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

Fusion and Technology for Nuclear Safety and Security Department (FSN)

Liquid Heavy Metal applications for particle accelerators

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Summary

Framework:

- Started collaboration with STI Group
- Reference people: M. Calviani, R. F. Ximenes

Summary:

- Presentation
- Liquid Heavy Metals
- Liquid Lead feasibility for BDF target
- Liquid Lead option for MuC target

Presentation – ENEA Brasimone

Research activities:

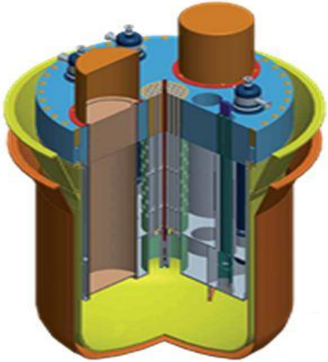
- Nuclear Fusion → Tritium Breeding from liquid Pb-Li
- Nuclear Fission Gen-IV → Lead/LBE-cooled Fast Reactors

Main focus:

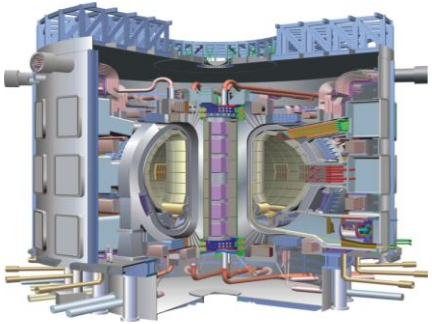
- Tritium Breeding from liquid Pb-Li
- Lead/LBE-cooled Fast Reactors

Capabilities:

- Experiment design & ops
- Numerical simulations
- Corrosion and chem analysis

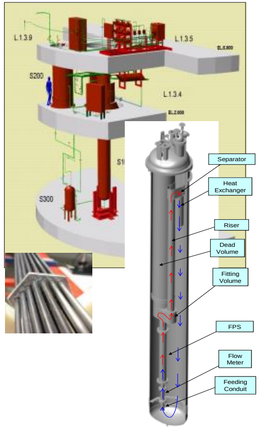


GEN IV LFR – ANN/ENEA ALFRED
Nuclear Fission Technology



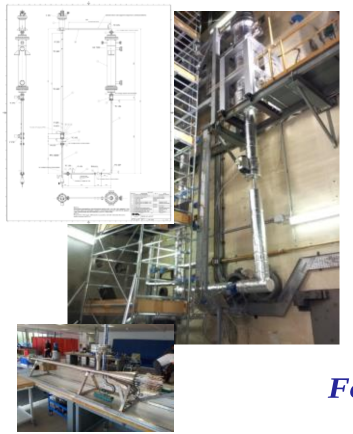
ITER / DEMO
Nuclear Fusion Technology

Presentation – Nuclear Gen-IV Experiments



CIRCE

90 LBE tons pool with instrumented bundle and 1to1 scale HX.
FPS power 900 kW

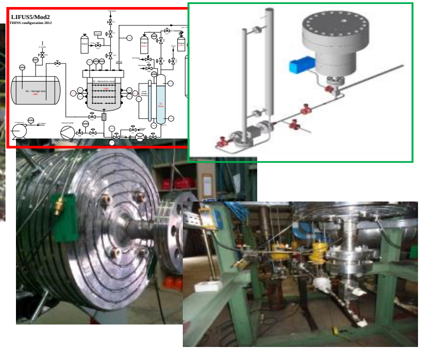


NACIE-UP

Natural/gas-lift circulation LBE loop with 19-pin instrumented **pin bundle.**

HELENA

Forced circulation Lead loop with mechanical pump, corrosion test section and valve test section



LIFUS5

Facility with several test sections to investigate ***water/LBE interaction*** and SGTR phenomena

CFD
SYS-TH
SIMMER-III and IV

↔

Neutronic
Fuel
Coupling

Other large and small scale exp facilities

Presentation – Nuclear Fusion Experiments

EBBTF (European Breeding Blanket Test Facility)

HeFus

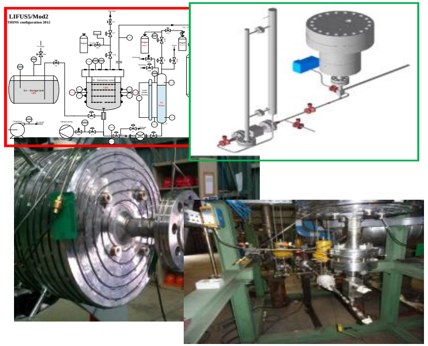
He cooled loop aimed at qualifying mock-ups HCPB/HCLL of the ITER TBM

IELLO

PbLi cooled loop aimed at qualifying mock-ups HCLL of the ITER TBM

TRIEX

Investigation on Tritium Extraction Systems for HCLL/WCLL blanket (ITER and DEMO)



LIFUS5

To investigate safety in WCLL breeding blanket (i.e. PbLi water reaction, set up of chemical reaction model in SIMMER-III code)

Other large and small scale exp facilities

CFD
SYS-TH
SIMMER-III and IV

↔

Neutronic

Coupling

Heavy Liquid Metals

Lead

Density: 10660~9000 kg m^{-3}
Melts: 600 K
Boils: 2020 K

LBE

Density: 10100~8500 kg m^{-3}
Melts: 398 K
Boils: 1930 K

Technological aspects:

- Steel corrosion at T > 450°C (slow process, 10^3 hrs)
- Stagnation areas in loop to be avoided (O_2 accumulation, local freezing)
- Ambient pressure ops

Radiological aspects:

- Pb is neutron multiplier: n – 2n
- ^{210}Po production under neutron irradiation in pure lead is ~10^4 less than in LBE[1]
- Studies are being conducted for MHYRRA ADS reactor to verify Polonium production under proton irradiation[2]

[1]Toshinsky et al, 2020
[2]Choudhury et al, 2018

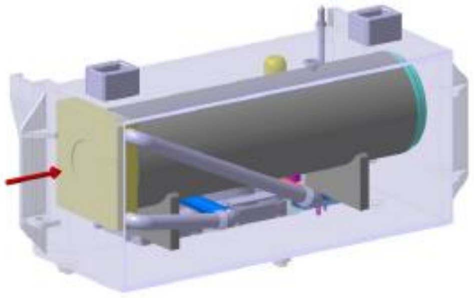
Liquid Lead BDF Target

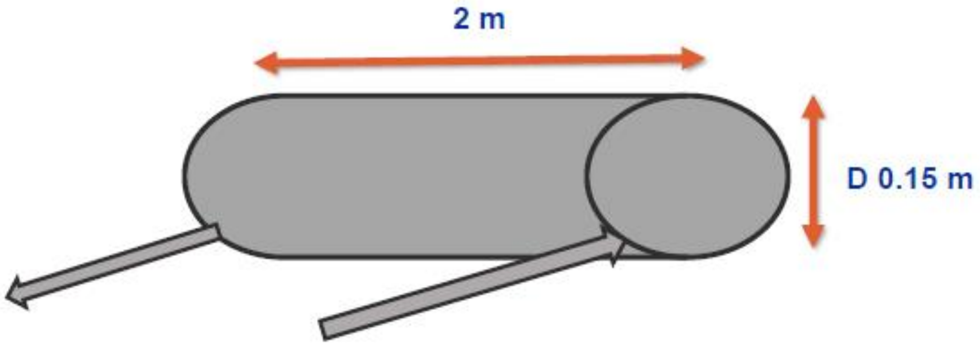
SPS Beam Dump Facility Project

- ECN3 Complex
- Pulse: 1s spill every 7.2s,
- P_{AVE}: 350kW
- Baseline: solid W + TZM

