LUMINOSITY ISSUES FOR THE e^-e^- OPTION OF THE TESLA LINEAR COLLIDER

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Abstract

The future TESLA linear e^+e^- collider can also be used for e^-e^- collisions at a center of mass energy of 500 GeV and beyond. 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 an intra-train feedback to stabilize the luminosity and possibilities to partly overcome the luminosity degradation of the e^-e^- mode.

1 INTRODUCTION

The rich physics potential of the TESLA linear collider designed for e^+e^- collisions at $\sqrt{s} = 500\,\mathrm{GeV}$ can be extended to explore e^-e^- interactions. It has been shown, that both spent e^-e^- beams can be safely extracted from the interaction point (IP) without changing the present e^+e^- layout [1]. In this report we discuss the achievable e^-e^- luminosity and its stabilization, for the given e^+e^- parameter set listed in Tab. 1. At TESLA, the luminosity is highly sensitive to beam separations Δy at the IP. This is due to the large disruption D_y of 25, a value beyond the accepted limit for the onset of the kink instability. In the case of e^+e^- collisions, the attracting forces 'pinch' the bunches enhancing 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 (see Fig. 1). A crossing angle does not degrade the luminosity as it is in the e^+e^- case [2]. Sources of beam separations are Lorentz force detuning, wakefield effects, quadrupole vibrations. A major concern is the displacement of the final doublets transferred one-to-one into a beam position offset at the IP, since a vertical separation between two bunches of $0.1\,\sigma_y = 5\,\text{Å}$ decreases the luminosity per bunch crossing by 17 % and of $1\,\sigma_y = 5\,\mathrm{nm}$ even by 76 % (see Fig. 1). From bunch train to bunch train (5 Hz) the beam separation is expected to be as large as $35\,\sigma_y$ [4]. Obviously, a system is required to steer the beams back to collision already within a few bunches of the train. A correction is feasible on a bunch-to-bunch basis, due to the large bunch spacing of 337 ns for TESLA.

Table 1: TESLA 500 parameter list.

Parameter	Symbol	Ref. Design
Center of mass energy	E_{cm}	500 GeV
Bunch charge	N	$2\cdot10^{10}$ 1/e
Bunches per train	n_b	2820
Bunch spacing	t_{b}	337 ns
Repetition rate	f_{rep}	5 Hz
Bunch length	σ_z	0.3 mm
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	$0.03\cdot10^{-6}$ m
Energy loss (beamstr.)	δ_b	3.3 %
Vertical Disruption	D_y	25
Luminosity e^+e^- mode	$\mathcal{L}^{+-}$	$3.4\cdot10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
Luminosity e^-e^- mode	$\mathcal{L}^{--}$	$0.47\cdot10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$

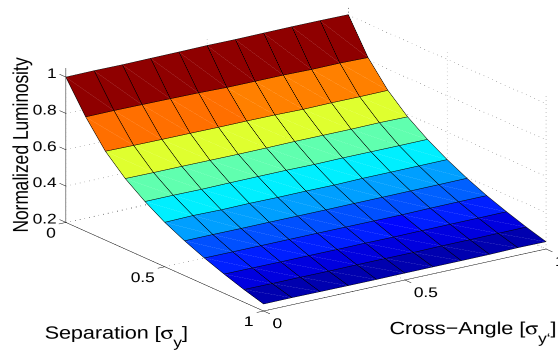

Figure 1: Normalized e^-e^- luminosity versus vertical beam separation and crossing angle (normalized to $\sigma_y = 5\,\mathrm{nm}$ and to $\sigma_{y'} = 12\,\mu\mathrm{rad}$ resp.). Machine parameters used are listed in Tab. 1. Luminosity calculations performed with GUINEA PIG [3].

2 FEEDBACK SYSTEM

The schematic layout of the intra-train feedback system for the of e^-e^- interactions is shown in Fig. 2. The aim is to design a fast and efficient system working at the bunch repetition frequency of 3.1 MHz.

A vertical separation Δy between two electron bunches at the IP becomes detectable even in a range well below the vertical beam size σ_y of 5 nm due to the strong beam-beam deflection (Fig. 3). The strong angular kick experienced by the bunches results in a measurable position shift at the final doublets located 3 m downstreams to the IP. Two beam position monitors (BPM) measure the positions of the incoming and spent bunch. A digital controller derives an estimate of the beam separation by means of a linear beam-beam deflection model. The correction is determined with a proportional-integral (PI) control algorithm. The P-

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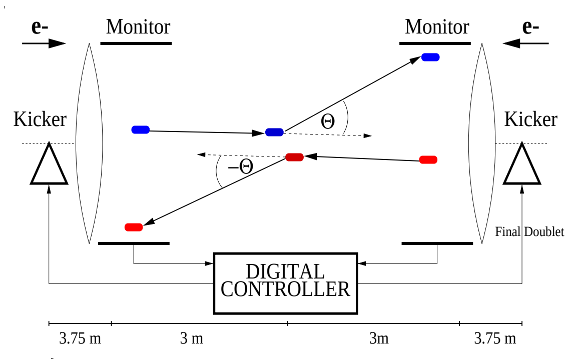

Figure 2: Layout of the e^-e^- feedback system at the IP.

