilde{E}^*(\vec{r'}_{\perp}, z, t)\rangle}{\left[\langle|\tilde{E}(\vec{r}_{\perp}, z, t)|^2\rangle\langle|\tilde{E}(\vec{r'}_{\perp}, z, t)|^2\rangle\right]^{1/2}} \ .$$

We consider the model of a stationary random process, meaning that γ_1 does not depend on time. We define the degree of transverse coherence as [16]:

$$\zeta = \frac{\int |\gamma_1(\vec{r}_{\perp}, \vec{r'}_{\perp})|^2 I(\vec{r}_{\perp}) I(\vec{r'}_{\perp}) \,\mathrm{d}\,\vec{r}_{\perp} \,\mathrm{d}\,\vec{r'}_{\perp}}{[\int I(\vec{r}_{\perp}) \,\mathrm{d}\,\vec{r}_{\perp}]^2} \ . \qquad (3)$$

Physical sense of this definition for ζ is the inverse number of transverse modes in the radiation pulse (see ref. [16] for more details).

The degeneracy parameter δ is defined as the number of photons per mode (coherent state):

$$\delta = \dot{N}_{ph} \tau_{\mathrm{c}} \zeta \ , \qquad (4)$$

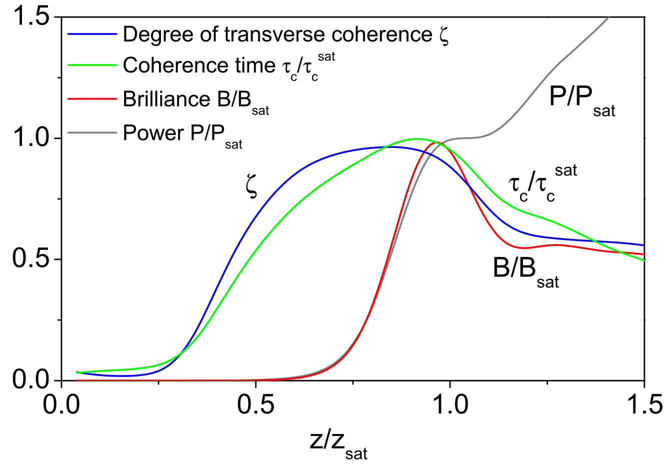

Fig. 1. Evolution of main characteristics of SASE FEL along the undulator: brilliance (red line), radiation power (black line), degree of transverse coherence (blue line), and coherence time (green line). Brilliance and radiation power are normalized to saturation values. Coherence time is normalized to the maximum value. Undulator length is normalized to saturation length. The plot has been derived from the parameter set corresponding to $2\pi\epsilon/\lambda = 1$. Calculations have been performed with the simulation code FAST [19].

where $\dot{N}_{ph}$ is the photon flux. Peak brilliance of the radiation from an undulator is defined as a transversely coherent spectral flux:

$$B_r = \frac{\omega \, \mathrm{d}\, \dot{N}_{ph}}{\mathrm{d}\, \omega} \frac{\zeta}{(\lambda/2)^2} = \frac{4\sqrt{2} c \delta}{\lambda^3} \ . \qquad (5)$$

When deriving right-hand term of the equation we used the fact that the spectrum shape of SASE FEL radiation in a high-gain linear regime and near saturation is close to Gaussian [21]. In this case the rms spectrum bandwidth σ_ω and coherence time obey the equation $\tau_c = \sqrt{\pi}/\sigma_\omega$.

Figure 1 shows evolution of main characteristics of SASE FEL along the undulator: brilliance, radiation power, degree of transverse coherence, and coherence time (this is numerical example typical for an x-ray FEL). For a considered parameter range the radiation power grows continuously along the undulator, so that there is no position where it achieves the maximum (what is usually understood as saturation point). On the other hand, if one traces evolution of the brilliance (or, degeneracy parameter) of the radiation along the undulator length there is always the point, which we define as the saturation point, where the brilliance reaches maximum value [16–18]. This always happens because transverse and longitudinal coherence get worse in the nonlinear regime and lead to a decrease of the brilliance despite the fact that the power grows steadily. We can formulate qualitatively that in the nonlinear regime coherence properties degrade faster than increase of the radiation power.

In the following we present characteristics of the radiation at the saturation point defined as the point where brilliance of the radiation reaches maximum value. We should state that in the Technical Design Report 2006 [3] and early studies we used a qualitative definition of the saturation point. As a consequence, saturation power may be uncertain within a factor of two. It has been also assumed that the radiation from a SASE FEL has nearly complete transverse coherence. The use of the strict definition and accounting for a finite degree of transverse coherence leads to the revision of the values for brilliance at saturation presented in earlier studies (and in the TDR 2006 [3] as well) by a factor of 2-3.

2.1 Optimized x-ray FEL

In the general case properties of the radiation are extracted from the results of numerical simulations with tim-dependent FEL simulation code. In the case of so-called optimized x-ray FEL it is possible to obtain analytical approximations for main characteristics of the radiation. With given values for the parameters of the electron beam and undulator there is optimum value of the focusing beta function β_{opt} providing minimum gain length L_{g}. In the case of negligibly small energy spread we have [15]:

$$\begin{aligned} L_{\mathrm{g}} &\simeq 1.67 \left(\frac{I_A}{I}\right)^{1/2} \frac{(\epsilon_n \lambda_{\mathrm{w}})^{5/6}}{\lambda^{2/3}} \frac{(1+K^2)^{1/3}}{K A_{JJ}} \ , \\ \beta_{\mathrm{opt}} &\simeq 11.2 \left(\frac{I_A}{I}\right)^{1/2} \frac{\epsilon_n^{3/2} \lambda_{\mathrm{w}}^{1/2}}{\lambda K A_{JJ}} \ . \end{aligned} \tag{6}$$

Here $\epsilon_{\mathrm{n}} = \epsilon\gamma$, ϵ is emittance of the electron beam, and $I_A = mc^3/e \simeq 17$ kA is Alfven's current. Note that Eq. (6) is accurate in the range $1 < 2\pi\epsilon/\lambda < 5$.

Analysis of FEL equations tells us that in this case the physical parameters describing operation of the optimized FEL are only functions of the parameter $\hat{\epsilon} = 2\pi\epsilon/\lambda$ [16]. Application of similarity techniques allows us to derive universal parametric dependencies of the output characteristics of the radiation at the saturation point. Within accepted approximations normalized output characteristics of a SASE FEL at the saturation point are functions of only two parameters: $\hat{\epsilon} = 2\pi\epsilon/\lambda$ and the number of electrons in the volume of coherence $N_{\mathrm{c}} = I N_{\mathrm{g}} \lambda/(ec)$, where $N_{\mathrm{g}} = L_{\mathrm{g}}/\lambda_{\mathrm{w}}$ is the number of undulator periods per gain length. Characteristics of practical interest are: saturation length L_{sat}, saturation efficiency $\eta = P/P_{\mathrm{b}}$ (ratio of the radiation power to the electron beam power $P_{\mathrm{b}} = \gamma mc^2 I/e$), coherence time τ_{c}, degree of transverse coherence ζ, degeneracy parameter δ, and brilliance B_{r}.

Applications of similarity techniques to the results of numerical simulations of a SASE FEL [16] gives us the following result:

$$
\begin{aligned}
\hat{L}_{\rm sat} &= \Gamma L_{\rm sat} \simeq 2.5 \times \hat{\epsilon}^{5/6} \times \ln N_{\rm c} \ , \\
\hat{\eta} &= P/(\bar{\rho} P_{\rm b}) \simeq 0.17/\hat{\epsilon} \ , \\
\hat{\tau}_{\rm c} &= \bar{\rho}\omega\tau_{\rm c} \simeq 1.16 \times \sqrt{\ln N_{\rm c}} \times \hat{\epsilon}^{5/6} \ , \\
\sigma_\omega &= \sqrt{\pi}/\tau_{\rm c} \ .
\end{aligned}
\qquad (7)
$$

These expressions provide reasonable practical accuracy for $\hat{\epsilon} \gtrsim 0.5$. Here we normalized FEL characteristics using the gain parameter Γ and the efficiency parameter $\bar{\rho}$ [21]:

$$
\Gamma = \left[\frac{I}{I_{\rm A}} \frac{8\pi^2 K^2 A_{\rm JJ}^2}{\lambda \lambda_{\rm w} \gamma^3} \right]^{1/2} \ , \qquad \bar{\rho} = \frac{\lambda_{\rm w} \Gamma}{4\pi} \ . \qquad (8)
$$

2.2 Estimations in the framework of the one-dimensional model

An estimation of SASE FEL characteristics is frequently performed in the framework of the one-dimensional model in terms of the FEL parameter ρ [27]:

$$
\rho = \frac{\lambda_{\rm w}}{4\pi} \left[\frac{4\pi^2 j_0 K^2 A_{\rm JJ}^2}{I_A \lambda_{\rm w} \gamma^3} \right]^{1/3} \ , \qquad (9)
$$

where $j_0 = I/(2\pi\sigma^2)$ is the beam current density, $\sigma = \sqrt{\beta\epsilon_{\rm n}/\gamma}$ is rms transverse size of the electron beam, and β is external focusing beta function. Basic characteristics of the SASE FEL are estimated in terms of the parameter ρ and number of cooperating electrons $N_{\rm c} = I/(e\rho\omega)$. Here we present a set of simple formulae extracted from [21–23]:

The field gain length:	$L_{\rm g} \sim \frac{\lambda_{\rm w}}{4\pi\rho}$
Saturation length:	$L_{\rm sat} \sim \frac{\lambda_{\rm w}}{4\pi\rho} \left[3 + \frac{\ln N_{\rm c}}{\sqrt{3}}\right]$
Saturation efficiency	ρ
The power gain at saturation:	$G \simeq \frac{1}{3} N_{\rm c} \sqrt{\pi \ln N_{\rm c}}$
Effective power of shot noise	$\frac{P_{\rm sh}}{\rho P_{\rm b}} \simeq \frac{3}{N_{\rm c}\sqrt{\pi \ln N_{\rm c}}}$
Coherence time at saturation:	$\tau_{\rm c} \simeq \frac{1}{\rho\omega} \sqrt{\frac{\pi \ln N_{\rm c}}{18}}$
Spectrum bandwidth:	$\sigma_\omega = \sqrt{\pi}/\tau_{\rm c}$

In many cases this set of formulas can help quickly estimate main parameters of a SASE FEL but it does not provide complete self-consistent basis for optimization of this device.

2.3 *Higher harmonics*

Radiation of SASE FEL operating in the saturation regime contains contribution of higher harmonics. In the case of cold electron beam relative contributions of the higher odd harmonics to the FEL power are functions of the only undulator parameter K [24]:

$$\frac{\langle W_3 \rangle}{\langle W_1 \rangle}|_{\rm sat} = 0.094 \times \frac{K_3^2}{K_1^2} \, , \qquad \frac{\langle W_5 \rangle}{\langle W_1 \rangle}|_{\rm sat} = 0.03 \times \frac{K_5^2}{K_1^2} \, . \tag{10}$$

Here $K_h = [J_{(h-1)/2}(Q) - J_{(h+1)/2}(Q)]$, $Q = hK^2/[2(1 + K^2)]$, and h is an odd integer.

Power of the higher harmonics is subjected to larger fluctuations than the power of the fundamental harmonic. The coherence time in the saturation scales inversely proportional to the harmonic number, while relative spectrum bandwidth does not depend on the harmonic number.

The energy spread in the electron beam suppresses power of the higher harmonics. In the framework of the one-dimensional theory power of this effect is described with the energy spread parameter $\hat{\Lambda}_{\rm T}^2 = \langle (\Delta E)^2 \rangle / (\rho E_0)^2$ [21]. Here $\langle (\Delta E)^2 \rangle$ is the rms energy spread, and $E_0 = \gamma mc^2$ is nominal energy of electrons. The result given by (10) is generalized to the case of finite energy spread with the plot presented in Fig. 3. Within practical range of $\hat{\Lambda}_{\rm T}^2$ this suppression can be about a factor of 3 for the 3rd harmonic, and about an order of magnitude for the 5th harmonic. An estimate describing contribution of the energy spread and emittance can be done in terms of an effective energy spread $\langle (\Delta E)^2 \rangle_{\rm eff} / E_0^2 = \langle (\Delta E)^2 \rangle / E_0^2 + 2\gamma_z^4 \epsilon^2 / \beta^2$, where γ_z is longitudinal relativistic factor ($\gamma_z^2 = \gamma^2 / (1 + K^2)$). The plot in Fig. 3 covers practical range of parameters for X-ray FELs. The saturation length at $\hat{\Lambda}_{\rm T}^2 = 0.5$ is increased by a factor of 1.5 with respect to the ”cold” beam case $\hat{\Lambda}_{\rm T}^2 = 0$.

Contribution of even harmonics is pretty much dependent on tuning of the machine. In an ideal case it is expected to be very small [25]. For ”reasonably good” tuning the intensity of the 2nd harmonic can be by an order of magnitude below the intensity of the 3rd harmonic [4, 26].

3 Baseline parameters of the electron beam and undulator

Baseline option of the European XFEL assumed operation at a fixed charge of 1 nC, peak beam current 5 kA, normalized rms emittance 1.4 mm-mrad, rms energy

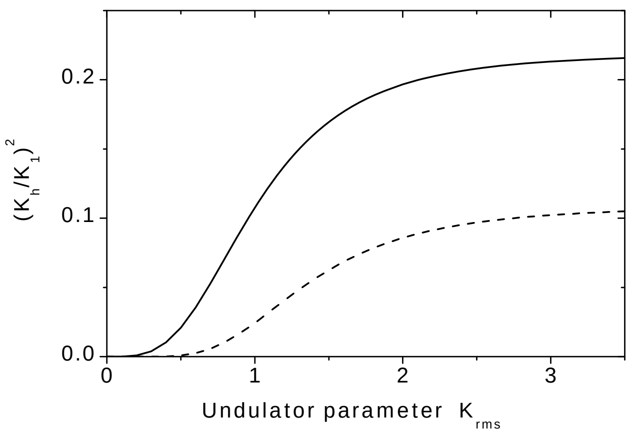

Fig. 2. Ratio of coupling factors, $(K_h/K_1)^2$, for the 3rd (solid line) and the 5th (dashed line) harmonics with respect the fundamental harmonic versus rms value of undulator parameter K_{rms}.

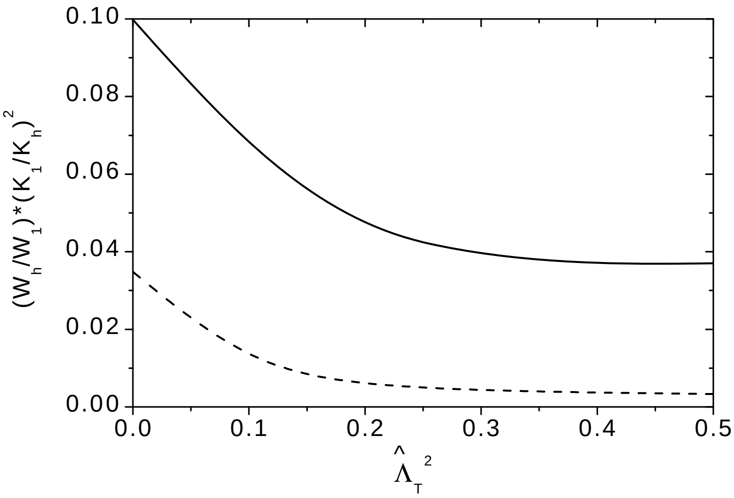

Fig. 3. Normalized power ratio at saturation, $(W_h/W_1) \times (K_1/K_h)^2$, for the 3rd (solid line) and 5th (dashed line) harmonic as a function of energy spread parameter $\hat{\Lambda}_{\mathrm{T}}^2$. SASE FEL operates at saturation.

spread 1 MeV, rms pulse duration 80 fs [3]. First revision of the baseline parameters has been performed in April 2010 by W. Decking, M. Dohlus, T. Limberg, and I. Zagorodnov. Table 8 presents an approximation of the results of start-to-end-simulation of the beam in terms of gaussian beam having the same FWHM duration as lasing fraction of simulated beam. Inconsistency of rms bunch charge, peak current, and rms pulse width is resolved by the prsence of non-gaussian tails (about 20% of the bunch charge) do not contribute to the lasing process. Relevant overview of the photon beam properties has been presented in [11]. Next iteration of the parameter revision has been performed in the end of 2010 (see Table 9). Difference with previous iteration was application of optimized compression scheme while initial parameters of the electron beam from the gun were the same. In some sense parameters of April, 2010 and December, 2010 present two possible realization of the beam formation system, and both can be realized in practice. Note that simplified model of the electron bunch presented in Table 9 predicts only natural FEL bandwidth of the radiation ignoring chirp of energy in the electron beam. Full output of start-to-end simulations can be found on the web page of the Beam Dynamics Group [12]. Results of FEL simulations in selected points using these raw data are presented there as well.

In the end of 2010 it has been decided to change period length of SASE1 and SASE2 undulators. Now both undulators have the same period length of 4 cm and the same total magnetic length 165 m. Baseline option of SASE3 assumed helical device [3]. Present start-up scenario of the European XFEL assumes planar option for SASE3 with period length of 6.8 cm and magnetic length 105 m.

Scenario of FEL operation presented in the XFEL TDR 2006 assumed opera-

Table 8
Properties of the electron beam at the undulator entrance
(April 2010 revision [9])

Bunch charge	nC	0.1	0.25	0.5	1
Peak beam current	A	2500	3000	4000	5000
Normalized rms emittance	mm-mrad	0.42	0.6	0.77	1.05
rms energy spread	MeV	2.9	2.6	2.3	2
rms pulse duration	fs	12	25	40	60

Table 9
Properties of the electron beam at the undulator entrance
(December 2010 revision [14])

Bunch charge	nC	0.02	0.1	0.25	0.5	1
Peak beam current	kA	4.5	5	5	5	5
Normalized rms emittance	mm-mrad	0.32	0.39	0.6	0.7	0.97
rms energy spread	MeV	4.1	2.9	2.5	2.2	2
rms pulse duration	fs	1.2	6.4	16.6	30.6	76.6

Table 10
Undulators at the European XFEL
(December 2010 revision [13])

	Units	SASE1 SASE2	SASE3
Period length	cm	4	6.8
Minimum gap	cm	1	1
Maximum peak field	T	1.2	1.7
Total magnetic length	m	175	105

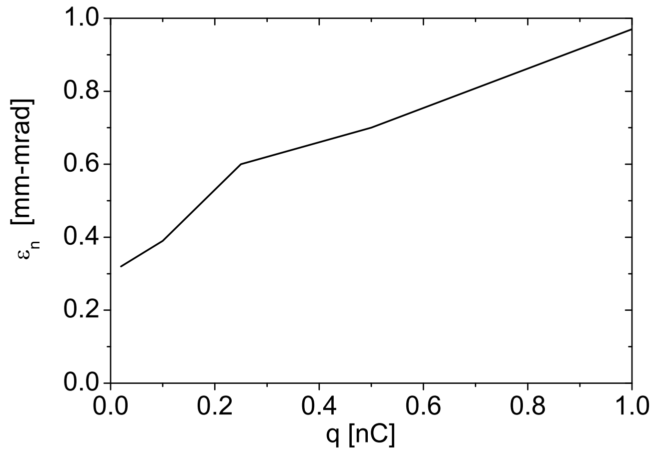

Fig. 4. Normalized rms emittance versus bunch charge for baseline parameters of the electron beam (December 2010 revision).

tion at a fixed energy of electrons of 17.5 GeV. SASE1 assumed to operate around 0.1 nm wavelength. Wavelength ranges 0.1 - 0.4 nm and 0.4 -1.6 nm covered by means of appropriate tuning of the undulator gap of SASE2 and SASE3, respectively. Present day scenario of the EXFEL operation assumes additionally covering of the extended wavelength range by means of changing the energy of electrons. Therefore, three electron energies are fixed for this purpose: 17.5 GeV, 14 GeV, and 10.5 GeV [13].

4 Operation of SASE1 (SASE2)

In the following we describe operation of the European XFEL driven by the electron beam with new baseline parameters presented in Table 9. Period of the undulator is equal to 4 cm for SASE1 (SASE2), and it is 6.8 cm for SASE3 [13]. An overview of the radiation properties covers operation of SASE FELs at three electron energies of 10.5 GeV, 14 GeV, and 17.5 GeV. Parameters of SASE FELs are optimized for minimum gain length which is provided by an appropriate choice of the focusing beta function. Minimum value of the beta function is set to 15 meters. In the parameter range of the European XFEL this situation always happens for SASE3, and for long wavelengths above 0.2 nm for SASE1 (SASE2) (see Fig. A.3).

We start with description of general features of amplification process using as an example SASE1 (SASE2) operating with bunch charge 250 pC and radiation wavelength 0.1 nm and 0.15 nm. Electron energy is 14 GeV. Figure 5 show evolution of the radiation pulse energy along the undulator. The radiation pulse energy grows continuously with the undulator length. Other characteristics of the radiation evolve with the undulator length as well. An example here is behavior of the spot size of the radiation and angular divergence of the radiation (see Fig. 6). The value of peak brilliance reaches its maximum value at the saturation point shown by circles in Fig. 5. Reduction of the radiation wavelength leads to an increase of the saturation length. (see Fig. A.4). Available undulator length defines minimum achievable radiation wavelength. This quantity calculated for the undulator length of 165 meters is shown in Fig. A.2. Saturation length is also increased with the value of the bunch charge (due to larger value of emittance for higher bunch charges).

Figures 7 and 8 show temporal structure of the radiation pulse in the saturation regime. Radiation pulse consists of large number of wavepackets (spikes) having typical pulse duration of about coherence length. Total FWHM radiation pulse duration is defined by the lasing fraction of the electron pulse, and is increasing with the bunch charge (see Fig. A.1). Figure 8 presents spectral structure of the radiation pulse. Single shot spectrum consists of spikes with typical width of the spike in spectrum inversely proportional to the pulse duration. We present in Fig. 9 distributions of the radiation intensity in the near and far zone.

In sections A and C we present main characteristics of SASE1 (SASE2) operating in the saturation regime. An overview of parameter space is performed in graphical form, and detailed characteristics are compiled in a set of tables. Tables also contain properties of the 3rd and the 5th harmonic which are of practical interest. General parameters of incoherent radiation are included in the tables as well. Averaged characteristics were calculated for the following pulse pattern: macropulse repetition rate 10 Hz, macropulse duration 600 μs, and micropulse repetition rate 4.5 MHz (27000 pulses per second). To give easier guide we present main saturation characteristics in the form of plots in Figs. A.1 - 10. Red dashed line presents characteristics corresponding to the minimum radiation wavelength defined by the undulator length of 165 meters. Horizontal axis on these plots is operating bunch charge, and vertical axis is radiation wavelength. The value of the operating bunch charge defines all slice characteristics of the electron beam in agreement with Table 9. Radiation pulse length in the saturation regime is defined by the electron pulse length which is also function of the bunch charge (see Fig. A.1).

Figure A.2 shows minimum wavelength of SASE1 (SASE2) versus bunch charge for three different operating energies 10.5 GeV, 14 GeV, and 17.5 GeV. Minimum wavelength is defined by the condition of the saturation at the undulator length of 165 meters. Safe operation at 0.1 nm wavelength can be achieved in the whole operating range of electron energies an bunch charges. Shorter wavelengths can be achieved at higher beam energies and smaller bunch charges. Operation of SASE1 (SASE2) at the energy 17.5 GeV allows FEL saturation at the wavelength of 0.05 nm almost for all charges.

With given parameters of the electron beam, tuning of the amplification process to the maximum gain is performed by means of an appropriate choice of focusing beta function. Contour plots presented in Fig. A.3 give an overview of required values of external focusing. A limit for minimum beta function is set to 15 meters. Larger values of beta function are required for effective operation at shorter wavelengths. Parameter space with beta function larger than 15 meters is described well as an optimized XFEL (See section 2.1).

Plots for saturation length are presented in Fig. A.4. As we already mentioned, saturation at shorter wavelength can be achieved in a longer undulator. Saturation at longer wavelengths is achieved at shorter undulator length. It is foreseen that an extra undulator length can be used in several ways: for obtaining higher radiation power with undulator tapering, or multi-color mode of operation [3, 28–30].

Tabulated properties of SASE1 (SASE2) are presented in Tables C1-C14, and graphical overview of main characteristics of SASE1 (SASE2) operating in the saturation regime are presented in Section A:

- Radiation pulse duration (Fig. A.1);
- Minimum radiation wavelength (Fig. A.2);
- Optimum focusing beta function (Fig. A.3);
- Saturation length (Fig. A.4);
- Peak radiation power (Fig. A.5);
- Peak brilliance (Fig. A.6);
- Average brilliance (Fig. A.7);
- Energy in the radiation pulse (Fig. A.8);
- Number of photons per pulse (Fig. A.9);
- Average photon flux (Fig. A.10);
- Angular divergence of the radiation (Fig. A.11);
- Spot size of the radiation source (Fig. A.12);
- Coherence time (Fig. A.13);
- Spectrum width (Fig. A.14);
- Degree of transverse coherence (Fig. A.15);
- SASE induced energy spread (Fig. A.16).

We will not describe all plots and tables, assuming that potential users will find all essential information there. We would like to make several notes only.

For experiments relying on a high degree of transverse coherence it is important to remember that SASE FEL does not provide complete transverse coherence (Fig. A.15) [16–18]. For an optimized x-ray FEL it is defined by the quantity $\hat{\epsilon} = 2\pi\epsilon/\lambda$, and higher degree of transverse coherence is achieved at higher electron energies. For instance, saturation at 0.1 nm is available at 10.5 GeV. However, degree of transverse coherence is less than 50% for bunch charge 1 nC.

Another remark refers to radiation pulse energies, average photon flux, and average brilliance. Within parameter space of the European XFEL these quantities grow continuously with the bunch charge. Thus, operation at higher charges is preferable mode of operation for ”flux hungry” experiments.

Angular divergence of the radiation is a delicate topic. First we note that these are not static characteristics. Even for perfectly matched electron beam and undulator their values depend on the undulator length. In practical life amplification process is not ideal, and the gain curve is subjected to tuning procedure which may be not reproducible. First visible consequence is change of the radiation intensity which is accompanied by relevant change of the spot size and divergence. This kind of effects has been observed at LCLS and FLASH. There can be another effect related to mismatch of different slice properties of the electron bunch. For instance, this can be spread of trajectories in the different parts of the electron bunch. Angle deviations on a scale of a fraction of coherent angle do not prevent lasing, but lead to an increase of the angular divergence. Our analysis of LCLS operation shows that this is the most probable effect defining increase of the angular divergence up to 50%. Collective effects may disturb electron beam introducing strong energy chirp. A consequence of this effect mat be modification of the beam radiation mode and increase of the angular divergence.

4.1 Electron beam properties at the exit of SASE1 (SASE2)

Electron beam passing undulator emits incoherent radiation. The effects related to this process are energy loss of the electrons, and growth of the energy spread in the electron beam due to quantum nature of incoherent radiation. We find from Tables C1-C14 that an effect of energy loss is a pronouncing one, and undulator tapering should be applied to compensate it. An effect of quantum diffusion is not negligible as well. Maximum values 35.8 MeV for energy loss and 2.9 MeV for rms energy spread occur at maximum energy of 17.5 GeV and minimum undulator gap.

When FEL amplification process enters nonlinear stage, electrons start to loose energy, and energy spread in the electron beam grows as well. Figure 10 illustrate this process for the case of electron energy of 14 GeV and radiation wavelength 0.1 nm. We see that electron beam heats up considerably with respect to initial energy spread (see Table 9). and with respect to the growth of the energy spread due to quantum fluctuations of incoherent radiation (0.9 MeV in this case). Figure A.16 presents plots for energy spread in the electron beam for SASE1 (SASE2) operating in the saturation versus bunch charge and operating wavelength. Value of FEL induced energy spread is important for operation of SASE3 as an afterburner using spent electron beam from SASE1.

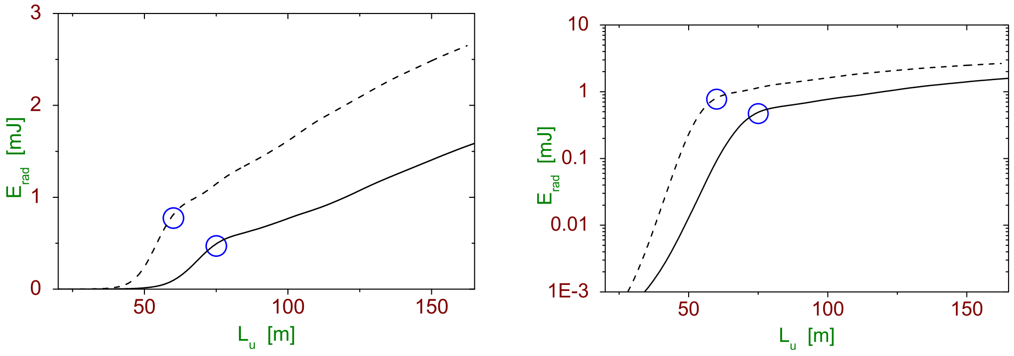

Fig. 5. Energy in the radiation pulse for SASE1 (SASE2) versus undulator length. Electron energy is 14 GeV, bunch charge is 250 pC. Solid curve and dashed curve refer to the case of 0.1 nm and 0.15 nm radiation wavelength, respectively. Circles show saturation point. Left plot: linear scale. Right plot: logarithmic scale.

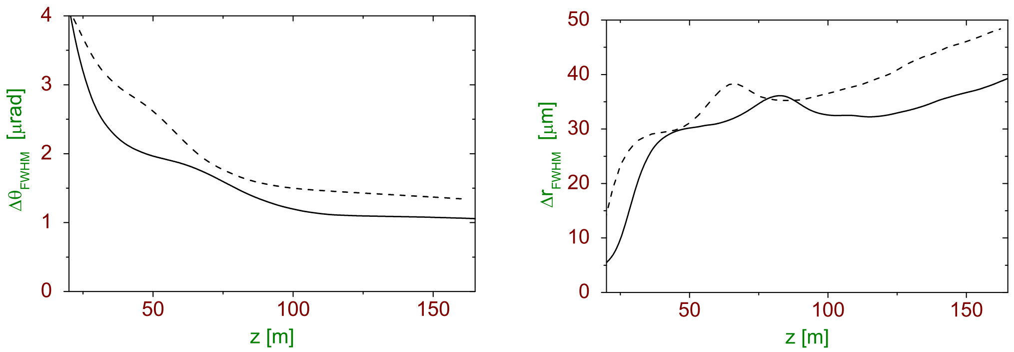

Fig. 6. Radiation spot size (right plot) and angular divergence of the radiation for SASE1 (SASE2) versus undulator length. Electron energy is 14 GeV, bunch charge is 250 pC. Solid curve and dashed curve refer to the case of 0.1 nm and 0.15 nm radiation wavelength, respectively.

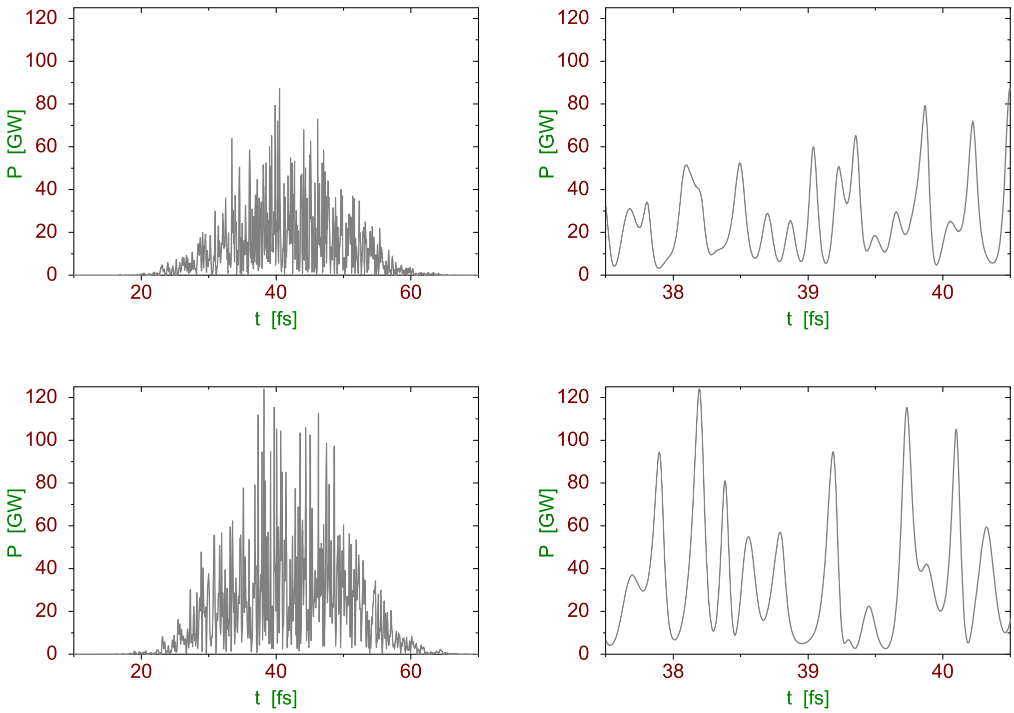

Fig. 7. Temporal structure of the radiation pulse from SASE1 (SASE2). Electron energy is 14 GeV, bunch charge is 250 pC. Top and bottom plots refer to the case of 0.1 nm and 0.15 nm radiation wavelength, respectively. SASE FEL operates in the saturation.

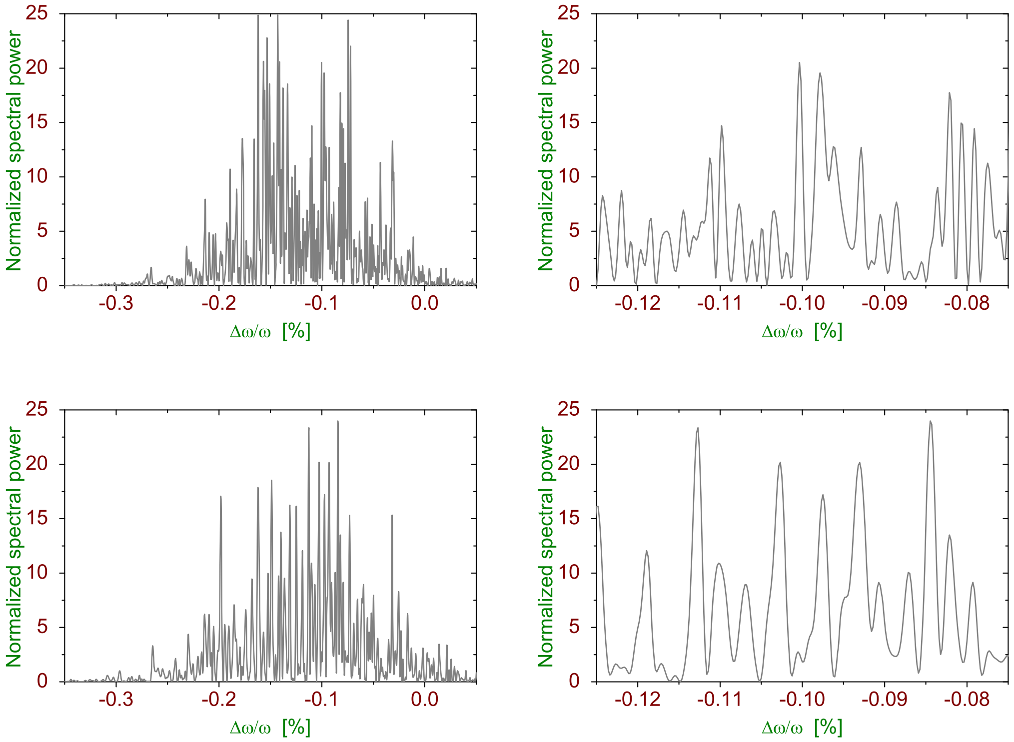

Fig. 8. Spectral structure of the radiation pulse from SASE1 (SASE2). Electron energy is 14 GeV, bunch charge is 250 pC. Top and bottom plots refer to the case of 0.1 nm and 0.15 nm radiation wavelength, respectively. SASE FEL operates in the saturation.

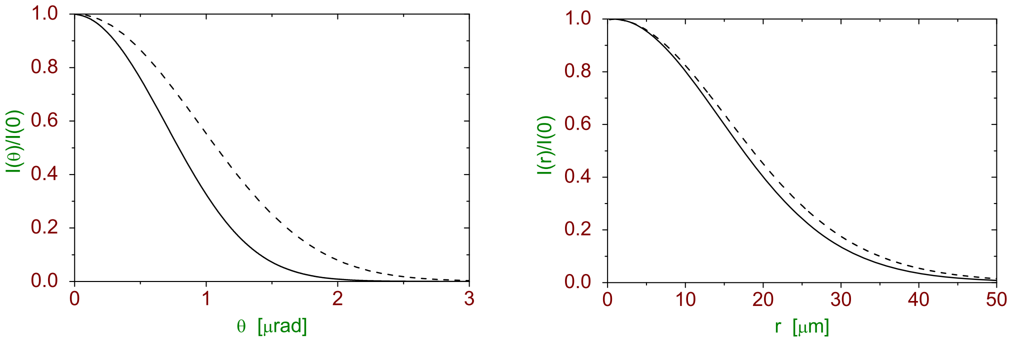

Fig. 9. Distribution of the radiation intensity in the far zone (left plot) and near zone (right plot). from SASE1 (SASE2). Electron energy is 14 GeV, bunch charge is 250 pC. Solid curve and dashed curve refer to the case of 0.1 nm and 0.15 nm radiation wavelength, respectively. SASE FEL operates in the saturation.

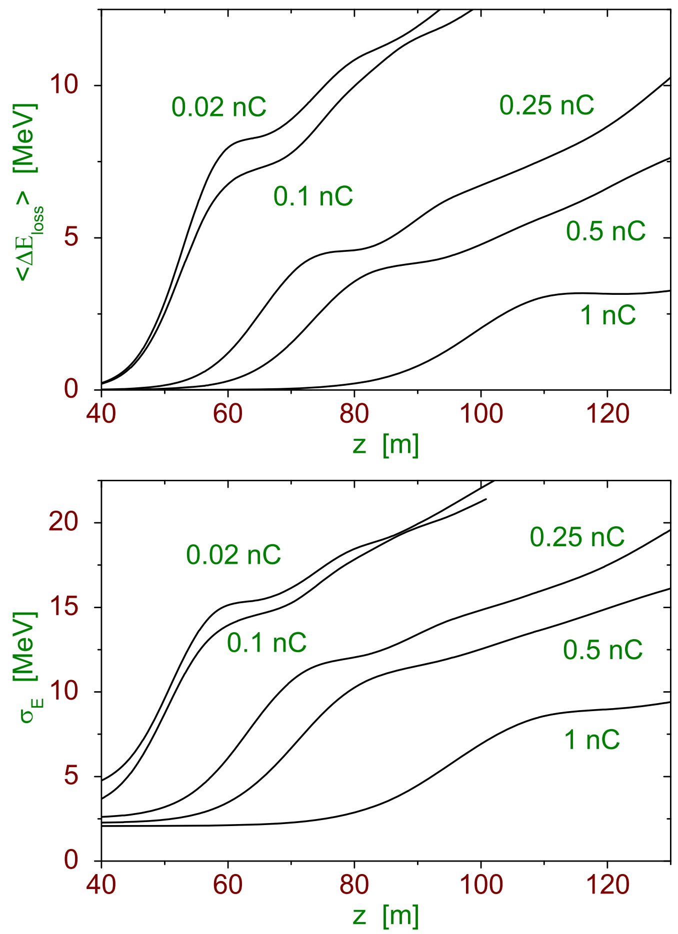

Fig. 10. Energy loss (top) and rms energy spread in the electron beam for SASE1 (SASE2) versus undulator length. Electron energy is equal to 14 GeV, radiation wavelength is 0.1 nm. Parameters of the electron beam are presented in Table 9. Focusing beta function is optimized for minimum gain length (see Fig. A.3).

5 Operation of SASE3

Period length of SASE3 undulator is equal to 6.8 cm, magnetic length of the undulator is equal to 105 m. If we consider baseline parameters of the electron beam only, we find that undulator length is much larger than the saturation length at the shortest wavelength (0.4 nm at the electron energy of 17.5 GeV). However, the choice of the undulator length has been defined by additional considerations aiming in extension of user capabilities. The first perspective option is operation of SASE3 as an afterburner using spent electron beam from SASE1. This will allow to organize simultaneous operation f users at SAS1 and SASE3 beamlines. Second, with extra undulator length we can organize undulator tapering. This will allow to increase significantly radiation pulse energy (photon flux). A long undulator with tunable gap may be used for generation of several wavelengths with an application of betatron switcher technique proposed in [29]. This scheme is realized with installation of a fast kicker in front of the undulator to give different angular kicks to different groups of bunches (a bunch pattern for each group is defined by users requests). For every group a kick is compensated statically at one location in the undulator by moving transversely a quadrupole, i.e. by using it as a steerer. After that location the bunches of this group go straight and lase to saturation in a part of an undulator (sub-undulator), of which magnetic field is tuned to a desired wavelength (see Fig. 16 for illustration). In other sub-undulators the trajectory of this group strongly deviates from the straight path, and bunches of this group do not lase. In a given sub-undulator only one group of bunches lases to saturation, orbits of other groups are strongly disturbed. So, every group lases in its own sub-undulator, of which magnetic field is tuned to a requested wavelength. A length of a sub-undulator is chosen such that a betatron phase advance per its length is π (or multiple of π) on the one hand, and the length is multiple of a length of an elementary cell on the other hand.

5.1 Operation of SASE3 with fresh electron bunches

We start with illustration of specific numerical example. SASE3 is driven by the electron beam with baseline parameters, i.e. it is assumed that electron beam is not disturbed by FEL interaction in SASE1 undulator. Bunch charge is 250 pC, and electron energy is equal to 14 GeV. We highlight operation of SASE3 for two wavelengths: 0.4nm and 2.5 nm (see Figs. 11 - 15).

Behavior of the gain curves is pretty much similar to that discussed in the previous section for SASE1 (SASE2): exponential growth, saturation, and operation in the nonlinear regime when radiation energy increases along remaining undulator length for the price of brilliance reduction. Higher pulse energies occur at longer wavelengths. Other properties of the radiation are not fixed, but also evolve with the undulator length. An important characteristic here are the radiation spot size and angular divergence of the radiation intensity in the far zone (Figure 12).

Figures 13 - 15 show typical features of the radiation in the saturation regime: temporal and spectral structure of the radiation pulse, and intensity distributions in the near and far zone. Radiation with shorter wavelengths has shorter coherence time and is more collimated, nearly proportional to the wavelength. This happens because of the following reason. Focusing beta function is always equal to 15 meters for SASE3, thus electron beam size in the same as well. Beam radiation mode exhibits relatively weak dependence on the wavelength since SASE3 operates in the regime of diffraction limited beam. Taking into account that phase volume of the radiation is about wavelength, we find that angular divergence of the radiation should grow proportionally to the wavelength.

Complete overview of the radiation properties of SASE3 operating in the saturation regime is presented in Sections B and D.

Tabulated properties of SASE3 are presented in Tables D1-D18, and graphical overview of main characteristics operating in the saturation regime are presented in Section B. Operation of SASE3 driven by ”resh” bunches, i.e. not disturbed by FEL interaction in SASE1 undulator is presented on the plots:

- Minimum radiation wavelength (Fig. B.2);
- Saturation length (Fig. B.3);
- Peak radiation power (Fig. B.4);
- Peak brilliance (Fig. B.5);
- Average brilliance (Fig. B.6);
- Energy in the radiation pulse (Fig. B.7);
- Number of photons per pulse (Fig. B.8);
- Average photon flux (Fig. B.9);
- Angular divergence of the radiation (Fig. B.10);
- Spot size of the radiation source (Fig. B.11);
- Coherence time (Fig. B.12);
- Spectrum width (Fig. B.13).

Note that application of fast kicker for suppression of amplification process in SASE1 provides radical solution for decoupling of operation of SASE1 and SASE3 [29]. A fast kicker is installed in front of the SASE1 undulator. It gives an angular kicks to selected bunches in the train. Thus, these bunches perform betatron oscillations and do not lase in SASE1. A stationary steerer is installed between SASE1 and SASE3 undulators which compensates angular kick of the fast kicker. As a result, these ”fresh” bunches (not disturbed by amplification process in SASE1) produce radiation in SASE3 undulator (see Fig. 16 for illustration).

With new parameter set for the electron beam presented in Table 9 there are a lot of possible tuning of the amplification process in SASE1. Different tuning provide different energy spread in the electron beam as it is illustrated in Fig. A.16. Three options for the electron beam energy are under discussion at the moment: 17.5 GeV, 14 GeV, and 10.5 GeV. Thus, operation of SASE3 as an afterburner becomes to be rather tricky.

Figure B.14 shows the dependence of minimum wavelength in SASE3 on bunch charge and energy spread in the electron beam. We see that minimum wavelength increases with the energy spread in the electron beam. When energy spread in the electron beam exceeds 25 MeV it becomes impossible to reach saturation even at the longest radiation wavelength.

Figure A.16 shows values of the FEL induced energy spread for the case when SASE1 operates in the saturation regime. Induced energy spread is higher for small emittances (small charges). Comparison with Fig. B.14 tells us that simultaneous operation of SASE1 and SASE3 at small charges becomes impossible when radiation wavelength exceeds 0.12 nm, 0.15 nm, and 0.17 nm at the electron energy 17.5 GeV, 14 GeV, and 10.5 GeV, respectively. However, some window of operating wavelengths remains at higher charges. When process of amplification in SASE1 enters deep nonlinear regime, energy spread grows with the growth of the radiation power. To study parameter range of SASE3 as an afterburner, we fixed two charges 0.25 nC and 1 nC. We consider three power levels of SASE1 in terms of saturation power: P_{sat}, $1.5 \times P_{\mathrm{sat}}$, and $2 \times P_{\mathrm{sat}}$. Plots defining available operating range of simultaneous operation of SASE1 and SASE3 are presented in Fig. B.15. All wavelengths above relevant curves on the plots are available for operation. Minimum wavelength is defined by the condition of saturation at the length of SASE3 undulator of 100 meters. Operation of SASE1 at the saturation level leaves relatively large area available for simultaneous operation of SASE1 and SASE3. Increase of the pulse energy in SASE1 essentially limits possibilities for simultaneous operation. Degradation of the beam quality in the SASE1 undulator leads to the reduction of the radiation power in the SASE3 undulator. Figures B.16 - B.18 present power levels of SASE3. We see that they remain to be sufficiently high. General rule is very simple. Degradation of the electron beam after SASE1 is less for shorter operating wavelengths and smaller level of the output power in SASE1.

