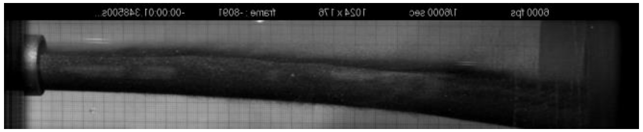
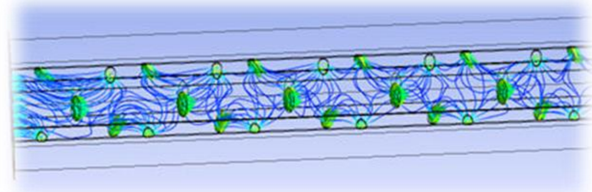
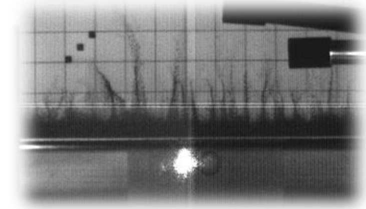
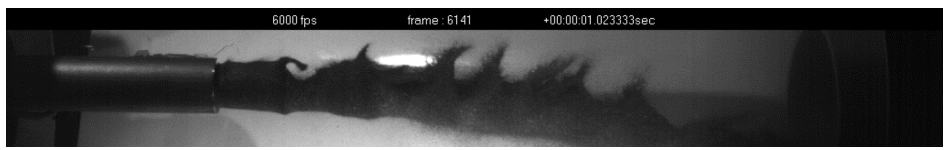






Muon Collider target: Visions and Opportunities



Chris Densham

STFC Rutherford Appleton Laboratory, UK

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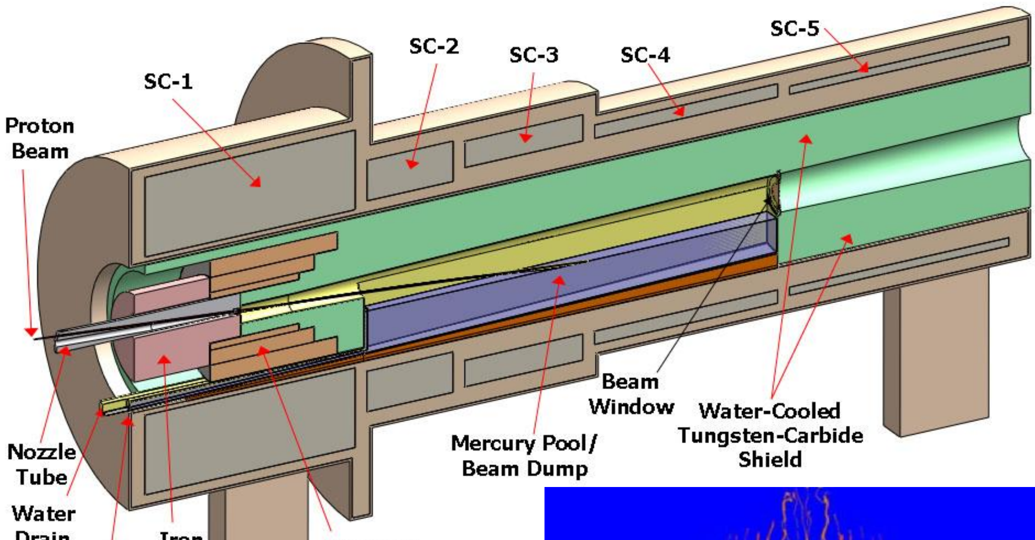
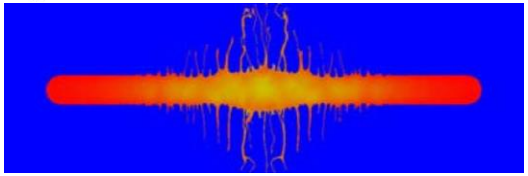
Muon Collider baseline: free mercury jet

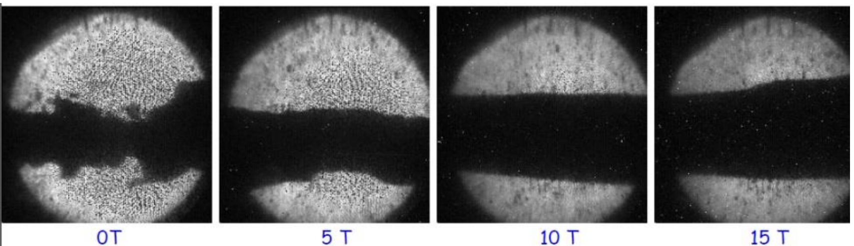


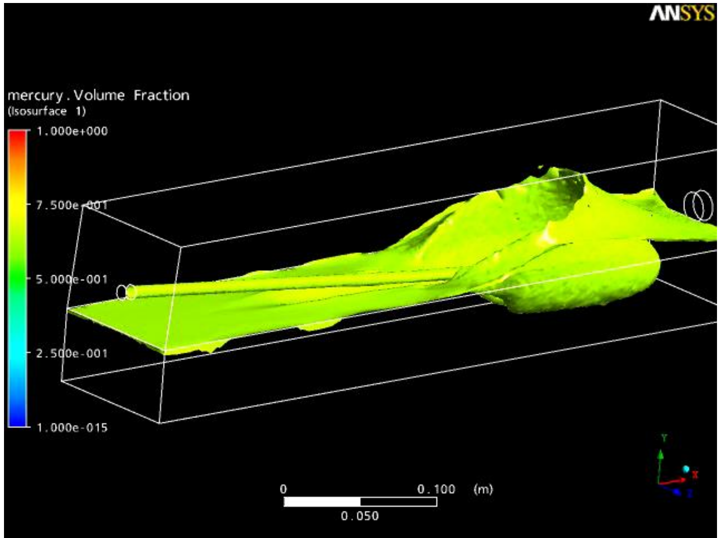
- Baseline liquid mercury target configuration for a Neutrino Factory / Muon Collider
- 20T solenoid captures both signs of pions generated by interaction of proton beam with mercury jet
- Many severe challenges remain, e.g. solenoid, mercury dump, cavitation, radiochemistry, safety, etc



Magnetohydrodynamic simulation of pulsed beam interaction with mercury jet

MERIT mercury jet experiment at CERN demonstrated suppression of filamentation by solenoidal magnetic field





