R&D TOWARDS A LASER BASED BEAM SIZE MONITOR FOR THE FUTURE LINEAR COLLIDER

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Abstract

Laser wires will play an important role as the standard monitor for beam size measurements with micrometre resolution for the beam delivery system at any future linear collider. Some R&D work is still necessary to elevate preliminary laser wire designs to a compact, non-invasive and fast-scanning device. In this paper the latest R&D together with recent measurements and simulations are presented. Schemes to measure the beam size in a bunch train and from train-to-train are presented together with an evaluation of scanning techniques meeting these requirements. Results from simulations and measurements with a laser focus system and of a proposed Compton calorimeter are reported. Furthermore plans are outlined for the installation of a fast laser wire experiment at the PETRA accelerator at DESY.

1 INTRODUCTION

The principle of laser wire operation is illustrated in Fig. 1, where light from a laser is focused down to a small spot and scanned across the incoming electron beam. The resulting Compton-scattered photons are detected downstream and the measurement of the total energy of these photons as a function of laser spot position yields the electron bunch transverse dimensions. In the following, the various components are discussed in more detail and progress towards building a working system is reported.

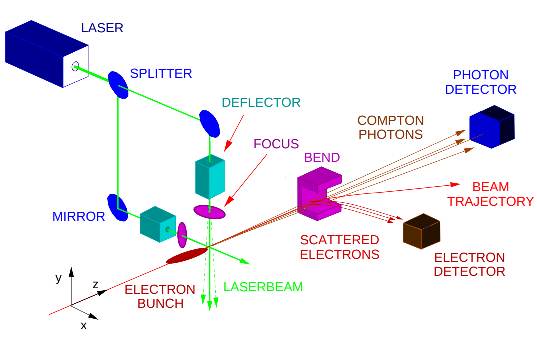

Figure 1: A generic laser wire profile monitor.

2 FOCUSING OPTICS

For a gaussian laser beam the RMS spot size at the interaction should be smaller than the electron beam size $\sigma_o \leq \sigma_y$. At PETRA the electron beam has dimensions of $\sigma_y = 20 - 30$ μm and $\sigma_x = 200 - 300$ μm leading to $\sigma_o = 5 - 10$ μm and a Rayleigh range of at least $z_R \geq 300$ μm in order to accommodate completely the horizontal beam size. High laser peak power between $P_{max} = 1 - 10$ MW is necessary to obtain a good signal-to-noise ratio [1]. Thus the laser optics has to withstand this amount of power and, for flexibility, should be able to work with at least the first two laser harmonics. The back focal length should be $BFL \simeq 150$ mm to incorporate scanning and diagnostic mirrors (see Fig. 2). In order to conform with the above requirements, an air-spaced achromatic laser objective with three lenses was chosen.

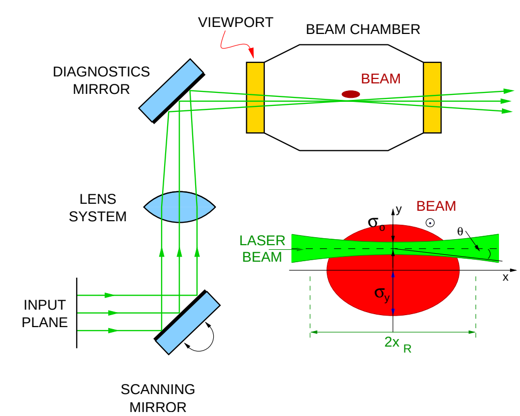

Figure 2: Layout of scanning and focusing system.

The laser beamline around the focusing triplet was simulated using the ZEMAX code [2]. To first order (neglecting abberations) the minimum spot radius is determined by the f-number $f\#$ of the lens, the mode quality M^2 and the laser wavelength λ according to $\omega_o \approx M^2 \lambda f\#$. The simulation code also allows for higher orders from spherical abberations and coma.

2.1 Measurements

Spot size measurements with the proposed lens triplet were performed in order to study the focusing, beam propagation around the best focus, and tolerances. Knife edge scanning with a piezo driven razor blade was chosen as the measurement technique because of its simplicity and high precision. This technique involves passing a blade between the laser beam and a photo detector and measuring the light intensity as a function of blade position, thereby providing the integrated laser beam profile.

