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EMITTANCE DAMPING CONSIDERATIONS FOR TESLA

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ABSTRACT
Two schemes are considered to avoid very large damping rings for TESLA. The first (by K.F.) makes use of the linac tunnel to accomodate most of the damping "ring" structure, which is, in fact, not a ring any more but a long linear structure with two small bends at each of its ends ("dog–bone"). The other scheme (by J.R.) is based on a positron (or electron, respectively) recycling scheme. It makes use of the specific TESLA property, that the full bunch train is much longer (240 km) than the linac length. The spent beams are recycled seven times after interaction, thus reducing the number of bunches to be stored in the damping ring by a factor of eight. Ultimately, this scheme can be used to operate TESLA in a storage ring mode ("storage linac"), with no damping ring at all. Finally, a combination of both schemes is considered.

1. INTRODUCTION

The leading argument in the discussion of superconducting vs. normal conducting linear colliders is the efficiency of rf power conversion into beam power. With a highly efficient superconducting linear collider, it is possible to accelerate a large number of particles and thus to obtain the desired luminosity at relaxed beam emittance tolerances. Due to the long filling time of the rf sections, a very long bunch train ($800\mu sec$ for TESLA, see table 1) will be characteristic for superconducting linear colliders. The production and damping of a huge number of particles leads, however, to some increased requirements for the particle sources and for the damping rings.

As far as damping rings are concerned, there are three complications with such large intensities and long bunch trains:

1. The TESLA design foresees a bunch train of $800 \times 10^{-6} s \times c = 240\ km$ length. Obviously, this bunch train can only be stored in a damping ring with a compressed bunch spacing, and it must be expanded when extracted out of it. To this end, very fast kickers will be required. Assuming a damping ring with a circumference C, and

$$\frac{240\ km}{C} = n \quad (1)$$

we find the bunch spacing in the ring to be (τ_b =bunch spacing in the linac)

$$\tau_{ring} = \frac{1}{n} \cdot \tau_b = \frac{1}{n} \cdot 1\ \mu s \quad (2)$$

Parameter	Symbol	
c.m. energy	E	500 GeV
Design luminosity	L	$2.6 \cdot 10^{33} cm^{-2} s^{-1}$
Two-linac active length	L	20 000 m
Linac repetition rate	f_{rep}	10 Hz
Number of particles/bunch	N	$5 \cdot 10^{10}$
Number of bunches per pulse	n	800
Bunch spacing	τ_b	$1\ \mu s$
Avg. beam power per beam	P_b	16.5 MW
Klystron pulse length	τ_p	$1300\ \mu s$
Horizontal normalized emittance	ϵ_x^N	$2 \cdot 10^{-5} m$
Vertical normalized emittance	ϵ_y^N	$10^{-6} m$
Horizontal β at IP	β_x^*	25 mm
Vertical β at IP	β_y^*	2 mm
Bunch length	σ_s	1 mm

Table 1: Main TESLA parameters used in this paper

The ejection kicker has to operate with a rise time $\tau_r < \tau_{ring}$ at $1/\tau_b = 1MHz(!)$ repetition rate.

2. Even if $\tau_r = 20ns, \tau_{ring} = 25ns$ is assumed, Eqs.1,2 yield $n = 40$, $C = 6\ km$. (note that for 1600 bunches, $\tau_b = 0.5\mu s$, $C = 12\ km$ would be required!). Thus, very large damping rings seem to be inevitable for TESLA.

3. Due to the bunch train compression, the mean current in the damping ring will be

$$I_{ring} = n \times I_{linac} = n \times 8\ mA$$

With n in the order of 40, a broad band multi-bunch feedback system of n/2 MHz band width is required to store that large current.

2. THE DOG-BONE DAMPING STRUCTURE

Even if an existing large storage ring like HERA-E will be used as the damping ring [1], the requirements for the feedback system and the kicker are still beyond present day technology.

In order to make the circumference of the damping ring very large and to reduce the cost of the damping ring, we suggest a "dog-bone" design, with long straight sections within the tunnel of the main linac and two small rings, connecting the straight sections at both ends [1] (see Fig. 1).

[1] A similar idea was proposed by D. Trines during the LC91 workshop in Protvino

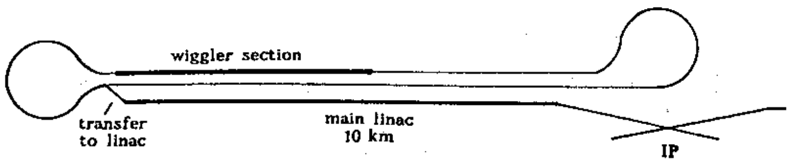

Figure 1: A dog-bone like damping scheme for TESLA with circumference $C \approx 20\ km$. The major part of emittance damping is due to a long wiggler section.

The dog-bone shape offers a large flexibility concerning the circumference of the ring and the resulting requirements for the feedback system and the kickers. The final design has to be optimized with respect to technical feasibility and cost. In this paper, we will outline the possible parameter space and proof the principal of the design only.

