Electron-Electron Collisions at TESLA

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Abstract. Electron-electron collisions at the future TESLA linear collider is a promising complement to e^+e^- collisions. A critical issue for the physics potential of this option is the achievable luminosity. For e^+e^- collisions, the pinch effect enhances the luminosity, while due to the repelling forces for e^-e^- collisions, the luminosity is significantly reduced and is more sensitive to beam separations. This report discusses the e^-e^- option for TESLA and the expected luminosity.

INTRODUCTION

The TESLA linear collider is designed for e^+e^- collisions at $\sqrt{s} = 500\,\mathrm{GeV}$ and beyond. Basic parameters are given in Tab. 1. In this report, aspects of

TABLE 1. TESLA 500 parameter list.

Parameter	Symbol	Ref. Design
Center of mass energy	E_{cm}	500 GeV
Bunch charge	N	$2{\cdot}10^{10}\ 1/e$
Bunches per train	n_b	2820
Bunch spacing	t_{b}	337 ns
Repetition rate	f_{rep}	5 Hz
Bunch length	σ_z	300 μm
Horiz. beam size at IP	σ_x	553 nm
Vert. beam size at IP	σ_y	5 nm
Vert. divergence at IP	$\sigma_{y'}$	12.3 μrad
Vert. emittance (norm.)	ϵ_y	$0.03{\cdot}10^{-6}$ m
Energy loss (beamstr.)	δ_b	3.3 %
Vertical Disruption	D_y	25
Luminosity e^+e^- mode	$\mathcal{L}^{+-}$	$3{\cdot}10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
Luminosity e^-e^- mode	$\mathcal{L}^{--}$	$0.5{\cdot}10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$

colliding two electron beams in TESLA to explore the rich physics potential of e^-e^- interactions [1] are discussed. At linear colliders, the luminosity is highly sensitive to beam separations at the interaction point. In the case of e^+e^- collisions, the attracting electromagnetic forces 'pinch' the bunches and thus enhance the luminosity. However, for equally charged beams (e^-e^-), the electrons repel and disrupt the beam: the luminosity is significantly reduced and is more sensitive to beam separations (Fig. 1). A vertical separation between two bunches of 10 % of

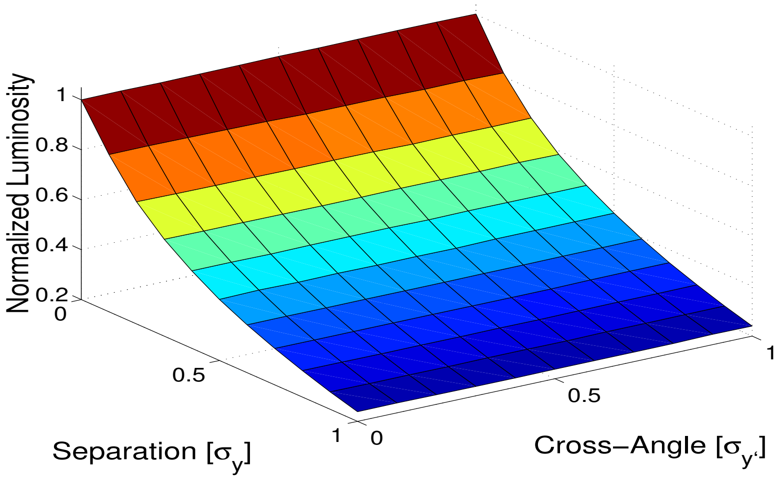


FIGURE 1. Normalized e^-e^- luminosity versus vertical beam separation and crossing angle (normalized to $\sigma_y = 5\,\mathrm{nm}$ and to $\sigma_{y'} = 12\,\mu\mathrm{rad}$ resp.). Machine parameters used are listed in Tab. 1. Luminosity calculations performed with GUINEA PIG.

the vertical beam size (= 5 Å) already decreases the luminosity per bunch crossing by 17 %, a 5 nm separation even by 76 %. From simulations taking ground motion into account, beam separations from bunch train to bunch train as large as 35 σ_y are expected [6]. Obviously, a system is required to steer the beams back to collision already within a few bunches of the train and to maintain the residual train in collision.

