COMPARATIVE CONCEPTUAL DESIGNS OF LIQUID LEAD ABSORBERS FOR THE FCC-ee BEAMSTRAHLUNG DUMP

S. Candido *[1], R. F. Ximenes[1], M. Calviani [1], R. Seidenbinder[1],
A. Perillo-Marcone[1], G. Lerner[1], A. Frasca[1], A. Lechner[1]
M. Tarantino[2], C. Carrelli[2], L. Tricarico[2], Louise Jorat[1], G. Banks[1]
[1]CERN - European Laboratory for Particle Physics, CH-1211 Geneva, Switzerland
[2]ENEA - Agenzia nazionale per le nuove tecnologie, Brasimone, Italy

Abstract

At CERN's Future Circular Collider (FCC-ee), the beamstrahlung photon beams produced at each interaction point carry several hundred kilowatts of power, requiring a reliable and thermally efficient absorber. Building upon an initial slope-based liquid-lead concept, this work investigates two improved configurations: 1) a double-slope geometry, designed to mitigate photon backscattering observed in earlier designs; and 2) an inclined slope section with an accumulation pool at the back, intended to maximize photon absorption, reduce system size, and ensure thermal and flow stability. Both concepts operate under an inert argon atmosphere and target an effective absorption thickness of 10–20 cm, with a liquid-lead mass flow rate of approximately 300 kg/s. Monte Carlo simulations are employed to compute photon energy deposition, while multiphase computational fluid dynamics (CFD) analyses characterize the coupled thermal and hydrodynamic behavior. The results compare the performance of the two configurations and identify key parameters for further optimization of the FCC-ee liquid-lead photon dump system.

INTRODUCTION

The proposed CERN Future Circular Collider (FCC) will initially operate as a high-luminosity electron–positron collider (FCC-ee) [1, 2]. During each bunch crossing, strong electromagnetic beam–beam interactions generate beamstrahlung (BS) radiation, producing two intense photon beams at every interaction point. At the Z pole, each beam carries an average power of approximately 370 kW [3], creating a significant power load that must be safely absorbed downstream of the collision region. Dedicated photon absorbers are required to dissipate this radiation while protecting accelerator components and ensuring stable collider operation.

Solid absorbers based on materials such as graphite face important limitations under these operating conditions due to temperature limitations, thermally-induced fatigue and radiation damage. Circulating heavy liquid metals offers an attractive alternative, as the flowing medium continuously renews the interaction region thus efficiently transporting heat away from the beam interaction zone, besides mitigating potential radiation damage and structural limitations of the absorber. Among candidate materials, liquid lead is particularly suitable due to its high density and atomic number, which provide efficient photon absorption, combined with a melting temperature compatible with operation at around 400 °C and high heat capacity [4, 5]. Furthermore, a flowing liquid absorber can tolerate temporary power excursions that may occur due to beam misalignments at the interaction point [6].

The beamstrahlung photons propagate in a narrow forward cone along the outgoing beam direction and are intercepted by the dump located approximately 500 m from the interaction point in order to maintain adequate separation from the circulating beams. Monte Carlo simulations using the FLUKA radiation transport code [7–10] indicate that a Pb absorber volume of approximately 70 cm×70 cm with an effective lead thickness of about $d_{\text{eff}} \approx 20$ cm is required to absorb most of the incident beamstrahlung power [11].

To achieve this effective interaction thickness while remaining within the hydraulic constraints of a circulating liquid-lead loop, different absorber geometries can be considered. Two candidate concepts investigated in this work are illustrated in Fig. 1.

