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# High Luminosity with TESLA-500

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## 1. Introduction

The primary goal of the TESLA-500 design work during the past years has been to arrive at a consistent overall layout of the linear collider facility including all subsystems, which safely guarantees the "standard" value for the luminosity of $6 \cdot 10^{33}$ $cm^{-2}$ $s^{-1}$. This design study has by now been completed and is documented in ref. [1]. It is one of the strongest arguments in favour of choosing the superconducting linac that this luminosity is achieved with very relaxed requirements for the alignment and stability of the components in the accelerator and in the Final Focus system, in comparison with conventional linear collider approaches. One may expect then that by reducing the large safety margins concerning beam stability in TESLA opens up a considerable upgrade potential for the luminosity. A thorough investigation of the TESLA luminosity potential will require to re-consider the design of all collider subsystems in full detail. In this paper, I focus on more basic considerations concerning scaling of the beam parameters and identifying potential problems when a luminosity upgrade by a large factor is to be realised.

## 2. Scaling of Interaction Parameters

According to the general scaling rule for a linear collider (centre-of-mass energy $E_{cm}$) the basic limitations for the luminosity are the power transfer efficiency $\eta$, the beamstrahlung $\delta_B$ and the normalised vertical emittance $\varepsilon_y$:

$$L \propto \eta \frac{P_{AC}}{E_{cm}} \cdot \sqrt{\frac{\delta_B}{\varepsilon_y}} \tag{1}$$

The TESLA reference design [1] has a power consumption $P_{AC}$ close to 100 MW which seems to be a reasonable upper limit. We also limit the beamstrahlung to 3% in order to maintain a low background in the detector, a good energy resolution and a reasonable quality of the spent e- beam which drives the positron source. A higher luminosity therefore has to come from $\eta$ and (mainly) $\varepsilon_y$. Modifications of the main linac to increase $\eta$ will not be discussed here in detail. It should be noted, though, that an increase of the linac fill factor, essentially by reducing the spacing between cavities, would be beneficial not only for the energy reach of TESLA but also for the luminosity. For a given $E_{cm}$ = 500 GeV and a fixed site length, a higher fill factor allows to reduce the gradient. The resulting savings in cryo power (especially when taking into account that the unloaded Q can be higher than the present design value of $5 \cdot 10^9$) can be invested into RF-power to accelerate a higher pulse current. That would reduce the loaded $Q_{ext}$ and the filling time, resulting also in a longer beam pulse and less additional RF-power for gradient stabilisation. The potential gain in $\eta$ is realistically limited to 30…50 percent, but a number of questions related to such a modification still need to be studied in more detail [2]. It becomes clear that the main factor for a large increase in luminosity must be achieved by reducing $\varepsilon_y$. If we set an ambitious goal for the ultimate TESLA luminosity of about $5 \cdot 10^{34}$ cm$^{-2}$ s$^{-1}$, this means that the vertical emittance at the IP must be reduced by about a factor of 30…50 from the reference design value of $2.5 \cdot 10^{-7}$ m.

The first potential problem which arises concerns the disruption parameter:

$$D_{x,y} \approx \frac{2N_e r_e \sigma_z}{\sigma_x \sigma_{x,y} \gamma} \tag{2}$$

In the reference design we have $D_y \approx 18$, just at the border of the regime where the single bunch kink instability (a collective beam-beam effect) starts becoming strong (see e.g. [3]). There is not a hard limit on $D_y$ from this instability, but the collective excitations of the bunches during the interaction become stronger and the luminosity more sensitive to small vertical offsets of the bunches w.r.t. each other. On the other hand, a large $D_y$ can even be beneficial in context with the so called "travelling focus" scheme [4,5], where the β-function at the IP becomes smaller than the bunch length. For very large $D_y$, predictions of the luminosity in the presence of orbit offsets are difficult, since beam-beam simulation codes applied in this extreme regime do not always yield stable and reliable results. The question of maximum affordable vertical disruption needs more studies before it can be settled. I will in the following consider two cases: (a) with constant $D_y$, (b) with $D_y \propto \varepsilon_y^{-1/2}$. The possibility of choosing a compromise scaling between (a) and (b) is obvious.

The luminosity and the disruption parameter are simply related:

$$D_y \propto \frac{L}{\eta P_{AC}} \cdot \sigma_z \tag{3}$$

Thus the only way to maintain a constant disruption for case (a) is to scale $\sigma_z \propto \varepsilon_y^{1/2}$. Maintaining an approximately constant beamstrahlung,

$$\delta_B \approx -0.86 \frac{r_e^3 N_e^2 \gamma}{\sigma_z \sigma_x^2}\ , \tag{4}$$

then requires to scale $N_e/\sigma_x \propto \sigma_z^{1/2} \propto \varepsilon_y^{1/4}$. Since a smaller bunch charge is beneficial for beam dynamics in both the linac and the damping ring, the choice $N_e \propto \varepsilon_y^{1/4}$ at constant horizontal spot size seems to be preferable.

For case (b), a lower bunch charge $N_e$ seems necessary to preserve a much smaller emittance in the linac (see below). In this case constant beamstrahlung leads to scaling $\sigma_x \propto N_e$ and, if the beam divergence at the IP is to be kept constant, $\beta_x \propto N_e$ *and* $\varepsilon_x \propto N_e$.

