Compton Scattering Techniques for the Measurement of the Transverse Beam Size at Future Linear Collider

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At several locations of the beam delivery system (BDS) of a future linear collider (FLC), beam spot sizes ranging from several hundreds to a few micrometers have to be measured. The large demagnification of the beam in the BDS and the high beam power puts extreme conditions on any measuring device. With conventional techniques at their operational limit in FLC scenarios, new methods for the detection of the transverse beam size have to be developed. Laser based techniques are capable of measuring high power beams with sizes in the micrometer range. General aspects and critical issues of a generic device based on Compton scattering are outlined and specific solutions proposed.

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I. MOTIVATION

High luminosity is the key to many of the physics processes of special interest at the Future Linear Collider. This fundamental point is the main physics motivation for this project and justifies considerable efforts to ensure that the accelerator can deliver on its excellent luminosity potential. The case for the highest luminosities is now globally accepted and all the Linear Collider proposals currently have this as their goal, with quoted luminosities of a few$\times 10^{34}$ $\mathrm{cm}^2\mathrm{s}^{-1}$. The key motivation for this project is to add to the arsenal of tools that the machine will need to maximize its luminosity performance. In particular this project aims to provide a reliable and flexible method of obtaining real-time information on the emittance and quality of the beam and hence to allow feedback for maximizing the luminosity.

II. EMITTANCE MEASUREMENT

In this project we limit our attention to the measurement of the electron beam transverse phase space (transverse emittance) because it is the fundamental determining factor for the final transverse beam-spot size at the interaction point (IP). It is important to keep the emittance low so as to maximize the luminosity at the IP and much effort is spent in designing the accelerator and beam delivery system (BDS) to avoid sources of emittance growth. The BDS generically consists of approximately a kilometer of beam optics providing collimation, chromatic correction and final focusing. There are many potential sources of emittance growth which in general will be time dependent and will require continuous measurement and feedback to correct.

The aim is to measure the emittance of the beam to better than 10% as it approaches the IP and this will require a number of profile measurements with the same precision along the BDS. In Tab. I beam profile parameters for FLC designs are listed.

		CLIC	NLC/JLC	TESLA
BDS	$\sigma_x[\mu\text{m}]$	3.4 to 15	7 to 50	20 to 150
	$\sigma_y[\mu\text{m}]$	0.35 to 2.6	1 to 5	1 to 25
IP	$\sigma_x^\star[\text{nm}]$	196	335	535
	$\sigma_y^\star[\text{nm}]$	4.5	4.5	5

TABLE I: Beam spot sizes for various Linear Collider designs. Quoted are numbers for CLIC [1], NLC/JLC [2], and TESLA [3].

A set of transverse profile measurements at several points along the beam line separated by a sufficient betatron phase advance can be translated into a determination of the emittance. At least four scanning stations will be required for each lepton beam, possibly fired by a single laser system plus laser beam transportation. Each station will need to provide a profile along three directions, as required to specify an ellipse. Relating a set of such transverse profiles to the emittance and optimizing the layout of scanning stations within a BDS design will form an interesting parallel project, that will be addressed via detailed simulations.

The electron bunch transverse profile has been measured in the past by intersecting the electron beam with a solid wire and by counting the subsequent background rate as a function of the relative position of wire and bunch. Using this technique, resolutions of typically a few μm can be obtained, at the expense of some disruption to the beam. This technique cannot be used universally at the LC, however, because the beam-spot sizes can be much smaller, the need for continuous measurement precludes an invasive technique and the intensities are so great that the wires would be quickly damaged, even if swept rapidly through the beam. For these reasons, it is necessary to develop a novel technique that can run continuously and reliably during machine operation, that does not get destroyed by the beam and that can be sufficiently fast so as to be sensitive to individual electron bunches within the bunch train. All these advantages could in principle be provided using optical scattering structures. Several schemes have been proposed to use optical scattering structures to serve as diagnostics to measure the bunch length and the beam profile [4]. Common to all optical scattering structures is that they must have features smaller or similar in size to the particle beam under measurement. Several types of laser spot structures can be generated with common optical setups. In the following some optical structures are listed together with their performance rating:

Laser wire (gaussian profile) The laser beam is here focused to a small gaussian spot with radius ω_o. If we consider a diffraction limited, finely focused beam waist, the minimal achievable spot radius is given by $\omega_o = \lambda/(\pi\theta)$, where λ denotes the laser wavelength and θ the half opening angle of the laserbeam at the waist (see Fig.1). The distance over which the laser beam

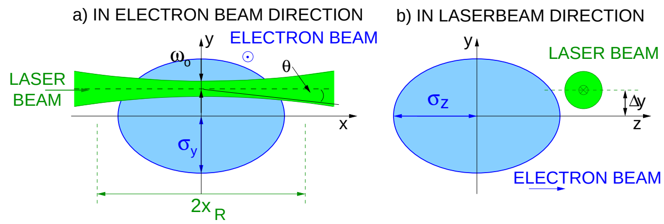

FIG. 1: Scheme of a gaussian laser beam focused to its diffraction limit scanned over an electron beam.

diverges to $\sqrt{2}$ of its minimum size is called the Rayleigh range x_R and defines the usable length of the laser wire. The smallest achievable spot size with diffraction limited optics is in the order of $\omega_o \sim \lambda$. With Nd:YLF or YAG laser working at higher harmonics electron spot sizes from $\sigma_y > 350$nm can be measured with high accuracy. The laser beam power must be in the order of a couple of MW to yield a few thousand Compton photons per scan spot. Critical issues of a laser wire design are the diffraction limited optics, which must withstand such a high beam power and the scanning system, enabling intra-train scanning of consecutive bunches.

Laser wire (dipole mode) The resolution of the laser wire can be enhanced by generating an artificial transverse dipole mode by means of a lambda half waveplate, where half of the gaussian is shifted in phase by 90^o. Such a waveplate can easily be installed in the optical path of the laser wire and would enhance the resolution of the device by roughly a factor of two aiming at beam sizes in a region from 250nm $< \sigma_y <$ 500nm.

Laser Interferometer Towards beam sizes in the nanometer range, a standing wave interference pattern generated by crossing two laser beams has been proposed and successfully tested at the FFTB experiment [5]. The fringe spacing of the interference pattern (see Fig. 2) depends on the laser wavelength and on the crossing angle. The electron beam is moved over the pattern and the Compton scattered photons are detected. If the beam size is small compared to the fringe spacing, a modulation of the Compton signal is observed which is proportional to the transverse electron beam size. This modulation vanishes if the beam size is large compared to the fringe spacing. The smallest observed spot size with this technique was about 58 nm [6].

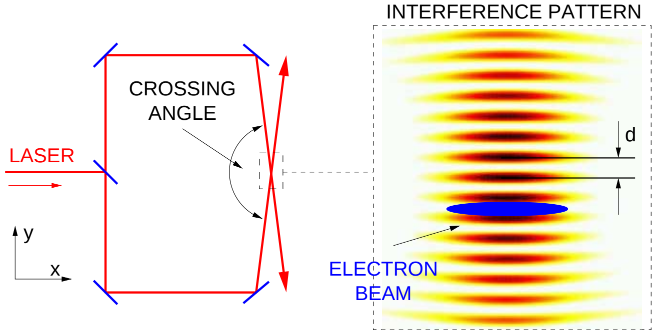

FIG. 2: Scheme for the generation of an interference pattern with fringe spacing d.

