HIGH ENERGY DENSITY IRRADIATION WITH THE MAMI LINAC*

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Abstract

In order to build a positron source for the ILC, a high energy density irradiation is needed to test the used materials. At the MAMI injector linear accelerator (ILAC) such a radiation can be provided at different electron energies. With a macro pulsed source it is possible to imitate a year-long radiation at the ILC within several hours. Small transverse beam sizes need to be provided with the focusing system and be measured at high beam currents using transition radiation and beam loss measurements on pin holes.

MOTIVATION

The international linear collider (ILC) is a planned electron-positron-collider with a length of about 31 km and a center of mass energy of 500 GeV. The machine will operate in a pulsed mode with a time structure of 1 ms long bunch trains and a repetition rate of 5 Hz (Fig. 1). In order to produce positrons, the final accelerated electron beam is guided through an undulator. The generated radiation hits a target at which positrons are generated due to pair production. These positrons are then accelerated and guided towards the interaction point (See Fig. 2).

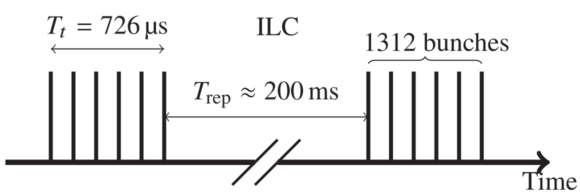

Figure 1: Time structure of the pulses at ILC.

POSITRON TARGET

Pulsed undulator radiation penetrates a rotating titanium alloy target in order to produce positrons (Fig. 3). The incoming macro pulsed light beam frequently heats up the target. The fast alternating temperature leads to mechanical stress in the target material. It is mandatory to predict the long term behavior of the material foreseen for the target, since frequent target failures are not acceptable at ILC. These conditions can be imitated at the MAMI linear injector. This is due to the fact that the main dissipative interaction in the Positar is caused by electrons which are generated by Compton scattering of the undulatar photons. Since it is at present not possible to generate such a photon beam (this would mean to actually build a large fraction of the ILC) electrons of the MAMI ILAC are injected directly into a small volume where they will have the same interactions at similar energies. An important aspect is that the energy density introduced into the volume during a macro pulse can be made similar to the one foreseen at *PosiTar*. This can be achieved since the beam can be arbitrarily focused. However, due to the enormous photon flux foreseen for the *PosiTar* the area of the impinging electron beam has to be rather small.

MAMI LINEAR INJECTOR

With the MAMI linear injector, a macro pulsed, chopped, cw electron -beam can be provided in order to fulfill the desired conditions. The parameters of the beam are shown in Table 1. At 3.5 MeV ($\beta \cdot \gamma = 7.8$) most of the kinetic energy of the electrons gets lost due to collision processes. According to the Bethe-Bloch-formula, this is in the range of the ionization minimum [1]. With the thickness of the target $d_{\mathbf{target}} = 0.2$ mm and density $\rho_{\mathbf{Ti}} = 4.5\,\mathrm{g\,cm^{-3}}$, this leads to an energy deposition of

Table 1: MAMI Injector Beam Parameters

Parameter	**Value**
Operation frequency	2.45 GHz
Beam energy	3.5 MeV
Maximum average current	100 µA
Transversal beam size (RMS)	<200 µm
Possibility of macro pulsing	yes

$$\frac{\mathrm{d}E}{\mathrm{d}x} \cdot d_{\mathrm{target}} \approx 2\frac{\mathrm{MeV\,cm^2}}{\mathrm{g}} \cdot \rho_{\mathbf{Ti}} \cdot d_{\mathrm{target}} = 180\,\mathrm{keV}.$$

Due to the small energy loss of 180 keV, the energy deposition can be treated as constant within the depth of the target. This is also the case at the ILC. Simulations performed at DESY by the *PosiTar* colleagues have shown that the ILC conditions can be imitated with an average current of $I_{\mathrm{avg}} = 50\,\mu\mathrm{A}$, a duty cycle of 20 %, and a macro pulse length of $T_{\mathrm{pulse}} = 5$ ms, if the transverse beam size can be focused to be smaller than $R_{\mathrm{beam}} = 300\,\mu\mathrm{m}$. These parameters can be reached with the MAMI injector (Tab. 1). This results in a peak energy deposition density (PEDD) of 66 J g^{-1}. At the ILC the PEDD is between 40 J g^{-1} and 50 J g^{-1} for the target and 55 J g^{-1} for the exit window [2].

