EDDY CURRENT STUDIES FROM THE UNDULATOR-BASED POSITRON SOURCE TARGET WHEEL PROTOTYPE

I.R. Bailey[1,2*], C. Brown[5], J.A. Clarke[1,3], J. Gronberg[5], L. Hagler[5], L.J. Jenner[6], T. Piggott[5], D.J. Scott[1,3], L. Zang[1,4]
[1] Cockcroft Institute, Daresbury Campus, Warrington, Cheshire, WA4 4AD, UK
[2] Department of Physics, Lancaster University, Lancaster, LA1 4YB, UK
[3] STFC Daresbury Laboratory, Warrington, Cheshire, WA4 4AD, UK
[4] Department of Physics, University of Liverpool, Liverpool, L69 7ZE, UK
[5] Lawrence Livermore National Lab [†], Livermore, CA 94551, USA
[6] Department of Physics, Imperial College London, London, SW7 2AZ, UK

Abstract

The efficiency of future positron sources for the next generation of high-energy particle colliders (e.g. ILC, CLIC, LHeC) can be improved if the positron-production target is immersed in the magnetic field of adjacent capture optics. If the target is also rotating to reduce the energy deposition density of the incident beam then eddy currents may be induced and lead to additional heating and stresses. In this paper we present data from a rotating target wheel prototype for the baseline ILC positron source. The wheel has been operated at revolution rates up to 1800 rpm in fields up to 1.5 T. Comparisons are made between torque data obtained from a transducer on the target drive shaft and the results of finite-element simulations. Rotordynamics issues are presented and future experiments on other aspects of the positron source target station are considered.

INTRODUCTION

In the baseline design for the ILC positron source [1] the high-energy (150 GeV) electron beam from the electron linac will be diverted through a helical undulator insertion device 147 m in length, generating gamma rays with an average energy close to 10 MeV. The average power of the resulting photon beam will be approximately 131 kW, with each bunch of order 10^{13} photons carrying a total energy of approximately 10 J. The beam will pass through a collimator [2] 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 subsequent average heat load associated with the beam will be approximately 10.5 kW, where this number depends on the positron capture efficiency of the capture optics and the aperture of the collimator.

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 [3]. However, the braking and heating effects of eddy currents generated in the target wheel rim lessen the advantage of reducing the photon beam power and hence must be understood.

A first prototype of the target wheel has been constructed [4] with the aim of investigating the eddy currents and benchmarking the associated numerical simulations. At a rim velocity of 100 m/s 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 [5, 6].

The prototype design and instrumentation is described below followed by a summary of the results obtained.

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 figure 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 resistivity of the wheel rim alloy is taken from the literature to be 1.78×10^{-2} Ωm. Measurements of the resistance of samples of the wheel are pending.

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 measurements of the thickness of the material. 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.

A (constant) magnetic field is generated by a water-

* i.r.bailey@cockcroft.ac.uk
† This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48.

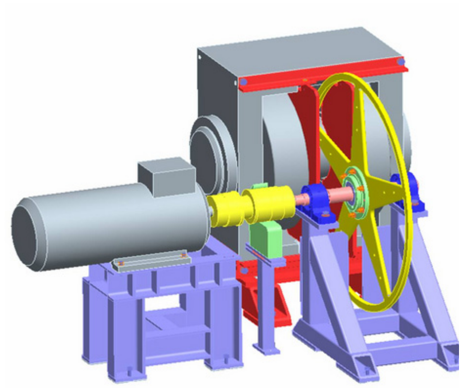

Figure 1: A 3d model of the target wheel prototype. The motor (light grey) is shown on the left, and the dipole magnet (light grey) is shown on the right behind the wheel (yellow). The torque transducer (yellow) is shown on the drive shaft (pink).

cooled dipole electromagnet with cylindrical pole caps 250 mm in diameter. The magnet support structure allows 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 magnet pole caps. Alignment and balancing specifications as well as the safety considerations associated with rotating the wheel at high speeds have been discussed in previous proceedings [4].

