A PROTOTYPE TARGET WHEEL FOR THE ILC POSITRON SOURCE

I.R. Bailey[1,2*], D.G. Clarke[3], J.A. Clarke[1,3], K.P. Davies[3], A.G. Gallagher[3],
J. Gronberg[5], L. Hagler[5], L.J. Jenner[1,2], C.J. Nelson[4], T. Piggott[5]
[1] Cockcroft Institute, Daresbury Campus, Warrington, Cheshire, WA4 4AD, UK
[2] Department of Physics, University of Liverpool [†], Liverpool, L69 7ZE, UK
[3] STFC Daresbury Laboratory, Warrington, Cheshire, WA4 4AD, UK
[4] STFC Rutherford Appleton Laboratory, Didcot, OX11 0QX, UK
[5] Lawrence Livermore National Lab [‡], Livermore, CA 94551, USA

Abstract

In this paper we describe the design, construction and commissioning of a prototype based on the positron production target wheel planned for the International Linear Collider (ILC) positron source. The efficiency of the current baseline positron source design for the ILC can be improved if the conversion target is partially immersed in the magnetic field of the capture optics, thereby increasing the overall capture efficiency for positrons by a factor of two or more. However, immersion of the rotating target wheel generates strong eddy currents leading to additional heating and stresses on the wheel. The primary purpose of our prototype, which has been assembled at Daresbury Laboratory, is to investigate the effects of eddy currents induced in a titanium alloy wheel moving with rim speeds up to 100 ms^{-1} in magnetic fields of the order of 1 T.

INTRODUCTION

In the baseline design for the ILC positron source [1] the high-energy (150 GeV) electron beam from the electron linac is diverted through a beamline containing a helical undulator insertion device 147 m in length with a period of 1.15 cm, generating gamma rays with an average energy close to 10 MeV. A prototype undulator module with parameters close to those specified for the ILC has recently been constructed by the HeLiCal collaboration [2].

The average integrated power of the photon beam generated by the ILC undulator will be approximately 131 kW, with each bunch of photons carrying a total energy of approximately 10 J and consisting of order 10^{13} photons. The beam will pass through a collimator [3] before being incident on the rim of a Ti 6%Al 4%V target wheel 0.4 radiation lengths thick.

The proposed target wheel comprises a circular rim 1 m in diameter connected to a central drive shaft by five equally-spaced radial struts. The wheel will be oriented with the photon beam parallel to the drive shaft, such that photons will strike the rim, which will have a radial width of 30 mm. The target will be positioned at least 500 m downstream of the centre of the undulator, giving a photon beam spot with a rms radius of at least 2 mm. As the target wheel will be housed in a vacuum vessel at a pressure of 10^{-7} Torr or less, the wheel will be water-cooled and the water will flow through the hollow drive shaft via a rotating union and through an internal channel contained inside the target rim.

Particle tracking simulations [4] predict that approximately 8% of the power of the photon beam will be dissipated in the target. The average energy density in the region of the target rim struck by a photon macropulse (2625 bunches in 1 ms) is therefore expected to be approximately 900 J/g for a static target, which reduces to 40 J/g when the rim is rotated at the design speed of 100 ms^{-1}. At this speed, the target will rotate approximately 12° over the duration of a macropulse and undergo a rotation of more than six full revolutions between consecutive macropulses.

Positrons emitted from the target wheel are to be focused in a pulsed flux concentrator device before being accelerated first to 400 MeV by normally-conducting r.f. cavities, and subsequently to 5 GeV by a superconducting booster linac before finally being injected into a damping ring. The capture efficiency of the positron source can be substantially improved if the conversion target is partially immersed in the magnetic field of the capture optics [5]. However, the effect of eddy currents generated in the target wheel rim due to the interaction between the rotating metal surface and the magnetic field must be taken into account.

We are currently finishing construction of a first prototype of the target wheel with the aim of investigating the eddy currents and benchmarking the associated numerical simulations. At a rim velocity of 100 ms^{-1} and a magnetic field strength of 1 T simulations predict eddy current power loads in the prototype of several kW, but estimates differ widely depending on the assumptions made in the computer models [6, 7].

The mechanical design and data acquisition system for the prototype are discussed below followed by a description of the proposed experimental programme.

