Beamstrahlung dump concepts, design, considerations & R&D roadmap

R. Ximenes, R. Seidenbinder, K. Bisgaard Christensen, S. Candido, A. Frasca, A. Lechner, G. Lerner, A. Perillo-Marcone, M. Widorski, **M. Calviani** (CERN), C. Carrelli, M. Tarantino (ENEA)

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Introduction & objectives

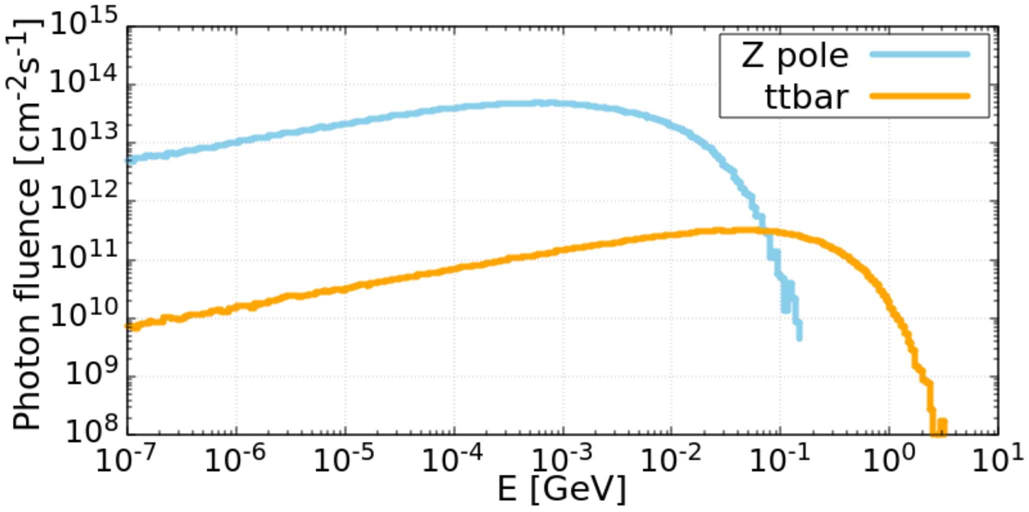
- Operation of FCCee will involve the **production of a high-energy, high-power photon beam** both sides of the IP *
- A **new generation of beam intercepting devices** is required to cope with the challenge
- Initial considerations aimed at **supporting the feasibility stage** and **provide input for CE** and for **environmental impact**
- Will also provide a **first roadmap towards realisation**

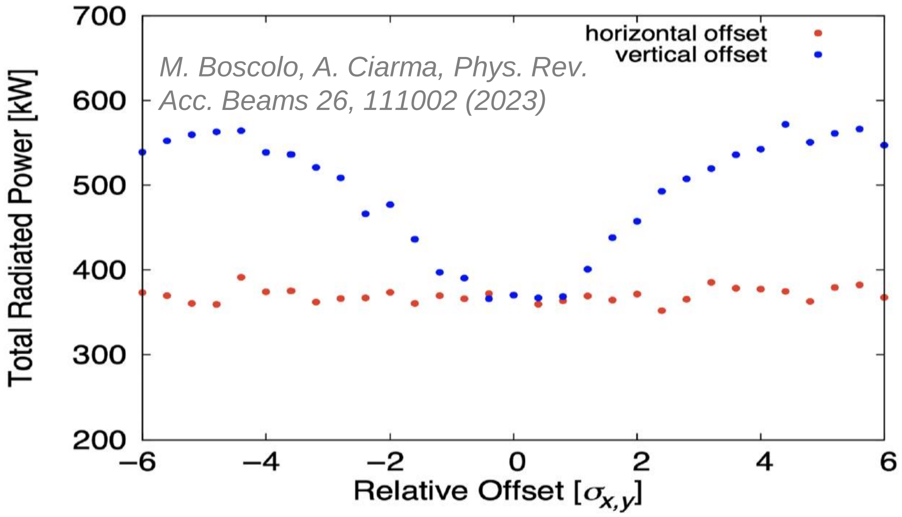
* *M. Boscolo, A. Ciarma, Phys. Rev. Acc. Beams 26, 111002 (2023)*

Beamstrahlung radiation source

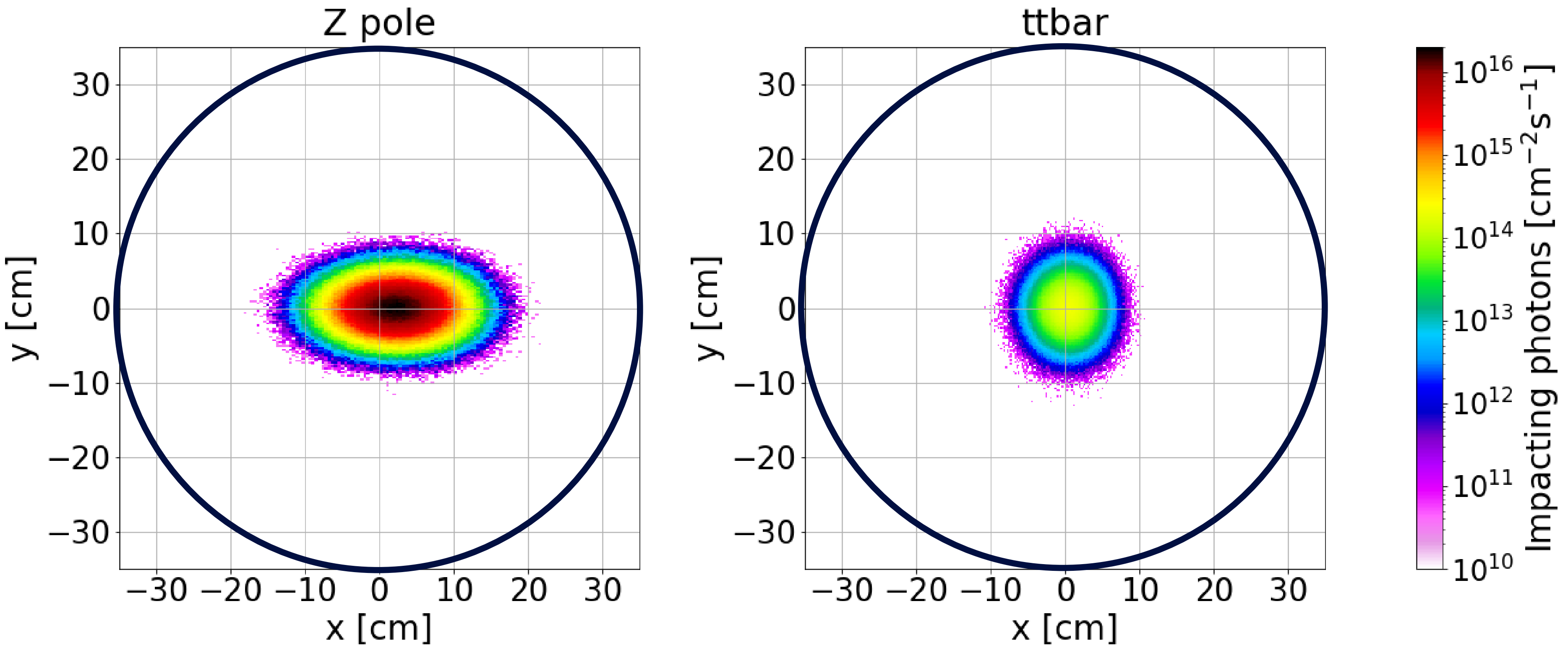
- Nominal power ~370 kW for Z_0 and ~80kW for ttbar, with very high energy photons (~100 MeV for Z_0 and several GeVs for ttbar)

- In case of vertical offsets between beams at the IP, power up to **500-600 kW**





Beamstrahlung photon beam spot on dump (at 500m)



