FCC

STATUS OF THE BEAMSTRAHLUNG DUMP DESIGN

S. Candido, R. Ximenes, R. Seidenbinder, A. Frasca, A. Lechner, G. Lerner, A. Perillo-Marcone, M. Widorski, G. Lavezzari, M. Calviani (CERN), C. Carrelli, L. Tricarico, M. Tarantino (ENEA)

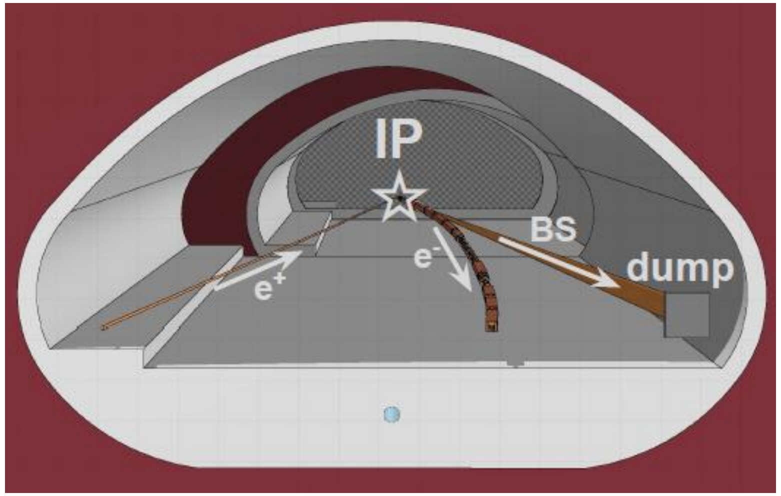
FCC week 2025 – Vienna

Introduction

- Operation of FCCee will involve the **production of a high-energy, high-power photon beam** both sides of the IP*

- As proposed preliminary at FCC week 2024, **Liquid Metal Pb technologies** are promising for use in particle accelerators, specifically for cases of a **quasi-CW energy deposition as the BS radiation**, offering advantages that traditional solid technologies cannot provide.

> ➢ Since FCC week 2024, **major developments were made with the collaboration with ENEA Brasimone on enhancement of the liquid lead hydraulic system and its feasibility**



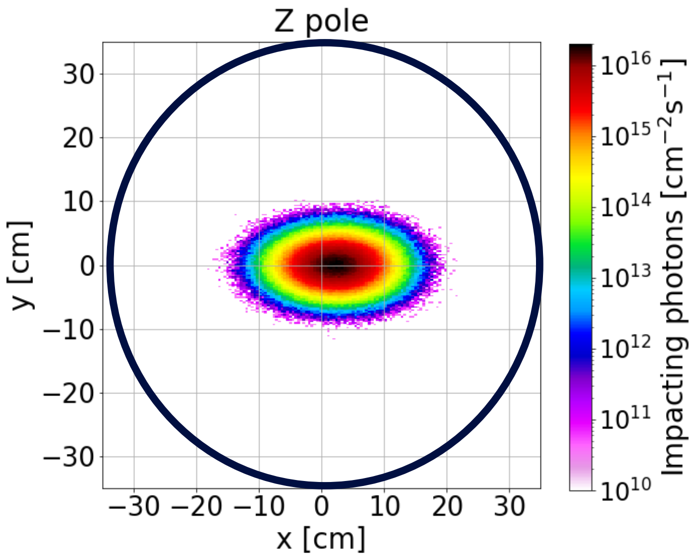
* *M. Boscolo, A. Ciarma, Phys. Rev. Acc. Beams 26, 111002 (2023)*

Beamstrahlung photon beam spot on dump (at 500m)

- Its **located at 500 m from IP**, to have sufficient separation between the beamstrahlung (BS) line & booster line & as much diluted beam as possible
- Nominal power **~370 kW for Z0 and ~80kW for ttbar**, with very high energy photons (~100 MeV for Z0)
- In case of vertical offsets, **up to 500kW**

From FLUKA calculations

Operation Mode	Z pole	ttbar
Mean energy [MeV]	1.78	62.28
Power per beam [kW]	370.21	77.06
Power abs. in windows	4.01%	0.41%
Power required for the Dump [kW]	355.163	74.0348



σ_x ~4.6 cm σ_y ~2.5 cm

Considering the v22 optics: Beam Intensity 1.3 × 10^{18} photons/s (@ Z pole)

Concepts for Liquid Lead Beamstrahlung dump

- Monte Carlo FLUKA simulations* showed that **it is required a volume of <u>70x70</u> x <u>20</u> cm** for the full absorption of the BS radiation

  (Transverse)

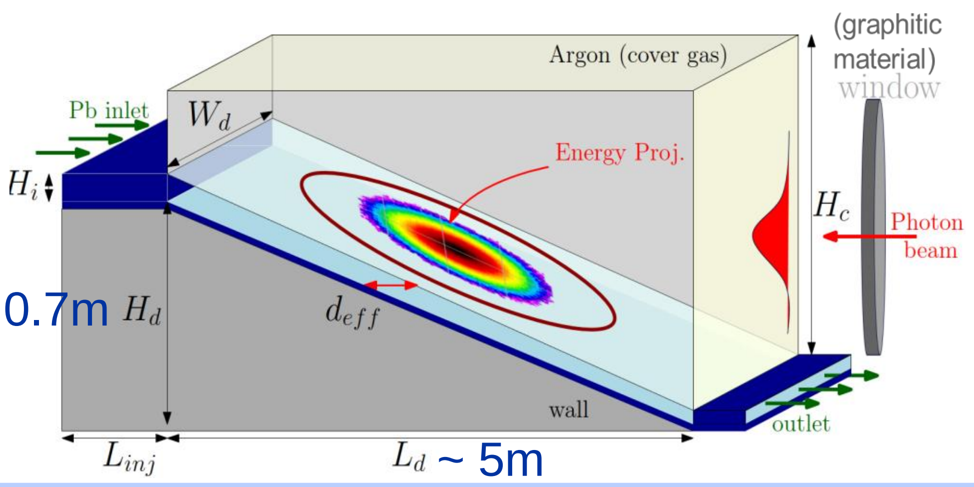
  Effective thickness (direction of the beam)

*A. Frasca, IPAC24

- A first concept of a **single vertical curtain flow as proven to be unfeasible due to the required high flow rate** (>1500kg/s)

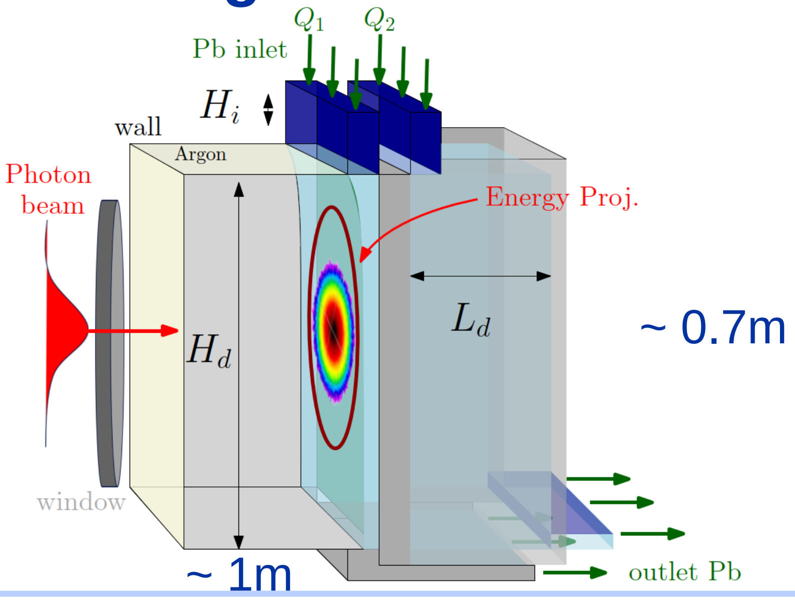
Option A

Slope System



Option B

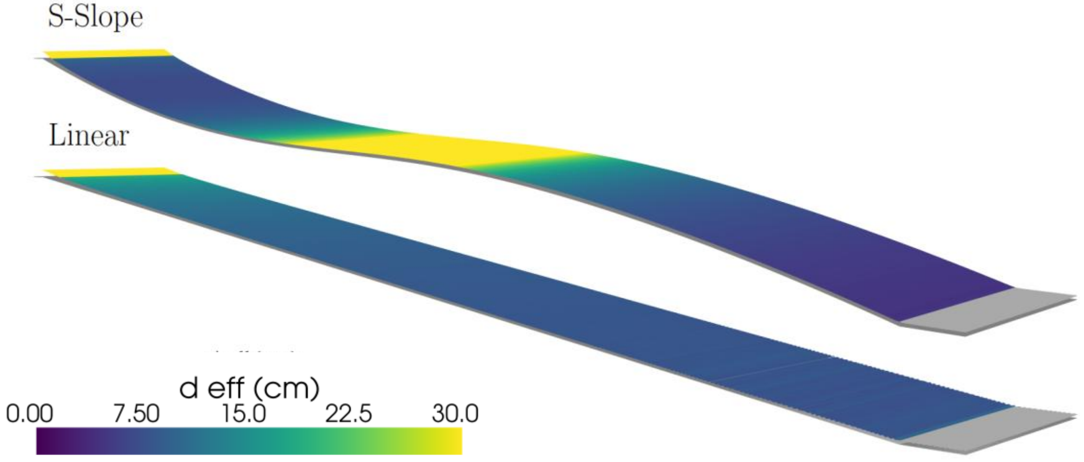
Free-Falling Thin Curtain + Box

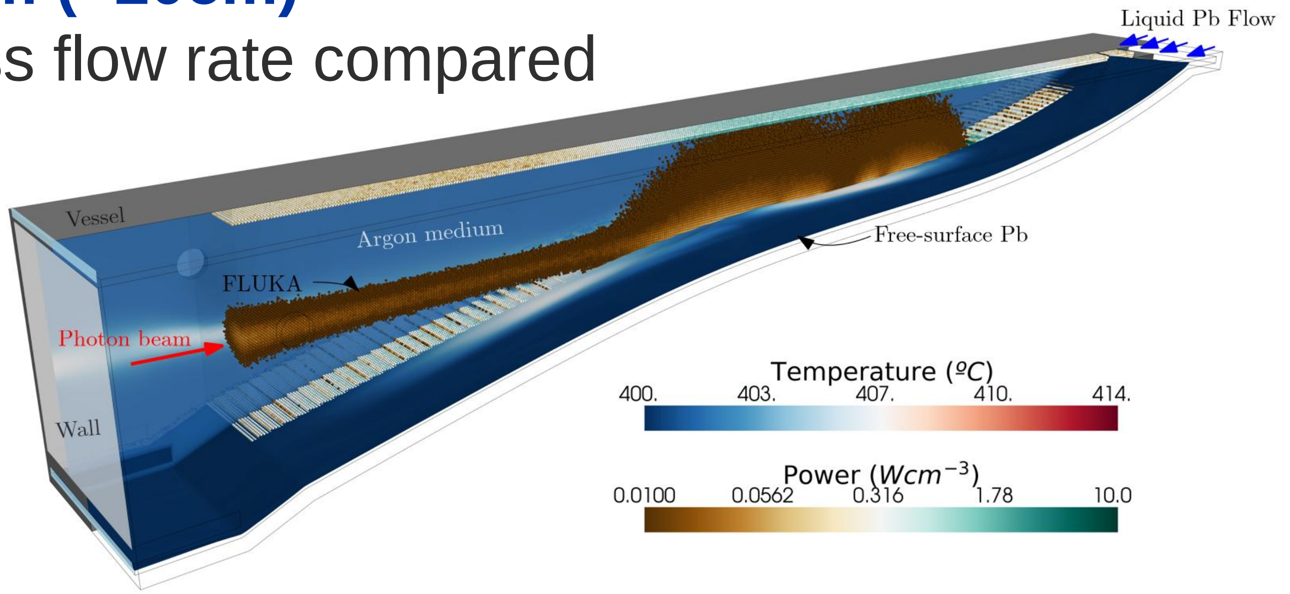


Optimization of the Slope Concept
Linear vs S-Curve

Optimization objective is to **maximize the effective thickness** of the liquid Pb flow while keeping a **maximum flow rate of 300 kg/s***.