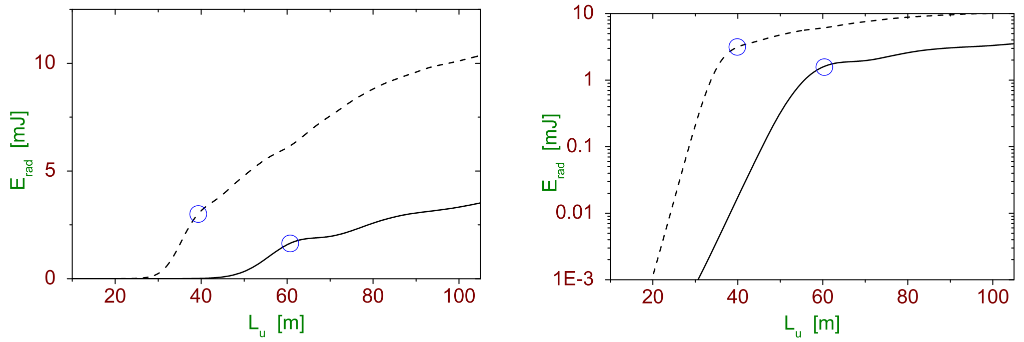

Fig. 11. Energy in the radiation pulse for SASE3 versus undulator length. Electron energy is 14 GeV, bunch charge is 250 pC. Solid curve and dashed curve refer to the case of 0.4 nm and 2.5 nm radiation wavelength, respectively. Circles show saturation point. Left plot: linear scale. Right plot: logarithmic scale.

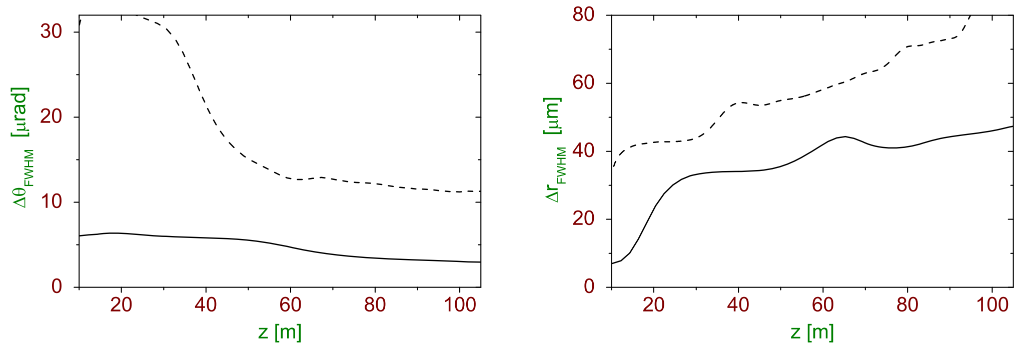

Fig. 12. Radiation spot size (right plot) and angular divergence of the radiation for SASE3 versus undulator length. Electron energy is 14 GeV, bunch charge is 250 pC. Solid curve and dashed curve refer to the case of 0.4 nm and 2.5 nm radiation wavelength, respectively.

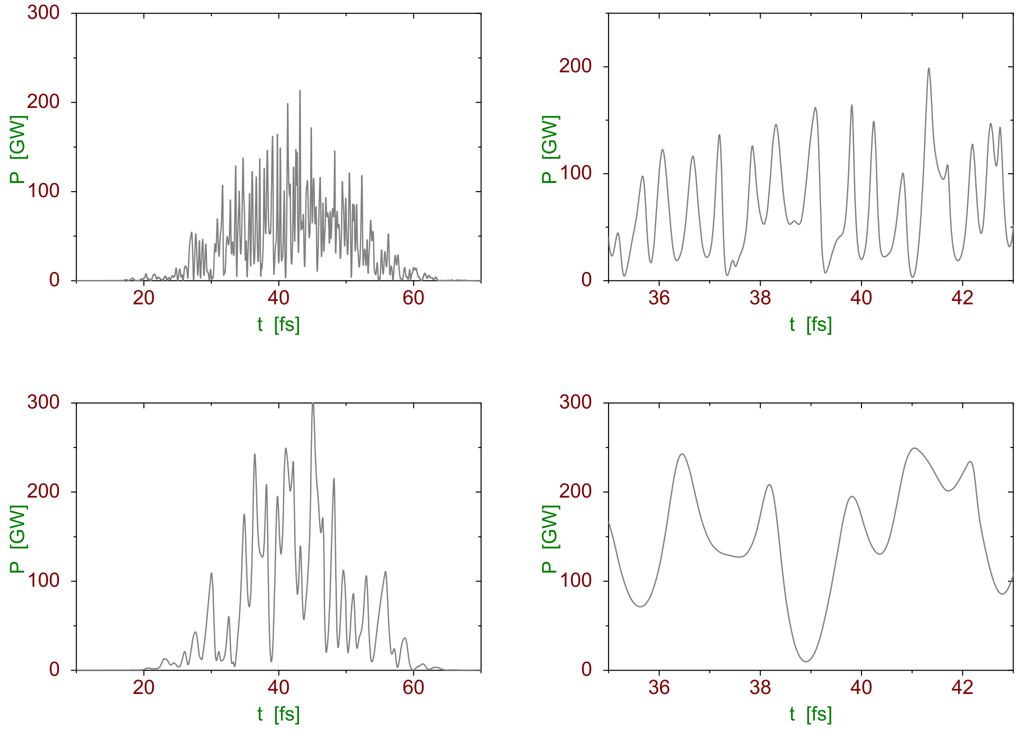

Fig. 13. Temporal structure of the radiation pulse from SASE3. Electron energy is 14 GeV, bunch charge is 250 pC. Top and bottom plots refer to the case of 0.4 nm and 2.5 nm radiation wavelength, respectively. SASE FEL operates in the saturation.

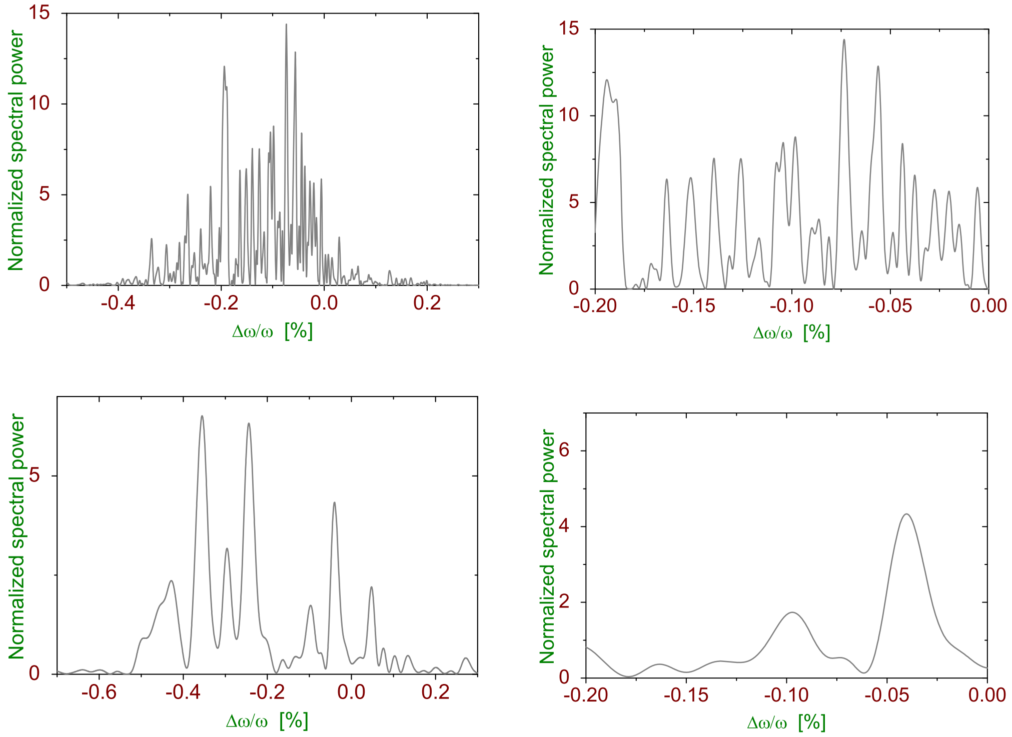

Fig. 14. Spectral structure of the radiation pulse from SASE3. Electron energy is 14 GeV, bunch charge is 250 pC. Top and bottom plots refer to the case of 0.4 nm and 2.5 nm radiation wavelength, respectively. SASE FEL operates in the saturation.

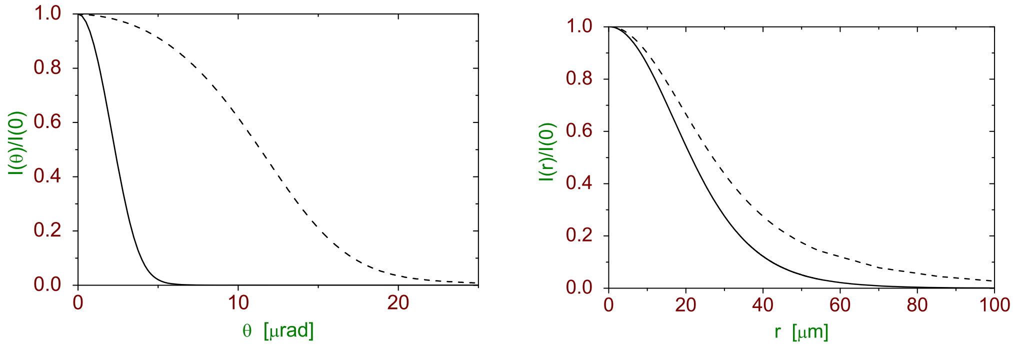

Fig. 15. Distribution of the radiation intensity in the far zone (left plot) and near zone (right plot). from SASE3. Electron energy is 14 GeV, bunch charge is 250 pC. Solid curve and dashed curve refer to the case of 0.4 nm and 2.5 nm radiation wavelength, respectively. SASE FEL operates in the saturation.

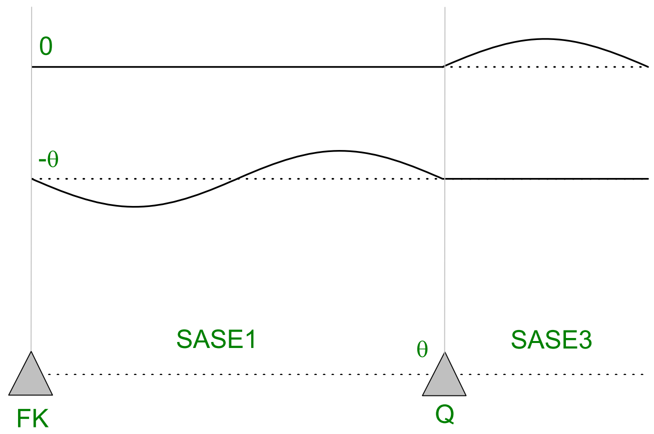

Fig. 16. A schematic illustration of the betatron switcher for decoupling of operation of SASE1 and SASE3. Here ”FK” stands for a fast kicker (giving different kicks to selected bunches) and ”Q” for a quadrupole or a static steer (giving the same static kick to all bunches). Lasing to saturation takes place only on straight sections of beam orbit. Bunches not disturbed by fast kicker lase only in SASE1 (top curve), while those deflected by fast kicker lase in SASE3 only (bottom curve).

5.3 An option of high charge operation

In order to explore the high charge option let us perform a brief analysis for the case of the European XFEL keeping the baseline value of the peak beam current of 5 kA fixed and scaling the emittance linearly and as a square root of charge. Operation of SASE FELs in a short (around 0.1 nm) wavelength range is well described with the case of optimized XFEL [16, 18]. In this parameter range the peak power in the saturation regime scales inversely proportional to the emittance. As a result, the radiation pulse energy grows proportionally to $q^{1/2}$. For instance, for SASE1 operating at 0.1 nm wavelength, we expect an increase of the radiation pulse energy by approximately factor of 2 for the 1 nC case with respect to the 0.25 nC case.

The situation changes qualitatively for the case of SASE3 operating at longer wavelengths. Let us consider the case of SASE3 operating at the energy of 17.5 GeV and radiation wavelength 1.6 nm. The undulator period is equal to 6.8 cm, and the undulator length is equal to 100 m. We fix the peak current [1] to 5 kA, change the bunch charge in the range 0.25 nC - 3 nC and assume emittance scaling as $q^{1/2}$ and q as suggested by the measurements. The reference point is a charge of 1 nC and a normalized emittance of 1 mm mrad. The value of the external beta function is equal to 15 m. This range of FEL parameters corresponds to the diffraction limited (thin) electron beam when saturation length and FEL efficiency at saturation slowly evolve with the value of the emittance, in fact - logarithmically [21] (see Fig. 17). As a result, we can expect linear growth of the radiation pulse energy with charge. The results of simulations with the code FAST [19] confirm this simple physical consideration (see Fig. 18). Increase of the bunch charge from 0.25 nC to 3 nC results in an increase of the radiation pulse energy nearly by an order of magnitude. An essential feature of the SASE3 undulator is its extended length for operation as an afterburner of the electron beam used in the SASE1 undulator. This extra undulator length can be effectively used for the undulator tapering and increases the FEL efficiency when operating with ”fresh” electron bunches not disturbed in

[1] We did that for simplicity. Actually, one can compress bunches with higher charges to larger values of the peak current, thus reaching higher FEL pulse energies, especially with undulator tapering. For example, an increase of the peak current from 5 kA to 7.5 kA results in the increase of the pulse energy by 30 %.
For a given pulse length in the injector and at a given final current the compression factor is smaller for larger charges, so that compression stability is better. Thus, one can increase compression factor and keep good stability of the final current. Concerning CSR (coherent synchrotron radiation) effect in the bunch compressors, it is scaled (in a simple model) as $I/\sigma_z^{1/3}$, i.e. for the same peak current it is weaker for larger charges. Thus, one can increase peak current. Also, CSR-induced emittance growth adds quadratically to the initial emittance from the injector. The latter is larger for higher charges, so that one can allow for a larger CSR-induced part. As a result, one can significantly increase peak current for charges in the range 1-3 nC.

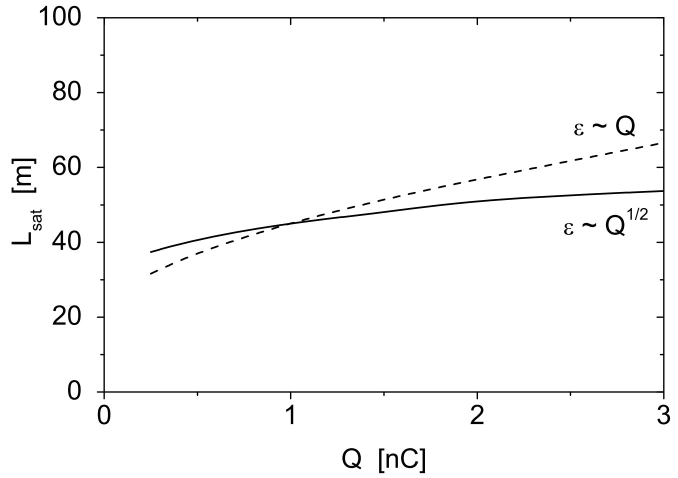

Fig. 17. Saturation length for SASE3 versus bunch charge. Electron energy is 17.5 GeV, radiation wavelength is 1.6 nm. Solid and dashed lines refer to the scaling of the emittance as Solid and dashed lines correspond to the emittance scaling as $q^{1/2}$, and q, respectively.

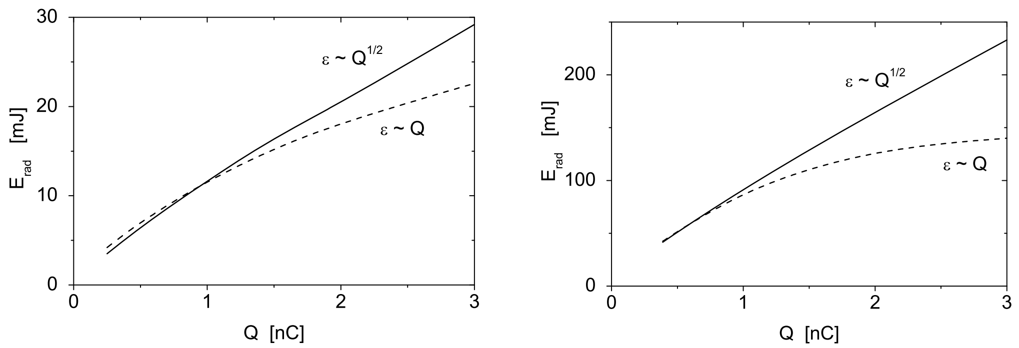

Fig. 18. Energy in the radiation pulse versus bunch charge for SASE3 at the European XFEL. Left plot: FEL operates in the saturation regime. Right plot: operation with tapered parameters for the undulator length of 100 meters. Electron energy is 17.5 GeV, radiation wavelength is 1.6 nm. Solid and dashed lines correspond to the emittance scaling as $q^{1/2}$, and q, respectively.

SASE1. Figure 19 shows evolution of the energy in the radiation pulse for bunch charge of 2 nC. We see from the lower plot in Fig. 18 that pulse energies above 0.2 J can be achieved for $\epsilon_n \propto q^{1/2}$. In any case, even for the unfavorable case of $\epsilon_n \propto q$, we still can expect significant benefit for SASE3 operation with pulse energies about a factor of 2 above the baseline values for a bunch charge of 1 nC.

Recently PITZ performed experiment on production of high charge electron bunches [31, 32]. Experimental results demonstrated good properties of the electron beam in terms of emittance. Within the accuracy of measurements performed at the bunch charge of 2 nC we observe that the scaling of the emittance produced

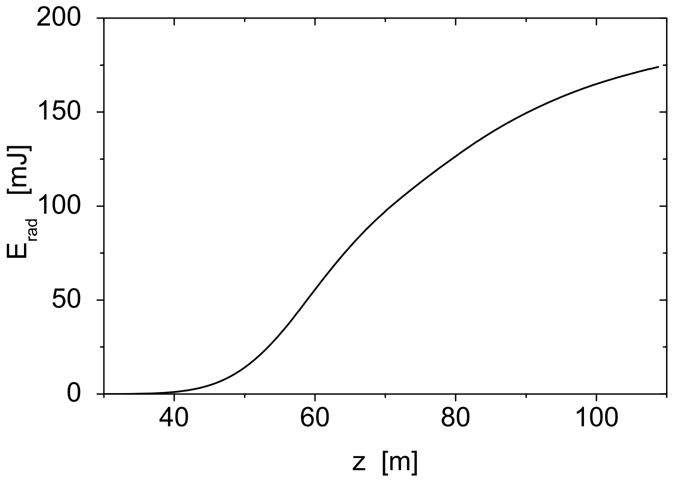

Fig. 19. Energy in the radiation pulse for SASE3 with tapered undulator. Electron energy is 17.5 GeV, radiation wavelength is 1.6 nm, bunch charge is 2 nC, normalized rms emittance is 1.4 mm-mrad, peak beam current is 5 kA.

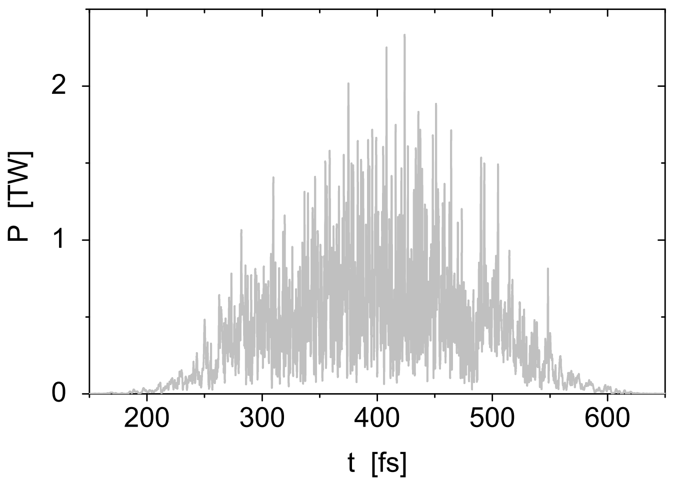

Fig. 20. Temporal structure of the radiation pulse from SASE3 with tapered undulator at the undulator length 100 m. Electron energy is 17.5 GeV, radiation wavelength is 1.6 nm, bunch charge is 2 nC, normalized rms emittance is 1.4 mm-mrad, peak beam current is 5 kA.

by an optimized XFEL gun lies somewhere in-between of linear and square root dependence on charge. A value of 1.4 mm mrad for the normalized emittance at the charge of 2 nC has been used in the simulations. This implies a certain safety margin to the measured values. SASE FEL simulations based on these assumptions for the electron beam demonstrate the possibility to generate very high pulse energies of 0.1 ... 0.2 J and peak powers above 1 TW in the SASE3 undulator (see Fig. 20).

Acknowledgments

Results presented in this report have been discussed at the meetings devoted to revision of parameter space of the European XFEL. We are grateful to our colleagues from DESY and European XFEL for fruitful collaboration during this work: M. Altarelli, C. Bressler, R. Brinkmann, W. Decking, T. Limberg, M. Meyer, S. Molodtsov, J. Pflueger, A. Schwarz, H. Sinn, T. Tschentscher, and H. Weise. We thank our colleagues from the Beam Dynamics Group for providing us with parameters of the electron beam, especially W. Decking, M. Dohlus, T. Limberg, and I. Zagorodnov. We are grateful to M. Krasilnikov and F. Stephan for fruitful collaboration on high charge option. We thank R. Brinkmann for interest in this work and support.

References

[1] P. Emma et al., Nature Photonics, 4, p. 641, 2010.

[2] J. Arthur et al., Linac Coherent Light Source (LCLS), Conceptual Design Report, SLAC-R593 (SLAC, Stanford 2002)
(see also http://www-ssrl.slac.stanford.edu/lcls/cdr).

[3] M. Altarelli et al. (Eds.), XFEL: The European X-Ray Free-Electron Laser. Technical Design Report, Preprint DESY 2006-097, DESY, Hamburg, 2006 (see also http://xfel.desy.de).

[4] W. Ackermann et al., Nature Photonics 1, 336-342 (2007).

[5] S. Rimjaem et al., Proc. IPAC'10 Conference, TUPE011.

[6] S. Rimjaem et al., Proc. FEL 2010 Conference, WEPB09.

[7] I. Zagorodnov and M. Dohlus, Preprint DESY 10-102, DESY, Hamburg, 2010.

[8] I. Zagorodnov, Proc. FEL 2010 Conference, WEOBI2.

[9] Data by T. Limberg and W. Decking by April 12, 2010 present approximation of the results of start-to-end-simulation for lasing fraction of the beam in terms of gaussian beam with uniform along the bunch emittance and energy spread. Inconsistency of rms bunch charge, peak current, and rms pulse width is resolved by an assumption that non-gaussian tails (about 20% of the bunch charge) do not contribute to the lasing process.

[10] I. Zagorodnov: Results and analysis of s2e simulations of the European XFEL are located on web page of the Beam Dynamics Group http://www.desy.de/xfel-beam/s2e.

[11] E.A. Schneidmiller and M.V. Yurkov, DESY Print TESLA FEL 2010-06, DESY, Hamburg, 2010.

[12] Contributions by W. Decking, M. Dohlus, T. Limberg, and I. Zagorodnov. Up-to-date output of start-to-end simulations, talks and reports are located on web page of the Beam Dynamics Group http://www.desy.de/xfel-beam/s2e.

[13] T. Tschentscher, European XFEL Technical Note XFEL.EU TN-2011-001.

[14] Data by T. Limberg and W. Decking by December 20, 2010 present approximation of the results of start-to-end-simulation for lasing fraction of the beam in terms of gaussian beam with uniform along the bunch emittance and energy spread.

[15] E.L. Saldin, E. A. Schneidmiller, and M.V. Yurkov, Opt. Commun. 235(2004)415.

[16] E.L. Saldin, E.A. Schneidmiller, and M.V. Yurkov, Opt. Commun. 281(2008)1179.

[17] E.L. Saldin, E.A. Schneidmiller, and M.V. Yurkov, Opt. Commun. 281(2008)4727.

[18] E.L. Saldin, E.A. Schneidmiller, and M.V. Yurkov, New J. Phys. 12 (2010) 035010.

[19] E.L. Saldin, E.A. Schneidmiller and M.V. Yurkov, Nucl. Instrum. and Methods A 429 (1999) 233.

[20] J. Goodman, Statistical Optics, (John Wiley and Sons, New York, 1985).

[21] E.L. Saldin, E.A. Schneidmiller, M.V. Yurkov, “The Physics of Free Electron Lasers” (Springer-Verlag, Berlin, 1999).

[22] R. Bonifacio, et al., Phys. Rev. Lett. 73(1994)70.

[23] E. L. Saldin, E. A. Schneidmiller, and M. V. Yurkov, Opt. Commun. 148(1998)383.

[24] E.L. Saldin, E.A. Schneidmiller and M.V. Yurkov, Phys. Rev. ST Accel. Beams 9(2006)030702.

[25] G. Geloni, E.L. Saldin, E.A. Schneidmiller and M.V. Yurkov, Optics Communications 271(2007)207.

[26] D. Ratner et al., Phys. Rev. ST Accel. Beams 14 (2011)060701.

[27] R. Bonifacio, C. Pellegrini and L.M. Narducci, Opt. Commun. 50(1984)373.

[28] E.L. Saldin, E.A. Schneidmiller and M.V. Yurkov, DESY Print TESLA FEL 2004-02, DESY, Hamburg, 2004.

[29] R. Brinkmann, E.A. Schneidmiller, M.V. Yurkov, Possible Operation of the European XFEL with Ultra-Low Emittance Beams, Nucl. Instrum. and Methods **A616**(2010)81–87.

[30] G. Geloni, V. Kocharyan, and E.L. Saldin, DESY Print DESY 10-006, DESY, Hamburg, 2010.

[31] S. Rimjaem et al., Emittance for Different Bunch Charges at the Upgraded PITZ Facility, Proc. FEL 2011 Conference (Shanghai, China, 2011), THPA06.

[32] M. Krasilnikov et al., An option of high charge operation for the European XFEL, Proc. FEL 2011 Conference (Shanghai, China, 2011), THPA08.

A Plots of the radiation properties of SASE1 (SASE2) in the saturation regime

In this section we present graphical overview of main characteristics of SASE1 (SASE2) operating in the saturation regime:

- Radiation pulse duration (Fig. A.1);
- Minimum radiation wavelength (Fig. A.2);
- Optimum focusing beta function (Fig. A.3);
- Saturation length (Fig. A.4);
- Peak radiation power (Fig. A.5);
- Peak brilliance (Fig. A.6);
- Average brilliance (Fig. A.7);
- Energy in the radiation pulse (Fig. A.8);
- Number of photons per pulse (Fig. A.9);
- Average photon flux (Fig. A.10);
- Angular divergence of the radiation (Fig. A.11);
- Spot size of the radiation source (Fig. A.12);
- Coherence time (Fig. A.13);
- Spectrum width (Fig. A.14);
- Degree of transverse coherence (Fig. A.15);
- SASE induced energy spread (Fig. A.16).

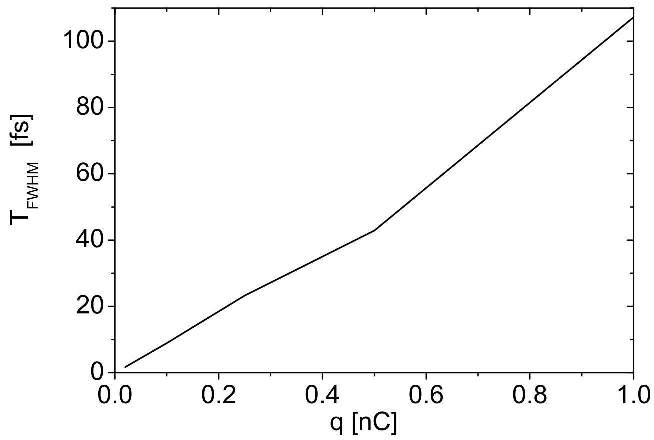

Fig. A.1. FWHM radiation pulse duration in the saturation versus bunch charge for baseline parameters of the electron beam as of December, 2010.

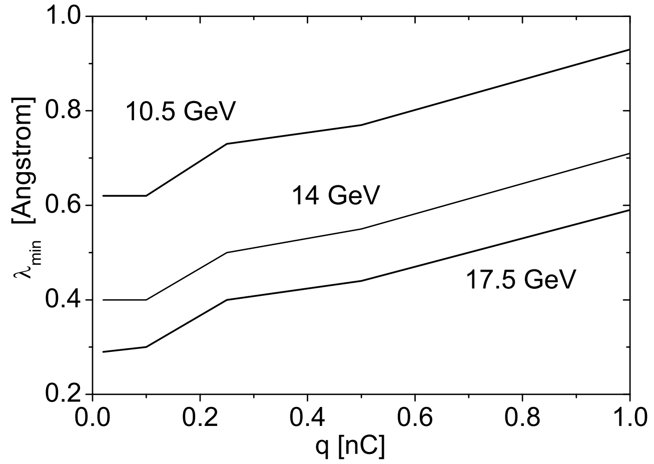

Fig. A.2. Minimum radiation wavelength for SASE1 (SASE2) versus bunch charge for electron energy 10.5 GeV, 14 GeV, and 17.5 GeV. Undulator length is equal to 165 meters.

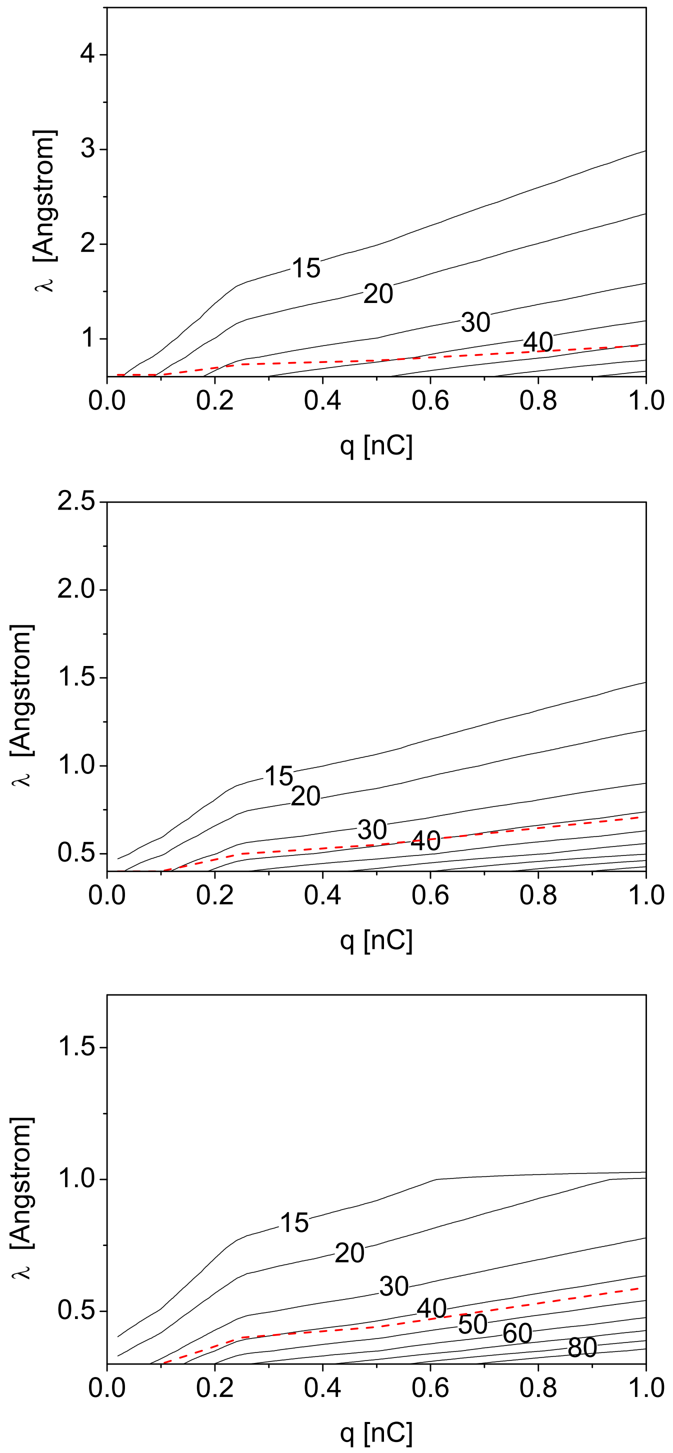

Fig. A.3. Optimum focusing beta function for SASE1 (SASE2) versus bunch charge and operating wavelength. Numbers on contour lines denote units of meters. Top, middle and bottom plots correspond to the electron energy of 10.5 GeV, 14 GeV, and 17.5 GeV, respectively. Red dashed curve shows minimum of the radiation wavelength at the undulator length of 165 m. Parameters of the electron beam are presented in Table 9. Limit for minimum beta function is set to 15 meters.

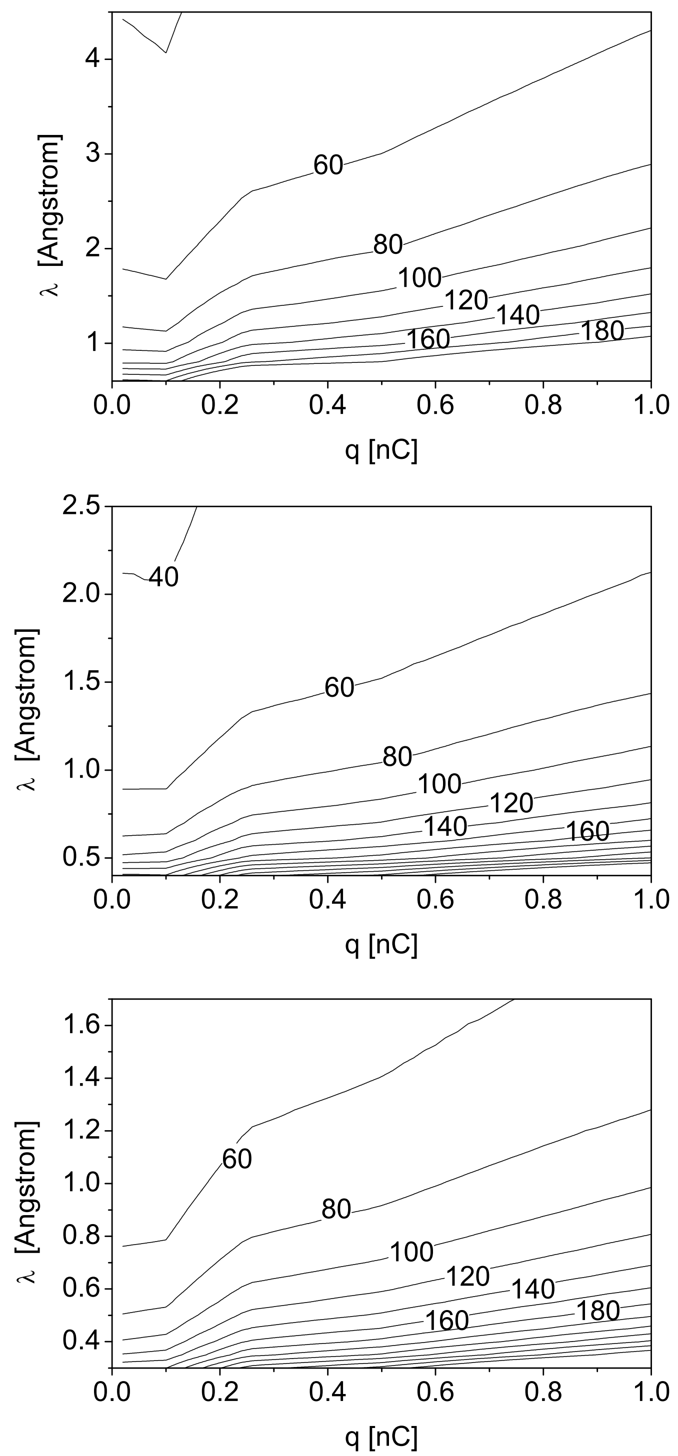

Fig. A.4. Saturation length for SASE1 (SASE2) versus bunch charge and operating wavelength. Numbers on contour lines denote units of meters. Top, middle and bottom plots correspond to the electron energy of 10.5 GeV, 14 GeV, and 17.5 GeV, respectively. Parameters of the electron beam are presented in Table 9. Focusing beta function is optimized for minimum gain length (see Fig. A.3).

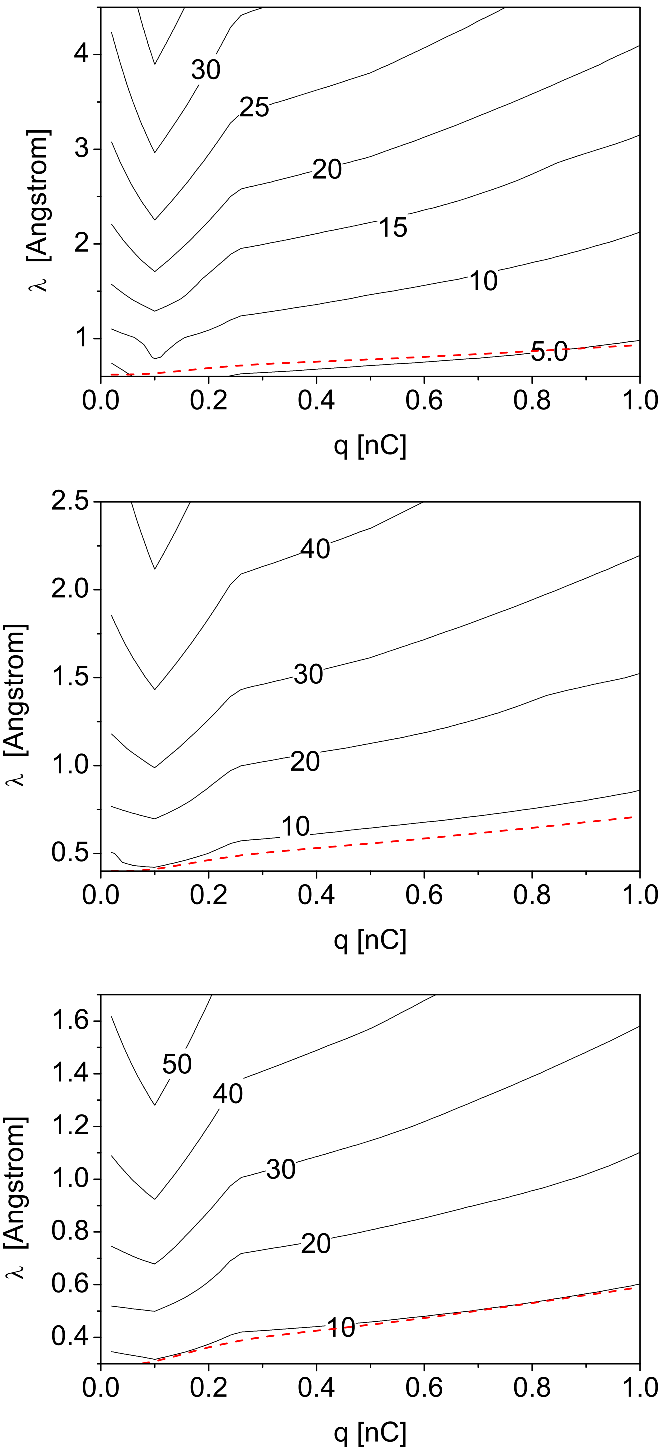

Fig. A.5. Peak radiation power for SASE1 (SASE2) operating in the saturation versus bunch charge and operating wavelength. Numbers on contour lines denote units of MW. Top, middle and bottom plots correspond to the electron energy of 10.5 GeV, 14 GeV, and 17.5 GeV, respectively. Red dashed curve shows minimum of the radiation wavelength at the undulator length of 165 m. Parameters of the electron beam are presented in Table 9. Focusing beta function is optimized for minimum gain length (see Fig. A.3).

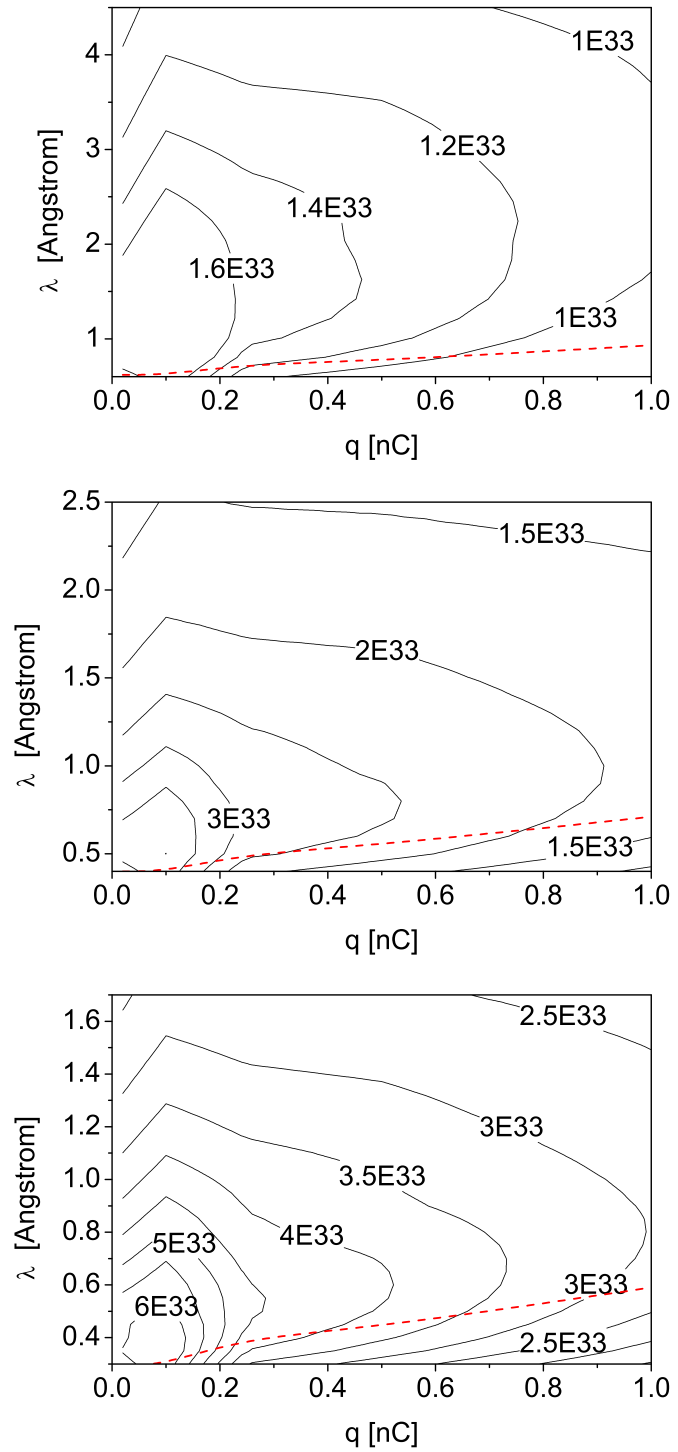

Fig. A.6. Peak brilliance for SASE1 (SASE2) operating in the saturation versus bunch charge and operating wavelength. Numbers on contour lines denote units of photons/sec/mm^2/rad^2/0.1% bandwidth. Top, middle and bottom plots correspond to the electron energy of 10.5 GeV, 14 GeV, and 17.5 GeV, respectively. Red dashed curve shows minimum of the radiation wavelength at the undulator length of 165 m. Parameters of the electron beam are presented in Table 9. Focusing beta function is optimized for minimum gain length (see Fig. A.3).

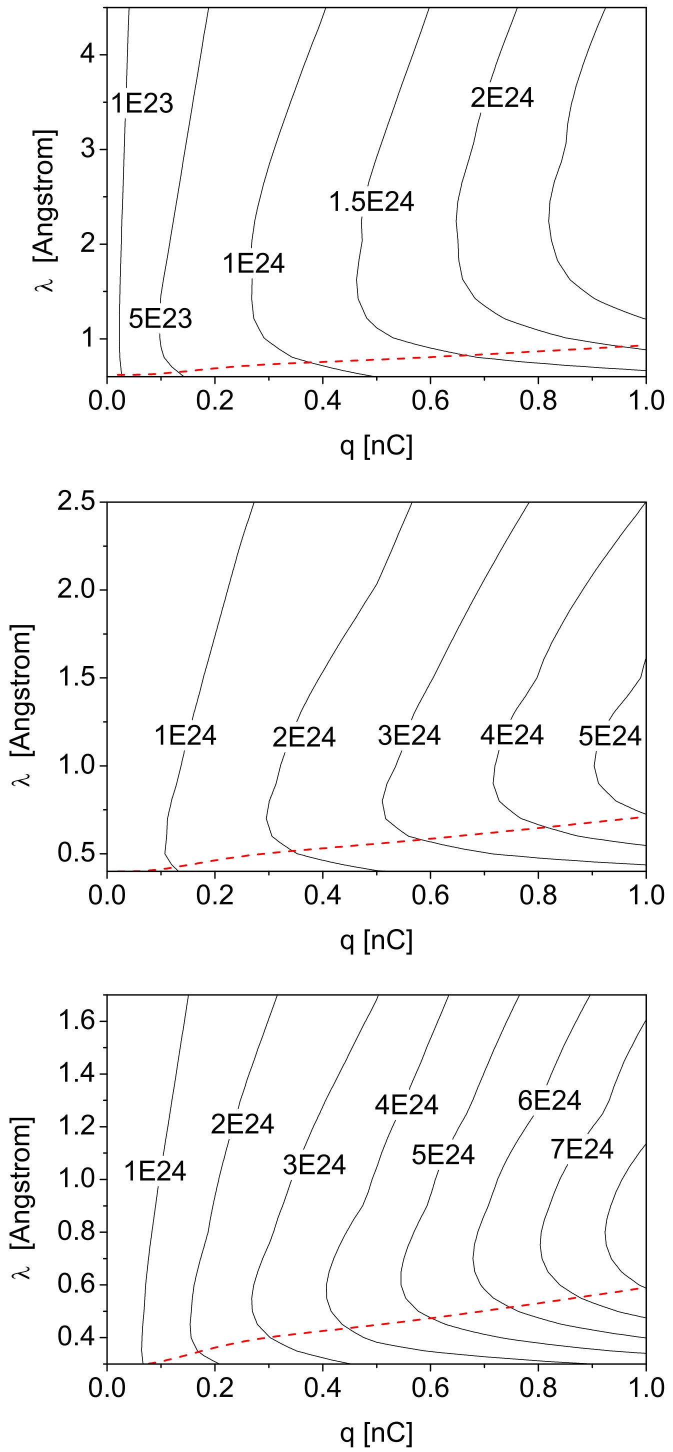

Fig. A.7. Average brilliance for SASE1 (SASE2) operating in the saturation versus bunch charge and operating wavelength. Numbers on contour lines denote units of photons/sec/mm^2/rad^2/0.1% bandwidth. Top, middle and bottom plots correspond to the electron energy of 10.5 GeV, 14 GeV, and 17.5 GeV, respectively. Red dashed curve shows minimum of the radiation wavelength at the undulator length of 165 m. Parameters of the electron beam are presented in Table 9. Focusing beta function is optimized for minimum gain length (see Fig. A.3).