INSTALLATION

The irradiation takes place at extraction beam line *SF35*. Targets and diagnostic screens are mounted on a holder (Fig. 4). This holder can be moved under vacuum to different positions using a so-called scanner. The arrangement

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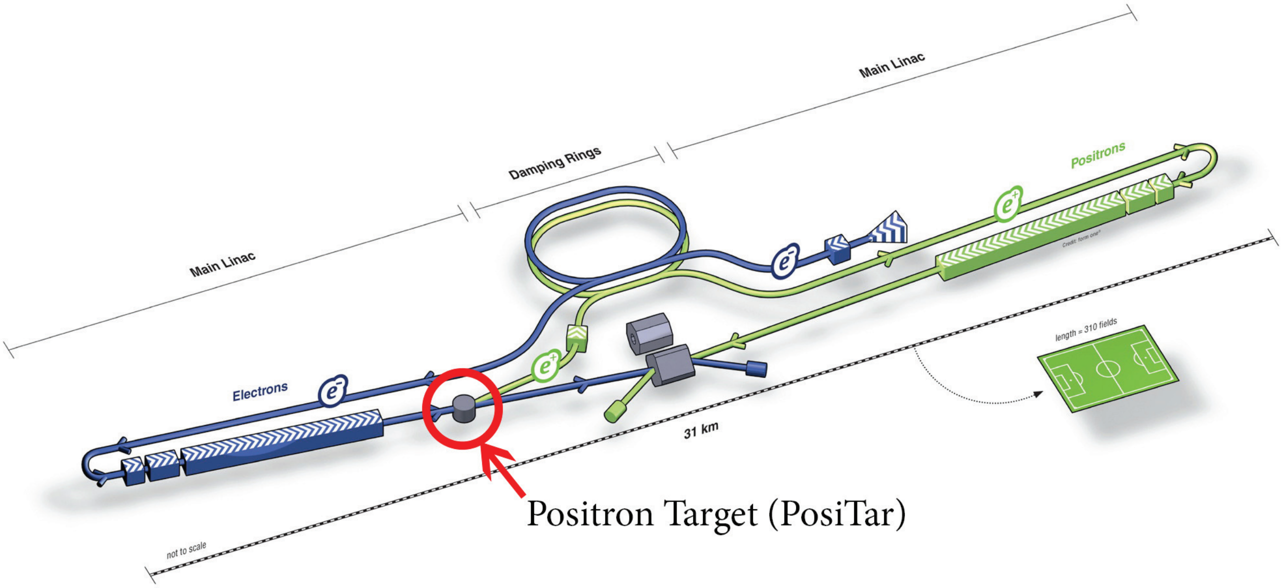

Figure 2: Schematic sketch of the ILC -beam line. [3]

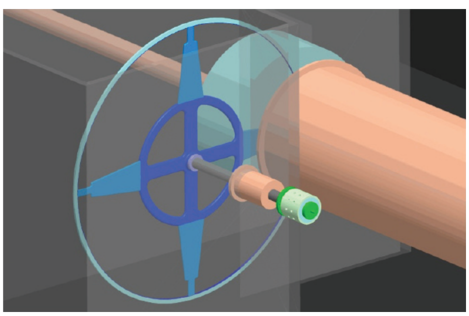

Figure 3: Layout of the positron target. The target is a rotating disc with a diameter of 1 m in order to reduce local stress. Picture taken from [4].