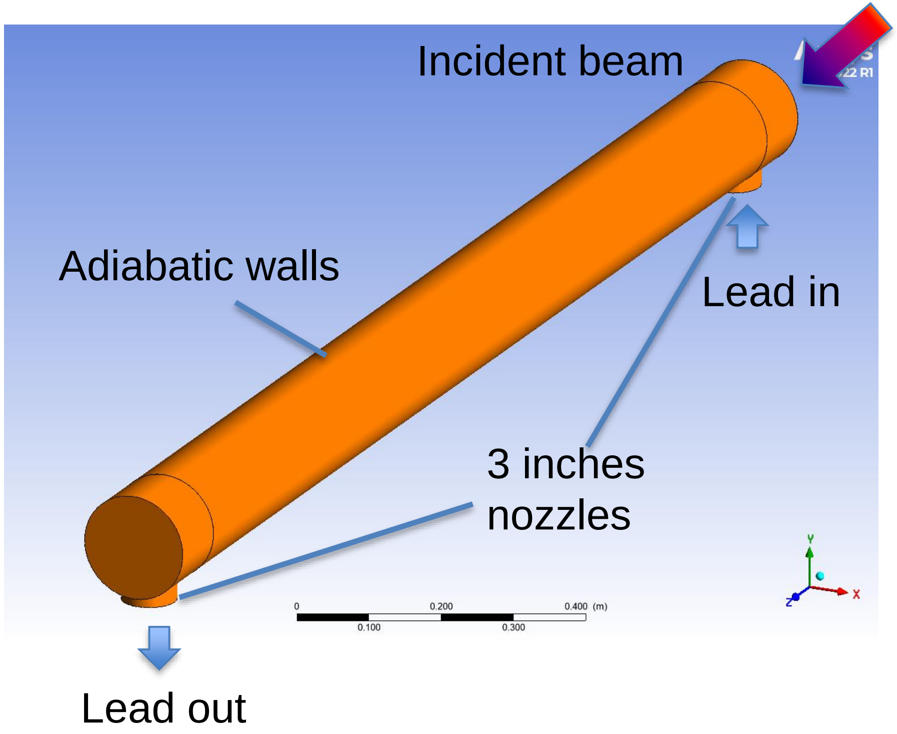
Liquid Lead Proposal

- Target: pure Pb, D150 x L2000 mm
- Loop with circulating pump, HX



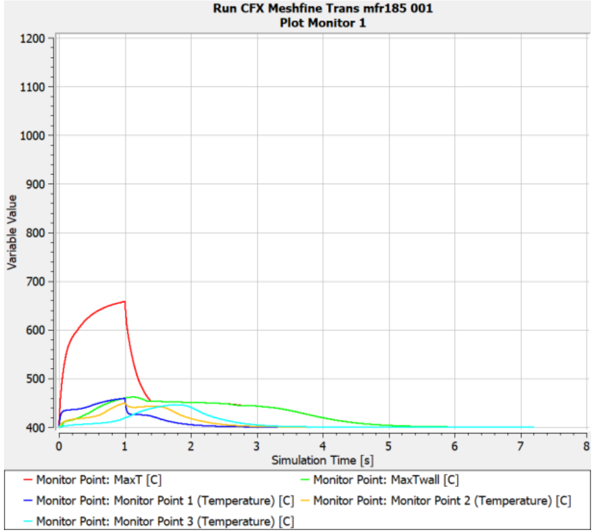


BDF Target: CFD model

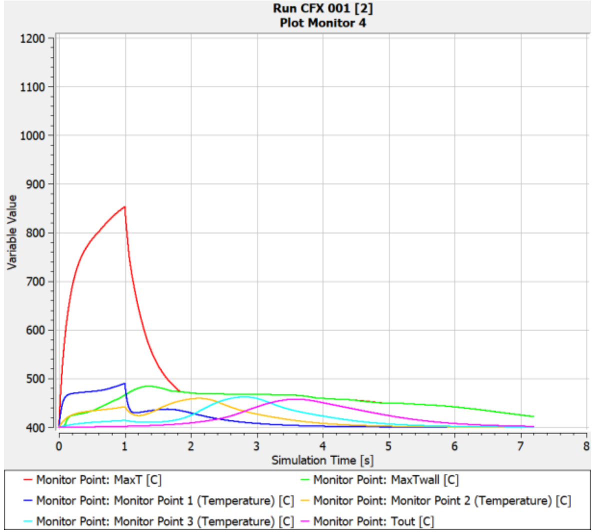


- Inlet@400 °C, flow equi-current with beam
- Average velocity in the pipe:
  - 1 m/s (mfr 185 kg/s),
  - 0.5 m/s (mfr 96.5 kg/s)
  - 0.25 m/s (mfr 46.25 kg/s)
- ANSYS CFX, RANS model SST k-omega y+=1 (boundary layer fully resolved) Mesh 2.2MNodes
- Transient calculations time step $5 \cdot 10^{-4}$s
- Power map provided by CERN (BDF_Pb_heatLoad_CFX.txt)

