Design of an 18 MW vortex flow water beam dump for 500 GeV electrons/positrons of an international linear collider

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ABSTRACT

Beam dumps are essential components of any accelerator system. They are usually located at the end of the beam delivery systems and are designed to safely absorb and dissipate the particle energy. In the second stage of the proposed International Linear Collider (ILC), the electron and positron beams are accelerated to 500 GeV each (1 TeV total). Each bunch will have 2×10^{10} electrons/positrons, and 2820 bunches form one beam bunch train with time duration of 0.95 ms and 4 Hz frequency. The average beam power will be 18 MW with a peak power of 4.5 GW. The FLUKA code was used to determine the power deposited by the beam at all critical locations. This data forms the input into the thermal hydraulic analysis CFD code for detailed flow and thermal evaluation. Both 2D and 3D flow analyses were carried out at all the critical regions to arrive at optimum geometry and flow parameters of the beam dump. The generation and propagation of pressure waves due to rapid deposition of heat has also been analyzed.

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1. Introduction

Beam dumps are essential components of any accelerator system. They are usually located at the end of beam delivery systems and are designed to safely absorb and dissipate the particle energy. Many types of beam dumps have been used in the past (solid, liquid, high-Z, low-Z, etc.) depending upon the type of particle, its energy, and beam intensity [1]. With the increase of beam energy and intensity, it becomes increasingly difficult to absorb and dissipate the beam using solid material beam dumps due to the limitations imposed by the thermal conduction to extract the heat. Beam dumps utilizing a liquid power absorption medium and forced convection to extract the heat are ideally suited to manage high energy and high intensity beams. A beam dump concept based on forced convection was developed and successfully operated at the Stanford Linear Accelerator Center to absorb and dissipate electron beams up to

2.2 MW [1]. The main beam dump proposed for a future ILC is based on this principle. Here water is injected azimuthally with an appropriate velocity near the outer periphery of the dump vessel through an inlet water header. It is located parallel to the direction of beam propagation leading to a vortex-type flow. The water is collected in an outlet water header located along the center of beam dump. The beam and the resulting cascade shower pass through the dump at a suitable radial distance from the dump axis. Fig. 1 depicts a schematic of the beam dump. The required length of the beam dump is determined by the energy deposited by the beam in the downstream end plate. The required diameter of the beam dump is dictated by the energy deposited in the vessel shell at the z-location of maximum power dissipation. The heat generated in the dump tank must be sufficiently small for the dump cooling water to remove it in a way that maintains the wall temperature in contact with water below the boiling temperature and for which thermal stresses are below allowable values. This type of beam dump also requires a beam entry window. The latter must be thin enough to minimize the energy deposited by the beam, and at the same time sufficiently thick to withstand the hydrodynamic pressures

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Fig. 1. Schematic of the water beam dump of vortex-type flow.

generated in the dump tank. The speed/frequency of beam sweep is determined from the following considerations: (i) the frequency should be as low as possible, to minimize the technical difficulties and power and (ii) the ILC bunch train, which is of ~ 1 ms duration, should make at least one full circle on the window. Based on this, the sweep frequency is selected to be ~ 1 kHz.

Details of the Beam Dump designed for the proposed ILC system are presented. The adopted parameters of the electron/positron beams are summarized below [2].

ILC Beam parameters

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 and $\sigma_y = 0.27$ mm
Energy in one bunch train:	4.5 MJ
Number of bunch trains per second:	4
Beam power (average):	18 MW
Beam power (peak):	4.5 GW
Beam sweep radius:	6 cm
Beam sweep frequency	~ 1 kHz

These parameters correspond to the maximum beam expected to be delivered to the ILC detector. Detailed energy deposition distributions by the beam are determined using the FLUKA code (a high energy particle interaction code developed at CERN [3]). The data derived thereof formed the input for a detailed Computational Fluid Dynamic analysis (CFD) using the FLUENT code [4]. Extensive parametric analysis of flow and geometry has been carried out to arrive at optimum values. The following sections give an accounting of the studies.

2. Beam bunch train energy deposition in the Beam Dump

As explained earlier, energy deposition by the beam bunch train through various processes was estimated for the entire region using FLUKA. Initial analysis quickly showed that the beam entrance window would fail from excessive power deposition per unit volume, unless either the transverse beam size was enlarged or the beam was rastered or swept. The latter solution was adopted. The maximum energy density deposited as a function of sweep radius is shown in Fig. 2. Based on this data, that radius was chosen to be 6 cm (the smallest radius for which the beam power density could still be removed by water as a coolant).

Another important effect accounts for the asymmetric cross-section of the ILC beam ($\sigma_x = 2.42$ mm and $\sigma_y = 0.27$ mm). When the beam is swept, the energy density will not be uniform radially (see Fig. 3). To capture the maximum energy density, heat data was generated for a beam orientation of $\Phi = \pi/2$.

Fig. 2. Effect of beam sweeping radius on maximum energy density deposition in water.

Maximum Energy Density Variation Along the Sweep Path

Fig. 3. Variation of energy density around the sweep path due to unequal σ_x and σ_y ($\sigma_x \gg \sigma_y$) for a 6 cm beam sweep.

