



Solenoid interaction with a liquid Pb target

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Target system





Target system development

Moving from 2MW to 4MW requires rethink the baseline C-Target
Identify possible options and R&D.

Define a system conceptual design based on liquid technologies

Estimate implications of the solenoid magnetic field interaction with heavy metal flow



Target options



As discussed in 2024, CERN leading C-Target system studies & liquid-Pb option with ENEA. RAL & Warwick University leading fluidized W option.





Liquid Pb Technologies



Liquid technologies are promising for use in particle accelerators, offering advantages that traditional solid technologies cannot provide.

Solid Targets/Dumps

- Poor thermal shock resistance
- Poor heat removal
- No corrosion
- No fluid unwanted behavior (eg cavitation)

Liquid Targets/Dumps

- High thermal shock resistance
- Hight efficiency in heat removal
- Possibility fluid unwanted behavior (eg cavitation, MHD)
- Possible corrosion.
- Good resistance to radiation damage.

Design requires multiphysics simulation including:

- Magnetic Field inclusion (Magnetohydrodynamics)
- Energy deposition of the Proton Beam (eg, shock waves)







Liquid Pb Target Concept



CERN

Requiremets from Particle Pysics

For the target, the dimensions of the interaction region are crucial and strictly defined, as they affect particle production. **Demanding condition:**

- Estimated target region: Ø3.0 x 50.9 cm
- p+ beam dynamics: 2 ns, 5 Hz, 2 MW 4MW



Concept developed by ENEA

The hydraulic system design performed by ENEA demonstrated the feasibility of generating a liquid lead curtain and identified its key parameters.



C. Carrelli, M. Tarantino, I.Di Piazza, P.C. Puviani et al. (ENEA collaboration)

This work focus on the liquid curtain dynamics, implications due to the magnetic field, and fast energy deposititon on the liquid lead.

25

20

15 [_

0^m

2500





Considering as alternative option for the C-Target > 2MW

Free Falling Curtain

- Flow rate around 100-150 kg/s
- Flow perpendicular to the Magnetic Field: MHD instabilities Lorenz Force not negligible
- Vertical height necessary to maintain the curtain showed to be problematic to the pions yield



Liquid Jet

- Lower flow rate but Higher velocity on the nozzle
- Higher probability of stabilization due to the strong 2 phase interaction
- Flow mostly parallel to the Magnetic Field: low Lorenz force





Numerical Model for MHD

1) Beam Pulse



Numerical model:

- Multiphase: VoF (+Level-Set)
- Turbulence: $k \omega SST$
- Transient calculation [0, 1.0]s
- Explicit VoF (CFL 1)
- Static mesh with cell size $D_i/64$

MHD Momentum conservation

$$\rho\left(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u}\right) = -\nabla p + \mu \nabla^2 \mathbf{u} + \mathbf{J} \times \mathbf{B} + \rho \mathbf{g} + \sigma_{\mathrm{st}} \kappa \nabla \alpha$$

Validation of the MHD model using the canonical Hartmann problem.

Simplified Geometry for Study of MagnetoHydrodynamic Effects on Liquid Ob Energy pulse $\rightarrow 2ns, 5Hz$ Curtain $\Delta t = \frac{2ns}{10}$ Liquid Pb Inlet 2) Immediate Post-Pulse Phase Pressure inlet Argon @ 1bar $1ms < \tau_{\mu}, \tau_{\gamma}, \tau_{MHD} < 10\mu s$ 3) Long-term effects $\tau_T = \frac{L^2}{\alpha} \cong 7.4 \text{ s}, \ \alpha = \frac{k}{\rho_c c_n}$ optimal target region Pressure Outlet free surface Pb-Ar



Solenoid Magnetic Field







Initial studies for MHD calibration

• The vessel is filled with purified argon to prevent oxidation.

Temperature must stay above lead's melting point but below levels that risk corrosion with the vessel walls \rightarrow Thermo-fluid two–phase simulations are then necessary

Falling liquid lead accelerates, narrowing the cross-section - beam alignment is critical. Two positions are considered:



- Influence of the Argon, eg, Kelvin-Helmholtz Instability
- Influence of the Magnetic field on the axial direction
- Effect of the walls, conductive vs non conductive

Space discretization for CFD calculations

 $T_i = 400 \ ^{\circ}\text{C}$

 $\dot{m}_i = 150 \text{ kg/s}$

 $L_{in} = 8 \ cm$ $w_{in} = 4 \ cm$

 $H_{inlet-center} = 6 \, cm$

CASE B

CASE A

Flow conditions:





11 🦳







The proposed **lead target geometry as curtain was found that reduces the muon/pion yield** while increasing the radiation load to the HTS coils.

The reduction of the yield is greatly due to the necessary vertical height to form the curtain.

The required length and radius for a liquid lead rod were calculated by re-scaling the graphite rod dimensions, based on the ratio of inelastic scattering lengths for 5 GeV protons¹.

