ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-TUPWA048

RADIATIVE COOLED TARGET FOR THE ILC POLARIZED POSITRON SOURCE*

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Abstract

The target for the polarized positron source of the future International Linear Collider (ILC) is designed as wheel of 1 m diameter spinning with 2000 revolutions per minute to distribute the heat load. The target system is placed in vacuum since exit windows would not stand the load. In the current ILC design, the positron target is assumed to be water-cooled. Here, as an alternative, radiative cooling of the target has been studied. The energy deposition in the target is the input for ANSYS simulations. They include the temperature evolution as well as the corresponding thermo-mechanical stress in the target components. A principal design is suggested for further consideration.

INTRODUCTION

The ILC will provide e^+e^- collisions in the energy range from 250 to 500 GeV, upgradeable to 1 TeV [1]. The positron beam – 3×10^{10} e^+/bunch, 1312 bunches/pulse (2625 for the high luminosity option) and 5 Hz repetition rate – will be produced using the e^- beam which passes a superconducting helical undulator up to 231 meters long to generate circularly polarized photons [2]. The polarized photons hit a Titanium-alloy target located 400 m downstream the undulator to produce polarized positrons [3]. Depending on the undulator parameters, a polarization of about 30% can be achieved for the positron beam which can be enhanced up to 50% using a photon collimator [4]. The corresponding intensity reduction of the positron beam has to be compensated by a longer undulator section.

The typical total average power deposited in the positron target is about 5 kW corresponding to 1.4 MW during the pulse. This power is deposited in the 0.4 radiation length thick Ti6Al4V target ($0.4\,X_0 = 1.48$ cm). In order to distribute the heat load of the photon beam, a target wheel of radius $r = 0.5$ m is proposed. It rotates with 2000 revolutions per minute (rpm) corresponding to a rim velocity of $v = 100$ m/s. The wheel rotates in vacuum since exit windows would not stand the load. Based on first results of running a target wheel prototype [5], it is expected that the proposed water cooling will be a challenge. An alternative could be cooling by thermal radiation: the heat deposited in the Ti alloy target diffuses to a radiator filling the inner part of the wheel. This radiator is rotated and radiates the heat to a stationary cooler. It is also located in the vacuum, opposite of the radiator, and it is water-cooled.

The energy loss calculated with FLUKA Monte Carlo code [6] for the parameter set 500 GeV (high luminosity) and a collimated photon beam with $r = 1$ mm which corresponds to 50% positron polarization. The photon beam hits the target rim with 2625 bunches in a train of 961 μs duration and 5 Hz repetition rate. A photon beam power of about 80 kW is required to achieve a positron beam with 50% polarization and a bunch charge of 3.2 nC. About 4 – 5 kW is deposited in the target. The instantaneous temperature rise per bunch train in the rotating target is roughly 120 K per bunch train since the heat load is distributed on the rotating wheel rim (almost 200 K for the high luminosity option). Only after about 7.4 seconds the beam hits the same place again. The heat dissipation in the target as well as stress and deformation in the target wheel system are calculated with ANSYS [7].

RADIATIVE COOLING

Following the Stefan-Boltzmann radiation law,

$$W = \sigma \epsilon A G (T^4 - T_{\rm cool}^4)\,, \qquad (1)$$

where $\sigma = 5.67 \times 10^{-8}$ W m^{2}K^4 is the Stefan-Boltzmann constant, ϵ the effective surface emissivity, A the surface area and G a geometric form factor, a radiative area $A > 1.6$ m^2 is required to remove 5 kW from the positron target assuming $\epsilon = 0.8$, $T = 250\,°$C, $T_{\rm cool} = 20°$C, $G = 1$.

Temperature Distribution in a Simplified Model

The average energy deposition in the target is 5 kW, the precise value depends on the centre-of-mass energy and the luminosity. As a first ansatz a simple model is considered: The target wheel is a full disk of thickness 1.4 cm. The rim is made of Ti6Al4V and has an emissivity of $\epsilon = 0.25$; the radiative inner part is made of copper with $\epsilon_{\rm radiator} = 0.7$. The radiation of 5.125 kW is into the environment of $T_{\rm cool} = 22\,°$C. The resulting stationary radial temperature profile is shown in Fig. 1. The thermal conductivity in Ti alloy is substantially lower than in copper so that the temperature gradient is steep. To avoid temperatures in the target rim above the recommended limits for long-term operation, the contact between target and radiator must be designed accordingly.