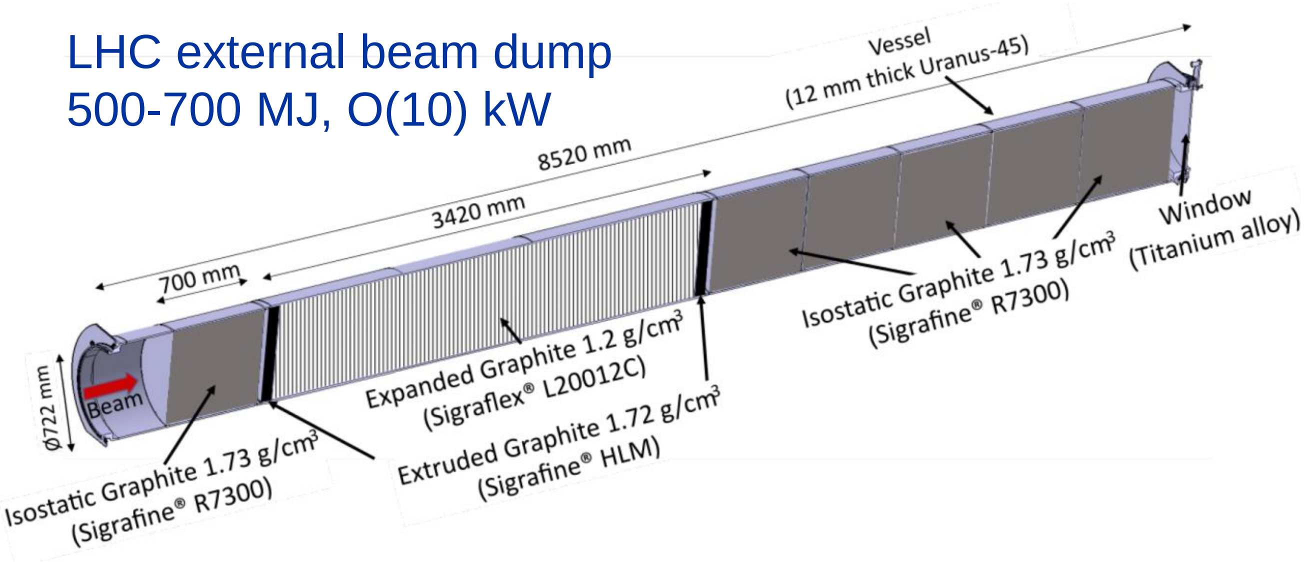
σ_x ~4.6 cm
σ_y ~2.5 cm

σ_x ~2.2 cm
σ_y ~2.5 cm

Considerations & limits of solid absorbers

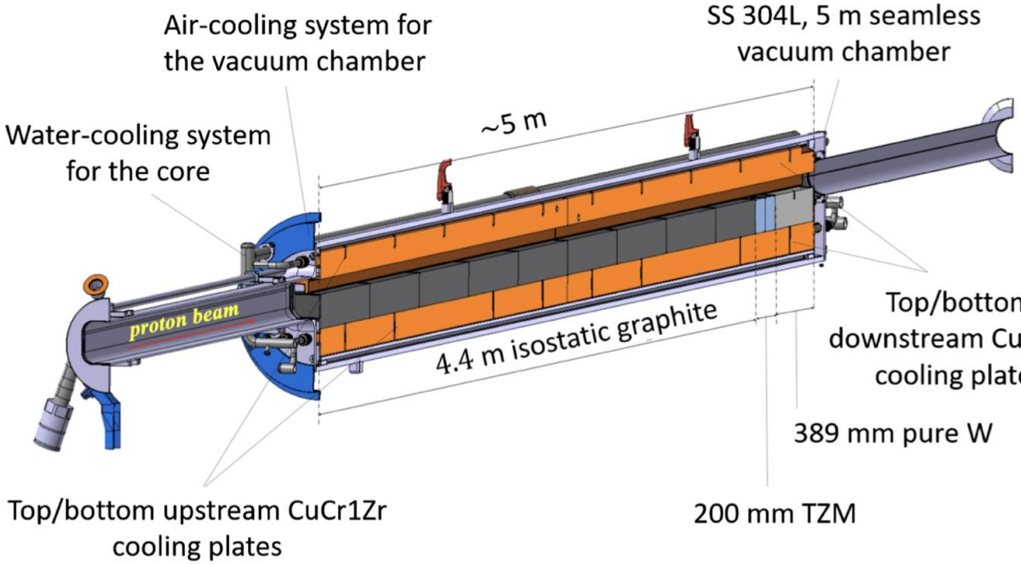
As a first assumption we considered the use of **graphite as absorbing material**, capitalizing from the existing CERN's experience in these types of absorbers

LHC external beam dump
500-700 MJ, O(10) kW



J. Maestre et al. 2021 JINST 16 P11019

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



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

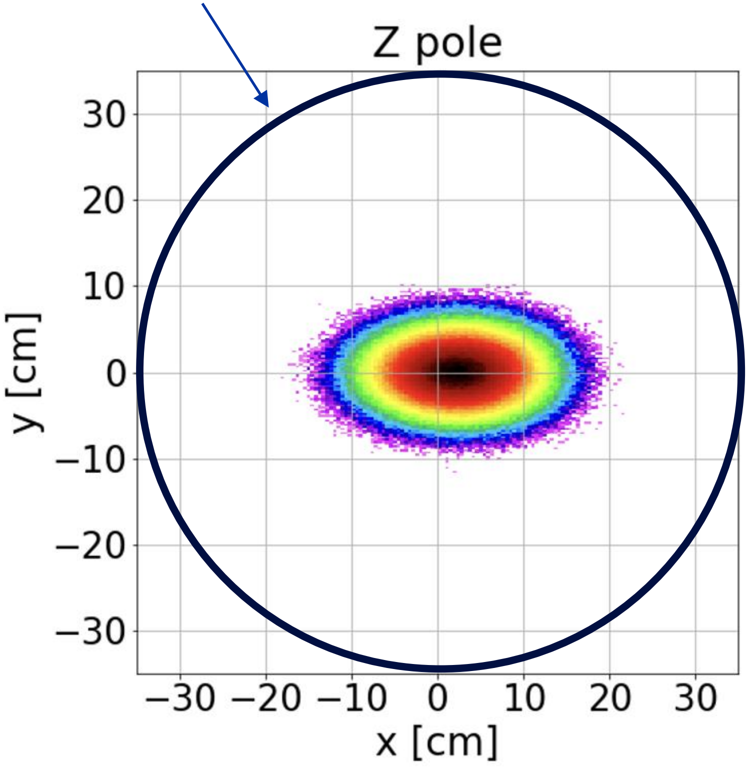
Considerations & limits of solid absorbers

- **Graphite** (ρ=1.2-1.8 g/cm^3) is an excellent material for energy absorption due to its robustness and capability for high T operation (& rather good radiation hardness)
- **Operation in UHV limited at ±1200 °C** due to vapor pressure
- Higher temperatures only possible under inert gas operation (e.g. (HL)LHC beam dump)
- Unfortunately, **thermal conductivity is rather poor** (50-70 W/m*K), hence material not very adapted for high steady state power deposition for big volumes

How would a TDE-like solution would perform?

- Dump likely have a **±60-70 cm ⌀,** L~300/350 cm
- Assuming a peripheral cooling, **T_{gr} >4000 °C** for Z_0 operation in case of vertical offset
  - Stresses appears **beyond the limit for nominal operation**
  - Conditions **limited by the thermal conductivity of graphitic-material**, rather than on external cooling
- **For the time being, no-go for this option**

700 mm diameter footprint



What if we go liquid?

- We started investigating the option of using **pure liquid Pb**
  - Operational temperature **between 400 °C and 480 °C**
  - **Rather insensitive to total power deposited**
  - No Pb-Bi eutectic system considered now due to **complex chemistry**, requirement to **keep temperature under well precise control** as well as due to **Po production from Bi**
  - Synergetic with other initiatives at CERN
- A flowing system of Pb in case of a **quasi-CW energy deposition would be a good fit** for the requirement of FCCee BS absorber

Advantages of a liquid Pb absorber (I/II)

- Pb is an **”ideal” photon absorber** material
- Absorption and dissipation of thermal power from the beam is “trivial”
- Absence of beam-induced thermo-mechanical stresses
- **No long-term degradation** of dump materials (radiation damage, fatigue, etc.)
- Dilution of radionuclide inventory within total absorber volume
- Flexible waste disposal preparation

Advantages of a liquid Pb absorber (II/II)

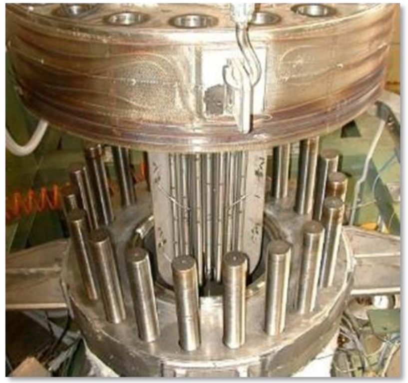
- Actual **heat exchange with coolant medium can be located away** from absorber (and could be air)
- Known liquid Pb thermo-hydraulics and experience building loops by collaborators
- No need for vacuum vessel nor pressure vessel – **operation at atmospheric pressure with cover gas**
- At foreseen operational temperatures, no issue with chemical compatibility, corrosion & erosion on conventional stainless steels (AISI304/316)
- Synergistic with other activities at CERN and with societal applications

Pure Pb liquid loops @ENEA

Lead technology for LFRs has been in development for over 20 years in Europe, mainly at ENEA

CIRCE Large pool (90 tons LBE)

NACIE-UP loop



LIFUS-5 Separate Effect facility

LECOR Corrosion Loop

BIDONE Lead-Pool

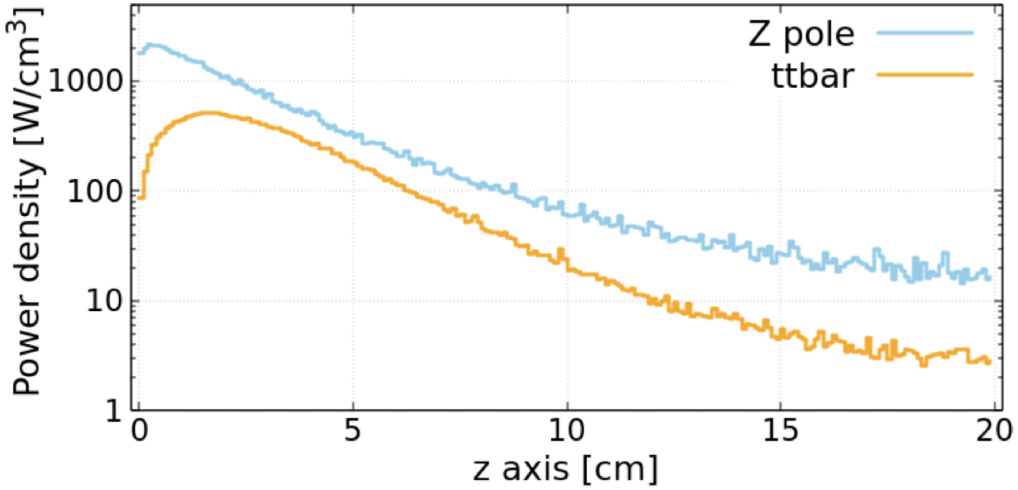
RACHELE (Coolant chemistry lab)