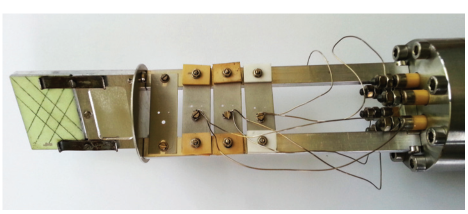

Figure 4: Holder for multiple targets. Two screens on top of the targets are needed for beam optimization. The multiple feedthroughs/wires serve to measure the temperatures and currents on the different targets.

at *SF 35* is shown in Fig. 5. The targets are isolated from the holder with ceramics and are connected with two thermocouple wires. So it is possible to measure temperature and current during irradiation. Two screens are mounted at an angle of 45° and can be observed through a window with a camera. A Faraday -cup is installed after the scanner to measure the total beam current. A quadrupole triplet is installed in front of the scanner in order to reduce transverse beam size.

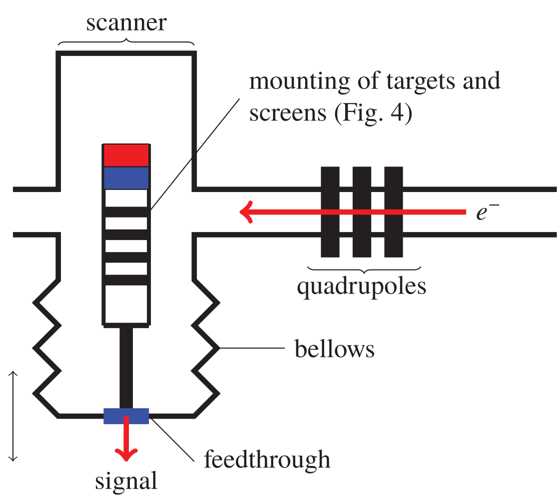

Figure 5: Arrangement to irradiate multiple targets at SF 35.

BEAM DIAGNOSTICS

One criterion which has to be fulfilled is a small transverse beam size at the position of the targets. In this arrangement, we have three ways to measure this quantity. One has to consider that the shape and size of the beam change at higher currents due to space charge and characteristics of the source.

Fluorescent Screen

For low currents (some nA), a fluorescent screen is placed at an angle of 45° into the beam and is observed by a camera. It is used to align the beam optically at the center of the targets and to do first transverse optimizations. This screen cannot be used at higher currents because it gets damaged by excessive thermal dissipation. Another reason is that the signal is getting too bright to determine the exact shape of the beam. Nevertheless it is necessary to do a coarse adjustment

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of each element in the accelerator. An adjustment only at high currents is not possible due to radiation issues.

Optical Transition Radiation (OTR)

If a charged particle passes two materials with different dielectric constants, OTR is emitted. In this case, a standard aluminum foil with a diameter of 15 µm is placed into the beam. Aluminum has a small density, and the foil is thin enough for most of the beam to pass through it without heating it too much. As long as the foil is thicker than the wavelength of the emitted OTR (15 µm >>∼ 600 nm), the intensity is nearly independent of the frequency ω [5]. The whole visible range can be used equally well for measurements. There is only a dependency on the emitting angle Θ (Fig. 6). The OTR power emitted in backward direction can be written as follows.

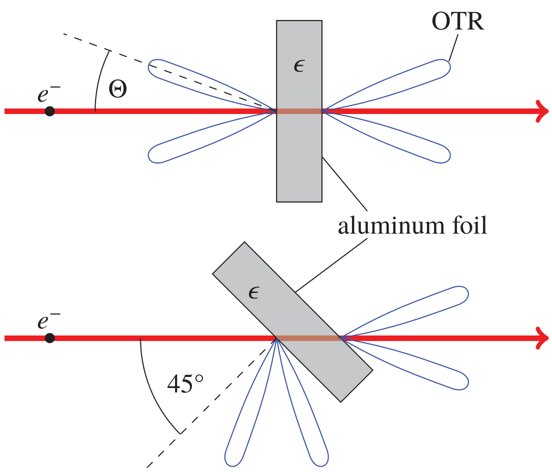

Figure 6: Scheme of emitted OTR (blue) at the aluminum foil perpendicular to the beam and at an angle of 45°. In the latter case, OTR can be observed easily at an angle of ≈ 90°. [6]

$$W(\omega, \Theta) \approx W(\Theta) = \frac{e^2}{4\pi^3 \epsilon_0 c} \frac{\beta^2 \sin^2 \Theta}{(1 - \beta^2 \cos^2 \Theta)^2} \quad [5]$$