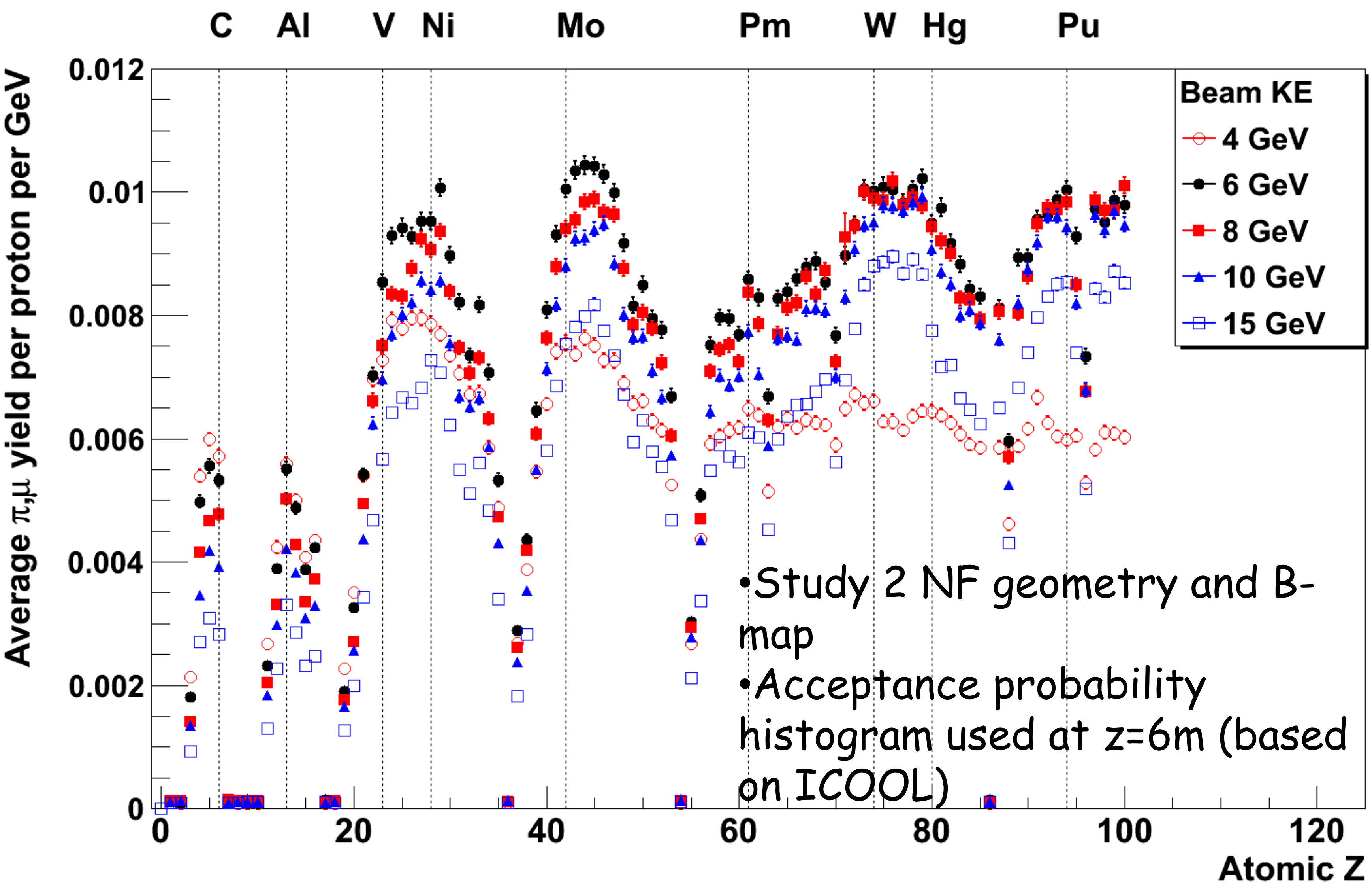
A few notes for Muon Collider Targets

c/o Bob Zwaska talk yesterday at the US Muon Collider Forum

- Most comparable configuration is Mu2e – challenging at 8 kW @ 8 GeV.
  - Extrapolation to Mu2e-II (100 kW @ 1 GeV) has no present solution
  - Cannot Extrapolate to historical Muon Collider (4 MW @ few GeV)
- Higher proton beam energy is better for the target (less power deposited in target for the same beam power)
- Separating target from optics is very beneficial
  - Has the capacity to allow rotation and more robust support systems
  - Can more forward production from higher-energy protons be used?
- Muon collider requirements on precision may be less strict
- Machine Protection is vitally important at high power. Targets and facilities must have this built in from the beginning.
- Attempt to avoid liquid targets. Enormous investment and R&D, many risks. SNS, ESS, J-PARC have all decided against liquid targets for new target stations

Pion/muon yields for different target Z's and beam energies (J.Back)

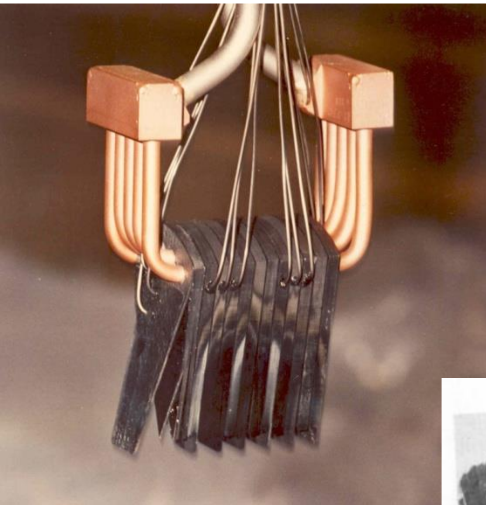
Low Z target is a candidate – reported at end of MAP study



- Study 2 NF geometry and B-map
- Acceptance probability histogram used at z=6m (based on ICOOL)

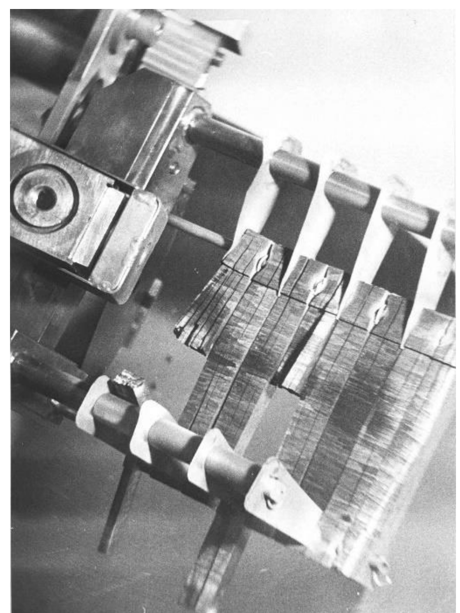
Water cooled graphite targets

The ultimate destiny for all graphite targets:



LAMPF
fluence
10^22
p/cm2

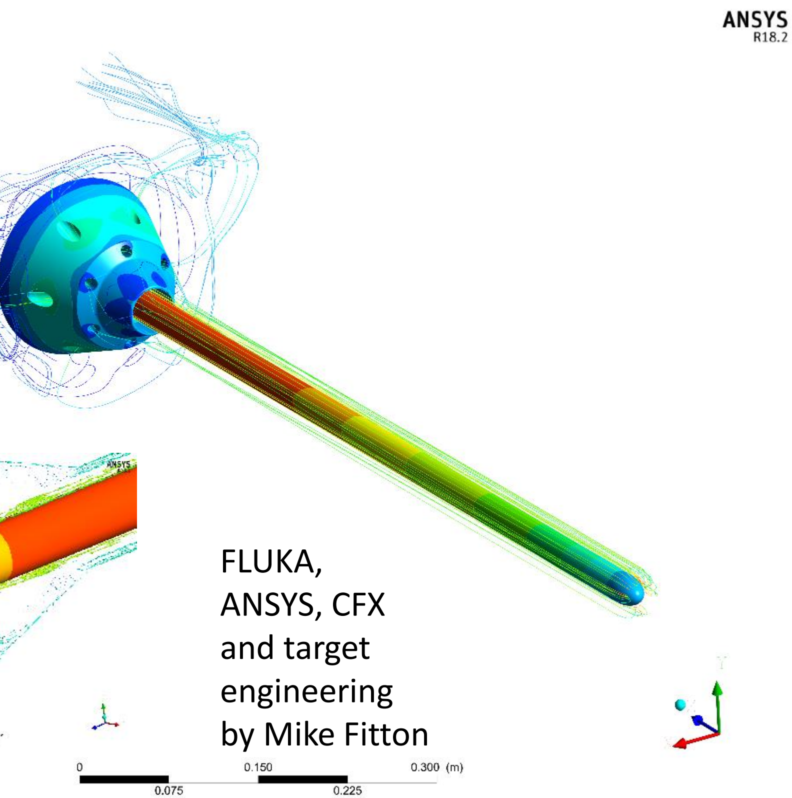
PSI fluence
10^22 p/cm2



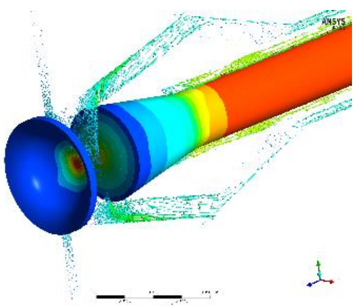
NuMI-MINOS
10^22 p/cm2

T2K graphite target – 10 years experience

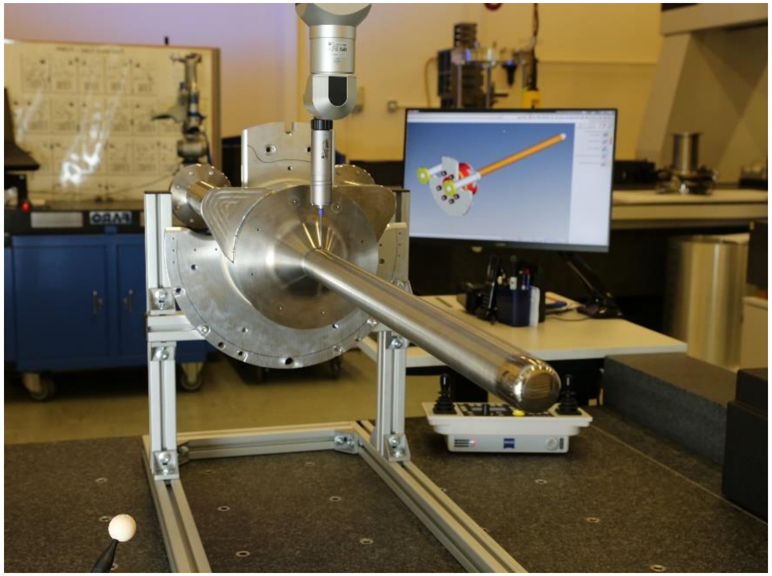
- Target designed for 750 kW at 30 GeV
- Upgraded prototype for 1.3 MW under construction



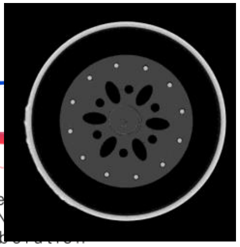
Helium cooling streamlines

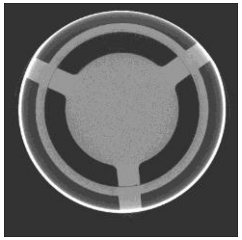


FLUKA, ANSYS, CFX and target engineering by Mike Fitton



Survey of T2K target using Co-ordinate Measuring Machine (CMM) at RAL.