At maximum, the circumference of the dog-bone structure would be two times the length of the linac, i.e. $\approx 40\ km$. In this case, however, one would need to bypass the interaction region. Therefore we consider a ring of max. $\approx 20\ km$ in this paragraph.
With $C = 20\ km$ we get:

$$\begin{aligned} n &= 12 \\ \tau_{ring} &= 83\ ns \\ I_{ring} &= 96\ mA \\ \text{band width of feedback system} &= 6 MHz \end{aligned}$$

With the repetition frequency of the linac $\nu_{rep} = 10\ Hz$ a bunch can perform 1500 revolutions in the ring between the successive rf pulses. In order to reach the equilibrium emittance, we need at least 5 damping times τ_D. Therefore, τ_D has to be at most $300 \times T_0$, where T_0 stands for the revolution time. With

$$\tau_D = 2\frac{E \cdot T_0}{U_C} \tag{3}$$

(E = particle energy of the beam) we obtain the energy loss per turn U_C to be:

$$U_C \geq \frac{E}{150} \tag{4}$$

It is easy to see that, even with an optimized damping ring lattice, it is impossible to get both that large energy loss and small emittance if synchrotron radiation only takes place in the bending sections at the ends of the dog-bone. Therefore the major part of U_C will be radiated in a long wiggler section located in the straight part of the dog-bone.
The loss per meter in a wiggler is given by

$$\frac{\langle P_\gamma \rangle}{c}[GeV/m] = 3.3 \cdot 10^{-13}\gamma^2 B[T]^2 \tag{5}$$

Eqs.4 and 5 can be combined into

$$B^2 L \geq \frac{1.03 \cdot 10^7}{\gamma} T^2 m \tag{6}$$

L is the length of the wiggler section.
We can estimate the maximum tolerable damping ring energy from R. Brinkmann's damping ring design [2] if we adopot his 650 m long lattice for our end bends. Its normalized emittance scales as

$$\epsilon_x^N = 2.2 \cdot 10^{-7} m \cdot [E/GeV]^3 \tag{7}$$

If this is compared to the TESLA design emittance

$$\epsilon_x^N(TESLA) = 2 \cdot 10^{-5} m$$

we get $E < 4.5\ GeV$.
This is true only as long as the emittance growth and damping in the wiggler section is negligible. Since the wiggler considerably contributes to radiation damping, the beam energy might be even larger. The condition for the emittance growth in the wiggler to be tolerable is (note that the wiggler is traversed τ_D/T_0 times per damping time; for details see ref.[4])

$$\Delta\epsilon_x(\text{per wiggler passage}) = \frac{2.1 \cdot 10^{-15}}{m^3 T^5}\beta\lambda^2 B^5 L < \frac{T_0}{\tau_D}\frac{2 \cdot 10^{-5} m}{\gamma}$$

β = mean beta function in the wiggler section,
λ = period length of the wiggler

Using Eqs.3, 5 we get, in addition to Eq.6, the condition [5]

$$\beta\lambda^2 B^3 < 3.1\ m^3 T^3 \tag{8}$$

which is, remarkably, independent of energy.

Eq.6 suggests to choose the energy as high as possible to reduce the wiggler length and its field strength. We choose 4.5 GeV, because then we know that the emittance contribution from the end bends is tolerable. The parameters of the wiggler then may cover the range from

$$B = 1.5\,T \quad L = 520\,m \quad \beta = 20\,m \quad \lambda = 0.2\,m$$

up to

$$B = 0.26\,T \quad L = 17\,300\,m \quad \beta = 100\,m \quad \lambda = 1.3\,m$$

The beta-function is kept quite large to reduce the number of cells and thus the chromaticity in the straight sections.

With respect to lattice design, the momentum compaction factor α may easily be of the order of 10^{-6}. Thus a bunch length of 1 mm can be achieved, so that no extra bunch compressor is needed. However, a larger bunch length (i.e. larger α and stronger longitudinal focusing) will be required in the damping ring due to the microwave instability. Therefore the momentum compaction contribution of the wiggler section must be increased. This contribution is approximately given by

$$\alpha_{wiggler} \approx -\frac{1}{2}\left(\frac{ec}{2\pi E}\lambda B\right)^2$$

i.e. it is in conflict with Eq.8 if (say) $\alpha_{wiggler} = 0.0002$ is desired. As a possible solution it is proposed to use a second wiggler with much larger period length and weak magnetic field. In this second wiggler, radiation damping and emittance growth are negligible, but $\alpha_{wiggler}$ can be made large. From that point of view, a somewhat smaller beam energy might be more favourable. This has to be worked out in more detail.

Even if this second wiggler is needed to increase the momentum compaction factor, it is possible to keep the total length of both wigglers within a small fraction of the total circumference. The rest of the straight sections will be simple FODO structures. As the required wiggler length scales with the circumference of the ring (if arcs are neglected), the lengths of both the ring and the wigglers can be reduced if faster kickers are available and if the multibunch instability is considered to be manageable.

3. ELECTRON/POSITRON RECYCLING AND THE STORAGE LINAC MODE OF TESLA

It has been shown in ref.[4] that the spent beam of a linear collider can be recycled, if it passes a several kilometer long wiggler section, where it loses most of its energy into synchrotron radiation. If B denotes the rms magnetic field in the wiggler, the beam energy decreases according to

$$\gamma(s) = \frac{\gamma_0}{1 + \Phi\gamma_0 B^2 s} \qquad (9)$$

γ_0 is the relativistic factor at the beginning of the section, s is the longitudinal coordinate, and

$$\Phi = \frac{q^4}{6\pi\varepsilon_0 m_0^3 c^4} = 6.466 \cdot 10^{-10} m^{-1} T^{-2}$$

