DESIGN OF AN 18 MW BEAM DUMP FOR 500 GEV ELECTRON/POSITRON BEAMS AT AN ILC*

D. Walz, J. Amann, R. Arnold, A. Seryi, SLAC, Stanford, U.S.A
P. Satyamurthy, P. Rai, V. Tiwari, K. Kulkarni, BARC, Mumbai, India.
H. Vincke, CERN, Geneva, Switzerland

Abstract

This article presents a report on the progress made in designing 18 MW water based Beam Dumps for electrons or positrons for an International Linear Collider (ILC). Multi-dimensional technology issues have to be addressed for the successful design of the Beam Dump. They include calculations of power deposition by the high energy electron/positron beam bunch trains, computational fluid dynamic analysis of turbulent water flow, mechanical design, process flow analysis, hydrogen/oxygen recombiners, handling of radioactive 7Be and 3H, design of auxiliary equipment, provisions for accident scenarios, remote window exchanger, radiation shielding, etc. The progress made to date is summarized, the current status, and also the issues still to be addressed.

INTRODUCTION AND PARAMETERS

The task force team studied the various aspects of the SLAC 2.2MW water beam dump and used it as the starting basic reference design for an ILC Beam dump, since it has all features required of an ILC beam dump (at a lower power level) but of proven design [1]. This includes the use of a vortex-like flow pattern to dissipate and remove the energy deposited by the beam, the beam dump entrance window and its special cooling method, a remotely operable window exchange mechanism, a hydrogen recombiner, handling of radioactive 7Be and 3H, a tail catcher to attenuate the residual beam energy remaining after the vortex flow region, as well as related primary and secondary cooling loops.

The following beam parameters have been taken as reference for designing the beam dump [2]: Electron/Positron energy: 500 GeV; Number of electrons/positrons per bunch: 2×10^{10} ; Number of bunches per train: 2820; Duration of the bunch train: 0.95 ms; Beam size: $\sigma_x = 2.42$ mm & $\sigma_y = 0.27$ mm; Energy in one bunch train: 4.5 MJ; Number of bunch trains per second: 4; Beam power: 18 MW; Beam sweep radius: 6 cm. The conceptual beam dump design was carried out with these reference parameters.

FLUKA ANALYSIS

To design the beam dump, accurate details of beam power deposition by various processes have to be estimated for the entire region. To obtain this data, the high energy particle interaction code – FLUKA-developed at CERN was used [3]. The FLUKA calculations performed at BARC were also independently performed by Heinz Vincke at CERN.

Analysis was carried out to arrive at an optimum sweep radius. The maximum power density deposited as a function of minimum sweep radius was studied. For a 6 cm beam sweep and a 500 GeV beam, the maximum value found was ~ 240 J/cm^3 (the corresponding sweep radius for 250 GeV is ~3cm). Initially, a detailed analysis was done for an 8cm beam sweep with a maximum power density of ~160 J/cm^3. A related CFD analysis indicated that it is possible to reduce the sweep radius to 6cm for 500 GeV.

An important effect that has to be accounted for is due to the asymmetric cross section of the ILC beam (σ_x = 2.42 mm & σ_y = 0.27 mm). Because of this, when the beam is swept, the power deposition density will not be radially uniform. To capture the maximum power density, data was generated for a beam orientation of $\Phi = \pi/2$.

Multiple FLUKA runs were taken with different bin sizes to obtain 1) power deposition in the water and 2) power deposited in the vessel walls. The power dissipated in the water from one pulse train was studied. The energy deposited in the vessel walls will depend on the location of the beam. Two cases were considered: 1) the beam centroid is at a radius of 0.45m away from the beam dump axis and 2) the beam centroid at 0.35 m away from beam dump axis. The longitudinal heat profile generated in the dump vessel was determined. The heat deposited in the end wall made of flat plate of 70mm thickness was also calculated. The data was converted into a functional relationship to use it as input into the CFD analysis.

A FLUKA analysis was carried out to determine the beam power distribution in the entrance window. The choice for the material was Titanium Alloy (Ti- 6Al- 4V) on account of its high temperature strength properties, low modulus of elasticity and low co-efficient of thermal expansion. The power density distribution calculated by FLUKA was used to make a functional fit of the data for the CFD analysis. The total power deposited is ~25 W with a maximum heat density of 21 J/cm^3.

Details of beam power extracted by the beam dump have been evaluated. Negligible radiation escapes from the front wall. Approximately 27 kW of radiation escapes from the cylindrical portion of the dump tank, and << 1.5 kW of radiation escapes from the back end plate.

