Considerations on Muon Collider Targetry

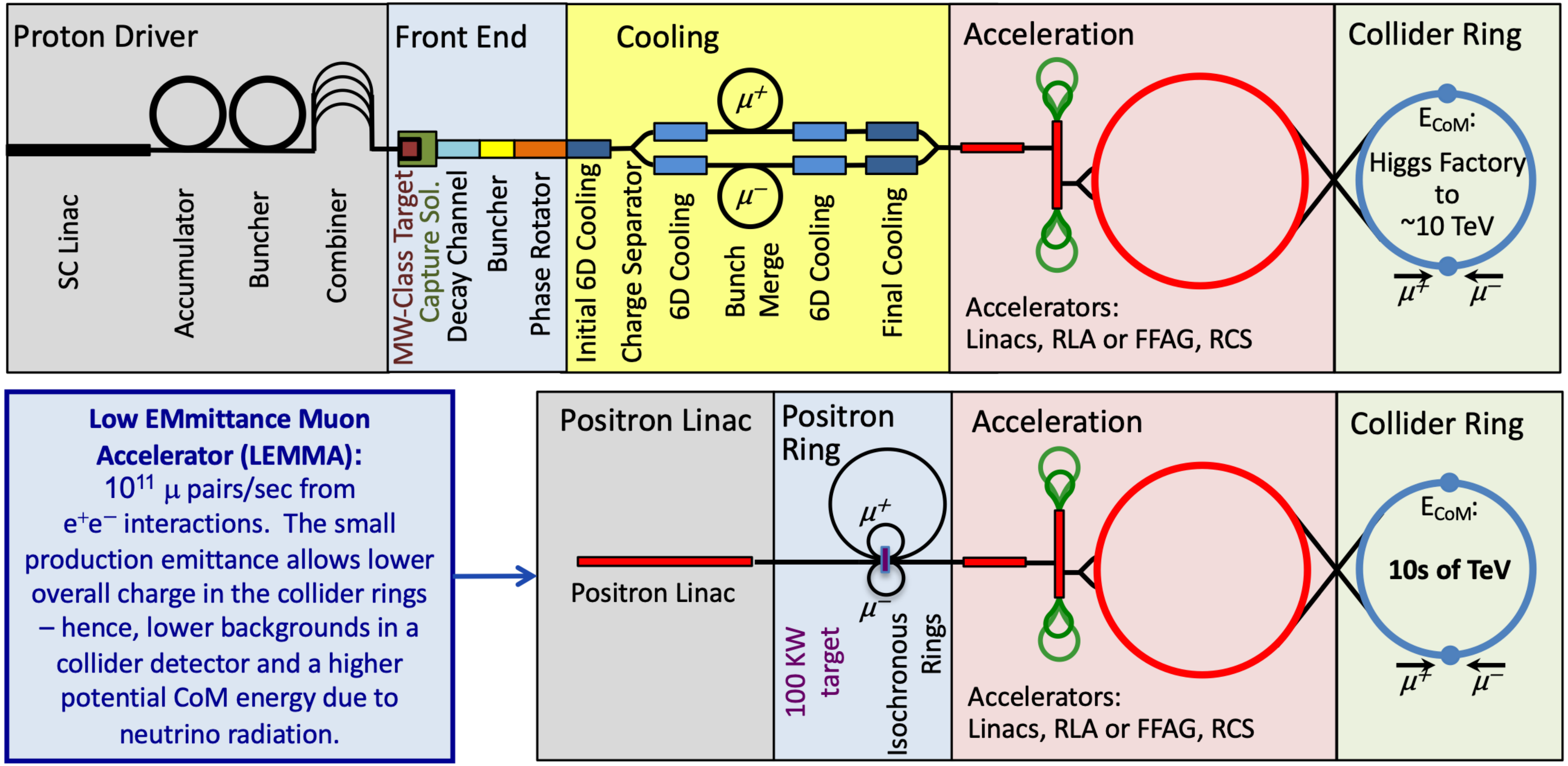
M. Calviani, I. Efthymiopoulos (CERN), C. Densham, T. Davenne, D. Wilcox, C. Rogers (RAL), K. Long (Imperial), M. Palmer (BNL), N. Pastrone, M. Bauce (INFN), R. Li Voti (INFN & Sapienza), G. Cesarini (Sapienza)

25th March 2021

Outline

- Introduction to Targetry Challenges for Muon Collider
- Target options and R&D prospects
- Prototyping and Beam Tests
- Muon Collider Test Facility considerations
- Conclusions

Targetry activities for Muon Collider



Low EMmittance Muon Accelerator (LEMMA):
10^{11} μ pairs/sec from e^+e^- interactions. The small production emittance allows lower overall charge in the collider rings – hence, lower backgrounds in a collider detector and a higher potential CoM energy due to neutrino radiation.

Targetry activities for Muon Collider

- **Expected challenges of Muon Collider Target Systems**
  - Proton on target delivery systems
  - Production target
  - Capture/focusing solenoid or horn/reflector system
  - Proton and secondary particle beam dump
  - Decay channel
  - Shielding system for neighbouring system
  - Target Complex and remote handling equipment
  - Radiation protection and environmental considerations
  - Radioactive waste

Targetry activities for Muon Collider
Assumptions & Requirements

- **Multi-MW pulsed proton beam (e.g., 1-4 MW, 5-10 GeV range)**
  - Must withstand the impact of intense proton focused beam
  - Energy deposition in the ballpark of **10-100 kJ/pulse**
  - Deposited target roughly between **15-30% of total beam power (300 kW for 1 MW beam)**
- **Target materials ranging from graphite to Hg/Ta, with different performances for the FE and later section – nuclear interaction length at around 2-3 λ**
- **Need to capture both signs of π/μ as input to FE channel → solenoid**
- **Proton beam dump essential – roughly 30-50% of impinging beam energy/power, plus capable of sustaining accident scenarios (full beam)**
- **Large fraction of (thermal) energy still deposited in the neighbouring equipment**
- **Reliability is a key factor & remote handling with handling area for maintenance and repair works**

Targetry activities for Muon Collider
Assumptions & Requirements

- **Target and dump robustness – minimum lifetime of the target could be an important design parameter**
  - e.g., max 1 exchange per year?
  - SNS neutron Hg targets (at 1.4 MW) are exchanged ±1-3 times per year
- **Lifetime of solenoids should be at least equivalent or larger**
- **Radiation load to neighbouring equipment**
  - Thermal energy deposited in shielding and solenoid/horns systems – SC quench – what are the limits that should be respected?
- **3D engineering design of Target Sytems with front-end essential to validate feasibility and costs**
- **Need to think about radioactive waste disposal**

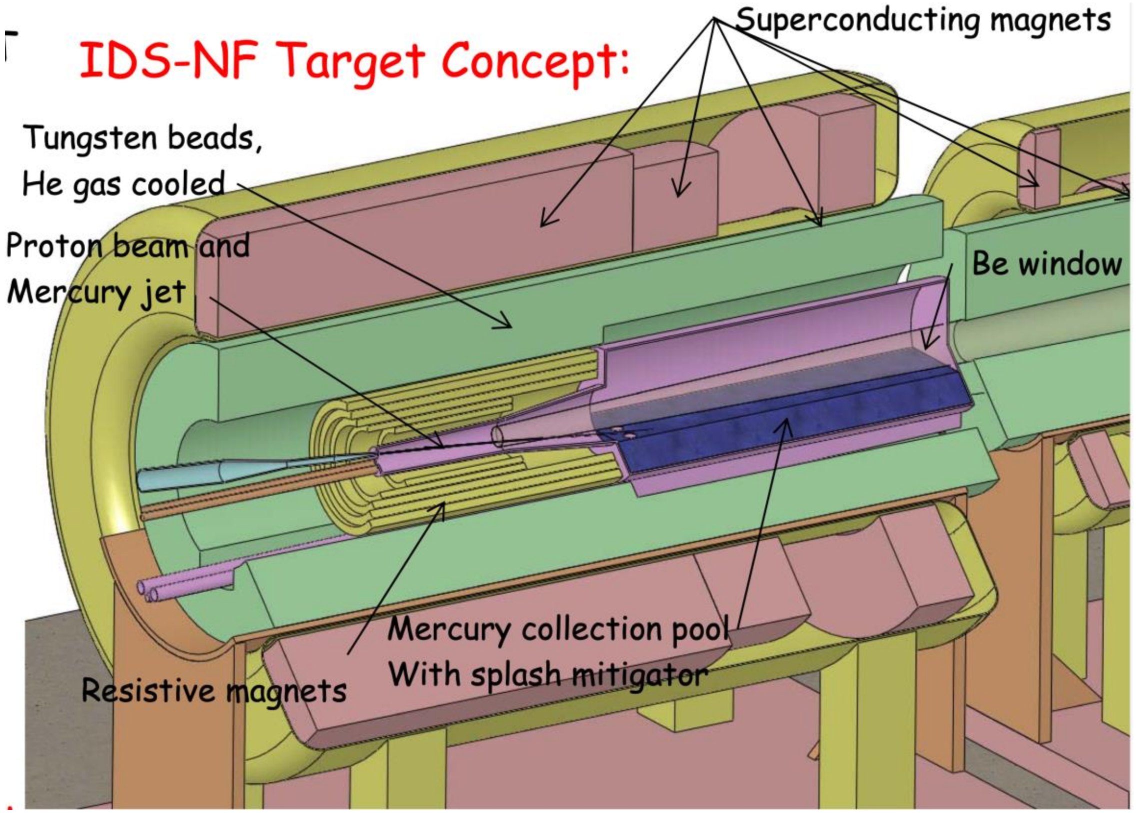
Considerations about Hg targets

- **Historically the baseline target for MUC Targetry, then later moved to carbon for the in the initial staging**