HELENA Lead Technology Loop

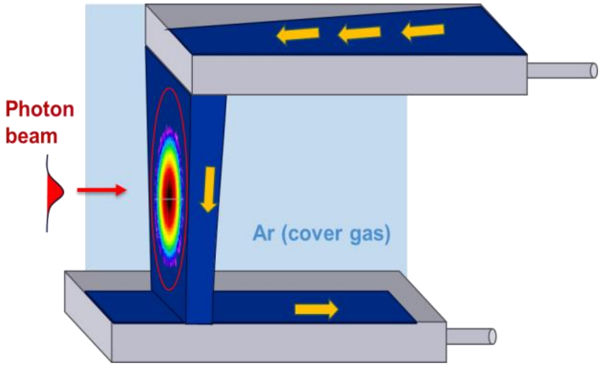
Lead Mechanical Laboratory

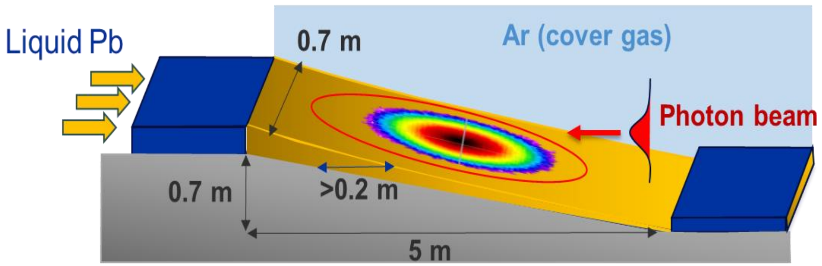
First implementation of a pure Pb system

- We first considered the option of a "curtain"-like free surface Pb system (top-bottom), **20 cm thick**, to maintain a compact design (>90% of power)
- But due to the size of the required impacted volume (700x700x200), the total mass flow would be **more than 1500 kg/s**



Curtain vs. slide flow

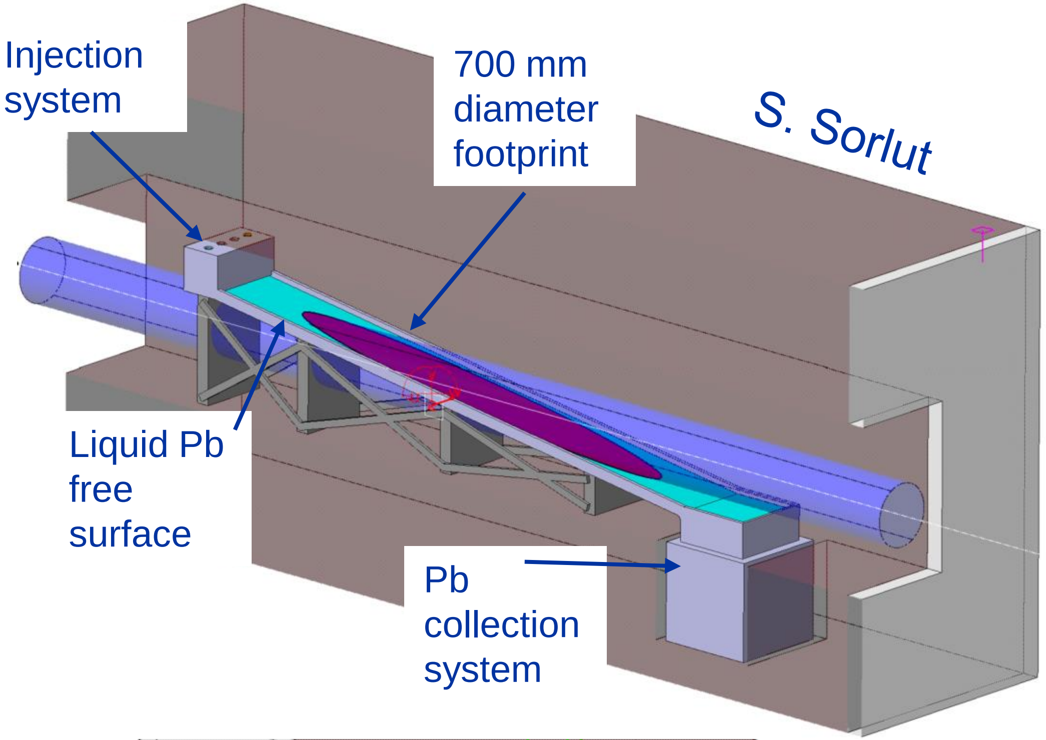


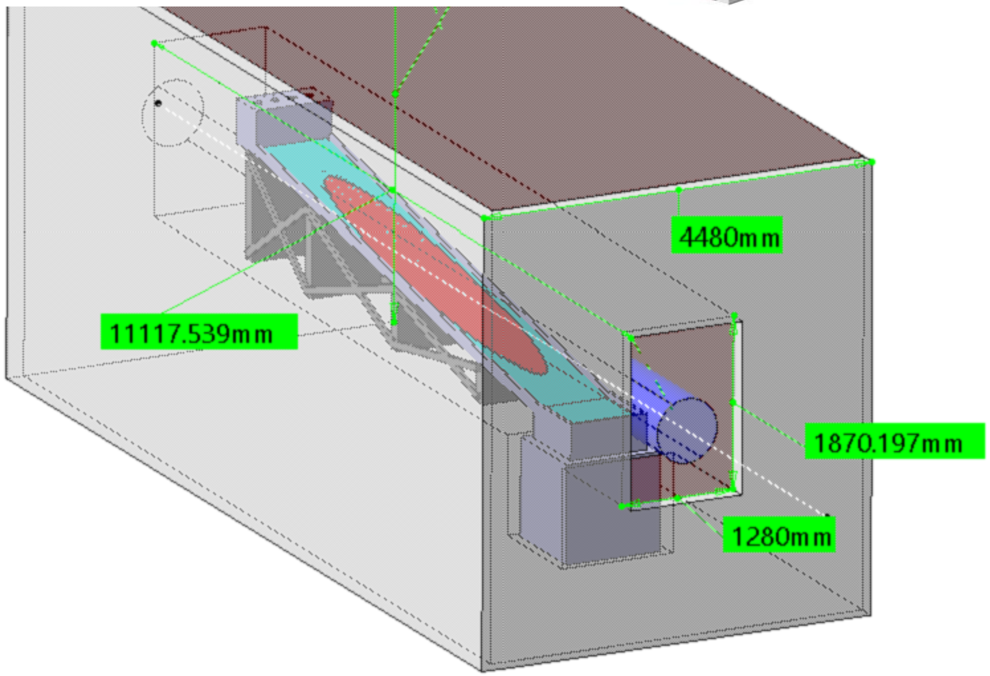


A "slide flow" system is therefore proposed, to reduce the mass flow, while keeping the size reasonable

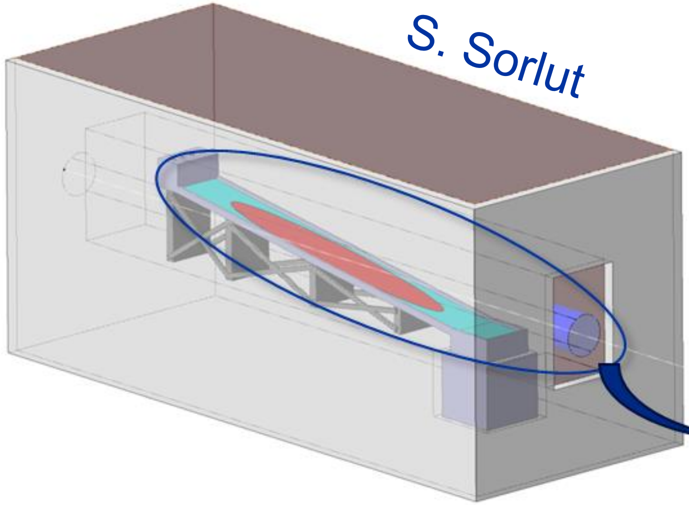
First implementation

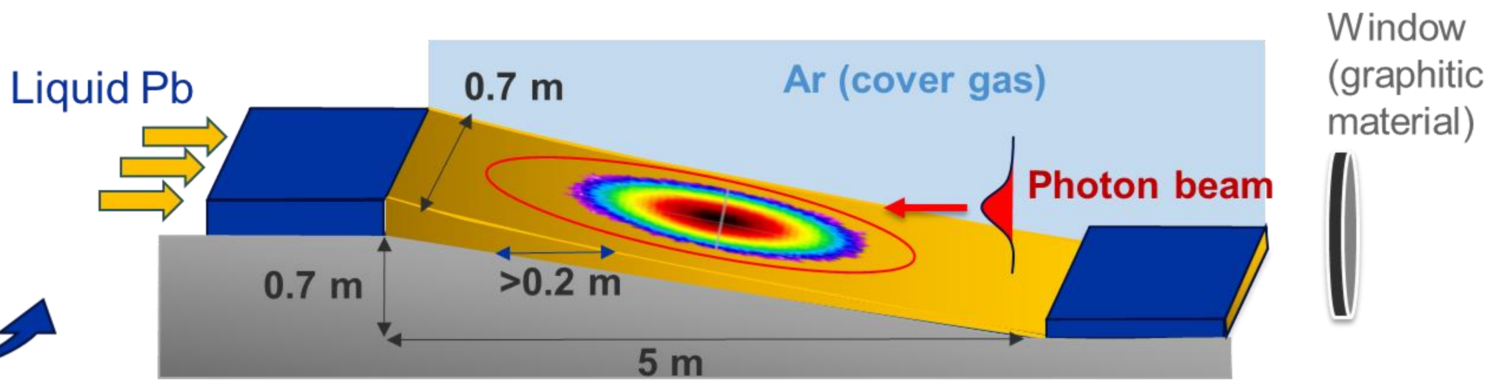
- **Slide flow oriented at 8 degrees**
- Effective free surface Pb thickness of about 30-40 mm, but **effective depth seen by photons of >200 mm**
- Shielding around the dump of **150 cm of Fe** in all direction
- Pb in purified **argon atmosphere at 1 bar(a)** to avoid oxidation
- **Vacuum window(s)** required upstream





