CONCEPTUAL COMPARISON OF LIQUID LEAD FLOW CONFIGURATIONS FOR A MUON COLLIDER TARGET

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Abstract

Liquid lead is under investigation at CERN as a candidate material for a multi-MW class production target for a future Muon Collider. A free-surface curtain was initially proposed to decouple structural walls from beam-driven shock waves resulting from the high instantaneous energy deposition on the target material. However, later studies revealed that the large vertical extent required for this configuration limits the particle production efficiency, which motivated the development of a jet concept proposed in this work. Because the target operates within a 20 T solenoidal magnetic field, magnetohydrodynamic (MHD) effects are expected to influence the liquid-metal flow. Estimates indicate operation at low magnetic Reynolds numbers (between 0.2 and 0.3), where electromagnetic induction is weak but Lorentz forces can significantly affect flow stability and hydraulic performance. Both configurations are analysed using coupled multiphase computational fluid dynamics-magnetohydrodynamics (CFD-MHD) simulations in the quasi-static approximation to investigate current distribution, electromagnetic damping, and free-surface deformation. The comparison highlights the main physical trade-offs between the two concepts and defines the next optimisation steps for nozzle geometry and hydraulic load.

INTRODUCTION

A production target for a future Muon Collider facility must withstand high average power and extremely intense proton beams while operating in a harsh radiation and magnetic environment. In particular, the target system must dissipate multi-megawatt beam power while being located inside a strong solenoidal magnetic field used for the capture of secondary pions and muons. These conditions pose severe challenges for conventional solid targets in terms of thermal shock resistance, radiation damage, and heat removal [1].

Liquid metal targets offer an attractive alternative, as the flowing medium continuously removes the heat, can tolerate large instantaneous power densities and is not subjected to long-term fatigue nor radiation damage. Liquid lead (Pb) is a promising candidate due to its heat capacity and relatively low melting temperature. Similar concepts have previously been explored in high-power target experiments, notably the MERIT experiment, which demonstrated the feasibility of liquid mercury jets interacting with intense proton beams [2].

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For the Muon Collider target currently under development at CERN, the baseline solution consists of an 80 cm long isostatic graphite rod, originally studied for a proton beam power of 1.5 MW [3]. An upgrade of the proton driver to 10 GeV and 4 MW is under consideration to improve collider performance [4]. Furthermore, the proton driver is expected to deliver proton pulses at 5 Hz, with bunch lengths of approximately 2 ns. At these beam parameters, the limitations of solid materials become increasingly critical, motivating the investigation of liquid metal target concepts.

Previous studies investigated the feasibility of a free-falling liquid lead curtain operating inside the strong magnetic field of approximately 20 T required for particle capture [5]. Multiphase MHD simulations showed that the interaction between the conductive liquid and the magnetic field can significantly alter the flow behaviour and induce instabilities [6].

Particle-matter interaction studies showed that a rod-like configuration increases the pion and positive muon yield by approximately 10%, and the negative muon yield by up to 40%, compared with the baseline graphite target, while curtain-like geometries tend to reduce the yield due to the larger material interception of secondary particles [7].

Building on these studies, the present work investigates two liquid lead flow configurations for a Muon Collider target: a free-falling curtain and a jet-like concept aimed at approaching the ideal rod interaction geometry. A schematic representation of the two concepts inside the Muon Collider target region is shown in Fig. 1.

PROBLEM DEFINITION

For the present conceptual analysis, the ideal pion production interaction region is approximated as a cylindrical rod of length and radius $(L_t, R_t) = (50.9, 1.5)$ cm, where L_t corresponds to approximately three nuclear interaction lengths [7]. The objective is to assess how two different flowing liquid-metal configurations can occupy this region while remaining hydraulically and magnetohydrodynamically stable. In both cases, argon is used as the cover gas due to its chemical compatibility with liquid lead and inert behavior at high temperature.

The first configuration corresponds to the free-falling curtain concept previously investigated in [6]. Liquid lead is injected through a rectangular inlet with a thickness of $W_i = 4$ cm and length $L_i = 50.9$ cm, with an inlet height of 4 cm to allow the flow to develop before reaching the