An overview of the approximate scaling rules for reduced vertical emittance for both cases is given in Table 1. In Table 2 a list of scaled parameters (taking the reference design [1] as the starting point) based on an emittance reduction by a factor of 50 is given. In the following, the impact of such a parameter scaling on the collider sub-systems will be discussed.

| Parameter | case (a) | case (b) |
|---|---|---|
| Bunch length $\sigma_z$ | $\varepsilon_y^{1/2}$ | const. |
| Bunch charge $N_e$ | $\varepsilon_y^{1/4}$ | $(\sim \varepsilon_y^{1/4})^{*)}$ |
| Hor. emittance $\varepsilon_x$ | const. | $N_e$ |
| Beta functions $\beta_{x,y}$ | const., $\varepsilon_y^{1/2}$ | $N_e$, const. |
| Spot size $\sigma_{x,y}$ | const., $\varepsilon_y^{3/4}$ | $N_e$, $\varepsilon_y^{1/2}$ |
| Disruption $D_y$ | const. | $\varepsilon_y^{-1/2}$ |
| Bunch spacing | $\varepsilon_y^{1/4}$ | $N_e$ |
| Luminosity | $\varepsilon_y^{-1/2}$ | $\varepsilon_y^{-1/2}$ |

**Table 1:** Scaling of the interaction parameters with vertical emittance for the cases with constant vertical disruption (a) and with constant bunch length (b), respectively. The luminosity scaling assumes an unchanged pinch enhancement factor (~ 1.6). More precise values must be obtained from computer simulations.
*): the scaling of bunch charge depends on the way emittance preservation in the linac is provided, see section 3. The quoted scaling represents a reasonable compromise.

| Parameter | case (a) | case (b) |
|---|---|---|
| Bunch length $\sigma_z$ [mm] | 0.1 | 0.7 |
| Bunch charge $N_e$ [$10^{10}$] | 1.4 | ~1.4 |
| Hor. emittance $\varepsilon_x$ [$10^{-5}$ m] | 1.4 | ~0.54 |
| Beta functions $\beta_{x,y}$ [mm] | 25, 0.1 | ~9.6, 0.7 |
| Spot size $\sigma_{x,y}$ [nm] | 845, 1.0 | ~326, 2.7 |
| Disruption $D_y$ | 18 | 126 |
| Bunch spacing | 273 | ~273 |
| Luminosity (const. $\eta$, $P_{AC}$) [$10^{34}$ cm$^{-2}$ s$^{-1}$] | 4.2 | 4.2 |

**Table 2:** Values for the scaled interaction parameters with a vertical emittance of $5 \cdot 10^{-9}$m, reduced by a factor of 50 compared to the reference design value of $2.5 \cdot 10^{-7}$ m. Note that $\varepsilon$ means "normalised emittance" throughout this paper.

## 3. Main Linac

In the reference design the emittance dilution in the TESLA linac amounts to about 12% with alignment tolerances of 0.5mm for the cavities and 0.1mm for the quads/BPM's and simple one-to-one orbit correction. The dilution is essentially due to single bunch effects (about 6% each from spurious dispersion and from transverse short-range wakefields). The emittance dilution can be further reduced when the effective alignment of the BPM's w.r.t. the quadrupoles is improved by beam-based procedures. The BPM alignment error $\delta_{BPM}$ is in that case replaced by the BPM resolution, which is expected to be at least an order of magnitude smaller (<0.01mm instead of 0.1mm). Since the dispersive emittance dilution scales as $\sim\sigma_E^2\delta_{BPM}^2$, it will not be a serious problem even for an emittance reduced by a factor of 50, unless the bunch energy spread $\sigma_E$ is increased significantly. In principle, the optimisation of the focusing lattice in the linac also has to be re-considered with modified parameters. This has not been taken into account here and in the following.

The emittance dilution from the short-range transverse wakefield scales approximately as

$$\frac{\Delta\varepsilon}{\varepsilon}\left(W_{trans}\right) \propto \frac{N_e^2 f(\sigma_z)}{\varepsilon}\cdot\delta_{cav}^2 \tag{5}$$

where $f(\sigma_z) \approx \sigma_z$ for a single cavity and $f(\sigma_z) \approx \sigma_z^2$ for an infinite periodic array of cavities. Calculations of the short-range longitudinal wakefield [6] have shown that one module with 8 cavities already exhibits the transition to the periodic regime. Taking $f(\sigma_z) \approx \sigma_z^{3/2}$ as a reasonable approximation to the correct scaling, the emittance dilution for case (a) goes as

$$\frac{\Delta\varepsilon}{\varepsilon}\left(W_{trans}\right) \propto \varepsilon^{1/4}\cdot\delta_{cav}^2 \quad , \tag{6}$$

which is obviously not a problem since the cavity alignment tolerances $\delta_{cav}$ could even be relaxed at lower emittance. In case (b), keeping the relative emittance dilution constant with the same alignment tolerances would require to reduce the bunch charge rather drastically, $N_e \propto \varepsilon_y^{1/2}$. The necessary simultaneous reduction of bunch spacing and horizontal emittance (see section 2) seems problematic, so that a compromise between reduced $N_e$ and tighter tolerances may be a better solution. With $N_e \propto \varepsilon_y^{1/4}$ the estimated emittance dilution goes up to about 50% for $\varepsilon_y = 5\cdot10^{-9}$m. Taking into account that an empirical minimisation of the short-range wakefield effect can be achieved by means of non-dispersive orbit bumps, tighter alignment tolerances may not be required also in this case.