INSTRUMENTATION

The prototype is fitted with a range of instruments in order to measure the effects of the magnetic field on the wheel's rotation. Data from these devices is logged using two PC's which are also used to control the motor and magnet power supply. The principle instrument is a rotary torque sensor comprised of strain gauges which is mounted on the drive shaft of the prototype. This allows for measurements of the axial torque acting on the wheel at rates of up to 3 kHz. Vibrations of the system are detected by uniaxial piezoelectric accelerometers mounted vertically on each of the two bearing units. Infra-red sensors (single-pixel thermal cameras) are used to monitor the temperature of the target rim, whilst thermocouple interlocks in the magnet protect it from overheating. The angular velocity of the drive shaft is monitored by optical encoders in both the torque transducer unit and in the motor controller. Finally, a Hall probe temporarily attached to the wheel rim was used to measure the magnetic field between the pole caps.

SIMULATIONS

A range of simulations have been produced to model the eddy current formation in the wheel rim. The first of these is a simple spokeless model developed using OPERA3D and the ELEKTRA software package from Vector Fields Software [7]. The magnet is modelled as two solenoidal coils, one on either side of the target wheel, with steel pole caps and return yoke optionally considered in order to more accurately model the measured field. The measured field and the modelled fields both with and without a return yoke are shown in figure 2 for an immersion depth of 50.25 mm. The immersion depth is defined as the length of overlap between the magnet polecap and the outer edge of the wheel rim as measured along a line between the centre of the wheel and the centre of the polecaps. The field measurements were obtained whilst a current of 100 A was supplied to the dipole magnet, and the current circulating in the simulated solenoids was then adjusted until good agreement was found with the measured peak flux density. The effect on the predicted torque of including the polecaps varies from increases of approximately 1% at 0.5 T to increases of approximately 20% at 1.5 T.

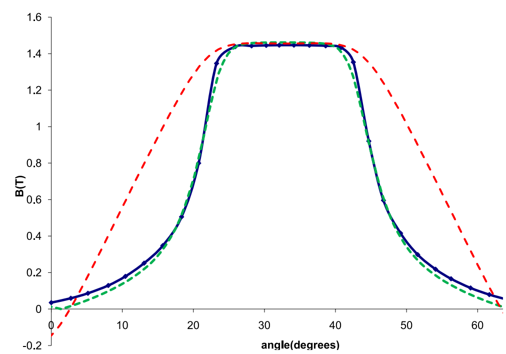

Figure 2: The magnetic flux density in Tesla is shown as a function of the angle in degrees around the wheel rim from an arbitrary zero position. The measured values are shown in blue, the air-cored solenoid model is shown in red dashes, and the steel-cored solenoid model is shown with green dots.

A more sophisticated model was developed using OPERA3D and the CARMEN software package also from Vector Fields Software to take into account the effect of the spokes of the wheel passing through the fringe fields. The predictions of this model are in agreement with a similar model developed by some of the authors at LLNL.

TORQUE MEASUREMENTS

Torque measurements were initially carried out for the rotating wheel without the magnetic field in order to characterize the frictional forces associated with the mechanical assembly. This torque due to frictional forces was found to be well-described by a second-order polynomial and reached values of 15.0 Nm at 1500 rpm with a maximum residual value of 0.2 Nm between the data and the fitted polynomial. All data obtained in the presence of the magnetic field was later adjusted by subtracting the frictional forces given by this polynomial from the measured values.

With the magnet powered, torque data was obtained at intervals of approximately 100 rpm between 100 rpm and 1500 rpm inclusive and was also found to be well-described by a second order polynomial function for each value of the immersion depth and peak magnetic flux density. Figure 3 shows the polynomial obtained from the measured average torque as a function of the wheel operating speed for a peak magnetic field of approximately 0.5 T and immersion depths of 20.25 mm, 30.25 mm and 50.25 mm, where each average was obtained over a period of 180 s. The data has been extrapolated up to 2000 rpm which exceeds the operating speed of 1900 rpm planned for the ILC target. Operating the wheel at speeds above 1500 rpm for prolonged periods was logistically challenging due to the loud noise associated with the wheel's motion through air. This is a limitation of the prototype assembly, as in practice the target wheel would be held at high vacuum when in use inside a positron source.