In addition, the *fractional* energy width $\sigma_\gamma(s)/\gamma(s)$ is damped according to

$$\frac{\sigma_\gamma(s)}{\gamma(s)} = \frac{\gamma(s)}{\gamma_0}\sqrt{\Gamma\gamma_0^2 B\left(\frac{1}{\gamma(s)} - \frac{1}{\gamma_0}\right) + \left(\frac{\sigma_{\gamma_0}}{\gamma_0}\right)^2} \qquad (10)$$

with $\Gamma = \frac{3}{2}\frac{55}{24\sqrt{3}}\frac{q\lambda_c}{m_0 c} \approx 4.5 \cdot 10^{-10} T^{-1}$.
As an example, we consider a first wiggler section of $B = 1.8\,T$ and $L = 2500\,m$ length. At its end, the beam energy is 70 GeV ($\gamma_0 = 5 \cdot 10^5$, corresponding to 250 GeV, is assumed). At this point, the radiated power is small enough (of the order of 1 kW/m) that a superconducting wiggler can be used which is much more efficient at lower γ. We assume $B = 5.2\,T, L = 2500\,m$ in the second wiggler section and end up at 10 GeV, see fig.2.

The relative energy width is 0.7 % at the end. Since the synchrotron radiation is radiated into a narrow cone of $1/\gamma(s)$ opening angle, the emittance generated from fluctuations of the transverse momenta of synchrotron radiation photons is very small. With Eq.(46) of ref.[4] it can be estimated at

$$\Delta\epsilon = \Phi\Gamma\beta B^3 L$$

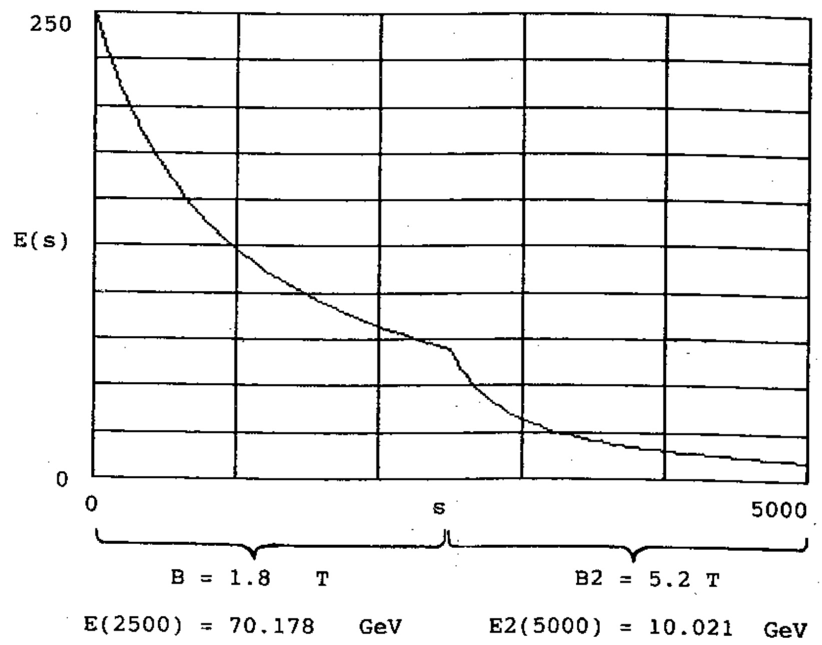

Figure 2: Radiative particle deceleration in a two-stage scheme with 1.8 T for 2500 m and 5.2 T for another 2500 m. In parallel with the radiative deceleration, the relative energy width is damped. The emittance stays constant during radiative deceleration, i.e. the *normalized* emittance is damped as well.

With $\beta = 50\,m$ we get $\Delta\epsilon = 5 \cdot 10^{-12} m$ at the end of the second wiggler, which is 10 times smaller than the TESLA vertical design emittance at 10 GeV. Therefore this contribution will be neglected within this paper. As the treatment of this effect in ref.[4] was approximate only, it should ,however, be investigated more carefully in a detailed analysis. Due to adiabatic damping, the emittance is compressed by a factor of 250 GeV/10 GeV = 25 during acceleration from 10 GeV up to 250 GeV. Thus, if the decelerated beam is immediately reinjected into the main linac, the emittance would be damped by a factor of 25 per turn.

We will return to this option later; in the moment we assume, that the beam emittance has been damped to the desired value in a damping ring before injected into the main linac, so that the only requirement is, for the moment, that the normalized emittance is not increased during the recycling process. We realize, however, that only 1/8 of the total number of 800 bunches per pulse must be stored in that damping ring, if the recycling scheme is adopted: The total length of the bunch train within one cycle is $2 \times (length\ of\ main\ linac + length\ of\ wiggler\ section) \approx 30$ km, corresponding to 100 bunches at 1 μs bunch distance. Thus, the recycling loop is filled once with 100 bunches from the damping ring, and then those 100 bunches are recirculated 7 times to produce the desired luminosity. The total number of cycles (here assumed to be eight) is only limited by the length of the rf pulse, and so is the luminosity. In any case, the number of bunches to be produced and stored is only 100, and the damping ring size may be reduced by a factor of eight. Fig. 3 shows a sketch of the system.
If it turns out that electrons can be generated with the desired phase space density right from the gun, no electron damping ring is required at all, and the recycling scheme is required for positrons only. There are two limiting effects of this scheme, which will now be discussed: a) particle losses and b) emittance growth.

a) particle losses

At first sight one might guess that a considerable fraction of the beam is lost during the collision at the interaction point (IP), or just afterwards, due to the beam-beam interaction. During interaction, the beam divergence is increased (disruption) and the beam energy distribution is considerably smeared because of beamstrahlung. One should realize, however, that beam losses must be carefully avoided in the inteaction region (IR) anyway, because background rates in the detector would become intolerably high, and because of damaging beam optics elements. Note that the mean electric power of each TESLA beam amounts to 16 MW, so that the thermal stress from (say) one percent of the beam (160 kW) would be extremely critical, not to talk about the background rates. Some ideas how the spent beam optics might look like can be found in refs.[4],[6].