- ✓ **A "S" curve is optimized, achieving a high effective thickness in the centre of the beam (>20cm)**
- ✓ Decrease of the necessary inlet mass flow rate compared with a free-falling curtain

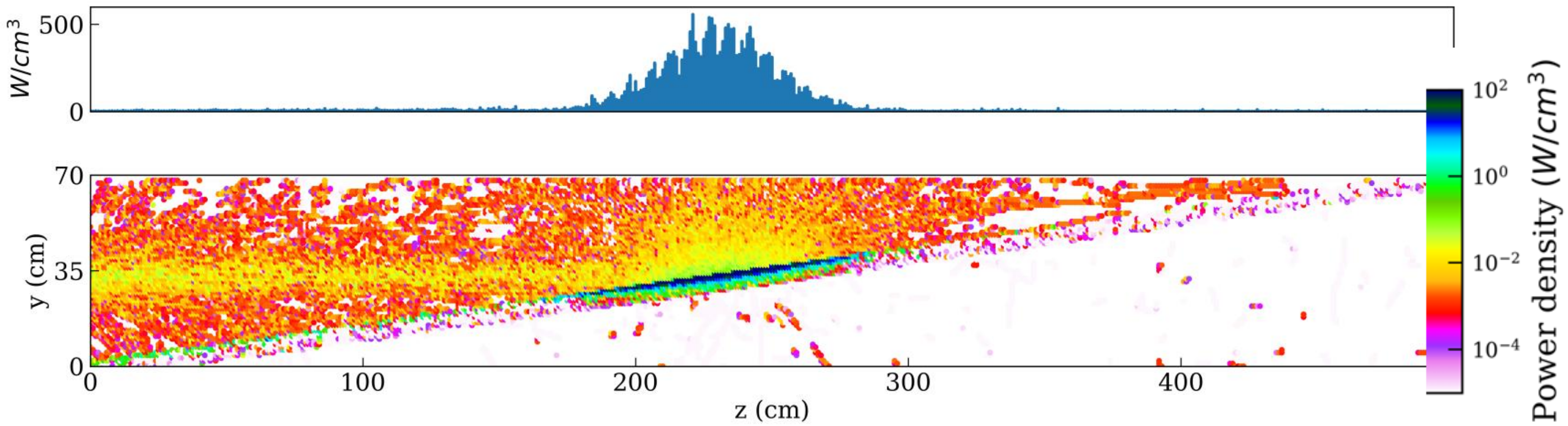




* Due to constrains of the hydraulic system (space/pump)

Monte Carlo Simulations for Power Deposition

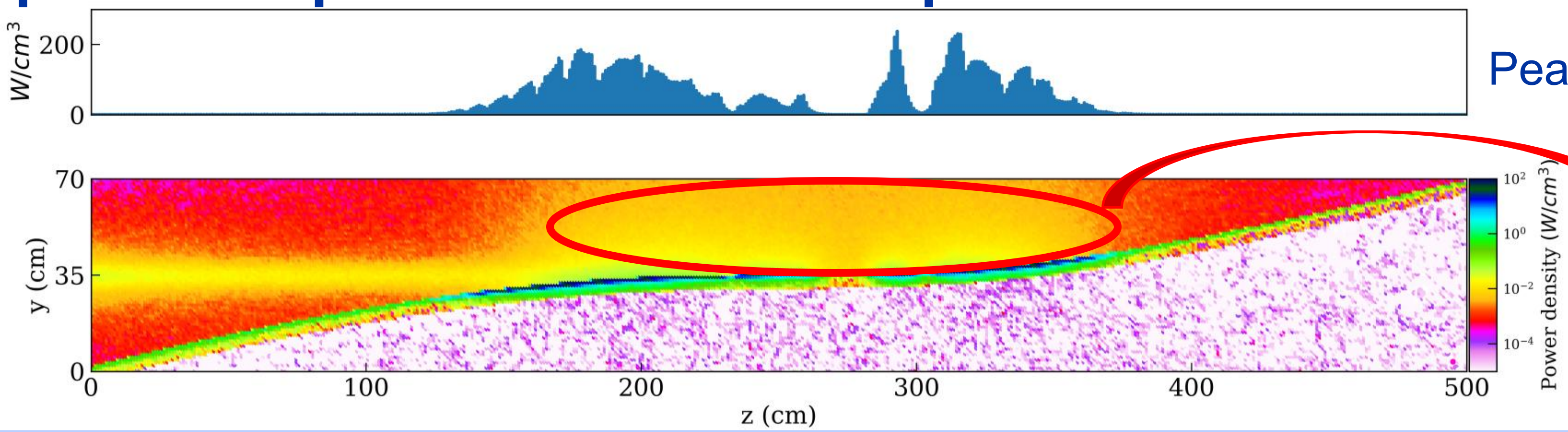
Option A: Linear Slope (8º inclination)



Single pick peak power
$\sim 500W/cm^3$

- Some very small penetration bellow the liquid lead

Option B: Optimized S Curve Slope

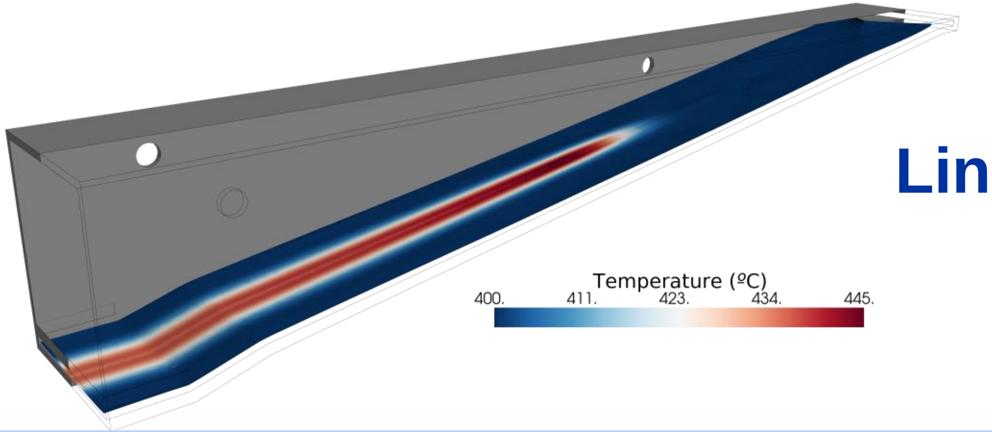


Peak “dituled” in two $\sim 250W/cm^3$

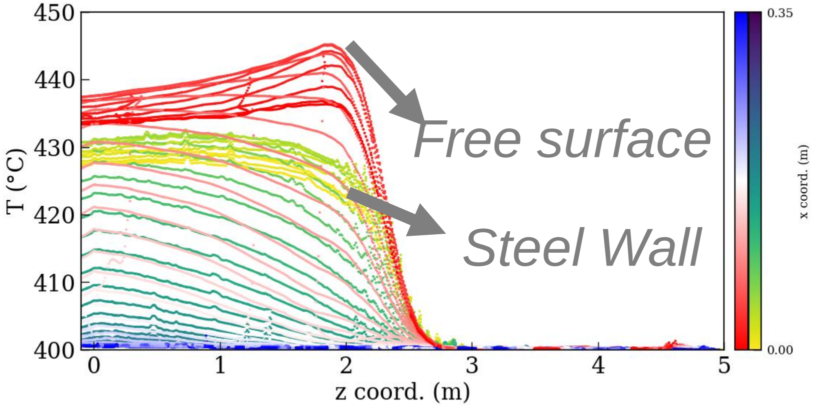
Due to shallow angle of interaction, photon beam is scattered upwards!

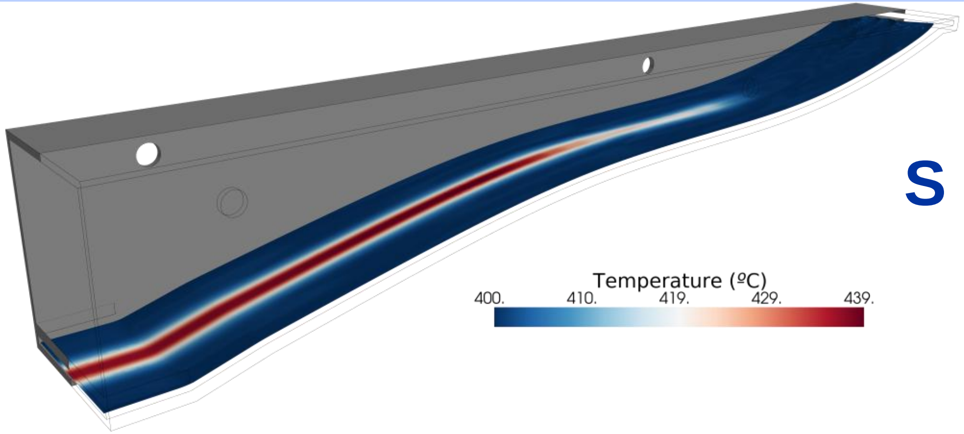
Thermofluid dynamics Liquid Pb Slope

The S Slope can manage and dilute the energy deposition of the photon beam with **values bellow 450ºC,** for having low rates of erosion (O) 0.1 µm/year.

