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Development of a pump-probe facility combining a far-infrared source with laser-like characteristics and a VUV free electron laser

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Abstract

The TESLA Test Facility (TTF) at DESY is a facility producing sub-picosecond electron pulses for the generation of VUV or soft X-ray radiation in a free electron laser (FEL). The same electron pulses would also allow the direct production of high-power coherent radiation by passing the electron beam through an undulator. Intense, coherent far-infrared (FIR) undulator radiation can be produced from electron bunches at wavelengths longer than or equal to the bunch length. The source described in this paper provides, in the wavelength range 50–300 μm, a train of about 1–10 ps long radiation pulses, with about 1 mJ of optical energy per pulse radiated into the central cone. The average output power can exceed 50 W. In this conceptual design, we intend to use a conventional electromagnetic undulator with a 60 cm period length and a maximum field of 1.5 T. The FIR source will use the spent electron beam coming from the VUV FEL which allows one to significantly extend the scientific potential of the TTF without interfering with the main option of the TTF FEL operation. The pulses of the coherent FIR radiation are naturally synchronized with the VUV pulses from the main TTF FEL, enabling pump-probe techniques using either the FEL pulse as a pump or the FIR pulse as a probe, or vice versa. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

The FIR range of the electromagnetic spectrum is not well covered by intense sources except for a few operating FELs. The analysis of the parameters of existing FIR FELs shows that practical sources of broadly tunable, powerful, coherent FIR radiation remains essentially unavailable at wavelengths beyond 200 μm [1–3]. This situation, however, might change soon. The development of magnetic bunch compression systems, together with advances in superconducting accelerator technology and design, now offers the new

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possibility of laser-like sources in the far-infrared wavelength range. The generation of relativistic, sub-picosecond electron pulses allows the direct production of high-power, coherent, narrow-band, FIR radiation by passing the electron beam through an undulator. This provides a reliable and easily tunable powerful source of FIR radiation for scientific applications [4,5].

The TTF is a facility producing sub-picosecond electron pulses (50 μm rms) for the generation of VUV or soft X-ray radiation. Utilizing these sub-picosecond electron bunches can also provide broadband FIR source. Intense, coherent FIR radiation can be produced from sub-picosecond electron bunches at wavelengths longer than or equal to the bunch length. The total radiation from an electron bunch is the summation of the electric fields emitted by each individual electron and the total radiated energy is then equal to the square of the total electric field. The coherent radiation energy is proportional to the square rather than linearly proportional to the number of radiating electrons. Since there are 6×10^9 electrons in each bunch, the radiation intensity is enhanced by this large factor over the incoherent radiation. This paper describes such a coherent source, proposed as part of the TTF FEL user facility. The FIR source addresses the needs of the science community for a high-brightness, tunable source covering a broad region of the far-infrared spectrum — from 50 to 300 μm. The FIR radiator described in this paper provides a train of about 1–10 ps long pulses with up to 1 mJ of optical energy per pulse into the central cone. The average output power can exceed 50 W.

The pump-probe technique is one of the most promising methods for the application of a high power FIR source [6]. It is the aim of the present project to develop a user facility for pump-probe experiments in the picosecond regime, combining FIR and short-wavelength FEL radiation. The TTF will allow, for the first time, the integration of a far-infrared coherent radiation source and a VUV beamline. One type of experiment will use the VUV FEL beam as a pump and the far-infrared photon beam as a probe; in this mode, researchers will be able to study the vibrational structure of highly excited and superexcited molecules. The other mode (far-infrared beam pump and VUV beam probe) can be used to study cluster energetics and dynamics. The FIR radiation can be used to excite the clusters, which can subsequently be dissociated or ionized by the VUV radiation. Spectroscopic and structural information can thus be extracted. Spectroscopy of gas-phase free radicals will also benefit from the FIR beam pump and VUV beam probe experiments. In these experiments, a cold molecular beam containing a small concentration of radicals would be excited by the intense FIR beam, tunable across the absorption spectrum. Since the density of radicals in the beam is not high enough to allow the direct measurement of absorption, a VUV beam from the TTF FEL would be used to detect the infrared-exited states of molecules by selectively ionizing the vibrationally excited radicals.

