A Large Aperture Final Focus System for TESLA

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Abstract

An alternative set of beam parameters at the IP is presented for TESLA. Thanks to a larger aspect ratio, it allows a substantial reduction of the beamstrahlung effect. The optics of a final focus system based on the standard sextupole correction of the chromatic aberrations is described. The particularity of this system is, along with the 3 m long last drift space, the large aperture of the last quadrupoles, possibly superconducting, which permits the clearance of the disrupted beams and beamstrahlung photons. Due to the large bunch separation in TESLA, head-on collisions are therefore possible with this system. Its energy acceptance and misalignment tolerances are analyzed.

I. BEAM PARAMETERS

The beam sizes at the interaction point (IP) usually proposed [1] for the 500 GeV center of mass energy, high current option of TESLA, with $N = 5.\,10^{10}$ particles per bunch and 800 bunches per 10Hz pulse, are

$$\sigma_x^* = 640\,\mathrm{nm}\ ,\ \sigma_y^* = 100\,\mathrm{nm}\ \text{ and }\ \sigma_z = 1\,\mathrm{mm}, \qquad (1)$$

yielding the Gaussian luminosity $\mathcal{L} = 2.5\,10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. Given the normalized emittances considered in the TESLA linac, namely

$$\epsilon_{n,x} = 20.10^{-6}\,\mathrm{m.rad}\ ,\ \epsilon_{n,y} = 10^{-6}\,\mathrm{m.rad}\ , \qquad (2)$$

these beam sizes are achieved with $\beta_x^* = 10$ mm and $\beta_y^* = 5\,\mathrm{mm}$. These parameters are rather conservative as far as the aspect ratio $R = \sigma_x^*/\sigma_y^* = 6.4$ is concerned. A much flatter beam at the IP can be easily produced by the final focus optics. The limit on the large aspect ratio arises from 3 constraints:

1. the "hour-glass" luminosity reduction imposes $\beta_y^* > \sigma_z$.
2. the spot sizes at the IP are limited by the emittance growth due to synchrotron radiation in the last quadrupoles ("Oide effect"). For the optics described in the next section and the normalized emittances given above, this limit is around 35 nm for the vertical spot size, and 400 nm for the horizontal one.
3. the disruption parameter must be small enough to prevent a kink instability from occurring when the two beams collide with a vertical offset.

The beam spot sizes

$$\sigma_x^* = 1000\,\mathrm{nm}\ \text{ and }\ \sigma_y^* = 64\,\mathrm{nm}\ , \qquad (3)$$

corresponding to $\beta_x^* = 24.5$ mm and $\beta_y^* = 2$ mm, lead to the same Gaussian luminosity with an aspect ratio $R = 15.6$. This parameter set obviously fulfills the first two constraints and the vertical disruption parameter only increases from 8.0 to 8.7. In order to check the third constraint, a plot of the luminosity as a function of the vertical offset as calculated with the program RBEAM [2] is shown in Figure 1. The observed reduction

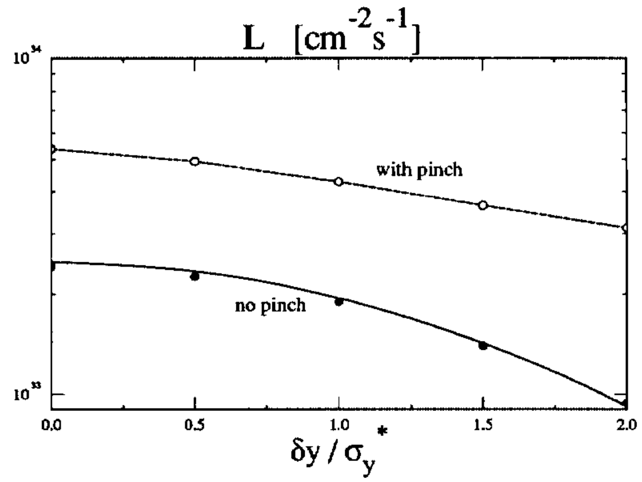

Figure 1 Luminosity vs. vertical offset (full and empty circles are results from RBEAM, the full curve is the analytic prediction)

is not faster than predicted analytically when the beam-beam forces are neglected (full curve). This expected behaviour strongly suggests that the kink instability does not show up, even for the flat beam parameters.