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

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MECHANICAL DESIGN

The prototype wheel closely resembles the baseline target but does not have internal water cooling channels, and is designed to be operated in air rather than in a vacuum. A drawing of the wheel and the target assembly is shown in Fig. 1.

The wheel has been manufactured from the same titanium alloy as specified for the baseline target and has the same outer diameter, radial wheel width and number of spokes. The thickness of the prototype wheel rim has been measured to be 15.6 ± 0.1 mm, where the uncertainty corresponds to the rms variation in the thickness of the material. The wheel has been balanced to a balancing quality grade of G2.5, and has a small residual unbalance measured to be approximately 0.8 g. A central drive shaft connects the wheel via a torsionally-stiff flexible coupling and torque transducer assembly to a 15 kW drive motor. The shaft is supported by two Plummer block bearing units mounted on a custom-made frame. The motor stands on a separate frame, and the motor and the wheel have been aligned using a laser tracker to a radial alignment tolerance of ± 0.42 mm and an angular alignment tolerance of $\pm 0.75^\circ$ as required by the torque transducer assembly, which is itself balanced to balancing quality grade G2.5.

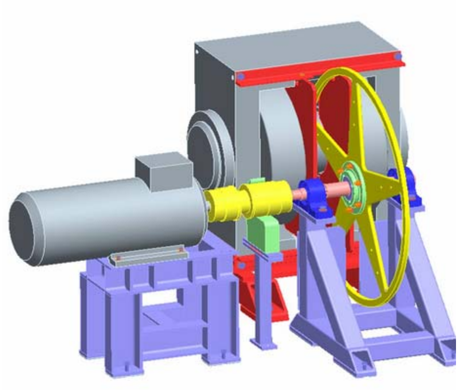

Figure 1: A 3d model of the target wheel prototype. The motor (light grey) is shown on the left, and the dipole magnet (light grey) is shown on the right behind the wheel (yellow). The torque transducer (yellow) is shown on the drive shaft (pink).

A (constant) magnetic field will be generated by a water-cooled dipole electromagnet with cylindrical pole caps 250 mm in diameter. The magnet support structure (shown in red in Fig. 1) will allow the fraction of the wheel rim immersed in the high-field region to be adjusted by varying the relative distance between the centre of the wheel and the centre of the pole caps. The minimum pole gap envisaged during operation of the rotating wheel is 50 mm, which corresponds to a maximum peak field of 1.5 T. The magnet geometry limits the maximum length of the immersed arc of the wheel rim to be 190 mm as illustrated in Fig. 2.

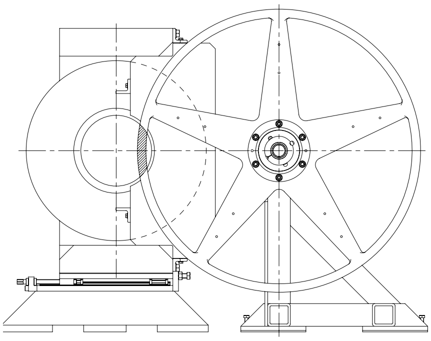

Figure 2: Diagram showing a transverse slice of the prototype assembly. The immersed arc of the target wheel rim is shown cross-hatched.

OPERATIONAL CONSIDERATIONS

Two independent finite element analyses of the stresses on the wheel during operation have been carried out and cross-checked against each other. The models are in good agreement and show the maximum deformation of the wheel rim due to inertial loads at an angular velocity of 2000 rpm to be 0.29 mm, whilst the regions of maximum stress are predicted to be located either side of each spoke, with a peak value of 126 MPa. The maximum stress predicted is well below the minimum tensile strength of the titanium alloy (960 MPa). Notwithstanding these results, it is intended to house the whole target assembly inside local guarding to contain the wheel in the event of a catastrophic failure during operation. The total kinetic energy of the wheel at 2000 rpm is approximately 50 kJ. Preliminary calculations suggest steel plates with a thickness between 5 mm and 20 mm will be needed, where the variation depends on the plastic deformation properties of the grade of steel chosen. Additional protection for personnel and equipment will be provided by sandbags where appropriate. When the guarding is not in place, the wheel is restricted to run at angular velocities of 60 rpm or less.