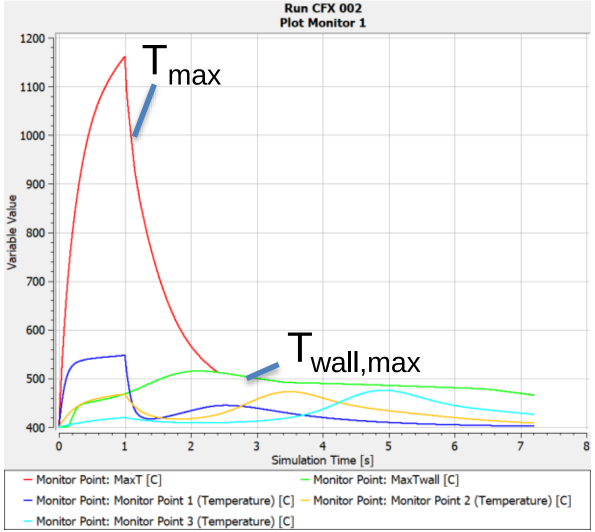
BDF Target: temperatures



mfr 185 kg/s



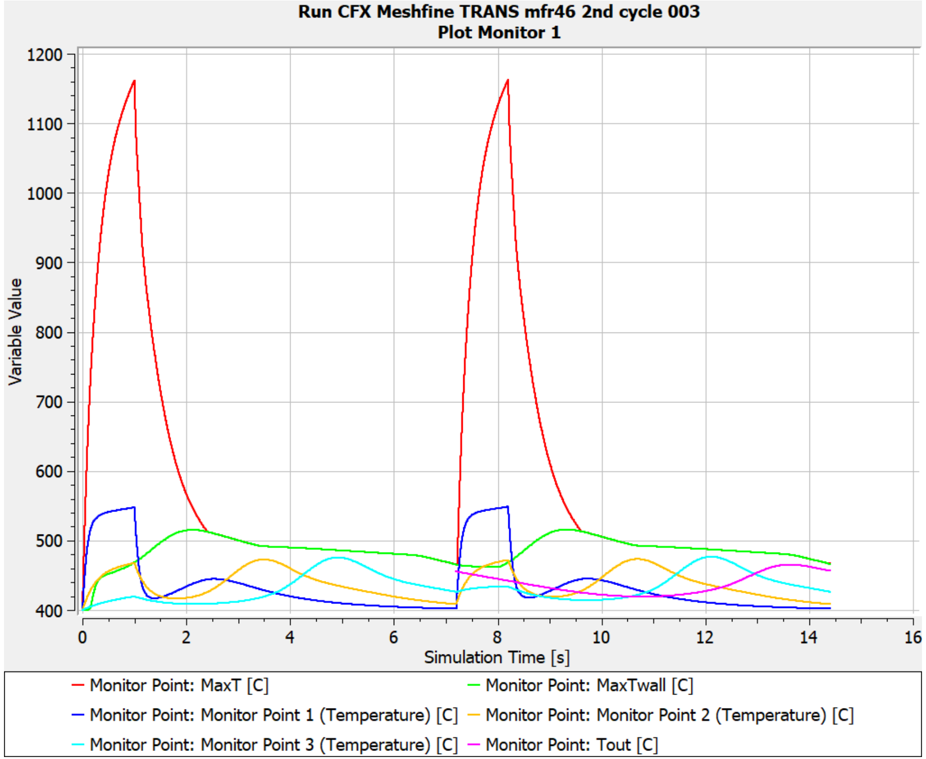
mfr 92.5 kg/s



mfr 46.25 kg/s

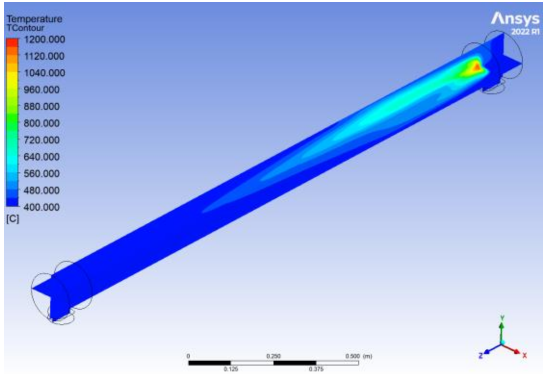
The solution @185 kg/s (1 m/s in the target) ensures that at the beginning of next pulse (7.2s) the target is completely cooled at 400°C. For lower flow rates further investigation are needed to explore the behaviour in the 2° cycle. Mfr 46.25 is still 550°C below the boiling point for lead. Wall temperature is under control.

BDF Target: 46 kg/s



mfr 46.25 kg/s (u=0.25 m/s)

- Max internal temperature **1163°C**, with more than 600°C margin for boiling
- Max wall temperature about **520 °C** (at the end of 1s power deposition)
- These values are very comfortable from an engineering point of view for material resistance
- Lower flow rate better for loop engineering (pump, pressure losses, lead inventory)