The beneficial effect expected on the beamstrahlung reduction from the large aspect ratio is illustrated in Figure 2 and in Table 1. The integral of the differential luminosity $\int_s^{s_{max}} (d\mathcal{L}/ds')ds'$, calculated with RBEAM, is plotted in Figure 2. It is higher for $R = 15.6$ than for $R = 6.4$ as long as the c.m. energy is larger than 95% of the maximum energy. This is true even though the total luminosity is about a

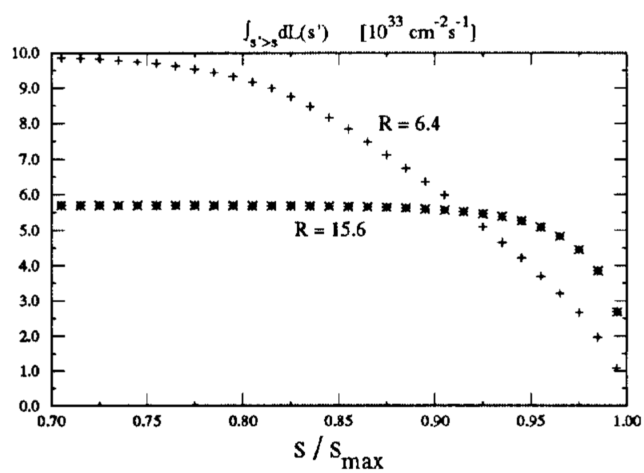

Figure 2 Integrated differential luminosity spectrum for TESLA

factor 2 larger for $R = 6.4$ due to a larger pinch enhancement factor. The average relative c.m. energy loss, calculated from these luminosity spectra, is equal to 1.0% in the flat beam case and 4.6% in the other case, showing a substantial improvement in the energy resolution of the collisions. This is in agreement with the results, given in Table 1, of the comparison of 3 different beam-beam simulation programs [3] for the $e^+e^-, e\gamma$ and $\gamma\gamma$ luminosities and for the average relative energy loss ("beamstrahlung parameter"). Although slightly different, the

R	Program	$\mathcal{L}_{ee}$	$\mathcal{L}_{e\gamma}$	$\mathcal{L}_{\gamma\gamma}$	δ
6.4	MACPAR	11.7	19	43	9.3%
	ABEL	13.7	23	57	9.5%
	RBEAM	13.2			7.8%
15.6	MACPAR	8.0	7.2	8.8	3.0%
	ABEL	8.8	7.9	9.3	2.9%
	RBEAM	7.3			1.9%

Table 1 Luminosity per crossing (in units of $10^{29}\mathrm{cm}^{-2}$) and beamstrahlung parameter for two sets of TESLA parameters

results derived from the 3 programs are consistent in showing that the flat beam parameters lead to a significant reduction of the beamstrahlung photon emission and background. Accordingly, and as a last comparison between the two parameter sets, the quadratic average of the beam disruption angle drops from $520\,\mu$rad to $270\,\mu$rad for the flat beam case.

II. THE LARGE APERTURE OPTICS

A final focus system (FFS) is essentially a low-beta telescopic system transfering the beam from the end of the collimation section after the linac, to the IP. The strong chromaticity of the last focusing doublet is corrected, in the standard way [4], by placing sextupole pairs into a region where non-zero dispersion is created by bending magnets. The system described here derives from the CLIC FFS design [5], adapted and optimized for the flat beam parameters introduced in the preceding section. A system optimized for the other parameter set would have very similar characteristics.

A. General description

We assume upright beam ellipses with $\beta_x = 113.4\,$m and $\beta_y = 19.5\,$m at the entrance of the FFS, corresponding to a 250 GeV beam exiting from a 90°constant beta FODO lattice with 24 TESLA superconducting cavities per half-cell [6]. The total demagnifications to achieve with the FFS are therefore 68.0 horizontally and 98.7 vertically. The lattice of the FFS, displayed in Figure 3, contains 3 modules:

1. a matching telescope of 8.5×5.8 demagnifications.
2. a chromatic correction section (CCS) containing two pairs of identical sextupoles, all separated by π phase-shift. The first pair, correcting the horizontal chromaticity, is located at the maxima of β_x (full line), and the second pair, for the vertical correction, is located at the maxima of β_y (dashed line).
3. a final telescope of 8×17 demagnifications.