- **Clear advantages in terms of density, already liquid, radiation-damage prone, probably the only solution for 4 MW, etc.**
  - π^+/π^- ratio more convenient than low Z material

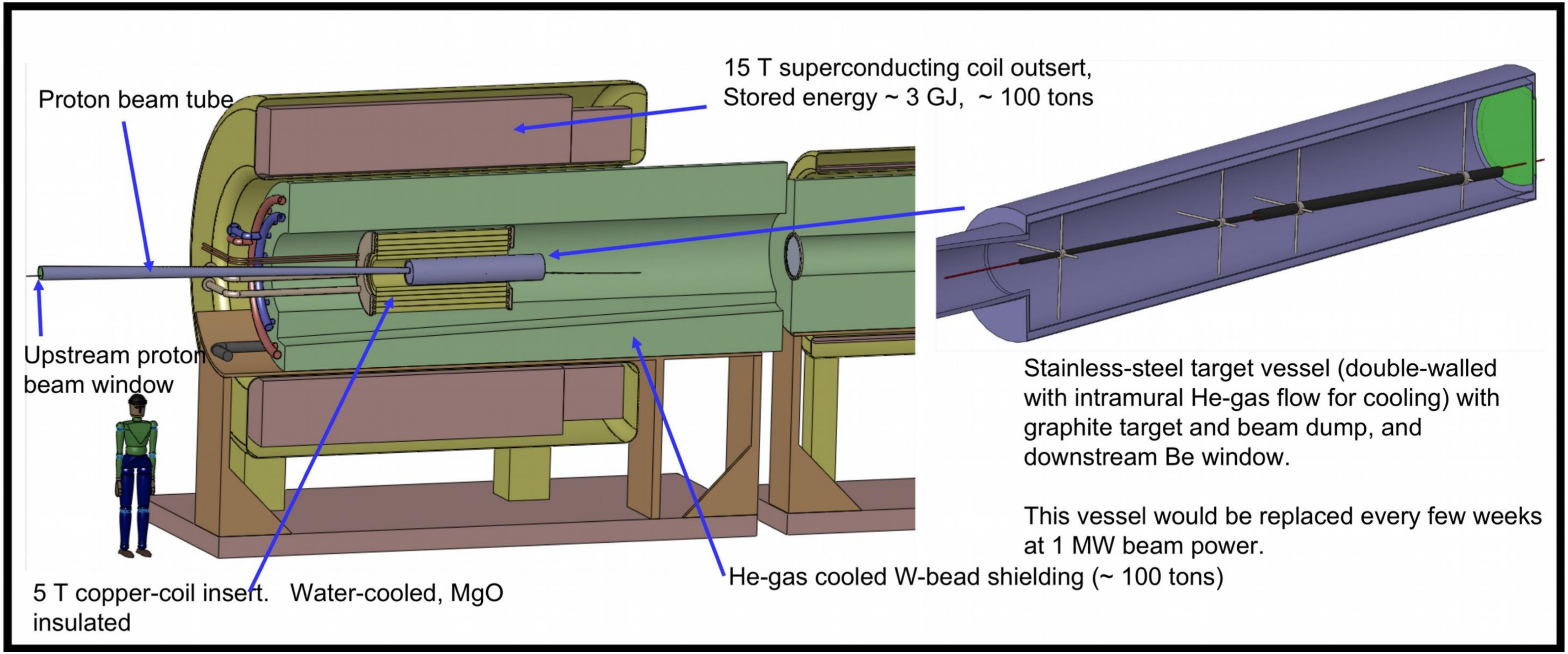
- **MERIT experiment proof-of-principle**

- **Could it be *realistically* considered as a solution for a MUC?**
  - Discussions during Muon Collider meeting 14th December 2020



KT McDonald, NuFact15

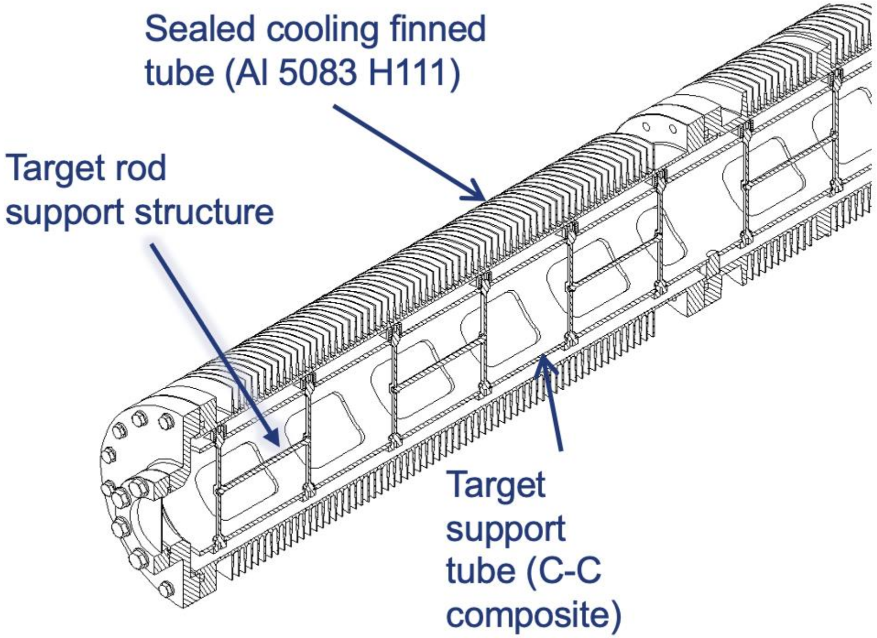
Solid (or semi-solid) target systems

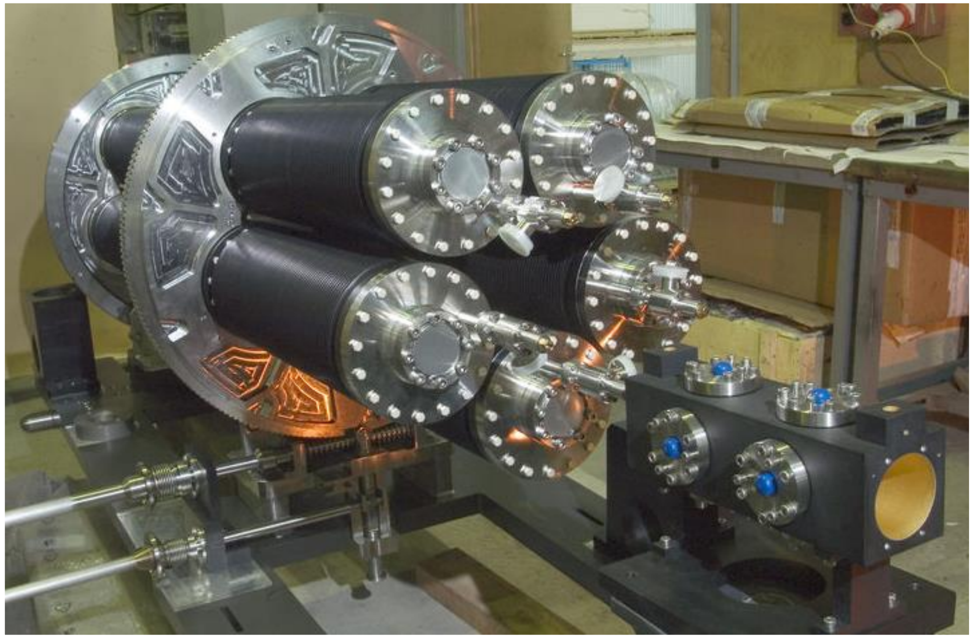


C. Rogers, STFC – from MAP studies & K.T. McDonald *et al.* IPAC2014-TUPRI008

Technological alternatives
Graphite target

- **CNGS target was operated up to 520 kW beam power**
  - But capable of accepting up to 750 kW on target
  - Radiative-cooled, graphite operating in vacuum (or He) at high temperature (±1500 C)
  - Operating at high T reduces issues of radiation damage thanks to annealing
  - 130 cm long (±3 λ)





Technological alternatives
Graphite target - Summary

- **With some careful design optimisation and R&D, the target could potentially withstand up to 1.5-1.7 MW beam power on target**

- **Graphite is largely employed in the HEP Community and extensively at CERN across the spectrum of energy density and power**
  - Synergies with use of 3D carbon-carbon material already employed at CERN in TCDIL collimators, significantly larger shock resistant and increase thermal conductivity

- **No macroscopic effect on muon fluence at the end of operation ($1.85*10^{20}$ POT) ±1.5 DPA – just at the lower threshold of MUC**
  - But what about long-term damage on graphitic material and Be windows?