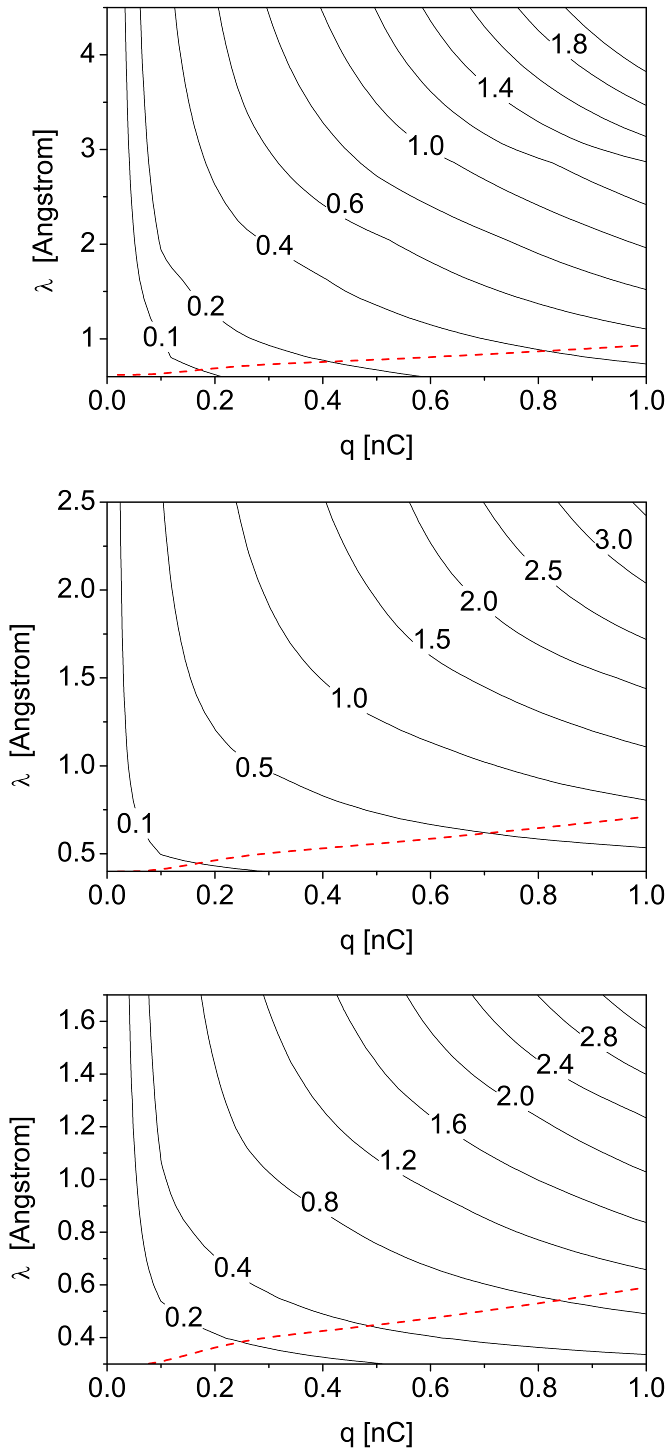

Fig. A.8. Energy in the radiation pulse for SASE1 (SASE2) operating in the saturation versus bunch charge and operating wavelength. Numbers on contour lines denote units of mJ. Top, middle and bottom plots correspond to the electron energy of 10.5 GeV, 14 GeV, and 17.5 GeV, respectively. Red dashed curve shows minimum of the radiation wavelength at the undulator length of 165 m. Parameters of the electron beam are presented in Table 9. Focusing beta function is optimized for minimum gain length (see Fig. A.3).

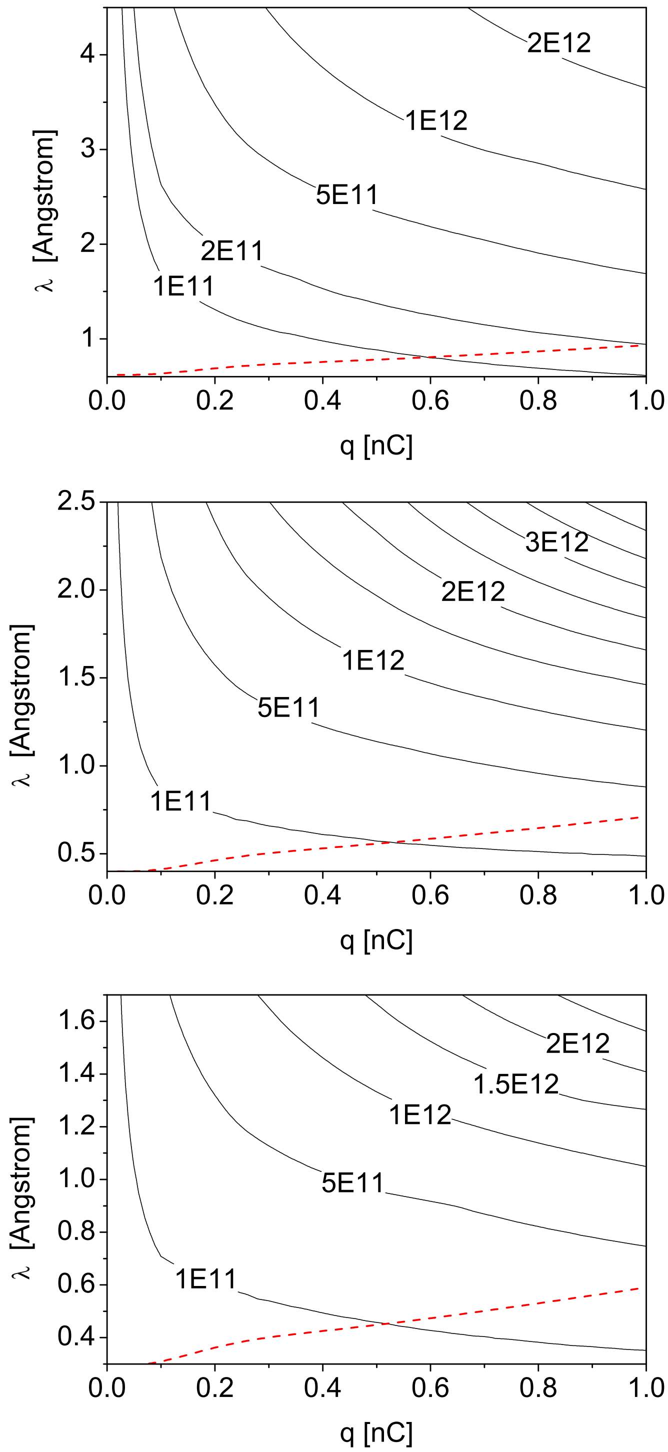

Fig. A.9. Number of photons in the radiation pulse for SASE1 (SASE2) operating in the saturation versus bunch charge and operating wavelength. Numbers on contour lines denote number of photons. Top, middle and bottom plots correspond to the electron energy of 10.5 GeV, 14 GeV, and 17.5 GeV, respectively. Red dashed curve shows minimum of the radiation wavelength at the undulator length of 165 m. Parameters of the electron beam are presented in Table 9. Focusing beta function is optimized for minimum gain length (see Fig. A.3).

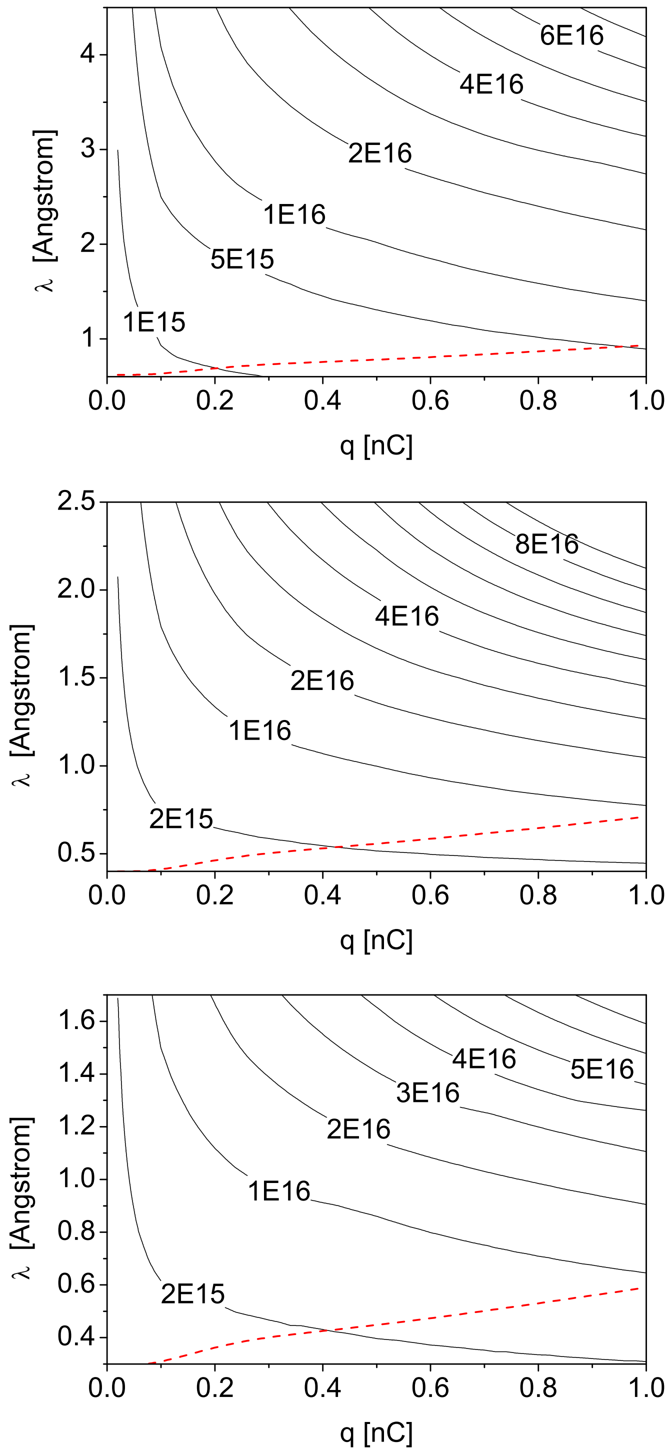

Fig. A.10. Average photon flux for SASE1 (SASE2) operating in the saturation versus bunch charge and operating wavelength. Numbers on contour lines denote number of photons per second. Top, middle and bottom plots correspond to the electron energy of 10.5 GeV, 14 GeV, and 17.5 GeV, respectively. Red dashed curve shows minimum of the radiation wavelength at the undulator length of 165 m. Parameters of the electron beam are presented in Table 9. Focusing beta function is optimized for minimum gain length (see Fig. A.3).

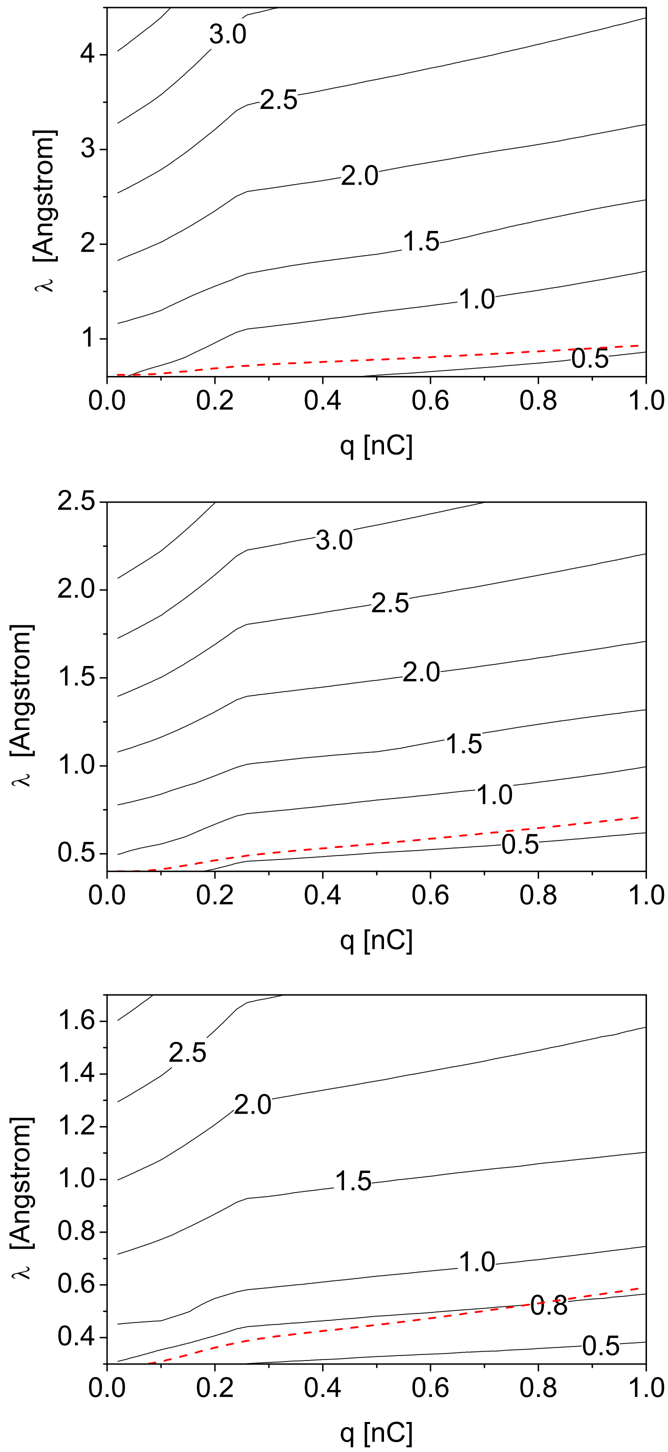

Fig. A.11. FWHM angular divergence of the radiation for SASE1 (SASE2) operating in the saturation versus bunch charge and operating wavelength. Top, middle and bottom plots correspond to the electron energy of 10.5 GeV, 14 GeV, and 17.5 GeV, respectively. Numbers on contour lines denote units of μrad. Red dashed curve shows minimum of the radiation wavelength at the undulator length of 165 m. Parameters of the electron beam are presented in Table 9. Focusing beta function is optimized for minimum gain length (see Fig. A.3).

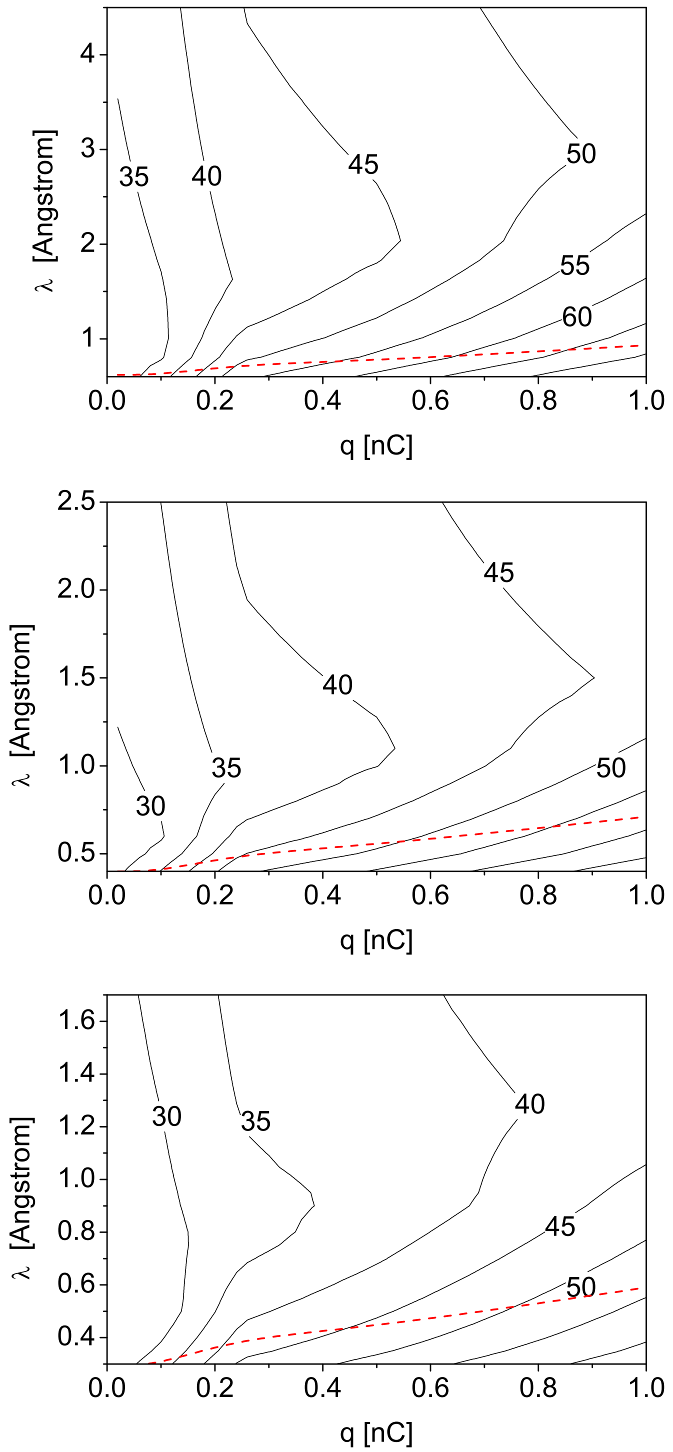

Fig. A.12. FWHM spot size of the radiation for SASE1 (SASE2) operating in the saturation versus bunch charge and operating wavelength. Top, middle and bottom plots correspond to the electron energy of 10.5 GeV, 14 GeV, and 17.5 GeV, respectively. Numbers on contour lines denote units of μm. Red dashed curve shows minimum of the radiation wavelength at the undulator length of 165 m. Parameters of the electron beam are presented in Table 9. Focusing beta function is optimized for minimum gain length (see Fig. A.3).

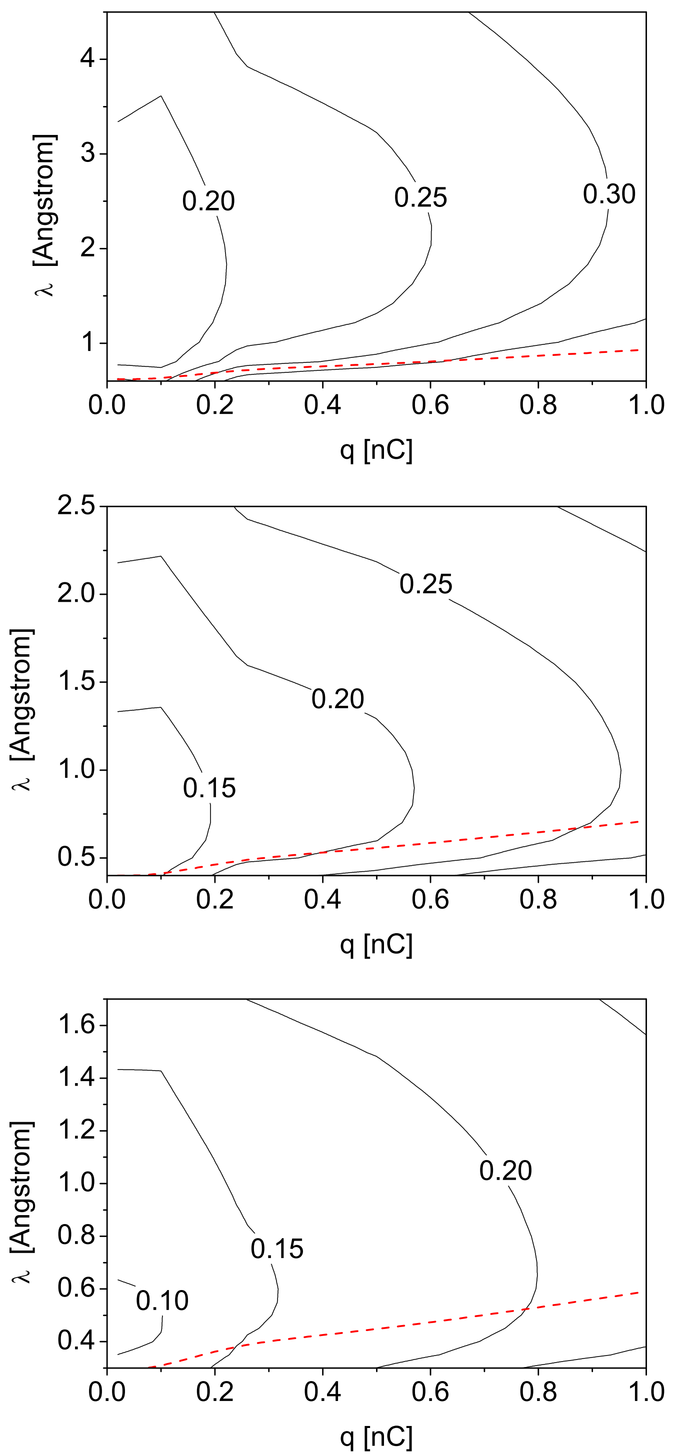

Fig. A.13. Coherence time of the radiation for SASE1 (SASE2) operating in the saturation versus bunch charge and operating wavelength. Top, middle and bottom plots correspond to the electron energy of 10.5 GeV, 14 GeV, and 17.5 GeV, respectively. Numbers on contour lines denote units of fs. Red dashed curve shows minimum of the radiation wavelength at the undulator length of 165 m. Parameters of the electron beam are presented in Table 9. Focusing beta function is optimized for minimum gain length (see Fig. A.3).

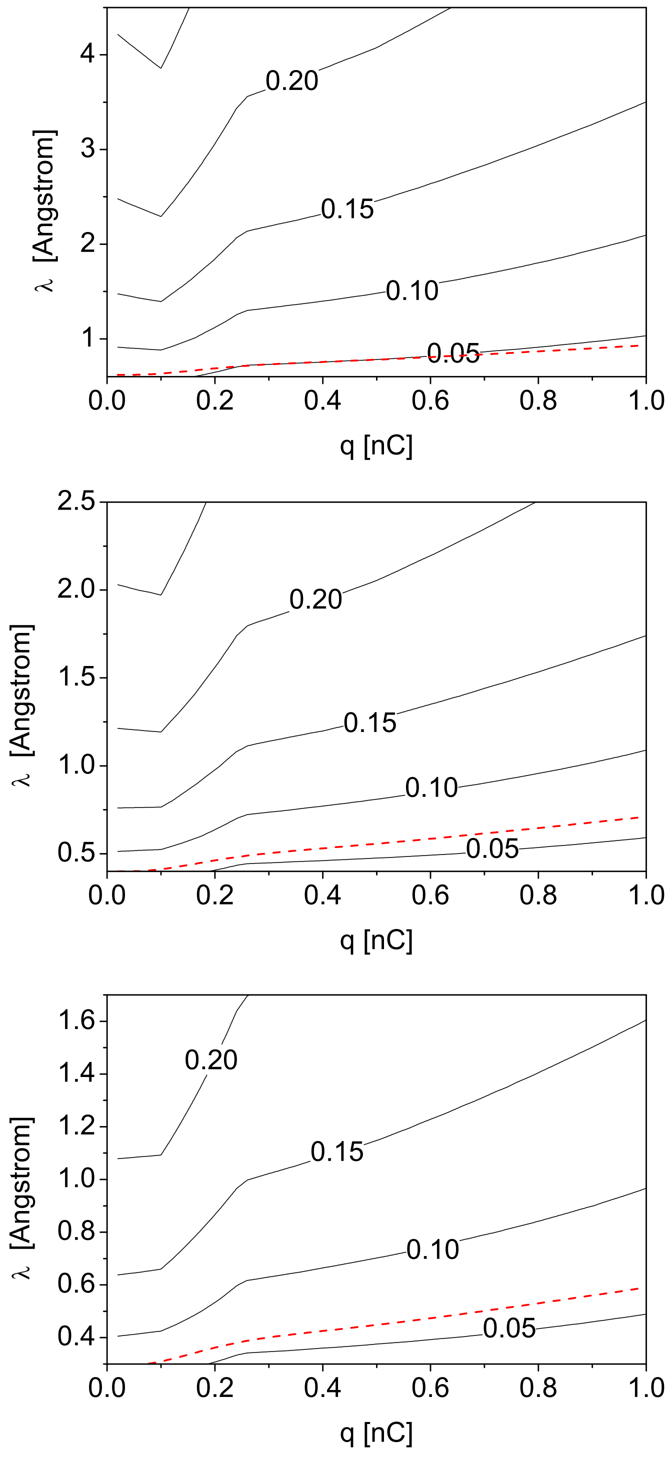

Fig. A.14. FWHM Spectrum width $\Delta\omega/\omega$ of the radiation for SASE1 (SASE2) operating in the saturation versus bunch charge and operating wavelength. Top, middle and bottom plots correspond to the electron energy of 10.5 GeV, 14 GeV, and 17.5 GeV, respectively. Numbers on contour lines denote units of %. Red dashed curve shows minimum of the radiation wavelength at the undulator length of 165 m. Parameters of the electron beam are presented in Table 9. Focusing beta function is optimized for minimum gain length (see Fig. A.3).

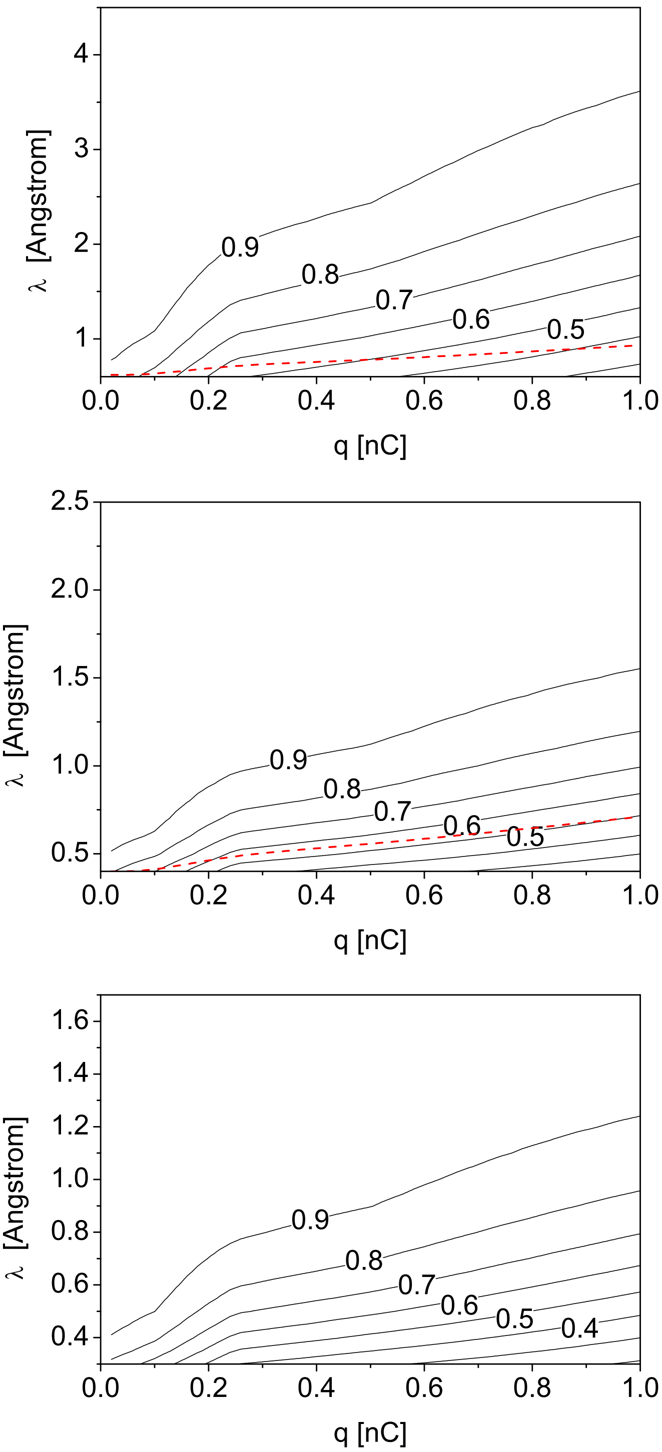

Fig. A.15. Degree of transverse coherence of the radiation for SASE1 (SASE2) operating in the saturation versus bunch charge and operating wavelength. Top, middle and bottom plots correspond to the electron energy of 10.5 GeV, 14 GeV, and 17.5 GeV, respectively. Red dashed curve shows minimum of the radiation wavelength at the undulator length of 165 m. Parameters of the electron beam are presented in Table 9. Focusing beta function is optimized for minimum gain length (see Fig. A.3).

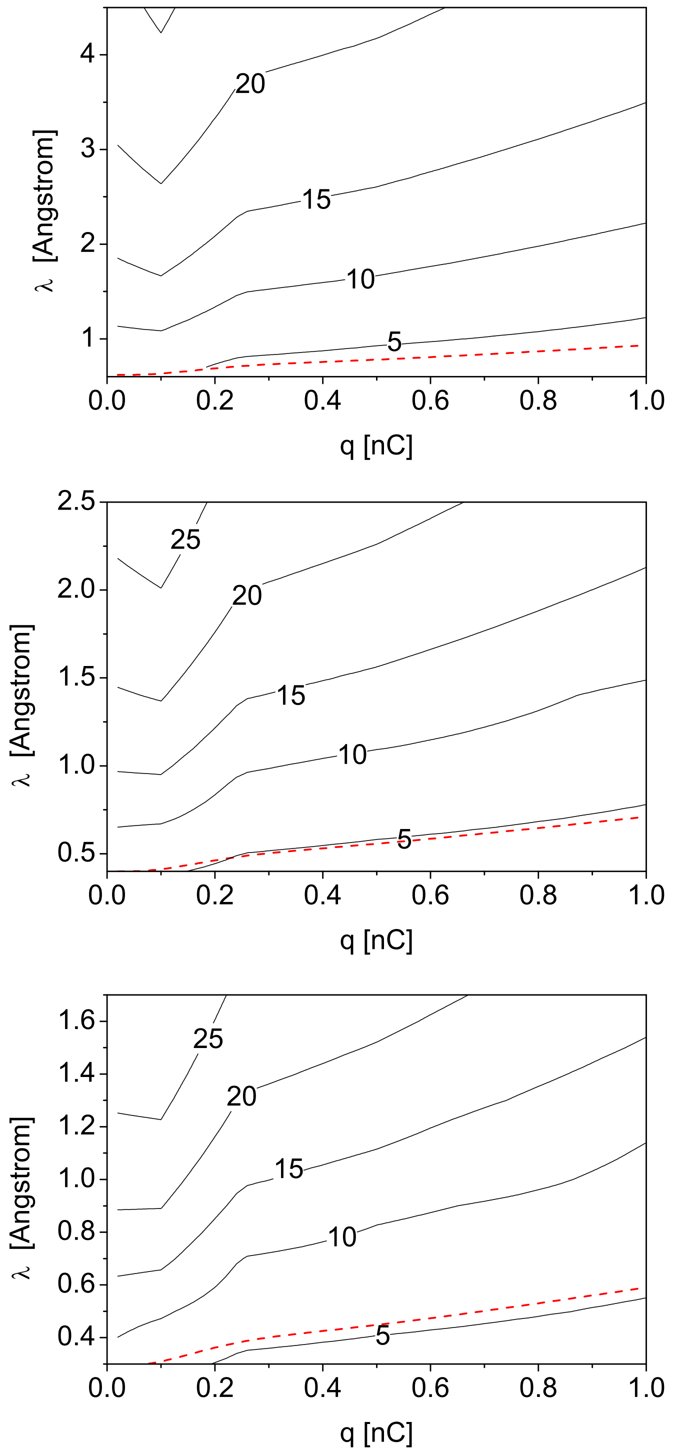

Fig. A.16. Energy spread in the electron beam (rms) for SASE1 (SASE2) operating in the saturation versus bunch charge and operating wavelength. Top, middle and bottom plots correspond to the electron energy of 10.5 GeV, 14 GeV, and 17.5 GeV, respectively. Numbers on contour lines denote units of MeV. Red dashed curve shows minimum of the radiation wavelength at the undulator length of 165 m. Parameters of the electron beam are presented in Table 9. Focusing beta function is optimized for minimum gain length (see Fig. A.3).

B Plots of the radiation properties of SASE3 in the saturation regime

In this section we present graphical overview of main characteristics of SASE3 operating in the saturation regime. Plots are divided in two grooups. The first one describes operation of SASE3 driven by ”resh” bunches, i.e. not disturbed by FEL interaction in SASE1 undulator. These plots are:

- Minimum radiation wavelength (Fig. B.2);
- Saturation length (Fig. B.3);
- Peak radiation power (Fig. B.4);
- Peak brilliance (Fig. B.5);
- Average brilliance (Fig. B.6);
- Energy in the radiation pulse (Fig. B.7);
- Number of photons per pulse (Fig. B.8);
- Average photon flux (Fig. B.9);
- Angular divergence of the radiation (Fig. B.10);
- Spot size of the radiation source (Fig. B.11);
- Coherence time (Fig. B.12);
- Spectrum width (Fig. B.13).

Operation of SASE3 as an afterburner is described with the following plots:

- Minimum wavelength (in units of Å) of SASE3 versus bunch charge and energy spread in the electron beam (Fig. B.14);
- Minimum wavelength of SASE3 versus operating wavelength of SASE1 (Fig. B.15);
- Peak saturation power of SASE3 versus wavelength of SASE1 and SASE3 (Figs. B.16, B.17, and B.18).

Radiation pulse duration in saturation ia the same for both modes of operation (see Fig. B.1).

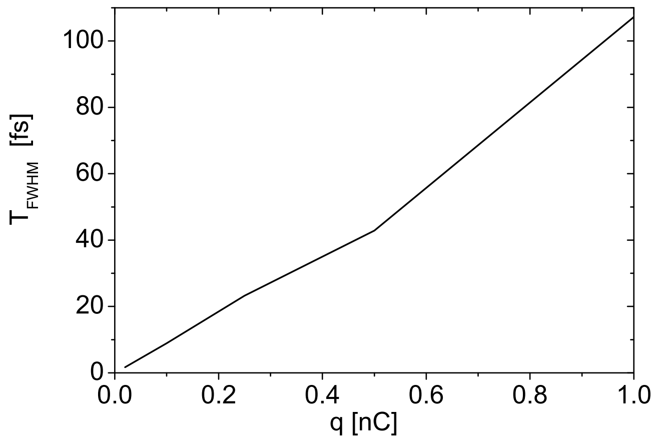

Fig. B.1. FWHM radiation pulse duration in the saturation versus bunch charge for baseline parameters of the electron beam as of December, 2010.

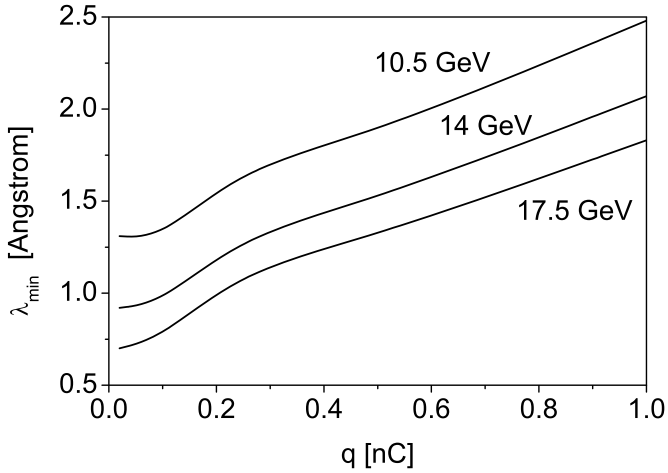

Fig. B.2. Minimum radiation wavelength for SASE3 versus bunch charge for electron energy 10.5 GeV, 14 GeV, and 17.5 GeV. Undulator length is equal to 100 meters. Parameters of the electron beam are presented in Table 9.

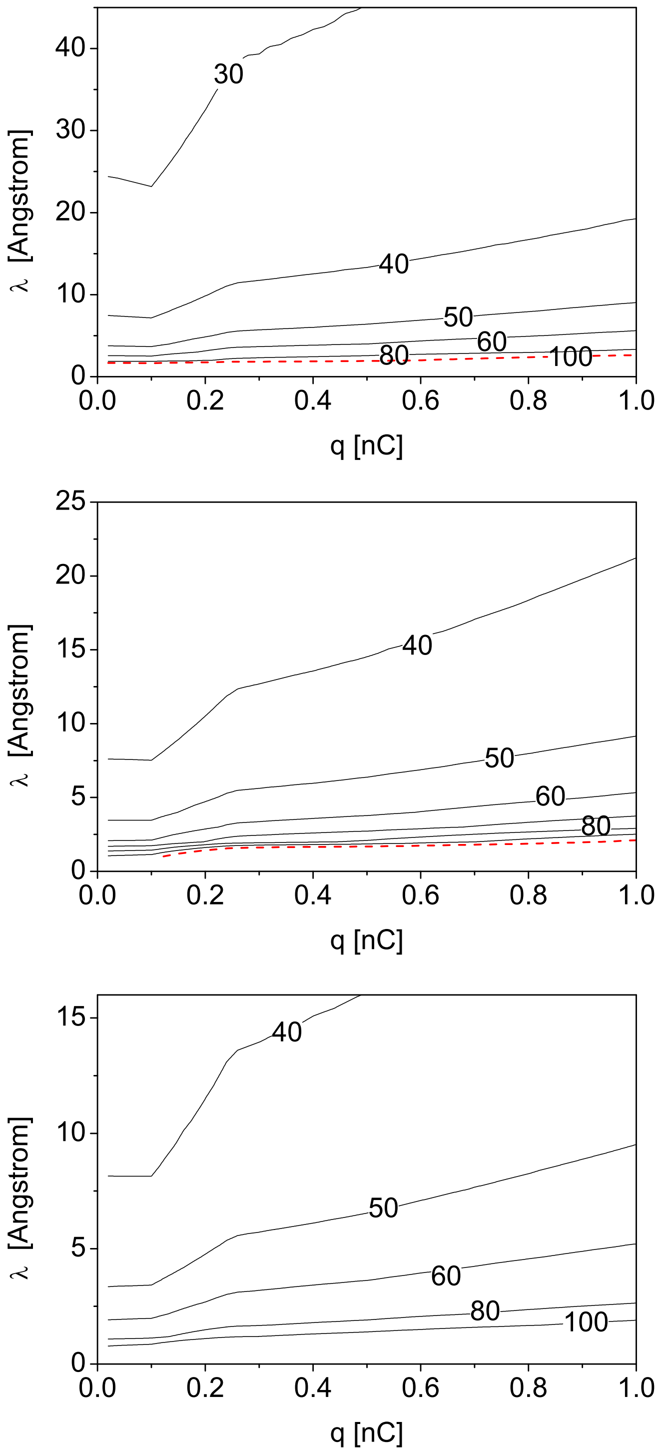

Fig. B.3. Saturation length for SASE3 versus bunch charge and operating wavelength. Numbers on contour lines denote units of meters. Top, middle and bottom plots correspond to the electron energy of 10.5 GeV, 14 GeV, and 17.5 GeV, respectively. Parameters of the electron beam are presented in Table 9. Focusing beta function is optimized for minimum gain length.

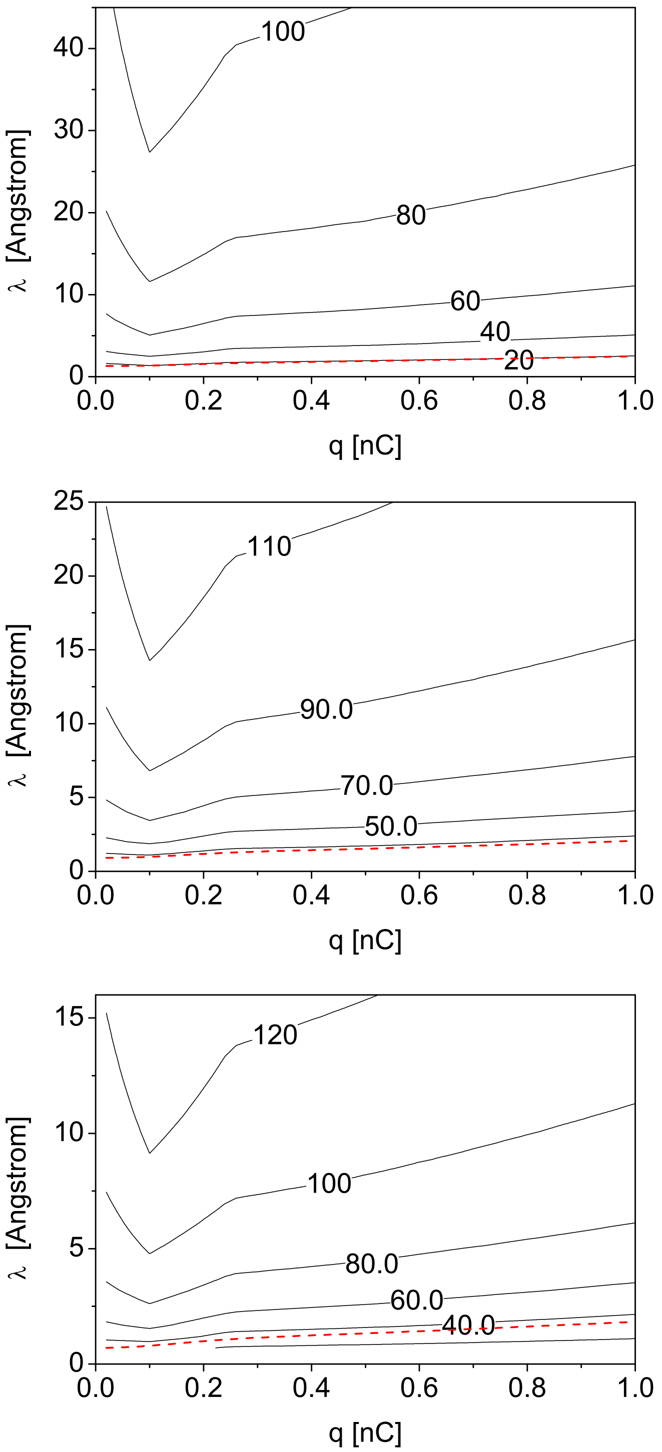

Fig. B.4. Peak radiation power for SASE3 operating in the saturation versus bunch charge and operating wavelength. Numbers on contour lines denote units of GW. Top, middle and bottom plots correspond to the electron energy of 10.5 GeV, 14 GeV, and 17.5 GeV, respectively. Red dashed curve shows minimum of the radiation wavelength at the undulator length of 100 m. Parameters of the electron beam are presented in Table 9.

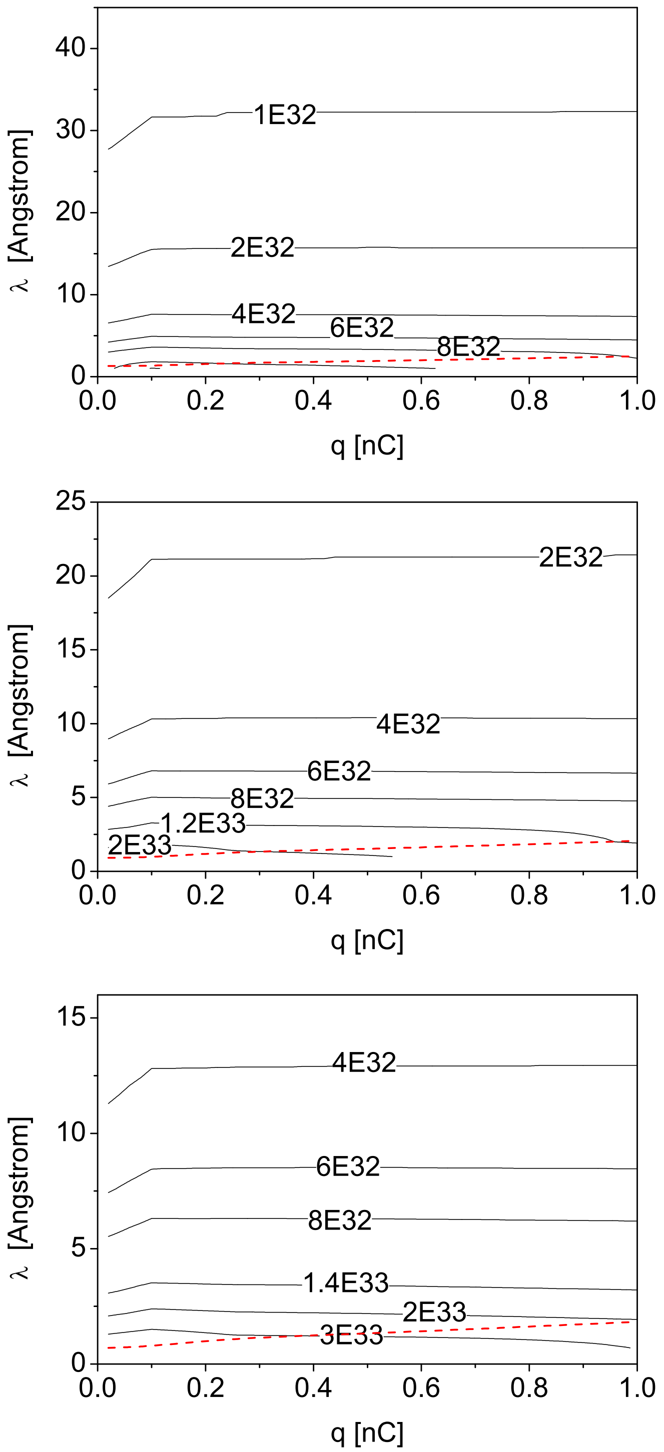

Fig. B.5. Peak brilliance for SASE3 operating in the saturation versus bunch charge and operating wavelength. Numbers on contour lines denote units of photons/sec/mm^2/rad^2/0.1% bandwidth. Top, middle and bottom plots correspond to the electron energy of 10.5 GeV, 14 GeV, and 17.5 GeV, respectively. Red dashed curve shows minimum of the radiation wavelength at the undulator length of 100 m. Parameters of the electron beam are presented in Table 9.