The decisive reason for particle losses within the IR is angular disruption. the *maximum* disruption angle is typically 0.5 mrad (both horizontally and vertically) which is only some factor ten larger than the natural beam divergence at the IP. Only a very small fraction of the particles (of the order of 10^{-6}) will suffer larger angles due to simultaneous occurrance of large energy loss and large disruption. This will be a serious topic for background considerations, eventually leading to much larger aperture requirements than what is needed for our purpose, the more so since the fan of beamstrahlung photons will have an even larger opening angle. In ref.[4] it

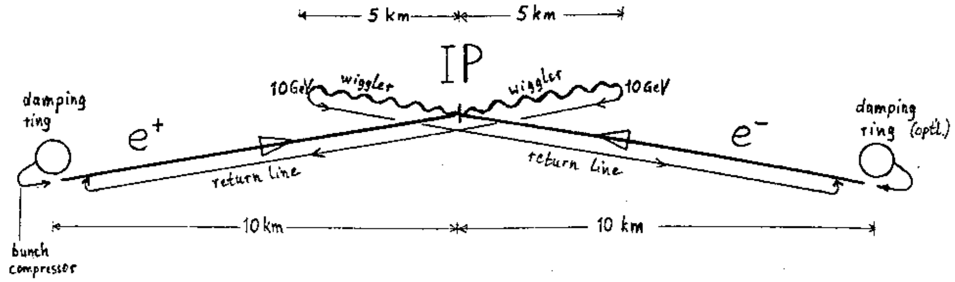

Figure 3: Particle recyling scheme for TESLA. As the design length of the TESLA bunch train is 240 km, it can be realized by a 30 km long bunch train circulating 8 times. The emittance growth at the interaction point is compensated by damping of longitudinal and transverse emittances in the radiative deceleration section. The damping ring can be 8 times smaller, because it has to deliver only 100 bunches (1/8 of the design value of 800). Positrons are recovered and stored for the next pulse, thus greatly reducing the demands on the positron source.
The crossing angle is in fact much smaller than in this sketch, so that nearly everything fits into one straight tunnel.

is shown that the final focus quadrupoles can be constructed and arranged in a way that much more than 99.9 % of the disrupted beam clears the final focus quadrupoles of the respective oncoming beam. For our purpose we don't care any more about the fate of 0.1 % of the beam and conclude that the beam loss in the IR is below 10^{-3}.

The main complication with recovery of the disrupted beam, however, is not disruption but the large energy spread due to the beamstrahlung. It requires an energy band width of the recovery optics of some 10 %. This would be impossible with the recovery optics perfectly matched to the disrupted beam. That problem will be discussed in the next section. With respect to particle losses we realize that the beam emittance is still extremely small after interaction (of the order of $10^{-10} m$ or smaller). Using a sufficiently large (mismatched) β at the IP, however, it is no problem to achieve an energy acceptance of $\pm 10\%$ in a straight transfer line, the more so since the fractional energy width is decreased to some $\pm 3\%$ within approx. 1 km due to radiation damping in the wiggler, see Eq.10 (note that there is *no* adiabatic antidamping during radiative deceleration!).

Thus, if we assume an acceptance of (only) 10^{-6}m in the recycling section, a mismatch of more than 10^4 would be tolerable from the particle loss point of view. We conclude that only particles in the extreme tails of the phase space and energy distribution will be lost, which we estimate at 1 % [2], so that, in the last of our eight turns, the beam intensity will be at least 93 % of the initial one.

[2] To avoid confusion it is noted that in ref.[4] the recycling efficiency was estimated at only 90 % to simplify the reasoning, because this was a less critical parameter in that paper.

b) emittance growth

This is the most critical problem in the recycling scheme, since only the factor of 250 GeV/10 GeV gained from adiabatic damping in the main linac can be sold to emittance growth in the recycling section. Otherwise, the beam size would increase from turn to turn and the luminosity would drop down. Emittance growth occurs due to beamstrahlung/disruption and due to quantum excitation in the wiggler section. The maximum disruption angle is estimated at [7][8]

$$\hat{\Theta}_{x,y} = \frac{2r_e N}{\gamma\sigma_x} k_{x,y} \left[1 + \left(\frac{D_{x,y}}{2}\right)^5\right]^{-\frac{1}{6}} \qquad (11)$$

(for flat beams, with $k_x \approx 0.75$ and $k_y \approx 1.25$)

$D_{x,y}$ is the disruption parameter

$$D_{x,y} = \frac{2r_e N\sigma_s}{\gamma\sigma_{x,y}(\sigma_x + \sigma_y)} \qquad (12)$$

The rms disruption angle σ_D is approx. one third of $\hat{\Theta}_{x,y}$. Thus σ_D is about three times the natural beam divergence σ'^* at the IP. We describe the emittance growth due to disruption by the factor C^D:

$$C^D_{x,y} = \sqrt{\left(\frac{\hat{\Theta}_{x,y}}{3\sigma'^*}\right)^2 + 1} \qquad (13)$$