Multiple FLUKA runs were taken with different bin sizes to obtain (1) power deposition in the water (smallest bin size taken was 0.05 mm in radial direction and 2 mm in the z-direction); (2) heat deposited in the vessel wall (smallest bin size taken was 0.005236 rad along the phi direction); (3) power deposited in the window; and (4) overall power deposited in the beam dump and

beam energy lost from the dump. Photonuclear reaction is not used for heat deposition calculation as its effect is very small. Cut off for electron and photon is taken as 1.511 MeV and 0.333 MeV respectively in FLUKA calculation. The power dissipated in the water from one bunch train is shown in Fig. 4(a), and the radially integrated longitudinal power deposition by 4 beam bunch trains is shown in Fig. 4(b). The energy deposited in the cylindrical portion of the vessel wall depends on the radial location of the beam, which was taken at 0.35 m (beam centroid) from the beam dump axis. The longitudinal power deposited in the dump vessel wall was determined (see Fig. 5). The heat flux in the end wall (flat plate of 3 in. thickness and made of stainless steel TYPE 316LN) is shown in Fig. 6. Fig. 7 gives the energy density distribution calculated in the window made of titanium alloy (Ti-6Al-4V). This was chosen on account of its high-temperature strength properties, low modulus of elasticity, and low co-efficient of thermal expansion [5]. The total power deposited in the window is ~ 25 W, with a maximum energy density of 21 J/cm^3 .

Fig. 4. (a) Energy deposited by one bunch train in water (beam propagating along the z -axis). (b) Radially integrated longitudinal power density.

Fig. 5. Longitudinal Power Density in SS Vessel Wall (1.8 m diameter and 25.4 mm thickness) for the Beam Path at 0.35 m from Dump Tank axis.

Fig. 6. Heat Flux in the 76.2 mm thick end wall of the beam dump (r corresponds to the radial distance from the centroid of the beam).

The FLUKA-generated data was converted into a functional relationship using MATLAB for the CFD analysis.

Fig. 8 gives the details of beam power extracted by the beam dump. Negligible radiation escapes from the front wall. Approximately 48 kW of radiation escapes from the cylindrical portion of the dump tank, and < 1.0 kW of radiation escapes from back end plate. Some conservatism was added to these values, by including the photonuclear reactions option in FLUKA. To further reduce radial leakage of energy from the beam dump, additional iron shielding followed by concrete has been proposed [6].

3. Thermal-Hydraulic analysis

A detailed Computational Fluid Dynamic (CFD) analysis was carried out to optimize the geometry and flow parameters for the

beam dump using the FLUENT package [4]. Based on the FLUKA heat data and end wall thermal analysis, it became necessary to have an 11 m long beam dump of 1.8 m diameter. It contains two 8 in. inlet headers along the entire length, located opposite to each other and at a distance of 0.7 m from the beam dump center line. A 4.4 mm wide slot nozzle, with flow diverters, is provided in both headers along the entire length, and at an angle of 90° to the radial direction to inject water either clock-wise (or anti-clock-wise) into the beam dump. Water is supplied into the inlet headers from the end wall side. The outlet header is 10 in. pipe, is located at the center of the beam dump, and runs parallel to the dump axis. The water from the dump tank flows into the outlet header through a large number of perforations.

3.1. Flow modeling

The FLUKA data indicated five locations experiencing intense thermal effects: (i) the location where the maximum power density in water is found, at a depth of $z=1.8$ m ($\approx 5.04 X_0$, where X_0 is the radiation length); this is short of shower maximum with a peak energy density of 238 J/cm^3 ; (ii) the location of radially integrated maximum power deposition in water [$z=2.9$ m ($\approx 8.1 X_0$), and radially integrated power of 54 kW/cm]; (iii) the location where maximum power is deposited in the vessel wall at $z=4.3$ m; (iv) the window, located in the front wall; (v) the end wall of the beam dump; and (vi) the inlet header.

Fig. 7. Energy Density distribution in window.

Based on the preliminary flow analysis, a total mass flow rate of 209 kg/s (104.5 kg/s in each of the inlet headers) was taken. Water inlet temperature was assumed to be at 50°C as dictated by the primary coolant loop and heat exchanger. The bulk outlet temperature would be 71°C for 18 MW average beam power.

A time dependent 3D flow modeling could, in principle, have been carried out for the entire beam dump. However, the requirement of very small time increments (0.05 ms during beam presence), when coupled with very fine mesh size (less than beam size) in the region of highest beam power deposition resulted in computational time and memory demands that were very large and exceeded the available resources. In view of this, the analysis was performed only at critical locations as indicated above. Depending on location and flow behavior, either a 2D or 3D analysis was done. For the flow parameters selected, the flow is turbulent in all the regions. The RNG $k-\epsilon$ turbulent flow model was chosen for modeling turbulence in vortex-type flow and the standard $k-\epsilon$ turbulent model was selected for the window cooling [7]. However, there was little variation when other models were used.

Based on the inlet header exit velocity profile along the z -axis, an average azimuthal velocity of 2.17 m/s (a conservative value) was selected for all the 2D cases ((i), (ii) and (iii) as indicated above). For the end wall analysis (3D), an average velocity of 1.7 m/s was chosen. Additionally, the inlet z -component of the velocity was not considered, as it has negligible effect on the temperature distribution. The pressure in the beam dump was assumed to be at 10 bar , for which the corresponding boiling temperature of water is 180°C . To retain a safety margin of 20°C in the design criteria, the water temperature should be kept below 160°C everywhere.

