INSTRUMENTATION AT THE INTERACTION REGION OF A LINEAR e^+e^- COLLIDER

S. SCHREIBER
Deutsches Elektronen-Synchrotron, 22603 Hamburg, Germany

A future TeV-scale linear e^+e^- collider will operate with ambitious beam parameters at the interaction region in order to achieve the luminosity required for physics experiments. It will be essential to measure and monitor relevant beam parameters close to the interaction point in order to obtain and maintain high luminosity. This report gives an overview on the beam parameters to be measured and discusses examples of proposals for the required instrumentation and their implementation in the interaction region.

1 Introduction

A stable operation of a TeV-scale linear e^+e^- collider with the highest luminosity possible will be a key requirement for the success of the physics program. To obtain a luminosity in the $10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ range, ambitious beam parameters like low emittance and nanometer scale beam sizes at the interaction point (IP) have been proposed[1,2]. Beam parameters will be measured at various places in the linac and in the beam delivery system (BDS). However, due to the large demagnification (× 200 to 300), it is hardly possible to accurately predict the beam parameters at the IP from the measurements in the BDS alone. Instrumentation in the interaction region (IR) is therefore required to achieve optimal beam quality. But it has to be considered as well, that place constraints close to the vertex detector require the instruments being as compact and least invasive as possible.

2 Overview on Beam Parameters

Table 1 gives an overview on relevant beam parameters to be measured after acceleration, either up- or downstreams the IR, most of them in the BDS. This report concentrates on those parameters to be measured in the interaction region. The table also gives typical values and resolutions required.

To summarize and ordering the items by priority, the following parameters have to be considered to be measured in the IR: relative luminosity (beam aberrations), vertical beam spot size, beam position, vibration and drift of the final quadrupoles, horizontal beam spot size, and beam induced particle background. Other parameters of importance like vertical and horizontal emittance, energy, energy spread, and beam polarization will be measured in the

Table 1: Relevant beam parameters to be measured. It is indicated, if the measurement should be in the interaction region (IR) or if a measurement elsewhere is sufficient: in the beam delivery system (BDS), up- or downstreams the IR. Typical values and resolution required are given. The exact numbers depend on the specific collider proposal.

parameter	measured at	value	resolution
vertical spot size	IR	3 to 5 nm	few %
horizontal spot size	IR	200 to 500 nm	few %
bunch length	BDS	90 to 400 μm	few %
emittance	BDS	0.01 to 0.1 μm (vert.)	few %
energy	ds IR	250 to 500 GeV	10^{-4}
energy spread	ds IR	10^{-3}	1 %
beam position	IR	–	1 to 5 μm
beam jitter and drift	IR	–	10 nm
vibration	IR	–	10 nm
beam polarization	us or ds IR	60 (e^+) to 80 % (e^-)	1 %
beam phase stability	BDS	2° (X-band)	–
rel. luminosity	IR	–	1 %
luminosity spectrum	IR	–	1 %
background	IR	–	–
bunch charge	BDS	0.6 to 3.5 nC	few %

beam delivery system or downstreams of the IP. They are not discussed in this report.

Highest priority is given to the measurement of the relative luminosity and the vertical beam size. A luminosity monitor allows to correct for beam aberrations and to optimize collision parameters. The optimization of the vertical beam size is of utmost importance, since it limits the achievable luminosity and is the most difficult one to achieve. Once collision is established, beam position measurements are required to stabilize the collision with feedback systems. Beam position monitors (BPM) will also serve to measure beam jitter and drifts of the beam in respect to the final quadrupoles.

Some of these measurements will be performed from bunch to bunch, eg. the beam position for a feedback system. For most other monitors, it is sufficient to measure from train to train, since the beam should be sufficiently stable during one bunch train[2]. Measurements of vibrations of critical elements in the IR like the final quadrupoles are helpful to justify this assumption. However, especially in cases, where a feedback system to maintain collision is not easily realizable, vibration measurements together with a stabilization of the final quadrupoles are essential.[3]

Most of the resolutions required for the various measurements are not very ambitious and can be realized by known techniques. One exception is the measurement of vertical beam spot sizes below 10 nm. Resolutions required for the BPMs are in the range of 1 to 5 μm. This has already been achieved with present technologies. However, for vibration and drift measurements, the BPM resolution should approach the vertical spot size.