CFD ANALYSIS

A detailed CFD (Comutational Fluid Dynamic) analysis was done to optimize the geometry and flow parameters for the beam dump using the FLUENT package [4] for succcessfully extracting the beam power. Based on the FLUKA heat data, it was decided to have a 11m long beam dump with 1.8m dia. It contains two 8 inch inlet headers, located opposite to each other and at a distance of 0.7m from the beam dump center line along the entire length. A 4.4 mm wide slot nozzle is provided in both headers along the entire lengh at an angle of 90^0 to the radial direction for injecting the water, either clock-wise (or anticlockwise), into the beam dump. The outlet header is 10 inch pipe, is located at the center of the beam dump and runs parallel to the dump axis. The heated water from the dump tank enters into the outlet header through a large number of perforations.

The FLUKA data indicated five locations of importance along the z-axis: i) the location where the maximum heat density is found at a depth of 1.8m (≡ 5.04 X_0) and short of shower maximum with a peak heat density of 238J/cm3; ii) location of radially integrated maximum heat deposition (at 2.9 m and radially integrated heat of 54 kW/cm); iii) location where maximum radially integrated heat deposited in the vessel (at 4.2 m when the beam centroid is located at r=0.45m, and 4.5 m when located at r=0.35m); iv) window; and v) end plate of the beam dump.

A total mass flow rate of 209 kg/s was taken based on the preliminary flow analysis (further analysis to reduce the flow rate by providing a variable slot width in the headers is underway). Water inlet temperature was assumed to be 50^0C as dictated by the primary coolant loop. The bulk outlet temperature will be 73^0C for 18 MW average beam power. The water inlet velocity at the slot exit is 2.17 m/s. The flow is equally distributed between the two inlet headers. The flow is turbulent and the RNG k-ε turbulent flow model was chosen (there was little variation when other models were used).

A 2-D time-dependent flow analysis was performed for 3 locations along the z-direction as mentioned above for two radial beam locations (cases i, ii and iii). A Conjugate heat transfer analysis was carried out to determine the temperature distribution in the vessel. FLUKA power data were converted to a functional relationship and used as input. Multi-block grids with very fine mesh (in the beam transverse region) were generated to capture power data and determine precise temperature. Variable time intervals were taken, one during the bunch train power deposition (0.05ms for the 0.95ms beam power deposition and 1ms for the remainder of the time). Initially, solutions were obtained for the velocity field, and then beam heating was introduced. Next, the code was run for 18MW steady state power input. After obtaining the steady state solution, the code was run for the transient case for a sufficiently long time to obtain a quasi-steady solution.

Figure 1, depicts steady state solutions for the velocity field. Fig. 2 shows the maximum temperature variation as function of time with a peak of 155^0C. The maximum temperature variation as a function of time is ~30^0C. The temperature distribution in the vessel wall at this z-location was also considered. The maximum vessel temperature is 97^0 C and the minimum is 81^0C. Further, from the transient solution, it was found that the maximum temperature fluctuation is < 0.05C (due to the large thermal inertia of the vessel).

A similar analysis was done for the maximum heat density location at 1.8m. The maximum temperature is 130^0C and the variation as function of time is 36^0C.

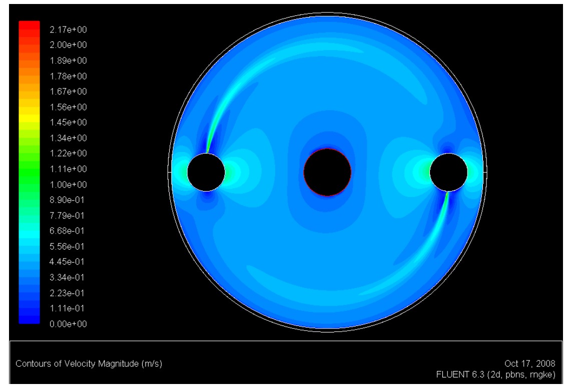

Figure 1: Velocity contours (inlet velocity: 2.17m/s, mass flux: 19kg/m/s).

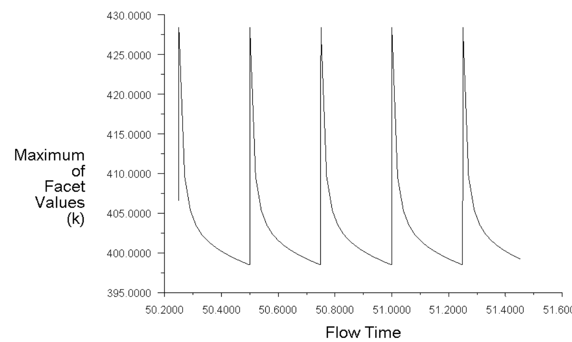

Figure 2: Maximum temperature variation as a function of time at z = 2.9m ≡ 8.1Xo (Max Temp = 155^0C).

From the analysis of the two cases above, it can be concluded that the maximum temperature in the water in the entire beam dump will not exceed 155^0C. The water pressure in the dump tank will be maintained at 10 bar pressure, which corresponds to a boiling temperature of 180^0C. Thus, a margin of 25^0C to water boiling was provided.