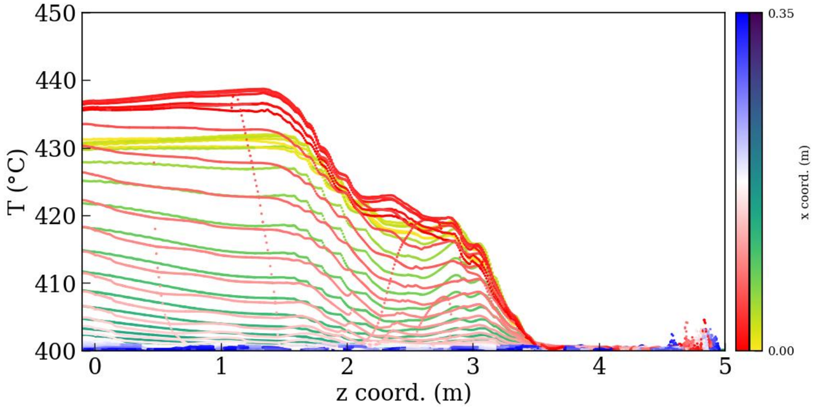


Linear 8º Slope



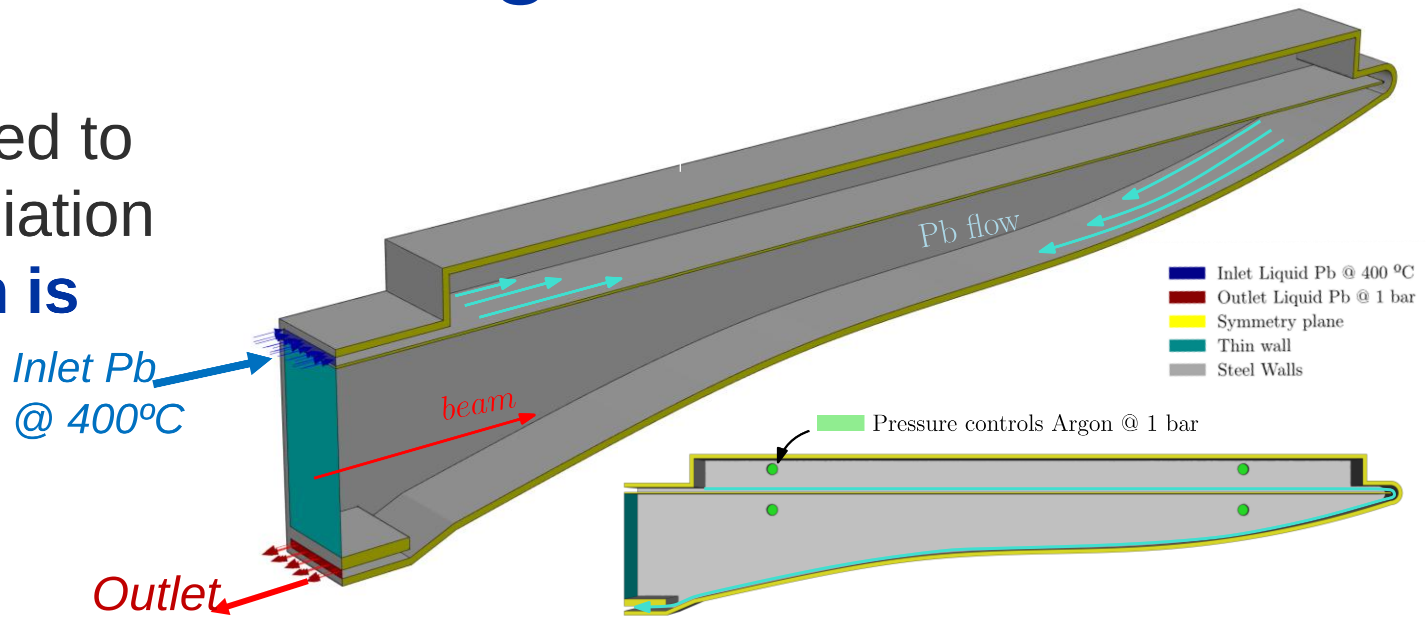


S Curve Slope

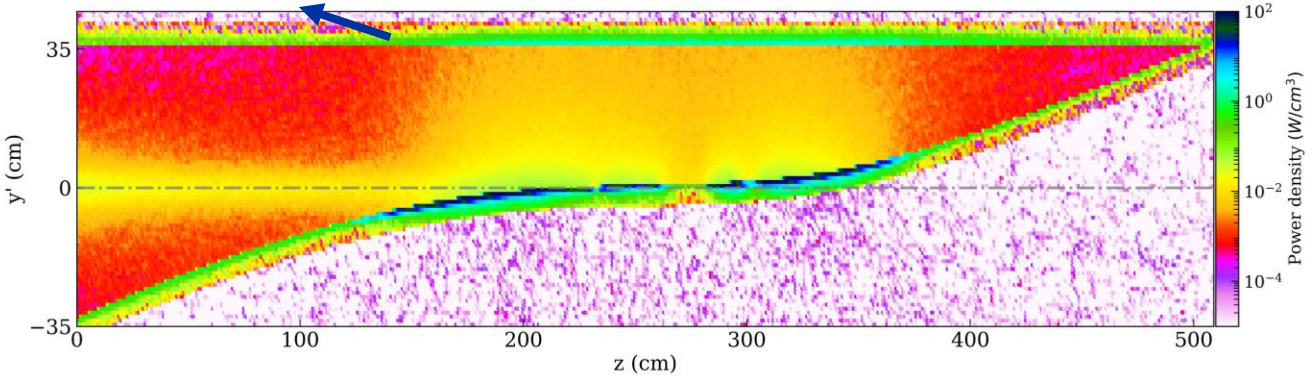


Double Slope for Backscattering Solution

- ✓ A second **upper slope** is added to absorb the backscattering radiation
- ✓ **The backscattered radiation is mitigated**



1cm steel plate



Power absorption in each component*

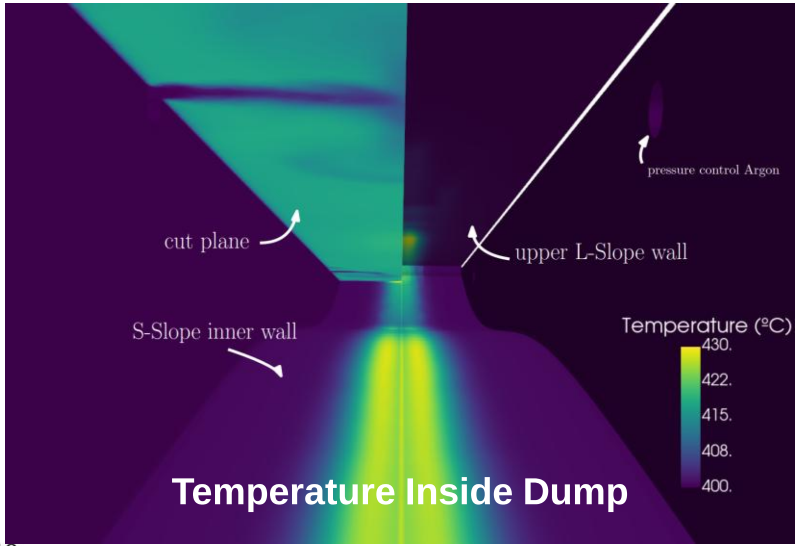
- CFC window = 13.7kW
- «Main» Liquid lead: 248.1 kW
- SS upper support: 36.45 kW
- Upper liquid lead slope: 13.86 kW
- Side walls: ~10 kW

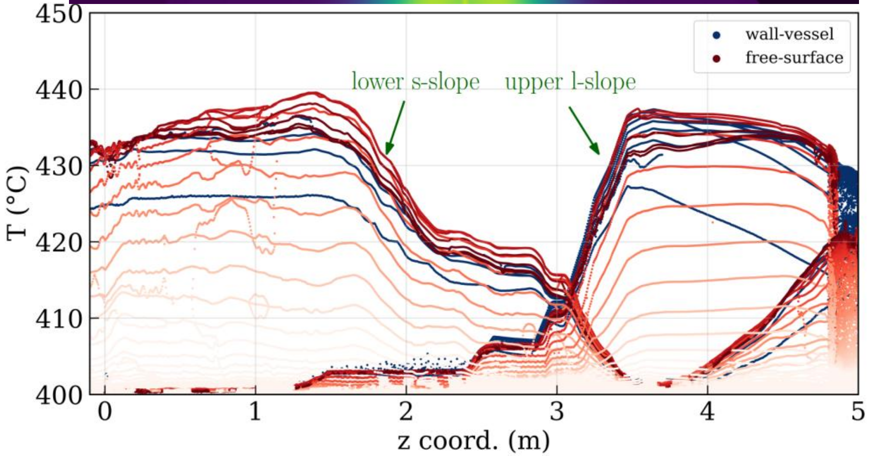
total: 345.8 kW (~94% of BS)

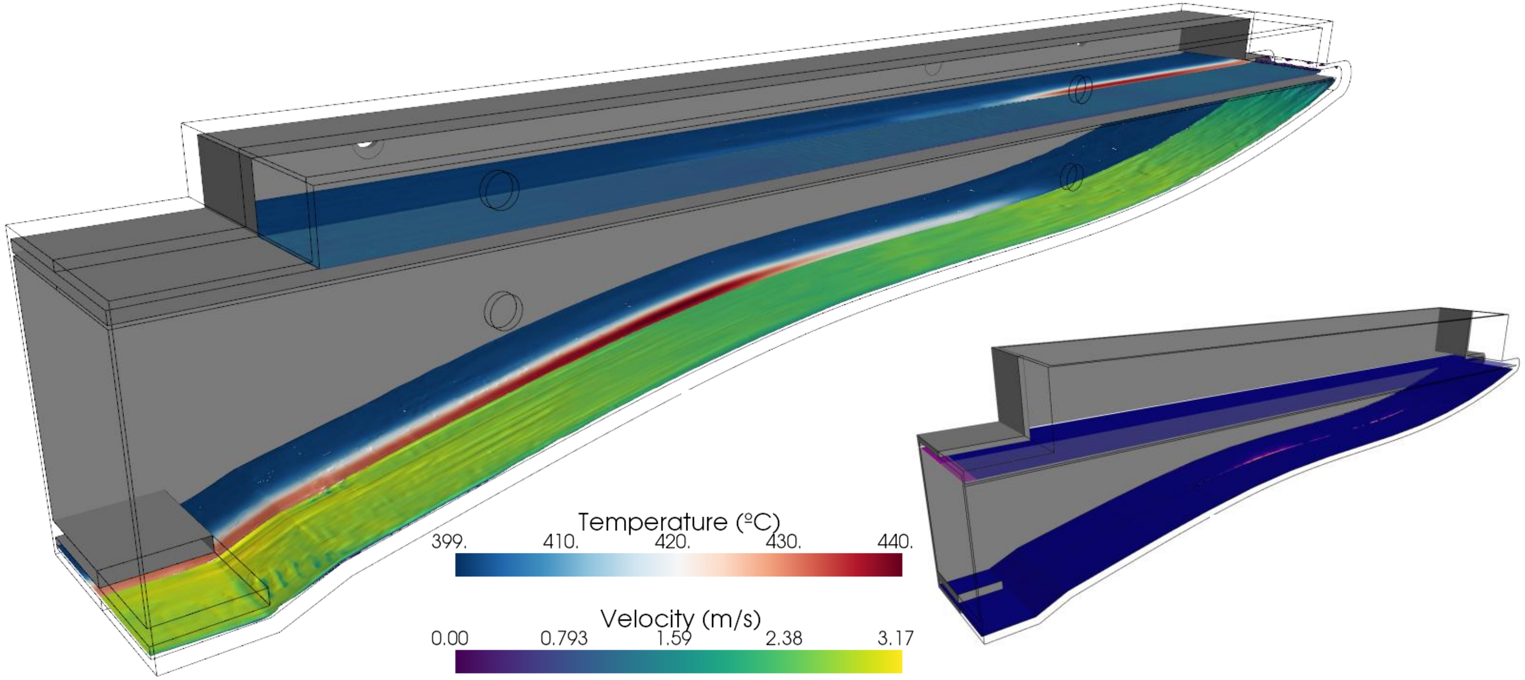
* ~24kW are dispersed around the dump, check https://indico.cern.ch/event/1483148/

Double-Slope dump concept: Thermal and Structural

Double slope is **capable of "trap" all the energy from the backscattering**!



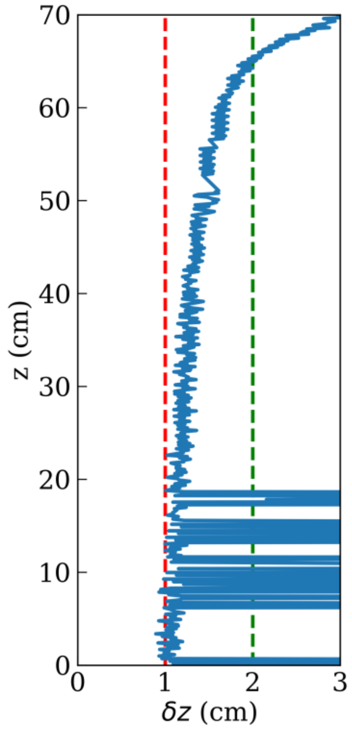




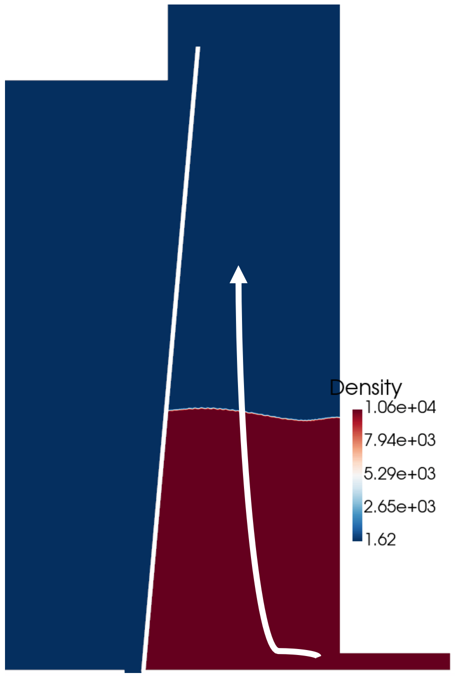
- ✓ Thermofluid simulations shows **acceptable range of temperature and velocity of the liquid lead**
- ✓ Thermomechanical simulation shows an **acceptable stress (11MPa von mises max stress) due to the heat and weight of the Pb (~.8ton)** in the upper steel plate

Compact Liquid Lead Concept

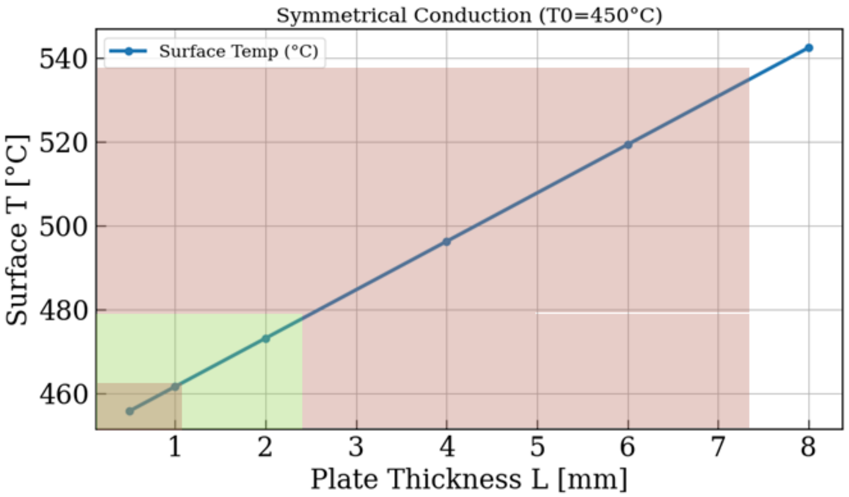
- ❖ A **fully vertical curtain is not stable** and detachment from the wall is not controllable
- ✓ A tilted steel wall can be used to generate the "curtain" more stably, keeping a **very small inclination to prevent the backscattering effect**