Emittance growth due to beamstrahlung sensitively depends on the rms fractional energy width after collision, i.e. on beam intensities and beam sizes of the oncoming beam. We use the parametrization

$$\frac{\sigma_\epsilon}{E} = 6\cdot 10^{-36} m^2 \left(\frac{N}{\sigma_x^* + \sigma_y^*}\right) \qquad (14)$$

It has been shown in ref.[3] that a final focus system with momentum bandwidth of ± 0.02 can be built. We adopt this solution for the optics collecting the disrupted beam. Therefore, as long as $\sigma_\epsilon/E \leq 0.02$, the emittance growth factor due to beamstrahlung $C^{BS}_{x,y}$ is close to $C^D_{x,y}$ (this additional factor $C^D_{x,y}$ reflects the fact that if the divergence is increased by $C^D_{x,y}$, the emittance increases by $\left(C^D_{x,y}\right)^2$, if β^* of the collection optics has to be taken equal to β^* of the final focus optics).

The emittance growth due to chromaticity for $\sigma_\epsilon/E > 0.02$ would be linear in σ_ϵ for a purely linear transfer line. We use a quadratic dependence to take into account the effect of sextupoles. Thus the emittance growth factor due to beamstrahlung is in total

$$C^{BS}_{x,y} = C^D_{x,y}\left[\left(\frac{\sigma_\epsilon/E}{0.02}\right)^2 + 1\right] \qquad (15)$$

The emittance growth in a wiggler section of length L has been estimated in ref.[4] at

$$\Delta\epsilon^W = \frac{2.1\cdot 10^{-15}}{m^3 T^5}\beta\lambda^2 B^5 L \qquad (16)$$

where β is the average beta function in the wiggler and λ its period length. If a helical wiggler is used, $\Delta\epsilon^W$ is applicable both in horizontal and vertical directions. We suggest to use an elliptical wiggler which might be quite simple to be realized from a superconducting double helix. For a vertical rms field component of 5.2 T and a horizontal one of 2.4 T we get ($L = 2500\ m$)

$$\begin{aligned}\Delta\epsilon_x^W &= 5\cdot 10^{-10}\ m\\ \Delta\epsilon_y^W &= 10^{-11}\ m\end{aligned} \qquad (17)$$

if we assume a peroid length of $\lambda(s.c.) = 22\ mm$. For this estimation, an average beta function of $\beta = 50\ m$ has been used, i.e. quadrupoles every 20 m or so. Due to the B^5 dependence, the first 1.8 T wiggler section does not contribute significantly as long as $\lambda(n.c.)$ does not exceed 300 mm in this section. Following ref.[4] it can be shown that orbit errors in the wigglers must be controlled such that the spurious dispersions are below 8 mm (hor.) and 1 mm (vert.), respectively. To guarantee this, similar orbit correction techniques can be applied as in the main linac.

Taking it all together, the emittance $\epsilon(n)$ at the n-th interaction is given by

$$\epsilon_z(n) = \frac{10}{250}\left(\Delta\epsilon_z^W + C_z^D\cdot C_z^{BS}\cdot\epsilon_z(n-1)\right) \qquad (18)$$

($z = x$ or y). These equations govern the development of the luminosity, disruption, beamstrahlung, etc. from turn to turn. This development is illustrated in fig. 4, where TESLA design emittance values have been used in the first turn. Due to the overall damping effect of the recycling scheme, however, the design luminosity is achieved with only 70 % of the design bunch population! Of course, this could have been achieved as well with a small emittance damping ring, and it sets the well known tight tolerances on the main linac alignment. One can, on the other hand, also relax the requirements on tolerances and wiggler period length to just reproduce the design emittance after each turn. Emittance growth and emittance damping will be balanced at $\lambda(s.c.) \approx 30mm$ and spurious dispersion values of 10 mm (both hor. and vert.).

c) emittance oscillations

If tolerances are set sufficiently tight so that $\Delta\epsilon^W_{x,y}$ are very small (e.g. $\Delta\epsilon_x^W = 10^{-10}m$, $\Delta\epsilon_y^W = 10^{-11}m$), there is a critical bunch population where an instability mechanism sets in: After the first turn the emittance is so small that the luminosity is large in the second turn, but then the beamstrahlung/disruption will be very large as well. Thus, in the third turn, the emittance is very large with the contrary effect, and so on. This is illustrated in fig.5.

Below the critical bunch population, the luminosity *smoothly* attains its maximum. For the parameters used in fig. 5, this critical value is about $1.5\cdot 10^{10}$ particles per bunch, see fig. 6. This means that with setting tight tolerances in the recycling section, one can increase the specific luminosity (luminosity per bunch current), but not necessarily the total luminosity. Therefore, to get the design luminosity without this kind of oscillations, it might turn out to be necessary to intentionally avoid too small beam sizes during recycling.

In this simple model it is assumed that both electron and positron beams behave symmetrically, i.e. they start with exactly equal parameters and are both recycled by identical systems.