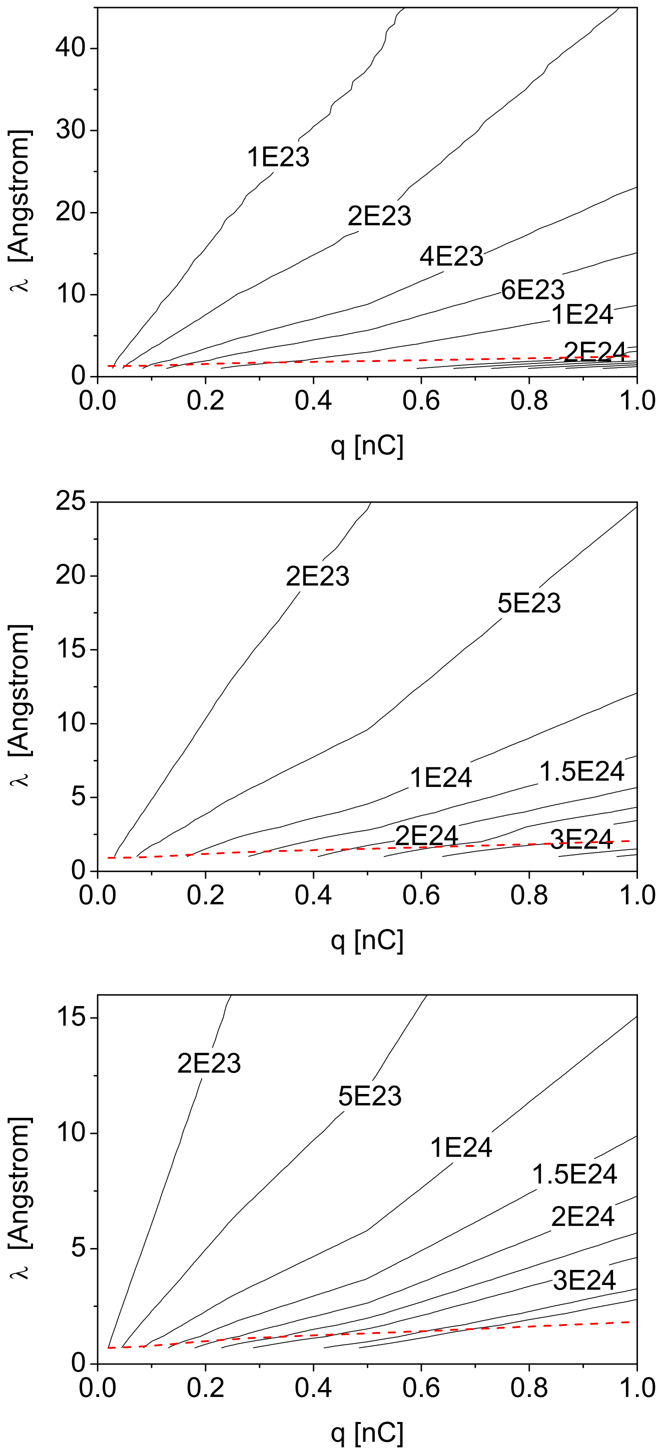

Fig. B.6. Average brilliance for SASE3 operating in the saturation versus bunch charge and operating wavelength. Numbers on contour lines denote units of photons/sec/mm^2/rad^2/0.1% bandwidth. Top, middle and bottom plots correspond to the electron energy of 10.5 GeV, 14 GeV, and 17.5 GeV, respectively. Red dashed curve shows minimum of the radiation wavelength at the undulator length of 100 m. Parameters of the electron beam are presented in Table 9.

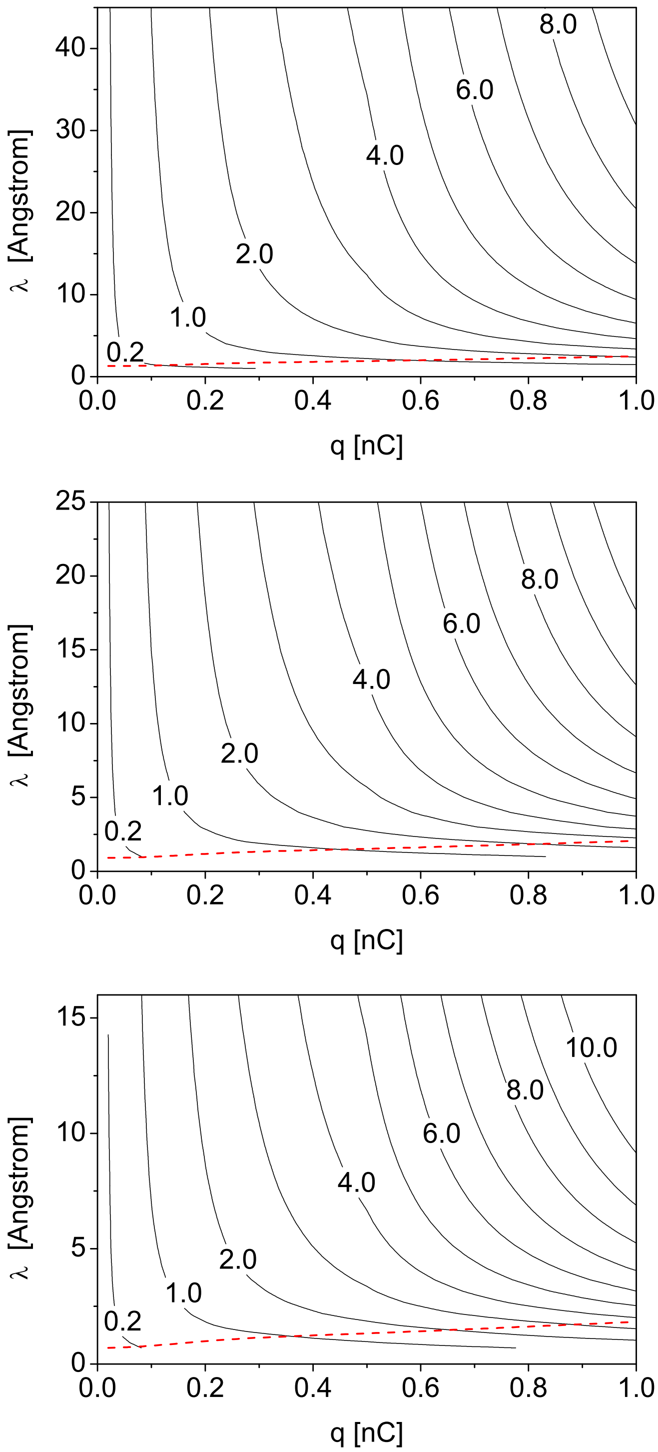

Fig. B.7. Energy in the radiation pulse for SASE3 operating in the saturation versus bunch charge and operating wavelength. Numbers on contour lines denote units of mJ. Top, middle and bottom plots correspond to the electron energy of 10.5 GeV, 14 GeV, and 17.5 GeV, respectively. Red dashed curve shows minimum of the radiation wavelength at the undulator length of 100 m. Parameters of the electron beam are presented in Table 9.

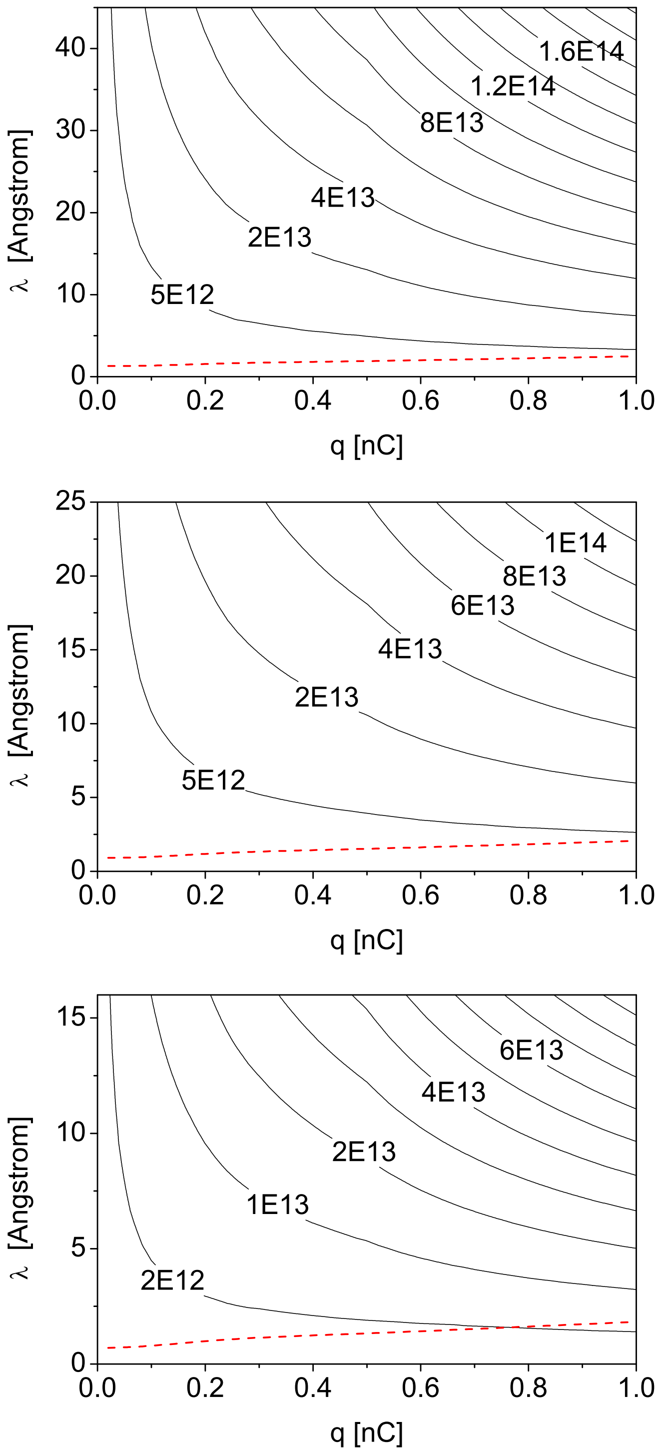

Fig. B.8. Number of photons in the radiation pulse for SASE3 operating in the saturation versus bunch charge and operating wavelength. Numbers on contour lines denote number of photons. Top, middle and bottom plots correspond to the electron energy of 10.5 GeV, 14 GeV, and 17.5 GeV, respectively. Red dashed curve shows minimum of the radiation wavelength at the undulator length of 100 m. Parameters of the electron beam are presented in Table 9.

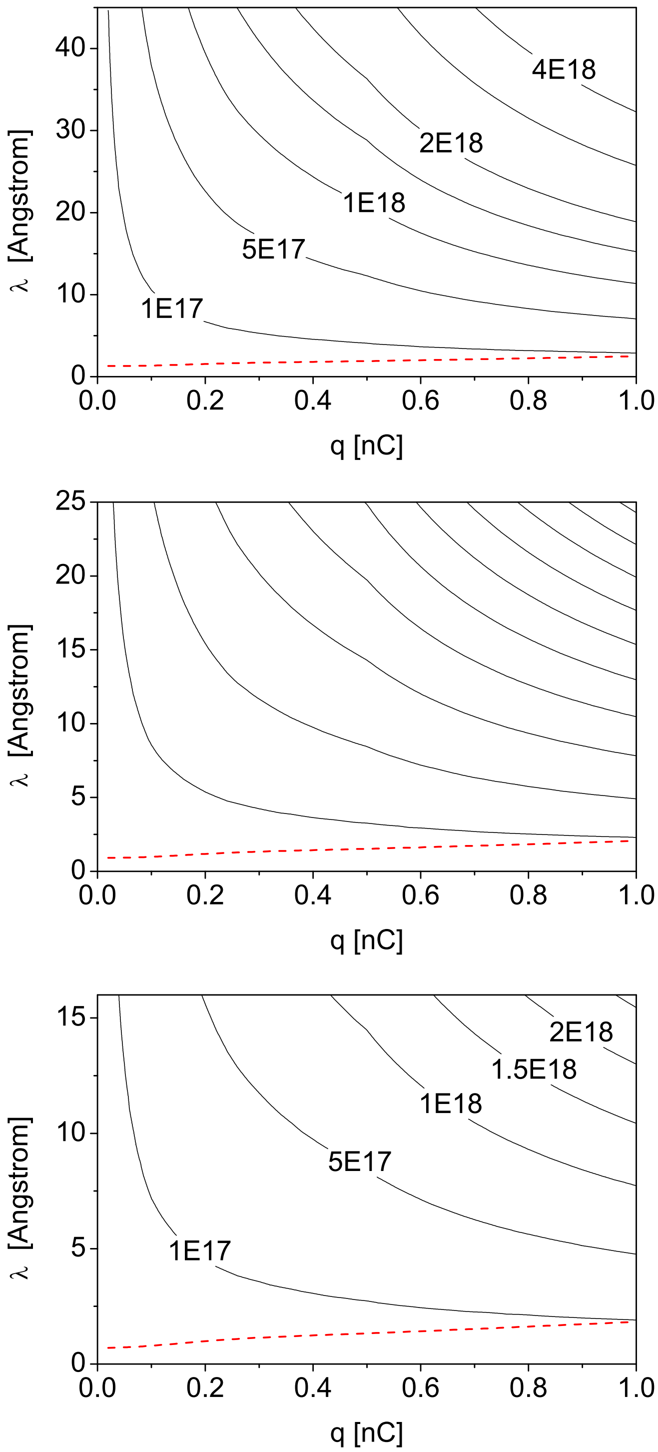

Fig. B.9. Average photon flux for SASE3 operating in the saturation versus bunch charge and operating wavelength. Numbers on contour lines denote number of photons per second. Top, middle and bottom plots correspond to the electron energy of 10.5 GeV, 14 GeV, and 17.5 GeV, respectively. Red dashed curve shows minimum of the radiation wavelength at the undulator length of 100 m. Parameters of the electron beam are presented in Table 9.

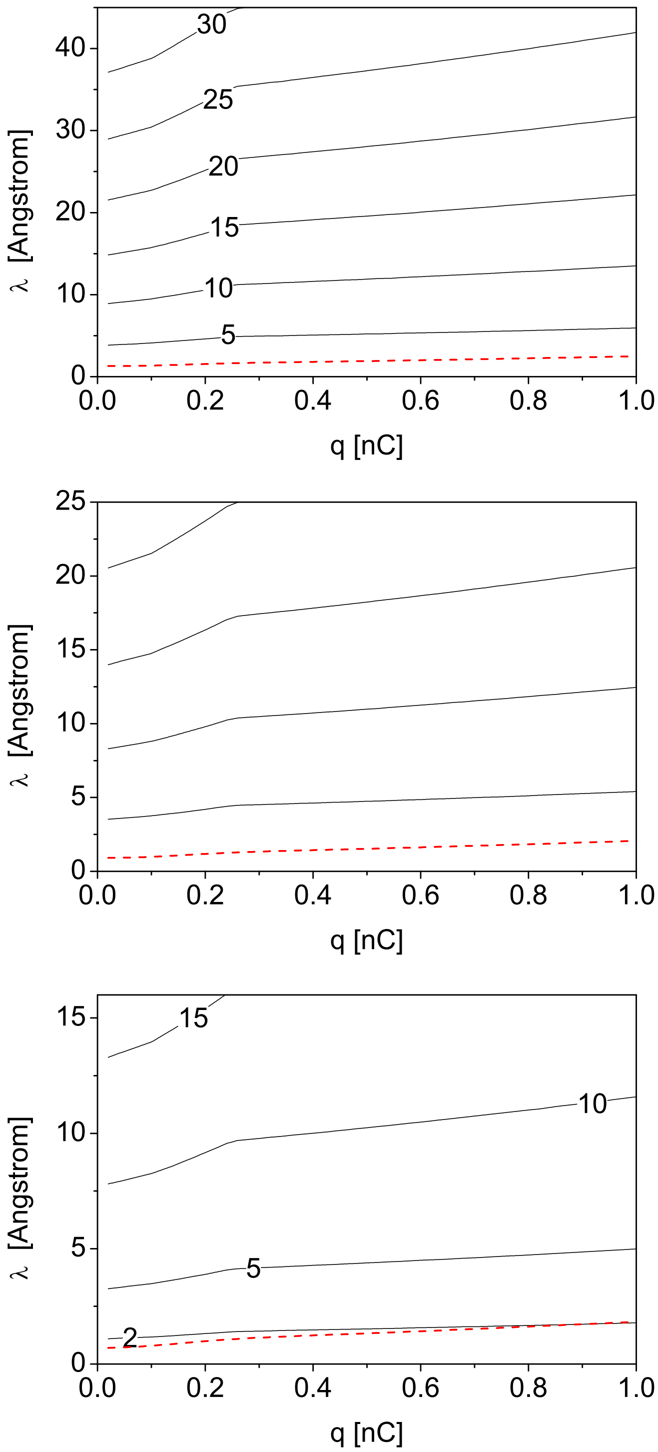

Fig. B.10. FWHM angular divergence of the radiation for SASE3 operating in the saturation versus bunch charge and operating wavelength. Top, middle and bottom plots correspond to the electron energy of 10.5 GeV, 14 GeV, and 17.5 GeV, respectively. Numbers on contour lines denote units of μrad. Red dashed curve shows minimum of the radiation wavelength at the undulator length of 100 m. Parameters of the electron beam are presented in Table 9.

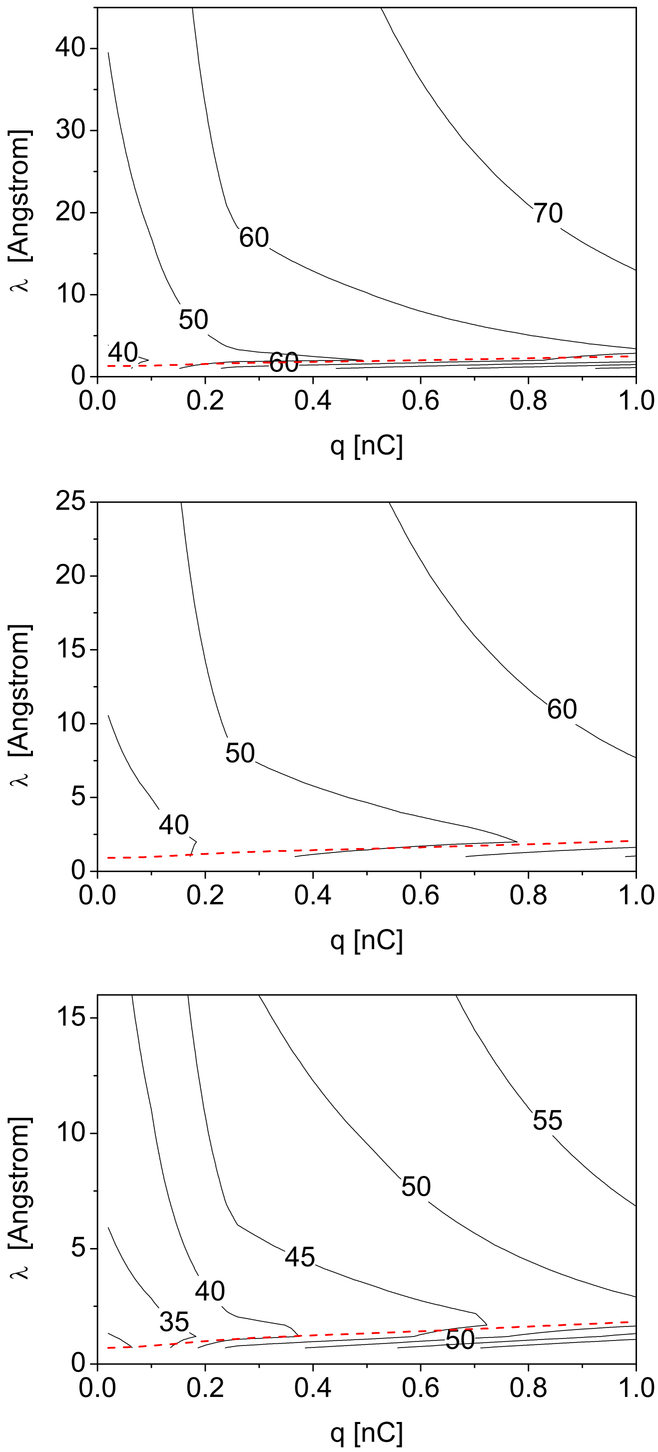

Fig. B.11. FWHM spot size of the radiation for SASE3 operating in the saturation versus bunch charge and operating wavelength. Top, middle and bottom plots correspond to the electron energy of 10.5 GeV, 14 GeV, and 17.5 GeV, respectively. Numbers on contour lines denote units of μm. Red dashed curve shows minimum of the radiation wavelength at the undulator length of 100 m. Parameters of the electron beam are presented in Table 9.

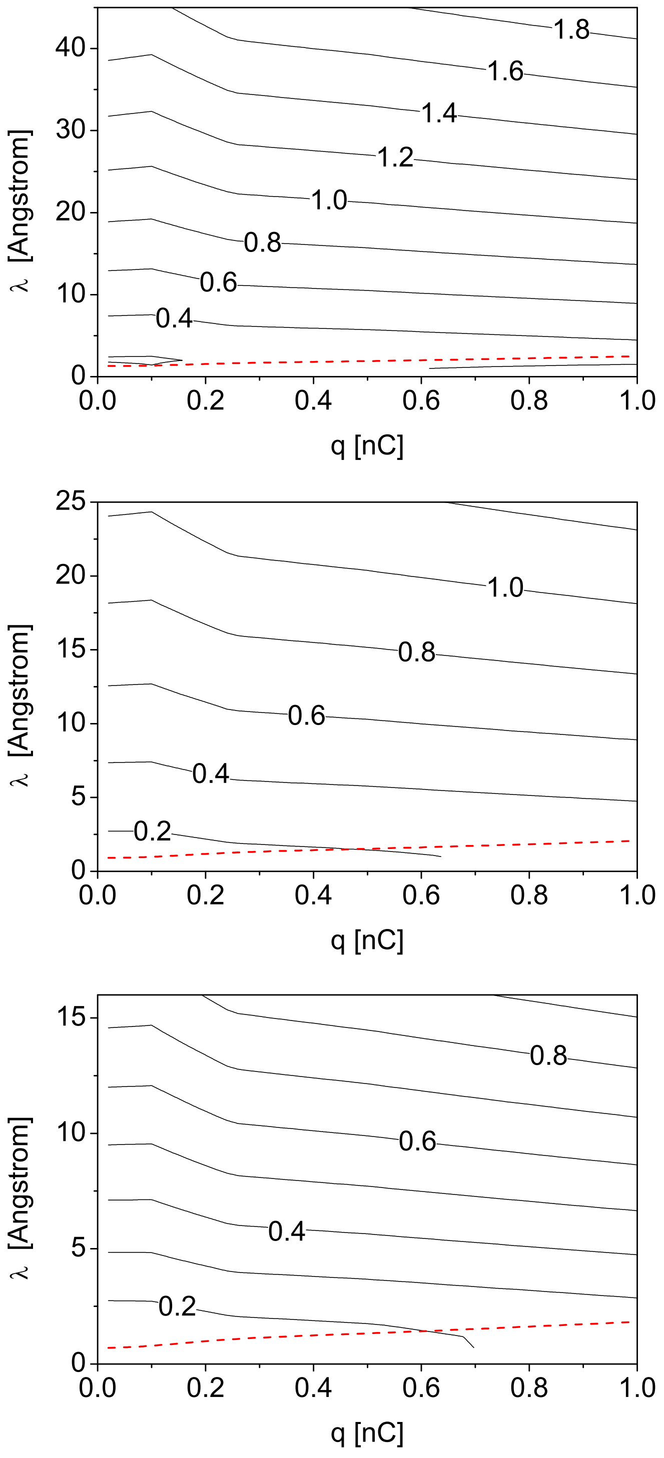

Fig. B.12. Coherence time of the radiation for SASE3 operating in the saturation versus bunch charge and operating wavelength. Top, middle and bottom plots correspond to the electron energy of 10.5 GeV, 14 GeV, and 17.5 GeV, respectively. Numbers on contour lines denote units of fs. Red dashed curve shows minimum of the radiation wavelength at the undulator length of 100 m. Parameters of the electron beam are presented in Table 9.

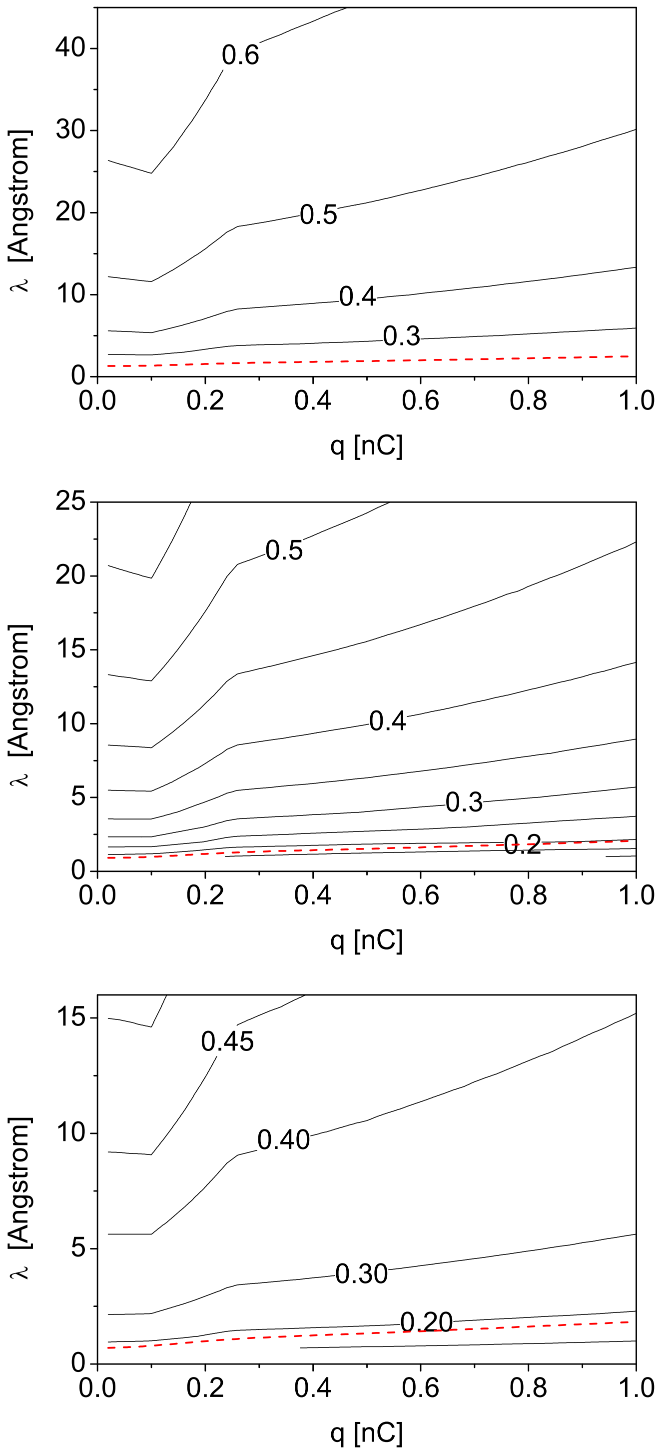

Fig. B.13. FWHM Spectrum width $\Delta\omega/\omega$ of the radiation for SASE3 operating in the saturation versus bunch charge and operating wavelength. Top, middle and bottom plots correspond to the electron energy of 10.5 GeV, 14 GeV, and 17.5 GeV, respectively. Numbers on contour lines denote units of %. Red dashed curve shows minimum of the radiation wavelength at the undulator length of 100 m. Parameters of the electron beam are presented in Table 9.

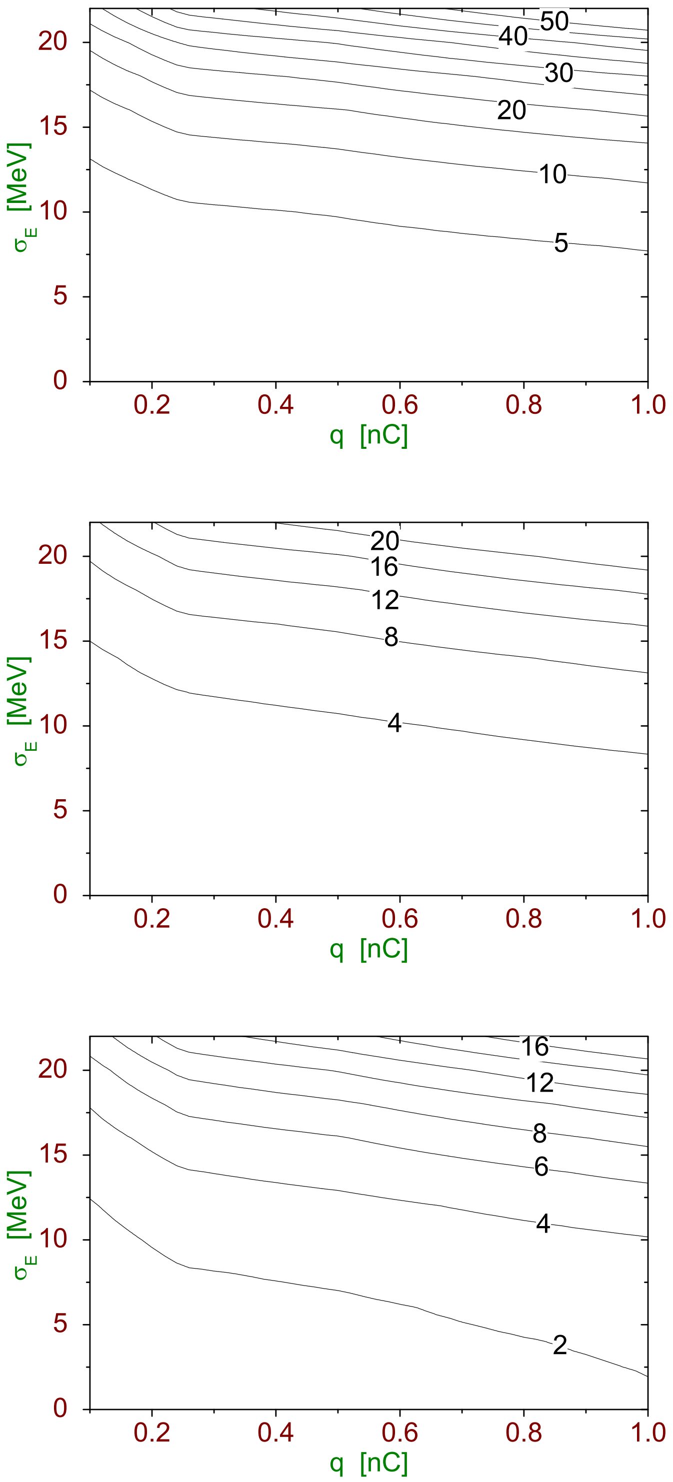

Fig. B.14. Minimum wavelength (in units of Å) of SASE3 versus bunch charge and energy spread in the electron beam. Undulator length is equal to 100 m. Minimum focusing beta function is equal to 15 m. Top, middle, bottom plot correspond to the energy of electrons 10.5 GeV, 14 GeV, and 17.5 GeV. Parameters of SASE3 are optimized for minimum gain length.

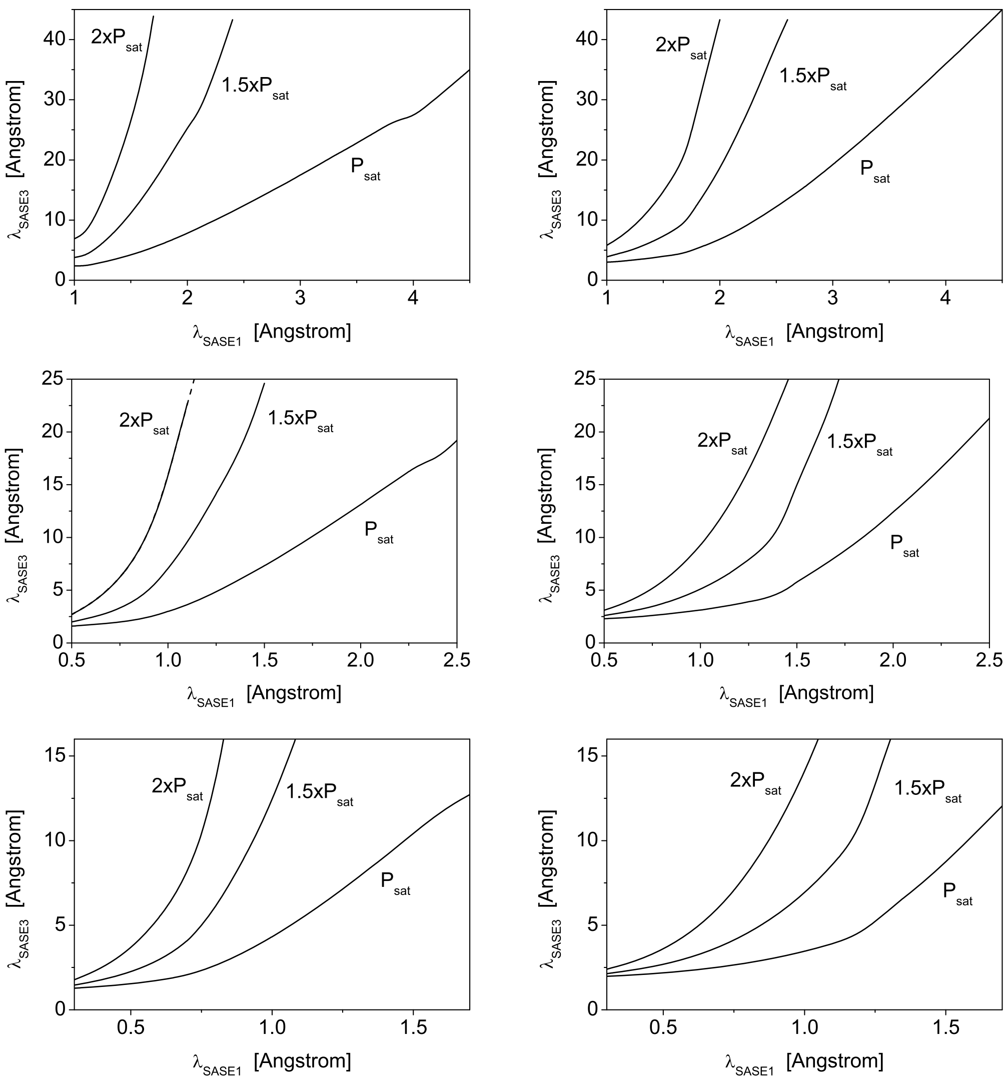

Fig. B.15. Operation of SASE3 as an afterburner: minimum wavelength of SASE3 versus operating wavelength of SASE1 for different electron energies. Minimum wavelength is defined by the condition of saturation at the length of SASE3 undulator of 100 meters. Upper, middle, and lower plots correspond to electron energy of 10.5 GeV, 14 GeV, and 17 GeV, respectively. Left column and right column correspond to bunch charge of 0.25 nC and 1 nC. Each plot contains three curves corresponding to different power of SASE1 in terms of saturation power: P_{sat}, $1.5 \times P_{\mathrm{sat}}$, and $2 \times P_{\mathrm{sat}}$.

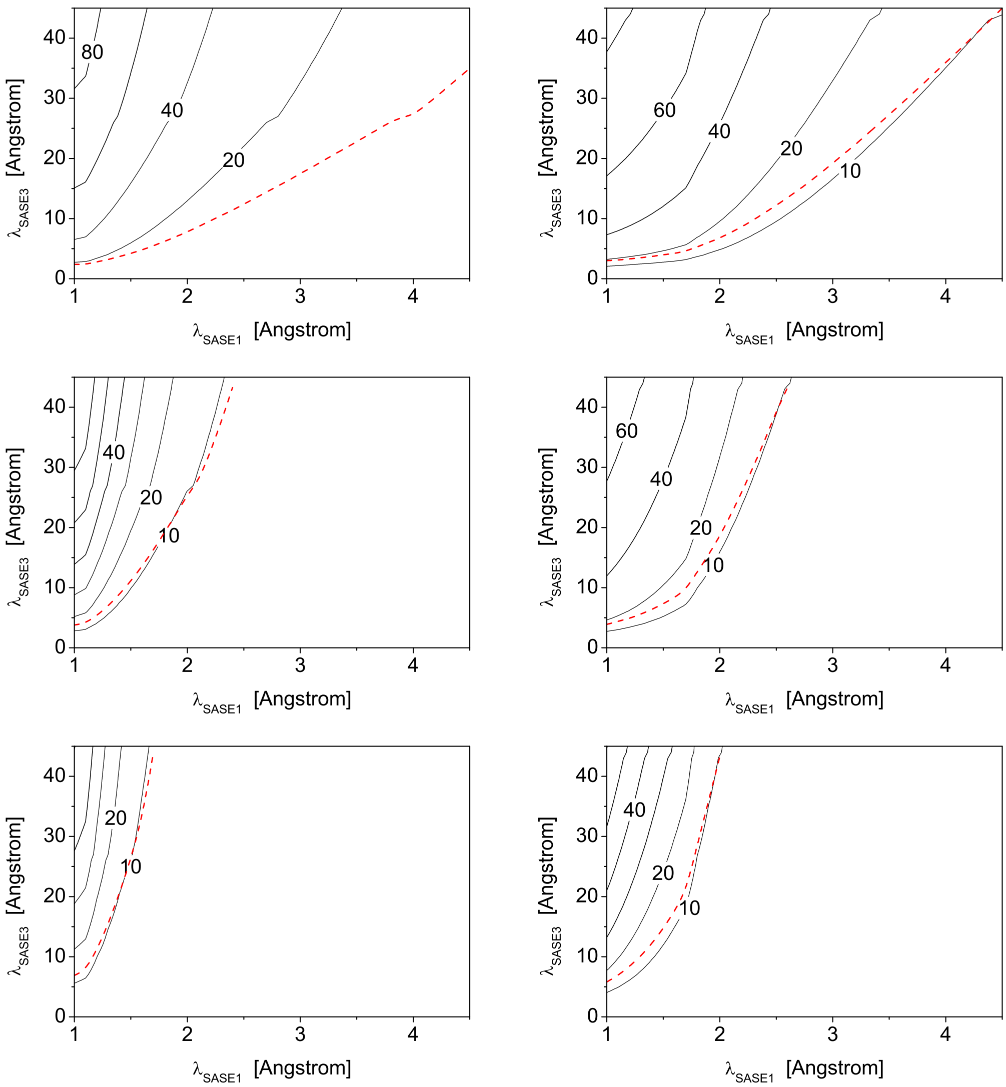

Fig. B.16. Operation of SASE3 as an afterburner: peak saturation power of SASE3 versus wavelength of SASE1 and SASE3. Numbers on contour lines denote units of GW. Dashed line shows minimum wavelength of SASE3 for the undulator length of SASE3 of 100 meters. Electron energy is equal to 10.5 GeV. Upper, middle, and lower plots correspond to different power of SASE1 in terms of saturation power: P_{sat}, $1.5 \times P_{\mathrm{sat}}$, and $2 \times P_{\mathrm{sat}}$. Left column and right column correspond to bunch charge of 0.25 nC and 1 nC.

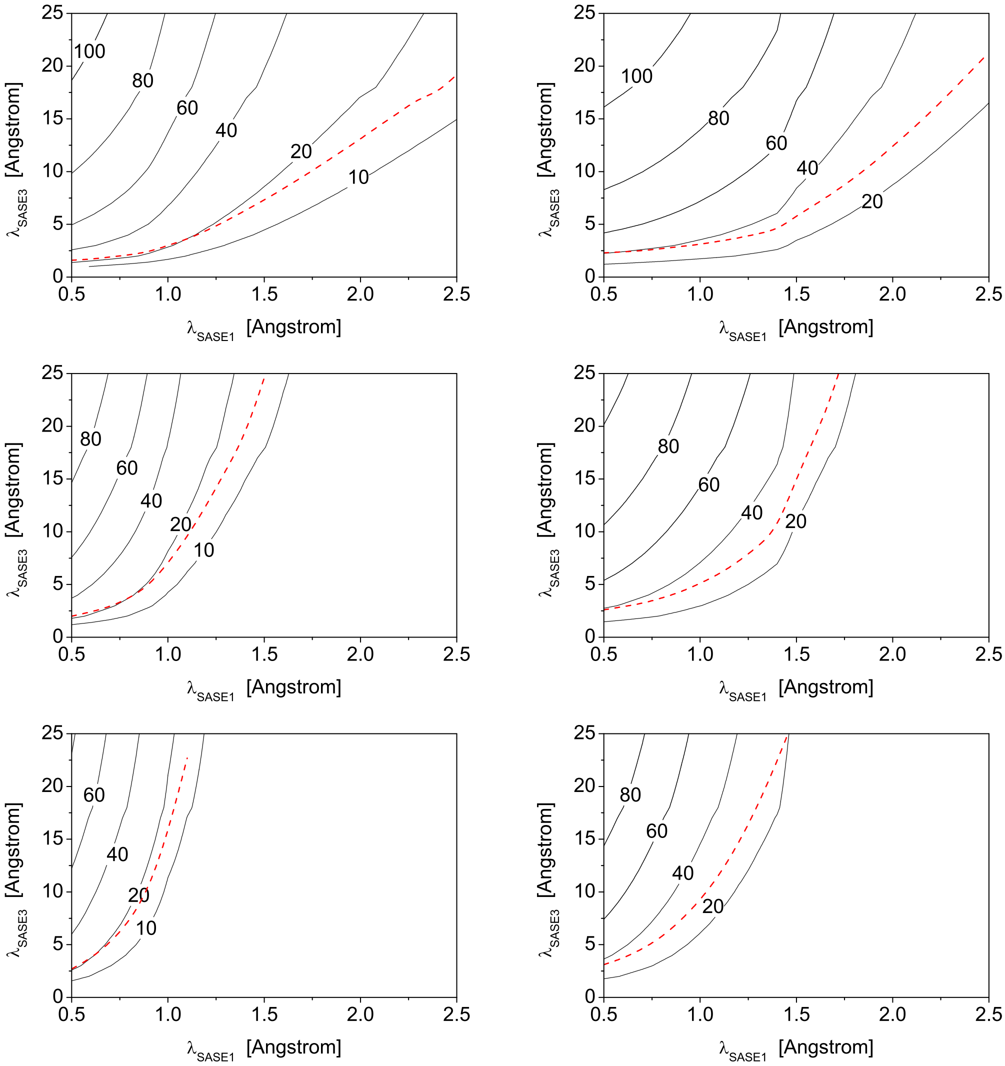

Fig. B.17. Operation of SASE3 as an afterburner: peak saturation power of SASE3 versus wavelength of SASE1 and SASE3. Numbers on contour lines denote units of GW. Dashed line shows minimum wavelength of SASE3 for the undulator length of SASE3 of 100 meters. Electron energy is equal to 14 GeV. Upper, middle, and lower plots correspond to different power of SASE1 in terms of saturation power: $P_{\rm sat}$, $1.5 \times P_{\rm sat}$, and $2 \times P_{\rm sat}$. Left column and right column correspond to bunch charge of 0.25 nC and 1 nC.

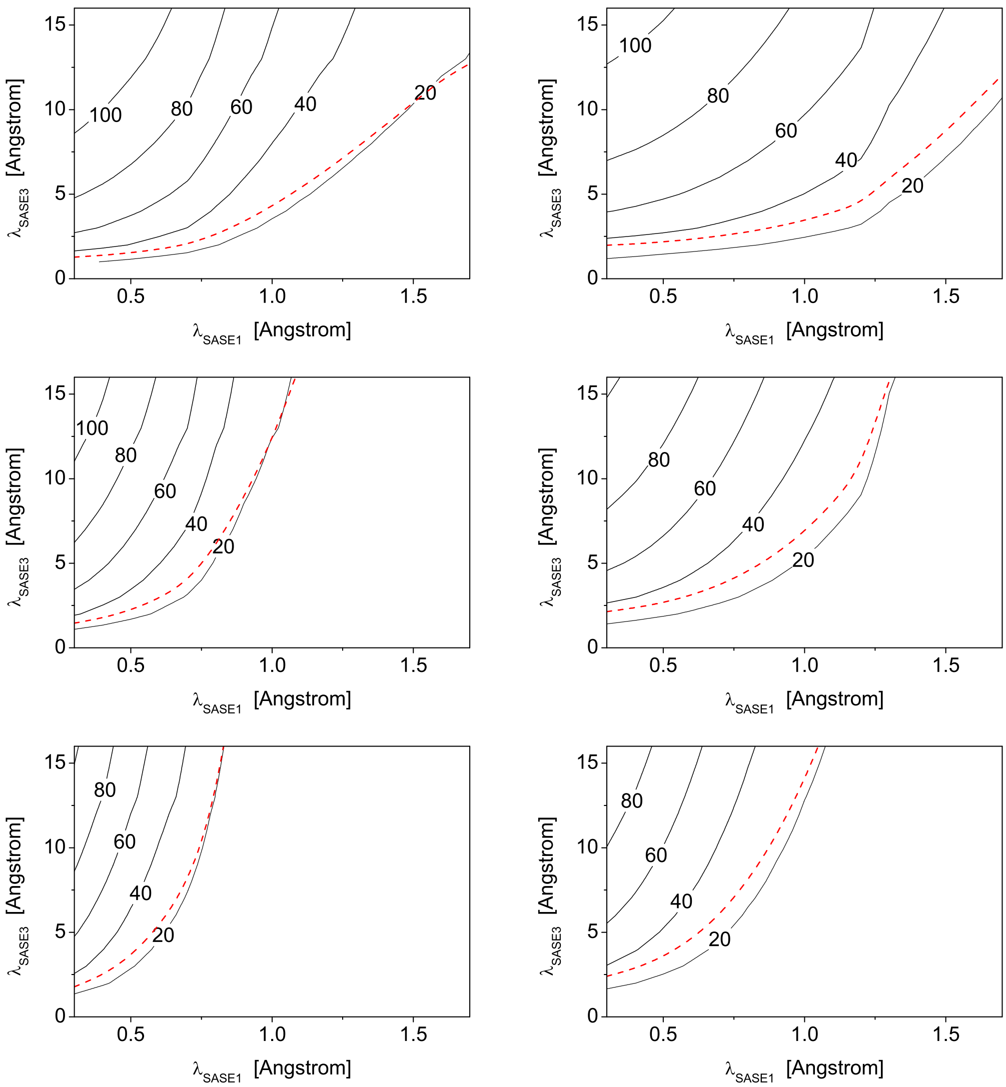

Fig. B.18. Operation of SASE3 as an afterburner: peak saturation power of SASE3 versus wavelength of SASE1 and SASE3. Numbers on contour lines denote units of GW. Dashed line shows minimum wavelength of SASE3 for the undulator length of SASE3 of 100 meters. Electron energy is equal to 17.5 GeV. Upper, middle, and lower plots correspond to different power of SASE1 in terms of saturation power: $P_{\rm sat}$, $1.5 \times P_{\rm sat}$, and $2 \times P_{\rm sat}$. Left column and right column correspond to bunch charge of 0.25 nC and 1 nC.

