DEVELOPMENT OF A POSITRON PRODUCTION TARGET FOR THE ILC POSITRON SOURCE

I.R. Bailey[1,3*], V. Bharadwaj[4], P. Cooke[3], J.B. Dainton[1,3], J. Gronberg[2], D. Mayhall[2],
T. Piggott[2], D.J. Scott[1,3], J. Sheppard[4], W. Stein[2], P. Sutcliffe[3]
[1] Cockcroft Institute, Daresbury Laboratory, Warrington, Cheshire, WA4 4AD, UK
[2] Lawrence Livermore National Lab [†], Livermore, CA 94551, USA
[3] Department of Physics, University of Liverpool [‡], Liverpool, L69 7ZE, UK
[4] Stanford Linear Accelerator Center [§], PO Box 20450, Stanford, CA 94309, USA

Abstract

The future International Linear Collider (ILC) will require of order 10^{14} positrons per second to fulfil its luminosity requirements. The current baseline design produces this unprecedented flux of positrons using an undulator-based source. In this concept, a collimated beam of photons produced from the action of an undulator on the main electron beam of the ILC is incident on a conversion target. Positrons produced in the resulting electromagnetic shower can then be captured, accelerated and injected into a damping ring. The positron source community is pursuing several alternative technologies to develop a target capable of long-term operation in the intense photon beam.

In the design being developed jointly by Lawrence Livermore National Laboratory (LLNL), Stanford Linear Accelerator Center (SLAC), the University of Liverpool and the Cockcroft Institute a thin (0.4 radiation length) water-cooled titanium alloy target wheel of diameter 2 m is rotated at approximately 1000 rpm to spread the incident power of each pulse over a wide area. We review the role of the target in the positron source and present the latest target design.

INTRODUCTION

In collaboration with colleagues at SLAC and the University of Liverpool, LLNL has developed a conceptual design for a rotating water-cooled titanium alloy target wheel and its associated support systems for use in the ILC positron source. The University of Liverpool and other UK groups are currently in the process of adding engineering detail to the design with a view to producing a series of prototypes.

Throughout this document it is assumed that the undulator-based source will remain the baseline technology for the ILC [1], but the target system described here could be adapted for use in the alternative Compton backscattering source [1] if required.

The remainder of this paper outlines the current status of the target design project.

PHOTON BEAM CHARACTERISTICS

The intense photon beam from the helical undulator will have the same bunch structure as the main ILC electron beam: nominally 5 pulses per second where each pulse consists of 2820 bunches of 1 ps duration with 308 ns between bunches. The helical undulator has a baseline length of 100 m, a period of 10 mm and a deflection parameter (K-factor) of 1.0, giving a first harmonic photon energy of 10 MeV when operated at the 150 GeV energy point of the electron linac. The undulator length has been determined assuming that the target is immersed in the magnetic field of the capture optics, which maximizes the positron capture efficiency. In other target configurations the length of the undulator may vary.

For reference, the energy spectrum of the photons emitted from a perfectly aligned continuous helical undulator simulated by the SPECTRA [2] software package using the baseline design specifications is shown in figure 1. Details of design studies and prototypes for realistic ILC helical undulator modules can be found in [3, 4].

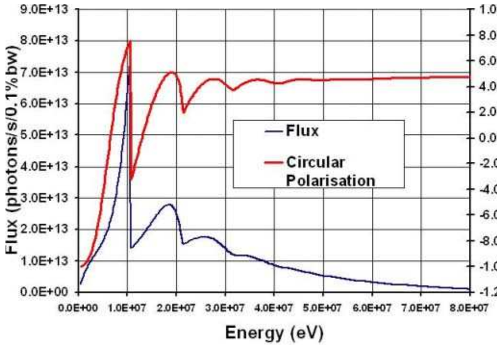

Figure 1: Baseline undulator photon energy spectrum shown in blue, and the degree of right-handed circular polarization shown in red.