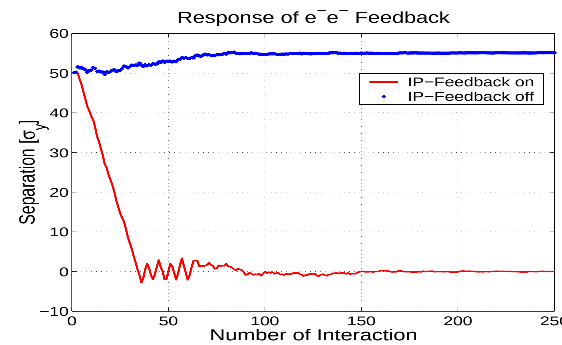

Figure 4: Response of time-varying controller. The aggressive model brings the beams within 35 bunches (interactions) into collision, the switch to the moderate model insures a high correction accuracy for the subsequent bunches.

controller ensures a fast response to incoming disturbances. The I-controller is needed to remove the steady state error in the case of a step disturbance. Correction kicks are applied to subsequent bunches with a latency of two bunches by two kickers. Commonly available kickers have a sufficiently short field rise time of 25 ns and produce a kick of up to 0.12 $\mu\mathrm{rad}$ at a beam energy of 250 GeV [5]. Two kickers are sufficient to cover a control range of $\pm 100\,\sigma_y$. A time varying controller with two models of the beam-

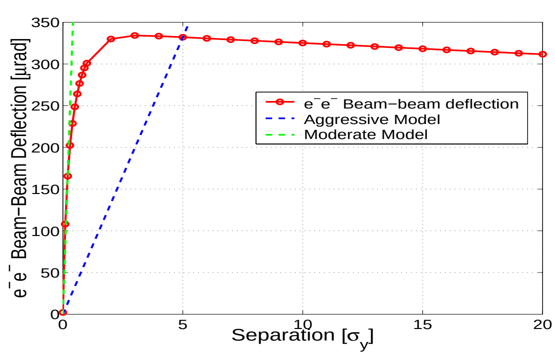

Figure 3: Beam-beam deflection as a function of beam separation for e^-e^- interaction in TESLA and the two linear models used by the time varying controller.

beam deflection is used as indicated in Fig. 3. The *aggressive* model, is given by $\Phi = 64.4/\mu\mathrm{rad} \cdot \Delta y/\sigma_y$ It provides a fast response to large separations, but poor correction accuracy. Only 35 bunches are required to correct an bunch train separation of $50\,\sigma_y$. However, the collisions of the following bunches can barely be kept within $1.6\,\sigma_y$, since the model strongly overestimates small bunch separations. The correction accuracy is improved to a fraction of the vertical beam size, by switching to a *moderate* model: $\Phi = 1000/\mu\mathrm{rad} \cdot \Delta y/\sigma_y$. This model is characterized by a negligible noise amplification and a slow step response. The correction accuracy achieved is $0.02\,\sigma_y$.

Figure 4 shows the simulated feedback response to a stationary bunch train separation of $50\,\sigma_y$. The simulation includes the following effects: residual beam position offsets due to higher-order mode effects in the linac; finite BPM resolution and analog-to-digital signal quantization of 5 μm; kicker field imperfections of 0.1 %; random variation of the beam-beam deflection by 10 % to include fluctuations, e.g. in bunch charge, bunch length, or beam size.

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

3 LUMINOSITY IMPROVEMENTS

The enhancement or reduction of the luminosity is described by the disruption (de-)enhancement factor H_D. It is 2 for e^+e^- with TESLA parameters, but only 0.34 for e^-e^-. There is no complete analytical expression for H_D (see e.g. [6]), therefore, a simulation of the beam-beam interaction is used to evaluate the luminosity [3].