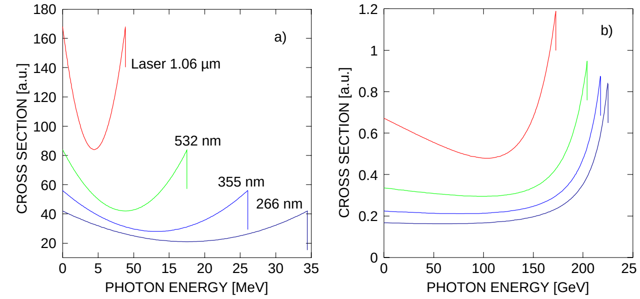

FIG. 3: Compton cross section for the first four harmonics of an Nd:YAG laser scanning a 1 GeV (a)and 250 GeV (b) electron beam.

III. LASER WIRE SETUP

The setup for a laser wire beam profile monitor is sketched in Fig. 7. A high power laser beam is divided into two different optical paths for scanning the horizontal and vertical beam size. The scanning is foreseen to be done either with piezo-driven mirrors or with acousto-optic scanners. Before the interaction with the electron beam the laser beams are focused. The electron beam is then bent away while the Compton scattered photons travel along a straight line where they are detected with a calorimeter. Scattered electrons will be bent more strongly than particles with the nominal beam energy enabling detection at a location after the bending magnet.

IV. COMPTON SCATTERING

In the classical limit with photon energies smaller than the electron energy and with electrons at rest, photon electron scattering is described by Thomson scattering. For high-energy photons non-classical effects must be taken into account leading to Compton scattering. With moving electrons the process is called inverse Compton scattering, where the moving electrons transfer energy to the photons yielding substantial fluxes of photons in the optical to X-ray region [7]. For the LWS, the total energy of the scattered photons per electron bunch laser pulse crossing is considered as the signal process. The number of photons N_C is directly proportional to the laser beam power P_L and wavelength λ according to [4]

$$N_C = N_b \frac{P_L \sigma_C \lambda}{c^2 h} \frac{1}{\sqrt{2\pi}\sigma_s} \exp\left(\frac{-y^2}{2\sigma_s^2}\right) \tag{1}$$

where N_b is the number of electrons in a bunch, y the relative offset between laser and electron beam and $\sigma_s^2 \equiv \sigma_y^2 + \omega_o^2$ the overlap region. The electron beam size is σ_y and the laser beam waist at the interaction point is ω_o. The Compton cross section σ_C is in Fig. 3 evaluated for two scenarios: One for a typical linear collider test facility beam energy (1 GeV), where sub-systems of a LWS will be tested and for a typical linear collider beam delivery system energy (250 GeV). Currently a Nd:YAG based laser system is the instrument of choice because of its performance capabilities with respect to high power and small spot size.

V. BACKGROUND SOURCES

For the use of a LWS, the background conditions at the detector locations are of interest. The biggest source of background photons in the low energy region is synchrotron radiation emitted by the electron beam in bending magnets. The spectrum of synchrotron radiation is characterized by the critical energy with divides the total number of photons according to their energy and is for beam energies of several GeV in the keV region. Another background source arises from beam gas scattering. Here the electrons in the beam interact with the residual gas. In elastic collisions the trajectory of the electron is deflected resulting in an increase of the betatron amplitude. Particles with enlarged betatron amplitude can get out of the acceptance of the beam optics and hit the vacuum chamber where they create electromagnetic shower. With inelastic collisions energy is transferred from the colliding electron to the atom of the residual gas. If the electron looses energy by emitting photons as it is deflected by the electric fields within the gas this process is called bremsstrahlung. Bremsstrahlung is the dominant process at high energies with a cross section combined from the individual cross sections from photon emission at the nucleus $\sigma \sim Z^2$ (atomic number Z) and emission at the bound electron $\sigma \sim Z$. The bremsstrahlung spectrum for emitted photons with energy E_γ goes up to the beam energy E_b proportional to $(E_\gamma/E_b)^{-1}$. Both spectra, for synchrotron radiation and bremsstrahlung are plotted in Fig. 4.

VI. TEST OPTIONS

It is planned to install a complete laser wire scanner at the PETRA accelerator at DESY in summer 2002.