This leads to an angle Θ_{max} with the maximum intensity of the OTR.

$$\Theta_{max} = \pm \sin^{-1}\left(\frac{1}{\beta\gamma}\right) \approx \pm\frac{1}{\beta\gamma} = \pm\frac{1}{7.8} = 7.38°$$

This is a problem because it is very difficult to observe the signal so close to the beam line. By mounting the aluminum foil at an angle of 45°, the maximum of the emitted OTR will be at an angle of $\Theta'_{max} = 90° \pm 1/\beta\gamma$ [6]. This arrangement allows to observe the maximum emitted OTR intensity at an angle of ≈ 90° to the beam. Fig. 7 shows three pictures of the transition radiation taken at different beam currents. It is evident that the spot becomes larger with increasing current. In this case, no re-optimizations have been done at the higher currents. Without this method, it would not be possible to guarantee small beam sizes at the desired currents. When performing optimizations, one has to take into account that the foil can be damaged. This can lead to a deformation and thus to a distortion of the OTR picture.

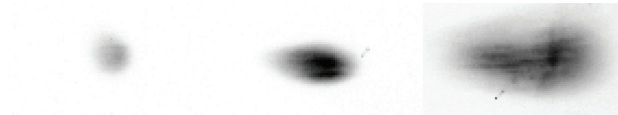

Figure 7: Emitted OTR from aluminum foil at three different beam currents (from left to right: 10 µA, 50 µA, 100 µA). Broadening of the beam spot due to space charge and emitting mechanism of the source. Black/white inverted for better recognizability. [6]

Beam Loss Measurement on Pin Hole

This method is mainly used to locate the electron beam on the target surface but can also be used to verify the measured beam diameters with the OTR technique. A hole with a diameter of 1 mm is drilled in each target. Since all of them are isolated and connected with wires, a signal that is proportional to the beam current will be observed. It will be reduced if the beam is directed towards the hole. Then, the relative reduction allows to infer the size of the beam if an assumption on the intensity distribution is made. In this way, the beam is located on the target, and the desired position can be reached by moving the scanner. Taking the ratio of the two measured currents and with knowledge of the hole diameter, it is possible to determine the transverse beam size. Tab. 2 shows the transverse beam size at a beam current of 50 µA measured with the two methods above. σ_1 and σ_2 indicate the smallest and largest radius of the beam. The OTR observation shows that the beam is indeed circular to good approximation. The deviation is probably due to the fact that a model of the beam has to be created in order to get an result from the current measurement. In this case, the model used is a two-dimensional Gauss, which differs a bit from the real shape of the beam.

Table 2: Transversal beam size obtained with the OTR technique and the current measurement in comparison. [6]

	σ_1[µm]	σ_2[µm]
OTR	281	254
Current measurement	319	277
Deviation	12 %	9 %

CONCLUSION

The diagnostic tools developed for the experiment described in this paper have been very useful and high energy densities in the target have been achieved. The material tests for the ILC positron source as well as for the exit window of the arrangement have been running until now with success. The observations resulting from the irradiations are presented in another contribution to this conference [2].

REFERENCES

[1] R. William Leo, "Passage of Radiation Through Matter", in *Techniques for Nuclear and Particle Physics Experiments*, Lausanne, Switzerland, Springer, 1987, pp. 24-33.

[2] A. Ushakov et al., "Material Test for the ILC Positron Source", Presented at IPAC 2017, TUPAB002, this conference.

[3] Linear Collider Collaboration, `https://www.linearcollider.org`

[4] ILC Technical Design Report Vol.3 (2013).

[5] V.L.Ginzburg and I.M.Frank, ZhETF 16, 15 (1946); A shortened (English) version: Frank, I. M. and Ginzburg, V. L., J. Phys. USSR 9,353 (1945).

[6] T. Beiser, "Quadrupol-Fokussierungssystem für Materialtests zum ILC Positronentarget", Diploma thesis, Institut für Kernphysik, Johannes Gutenberg-Universität, Mainz, Germany, 2017.

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