T@1s

BDF Target: wall temperature

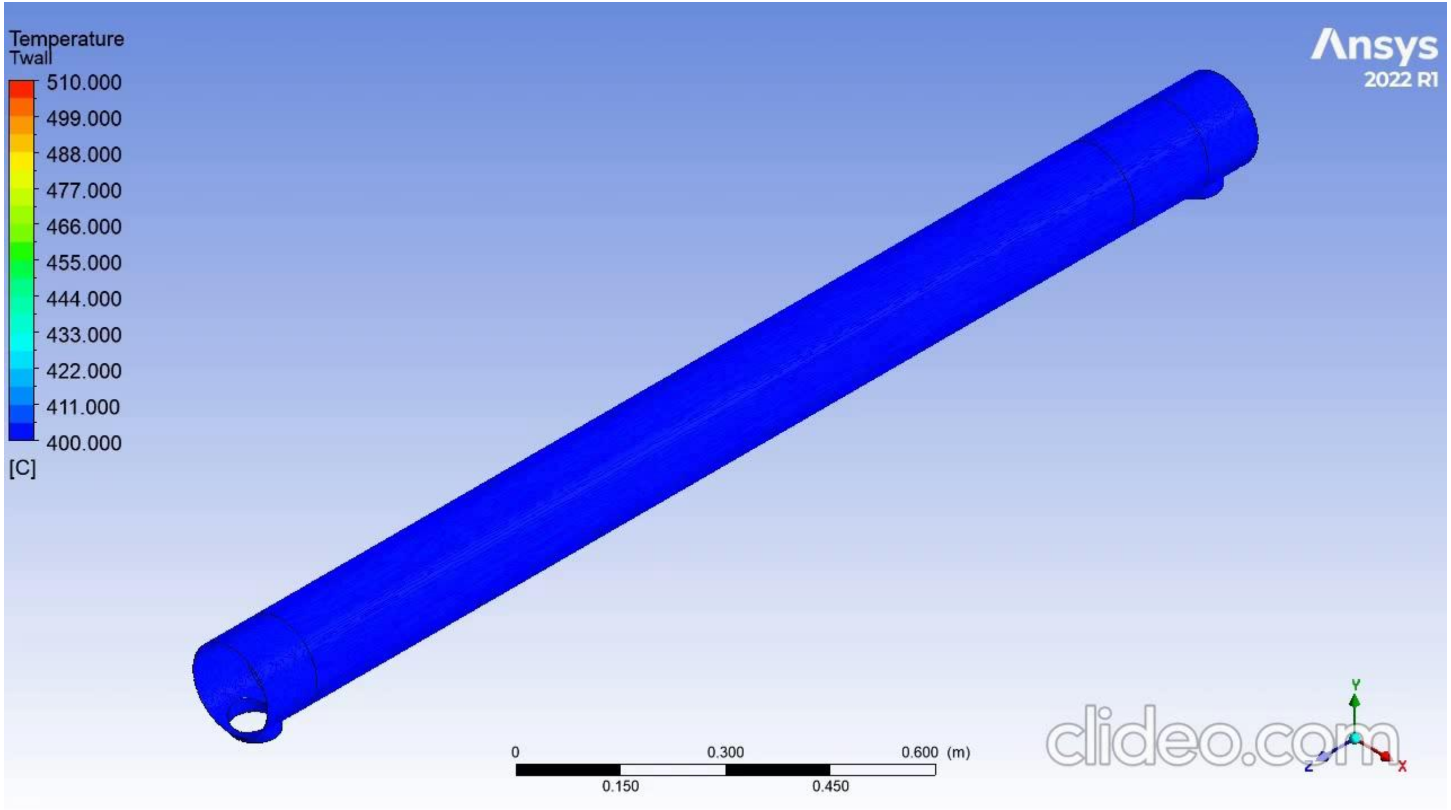
Twall@46.25kg/s

7.2s cycle with internal power generation pulse 1s

2 cycles

The expansion tank in the loop will dump bulk outlet temperature oscillation from the target