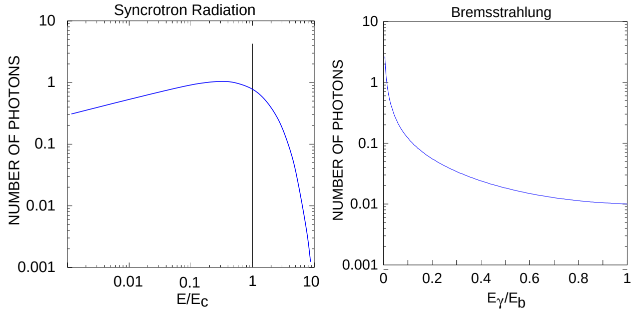

FIG. 4: Photon spectrum from synchrotron radiation and bremsstrahlung.

While beam sizes at PETRA ($10 - 100$ μm) are comparable with typical FLC BDS numbers, the energy of the electron beam is lower in the range from $4.5 - 12$ GeV. The results from background measurements show that a sufficient signal to noise ratio can be reached even with a medium power laser with peak power less than 10 MW. In Spring 2002 tests of subsystems of a laser wire are planned at CTF2/3.

VII. SIMULATIONS

The aim of the simulation studies is a full Monte Carlo simulation of the signal (Compton) and all relevant background processes. This includes the modeling of the complete measurement setup, from the scattering process to the analog-digital-converter (ADC) of the readout electronics of the detector. This is of fundamental importance for the specification of the laser system and the detector. So far the Compton process is modeled in a realistic accelerator environment including beam pipe, magnets, and vacuum windows. The parameter set for the electron beam is closely related to the PETRA positron storage ring at DESY in Hamburg, because prototype tests of a LWS are foreseen with this machine. The simulation work is carried out in the Geant4 [8] framework. The standard toolkit is used for multiple scattering process while the low energy electromagnetic toolkit [9] is used for Compton and Rayleigh scattering, photoeffect, bremsstrahlung, and ionization in the low energy region. A specific Monte Carlo generator [10] is implemented for synchrotron radiation photons. In Fig. 5 simulation results are shown for the Compton process with PETRA accelerator parameters. The low energy peak in the spectrum is caused by multiple scattering processes at low energy in the vacuum window, which consists of a 2 mm stainless steel plate. Full Monte Carlo simulations of the background processes are under way.

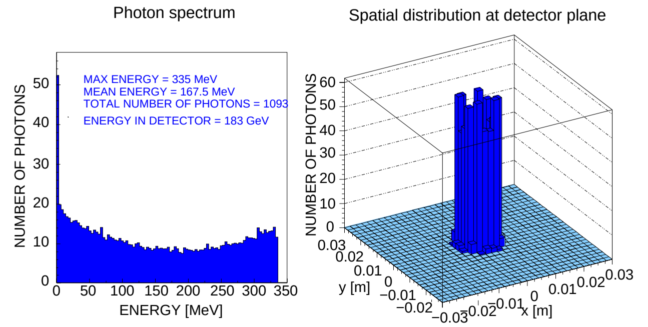

FIG. 5: Photon spectrum of Compton photons simulated with Geant4. Scattering of a 10 MW peak power green ($\lambda = 532$ nm) laser beam with 1 μm spot size at a 4.5 GeV electron beam with transverse beam size of 100 μm. For the spatial distribution calculation the detector place was set 4 m away from the interaction.

VIII. BACKGROUND MEASUREMENTS

Preliminary background measurements have been performed at the positron storage ring PETRA. Two locations were used for the measurements at two different energies. In Fig. 8 the measurement setup is depicted.