C Tables of the radiation properties of SASE1 (SASE2)in the saturation regime

This section contains practical tables of the radiation properties for SASE1 (SASE2) operating in the saturation regime. Saturation is defined as the point where brilliance reaches maximum value (see Section 2 for more details). All data presented in the tables are generated by the code based on tabulated results of numerical simulations with three-dimensional, time-dependent code FAST [19]. Tables cover properties of the fundamental, 3rd, and the 5th harmonic. Accuracy of tabulation is 10 to 20 per cent which is sufficient for practical purposes. It happens at the margins of operating wavelength ranges that saturation length for higher charges exceeds undulator length. We do not exclude these charges from tables to give the reader an idea about required undulator length.

Numbers for brilliance are in units of photons/sec/mm^2/mrad^2/0.1% bandwidth.

Main characteristics of the undulator, electron beam, and incoherent radiation are included in the tables as well.

Parameters of the FEL theory are presented with one-dimensional and three-dimensional efficiency parameter ρ and $\bar{\rho}$, number of electrons in the volume of coherence N_c, and emittance parameter $\hat{\epsilon} = 2\pi\epsilon/\lambda$. This set of physical parameters is sufficient for quick physical estimation of main characteristics of SASE FEL as we described in Section 2.

Table C.1

Saturation characteristics of SASE1 (SASE2): 17.5 GeV, 0.03 nm

#						
Electron beam:						
#						
Energy of electrons	GeV	17.5				
Bunch charge	nC	.200E-01	.100	.250	.500	1.00
Peak current	kA	4.50	5.00	5.00	5.00	5.00
rms normalized emittance	mm-mrad	.320	.390	.600	.700	.970
rms energy spread	MeV	4.10	2.90	2.50	2.20	2.00
rms bunch length	micrometr	.360	1.92	4.98	9.17	23.0
Focusing beta function	m	22.8	32.7	59.1	75.2	116.
rms size of electron beam	micrometr	14.6	19.3	32.2	39.2	57.3
Repetition rate	1/sec	.270E+05				
Electron beam power	kW	9.45	47.2	118.	236.	472.
#						
Undulator:						
#						
Undulator period	cm	4.00				
Undulator peak field	T	.330				
Undulator parameter K (rms)	#	.871				
Undulator gap	cm	2.30				
Undulator length	m	165.				
#						
Properties of the 1st harmonic in the saturation:						
#						
Radiation wavelength	nm	.300E-01				
Photon energy	keV	41.3				
Pulse energy	mJ	.185E-01	.947E-01	.160	.252	.456
Peak power	GW	11.0	10.6	6.87	5.89	4.25
Average power	W	.499	2.56	4.31	6.81	12.3
FWHM spot size	mikrometr	24.7	30.6	44.2	51.2	67.1
FWHM angular divergence	microrad	.724	.625	.499	.454	.386
Coherence time	fs	.980E-01	.995E-01	.151	.171	.238
FWHM spectrum width, dw/w	%	.722E-01	.711E-01	.469E-01	.414E-01	.297E-01
Degree of transverse coherence	#	.775	.663	.401	.319	.186
Radiation pulse duration	fs	1.68	8.96	23.2	42.8	107.
Number of longitudinal modes	#	17	90	154	251	450
Fluctuations of the pulse energy	%	8.08	3.51	2.69	2.10	1.57
Degeneracy parameter	#	.126E+09	.105E+09	.627E+08	.485E+08	.284E+08
Number oh photons per pulse	#	.279E+10	.143E+11	.241E+11	.381E+11	.688E+11
Average flux of photons	ph/sec	.753E+14	.386E+15	.650E+15	.103E+16	.186E+16
Peak brilliance	#	.791E+34	.661E+34	.394E+34	.305E+34	.178E+34
Average brilliance	#	.359E+24	.160E+25	.247E+25	.352E+25	.517E+25
Saturation length	m	158.	161.	248.	282.	398.
Power gain length	m	9.10	9.20	13.8	15.5	21.4
SASE induced energy loss	MeV	2.44	2.11	1.37	1.18	.850
SASE induced energy spread	MeV	7.46	6.12	4.30	3.72	2.95
#						
Properties of the 3rd harmonic in the saturation:						
#						
Radiation wavelength	nm	.100E-01				
Photon energy	keV	124.				
Contribution to the total power	P3/P	.297E-02	.297E-02	.297E-02	.297E-02	.296E-02
Pulse energy	microJ	.548E-01	.281	.473	.748	1.35
Average power	W	.148E-02	.759E-02	.128E-01	.202E-01	.365E-01
Number oh photons per pulse	#	.276E+07	.141E+08	.238E+08	.376E+08	.680E+08
Average flux of photons	ph/sec	.744E+11	.382E+12	.643E+12	.102E+13	.183E+13
Coherence time	fs	.327E-01	.332E-01	.503E-01	.569E-01	.795E-01
FWHM spectrum width, dw/w	%	.722E-01	.711E-01	.469E-01	.414E-01	.297E-01
#						
Properties of the 5th harmonic in the saturation:						
#						
Radiation wavelength	nm	.600E-02				
Photon energy	keV	207.				
Contribution to the total power	P5/P	.492E-04	.492E-04	.492E-04	.492E-04	.492E-04
Pulse energy	microJ	.909E-03	.466E-02	.785E-02	.124E-01	.224E-01
Average power	W	.245E-04	.126E-03	.212E-03	.335E-03	.605E-03
Number oh photons per pulse	#	.274E+05	.141E+06	.237E+06	.375E+06	.677E+06
Average flux of photons	ph/sec	.741E+09	.380E+10	.640E+10	.101E+11	.183E+11
Coherence time	fs	.196E-01	.199E-01	.302E-01	.342E-01	.477E-01
FWHM spectrum width, dw/w	%	.722E-03	.711E-03	.469E-03	.414E-03	.297E-03
#						
Incoherent radiation:						
#						
Critical wavelength	nm	.185E-01				
Critical energy of SR	keV	67.2				
SR induced energy loss	MeV	3.48				
SR induced energy spread	MeV	.559				
SR power	W	1.88	9.41	23.5	47.0	94.1
#						
Parameters of FEL theory:						
#						
Efficiency parameter (1D)	#	.452E-03	.388E-03	.276E-03	.242E-03	.188E-03
Efficiency parameter (3D)	#	.161E-02	.169E-02	.169E-02	.169E-02	.169E-02
N of electrons in coherence volume	#	.128E+07	.144E+07	.215E+07	.243E+07	.335E+07
Emittance parameter	#	1.96	2.39	3.67	4.28	5.93

Table C.2

Saturation characteristics of SASE1 (SASE2): 17.5 GeV, 0.04 nm

#						
Electron beam:						
#						
Energy of electrons	GeV	17.5				
Bunch charge	nC	.200E-01	.100	.250	.500	1.00
Peak current	kA	4.50	5.00	5.00	5.00	5.00
rms normalized emittance	mm-mrad	.320	.390	.600	.700	.970
rms energy spread	MeV	4.10	2.90	2.50	2.20	2.00
rms bunch length	micrometr	.360	1.92	4.98	9.17	23.0
Focusing beta function	m	15.2	21.2	38.8	49.2	76.4
rms size of electron beam	micrometr	11.9	15.5	26.1	31.7	46.5
Repetition rate	1/sec	.270E+05				
Electron beam power	kW	9.45	47.2	118.	236.	472.
#						
Undulator:						
#						
Undulator period	cm	4.00				
Undulator peak field	T	.439				
Undulator parameter K (rms)	#	1.16				
Undulator gap	cm	1.97				
Undulator length	m	165.				
#						
Properties of the 1st harmonic in the saturation:						
#						
Radiation wavelength	nm	.400E-01				
Photon energy	keV	31.0				
Pulse energy	mJ	.270E-01	.138	.233	.369	.666
Peak power	GW	16.1	15.4	10.0	8.60	6.21
Average power	W	.729	3.74	6.30	9.95	18.0
FWHM spot size	mikrometr	22.2	27.2	39.5	45.6	60.0
FWHM angular divergence	microrad	.977	.853	.678	.618	.524
Coherence time	fs	.843E-01	.890E-01	.133	.151	.208
FWHM spectrum width, dw/w	%	.112	.106	.709E-01	.624E-01	.454E-01
Degree of transverse coherence	#	.893	.818	.575	.480	.301
Radiation pulse duration	fs	1.68	8.96	23.2	42.8	107.
Number of longitudinal modes	#	20	101	175	283	517
Fluctuations of the pulse energy	%	7.45	3.32	2.52	1.98	1.47
Degeneracy parameter	#	.244E+09	.226E+09	.154E+09	.126E+09	.780E+08
Number oh photons per pulse	#	.543E+10	.278E+11	.469E+11	.742E+11	.134E+12
Average flux of photons	ph/sec	.147E+15	.752E+15	.127E+16	.200E+16	.362E+16
Peak brilliance	#	.645E+34	.600E+34	.409E+34	.333E+34	.207E+34
Average brilliance	#	.293E+24	.145E+25	.257E+25	.385E+25	.598E+25
Saturation length	m	102.	108.	163.	187.	259.
Power gain length	m	5.91	6.20	9.14	10.3	14.1
SASE induced energy loss	MeV	3.57	3.09	2.01	1.72	1.24
SASE induced energy spread	MeV	9.98	8.39	5.70	4.91	3.74
#						
Properties of the 3rd harmonic in the saturation:						
#						
Radiation wavelength	nm	.133E-01				
Photon energy	keV	93.0				
Contribution to the total power	P3/P	.467E-02	.469E-02	.464E-02	.463E-02	.463E-02
Pulse energy	microJ	.126	.649	1.08	1.71	3.08
Average power	W	.340E-02	.175E-01	.292E-01	.461E-01	.832E-01
Number oh photons per pulse	#	.846E+07	.435E+08	.726E+08	.115E+09	.207E+09
Average flux of photons	ph/sec	.228E+12	.117E+13	.196E+13	.309E+13	.558E+13
Coherence time	fs	.281E-01	.297E-01	.443E-01	.504E-01	.692E-01
FWHM spectrum width, dw/w	%	.112	.106	.709E-01	.624E-01	.454E-01
#						
Properties of the 5th harmonic in the saturation:						
#						
Radiation wavelength	nm	.800E-02				
Photon energy	keV	155.				
Contribution to the total power	P5/P	.124E-03	.124E-03	.123E-03	.123E-03	.123E-03
Pulse energy	microJ	.335E-02	.172E-01	.288E-01	.454E-01	.820E-01
Average power	W	.903E-04	.465E-03	.776E-03	.123E-02	.221E-02
Number oh photons per pulse	#	.135E+06	.693E+06	.116E+07	.183E+07	.330E+07
Average flux of photons	ph/sec	.364E+10	.187E+11	.312E+11	.493E+11	.891E+11
Coherence time	fs	.169E-01	.178E-01	.266E-01	.302E-01	.415E-01
FWHM spectrum width, dw/w	%	.112E-02	.106E-02	.709E-03	.624E-03	.454E-03
#						
Incoherent radiation:						
#						
Critical wavelength	nm	.139E-01				
Critical energy of SR	keV	89.5				
SR induced energy loss	MeV	6.18				
SR induced energy spread	MeV	.827				
SR power	W	3.34	16.7	41.7	83.4	167.
#						
Parameters of FEL theory:						
#						
Efficiency parameter (1D)	#	.605E-03	.525E-03	.372E-03	.326E-03	.253E-03
Efficiency parameter (3D)	#	.176E-02	.186E-02	.186E-02	.186E-02	.186E-02
N of electrons in coherence volume	#	.111E+07	.129E+07	.190E+07	.216E+07	.293E+07
Emittance parameter	#	1.47	1.79	2.75	3.21	4.45

Table C.3

Saturation characteristics of SASE1 (SASE2): 17.5 GeV, 0.05 nm

#						
Electron beam:						
#						
Energy of electrons	GeV	17.5				
Bunch charge	nC	.200E-01	.100	.250	.500	1.00
Peak current	kA	4.50	5.00	5.00	5.00	5.00
rms normalized emittance	mm-mrad	.320	.390	.600	.700	.970
rms energy spread	MeV	4.10	2.90	2.50	2.20	2.00
rms bunch length	micrometr	.360	1.92	4.98	9.17	23.0
Focusing beta function	m	15.0	15.3	28.2	35.7	55.8
rms size of electron beam	micrometr	11.8	13.2	22.2	27.0	39.8
Repetition rate	1/sec	.270E+05				
Electron beam power	kW	9.45	47.2	118.	236.	472.
#						
Undulator:						
#						
Undulator period	cm	4.00				
Undulator peak field	T	.526				
Undulator parameter K (rms)	#	1.39				
Undulator length	m	165.				
#						
Properties of the 1st harmonic in the saturation:						
#						
Radiation wavelength	nm	.500E-01				
Photon energy	keV	24.8				
Pulse energy	mJ	.320E-01	.179	.302	.478	.863
Peak power	GW	19.0	20.0	13.0	11.2	8.05
Average power	W	.863	4.84	8.16	12.9	23.3
FWHM spot size	mikrometr	25.1	24.9	36.3	41.8	55.2
FWHM angular divergence	microrad	1.09	1.08	.857	.781	.660
Coherence time	fs	.991E-01	.866E-01	.128	.146	.199
FWHM spectrum width, dw/w	%	.119	.136	.918E-01	.806E-01	.592E-01
Degree of transverse coherence	#	.942	.901	.711	.618	.419
Radiation pulse duration	fs	1.68	8.96	23.2	42.8	107.
Number of longitudinal modes	#	17	103	181	293	538
Fluctuations of the pulse energy	%	8.08	3.28	2.48	1.95	1.44
Degeneracy parameter	#	.447E+09	.393E+09	.299E+09	.254E+09	.169E+09
Number oh photons per pulse	#	.804E+10	.451E+11	.761E+11	.120E+12	.217E+12
Average flux of photons	ph/sec	.217E+15	.122E+16	.205E+16	.324E+16	.586E+16
Peak brilliance	#	.606E+34	.533E+34	.405E+34	.344E+34	.229E+34
Average brilliance	#	.275E+24	.129E+25	.254E+25	.398E+25	.663E+25
Saturation length	m	84.2	83.9	126.	144.	199.
Power gain length	m	4.62	4.83	7.07	8.02	10.8
SASE induced energy loss	MeV	4.23	4.00	2.60	2.23	1.61
SASE induced energy spread	MeV	11.5	10.6	7.09	6.10	4.57
#						
Properties of the 3rd harmonic in the saturation:						
#						
Radiation wavelength	nm	.167E-01				
Photon energy	keV	74.4				
Contribution to the total power	P3/P	.601E-02	.579E-02	.562E-02	.561E-02	.559E-02
Pulse energy	microJ	.192	1.04	1.70	2.68	4.82
Average power	W	.518E-02	.280E-01	.459E-01	.724E-01	.130
Number oh photons per pulse	#	.161E+08	.870E+08	.143E+09	.225E+09	.404E+09
Average flux of photons	ph/sec	.435E+12	.235E+13	.385E+13	.607E+13	.109E+14
Coherence time	fs	.330E-01	.289E-01	.428E-01	.488E-01	.664E-01
FWHM spectrum width, dw/w	%	.119	.136	.918E-01	.806E-01	.592E-01
#						
Properties of the 5th harmonic in the saturation:						
#						
Radiation wavelength	nm	.100E-01				
Photon energy	keV	124.				
Contribution to the total power	P5/P	.203E-03	.190E-03	.183E-03	.182E-03	.182E-03
Pulse energy	microJ	.650E-02	.340E-01	.553E-01	.872E-01	.157
Average power	W	.175E-03	.919E-03	.149E-02	.235E-02	.424E-02
Number oh photons per pulse	#	.327E+06	.171E+07	.278E+07	.438E+07	.790E+07
Average flux of photons	ph/sec	.883E+10	.462E+11	.751E+11	.118E+12	.213E+12
Coherence time	fs	.198E-01	.173E-01	.257E-01	.293E-01	.398E-01
FWHM spectrum width, dw/w	%	.119E-02	.136E-02	.918E-03	.806E-03	.592E-03
#						
Incoherent radiation:						
#						
Critical wavelength	nm	.116E-01				
Critical energy of SR	keV	107.				
SR induced energy loss	MeV	8.87				
SR induced energy spread	MeV	1.07				
SR power	W	4.79	23.9	59.9	120.	239.
#						
Parameters of FEL theory:						
#						
Efficiency parameter (1D)	#	.671E-03	.645E-03	.456E-03	.401E-03	.310E-03
Efficiency parameter (3D)	#	.183E-02	.193E-02	.193E-02	.193E-02	.193E-02
N of electrons in coherence volume	#	.108E+07	.126E+07	.184E+07	.209E+07	.282E+07
Emittance parameter	#	1.17	1.43	2.20	2.57	3.56

Table C.4

Saturation characteristics of SASE1 (SASE2): 17.5 GeV, 0.08 nm

#						
Energy of electrons	GeV	17.5				
Bunch charge	nC	.200E-01	.100	.250	.500	1.00
Peak current	kA	4.50	5.00	5.00	5.00	5.00
rms normalized emittance	mm-mrad	.320	.390	.600	.700	.970
rms energy spread	MeV	4.10	2.90	2.50	2.20	2.00
rms bunch length	micrometr	.360	1.92	4.98	9.17	23.0
Focusing beta function	m	15.0	15.0	15.0	18.3	28.9
rms size of electron beam	micrometr	11.8	13.1	16.2	19.3	28.6
Repetition rate	1/sec	.270E+05				
Electron beam power	kW	9.45	47.2	118.	236.	472.
#						
Undulator:						
#						
Undulator period	cm	4.00				
Undulator peak field	T	.727				
Undulator parameter K (rms)	#	1.92				
Undulator length	m	165.				
#						
Properties of the 1st harmonic in the saturation:						
#						
Radiation wavelength	nm	.800E-01				
Photon energy	keV	15.5				
Pulse energy	mJ	.536E-01	.317	.530	.792	1.43
Peak power	GW	31.9	35.4	22.8	18.5	13.3
Average power	W	1.45	8.57	14.3	21.4	38.6
FWHM spot size	mikrometr	26.5	28.4	33.2	35.0	46.5
FWHM angular divergence	microrad	1.65	1.55	1.32	1.28	1.07
Coherence time	fs	.119	.119	.150	.147	.198
FWHM spectrum width, dw/w	%	.158	.158	.125	.128	.953E-01
Degree of transverse coherence	#	.960	.958	.911	.863	.705
Radiation pulse duration	fs	1.68	8.96	23.2	42.8	107.
Number of longitudinal modes	#	14	75	155	292	542
Fluctuations of the pulse energy	%	8.91	3.85	2.68	1.95	1.43
Degeneracy parameter	#	.147E+10	.163E+10	.126E+10	.942E+09	.749E+09
Number oh photons per pulse	#	.216E+11	.128E+12	.213E+12	.319E+12	.576E+12
Average flux of photons	ph/sec	.582E+15	.345E+16	.576E+16	.861E+16	.156E+17
Peak brilliance	#	.487E+34	.539E+34	.416E+34	.312E+34	.248E+34
Average brilliance	#	.221E+24	.130E+25	.261E+25	.361E+25	.718E+25
Saturation length	m	63.6	63.7	80.5	90.5	123.
Power gain length	m	3.30	3.33	4.41	5.03	6.71
SASE induced energy loss	MeV	7.09	7.08	4.56	3.70	2.67
SASE induced energy spread	MeV	18.5	18.3	11.9	9.68	7.09
#						
Properties of the 3rd harmonic in the saturation:						
#						
Radiation wavelength	nm	.267E-01				
Photon energy	keV	46.5				
Contribution to the total power	P3/P	.102E-01	.101E-01	.720E-02	.704E-02	.686E-02
Pulse energy	microJ	.547	3.20	3.82	5.58	9.81
Average power	W	.148E-01	.865E-01	.103	.151	.265
Number oh photons per pulse	#	.734E+08	.430E+09	.512E+09	.748E+09	.132E+10
Average flux of photons	ph/sec	.198E+13	.116E+14	.138E+14	.202E+14	.355E+14
Coherence time	fs	.397E-01	.397E-01	.501E-01	.489E-01	.660E-01
FWHM spectrum width, dw/w	%	.158	.158	.125	.128	.953E-01
#						
Properties of the 5th harmonic in the saturation:						
#						
Radiation wavelength	nm	.160E-01				
Photon energy	keV	77.5				
Contribution to the total power	P5/P	.712E-03	.692E-03	.299E-03	.287E-03	.277E-03
Pulse energy	microJ	.381E-01	.220	.158	.227	.396
Average power	W	.103E-02	.593E-02	.427E-02	.614E-02	.107E-01
Number oh photons per pulse	#	.307E+07	.177E+08	.127E+08	.183E+08	.319E+08
Average flux of photons	ph/sec	.829E+11	.477E+12	.344E+12	.494E+12	.860E+12
Coherence time	fs	.238E-01	.238E-01	.301E-01	.294E-01	.396E-01
FWHM spectrum width, dw/w	%	.158E-02	.158E-02	.125E-02	.128E-02	.953E-03
#						
Incoherent radiation:						
#						
Critical wavelength	nm	.837E-02				
Critical energy of SR	keV	148.				
SR induced energy loss	MeV	16.9				
SR induced energy spread	MeV	1.70				
SR power	W	9.15	45.7	114.	229.	457.
#						
Parameters of FEL theory:						
#						
Efficiency parameter (1D)	#	.803E-03	.779E-03	.675E-03	.600E-03	.462E-03
Efficiency parameter (3D)	#	.189E-02	.200E-02	.200E-02	.200E-02	.200E-02
N of electrons in coherence volume	#	.124E+07	.139E+07	.184E+07	.210E+07	.280E+07
Emittance parameter	#	.734	.894	1.38	1.61	2.22

Table C.5

Saturation characteristics of SASE1 (SASE2): 17.5 GeV, 0.1 nm

#						
Electron beam:						
#						
Energy of electrons	GeV	17.5				
Bunch charge	nC	.200E-01	.100	.250	.500	1.00
Peak current	kA	4.50	5.00	5.00	5.00	5.00
rms normalized emittance	mm-mrad	.320	.390	.600	.700	.970
rms energy spread	MeV	4.10	2.90	2.50	2.20	2.00
rms bunch length	micrometr	.360	1.92	4.98	9.17	23.0
Focusing beta function	m	15.0	15.0	15.0	15.0	21.0
rms size of electron beam	micrometr	11.8	13.1	16.2	17.5	24.4
Repetition rate	1/sec	.270E+05				
Electron beam power	kW	9.45	47.2	118.	236.	472.
#						
Undulator:						
#						
Undulator period	cm	4.00				
Undulator peak field	T	.835				
Undulator parameter K (rms)	#	2.21				
Undulator length	m	165.				
#						
Properties of the 1st harmonic in the saturation:						
#						
Radiation wavelength	nm	.100E+00				
Photon energy	keV	12.4				
Pulse energy	mJ	.635E-01	.381	.697	1.10	1.80
Peak power	GW	37.8	42.5	30.0	25.6	16.8
Average power	W	1.71	10.3	18.8	29.6	48.7
FWHM spot size	mikrometr	27.3	29.2	34.2	36.2	42.7
FWHM angular divergence	microrad	2.00	1.88	1.60	1.52	1.35
Coherence time	fs	.135	.134	.164	.178	.201
FWHM spectrum width, dw/w	%	.175	.176	.144	.132	.117
Degree of transverse coherence	#	.960	.960	.950	.927	.820
Radiation pulse duration	fs	1.68	8.96	23.2	42.8	107.
Number of longitudinal modes	#	12	67	142	241	533
Fluctuations of the pulse energy	%	9.62	4.07	2.80	2.15	1.44
Degeneracy parameter	#	.246E+10	.275E+10	.235E+10	.212E+10	.139E+10
Number oh photons per pulse	#	.319E+11	.192E+12	.351E+12	.552E+12	.907E+12
Average flux of photons	ph/sec	.862E+15	.517E+16	.947E+16	.149E+17	.245E+17
Peak brilliance	#	.417E+34	.467E+34	.399E+34	.360E+34	.237E+34
Average brilliance	#	.189E+24	.113E+25	.250E+25	.417E+25	.685E+25
Saturation length	m	57.6	57.5	70.6	76.6	100.
Power gain length	m	2.93	2.94	3.71	4.11	5.45
SASE induced energy loss	MeV	8.40	8.50	6.00	5.12	3.36
SASE induced energy spread	MeV	21.8	21.9	15.5	13.2	8.80
#						
Properties of the 3rd harmonic in the saturation:						
#						
Radiation wavelength	nm	.333E-01				
Photon energy	keV	37.2				
Contribution to the total power	P3/P	.123E-01	.127E-01	.889E-02	.790E-02	.728E-02
Pulse energy	microJ	.780	4.84	6.20	8.66	13.1
Average power	W	.211E-01	.131	.167	.234	.355
Number oh photons per pulse	#	.131E+09	.811E+09	.104E+10	.145E+10	.220E+10
Average flux of photons	ph/sec	.353E+13	.219E+14	.281E+14	.392E+14	.594E+14
Coherence time	fs	.449E-01	.447E-01	.547E-01	.593E-01	.670E-01
FWHM spectrum width, dw/w	%	.175	.176	.144	.132	.117
#						
Properties of the 5th harmonic in the saturation:						
#						
Radiation wavelength	nm	.200E-01				
Photon energy	keV	62.0				
Contribution to the total power	P5/P	.110E-02	.119E-02	.489E-03	.364E-03	.310E-03
Pulse energy	microJ	.701E-01	.455	.341	.399	.560
Average power	W	.189E-02	.123E-01	.920E-02	.108E-01	.151E-01
Number oh photons per pulse	#	.705E+07	.458E+08	.343E+08	.401E+08	.563E+08
Average flux of photons	ph/sec	.190E+12	.124E+13	.925E+12	.108E+13	.152E+13
Coherence time	fs	.269E-01	.268E-01	.328E-01	.356E-01	.402E-01
FWHM spectrum width, dw/w	%	.175E-02	.176E-02	.144E-02	.132E-02	.117E-02
#						
Incoherent radiation:						
#						
Critical wavelength	nm	.729E-02				
Critical energy of SR	keV	170.				
SR induced energy loss	MeV	22.3				
SR induced energy spread	MeV	2.08				
SR power	W	12.1	60.3	151.	301.	603.
#						
Parameters of FEL theory:						
#						
Efficiency parameter (1D)	#	.870E-03	.843E-03	.731E-03	.694E-03	.556E-03
Efficiency parameter (3D)	#	.191E-02	.201E-02	.201E-02	.201E-02	.201E-02
N of electrons in coherence volume	#	.137E+07	.153E+07	.194E+07	.214E+07	.284E+07
Emittance parameter	#	.587	.716	1.10	1.28	1.78

Table C.6

Saturation characteristics of SASE1 (SASE2): 17.5 GeV, 0.15 nm

#						
Electron beam:						
#						
Energy of electrons	GeV	17.5				
Bunch charge	nC	.200E-01	.100	.250	.500	1.00
Peak current	kA	4.50	5.00	5.00	5.00	5.00
rms normalized emittance	mm-mrad	.320	.390	.600	.700	.970
rms energy spread	MeV	4.10	2.90	2.50	2.20	2.00
rms bunch length	micrometr	.360	1.92	4.98	9.17	23.0
Focusing beta function	m	15.0	15.0	15.0	15.0	15.0
rms size of electron beam	micrometr	11.8	13.1	16.2	17.5	20.6
Repetition rate	1/sec	.270E+05				
Electron beam power	kW	9.45	47.2	118.	236.	472.
#						
Undulator:						
#						
Undulator period	cm	4.00				
Undulator peak field	T	1.06				
Undulator parameter K (rms)	#	2.79				
Undulator length	m	165.				
#						
Properties of the 1st harmonic in the saturation:						
#						
Radiation wavelength	nm	.150				
Photon energy	keV	8.27				
Pulse energy	mJ	.809E-01	.490	.994	1.65	3.04
Peak power	GW	48.1	54.7	42.8	38.6	28.4
Average power	W	2.18	13.2	26.8	44.6	82.1
FWHM spot size	mikrometr	28.6	30.6	36.0	38.2	43.0
FWHM angular divergence	microrad	2.83	2.66	2.28	2.16	1.91
Coherence time	fs	.173	.172	.203	.217	.256
FWHM spectrum width, dw/w	%	.205	.206	.174	.163	.138
Degree of transverse coherence	#	.960	.960	.960	.960	.941
Radiation pulse duration	fs	1.68	8.96	23.2	42.8	107.
Number of longitudinal modes	#	10	52	114	198	418
Fluctuations of the pulse energy	%	10.5	4.62	3.12	2.37	1.63
Degeneracy parameter	#	.602E+10	.682E+10	.630E+10	.605E+10	.516E+10
Number oh photons per pulse	#	.610E+11	.370E+12	.750E+12	.125E+13	.229E+13
Average flux of photons	ph/sec	.165E+16	.999E+16	.202E+17	.337E+17	.620E+17
Peak brilliance	#	.302E+34	.342E+34	.316E+34	.304E+34	.259E+34
Average brilliance	#	.137E+24	.829E+24	.199E+25	.352E+25	.751E+25
Saturation length	m	49.5	49.4	58.5	62.4	74.0
Power gain length	m	2.45	2.44	2.93	3.15	3.85
SASE induced energy loss	MeV	10.7	10.9	8.55	7.71	5.67
SASE induced energy spread	MeV	27.6	28.0	21.9	19.8	14.6
#						
Properties of the 3rd harmonic in the saturation:						
#						
Radiation wavelength	nm	.500E-01				
Photon energy	keV	24.8				
Contribution to the total power	P3/P	.152E-01	.163E-01	.134E-01	.120E-01	.880E-02
Pulse energy	microJ	1.23	8.00	13.3	19.9	26.8
Average power	W	.331E-01	.216	.360	.537	.723
Number oh photons per pulse	#	.309E+09	.201E+10	.335E+10	.500E+10	.673E+10
Average flux of photons	ph/sec	.833E+13	.543E+14	.904E+14	.135E+15	.182E+15
Coherence time	fs	.576E-01	.573E-01	.678E-01	.722E-01	.854E-01
FWHM spectrum width, dw/w	%	.205	.206	.174	.163	.138
#						
Properties of the 5th harmonic in the saturation:						
#						
Radiation wavelength	nm	.300E-01				
Photon energy	keV	41.3				
Contribution to the total power	P5/P	.178E-02	.208E-02	.134E-02	.104E-02	.469E-03
Pulse energy	microJ	.144	1.02	1.33	1.72	1.43
Average power	W	.388E-02	.275E-01	.360E-01	.464E-01	.385E-01
Number oh photons per pulse	#	.217E+08	.154E+09	.201E+09	.259E+09	.215E+09
Average flux of photons	ph/sec	.585E+12	.415E+13	.544E+13	.700E+13	.581E+13
Coherence time	fs	.345E-01	.344E-01	.407E-01	.433E-01	.513E-01
FWHM spectrum width, dw/w	%	.205E-02	.206E-02	.174E-02	.163E-02	.138E-02
#						
Incoherent radiation:						
#						
Critical wavelength	nm	.576E-02				
Critical energy of SR	keV	215.				
SR induced energy loss	MeV	35.8				
SR induced energy spread	MeV	2.94				
SR power	W	19.3	96.6	242.	483.	966.
#						
Parameters of FEL theory:						
#						
Efficiency parameter (1D)	#	.100E-02	.970E-03	.840E-03	.798E-03	.716E-03
Efficiency parameter (3D)	#	.192E-02	.203E-02	.203E-02	.203E-02	.203E-02
N of electrons in coherence volume	#	.172E+07	.191E+07	.229E+07	.246E+07	.301E+07
Emittance parameter	#	.391	.477	.734	.856	1.19

Table C.7

Saturation characteristics of SASE1 (SASE2): 14 GeV, 0.04 nm

#						
Electron beam:						
#						
Energy of electrons	GeV	14.0				
Bunch charge	nC	.200E-01	.100	.250	.500	1.00
Peak current	kA	4.50	5.00	5.00	5.00	5.00
rms normalized emittance	mm-mrad	.320	.390	.600	.700	.970
rms energy spread	MeV	4.10	2.90	2.50	2.20	2.00
rms bunch length	micrometr	.360	1.92	4.98	9.17	23.0
Focusing beta function	m	18.8	27.3	49.3	63.0	97.3
rms size of electron beam	micrometr	14.8	19.7	32.9	40.1	58.7
Repetition rate	1/sec	.270E+05				
Electron beam power	kW	7.56	37.8	94.5	189.	378.
#						
Undulator:						
#						
Undulator period	cm	4.00				
Undulator peak field	T	.268				
Undulator parameter K (rms)	#	.708				
Undulator gap	cm	2.56				
Undulator length	m	165.				
#						
Properties of the 1st harmonic in the saturation:						
#						
Radiation wavelength	nm	.400E-01				
Photon energy	keV	31.0				
Pulse energy	mJ	.160E-01	.820E-01	.138	.219	.395
Peak power	GW	9.53	9.16	5.95	5.10	3.68
Average power	W	.432	2.22	3.73	5.90	10.7
FWHM spot size	mikrometr	25.7	32.0	46.2	53.6	70.3
FWHM angular divergence	microrad	.911	.780	.624	.567	.481
Coherence time	fs	.134	.132	.202	.227	.319
FWHM spectrum width, dw/w	%	.702E-01	.715E-01	.467E-01	.415E-01	.296E-01
Degree of transverse coherence	#	.806	.702	.438	.352	.208
Radiation pulse duration	fs	1.68	8.96	23.2	42.8	107.
Number of longitudinal modes	#	13	68	115	188	336
Fluctuations of the pulse energy	%	9.25	4.04	3.11	2.43	1.82
Degeneracy parameter	#	.208E+09	.171E+09	.106E+09	.823E+08	.491E+08
Number oh photons per pulse	#	.322E+10	.165E+11	.278E+11	.440E+11	.794E+11
Average flux of photons	ph/sec	.870E+14	.446E+15	.751E+15	.119E+16	.214E+16
Peak brilliance	#	.550E+34	.452E+34	.281E+34	.218E+34	.130E+34
Average brilliance	#	.249E+24	.109E+25	.176E+25	.252E+25	.377E+25
Saturation length	m	164.	162.	252.	285.	403.
Power gain length	m	9.25	9.07	13.7	15.4	21.3
SASE induced energy loss	MeV	2.12	1.83	1.19	1.02	.736
SASE induced energy spread	MeV	6.78	5.50	3.93	3.41	2.74
#						
Properties of the 3rd harmonic in the saturation:						
#						
Radiation wavelength	nm	.133E-01				
Photon energy	keV	93.0				
Contribution to the total power	P3/P	.190E-02	.190E-02	.190E-02	.190E-02	.190E-02
Pulse energy	microJ	.304E-01	.156	.263	.415	.750
Average power	W	.821E-03	.421E-02	.709E-02	.112E-01	.202E-01
Number oh photons per pulse	#	.204E+07	.105E+08	.176E+08	.278E+08	.503E+08
Average flux of photons	ph/sec	.551E+11	.282E+12	.476E+12	.752E+12	.136E+13
Coherence time	fs	.447E-01	.440E-01	.673E-01	.758E-01	.106
FWHM spectrum width, dw/w	%	.702E-01	.715E-01	.467E-01	.415E-01	.296E-01
#						
Properties of the 5th harmonic in the saturation:						
#						
Radiation wavelength	nm	.800E-02				
Photon energy	keV	155.				
Contribution to the total power	P5/P	.198E-04	.199E-04	.198E-04	.198E-04	.198E-04
Pulse energy	microJ	.318E-03	.163E-02	.275E-02	.434E-02	.784E-02
Average power	W	.858E-05	.440E-04	.741E-04	.117E-03	.212E-03
Number oh photons per pulse	#	.128E+05	.655E+05	.110E+06	.175E+06	.315E+06
Average flux of photons	ph/sec	.345E+09	.177E+10	.298E+10	.471E+10	.851E+10
Coherence time	fs	.268E-01	.264E-01	.404E-01	.455E-01	.638E-01
FWHM spectrum width, dw/w	%	.702E-03	.715E-03	.467E-03	.415E-03	.296E-03
#						
Incoherent radiation:						
#						
Critical wavelength	nm	.355E-01				
Critical energy of SR	keV	34.9				
SR induced energy loss	MeV	1.47				
SR induced energy spread	MeV	.273				
SR power	W	.795	3.98	9.94	19.9	39.8
#						
Parameters of FEL theory:						
#						
Efficiency parameter (1D)	#	.497E-03	.426E-03	.303E-03	.265E-03	.206E-03
Efficiency parameter (3D)	#	.163E-02	.172E-02	.172E-02	.172E-02	.172E-02
N of electrons in coherence volume	#	.174E+07	.189E+07	.285E+07	.320E+07	.444E+07
Emittance parameter	#	1.83	2.24	3.44	4.01	5.56

Table C.8

Saturation characteristics of SASE1 (SASE2): 14 GeV, 0.05 nm

#						
Electron beam:						
#						
Energy of electrons	GeV	14.0				
Bunch charge	nC	.200E-01	.100	.250	.500	1.00
Peak current	kA	4.50	5.00	5.00	5.00	5.00
rms normalized emittance	mm-mrad	.320	.390	.600	.700	.970
rms energy spread	MeV	4.10	2.90	2.50	2.20	2.00
rms bunch length	micrometr	.360	1.92	4.98	9.17	23.0
Focusing beta function	m	15.0	19.2	34.9	44.5	69.3
rms size of electron beam	micrometr	13.2	16.5	27.7	33.7	49.5
Repetition rate	1/sec	.270E+05				
Electron beam power	kW	7.56	37.8	94.5	189.	378.
#						
Undulator:						
#						
Undulator period	cm	4.00				
Undulator peak field	T	.355				
Undulator parameter K (rms)	#	.936				
Undulator length	m	165.				
#						
Properties of the 1st harmonic in the saturation:						
#						
Radiation wavelength	nm	.500E-01				
Photon energy	keV	24.8				
Pulse energy	mJ	.164E-01	.116	.196	.309	.558
Peak power	GW	9.77	13.0	8.42	7.22	5.21
Average power	W	.443	3.13	5.28	8.35	15.1
FWHM spot size	mikrometr	27.2	28.9	41.9	48.5	63.9
FWHM angular divergence	microrad	1.01	1.00	.799	.726	.614
Coherence time	fs	.125	.111	.166	.188	.259
FWHM spectrum width, dw/w	%	.942E-01	.106	.708E-01	.625E-01	.454E-01
Degree of transverse coherence	#	.893	.818	.575	.480	.301
Radiation pulse duration	fs	1.68	8.96	23.2	42.8	107.
Number of longitudinal modes	#	13	81	140	227	413
Fluctuations of the pulse energy	%	9.25	3.70	2.82	2.21	1.64
Degeneracy parameter	#	.275E+09	.295E+09	.203E+09	.164E+09	.102E+09
Number oh photons per pulse	#	.413E+10	.292E+11	.492E+11	.778E+11	.140E+12
Average flux of photons	ph/sec	.111E+15	.788E+15	.133E+16	.210E+16	.379E+16
Peak brilliance	#	.373E+34	.401E+34	.275E+34	.223E+34	.139E+34
Average brilliance	#	.169E+24	.969E+24	.173E+25	.257E+25	.401E+25
Saturation length	m	106.	108.	165.	187.	261.
Power gain length	m	5.93	6.13	9.08	10.2	14.0
SASE induced energy loss	MeV	2.17	2.59	1.68	1.44	1.04
SASE induced energy spread	MeV	6.89	7.21	4.97	4.29	3.32
#						
Properties of the 3rd harmonic in the saturation:						
#						
Radiation wavelength	nm	.167E-01				
Photon energy	keV	74.4				
Contribution to the total power	P3/P	.340E-02	.340E-02	.338E-02	.338E-02	.338E-02
Pulse energy	microJ	.558E-01	.395	.661	1.04	1.89
Average power	W	.151E-02	.107E-01	.179E-01	.282E-01	.509E-01
Number oh photons per pulse	#	.467E+07	.331E+08	.554E+08	.876E+08	.158E+09
Average flux of photons	ph/sec	.126E+12	.893E+12	.150E+13	.236E+13	.427E+13
Coherence time	fs	.417E-01	.369E-01	.555E-01	.628E-01	.865E-01
FWHM spectrum width, dw/w	%	.942E-01	.106	.708E-01	.625E-01	.454E-01
#						
Properties of the 5th harmonic in the saturation:						
#						
Radiation wavelength	nm	.100E-01				
Photon energy	keV	124.				
Contribution to the total power	P5/P	.645E-04	.645E-04	.643E-04	.643E-04	.643E-04
Pulse energy	microJ	.106E-02	.749E-02	.126E-01	.199E-01	.359E-01
Average power	W	.286E-04	.202E-03	.340E-03	.536E-03	.969E-03
Number oh photons per pulse	#	.532E+05	.377E+06	.633E+06	.999E+06	.181E+07
Average flux of photons	ph/sec	.144E+10	.102E+11	.171E+11	.270E+11	.487E+11
Coherence time	fs	.250E-01	.222E-01	.333E-01	.377E-01	.519E-01
FWHM spectrum width, dw/w	%	.942E-03	.106E-02	.708E-03	.625E-03	.454E-03
#						
Incoherent radiation:						
#						
Critical wavelength	nm	.268E-01				
Critical energy of SR	keV	46.2				
SR induced energy loss	MeV	2.57				
SR induced energy spread	MeV	.394				
SR power	W	1.39	6.95	17.4	34.8	69.5
#						
Parameters of FEL theory:						
#						
Efficiency parameter (1D)	#	.627E-03	.560E-03	.397E-03	.348E-03	.269E-03
Efficiency parameter (3D)	#	.185E-02	.195E-02	.195E-02	.195E-02	.195E-02
N of electrons in coherence volume	#	.139E+07	.160E+07	.237E+07	.267E+07	.364E+07
Emittance parameter	#	1.47	1.79	2.75	3.21	4.45

Table C.9

Saturation characteristics of SASE1 (SASE2): 14 GeV, 0.08 nm

#						
Electron beam:						
#						
Energy of electrons	GeV	14.0				
Bunch charge	nC	.200E-01	.100	.250	.500	1.00
Peak current	kA	4.50	5.00	5.00	5.00	5.00
rms normalized emittance	mm-mrad	.320	.390	.600	.700	.970
rms energy spread	MeV	4.10	2.90	2.50	2.20	2.00
rms bunch length	micrometr	.360	1.92	4.98	9.17	23.0
Focusing beta function	m	15.0	15.0	17.7	22.5	35.5
rms size of electron beam	micrometr	13.2	14.6	19.7	24.0	35.4
Repetition rate	1/sec	.270E+05				
Electron beam power	kW	7.56	37.8	94.5	189.	378.
#						
Undulator:						
#						
Undulator period	cm	4.00				
Undulator peak field	T	.536				
Undulator parameter K (rms)	#	1.42				
Undulator length	m	165.				
#						
Properties of the 1st harmonic in the saturation:						
#						
Radiation wavelength	nm	.800E-01				
Photon energy	keV	15.5				
Pulse energy	mJ	.354E-01	.215	.347	.549	.991
Peak power	GW	21.1	24.0	14.9	12.8	9.24
Average power	W	.955	5.81	9.37	14.8	26.8
FWHM spot size	mikrometr	28.5	30.5	34.9	40.3	53.5
FWHM angular divergence	microrad	1.54	1.44	1.31	1.20	1.00
Coherence time	fs	.131	.128	.148	.168	.228
FWHM spectrum width, dw/w	%	.144	.147	.127	.112	.828E-01
Degree of transverse coherence	#	.958	.948	.835	.762	.569
Radiation pulse duration	fs	1.68	8.96	23.2	42.8	107.
Number of longitudinal modes	#	13	70	157	254	471
Fluctuations of the pulse energy	%	9.25	3.98	2.66	2.09	1.54
Degeneracy parameter	#	.106E+10	.117E+10	.744E+09	.661E+09	.482E+09
Number oh photons per pulse	#	.142E+11	.866E+11	.140E+12	.221E+12	.399E+12
Average flux of photons	ph/sec	.384E+15	.234E+16	.377E+16	.596E+16	.108E+17
Peak brilliance	#	.351E+34	.389E+34	.246E+34	.219E+34	.160E+34
Average brilliance	#	.159E+24	.940E+24	.155E+25	.253E+25	.462E+25
Saturation length	m	69.7	68.5	91.4	104.	142.
Power gain length	m	3.64	3.63	5.07	5.74	7.69
SASE induced energy loss	MeV	4.68	4.80	2.99	2.56	1.85
SASE induced energy spread	MeV	12.6	12.6	8.02	6.89	5.12
#						
Properties of the 3rd harmonic in the saturation:						
#						
Radiation wavelength	nm	.267E-01				
Photon energy	keV	46.5				
Contribution to the total power	P3/P	.696E-02	.690E-02	.578E-02	.574E-02	.569E-02
Pulse energy	microJ	.246	1.48	2.01	3.15	5.63
Average power	W	.665E-02	.401E-01	.542E-01	.850E-01	.152
Number oh photons per pulse	#	.330E+08	.199E+09	.269E+09	.423E+09	.756E+09
Average flux of photons	ph/sec	.892E+12	.537E+13	.727E+13	.114E+14	.204E+14
Coherence time	fs	.435E-01	.427E-01	.494E-01	.562E-01	.759E-01
FWHM spectrum width, dw/w	%	.144	.147	.127	.112	.828E-01
#						
Properties of the 5th harmonic in the saturation:						
#						
Radiation wavelength	nm	.160E-01				
Photon energy	keV	77.5				
Contribution to the total power	P5/P	.288E-03	.281E-03	.191E-03	.190E-03	.188E-03
Pulse energy	microJ	.102E-01	.605E-01	.664E-01	.104	.186
Average power	W	.275E-03	.163E-02	.179E-02	.281E-02	.503E-02
Number oh photons per pulse	#	.820E+06	.487E+07	.534E+07	.838E+07	.150E+08
Average flux of photons	ph/sec	.221E+11	.131E+12	.144E+12	.226E+12	.405E+12
Coherence time	fs	.261E-01	.256E-01	.296E-01	.337E-01	.455E-01
FWHM spectrum width, dw/w	%	.144E-02	.147E-02	.127E-02	.112E-02	.828E-03
#						
Incoherent radiation:						
#						
Critical wavelength	nm	.178E-01				
Critical energy of SR	keV	69.8				
SR induced energy loss	MeV	5.88				
SR induced energy spread	MeV	.700				
SR power	W	3.18	15.9	39.7	79.4	159.
#						
Parameters of FEL theory:						
#						
Efficiency parameter (1D)	#	.786E-03	.762E-03	.624E-03	.548E-03	.422E-03
Efficiency parameter (3D)	#	.205E-02	.216E-02	.216E-02	.216E-02	.216E-02
N of electrons in coherence volume	#	.137E+07	.151E+07	.211E+07	.240E+07	.321E+07
Emittance parameter	#	.917	1.12	1.72	2.01	2.78