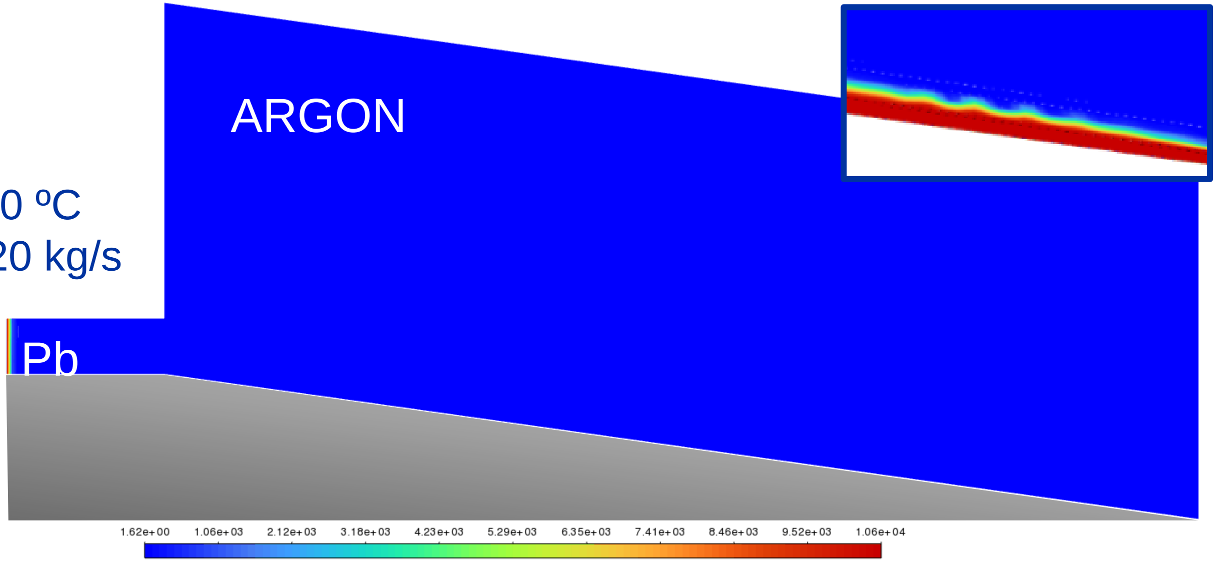
First implementation of a pure Pb system





2D CFD calculation
- Multiphase: VoF (+Level-Set)
- Turbulence: k-omega sst
- Transient [0, 2.823]s
- Explicit VoF (CFL 1)
- Inlet Height 0.3 m
- Inlet Flow rate 220 kg/s

T_i = 400 ºC
Q_i = 220 kg/s



Lead flow driven by:

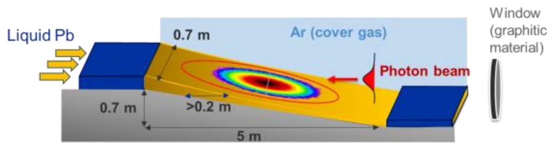
Instabilities
- Kelvin-Helmholtz
- Roll waves
- Turbulence

Forces:
- Gravity
- Friction
- Surface tension
- Viscosity

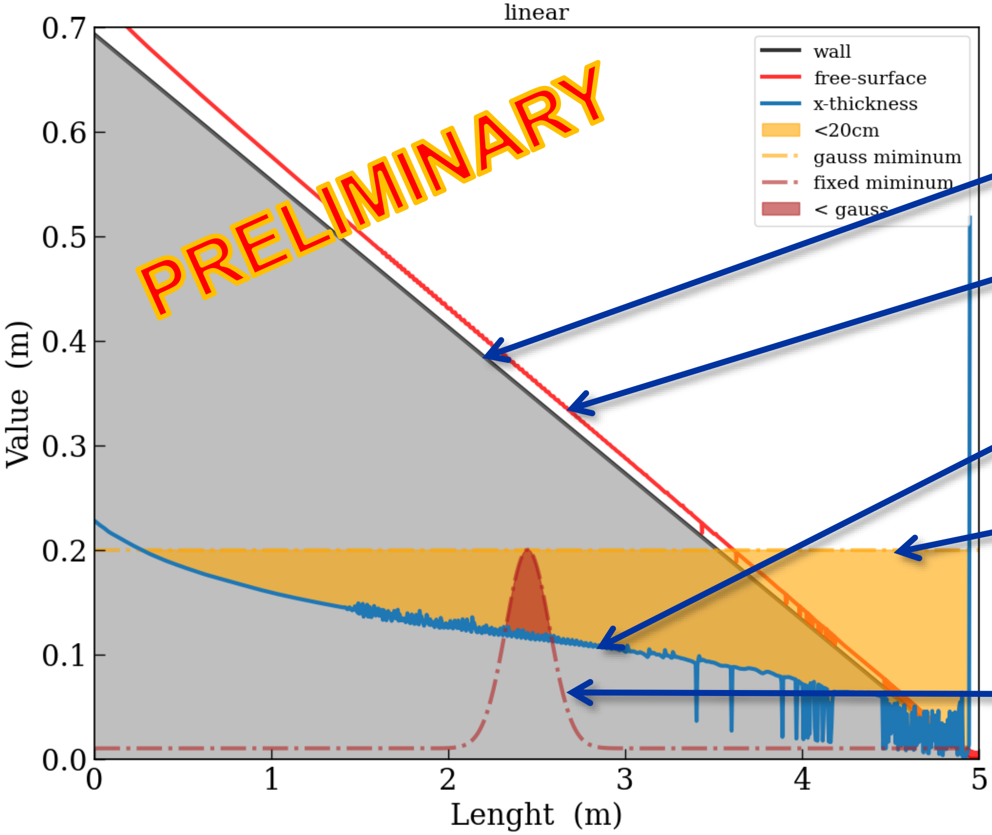
Geometry

Modelling and dimensioning of liquid Pb dump

Example of profile optimization to **minimize lead system** requirements

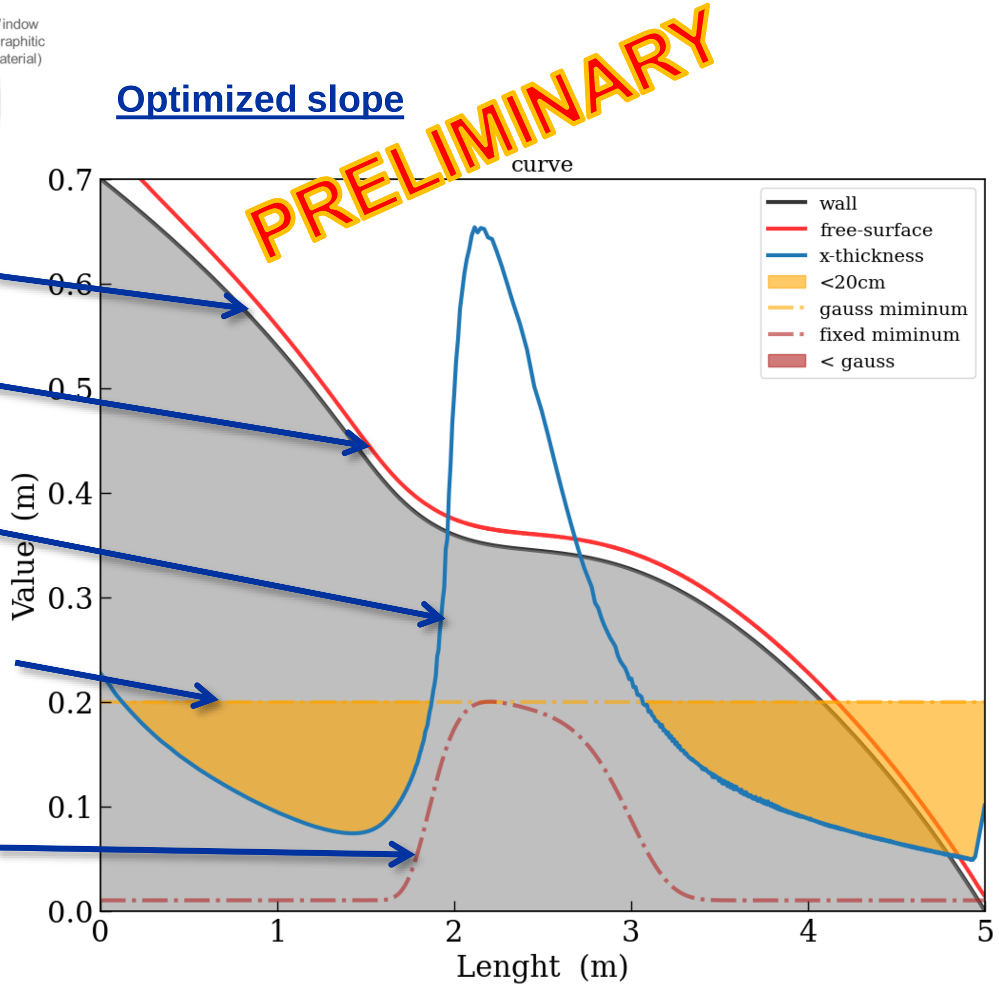


Simple slope (0.7x5m)