Thermal fatigue in the steel must be evaluated



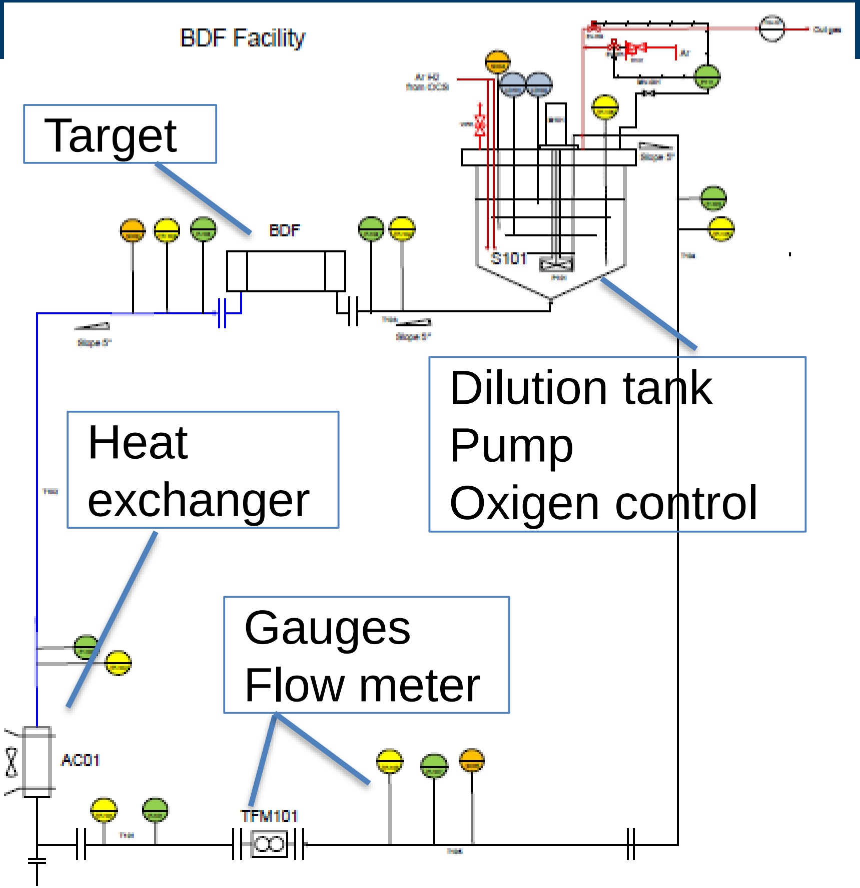
BDF Target: Lead Loop

Ongoing activities:

- Loop components sizing
- Target vessel
- Loop integration

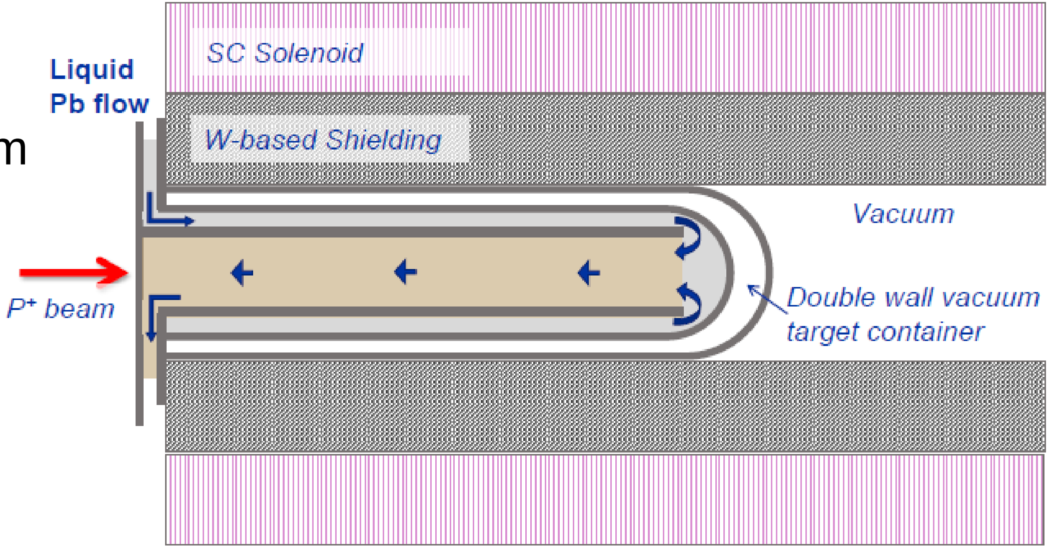
Challenges:

- Housing of components
- High-radiation environment



Liquid Lead MuC target

- Pulse: 2ns every 0.2s,
- P_{AVE}: 2 MW
- Target volume: D30 x L509 mm



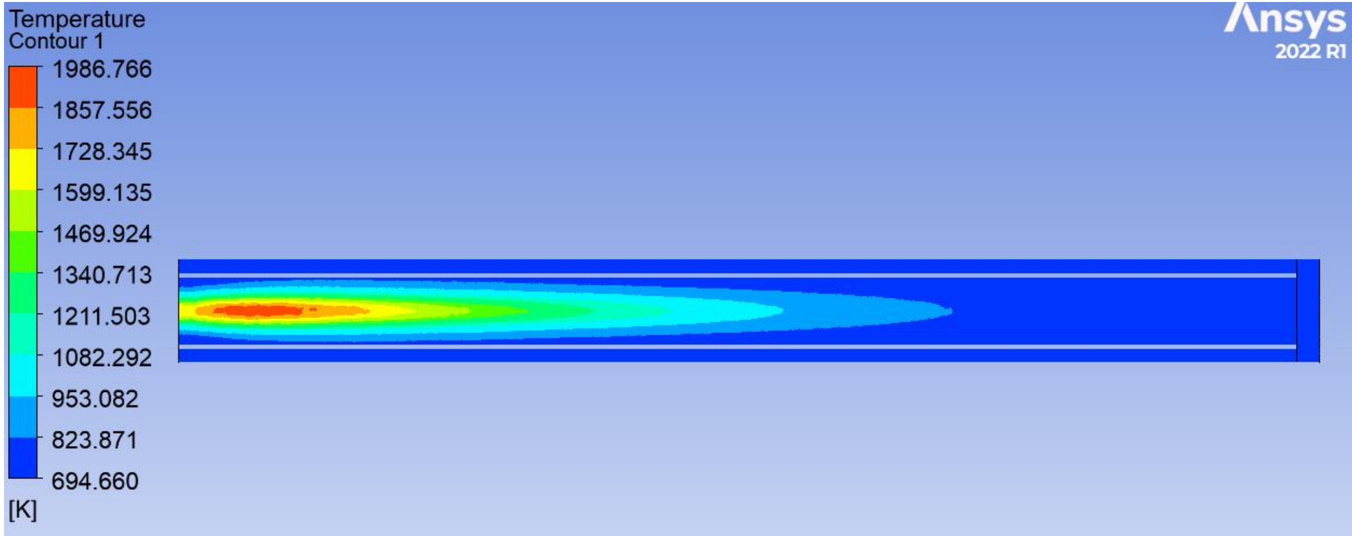
- Very high power density
- Limited available space
- MHD losses
- Risk of local lead vaporization

MuC target: temperatures

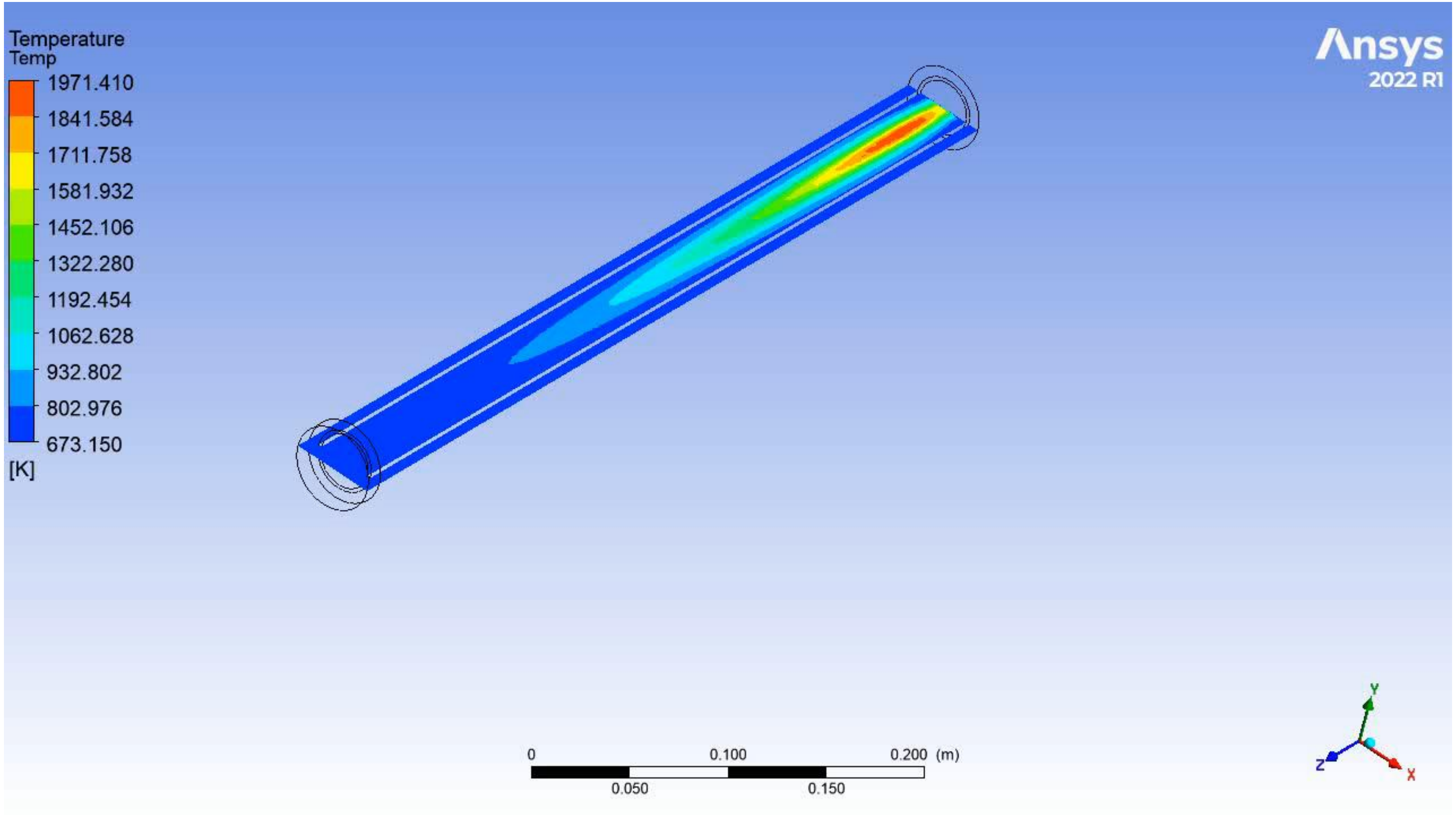
Thermal map calculated accounting for temperature-dependent properties: maximum temperature expected to be about 25 K below the boiling point. A beam 1.6% more powerful likely to flash the lead at the power peak. Opted for flow equi-current with beam direction to achieve dilution before high-temperature lead hit walls