In the following, two examples of instrumentation in the interaction region are discussed: the luminosity monitor and the beam size measurement.

3 Luminosity Monitor

Stabilization of the colliding beams is achieved with a feedback system based on the minimization of beam-beam kicks.[4] This system requires BPMs between the mask and the final quadrupole and kickers to steer the beam.

The beam-beam deflection scan method is a useful tool to tune the beam while in collision. It has little impact on the integrated luminosity and has been used successfully eg. at the SLC.[5] However, in the case of large vertical disruption this method fails to deconvolute the vertical spot size from the measurement. In this case, a combination of horizontal beam-beam deflection scans to measure the horizontal aberration and luminosity scans for the vertical aberration seams to be a feasible tool to tune the beam.[6] The luminosity measurement can be realized by two methods: (a) measuring the low angle radiative Bhabhas (bremsstrahlung) in a calorimeter situated several meters away from the IP, and (b) measuring the e^+e^--pair background in a calorimeter integrated into the inner part of the mask (Fig. 4(a)). In method (a), radiative Bhabhas will be measured background free in the energy gap between the background from pairs and from off momentum electrons (positrons) which have radiated beamstrahlung. The Bhabhas are being deflected by the final quadrupoles, and can be detected 8.5 m from the IP in a calorimeter around the beam pipe (TESLA case). 25 bunch crossings are sufficient to reduce the statistical error below 1 % allowing a complete scan within a bunch train.[6]

To correct linear aberrations which effect the vertical beam size, different scans have been proposed. Two examples of waist shift scans are shown in Fig. 1. A resolution of 1 % per measured point during the scan leads to a luminosity optimization with a precision expected to be better than 10^{-3}. For method (b), a calorimeter will be installed in the inner part of the mask to measure the energy of the beam induced pair background. The total energy deposited below 20 mrad is in the order of 30 TeV per bunch crossing[8] and poses thus a challenge for the detector construction. The advantage of this method compared to (a) is, that the relative resolution of 1 % can be reached

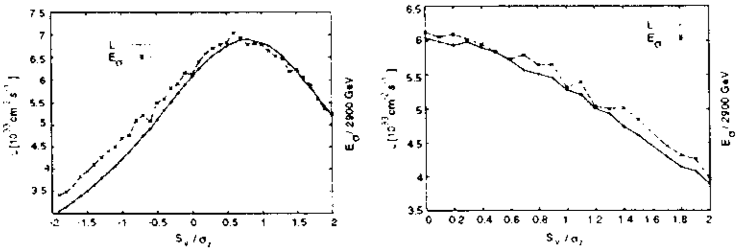

Figure 1: Comparison of luminosity L and energy E_σ deposited by the e^+e^- pairs in the inner part of the mask: (left) the two vertical waists are symmetrically shifted against each other along the beam axis by S_y with respect to the collision point; (right) two coinciding vertical waists are shifted together with respect to the collision point. (From TESLA CDR[7])

already with one bunch crossing.

4 Beam Size Monitor

A difficult task will be the measurement of the vertical beam spot size at the IP, which is in all linear collider proposals less than 10 nm. At the Final Focus Test Beam (FFTB), a method based on a laser interferometer[9] has been developed and successfully used to measure spot sizes down to 60 nm.[10] For the measurement of larger spot sizes in the range of 500 nm to some μm, a laser wire has been tested SLD.[11] Other methods have been proposed to measure nm spot sizes, eg. by measuring the angular distribution of the pair background.[12] Here, the vertical spot size is indirectly obtained by measuring the horizontal spot size and the aspect ratio. However, scanning methods are model dependent and cannot deconvolute the contributions from the opposite beam and thus leave the uncertainty which beam has to be corrected.