Table C.10

Saturation characteristics of SASE1 (SASE2): 14 GeV, 0.1 nm

#						
Electron beam:						
#						
Energy of electrons	GeV	14.0				
Bunch charge	nC	.200E-01	.100	.250	.500	1.00
Peak current	kA	4.50	5.00	5.00	5.00	5.00
rms normalized emittance	mm-mrad	.320	.390	.600	.700	.970
rms energy spread	MeV	4.10	2.90	2.50	2.20	2.00
rms bunch length	micrometr	.360	1.92	4.98	9.17	23.0
Focusing beta function	m	15.0	15.0	15.0	16.4	25.9
rms size of electron beam	micrometr	13.2	14.6	18.1	20.4	30.3
Repetition rate	1/sec	.270E+05				
Electron beam power	kW	7.56	37.8	94.5	189.	378.
#						
Undulator:						
#						
Undulator period	cm	4.00				
Undulator peak field	T	.628				
Undulator parameter K (rms)	#	1.66				
Undulator length	m	165.				
#						
Properties of the 1st harmonic in the saturation:						
#						
Radiation wavelength	nm	.100E+00				
Photon energy	keV	12.4				
Pulse energy	mJ	.441E-01	.272	.470	.700	1.26
Peak power	GW	26.3	30.3	20.2	16.3	11.8
Average power	W	1.19	7.34	12.7	18.9	34.1
FWHM spot size	mikrometr	29.3	31.3	36.6	37.0	49.2
FWHM angular divergence	microrad	1.87	1.75	1.49	1.51	1.27
Coherence time	fs	.143	.141	.175	.168	.226
FWHM spectrum width, dw/w	%	.164	.168	.134	.140	.104
Degree of transverse coherence	#	.960	.958	.911	.863	.705
Radiation pulse duration	fs	1.68	8.96	23.2	42.8	107.
Number of longitudinal modes	#	12	64	132	255	475
Fluctuations of the pulse energy	%	9.62	4.17	2.90	2.09	1.53
Degeneracy parameter	#	.182E+10	.205E+10	.162E+10	.119E+10	.944E+09
Number oh photons per pulse	#	.222E+11	.137E+12	.236E+12	.352E+12	.636E+12
Average flux of photons	ph/sec	.599E+15	.369E+16	.638E+16	.951E+16	.172E+17
Peak brilliance	#	.308E+34	.348E+34	.276E+34	.202E+34	.160E+34
Average brilliance	#	.140E+24	.843E+24	.173E+25	.234E+25	.464E+25
Saturation length	m	61.3	60.3	75.4	83.2	113.
Power gain length	m	3.14	3.10	4.04	4.58	6.10
SASE induced energy loss	MeV	5.84	6.07	4.04	3.27	2.36
SASE induced energy spread	MeV	15.4	15.7	10.6	8.62	6.34
#						
Properties of the 3rd harmonic in the saturation:						
#						
Radiation wavelength	nm	.333E-01				
Photon energy	keV	37.2				
Contribution to the total power	P3/P	.904E-02	.942E-02	.684E-02	.654E-02	.639E-02
Pulse energy	microJ	.399	2.56	3.21	4.58	8.08
Average power	W	.108E-01	.691E-01	.867E-01	.124	.218
Number oh photons per pulse	#	.669E+08	.429E+09	.539E+09	.768E+09	.136E+10
Average flux of photons	ph/sec	.181E+13	.116E+14	.145E+14	.207E+14	.366E+14
Coherence time	fs	.478E-01	.468E-01	.585E-01	.560E-01	.753E-01
FWHM spectrum width, dw/w	%	.164	.168	.134	.140	.104
#						
Properties of the 5th harmonic in the saturation:						
#						
Radiation wavelength	nm	.200E-01				
Photon energy	keV	62.0				
Contribution to the total power	P5/P	.538E-03	.597E-03	.267E-03	.246E-03	.239E-03
Pulse energy	microJ	.237E-01	.162	.126	.172	.302
Average power	W	.641E-03	.438E-02	.339E-02	.465E-02	.814E-02
Number oh photons per pulse	#	.239E+07	.163E+08	.126E+08	.173E+08	.303E+08
Average flux of photons	ph/sec	.645E+11	.441E+12	.341E+12	.468E+12	.819E+12
Coherence time	fs	.287E-01	.281E-01	.351E-01	.336E-01	.452E-01
FWHM spectrum width, dw/w	%	.164E-02	.168E-02	.134E-02	.140E-02	.104E-02
#						
Incoherent radiation:						
#						
Critical wavelength	nm	.151E-01				
Critical energy of SR	keV	81.9				
SR induced energy loss	MeV	8.09				
SR induced energy spread	MeV	.880				
SR power	W	4.37	21.8	54.6	109.	218.
#						
Parameters of FEL theory:						
#						
Efficiency parameter (1D)	#	.858E-03	.832E-03	.721E-03	.665E-03	.512E-03
Efficiency parameter (3D)	#	.209E-02	.220E-02	.220E-02	.220E-02	.220E-02
N of electrons in coherence volume	#	.147E+07	.162E+07	.211E+07	.239E+07	.318E+07
Emittance parameter	#	.734	.894	1.38	1.61	2.22

Table C.11

Saturation characteristics of SASE1 (SASE2): 14 GeV, 0.15 nm

#						
Electron beam:						
#						
Energy of electrons	GeV	14.0				
Bunch charge	nC	.200E-01	.100	.250	.500	1.00
Peak current	kA	4.50	5.00	5.00	5.00	5.00
rms normalized emittance	mm-mrad	.320	.390	.600	.700	.970
rms energy spread	MeV	4.10	2.90	2.50	2.20	2.00
rms bunch length	micrometr	.360	1.92	4.98	9.17	23.0
Focusing beta function	m	15.0	15.0	15.0	15.0	15.0
rms size of electron beam	micrometr	13.2	14.6	18.1	19.6	23.0
Repetition rate	1/sec	.270E+05				
Electron beam power	kW	7.56	37.8	94.5	189.	378.
#						
Undulator:						
#						
Undulator period	cm	4.00				
Undulator peak field	T	.815				
Undulator parameter K (rms)	#	2.15				
Undulator length	m	165.				
#						
Properties of the 1st harmonic in the saturation:						
#						
Radiation wavelength	nm	.150				
Photon energy	keV	8.27				
Pulse energy	mJ	.594E-01	.369	.729	1.20	2.10
Peak power	GW	35.4	41.2	31.4	28.0	19.6
Average power	W	1.60	9.97	19.7	32.4	56.7
FWHM spot size	mikrometr	30.8	32.9	38.6	40.9	46.0
FWHM angular divergence	microrad	2.66	2.50	2.13	2.01	1.78
Coherence time	fs	.178	.175	.209	.223	.269
FWHM spectrum width, dw/w	%	.198	.202	.169	.158	.132
Degree of transverse coherence	#	.960	.960	.958	.952	.890
Radiation pulse duration	fs	1.68	8.96	23.2	42.8	107.
Number of longitudinal modes	#	9	51	111	192	399
Fluctuations of the pulse energy	%	11.1	4.67	3.16	2.41	1.67
Degeneracy parameter	#	.457E+10	.523E+10	.474E+10	.449E+10	.353E+10
Number oh photons per pulse	#	.448E+11	.279E+12	.550E+12	.905E+12	.158E+13
Average flux of photons	ph/sec	.121E+16	.753E+16	.149E+17	.244E+17	.428E+17
Peak brilliance	#	.230E+34	.263E+34	.238E+34	.226E+34	.177E+34
Average brilliance	#	.104E+24	.636E+24	.149E+25	.261E+25	.513E+25
Saturation length	m	51.1	50.3	60.1	64.3	77.5
Power gain length	m	2.54	2.50	3.04	3.29	4.13
SASE induced energy loss	MeV	7.86	8.24	6.28	5.60	3.91
SASE induced energy spread	MeV	20.5	21.2	16.2	14.4	10.2
#						
Properties of the 3rd harmonic in the saturation:						
#						
Radiation wavelength	nm	.500E-01				
Photon energy	keV	24.8				
Contribution to the total power	P3/P	.125E-01	.138E-01	.108E-01	.957E-02	.744E-02
Pulse energy	microJ	.742	5.11	7.87	11.5	15.6
Average power	W	.200E-01	.138	.212	.310	.422
Number oh photons per pulse	#	.187E+09	.129E+10	.198E+10	.289E+10	.393E+10
Average flux of photons	ph/sec	.504E+13	.347E+14	.534E+14	.779E+14	.106E+15
Coherence time	fs	.595E-01	.584E-01	.696E-01	.744E-01	.895E-01
FWHM spectrum width, dw/w	%	.198	.202	.169	.158	.132
#						
Properties of the 5th harmonic in the saturation:						
#						
Radiation wavelength	nm	.300E-01				
Photon energy	keV	41.3				
Contribution to the total power	P5/P	.115E-02	.145E-02	.806E-03	.594E-03	.321E-03
Pulse energy	microJ	.683E-01	.537	.588	.712	.674
Average power	W	.184E-02	.145E-01	.159E-01	.192E-01	.182E-01
Number oh photons per pulse	#	.103E+08	.811E+08	.887E+08	.107E+09	.102E+09
Average flux of photons	ph/sec	.278E+12	.219E+13	.240E+13	.290E+13	.274E+13
Coherence time	fs	.357E-01	.350E-01	.418E-01	.446E-01	.537E-01
FWHM spectrum width, dw/w	%	.198E-02	.202E-02	.169E-02	.158E-02	.132E-02
#						
Incoherent radiation:						
#						
Critical wavelength	nm	.117E-01				
Critical energy of SR	keV	106.				
SR induced energy loss	MeV	13.6				
SR induced energy spread	MeV	1.28				
SR power	W	7.34	36.7	91.8	184.	367.
#						
Parameters of FEL theory:						
#						
Efficiency parameter (1D)	#	.995E-03	.965E-03	.836E-03	.794E-03	.712E-03
Efficiency parameter (3D)	#	.213E-02	.225E-02	.225E-02	.225E-02	.225E-02
N of electrons in coherence volume	#	.178E+07	.195E+07	.238E+07	.257E+07	.323E+07
Emittance parameter	#	.489	.596	.917	1.07	1.48

Table C.12

Saturation characteristics of SASE1 (SASE2): 14 GeV, 0.25 nm

#						
Electron beam:						
#						
Energy of electrons	GeV	14.0				
Bunch charge	nC	.200E-01	.100	.250	.500	1.00
Peak current	kA	4.50	5.00	5.00	5.00	5.00
rms normalized emittance	mm-mrad	.320	.390	.600	.700	.970
rms energy spread	MeV	4.10	2.90	2.50	2.20	2.00
rms bunch length	micrometr	.360	1.92	4.98	9.17	23.0
Focusing beta function	m	15.0	15.0	15.0	15.0	15.0
rms size of electron beam	micrometr	13.2	14.6	18.1	19.6	23.0
Repetition rate	1/sec	.270E+05				
Electron beam power	kW	7.56	37.8	94.5	189.	378.
#						
Undulator:						
#						
Undulator period	cm	4.00				
Undulator peak field	T	1.10				
Undulator parameter K (rms)	#	2.90				
Undulator length	m	165.				
#						
Properties of the 1st harmonic in the saturation:						
#						
Radiation wavelength	nm	.250				
Photon energy	keV	4.96				
Pulse energy	mJ	.782E-01	.486	1.04	1.78	3.59
Peak power	GW	46.5	54.2	44.7	41.6	33.5
Average power	W	2.11	13.1	28.0	48.1	97.0
FWHM spot size	mikrometr	32.6	35.0	41.2	43.6	49.2
FWHM angular divergence	microrad	4.11	3.87	3.32	3.14	2.79
Coherence time	fs	.246	.243	.282	.297	.341
FWHM spectrum width, dw/w	%	.239	.243	.209	.198	.173
Degree of transverse coherence	#	.960	.960	.960	.960	.958
Radiation pulse duration	fs	1.68	8.96	23.2	42.8	107.
Number of longitudinal modes	#	7	37	83	144	315
Fluctuations of the pulse energy	%	12.6	5.48	3.66	2.78	1.88
Degeneracy parameter	#	.138E+11	.159E+11	.152E+11	.149E+11	.137E+11
Number oh photons per pulse	#	.983E+11	.611E+12	.131E+13	.224E+13	.452E+13
Average flux of photons	ph/sec	.265E+16	.165E+17	.353E+17	.605E+17	.122E+18
Peak brilliance	#	.150E+34	.172E+34	.165E+34	.162E+34	.149E+34
Average brilliance	#	.681E+23	.417E+24	.104E+25	.187E+25	.432E+25
Saturation length	m	42.6	42.1	48.9	51.6	59.3
Power gain length	m	2.05	2.02	2.36	2.50	2.92
SASE induced energy loss	MeV	10.3	10.8	8.94	8.32	6.70
SASE induced energy spread	MeV	26.7	27.8	22.9	21.3	17.2
#						
Properties of the 3rd harmonic in the saturation:						
#						
Radiation wavelength	nm	.833E-01				
Photon energy	keV	14.9				
Contribution to the total power	P3/P	.155E-01	.173E-01	.159E-01	.152E-01	.123E-01
Pulse energy	microJ	1.21	8.39	16.5	27.1	44.0
Average power	W	.327E-01	.227	.445	.732	1.19
Number oh photons per pulse	#	.508E+09	.352E+10	.691E+10	.114E+11	.185E+11
Average flux of photons	ph/sec	.137E+14	.950E+14	.186E+15	.307E+15	.498E+15
Coherence time	fs	.821E-01	.809E-01	.939E-01	.990E-01	.114
FWHM spectrum width, dw/w	%	.239	.243	.209	.198	.173
#						
Properties of the 5th harmonic in the saturation:						
#						
Radiation wavelength	nm	.500E-01				
Photon energy	keV	24.8				
Contribution to the total power	P5/P	.186E-02	.234E-02	.195E-02	.179E-02	.109E-02
Pulse energy	microJ	.145	1.14	2.03	3.18	3.90
Average power	W	.392E-02	.307E-01	.548E-01	.859E-01	.105
Number oh photons per pulse	#	.365E+08	.286E+09	.511E+09	.801E+09	.981E+09
Average flux of photons	ph/sec	.986E+12	.772E+13	.138E+14	.216E+14	.265E+14
Coherence time	fs	.492E-01	.486E-01	.563E-01	.594E-01	.681E-01
FWHM spectrum width, dw/w	%	.239E-02	.243E-02	.209E-02	.198E-02	.173E-02
#						
Incoherent radiation:						
#						
Critical wavelength	nm	.868E-02				
Critical energy of SR	keV	143.				
SR induced energy loss	MeV	24.6				
SR induced energy spread	MeV	1.99				
SR power	W	13.3	66.5	166.	332.	665.
#						
Parameters of FEL theory:						
#						
Efficiency parameter (1D)	#	.119E-02	.115E-02	.997E-03	.947E-03	.849E-03
Efficiency parameter (3D)	#	.215E-02	.227E-02	.227E-02	.227E-02	.227E-02
N of electrons in coherence volume	#	.241E+07	.263E+07	.308E+07	.326E+07	.381E+07
Emittance parameter	#	.294	.358	.550	.642	.890

Table C.13

Saturation characteristics of SASE1 (SASE2): 10.5 GeV, 0.08 nm

#						
Electron beam:						
#						
Energy of electrons	GeV	10.5				
Bunch charge	nC	.200E-01	.100	.250	.500	1.00
Peak current	kA	4.50	5.00	5.00	5.00	5.00
rms normalized emittance	mm-mrad	.320	.390	.600	.700	.970
rms energy spread	MeV	4.10	2.90	2.50	2.20	2.00
rms bunch length	micrometr	.360	1.92	4.98	9.17	23.0
Focusing beta function	m	15.0	15.0	23.4	29.9	46.6
rms size of electron beam	micrometr	15.3	16.9	26.2	31.9	46.9
Repetition rate	1/sec	.270E+05				
Electron beam power	kW	5.67	28.3	70.9	142.	283.
#						
Undulator:						
#						
Undulator period	cm	4.00				
Undulator peak field	T	.314				
Undulator parameter K (rms)	#	.830				
Undulator length	m	165.				
#						
Properties of the 1st harmonic in the saturation:						
#						
Radiation wavelength	nm	.800E-01				
Photon energy	keV	15.5				
Pulse energy	mJ	.150E-01	.982E-01	.194	.306	.553
Peak power	GW	8.91	11.0	8.34	7.15	5.16
Average power	W	.404	2.65	5.23	8.27	14.9
FWHM spot size	mikrometr	31.8	33.9	42.1	48.8	64.3
FWHM angular divergence	microrad	1.38	1.29	1.20	1.09	.920
Coherence time	fs	.179	.168	.215	.242	.334
FWHM spectrum width, dw/w	%	.105	.112	.879E-01	.778E-01	.564E-01
Degree of transverse coherence	#	.936	.888	.687	.593	.395
Radiation pulse duration	fs	1.68	8.96	23.2	42.8	107.
Number of longitudinal modes	#	9	53	108	177	321
Fluctuations of the pulse energy	%	11.1	4.58	3.21	2.51	1.86
Degeneracy parameter	#	.602E+09	.657E+09	.495E+09	.413E+09	.275E+09
Number oh photons per pulse	#	.602E+10	.395E+11	.780E+11	.123E+12	.223E+12
Average flux of photons	ph/sec	.163E+15	.107E+16	.211E+16	.333E+16	.601E+16
Peak brilliance	#	.199E+34	.218E+34	.164E+34	.137E+34	.909E+33
Average brilliance	#	.904E+23	.526E+24	.103E+25	.158E+25	.263E+25
Saturation length	m	95.9	89.8	134.	152.	212.
Power gain length	m	5.06	4.86	7.26	8.17	11.2
SASE induced energy loss	MeV	1.98	2.19	1.67	1.43	1.03
SASE induced energy spread	MeV	6.50	6.29	4.93	4.26	3.30
#						
Properties of the 3rd harmonic in the saturation:						
#						
Radiation wavelength	nm	.267E-01				
Photon energy	keV	46.5				
Contribution to the total power	P3/P	.275E-02	.274E-02	.270E-02	.270E-02	.270E-02
Pulse energy	microJ	.411E-01	.269	.523	.826	1.49
Average power	W	.111E-02	.727E-02	.141E-01	.223E-01	.403E-01
Number oh photons per pulse	#	.552E+07	.361E+08	.702E+08	.111E+09	.200E+09
Average flux of photons	ph/sec	.149E+12	.975E+12	.189E+13	.299E+13	.540E+13
Coherence time	fs	.598E-01	.559E-01	.715E-01	.808E-01	.111
FWHM spectrum width, dw/w	%	.105	.112	.879E-01	.778E-01	.564E-01
#						
Properties of the 5th harmonic in the saturation:						
#						
Radiation wavelength	nm	.160E-01				
Photon energy	keV	77.5				
Contribution to the total power	P5/P	.413E-04	.411E-04	.405E-04	.405E-04	.405E-04
Pulse energy	microJ	.617E-03	.404E-02	.786E-02	.124E-01	.224E-01
Average power	W	.167E-04	.109E-03	.212E-03	.335E-03	.605E-03
Number oh photons per pulse	#	.497E+05	.325E+06	.632E+06	.999E+06	.180E+07
Average flux of photons	ph/sec	.134E+10	.878E+10	.171E+11	.270E+11	.487E+11
Coherence time	fs	.359E-01	.335E-01	.429E-01	.485E-01	.669E-01
FWHM spectrum width, dw/w	%	.105E-02	.112E-02	.879E-03	.778E-03	.564E-03
#						
Incoherent radiation:						
#						
Critical wavelength	nm	.538E-01				
Critical energy of SR	keV	23.0				
SR induced energy loss	MeV	1.14				
SR induced energy spread	MeV	.189				
SR power	W	.615	3.07	7.68	15.4	30.7
#						
Parameters of FEL theory:						
#						
Efficiency parameter (1D)	#	.711E-03	.689E-03	.514E-03	.450E-03	.349E-03
Efficiency parameter (3D)	#	.203E-02	.214E-02	.214E-02	.214E-02	.214E-02
N of electrons in coherence volume	#	.190E+07	.203E+07	.303E+07	.340E+07	.465E+07
Emittance parameter	#	1.22	1.49	2.29	2.68	3.71

Table C.14

Saturation characteristics of SASE1 (SASE2): 10.5 GeV, 0.1 nm

#						
Electron beam:						
#						
Energy of electrons	GeV	10.5				
Bunch charge	nC	.200E-01	.100	.250	.500	1.00
Peak current	kA	4.50	5.00	5.00	5.00	5.00
rms normalized emittance	mm-mrad	.320	.390	.600	.700	.970
rms energy spread	MeV	4.10	2.90	2.50	2.20	2.00
rms bunch length	micrometr	.360	1.92	4.98	9.17	23.0
Focusing beta function	m	15.0	15.0	16.8	21.4	33.5
rms size of electron beam	micrometr	15.3	16.9	22.1	27.0	39.8
Repetition rate	1/sec	.270E+05				
Electron beam power	kW	5.67	28.3	70.9	142.	283.
#						
Undulator:						
#						
Undulator period	cm	4.00				
Undulator peak field	T	.399				
Undulator parameter K (rms)	#	1.05				
Undulator length	m	165.				
#						
Properties of the 1st harmonic in the saturation:						
#						
Radiation wavelength	nm	.100E+00				
Photon energy	keV	12.4				
Pulse energy	mJ	.228E-01	.150	.264	.417	.754
Peak power	GW	13.6	16.8	11.4	9.74	7.03
Average power	W	.616	4.06	7.13	11.3	20.4
FWHM spot size	mikrometr	32.3	34.5	38.3	44.4	58.7
FWHM angular divergence	microrad	1.70	1.59	1.52	1.39	1.17
Coherence time	fs	.174	.164	.191	.216	.294
FWHM spectrum width, dw/w	%	.135	.143	.124	.109	.801E-01
Degree of transverse coherence	#	.957	.940	.806	.727	.528
Radiation pulse duration	fs	1.68	8.96	23.2	42.8	107.
Number of longitudinal modes	#	10	54	122	198	364
Fluctuations of the pulse energy	%	10.5	4.54	3.02	2.37	1.75
Degeneracy parameter	#	.114E+10	.130E+10	.879E+09	.770E+09	.550E+09
Number oh photons per pulse	#	.115E+11	.756E+11	.133E+12	.210E+12	.379E+12
Average flux of photons	ph/sec	.310E+15	.204E+16	.359E+16	.567E+16	.102E+17
Peak brilliance	#	.194E+34	.221E+34	.149E+34	.131E+34	.933E+33
Average brilliance	#	.878E+23	.535E+24	.935E+24	.151E+25	.270E+25
Saturation length	m	74.7	70.6	94.9	108.	149.
Power gain length	m	3.85	3.69	5.18	5.85	7.89
SASE induced energy loss	MeV	3.02	3.35	2.27	1.95	1.41
SASE induced energy spread	MeV	8.72	9.03	6.31	5.43	4.11
#						
Properties of the 3rd harmonic in the saturation:						
#						
Radiation wavelength	nm	.333E-01				
Photon energy	keV	37.2				
Contribution to the total power	P3/P	.449E-02	.461E-02	.410E-02	.409E-02	.408E-02
Pulse energy	microJ	.102	.693	1.08	1.71	3.07
Average power	W	.277E-02	.187E-01	.293E-01	.461E-01	.830E-01
Number oh photons per pulse	#	.172E+08	.116E+09	.182E+09	.287E+09	.516E+09
Average flux of photons	ph/sec	.464E+12	.314E+13	.491E+13	.774E+13	.139E+14
Coherence time	fs	.582E-01	.548E-01	.635E-01	.720E-01	.981E-01
FWHM spectrum width, dw/w	%	.135	.143	.124	.109	.801E-01
#						
Properties of the 5th harmonic in the saturation:						
#						
Radiation wavelength	nm	.200E-01				
Photon energy	keV	62.0				
Contribution to the total power	P5/P	.111E-03	.118E-03	.950E-04	.948E-04	.946E-04
Pulse energy	microJ	.254E-02	.178E-01	.251E-01	.396E-01	.713E-01
Average power	W	.685E-04	.480E-03	.678E-03	.107E-02	.193E-02
Number oh photons per pulse	#	.255E+06	.179E+07	.253E+07	.398E+07	.718E+07
Average flux of photons	ph/sec	.689E+10	.483E+11	.682E+11	.108E+12	.194E+12
Coherence time	fs	.349E-01	.329E-01	.381E-01	.432E-01	.589E-01
FWHM spectrum width, dw/w	%	.135E-02	.143E-02	.124E-02	.109E-02	.801E-03
#						
Incoherent radiation:						
#						
Critical wavelength	nm	.424E-01				
Critical energy of SR	keV	29.3				
SR induced energy loss	MeV	1.84				
SR induced energy spread	MeV	.261				
SR power	W	.991	4.96	12.4	24.8	49.6
#						
Parameters of FEL theory:						
#						
Efficiency parameter (1D)	#	.811E-03	.786E-03	.656E-03	.575E-03	.444E-03
Efficiency parameter (3D)	#	.222E-02	.234E-02	.234E-02	.234E-02	.234E-02
N of electrons in coherence volume	#	.181E+07	.192E+07	.270E+07	.305E+07	.411E+07
Emittance parameter	#	.978	1.19	1.83	2.14	2.97

Table C.15

Saturation characteristics of SASE1 (SASE2): 10.5 GeV, 0.15 nm

#						
Electron beam:						
#						
Energy of electrons	GeV	10.5				
Bunch charge	nC	.200E-01	.100	.250	.500	1.00
Peak current	kA	4.50	5.00	5.00	5.00	5.00
rms normalized emittance	mm-mrad	.320	.390	.600	.700	.970
rms energy spread	MeV	4.10	2.90	2.50	2.20	2.00
rms bunch length	micrometr	.360	1.92	4.98	9.17	23.0
Focusing beta function	m	15.0	15.0	15.0	15.0	18.8
rms size of electron beam	micrometr	15.3	16.9	20.9	22.6	29.8
Repetition rate	1/sec	.270E+05				
Electron beam power	kW	5.67	28.3	70.9	142.	283.
#						
Undulator:						
#						
Undulator period	cm	4.00				
Undulator peak field	T	.557				
Undulator parameter K (rms)	#	1.47				
Undulator length	m	165.				
#						
Properties of the 1st harmonic in the saturation:						
#						
Radiation wavelength	nm	.150				
Photon energy	keV	8.27				
Pulse energy	mJ	.362E-01	.238	.445	.716	1.21
Peak power	GW	21.5	26.5	19.1	16.7	11.3
Average power	W	.977	6.42	12.0	19.3	32.8
FWHM spot size	mikrometr	33.8	36.1	42.2	44.6	50.4
FWHM angular divergence	microrad	2.44	2.28	1.94	1.83	1.78
Coherence time	fs	.197	.188	.228	.245	.274
FWHM spectrum width, dw/w	%	.179	.188	.155	.144	.129
Degree of transverse coherence	#	.960	.960	.936	.901	.769
Radiation pulse duration	fs	1.68	8.96	23.2	42.8	107.
Number of longitudinal modes	#	9	48	102	175	392
Fluctuations of the pulse energy	%	11.1	4.81	3.30	2.52	1.68
Degeneracy parameter	#	.307E+10	.361E+10	.309E+10	.279E+10	.180E+10
Number oh photons per pulse	#	.273E+11	.179E+12	.336E+12	.540E+12	.916E+12
Average flux of photons	ph/sec	.737E+15	.484E+16	.907E+16	.146E+17	.247E+17
Peak brilliance	#	.154E+34	.181E+34	.155E+34	.140E+34	.904E+33
Average brilliance	#	.701E+23	.439E+24	.974E+24	.162E+25	.262E+25
Saturation length	m	56.5	54.0	65.8	70.7	91.9
Power gain length	m	2.82	2.70	3.38	3.70	4.90
SASE induced energy loss	MeV	4.79	5.30	3.83	3.34	2.26
SASE induced energy spread	MeV	12.9	13.8	10.1	8.80	6.11
#						
Properties of the 3rd harmonic in the saturation:						
#						
Radiation wavelength	nm	.500E-01				
Photon energy	keV	24.8				
Contribution to the total power	P3/P	.801E-02	.912E-02	.694E-02	.638E-02	.592E-02
Pulse energy	microJ	.290	2.17	3.09	4.57	7.19
Average power	W	.783E-02	.585E-01	.834E-01	.123	.194
Number oh photons per pulse	#	.729E+08	.545E+09	.777E+09	.115E+10	.181E+10
Average flux of photons	ph/sec	.197E+13	.147E+14	.210E+14	.310E+14	.488E+14
Coherence time	fs	.657E-01	.626E-01	.761E-01	.818E-01	.913E-01
FWHM spectrum width, dw/w	%	.179	.188	.155	.144	.129
#						
Properties of the 5th harmonic in the saturation:						
#						
Radiation wavelength	nm	.300E-01				
Photon energy	keV	41.3				
Contribution to the total power	P5/P	.408E-03	.568E-03	.282E-03	.231E-03	.203E-03
Pulse energy	microJ	.148E-01	.135	.125	.165	.246
Average power	W	.399E-03	.365E-02	.339E-02	.446E-02	.664E-02
Number oh photons per pulse	#	.223E+07	.204E+08	.189E+08	.249E+08	.371E+08
Average flux of photons	ph/sec	.602E+11	.550E+12	.511E+12	.673E+12	.100E+13
Coherence time	fs	.394E-01	.376E-01	.457E-01	.491E-01	.548E-01
FWHM spectrum width, dw/w	%	.179E-02	.188E-02	.155E-02	.144E-02	.129E-02
#						
Incoherent radiation:						
#						
Critical wavelength	nm	.303E-01				
Critical energy of SR	keV	40.9				
SR induced energy loss	MeV	3.58				
SR induced energy spread	MeV	.417				
SR power	W	1.93	9.67	24.2	48.3	96.7
#						
Parameters of FEL theory:						
#						
Efficiency parameter (1D)	#	.973E-03	.943E-03	.817E-03	.776E-03	.645E-03
Efficiency parameter (3D)	#	.238E-02	.251E-02	.251E-02	.251E-02	.251E-02
N of electrons in coherence volume	#	.198E+07	.211E+07	.264E+07	.289E+07	.383E+07
Emittance parameter	#	.652	.795	1.22	1.43	1.98

Table C.16

Saturation characteristics of SASE1 (SASE2): 10.5 GeV, 0.25 nm

#						
Electron beam:						
#						
Energy of electrons	GeV	10.5				
Bunch charge	nC	.200E-01	.100	.250	.500	1.00
Peak current	kA	4.50	5.00	5.00	5.00	5.00
rms normalized emittance	mm-mrad	.320	.390	.600	.700	.970
rms energy spread	MeV	4.10	2.90	2.50	2.20	2.00
rms bunch length	micrometr	.360	1.92	4.98	9.17	23.0
Focusing beta function	m	15.0	15.0	15.0	15.0	15.0
rms size of electron beam	micrometr	15.3	16.9	20.9	22.6	26.6
Repetition rate	1/sec	.270E+05				
Electron beam power	kW	5.67	28.3	70.9	142.	283.
#						
Undulator:						
#						
Undulator period	cm	4.00				
Undulator peak field	T	.783				
Undulator parameter K (rms)	#	2.07				
Undulator length	m	165.				
#						
Properties of the 1st harmonic in the saturation:						
#						
Radiation wavelength	nm	.250				
Photon energy	keV	4.96				
Pulse energy	mJ	.520E-01	.338	.708	1.21	2.34
Peak power	GW	31.0	37.7	30.5	28.2	21.8
Average power	W	1.40	9.12	19.1	32.6	63.2
FWHM spot size	mikrometr	35.9	38.4	45.1	47.7	53.7
FWHM angular divergence	microrad	3.79	3.56	3.05	2.88	2.55
Coherence time	fs	.259	.249	.291	.307	.357
FWHM spectrum width, dw/w	%	.228	.237	.202	.192	.165
Degree of transverse coherence	#	.960	.960	.960	.960	.941
Radiation pulse duration	fs	1.68	8.96	23.2	42.8	107.
Number of longitudinal modes	#	6	36	80	140	300
Fluctuations of the pulse energy	%	13.6	5.56	3.73	2.82	1.92
Degeneracy parameter	#	.966E+10	.113E+11	.107E+11	.105E+11	.922E+10
Number oh photons per pulse	#	.654E+11	.425E+12	.890E+12	.152E+13	.294E+13
Average flux of photons	ph/sec	.177E+16	.115E+17	.240E+17	.410E+17	.795E+17
Peak brilliance	#	.105E+34	.123E+34	.116E+34	.113E+34	.100E+34
Average brilliance	#	.476E+23	.298E+24	.729E+24	.131E+25	.290E+25
Saturation length	m	44.7	43.2	50.6	53.4	62.2
Power gain length	m	2.16	2.08	2.46	2.62	3.12
SASE induced energy loss	MeV	6.88	7.54	6.09	5.64	4.36
SASE induced energy spread	MeV	18.0	19.4	15.7	14.5	11.3
#						
Properties of the 3rd harmonic in the saturation:						
#						
Radiation wavelength	nm	.833E-01				
Photon energy	keV	14.9				
Contribution to the total power	P3/P	.119E-01	.141E-01	.124E-01	.117E-01	.900E-02
Pulse energy	microJ	.619	4.75	8.78	14.1	21.1
Average power	W	.167E-01	.128	.237	.382	.569
Number oh photons per pulse	#	.260E+09	.199E+10	.368E+10	.593E+10	.883E+10
Average flux of photons	ph/sec	.701E+13	.538E+14	.994E+14	.160E+15	.238E+15
Coherence time	fs	.862E-01	.830E-01	.971E-01	.102	.119
FWHM spectrum width, dw/w	%	.228	.237	.202	.192	.165
#						
Properties of the 5th harmonic in the saturation:						
#						
Radiation wavelength	nm	.500E-01				
Photon energy	keV	24.8				
Contribution to the total power	P5/P	.103E-02	.151E-02	.113E-02	.989E-03	.509E-03
Pulse energy	microJ	.535E-01	.510	.802	1.19	1.19
Average power	W	.144E-02	.138E-01	.217E-01	.323E-01	.322E-01
Number oh photons per pulse	#	.135E+08	.128E+09	.202E+09	.301E+09	.300E+09
Average flux of photons	ph/sec	.363E+12	.346E+13	.545E+13	.812E+13	.809E+13
Coherence time	fs	.517E-01	.498E-01	.582E-01	.614E-01	.715E-01
FWHM spectrum width, dw/w	%	.228E-02	.237E-02	.202E-02	.192E-02	.165E-02
#						
Incoherent radiation:						
#						
Critical wavelength	nm	.216E-01				
Critical energy of SR	keV	57.4				
SR induced energy loss	MeV	7.07				
SR induced energy spread	MeV	.681				
SR power	W	3.82	19.1	47.7	95.4	191.
#						
Parameters of FEL theory:						
#						
Efficiency parameter (1D)	#	.118E-02	.114E-02	.989E-03	.940E-03	.843E-03
Efficiency parameter (3D)	#	.246E-02	.259E-02	.259E-02	.259E-02	.259E-02
N of electrons in coherence volume	#	.253E+07	.271E+07	.321E+07	.341E+07	.406E+07
Emittance parameter	#	.391	.477	.734	.856	1.19

Table C.17

Saturation characteristics of SASE1 (SASE2): 10.5 GeV, 0.45 nm

#						
Electron beam:						
#						
Energy of electrons	GeV	10.5				
Bunch charge	nC	.200E-01	.100	.250	.500	1.00
Peak current	kA	4.50	5.00	5.00	5.00	5.00
rms normalized emittance	mm-mrad	.320	.390	.600	.700	.970
rms energy spread	MeV	4.10	2.90	2.50	2.20	2.00
rms bunch length	micrometr	.360	1.92	4.98	9.17	23.0
Focusing beta function	m	15.0	15.0	15.0	15.0	15.0
rms size of electron beam	micrometr	15.3	16.9	20.9	22.6	26.6
Repetition rate	1/sec	.270E+05				
Electron beam power	kW	5.67	28.3	70.9	142.	283.
#						
Undulator:						
#						
Undulator period	cm	4.00				
Undulator peak field	T	1.10				
Undulator parameter K (rms)	#	2.92				
Undulator length	m	165.				
#						
Properties of the 1st harmonic in the saturation:						
#						
Radiation wavelength	nm	.450				
Photon energy	keV	2.76				
Pulse energy	mJ	.701E-01	.448	.992	1.74	3.70
Peak power	GW	41.7	50.0	42.7	40.5	34.5
Average power	W	1.89	12.1	26.8	46.9	99.8
FWHM spot size	mikrometr	38.4	41.1	48.5	51.4	58.0
FWHM angular divergence	microrad	6.26	5.89	5.06	4.79	4.26
Coherence time	fs	.376	.366	.419	.439	.494
FWHM spectrum width, dw/w	%	.282	.290	.253	.242	.215
Degree of transverse coherence	#	.960	.960	.960	.960	.960
Radiation pulse duration	fs	1.68	8.96	23.2	42.8	107.
Number of longitudinal modes	#	4	25	55	98	217
Fluctuations of the pulse energy	%	16.7	6.67	4.49	3.37	2.26
Degeneracy parameter	#	.341E+11	.397E+11	.389E+11	.386E+11	.370E+11
Number oh photons per pulse	#	.159E+12	.101E+13	.225E+13	.393E+13	.837E+13
Average flux of photons	ph/sec	.428E+16	.274E+17	.606E+17	.106E+18	.226E+18
Peak brilliance	#	.634E+33	.739E+33	.724E+33	.719E+33	.689E+33
Average brilliance	#	.288E+23	.179E+24	.454E+24	.832E+24	.199E+25
Saturation length	m	36.3	35.4	40.7	42.6	48.1
Power gain length	m	1.71	1.66	1.91	2.00	2.27
SASE induced energy loss	MeV	9.27	10.0	8.54	8.11	6.89
SASE induced energy spread	MeV	24.0	25.7	21.9	20.8	17.7
#						
Properties of the 3rd harmonic in the saturation:						
#						
Radiation wavelength	nm	.150				
Photon energy	keV	8.27				
Contribution to the total power	P3/P	.150E-01	.173E-01	.168E-01	.168E-01	.152E-01
Pulse energy	microJ	1.05	7.74	16.6	29.1	56.3
Average power	W	.284E-01	.209	.449	.786	1.52
Number oh photons per pulse	#	.793E+09	.584E+10	.125E+11	.220E+11	.425E+11
Average flux of photons	ph/sec	.214E+14	.158E+15	.339E+15	.593E+15	.115E+16
Coherence time	fs	.125	.122	.140	.146	.165
FWHM spectrum width, dw/w	%	.282	.290	.253	.242	.215
#						
Properties of the 5th harmonic in the saturation:						
#						
Radiation wavelength	nm	.900E-01				
Photon energy	keV	13.8				
Contribution to the total power	P5/P	.173E-02	.234E-02	.220E-02	.220E-02	.179E-02
Pulse energy	microJ	.121	1.05	2.18	3.82	6.61
Average power	W	.327E-02	.283E-01	.588E-01	.103	.178
Number oh photons per pulse	#	.549E+08	.475E+09	.986E+09	.173E+10	.299E+10
Average flux of photons	ph/sec	.148E+13	.128E+14	.266E+14	.467E+14	.808E+14
Coherence time	fs	.751E-01	.731E-01	.838E-01	.877E-01	.988E-01
FWHM spectrum width, dw/w	%	.282E-02	.290E-02	.253E-02	.242E-02	.215E-02
#						
Incoherent radiation:						
#						
Critical wavelength	nm	.153E-01				
Critical energy of SR	keV	80.9				
SR induced energy loss	MeV	14.0				
SR induced energy spread	MeV	1.13				
SR power	W	7.58	37.9	94.8	190.	379.
#						
Parameters of FEL theory:						
#						
Efficiency parameter (1D)	#	.144E-02	.140E-02	.121E-02	.115E-02	.103E-02
Efficiency parameter (3D)	#	.248E-02	.262E-02	.262E-02	.262E-02	.262E-02
N of electrons in coherence volume	#	.361E+07	.389E+07	.447E+07	.469E+07	.532E+07
Emittance parameter	#	.217	.265	.408	.476	.659

D Tables of the radiation properties of SASE3 in the saturation regime

This section contains practical tables of the radiation properties for SASE3 operating in the saturation regime. Saturation is defined as the point where brilliance reaches maximum value (see Section 2 for more details). All data presented in the tables are generated by the code based on tabulated results of numerical simulations with three-dimensional, time-dependent code FAST [19]. Tables cover properties of the fundamental, 3rd, and the 5th harmonic. Accuracy of tabulation is 10 to 20 per cent which is sufficient for practical purposes. It happens at the margins of operating wavelength ranges that saturation length for higher charges exceeds undulator length. We do not exclude these charges from tables to give the reader an idea about required undulator length.

Numbers for brilliance are in units of photons/sec/mm^2/mrad^2/0.1% bandwidth.

Main characteristics of the undulator, electron beam, and incoherent radiation are included in the tables as well.

Parameters of the FEL theory are presented with one-dimensional and three-dimensional efficiency parameter ρ and $\bar{\rho}$, number of electrons in the volume of coherence N_c, and emittance parameter $\hat{\epsilon} = 2\pi\epsilon/\lambda$. This set of physical parameters is sufficient for quick physical estimation of main characteristics of SASE FEL as we described in Section 2.

Table D.1

Saturation characteristics of SASE3: 17.5 GeV, 0.1 nm

#						
Electron beam:						
#						
Energy of electrons	GeV	17.5				
Bunch charge	nC	.200E-01	.100	.250	.500	1.00
Peak current	kA	4.50	5.00	5.00	5.00	5.00
rms normalized emittance	mm-mrad	.320	.390	.600	.700	.970
rms energy spread	MeV	4.10	2.90	2.50	2.20	2.00
rms bunch length	micrometr	.360	1.92	4.98	9.17	23.0
Focusing beta function	m	15.0	15.0	18.5	23.4	37.5
rms size of electron beam	micrometr	11.8	13.1	18.0	21.9	32.6
Repetition rate	1/sec	.270E+05				
Electron beam power	kW	9.45	47.2	118.	236.	472.
#						
Undulator:						
#						
Undulator period	cm	6.80				
Undulator peak field	T	.349				
Undulator parameter K (rms)	#	1.57				
Undulator gap	cm	3.81				
Undulator length	m	105.				
#						
Properties of the 1st harmonic in the saturation:						
#						
Radiation wavelength	nm	.100E+00				
Photon energy	keV	12.4				
Pulse energy	mJ	.666E-01	.380	.615	.972	1.76
Peak power	GW	39.6	42.4	26.5	22.7	16.4
Average power	W	1.80	10.3	16.6	26.2	47.4
FWHM spot size	mikrometr	29.1	31.2	37.0	42.7	57.0
FWHM angular divergence	microrad	1.84	1.74	1.33	1.22	1.01
Coherence time	fs	.120	.121	.134	.153	.205
FWHM spectrum width, dw/w	%	.197	.195	.176	.154	.115
Degree of transverse coherence	#	.960	.960	.950	.927	.820
Radiation pulse duration	fs	1.68	8.96	23.2	42.8	107.
Number of longitudinal modes	#	14	74	173	280	524
Fluctuations of the pulse energy	%	8.91	3.87	2.53	1.99	1.46
Degeneracy parameter	#	.229E+10	.248E+10	.170E+10	.162E+10	.138E+10
Number oh photons per pulse	#	.335E+11	.191E+12	.309E+12	.489E+12	.883E+12
Average flux of photons	ph/sec	.905E+15	.517E+16	.835E+16	.132E+17	.238E+17
Peak brilliance	#	.389E+34	.421E+34	.288E+34	.275E+34	.234E+34
Average brilliance	#	.176E+24	.102E+25	.181E+25	.318E+25	.679E+25
Saturation length	m	86.8	88.1	112.	129.	173.
Power gain length	m	4.56	4.68	6.27	7.12	9.43
SASE induced energy loss	MeV	8.81	8.49	5.29	4.54	3.27
SASE induced energy spread	MeV	22.8	21.8	13.7	11.8	8.58
#						
Properties of the 3rd harmonic in the saturation:						
#						
Radiation wavelength	nm	.333E-01				
Photon energy	keV	37.2				
Contribution to the total power	P3/P	.983E-02	.914E-02	.676E-02	.660E-02	.631E-02
Pulse energy	microJ	.655	3.48	4.15	6.42	11.1
Average power	W	.177E-01	.939E-01	.112	.173	.299
Number oh photons per pulse	#	.110E+09	.583E+09	.697E+09	.108E+10	.186E+10
Average flux of photons	ph/sec	.296E+13	.157E+14	.188E+14	.290E+14	.501E+14
Coherence time	fs	.399E-01	.404E-01	.448E-01	.510E-01	.682E-01
FWHM spectrum width, dw/w	%	.197	.195	.176	.154	.115
#						
Properties of the 5th harmonic in the saturation:						
#						
Radiation wavelength	nm	.200E-01				
Photon energy	keV	62.0				
Contribution to the total power	P5/P	.672E-03	.562E-03	.261E-03	.248E-03	.228E-03
Pulse energy	microJ	.448E-01	.214	.160	.241	.400
Average power	W	.121E-02	.577E-02	.433E-02	.650E-02	.108E-01
Number oh photons per pulse	#	.451E+07	.215E+08	.161E+08	.242E+08	.402E+08
Average flux of photons	ph/sec	.122E+12	.581E+12	.435E+12	.654E+12	.109E+13
Coherence time	fs	.239E-01	.242E-01	.269E-01	.306E-01	.409E-01
FWHM spectrum width, dw/w	%	.197E-02	.195E-02	.176E-02	.154E-02	.115E-02
#						
Incoherent radiation:						
#						
Critical wavelength	nm	.175E-01				
Critical energy of SR	keV	71.0				
SR induced energy loss	MeV	2.48				
SR induced energy spread	MeV	.455				
SR power	W	1.34	6.68	16.7	33.4	66.8
#						
Parameters of FEL theory:						
#						
Efficiency parameter (1D)	#	.102E-02	.989E-03	.799E-03	.701E-03	.538E-03
Efficiency parameter (3D)	#	.186E-02	.196E-02	.196E-02	.196E-02	.196E-02
N of electrons in coherence volume	#	.126E+07	.144E+07	.192E+07	.218E+07	.289E+07
Emittance parameter	#	.587	.716	1.10	1.28	1.78

Table D.2

Saturation characteristics of SASE3: 17.5 GeV, 0.15 nm

#						
Electron beam:						
#						
Energy of electrons	GeV	17.5				
Bunch charge	nC	.200E-01	.100	.250	.500	1.00
Peak current	kA	4.50	5.00	5.00	5.00	5.00
rms normalized emittance	mm-mrad	.320	.390	.600	.700	.970
rms energy spread	MeV	4.10	2.90	2.50	2.20	2.00
rms bunch length	micrometr	.360	1.92	4.98	9.17	23.0
Focusing beta function	m	15.0	15.0	15.0	15.0	20.7
rms size of electron beam	micrometr	11.8	13.1	16.2	17.5	24.2
Repetition rate	1/sec	.270E+05				
Electron beam power	kW	9.45	47.2	118.	236.	472.
#						
Undulator:						
#						
Undulator period	cm	6.80				
Undulator peak field	T	.455				
Undulator parameter K (rms)	#	2.04				
Undulator length	m	105.				
#						
Properties of the 1st harmonic in the saturation:						
#						
Radiation wavelength	nm	.150				
Photon energy	keV	8.27				
Pulse energy	mJ	.902E-01	.531	1.01	1.61	2.69
Peak power	GW	53.7	59.3	43.4	37.5	25.1
Average power	W	2.43	14.4	27.2	43.4	72.7
FWHM spot size	mikrometr	30.4	32.7	38.5	40.8	48.5
FWHM angular divergence	microrad	2.60	2.45	2.11	2.00	1.56
Coherence time	fs	.150	.151	.181	.195	.210
FWHM spectrum width, dw/w	%	.236	.235	.195	.182	.168
Degree of transverse coherence	#	.960	.960	.960	.960	.941
Radiation pulse duration	fs	1.68	8.96	23.2	42.8	107.
Number of longitudinal modes	#	11	59	128	220	510
Fluctuations of the pulse energy	%	10.1	4.34	2.95	2.25	1.48
Degeneracy parameter	#	.582E+10	.647E+10	.568E+10	.529E+10	.375E+10
Number oh photons per pulse	#	.680E+11	.401E+12	.760E+12	.121E+13	.203E+13
Average flux of photons	ph/sec	.184E+16	.108E+17	.205E+17	.327E+17	.549E+17
Peak brilliance	#	.293E+34	.325E+34	.286E+34	.266E+34	.189E+34
Average brilliance	#	.133E+24	.787E+24	.179E+25	.308E+25	.546E+25
Saturation length	m	72.8	73.3	88.3	95.1	119.
Power gain length	m	3.68	3.71	4.61	5.06	6.46
SASE induced energy loss	MeV	11.9	11.9	8.67	7.50	5.02
SASE induced energy spread	MeV	30.7	30.4	22.3	19.3	13.0
#						
Properties of the 3rd harmonic in the saturation:						
#						
Radiation wavelength	nm	.500E-01				
Photon energy	keV	24.8				
Contribution to the total power	P3/P	.144E-01	.145E-01	.104E-01	.895E-02	.768E-02
Pulse energy	microJ	1.30	7.72	10.5	14.4	20.7
Average power	W	.351E-01	.208	.284	.388	.559
Number oh photons per pulse	#	.327E+09	.194E+10	.265E+10	.362E+10	.520E+10
Average flux of photons	ph/sec	.883E+13	.524E+14	.714E+14	.976E+14	.141E+15
Coherence time	fs	.499E-01	.502E-01	.603E-01	.649E-01	.701E-01
FWHM spectrum width, dw/w	%	.236	.235	.195	.182	.168
#						
Properties of the 5th harmonic in the saturation:						
#						
Radiation wavelength	nm	.300E-01				
Photon energy	keV	41.3				
Contribution to the total power	P5/P	.159E-02	.162E-02	.746E-03	.502E-03	.343E-03
Pulse energy	microJ	.143	.859	.752	.807	.923
Average power	W	.387E-02	.232E-01	.203E-01	.218E-01	.249E-01
Number oh photons per pulse	#	.216E+08	.130E+09	.113E+09	.122E+09	.139E+09
Average flux of photons	ph/sec	.584E+12	.350E+13	.306E+13	.329E+13	.376E+13
Coherence time	fs	.300E-01	.301E-01	.362E-01	.390E-01	.421E-01
FWHM spectrum width, dw/w	%	.236E-02	.235E-02	.195E-02	.182E-02	.168E-02
#						
Incoherent radiation:						
#						
Critical wavelength	nm	.134E-01				
Critical energy of SR	keV	92.7				
SR induced energy loss	MeV	4.22				
SR induced energy spread	MeV	.669				
SR power	W	2.28	11.4	28.5	57.0	114.
#						
Parameters of FEL theory:						
#						
Efficiency parameter (1D)	#	.119E-02	.115E-02	.996E-03	.946E-03	.762E-03
Efficiency parameter (3D)	#	.190E-02	.200E-02	.200E-02	.200E-02	.200E-02
N of electrons in coherence volume	#	.152E+07	.171E+07	.212E+07	.233E+07	.297E+07
Emittance parameter	#	.391	.477	.734	.856	1.19

Table D.3

Saturation characteristics of SASE3: 17.5 GeV, 0.2 nm

#
Electron beam:
#

Energy of electrons	GeV	17.5				
Bunch charge	nC	.200E-01	.100	.250	.500	1.00
Peak current	kA	4.50	5.00	5.00	5.00	5.00
rms normalized emittance	mm-mrad	.320	.390	.600	.700	.970
rms energy spread	MeV	4.10	2.90	2.50	2.20	2.00
rms bunch length	micrometr	.360	1.92	4.98	9.17	23.0
Focusing beta function	m	15.0	15.0	15.0	15.0	15.0
rms size of electron beam	micrometr	11.8	13.1	16.2	17.5	20.6
Repetition rate	1/sec	.270E+05				
Electron beam power	kW	9.45	47.2	118.	236.	472.