85º ~1cm curtain

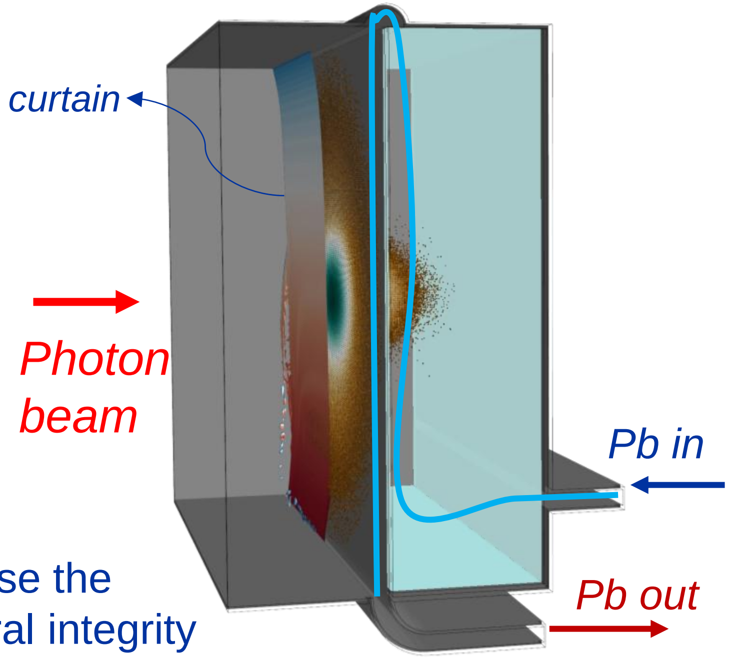


Effect of Thickness of the supporting wall



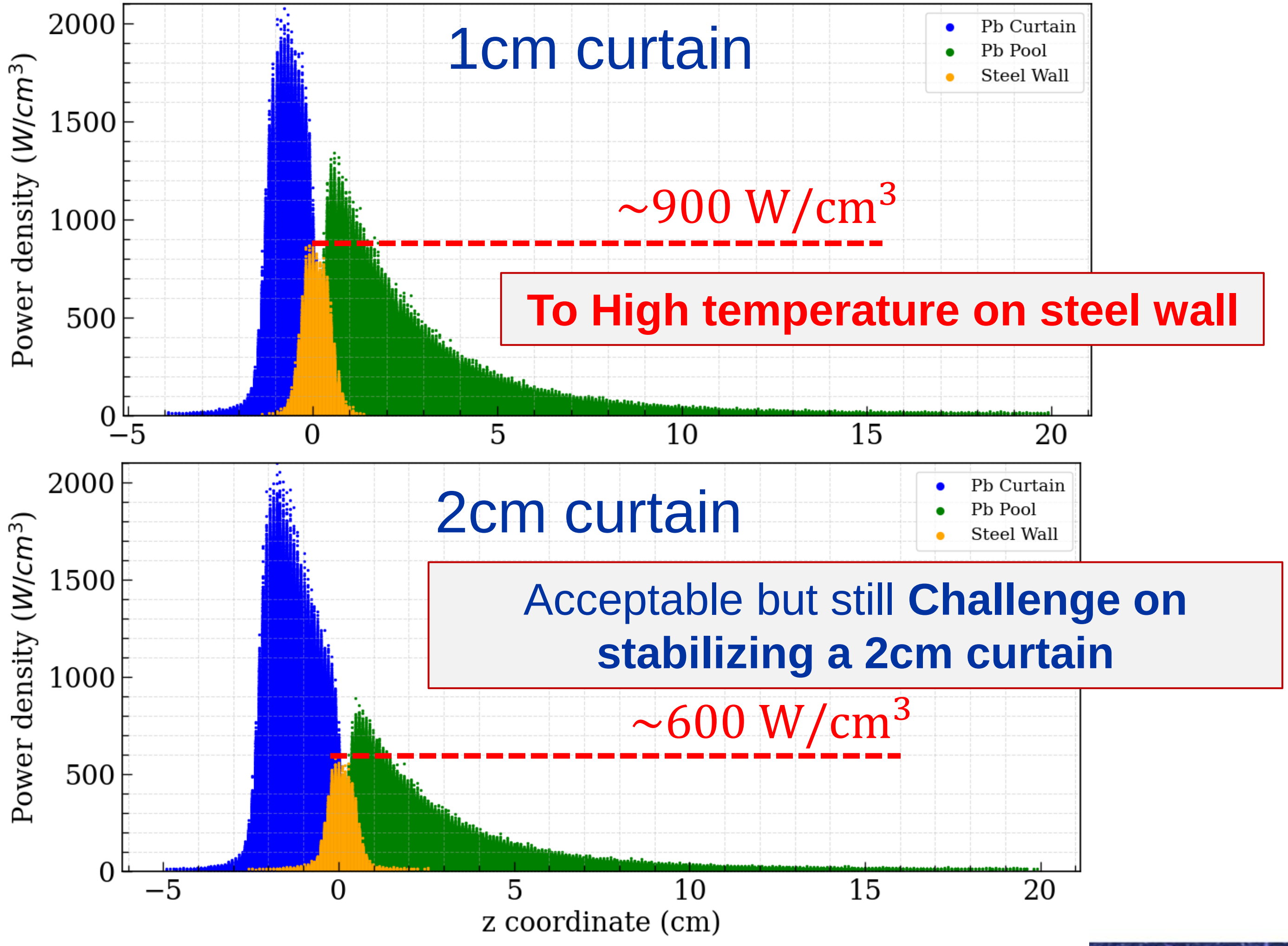
- ❖ Higher thickness of the steel wall will increase the temperature and lower compromise structural integrity

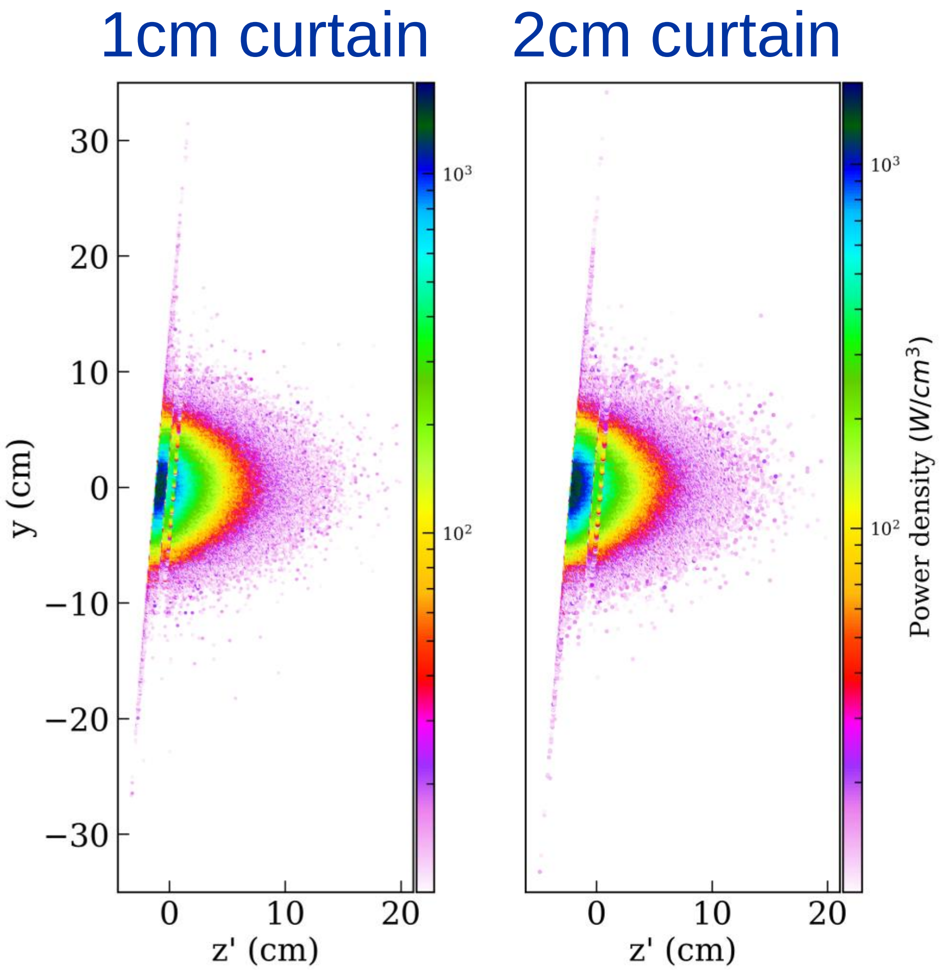
Concept design



Tilted Curtain + Pool of Liquid Pb

The front wall of the box is **tilted 5º** to ensure a stable flow and no backscattering

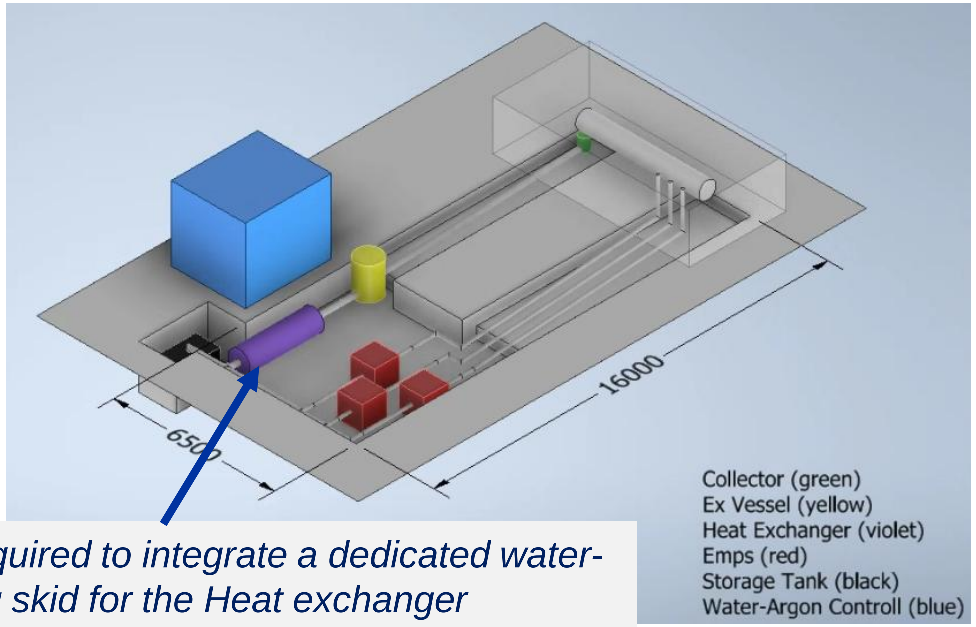




Concepts for Hydraulic System Integration

Option A:

Electromagnetic pumps in parallel



Still required to integrate a dedicated water-cooling skid for the Heat exchanger

- Three pumps in parallel to achieve 350 kg/s.
- Exchanger vessel: 700 dm3.
- Storage Tank: 2500 dm3.