2. Temporal coherent undulator radiation

The electron beam current is made up of moving electrons randomly arriving at the entrance to the undulator:

$$I(t) = (-e)\sum_{k=1}^{N} \delta(t - t_k)$$

where $\delta(\cdots)$ is the delta function, $(-e)$ is the charge of the electron, N is the number of electrons in a bunch, and t_k is the random arrival time of the electron at the undulator entrance. The electron bunch profile is described by the profile function $F(t)$. The beam current averaged over an ensemble of bunches can be written in the form:

$$\langle I(t) \rangle = (-e)NF(t).$$

The probability of arrival of an electron during the time interval $t, t + \mathrm{d}t$ is equal to $F(t)\,\mathrm{d}t$.

The radiation power at the frequency ω, averaged over an ensemble, is given by the expression:

$$\langle P(\omega) \rangle = p(\omega)[N + N(N-1)|\bar{F}(\omega)|^2]$$

where $p(\omega)$ is the radiation power from one electron and $\bar{F}(\omega)$ is the Fourier transform of the bunch profile function. For wavelengths shorter than the bunch length the form factor reduces to zero and approaches unity for longer wavelengths.

To optimally meet the needs of basic research with FIR coherent radiation, it is desirable to provide specific radiation characteristics. To generate these characteristics, radiation is produced from an undulator installed along the electron beam path. The undulator equation

$$\omega = 2ck_{\mathrm{w}}\gamma^2\left[1+\frac{K^2}{2}+\gamma^2\theta^2\right]^{-1}$$

tells us the frequency of radiation as a function of the undulator period $\lambda_{\mathrm{w}} = 2\pi/k_{\mathrm{w}}$, undulator parameter K, electron energy γ, and polar angle of observation θ. Note that for radiation within the cone of half angle

$$\theta_{\mathrm{con}} = \frac{\sqrt{1+K^2/2}}{\gamma\sqrt{N_{\mathrm{w}}}}$$

the relative spectral bandwidth is $\Delta\omega/\omega \simeq 1/N_{\mathrm{w}}$, where N_{w} is the number of undulator periods. The energy radiated into the central cone, for a single electron, is given by

$$\Delta\mathscr{E}_{\mathrm{con}} \simeq \pi e^2 A_{\mathrm{JJ}}^2 \omega_0 K^2/[c(1+K^2/2)].$$

Here $\omega_0 = 2\gamma^2 k_{\mathrm{w}}/(1+K^2/2)$ is the resonant frequency, $A_{\mathrm{JJ}} = [J_0(Q) - J_1(Q)]$, J_n is the Bessel function of nth order, and $Q = K^2/(4+2K^2)$. The coherent radiation enhances the energy radiated into the central cone by a factor of $N|\bar{F}(\omega_0)|^2$.

3. Facility description

In the far-infrared, beyond 200 μm, a source based on coherent undulator radiation has unique capabilities. In this paper, we propose to integrate such a source into the TESLA Test Facility at DESY [7,8]. This source will be able to deliver up to 800 μs long trains of FIR pulses at a separation of 111 ns with about 1–10 ps duration,[1] up to 1 mJ energy radiated into the central cone, and 50–300 μm wavelength. The superconducting linac will operate at about 1% duty factor, and the average output power of coherent FIR radiation can exceed 50 W.

We propose to install an additional undulator after the VUV SASE FEL. Because the FIR source uses the electron beam coming from the VUV FEL, the proposed source operates in a "parasitic" mode not interfering with the main mode of the VUV FEL operation (see Fig. 1). Starting points of the design are the project parameters of the electron beam after the VUV FEL at the TTF (see Table 1). The planar undulator is an inexpensive electromagnetic device with 10 periods, each 60 cm long. At the operation wavelength of the FIR source around 300 μm, the peak value of the magnetic field is about 1.5 T.

Coherent radiation produced by the electron bunch strongly depends on the bunch profile and charge. Fig. 2 shows the expected axial profile of the electron bunch from the TTF accelerator.[2] Using such a bunch, we can generate powerful FIR radiation in a wide wavelength band, from 50 to 300 μm (see Fig. 3). A unique feature of the TTF accelerator consists of the possibility to control, in a wide limit, the axial bunch profile by means of bunch compressors. Running of the TTF accelerator with shorter bunches would allow to shift the short wavelength boundary of the FIR spectrum below 50 μm. Another unique feature of the TTF accelerator is that it is capable of accelerating electron bunches with a bunch charge of about 10 nC, thus providing the possibility to generate FIR pulses with peak power exceeding a gigawatt level.