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In Fig. 3 the measurement setup is sketched. The laser light coming from a green HeNe laser is guided with a mirror into a Keplerian telescope for collimation. At the beam splitter half the beam power is guided into a Michelson interferometer while the other half passes another mirror before going through the focusing lens. Following this lens the focused beam is collected by a photo diode. The blade together with its interferometer mirror are moved by a piezo driven actuator. The step width of the piezo actuator is monitored constantly in the interferometer arm. For one complete scan of the beam profile and propagation several slices of the laser beam were measured in forward and reverse direction (see Fig. 4a for an example of one slice). This was repeated with a viewport window in the beam path between the focusing lens and the knife edge. The measured propagation of the beam envelope is shown in Fig. 4b. The minimum RMS spot size was obtained by a least square fit using the beam propagation model for gaussian beams [4]. The measured minimum RMS spot size is $\sigma_{o,w} = (5.34 \pm 0.02_{stat} \pm 0.07_{sys})$ μm with and $\sigma_{o,w/o} = (5.21 \pm 0.03 \pm 0.07)$ μm without viewport window. The input beam radius is $\sigma_{in} = (1.23 \pm 0.02)$ mm. All measurements agree with numerical simulations and, as expected from these simulations, the spot size is essentially unaffected by the presence of the viewports. The main effect of the viewport is to shift the waist by $\Delta z = (0.83 \pm 0.01 \pm 0.08)$ mm, which is a third of the viewport thickness of $t = 2.50$ mm. The main contributions to the systematic error are from diffraction effects at the razor blade, which will be tackled in future measurements using a collecting lens.

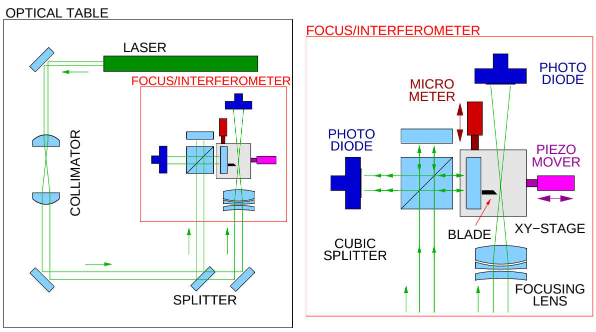

Figure 3: Laboratory setup to measure small laser spot sizes using the knife edge technique.

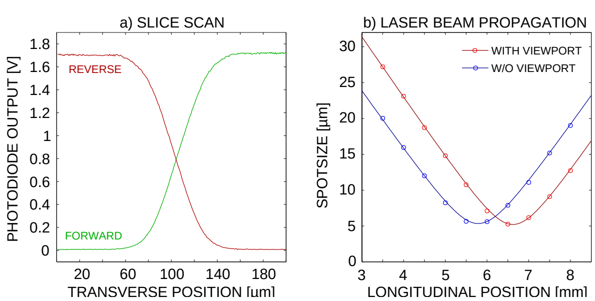

Figure 4: Left: One slice (measured forward and reverse) of the laser beam around the best focus. Right: RMS spot propagation around the best focus.

3 SCANNING

3.1 Requirements

The total scan range d should be in the order of $d = 10 \times \sigma_y$ the beam size under measurement (for TESLA the vertical beam size is $\sigma_y = 1 - 25$ μm, for PETRA $\sigma_y = 20 - 30$ μm). The minimum step width between two scanning points Δd and therefore the scan resolution is anticipated to be $\Delta d = \sigma_y/5$ to $\sigma_y/2$. Furthermore the scanner should preserve the mode quality of the laser beam, withstand the high laser peak power and be able to operate over long periods of time. Most importantly, the scanner must match the timing of the macro pulses delivered by the accelerator. TESLA produces bunch trains of 950 μs length with 2820 bunches each spaced by 337 ns and with a repetition rate of 5 Hz [5]. PETRA as a storage ring can be operated with any harmonic bunch spacing of the repetition rate of 130 kHz. For TESLA it is planned to scan the beam profile with at least ten scan points within one bunch train, which sets the minimum operation frequency of the scanner to 1 kHz and for the laser to 10 kHz. This serves as a guideline for the choice of scanner and for the tests at PETRA.

3.2 Candidate Technologies

There are two promising candidates: Acousto-optic (AO) scanners and piezo driven mirrors. AO scanners using Bragg reflection in a block of fused silica are able to operate at very high speed with random access times in the order of $\Delta t = 0.5$ μs enabling the scanning of every third bunch within TESLA parameters. The devices are also very compact and widely used in industry as Q-switches for high power lasers. The drawback of AO scanners is their low damage threshold and their need for anamorphic beam compression and expansion to match the laser beam profile into the scanner aperture. In addition, the mode quality is dramatically decreased with a diffraction efficiency in the order of 40% for full deflection.