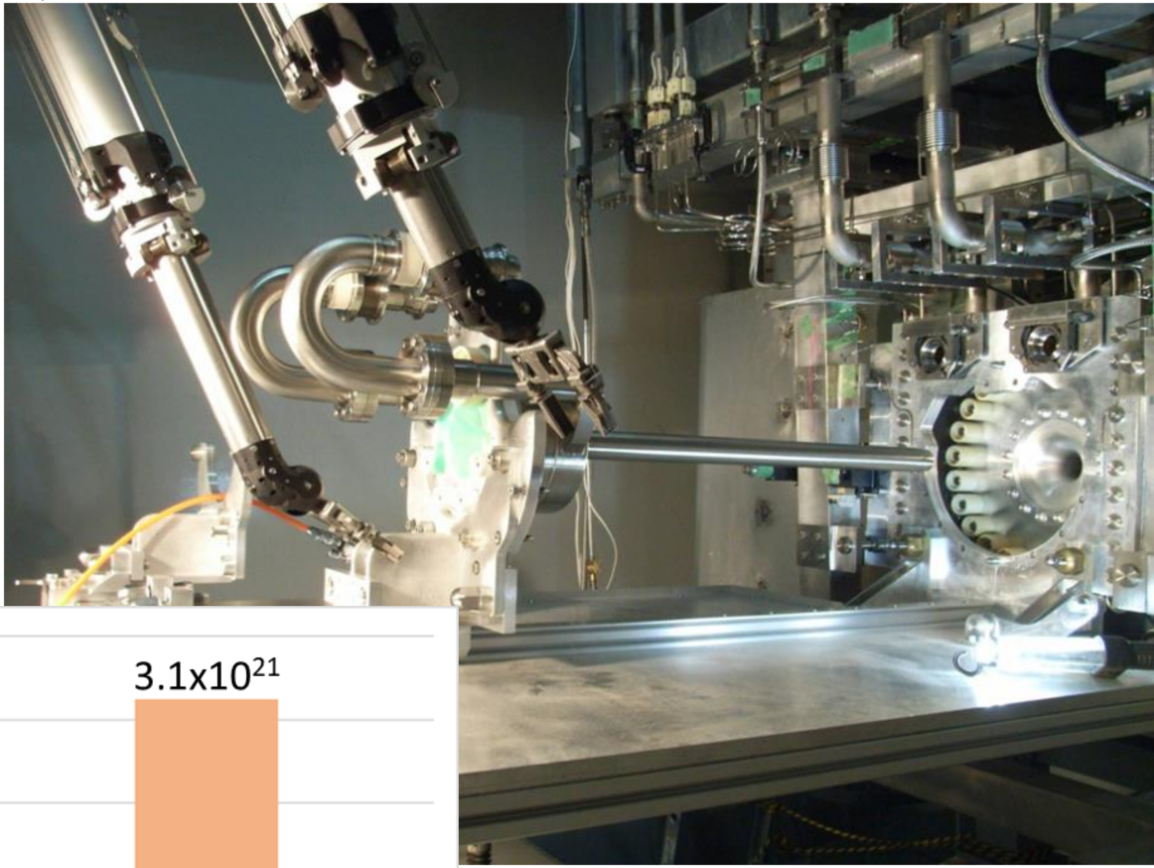




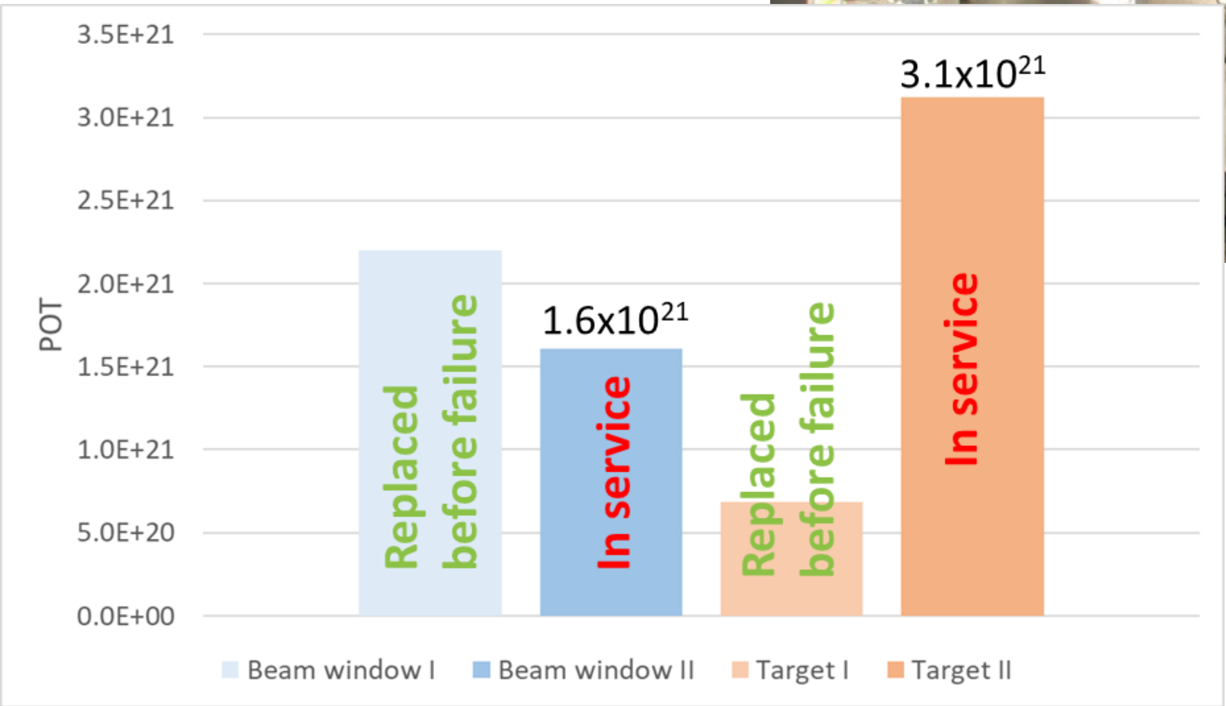
CT scans of new target

T2K: Stable operation at 500 kW

- Helium cooled (graphite runs hot to anneal radiation damage)
- No target failures to date
- One helium line ceramic isolator replacement