Many practical applications require the control of the shape and time characteristics of the FIR pulse. For instance, closely spaced picosecond FIR pulses with controllable phase relations are needed for coherent multi-photon excitation and selective excitation of, for example, certain molecular vibrations. The proposed FIR source provides wide possibilities to control and modify, in a well-defined manner, the shape of the radiation pulse on a picosecond time scale (see Fig. 4). The electron beam passing a uniform undulator produces an FIR pulse with a rectangular profile.

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[1] When the electron bunch moves along the undulator, the electromagnetic wave advances the electron beam by one wavelength at one undulator period.

[2] Calculations have been performed by T. Limberg.

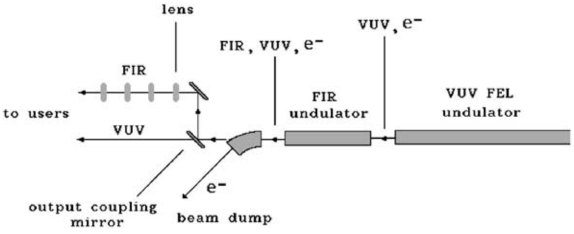

Fig. 1. Schematic layout of the FIR–VUV pump-probe facility.

Table 1
Parameters of the FIR coherent radiation source

Electron beam	
Energy	1000 MeV
Bunch charge	1 nC
Rms bunch length	50 μm
Normalized emittance	2π mm-mrad
Rms energy spread	2.5 MeV
Bunch repetition rate	9 MHz
Duty factor	1%
Undulator	
Type	Planar
Period	60 cm
Peak magnetic field	1.2–1.5 T
Number of periods	10
Output radiation	
Wavelength	50–300 μm
Bandwidth	transform-limited
Peak power	up to 100 MW
Average power	up to 50 W
Micropulse duration	1–10 ps
Micropulse energy	up to 1 mJ

FIR optical pulses can be shaped in a complicated manner by means of individual tuning of the magnetic field in each period.

The proposed FIR source is compatible with the layout of the TTF and the VUV FEL at DESY, and can be realized with minimal additional efforts. The undulator and outcoupling optical system can be installed in the unoccupied straight vacuum line used for the electron and VUV beamlines behind the dipole magnet separating the electron beam from the VUV beam (see Fig. 1). In order to make use of the FIR radiation an additional mirror is needed to couple out the major fraction of the optical power in the central cone and to direct it to the experimental area. The distance between the mirror and the exit of the second undulator is 10 m, the distance between the mirror and the exit of the FEL undulator is about 16 m. The minimum size of the hole in the outcoupling mirror is defined by the condition that VUV radiation losses due to hole aperture limitation should be avoided. The fraction of the output FEL power passing the mirror hole is calculated from the angular distribution of the VUV radiation (20 μrad rms). For a hole diameter of 2 mm the fraction of VUV power directed into the experimental area is close to 100%. Due to the angle-frequency correlation of the coherent

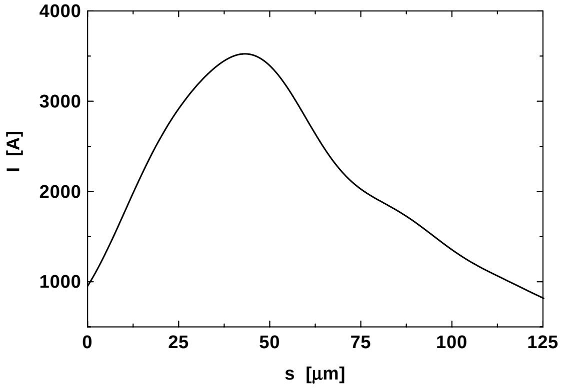

Fig. 2. Axial bunch profile of the electron bunch from TTF accelerator.