At 2000 K (close to boiling point) lead increase by 20% in volume from 400°C.

Average lead volume temperature increase is about 190 K.

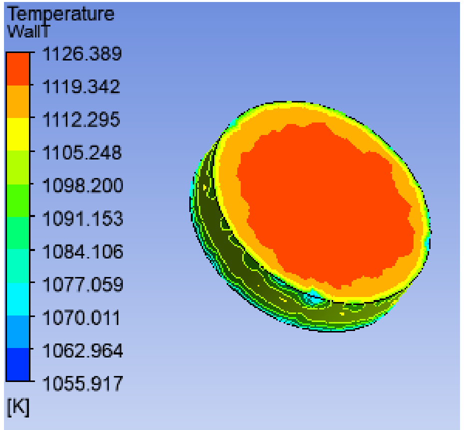


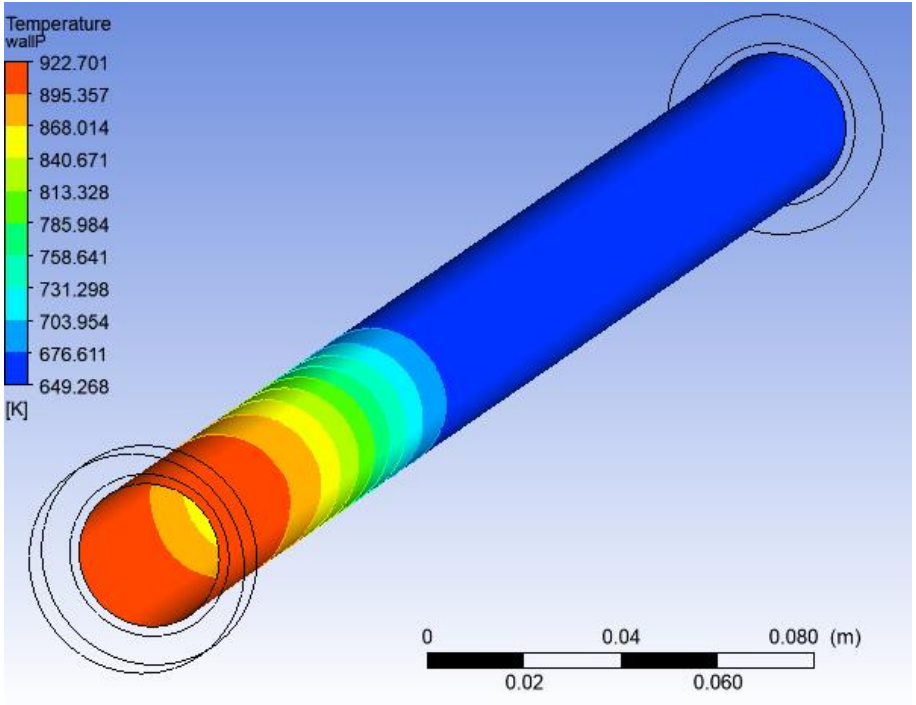
MuC target: temperatures



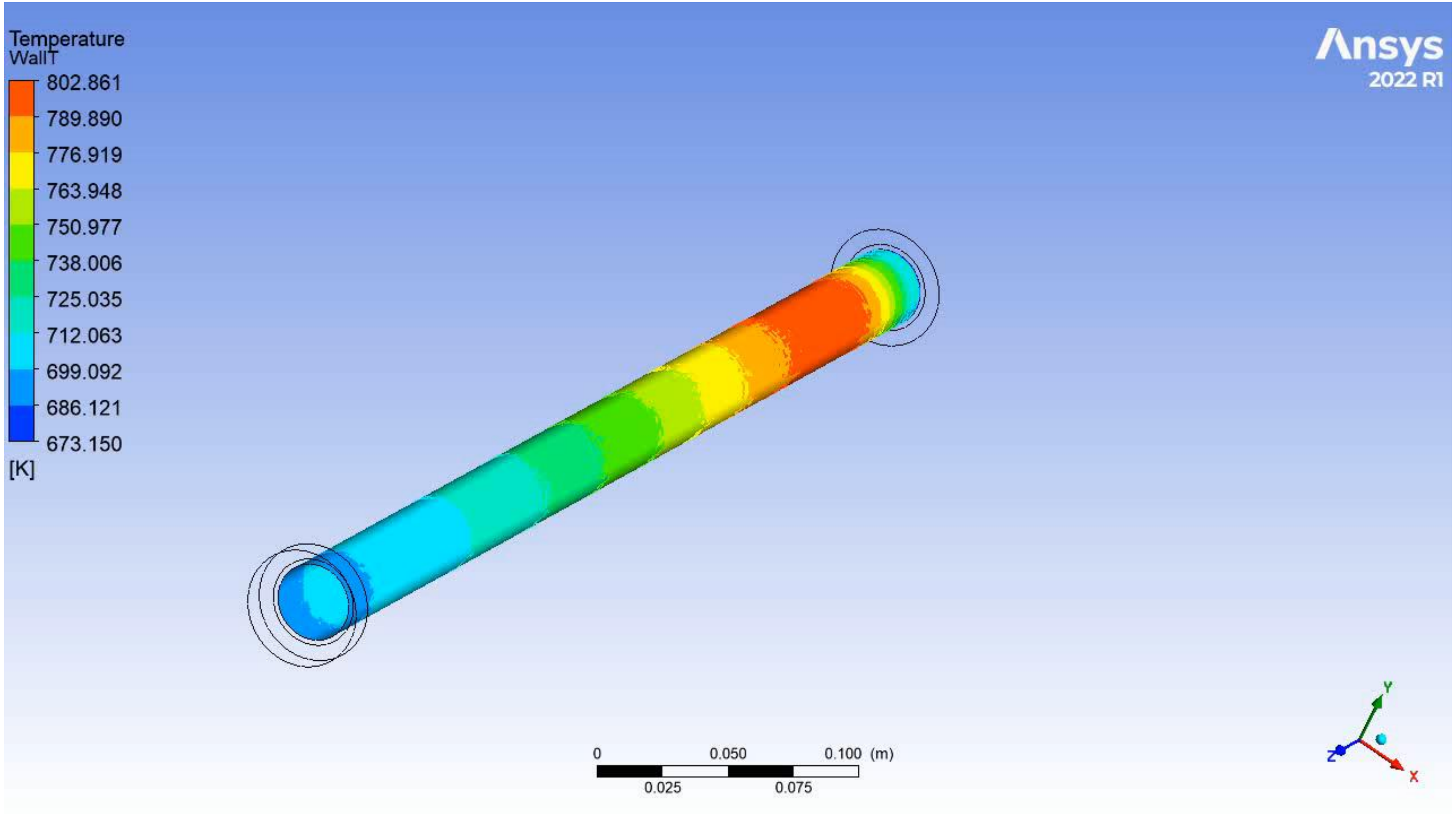
MuC target: wall temperatures

Adiabatic wall temperatures up to 650 °C (vessel), and 850 °C (beam window).





MuC target: wall temperatures



MuC target: Challenges

Thermo-mechanical:

- Vessel subjected to intense temperature gradient and values
- Regardless of flashing, likely pressure waves and vibrations due to quick lead thermal expansion.
- Beam window gets too hot for common vessel materials:
    - Beryllium?
    - Tungsten?
    - Interaction with Pb?

Integration:

- Limited space
- High radiation environment

MuC target: Next steps

Thermo-mechanical:
- Start analysing vessel behaviour
- Try material combination

CFD:
- Pressure wave analysis
- Lead flashing analysis

MHD:
- MHD losses evaluation →

Testing likely to be crucial in the development:
- Lead flashing effects on structures
- Material chemical compatibility

Magnetic Reynolds:

$$Re_m = \frac{\mu_0}{\sigma} uL = 0.0955 \ll 1$$

Where:

σ = electrical resistivity = (67.0 + 0.0471*T)*1e-8 [Ω m]
u = fluid velocity = 2.5 [m/s]
L = fluid typical length = 0.03 [m]

Estimated value of Re_m ensures there is no significant influence of fluid flow to the surrounding magnetic field

Conclusions

Liquid Heavy Metals have potentials to act as particle targets:

- Known and proven technology
- Low radiation damage
- Loops allow to decouple functions

Ongoing collaboration activities:

- BFD target
- MuC HLM target
- Early stages

Thank you!

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