4.1 Laser Interferometer

A laser beam with good coherence is split into two beams, which are combined to generate an interference pattern at the location of the electron beam (Fig. 2). The spacing between the fringes is a few times larger than the beam size to be measured. The electron beam is swept over the fringe pattern. The rate of Compton scattered photons is measured as a function of the beam sweep. The result is a modulated signal, with the modulation depth M being a direct measure of the beam size (Fig. 3a):

$$M(\sigma) = K|\cos\theta|e^{-2(\frac{2\pi}{\lambda}\sin\frac{\theta}{2})^2\sigma^2}$$

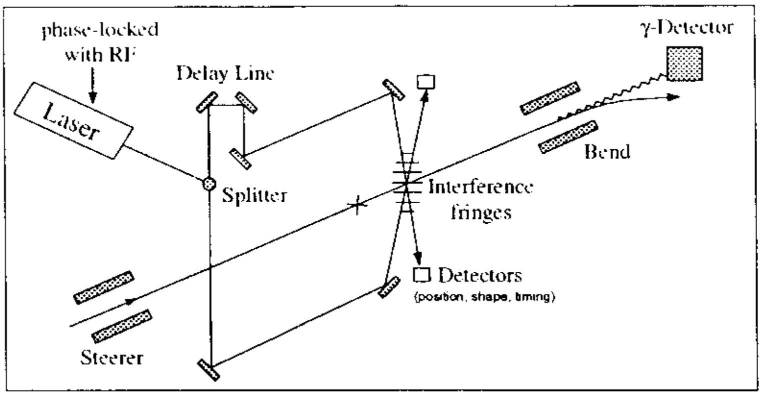

Figure 2: Principal components of the laser beam size monitor. The electron or positron beam is swept over the fringe pattern generated by the two arms of the split laser beam. The Compton scattered photons are measured as a function of the sweep.

If the angle θ between the laser arms is chooses to be close to 180°, the modulation depends only on the laser wavelength λ. Since the wavelength of a laser beam is precisely known, this method provides a direct measure of the absolute spot size. However, systematic corrections indicated by the factor K have to be applied. It has been shown, that these corrections can be kept below 10 %.[10]

The range of spot sizes accessible by the laser interferometer is determined by the wavelength of the laser and the resolvable modulation depth (Fig. 3b). With a careful setup and sufficient statistics, a modulation measurement of up to 0.95 and down to 0.05 should be possible. Assuming a standard laser source like Nd:YLF, a wavelength of 262 nm would allow to measure in the range from 51 nm down to 6.7 nm, a wavelength of 209 nm from 41 nm down to 5.3 nm, with the latter being extremely difficult to realize. This would just include the vertical beam size of TESLA, but not of NLC or JLC.

The electron position jitter in respect to the laser fringes has to be smaller than the bunch size to be measured. Therefore, the spot size measurement should be accompanied by a beam jitter measurement eg. with a high resolution BPM. The usefulness of the combination of spot size measurement and beam position and jitter measurement at the IP and the image point of the final focus system has been shown during the FFTB runs. A C-band cavity BPM has been developed, which reached a remarkable resolution of 25 nm.[13]

In order to be useful in a train by train beam correction scheme, one complete spot size measurement will be done within a pulse train. This is especially appealing in the TESLA case, where a large number of almost 3000

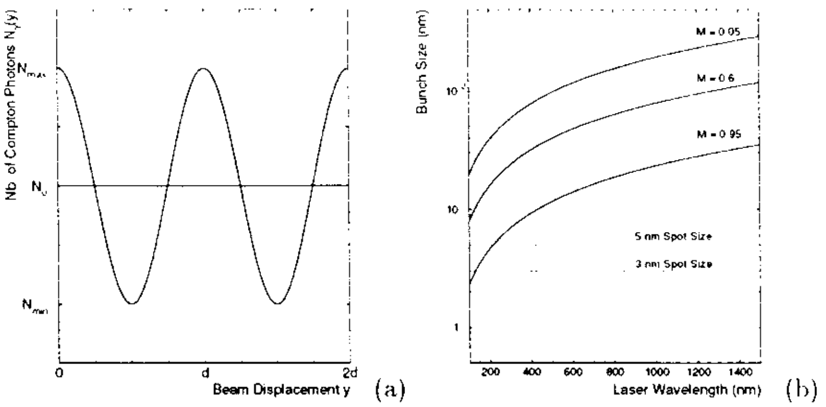

Figure 3: (a) Modulated Compton rate as a function of the beam displacement, d is the fringe distance. (b) Dynamic range of the laser beam size monitor as a function of laser wavelength. The lines indicate the measurable bunch sizes for a modulation depth M of 0.95, 0.6, and 0.05 ($\theta = 175°$).

bunches per train can be used. A suitable laser for this would be a mode-locked system synchronized to the electron bunch train. The expected Compton rate is large enough to collect sufficient statistics: $N_\gamma = 600 \cdot N_e/10^{10} \cdot P/\mathrm{MW}$. The number of electrons per pulse is typically $N_e = 10^{10}$, a laser beam power of $P = 1\,\mathrm{MW}$ is obtained by modern ps laser systems. One point of concern is the possible damage of optical elements by higher power UV laser radiation. This has to be carefully take into account for in the design of the monitor.