The second interesting technology is based on piezo driven platforms, where a laser mirror is moved by a small stack of piezo electric material sandwiched in a tilting platform. These platforms are able to operate in discrete and continuous mode with frequencies up to 5 kHz within specifications. Since these platforms deflect the laser beam with a mirror, the damage threshold is rather high and the beam distortion should be minimal.

Due to its high damage threshold and the versatility in operation mode, the first tests will be performed with a piezo tilting platform. Preparations are currently under way to perform spot size measurements during high frequency scanning and to quantify any resulting beam distortion.

4 DETECTOR

At every laser and electron bunch crossing, a burst of Compton scattered photons is released. The total scattered energy at each burst can then be used to determine the relative position of the laser and electron beams. A series of simulations and measurements are currently under way to determine the most suitable detector for measurements at PETRA and TESLA. The most stringent requirements at PETRA are imposed by the bunch separation (192 to 480 ns) and by space constraints at the beamline.

To avoid pile-up of events, the detector must have a decay time that is short relative to the bunch spacing, so a fast material is required. The material must also have a relatively high scintillation light output, be radiation hard and should have a small radiation length in order to contain fully the electromagnetic shower. The Compton photons are emitted within a small angle relative to the electron direction and so the active volume of the detector must be compact (i.e. possess a small Molière radius) so that it can fit close to the beampipe.

These requirements for the PETRA laser wire calorimeter have led to the choice of lead tungstate (PbWO4) as active material, a crystal whose characteristics [6] are listed in Tab. 1.

Radiation length	[mm]	8.90
Molière Radius	[mm]	22
Density	[g/cm^3]	8.28
Avg. #Photoelectrons/MeV		16
Decay time	[ns]	5–15

Table 1: Relevant PbWO4 characteristics.

A primary requirement of the PbWO4 calorimeter is that it must contain most of the shower resulting from the Compton scattered photons. The overall dimensions required for the crystal in the PETRA case were determined by detailed simulations within the Geant4 [7] framework, using a cuboid shaped crystal of variable length and width. In these simulations photons of energy 350 MeV, which is the maximum energy of a Compton-scattered photon from a 4.5 GeV electron beam, were projected towards the detector. The resulting relative energy containments for various crystal dimensions are shown in Fig. 5a. It can be seen that more than 90% of the incoming photon energy is contained within the crystal for an overall size of 54 mm in width and 150 mm in length, leading to the choice of a 3 by 3 matrix of crystals, each with dimensions $18 \times 18 \times 150$ mm. The energy resolution of such a matrix is presented in Fig. 5b as a function of the number of Compton-scattered photons for three beam energies relevant to the PETRA environment [3]. These simulations show that an energy resolution of better than 5% should be reached with a nominal 1000 Compton-scattered photons at a PETRA beam energy of 12 GeV.

These simulations will be tested against measurements using a PbWO4 crystal matrix at the DESY II test-beam, where detailed calibration and efficiency studies are planned.

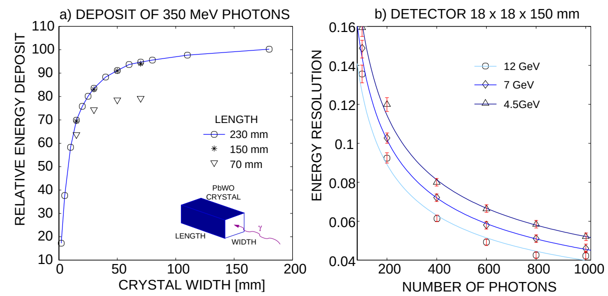

Figure 5: a) Relative energy containment for 350 MeV photons inside a PbWO crystal for three crystal lengths. b) Energy resolution for three beam energies.

5 SUMMARY

A broad range of studies are underway, aiming towards the installation of a prototype laser wire system at the PETRA storage ring. Detailed design studies, measurements and simulations have been performed for the final focus optics and the implementation of a fast scanning system based on piezo driven mirrors is currently under study. The vacuum chamber for the laser wire is now being constructed at DESY. Detailed simulations of the Compton calorimeter have been performed and test-beam measurements are imminent. Tests of the full scanning laser wire system are expected to take place in 2003.

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6 REFERENCES

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