

MECHANICAL DESIGN AND CHALLENGES OF THE FCC-ee ARC RADIATION SHIELDING

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Abstract

The FCC-ee faces numerous challenges in managing primary synchrotron radiation, which poses risks to machine components and tunnel equipment. Effective radiation shielding is essential to reduce equipment failure, prevent performance degradation, and minimize reliance on costly radiation-hard materials.

The shielding solution under consideration involves enclosing photon stoppers and the enclosing dipoles with shielding inserts and plates. With a total of 2840 dipoles, each containing 10 photon stoppers, this machine requires shielding for 28400 stoppers. A preliminary design, which is based on the use of lead, shows promising results in dose reduction; however, optimization is critical to manage costs, comply with integration constraints, and ensure manufacturing feasibility. Current estimates suggest that each stopper will require approximately 400 kg of shielding material, resulting in a total of 11360 tons of lead. Optimization efforts focus on refining the shielding's shape, size, and materials, as well as simplifying fabrication methods and installation processes, making large-scale implementation more efficient. Current goals include detailed cost estimates, assessment of spatial and integration requirements, and development of a robust design to ensure effective thermal management, mechanical integrity, and structural support while fulfilling the objective of significantly reducing the total ionizing dose in the tunnel.

INTRODUCTION

Over the past several years of LHC experiments, particle physics has evolved significantly. The proposed FCC-ee collider will precisely study the Z, W, Higgs, and top quarks, with strong potential to uncover new physics through both direct and indirect methods [1,2]. The operation of the FCC-ee machine will result in significant synchrotron radiation, requiring effective shielding to protect machine components and tunnel infrastructure [3]. The proposed solution consists of an assembly of lead blocks surrounding photon stoppers made of CuCr1Zr [4], with design efforts focused on optimizing material use, geometry, and integration within the tunnel. Pure lead is chosen for its high attenuation capability and cost-effectiveness as well as improved radiation protection considerations, though lead-antimony (PbSb) alloys are being considered for improved mechanical performance [5]. Key challenges include thermal management and ensuring mechanical stability. This paper presents the current engi-

neering developments and preliminary simulation results to guide further optimization.

SHIELDING OVERVIEW AND RADIATION BY PRIMARY SYNCHROTRON PHOTONS

In the FCC-ee, circulating electrons and positrons emit synchrotron radiation, generating a total power of 50 MW per beam along the 77 km long arcs. While the total emitted power remains constant across all operation modes, the $\bar{t}t$ mode (182.5 GeV, beam current 5.1 mA), results in the most challenging radiation environment. This is due to synchrotron radiation photons of significantly higher energy compared to others. To ensure the protection of accelerator components and systems in the tunnel, dedicated absorbers and shielding is required to mitigate radiation levels effectively.

A preliminary optimization of the shielding geometry has been conducted, concluding in the initial conceptual shielding design for the collider arcs illustrated in Fig. 1, where 1 and 2 (external and internal shield, respectively) correspond to the elements exposed to the highest synchrotron radiation.

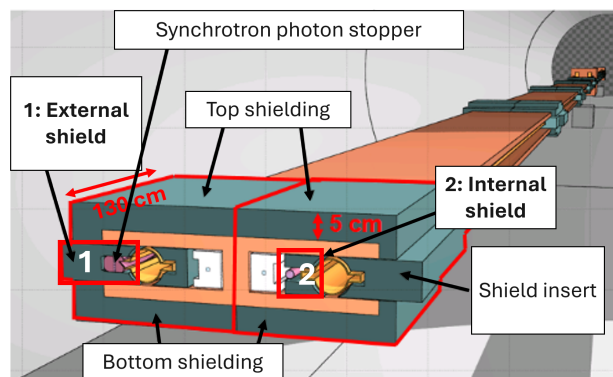


Figure 1: Preliminary conceptual radiation shielding design for the collider dipoles in the FCC-ee arcs [3].

FCC-ee SHIELDING DESIGN AND MATERIALS

Active cooling is needed for both internal and external shields, as passive dissipation to the environment from the 2840 shielded dipoles exceeds the tunnel ventilation capacity. One of the solutions involves embedding stainless steel pipes within cast lead. This design prevents direct water contact with lead (hence avoiding corrosion and erosion issues on Pb) while optimizing thermal contact resistance between the two materials, hence significantly improving heat dissipation [6,7]. The casting will take place within a stainless steel

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mold, which becomes part of the shielding itself, providing structural reinforcement and preventing direct human contact with lead, thus enhancing safety [8]. Another option, though less cooling-effective, would be clamping stainless steel pipes between rolled Pb plates.

However, lead's thermophysical properties make it prone to creep even under low stresses near room temperature [9]. Along with its machining difficulties, this may justify opting for a PbSb alloy, which is more resistant to deformation and easier to machine.