For all the CFD runs, the values that were typically chosen for the residuals in the convergence criteria are as follows: (i) continuity $\sim 10^{-5} - 10^{-7}$; (ii) velocity component $\sim 10^{-6}$; (iii) energy $\sim 10^{-6} - 10^{-8}$; (iv) turbulence energy $k \sim 10^{-5}$; and (v) turbulence dissipation $\epsilon \sim 10^{-4} - 10^{-5}$.

3.2. 2D flow analysis in the region of (1) radially integrated maximum linear power deposition, (2) maximum volumetric heat deposition, and (3) cylindrical portion of the vessel

A 2-D (symmetry along the z -direction) time dependent flow analysis in the radial plane was performed for 3 z -locations (cases 1, 2 and 3) as stated above for a beam trajectory located at a radial distance of 0.35 m from dump axis. A conjugate heat transfer analysis was carried out to determine the temperature distribution in the vessel. Multi-block grids with very fine mesh (in the beam traverse region) were generated to capture heat data and determine precise temperatures. Variable time steps: (i) 0.05 ms during the bunch train power deposition, and (ii) 1 ms for the remainder of the time. Beam heating was introduced only after obtaining a velocity field that had converged. After achieving a

Fig. 8. Overall Beam Power Extracted by the Beam Dump and Balance Escaping as Radiation.

steady state solution for time-averaged heat input, the code was subsequently run for the transient case for a sufficiently long time to obtain a quasi-steady periodic solution.

Fig. 9 shows steady state solutions for the velocity field. For the case of radially integrated maximum linear power density, the instantaneous temperature profile, just after heat deposition by the bunch train, is shown in Fig. 10 at a depth of $z=2.9$ m. Fig. 11 shows the maximum temperature variation as function of time. It can be seen that the maximum temperature is 155°C . The fluctuation of maximum temperature as a function of time is $\sim 30^\circ\text{C}$.

Similar analysis has been carried out for the location of maximum power density at a depth of $z=1.8$ m. The maximum temperature obtained is 130°C ; the fluctuation as function of time is 36°C and very much within the required specification. This analysis also shows that the thermal issues are more severe for the case of maximum linear power density than for the volumetric one. This is primarily because, even though local heat density is high, relatively cooler water enters the hot zone as less heat is deposited in the remainder of the region.

Fig. 9. Velocity contours (inlet velocity: 2.17 m/s; mass flux: 19 kg/m/s).

Fig. 10. Temperature distribution at the time when the beam train completes energy deposition at $z=2.9$ m $\approx 8.1 X_0$ (Maximum temperature: 155°C).

Fig. 11. Maximum temperature variation as a function of time at $z=2.9$ m ($\approx 8.1 X_0$) (Maximum temperature = 155°C).

Fig. 12. Details of the geometry used for the window cooling studies.

From the analysis for the above two cases it can be concluded that the maximum temperature in the water in the entire beam dump will not exceed 155°C , since the power deposited at all locations shows lower density.

As explained earlier, the maximum power deposition in the vessel wall depends on the radial location of the beam trajectory. In this case it is located at a depth of 4.3 m. Analysis has indicated that the temperature varies from a maximum of 91°C to a minimum of 66°C along the circumference. The transient variation is negligible ($< 0.05^\circ\text{C}$) due to the large thermal inertia of the vessel.

3.3. Window cooling analysis

It is proposed to cool the window with a single water jet of appropriate velocity (see Fig. 12). The window should be as thin as possible to reduce heat deposition by the beam and at the same time withstand high pressure. Based on this the window chosen is of 1 mm thickness and ellipsoidal in shape made of a titanium alloy. Due to the shape and location (as compared to the headers), it is expected that, there will be a stagnation zone of water near the window region (leading to inadequate cooling of the window) circulated by the main headers. Hence it is proposed to have a separate cooling system. The window diameter is taken as 300 mm. The diameter of the beam dump window is selected to balance the requirements of making the window large enough to minimize losses of photons (emission of bremsstrahlung photons during beam–beam collision) at the edges of the window and at the same time making it small enough so that it would be practical to manufacture it and still robust, keeping the losses of photon at the collimators in front of the beam dump reasonably small. Based on all these factors the diameter of the window is

selected. The water enters through a pipe of 17.4 mm internal diameter, with the outlet located near the window. After cooling the window, the water is allowed to mix with the main water system and drains through the outlet header. As indicated, 25 W of heat is deposited in the window with a maximum heat density of 21 J/cm^3 . A 3D flow analysis was carried out, which included the entire window, jet pipe, and flow region surrounding the window.

The flow analysis showed that an inlet pipe velocity of 0.1 m/s was adequate for window cooling. This corresponds to a mass flow rate of 0.024 kg/s. This water will mix with the main water and is drained through the common outlet header. Velocity profiles are shown in Fig. 13. In the region of beam entry, the tangential velocity is $\sim 0.045 \text{ m/s}$. Fig. 14 gives the window temperature distribution just when the bunch train has completed power deposition.

Fig. 13. Jet velocity near the window $\sim 0.045 \text{ m/s}$ (contours taken on a plane which slices the central jet pipe).

Fig. 14. Window temperature distribution just when the bunch train completes power deposition (Max temp: 74°C).

Fig. 15. Variation of maximum temperature in the window as a function of time (maximum: 74°C and $\Delta T \sim 9^\circ\text{C}$).