For the nominal parameters of the ILC electron beam, the average integrated power of the photon beam is approximately 145 kW where each bunch of photons carries

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[*] i.r.bailey@liverpool.ac.uk

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a total energy of approximately 11 J and consists of order 10^{13} photons prior to collimation. However, the ILC electron beam bunch structure is defined by a parameter plane rather than a fixed point. Taking into account the possible variation in parameters, the photon beam power incident on the target may be as high as 300 kW in some operating conditions.

Photons produced from a helical undulator are circularly polarised (see figure 1), where the degree of circular polarization depends on the energy of the photons and the angle at which they are produced. Positrons produced in the target from these polarised photons likewise exhibit a net longitudinal polarization which will depend on the degree of collimation of the incident photon beam. The production of polarised positrons may be of great importance to the physics reach of the ILC [5], but should not have a large impact on the target's specifications.

TARGET DESIGN

The target is composed of several subsystems: the target wheel, drive system, cooling system, vacuum system, remote-handling system and diagnostic and control systems. The current status of these subsystems is summarized in the following subsections.

Target Wheel

A CAD drawing of the target wheel is shown in figure 2; the wheel consists of an annular titanium alloy (Ti-6%Al-4%V) rim connected to a central drive shaft by four equally-spaced radial struts. The photon beam will be incident on the rim, which has a radial width of approximately 30 mm and a thickness of 0.4 radiation lengths (14 mm) in the beam direction. The target is positioned approximately 500 m downstream of the end of the undulator giving an incident spot size at the target of approximately 1 mm rms in radius (i.e. 95% of the photon beam power will be delivered in a circular spot of approximate diameter 4.0 mm).

Simulations using GEANT4 [6] suggest that less than 10% of the power of the photon beam will be dissipated in the target thermally. The maximum energy deposition in the target from each photon bunch of the nominal 145 kW photon beam is therefore expected to be approximately 2.4 J/g, and the total energy deposited by a pulse incident on a static target would be approximately 6.7 kJ/g. Rotating at 1000 rpm, the 1 m radius wheel moves by approximately 5° during a pulse duration and undergoes more than three full revolutions between pulses.

The characteristics of the target wheel and the results of simulations carried out by LLNL for a previous iteration of the design (a 1 m radius solid disc target wheel and a 220 kW photon beam) are summarized in table 1. In this case, the maximum allowable fatigue stress at the target operating temperature was found to be 8.3×10^8 Pa, a factor of 2 higher than the calculated peak stress.

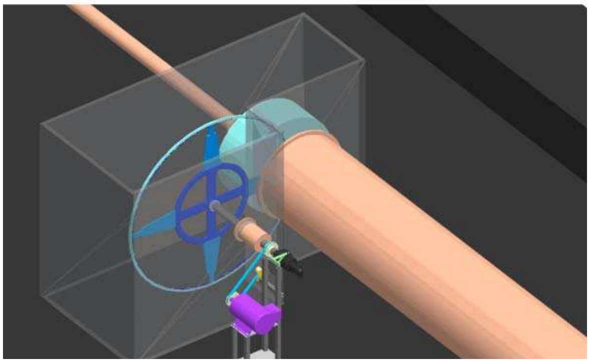

Figure 2: Drawing of the target wheel design. The drawing is oriented with the photon beam pipe in the top left and the wider positron beam pipe in the bottom right. The target wheel is mounted inside a vacuum vessel (shown translucent for clarity) where the rim of the wheel passes through the gap between the magnets of the capture optics and the entrance to the positron beam pipe. The drive shaft of the target wheel is attached to a motor via a pulley system.

Table 1: Target wheel parameters. (* indicates the value was calculated for a solid disc wheel.)

Wheel Diameter	2000	mm
Rim thickness	14	mm
Wheel RPM	1000	rpm
Rim velocity	100	m/s
Wheel stress from rotation*	3×10^7	Pa
Wheel stress from photon beam*	4×10^8	Pa
Maximum temperature increase*	411	°C
Target design lifetime	2	years

Cooling System

Cooling of the target is provided by an internal water-cooling channel with a circular cross-section 7 mm in diameter. The channel follows the radial curvature of the target at a radius of 0.98 m, and water is fed into the channel via a rotating coupling attached to the drive shaft.