#
Undulator:
#

Undulator period	cm	6.80
Undulator peak field	T	.541
Undulator parameter K (rms)	#	2.43
Undulator length	m	105.

#
Properties of the 1st harmonic in the saturation:
#

Radiation wavelength	nm	.200				
Photon energy	keV	6.20				
Pulse energy	mJ	.105	.629	1.28	2.13	3.91
Peak power	GW	62.8	70.2	55.2	49.7	36.5
Average power	W	2.85	17.0	34.6	57.5	106.
FWHM spot size	mikrometr	31.4	33.7	39.8	42.2	47.8
FWHM angular divergence	microrad	3.31	3.13	2.70	2.56	2.28
Coherence time	fs	.180	.181	.212	.226	.265
FWHM spectrum width, dw/w	%	.262	.261	.222	.209	.178
Degree of transverse coherence	#	.960	.960	.960	.960	.958
Radiation pulse duration	fs	1.68	8.96	23.2	42.8	107.
Number of longitudinal modes	#	9	50	110	190	405
Fluctuations of the pulse energy	%	11.1	4.71	3.18	2.42	1.66
Degeneracy parameter	#	.109E+11	.122E+11	.113E+11	.108E+11	.932E+10
Number oh photons per pulse	#	.106E+12	.633E+12	.129E+13	.214E+13	.394E+13
Average flux of photons	ph/sec	.287E+16	.171E+17	.348E+17	.578E+17	.106E+18
Peak brilliance	#	.232E+34	.260E+34	.240E+34	.229E+34	.198E+34
Average brilliance	#	.105E+24	.628E+24	.150E+25	.265E+25	.572E+25
Saturation length	m	65.8	66.2	77.8	82.9	97.5
Power gain length	m	3.26	3.27	3.92	4.22	5.15
SASE induced energy loss	MeV	14.0	14.0	11.0	9.93	7.30
SASE induced energy spread	MeV	35.8	35.9	28.3	25.4	18.7

#
Properties of the 3rd harmonic in the saturation:
#

Radiation wavelength	nm	.667E-01				
Photon energy	keV	18.6				
Contribution to the total power	P3/P	.166E-01	.172E-01	.142E-01	.127E-01	.906E-02
Pulse energy	microJ	1.75	10.8	18.2	27.0	35.5
Average power	W	.473E-01	.292	.492	.728	.957
Number oh photons per pulse	#	.587E+09	.362E+10	.611E+10	.905E+10	.119E+11
Average flux of photons	ph/sec	.159E+14	.978E+14	.165E+15	.244E+15	.321E+15
Coherence time	fs	.600E-01	.602E-01	.707E-01	.752E-01	.883E-01
FWHM spectrum width, dw/w	%	.262	.261	.222	.209	.178

#
Properties of the 5th harmonic in the saturation:
#

Radiation wavelength	nm	.400E-01				
Photon energy	keV	31.0				
Contribution to the total power	P5/P	.215E-02	.230E-02	.153E-02	.118E-02	.509E-03
Pulse energy	microJ	.227	1.45	1.97	2.52	1.99
Average power	W	.612E-02	.391E-01	.531E-01	.680E-01	.537E-01
Number oh photons per pulse	#	.456E+08	.292E+09	.396E+09	.507E+09	.401E+09
Average flux of photons	ph/sec	.123E+13	.787E+13	.107E+14	.137E+14	.108E+14
Coherence time	fs	.360E-01	.361E-01	.424E-01	.451E-01	.530E-01
FWHM spectrum width, dw/w	%	.262E-02	.261E-02	.222E-02	.209E-02	.178E-02

#
Incoherent radiation:
#

Critical wavelength	nm	.113E-01				
Critical energy of SR	keV	110.				
SR induced energy loss	MeV	5.96				
SR induced energy spread	MeV	.862				
SR power	W	3.22	16.1	40.2	80.5	161.

#
Parameters of FEL theory:
#

Efficiency parameter (1D)	#	.131E-02	.127E-02	.110E-02	.105E-02	.938E-03
Efficiency parameter (3D)	#	.192E-02	.202E-02	.202E-02	.202E-02	.202E-02
N of electrons in coherence volume	#	.180E+07	.201E+07	.240E+07	.259E+07	.316E+07
Emittance parameter	#	.294	.358	.550	.642	.890

Table D.4

Saturation characteristics of SASE3: 17.5 GeV, 0.4 nm

#						
Electron beam:						
#						
Energy of electrons	GeV	17.5				
Bunch charge	nC	.200E-01	.100	.250	.500	1.00
Peak current	kA	4.50	5.00	5.00	5.00	5.00
rms normalized emittance	mm-mrad	.320	.390	.600	.700	.970
rms energy spread	MeV	4.10	2.90	2.50	2.20	2.00
rms bunch length	micrometr	.360	1.92	4.98	9.17	23.0
Focusing beta function	m	15.0	15.0	15.0	15.0	15.0
rms size of electron beam	micrometr	11.8	13.1	16.2	17.5	20.6
Repetition rate	1/sec	.270E+05				
Electron beam power	kW	9.45	47.2	118.	236.	472.
#						
Undulator:						
#						
Undulator period	cm	6.80				
Undulator peak field	T	.797				
Undulator parameter K (rms)	#	3.58				
Undulator length	m	105.				
#						
Properties of the 1st harmonic in the saturation:						
#						
Radiation wavelength	nm	.400				
Photon energy	keV	3.10				
Pulse energy	mJ	.139	.842	1.87	3.25	6.91
Peak power	GW	83.0	94.0	80.6	75.9	64.5
Average power	W	3.76	22.7	50.6	87.8	187.
FWHM spot size	mikrometr	33.7	36.2	43.0	45.6	51.8
FWHM angular divergence	microrad	5.84	5.55	4.83	4.59	4.11
Coherence time	fs	.293	.293	.334	.350	.393
FWHM spectrum width, dw/w	%	.322	.322	.282	.269	.240
Degree of transverse coherence	#	.960	.960	.960	.960	.960
Radiation pulse duration	fs	1.68	8.96	23.2	42.8	107.
Number of longitudinal modes	#	6	31	70	122	273
Fluctuations of the pulse energy	%	13.6	5.99	3.98	3.02	2.02
Degeneracy parameter	#	.470E+11	.532E+11	.520E+11	.514E+11	.490E+11
Number oh photons per pulse	#	.281E+12	.169E+13	.377E+13	.654E+13	.139E+14
Average flux of photons	ph/sec	.757E+16	.457E+17	.102E+18	.177E+18	.376E+18
Peak brilliance	#	.124E+34	.141E+34	.138E+34	.136E+34	.130E+34
Average brilliance	#	.564E+23	.341E+24	.865E+24	.157E+25	.376E+25
Saturation length	m	53.9	54.0	61.8	64.8	72.9
Power gain length	m	2.58	2.57	2.94	3.09	3.51
SASE induced energy loss	MeV	18.4	18.8	16.1	15.2	12.9
SASE induced energy spread	MeV	47.2	48.0	41.2	38.7	32.9
#						
Properties of the 3rd harmonic in the saturation:						
#						
Radiation wavelength	nm	.133				
Photon energy	keV	9.30				
Contribution to the total power	P3/P	.193E-01	.201E-01	.194E-01	.190E-01	.172E-01
Pulse energy	microJ	2.69	16.9	36.3	61.9	119.
Average power	W	.727E-01	.457	.980	1.67	3.21
Number oh photons per pulse	#	.180E+10	.113E+11	.244E+11	.415E+11	.797E+11
Average flux of photons	ph/sec	.487E+14	.306E+15	.658E+15	.112E+16	.215E+16
Coherence time	fs	.976E-01	.977E-01	.111	.117	.131
FWHM spectrum width, dw/w	%	.322	.322	.282	.269	.240
#						
Properties of the 5th harmonic in the saturation:						
#						
Radiation wavelength	nm	.800E-01				
Photon energy	keV	15.5				
Contribution to the total power	P5/P	.294E-02	.318E-02	.297E-02	.286E-02	.232E-02
Pulse energy	microJ	.410	2.68	5.56	9.29	16.0
Average power	W	.111E-01	.723E-01	.150	.251	.433
Number oh photons per pulse	#	.165E+09	.108E+10	.224E+10	.374E+10	.645E+10
Average flux of photons	ph/sec	.445E+13	.291E+14	.604E+14	.101E+15	.174E+15
Coherence time	fs	.586E-01	.586E-01	.668E-01	.701E-01	.786E-01
FWHM spectrum width, dw/w	%	.322E-02	.322E-02	.282E-02	.269E-02	.240E-02
#						
Incoherent radiation:						
#						
Critical wavelength	nm	.764E-02				
Critical energy of SR	keV	162.				
SR induced energy loss	MeV	12.9				
SR induced energy spread	MeV	1.53				
SR power	W	6.98	34.9	87.3	175.	349.
#						
Parameters of FEL theory:						
#						
Efficiency parameter (1D)	#	.166E-02	.161E-02	.139E-02	.132E-02	.119E-02
Efficiency parameter (3D)	#	.193E-02	.203E-02	.203E-02	.203E-02	.203E-02
N of electrons in coherence volume	#	.284E+07	.315E+07	.361E+07	.380E+07	.430E+07
Emittance parameter	#	.147	.179	.275	.321	.445

Table D.5

Saturation characteristics of SASE3: 17.5 GeV, 0.8 nm

#						
Electron beam:						
#						
Energy of electrons	GeV	17.5				
Bunch charge	nC	.200E-01	.100	.250	.500	1.00
Peak current	kA	4.50	5.00	5.00	5.00	5.00
rms normalized emittance	mm-mrad	.320	.390	.600	.700	.970
rms energy spread	MeV	4.10	2.90	2.50	2.20	2.00
rms bunch length	micrometr	.360	1.92	4.98	9.17	23.0
Focusing beta function	m	15.0	15.0	15.0	15.0	15.0
rms size of electron beam	micrometr	11.8	13.1	16.2	17.5	20.6
Repetition rate	1/sec	.270E+05				
Electron beam power	kW	9.45	47.2	118.	236.	472.
#						
Undulator:						
#						
Undulator period	cm	6.80				
Undulator peak field	T	1.15				
Undulator parameter K (rms)	#	5.16				
Undulator length	m	105.				
#						
Properties of the 1st harmonic in the saturation:						
#						
Radiation wavelength	nm	.800				
Photon energy	keV	1.55				
Pulse energy	mJ	.171	1.04	2.40	4.24	9.50
Peak power	GW	102.	116.	103.	98.9	88.6
Average power	W	4.61	28.0	64.8	114.	256.
FWHM spot size	mikrometr	36.0	38.8	46.1	49.1	55.8
FWHM angular divergence	microrad	10.1	9.66	8.51	8.12	7.32
Coherence time	fs	.493	.492	.552	.575	.634
FWHM spectrum width, dw/w	%	.382	.384	.342	.328	.297
Degree of transverse coherence	#	.960	.960	.960	.960	.960
Radiation pulse duration	fs	1.68	8.96	23.2	42.8	107.
Number of longitudinal modes	#	3	18	42	74	169
Fluctuations of the pulse energy	%	19.2	7.86	5.14	3.87	2.56
Degeneracy parameter	#	.194E+12	.219E+12	.220E+12	.220E+12	.217E+12
Number oh photons per pulse	#	.687E+12	.417E+13	.965E+13	.170E+14	.382E+14
Average flux of photons	ph/sec	.186E+17	.112E+18	.261E+18	.460E+18	.103E+19
Peak brilliance	#	.641E+33	.727E+33	.729E+33	.728E+33	.719E+33
Average brilliance	#	.291E+23	.176E+24	.457E+24	.842E+24	.208E+25
Saturation length	m	45.7	45.7	51.4	53.6	59.2
Power gain length	m	2.12	2.11	2.37	2.47	2.72
SASE induced energy loss	MeV	22.6	23.1	20.6	19.8	17.7
SASE induced energy spread	MeV	57.7	59.0	52.7	50.5	45.2
#						
Properties of the 3rd harmonic in the saturation:						
#						
Radiation wavelength	nm	.267				
Photon energy	keV	4.65				
Contribution to the total power	P3/P	.204E-01	.210E-01	.208E-01	.208E-01	.204E-01
Pulse energy	microJ	3.49	21.7	50.0	88.3	194.
Average power	W	.941E-01	.587	1.35	2.38	5.24
Number oh photons per pulse	#	.468E+10	.292E+11	.671E+11	.118E+12	.260E+12
Average flux of photons	ph/sec	.126E+15	.787E+15	.181E+16	.320E+16	.702E+16
Coherence time	fs	.164	.164	.184	.192	.211
FWHM spectrum width, dw/w	%	.382	.384	.342	.328	.297
#						
Properties of the 5th harmonic in the saturation:						
#						
Radiation wavelength	nm	.160				
Photon energy	keV	7.75				
Contribution to the total power	P5/P	.329E-02	.348E-02	.343E-02	.343E-02	.330E-02
Pulse energy	microJ	.562	3.60	8.23	14.5	31.3
Average power	W	.152E-01	.972E-01	.222	.392	.845
Number oh photons per pulse	#	.453E+09	.290E+10	.663E+10	.117E+11	.252E+11
Average flux of photons	ph/sec	.122E+14	.783E+14	.179E+15	.316E+15	.680E+15
Coherence time	fs	.986E-01	.983E-01	.110	.115	.127
FWHM spectrum width, dw/w	%	.382E-02	.384E-02	.342E-02	.328E-02	.297E-02
#						
Incoherent radiation:						
#						
Critical wavelength	nm	.530E-02				
Critical energy of SR	keV	234.				
SR induced energy loss	MeV	26.9				
SR induced energy spread	MeV	2.64				
SR power	W	14.5	72.6	181.	363.	726.
#						
Parameters of FEL theory:						
#						
Efficiency parameter (1D)	#	.209E-02	.203E-02	.176E-02	.167E-02	.150E-02
Efficiency parameter (3D)	#	.193E-02	.204E-02	.204E-02	.204E-02	.204E-02
N of electrons in coherence volume	#	.469E+07	.518E+07	.580E+07	.605E+07	.668E+07
Emittance parameter	#	.734E-01	.894E-01	.138	.161	.222

Table D.6

Saturation characteristics of SASE3: 17.5 GeV, 1.6 nm

#						
Electron beam:						
#						
Energy of electrons	GeV	17.5				
Bunch charge	nC	.200E-01	.100	.250	.500	1.00
Peak current	kA	4.50	5.00	5.00	5.00	5.00
rms normalized emittance	mm-mrad	.320	.390	.600	.700	.970
rms energy spread	MeV	4.10	2.90	2.50	2.20	2.00
rms bunch length	micrometr	.360	1.92	4.98	9.17	23.0
Focusing beta function	m	15.0	15.0	15.0	15.0	15.0
rms size of electron beam	micrometr	11.8	13.1	16.2	17.5	20.6
Repetition rate	1/sec	.270E+05				
Electron beam power	kW	9.45	47.2	118.	236.	472.
#						
Undulator:						
#						
Undulator period	cm	6.80				
Undulator peak field	T	1.64				
Undulator parameter K (rms)	#	7.36				
Undulator length	m	105.				
#						
Properties of the 1st harmonic in the saturation:						
#						
Radiation wavelength	nm	1.60				
Photon energy	keV	.775				
Pulse energy	mJ	.203	1.23	2.89	5.14	11.8
Peak power	GW	121.	137.	124.	120.	110.
Average power	W	5.49	33.2	78.0	139.	320.
FWHM spot size	mikrometr	38.3	41.3	49.3	52.5	59.9
FWHM angular divergence	microrad	17.0	16.5	14.7	14.1	12.8
Coherence time	fs	.850	.844	.936	.972	1.06
FWHM spectrum width, dw/w	%	.444	.447	.403	.388	.356
Degree of transverse coherence	#	.960	.960	.960	.960	.960
Radiation pulse duration	fs	1.68	8.96	23.2	42.8	107.
Number of longitudinal modes	#	2	11	25	44	101
Fluctuations of the pulse energy	%	23.6	10.1	6.67	5.03	3.32
Degeneracy parameter	#	.795E+12	.897E+12	.899E+12	.901E+12	.903E+12
Number oh photons per pulse	#	.164E+13	.991E+13	.233E+14	.414E+14	.952E+14
Average flux of photons	ph/sec	.442E+17	.268E+18	.628E+18	.112E+19	.257E+19
Peak brilliance	#	.329E+33	.371E+33	.372E+33	.373E+33	.374E+33
Average brilliance	#	.149E+23	.898E+23	.234E+24	.432E+24	.108E+25
Saturation length	m	39.7	39.5	43.9	45.6	49.8
Power gain length	m	1.80	1.78	1.97	2.04	2.22
SASE induced energy loss	MeV	26.9	27.5	24.9	24.0	22.1
SASE induced energy spread	MeV	68.7	70.1	63.4	61.2	56.3
#						
Properties of the 3rd harmonic in the saturation:						
#						
Radiation wavelength	nm	.533				
Photon energy	keV	2.32				
Contribution to the total power	P3/P	.210E-01	.214E-01	.213E-01	.213E-01	.212E-01
Pulse energy	microJ	4.27	26.3	61.6	110.	251.
Average power	W	.115	.710	1.66	2.96	6.78
Number oh photons per pulse	#	.114E+11	.706E+11	.165E+12	.294E+12	.673E+12
Average flux of photons	ph/sec	.309E+15	.191E+16	.446E+16	.795E+16	.182E+17
Coherence time	fs	.283	.281	.312	.324	.353
FWHM spectrum width, dw/w	%	.444	.447	.403	.388	.356
#						
Properties of the 5th harmonic in the saturation:						
#						
Radiation wavelength	nm	.320				
Photon energy	keV	3.87				
Contribution to the total power	P5/P	.348E-02	.360E-02	.358E-02	.359E-02	.355E-02
Pulse energy	microJ	.707	4.44	10.4	18.5	42.0
Average power	W	.191E-01	.120	.280	.499	1.13
Number oh photons per pulse	#	.114E+10	.714E+10	.167E+11	.297E+11	.676E+11
Average flux of photons	ph/sec	.307E+14	.193E+15	.450E+15	.803E+15	.183E+16
Coherence time	fs	.170	.169	.187	.194	.212
FWHM spectrum width, dw/w	%	.444E-02	.447E-02	.403E-02	.388E-02	.356E-02
#						
Incoherent radiation:						
#						
Critical wavelength	nm	.371E-02				
Critical energy of SR	keV	334.				
SR induced energy loss	MeV	54.8				
SR induced energy spread	MeV	4.50				
SR power	W	29.6	148.	370.	739.	.148E+04
#						
Parameters of FEL theory:						
#						
Efficiency parameter (1D)	#	.264E-02	.256E-02	.222E-02	.211E-02	.189E-02
Efficiency parameter (3D)	#	.193E-02	.204E-02	.204E-02	.204E-02	.204E-02
N of electrons in coherence volume	#	.795E+07	.875E+07	.966E+07	.100E+08	.109E+08
Emittance parameter	#	.367E-01	.447E-01	.688E-01	.803E-01	.111

Table D.7

Saturation characteristics of SASE3: 14 GeV, 0.1 nm

```
#
Electron beam:
#
Energy of electrons               GeV        14.0
Bunch charge                      nC         .200E-01  .100      .250      .500      1.00
Peak current                      kA         4.50      5.00      5.00      5.00      5.00
rms normalized emittance          mm-mrad    .320      .390      .600      .700      .970
rms energy spread                 MeV        4.10      2.90      2.50      2.20      2.00
rms bunch length                  micrometr  .360      1.92      4.98      9.17      23.0
Focusing beta function            m          15.0      15.0      23.3      29.6      46.9
rms size of electron beam         micrometr  13.2      14.6      22.6      27.5      40.8
Repetition rate                   1/sec      .270E+05
Electron beam power               kW         7.56      37.8      94.5      189.      378.
#
Undulator:
#
Undulator period                  cm         6.80
Undulator peak field              T          .245
Undulator parameter K (rms)       #          1.10
Undulator gap                     cm         4.56
Undulator length                  m          105.
#
Properties of the 1st harmonic in the saturation:
#
Radiation wavelength              nm         .100E+00
Photon energy                     keV        12.4
Pulse energy                      mJ         .425E-01  .245      .411      .650      1.17
Peak power                        GW         25.3      27.3      17.7      15.2      11.0
Average power                     W          1.15      6.61      11.1      17.6      31.7
FWHM spot size                    mikrometr  31.6      33.8      43.1      49.8      66.3
FWHM angular divergence           microrad   1.72      1.61      1.23      1.12      .941
Coherence time                    fs         .134      .134      .160      .182      .245
FWHM spectrum width, dw/w         %          .176      .175      .147      .129      .961E-01
Degree of transverse coherence    #          .960      .958      .911      .863      .705
Radiation pulse duration          fs         1.68      8.96      23.2      42.8      107.
Number of longitudinal modes      #            13        67       145       235       437
Fluctuations of the pulse energy  %          9.25      4.07      2.77      2.17      1.59
Degeneracy parameter              #          .164E+10  .177E+10  .130E+10  .120E+10  .952E+09
Number oh photons per pulse       #          .214E+11  .123E+12  .207E+12  .327E+12  .591E+12
Average flux of photons           ph/sec     .577E+15  .332E+16  .559E+16  .883E+16  .160E+17
Peak brilliance                   #          .278E+34  .300E+34  .221E+34  .204E+34  .162E+34
Average brilliance                #          .126E+24  .725E+24  .139E+25  .236E+25  .468E+25
Saturation length                 m          97.5      97.8      135.      154.      209.
Power gain length                 m          5.18      5.30      7.45      8.44      11.2
SASE induced energy loss          MeV        5.62      5.46      3.54      3.04      2.19
SASE induced energy spread        MeV        14.9      14.2      9.37      8.05      5.93
#
Properties of the 3rd harmonic in the saturation:
#
Radiation wavelength              nm         .333E-01
Photon energy                     keV        37.2
Contribution to the total power   P3/P       .552E-02  .517E-02  .450E-02  .445E-02  .436E-02
Pulse energy                      microJ     .235      1.26      1.85      2.89      5.12
Average power                     W          .633E-02  .341E-01  .500E-01  .782E-01  .138
Number oh photons per pulse       #          .393E+08  .212E+09  .311E+09  .485E+09  .858E+09
Average flux of photons           ph/sec     .106E+13  .572E+13  .839E+13  .131E+14  .232E+14
Coherence time                    fs         .448E-01  .448E-01  .535E-01  .608E-01  .818E-01
FWHM spectrum width, dw/w         %          .176      .175      .147      .129      .961E-01
#
Properties of the 5th harmonic in the saturation:
#
Radiation wavelength              nm         .200E-01
Photon energy                     keV        62.0
Contribution to the total power   P5/P       .181E-03  .153E-03  .112E-03  .110E-03  .107E-03
Pulse energy                      microJ     .770E-02  .374E-01  .462E-01  .717E-01  .126
Average power                     W          .208E-03  .101E-02  .125E-02  .194E-02  .340E-02
Number oh photons per pulse       #          .775E+06  .377E+07  .465E+07  .721E+07  .127E+08
Average flux of photons           ph/sec     .209E+11  .102E+12  .126E+12  .195E+12  .342E+12
Coherence time                    fs         .269E-01  .269E-01  .321E-01  .365E-01  .491E-01
FWHM spectrum width, dw/w         %          .176E-02  .175E-02  .147E-02  .129E-02  .961E-03
#
Incoherent radiation:
#
Critical wavelength               nm         .389E-01
Critical energy of SR             keV        31.9
SR induced energy loss            MeV        .781
SR induced energy spread          MeV        .177
SR power                          W          .422      2.11      5.27      10.5      21.1
#
Parameters of FEL theory:
#
Efficiency parameter (1D)         #          .975E-03  .946E-03  .707E-03  .621E-03  .477E-03
Efficiency parameter (3D)         #          .194E-02  .205E-02  .205E-02  .205E-02  .205E-02
N of electrons in coherence volume  #        .143E+07  .162E+07  .228E+07  .259E+07  .345E+07
Emittance parameter               #          .734      .894      1.38      1.61      2.22
```

Table D.8

Saturation characteristics of SASE3: 14 GeV, 0.15 nm

#						
Electron beam:						
#						
Energy of electrons	GeV	14.0				
Bunch charge	nC	.200E-01	.100	.250	.500	1.00
Peak current	kA	4.50	5.00	5.00	5.00	5.00
rms normalized emittance	mm-mrad	.320	.390	.600	.700	.970
rms energy spread	MeV	4.10	2.90	2.50	2.20	2.00
rms bunch length	micrometr	.360	1.92	4.98	9.17	23.0
Focusing beta function	m	15.0	15.0	15.0	16.0	25.7
rms size of electron beam	micrometr	13.2	14.6	18.1	20.2	30.1
Repetition rate	1/sec	.270E+05				
Electron beam power	kW	7.56	37.8	94.5	189.	378.
#						
Undulator:						
#						
Undulator period	cm	6.80				
Undulator peak field	T	.339				
Undulator parameter K (rms)	#	1.52				
Undulator length	m	105.				
#						
Properties of the 1st harmonic in the saturation:						
#						
Radiation wavelength	nm	.150				
Photon energy	keV	8.27				
Pulse energy	mJ	.648E-01	.387	.691	1.04	1.88
Peak power	GW	38.6	43.1	29.7	24.3	17.5
Average power	W	1.75	10.4	18.7	28.1	50.7
FWHM spot size	mikrometr	32.9	35.2	41.5	41.9	56.1
FWHM angular divergence	microrad	2.45	2.30	1.98	1.75	1.46
Coherence time	fs	.157	.156	.192	.178	.238
FWHM spectrum width, dw/w	%	.225	.226	.184	.199	.149
Degree of transverse coherence	#	.960	.960	.958	.952	.890
Radiation pulse duration	fs	1.68	8.96	23.2	42.8	107.
Number of longitudinal modes	#	11	57	121	241	451
Fluctuations of the pulse energy	%	10.1	4.42	3.03	2.15	1.57
Degeneracy parameter	#	.438E+10	.489E+10	.412E+10	.310E+10	.279E+10
Number oh photons per pulse	#	.489E+11	.292E+12	.521E+12	.784E+12	.142E+13
Average flux of photons	ph/sec	.132E+16	.788E+16	.141E+17	.212E+17	.382E+17
Peak brilliance	#	.220E+34	.246E+34	.207E+34	.156E+34	.140E+34
Average brilliance	#	.999E+23	.594E+24	.130E+25	.180E+25	.406E+25
Saturation length	m	76.2	76.1	93.6	100.	135.
Power gain length	m	3.88	3.89	4.98	5.49	7.26
SASE induced energy loss	MeV	8.57	8.63	5.95	4.85	3.50
SASE induced energy spread	MeV	22.2	22.2	15.4	12.6	9.15
#						
Properties of the 3rd harmonic in the saturation:						
#						
Radiation wavelength	nm	.500E-01				
Photon energy	keV	24.8				
Contribution to the total power	P3/P	.106E-01	.107E-01	.735E-02	.668E-02	.630E-02
Pulse energy	microJ	.689	4.15	5.08	6.94	11.8
Average power	W	.186E-01	.112	.137	.187	.319
Number oh photons per pulse	#	.173E+09	.104E+10	.128E+10	.175E+10	.298E+10
Average flux of photons	ph/sec	.468E+13	.282E+14	.345E+14	.472E+14	.804E+14
Coherence time	fs	.523E-01	.521E-01	.639E-01	.593E-01	.792E-01
FWHM spectrum width, dw/w	%	.225	.226	.184	.199	.149
#						
Properties of the 5th harmonic in the saturation:						
#						
Radiation wavelength	nm	.300E-01				
Photon energy	keV	41.3				
Contribution to the total power	P5/P	.815E-03	.835E-03	.323E-03	.255E-03	.226E-03
Pulse energy	microJ	.528E-01	.323	.223	.265	.424
Average power	W	.143E-02	.872E-02	.602E-02	.715E-02	.114E-01
Number oh photons per pulse	#	.797E+07	.487E+08	.337E+08	.400E+08	.639E+08
Average flux of photons	ph/sec	.215E+12	.132E+13	.909E+12	.108E+13	.173E+13
Coherence time	fs	.314E-01	.313E-01	.383E-01	.356E-01	.475E-01
FWHM spectrum width, dw/w	%	.225E-02	.226E-02	.184E-02	.199E-02	.149E-02
#						
Incoherent radiation:						
#						
Critical wavelength	nm	.281E-01				
Critical energy of SR	keV	44.1				
SR induced energy loss	MeV	1.50				
SR induced energy spread	MeV	.279				
SR power	W	.807	4.04	10.1	20.2	40.4
#						
Parameters of FEL theory:						
#						
Efficiency parameter (1D)	#	.116E-02	.113E-02	.978E-03	.909E-03	.697E-03
Efficiency parameter (3D)	#	.207E-02	.218E-02	.218E-02	.218E-02	.218E-02
N of electrons in coherence volume	#	.160E+07	.179E+07	.229E+07	.252E+07	.334E+07
Emittance parameter	#	.489	.596	.917	1.07	1.48

Table D.9

Saturation characteristics of SASE3: 14 GeV, 0.2 nm

#						
Electron beam:						
#						
Energy of electrons	GeV	14.0				
Bunch charge	nC	.200E-01	.100	.250	.500	1.00
Peak current	kA	4.50	5.00	5.00	5.00	5.00
rms normalized emittance	mm-mrad	.320	.390	.600	.700	.970
rms energy spread	MeV	4.10	2.90	2.50	2.20	2.00
rms bunch length	micrometr	.360	1.92	4.98	9.17	23.0
Focusing beta function	m	15.0	15.0	15.0	15.0	16.8
rms size of electron beam	micrometr	13.2	14.6	18.1	19.6	24.4
Repetition rate	1/sec	.270E+05				
Electron beam power	kW	7.56	37.8	94.5	189.	378.
#						
Undulator:						
#						
Undulator period	cm	6.80				
Undulator peak field	T	.412				
Undulator parameter K (rms)	#	1.85				
Undulator length	m	105.				
#						
Properties of the 1st harmonic in the saturation:						
#						
Radiation wavelength	nm	.200				
Photon energy	keV	6.20				
Pulse energy	mJ	.790E-01	.477	.938	1.53	2.55
Peak power	GW	47.0	53.2	40.3	35.7	23.8
Average power	W	2.13	12.9	25.3	41.3	68.9
FWHM spot size	mikrometr	33.9	36.3	42.9	45.4	50.0
FWHM angular divergence	microrad	3.12	2.95	2.54	2.40	1.98
Coherence time	fs	.184	.184	.218	.233	.241
FWHM spectrum width, dw/w	%	.256	.257	.216	.202	.195
Degree of transverse coherence	#	.960	.960	.960	.960	.949
Radiation pulse duration	fs	1.68	8.96	23.2	42.8	107.
Number of longitudinal modes	#	9	49	107	184	445
Fluctuations of the pulse energy	%	11.1	4.76	3.22	2.46	1.58
Degeneracy parameter	#	.837E+10	.943E+10	.850E+10	.804E+10	.548E+10
Number oh photons per pulse	#	.794E+11	.480E+12	.943E+12	.154E+13	.257E+13
Average flux of photons	ph/sec	.215E+16	.129E+17	.255E+17	.415E+17	.694E+17
Peak brilliance	#	.178E+34	.200E+34	.180E+34	.170E+34	.116E+34
Average brilliance	#	.805E+23	.484E+24	.113E+25	.197E+25	.336E+25
Saturation length	m	67.4	67.2	80.1	85.7	103.
Power gain length	m	3.35	3.35	4.08	4.43	5.53
SASE induced energy loss	MeV	10.4	10.6	8.07	7.14	4.76
SASE induced energy spread	MeV	26.9	27.3	20.7	18.3	12.3
#						
Properties of the 3rd harmonic in the saturation:						
#						
Radiation wavelength	nm	.667E-01				
Photon energy	keV	18.6				
Contribution to the total power	P3/P	.137E-01	.143E-01	.110E-01	.963E-02	.745E-02
Pulse energy	microJ	1.08	6.84	10.3	14.7	19.0
Average power	W	.291E-01	.185	.279	.397	.514
Number oh photons per pulse	#	.362E+09	.229E+10	.347E+10	.494E+10	.638E+10
Average flux of photons	ph/sec	.977E+13	.619E+14	.937E+14	.133E+15	.172E+15
Coherence time	fs	.615E-01	.612E-01	.727E-01	.777E-01	.804E-01
FWHM spectrum width, dw/w	%	.256	.257	.216	.202	.195
#						
Properties of the 5th harmonic in the saturation:						
#						
Radiation wavelength	nm	.400E-01				
Photon energy	keV	31.0				
Contribution to the total power	P5/P	.142E-02	.157E-02	.868E-03	.617E-03	.322E-03
Pulse energy	microJ	.112	.750	.813	.944	.821
Average power	W	.302E-02	.203E-01	.220E-01	.255E-01	.222E-01
Number oh photons per pulse	#	.225E+08	.151E+09	.164E+09	.190E+09	.165E+09
Average flux of photons	ph/sec	.607E+12	.408E+13	.442E+13	.513E+13	.446E+13
Coherence time	fs	.369E-01	.367E-01	.436E-01	.466E-01	.482E-01
FWHM spectrum width, dw/w	%	.256E-02	.257E-02	.216E-02	.202E-02	.195E-02
#						
Incoherent radiation:						
#						
Critical wavelength	nm	.231E-01				
Critical energy of SR	keV	53.7				
SR induced energy loss	MeV	2.21				
SR induced energy spread	MeV	.370				
SR power	W	1.19	5.96	14.9	29.8	59.6
#						
Parameters of FEL theory:						
#						
Efficiency parameter (1D)	#	.130E-02	.126E-02	.109E-02	.104E-02	.895E-03
Efficiency parameter (3D)	#	.211E-02	.223E-02	.223E-02	.223E-02	.223E-02
N of electrons in coherence volume	#	.185E+07	.205E+07	.250E+07	.272E+07	.339E+07
Emittance parameter	#	.367	.447	.688	.803	1.11

Table D.10

Saturation characteristics of SASE3: 14 GeV, 0.4 nm

#						
Electron beam:						
#						
Energy of electrons	GeV	14.0				
Bunch charge	nC	.200E-01	.100	.250	.500	1.00
Peak current	kA	4.50	5.00	5.00	5.00	5.00
rms normalized emittance	mm-mrad	.320	.390	.600	.700	.970
rms energy spread	MeV	4.10	2.90	2.50	2.20	2.00
rms bunch length	micrometr	.360	1.92	4.98	9.17	23.0
Focusing beta function	m	15.0	15.0	15.0	15.0	15.0
rms size of electron beam	micrometr	13.2	14.6	18.1	19.6	23.0
Repetition rate	1/sec	.270E+05				
Electron beam power	kW	7.56	37.8	94.5	189.	378.
#						
Undulator:						
#						
Undulator period	cm	6.80				
Undulator peak field	T	.623				
Undulator parameter K (rms)	#	2.80				
Undulator length	m	105.				
#						
Properties of the 1st harmonic in the saturation:						
#						
Radiation wavelength	nm	.400				
Photon energy	keV	3.10				
Pulse energy	mJ	.110	.670	1.47	2.54	5.28
Peak power	GW	65.4	74.8	63.2	59.2	49.3
Average power	W	2.97	18.1	39.7	68.5	143.
FWHM spot size	mikrometr	36.4	39.1	46.3	49.2	55.8
FWHM angular divergence	microrad	5.56	5.27	4.57	4.34	3.87
Coherence time	fs	.292	.290	.333	.350	.395
FWHM spectrum width, dw/w	%	.323	.325	.283	.270	.239
Degree of transverse coherence	#	.960	.960	.960	.960	.960
Radiation pulse duration	fs	1.68	8.96	23.2	42.8	107.
Number of longitudinal modes	#	6	31	70	123	271
Fluctuations of the pulse energy	%	13.6	5.99	3.98	3.01	2.02
Degeneracy parameter	#	.369E+11	.419E+11	.406E+11	.400E+11	.376E+11
Number oh photons per pulse	#	.221E+12	.135E+13	.296E+13	.511E+13	.106E+14
Average flux of photons	ph/sec	.597E+16	.364E+17	.798E+17	.138E+18	.287E+18
Peak brilliance	#	.977E+33	.111E+34	.108E+34	.106E+34	.997E+33
Average brilliance	#	.443E+23	.269E+24	.676E+24	.123E+25	.289E+25
Saturation length	m	53.7	53.6	61.5	64.7	73.3
Power gain length	m	2.57	2.55	2.94	3.10	3.56
SASE induced energy loss	MeV	14.5	15.0	12.6	11.8	9.86
SASE induced energy spread	MeV	37.3	38.2	32.3	30.3	25.2
#						
Properties of the 3rd harmonic in the saturation:						
#						
Radiation wavelength	nm	.133				
Photon energy	keV	9.30				
Contribution to the total power	P3/P	.178E-01	.190E-01	.180E-01	.175E-01	.151E-01
Pulse energy	microJ	1.96	12.7	26.4	44.4	79.9
Average power	W	.529E-01	.343	.714	1.20	2.16
Number oh photons per pulse	#	.131E+10	.852E+10	.177E+11	.298E+11	.536E+11
Average flux of photons	ph/sec	.355E+14	.230E+15	.479E+15	.805E+15	.145E+16
Coherence time	fs	.973E-01	.968E-01	.111	.117	.132
FWHM spectrum width, dw/w	%	.323	.325	.283	.270	.239
#						
Properties of the 5th harmonic in the saturation:						
#						
Radiation wavelength	nm	.800E-01				
Photon energy	keV	15.5				
Contribution to the total power	P5/P	.250E-02	.282E-02	.254E-02	.241E-02	.176E-02
Pulse energy	microJ	.274	1.89	3.74	6.11	9.31
Average power	W	.741E-02	.511E-01	.101	.165	.251
Number oh photons per pulse	#	.110E+09	.761E+09	.150E+10	.246E+10	.375E+10
Average flux of photons	ph/sec	.298E+13	.206E+14	.406E+14	.664E+14	.101E+15
Coherence time	fs	.584E-01	.581E-01	.666E-01	.699E-01	.790E-01
FWHM spectrum width, dw/w	%	.323E-02	.325E-02	.283E-02	.270E-02	.239E-02
#						
Incoherent radiation:						
#						
Critical wavelength	nm	.153E-01				
Critical energy of SR	keV	81.2				
SR induced energy loss	MeV	5.06				
SR induced energy spread	MeV	.680				
SR power	W	2.74	13.7	34.2	68.4	137.
#						
Parameters of FEL theory:						
#						
Efficiency parameter (1D)	#	.166E-02	.161E-02	.139E-02	.132E-02	.119E-02
Efficiency parameter (3D)	#	.215E-02	.227E-02	.227E-02	.227E-02	.227E-02
N of electrons in coherence volume	#	.284E+07	.313E+07	.361E+07	.381E+07	.437E+07
Emittance parameter	#	.183	.224	.344	.401	.556

Table D.11

Saturation characteristics of SASE3: 14 GeV, 0.8 nm

#						
Electron beam:						
#						
Energy of electrons	GeV	14.0				
Bunch charge	nC	.200E-01	.100	.250	.500	1.00
Peak current	kA	4.50	5.00	5.00	5.00	5.00
rms normalized emittance	mm-mrad	.320	.390	.600	.700	.970
rms energy spread	MeV	4.10	2.90	2.50	2.20	2.00
rms bunch length	micrometr	.360	1.92	4.98	9.17	23.0
Focusing beta function	m	15.0	15.0	15.0	15.0	15.0
rms size of electron beam	micrometr	13.2	14.6	18.1	19.6	23.0
Repetition rate	1/sec	.270E+05				
Electron beam power	kW	7.56	37.8	94.5	189.	378.
#						
Undulator:						
#						
Undulator period	cm	6.80				
Undulator peak field	T	.909				
Undulator parameter K (rms)	#	4.08				
Undulator length	m	105.				
#						
Properties of the 1st harmonic in the saturation:						
#						
Radiation wavelength	nm	.800				
Photon energy	keV	1.55				
Pulse energy	mJ	.138	.846	1.94	3.42	7.60
Peak power	GW	82.2	94.4	83.6	79.9	70.9
Average power	W	3.73	22.8	52.4	92.4	205.
FWHM spot size	mikrometr	39.0	42.0	49.9	53.0	60.3
FWHM angular divergence	microrad	9.71	9.26	8.11	7.72	6.94
Coherence time	fs	.484	.481	.542	.565	.626
FWHM spectrum width, dw/w	%	.390	.392	.348	.333	.301
Degree of transverse coherence	#	.960	.960	.960	.960	.960
Radiation pulse duration	fs	1.68	8.96	23.2	42.8	107.
Number of longitudinal modes	#	3	19	43	76	171
Fluctuations of the pulse energy	%	19.2	7.65	5.08	3.82	2.55
Degeneracy parameter	#	.154E+12	.175E+12	.175E+12	.175E+12	.171E+12
Number oh photons per pulse	#	.556E+12	.341E+13	.782E+13	.138E+14	.306E+14
Average flux of photons	ph/sec	.150E+17	.919E+17	.211E+18	.372E+18	.826E+18
Peak brilliance	#	.509E+33	.581E+33	.579E+33	.578E+33	.567E+33
Average brilliance	#	.231E+23	.141E+24	.364E+24	.669E+24	.164E+25
Saturation length	m	44.8	44.7	50.5	52.7	58.4
Power gain length	m	2.09	2.07	2.33	2.43	2.70
SASE induced energy loss	MeV	18.3	18.9	16.7	16.0	14.2
SASE induced energy spread	MeV	46.8	48.2	42.7	40.8	36.2
#						
Properties of the 3rd harmonic in the saturation:						
#						
Radiation wavelength	nm	.267				
Photon energy	keV	4.65				
Contribution to the total power	P3/P	.196E-01	.205E-01	.203E-01	.203E-01	.198E-01
Pulse energy	microJ	2.71	17.3	39.4	69.6	150.
Average power	W	.731E-01	.468	1.07	1.88	4.06
Number oh photons per pulse	#	.363E+10	.233E+11	.529E+11	.933E+11	.201E+12
Average flux of photons	ph/sec	.981E+14	.628E+15	.143E+16	.252E+16	.544E+16
Coherence time	fs	.161	.160	.181	.188	.209
FWHM spectrum width, dw/w	%	.390	.392	.348	.333	.301
#						
Properties of the 5th harmonic in the saturation:						
#						
Radiation wavelength	nm	.160				
Photon energy	keV	7.75				
Contribution to the total power	P5/P	.304E-02	.331E-02	.326E-02	.326E-02	.309E-02
Pulse energy	microJ	.420	2.80	6.32	11.2	23.4
Average power	W	.113E-01	.757E-01	.171	.301	.633
Number oh photons per pulse	#	.338E+09	.226E+10	.509E+10	.898E+10	.189E+11
Average flux of photons	ph/sec	.912E+13	.609E+14	.137E+15	.243E+15	.510E+15
Coherence time	fs	.967E-01	.961E-01	.108	.113	.125
FWHM spectrum width, dw/w	%	.390E-02	.392E-02	.348E-02	.333E-02	.301E-02
#						
Incoherent radiation:						
#						
Critical wavelength	nm	.105E-01				
Critical energy of SR	keV	119.				
SR induced energy loss	MeV	10.8				
SR induced energy spread	MeV	1.19				
SR power	W	5.82	29.1	72.7	145.	291.
#						
Parameters of FEL theory:						
#						
Efficiency parameter (1D)	#	.209E-02	.203E-02	.176E-02	.167E-02	.150E-02
Efficiency parameter (3D)	#	.216E-02	.228E-02	.228E-02	.228E-02	.228E-02
N of electrons in coherence volume	#	.460E+07	.507E+07	.571E+07	.596E+07	.661E+07
Emittance parameter	#	.917E-01	.112	.172	.201	.278