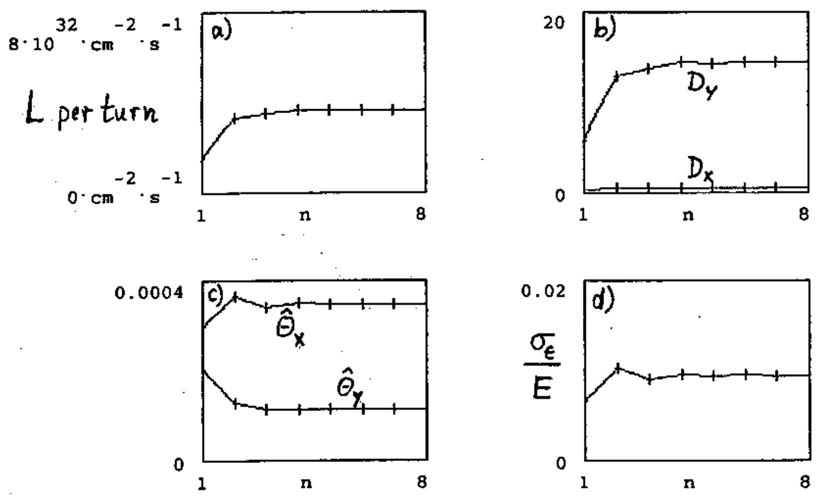

Figure 4: Development of (a) luminosity, (b) disruption parameters, (c) maximum disruption angles, and (d) rms fractional energy width after interaction as a function of the number of recycling turns. Parameters used are:
number of particles per bunch: $N = 3.5 \cdot 10^{10}$
norm. emittance on first turn: $\gamma\epsilon_x = \epsilon_x^N = 2{\cdot}10^{-5}\,m$, $\gamma\epsilon_y = \epsilon_y^N = 1{\cdot}10^{-6}\,m$
emittance generated in wiggler: $\Delta\epsilon_x^W = 5 \cdot 10^{-10}\,m$, $\Delta\epsilon_y^W = 10^{-11}\,m$
The total luminosity from all eight turns is $L = 2.7 \cdot 10^{33}\,cm^{-2}s^{-1}$.

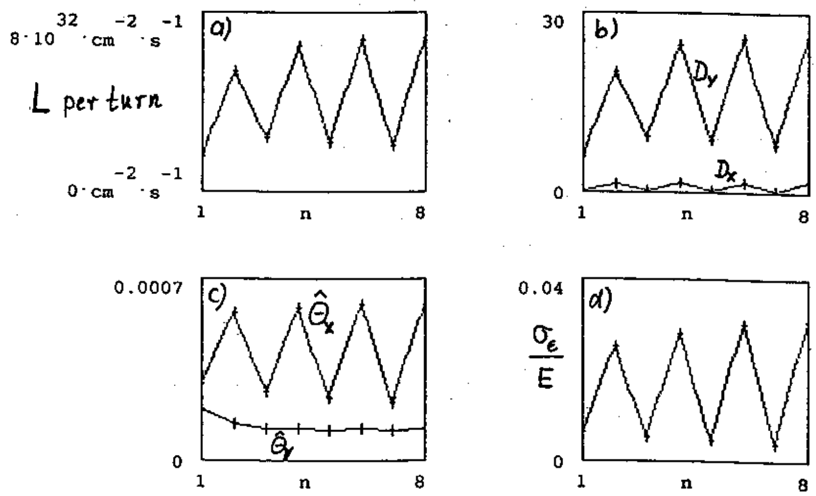

Figure 5: Development of (a) luminosity, (b) disruption parameters, (c) maximum disruption angles, and (d) rms fractional energy width after interaction as a function of the number of recycling turns. Parameters used are above the stability threshold:
number of particles per bunch: $N = 3.5 \cdot 10^{10}$
norm. emittance on first turn: $\gamma\epsilon_x = \epsilon_x^N = 2{\cdot}10^{-5}\,m$, $\gamma\epsilon_y = \epsilon_y^N = 1{\cdot}10^{-6}\,m$
emittance generated in wiggler: $\Delta\epsilon_x^W = 10^{-10}\,m$, $\Delta\epsilon_y^W = 10^{-11}\,m$
The total luminosity from all eight turns is $L = 3.4 \cdot 10^{33}\,cm^{-2}s^{-1}$.

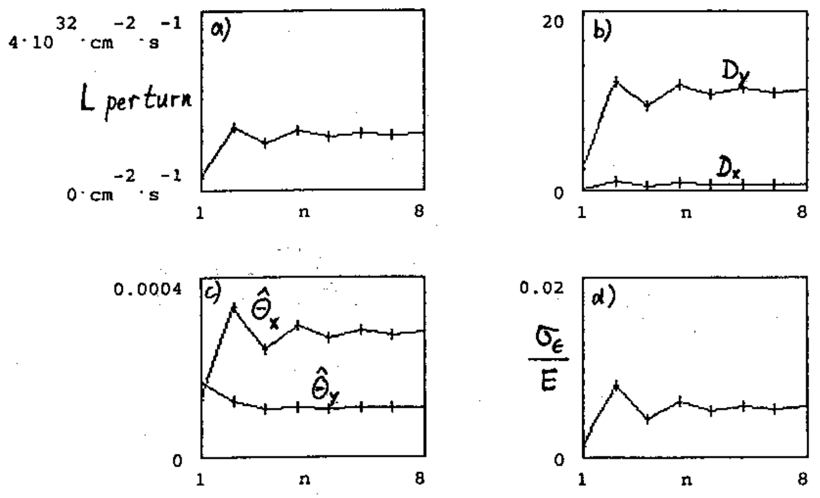

Figure 6: Development of (a) luminosity, (b) disruption parameters, (c) maximum disruption angles, and (d) rms fractional energy width after interaction as a function of the number of recycling turns. Parameters used are the same as in fig.5, except for N, which is now below the instability threshold:
number of particles per bunch: $N = 1.5\cdot10^{10}$
norm. emittance on first turn: $\gamma\epsilon_x = \epsilon_x^N = 2\cdot10^{-5}\,m$, $\gamma\epsilon_y = \epsilon_y^N = 1\cdot10^{-6}\,m$
emittance generated in wiggler: $\Delta\epsilon_x^W = 10^{-10}\,m$, $\Delta\epsilon_y^W = 10^{-11}\,m$
The total luminosity from all eight turns is $L = 0.9\cdot10^{33}\,cm^{-2}s^{-1}$.