Option B:

Centrifugal pumps

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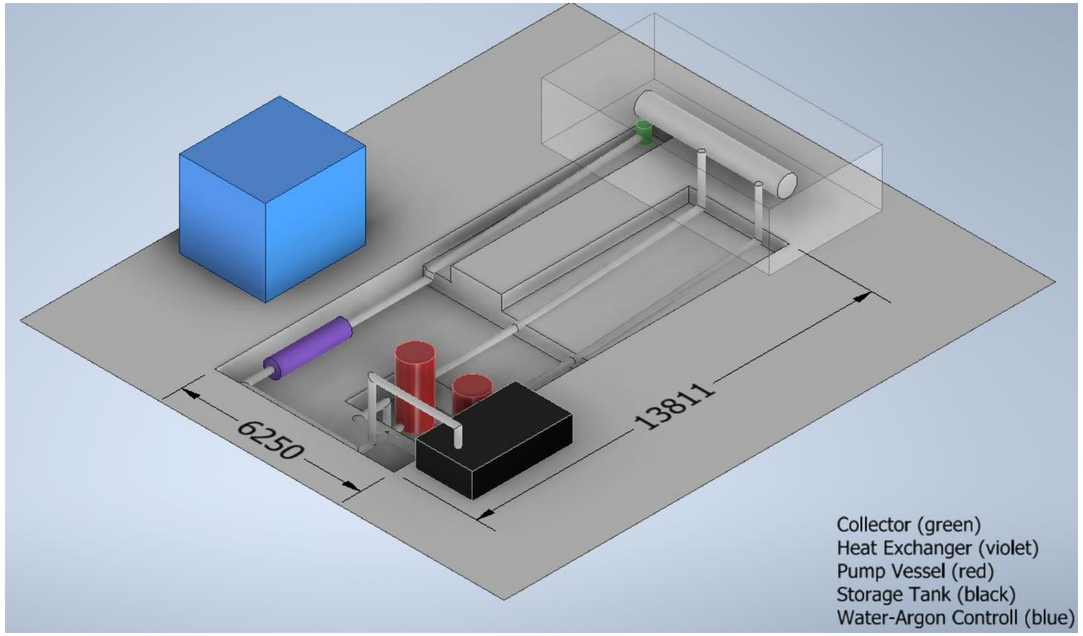
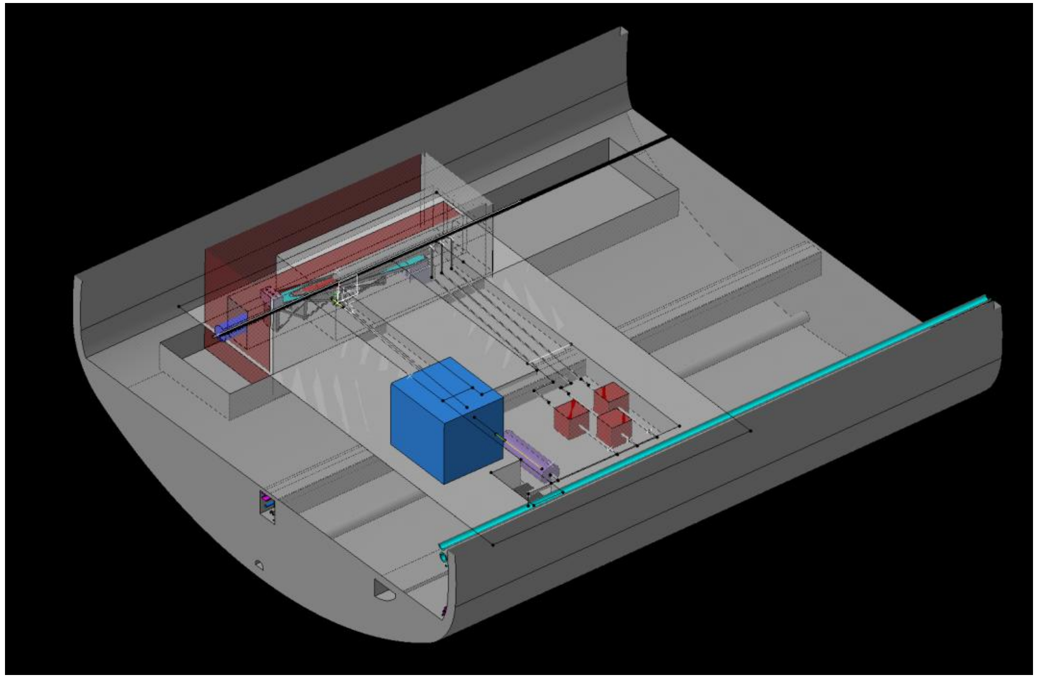


- Two centrifugal pumps: 1.5 m of NPSH.
- Pump vessel: 3000 dm3.
- Storage tank: 6000 dm3.

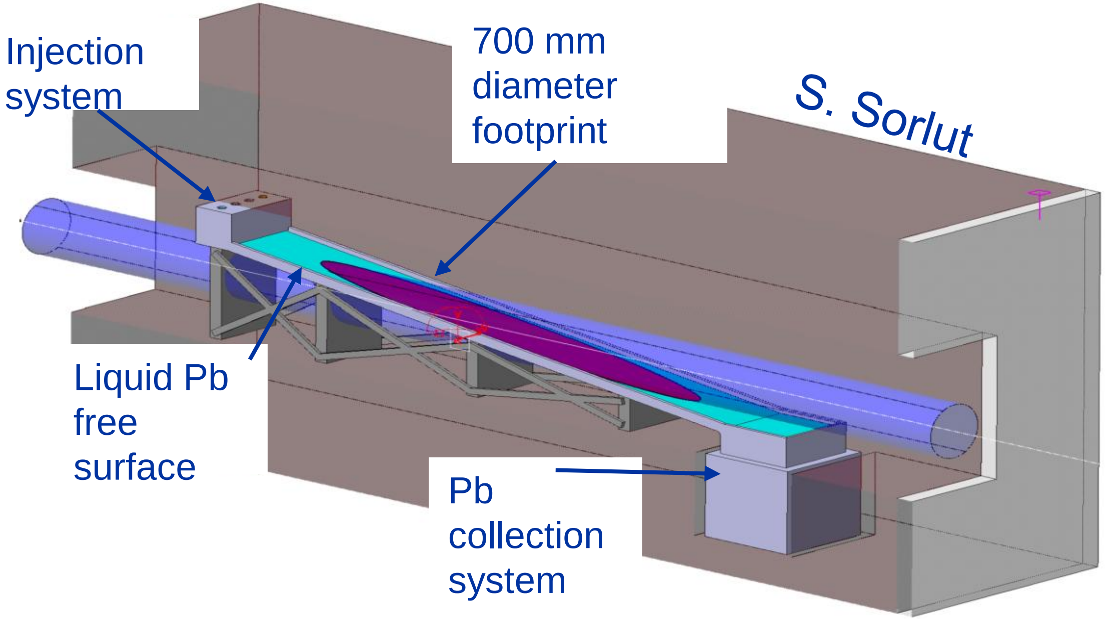
Centrifugal pumps are less recommended (moving parts) while EMP pumps are separated from the lead flow (better for operation)

Hydraulics & Integration

Our present integration model (still ongoing)



Integration model for single linear slope



- **Shielding** around the dump of 150 cm of Fe in all direction but, **not yet dimensioned/integrated**
- Vacuum window(s) required upstream

- Flow rate: **up to 350 kg/s (~ 1 m/s pipes)**
- Deposited power max: **500 kW**
- Avg. temp. : **400-460 °C** (no corrosion)
- Piping: DN100/DN300 Material: AISI 304/316
- Pressure losses: **< 1.5 bar**

Summary

Double slope configuration

- ✓ **Maintains the necessary effective thickness to absorb all the beam energy** and maintaining **acceptable values for temperature** and velocity.
- Requires a longer dump
- Ensures full, **unobstructed free surface contact** with the beam

Thin curtain + Box/Pool concept

- ➢ **One centimeter of Pb in front (curtain) is insufficient**, as 900 W/cm³ peak on steel wall remains excessively high. Photon decrease in lead is roughly exponential with thickness, so **+1cm/1.5cm increase on the curtain thickness would be enough**, although some design needs to be done to achieving this.

- ➢ **Practical experience on building and operating HLM systems in the sizes/specifications that we require is proven and showed by ENEA experience**
  - ➢ **Liquid option is flexible in terms of power absorption**, due to its material properties, but a **robust closed control loop needs to be established** to make sure that the liquid Pb temperature is well controlled under many circumstances.

Mid-term goals What we are looking for

- Conceptual system **design for the final FCC Beamstrahlung dumps**
  - **Choice between the different designs** from thermomechanical and hydraulic points of view
  - Consideration on the **variation of the required Power with the optics**. v24 showed a power decrease to 240.97 kW @Z pole, 20% reduction on the considered v22.
  - Design needs to consider **enough margin to absorb additional heat loads** (e.g. SR)
  - **Clear understanding of the operating regimes and accidents** are required in order to design such lead system (temporal and nominal)

- Advanced **system design for a reduced scale (1:2 or 1:3) prototype**
  - Prototyping a reduced scale (>1:2) experimental model is required to **gain expertise at CERN on liquid Pb hydraulic systems, reliability, instrumentation, etc.**
  - **Engineering design for the development of a prototype loop for Horizon 2030**

- **Investigate other R&D threads** related with the CERN application (e.g. materials compatibility, reliability of components, reduced/remote maintenance, instrumentation, etc)

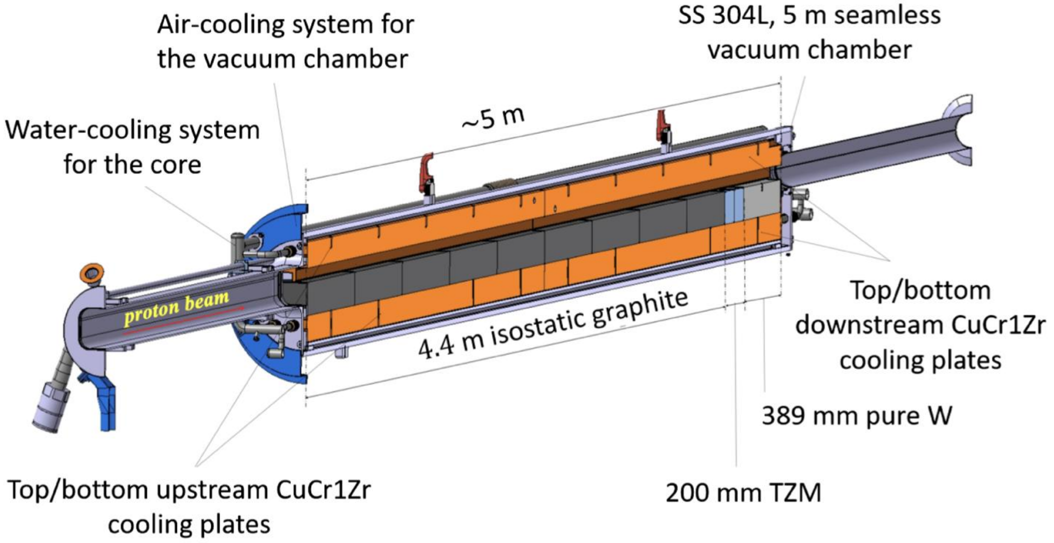
Extra Details

Comparison with solid absorbers

CERN's experience is vast in solid state absorbers*, e.g., graphite. Although, **liquid heavy metal flows requires new expertise** to the design, implementation and operation of hydraulic system and the BID itself.

Liquid Pb system combines **high-temperature hydraulics, two-phase flow, thermal stress, and radiation transport** in a single system - *never implemented in large accelerator facilities for photon dump*