FEEDBACK SYSTEM

A schematic layout of the intra-train feedback system for e^-e^- interactions is shown in Fig. 2. It is described in detail in [2,3] and is based on a similar system developed for e^+e^- collisions [4].

Due to the strong beam-beam deflection a vertical separation between two electron bunches at the interaction point (IP) becomes detectable, even in a range well below the vertical beam size of 5 nm. The angular kick results in a measurable position shift at beam position monitors mounted just in front of the final doublet on both sides, 3 m away from the IP. A resolution of at least 5 μm with a response time fast enough to separate the incoming bunches with the opposite spent beam bunches is required.

A digital controller derives an estimate of the beam separation by means of a time varying linear beam-beam deflection model, in contrast to the e^+e^- case, where a static model was sufficient. Correction kicks are applied to subsequent bunches. Figure 2 shows the simulated feedback response to an initial bunch train separation of $50\,\sigma_y$. The feedback starts with an aggressive model, which provides a fast response to large separations, but poor correction accuracy. The correction accuracy is improved to a 2 % of the vertical beam size by switching to a moderate model with a more accurate description of beam deflection for small beam separations.

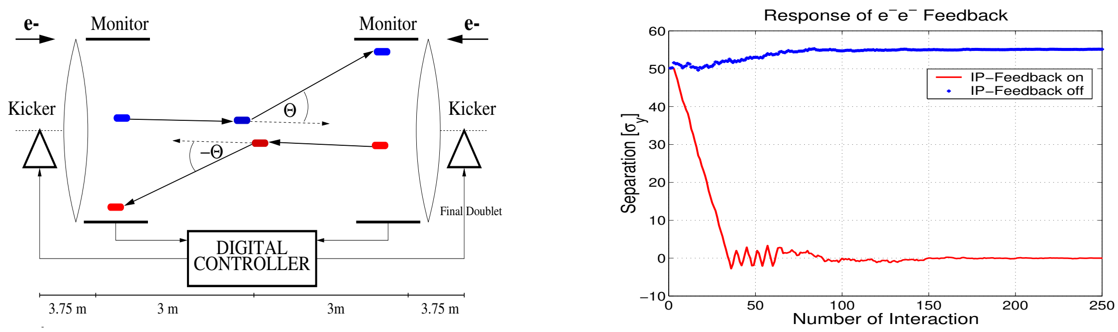


FIGURE 2. Layout of the e^-e^- feedback system at the interaction point (left). Response of the two step controller (right). The aggressive model brings the beams within 35 bunches (or interactions) into collision (lower curve). The switch to the moderate model after 50 interactions reduces the oscillations and insures a high correction accuracy for the subsequent bunches.

As a conclusion, the feedback system is capable of limiting the luminosity loss to a reasonable 6 % in case of an initial $50\,\sigma_y$ beam separation.

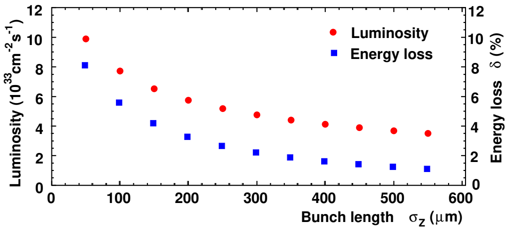
LUMINOSITY

For flat beams ($\sigma_y/\sigma_x \ll 1$) the luminosity for $E_{\rm cm} = 500\,\rm GeV$ can be expressed as

$$\mathcal{L} = 7.2{\cdot}10^{29}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}\frac{\eta P_{\rm AC}\,[\mathrm{MW}]}{\sqrt{\epsilon_y\,[\mathrm{m}]}}\sqrt{\delta_b}H_D \tag{1}$$

with $P_{\rm AC}$ the overall AC power consumption, η the AC-to-beam power efficiency, ϵ_y the normalized vertical emittance, and δ_b the average energy loss due to beamstrahlung. TESLA has chosen a reasonable power consumption of $P_{\rm AC} = 100\,\rm MW$. One advantage of TESLA is the favorable AC-to-beam power efficiency of $\eta = 22\,\%$ due to the use of superconducting accelerating structures.