The correlated relative energy spread in the bunch scales as $\sigma_{E,coh.} \propto N_e\cdot\sigma_z^{-1/2}\cdot h(\sigma_z)$. Here, $h(\sigma_z)$ takes two effects into account: First, for shorter bunches it becomes more difficult to reduce the energy spread by adjusting the RF-phase (at $\sigma_z = 0.7$mm a phase of 3.4° is used to reduce $\sigma_{E,coh.}$ by more than a factor of two). Second, a module of 8 cavities already shows the transition to the "periodic" regime, where the longitudinal wakefield becomes independent of bunch length [6]. Due to these counteracting effects it is difficult to simply scale the resulting energy spread when the bunch length is varied. We take $h(\sigma_z) \approx$ const. as a rough approximation and note that a more precise scaling can be derived from the numerical results given in [6]. Then for case (a) the coherent energy spread is unchanged ($5\cdot10^{-4}$), whereas it scales as $\sigma_{E,coh.} \propto N_e$ for case (b). It has to be observed, though, that the incoherent energy spread can quickly become dominant for the parameter regime of case (a) considered here: in the present design, $\sigma_{E,incoh.} = 1.4\%$ at the entrance and 1.4%·(3.2GeV/250GeV) = $1.8\cdot10^{-4}$ at the exit of the linac, smaller than the correlated energy spread (about $5\cdot10^{-4}$). For a bunch length of 0.1mm with unchanged longitudinal emittance (a rather realistic assumption, see section 4), the incoherent energy spread at the linac end is as large as $13\cdot10^{-4}$ and will dominate the dispersive emittance dilution over the entire linac length. The impact on the dispersive emittance dilution can only be studied in detail once the questions concerning modifications of the injection system (damping ring, one- or two-stage bunch compressor, see section 4) are settled.

The multi-bunch emittance growth from BBU driven by long-range HOM's amounts to only about 1% for the reference parameters with a HOM frequency spread of 1MHz and a rather weak damping provided by HOM-couplers at the cavity ends. Concerning multibunch BBU, earlier studies have shown [7] that the effect does not strongly change with reduced bunch spacing for constant beam pulse current. Without any modifications of the present HOM damping concept, the emittance growth from this source would be at the limit of being tolerable, 50% instead of 1%, with a 50-fold smaller $\varepsilon_y$. A reduction of the effect should be relatively simple: First, a larger HOM detuning spread can be arranged (intentionally, if not "automatically" present from manufacturing tolerances) which would lead to a faster initial decay of the wakefield with time. Second, the concept of removing the multibunch orbit distortion at some point inside and/or at the end of the linac with a fast kicker [8] can be applied. This device is particularly simple for TESLA, since the required bandwidth is only of the order of a few MHz.

The time scales on which corrections have to be applied have been estimated for the reference parameters assuming an ATL-like diffusive ground motion model. With $A = 4\cdot 10^{-6}$ $\mu m^2/m/s$ derived from HERA data, it is found that orbit correction has to be applied about every $10^4$s and beam based alignment only after several years of operation. These time scales will become shorter, very roughly in proportion with $\varepsilon_y$, but it is not expected to be a problem if orbit correction must be applied every few minutes and beam based alignment every few weeks. Pulse-to-pulse orbit jitter in the TESLA linac is removed by the fast feedback within the bunchtrain and can thus be ignored, except for the fact that the resolution of the orbit pickup of the feedback system must be able to cope with the reduced beam size. With $\varepsilon_y = 5\cdot 10^{-9}$, we have $\sigma_y \approx 1\mu m$ at the end of the linac, so that the feedback BPM's should resolve a few hundred nm. The cavity BPM's foreseen for TESLA should be able to fulfill this requirement [9].

## 4. Injection System

In this section, the impact of the parameter scaling on the e+ source, the damping ring and the bunch compressor is discussed.

### Positron Source

The modification of the interaction parameters has an influence on the positron source in so far as the properties of the spent beam change. The studies of the spent beam capture system have shown that the difficulties result from the blow-up of the horizontal beam emittance and of the energy spread during collision, whereas the vertical emittance is not a critical parameter. The reason is that the large horizontal angular divergence of the beam after the IP gives rise to large higher order chromatic, geometric and chromo-geometric aberrations in the following beam optical system. With constant beamstrahlung energy loss the energy spectrum of the spent beam changes in detail if the bunch length is reduced (scaling (a)), because a smaller number of higher-energy photons is radiated. However, a much more important effect is the change in the horizontal beam divergence. This can be seen as follows.