SPS internal beam dump ±5 MJ, O(300) kW



A. Francia et al, Phys. Rev. Acc. Beams 27, 043001 (2024)

CFD Numerical details

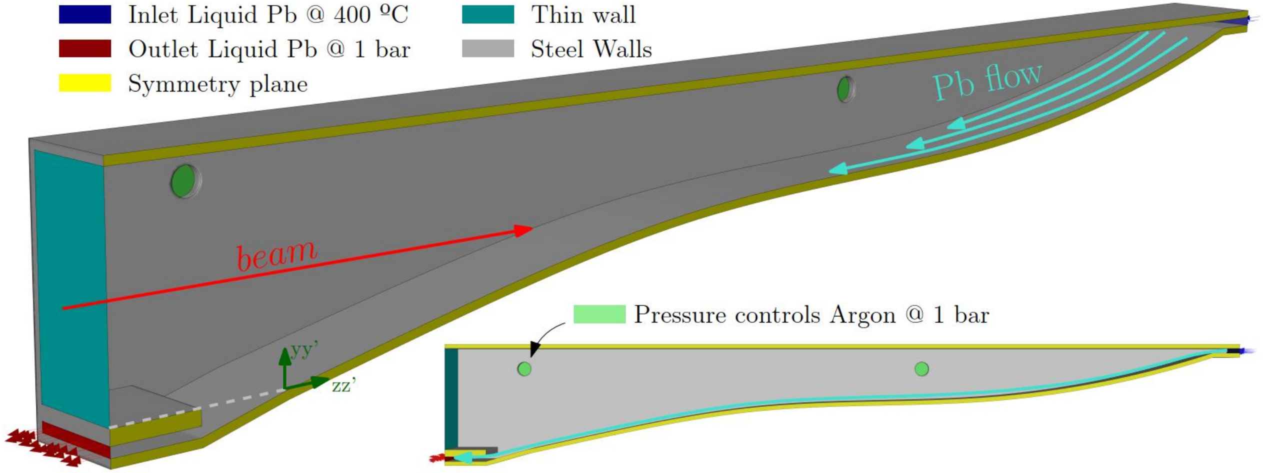
Proposed CFD Model

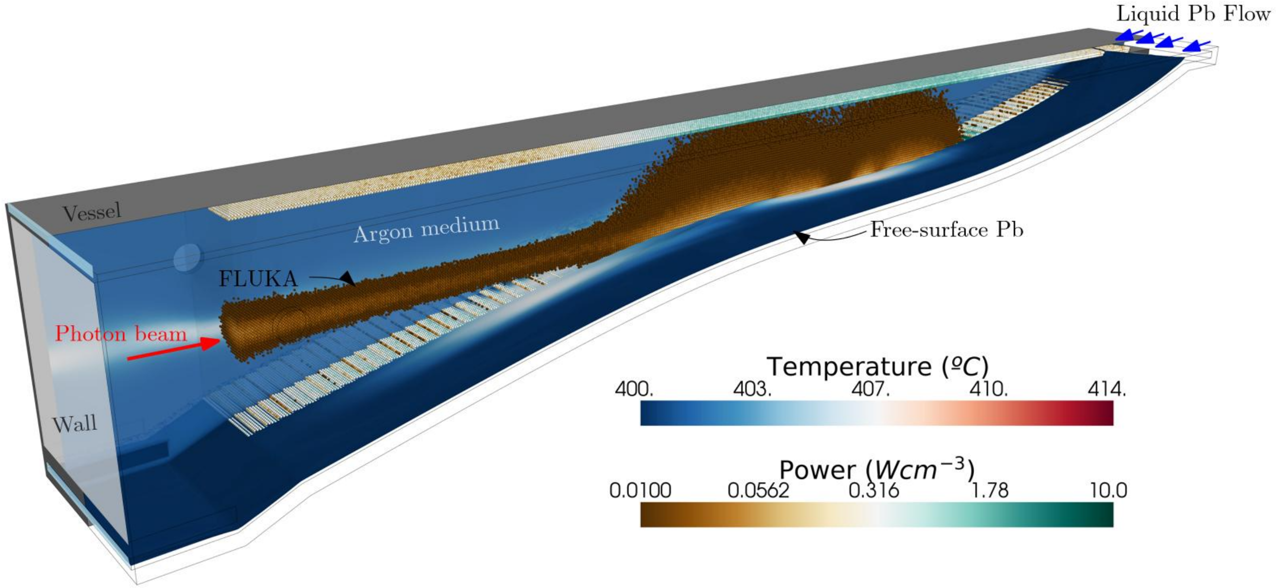
- **Solver Type**: Pressure-based / Transient
- **Multiphase Model:** Volume of Fluid (VOF) with Level-Set interface capturing (CSF method)
- **Turbulence model**: k–ω SST with ($y^+ \approx$ 1-5, due to low Pr number ~0.02)
- **Liquid Lead inlet Temperature**: 400º (Physical properties in function of T)
- **Simulation Time**: 0 – 3.0 s (Transient)
- **Time Stepping**: Adaptive time step to maintain CFL < 1
- **Convergence Criteria**: Residuals < 1e-5 / Mass conservation checked

Energy Source Term
FLUKA → x, y, z, Power Density MAP
Energy Source Term: Volumetric power density [W/m³] applied via UDF.
Phase-specific deposition controlled using local volume fractions (α_i):

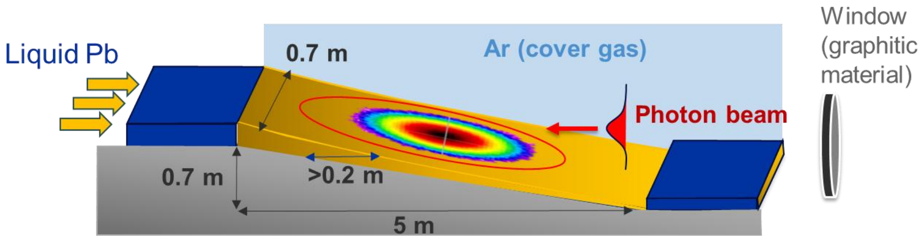
source_i = P_i(x, y, z) * alpha_i;

Ensures physically consistent energy input in each phase.



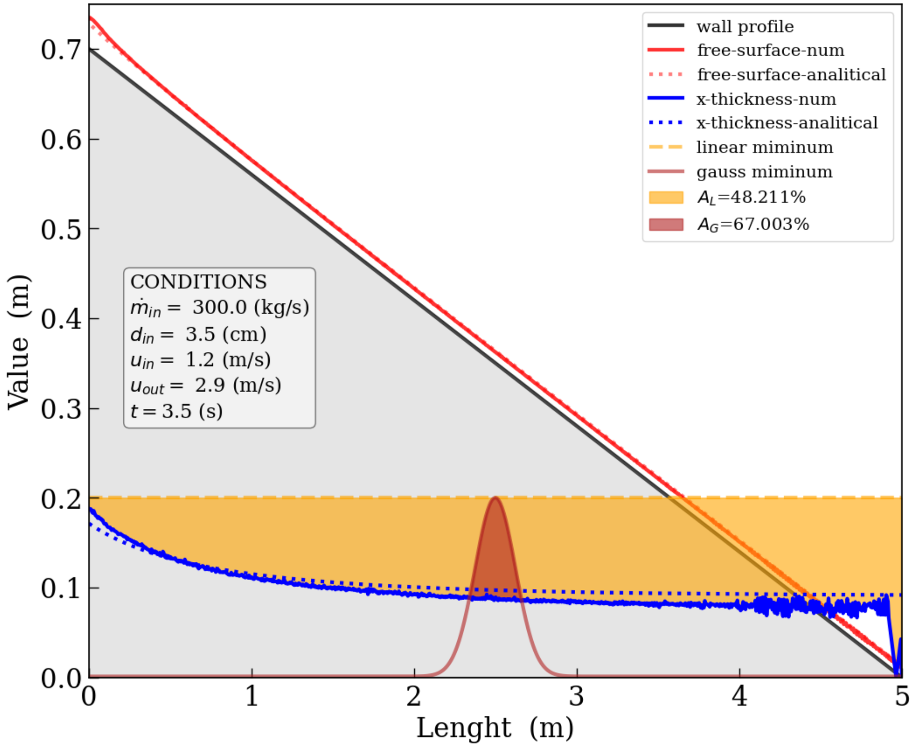


Optimization of the Slope
Linear vs S-Curve

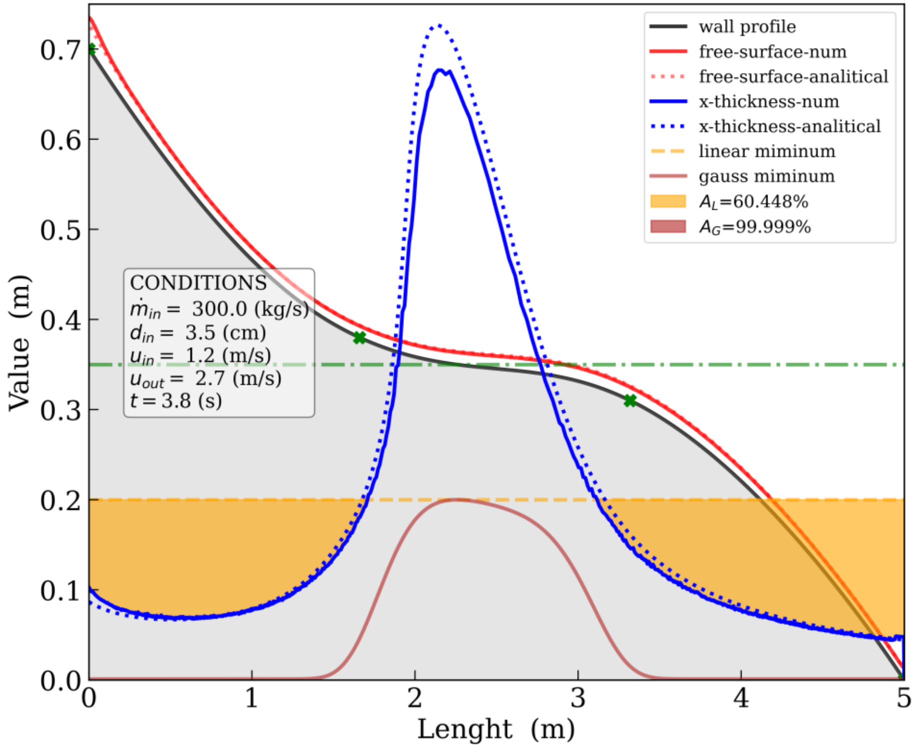


Optimization of the slope considering a Gauss distribution of the energy in the *x direction*

LINEAR



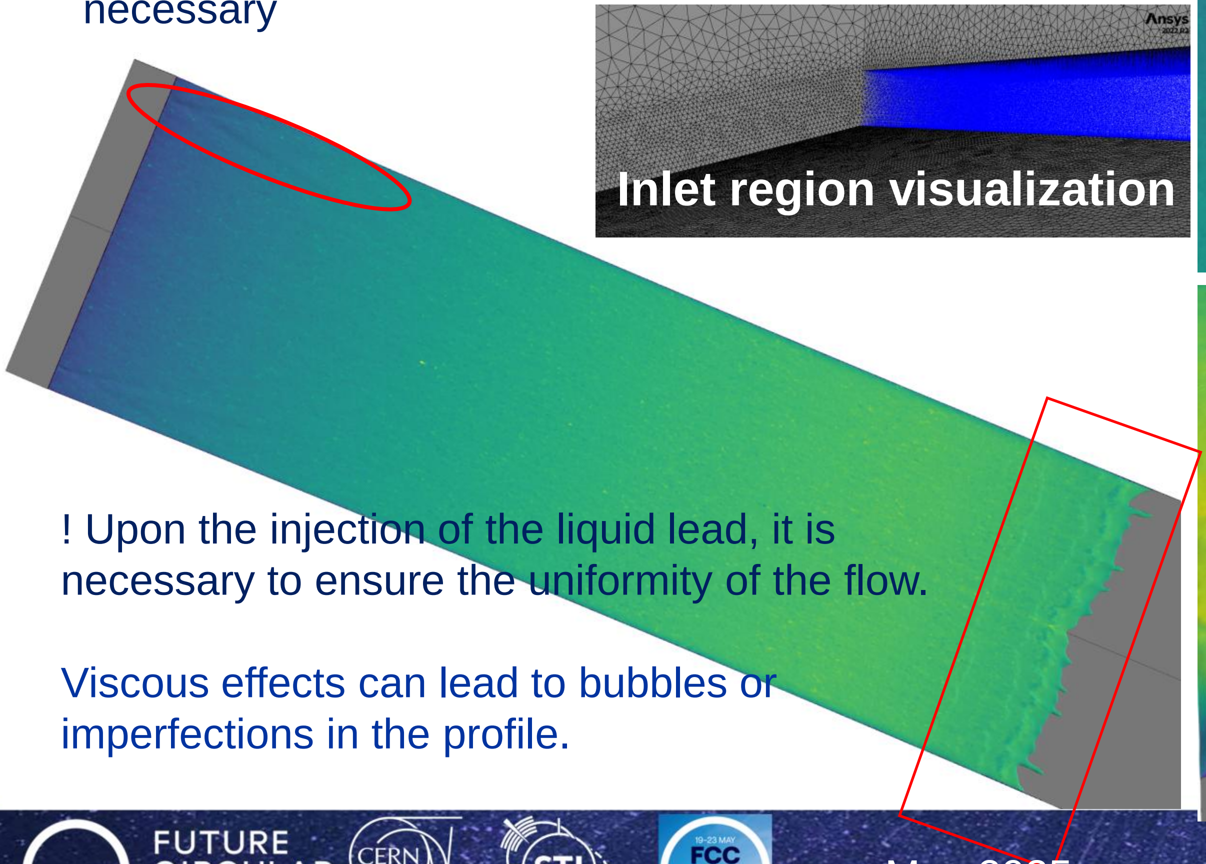
S-Curve

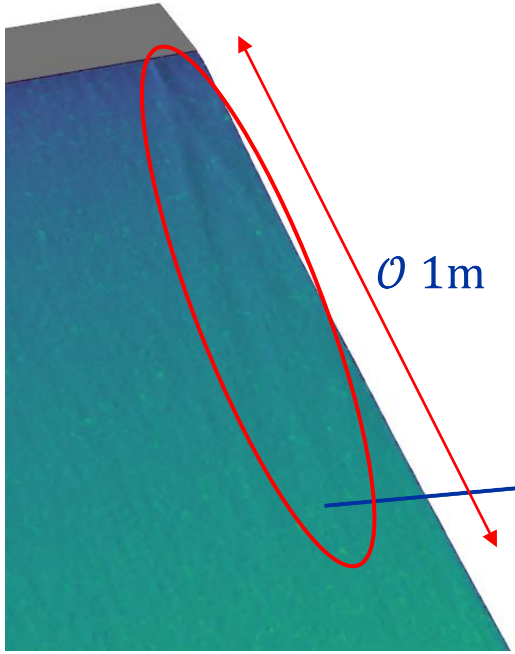


Validation with analytical prediction considering head loss due to friction using the Colebrook-White formula (a three-parameter approximation for free-surface flow) by *V. Bellos et al. (2018).*