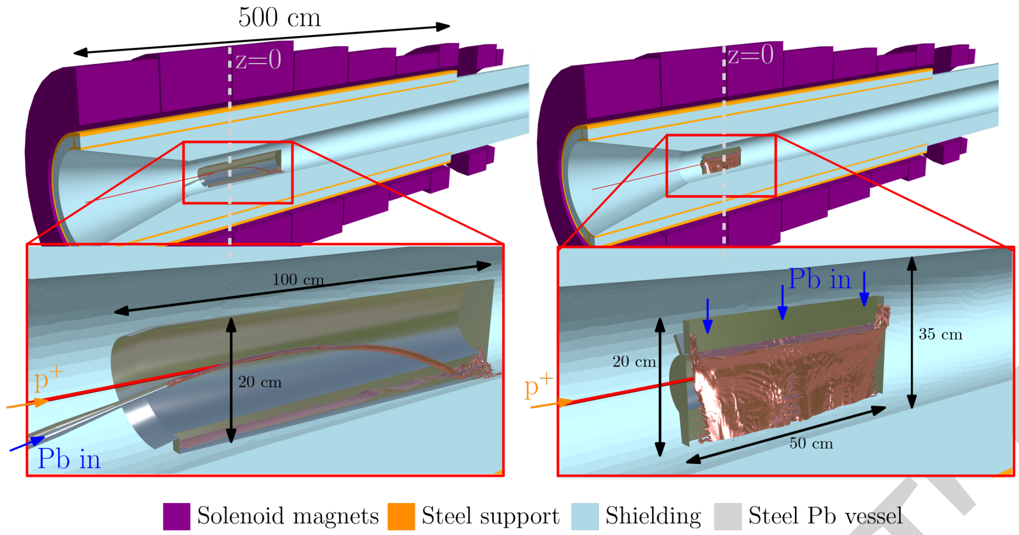

Figure 1: Schematic representation of the proposed liquid Pb target concepts inside the Muon Collider target region: (left) confined jet configuration and (right) free-falling curtain configuration.

interaction region. The falling liquid is contained inside a cylindrical vessel of 10 cm diameter, see Fig. 1. The curtain is operated at a mass flow rate of 100 kg/s, selected to maintain a continuous liquid cross-section with the desired dimensions at the center.

The second configuration corresponds to a forced jet concept aimed at approaching the ideal rod-like interaction geometry, with a 1 cm diameter and 30 cm length. In this case, liquid lead is injected through a converging nozzle inclined by 10°, with a mass flow rate of 3 kg/s, so that the jet remains approximately aligned with the required interaction region. Notably, the required mass flow rate is significantly lower due to the substantial reduction in liquid volume needed to form the interaction region.

The solenoid magnetic field varies along the beam line, reaching its maximum intensity at the target center. Figure 2 shows the axial magnetic field distribution used in the simulations. The target is assumed to operate at the center of the capture solenoid, where the magnetic field is dominated by its axial component and reaches approximately uniform $\mathbf{B}_z = 20\,\mathrm{T}$.

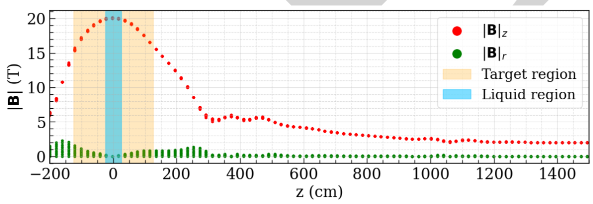

Figure 2: Solenoid magnetic field distribution along the beam axis inside the target region $r < 35$ cm.

NUMERICAL FRAMEWORK FOR FLUID DYNAMICS

The liquid–gas system is described using a Volume-of-Fluid (VOF) formulation [8]. Let $\alpha(\mathbf{x}, t) \in [0, 1]$ denote the liquid volume fraction, with $\alpha = 1$ corresponding to liquid lead and $\alpha = 0$ to the surrounding gas. The local mixture density and dynamic viscosity are defined as a function of this volume fraction [8]. Under the assumption of incompressible flow, the two-phase mixture occupying the domain $\Omega = \Omega_\ell \cup \Omega_g$ satisfies the conservation of mass and momentum,

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

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

where ρ is the density, $\mathbf{u}$ the velocity vector, p the pressure, μ the dynamic viscosity, and $\mathbf{F}$ represents external forces including gravity, surface tension at the liquid–gas interface and the Lorentz force resulting from the interaction between the electrically conducting liquid metal and the applied magnetic field.

The VOF method allows accurate tracking of the interface between liquid lead and the surrounding gas [9]. Pressure–velocity coupling is solved using the PISO algorithm with an adaptive time step maintaining a maximum Courant number of 0.3. Turbulence effects are represented using the k–ω SST model. Material properties for liquid lead are temperature dependent and taken from Ref. [10].

Since the flow operates at a low magnetic Reynolds number ($R_{\mathrm{em}} = \sigma \mu_0 L U \approx 0.2$–$0.3$), a quasi-static approximation is adopted, in which the magnetic field induced by the flow is negligible compared to the externally applied solenoidal field $\mathbf{B}_0$, such that $\mathbf{B} \approx \mathbf{B}_0$. The governing equations for the incompressible MHD system therefore reduce to,

$$\nabla^2 \phi = \nabla \cdot (\mathbf{u} \times \mathbf{B}_0), \tag{3}$$

$$\mathbf{J} = -\nabla \phi + \mathbf{u} \times \mathbf{B}_0, \tag{4}$$

where, ϕ represents the electric potential and $\mathbf{J}$ the induced current density [11, 12], and the electromagnetic body force acting on the fluid is $\mathbf{F}_e = \mathbf{J} \times \mathbf{B}_0$.