Target installation in horn



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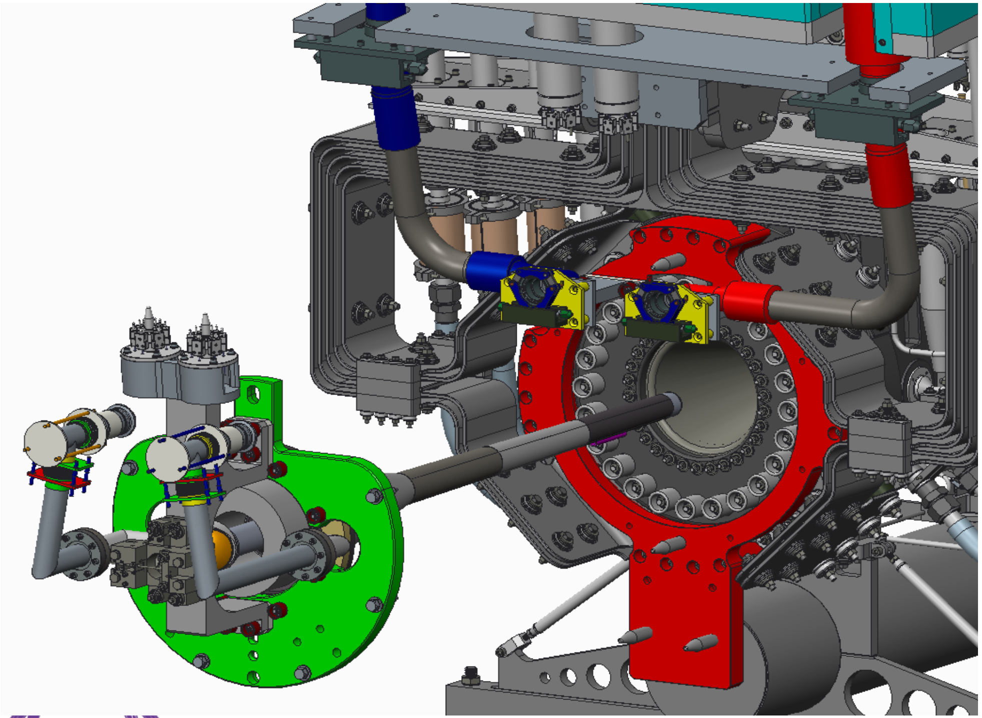
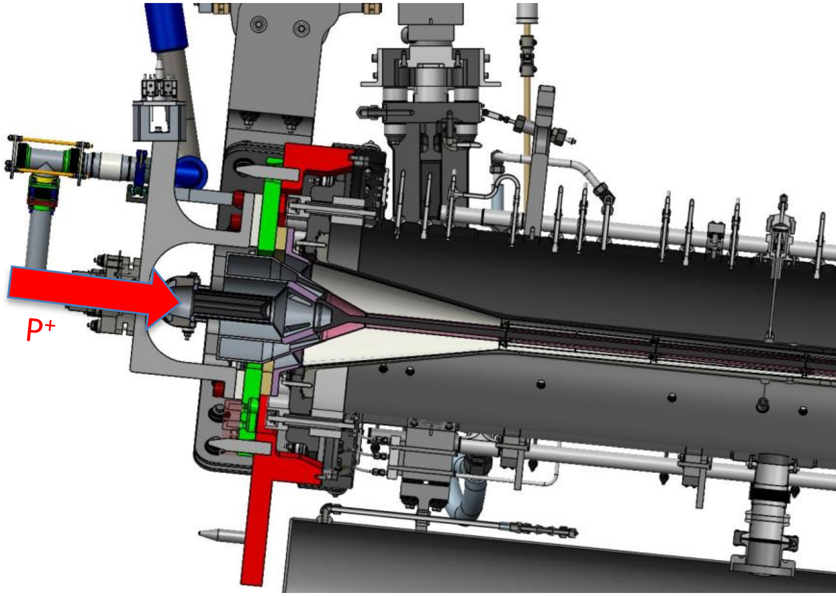
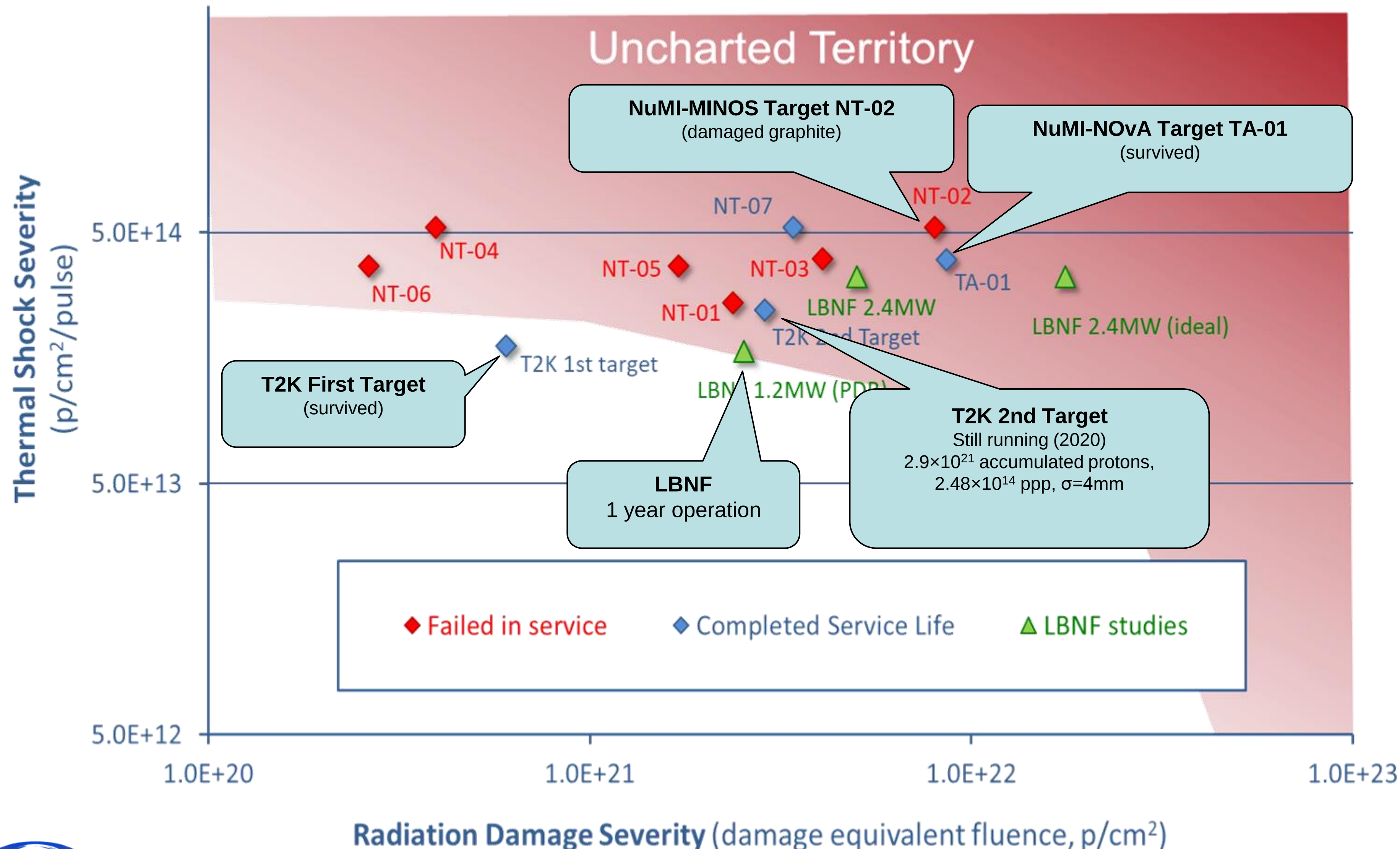
LBNF Target: Developed from T2K design

- Designed for 1.2 MW at 120 GeV – only 24 kW heat load in target (very efficient at producing secondaries)
- Only one helium line ceramic isolator failure (replaced)