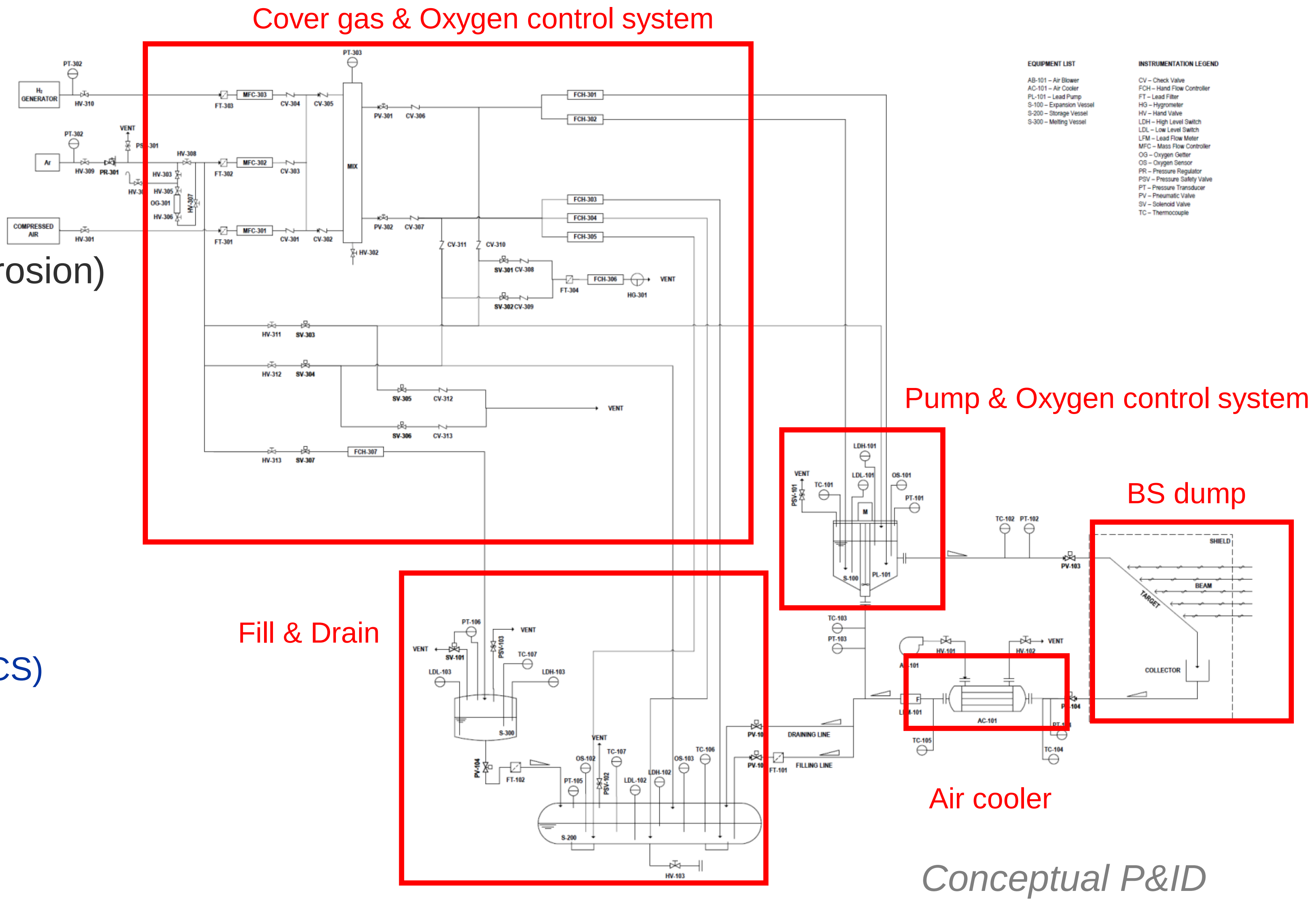
- Slope profile
- Pb free surface profile
- Depth seen by the beam
- Min depth required at peak of energy deposition
- Projection of beam profile across length

Optimized slope



General parameters for a liquid Pb absorber

- Flow rate: **up to 350 kg/s**
- Deposited power: **500 kW**
- Avg. vel. (dump) : **> 1 m/s**
- Avg. temp. : **400-420 °C** (no corrosion)
- Piping: DN100/DN300
- Material: AISI 304/316
- Vertical, mixed axial flow pump
- Pressure losses: **< 1.5 bar**
- Main systems:
  - Coolant purification system (OCS)
  - Cover gas system
  - Air cooler
  - Filling & drain system

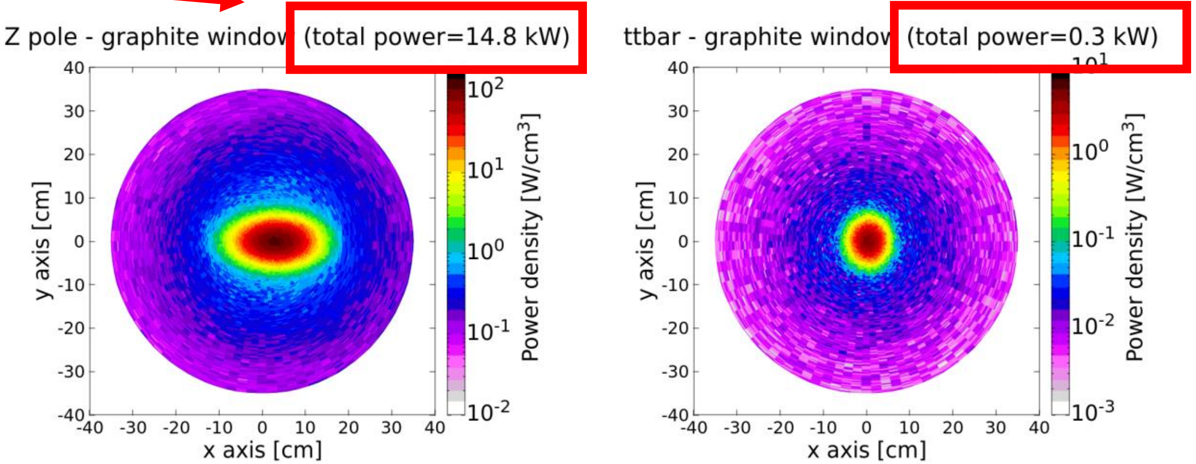


Conceptual P&ID

Considerations on windows

LHC TDE 10 mm TiGr5 windows

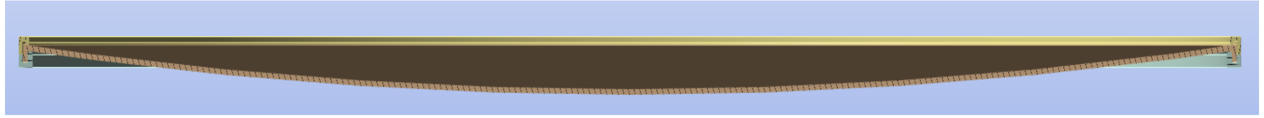
- All dump configurations will likely be operated in inert gas
- **Windows will be required** to separate the dumps from the UHV environment of FCCee
- Very large diameter (e.g. LHC TDE) means **large pressure-induced stresses** → tend to favor thick windows, which in turn means **high (total) power deposition**



e.g., for 20 mm thick windows

- Materials under considerations include beryllium & 3DCC graphite (e.g. TCDIL & HL TDE)

Further studies jointly STI & VSC required

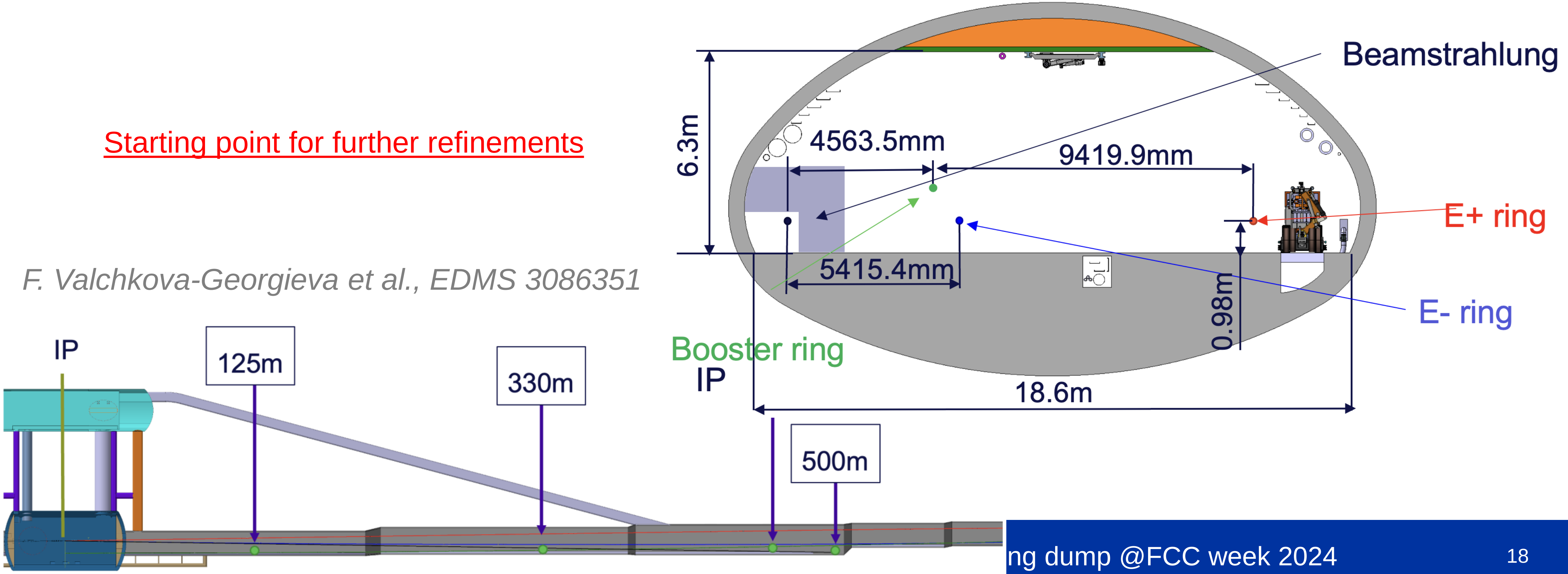


Integration constraints

- We assume the dump to be located at 500 m from IP, to have **sufficient separation between the beamstrahlung line & booster** line & **as much diluted beam as possible**