As the prototype does not have an internal cooling channel, this heat must be dissipated by another mechanism. Initial calculations show that convective cooling of the rotating wheel in air at room temperature will lead to an equilibrium temperature of the wheel rim of approximately 200° C. During operation the temperature is monitored as described in the data acquisition section below, and air from a centrifugal fan fitted with a dust filter is to be directed through the shielding by a duct in order to protect the magnet and transducers from overheating. In addition, the magnet is fitted with temperature interlocks which isolate the magnet in the event of the coils exceeding a temperature of 50° C. The resistances of the magnet coils are also monitored to ensure that they do not exceed their maximum rated value of $0.54\ \Omega$.

Excess vibrations of the system due to bearing wear or other failure of the prototype are detected by uniaxial accelerometers mounted vertically on each of the two bearing units. The accelerometers are rated to have a sensitivity of one thousandth of the acceleration due to gravity at sea-level at a readout rate of 1 kHz. One accelerometer is connected to a motor interlock which isolates the motor when the signal from the accelerometer exceeds an adjustable threshold. The second accelerometer is used by the data acquisition system. Additional machine protection and personnel safety is provided by motor interlocks fitted to all removable panels on the local guarding and to the door of the caged area in which the prototype is situated.

DATA ACQUISITION

The data acquisition system consists of two PC's interfaced to the power supplies (for the drive motor and the magnet) and to a suite of transducers via USB and serial ports. A rotary torque sensor comprised of strain gauges is mounted on the drive shaft to measure the axial torque acting on the wheel at rates of up to 3 kHz. Infra-red sensors (single-pixel thermal cameras) and thermocouples are used to monitor the temperature of the magnet pole caps, target rim, drive shaft and support structures. As the response of the infra-red sensors depends on the emissivity of the material whose temperature is being studied, calibration of the sensors is currently underway using a thermostatically-controlled heating element and off-cuts of the target wheel material that were produced during the wheel's manufacture. The angular velocity of the drive shaft is monitored by optical encoders both in the torque transducer unit and in the motor controller. As described above, the vibrations of the bearings are monitored using a uniaxial accelerometer. Finally, a Hall probe monitors the magnetic field between the pole caps.

EXPERIMENTAL PROGRAMME

The first phase of the experiment will aim to measure vibrations of the wheel as a function of angular velocity in the absence of a magnetic field. Data from the torque transducer and optical encoder will be logged and compared to provide a cross-check of the angular velocity measurement. Safe operating thresholds for the vibration interlock will be established and the characteristic Fourier spectra of the accelerometer signals will be recorded over a range of angular velocities up to 2000 rpm, and compared to the predictions of a rotordynamic model. Out of plane flex modes of the wheel are predicted to be excited at angular velocities close to 200 rpm and 1100 rpm. Special care will be taken near these critical speeds.

During the second (subsequent) phase of the experiment, the magnetic field strength and wheel speed will be systematically incremented in steps of 0.2 T and 50 rpm respectively, and the resulting torque and temperature readings will be compared with the predictions of the eddy current computer simulations. Data will be taken over a range of immersion depths of the rim in the magnetic field. Using information on the azimuthal angle of the wheel provided by the optical encoders, data taken whilst the spokes of the wheel are travelling through the magnetic field will be considered separately from data taken during the rest of the wheel's rotation so that the transient eddy currents in the spokes can be studied. Models of the effect of the transient eddy currents are currently under development. Simple analytical calculations based on the relative area of rim and spoke immersed in the field suggest that the transient increases in torque associated with the spokes will be less than 2% of the torque associated with the rim, where the distance between the centre of the wheel and the centre of the pole caps is taken as 0.57 m.

During the third phase of the experiment, the wheel will be operated at 2000 rpm for prolonged periods and the components will be monitored for wear. Additional studies with a replacement aluminium wheel are also under consideration in order to investigate the dependence of the eddy currents on the conductivity of the material.

SUMMARY AND OUTLOOK

A design for a titanium target wheel that satisfies the requirements of the ILC baseline positron source has been developed, and construction of a target wheel prototype to investigate eddy currents effects is almost complete. Initial commissioning of the wheel transducers at speeds of 60 rpm is ongoing, and faster operation of the wheel will commence when sufficient guarding is in place. It is anticipated that the experiment will be complete at the end of 2008. Results from the experiment will be useful in optimising the choice of target and capture optics designs for the ILC.

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