For stability reasons, the last optical elements, the mirror and focusing optics are preferably to be mounted onto the detector mask, which itself is a heavy rigid structure (Fig. 4(b)). Incorporating most of the optics into the mask reduces additional dead material inside the detector to a minimum. The laser and beam steering devices will be outside the detector. The mask will not extend down to the interaction point. Therefore, the electron or positron beam waist has to be shifted for the measurement away from the IP by 800 mm.

The horizontal spot sizes of all collider proposals are larger than the accessible range of the laser beam size monitor. A thinkable solution would be to reduce the angle θ between the split laser beams from 180° to the mask cone angle of $2 \times 83\,\mathrm{mrad}$. This would allow a measurement of spot sizes in the range between $150\,\mu\mathrm{m}$ and $1.2\,\mu\mathrm{m}$ ($\lambda = 523\,\mathrm{nm}$) with the cost of larger systematic uncertainties.

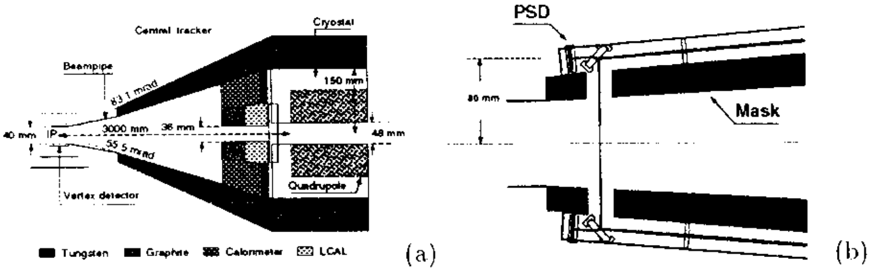

Figure 4: (a) Mask layout to suppress the background from pair creation. Indicated is the proposed position of the luminosity calorimeter (LCAL) and the BPM between the mask and the quadrupole cryostat. (b) Possible mechanical implementation of the optics for the laser beam size monitor into the mask. Indicating are position sensitive devices (PSD).

4.2 Laser Wire

The electron beam is swept over a strongly focused laser beam. The Compton signal is unfolded with the shape of the laser beam to extract the electron beam size. In order to reduce potential systematic errors due to uncertainties in the laser beam shape, the laser spot must be smaller than the beam size. To estimate the achievable spot size, the geometrical constraints at the IP have to be considered. For a suitable location of the laser wire in the IR, the last focusing mirror would have distance to the beam line of about $l = 100\,\mathrm{mm}$. Allowing a laser spot diameter at the mirror of $D = 30\,\mathrm{mm}$, the smallest achievable waist would be $w = 2\sigma_r = \frac{\lambda}{\pi}/\arctan(\frac{D}{2l}) \approx 2\lambda$. Choosing $\lambda = 262\,\mathrm{nm}$, a laser spot size down to $\sigma_r = 280\,\mathrm{nm}$ could in principle be realized under perfect conditions. This would just work for TESLA, but is too large for the other proposals. For this reason, a laser wire to measure the horizontal spot size at the IP seams not to be feasible.

5 Conclusion

Including beam instrumentation into the interaction region is difficult but necessary: a calorimeter for relative luminosity measurements inside the inner part of the mask, a laser interferometer to measure the vertical beam size, and beam position monitors for an orbit feedback system and for vibration measurements. Commissioning of the final focus system will certainly be done before the particle physics detector is in place. This will allow for testing of the proposed instrumentation, but leaves also room for additional equipment, eg. to measure beam induced backgrounds. Once the final focus is commissioned and the detector is in place, a minimum of instrumentation will still be required to verify, maintain, and optimize the beam quality.

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