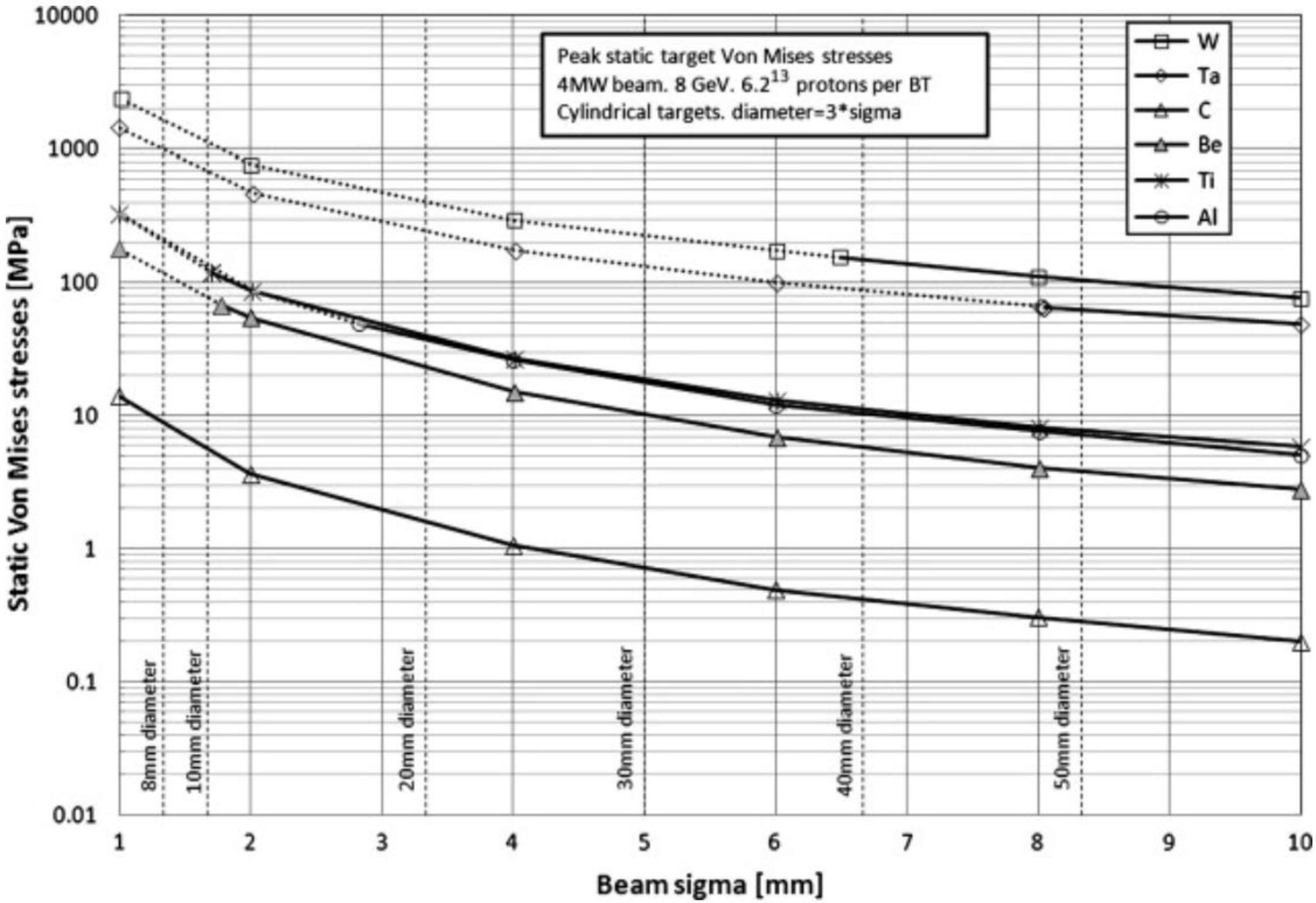




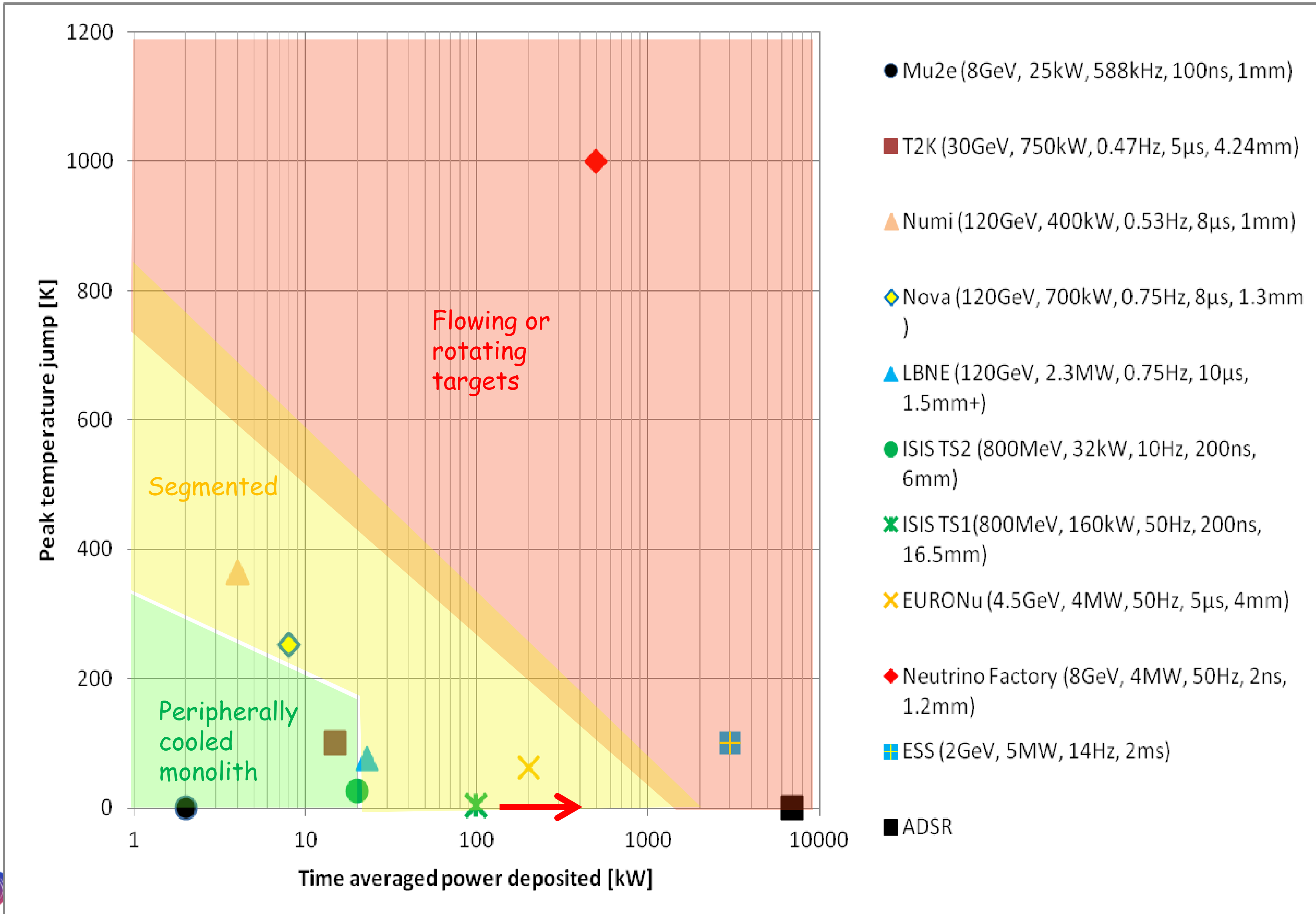
Graphite Neutrino Targets Exploratory Map



Stresses in different target materials as a function of beam rms radius



Limitations of target technologies



'Divide and Rule' for increased power

Dividing material is favoured since:

- Better heat transfer
- Lower static thermal stresses
- Lower dynamic stresses from intense beam pulses
- **Particle bed is a conventional solution**

Helium cooling is favoured (cf water) since:

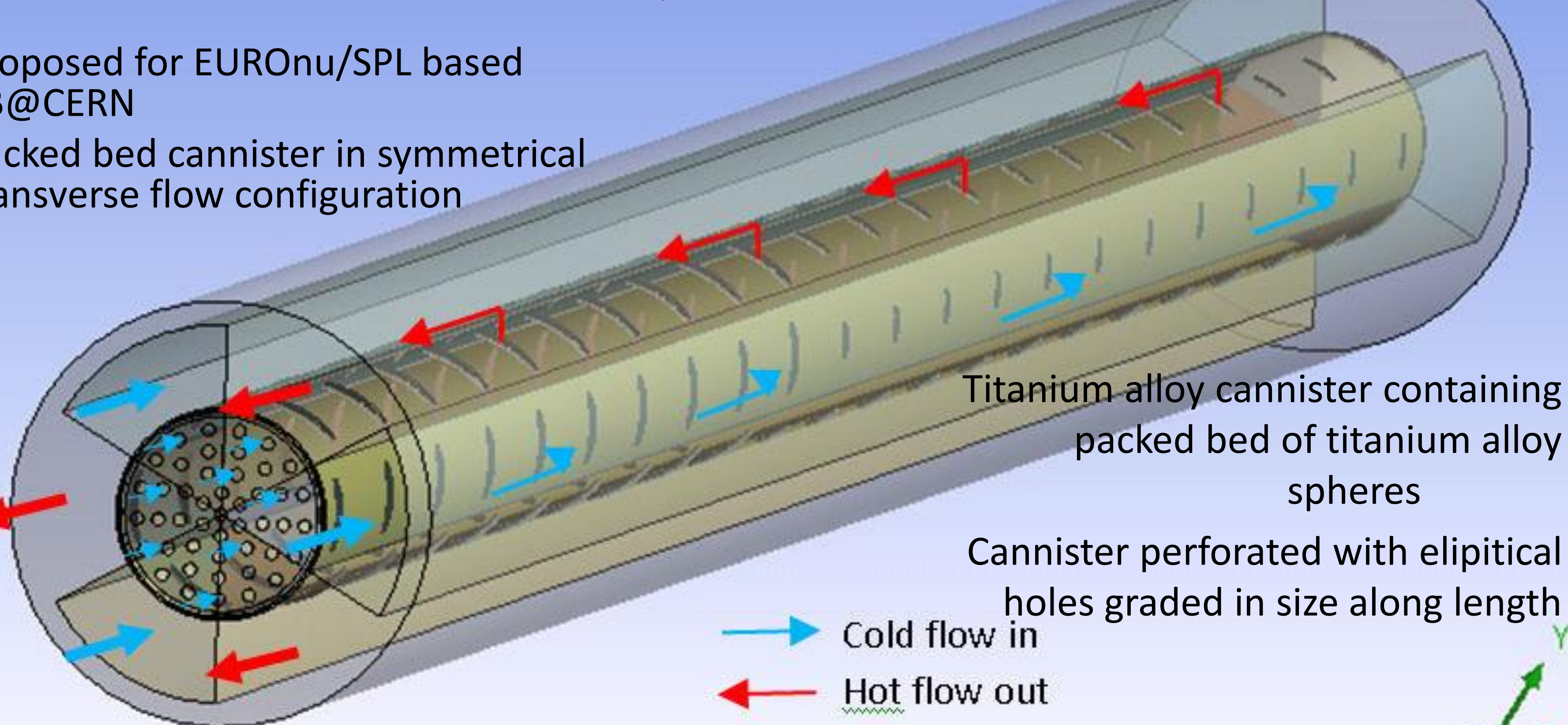
- No 'water hammer' or cavitation effects from pulsed beams
- Lower coolant activation, no radiolysis
- Negligible pion absorption – coolant can be within beam footprint
- For graphite, higher temperatures anneal radiation damage