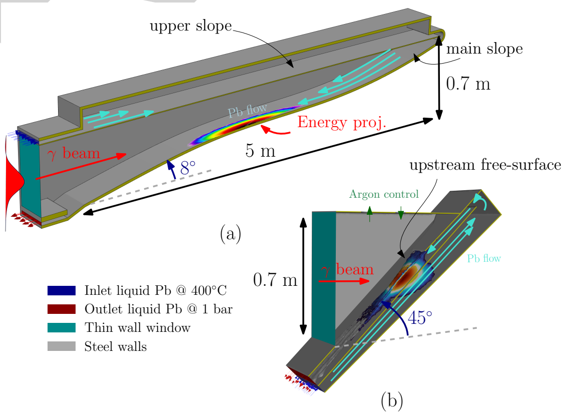


Figure 1: Conceptual layouts of the two liquid-lead absorber configurations considered for the FCC-ee beamstrahlung dump: (a) Double-Slope (DSlope) concept and (b) Compact Upstream Slope plus Pool (CUSP).

The first concept uses a sloped flowing lead layer to increase the effective photon path length inside the liquid without increasing the mass flow rate. A refined double-slope configuration is introduced to mitigate photon backscattering [12]. The second concept, referred to as the Compact Upstream Slope plus Pool (CUSP) [13], divides the absorption into two stages: a thin free-surface lead upstream flow

* silvio.candido@cern.ch

that intercepts the peak power of the photon beam and a downstream lead pool that absorbs the remaining energy.

These concepts where design taking in account several engineering constraints, one important is that the absorber must operate within the hydraulic limits of the circulating lead loop, which restrict the mass flow rate to approximately $\dot{m}_{\max}$ ~300 kg/s, due to technological limits [13]. In addition, the design must maintain acceptable structural temperatures (below 500 °C) to avoid corrosion and degradation of the steel vessel [14], while remaining compatible with the integration constraints in the FCC tunnel.

This paper compares the thermal-hydraulic behavior and photon absorption characteristics of these two concepts using coupled FLUKA [7–9] energy-deposition calculations and computational fluid dynamics simulations. The objective is to evaluate their feasibility within the common hydraulic and thermal constraints of the FCC-ee beamstrahlung dump system.

NUMERICAL FRAMEWORK FOR THERMO-FLUID CALCULATIONS

The governing equations of the two phase flow are the conservation of mass (continuity equation) and, the momentum conservation (Navier-Stokes equation), given respectively by,

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0, \quad (1)$$

$$\frac{\partial (\rho \mathbf{u})}{\partial t} + \nabla \cdot (\rho \mathbf{u}\mathbf{u}) = -\nabla p + \nabla \cdot (\mu \nabla \mathbf{u}) + \mathbf{F}, \quad (2)$$

$$\frac{\partial (\rho E)}{\partial t} + \nabla \cdot (\mathbf{u}\,(\rho E + p)) = \nabla \cdot (\kappa_{\text{eff}} \nabla T) + S_h, \quad (3)$$

where ρ is the mass density, $\mathbf{u}$ is the velocity vector, p is the pressure, μ is the dynamic viscosity, and $\mathbf{F}$ represents external forces, in this case gravity and surface tension at the liquid-gas interface. The Volume of Fluid (VoF) method, in ANSYS Fluent framework [15], is employed to track the interface between the liquid lead and the cover gas, allowing us to accurately capture the flow behavior of the liquid. This method solves the motion of two immiscible phases by tracking the volume fraction, α, in each computational cell and solving an advection equation of transport [16]. The physical properties, such as density ρ and viscosity μ, are calculated as weighted averages based on the volume fraction of each phase and in function of temperature, based on the data of [17]. Argon is chosen as the cover gas for the liquid lead system due to its inert nature, which minimizes the risk of chemical reactions with the liquid lead and its low thermal conductivity. The surface tension is given on function of temperature [17].

