Final Focus System with Superconducting Magnets in the Interaction Region of the TESLA Linear Collider

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Abstract

The TESLA final focus system is presented for a center of mass energy of 500 GeV. The effect of magnets misalignment and field errors is analyzed for this system using the recently available program FFADA. A design for the last doublet superconducting quadrupoles, based on the LHC quadrupoles, is proposed. Tolerances to higher multipole components in the last doublet have been analyzed as well as the effect of the detector solenoid.

1 INTRODUCTION

The basic idea of the TESLA design for 500 GeVcenter of mass energy is that the high luminosity is obtained with moderate beam spot sizes, $1\mu\mathrm{m}\times 64\mathrm{nm}$, at the interaction point (IP), as compared with other linear collider designs, and with a very high beam current. Hence the beta-functions at the IP are larger than in any other designs. This, together with the expected relative energy definition of the beam, eases the design of the final focus optics. This advantage is balanced by the difficulty to clear the spent beam power and the secondary background (synchrotron radiation and beamstrahlung photons, e^+-e^- pairs and hadronic jets). It is also used to offer a 6 meter long free space around the IP to design the detector and the interaction region (IR).

Another specific property of TESLA is the large $1\mu s$ separation of the bunches. It offers the possibility to collide the beams head-on and to separate them outside of the detector. In order to clear all the debris of the collision on axis through the IR, it is necessary to use superconducting magnets with a large enough aperture and gradient. If iron-free, these magnets need not be shielded by compensating solenoids to operate in the field of the detector solenoid. This allows a significant reduction in transverse dimension and weigth of the last doublets.

We present a version of the TESLA final focus system (FFS) adapted to the latest set of beam parameters for 500 GeVcenter of mass energy. This new version obeys the same general principles as the preceding one [1] but has been reduced in length down to 370 m. The total bandwidth of the order of 1.8% has been obtained by optimizing the beam demagnifications achieved in the first and final telescopes. The properties of this new system have been investigated by using the program FFADA [2]. In particular, the beam collimation requirements are calculated, the effect of magnet misalignment and field errors are analyzed and tolerances derived. A design for the superconducting magnets of the last doublet is proposed. It is based on the LHC magnet prototypes [3] which recently achieved 250 T/m with a physical aperture diameter of 48 mm [4]. Their higher multipole components are tolerable and a superimposed detector solenoid field requires a skew-quad correction.

2 BEAM AND OPTICS PARAMETERS

The beam parameters for the 500 GeVcm energy version of TESLA are as follows :

Energy	[GeV]	:	250.
Horizontal RMS at the IP	[nm]	:	1000.
Vertical RMS at the IP	[nm]	:	64.
Horizontal normalized emittance	[m]	:	2.0e-5
Vertical normalized emittance	[m]	:	1.0e-6
Longitudinal RMS	[mm]	:	1.0
Bunch population		:	5.0e+10
Repetition rate	[Hz]	:	8.0e+3

With these parameters, the values of the beta-functions at the IP are $\beta_x^* = 24.5$ mm and $\beta_y^* = 2.0$ mm.

The main optics and hardware parameters for the upgraded version of the TESLA FFS are given below :

Total length of the FFS		[m]	:	370.
Total horizontal demagnification			:	68.1
Total vertical demagnification			:	98.6
Parameters of Final Telescope				
Horizontal FT demagnification	XM = -R22		:	8.
Vertical FT demagnification	YM = -R44		:	30.
Length of last drift		[m]	:	3.0
Length of last but one drift		[m]	:	0.35
Polarity of last quadrupole			:	D
Pole-tip field of last doublet quads		[T]	:	6.
Aperture diam. of last doublet quads		[mm]	:	48.

These parameters have been input in the program FFADA [2] to derive the optics of the FFS and analyzed its properties.

3 THE LARGE APERTURE OPTICS

The lattice layout, the beta-functions and the dispersion, calculated with MAD [5], are presented in Fig.1. The momentum bandwidth estimated from the doubling of the beta-functions is ±0.9%. Fig.2 completes the chromatic analysis of the FFS by plotting, from tracking simulation results, the relative dependence of the spot sizes and luminosity on the rms energy spread of bunches with Gaussian energy distributions. It shows that the energy acceptance is limited by the blow-up of the horizontal spot size.