Low-Z target concepts preferred (static, easier)

Particle Bed Target Concept Solution

Proposed for EUROnu/SPL based SB@CERN

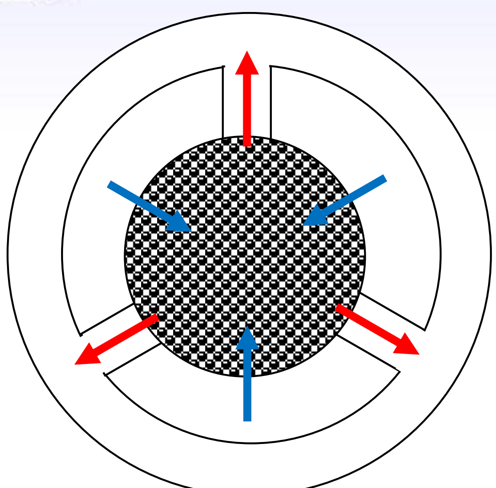
Packed bed cannister in symmetrical transverse flow configuration



Titanium alloy cannister containing packed bed of titanium alloy spheres

Cannister perforated with elipitical holes graded in size along length

T.Davenne



Model Parameters

Proton Beam Energy = 4.5GeV

Beam sigma = 4mm

Packed Bed radius = 12mm

Packed Bed Length = 780mm

Packed Bed sphere diameter = 3mm

Packed Bed sphere material : Titanium Alloy

Coolant = Helium at 10 bar pressure

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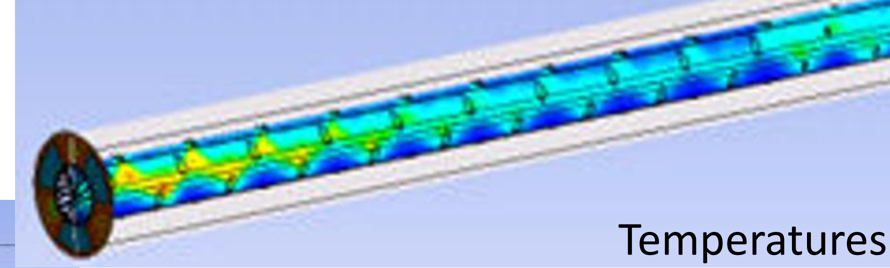
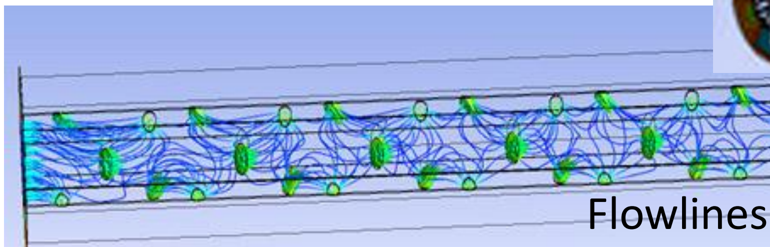
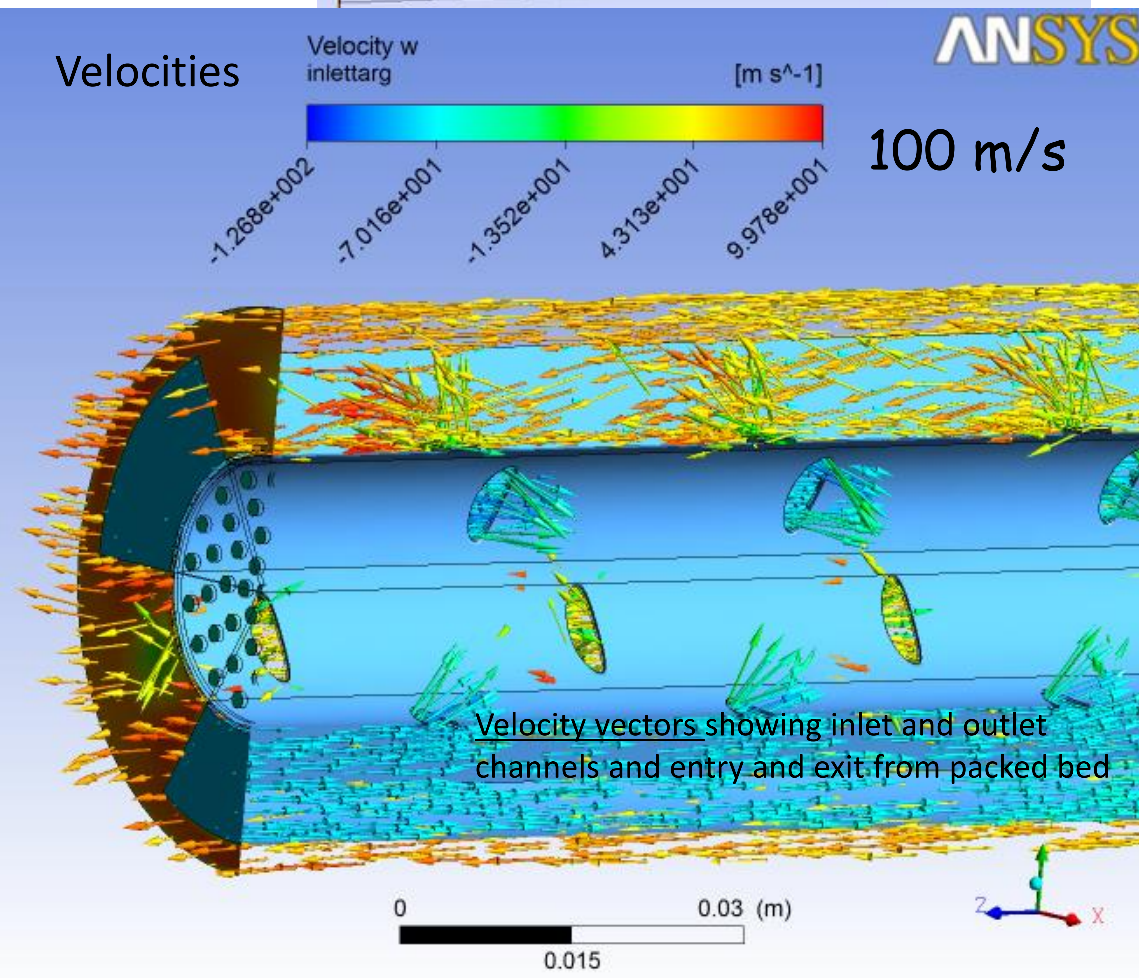
Packed Bed Model (T.Davenne)
FLUKA + CFX v13