Fig. 15 shows the variation of maximum window temperature as a function of time. As can be seen, the maximum temperature rises to 74°C when the beam is on. The variation of the maximum temperature as a function of time is $\sim 9^\circ\text{C}$. The analysis indicates that a single jet can effectively cool the window.

3.4. Beam dump end wall cooling

The end wall of the beam dump is a 3 in. thick SS316LN plate designed to withstand 20 bar pressure (10 bar due to operating pressure and 10 bar to account for the pressure transients generated due to rapid heating by the beam—details are presented in Section 6). Due to the large plate thickness, significant heat will be deposited by the beam and hence a detailed analysis was warranted. In fact, the required length of the beam dump is primarily dictated by the beam power deposited and the effective extraction of the energy by circulating water. FLUKA data showed that the highest power density in the end wall was 12.4 W/cm^2 ; the resultant heat flux was 5.3 W/cm^2 . A total of $\sim 2 \text{ kW}$ power is deposited in the wall. No separate additional cooling system needs to be provided; the main circulating water was shown to be adequate for cooling the end plate.

A velocity of 1.7 m/s was chosen for the inlet header as input for the analysis. This is based on 3D flow analysis of the inlet header which showed a reduced azimuthal velocity component in the entrance region of the exit slit (see Section 3.4).

The presence of the end wall warranted a 3-D flow analysis. The computational regions include 0.5 m of water along the z-direction, the cylinder, and the end walls of the beam dump (see Fig. 16). Fig. 17 represents the temperature distribution through the plate cross-section. As can be seen, the highest temperature on the internal wall surface is $\sim 77^\circ\text{C}$ and much below the local boiling temperature. On the outer surface, the maximum temperature on the wall is $\sim 130^\circ\text{C}$. Thermal stresses arising due to these temperature gradients have been estimated using ANSYS software. The maximum stress is found to be 13780 psi (see Fig. 18) and is within the allowable range.

3.5. Flow analysis of the inlet header

Since the proposed water supply to the inlet header is from one side only (rear) and in view of the long header length of 11 m, a detailed flow analysis of the inlet header was performed to determine the azimuthal (tangential) and longitudinal (axial) velocity components at the header exit. To enhance the azimuthal

Fig. 16. End wall including 0.5 m water region.

Fig. 17. Temperature distribution in the end plate at $x=0$.

velocity component, flow diverters were placed along the exit slot as shown in Fig. 19. An analysis without flow diverters indicated a significant axial velocity component in the entrance region of the exit slot, substantially reducing the azimuthal component. A 3D turbulent flow analysis was performed for a flow rate 104.5 kg/s (a total of 209 kg/s for two headers) to determine the velocity distribution with flow diverters.

The average azimuthal and axial velocities along the z -direction are shown in Figs. 20 and 21, respectively. As can be seen, even with flow diverters, there is a significant velocity z -component, ~ 0.44 m/s in the entrance regions (near the end wall) with the azimuthal component being ~ 1.7 m/s. Since there is no significant power deposition by the beam beyond ~ 5 m, the reduced azimuthal component has no effect on cooling. A velocity of 1.7 m/s is adequate to cool the end wall and extract the deposited power, as shown in Section 3.3.

Fig. 18. Von Mises stress distribution in the end wall.

Fig. 19. Inlet header with flow diverters in the exit slit.

4. Heat deposition in the inlet and outlet headers

The FLUKA code was used to evaluate the power deposited in the inlet headers as well as the outlet header to determine the possibility of formation of hot spots. The data are summarized below:

- (1) Total power deposited in outlet header: 62.3 kW (the temperature increase in the outlet header water is < 0.1 K).
- (2) Total power deposited in each of the inlet headers: ~ 1.54 kW (the temperature rise is negligible).

Thus, the proposed geometry and flow will adequately cool all the critical regions of the beam dump.

5. Beam Dump mechanical design concept

The Beam dump mechanical design is driven by the parameters and constraints developed from FLUKA simulations, CFD thermal hydraulic simulations, and analytic calculations. The existing 2.2 MW SLAC beam dump [1] provides a baseline design to consider features

Fig. 20. Variation of the Azimuthal velocity component at the exit of the inlet header.

Fig. 21. Variation of z-velocity component at the exit of the inlet header.

which might be incorporated into the 18 MW beam dump mechanical design concept. The first step in creating a mechanical design concept for the beam dump is to establish the basic mechanical design parameters of the dump vessel and thin window. The beam dump is a pressurized vessel containing heated water that is also radioactive. Consequently, for operation it must conform to the design and safety standards of the American Society of Mechanical Engineers Boiler and Pressure Vessel Code. Table 1 presents a summary of the parameters and constraints used for the 18 MW beam dump mechanical design concept. Fig. 22 shows a layout of the up beam head.

5.1. Mechanical design details (derived from ASME BPVC section VIII division I)

The beam dump vessel consists of a circular cylindrical shell of 1.8 m ID × 11 m L with both ends closed off by heads. Stainless steel

alloy 316LN was selected over the standard 316 L for its increased strength properties. The minimum required thickness for the beam dump vessel shell is 21 mm. The actual thickness for the beam dump shell will likely be 1 in. as this is a standard thickness for stainless steel plate. This extra thickness will provide a margin of safety over the 21 mm minimum to allow for wear due to erosion by the vortex flow and any corrosion (which is expected to be negligible) over the service life. The flat head design was selected to ensure that the vortex flow pattern created by the inlet headers extends over the full length of the vessel and to maximize heat transfer from the inside surface of the vessel heads. The flat head will have a thickness of 3 in. to withstand a pressure of 20 bar as explained earlier.

