POSITRON SOURCE TARGET SURVIVABILITY STUDIES

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Abstract

Energy deposition in the conversion targets of positron sources for future linear colliders will lead to thermal shock waves which could limit the targets' lifetimes. For the International Linear Collider baseline source, we have studied the energy deposition in a target taking the higher harmonics of the undulator radiation fully into account and applying hydrodynamical models for the resulting heat flow to determine the thermal stress in the target and to assess its survivability.

INTRODUCTION

To achieve the full physics potential of the ILC a source of polarized positrons with a flux of order 10^{14} positrons per second is required. This requirement can be met using a source based on a helical undulator [1, 2]. The undulator operates in the main ILC e^- beam generating high energy circularly polarized photons, which are incident on a target producing polarized positrons via an electromagnetic shower. The rapid energy deposition of the intense photon beam leads to a high heat load in the target and also strong thermal stresses and pressure shock waves. Hence, the production target has to be carefully designed to cope with these conditions, using e.g. a rotating target made of titanium alloy [3] (see Fig. 1) or alternatively liquid metal targets [4].

The thermal and pressure shock waves can be described by a hydrodynamical model [5]. Previous studies [6] have revealed possible problems with the survivability of the titanium alloy target in the ILC baseline design. In this contribution a detailed study is carried out taking the higher harmonics of the undulator radiation fully into account by simulating the initial energy deposition into the target with FLUKA [7] and using this as the starting point for the hydrodynamical evolution of the temperature and pressure distributions. In addition to these effects, the rotation of the target wheel in the magnetic field of the capture optics induces eddy currents which can give an additional thermal load of the same order as that from the beam itself. In the absence of a magnetic field or beam, the peak mechanical stress on the wheel caused by inertial forces when it rotates is found to be 126 MPa [8]. The net stresses from all causes have to be compared with the typical minimum tensile strength of grade 5 titanium of 960 MPa.

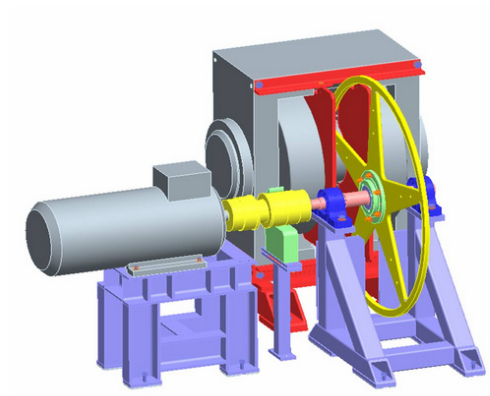

Figure 1: Setup of the positron source target wheel prototype constructed at Daresbury Laboratory, for details see [3].

ENERGY DEPOSITION IN TARGET

Angular Distribution of Undulator Radiation

In order to correctly model the energy deposition by the photon beam in the target the higher harmonics of the undulator radiation have to be taken into account. The energy distribution of the undulator radiation at the target surface is given by [9]

$$\frac{dW}{d\Omega} = \frac{8Ne^2\omega_0 K^2\gamma^4}{c(1+K^2+\gamma^2\theta^2)^3} \times \sum_{n=1}^{\infty} n^2 \left[J_n'^2(x_n) + \left(\frac{\gamma\theta}{K} - \frac{n}{x_n}\right)^2 J_n^2(x_n) \right]$$

with the Bessel functions of the first kind $J_n(x)$, $\gamma = E_{e^-}/m_e$, $x_n = 2Kn\gamma\theta/(1+K^2+\gamma^2\theta^2)$, $\omega_0 = 2\pi\beta^* c/\lambda_0$, $\beta^* = \beta\sqrt{1-(K/\gamma)^2}$ and the undulator parameters K, the period λ_0, the number of periods N and the e^- beam energy E_{e^-}. The radial distance r from the beam axis at the target surface is then $r = \theta d_{\mathrm{UT}}$ with the undulator-target distance d_{UT}.