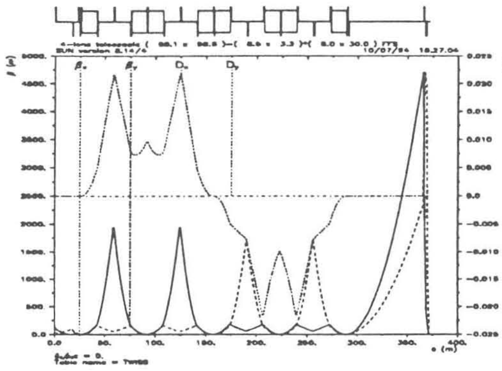


Figure 1: Lattice layout and orbit functions of the FFS.

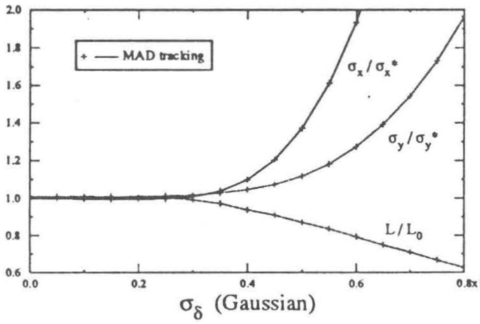


Figure 2: Dependence of the spot sizes and luminosity on the Gaussian rms relative energy spread.

3.1 *Beam collimation*

The main constraint on beam collimation comes from the synchrotron radiation emitted by the incoming beam in the last quadrupole doublet. Requiring that no photon hits the 48 mm circular exit aperture of the opposing doublet leads to the transverse collimation of the beam at $12\sigma_x \times 38\sigma_y$. With these requirements, a 3 cm diameter vertex detector located at the IP is safe from synchrotron radiation.

3.2 *Error analysis and alignment tolerances*

The effect of the 6-D displacements and gradient error of each quadrupole and sextupole of the FFS has been calculated with FFADA [2] in terms of the transverse (position and angular) offsets and dispersions, the longitudinal waist shift, the xy-coupling of the beam at the IP and of the resulting luminosity loss. Figs.3 and 4 show for instance the effect of the transverse displacement of each magnet on the IP beam offset and on the luminosity loss.

The tolerances on the uncorrelated vibrations of both the e$^+$ and e$^-$ FFS magnets, except the last doublets, are 190 nm horizontal and 48 nm vertical rms, for 2% luminosity loss without beam steering correction (fast vibrations). If the beam relative offset at the IP is corrected (slow vibrations), the luminosity loss is dominated by the spot size growth induced by dispersion, and the tolerances go up to 21 μm hor. and 400 nm vert. rms for a beam with 0.1% relative energy spread.

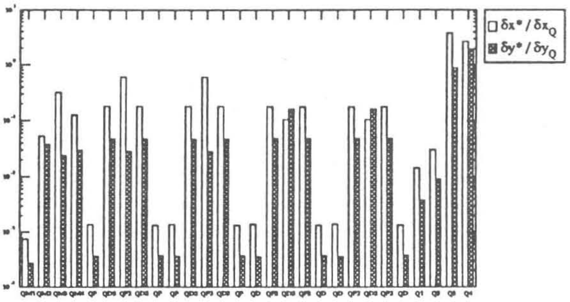


Figure 3: Ratio of IP offset to quadrupole transverse displacement.

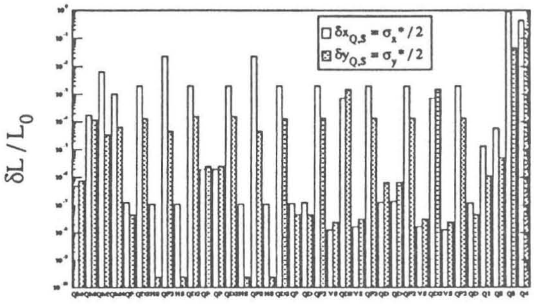


Figure 4: Relative luminosity loss for fixed quadrupole and sextupole displacements.

Tolerances on the transverse displacements of last doublet quadrupoles are essentially unchanged with respect to [1]. Finally, a 2% luminosity loss is induced by the displacement of a common support for the two doublets of about 100 μm horizontally and 20 μm vertically.

4 DESIGN OF THE SC QUADRUPOLE

The required characteristics of the quadrupoles (see Table 1) and the possibility to use superfluid helium lead to consider the prototype of the LHC lattice quadrupole [3] as the basic concept.

Gradient	250 T/m
Inner coil aperture	56 mm
Magnetic length	1.920 m and 1.274 m
Overall current density	560 A/mm^2
Peak field in conductor	7.8 T (Quad alone)
Peak field in conductor	8.4 T (with 3T-Solenoid)
Current	15900 A
inner coil diameter	56 mm
outer coil diameter	108 mm

Table 1: Superconducting Quadrupole Parameters

4.1 *Description*

The cross-section of the quadrupole and cryostat is shown in Fig.5. As compared to the LHC prototype, the iron core is removed to avoid saturation in the 3 T magnetic field of the detector solenoid. Even without the iron core, the transverse stray fields decrease fast enough not to perturb the physics (e.g. $B_y(y=0) = 0.005$ T at $x = 60$ cm).