Two jet configurations are considered:

• Case 1: Inlet diameter D_i 3 (cm)

DN Collider

• Case 2: Inlet diameter D_i 1 (cm)

In both cases, the goal is to achieve a stable jet region that replicates the behaviour of a solid rod as closely as possible, with a target length of 20–30 cm.

	Case 1	Case 2
<i>D_i</i> (cm) *	3	~1
x_p, y_p (m)	28.3, 2.43	23.0, 1.97
<i>u_i</i> (m/s)	4.0	3.6
$We = \frac{\rho u L}{\sigma}$	11,350	3,064
$Re = \frac{\rho u L}{\mu}$	570,411	171,123
$Oh = \frac{\mu}{\sqrt{\rho \ \sigma \ L}}$	0.0001	0.0003
$Bo = \frac{\rho g L^2}{\sigma}$	51.9	5.7



Numerical predictions

	Case 1	Case 2
D _i (cm)	3	~1
x_p , y_p (m)	28.3, 2.43	23.0, 1.97

Considering a Ballistic Trajectory, based on Newtonian motion equations we predict the trajectory

$$y(t) = h_{\text{inj}} + v_{y0} \cdot t - \frac{1}{2}gt^2$$

 $v_x[i] = v_x[i-1] - a_{\text{drag}} \cdot \Delta t$
 $v_y[i] = v_y[i-1] - g \cdot \Delta t - a_{\text{drag}} \cdot \Delta t$



Argon @1bar

Pb



3D CFD Liquid Jet



Kelvin-Helmholtz instability can be addressed by reducing the relative velocity liquid-argon



beam axis

Concept of liquid Jet with Pool

4.04



Due to the necessary relative high velocity of the jet (4m/s) at the end, a pool of liquid lead is considered in order to absorve the kinetic energy of the jet and not have a direct contact with the wall. Velocity (m/s) 3.03

0.00

Damping of kinetic energy with Pb pool







Solenoid Magnetic Field







Solenoid Magnetic Field



Effects due the magnetic field are less abrupt comparing with the vertical curtain, althout is possible to nice a break on the velocity \rightarrow Reducing cross section and lenght











Considering a ROD of liquid lead L30cm and R.5cm

Steady state power deposition extreme high comparing with the 1000 W/cm^3 on graphite \rightarrow Shock wave on Pb lead

 $f_{beam} = 5 \text{ Hz } v_{Pb} = 3 \text{ m/s for L30cm} \rightarrow f_{Pb} = 10 \text{ Hz}$

Graphite Lead 11.34 $\rho (g/cm^3)$ 1.8 c_p (J/kg K) 710 145

This means even if the shock wave disrupts the jet, it **will be renewed on time for the next beam impact** 10 GeV

5 GeV





Final considerations

Although the jet flows primarily in the direction of the beam, electric currents induced in the liquid can generate **Lorentz forces**, potentially affecting the vertical descent of the jet.

Induced currents in the free-falling curtain are expected to form near the surface (due to the skin effect) rather than within the bulk. This results in increased instability at the interface and surface heating, while the bulk remains unaffected.

- Analysing the energy density maps the rupture of the jet is expected, although around **0.1s-0.2s are required for recovering the jet**, compared to a beam frequency of 5Hz (0.2s), showing feasibility to recover the target jet in time for the next beam impact
- Although the renewal of the jet is not a problem, the shock must not reach the walls, thus the importance of shock wave R&D
- High-velocity impacts on walls must be avoided to prevent erosion, a pool can work as showed, but further MHD simulations needs to be performed with the full system
- Instabilities such as Kelvin–Helmholtz instability may arise at the interface. These can be mitigated by **co-injecting Argon** at the same velocity as the liquid metal.
- More refined computational mesh need to be used to asse the instability of the surface. Adaptative refinement for orders of $D_i/100$ in case of atomization of the jet

Thank you



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Carbon target & target systems considerations



- **Energy deposition & dpa studies** on the Target, windows, shielding, magnets, chicane >
- Parameterization study in view of **pion/muon yield optimization** >
- Conceptual Engineering study of Target & Target Systems, shielding, p+ dump -> feasibility
- ++ iteration loops with p+ driver, magnets, cooling •



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Graphite Target







Graphite vs Lead







Numerical considerations



Joule heating



$$\operatorname{Re}_{\mathrm{MHD}} = \frac{u L}{\eta}, \eta = \frac{1}{\mu_0 \sigma_{Pb}} \qquad \operatorname{Re}_{\mathrm{MHD}} < 0.1$$
$$(u < 2 m/s, L \approx 3 cm)$$

 Magnetic diffusion dominates over advection, induced fields should be relatively small

Base case for MHD verification

MHD loss in the pipes

$$\Delta P_{MHD} = \sigma_{Pb} \cdot B^2 \cdot w \cdot u$$





$$Q_{joule} = \sigma_{Pb} \cdot E^2 \cdot V$$
$$\Delta T = \frac{Q_{joule}}{\rho_{Pb} \cdot V \cdot c_{Pb}} = \frac{\sigma_{Pb} \left(\frac{\dot{m}}{\rho_{Pb} \cdot A} \cdot B\right)^2}{\dot{m} c_{Pb}} V$$