* Work supported by the German Federal Ministry of Education and Research, Joint Research Project R&D Accelerator "Spin Optimization", contract number 19XL7Ic4
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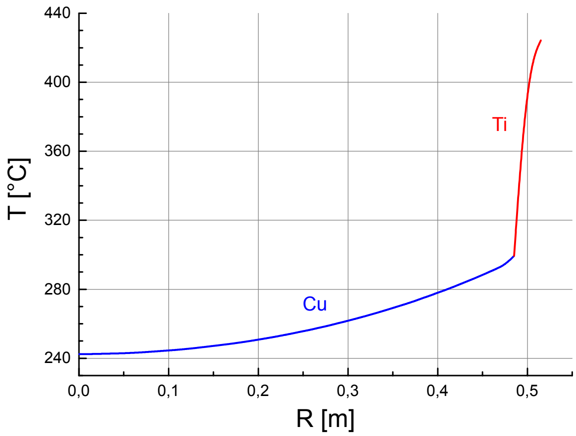

Figure 1: Stationary radial temperature profile in the disk with target rim and inner copper cooler.

PRINCIPAL DESIGN OF THE RADIATIVE COOLED TARGET WHEEL

The area of the simple disk as radiator in the 1 m-diameter target wheel has no safety margin for the cooling and is not sufficient if more than 5 kW are deposited in the target. So the solid radiator is designed with fins near the target rim for effective heat disposal. If necessary, the cooling area can be easily increased by additional fins. The wheel (target + radiator) is spinning in vacuum. Close to the wheel inside the vacuum a stationary cooler is located which is water-cooled. The thermal conductivity of the radiator must be high, so preferably materials like copper are recommended. The heat drifts from the Ti alloy target to the solid Cu radiator. Hence, the thermal contact between target material and radiator is very important. The heat exchange by radiation happens between rotating radiator and stationary cooler. It is evident that the surface emissivities of radiator and cooler must be stable over a long period in the harsh environment near the target.

It should be remarked that size and position of the cooler depends also on the integration into the source facility. Directly behind the Ti6Al4V target the optical matching device (OMD) is placed as sketched in Fig. 3. The distance between target exit side and OMD is only few millimeters.

Stationary Temperature Distribution, Stress and Deformation

Considering a target rim with $\epsilon = 0.25$, a Cu radiator and a Cu cooler with $\epsilon_{\mathrm{Cu}} = 0.7$, ANSYS simulations yield a stationary temperature distribution in target and radiator as shown in Fig. 4 for an energy deposition of 5.125 kW. The thermal load yields stress and deformation by expansion. The average von Mises stress is shown in Fig. 5 and reaches maximum values of 208 MPa. The peak values due to dynamic cyclic load still have to be added; also the stress due to centrifugal force is not included in the plot.

Thermal expansion yields deformation of the wheel and the radiator fins. The deformation by thermal expansion is

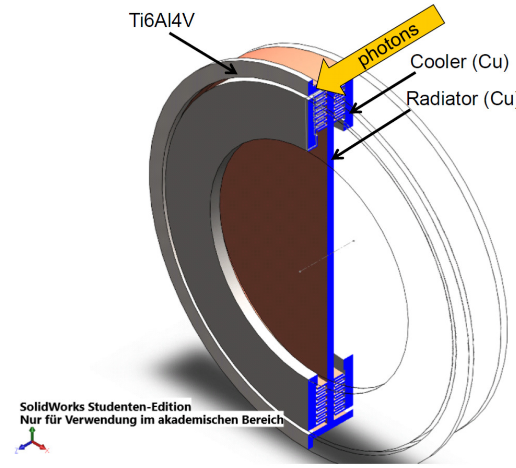

Figure 2: Sketch of the model showing the rotating wheel consisting of target rim and radiator with fins, and the stationary cooler.

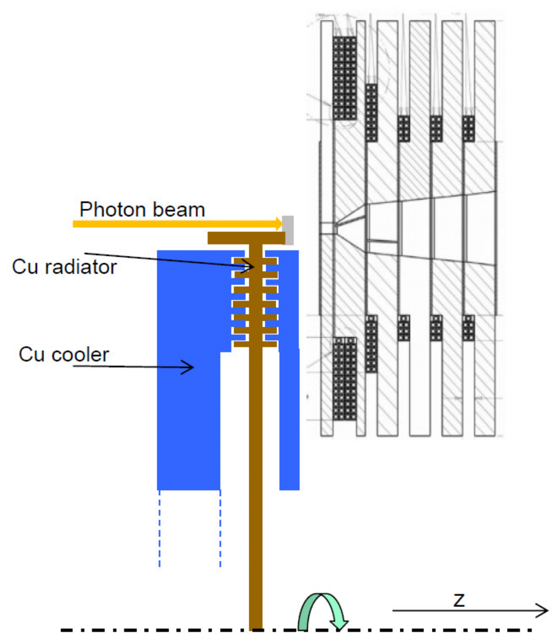

Figure 3: Sketch of the model showing the upper half cross section of target, radiator and cooler together with the OMD designed as pulsed flux concentrator at LLNL [5].

depicted in Fig. 6. It can be seen that the radius of the wheel increases by about 1.5 mm. This has to be taken into account positioning the cooler which has a lower temperature.