Comparison with the simulations shows that the effect of the spokes found from the CARMEN model is substantially greater than that observed in the data, but that the observed torques are bounded by the ELEKTRA and CARMEN model predictions. Analogous torque measurements for the maximum investigated flux density of 1.5 T at the maximum immersion depth of 50.25 mm extrapolate to approximately 100 Nm at 2000 rpm, corresponding to eddy current power losses of 21 kW.

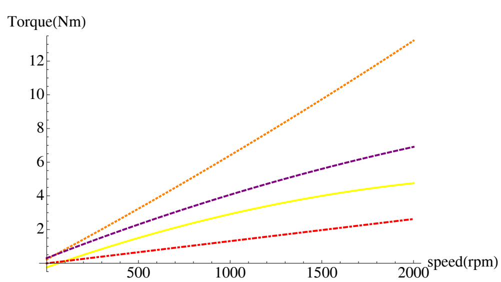

Figure 3: Second-order polynomials fitted to the measured torque values in Nm as a function of the wheel speed in rpm for a peak magnetic field of 0.5 T for immersion depths of 50.25 mm (orange dots), 30.25 mm (purple dashes) and 20.25 mm (yellow). The ELEKTRA prediction for 30.25 mm immersion is shown as the red dot-dash line.

ROTORDYNAMICS

Scans of the the measured torque obtained during gradual acceleration of the wheel at rates of approximately 6.6 rpm/s up to 1800 rpm show resonances due to motions of the wheel and assembly which are also visible in the signals detected by the accelerometers. The standard deviation of the measured torque in the absence of a magnetic field is shown in figure 4 at speeds up to 1200 rpm. Clear peaks are identifiable at integer multiples of 350 Hz which are assumed to be a harmonic series associated with the bearings. At speeds above 1400 rpm a broad band response is observed and is believed to be associated with the transition from laminar to turbulent flow of air between the wheel spokes. Similar measurements obtained with the magnet powered show a peak at approximately 850 rpm which corresponds closely to the prediction of the first torsional mode obtained from a finite element analysis of the wheel.

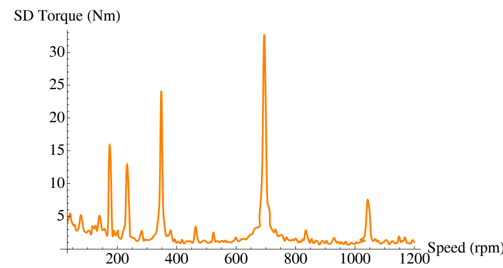

Figure 4: Standard deviation in torque in units of Nm for wheel speeds up to 1200 rpm.

SUMMARY AND OUTLOOK

The torque associated with eddy current production in the target wheel prototype has been measured for a range of immersion depths and magnetic flux densities. The torque data provides a useful resource against which the eddy current simulations will continue to be refined as no single model has yet been found which can accurately model the data for a range of flux densities. The measured torque values correspond to relatively modest heat loads of up to 4.7 kW when operating the wheel in fields of approximately 1 T at 1500 rpm, extrapolating to 8.0 kW at 2000 rpm. These loads should be within the capabilities of the water-cooling system designed for the ILC target wheel. The resonances observed in the torque data are consistent with our understanding of the rotordynamics of the wheel assembly. Work will continue on developing the simulations and further characterizing the target alloy while a further prototype is planned to investigate the reliability of the rotary vacuum seals and water feedthroughs associated with operating the wheel in a vacuum.

REFERENCES

[1] G. Aarons *et al.*, "ILC Reference Design Report", `http://www.linearcollider.org/`.

[2] L. Zang *et al.*, "Studies on the Role of a Photon Collimator for the ILC Positron Source", EPAC 2008 Conf. Proc. (2008).

[3] W. Liu *et al.*, PAC 2007 Conf. Proc. 2918 (2007).

[4] I. Bailey *et al.*, "A Prototype Target Wheel for the ILC Positron Source", EPAC 2008 Conf. Proc. (2008).

[5] S.P. Antipov *et al.*, PAC 2007 Conf. Proc. 2909 (2007).

[6] I.R. Bailey *et al.*, "A Study of the Mechanical and Magnetic Issues for a Prototype Positron Source", EPAC 2008 Conf. Proc. (2008).

[7] Vector Fields Software, `http://www.vectorfields.com/`.