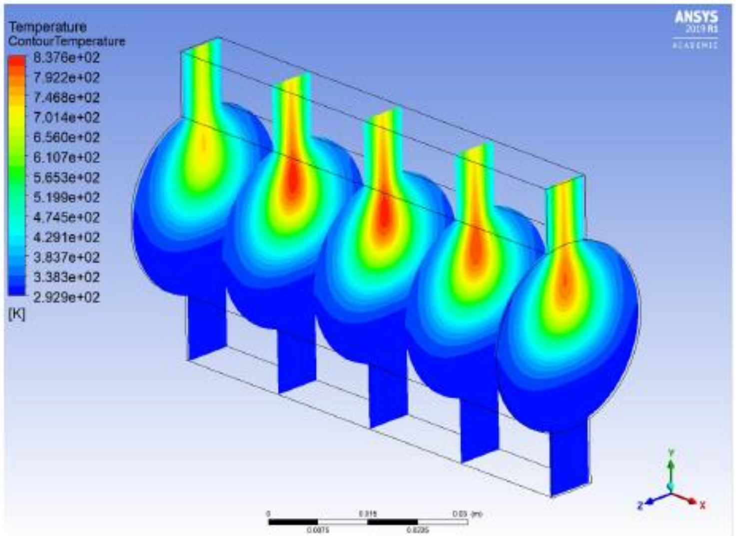


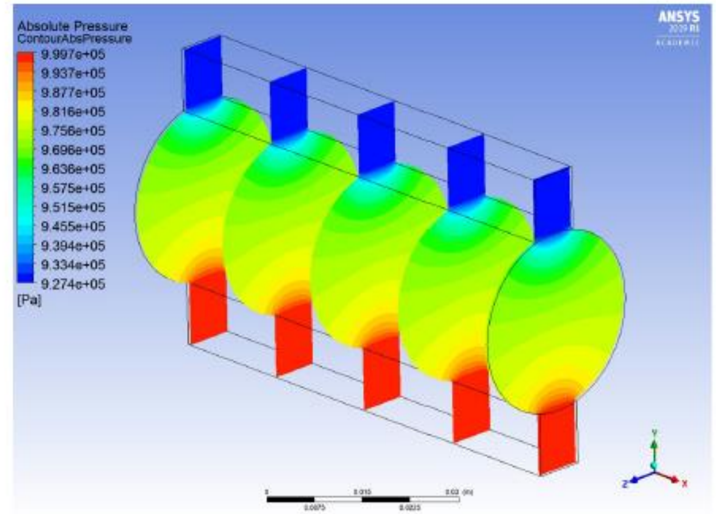
- Packed bed modelled as a porous domain
- Permeability and loss coefficients calculated from Ergun equation (dependant on sphere size)
- Overall heat transfer coefficient accounts for sphere size, material thermal conductivity and forced convection with helium
- Interfacial surface area depends on sphere size
- Acts as a natural diffuser - flow spreads through target easily

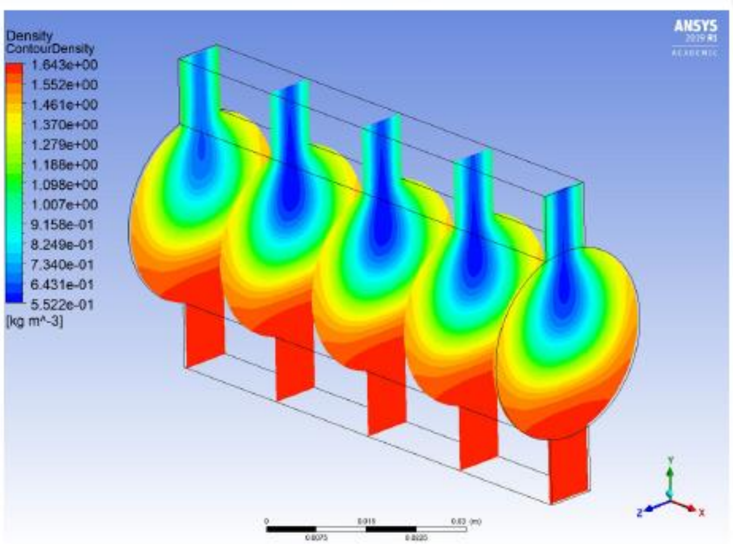
High Power Targets

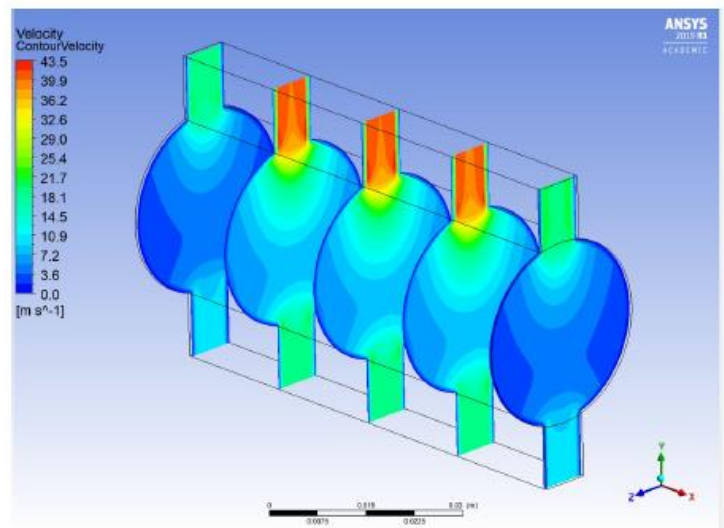
ESSnuSB particle bed target studies

Piotr Cupiał, Łukasz Łacny, Jacek Snamina









Particle bed challenges and limits – need for R&D

- High pressure drops, particularly for long thin target geometry
  - Need to limit gas pressure for beam windows
- Transverse flow reduces pressure drops
  - But difficult to get uniform temperatures and dimensional stability of container
- Radiation damage of container windows
- Possible vibration and erosion of spheres and container from pulsed beam and thermal cycling

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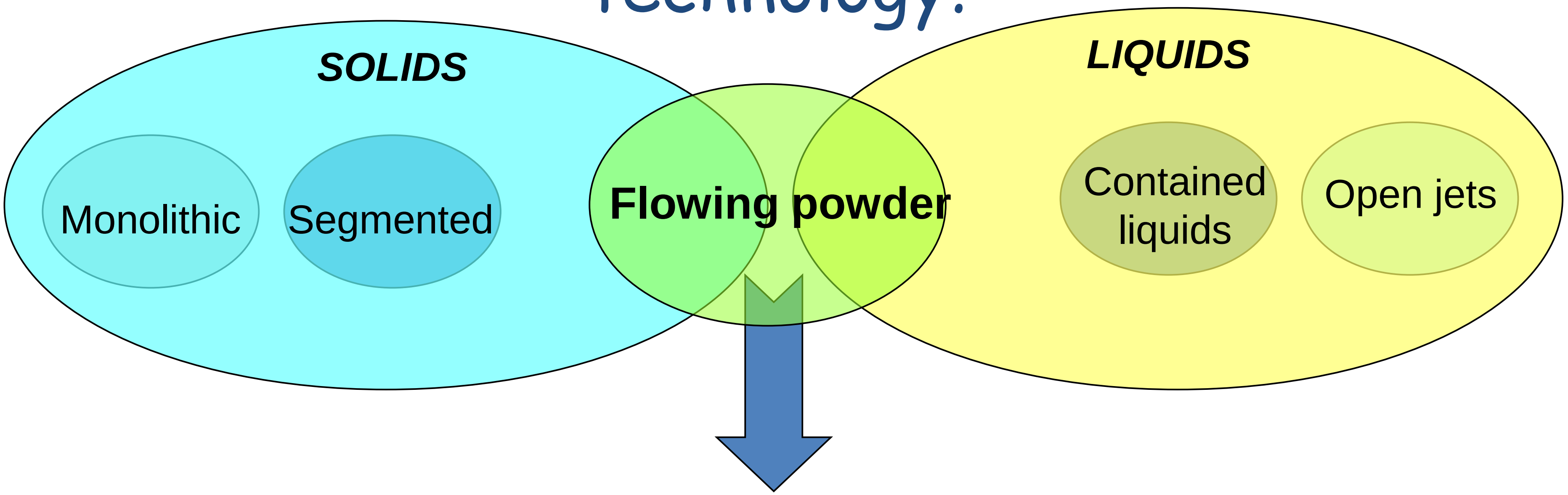
Fluidised powder: a 'missing link' target technology?