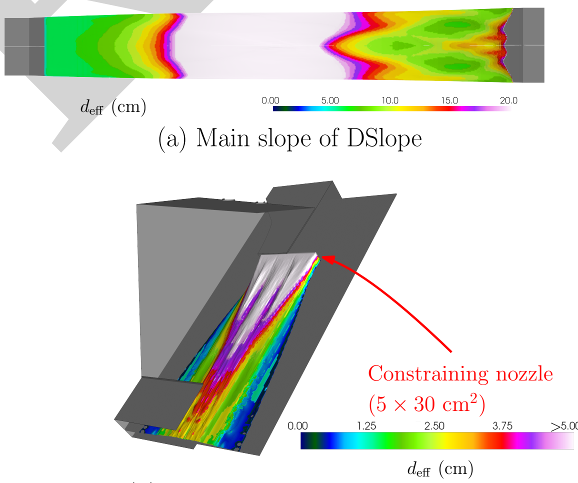
The mass flow rate is maintained constant at 300 kg s^{-1} at the inlet, considering the constrains for the hydraulic system, and two pressure inlet/outlet conditions are applied on the side walls to ensure that the argon can circulate under a pressure of 1 bar.

Using this numerical framework, 3D thermo-fluid simulations are performed by incorporating a volumetric power source, S_h, in the energy equation corresponding to the power deposition from the photon beam, in the corresponding material. The simulation uses the PISO (Pressure-Implicit with Splitting of Operators) scheme for pressure-velocity coupling, an adaptive time step to maintain a Courant number of 0.3, and the k-ω SST (Shear Stress Transport) turbulence model to resolve turbulent flow behavior.

RESULTS AND DISCUSSION

The main design challenge of the liquid-lead absorber is to maximize the effective interaction thickness d_{eff} (the thickness of liquid lead seen by the photon beam) while maintaining a feasible mass flow rate compatible with the hydraulic limits of the circulating loop. An optimized S-curve slope was introduced [12] to increase the effective interaction thickness near the peak power deposition region. However, due to the shallow interception angle, this configuration produces a significant amount of back-scattered photons. To mitigate this secondary effect, a Double-Slope (DSlope) configuration was proposed, as illustrated in Fig. 1(a).

Figure 2 shows the effective liquid-lead thickness along the main slope of the DSlope and CUSP upstream free-surface. In the DSlope concept, the main slope provides the primary photon interaction region while the upper slope intercepts the backscattered radiation. In the CUSP configuration, a constraining nozzle (5 × 30 cm^2) is introduced to concentrate the liquid flow in the high-intensity region and increase the effective thickness of the free-surface film where the beam first intercepts the absorber.

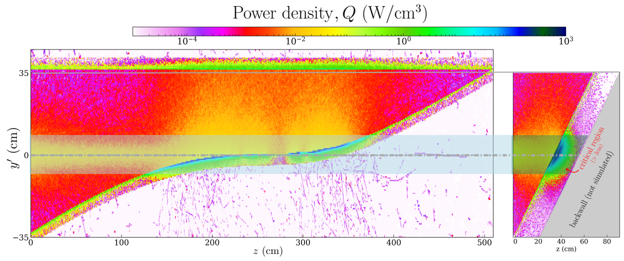


(a) Main slope of DSlope

(b) Upstream flow of CUSP

Figure 2: Effective thickness of liquid lead on the first interaction surface for (a) DSlope and (b) CUSP configurations.

The energy deposition generated by the beamstrahlung photons is evaluated using FLUKA Monte Carlo simulations. The photon source corresponds to a beamstrahlung photon rate of 1.3 × 10^{18} photons/s at the Z pole, derived from FCC-ee beam parameters [11]. The resulting power-density distributions inside the absorber are shown in Fig. 3.



(a) DSlope (b) CUSP

Figure 3: Power deposition obtained from FLUKA Monte Carlo simulations for (a) DSlope and (b) CUSP concepts. Coordinate y' is the beam axis.

In terms of peak power density, the DSlope configuration has peak values around 250 W/cm^3. This broader distribution is beneficial for thermal management, as it facilitates heat dissipation and prevents highly localized hot spots in the liquid metal.