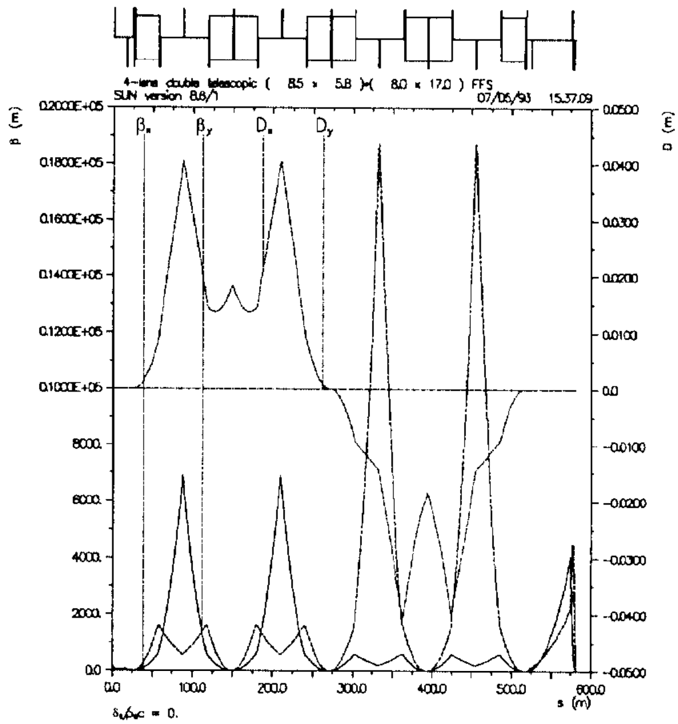

Figure 3 Lattice layout and orbit functions of the final focus sytem

The total length of the system is less than 600 m. The matching of the imperfect vertical and horizontal beam ellipses from the linac can be done at the first sextupole by using the 4 quadrupoles of the matching telescope and the first 2 quadrupoles of the CCS. The dispersion in the CCS is created by 8 identical 29 m long dipoles. The dipole field is 170 Gauss and the synchrotron power deposited by the beam is negligible. The final telescope is composed of a weak and a strong doublet separated by 50 m. The length of the final drift space before the IP is 3 m.

B. The energy acceptance

Dividing the total demagnifications between the matching and the final telescopes is done in such a way as to maximize the energy acceptance of the FFS. This acceptance can be estimated by calculating with MAD [7], the dependence of β_x^* and β_y^* on the energy offset δ. The bandwith of the system, defined as the doubling of the beta-functions, is $\pm1.1\%$. The energy acceptance can also be characterized, as in Figure 4, by the dependence of the spot sizes and luminosity on the Gaussian energy spread σ_δ of the beams.

C. The aperture of the last doublet

The integrated gradient of the quadrupoles of the last doublet are inversely proportional to their focal length. For a 3 m long last drift, the gradient can be as low as 300 T/m. In our design, the two quads then have a length of 1.2 m and 1.7 m, and are separated by 30 cm. This gradient can be obtained with 1.4 T pole-tip field permanent magnets of about 1 cm aperture. It also opens the possibility of using superconducting quadrupoles with an aperture of the order of 3.5 cm. For the flat beam parameters, these apertures are very large compared to the 407 μm horizontal and 110 μm vertical 1–σ maximum extension of the incoming beams. A 10–σ beam collimation could therefore be contemplated. Moreover, beamstrahlung simulations [3,8] indicate that the maximum angle of the outgoing disrupted electrons and emitted photons, are about 0.5 mrad and 1.1 mrad. Hence, even with an aperture of 1 cm, the central region of the opposing last doublet could clear the disrupted beams and no photon would hit the quadrupole face on the detector side. As a consequence head-on collisions, i.e. with zero crossing-angle, seem feasible with this large aperture optics. All these aspects must, however, be carefully studied by tracking simulations.