The mean-square of the horizontal beam divergence after the IP is given approximately (for horizontal disruption $D_x<1$) by:

$$\sigma_x'^2 \approx \sigma_x^2 \left(\frac{D_x}{\sigma_z}\right)^2 \qquad (7)$$

Introducing the beamstrahlung, which scales as $\delta_B \propto \gamma N_e^2/(\sigma_x^2\sigma_z)$, we obtain:

$$\sigma_x'^2 \propto \frac{\sigma_z}{\gamma^3}\delta_B \qquad (8)$$

Thus the scaling (a) leads to a reduced emittance of the spent beam, favourable for operating the e+ source with high efficiency and making the polarised source more realistic.

## Damping Ring

The combination of higher bunch charge density with reduced bunch spacing associated with a smaller vertical emittance turns out to cause particularly serious problems in the damping ring. The present design consists of a 17km long "dogbone"-shaped ring operating at 3.2GeV. The bunch spacing in the ring is 50ns for a train of 1130 bunches. This design already takes into account the possibility of increasing the number of bunches per RF-pulse in the linac, since the proposed "conventional" injection/ejection kicker concept [10] allows to reduce the bunch spacing to 10…15ns. However, the incoherent space charge tune shift already reaches a reasonable upper limit with the reference parameters because of the unfavourable (and very unconventional) ratio of ring circumference $C_{DR}$ to beam energy $\gamma_{DR}$:

$$\Delta Q_{y,incoh} \approx -\frac{N_e r_e}{(2\pi)^{3/2}\sqrt{\varepsilon_x\varepsilon_y}\,\sigma_{z,DR}} \cdot \frac{C_{DR}}{\gamma_{DR}^2} \approx -0.2 \qquad (\sigma_{z,DR} = 9\text{mm}) \qquad (9)$$

A much higher tune shift can not be accepted, because the associated vertical tune spread should fit at least between the linear (1st and 2nd order) resonances in the tune diagram, including some safety margin. In order to check the impact of the low-$\varepsilon_y$ parameter scaling on $\Delta Q_{y,incoh}$, we differentiate between two sub-cases of the scaling (a): reducing the bunch length in the damping ring and keeping the compression ratio in the one-stage bunch compressor constant (case (a.1)), keeping the bunch length in the damping ring constant and modifying the bunch compressor scheme (case (a.2)). The resulting tune shift is given by $\Delta Q \propto q(\varepsilon_y)\cdot C_{DR}/\gamma_{DR}^2$, where:

$$\text{case (a.1): } q(\varepsilon_y) = \varepsilon_y^{-3/4}, \quad \text{case (a.2): } q(\varepsilon_y) = \varepsilon_y^{-1/4}, \quad \text{case (b): } q(\varepsilon_y) = \varepsilon_y^{-3/8} \qquad (10)$$

Let us first discuss the consequences for the worst case (a.1). Keeping the tune shift constant by only reducing the ring circumference is obviously ruled out, since the bunch spacing becomes unreasonably small (note that $\Delta t_b \propto \varepsilon_y$ in this case, leading to 1ns spacing for $\varepsilon_y = 5\cdot10^{-9}$m). It is possible to distribute the bunch train over more than one ring, but this does not solve the problem unless one wants to accept 10 or more rings built on top of each other. The alternative is to increase the energy. The problem arising then is to maintain the horizontal emittance: for a given lattice, the emittance contribution from the dogbone arcs scales like $\varepsilon_{x,arc} \propto \gamma_{DR}^{6}$ as long as the damping is essentially determined by the wigglers[1]. The dogbone design has an emittance contribution from the arcs of 20% of the design value of the horizontal emittance at 3.2GeV. Allowing this contribution to go up to 50% (by reducing the emittance generated in the wigglers with lower field $B_W$ or stronger focusing; note that the wiggler contribution to $\varepsilon_x$ is energy independent for constant $B_W$), makes it possible to increase the energy somewhat, but by far not as much as required by the scaling ($\gamma_{DR} \propto \varepsilon_y^{-3/8}$). Limiting the emittance contribution from the arc at much higher beam energy is only possible by changing the lattice. If the FODO structure is kept, it is easy to show that there is no reasonable solution for an energy increase by a factor of about four ( $\approx 50^{3/8}$ ). Reducing the bend angle per cell at constant cell length, thus increasing the bending radius ρ and decreasing the dispersion, leads to $\varepsilon_{x,arc} \propto \gamma_{DR}^{6}/\rho^{4}$ and requires several km long arcs. Reducing the cell length $L_c$ with unchanged bending radius but much tighter focussing leads to $\varepsilon_{x,arc} \propto \gamma_{DR}^{6} \cdot L_c^{3}$ and requires about 800 cells in each of the two arcs. This is hardly a practical solution and the required extremely strong sextupoles would not leave sufficient dynamic aperture. It can not be excluded that with a different lattice type in the arcs the situation can be improved and a compromise solution compatible with the extremely unfavorable scaling (a.1) can be found, which incorporates a combination of using a small (2…4) number of shorter rings operating at moderately higher energy. This needs to be studied, as well as possibilities to choose a damping ring concept different from the dogbone design.