3D Fluid Dynamics

- ❖ Tridimensional two phase flow requires a extreme refinement level for accurate resolution of the curvature of the free-surface
- ❖ Due to high Reynold number (Re > 1e5) and low Pr number increase of the refinement on the wall is necessary

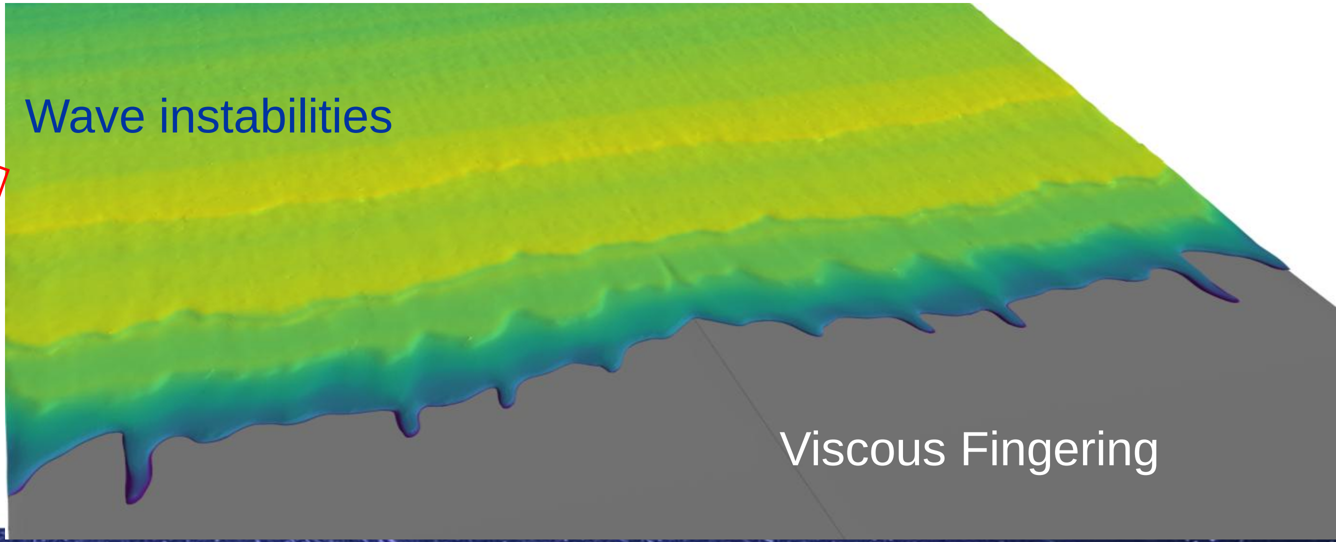




Additional Driving Factors captured only in 3D:

- Side Wall Friction
- Three-Dimensional Flow Structures
- Surface Tension Variations
- Boundary Layer Development

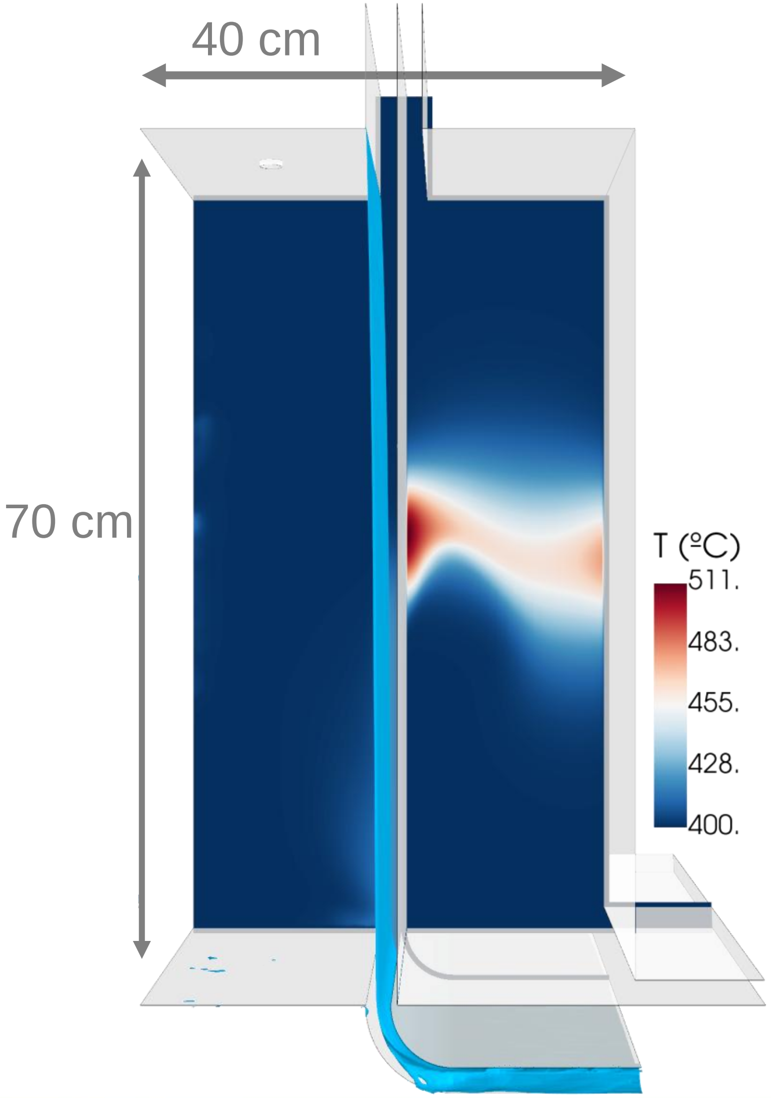
Surface tension deformation

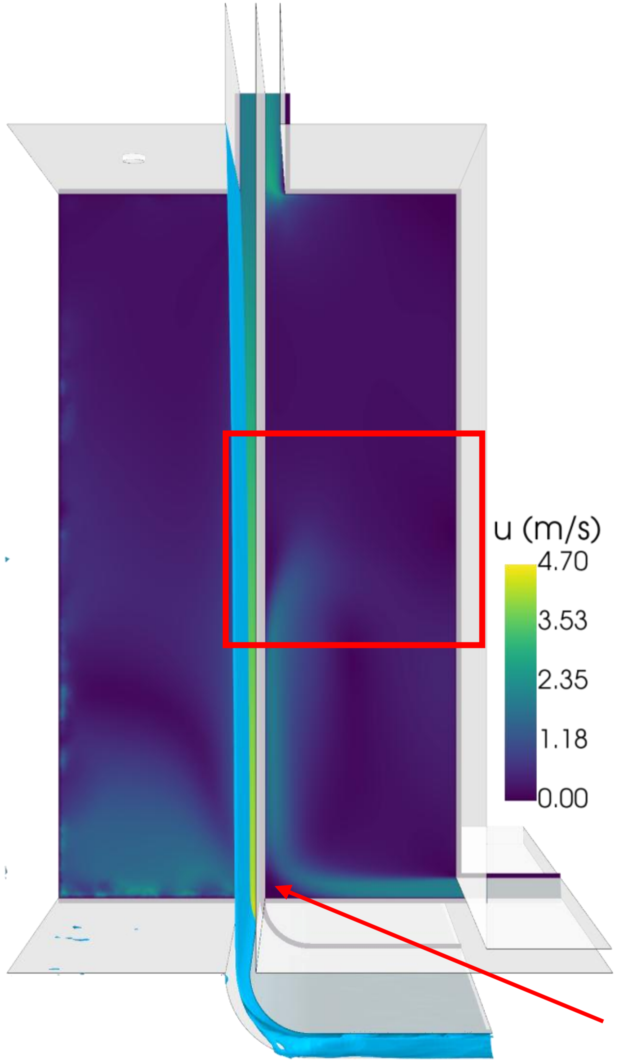


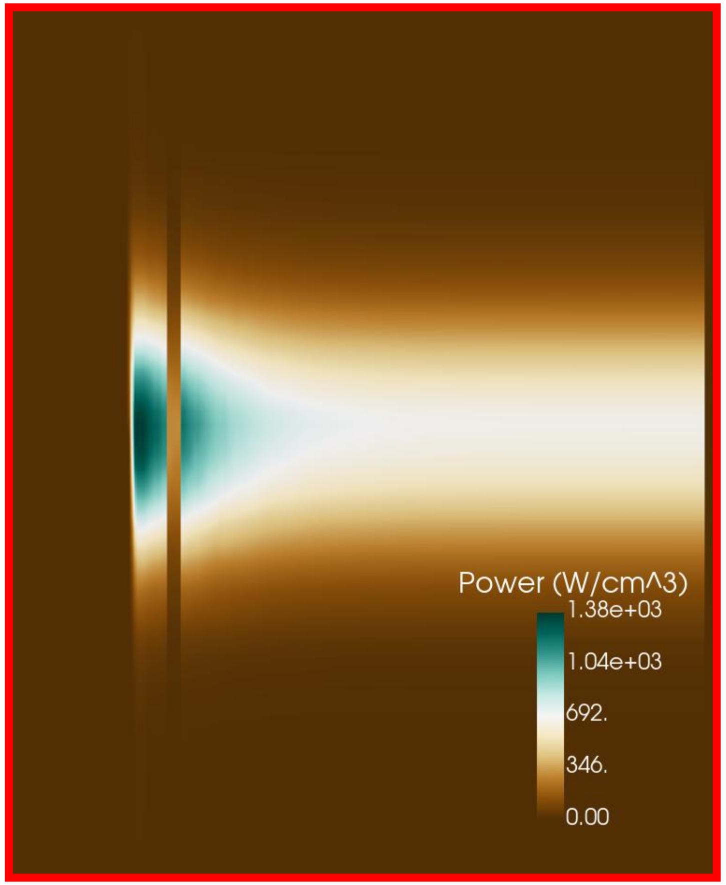
! Upon the injection of the liquid lead, it is necessary to ensure the uniformity of the flow.

Viscous effects can lead to bubbles or imperfections in the profile.