Type SS316LN Schedule-40 piping will be used for the inlet and outlet headers. The 8 in. inlet headers have a single longitudinal slot machined (with flow diverters) to create the water jet which induces the vortex flow in the beam dump vessel. The inlet headers are located 0.7 m from the center of the dump vessel in the horizontal plane. The 10 in. outlet header will have circular perforations all around to allow efficient removal of the heated water from the beam dump vessel. The outlet header is located at the center of the dump vessel. Both inlet and outlet headers enter the vessel from the end wall of the dump vessel.

The thin beam dump window is hemispherical in shape which provides the largest safety factor given a maximum thickness of 1 mm. The material choice for the dump window is titanium alloy Ti-6Al-4V which was selected for its unique properties as described in SLAC memorandum [5]. For a 1 mm thick, 300 mm ID hemispherical window the maximum allowable operating pressure is 32 bar or 464 psi which provides a safety factor of 1.6. A finite element structural analysis using ANSYS (Fig. 23) yields a maximum static stress of 11,183 psi at 10 bar, which agrees well with the analytic formula calculation of 11,130 psi. While this provides some confidence that the 1 mm thick window is well below the fatigue strength of 55,350 psi, thermo-mechanical simulations are needed to better understand the total static stress load on the thin window.

The window will be joined to a thicker flange to facilitate sealing via a metal gasket to the beam dump vessel. The inside of the window will be cooled by a single jet of water provided by a tubular nozzle. The window cooling nozzle is fed from an external supply connection, rather than an internal connection to the inlet headers. The beam dump window and sealing flange assembly is located 0.35 m from the center of the beam dump vessel in the vertical plane. Fig. 24 shows a cutaway view of the hemispherical dump window and window cooling nozzle.

The window is the most fragile component in the beam dump vessel. Its integrity is crucial to the safe retention of the radioactive cooling water of the system. It is conceivable that long term exposure to high energy and high intensity beams causes enough beam induced radiation damage to result in window material failure and water leakage. To mitigate the risk of a radioactive water leak or catastrophic rupture of the window, it will be prudent to periodically replace the beam dump window and metal gasket seal. Preliminary activation studies using FLUKA indicate that the beam dump window and surrounding area will become highly radioactive, precluding replacement by direct human contact. This implies that a means for remote exchange of the beam dump window must be provided. Telerobotics could provide a flexible and robust solution for the exchange of the window flange and metal gasket assembly as compared to the more complicated design of the in situ window change mechanism used for the 2.2MW SLAC beam dump. Telerobotics has been successfully used for many decades in the remote handling, repair and decommissioning of highly radioactive components in the nuclear power industry and at CERN.

While the basic mechanical design criteria for the 18 MW beam dump vessel and thin window have been established taking into consideration the requirements of the ASME BPVC, many questions

Table 1
Beam Dump Design Parameters and constraints.

Operating Parameters	
Maximum operating temperature	200 °C
Maximum operating pressure	20 bar or 290 psi
Minimum operating pressure	10 bar or 145 psi
Beam Dump Vessel	
Internal diameter	1.8 m
Length	11 m
Beam Dump Inlet Headers	
2 at Up-beam end of vessel	8 in. (203 mm) ID with longitudinal slots
Inlet header location	0.7 m from center on horizontal plane
Beam Dump Outlet Header	
1 at Up-beam end of vessel	10 in. (254 mm) ID with perforations all around
Outlet header location	Center of vessel
Beam Dump Thin Window	
Hemispherical Shape	Pressure on concave side
Internal diameter	300 mm
Maximum thickness	1 mm
Window location	0.35 m from center of vessel vertical plane
Window cooling	Single water jet

Fig. 22. Beam Dump Head Layout.

Fig. 24. Cutaway View of Hemispherical Window and Window Cooling Nozzle.

items and will likely be designed, engineered and fabricated by external vendors. However, a few components such as the thin window, window sealing, and remote exchange mechanisms are unique designs to this application and considered high risk due to their critical role in the reliability of the 18 MW beam dump.

6. Pressure waves induced in the beam dump

6.1. Formation of pressure fluctuations

The energy deposition resulting from each bunch of electrons interacting with the water results in constant volume heating of the water. This is associated with a pressure rise which is proportional to the temperature jump. The region of elevated

Fig. 23. Static Structural Stress Analysis for 1 mm Thick Hemispherical Window.

remain that must be answered through detailed engineering and testing. Within the scope of detailed engineering, many of the components of the 18 MW beam dump are standard off-the-shelf

pressure immediately starts to spread by propagation of acoustic pressure waves. The restoring beam and bunch train structure spreads the energy deposition from each bunch in space and time. The result is a series of adjacent pressure spikes that each send out pressure waves. The pressure waves from each bunch spread through the beam dump reflecting from the beam dump walls and also interfering with each other creating complex pressure fluctuations.

Understanding the pressure fluctuations in the water beam dump is important in order to determine the pressure that will have to be accommodated by critical components such as the beam dump window and also to determine whether the pressure fluctuations could result in cavitation of the water. An analysis of the induced pressure waves following a complete bunch train is carried out using FLUKA and AUTODYN.