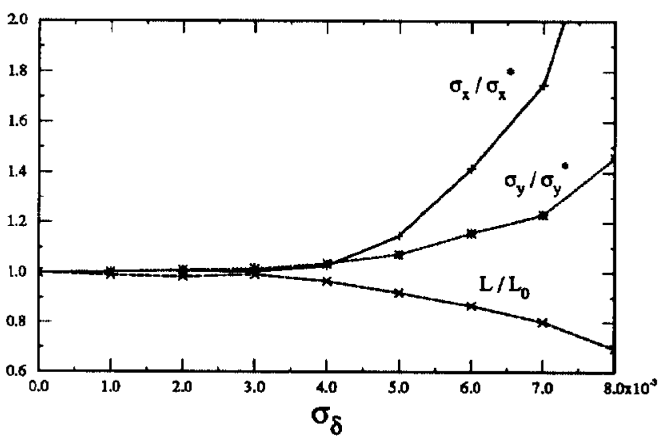

Figure 4 Energy acceptance of the final focus sytem

D. Separation of the beams

At zero crossing-angle it is necessary to separate the bunches in order to avoid unwanted collisions. The bunch spacing is foreseen to be 300 m (1 μs) in TESLA, and separation may thus easily take place in the 50 m free space after the last doublet. A 250 KV electrostatic voltage over a 4 cm gap, compensated by a magnetic field to keep the trajectory of the incoming bunch straight, induces a transverse separation of 6 cm with a deflection angle of 2.5 mrad after 50 m. This should allow to further deflect the outgoing beam by using a septum magnet.

III. ALIGNMENT TOLERANCES

In order to investigate the sensitivity of this beam line to misalignments, we first consider the loss of luminosity resulting from ground vibrations affecting all magnets *on both sides of the* IP, except the last doublets which are then treated separately. Luminosities are calculated from the beam distributions at the IP and the pinch enhancement is not taken into account.

Assuming uncorrected (jitter) and uncorrelated vibrations of identical amplitudes $\sigma_{\delta x}$ and $\sigma_{\delta y}$, the luminosity loss induced by each element adds up quadratically, to yield

$$\mathcal{L} = \mathcal{L}_0\left(1 - 0.64(\sigma_{\delta x}/\sigma_x^*)^2 - 0.13\left(\sigma_{\delta y}/\sigma_y^*\right)^2\right) . \quad (4)$$

Hence, a 10% luminosity loss corresponds to vertical vibrations of around 56 nm rms.

The issue of the alignment of the last doublet quadrupoles is of course critical, especially in the case of SC quadrupoles envisaged above. Most probably the two opposing doublets will have a common support to ensure the best possible alignment of the 4 quadrupoles relative to each other. Neglecting the weak sensitivity to the absolute displacement of the two doublets (i.e. that of the common support), the luminosity is found to depend only on the relative misalignments of the opposing focusing quadrupoles $\Delta x_{\mathrm{F}} = (\delta x_{\mathrm{F}}^+ - \delta x_{\mathrm{F}}^-)$ and $\Delta y_{\mathrm{F}} = (\delta y_{\mathrm{F}}^+ - \delta y_{\mathrm{F}}^-)$ on the one hand, and of the opposing defocusing quadrupoles $\Delta x_{\mathrm{D}} = (\delta x_{\mathrm{D}}^+ - \delta x_{\mathrm{D}}^-)$ and $\Delta y_{\mathrm{D}} = (\delta y_{\mathrm{D}}^+ - \delta y_{\mathrm{D}}^-)$ on the other. For small displacements the luminosity loss is given by

$$\begin{aligned}\delta\mathcal{L}/\mathcal{L}_0 = {} & 3.8(\Delta x_{\mathrm{F}}/\sigma_x^*)^2 + 1.9(\Delta x_{\mathrm{D}}/\sigma_x^*)^2 - 5.3\Delta x_{\mathrm{F}}\Delta x_{\mathrm{D}}/\sigma_x^{*2} \\ & + 0.22(\Delta y_{\mathrm{F}}/\sigma_y^*)^2 + 0.94(\Delta y_{\mathrm{D}}/\sigma_y^*)^2 - 0.91\Delta y_{\mathrm{F}}\Delta y_{\mathrm{D}}/\sigma_y^{*2} . \end{aligned} \quad (5)$$

Finally, let us point out that one might obtain better tolerances by trying different optimizations of the FFS and compromising on the momentum bandwidth.

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