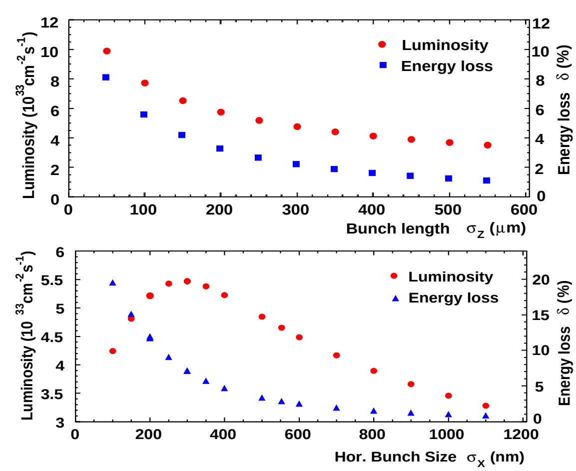

Figure 5: Luminosity as a function of the bunch length and horizontal bunch size for e^-e^- collisions using the TESLA parameters of Tab. 1. Simulations are performed with GUINEA PIG.[3]

In the case of flat beams ($\sigma_y/\sigma_x \ll 1$) the luminosity for

Table 2: Luminosity and average beam energy loss due to beamstrahlung for e^-e^- collisions for different bunch lengths and horizontal beam sizes. The TESLA parameters in Tab. 1 have been used.

$\sigma_z\,(\mu\mathrm{m})$	$\sigma_x\,(\mathrm{nm})$	$\delta_b\,(\%)$	$\mathcal{L}\,(10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1})$
400	553	1.6	4.1
300	553	2.2	4.7
200	553	3.3	5.7
100	553	5.6	7.7
50	553	8.1	9.9
300	300	7.2	5.5
300	100	19.6	4.2

$E_{\mathrm{cm}} = 500\,\mathrm{GeV}$ can be expressed as

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

with P_{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. Since it is trivial to increase the luminosity by increasing the power consumption, we limit the P_{AC} to $100\,\mathrm{MW}$. TESLA has a favourable AC to beam power efficiency of $\eta = 22\,\%$ due to the use of superconducting accelerating structures. The e^-e^- luminosity calculated for TESLA parameters is $4.7 \cdot 10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (H_D = 0.34) compared to $34 \cdot 10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (H_D = 2.0) for the e^+e^- case (see Tab. 1). Since the vertical emittance of $3{\cdot}10^{-8}$ m is already very demanding, the only reasonable way to improve the luminosity is to allow a larger average beam energy loss δ_b. In addition, one can expect a larger H_D for smaller vertical disruption D_y. Looking at the analytical expressions for δ_b and D_y,

$$\delta_b = 0.86\frac{r_e^3\gamma N^2}{{\sigma_x}^2\sigma_z}\,, \quad \text{and} \quad D_y = \frac{2Nr_e}{\gamma\sigma_x\sigma_y}\sigma_z\,, \qquad (2)$$

the bunch length σ_z is the only adequate parameter to tune. (Here, 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 showed, that a compression to $\sigma_z = 300\,\mu$m is indeed possible, which yields to an increase in luminosity and to a better performance of the feedback system as for the previous case of $\sigma_z = 400\,\mu$m [7].

The luminosity is enlarged by a reduction of the bunch length, with the expense of an increased beamstrahlung induced energy loss δ_b (see Fig. 5 and Tab. 2). A moderate increase of δ_b seems to be tolerable for physics, since the luminosity spectrum of e^-e^- collisions is narrower than the spectrum for e^+e^- (Fig. 6). A bunch length reduction does not spoil the spectrum significantly.

An additional gain in luminosity is achieved by reducing the horizontal spot size down to $300\,\mu$m (see Fig. 5 and Tab. 2). In this case, the luminosity increases by 14 %, but δ_b is enlarged significantly to 7.2 %.

4 CONCLUSION

The large disruption parameter for the high luminosity TESLA parameters demands a sophisticated beam stabilization system for beam collisions. The intra-train feedback system is capable of limiting the maximum luminosity loss to 6 % in the case of an initial beam separation of $50\,\sigma_y$. The e^-e^- luminosity for the TESLA e^+e^- parameters is by a factor of 7.6 smaller than the e^+e^- luminosity due to the anti-pinch effect. A further increase of luminosity is only possible by reducing the bunch length and the horizontal spot size with the expense of a larger energy loss.

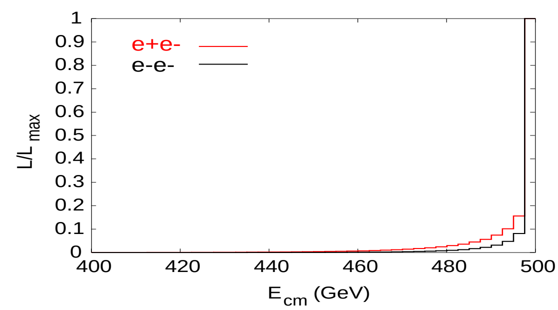

Figure 6: Normalized luminosity spectrum for e^-e^- collisions compared to e^+e^-. TESLA high luminosity parameters from Tab. 1 are used.

5 ACKNOWLEDGMENT

We would like to thank O. Napoly, R. Brinkmann, and N. Walker for their support and fruitful discussions.

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