In the analysis a ‘worst case’ assumption is made that the walls of the beam dump are rigid and that there is no gas mixed in with the water. Flexibility of the beam dump and also gas contained in the water both have the effect of reducing the magnitude of pressure waves. However, for simplicity and to calculate the worst possible scenario from a safety stand point, these pressure reducing mechanisms are ignored. If the beam dump had completely rigid walls i.e. no expansion when the pressure waves interact with the walls, they will be completely reflected and there will be no loss of energy during this reflection.

6.2. The model

To calculate pressure in the beam dump with AUTODYN, the energy deposition data from FLUKA is used as input for the AUTODYN hydrodynamics code. A user subroutine interpolates between the FLUKA output data and the AUTODYN mesh so as to place the correct amount of energy in each cell and at each time step of the AUTODYN model. Figs. 25(a) and (b) shows contours of energy deposition following the complete bunch train. The beam dump geometry is defined with a Lagrange mesh which internally expands and contracts as the pressure waves move through the water. The geometry used is simply an 11 m long 1.8 m diameter cylinder with the beam center being 0.35 m eccentric from the beam dump axis. The beam dump is a very large volume by comparison to the computational cell volume that is required to accurately resolve the energy deposition of the beam, which has a beam sigma of 0.27 mm in one direction. As such creating an appropriate mesh for a complete model of the beam dump is challenging. In addition due to the asymmetry of the beam with respect to the target, no symmetry planes exist to reduce the mesh size.

The mesh that has been created has significant refinement on the beam axis and then expands towards the outer surfaces of the cylinder. Even with this level of refinement, the mesh will still be coarser than ideal in the region of energy deposition. This results in some averaging on a local basis; this should, however, not affect the global results at the beam dump internal surfaces. Fig. 27(a) shows two results for the pressure at the window calculated with two mesh sizes in the region of energy deposition (coarse = 4 mm × 100 mm and fine = 2 mm × 50 mm); this means the details of the energy deposition are being resolved to different levels. It indicates that the global result of pressure at the window is fairly insensitive to the detail of the local energy deposition. As a further check, an additional model of a 10 mm slice of the beam dump at z = 2 m (where the peak energy deposition occurs) was created with a higher mesh resolution throughout and a mesh size of 0.5 mm × 10 mm on beam axis. In this model the energy deposition region is resolved in significantly more detail. The two axial section surfaces were fixed in the z-direction and the outer rim surface was completely rigid.

AUTODYN solves the continuity, momentum and energy equations using an equation of state to obtain closure of the complete set of equations. The Mie Gruneisen shock equation of state used

Fig. 25. (a) Contour plot of energy deposition at a section through the beam dump. (b) Contour plot of energy deposition at a section through the beam dump.

takes the following form [8]:

$$p = p_H + \Gamma \rho (e - e_H),$$

where e is the energy per unit volume and p_H and e_H are the known functions of volume on the Shock Hugoniot curve. However, when compression of the material is small, which is the case for elastic compressions, then these two terms approach zero resulting in a much simpler equation of state which relates pressure to density and internal energy. It effectively describes a process of constant volume heating at each infinitesimal computational time step:

$$\delta p = \Gamma \rho \delta e,$$

where Γ is the Gruneisen Gamma and is defined as follows:

$$\Gamma = v \frac{\partial p}{\partial e} \bigg|_v,$$

where v is the volume. An explicit time stepping method is used to solve the set of equations simultaneously at each time step. The Courant number stability criterion ensures the time steps are small

enough that the dynamics are captured and in this way the solution remains stable. Conservation of total energy is the criterion for convergence of each time step.

A hydrodynamic tensile failure model is employed so that, if the pressure in the water becomes negative, the water will “fail” and not support any tension. If tensile failure occurs this is an indication of the possibility of cavitation.

The inputs for the AUTODYN water model are as follows:

Gruneisen Gamma=0.321
Reference temperature=335 K
Density=983 kg/m³
Heat capacity=3965 J/kgK
Velocity of sound=1554 m/s
Hydro tensile limit=−11 bar

These values infer a volumetric thermal expansion coefficient of $5.27 \times 10^{-4} \text{ K}^{-1}$ which corresponds to a water temperature of 62 °C.

The results from the slice model show the details of temperature and pressure induced in the water in the region of the maximum energy deposition. The peak temperature rise is calculated at 52 °C and occurs one quarter and three quarters of the way through the raster rotation. The peak pressure occurs after the energy of the first few bunches of the train is deposited in close proximity but before the developing pressure wave has had chance to move any appreciable distance. Fig. 26(a) shows a peak pressure rise of 34 bar above the 10 bar operating pressure, this means pressures as high as 44 bar are predicted in this slice. As the generated pressure starts to propagate outward, the peak pressure reduces to below 10 bar and, due to the rarefaction caused by the spreading waves, a region where the pressure dips below the operating pressure follows the rastering beam (Fig. 26b). The lowest value seen throughout most of the bunch train approaches −6 bar (relative to the 10 bar operating pressure). Throughout most of the bunch train this pressure dip is counteracted by the continuing addition of local pressure spikes as a result of adjacent bunches. However, immediately after the complete bunch train has passed, no further energy deposition

Fig. 26. (a) Peak predicted pressure occurring after twelve bunches. (b) Beam creates high pressure region which is followed by low pressure rarefaction region. (c) Pressure at the end of the bunch train reaching −10.4 bar relative to the 10 bar operating pressure. (d) Bulk failure of the water material model indicating the pressure has reached a negative value.

occurs; as the generated pressure propagates away the pressure dips to a new low and is predicted to result in a tensile failure of the water (Fig. 26(c) and (d)). As such, there is a good chance of cavitation occurring at the end of the bunch train. The pressure on the rigid outer radial surface of the slice model reaches a maximum of 15 bar. This is in agreement with the predictions made from the complete beam dump model.