Starting point for further refinements

F. Valchkova-Georgieva et al., EDMS 3086351

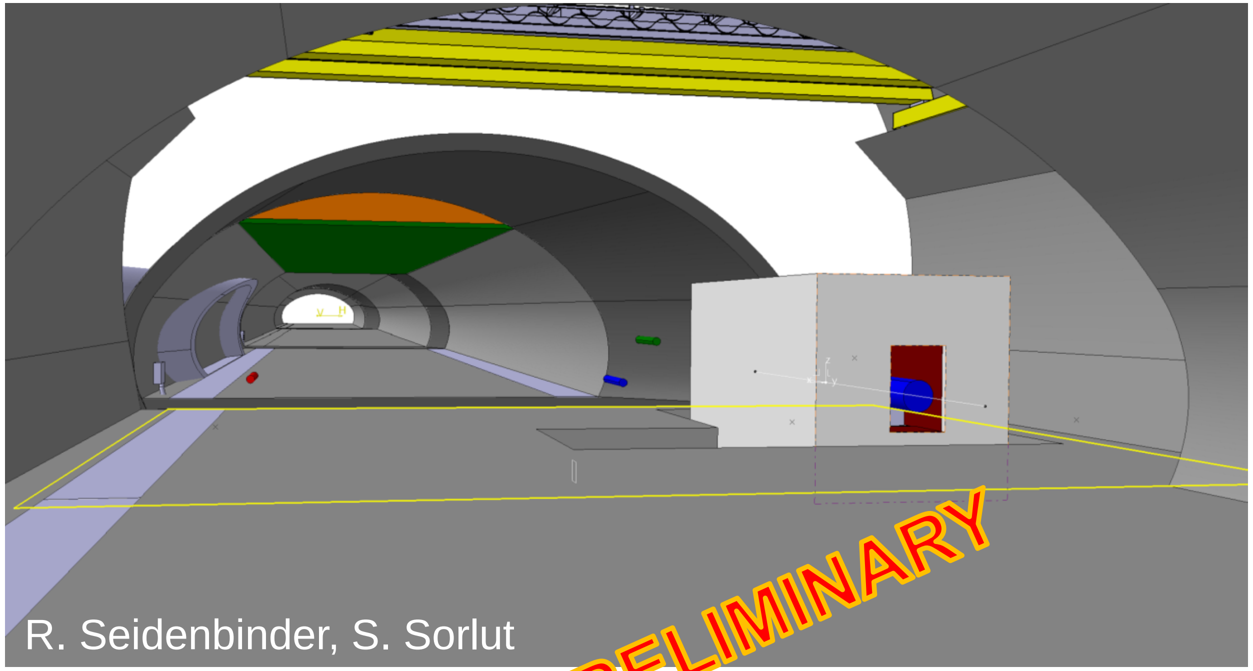


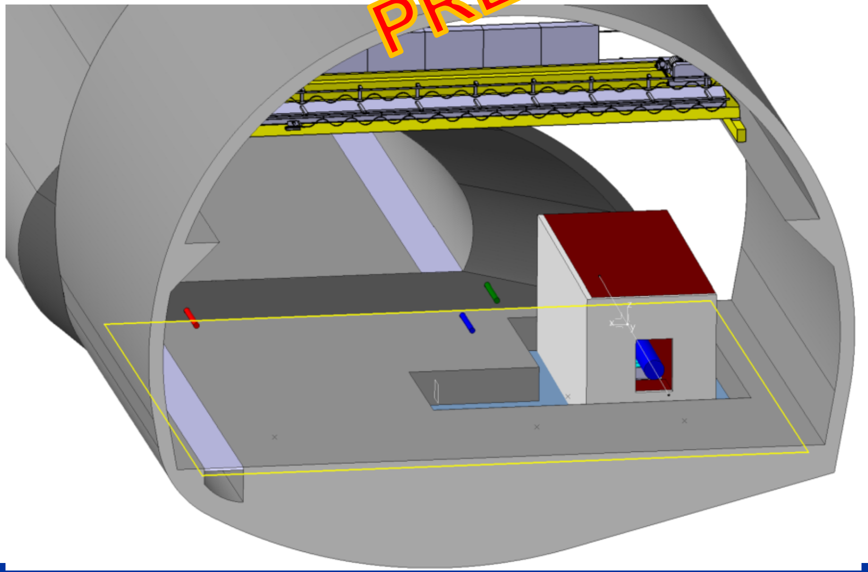
Integration constraints - proposed extension

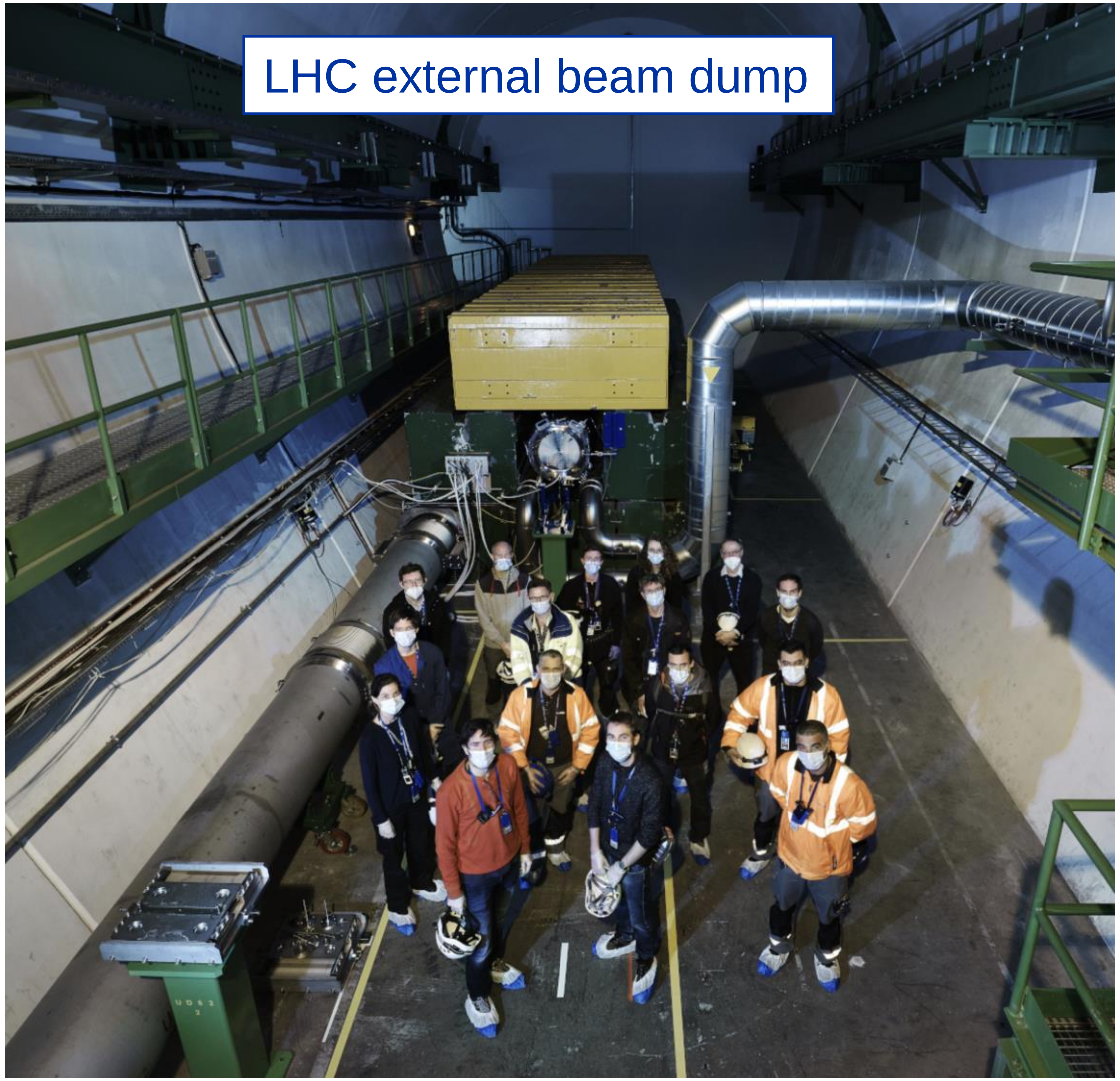
- **Dedicated crane required for the area**, capacity likely **between 10 and 20 tons**

- **Recess below the ground level to avoid soil activation** required
  - Extended to place the Pb draining tank & various subsystems
  - O(40) ton/m^2 needed