If, for instance, only positrons will be recycled while electrons are generated by a high brilliance gun, the instability will not take place, and the potential gain of luminosity is smaller.

Finally, there is the option to intentionally scrape the tails in the energy distribution much more drastically to gain damping efficiency for the core of the beam. If then, as a consequence, (say) 10 % of the beam is lost, this loss can be compensated by the positrons which are generated in passing on *each* turn anyway. This option, which requires a bypass of the IP, is explained in more detail in the next section.

d) The storage linac mode of TESLA

It is obvious from the previous sections that the recovery system possesses an effective and fast emittance damping property. If a large emittance beam is circulated, its emittance is reduced by a factor of 250 GeV/10 GeV on each turn. This feature offers the possibility to do without any damping ring at all:

Since positrons are generated at a normalized emittance of $\epsilon_{x,y}^N \approx 0.01\,m$, two turns are required to achieve the design horizontal emittance ($0.01\,m/(25\cdot25) < 2\cdot10^{-5}\,m$) and three turns for the vertical emittance ($0.01\,m/(25\cdot25\cdot25) < 1\cdot10^{-6}\,m$). As electrons are generated at very low emittance, they need at most one turn. Nevertheless the electron linac will be started some 70 μs before the positron linac, because electrons are needed to generate positrons, which cannot be restored in the damping ring for the next pulse in this configuration. Fig. 7 shows a sketch of this "TESLA storage linac" and its timing. It is seen that a bypass of the IP is included for positrons. This bypass is required because the positron beam is too large in the first three turns to pass the final focus system. It offers the additional option that three low intensity spare positron bunches per each main bunch can *parasitically* be damped in each cycle if they are placed with 250 ns distance into buckets between the main bunches, see fig. 8. Note that positrons will be produced continously every 1 μs anyway (without injuring the driving electron beam quality if the wiggler based positron source is used [6]), and a time delay of 250 ns is easily realized by a short end saving 75 m in the recycling transfer line. It is, by the way, likely that a bypass of the interaction region will be highly desirable anyway, e.g. for commissioning and beam based alignment purposes.

A kicker of 250 ns rise time operating at 1 MHz will be required to separate these spare bunches from the main ones. In each turn, one of these spare bunches (namely the oldest one which has performed 3 cycles already) can be added to the respective main bunch to balance particle losses. This can be done in a dispersive section (e.g. a bending magnet) at low energy. If the bunches are merged with say 10 % difference in energy, the transverse phase space density really increases without violating Liouville's theorem. The timing is sketched in fig. 8.

If the additional spare bunches contain only some 10 % of the design intensity, the additional beam power to be supplied is about 5 MW per beam, if $5\cdot10^{10}$ is assumed for the main bunches. One gains, however, a much larger factor in luminosity, since the recovery optics is not forced to take care of the the low energy tail in the energy distribution of the disrupted beam if 10 % can be lost on each turn. Therefore the damping efficiency is improved considerably, ultimately leading to smaller bunch sizes and increased luminosity. In the extreme case it might turn out to be favourable to operate with $N = 2.5\cdot10^{10}$ in the main bunches only, but $8\cdot10^9$ in the spare