A Cs(I) crystal ($1.5 \times 1.5 \times 10$ cm^3) mounted to a photomultiplier was used. The crystal and the photomultiplier are packed together with a support structure in a light tight box made of lead. An aperture is drilled on the side facing the electron beam. The whole package is taped with black tape and positioned at the two locations tangent to the beampipe and 30 cm away from the dipole magnets to avoid any electromagnetic effects on the detector. Before making the measurements the detector together with its readout electronics were calibrated in terms of energy using a radioactive source. The beam parameters of the positron beam at PETRA relevant for the measurements are gathered in Tab. II Results

Beam energy	4.5 and 7	GeV
Beam current	1.55 to 1.77	mA
Particles per bunch	7.5 to 8.5	10^{10}
Repetition rate	130	kHz
Bending angle	28.08	mrad
Vacuum pressure	1 and 2	10^{-10}mbar

TABLE II: PETRA beam parameters relevant for background measurements.

from measurements at the two locations with two beam energies are plotted in Fig. 6. Synchrotron radiation and bremsstrahlung are the two dominant background sources. The energy of the photons from synchrotron radiation at 4.5 GeV is too low ($E_C \simeq 1$ keV) to pass the beampipe material. At 7 GeV the background is a superposition of synchrotron radiation with strong components of bremsstrahlung. At location two, after the long straight section, the electrons have to pass through

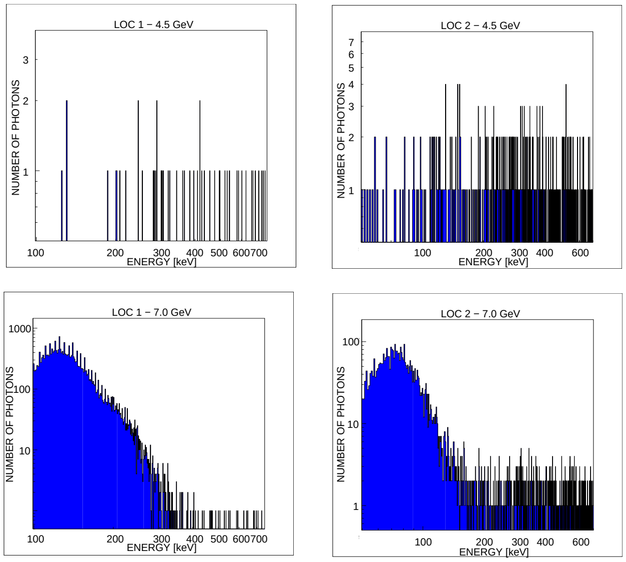

FIG. 6: Background spectra measured at PETRA. Data was taken over a 1 sec long period for each measurement.

about 16 times more residual gas, which increases the rate of bremsstrahlung by that amount.

IX. CONCLUSIONS

It is anticipated that laser wire scanners will be the standard beam size instrumentation tool for the beam delivery system of all FLC designs. First design idea exists with the prototype setup tested at SLC/SLD [11]. Our aim is to elevate this design to a compact, non-invasive device where a high-power pulsed laser is scanned across the electron beam with novel scanning techniques. Furthermore background measurements at the PETRA accelerator have been performed, enabling laser and detector specification for a system test of a laser wire scanner. A much faster detector, made of lead tungstate, is under study. It might enable a 10 MHz sampling rate which is the nominal bunch rate at PETRA.

