A STUDY OF MECHANICAL AND MAGNETIC ISSUES FOR A PROTOTYPE POSITRON SOURCE TARGET

I.R. Bailey[1,2], D.G. Clarke[3], J.A. Clarke[1,3], K.P. Davies[3], A.J. Gallagher[3], J. Gronberg[4], L. Hagler[4], S. Hesselbach[5], L.J. Jenner[1,2*], C.J. Nelson[1,2], T. Piggott[4], J.H. Rochford[6]
[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] Lawrence Livermore National Lab [‡], Livermore, CA 94551, USA
[5] Institute of Particle Physics Phenomenology, University of Durham, UK
[6] STFC Rutherford Appleton Laboratory, Didcot, OX11 0QX, UK

Abstract

In order to construct a high yield, positron source that can meet the intensity requirements of future facilities, a robust conversion target is needed. One solution is to use a rotating titanium alloy wheel upon which a beam of photons is incident. The efficiency of capturing the resulting positrons can be optimised by immersing this system in a magnetic field. As described elsewhere [1], a prototype of such a target has been built at Daresbury Laboratory, to investigate the mechanical challenges associated with its construction and to study the magnetic effects that the wheel will experience. In this paper, predictions of the eddy current power losses in the target prototype obtained from magnetic modelling simulations are presented, and an initial analysis of the thermal shocks that the ILC target wheel is expected to experience due to beam loading during operation is described.

INTRODUCTION

In the baseline design for the ILC positron source the high-energy (150 GeV) electron beam from the electron linac is diverted through a beamline containing a helical undulator to generate gamma rays with an average energy close to 10 MeV.

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 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 downstream of the undulator such that the photon beam spot will have an rms radius of at least 2 mm.

Particle tracking simulations predict that approximately 8% of the power of the photon beam will be dissipated in the target. Despite the fact that the wheel rotates to mitigate the effects of the intense beam incident upon it, simulations must be carried out to ensure the target is capable of surviving in this environment. The possibility of damage or fracture due to shock waves in the real target wheel is considered later in this paper. Results from one model are presented in the following section.

The efficiency of the positron source design can be substantially improved if the conversion target is partially immersed in the magnetic field of the positron capturing optics, the next element in the beamline after the target itself. 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 of the adjacent capture optics must be taken into account.

The construction of a first prototype of the target wheel has nearly been completed with the aim of investigating the eddy currents and benchmarking the associated numerical simulations. The wheel will be partially immersed in the field of a GMW 3474-140 250 mm dipole electromagnet to simulate the effect of the capture optics. 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 approximately 10 kW but estimates differ widely depending on the assumptions made in the computer models.

MAGNETIC MODELLING

The eddy currents in the target wheel are calculated in Vector Fields Opera [2] using the ELEKTRA rotational solver. ELEKTRA uses a combination of vector and reduced potentials to model time varying electromagnetic field problems. The rotational solver also includes the effects of motion induced eddy currents about a given rotational axis. In reality the target wheel model is not fully axially symmetric due to the spokes, however under the assumption that the interaction of the disk with the magnetic

* l.j.jenner@dl.ac.uk

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field is localised to the rim of the wheel the geometry can be represented as being axially symmetric, see Fig 1.

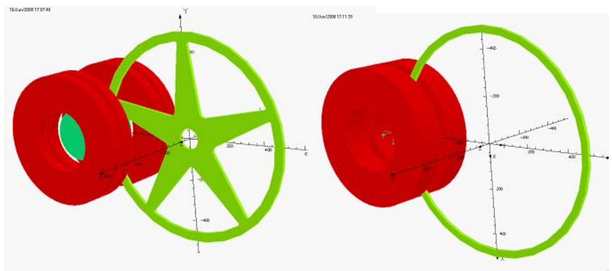

Figure 1: Left: Showing an engineering drawing of the prototype 5-spoked wheel (green). Right: The simplified, axially symmetric model used to allow modelling in ELEKTRA. The solenoidal coils (red) are approximately equivalent to the pole caps of the dipole magnet being used in the prototype tests.