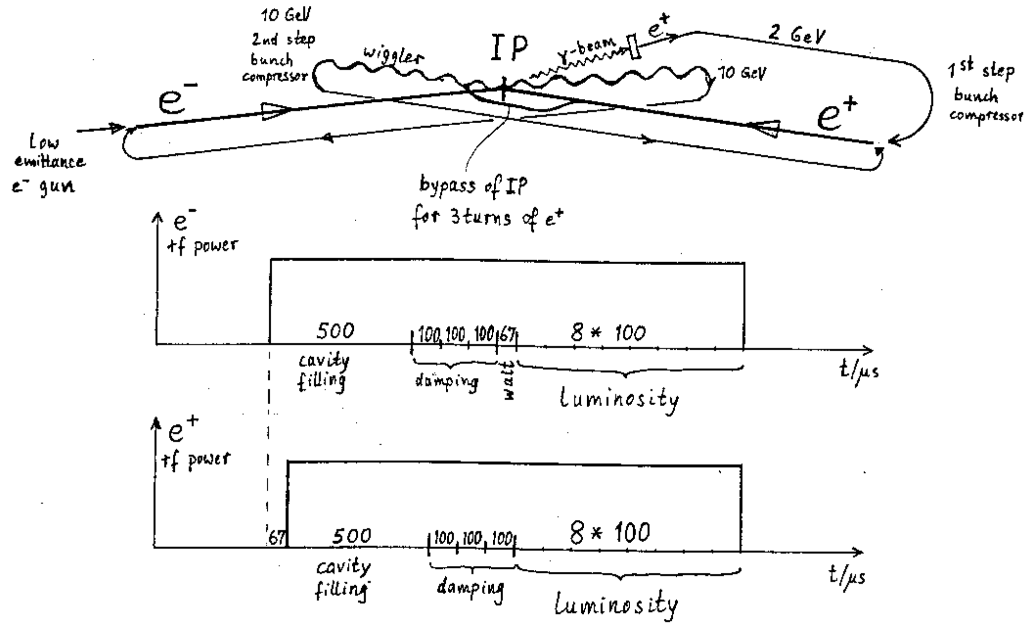

Figure 7: Scheme of the TESLA storage linac with no damping ring at all. Positrons are damped during three turns preceding the luminosity turns. The bypass of the IP is used by the undamped bunches. It offers the additional option to parasitically damp low intensity spare bunches, which can be used to refill the recycled bunches. The price for saving the damping rings is about 30 MW wall plug power, which is required to extend the rf pulse by 370 μs. The two lower diagrams show the utilization of the extended rf pulses. The e^- linac has to start 67 μs before the e^+ linac, which is the time to pass the e^- linac, to generate positrons, and (for the positrons) to reach the entrance of the e^+ linac.

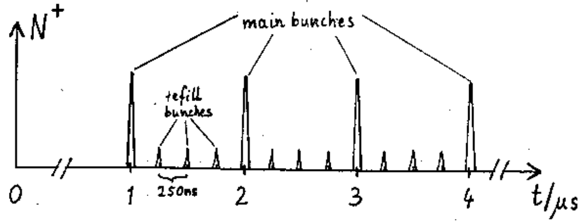

Figure 8: Timing structure of the positron bunch train with low intensity refill bunches between the main bunches. These spare bunches are generated by the positron source anyway. On each turn, the spare bunches are damped by a factor of 25 and shifted by 250 ns. They do not suffer interaction as they bypass the IP. After three turns, the spare bunches are added to the respective main ones in a dispersive section to restore (or increase) their transverse phase space density.

bunches, so that only the core of the beam (containing 70 %) must be recovered on each turn. Then the energy band width of the recovery optics is not an issue any more, and the emittance damping might be so effective that more than the design luminosity is achieved (at reduced beam energy spread at interaction!). If this luminosity gain exceeds 20 %, the additional power consumption due to the lengthening of the rf pulse by 370 μs will be overcompensated.

A bunch compressor can be included in the 180° bend after the wiggler section. As it will be traversed at least 3 times by each bunch, a moderate compression factor is sufficient (say 3). Its rf part should operate in a *de*celerating mode to simplify the bends.

Alignment tolerances will be surely more critical in this scheme than in the "standard" TESLA design but they are still generous compared to many other linear collider studies. It is stressed that the possibility to operate the linear collider in a storage mode is a unique feature of TESLA because of its extremely long rf pulses.

It is obvious from the previous reasoning that the recycling/storage mode relies on assumptions on both the bandwidth of the recovery optics and the emittance growth in the wiggler sections. Since lots of nonlinear particle dynamics is involved, more careful numerical investigations are required to decide whether the recovery option is a realistic one for TESLA. One should not forget, however, that in *any* damping ring concept, the major part of radiation damping takes place in wiggler sections. If one compares the number of wiggler periods to be traversed within one damping time, one easily finds that this number is typically one order of magnitude *larger* ($\approx 10^6$) in "conventional" damping rings than in the recycling section. Also, in the latter one the particle energy is much larger and the beam size is always well below 1 mm, in contrast to a "conventional" damping ring.

4. DOG-BONE PLUS RECYCLING

If the dog-bone damper and the recycling scheme are combined, a very flexible damping system is achieved, see fig. 9. The dog-bone should be extended, in this case,

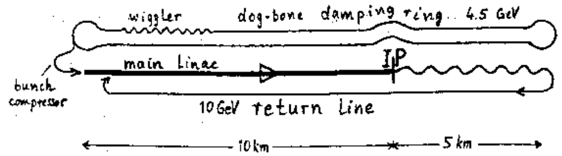

Figure 9: Combination of a long dog-bone damping ring and the recycling scheme. To avoid confusion, only the arrangement for *one* particle species is shown (e.g. positrons). Most of the long transfer lines are simple FODO channels with quadrupoles every 500 m or so.

over the IP to attain 30 km circumference, because then the bunch spacing of $1\mu s$ will be the same everywhere in TESLA. Then, the requirements on kicker rise times and repetition rates

are not an issue, and, with a mean current of 8 mA in 100 bunches, multi-bunch instabilities are not critical any more. Also, rf power consumption is greatly reduced.
Finally, in table 2 the alternative damping schemes for TESLA are compared.

5. ACKNOWLEDGEMENTS

We gratefully acknowledge discussions with R. Brinkmann and D. Degèle.

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scheme	d.r. energy [GeV]	# bunches stored	bunch spacing in damping ring/ns	rep.rate of kickers/MHz	minimum length of wigglers/m	wall plug power for rf/MW	disadvantage	risk
large (C=6km) circular d.r.	14	800	25	1	40	20	very fast kickers, high intensity, 6 km extra tunnel	kickers, m.b. instabilities
dog-bone	4.5	800	83	1	740	6	many bunches, fast kickers, 20 km lattice	kickers, wiggler
recycling + small d.r.	3	100	25	1	5000	< 1	very fast kickers, long wigglers	kickers, m.b. instabilities, wiggler, disruption
recycling + IR–bypass	—	100	no d.r.	1	5000	30	fast IR–bypass, extended rf pulse	wiggler, disruption
recycling + dog-bone	4.5	100	1000	10 Hz	5000 + 740	1	long wigglers, 50 km lattice	wigglers, disruption

Table 2: Comparison of different damping ring (d.r.) schemes for TESLA