Technological alternatives

Graphite target – Future proposal R&D

- **Synergistic approach with ongoing projects at CERN – including HL-LHC and FCC – characterisation of advanced materials for BIDs – from 1.1 to 1.8 g/cm^3**
  - Thermo-physical and mechanical properties from RT to HT (±2000 C)
  - Characterisation at high strain rate (±10$^{3\text{-}4}$ s^{-1})
  - Collaboration with external laboratories
- **Advanced FEA modelling and CFD for heat evacuation – measurement of HTC from target vessel to cooling medium**
- **Autopsy of CNGS target (profiting from possible AWAKE clean-up of TCC4 during LS3) in an external laboratory to extract and study the behaviour of carbon rods**
- **Long-term radiation damage of 3D CC with high energy proton beams**

3D CC tested at HiRadMat – employed in TCDIL collimators (F.X. Nuiry, SY-STI-TCD)

Technological alternatives
Packed-bed target design

Science & Technology Facilities Council

Packed Bed Target Design Concept
(for EURONu)

Tristan Davenne, Ottone Caretta, Peter Loveridge, Chris Densham (RAL);
Andrea Longhin, Marco Zito (CEA Saclay) ;
Benjamin Lepers, Christophe Bobeth, Marcos Dracos (Universite de Strasbourg)

4th High Power Targetry Workshop
May 2nd to May 6th 2011
Malmö, Sweden
Organized by the European Spallation Source, Lund

High Power Targets

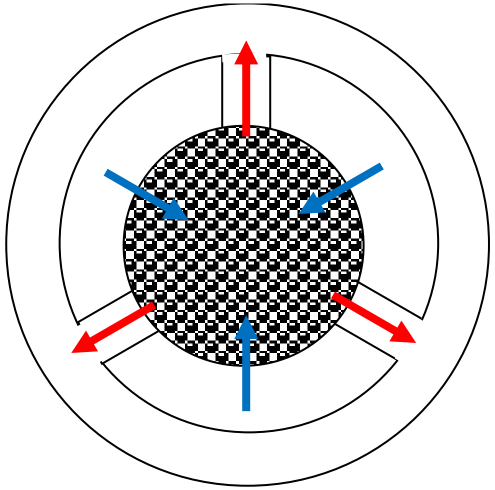
Science & Technology Facilities Council

Why consider a packed bed target?

- Large surface to volume ratio, large surface area for heat transfer
- Coolant can pass close to maximum energy deposition
- High heat transfer coefficients
- Low quasi static thermal stress
- Low inertial stress
- If stress levels in a simpler 'T2K style' solid target are unacceptable.

High Power Targets

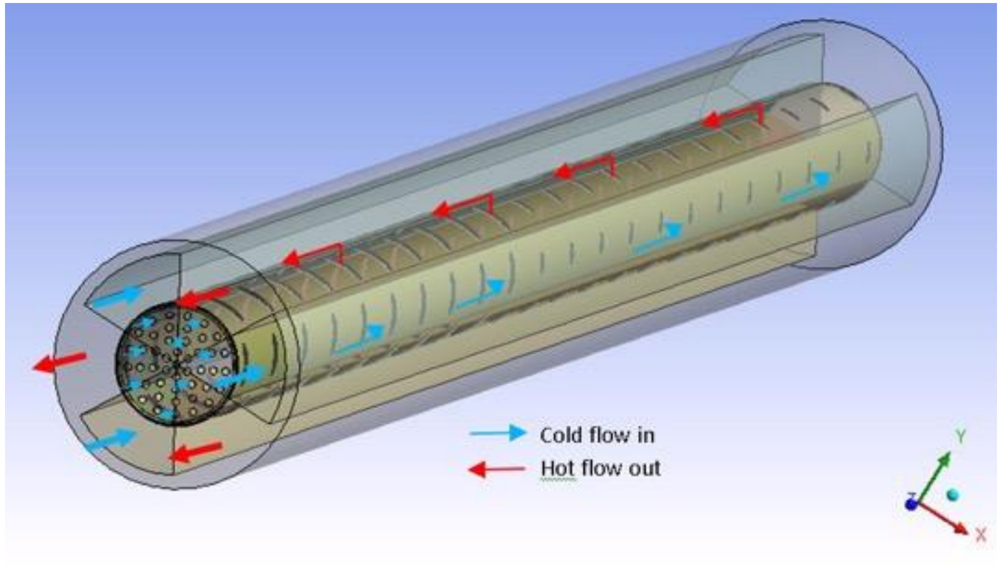
Technological alternatives
Packed-bed target design



- **Packed bed canister in symmetrical transverse flow configuration**
- **Titanium-alloy canister containing packed bed of Ti-alloy spheres**
- **Canister perforated with elliptical holes**

Packed Bed Targets have the following characteristics

- Large surface area for heat transfer
- Coolant able to access areas with highest energy deposition
- Inherently small thermal stress
- Minimal inertial stress if pulse length>oscillation time (stress waves due to rapid heating + off axis beam induced oscillations)
- High heat dissipation capability
- Pressurised cooling gas required at high power levels to keep pressure drop down
- Significant gas compressors or blowers required
- Bulk density lower than solid density, use of different materials to recover density can be a solution
- Radiation damage of windows and containment an issue



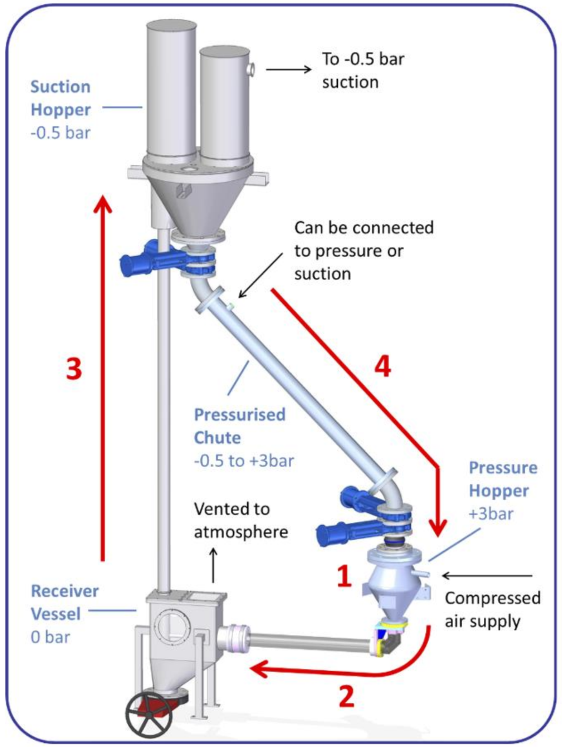
Technological alternatives
Packed-bed target design – R&D

- **Induction heating tests to measure heat transfer efficiency from packed bed**
  - Packed bed placed in an alternating magnetic field.
  - Eddy currents induced in conductive spheres.
  - Resultant Joule heating provides internal heating of spheres
- **Test of Pressure drop of a packed bed design**
- **Proton beam test at HiRadMat or similar facility**

Technological alternatives
Fluidised W powder

Fluidised Tungsten Powder Studies

- Test rig built and operated at Rutherford Appleton Laboratory from 2009-2018
- Demonstrated key powder handling processes:
  - Suction lift of powder (lean phase fluidisation)
  - Pneumatic conveying of dense phase powder (~50% volume fraction)
  - Ejection of powder as a dense fluidised jet (~40% volume fraction)
  - Continuous recirculation of powder, allowing for an uninterrupted stream of target material



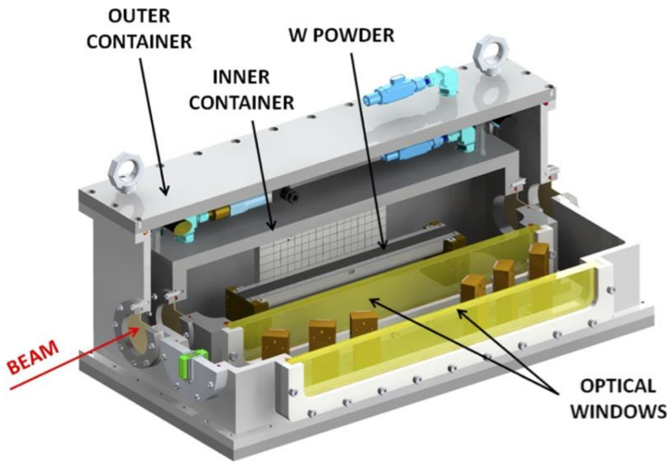
Key components of RAL fluidised powder rig

[1] O. Caretta, C. J. Densham, T. W. Davies and R. Woods, "Preliminary Experiments on a Fluidised Powder Target," in Proceedings of EPAC08, WEPP161, Genoa, Italy, 2008.
[2] C. J. Densham, O. Caretta and P. Loveridge, "The potential of fluidised powder target technology in high power accelerator facilities," in Proceedings of PAC09, WE1GRC04, Vancouver, BC, Canada, 2009.
[3] T. Davies, O. Caretta, C. Densham and R. Woods, "The production and anatomy of a tungsten powder jet," *Powder Technology*, vol. 201, no. 3, pp. 296-300, 2010.