It is interesting in this context to re-consider the 6.3km circular ring originally proposed as a damping ring for TESLA [11]. This concept is based on the HERA electron ring. It was not investigated in more detail in the past, because of the limitation on the maximum number of bunches for this ring length, but this limitation can be overcome by building more than one ring. Using the existing HERA e-ring lattice, scaled to a phase advance of 90° per arc cell, the required horizontal emittance of $\varepsilon_x = 1.2 \cdot 10^{-5}$ m and damping time of $\tau_{x,y} = 30$ms can be achieved at an operation energy of 12GeV with ~40m of wigglers. Due to the high beam energy, the space charge tune shift limitation would be practically eliminated. According to HERA-e beam optics studies [12], the dynamic aperture would be more than sufficient (normalised acceptance > 0.1m). One disadvantage of the HERA-ring solution is that the options for e/p collisions and for the electron stretcher ring (see appendix B in ref [1]) would likely be ruled out, if the HERA tunnel has to accommodate several damping rings.

If the bunch length can be maintained at the present value of 9mm (cases (a.2) and (b)), the space charge limitation is a less significant problem. For case (a.2) the required scaling is $\gamma_{DR} \propto \varepsilon_y^{-1/8}$ or $C_{DR} \propto \varepsilon_y^{1/4}$. Thus a somewhat shorter ring (say, by a factor 1.2…1.5) together with a slightly higher energy would be sufficient. There is no need for a major change of the present damping ring concept. The issue of squeezing $\sigma_z$ is, of course, shifted to the bunch compressor system (see below). For case (b) the scaling is stronger, $\gamma_{DR} \propto \varepsilon_y^{-3/16}$ or $C_{DR} \propto \varepsilon_y^{3/8}$ and must be accompanied by a reduction of the horizontal emittance, $\varepsilon_x \propto \varepsilon_y^{1/4}$. There are good chances that a solution for the dogbone ring with modified arc lattice can be found, which satisfies the boundary

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[1] If the emittance of the beam injected into the ring is unchanged, the damping time has to be decrease logarithmically with the required vertical emittance at ejection. This weak dependence is neglected here, but must not be forgotten for the final layout of the damping ring.

conditions, especially if the beam is distributed to two shorter rings (see also section 6).

So far it has not been discussed how the smaller vertical emittance could actually be obtained in the ring. A fundamental limit is due the opening angle of the synchrotron radiation and is given approximately by (see e.g. [13]):

$$\varepsilon_{y,\min} \approx 0.5\left\langle \beta_y \right\rangle \frac{\sigma_{E,DR}^2}{\gamma_{DR}} \tag{11}$$

For the present layout of the dogbone ring with $\langle\beta_y\rangle = 10$m in the wigglers this yields $\varepsilon_{y,\min} \approx 10^{-9}$m. It could even be further reduced by tighter focusing in the wiggler sections, but in practice the lower limit on $\varepsilon_y$ will rather be determined by vertical orbit errors and betatron coupling.

One method to reduce the spurious vertical dispersion is to improve the effective alignment of the magnets and BPM's with beam-based procedures. In the HERA electron ring this has been successfully demonstrated using the "shunt" technique [14]. An improvement of the vertical emittance by an order of magnitude is realistic with this method, according to computer simulation results for the dogbone ring. In addition, orbit bumps can be used to correct the residual dispersion empirically (by minimising the vertical beam size). The betatron coupling can be compensated with skew quadrupoles. These points need careful investigation to determine the "practical" limit on the vertical emittance. The stability of the emittance in the presence of orbit drift caused by ground motion is another important issue in this context. For the dogbone ring an emittance dilution of $\Delta\varepsilon_y/\Delta t \approx 10^{-11}$ m/s has been estimated with an ATL ground motion model, assuming $A=4\cdot10^{-6}$ $\mu$m$^2$/m/s. Keeping $\Delta\varepsilon_y < 10^{-9}$ m requires orbit steering about once per minute, which seems realistic. This estimate has to be updated, if the ring lattice is modified.

Beam-gas and intra-beam scattering, not a serious problem for the reference design, can become significant at lower emittance. A vacuum pressure below $10^{-10}$ mbar seems necessary to avoid emittance growth of the core of the beam if $\varepsilon_y$ is 50 times lower. It remains to be shown whether this requirement is also sufficient to avoid emittance growth from the fast beam-ion instability [15] in the electron ring.

The intrabeam scattering growth rates can only be investigated in detail once the modifications of the ring lattice are better defined. A rough estimate shows that as long as the average $\beta$-functions in the ring do not change much, the dependence on the vertical emittance is weak for all three cases considered, assuming that $\gamma_{DR}$ is scaled to keep the incoherent tune shift constant according to eq. (10). One has to be careful, though, with estimating the vertical growth rate once the temperature is comparable to or smaller than the longitudinal one.