THERMOMECHANICAL STUDIES

Using FLUKA code [10, 11], it is determined that both the external and internal shields absorb an average peak thermal power of 640 W each from synchrotron radiation during nominal operation in the \bar{it} mode [3]. The external shield is a single piece, while the internal shield consists of separated top and bottom plates, leaving space for the integration of a cooling pipe with additional functions beyond the scope of this paper. Thermomechanical simulations assess the mechanical response to beam-induced temperature gradients under steady-state conditions, using pure lead as a conservative reference due to its lower mechanical strength, with PbSb expected to further enhance stability.

Boundary conditions The support method for each shielding element is yet to be determined. For now, both internal and external shielding components are modeled with constraints on their bottom surfaces to prevent vertical displacement, as they will rest on other structural elements. The remaining faces are left free to expand. While the exact support mechanism is still under evaluation, this setup offers a reasonable preliminary approach.

Heat dissipation is handled through natural convection, with an assumed heat transfer coefficient of $3 \text{ W}/(\text{m}^2 \text{ } ^\circ\text{C})$ to the surrounding environment, and forced convection is employed via the stainless steel cooling pipes with Dittus-Boelter correlation [12], assuming they are embedded into cast lead. To simplify the model, the pipes were omitted due to their thin structure and negligible thermal resistance. The heat transfer coefficient for water flow was calculated for various mass flow rates.

Mechanical analysis follows two approaches: one evaluates plastic deformation using a multi-linear isotropic hardening model, while the other assesses creep behavior across temperatures. These models determine the material's resistance to beam-induced energy deposition and the potential need for a higher-performance alloy like PbSb.

Steady state thermomechanical response This preliminary analysis aims to determine whether active cooling is necessary only for heat management or also crucial for the shielding's long-term integrity.

Figure 2 portrays how an average thermal power of 640 W is enough to partly melt the external and internal shielding without appropriate cooling, since lead has a melting point of 327°C . This highlights the critical need for active cooling,

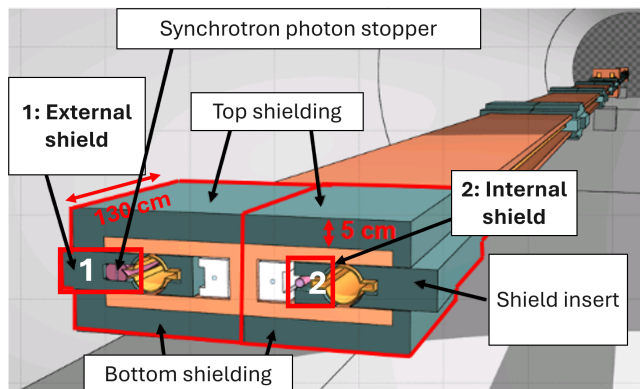


Figure 2: Steady state thermal simulations without cooling: (a) external shield; (b) internal shield.

not only to prevent heat from accumulating in the tunnel but also to ensure the structural integrity and longevity of the shield. Incorporating 8 mm diameter stainless steel cooling pipes with a flow rate of 0.75 l/min effectively reduces temperatures, as shown in Fig. 3. This corresponds to a water velocity of 0.25 m/s, while the maximum considered flow rate (6 l/min) reaches 2 m/s. Although the lower flow rate may fall within the laminar-turbulent transition range, it still demonstrates that minimal cooling is sufficient to achieve significant temperature reduction.

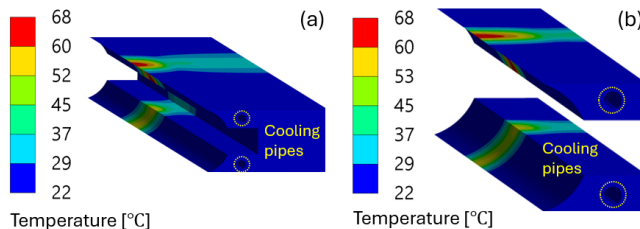


Figure 3: Steady state thermal simulations with water cooling pipes: (a) external shield; (b) internal shield.

As shown in Table 1, the temperatures reached when including cooling pipes in both shielding components are nearly identical, indicating that the connecting shield element between the top and bottom plates of the internal shield has a minimal impact on the overall thermal performance.

Table 1: Maximum temperature at different water flow rates for external and internal shields.

Water flow rate (l/min)	Max. Temperature [$^\circ\text{C}$]	
	External shield	Internal shield
6	51	51
3	55	56
1.5	61	61
0.75	68	69

Plastic behavior In the regions where the highest energy density deposition occurs, beam-induced stress concentrations exceed the yield strength of the material and

cause plastic deformation in both the internal and external shield elements. However, since the stress levels remain relatively low, the resulting plasticity is acceptable (see Fig. 4). Nonetheless, incorporating a container around the shielding could provide additional structural support, helping to further reduce deformation and enhance overall stability.