The results from the complete beam dump model show the pressure on the internal surfaces of the cylindrical beam dump as a result of a single bunch train. The peak pressure in the region of the window is 12.5 bar which is 2.5 bar above the beam dump operating pressure. This occurs 1.5 ms after the bunch train which is an equivalent time for acoustic waves to travel from the peak energy deposition region ($z=2$ m) to the window (Fig. 27(a) and (b)). The peak pressure on the internal surface of the beam dump approaches 15 bar and occurs at $z=2$ m (Fig. 27(c) and (d)). The added complexity of a flexible beam dump structure and gas contained within the water mean that this is a worst case calculation and the pressure

fluctuations at the internal surfaces are not expected to be as high as this. Pressures below the 10 bar operating pressure will occur at the internal surfaces of the beam dump as a result of the pressure waves but excursions should not be high enough to cause cavitations at these surfaces.

Since the dump tank is designed withstand 20 bar pressure, they can withstand the additional pressure arising due to pressure waves. Also the high local water pressure is not an issue. The major issue is the possibility of local volume boiling of water due to reduction in the pressure to 4 bar during energy deposition by the electron bunches from the same bunch train followed by cavitation near the end of the bunch train. The reduction in the local transient pressure will have no effect on the next bunch train since the next bunch train arrives only after ~ 249 ms. By then the pressure wave will have been dissipated. The issue is what will happen when subsequent electron bunches of the same bunch train arrive and encounter a local steam pocket. This will shift some of the energy deposition further down beam and

Fig. 27. (a) Pressure on the internal surface of the beam dump window calculated with two levels of mesh density. (b) Pressure contours after 2.6 ms showing the peak pressure at the window. (c) Pressure on the internal surface of the beam dump at selected gage points (gage 2 sees the maximum recorded pressure). (d) Pressure contours on the internal surfaces of the beam dump after 1.5 ms, showing peak calculated pressure on beam dump wall relative to 10 bar operating pressure.

Fig. 28. Coolant circuit details.

A valve located just downstream of the main pump discharge allows bypassing a small amount of flow to feed a nozzle for generation of a pressure differential (ejector pump principle) across the hydrogen–oxygen recombiner. This enables the flow of radiolytically-evolved gases through the platinum–palladium catalytic bed (located on top of the surge tank gas space) for recombination.

The details of the surge tank size and the recombiner system to mitigate the expected maximum rate of hydrogen evolution of ~ 6 l/s have yet to be designed. However, preliminary details of catalytic recombiners are presented in Section 8. The catalytic capacity and gas flow rate will be sufficient to limit the H_2 -concentration in the surge tank gas space to less than 1% at all times.

An auxiliary water circuit will be provided to supply water to the space between the two seals of the double-seal pump. The water pressure in this loop must be above that developed by the main pump. This ensures that a leak in the inner or primary pump seal results in only inflow from the seal circuit into the primary water loop and not vice versa (to avoid leakage of radioactive water into the pump/heat exchanger/surge tank holding container). The loop will be designed for a pressure above that of the process water in the pump. Level indicators will be provided in the seal water tank to monitor any leakages to the primary water loop.

The layout logistics of various components will depend upon the location of an ILC. Should it be sited in the US, it is likely to be placed underground at a depth of order 100 m [10]. In this case, it is proposed to locate all equipment, other than the beam dump and storage tank, at ground level, for reasons of cost reduction, accessibility, and ease of maintenance of equipment, etc. For such a configuration, the piping of the primary coolant will be lengthy (~ 250 m) and pumping power will be substantial. Choosing an appropriate pipe diameter will be important.

The LCW coolant loop for heat extraction in the heat exchanger contains water at 32 °C from the cooling tower, at a flow rate of 330 kg/s. The heat exchanger outlet water returns to the cooling tower at 45 °C for heat rejection. These pipe lines will be of 20 in. diameter.

In addition, provision will be made for LCW makeup in both surge tank and sealant circuits.

A low pressure holding tank with the capacity to store the entire volume of water in the coolant loop will be provided. This tank will be used to drain the beam dump water into during periodic window changes. After this procedure, the storage tank water will be pumped back to the main loop via the surge tank.

Water that might have leaked purposely or accidentally from either the beam dump, the surge tank, or any part of the radioactive water loop will be collected in a sump of appropriate size. From there it can (after filtering) be pumped back to the surge tank or elsewhere for disposal.

Details of these processes have yet to be worked out.