Table D.12

Saturation characteristics of SASE3: 14 GeV, 1.6 nm

#						
Electron beam:						
#						
Energy of electrons	GeV	14.0				
Bunch charge	nC	.200E-01	.100	.250	.500	1.00
Peak current	kA	4.50	5.00	5.00	5.00	5.00
rms normalized emittance	mm-mrad	.320	.390	.600	.700	.970
rms energy spread	MeV	4.10	2.90	2.50	2.20	2.00
rms bunch length	micrometr	.360	1.92	4.98	9.17	23.0
Focusing beta function	m	15.0	15.0	15.0	15.0	15.0
rms size of electron beam	micrometr	13.2	14.6	18.1	19.6	23.0
Repetition rate	1/sec	.270E+05				
Electron beam power	kW	7.56	37.8	94.5	189.	378.
#						
Undulator:						
#						
Undulator period	cm	6.80				
Undulator peak field	T	1.30				
Undulator parameter K (rms)	#	5.86				
Undulator length	m	105.				
#						
Properties of the 1st harmonic in the saturation:						
#						
Radiation wavelength	nm	1.60				
Photon energy	keV	.775				
Pulse energy	mJ	.166	1.01	2.38	4.24	9.71
Peak power	GW	99.0	113.	102.	99.0	90.5
Average power	W	4.49	27.4	64.3	115.	262.
FWHM spot size	mikrometr	41.6	44.8	53.4	56.8	64.8
FWHM angular divergence	microrad	16.6	16.0	14.2	13.5	12.3
Coherence time	fs	.824	.817	.909	.945	1.03
FWHM spectrum width, dw/w	%	.458	.462	.415	.399	.365
Degree of transverse coherence	#	.960	.960	.960	.960	.960
Radiation pulse duration	fs	1.68	8.96	23.2	42.8	107.
Number of longitudinal modes	#	2	11	26	45	104
Fluctuations of the pulse energy	%	23.6	10.1	6.54	4.97	3.27
Degeneracy parameter	#	.630E+12	.715E+12	.720E+12	.723E+12	.723E+12
Number oh photons per pulse	#	.134E+13	.817E+13	.192E+14	.341E+14	.782E+14
Average flux of photons	ph/sec	.361E+17	.220E+18	.517E+18	.922E+18	.211E+19
Peak brilliance	#	.261E+33	.296E+33	.298E+33	.299E+33	.299E+33
Average brilliance	#	.118E+23	.716E+23	.187E+24	.346E+24	.867E+24
Saturation length	m	38.5	38.2	42.7	44.4	48.6
Power gain length	m	1.75	1.73	1.91	1.99	2.17
SASE induced energy loss	MeV	22.0	22.6	20.5	19.8	18.1
SASE induced energy spread	MeV	56.2	57.8	52.3	50.5	46.2
#						
Properties of the 3rd harmonic in the saturation:						
#						
Radiation wavelength	nm	.533				
Photon energy	keV	2.32				
Contribution to the total power	P3/P	.205E-01	.211E-01	.211E-01	.211E-01	.210E-01
Pulse energy	microJ	3.41	21.4	50.2	89.7	204.
Average power	W	.921E-01	.578	1.35	2.42	5.51
Number oh photons per pulse	#	.915E+10	.574E+11	.135E+12	.241E+12	.547E+12
Average flux of photons	ph/sec	.247E+15	.155E+16	.363E+16	.650E+16	.148E+17
Coherence time	fs	.275	.272	.303	.315	.344
FWHM spectrum width, dw/w	%	.458	.462	.415	.399	.365
#						
Properties of the 5th harmonic in the saturation:						
#						
Radiation wavelength	nm	.320				
Photon energy	keV	3.87				
Contribution to the total power	P5/P	.332E-02	.352E-02	.350E-02	.353E-02	.349E-02
Pulse energy	microJ	.553	3.57	8.34	15.0	33.8
Average power	W	.149E-01	.963E-01	.225	.404	.914
Number oh photons per pulse	#	.890E+09	.574E+10	.134E+11	.241E+11	.545E+11
Average flux of photons	ph/sec	.240E+14	.155E+15	.363E+15	.650E+15	.147E+16
Coherence time	fs	.165	.163	.182	.189	.207
FWHM spectrum width, dw/w	%	.458E-02	.462E-02	.415E-02	.399E-02	.365E-02
#						
Incoherent radiation:						
#						
Critical wavelength	nm	.729E-02				
Critical energy of SR	keV	170.				
SR induced energy loss	MeV	22.2				
SR induced energy spread	MeV	2.05				
SR power	W	12.0	59.9	150.	300.	599.
#						
Parameters of FEL theory:						
#						
Efficiency parameter (1D)	#	.264E-02	.256E-02	.222E-02	.210E-02	.189E-02
Efficiency parameter (3D)	#	.216E-02	.228E-02	.228E-02	.228E-02	.228E-02
N of electrons in coherence volume	#	.771E+07	.847E+07	.939E+07	.975E+07	.107E+08
Emittance parameter	#	.459E-01	.559E-01	.860E-01	.100	.139

Table D.13

Saturation characteristics of SASE3: 14 GeV, 2.5 nm

#						
Electron beam:						
#						
Energy of electrons	GeV	14.0				
Bunch charge	nC	.200E-01	.100	.250	.500	1.00
Peak current	kA	4.50	5.00	5.00	5.00	5.00
rms normalized emittance	mm-mrad	.320	.390	.600	.700	.970
rms energy spread	MeV	4.10	2.90	2.50	2.20	2.00
rms bunch length	micrometr	.360	1.92	4.98	9.17	23.0
Focusing beta function	m	15.0	15.0	15.0	15.0	15.0
rms size of electron beam	micrometr	13.2	14.6	18.1	19.6	23.0
Repetition rate	1/sec	.270E+05				
Electron beam power	kW	7.56	37.8	94.5	189.	378.
#						
Undulator:						
#						
Undulator period	cm	6.80				
Undulator peak field	T	1.64				
Undulator parameter K (rms)	#	7.36				
Undulator length	m	105.				
#						
Properties of the 1st harmonic in the saturation:						
#						
Radiation wavelength	nm	2.50				
Photon energy	keV	.496				
Pulse energy	mJ	.185	1.13	2.66	4.75	11.0
Peak power	GW	110.	126.	115.	111.	102.
Average power	W	5.00	30.5	71.9	128.	297.
FWHM spot size	mikrometr	43.2	46.7	55.7	59.3	67.7
FWHM angular divergence	microrad	23.1	22.4	20.0	19.2	17.5
Coherence time	fs	1.17	1.16	1.28	1.33	1.45
FWHM spectrum width, dw/w	%	.502	.507	.459	.443	.407
Degree of transverse coherence	#	.960	.960	.960	.960	.960
Radiation pulse duration	fs	1.68	8.96	23.2	42.8	107.
Number of longitudinal modes	#	1	8	18	32	74
Fluctuations of the pulse energy	%	33.3	11.8	7.86	5.89	3.87
Degeneracy parameter	#	.156E+13	.177E+13	.178E+13	.178E+13	.179E+13
Number oh photons per pulse	#	.233E+13	.142E+14	.335E+14	.597E+14	.138E+15
Average flux of photons	ph/sec	.629E+17	.383E+18	.904E+18	.161E+19	.373E+19
Peak brilliance	#	.170E+33	.192E+33	.193E+33	.193E+33	.194E+33
Average brilliance	#	.770E+22	.464E+23	.121E+24	.224E+24	.563E+24
Saturation length	m	35.3	35.0	38.7	40.2	43.7
Power gain length	m	1.58	1.56	1.71	1.77	1.92
SASE induced energy loss	MeV	24.5	25.2	22.9	22.2	20.5
SASE induced energy spread	MeV	62.6	64.3	58.5	56.6	52.3
#						
Properties of the 3rd harmonic in the saturation:						
#						
Radiation wavelength	nm	.833				
Photon energy	keV	1.49				
Contribution to the total power	P3/P	.209E-01	.213E-01	.213E-01	.214E-01	.213E-01
Pulse energy	microJ	3.87	24.1	56.7	101.	234.
Average power	W	.104	.650	1.53	2.74	6.32
Number oh photons per pulse	#	.162E+11	.101E+12	.238E+12	.425E+12	.982E+12
Average flux of photons	ph/sec	.438E+15	.272E+16	.642E+16	.115E+17	.265E+17
Coherence time	fs	.392	.388	.428	.444	.482
FWHM spectrum width, dw/w	%	.502	.507	.459	.443	.407
#						
Properties of the 5th harmonic in the saturation:						
#						
Radiation wavelength	nm	.500				
Photon energy	keV	2.48				
Contribution to the total power	P5/P	.344E-02	.359E-02	.358E-02	.360E-02	.358E-02
Pulse energy	microJ	.638	4.05	9.54	17.1	39.4
Average power	W	.172E-01	.109	.257	.462	1.06
Number oh photons per pulse	#	.160E+10	.102E+11	.240E+11	.430E+11	.990E+11
Average flux of photons	ph/sec	.433E+14	.275E+15	.648E+15	.116E+16	.267E+16
Coherence time	fs	.235	.233	.257	.266	.289
FWHM spectrum width, dw/w	%	.502E-02	.507E-02	.459E-02	.443E-02	.407E-02
#						
Incoherent radiation:						
#						
Critical wavelength	nm	.580E-02				
Critical energy of SR	keV	214.				
SR induced energy loss	MeV	35.1				
SR induced energy spread	MeV	2.88				
SR power	W	18.9	94.6	237.	473.	946.
#						
Parameters of FEL theory:						
#						
Efficiency parameter (1D)	#	.306E-02	.297E-02	.257E-02	.244E-02	.219E-02
Efficiency parameter (3D)	#	.216E-02	.228E-02	.228E-02	.228E-02	.228E-02
N of electrons in coherence volume	#	.109E+08	.119E+08	.131E+08	.136E+08	.147E+08
Emittance parameter	#	.294E-01	.358E-01	.550E-01	.642E-01	.890E-01

Table D.14

Saturation characteristics of SASE3: 10.5 GeV, 0.15 nm

#						
Electron beam:						
#						
Energy of electrons	GeV	10.5				
Bunch charge	nC	.200E-01	.100	.250	.500	1.00
Peak current	kA	4.50	5.00	5.00	5.00	5.00
rms normalized emittance	mm-mrad	.320	.390	.600	.700	.970
rms energy spread	MeV	4.10	2.90	2.50	2.20	2.00
rms bunch length	micrometr	.360	1.92	4.98	9.17	23.0
Focusing beta function	m	15.0	15.0	17.3	22.0	34.7
rms size of electron beam	micrometr	15.3	16.9	22.5	27.4	40.5
Repetition rate	1/sec	.270E+05				
Electron beam power	kW	5.67	28.3	70.9	142.	283.
#						
Undulator:						
#						
Undulator period	cm	6.80				
Undulator peak field	T	.207				
Undulator parameter K (rms)	#	.929				
Undulator gap	cm	4.95				
Undulator length	m	105.				
#						
Properties of the 1st harmonic in the saturation:						
#						
Radiation wavelength	nm	.150				
Photon energy	keV	8.27				
Pulse energy	mJ	.350E-01	.218	.380	.601	1.08
Peak power	GW	20.8	24.3	16.4	14.0	10.1
Average power	W	.945	5.87	10.3	16.2	29.3
FWHM spot size	mikrometr	36.6	39.2	44.6	51.5	68.4
FWHM angular divergence	microrad	2.22	2.09	1.72	1.56	1.31
Coherence time	fs	.188	.183	.204	.232	.313
FWHM spectrum width, dw/w	%	.188	.193	.173	.152	.113
Degree of transverse coherence	#	.960	.960	.936	.901	.769
Radiation pulse duration	fs	1.68	8.96	23.2	42.8	107.
Number of longitudinal modes	#	9	49	114	185	342
Fluctuations of the pulse energy	%	11.1	4.76	3.12	2.45	1.80
Degeneracy parameter	#	.285E+10	.321E+10	.236E+10	.221E+10	.184E+10
Number oh photons per pulse	#	.264E+11	.164E+12	.287E+12	.453E+12	.819E+12
Average flux of photons	ph/sec	.713E+15	.443E+16	.774E+16	.122E+17	.221E+17
Peak brilliance	#	.143E+34	.162E+34	.119E+34	.111E+34	.925E+33
Average brilliance	#	.649E+23	.391E+24	.744E+24	.129E+25	.268E+25
Saturation length	m	91.7	89.1	115.	132.	180.
Power gain length	m	4.70	4.63	6.28	7.10	9.49
SASE induced energy loss	MeV	4.63	4.86	3.27	2.80	2.02
SASE induced energy spread	MeV	12.5	12.7	8.71	7.48	5.53
#						
Properties of the 3rd harmonic in the saturation:						
#						
Radiation wavelength	nm	.500E-01				
Photon energy	keV	24.8				
Contribution to the total power	P3/P	.434E-02	.439E-02	.348E-02	.344E-02	.336E-02
Pulse energy	microJ	.152	.955	1.32	2.06	3.65
Average power	W	.410E-02	.258E-01	.357E-01	.557E-01	.985E-01
Number oh photons per pulse	#	.382E+08	.240E+09	.332E+09	.519E+09	.917E+09
Average flux of photons	ph/sec	.103E+13	.649E+13	.897E+13	.140E+14	.248E+14
Coherence time	fs	.628E-01	.609E-01	.681E-01	.774E-01	.104
FWHM spectrum width, dw/w	%	.188	.193	.173	.152	.113
#						
Properties of the 5th harmonic in the saturation:						
#						
Radiation wavelength	nm	.300E-01				
Photon energy	keV	41.3				
Contribution to the total power	P5/P	.112E-03	.115E-03	.659E-04	.647E-04	.629E-04
Pulse energy	microJ	.391E-02	.250E-01	.250E-01	.389E-01	.682E-01
Average power	W	.106E-03	.676E-03	.676E-03	.105E-02	.184E-02
Number oh photons per pulse	#	.590E+06	.378E+07	.378E+07	.587E+07	.103E+08
Average flux of photons	ph/sec	.159E+11	.102E+12	.102E+12	.158E+12	.278E+12
Coherence time	fs	.377E-01	.365E-01	.409E-01	.464E-01	.627E-01
FWHM spectrum width, dw/w	%	.188E-02	.193E-02	.173E-02	.152E-02	.113E-02
#						
Incoherent radiation:						
#						
Critical wavelength	nm	.817E-01				
Critical energy of SR	keV	15.2				
SR induced energy loss	MeV	.314				
SR induced energy spread	MeV	.790E-01				
SR power	W	.170	.848	2.12	4.24	8.48
#						
Parameters of FEL theory:						
#						
Efficiency parameter (1D)	#	.108E-02	.104E-02	.863E-03	.757E-03	.583E-03
Efficiency parameter (3D)	#	.213E-02	.224E-02	.224E-02	.224E-02	.224E-02
N of electrons in coherence volume	#	.195E+07	.213E+07	.289E+07	.327E+07	.437E+07
Emittance parameter	#	.652	.795	1.22	1.43	1.98

Table D.15

Saturation characteristics of SASE3: 10.5 GeV, 0.2 nm

```
#
Electron beam:
#
Energy of electrons                 GeV       10.5
Bunch charge                        nC        .200E-01  .100      .250      .500      1.00
Peak current                        kA        4.50      5.00      5.00      5.00      5.00
rms normalized emittance            mm-mrad   .320      .390      .600      .700      .970
rms energy spread                   MeV       4.10      2.90      2.50      2.20      2.00
rms bunch length                    micrometr .360      1.92      4.98      9.17      23.0
Focusing beta function              m         15.0      15.0      15.0      15.0      22.3
rms size of electron beam           micrometr 15.3      16.9      20.9      22.6      32.4
Repetition rate                     1/sec     .270E+05
Electron beam power                 kW        5.67      28.3      70.9      142.      283.
#
Undulator:
#
Undulator period                    cm        6.80
Undulator peak field                T         .271
Undulator parameter K (rms)         #         1.22
Undulator gap                       cm        4.33
Undulator length                    m         105.
#
Properties of the 1st harmonic in the saturation:
#
Radiation wavelength                nm        .200
Photon energy                       keV       6.20
Pulse energy                        mJ        .491E-01  .306      .563      .891      1.56
Peak power                          GW        29.2      34.2      24.2      20.8      14.6
Average power                       W         1.32      8.27      15.2      24.1      42.2
FWHM spot size                      mikrometr 37.5      40.2      47.3      50.1      60.4
FWHM angular divergence             microrad  2.87      2.70      2.32      2.19      1.80
Coherence time                      fs        .203      .198      .241      .260      .292
FWHM spectrum width, dw/w           %         .232      .238      .196      .181      .162
Degree of transverse coherence      #         .960      .960      .958      .952      .890
Radiation pulse duration            fs        1.68      8.96      23.2      42.8      107.
Number of longitudinal modes        #           8        45        96       165       367
Fluctuations of the pulse energy    %         11.8      4.97      3.40      2.59      1.74
Degeneracy parameter                #         .573E+10  .654E+10  .563E+10  .518E+10  .381E+10
Number oh photons per pulse         #         .494E+11  .308E+12  .567E+12  .896E+12  .157E+13
Average flux of photons             ph/sec    .133E+16  .833E+16  .153E+17  .242E+17  .425E+17
Peak brilliance                     #         .121E+34  .139E+34  .119E+34  .110E+34  .808E+33
Average brilliance                  #         .551E+23  .335E+24  .749E+24  .127E+25  .234E+25
Saturation length                   m         74.2      72.5      88.5      95.5      125.
Power gain length                   m         3.71      3.65      4.60      5.07      6.65
SASE induced energy loss            MeV       6.49      6.84      4.85      4.16      2.92
SASE induced energy spread          MeV       17.0      17.7      12.6      10.8      7.70
#
Properties of the 3rd harmonic in the saturation:
#
Radiation wavelength                nm        .667E-01
Photon energy                       keV       18.6
Contribution to the total power     P3/P      .793E-02  .853E-02  .613E-02  .548E-02  .510E-02
Pulse energy                        microJ    .389      2.61      3.46      4.89      7.98
Average power                       W         .105E-01  .706E-01  .933E-01  .132      .215
Number oh photons per pulse         #         .131E+09  .877E+09  .116E+10  .164E+10  .268E+10
Average flux of photons             ph/sec    .352E+13  .237E+14  .313E+14  .442E+14  .722E+14
Coherence time                      fs        .677E-01  .660E-01  .803E-01  .866E-01  .973E-01
FWHM spectrum width, dw/w           %         .232      .238      .196      .181      .162
#
Properties of the 5th harmonic in the saturation:
#
Radiation wavelength                nm        .400E-01
Photon energy                       keV       31.0
Contribution to the total power     P5/P      .430E-03  .512E-03  .223E-03  .169E-03  .145E-03
Pulse energy                        microJ    .211E-01  .157      .126      .150      .228
Average power                       W         .570E-03  .424E-02  .339E-02  .406E-02  .614E-02
Number oh photons per pulse         #         .425E+07  .316E+08  .253E+08  .303E+08  .458E+08
Average flux of photons             ph/sec    .115E+12  .853E+12  .683E+12  .817E+12  .124E+13
Coherence time                      fs        .406E-01  .396E-01  .482E-01  .520E-01  .584E-01
FWHM spectrum width, dw/w           %         .232E-02  .238E-02  .196E-02  .181E-02  .162E-02
#
Incoherent radiation:
#
Critical wavelength                 nm        .623E-01
Critical energy of SR               keV       19.9
SR induced energy loss              MeV       .540
SR induced energy spread            MeV       .115
SR power                            W         .292      1.46      3.64      7.29      14.6
#
Parameters of FEL theory:
#
Efficiency parameter (1D)           #         .125E-02  .121E-02  .105E-02  .997E-03  .783E-03
Efficiency parameter (3D)           #         .230E-02  .242E-02  .242E-02  .242E-02  .242E-02
N of electrons in coherence volume  #         .205E+07  .224E+07  .282E+07  .311E+07  .408E+07
Emittance parameter                 #         .489      .596      .917      1.07      1.48
```

Table D.16

Saturation characteristics of SASE3: 10.5 GeV, 0.4 nm

#						
Electron beam:						
#						
Energy of electrons	GeV	10.5				
Bunch charge	nC	.200E-01	.100	.250	.500	1.00
Peak current	kA	4.50	5.00	5.00	5.00	5.00
rms normalized emittance	mm-mrad	.320	.390	.600	.700	.970
rms energy spread	MeV	4.10	2.90	2.50	2.20	2.00
rms bunch length	micrometr	.360	1.92	4.98	9.17	23.0
Focusing beta function	m	15.0	15.0	15.0	15.0	15.0
rms size of electron beam	micrometr	15.3	16.9	20.9	22.6	26.6
Repetition rate	1/sec	.270E+05				
Electron beam power	kW	5.67	28.3	70.9	142.	283.
#						
Undulator:						
#						
Undulator period	cm	6.80				
Undulator peak field	T	.444				
Undulator parameter K (rms)	#	1.99				
Undulator length	m	105.				
#						
Properties of the 1st harmonic in the saturation:						
#						
Radiation wavelength	nm	.400				
Photon energy	keV	3.10				
Pulse energy	mJ	.774E-01	.484	1.04	1.78	3.57
Peak power	GW	46.1	54.0	44.6	41.5	33.3
Average power	W	2.09	13.1	28.0	48.0	96.4
FWHM spot size	mikrometr	40.2	43.2	51.0	54.1	61.2
FWHM angular divergence	microrad	5.18	4.90	4.23	4.00	3.57
Coherence time	fs	.298	.292	.338	.356	.407
FWHM spectrum width, dw/w	%	.317	.322	.279	.265	.232
Degree of transverse coherence	#	.960	.960	.960	.960	.960
Radiation pulse duration	fs	1.68	8.96	23.2	42.8	107.
Number of longitudinal modes	#	6	31	69	120	263
Fluctuations of the pulse energy	%	13.6	5.99	4.01	3.04	2.06
Degeneracy parameter	#	.265E+11	.305E+11	.291E+11	.285E+11	.262E+11
Number oh photons per pulse	#	.156E+12	.973E+12	.209E+13	.358E+13	.719E+13
Average flux of photons	ph/sec	.420E+16	.263E+17	.564E+17	.966E+17	.194E+18
Peak brilliance	#	.702E+33	.808E+33	.772E+33	.756E+33	.694E+33
Average brilliance	#	.318E+23	.195E+24	.484E+24	.874E+24	.201E+25
Saturation length	m	54.8	53.9	62.5	65.8	75.5
Power gain length	m	2.63	2.58	3.01	3.19	3.72
SASE induced energy loss	MeV	10.2	10.8	8.93	8.30	6.66
SASE induced energy spread	MeV	26.4	27.7	22.9	21.3	17.1
#						
Properties of the 3rd harmonic in the saturation:						
#						
Radiation wavelength	nm	.133				
Photon energy	keV	9.30				
Contribution to the total power	P3/P	.146E-01	.162E-01	.149E-01	.142E-01	.114E-01
Pulse energy	microJ	1.13	7.83	15.4	25.3	40.7
Average power	W	.306E-01	.211	.416	.683	1.10
Number oh photons per pulse	#	.759E+09	.525E+10	.103E+11	.170E+11	.273E+11
Average flux of photons	ph/sec	.205E+14	.142E+15	.279E+15	.458E+15	.736E+15
Coherence time	fs	.992E-01	.975E-01	.113	.119	.136
FWHM spectrum width, dw/w	%	.317	.322	.279	.265	.232
#						
Properties of the 5th harmonic in the saturation:						
#						
Radiation wavelength	nm	.800E-01				
Photon energy	keV	15.5				
Contribution to the total power	P5/P	.164E-02	.203E-02	.170E-02	.154E-02	.927E-03
Pulse energy	microJ	.127	.983	1.76	2.74	3.31
Average power	W	.342E-02	.265E-01	.475E-01	.741E-01	.894E-01
Number oh photons per pulse	#	.511E+08	.395E+09	.708E+09	.110E+10	.133E+10
Average flux of photons	ph/sec	.138E+13	.107E+14	.191E+14	.298E+14	.360E+14
Coherence time	fs	.595E-01	.585E-01	.676E-01	.711E-01	.814E-01
FWHM spectrum width, dw/w	%	.317E-02	.322E-02	.279E-02	.265E-02	.232E-02
#						
Incoherent radiation:						
#						
Critical wavelength	nm	.381E-01				
Critical energy of SR	keV	32.5				
SR induced energy loss	MeV	1.44				
SR induced energy spread	MeV	.232				
SR power	W	.779	3.90	9.74	19.5	39.0
#						
Parameters of FEL theory:						
#						
Efficiency parameter (1D)	#	.164E-02	.159E-02	.138E-02	.131E-02	.118E-02
Efficiency parameter (3D)	#	.245E-02	.258E-02	.258E-02	.258E-02	.258E-02
N of electrons in coherence volume	#	.290E+07	.316E+07	.369E+07	.391E+07	.457E+07
Emittance parameter	#	.245	.298	.459	.535	.741

Table D.17

Saturation characteristics of SASE3: 10.5 GeV, 0.8 nm

#						
Electron beam:						
#						
Energy of electrons	GeV	10.5				
Bunch charge	nC	.200E-01	.100	.250	.500	1.00
Peak current	kA	4.50	5.00	5.00	5.00	5.00
rms normalized emittance	mm-mrad	.320	.390	.600	.700	.970
rms energy spread	MeV	4.10	2.90	2.50	2.20	2.00
rms bunch length	micrometr	.360	1.92	4.98	9.17	23.0
Focusing beta function	m	15.0	15.0	15.0	15.0	15.0
rms size of electron beam	micrometr	15.3	16.9	20.9	22.6	26.6
Repetition rate	1/sec	.270E+05				
Electron beam power	kW	5.67	28.3	70.9	142.	283.
#						
Undulator:						
#						
Undulator period	cm	6.80				
Undulator peak field	T	.666				
Undulator parameter K (rms)	#	2.99				
Undulator length	m	105.				
#						
Properties of the 1st harmonic in the saturation:						
#						
Radiation wavelength	nm	.800				
Photon energy	keV	1.55				
Pulse energy	mJ	.103	.638	1.45	2.54	5.57
Peak power	GW	61.0	71.2	62.3	59.4	51.9
Average power	W	2.77	17.2	39.1	68.7	150.
FWHM spot size	mikrometr	43.1	46.4	55.0	58.5	66.4
FWHM angular divergence	microrad	9.17	8.71	7.58	7.20	6.45
Coherence time	fs	.479	.472	.535	.559	.622
FWHM spectrum width, dw/w	%	.393	.399	.352	.337	.303
Degree of transverse coherence	#	.960	.960	.960	.960	.960
Radiation pulse duration	fs	1.68	8.96	23.2	42.8	107.
Number of longitudinal modes	#	4	19	43	77	172
Fluctuations of the pulse energy	%	16.7	7.65	5.08	3.80	2.54
Degeneracy parameter	#	.113E+12	.130E+12	.129E+12	.128E+12	.125E+12
Number oh photons per pulse	#	.413E+12	.257E+13	.582E+13	.102E+14	.224E+14
Average flux of photons	ph/sec	.111E+17	.694E+17	.157E+18	.277E+18	.605E+18
Peak brilliance	#	.374E+33	.431E+33	.427E+33	.425E+33	.413E+33
Average brilliance	#	.170E+23	.104E+24	.268E+24	.492E+24	.120E+25
Saturation length	m	44.4	43.9	49.9	52.1	58.1
Power gain length	m	2.07	2.03	2.31	2.41	2.70
SASE induced energy loss	MeV	13.6	14.2	12.5	11.9	10.4
SASE induced energy spread	MeV	34.8	36.4	31.8	30.4	26.5
#						
Properties of the 3rd harmonic in the saturation:						
#						
Radiation wavelength	nm	.267				
Photon energy	keV	4.65				
Contribution to the total power	P3/P	.179E-01	.193E-01	.190E-01	.190E-01	.181E-01
Pulse energy	microJ	1.83	12.3	27.5	48.4	101.
Average power	W	.494E-01	.332	.742	1.31	2.73
Number oh photons per pulse	#	.245E+10	.165E+11	.369E+11	.649E+11	.136E+12
Average flux of photons	ph/sec	.663E+14	.445E+15	.995E+15	.175E+16	.366E+16
Coherence time	fs	.160	.157	.178	.186	.207
FWHM spectrum width, dw/w	%	.393	.399	.352	.337	.303
#						
Properties of the 5th harmonic in the saturation:						
#						
Radiation wavelength	nm	.160				
Photon energy	keV	7.75				
Contribution to the total power	P5/P	.251E-02	.292E-02	.284E-02	.285E-02	.259E-02
Pulse energy	microJ	.257	1.86	4.11	7.24	14.4
Average power	W	.693E-02	.503E-01	.111	.196	.389
Number oh photons per pulse	#	.207E+09	.150E+10	.330E+10	.583E+10	.116E+11
Average flux of photons	ph/sec	.558E+13	.405E+14	.892E+14	.157E+15	.313E+15
Coherence time	fs	.959E-01	.945E-01	.107	.112	.124
FWHM spectrum width, dw/w	%	.393E-02	.399E-02	.352E-02	.337E-02	.303E-02
#						
Incoherent radiation:						
#						
Critical wavelength	nm	.254E-01				
Critical energy of SR	keV	48.8				
SR induced energy loss	MeV	3.25				
SR induced energy spread	MeV	.422				
SR power	W	1.76	8.78	21.9	43.9	87.8
#						
Parameters of FEL theory:						
#						
Efficiency parameter (1D)	#	.209E-02	.202E-02	.175E-02	.167E-02	.149E-02
Efficiency parameter (3D)	#	.248E-02	.262E-02	.262E-02	.262E-02	.262E-02
N of electrons in coherence volume	#	.457E+07	.499E+07	.565E+07	.591E+07	.661E+07
Emittance parameter	#	.122	.149	.229	.268	.371

Table D.18

Saturation characteristics of SASE3: 10.5 GeV, 1.6 nm

#						
Electron beam:						
#						
Energy of electrons	GeV	10.5				
Bunch charge	nC	.200E-01	.100	.250	.500	1.00
Peak current	kA	4.50	5.00	5.00	5.00	5.00
rms normalized emittance	mm-mrad	.320	.390	.600	.700	.970
rms energy spread	MeV	4.10	2.90	2.50	2.20	2.00
rms bunch length	micrometr	.360	1.92	4.98	9.17	23.0
Focusing beta function	m	15.0	15.0	15.0	15.0	15.0
rms size of electron beam	micrometr	15.3	16.9	20.9	22.6	26.6
Repetition rate	1/sec	.270E+05				
Electron beam power	kW	5.67	28.3	70.9	142.	283.
#						
Undulator:						
#						
Undulator period	cm	6.80				
Undulator peak field	T	.968				
Undulator parameter K (rms)	#	4.34				
Undulator length	m	105.				
#						
Properties of the 1st harmonic in the saturation:						
#						
Radiation wavelength	nm	1.60				
Photon energy	keV	.775				
Pulse energy	mJ	.126	.783	1.83	3.26	7.38
Peak power	GW	75.1	87.4	78.8	76.0	68.8
Average power	W	3.41	21.1	49.4	87.9	199.
FWHM spot size	mikrometr	46.1	49.7	59.1	62.9	71.5
FWHM angular divergence	microrad	15.9	15.2	13.4	12.7	11.5
Coherence time	fs	.802	.791	.885	.920	1.01
FWHM spectrum width, dw/w	%	.470	.477	.426	.410	.373
Degree of transverse coherence	#	.960	.960	.960	.960	.960
Radiation pulse duration	fs	1.68	8.96	23.2	42.8	107.
Number of longitudinal modes	#	2	11	26	47	106
Fluctuations of the pulse energy	%	23.6	10.1	6.54	4.86	3.24
Degeneracy parameter	#	.465E+12	.534E+12	.538E+12	.540E+12	.537E+12
Number oh photons per pulse	#	.102E+13	.630E+13	.147E+14	.262E+14	.594E+14
Average flux of photons	ph/sec	.274E+17	.170E+18	.398E+18	.708E+18	.160E+19
Peak brilliance	#	.193E+33	.221E+33	.223E+33	.224E+33	.223E+33
Average brilliance	#	.874E+22	.535E+23	.140E+24	.259E+24	.644E+24
Saturation length	m	37.4	37.0	41.5	43.2	47.5
Power gain length	m	1.70	1.67	1.86	1.94	2.13
SASE induced energy loss	MeV	16.7	17.5	15.8	15.2	13.8
SASE induced energy spread	MeV	42.8	44.7	40.2	38.8	35.2
#						
Properties of the 3rd harmonic in the saturation:						
#						
Radiation wavelength	nm	.533				
Photon energy	keV	2.32				
Contribution to the total power	P3/P	.195E-01	.205E-01	.204E-01	.206E-01	.204E-01
Pulse energy	microJ	2.46	16.0	37.4	66.9	150.
Average power	W	.663E-01	.433	1.01	1.81	4.06
Number oh photons per pulse	#	.659E+10	.430E+11	.100E+12	.180E+12	.404E+12
Average flux of photons	ph/sec	.178E+15	.116E+16	.271E+16	.485E+16	.109E+17
Coherence time	fs	.267	.264	.295	.307	.337
FWHM spectrum width, dw/w	%	.470	.477	.426	.410	.373
#						
Properties of the 5th harmonic in the saturation:						
#						
Radiation wavelength	nm	.320				
Photon energy	keV	3.87				
Contribution to the total power	P5/P	.299E-02	.331E-02	.329E-02	.334E-02	.328E-02
Pulse energy	microJ	.378	2.59	6.03	10.9	24.2
Average power	W	.102E-01	.699E-01	.163	.293	.653
Number oh photons per pulse	#	.608E+09	.417E+10	.971E+10	.175E+11	.390E+11
Average flux of photons	ph/sec	.164E+14	.113E+15	.262E+15	.472E+15	.105E+16
Coherence time	fs	.160	.158	.177	.184	.202
FWHM spectrum width, dw/w	%	.470E-02	.477E-02	.426E-02	.410E-02	.373E-02
#						
Incoherent radiation:						
#						
Critical wavelength	nm	.175E-01				
Critical energy of SR	keV	70.9				
SR induced energy loss	MeV	6.87				
SR induced energy spread	MeV	.736				
SR power	W	3.71	18.5	46.3	92.7	185.
#						
Parameters of FEL theory:						
#						
Efficiency parameter (1D)	#	.264E-02	.256E-02	.221E-02	.210E-02	.189E-02
Efficiency parameter (3D)	#	.249E-02	.263E-02	.263E-02	.263E-02	.263E-02
N of electrons in coherence volume	#	.751E+07	.820E+07	.915E+07	.951E+07	.104E+08
Emittance parameter	#	.612E-01	.745E-01	.115	.134	.185

Table D.19

Saturation characteristics of SASE3: 10.5 GeV, 3.2 nm

#						
Electron beam:						
#						
Energy of electrons	GeV	10.5				
Bunch charge	nC	.200E-01	.100	.250	.500	1.00
Peak current	kA	4.50	5.00	5.00	5.00	5.00
rms normalized emittance	mm-mrad	.320	.390	.600	.700	.970
rms energy spread	MeV	4.10	2.90	2.50	2.20	2.00
rms bunch length	micrometr	.360	1.92	4.98	9.17	23.0
Focusing beta function	m	15.0	15.0	15.0	15.0	15.0
rms size of electron beam	micrometr	15.3	16.9	20.9	22.6	26.6
Repetition rate	1/sec	.270E+05				
Electron beam power	kW	5.67	28.3	70.9	142.	283.
#						
Undulator:						
#						
Undulator period	cm	6.80				
Undulator peak field	T	1.39				
Undulator parameter K (rms)	#	6.22				
Undulator length	m	105.				
#						
Properties of the 1st harmonic in the saturation:						
#						
Radiation wavelength	nm	3.20				
Photon energy	keV	.387				
Pulse energy	mJ	.151	.931	2.20	3.93	9.11
Peak power	GW	90.0	104.	94.6	91.7	84.9
Average power	W	4.08	25.1	59.3	106.	246.
FWHM spot size	mikrometr	49.1	53.0	63.2	67.3	76.8
FWHM angular divergence	microrad	26.9	26.0	23.2	22.2	20.2
Coherence time	fs	1.37	1.35	1.50	1.55	1.69
FWHM spectrum width, dw/w	%	.549	.557	.503	.486	.447
Degree of transverse coherence	#	.960	.960	.960	.960	.960
Radiation pulse duration	fs	1.68	8.96	23.2	42.8	107.
Number of longitudinal modes	#	1	7	16	28	63
Fluctuations of the pulse energy	%	33.3	12.6	8.33	6.30	4.20
Degeneracy parameter	#	.191E+13	.217E+13	.219E+13	.220E+13	.222E+13
Number oh photons per pulse	#	.243E+13	.150E+14	.354E+14	.633E+14	.147E+15
Average flux of photons	ph/sec	.657E+17	.404E+18	.955E+18	.171E+19	.396E+19
Peak brilliance	#	.989E+32	.113E+33	.113E+33	.114E+33	.115E+33
Average brilliance	#	.449E+22	.272E+23	.711E+23	.132E+24	.332E+24
Saturation length	m	32.3	31.9	35.4	36.7	40.0
Power gain length	m	1.44	1.41	1.55	1.61	1.75
SASE induced energy loss	MeV	20.0	20.8	18.9	18.3	17.0
SASE induced energy spread	MeV	51.1	53.0	48.3	46.8	43.3
#						
Properties of the 3rd harmonic in the saturation:						
#						
Radiation wavelength	nm	1.07				
Photon energy	keV	1.16				
Contribution to the total power	P3/P	.204E-01	.210E-01	.210E-01	.211E-01	.211E-01
Pulse energy	microJ	3.08	19.6	46.2	83.1	192.
Average power	W	.831E-01	.529	1.25	2.24	5.19
Number oh photons per pulse	#	.165E+11	.105E+12	.248E+12	.446E+12	.103E+13
Average flux of photons	ph/sec	.446E+15	.284E+16	.670E+16	.120E+17	.278E+17
Coherence time	fs	.458	.452	.499	.518	.563
FWHM spectrum width, dw/w	%	.549	.557	.503	.486	.447
#						
Properties of the 5th harmonic in the saturation:						
#						
Radiation wavelength	nm	.640				
Photon energy	keV	1.94				
Contribution to the total power	P5/P	.328E-02	.350E-02	.350E-02	.353E-02	.351E-02
Pulse energy	microJ	.496	3.26	7.68	13.9	32.0
Average power	W	.134E-01	.879E-01	.207	.375	.864
Number oh photons per pulse	#	.160E+10	.105E+11	.247E+11	.447E+11	.103E+12
Average flux of photons	ph/sec	.431E+14	.283E+15	.668E+15	.121E+16	.278E+16
Coherence time	fs	.275	.271	.300	.311	.338
FWHM spectrum width, dw/w	%	.549E-02	.557E-02	.503E-02	.486E-02	.447E-02
#						
Incoherent radiation:						
#						
Critical wavelength	nm	.122E-01				
Critical energy of SR	keV	102.				
SR induced energy loss	MeV	14.1				
SR induced energy spread	MeV	1.26				
SR power	W	7.61	38.1	95.1	190.	381.
#						
Parameters of FEL theory:						
#						
Efficiency parameter (1D)	#	.332E-02	.322E-02	.279E-02	.265E-02	.238E-02
Efficiency parameter (3D)	#	.249E-02	.263E-02	.263E-02	.263E-02	.263E-02
N of electrons in coherence volume	#	.127E+08	.138E+08	.152E+08	.158E+08	.171E+08
Emittance parameter	#	.306E-01	.373E-01	.573E-01	.669E-01	.927E-01

Table D.20

Saturation characteristics of SASE3: 10.5 GeV, 5 nm

#						
Electron beam:						
#						
Energy of electrons	GeV	10.5				
Bunch charge	nC	.200E-01	.100	.250	.500	1.00
Peak current	kA	4.50	5.00	5.00	5.00	5.00
rms normalized emittance	mm-mrad	.320	.390	.600	.700	.970
rms energy spread	MeV	4.10	2.90	2.50	2.20	2.00
rms bunch length	micrometr	.360	1.92	4.98	9.17	23.0
Focusing beta function	m	15.0	15.0	15.0	15.0	15.0
rms size of electron beam	micrometr	15.3	16.9	20.9	22.6	26.6
Repetition rate	1/sec	.270E+05				
Electron beam power	kW	5.67	28.3	70.9	142.	283.
#						
Undulator:						
#						
Undulator period	cm	6.80				
Undulator peak field	T	1.74				
Undulator parameter K (rms)	#	7.82				
Undulator length	m	105.				
#						
Properties of the 1st harmonic in the saturation:						
#						
Radiation wavelength	nm	5.00				
Photon energy	keV	.248				
Pulse energy	mJ	.168	1.03	2.45	4.38	10.2
Peak power	GW	99.9	115.	105.	102.	94.9
Average power	W	4.53	27.8	66.1	118.	275.
FWHM spot size	mikrometr	51.0	55.1	65.9	70.1	80.1
FWHM angular divergence	microrad	37.1	36.1	32.6	31.3	28.7
Coherence time	fs	1.97	1.94	2.13	2.20	2.38
FWHM spectrum width, dw/w	%	.599	.609	.554	.536	.496
Degree of transverse coherence	#	.960	.960	.960	.960	.960
Radiation pulse duration	fs	1.68	8.96	23.2	42.8	107.
Number of longitudinal modes	#	1	5	11	19	45
Fluctuations of the pulse energy	%	33.3	14.9	10.1	7.65	4.97
Degeneracy parameter	#	.474E+13	.538E+13	.541E+13	.543E+13	.545E+13
Number oh photons per pulse	#	.422E+13	.259E+14	.615E+14	.110E+15	.256E+15
Average flux of photons	ph/sec	.114E+18	.700E+18	.166E+19	.297E+19	.691E+19
Peak brilliance	#	.644E+32	.730E+32	.733E+32	.736E+32	.739E+32
Average brilliance	#	.292E+22	.177E+23	.460E+23	.852E+23	.214E+24
Saturation length	m	29.7	29.3	32.3	33.4	36.2
Power gain length	m	1.30	1.28	1.40	1.44	1.56
SASE induced energy loss	MeV	22.2	23.0	21.1	20.4	19.0
SASE induced energy spread	MeV	56.7	58.8	53.7	52.2	48.4
#						
Properties of the 3rd harmonic in the saturation:						
#						
Radiation wavelength	nm	1.67				
Photon energy	keV	.744				
Contribution to the total power	P3/P	.208E-01	.213E-01	.213E-01	.214E-01	.213E-01
Pulse energy	microJ	3.48	21.9	52.1	93.5	217.
Average power	W	.941E-01	.592	1.41	2.53	5.86
Number oh photons per pulse	#	.292E+11	.184E+12	.437E+12	.784E+12	.182E+13
Average flux of photons	ph/sec	.789E+15	.497E+16	.118E+17	.212E+17	.491E+17
Coherence time	fs	.656	.645	.709	.733	.793
FWHM spectrum width, dw/w	%	.599	.609	.554	.536	.496
#						
Properties of the 5th harmonic in the saturation:						
#						
Radiation wavelength	nm	1.00				
Photon energy	keV	1.24				
Contribution to the total power	P5/P	.341E-02	.357E-02	.357E-02	.360E-02	.359E-02
Pulse energy	microJ	.572	3.69	8.74	15.8	36.5
Average power	W	.154E-01	.995E-01	.236	.426	.987
Number oh photons per pulse	#	.288E+10	.185E+11	.440E+11	.793E+11	.184E+12
Average flux of photons	ph/sec	.777E+14	.501E+15	.119E+16	.214E+16	.496E+16
Coherence time	fs	.393	.387	.425	.440	.476
FWHM spectrum width, dw/w	%	.599E-02	.609E-02	.554E-02	.536E-02	.496E-02
#						
Incoherent radiation:						
#						
Critical wavelength	nm	.971E-02				
Critical energy of SR	keV	128.				
SR induced energy loss	MeV	22.2				
SR induced energy spread	MeV	1.77				
SR power	W	12.0	60.0	150.	300.	600.
#						
Parameters of FEL theory:						
#						
Efficiency parameter (1D)	#	.386E-02	.374E-02	.324E-02	.308E-02	.276E-02
Efficiency parameter (3D)	#	.250E-02	.263E-02	.263E-02	.263E-02	.263E-02
N of electrons in coherence volume	#	.180E+08	.196E+08	.214E+08	.221E+08	.239E+08
Emittance parameter	#	.196E-01	.238E-01	.367E-01	.428E-01	.593E-01

List of Figures

List of Tables