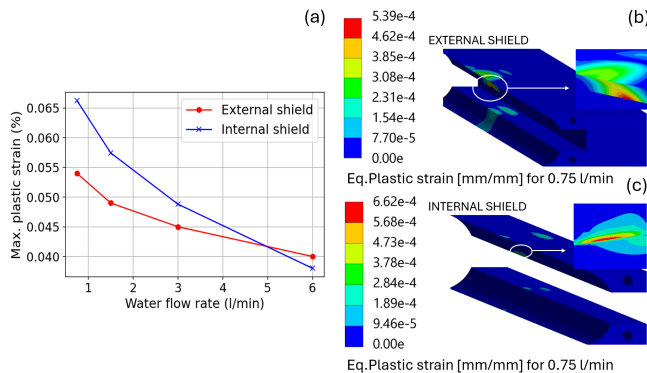


Figure 4: Equivalent plastic strain: (a) dependent on the water flow rate; (b) external shield at 0.75 l/min; (c) internal shield at 0.75 l/min.

Creep studies Lead is prone to creep due to its high material diffusivity and weak metallic bonding, which contribute to diffusion and dislocation creep mechanisms, respectively. As a result, it can undergo gradual deformation under sustained mechanical stress, even near room temperature [13]. A detailed study of its long-term behavior over the 15-year operational span of FCC-ee, scheduled to begin in the mid-2040s [14], is essential. While other modes will operate, the $\dot{\epsilon}$ mode is the most damaging for the shielding; thus, for simplicity and to be conservative, the analysis assumes it runs continuously for the entire 15 years. Deformation mechanism maps provide valuable insights into this phenomenon. At CERN, pure lead at high temperatures is a well-studied material with extensively documented thermo-physical properties [6, 13]. To analyze creep deformation, Norton's equation is used to model power law creep while neglecting diffusional flow [15]. Although this last assumption tends to overestimate creep strain, it ensures a conservative assessment. As illustrated in Fig. 5, a shift between deformation regimes occurs around 1 MPa. Furthermore, the activation energy in Norton's equation is omitted, and instead, a separate function is provided for each temperature.

As shown in Fig. 6 (a–c), the calculated creep strain is within acceptable limits for the expected service life. However, future design changes or more restrictive contact definitions could lead to increased values.

FUTURE CONSIDERATIONS

During the conceptual phase, factors such as water flow, energy input, and cooling pipe placement could affect the shielding's thermomechanical performance. While these may increase beam-induced strains, no significant issues

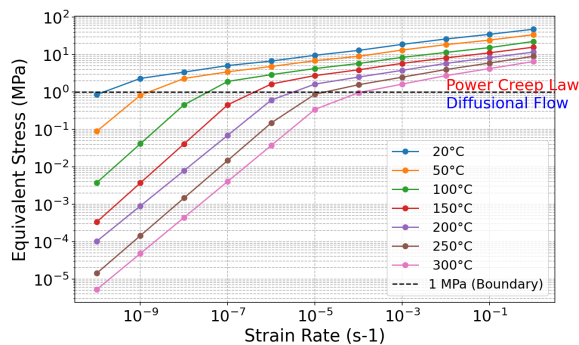


Figure 5: Creep strain rate in pure lead for different values of temperature and von Mises stress [9, 13].

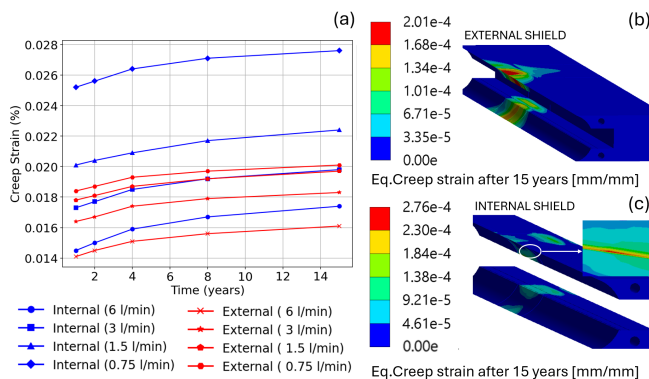


Figure 6: Equivalent creep strain rate (a) during 15 years of operation, (b) for external shield after 15 years of operation, (c) for internal shield after 15 years of operation.

with temperature, strain, or creep have been identified so far. Both materials are being considered, with PbSb as a potential option if additional mechanical reinforcement is needed.

For series production, the focus is on simplifying logistics, handling, and transport. Integrating cooling pipes into cast lead remains difficult, so an alternative using Pb rolled plates with clamped stainless steel pipes is under consideration. Although this may reduce cooling efficiency, higher flow rates could compensate. The construction of a prototype shielding is planned to explore potential limitations and gain clearer insight into technical challenges, logistics, and costs.

CONCLUSIONS

The proposed radiation shielding design uses lead, with efforts to reduce costs and improve integration. Active cooling via stainless steel pipes embedded in lead is key to managing heat and ensuring structural integrity. Current studies show no major thermomechanical issues, though design changes, higher heat inputs, or cooling layout could pose risks. Lead-antimony alloys may be considered to address material limits. A mock-up prototype will help identify potential challenges and guide optimization for design optimization, integration within the dipole, and cost efficiency.

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