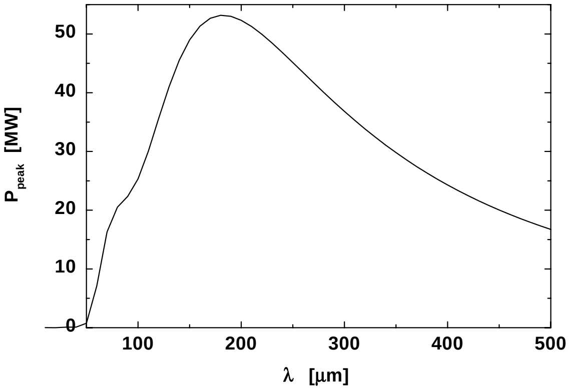

Fig. 3. Peak power of FIR source at the TESLA Test Facility produced by the bunch with axial profile plotted in Fig. 2.

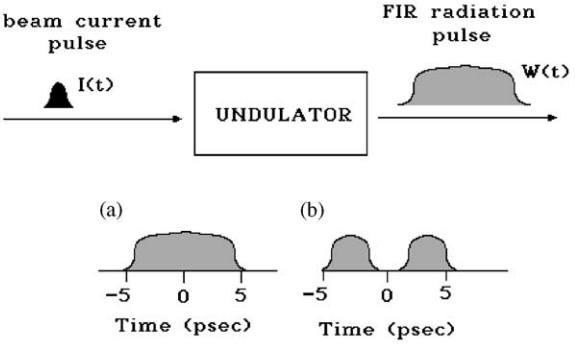

Fig. 4. FIR pulse profiles generated by the FIR undulator in the central cone (300 μm wavelength). Plot (a) illustrates the pulse produced by a uniform undulator (rectangular pulse of 10 ps duration). Plot (b) illustrates the case when four central poles are switched off (two pulses of 3 ps duration each delayed by 3 ps).

undulator radiation the required frequency bandwidth of radiation could be provided by angular selection. To provide a natural selection of coherent radiation in the central cone ($\theta_{\mathrm{con}} \simeq 5$ mrad), the radius of the mirror should be equal to 6 cm at a distance of about 10 m between the exit of the second undulator and the mirror.

The operation of the proposed FIR source is insensitive to the emittance of the electron beam, since the condition of the optimal electron beam's transverse size is: $\sigma^2 \ll Lc/\omega \simeq 1\ \mathrm{cm}^2$, where L is the undulator length. The analysis of the parameters of the FIR source has shown that it will operate reliably even for an emittance exceeding the project value of 2π mm mrad by two orders of magnitude.

An undulator is a sequence of bending magnets where particles with different energies have different path length. As a result, the energy spread in the beam leads to the bunch lengthening in the undulator. When an electron bunch passes the FIR undulator, radiation interaction induces additional energy spread in the electron beam which can also lead to bunch lengthening. Recently, the problem connected with radiative interaction of the particles in a line-charge microbunch moving in an undulator has been investigated analytically [9]. In the case of a Gaussian bunch profile the induced energy spread $\Delta\mathcal{E}_{\mathrm{f}}$ is given by

$$\frac{\Delta\mathcal{E}_{\mathrm{f}}}{\mathcal{E}} = \frac{r_{\mathrm{e}} N K^2 L}{\sqrt{2\pi}\sigma_z^2 \gamma^3} G(p, K) \qquad (1)$$

where, r_{e} is the classical electron radius, $p = k_{\mathrm{w}}\sigma_z\gamma^2/[(1 + K^2/2)]$ is the bunch length parameter, and σ_z is the rms bunch length. Parameters of the FIR source project are: $N = 6 \times 10^9$, $\sigma_z = 50\ \mu\mathrm{m}$, $K = 70$ (for 200 μm wavelength), $L = 6$ m, and $\gamma = 2 \times 10^3$. The value of G is $G \simeq 0.5$. Substituting these values into (1), we obtain an induced correlated energy spread at the exit of undulator $\Delta\mathcal{E}_{\mathrm{f}}/\mathcal{E} \simeq 2\%$. This leads to an increase of the bunch length:

$$\Delta l_{\mathrm{b}} \simeq \frac{L(1 + K^2/2)\Delta\mathcal{E}_{\mathrm{f}}}{2\gamma^2 \quad\ \mathcal{E}} \simeq 20\ \mu\mathrm{m}.$$

Since this value is much less than the radiation wavelength $\lambda \simeq 100\ \mu\mathrm{m}$, we can conclude that bunch decompression in the undulator due to induced energy spread should not be a serious limitation in our case.

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