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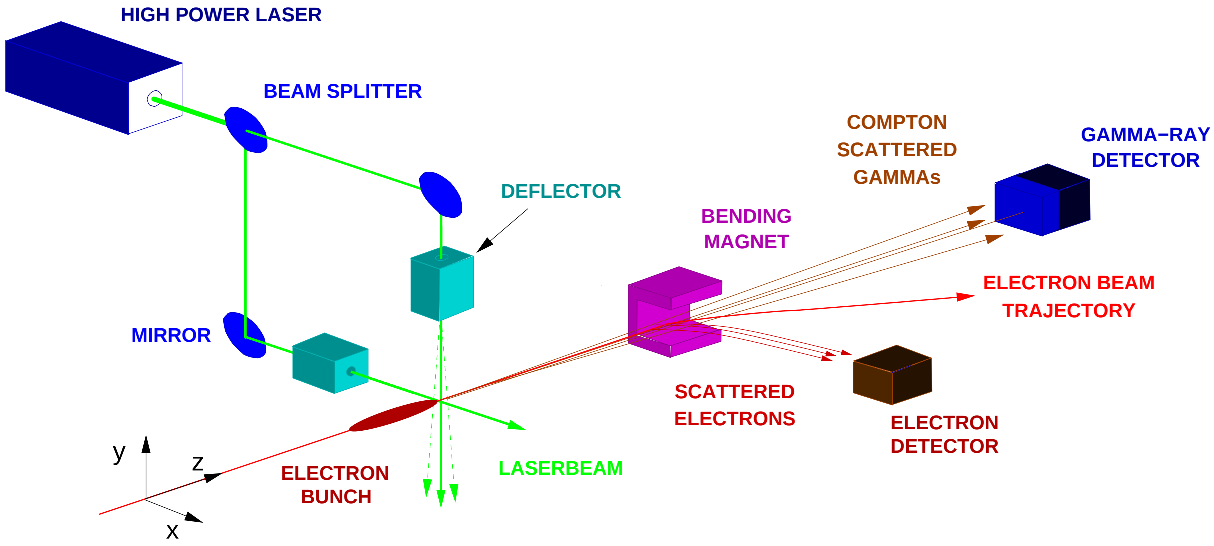

FIG. 7: Schematic setup for a laser wire beam profile monitor.

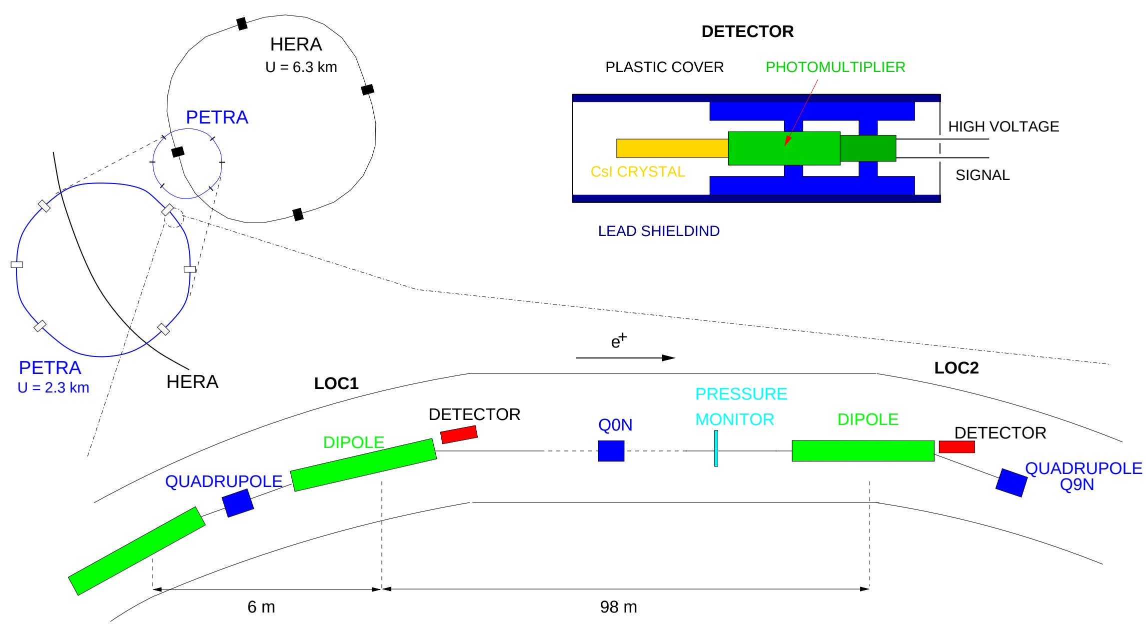

FIG. 8: Schematic setup for background measurements at PETRA.