To evaluate the thermal response of the absorber, the volumetric power source obtained from FLUKA is introduced into the CFD simulations, for each corresponding material (Pb, Argon and Steel). The energy deposition is applied once the liquid-lead flow reaches a hydrodynamic steady state, which occurs after approximately 3 seconds. The simulations then continue for an additional 12 seconds to reach thermal steady-state conditions.

Figure 4 shows the resulting temperature field and velocity distribution for the DSlope configuration. The temperature increase remains moderate due to the strong convective transport provided by the flowing liquid lead.

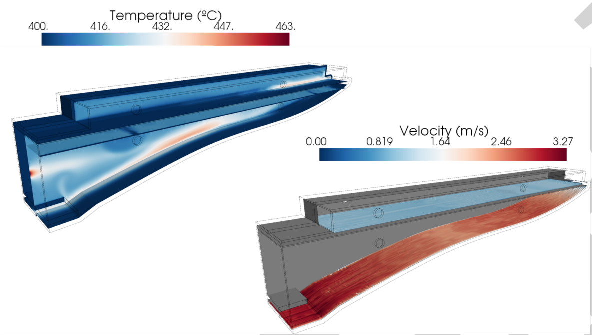


Figure 4: Temperature field and velocity magnitude for the DSlope concept.

The CUSP configuration, shown in Fig. 5, intercepts the peak power with a thin free-surface liquid film while the remaining energy is dissipated in a downstream lead pool. The main thermal constraint in this configuration is to ensure that the steel vessel temperature remains below the design limit of 500 °C, which is imposed by material constraints related to corrosion and high-temperature degradation of the steel in contact with liquid lead.

Compared with the DSlope absorber, the CUSP configuration achieves similar overall photon absorption in a significantly more compact geometry. The peak power is intercepted by the continuously renewed liquid film, while the downstream pool absorbs the remaining power. This

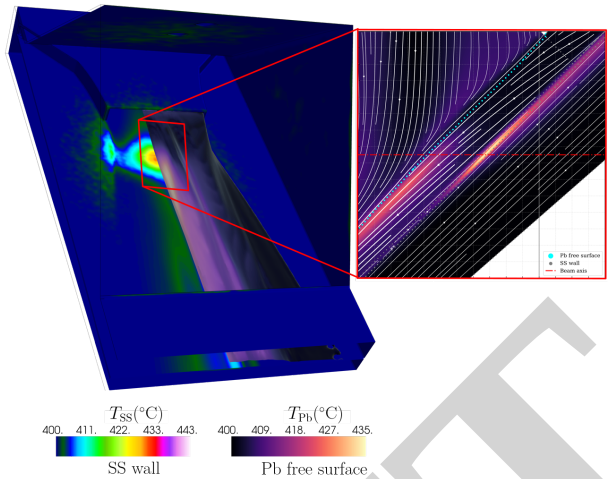


Figure 5: Temperature distribution for the CUSP concept showing the steel wall and liquid lead free surface.

configuration therefore reduces the system footprint while maintaining acceptable thermal margins.

SUMMARY

Both absorber configurations demonstrate similar thermal behavior and remain within the operational temperature limits of the liquid-lead system. In both cases, the flowing lead efficiently removes the deposited heat, preventing the steel vessel temperature from exceeding the design limit of approximately 500 °C.

The main differences between the concepts arise from their geometric configuration and integration implications. The DSlope concept distributes the energy deposition over a longer interaction path, resulting in smoother thermal gradients and a more stable but bigger free-surface flow. However, achieving the required effective thickness requires a structure of approximately 5 m in length, which increases the overall footprint and integration complexity of the absorber system.

In contrast, the CUSP configuration achieves comparable photon absorption within a significantly more compact geometry by combining a thin free-surface lead film with a downstream accumulation pool. This approach reduces the system length to approximately 1 m, improving integration. However, the compact design introduces additional engineering challenges. In particular, the central steel wall that guides the liquid lead flow becomes a critical structural element, as it must simultaneously withstand thermal loads and support the hydrodynamic forces generated by the flowing lead film.

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