The radial distributions of the undulator radiation for $E_{e^-} = 250$ GeV and $E_{e^-} = 150$ GeV are shown in Fig. 2. The radiation is much more strongly peaked around the beam axis for the higher energy with possibly adverse effects for the target survivability. It can also be seen, that for $K \sim 1$ a Gaussian approximation which corresponds to the first harmonic ($n = 1$) clearly underestimates the area where the beam hits the target whereas for smaller $K = 0.5$ the Gaussian approximation is better. This needs to be taken into account when considering previous studies which relied on this approximation.

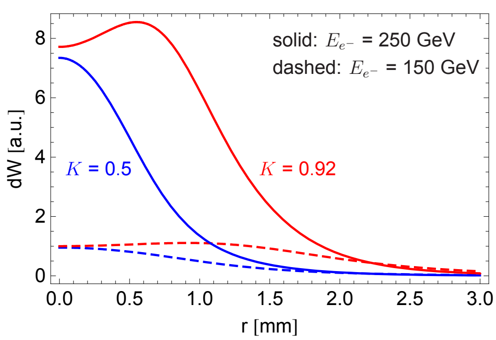

Figure 2: Undulator radiation at target surface for $E_{e^-} = 250$ GeV (solid) and $E_{e^-} = 150$ GeV (dashed) with $d_{\mathrm{UT}} = 500$ m, $K = 0.92$ (red) and $K = 0.5$ (blue) in the normalization $dW(K = 0.92, E_{e^-} = 150\ \mathrm{GeV}, \theta \to 0) \equiv 1$.

FLUKA Simulation

We have carried out a simulation of the energy deposition of a single bunch into a titanium alloy target with FLUKA [7] including the higher harmonics of the undulator radiation. The resulting energy density deposited in the whole target wheel is visualized in Fig. 3. The same energy density deposited in a smaller volume is shown in Fig. 4 whereas Fig. 5 gives the contour of this energy density inside which 90% of the bunch energy is deposited, i.e. this contour marks the target volume where 90% of the energy is deposited after the bunch completely traversed the target.

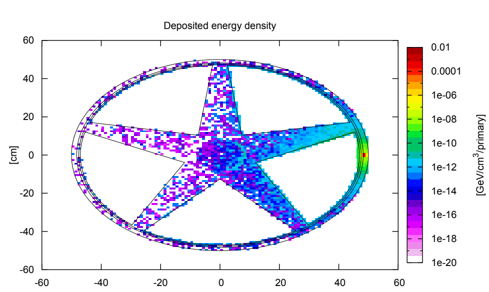

Figure 3: Energy density from a FLUKA simulation of the initial energy deposition into the whole target wheel.

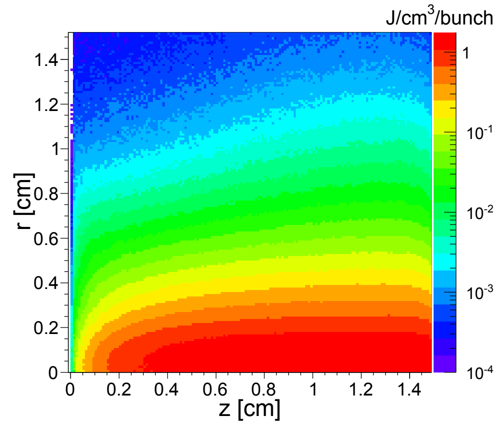

Figure 4: Energy density from a FLUKA simulation of the initial energy deposition into a 15 mm thick Ti-6%Al-4%V target by one bunch of the undulator radiation for $K = 0.92$, $\lambda_0 = 11.5$ mm and $d_{\mathrm{UT}} = 500$ m.

Figure 5 also shows the respective contours inside which 90% of the bunch energy is deposited for a Gaussian photon distribution [5] corresponding to the first harmonic of the undulator radiation with radial dimension $\sigma_\perp = 1.5$ mm–2.5 mm, cf. Fig. 2. This indicates that for $K = 0.92$ a Gaussian approximation for the undulator radiation underestimates the size of the target volume into which the energy is deposited.