The enhancement or reduction of the luminosity is described by the factor H_D. It is around 2 for e^+e^- collisions, but for e^-e^- a value around 1/3 is expected due to the repelling forces for like sign charged particles. Unfortunately, there is no complete analytical expression for H_D (see e.g. [7]), therefore, a simulation of the beam-beam interaction is used to evaluate the luminosity (GUINEA-PIG [5]). Figure 3 shows the simulated luminosity and average energy loss due to beamstrahlung as a function of bunch length and horizontal spot size. All calculations are based on the TESLA parameters from Table 1.



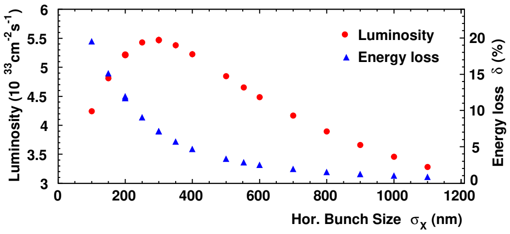


FIGURE 3. Luminosity and energy loss due to beamstrahlung for e^-e^- collisions as a function of the bunch length and horizontal bunch size. Parameters from Table 1 have been used.

Since the vertical emittance of $3{\cdot}10^{-8}$ m is already very demanding, Equ. (1) shows, that one has to allow for a larger beamstrahlung induced energy loss δ_b to improve the e^-e^- luminosity. In addition, one can expect a larger H_D by decreasing the vertical disruption D_y. Looking at the analytical expressions for δ_b and D_y, $\delta_b = 0.86\, r_e^3 \gamma N^2/({\sigma_x}^2 \sigma_z)$ and $D_y = 2N r_e \sigma_z/(\gamma \sigma_x \sigma_y)$, the bunch length σ_z is an adequate parameter to tune. N denotes the bunch charge, r_e the classical electron radius, γ the Lorentz factor, and $\sigma_{x,y}$ the horizontal and vertical beam sizes respectively. A reevaluation of the bunch compressor scheme for TESLA show, that a compression down to $\sigma_z = 300\,\mu$m is possible. This yields in an increase of luminosity and in a better performance of the feedback system compared to the previous case of $\sigma_z = 400\,\mu$m [2].

The e^-e^- luminosity calculated for $\sigma_z = 300\,\mu$m is $0.47{\cdot}10^{34}\,\mathrm{cm^{-2}s^{-1}}$ with $H_D = 0.34$. The beamstrahlung induced energy loss δ_b is 2.2 %. A further increase of δ_b seems to be tolerable for physics, since the luminosity spectrum for e^-e^- collisions is narrower than the spectrum for e^+e^-.

An additional gain in luminosity is achieved by reducing the horizontal spot size down to $300\,\mu$m. In this case, the luminosity increases by 14 % to $0.55{\cdot}10^{34}\,\mathrm{cm^{-2}s^{-1}}$, but δ_b is enlarged significantly to 7.2 %.

POLARIZATION AND SPENT BEAM EXTRACTION

A polarized electron source is already included in the design of TESLA. [8] The source is based on a laser driven gun using a strained lattice GaAs cathode. The expected polarization is 80 %. For the e^-e^- option, a second gun will be installed close to the positron source near the interaction point. The sources will allow to select the polarization states, which is an important feature to study the physics of e^-e^- collisions.

Extraction of the spent beam through the final doublet to the beam dump is possible without reversing any magnetic field or modifications of the beam line. Losses during extraction are at no places more than 1.5 kW. [9]

CONCLUSION

A large disruption parameter as it is the case for TESLA demands a beam stabilization system to bring and maintain beams in collisions. An intra-train feedback system which uses two beam deflection models is capable of limiting the maximum luminosity loss to 6 % in the case of an initial beam separation of $50\,\sigma_y$. The expected e^-e^- luminosity for TESLA 500 is $5{\cdot}10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ corresponding to about $100\,\mathrm{fb}^{-1}$ per year. A further increase of luminosity is possible by reducing the horizontal spot size with the expense of a larger beamstrahlung induced energy loss. Polarized electron sources are expected to deliver 80 % polarization for both beams with selectable polarization states. Spent beam extraction can be done without modifications of the present beam line layout.

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