Compact Liquid Lead Concept – Thermofluids







Stagnation point! To be avoid in Pb flow

Conceptual P&ID

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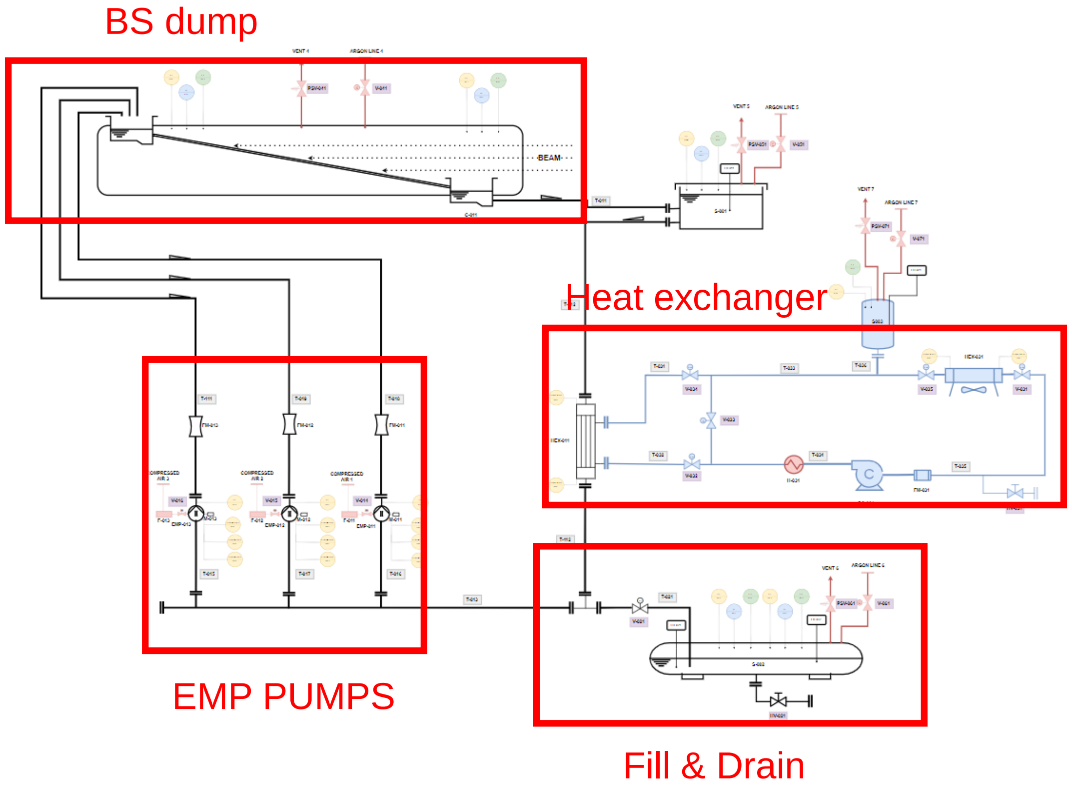
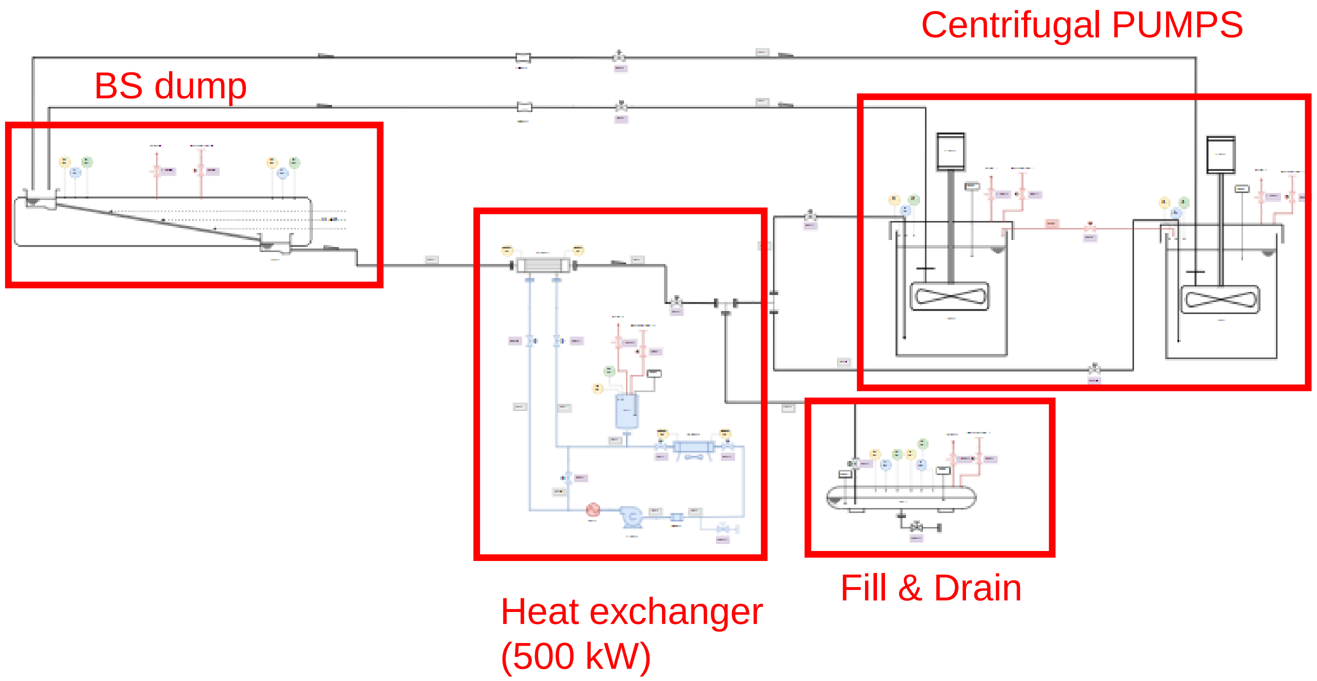
- The liquid lead loop must be positioned below the collector's free surface.
- Water-Argon control: ~ L(3.5m),L1(3.5m),H(3m).
- Heat exchanger: water 16 bar.
- Collector: 75 dm3.

Conceptual P&ID for the 2 hydraulic proposals

Electromagnetic Pumps



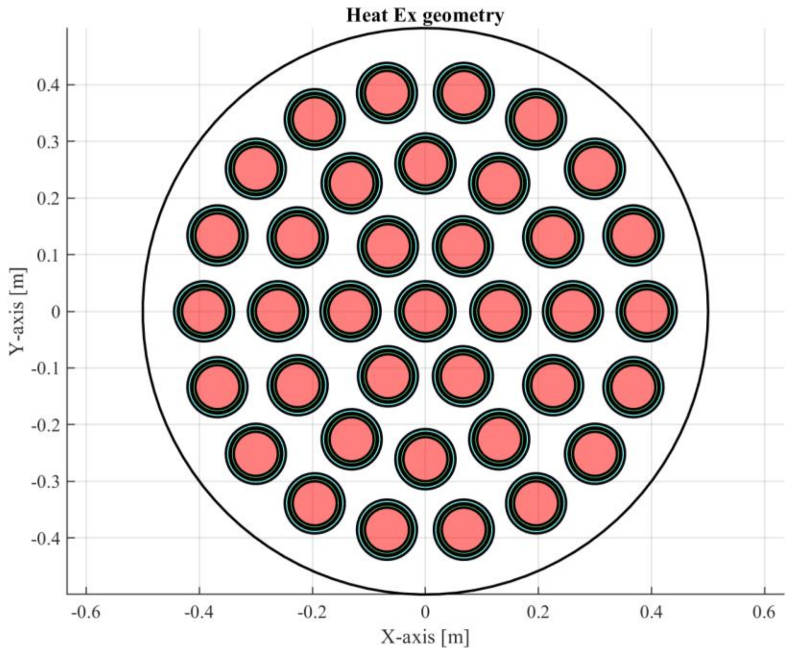
Centrifugal Pumps



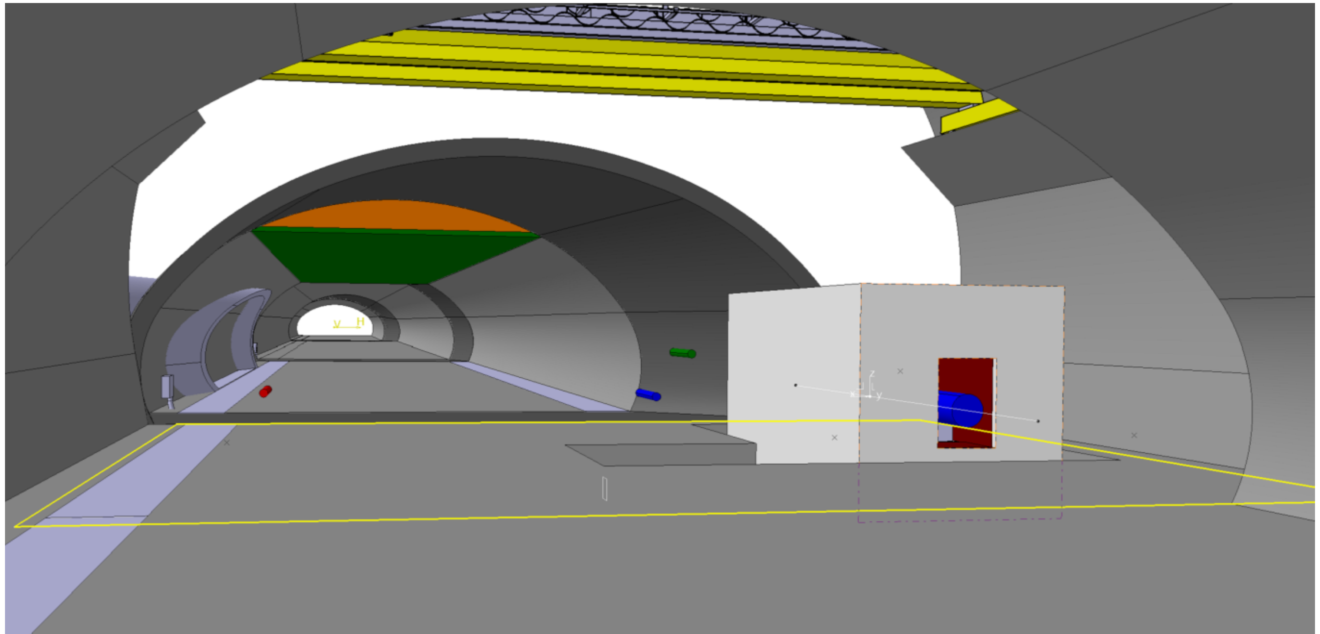
Heat Exchanger Details

Main data

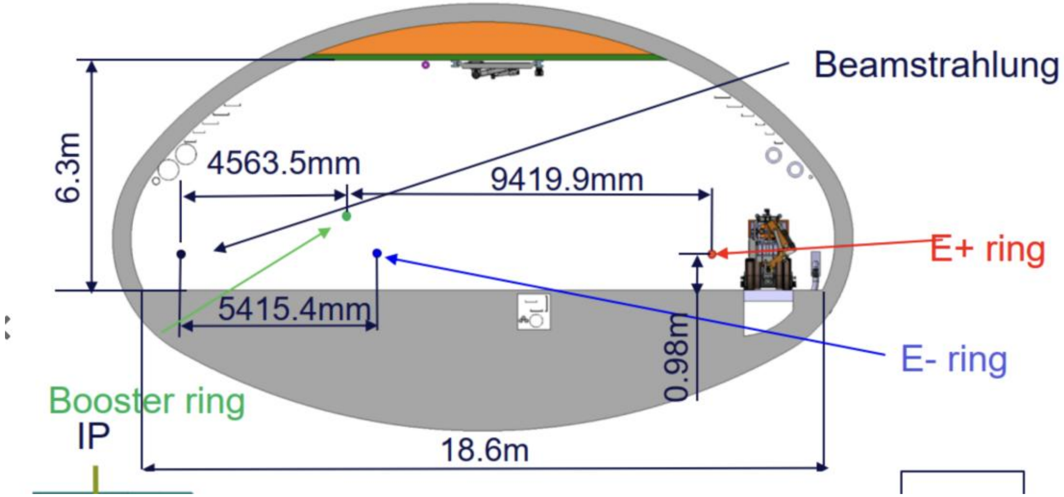
- Shell in tube exchanger: 37 tubes, 500 kW.
- Thermal gap helium 1 bar (k=0.24 W/Km): 4mm.
- Liquid lead loop (350 kg/s) – 16 bars water loop (20 kg/s).
- Piping: 3'' S40 (lead pipe), 4'' S80(water pipe)
- Water temperature: 120°C (inlet) – 125°C (outlet).
- Pressure drops: Lead (0.01 bars), Water (negligible).
- Overall dimensions: D~1m, L~3.1m.



Visualization of the integration on the tunnel



R. Seidenbinder, S. Sorlut



Advantages of a liquid Pb absorber

Heavy Liquid Metal (eg Pb) technologies are promising for use in particle accelerators, specifically for **cases of a quasi-CW energy deposition as the BS radiation**, offering advantages that traditional solid technologies cannot provide as,

- No long-term degradation of dump materials (radiation damage, fatigue, etc.)
- Dilution of radionuclide inventory within the total absorber volume
- Flexible waste disposal preparation
- No need for vacuum vessel nor pressure vessel – operation at atmospheric pressure with cover gas
- Absence of beam-induced thermo-mechanical stresses

Since FCC week 2024, major developments were made with the collaboration with ENEA Brasimone on liquid lead hydraulic system (pumps, heat exchanger, etc.)

ENEA
Italian National Agency for New Technologies, Energy and Sustainable Economic Development

Two-slope dump concept – Thermofluid dynamics

The double slope concept maintains the **temperature of lead bellow the 450ºC**.

Thermomechanical simulation show an **acceptable stress due to the heat and weight of the Pb (~.8ton)** in the upper steel plate