The conductor is a keystone cable whose bare dimensions are approximately $13.05 \times (1.7 \div 2.16)$. The coils are made of two shells without splice between them. The stainless steel collars are strong enough to cancel the electromagnetic forces. The collaring process consists of setting subsequent pairs of collars in direction perpendicular to each other along the entire coil length. The prestress needed to avoid any motion in the coils during excitation is given by the insertion of eight tapered keys at the outside of the collars. The collared coil is then centered in the helium vessel by mean of four keys. The coil mechanical center is defined by the intersection of the two perpendicular planes of two opposite keys. The helium vessel is a rough tube, machined precisely ($\sim 25\mu$m) to give the correct position of the centering keys. Its thickness is enough to withstand the pressure drop in case of quench and to give the axial rigidity necessary to reduce the magnet sag. Two screens at 4.2 K and 70 K are necessary to intercept the radiations coming from the room temperature vacuum tank. The distances between parts at different temperatures are chosen to be 40 mm. This leads to a weight of about 305 Kg/m.

4.2 *Field Quality*

The magnet harmonic content is parametrized by the coefficients of the relative multipole expansion

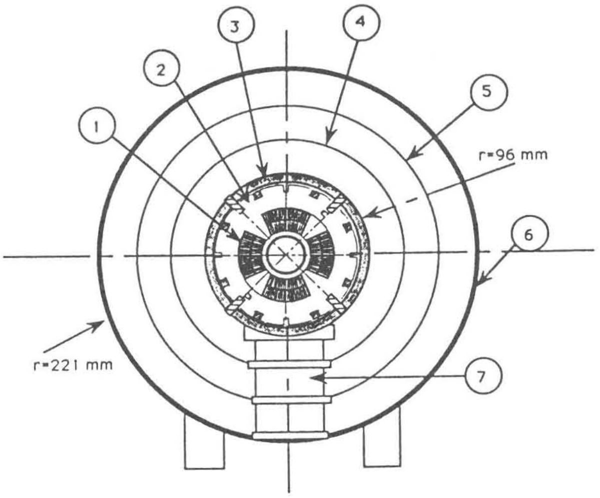
$$B_y + iB_x = B(r_0) \sum_{n \geq 2} (b_n + ia_n)(x + iy/r_0)^{n-1}$$

at the reference radius r_0. The beam spot size at the IP is mostly sensitive to the normal and skew sextupolar coefficients b_3 and a_3. Using $r_0 = 1$ cm, a 2% spot size growth is induced by a sextupole error $a_3 = 6.7 \times 10^{-4}$ or $b_3 = 1.8 \times 10^{-3}$, or over 10^{-2} for the higher multipoles. In practice, all b_n and a_n coefficients can easily be made smaller than 7×10^{-4}.

4.3 *Alternative*

Using Nb_3Sn instead of NbTi as superconducting material would lead to one of the following changes:

1. use of 4.2 K helium instead of 1.8 K superfluid helium. This option would permit to remove one screen and to decrease the outer diameter by about 80 mm;
2. work at 1.8 K with the same gradient and increase the magnet aperture since the superconductor can stand at a higher magnetic field;
3. work at 1.8 K with the same aperture and increase the gradient.



1 Coils, 2 Stainless steel collars, 3 Inertia tube, 4 Screen @ 4.2 K, 5 Screen @ 70 K, 6 vacuum tank, 7 Support

Figure 5: Quadrupole cross-section.

Although these options are attractive, the Nb_3Sn technology is not yet well mastered: it would lead to challenging R&D work and to a modified design since the mechanics and the quench protection in particular would be more constraining.

4.4 *Effect of the Main Solenoid*

Operating the iron-free quadrupole in a longitudinal solenoid field of 3 T shifts the operating point to about 90% of the critical field. Increasing the safety margin can be achieved either by progress to come on the maximum current sustained in SC cables or by reducing the focusing gradient of about 10%. Opticswise, the detector solenoid field is harmless as long as it does not extend, even partially, over the last doublet and superimposes over the quadrupole field. It then induces a blow up of the horizontal and vertical beam spot sizes at the IP. However this effect can be compensated completely with one skew quadrupole in front of the solenoid [6].

5 REFERENCES

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