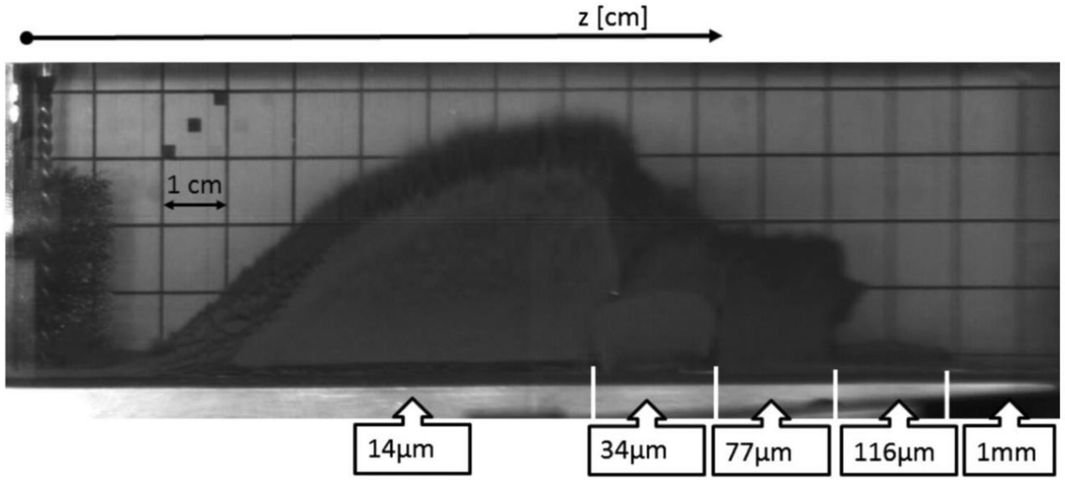
Technological alternatives
Fluidised W powder

Fluidised Tungsten Powder Studies

- Two in-beam experiments carried out at CERN's HiRadMat facility
  - Beam induced lifting of the powder was observed
  - Eruption velocities much lower than for liquid mercury at the same energy density



HiRadMat Experiment Container



Response of various size spherical tungsten particles to 2E11 protons

[1] O. Caretta, T. Davenne et al., "Response of a tungsten powder target to an incident high energy proton beam," Physical review special topics - accelerators and beams, vol. 17, no. 10, DOI: 10.1103/PhysRevSTAB.17.101005, 2014.
[2] O.Caretta, P.Loveridge et al., "Proton beam induced dynamics of tungsten granules," Physical Review Accelerators and Beams, vol. 21, no. 3, DOI: 10.1103/PhysRevAccelBeams.21.033401, 2018.
[3] T. Davenne, P. Loveridge et al., "Observed proton beam induced disruption of a tungsten powder sample at CERN," Physical Review Accelerators and Beams, vol. 21, no. 7, DOI: 10.1103/PhysRevAccelBeams.21.073002, 2018.

Technological alternatives
Fluidised W powder

Fluidised Tungsten Powder – Summary

- Advantages:
  - Can withstand extremely high energy density
  - Fluidised powder handling technology is well-established in industry
  - Lower eruption velocity than liquid mercury, and no cavitation damage
- Challenges:
  - More R+D required to mitigate erosion of containment during long term operation
  - Tungsten is much more dense than materials handled in industry; existing flow equations and plant designs may need to be modified
  - Diagnostics and process control must be developed to ensure reliable long-term operation
- These challenges can be addressed with cost effective off-line testing

Technological alternatives
Fluidised W powder

Fluidised Tungsten Powder – Future R+D

- Measurement of erosion rates, and development of improved components to mitigate erosion risk
- Development of powder circuit design to minimise or eliminate the need to have moving parts such as slide valves in contact with the powder
- Measurement of heat transfer to and from flowing tungsten powder
- Development of improved diagnostics for automated operation and fault detection
- Investigate the use of spherical powder to improve flow characteristics

Technological alternatives
Pb-Bi eutectic or La-based liquid targets

- **Pb-Bi target eutectic (LBE) could be a potential alternative to Hg liquid targets**
  - Operational temperature 600 C – but also challenging operation (e.g. MEGAPIE@PSI experience)
- **Developed for several applications around the world and more recently at CERN for the ISOLDE facility (LIEBE Project)**

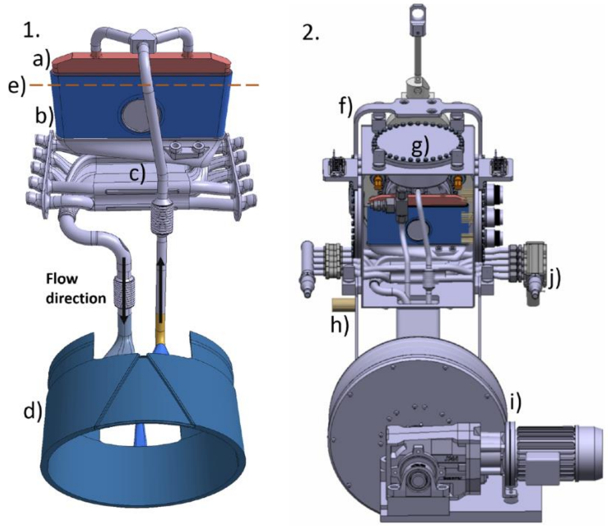
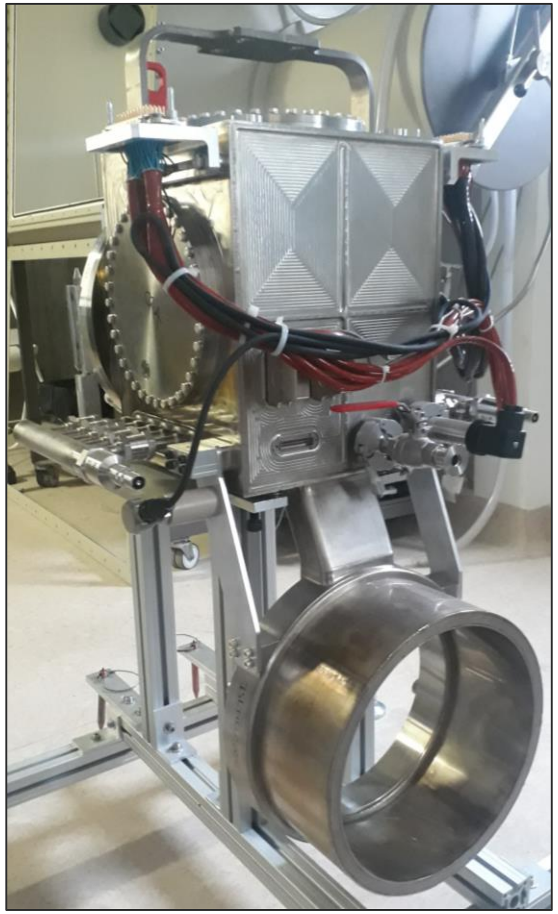


Fig. 1. Schematic of the LIEBE prototype. 1. Liquid metal loop: a) irradiation chamber, b) diffusion chamber, c) heat exchanger (HEX), d) EM pump channel, e) proton beam path. 2. Second envelope f) robot handle, g) LBE tank, h) accelerometer, i) EM pump, j) water electrovalves.