- Tunnel xsection is **to be extended**



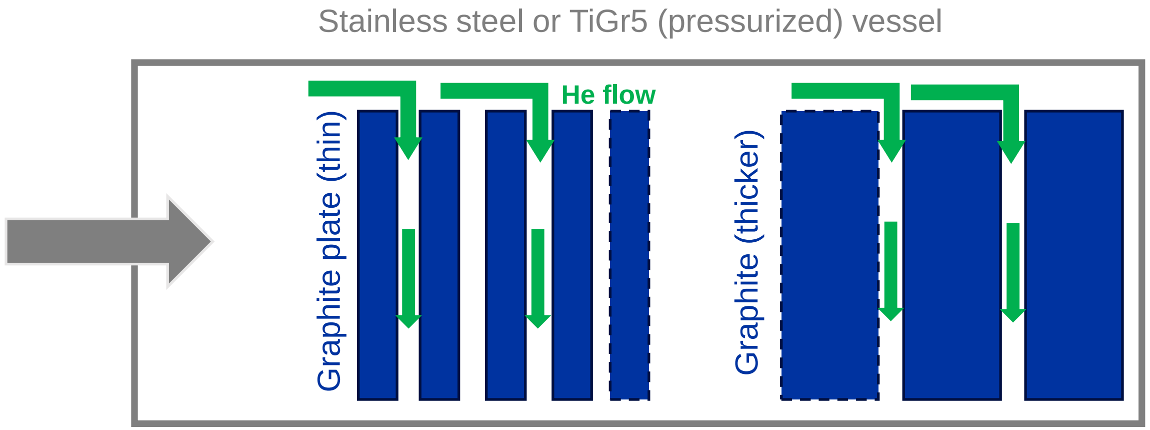



LHC external beam dump


SPS internal beam dump

Do we have any other plan B?

- **Evolutionary design of LHC beam dump assembly**
  - **Segmented graphite absorber** (plates of several mm up to cm thick, enclosed in a pressurized vessel
  - **Cooled by (very pure, e.g. oxidation) helium gas** in a closed loop
  - Dump would be **~5-6 meters long with a large He station nearby**
- Space occupancy will likely be similar to plan A



Ideas to be explored in the next few months

Proposal for R&D paths and definition of a long-term strategy

- Priority is to match the **FCCee project requirements**
  - Feasibility confirmed with an update of cost estimate by end of 2024 (Cat 3) + CE input
  - Introduction of BS monitor & design of the photon dump line
  - Baseline for environmental impact by end of 2025 (in collaboration with RP)
- Work **in parallel between the liquid Pb and the He-cooled graphite**
  - Definition of a **preferred option by end of 2025**
- Development of a **functional prototype by 2028-30**
  - Operation for reliability checks and confirmation of design assumptions
  - Potential for beam test (e.g. electron beam)
- **Mock-up of final assembly by O(2035)**

Further discussions in one of the next ATDC

home.cern

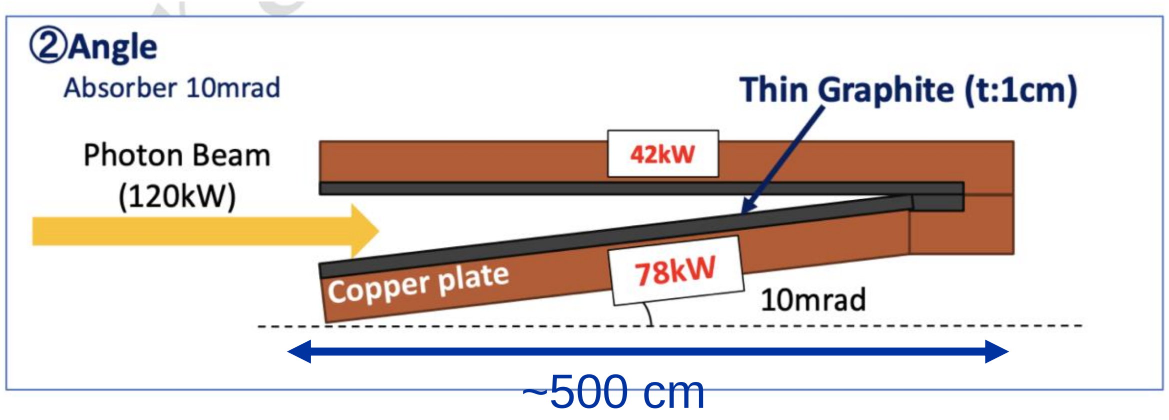
CERN/ENEA collaboration

- In 2022, CERN & Italian National Agency for New Technologies, Energy and Sustainable Economic Development signed an agreement to **develop new beam-intercepting devices using liquid-lead technologies** (link)

Do we have any other plan B?

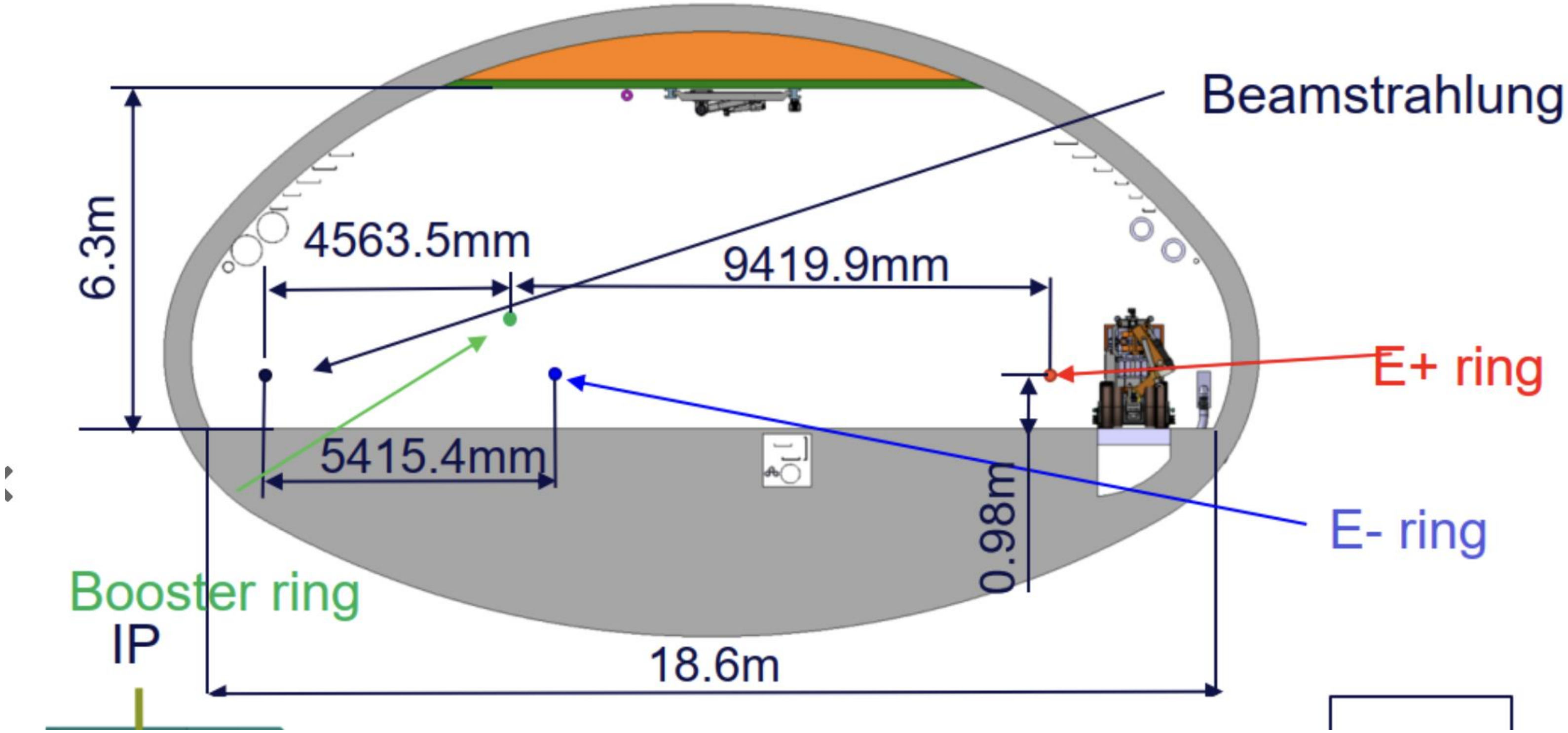
- ILC colleagues (Y. Morikawa & co.) have been working on a **120 kW photon absorber** based on graphite on a Cu substrate acting as sink (à-la-TIDVG)