No matter which parameter scaling is applied, it will be difficult to reduce or even keep constant the longitudinal emittance $\varepsilon_z = \gamma_{DR}\sigma_{E,DR}\sigma_{z,DR}$ in the damping ring. For a given magnetic field $B_W$ in the wiggler, $\sigma_{E,DR} \propto \gamma_{DR}^{1/2}$ and thus $\varepsilon_z \propto \gamma_{DR}^{3/2}\sigma_{z,DR}$. Reducing the wiggler field yields an improvement, since $\sigma_E \propto B_W^{1/2}$, but the wiggler length $L_W$ must scale like $1/(\gamma_{DR}B_W^2)$ for constant damping time. Assuming a constant $L_W$ allows to scale the wiggler field as $B_W \propto \gamma_{DR}^{-1/2}\, C_{DR}^{1/2}$. The resulting incoherent energy spread at the end of the linac, scaled from the present value of $\sigma_{E,\text{incoh}} = 1.4\%\cdot(3.2\text{GeV}/250\text{GeV}) = 1.8\cdot10^{-4}$, is summarised in Table 3 for the different cases and for the possibilities of either shortening the ring or increasing the energy (a compromise between these two basic ring modifications is obviously also possible and in practice likely to lead to the best solution).

| Scaling | $\sigma_E$ ($C_{DR}$ const.) | $E_{DR}$ [GeV] | $\sigma_E$ ($\gamma_{DR}$ const.) | $C_{DR}$ [km] |
|---|---|---|---|---|
| (a.1) | $1.1\cdot10^{-3}$ | 13.9 | (not practical) | (0.9) |
| (a.2) | $2.3\cdot10^{-3}$ | 5.2 | $9.9\cdot10^{-4}$ | 6.4 |
| (b) | $4.5\cdot10^{-4}$ | 6.7 | $1.3\cdot10^{-4}$ | 3.9 |

**Table 3:** Incoherent energy spread at the end of the 250 GeV linac for the different cases of parameter scaling and for the scenarios where either the damping ring energy or the circumference is scaled according to eq. (9). A vertical emittance of $5\cdot10^{-9}$ is assumed in the damping ring. The total length of the wigglers is kept constant (at 388m as in the reference design) and the wiggler field is scaled to maintain an unchanged damping time (33ms).

Issues concerning collective instabilities in the damping ring have only been investigated at a rather preliminary level so far. The number of RF-cavities, one of the major contributions to the ring impedance, has to be increased with beam energy, but also goes down when the ring is shortened. So, depending on the compromise solution eventually chosen, the ring impedance does not necessarily go up, whereas a higher energy is beneficial for the beam stability. In case of a shorter bunch, accompanied with a smaller momentum compaction factor and a lower synchrotron tune, the longitudinal single bunch stability must be carefully studied. The reduced bunch charge will be an advantage here.

### Bunch Compressor

The impact on the bunch compressor system has several aspects. Cases (a.1) and (b) allow to maintain a one-stage compressor concept, with the same compression ratio as in the present design (about 13). However, the compressor may have to be operated at a higher beam energy and, for case (a.1), the bunches extracted from the damping ring are already shorter ($\propto \varepsilon_y^{1/2}$). In this latter case, using TESLA L-band cavities for the compressor RF-system would require a very significant increase of the voltage ($U_{RF}$ = 200MV for the reference design), given by $U_{RF} \propto \gamma_{DR}\sigma_{E,DR} / \sigma_z$. This leads to $U_{RF}$ = 7GeV for the worst case of scaling the energy to 13.9GeV (Table 3). A better solution may be to use a higher harmonic RF-system, e.g. at 3.9GHz. For case (b) the situation is less critical, one has to raise the voltage $U_{RF} \propto \gamma_{DR}\sigma_{E,DR} \propto \gamma_{DR}^{3/2}$. A higher beam energy has the additional disadvantage that the compressor magnet lattice has to be increased in length in order to limit emittance dilution from synchrotron radiation. The tolerances required to preserve the vertical emittance will be tighter by roughly an order of magnitude.

For case (a.2) a 2nd compressor stage is unavoidable. It has to provide further compression by up to a factor of 7 ($\propto \varepsilon_y^{-1/2}$). Therefore it has to be operated at an energy at least higher by the same factor than the damping ring energy, which means at 35...40GeV in the worst case. This does not seem practical (note that the 2nd stage bunch compressor for the NLC operates at 10GeV [16]). Furthermore, this first section of the TESLA linac would have to run far off-crest (up to about 40°) to supply the required correlated energy spread.