T. Stora et al., SY-STI-RBS

Technological alternatives
Pb-Bi eutectic or La-based liquid targets

- **Synergistic with community of radioactive beam physics (e.g. ISOLDE, ISOL@MYRRHA) - there might be the potential to explore lanthanum eutectics (lower melting T) to be considered for operation in a LIEBE loop**
- **R&D would be required to validate LIEBE++ with beam**
- **R&D on thermo-physical properties of the eutectic plus reliability of the mechanical systems over long-term operation**

T. Stora, F. Boix-Pamies https://doi.org/10.1016/j.nimb.2019.06.043

Proton beam dump considerations

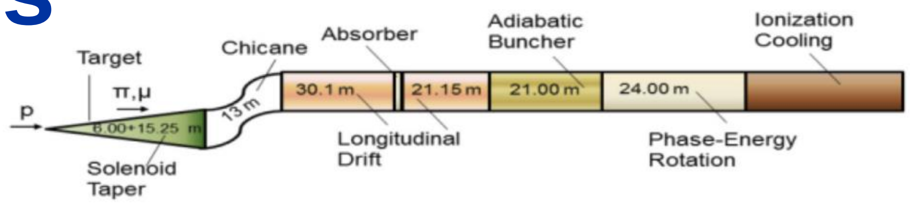
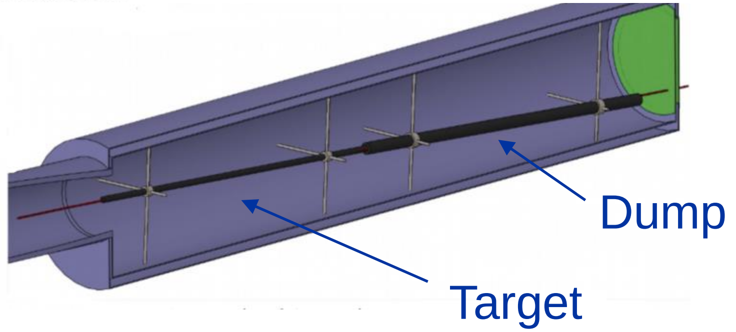


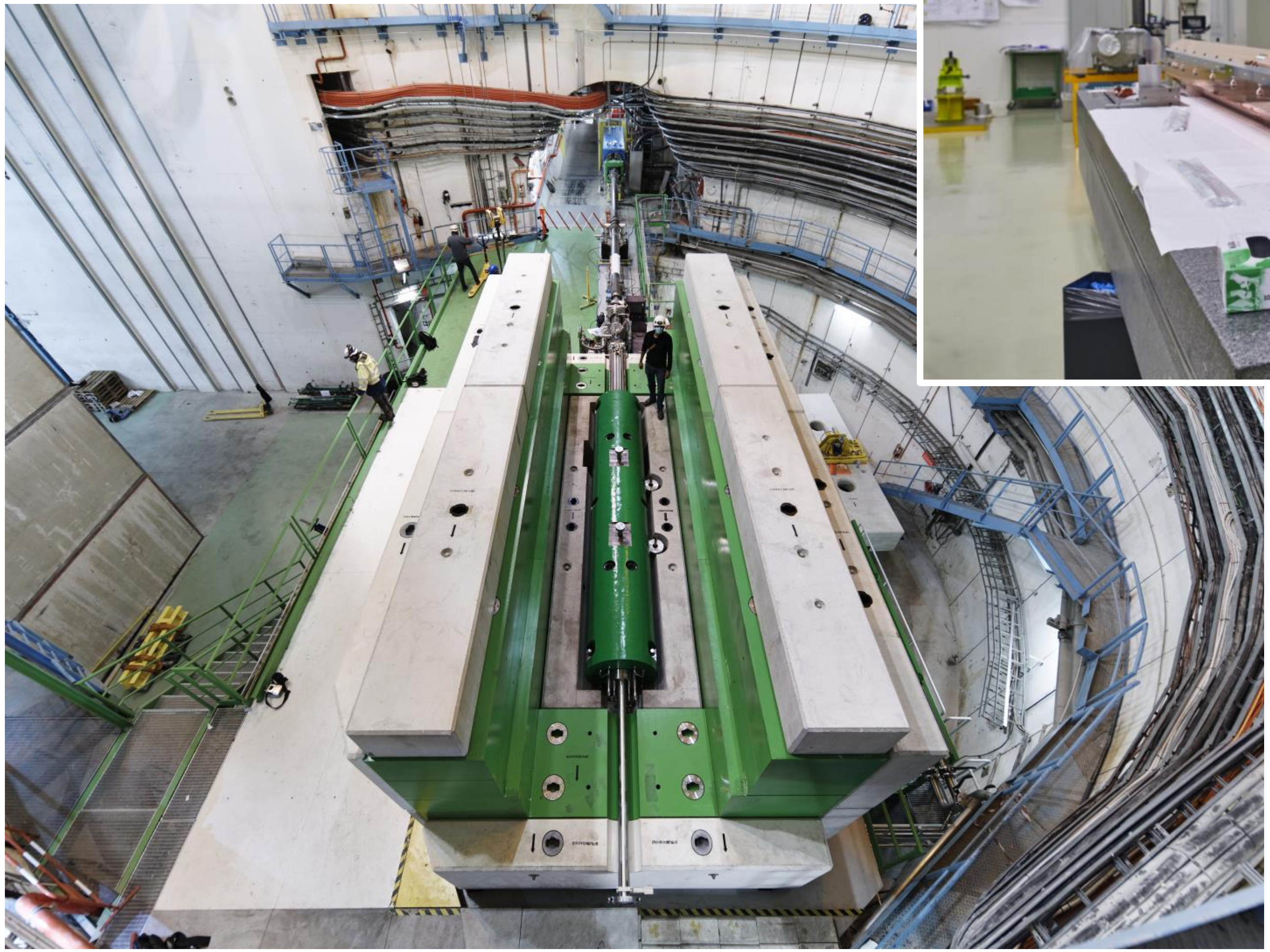
Figure 4. Layout of the Front End with a chicane and absorber.



- **Location of proton beam dump will determine its size and constraints (shielding, accessibility, handling, cooling ancillaries)**
- **Can we really build a dump inside the solenoid and/or chicane prior to the FE ? Feasibility?**

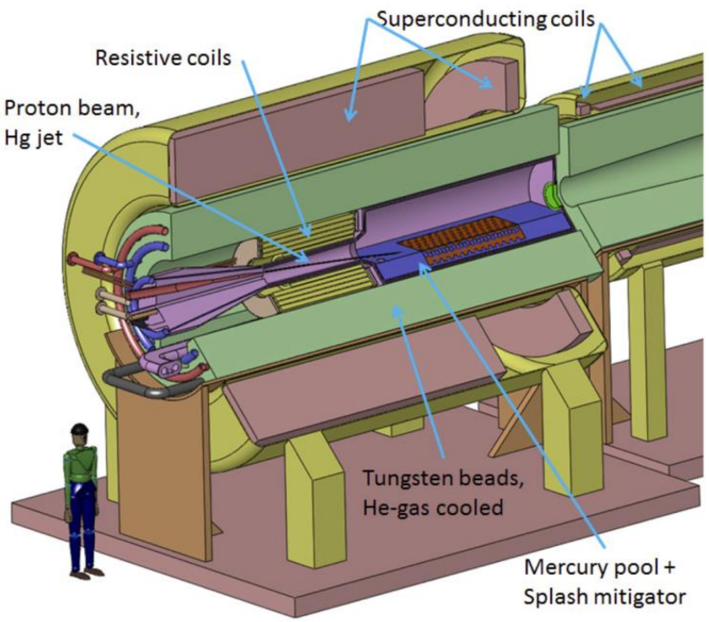
- **Proton dump will absorb up to 50% of the primary beam power - significant requirements of cooling as well as production of stray radiation**
- **Must be easily accessible due to requirement to access it**

Interlude - 300 kW beam dump for 450 GeV/c beam



Solenoidal magnet

- **A big challenge, for many aspects one of the least developed so far**
- **±20 T magnet, plus tapering down to 1.5 T**
- **Significant radiation heat load**
  - Shielded with high Z material: e.g., cooled W beads
  - **Quench limits (steady state losses)** will dictate requirements → need updated Monte Carlo estimates



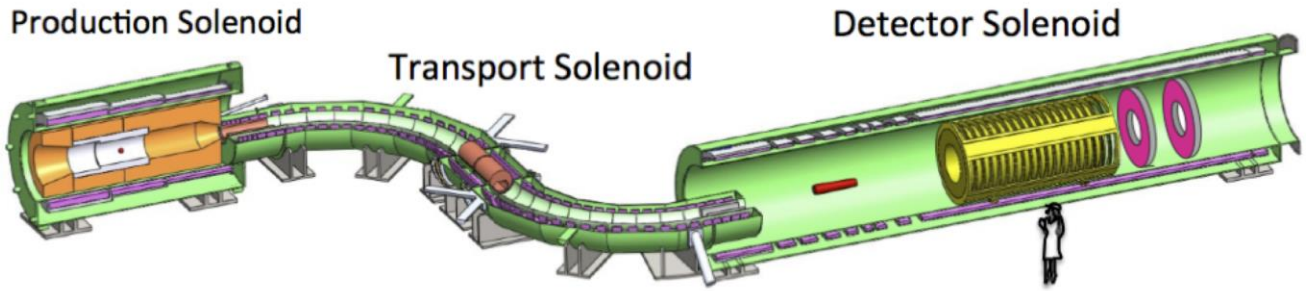
- **Optimized shape will also depend on the final target configuration**
- **R&D urgent and fundamental for this system, probably including prototyping and heat load testing in collaboration with magnet experts**

Solenoidal magnet
What can we learn from planned facilities?