8. Radiolysis and hydrogen recombiner system

In addition to residual radioactivity, radiolysis (dissociation of the water molecule in the presence of radiation) presents very important problems for the beam dump system. The results are free radicals, ions and new molecules. Two products of the radiolysis process are of particular importance in the operation of a radioactive water system. The first is hydrogen peroxide, H_2O_2 . It is an oxidizing agent and may have a positive or negative influence on the corrosion behavior of the materials used in the system. Experimental results indicate that metals which derive their corrosion resistance from a dense, insoluble oxide film on the surface have lower corrosion rates in water containing H_2O_2 than in water without that agent. The second product is hydrogen,

H_2 , which, after saturation of the water, appears as a gas. The presence of air can quickly result in an explosive mixture. Therefore, the precise knowledge of hydrogen evolution rates as function of direct power deposition in the cooling water is a necessity for developing an appropriate recombiner to safely operate radioactive water systems.

The linear energy transfer (LET) in water for electrons with kinetic energy, $E_0 > 0.5$ MeV, i.e., the amount of energy lost per unit distance traveled, is approximately 2 MeV/cm. This energy is lost in discrete amounts averaging about 100 eV per event. The energy usually converts within less than 10^{-12} s into heat. Water molecules are excited in the region where this energy transfer occurs; such a region is called a spur. The energy deposition reaches a maximum at the end of the track of a charged particle and results in formation of a high temperature region, called a thermal spike.

During the pulse, high concentrations of free radicals such as H^+ and $(OH)^-$ are formed in the spur. Some of these radicals will react with one another, while others might diffuse out of the spur into the bulk water. The reactions within the spur will yield H_2 , OH, H_2O_2 and others. They can be symbolically represented as

The radicals diffusing into the bulk water volume can increase in concentration to a point where they not only react with the H_2 , H_2O , and H_2O_2 , but also with one another to form more H_2 and H_2O_2 . Since the solubility of hydrogen in water is only about 0.8×10^{-3} mol/l, there will be, after a certain time, a net evolution of free hydrogen. Once equilibrium concentration is reached, hydrogen peroxide is expected to also decompose due to radiation and other chemical reactions, and a net evolution of O_2 can be expected.

Theoretical quantitative predictions of evolution rates are a complicated task with unknown rate constants. Measurements of free hydrogen evolution after reaching steady state conditions have been made [11] using an electron linac. The rate of generation was found to be ~ 0.3 l/MW s.

Based on this measured rate, the estimated evolution of H_2 for 18 MW beam power will be ~ 5.4 l/s. This is an upper limit, since a small fraction of the beam power is absorbed and dissipated in solid materials at the downbeam end of the dump and in the cylindrical vessel. Since the lower explosive limit (LEL) of hydrogen in air is $\sim 4\%$, and the concentrations allowed in industry and acceptable to underwriters is maximally 50% LEL or 2% H_2 in air, the recombiner system is designed not to exceed a maximum value of 1% H_2 in air.

Extensive tests and experience at SLAC demonstrated that a catalyst consisting of a high-nickel stainless steel ribbon coated with platinum and palladium, in form of mats that look like a coarse steel wool, will sufficiently reduce the H_2 concentration in one pass if the mat thickness is ~ 6.4 cm. Extending the SLAC design, an ILC recombiner would need ≤ 1700 cm² inlet cross-section and $\leq 10,650$ cm³ of catalyst volume. This could be accomplished with a ~ 18 in. diameter mat in an 18 in. diameter pipe, 2–1/2 in. deep.

Alternatively, a catalyst in form of small coils ('helicat material'), using the same platinum/palladium active surface could be employed. This allows 5 times the capacity of catalyst per unit volume than the earlier version. The 2–1/2 in. depth dimension could thus be reduced to < 2.5 cm. The coils are small and can be "poured" into any shape container. The bulk density of this material is 0.65 g/cm³ (there are ~ 35 coils per cm³ or $\sim 10^6$ coils per ft³). The main advantages of this system are as follows: (i) the coils are mechanically strong and have thermal shock resistance; (ii) it is a proven system (some of the catalyst at SLAC is of this variety); and (iii) long life (none of the catalysts at SLAC had to ever be replaced because they wore out).

Fig. 29. Power depositions in the entire dump region (average of $y = -342.5$ cm and $+342.5$ cm).

The catalyst bed is in a recombiner housing and the gases are “pumped” through the catalyst by means of an ejector pump-type setup. A nozzle below the catalyst supplied by water from the main pump discharge provides the motive power, creating a negative pressure below the catalyst bed. The water droplets from the water jet also condense and cool the water vapor after recombination. The gases from the surge tank are preheated to ~ 65 °C before entering the catalyst bed for greater recombination efficiency. For the ILC, a catalyst bed would require ≤ 3 kg of catalyst material of the “Heli Cat” variety.

9. Thermal analysis of shielding

Preliminary studies related to shielding and radioactivity have been carried out using the FLUKA code. Based on this analysis, a shielding of 50 cm iron over the beam dump followed by 200 cm Borcrete (Concrete + 5% boron) was used for the detailed analysis to evaluate the heat load. The results are summarized in Fig. 29. Approximately 42.5 kW of heat will be deposited in the iron

shield and 0.76 kW in the Borcrete. The analysis shows that active cooling will be necessary in the iron.

10. Summary and conclusions

The foregoing presents a summary of the detailed thermal-hydraulic analysis that was carried out to pave the way for the design of an 18 MW beam dump for an ILC. The required geometry, flow parameters have been optimized. Primary coolant loop, chemical and radiological issues have been analyzed. Major issues still to be addressed include prompt and residual radioactivity, safety, remote window exchange etc.

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