Some potential advantages of a flowing powder:

Quasi-liquid

Resistant to shock waves

Favourable heat transfer

Few moving parts

Mature technology

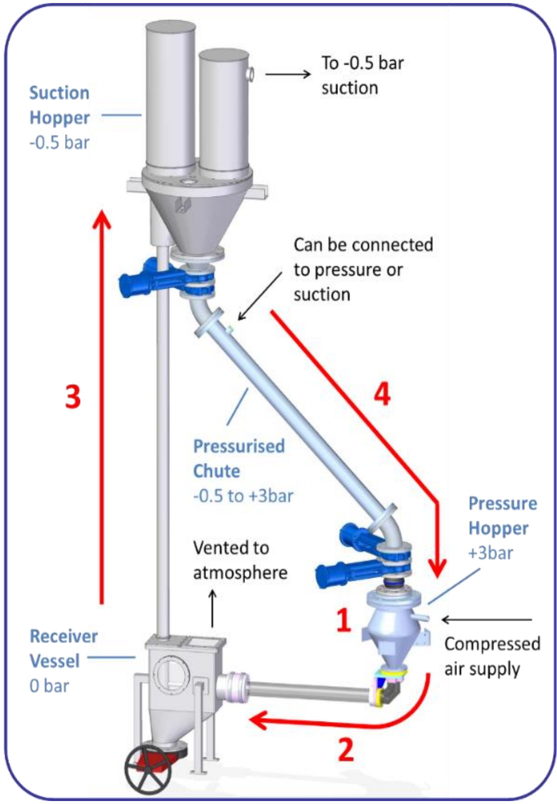
Most areas of concern can be tested off-line

Fluidised tungsten powder technology

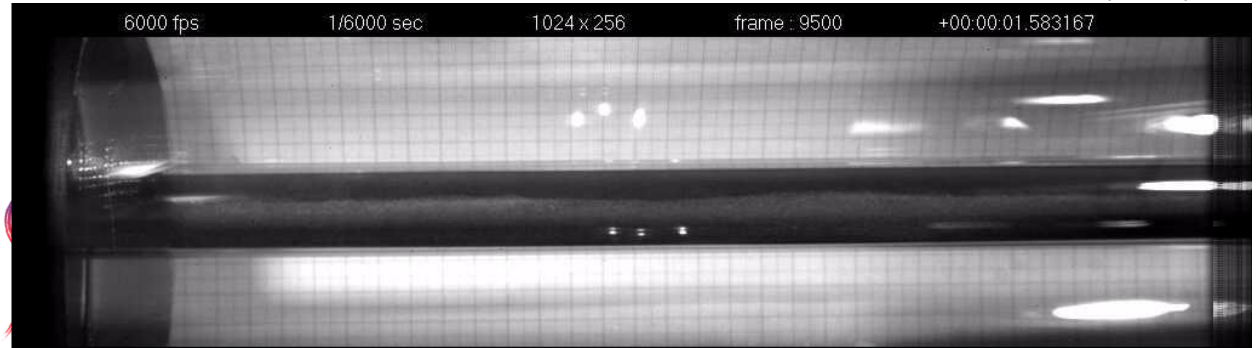
- High Z refractory metal – maximal production of pions
- Alternative to Muon Collider liquid mercury jet
- Pneumatically (helium) recirculated tungsten powder
- An innovative generic target system exploiting well-established granular flow technology
- Demonstrated off-line at RAL
- 1st in-beam experiment on mixed crystalline powder sample carried out at HiRadMat facility, CERN in 2012
- 2nd HiRadMat experiment carried out in 2015

Fluidised Tungsten Powder Experiments (Offline)

- 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



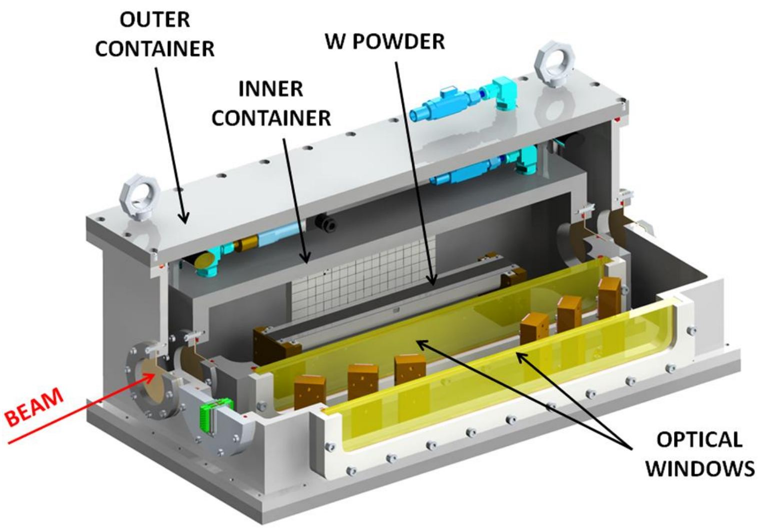
[1] O. Caretta, C. J. Densham, T. W. Davies and R. Woods, "Preliminary Experiments on a Fluidised Powder Target," in Proceedings of EPAC08, WEPP161, Genoa, Italy, 2008.

[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.

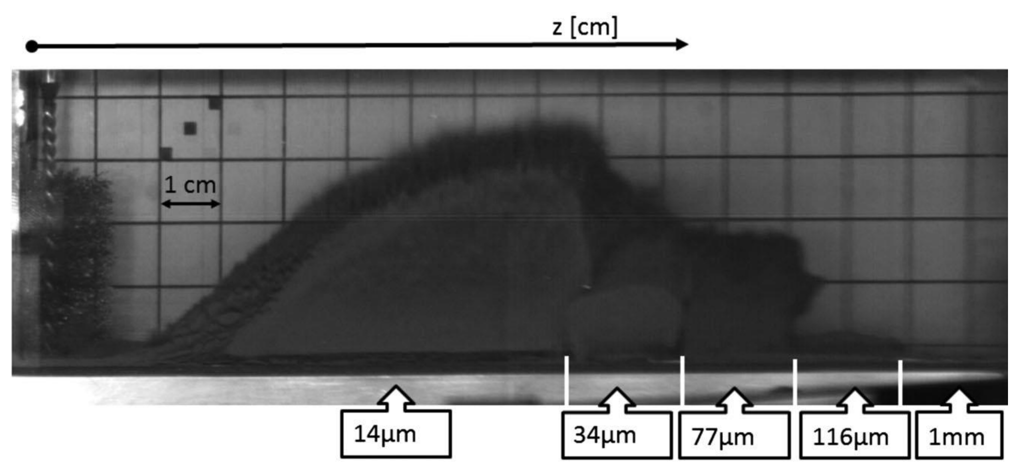
[3] T. Davies, O. Caretta, C. Densham and R. Woods, "The production and anatomy of a tungsten powder jet," *Powder Technology*, vol. 201, no. 3, pp. 296-300, 2010.

Tungsten Powder Experiments (Online)

- Two in-beam experiments carried out at CERN's HiRatMat facility
  - Beam induced lifting of the powder was observed
  - Eruption velocities 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.

Online experiments at HiRadMat

- Disruption of granular tungsten observed in vacuum
- Deduced to be electrostatic effect

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Fluidised Tungsten Powder – Future R+D

- Selection of container materials (SiC-SiC composite?)
- Measurement of erosion rates, and development of improved components to mitigate erosion risk
- Development of powder circuit design to minimise or *eliminate* moving parts such as slide valves in contact with the powder
- Measurement of heat transfer between flowing tungsten powder and container wall
- Development of improved diagnostics for automated operation and fault detection
- Investigate the use of spherical powder to improve flow characteristics

Summary and commentary

- Previous MC baseline of high-Z liquid metal target best avoided (liquid Hg likely excluded at CERN ref Marco Calviani)
- Low-Z more feasible than High-Z
  - (Plus lower neutron load on SC solenoid)
- Graphite has an excellent pedigree as a target material – well worth pursuing for a MC
  - May need larger radius than physics optimum
  - Lifetime limited
- If monolithic target not feasible, try a packed particle bed target (NB bulk fraction c.50%)
- If High-Z is strongly favoured, then fluidised tungsten powder offers an interesting potential technology
  - Needs a (mostly) off-line research programme plus more pulsed beam experiments at HiRadMat
- The optimum target is one that works – continuously and reliably!
- Materials science - cross-cutting issue for any target technology…

RaDIATE Collaboration

Radiation Damage In Accelerator Target Environments

Broad aims are threefold:

www-radiate.fnal.gov

- to generate new and useful materials data for application within the **accelerator** and **fission/fusion** communities
- to recruit and develop new scientific and engineering experts who can **cross the boundaries** between these communities
- to initiate and coordinate a **continuing synergy** between research in these communities, benefitting both **proton accelerator applications** in science and industry and **carbon-free energy technologies**

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Argonne National Laboratory
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European Spallation Source
CERN
Oak Ridge National Laboratory
Los Alamos National Laboratory EST. 1943
Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas
FRIB
Pacific Northwest National Laboratory