RESULTS AND DISCUSSION

The influence of the magnetic field on the stability of the liquid flow was first analyzed using the curtain configuration, see Fig. 3. In the absence of a magnetic field the liquid curtain maintains a stable profile governed primarily by gravity, viscosity and surface tension. When a magnetic field of $|\mathbf{B}_0| = 20$ T is applied, significant changes in the curtain behavior are observed. Instabilities initially develop near the side walls and progressively propagate across the liquid sheet. These distortions are driven by Lorentz forces arising from the interaction between the imposed magnetic field and the induced electric currents within the liquid metal, which are strongest in the near-wall regions. Concurrently, the magnetic field exerts a damping effect on the flow, suppressing velocity fluctuations and promoting a more uniform velocity distribution in the bulk.

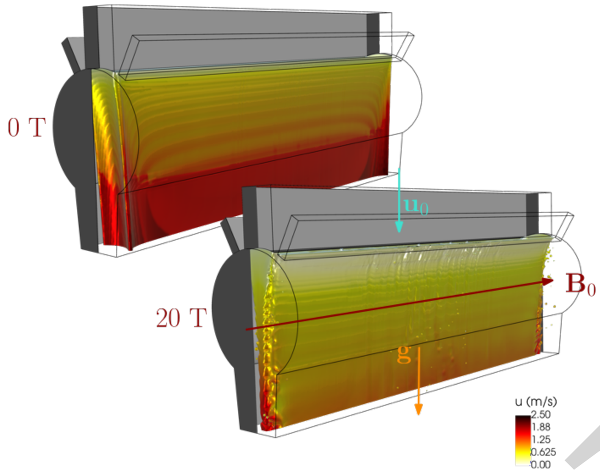

Figure 3: Effect of the external magnetic field on the free-falling liquid Pb curtain: (top) $|\mathbf{B}_0| = 0$ T and (bottom) $|\mathbf{B}_0| = 20$ T. Results for a mass flow rate of 100 kg/s.

For the jet configuration, the comparison between the cases without magnetic field and with a 20 T magnetic field shows that, in the absence of magnetic field, the jet cross-section remains close to the nozzle dimensions, exhibiting only minor deformation along the streamwise direction. When the 20 T magnetic field is applied, the jet undergoes a pronounced anisotropic deformation, characterized by a contraction in one transverse direction and a simultaneous expansion in the orthogonal direction. This distortion develops progressively along the jet and becomes significant only after approximately 0.4 m from the nozzle. Upstream of this location the jet remains relatively stable, whereas further downstream the deformation increases markedly. This behavior is consistent with the jet trajectory visible in Fig. 4, where the flow begins to acquire a vertical velocity component perpendicular to the magnetic field. The resulting Lorentz forces modify the momentum distribution within the liquid metal, leading to a pronounced elongation of the jet cross-section in the vertical direction while the overall cross-sectional area remains approximately conserved.

One important concern associated with the jet concept is the required injection velocity, approximately 3 m/s, which may lead to significant mechanical erosion [10] at the nozzle and therefore requires dedicated engineering solutions.

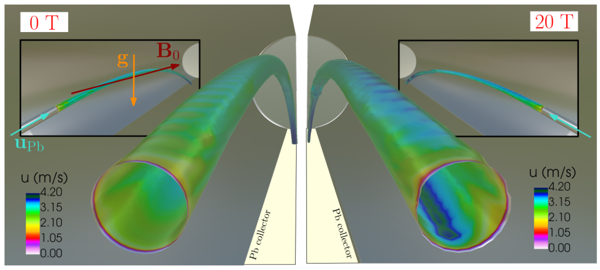

Figure 4: Comparison of the liquid Pb jet free surface without magnetic field and with a 20 T magnetic field, colored by velocity magnitude. Results for a mass flow rate of 3 kg/s.

SUMMARY

This work presents a comparison between two liquid lead flow configurations proposed for a future Muon Collider production target: a free-falling curtain and a confined jet.

The curtain configuration provides a stable interaction region, however, the large vertical extension required may limit the achievable particle production efficiency [7]. While the jet configuration allows the interaction region to approach an ideal rod-like geometry that may enhance muon production efficiency by reducing surrounding material. From the magnetohydrodynamic studies no significant disturbances happen in the desired interaction region, and the main challenges associated with this concept arise from the required jet velocity and the potential erosion at the injection nozzle.

Further studies on the impact of the fast, high-energy beam are required to assess the thermal-shock behavior expected in the heavy liquid metal and to identify possible mitigation strategies.

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