As was explained earlier, the maximum power deposition in the vessel cylinder wall depends on the radial beam centroid location. For the 0.45m radial beam location, it is at a depth of 4.2 m. The azimuthal temperature variation in the vessel wall at this depth between maximum and minimum ranges from 95^0C to 70^0 C with negligible transient variation. Preliminary analysis indicates negligible thermal stresses. For the 0.35m radial beam location, these effects will be even less than for the case of the 0.45m radial beam location.

An similar analysis was also performed for the radial beam location at 0.35m from dump tank axis. Almost identical temperature distributions were obtained. Hence it can be concluded that any location between 0.35m and 0.45m is acceptable. The exact location will be decided based on the mechanical design.

It is proposed to cool the window with a single jet from a suitable supply located near the window. The window chosen is of hemispherical shape of 1mm thick and made of a high strength titanium alloy. FLUKA analysis indicated that 25W of beam power with maximum heat source of 21W/cm3 will be deposited in the window. Results are shown in Fig.3 .

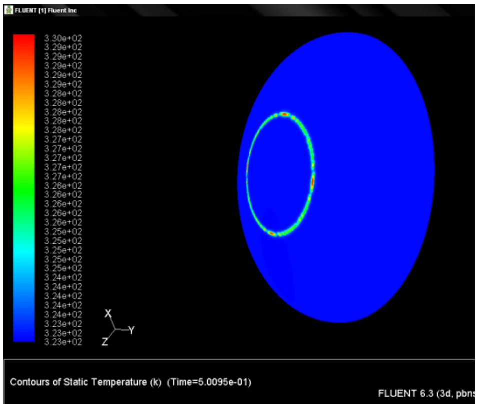

Figure 3: Window temperature distribution at completion of beam bunch train energy deposition. (Max temp : 57^{0}C).

The variation of maximum window temperature as a function of time shows that the maximum temperature rises to 77^{0}C when the beam is on; the variation of the maximum temperature as a function of time is ~9^{0}C.

The analysis indicates that a single jet can effectively cool the window. Currently, optimization studies are being performed to reduce the jet velocity and optimize angle of jet impingement on the window.

The end wall of the beam dump will be a 3 inch thick SS316LN plate. Due to the large plate thickness, significant heat will be deposited by the beam and hence it requires proof that the water in the dump tank adequately cools the hot spot without any local boiling. FLUKA data indicated that the highest heat density in the end wall was 12.5 W/cm3 and the heat flux was 5.3 W/cm2. A total of ~2 kW heat is deposited in the wall.

To reflect the presence of the end wall, it became neccessary to carry out a 3D flow analysis. The computational region includes 0.5m of water, the cylindrical and end walls of the beam dump. The radial velocity contours at a distance 50mm away from the wall, and the radial temperature distribution on the external surface and the surface in contact with water were considered. The temperature distribution along the plate cross-section was analized. As was shown, the highest temperature on the internal wall surface is ~70^{0}C and much below the boiling temperature. On the outer surface, the maximum temperature is ~120 ^{0}C. The results are shown in Fig.4. Detailed thermo-mechanical stress calculations have indicated the thermo-mechanical stresses are well below acceptable values.

An analysis was also performed with a single water inlet header. Since the total length of the header is 11 m, it is prudent to analyse the effect of pressure drop along the length of the header and its effect on the exit velocity and mass flow. A 3-D analysis was done for 2.17 m/s for the header. For an inlet header with a slot nozzle, the analysis indicated a significant velocity variation in the z direction leading to reduced radial velocity. To enhance the radial component of the velocity to the required values and reduce the z-variation, flow diverters have been intoduced in the exit slot of the Inlet Headers. Preliminary analysis indicated that the necessary radial velocity can be achieved. Detailed analysis is in progress.

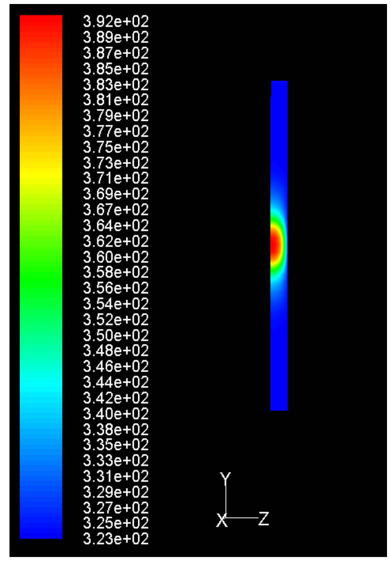

Figure 4: Temperature distribution across the cross-section of the End plate.

CONCLUSION

Design of an 18MW beam dump for ILC has been carried out. Most of the thermal-hydraulic issues have been addressed. More details will be published in subsequent reports.

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