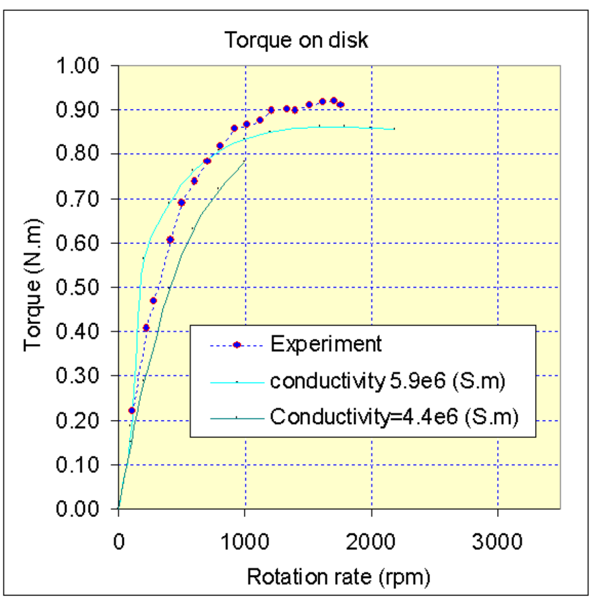

Figure 2: Showing the calculated values for the torque expected at incremental rotation rates and benchmarked against real copper disk measurements.

The rim of the titanium alloy wheel material is modelled to have a thickness of 14 mm, an outer radius of 0.5 m, an inner radious of 0.47 m and a conductivity of 9.26x10^5 S/m. Since the code models the field penetration into a moving material it is essential to have a mesh density smaller then the characteristic skin depth of the components being modelled. The nominal rotational speed of the final target wheel will be $\sim$2000 rpm, and the prototype is designed match this. If we assume that one rotation is comparable to one cycle of an oscillating electromagnetic field, then the frequency is $\sim$40 Hz, yielding an estimate of $\sim$6 mm for the skin depth for this regime. The ELEKTRA modeller has been benchmarked against some experimental data produced by measuring the torque of a spinning copper disk in a magnetic field, carried at out at LLNL/SLAC [3]. The model was found to be in good agreement with the experiment giving confidence in its predictions, as seen in Fig 2. A typical output of the ELEKTRA simulation is shown in Fig 3.

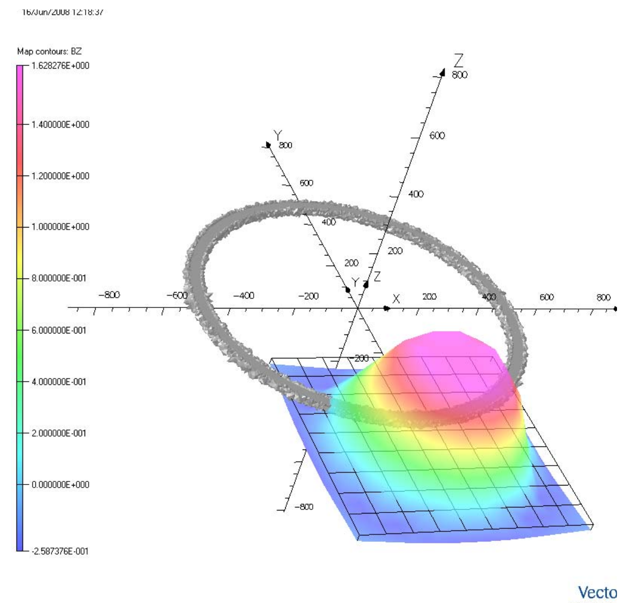

Figure 3: Showing the Opera model of the titanium wheel (grey) immersed in the field region between the coils. The field strength along the z-axis is shown as a coloured contour plot superimposed on the wheel. The peak field strength is 1.6 T.

The simulation is carried out for various speeds and field strengths, which will be mimicked in the prototype experimental program. The distance into the field that the wheel rim is moved, or the immersion depth, is also varied in simulation and in experiment. The immersion depth affects the total area of the wheel that is within the field at any one time and also the amount to which it experiences the strongest and most homogenous field that the magnet produces.

Fig 4 shows the gradually rising eddy currents as the speed of the wheel increases. As expected, the simulation also shows that a lesser immersion into the field causes the wheel to experience a lower peak field and hence less power loss. The nominal working point of the real target wheel will be 2000 rpm in a 1.16 T magnetic field. A simulation tailored to these parameters yields an expected eddy current power loss of 3 kW at an immersion depth of 248 mm. These eddy currents create a magnetic force which opposes the motion of the wheel in the dipole field. The simulation calculates this force to be 30 N, corresponding to a torque of 17 Nm.