## 5. Beam Delivery System

In the present version, the TESLA beam delivery system, laid out for a maximum beam energy of 400GeV, is relatively short, about 1.1km per beam. The main reasons are the comparatively large β-functions at the IP (0.7mm in the vertical plane, which is a factor of 7 larger than what has been demonstrated at the FFTB) and the relaxed collimation requirements thanks to the large final quadrupole aperture. With smaller β-functions ($\beta_y \propto \varepsilon_y^{1/2}$ for case (a) and $\beta_x \propto \varepsilon_y^{1/4}$ for case (b)) these advantages are lost to a certain extend. In the most extreme case (scaling (a), $\varepsilon_y = 5 \cdot 10^{-9}$m) the vertical β-function is equal to the design value for the X-band version of a linear collider [16,17]. One may thus conclude that the respective Final Focus System design could be adopted, however scaled down in length because of the smaller maximum beam energy (400GeV instead of 750GeV). Still some additional tunnel length (a few hundred meters) has to be reserved to accommodate this upgrade. Orbit jitter will still be removed by the fast orbit feedback, which does not have to be modified conceptually, but needs a better resolution of the orbit pickups and must cope with a smaller bunch spacing[2]. Alignment tolerances have to be tighter because of the smaller spot size and, for case (b), also because of the larger beam energy spread. This needs to be studied in detail once a modified delivery system has been set up, but an approximate scaling can be easily derived. Assuming that spurious vertical dispersion is the dominant effect diluting the spot size, the tolerable alignment errors scale roughly as $(\varepsilon_y\beta_y)^{1/2}/\sigma_E$. Compared to the reference design, this factor varies between 0.02 and 0.14 (depending on the parameter scaling) if we go down in emittance by a factor of 50. Based on the diffusive ground motion model calculations for the standard parameters (with *A* as given above), the time scale on which orbit correction has to be applied to limit the luminosity reduction to less than 10% can also be predicted. The result is that in the worst case one-to-one correction would have to be applied about every 100ms and about every 6s for the most advantageous case (the application of the ATL-rule to estimate ground motion effects may be questionable on this time scale). Whereas the latter requirement can be met by a pulse-to-pulse based slow feedback, the most extreme case requires several additional fast feedback systems to be integrated at strategic positions in the beam delivery lattice.

The impact on the collimation system is threefold. The mechanical stress limit in the spoilers is reached faster with reduced beam cross section, the collimator gaps must be smaller with lower $\beta_y$ and/or $\beta_x$ at the IP and emittance dilution from wakefields becomes more critical. The first point seems to rule out Titanium as the spoiler material, unless the beam optics in the collimation section are drastically modified (the possibility of adding a non-linear "beam size spoiler" is presently under study). Graphite spoilers would still be able to withstand a sufficiently long fraction of the beam pulse, before the safety dump system can be triggered. In this case, coating with a good conductor (Cu, Au) is indispensable to keep the resistive wall wakefield within limits. Provided that this is possible, with the existing collimation system layout an emittance dilution of $\Delta\varepsilon_y/\varepsilon_y \approx 10\%$ is calculated for a one sigma orbit offset at the spoiler under worst case (scaling (a)) conditions. Since the system can be re-

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[2] Note that the bunch spacing will remain above 200ns, which is still sufficient to keep the head-on collision geometry with electrostatic separators.

optimised (taper length of spoilers, larger β-function), the expected emittance dilution would be tolerable.

## 6. Compromise Upgrade Scenario

The above discussion shows that on the way to push the TESLA luminosity to its limits, a number of open questions concerning the layout of certain collider subsystems arise. It is difficult at this stage to give a clear direction for optimising the TESLA-500 design for ultimate luminosity. Furthermore, several important points (e.g. instrumentation required to measure and stabilise the beam size in the beam delivery system, including the IP, longitudinal wakefields in the beam delivery vacuum system [18], ion- and photoelectron-trapping problems, etc.) have not been addressed in this note.

The investigated scaling rules for the damping ring and bunch compressor systems indicate that it would be very difficult to achieve a bunch length reduction which allows to keep the disruption parameter below ~20 when the vertical emittance is to be decreased by an ambitious factor of 50. It seems reasonable that one has to make a compromise between the scalings (a) and (b). Even then, the implications for the injection system are serious. One should also keep in mind that some of the required modifications have to be incorporated already for the 1st stage of TESLA, when one would operate with less ambitious parameters. This affects, for instance, the length of the beam delivery system, the space which must be foreseen for the bunch compressor and the basic concept for the damping rings.

In order to make a specific suggestion on how the present TESLA design could be modified as a guideline for further studies, I would like to present a compromise solution for a luminosity upgrade in three steps (Stages I, II and III, with parameters as summarised in Table 4). It is based on the following assumptions:

- An increase of the overall linac fill factor from 66% to 76%. This allows to lower the gradient to 21.7MV/m, at $Q_0=10^{10}$. The potential gain in average beam power is about 37% (at constant repetition rate and AC-power) from higher beam pulse current and longer flat-top because of the reduced cavity filling time. Provided that this modification of the linac is technically feasible, the resulting gain in luminosity is available already at the initial stage of operation. This modified version of TESLA, without change of the spot size at the IP, will be called "Stage-I" in the following and is supposed to eventually replace the original reference design.

- Shortening the damping ring by a factor of two and increasing the energy. The dogbone layout is maintained, but with a modified lattice: the number of FODO cells in the arcs is increased (at constant cell length) and the field strength of the wigglers is reduced. The demand for the kicker pulse width is close to what we presently consider feasible already for Stage-I of operation. If a faster kicker kicker system turns out impractical for later upgrades with reduced bunch spacing (Stages II and III), there remains the possibility to build a second ring on top of the first one. Except for the reduced bunch spacing, the shorter ring has advantages already for Stage-I. The costs for the wigglers, the RF-system and the straight section magnet and vacuum systems are reduced, which overcompensates the increase in cost for the somewhat longer arcs. The total chromaticity from the straight sections is lower and its compensation is distributed over a larger number of arc cells, which also contribute less chromaticity because of the lower phase advance per cell. The new ring concept provides a sufficient flexibility to allow for an upgrade path with a vertical emittance reduced by an order of magnitude (Stage-II), and, pushing the parameters to the limit, by another factor of 4 (Stage-III). Of course, the consequences of tightening the focusing for stages II and III for the dynamic aperture and for the alignment tolerances required to achieve the small emittance still need to be studied in detail. It would also be instructive to re-investigate the circular ring solution for the damping ring and to compare its properties to the one of the dogbone approach.