- **What can we learn from facilities under construction and/or considerations?**

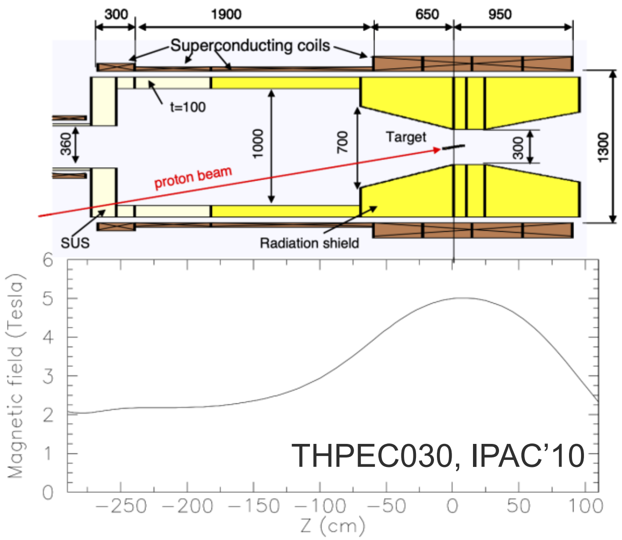
- **Mu2e experiment at FNAL**
  - Production Solenoid (PS, ±5 T) and Heat & Radiation Shielding (HRS) (3 orders of magnitude reduction)
  - 8 kW, 8 GeV p beam

- **COMET experiment at J-PARC**
  - Similar requirements to Mu2e



FERMILAB-CONF-11-255-TD

Parameter	Unit	Value
Peak absorbed dose	kGy/yr	270
Peak lifetime absorbed dose	MGy	5.4
Peak power density	μW/g	13
Total CM dynamic heat load	W	53
Peak DPA	1/yr	$2.9 \cdot 10^{-5}$



THPEC030, IPAC'10

Solenoidal magnet
What can we learn?

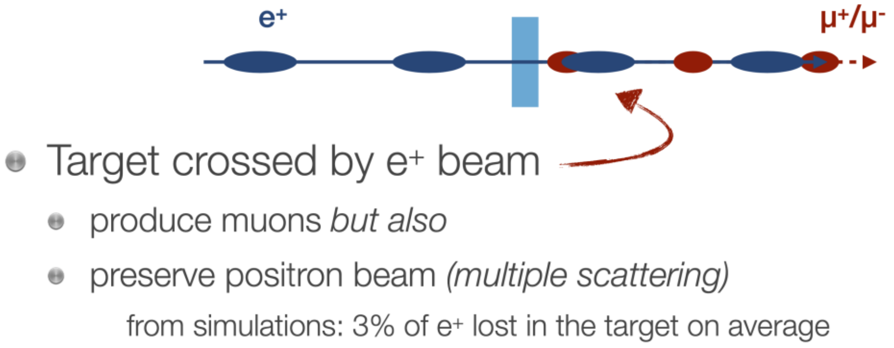
- **±1 MW vs. 8 kW**
  - Assuming same requirements in the SC solenoid in terms of peak power density, shielding shall be improved by **further 2 orders of magnitude**
  - Both in terms of **heat load** but also for **neutral and charged particle damage** (e.g., electrical resistivity degradation in the superconducting coils)
  - **Peak lifetime dose could reach ±500 MGy**
- **Critical R&D is required on this component – synergies with future projects, such as FCChh or… ?**
- **Prototyping and experimental testing**

LEMMA scheme

- **Positron driven muon source for a muon collider (1905.05747)**
- **Targets made out of C and Be (Li proposed as well)**
- **Options to be further investigated, probably tested – synergies with existing programs at CERN possible**
- **R&D required!**

LEMMA scheme

- **O(100 kW) to be deposited in very thin (0.3 X_0) targets**
  - C, Li or Be
  - Minimize beam emittance and e^+ losses
  - Maximize $\mu^+\mu^-$ production rate
  - Studies on multiple "serial" targets



- **R&D required on target performances**
  - Plan to execute experimental tests with laser
  - As well as with electron beams (@MAMI)

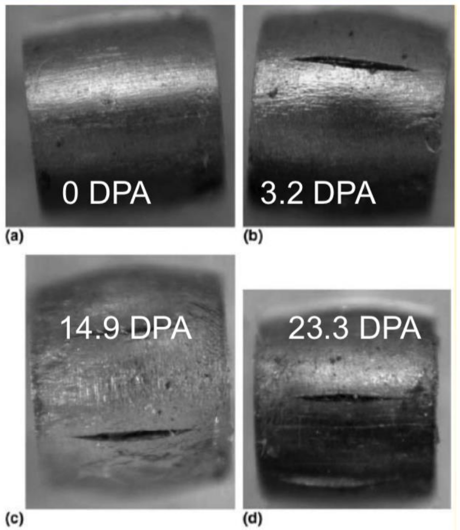
Targetry material R&D
Long term radiation damage

- **Recent major accelerator facilities have been limited in beam power & operation time by BIDs survivability**

- **To maximize the benefit of high-power/intensity machines, these challenges must be addressed in time**
  - Provide critical input to design, construction and operation
  - E.g. LBNF, J-PARC/T2K/T2HK, MLF-2nd TS, HL-LHC, FCC, BDF, ESS etc....

Radiation Damage Effects

- **Displacements in crystal lattice, expressed as Displacements Per Atom (DPA)**
  - Embrittlement / Creep / Swelling
  - Fracture toughness reduction
  - Thermal/electrical conductivity reduction
  - Change of thermal expansion coefficient / modulus of elasticity
  - Fatigue response
  - Accelerated corrosion
  - Void formation/ embrittlement caused by Hydrogen/Helium gas production (expressed as atomic parts per million per DPA, appm/DPA)
- **Recent high-intensity proton target facilities meet irradiation with a few to several DPA**
  - Effects from low energy neutron irradiations (as fusion/fission reactor materials) do not equal effects from high energy proton irradiations