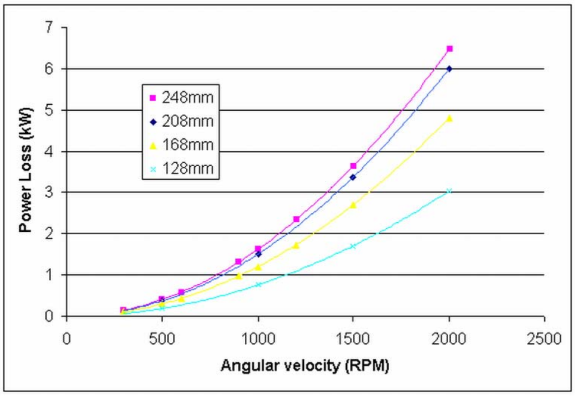

Figure 4: Showing how Eddy Current Power Loss varies with Speed at four different immersion depths at 1.6T.

ANALYSIS OF THERMAL SHOCKS IN THE TARGET

During the operation of the target at the ILC, the rapid energy deposition from the photon beam will cause a pressure shock wave which may damage the target. The shock wave can be described by a hydrodynamical model for the temperature $T = T(\vec{x}, t)$ and pressure $p = p(\vec{x}, t)$ [5].

Initial simulations carried out at LLNL [4] showed that the stresses on the target would be within acceptable limits, but more recent studies at Cornell [6] have shown greater negative pressures associated with the shock wave on the downstream face of the target, which could lead to a failure of the target. In [6] the distribution of the energy deposition has been modelled by a Gaussian approximation,

$$\dot{Q} = \frac{2cQ_{\text{bunch}}}{\pi\sqrt{\pi}\sigma_z\sigma_\perp^2 l_T}\frac{z}{l_T}\exp\left(-\frac{(z-ct)^2}{\sigma_z^2}\right)\exp\left(-\frac{r^2}{\sigma_\perp^2}\right), \quad (1)$$

with the energy deposited by one bunch $Q_{\text{bunch}} = \int \dot{Q}(\vec{x}, t) dV dt$, the bunch dimensions $\sigma_z, \sigma_\perp$ and the target thickness l_T.

In order to check these assumptions, we have compared the resulting energy distribution of Eq. (1) with a FLUKA simulation of the energy deposition in the target, where higher harmonics of the undulator radiation are included and hence the photon beam intensity extends to larger r than for a Gaussian distribution [7]. In Fig. 5 the contours of the volume are shown where 90% of the bunch energy is deposited for both the FLUKA simulation and the Gaussian approximation according to Eq. (1). For the more realistic FLUKA simulation the energy is deposited in a considerably larger volume than for the Gaussian approximation. Although this result casts some doubt on the applicability of the Cornell model in this case, further studies of the hydrodynamic models will be needed to investigate the survivability of the target.

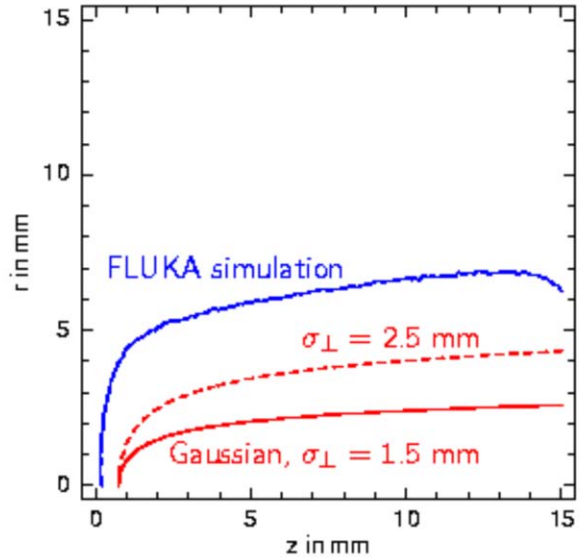

Figure 5: Contours of the volume where 90% of the bunch energy is deposited for a FLUKA simulation and the Gaussian approximation of Eq. (1).

SUMMARY AND OUTLOOK

A design for a titanium target wheel that satisfies the requirements of the ILC baseline positron source has been developed, and benchmarking of magnetic simulations against real data is underway.

In our simplified model, at 2000 rpm in a realistic field of 1.16 T, calculations show that the wheel will be susceptible to maximum eddy current power losses of 3 kW. The associated opposing force is 30 N, corresponding to a torque of 17 Nm.

Current results appear to indicate that a gaussian distribution is insufficient to describe the particle flow through the target, which could have a positive bearing on the survivability of the titanium wheel. However, before firm conclusions can be drawn the heat flow and the pressure wave have to be simulated with the full hydrodynamical model.

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