- A single stage bunch compressor is foreseen, however with increasing demand for the compression ratio (up to a factor of 20) in going from TESLA Stage-I to Stage-III and operating at higher beam energy than in the reference design. The necessary modifications of the compressor layout have to be investigated.

- The beam delivery system has to be modified such that it can accommodate a reduction in the β-functions at the IP by a factor of two horizontally and 2.3 vertically. It should be noted that the demand for the system from the point of view of beam optics (β-functions, momentum acceptance) still remains less ambitious than for the systems designed for the X-band versions of a Linear Collider [16,17].

## 7. Conclusion

The above considerations are clearly not sufficient to draw a final conclusion on the TESLA luminosity potential. However, a reasonable upgrade path for the machine performance can be defined already with this rather preliminary analysis.

It can be seen from Table 4 that at Stage-II the spot size at the IP would be similar to the one foreseen for 500GeV X-Band designs, but with TESLA being capable of providing a 3...4 times higher luminosity. With the ultimate upgrade of Stage-III, the luminosity advantage would amount to almost an order of magnitude. For this case, even a further upgrade with the Travelling Focus concept is conceivable, which may raise the achievable luminosity close to the $10^{35}cm^{-2}s^{-1}$ level.

| | **ref. design** | **Stage-I** | **Stage-II** | **Stage-III** |
|---|---|---|---|---|
| **General Parameters** | | | | |
| # of bunches p.p. | 1130 | 1410 | 2820 | 4028 |
| pulse length [$\mu$s] | 800 | 950 | 950 | 950 |
| bunch spacing $\Delta t_b$ [ns] | 708 | 674 | 337 | 236 |
| bunch charge $N_e$ [$10^{10}$] | 3.63 | 4.0 | 2.0 | 1.4 |
| pulse current [mA] | 8.2 | 9.5 | 9.5 | 9.5 |
| av. beam power [MW] | 8.3 | 9.5 | 9.5 | 9.5 |
| emittance at IP $\varepsilon_{x,y}$ [$10^{-6}$ m] | 14, 0.25 | 14, 0.25 | 10, 0.03 | 8, 0.0075 |
| $\beta_{x,y}$ at IP [mm] | 25, 0.7 | 25, 0.7 | 15, 0.4 | 12.7, 0.3 |
| spot size at IP $\sigma_{x,y}$ [nm] | 845, 19 | 845, 19 | 558, 5 | 459, 2.1 |
| bunch length at IP $\sigma_z$ [mm] | 0.7 | 0.7 | 0.4 | 0.3 |
| beamstrahlung $\delta_B$ [%] | 2.5 | 3.0 | 3.0 | 3.0 |
| vert. Disruption $D_y$ | 18 | 20 | 33 | 50 |
| luminosity [$10^{34}$ cm$^{-2}$ s$^{-1}$] | 0.6 | 0.9 | 2.6 | 5.2 |
| **Damping Ring** | | | | |
| energy $E_{DR}$ [GeV] | 3.2 | 3.9 | 3.9 | 4.3 |
| circumference $C_{DR}$ [km] | 17 | 8.5 | 8.5 | 8.5 |
| arc radius [m] | 60 | 85 | 85 | 85 |
| arc FODO cell phase advance $\Phi_c$ [deg.] | 90 | 60 | 75 | 108 |
| wiggler length [m] | 388 | 350 | 350 | 350 |
| wiggler field $B_W$ [T] | 1.5 | 1.06 | 1.06 | 1.06 |
| transverse damping time [ms] | 33.8 | 31 | 31 | 28 |
| RF voltage [MV] | 25 | 16 | 16 | 19 |
| emittance at extraction $\varepsilon_{x,y,DR}$ [$10^{-6}$ m] | 12, 0.2 | 12, 0.2 | 8, 0.02 | 6, 0.005 |
| energy spread $\sigma_{E,DR}$ [$10^{-3}$] | 1.0 | 0.093 | 0.093 | 0.097 |
| bunch length $\sigma_{z,DR}$ [mm] | 9.5 | 9 | 6 | 6 |
| incoh. space charge $\Delta Q_{incoh}$ | 0.18 | 0.07 | 0.20 | 0.27 |
| bunch compression ratio | 13.3 | 12.7 | 15 | 20 |
| compressor RF voltage [MV] (at 1.3 GHz) | 200 | 220 | 400 | 600 |

**Table 4:** Proposed modified TESLA-500 parameters for higher luminosity in comparison with the reference design. The values for the beamstrahlung and for the luminosity quoted are scaled numbers, which need to be confirmed by beam-beam simulations (a constant pinch enhancement factor has been assumed for all versions). Some of the damping ring parameters have been obtained from scaling of basic lattice properties. More precise values must be determined from a detailed design study.

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