Tungsten, 800MeV proton irradiation at LANSE

after compression to ~20% strain at room temperature

S. A. Maloy, et al., Journal of Nuclear Materials 343 (2005) 219-226.

T.Ishida WG1 NuFact2018, Blacksburg, Virginia, USA, August 13, 2018 5

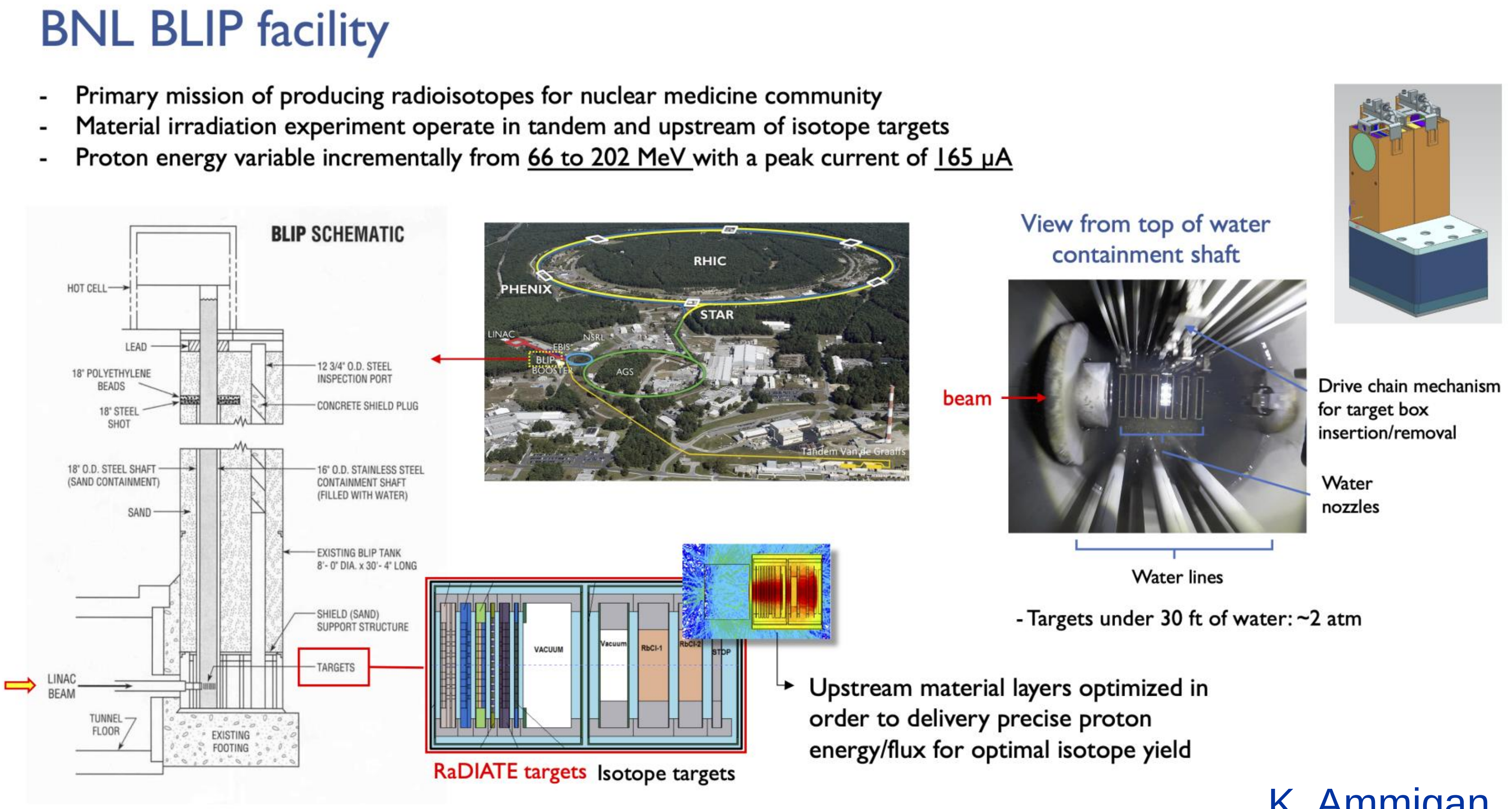
Targetry material R&D

Long term radiation damage – RaDIATE

- **Objective**
  - Harness existing expertise in nuclear materials and accelerator targets
  - Generate new and useful materials data for application within the accelerator and fission/fusion communities
- **Activities include:**
  - **PIE of materials taken from existing beamline** as well as **new irradiations** of candidate target materials at low energy and high energy beam facilities
  - **Thermal shock experiments** at HiRadMat

Targetry material R&D

BNL BLIP



- 0.1 DPA (C) for ±2 months irradiation
- ±2-5 DPA for high Z materials

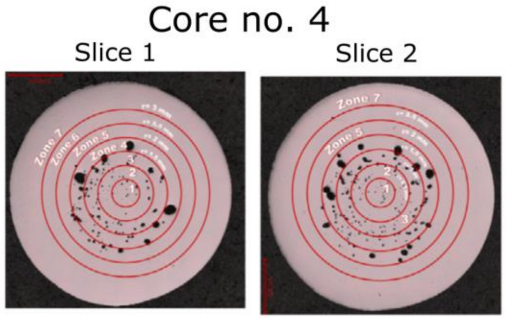
K. Ammigan, FNAL

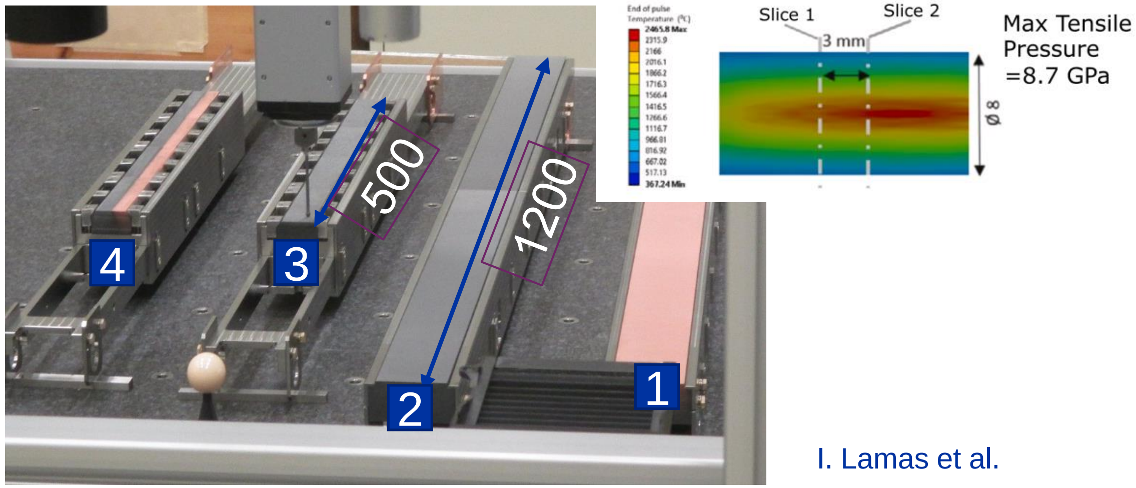
Charged particle beam testing

- **[HiRadMat facility](#) at CERN extensively employed in the last few years for multiple single shot testing for beam intercepting devices**
  - Could be of use for analysing specific items of Muon Collider systems (e.g., prototype target technology, material subjected to high dynamic load)
  - ±1-2*10^{15} POT/experiment, 440 GeV/c, up to 3.5*10^{13} ppp

https://doi.org/10.1016/j.euromechsol.2020.104149

C. Torregrosa et al.

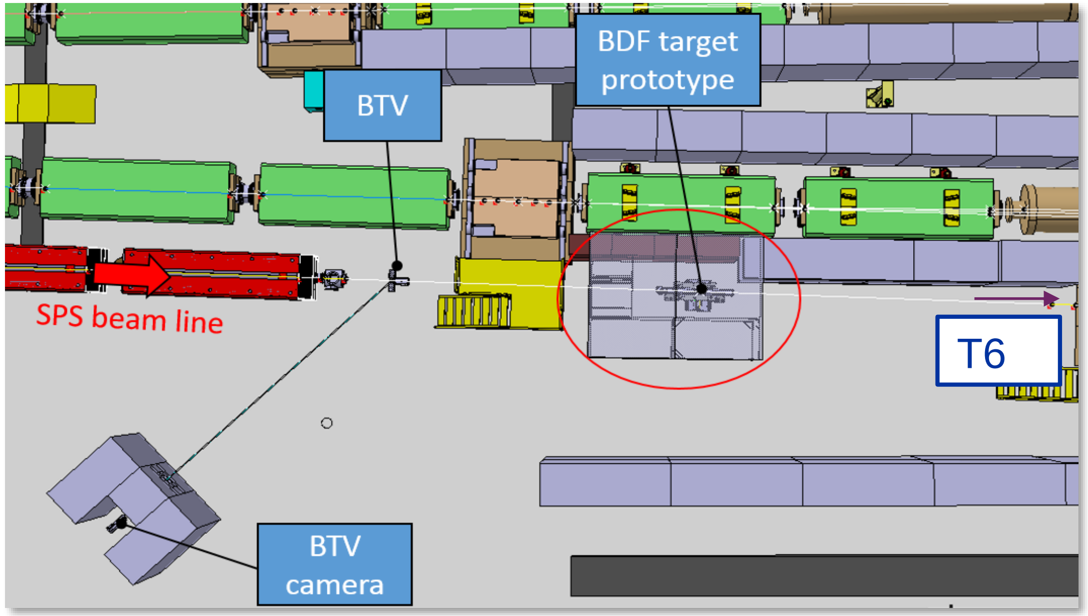


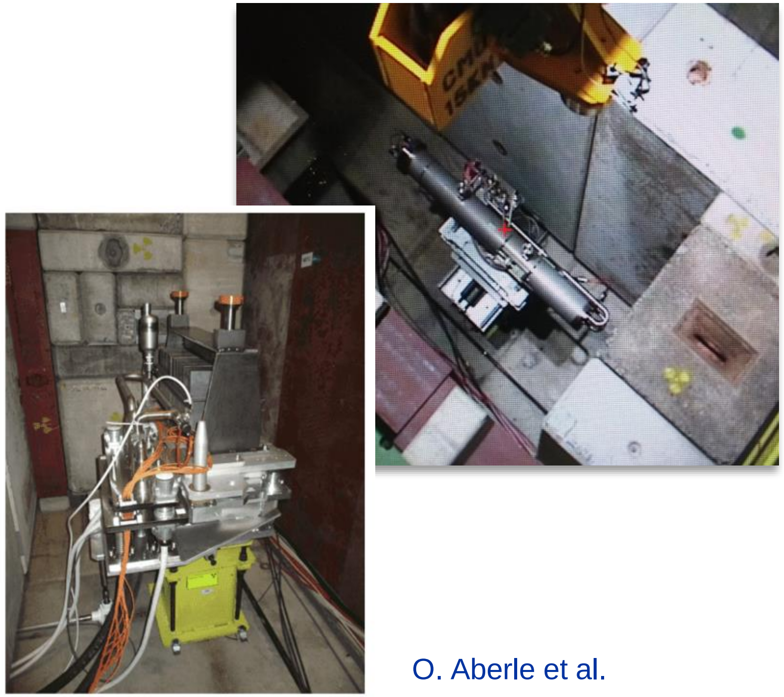


I. Lamas et al.

Charged particle beam testing

- **In the framework of the Beam Dump Facility Study, a high intensity slow extraction test area was setup in the TCC2 Target Area at CERN**
  - ±400 GeV/c, up to several 10^{13} p/pulse, >10^{16} POT possible (competition with beam to T6 though)
- **Could be potential employed to validate certain aspects of MUC Targetry systems**
  - E.g. target & solenoid for example