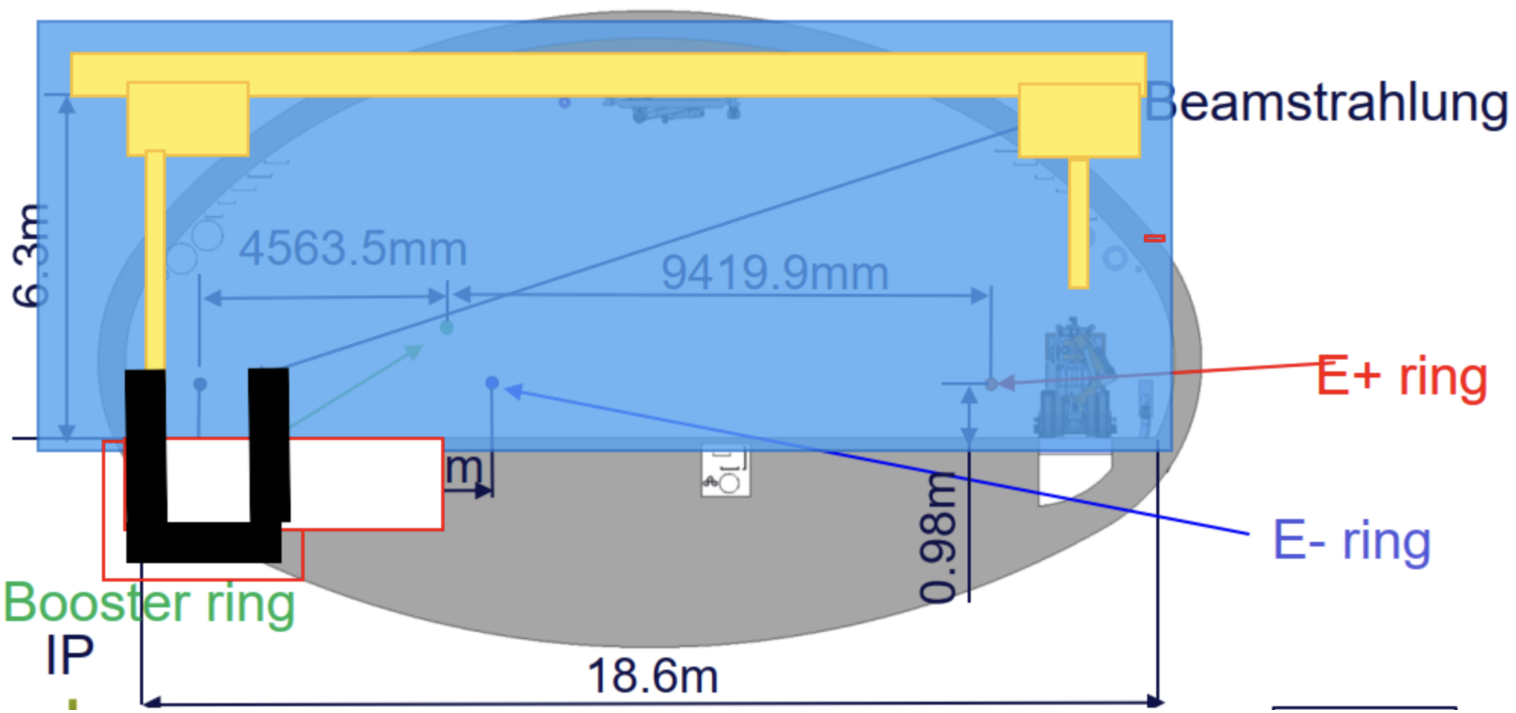
- Noted aspects:
  - Susceptibility to **radiation damage**
  - Unclear thermal & mechanical barrier reliability between graphite & Cu
  - Viability of this option at 500 kW questioned



Y. Morikawa & co. (POSIPOL2018)

Other options include "waterfall" system, not favoured (at least at CERN) due to significant tritium production


Beamstrahlung
6.3m
4563.5mm
9419.9mm
E+ ring
5415.4mm
0.98m
E- ring
Booster ring
IP
18.6m



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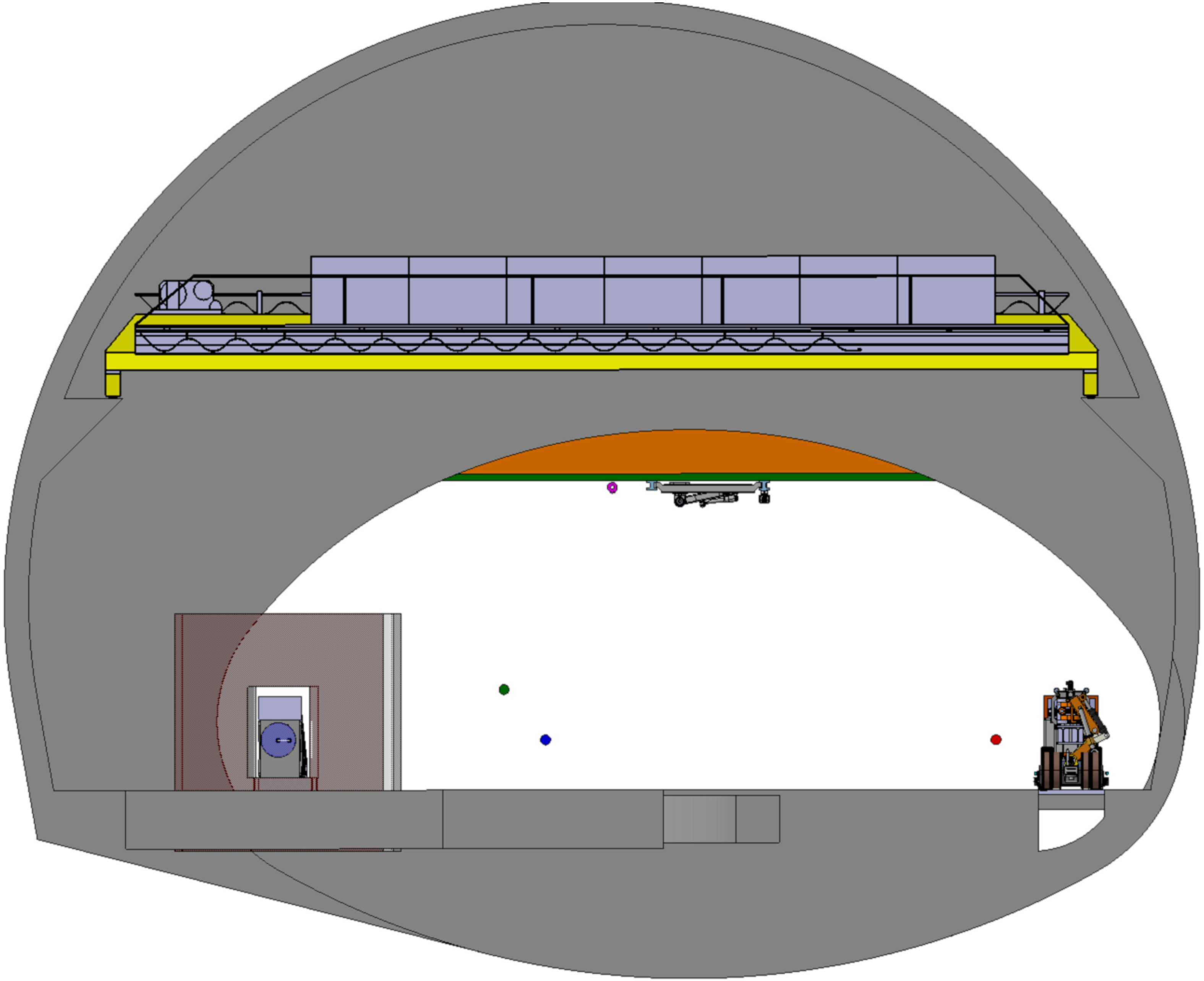
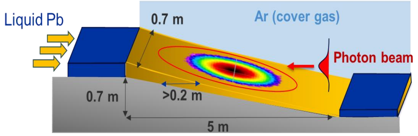
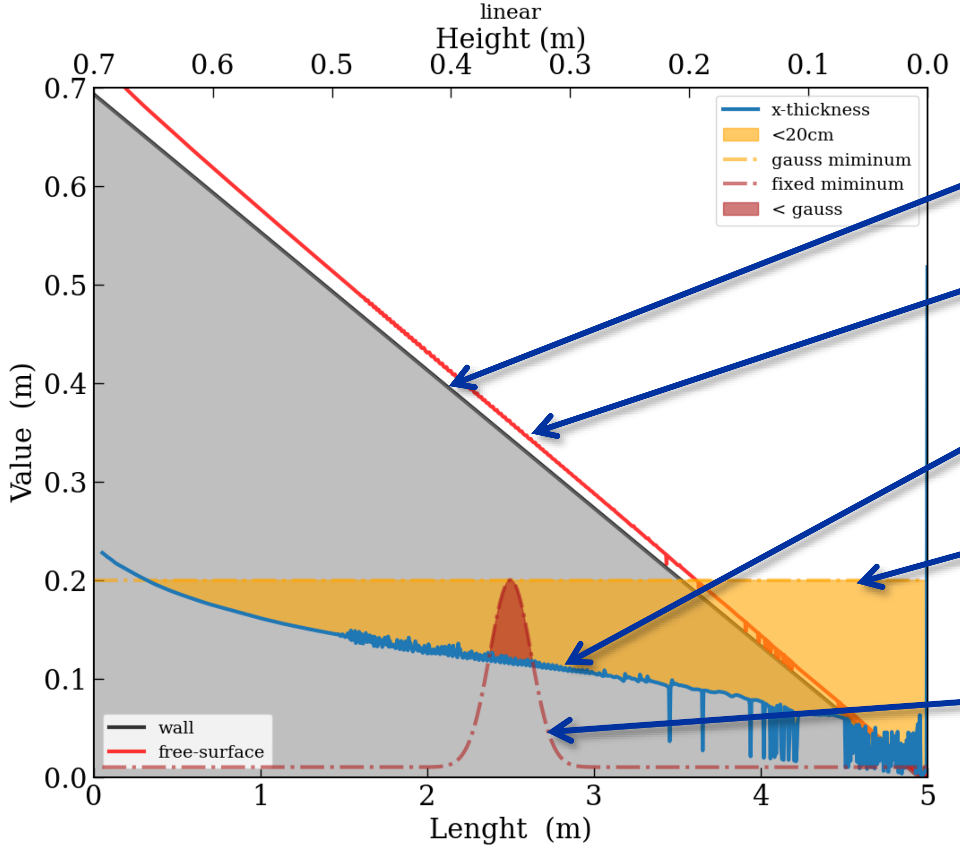


First implementation of a pure Pb system

Example of profile optimization to minimize lead system requirements
(preliminary assessment!)



Simple slope (0.7x5m)



Slope profile

Pb free surface profile

Depth seen by the beam

Min depth required at peak of energy deposition

Projection of beam profile in y

Optimized slope