A water flow velocity of 5 m/s is foreseen in order to obtain a convective heat transfer coefficient (from Nusselt correlations) of 20 kW/m^2/°C between the tube walls and the bulk water flow. Simulations carried out for the earlier solid disc design show that, for these heat transfer conditions, the water does not heat up by more than 8 °C as it flows through the wheel, the tube wall temperature is less than 5°C above the water bulk temperature, and the water flow pressure drop in the system is less than 7×10^4 Pa. Preliminary studies of the current design show that the water is expected to heat by approximately 12 °C.

Vacuum System

The target wheel is mounted in a vacuum vessel at a pressure determined by the vacuum requirements of the accelerating cavity downstream of the target (nominally 10^{-8} Torr) and the amount of differential pumping that can be achieved between the target and the cavity. The quality of the vacuum will be limited by outgassing from the target and leakage from the seals associated with the remote-handling system.

The target drive shaft penetrates the vacuum vessel wall into the surrounding air space, and a rotating vacuum feedthrough is employed to allow a vacuum seal to be maintained around the rotating shaft. A ferrofluidic feedthrough, such as those manufactured by Rigaku Vacuum Products [7], is thought to be appropriate.

Eddy Currents

A strong magnetic field will be needed to maximize the capture efficiency of the positrons emerging from the back of the target, and hence reduce the required power of the photon beam. In the current design, the target rim is assumed to be placed in the tapering axially-aligned magnetic field of a superconducting Adiabatic Matching Device (AMD). The strength of the resulting magnetic field at the surface of the target may be as high as 6 T, which will generate large eddy currents when the target is rotated.

The average eddy current power loss for a 1 m radius disc target wheel is estimated to be 2 MW. The estimated power loss for the current rim design is only 15 kW, and it is for this reason that the rim design has been adopted. The absolute values of the eddy current power loss (obtained using the Maxwell 3D software package [8]) have yet to be calibrated against experimental data being gathered at SLAC and should therefore be treated only as preliminary indications of the true power loss.

In principle, eddy currents can be further reduced by introducing laminations into the target wheel or by the use of a warm pulsed AMD design currently under investigation.

Radiation and Remote Handling

Preliminary radiation damage calculations using the codes FLUKA [9] and SPECTER [10] show that the induced displacements per atom (dpa) in the target lie far below the maximum acceptable value of 0.5 dpa, even after 2 years of continuous operation in the photon beam. This conclusion is supported by a recent study of the target radiation environment which can be found in [11].

Studies of target designs for other positron sources [12], as well as ongoing analyses of the current ILC positron target design predict levels of activation of approximately 100 mSv/h close to the target. The recommended whole-body exposure limits for radiation workers in the EU is 20 mSv/yr [13], and it is therefore essential to include adequate shielding and remote handling equipment in the design. A general discussion of radiological problems at high-energy electron-positron converters can be found in reference [14].

The current design features a 'horizontal' remote-handling system, as used at the ISIS second target station [15], in which the vault consists of an inner vacuum vessel and two outer hot cells surrounded by concrete shielding. When a target fault develops, the hot spare target is deployed into the beam whilst the faulty target is withdrawn into its hot cell where it can be repaired using manipulator arms.

The target and positron capture optics will be moved between the vacuum vessel and the cells as a single unit, passing through ports sealed by pneumatic seals.

An alternative 'vertical' remote-handling design is also being investigated. This design may be simpler and more cost-effective if shown to be viable.

SUMMARY AND OUTLOOK

A design for a titanium target wheel that satisfies the requirements of the ILC baseline positron source has been developed, and the design of the remote-handling and other systems are in progress. Construction will soon begin on a series of target wheel prototypes which will be tested for mechanical and thermal stability leading to a mature technical design for inclusion in the future ILC Technical Design Report.

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