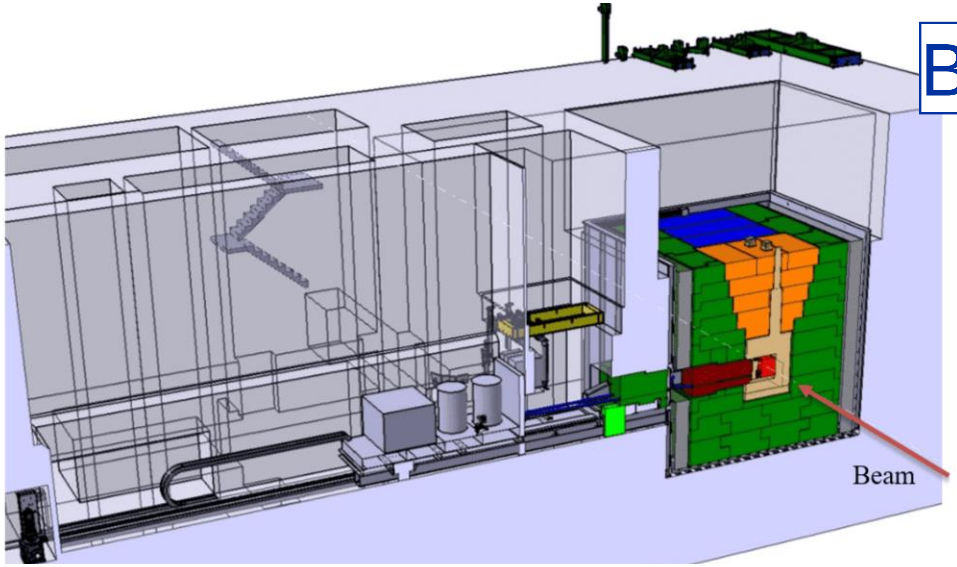
O. Aberle et al.

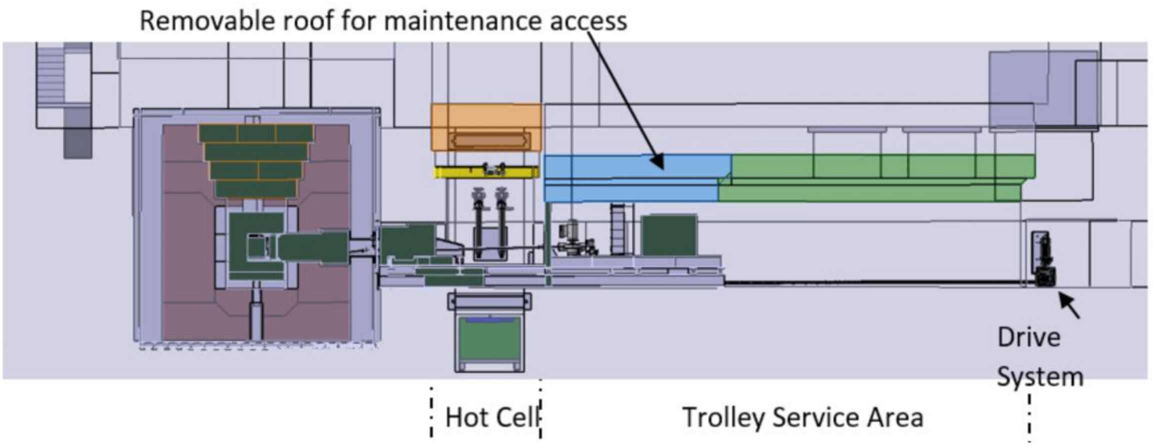
MUC Target Complex considerations

- **Facility will need to comply with very stringent radiation and environmental protection considerations**
  - Not only neutrino radiation, but neutron stray radiation, air activation at site boundary will be critical
  - Installation in the molasse (bedrock, as CNGS) will simplify many radiation protection constraints
- **Reminder: likely ±Sv/h dose rate on large volume components close to production target system/dump**
  - Fully remote handling of components is mandatory, no hands-on intervention
  - Should favour vertical handling (over side access, compliant with ITER remote handling code of practice)
  - Radioactive waste consideration (reuse as much as possible existing material, maximize reliability, etc.)
- **Optimisation of ancillary services (cooling and ventilation, electrical, etc.) shall be though from the beginning**
- **All points relevant and applicable to provide feasibility and a realistic cost estimate ballpark as part of the conceptual design**

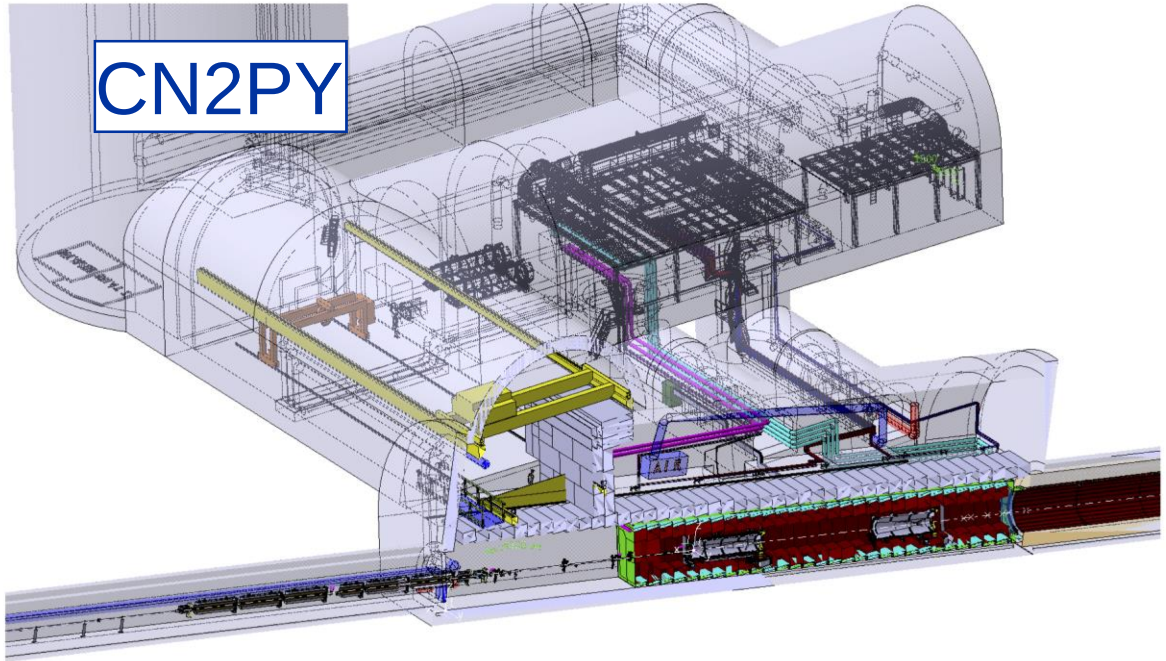
MUC Target Complex considerations

BDF

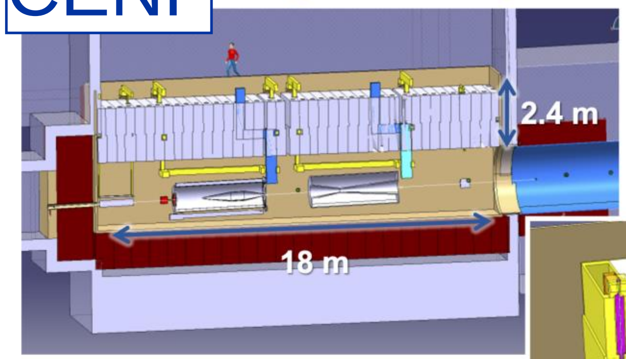




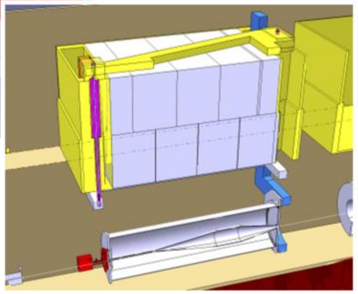
CN2PY



CENF



Integration of target trench, 3x3 m², matching DP diameters



Preliminary design of the support module, pure vertical movements

Integral testing in a "MUC demonstrator" facility

- **Integral beam test of the MUC Target Systems in a demonstrator will be fundamental to assess the performances and reliability of the different components**
  - … including connection with the downstream front-end
  - Final objective of muon cooling demonstration
- **Realistically one could think of a facility ±100 kW (1/10 of nominal beam power) but with similar pulse intensity (equivalent energy density)**
  - Could be reusing existing infrastructure and beams or thinking about a green field scenario
  - Synergies with physics facilities?

Conclusions

- **MUC Targetry is one of the most challenging systems currently being explored (in both p^+ and electron driven schemes)**
  - Could be one of the bottleneck of the MUC if not validated
  - Some of the items have never been explored in depth
- **A rich R&D program is in preparation, including off-line and beam tests of components – need to be careful on resource availability**
- **Medium/long term plan to build an integral test facility / demonstrator would be fundamental to validate the key performance factor of the Targetry Systems**

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