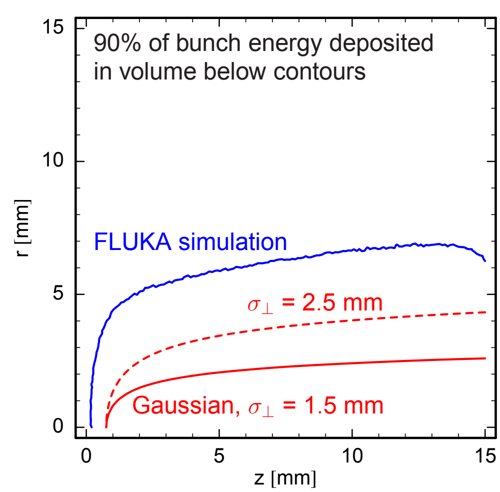

Figure 5: Contour of the energy density under which 90% of the bunch energy is deposited for the FLUKA simulation, Fig. 4, (blue) and Gaussian distributions (red) with radial dimension $\sigma_\perp$.

Figure 6 shows the temperature profile and the stress induced by the beam for a rotating target in a simple model to take the rotation of the wheel and the accumulation of the energy deposition of the subsequent bunches in the pulse into account. The effective stress in this model stays well below the limit of 960 MPa for titanium.

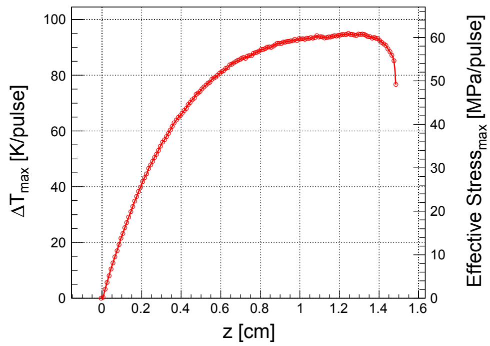

Figure 6: Temperature profile and stress induced by the beam for one pulse in the rotating target for an undulator length of 100.6 m.

Hydrodynamical Model

In order finally to assess the target survivability the resulting temperature and pressure distributions from the energy deposition of the photon beam have to be evolved by solving the respective hydrodynamical partial differential equations. The energy deposition of one bunch proceeds at a timescale of $\sim 10^{-11}$ s and is hence instantaneous in comparison to the hydrodynamical evolution which proceeds at a timescale of $\sim 10^{-7}$ s governed by the speed of sound. However, within the timescale of $\sim 10^{-7}$ s the next bunch hits the target which leads to an accumulation of the deposited energy which also has to be taken properly into account together with the rotation of the target wheel.

HEATING BY EDDY CURRENTS

In addition to heat deposition from the incident beam the rotation of the baseline target in the field of the adjacent capture optics leads to eddy current heating. The benefits in capture efficiency of immersing the target in the field are offset by the additional thermal and mechanical stress on the target wheel. At a rim velocity of $100\ \mathrm{ms}^{-1}$ in a constant magnetic field of ~ 1 T the energy deposition in one complete rotation averaged over the volume of the rim of the target wheel is predicted to be around 13 J/kg.

In order to study these effects a prototype of the baseline target wheel described elsewhere [3] has been constructed at Daresbury Laboratory, see Fig. 1. Initial data from the experiment with rim velocities up to $25\ \mathrm{ms}^{-1}$ and static magnetic fields of ~ 0.5 T giving axial torques of ~ 1 Nm show broad agreement with the numerical simulations presented previously [3]. However, more recent simulations predict that transient effects associated with the passage of the target wheel spokes through the fringe fields of the magnet could substantially increase the eddy current power above previous predictions. At a rim speed of $100\ \mathrm{ms}^{-1}$ the effect of eddy current loops through the spokes is predicted to increase the retarding torque and hence the power loss by a factor of three compared to the effect of the wheel rim alone. Analysis of the data to search for this effect is ongoing.

CONCLUSIONS AND OUTLOOK

We have analyzed the energy deposition into the target of the ILC positron source from the incident photon beam and from eddy currents in the target wheel. We have shown that the higher harmonics of the undulator radiation have to be taken properly into account when simulating the initial energy density deposited by the photon beam. The evaluation of the energy deposition in the target has to include the instantaneous heating together with the time-dependent propagation of the pressure in the material. The analysis of the following pressure shock waves within an hydrodynamical model is underway. The energy deposition from eddy currents is of the same order as that from the photon beam and has also to be fully considered when assessing the target survivability. A study taking the eddy currents in the target wheel spokes into account is presently ongoing.

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