Mechanical Issues

The mass of the wheel is of order 100 kg. This results in an energy of about 0.5 MJ stored in the wheel which is important for safety issues.

The fast rotation creates additional stress due to centrifugal force of roughly 110 MPa. However, stress and deformation in the heated regions depend on the temperature which is not equally distributed.

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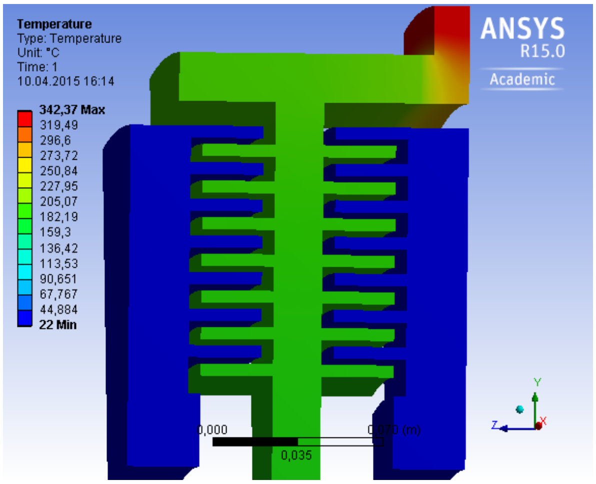

Figure 4: Stationary temperature distribution in the target and radiator.

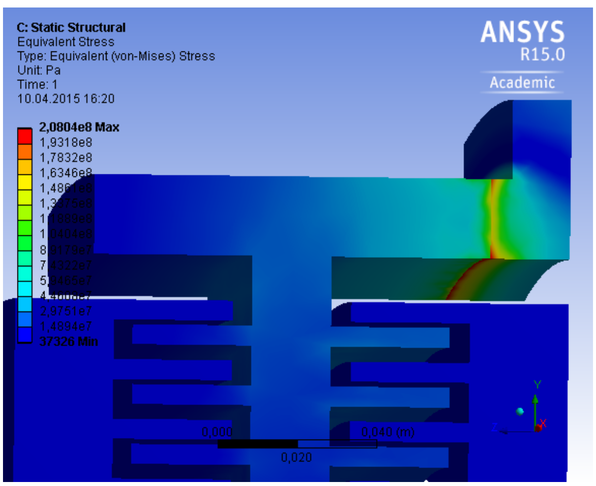

Figure 5: Equivalent von Mises stress.

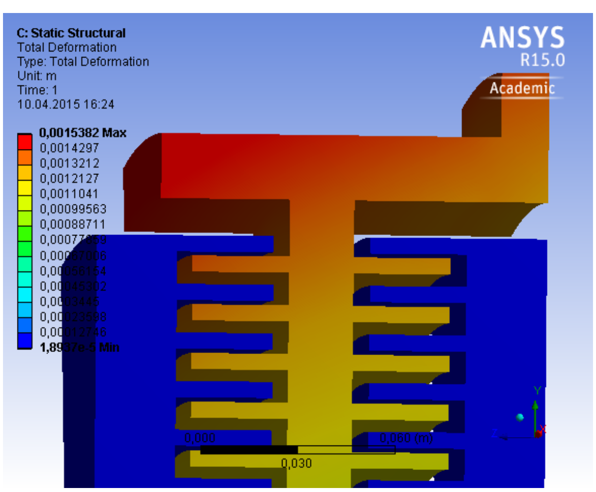

Figure 6: Total deformation due to heat load; rotation is not taken into account.

To avoid unbalances and too high stress, symmetry issues must be respected. The support of the shaft has to be optimized to minimize vibrations in the system.

Since target, radiator and cooler must be in vacuum, it is recommended that the rotor is placed inside the vacuum while the stator is outside. The rotating magnetic bearing is inside the vacuum. If required, differential pumping for adequate vacuum can be arranged.

SUMMARY

The design of a radiative cooled ILC positron target system is under study. The simulations performed using ANSYS show that radiative cooling is a very promising option. For the final design, the temperature distribution and heat transfer as well as the stress in the whole system have still to be considered in detail including the wheel rotation. In particular, the thermal contact between the target and the radiator is important.

To optimize the design for long-term operation the dynamic load and limitations due to fatigue properties of the materials have to be taken into account. Alternative materials for the positron target with good heat conduction could be helpful, also a radiator material lighter as copper but with high thermal diffusion coefficient is desired. The system must be tested and optimized constructing and testing a mock-up.

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