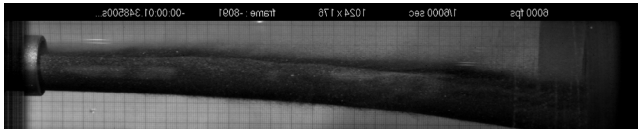
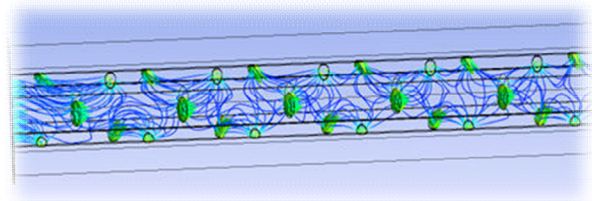
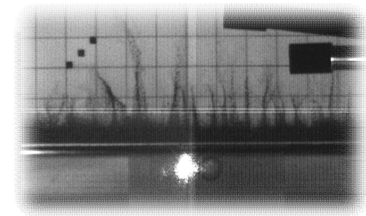
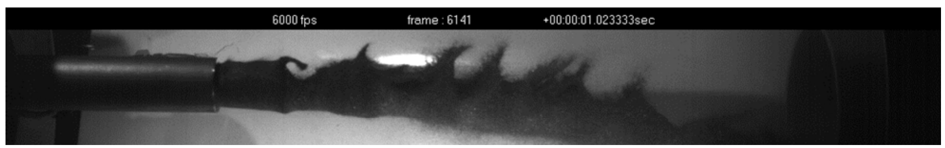




Muon Collider Target Technology
From graphite rods to moving tungsten powder



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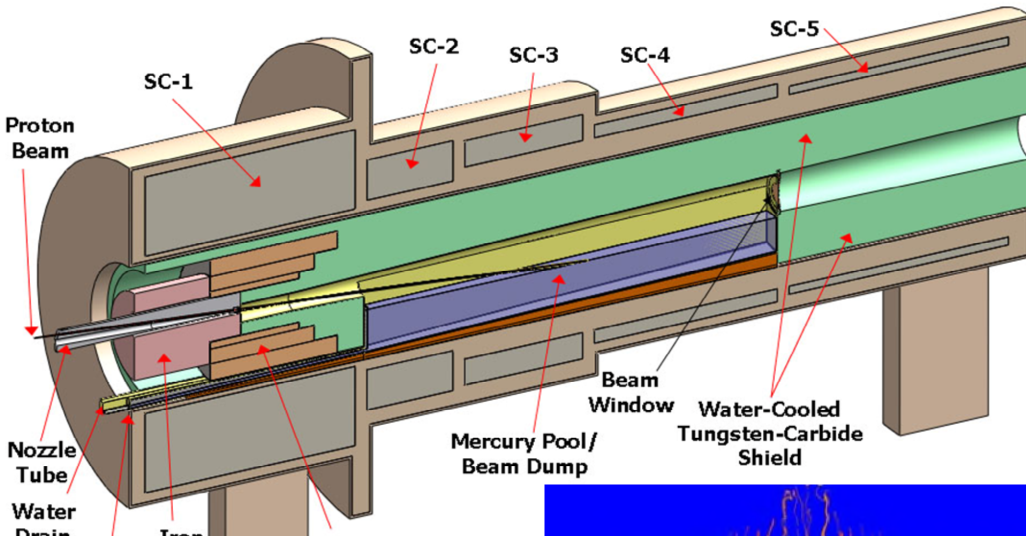
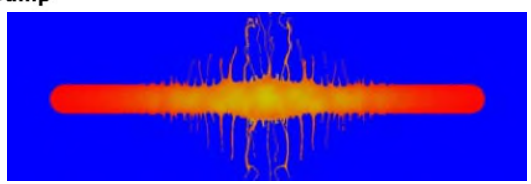
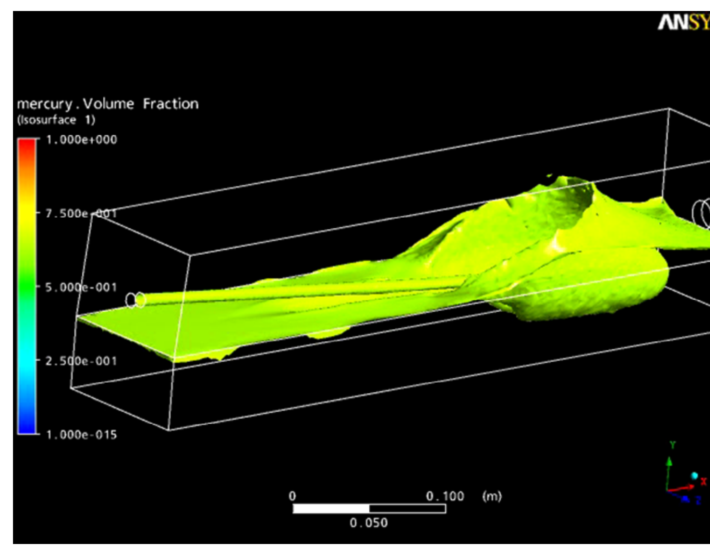
Previous Muon Collider baseline: free mercury jet



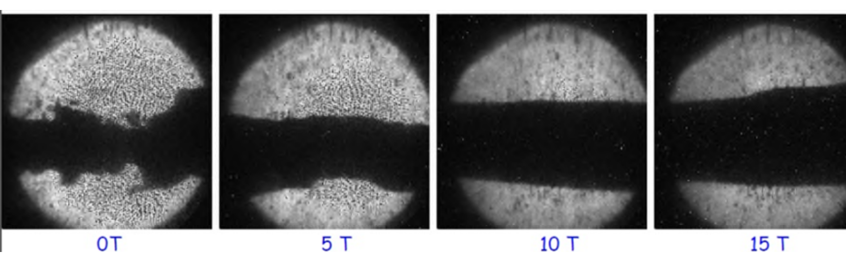
- Baseline liquid mercury target configuration for a Neutrino Factory / Muon Collider
- 20T solenoid captures both signs of pions generated by interaction of proton beam with mercury jet
- Many severe challenges remain, e.g. solenoid, mercury dump, cavitation, radiochemistry, safety, etc



Magnetohydrodynamic simulation of pulsed beam interaction with mercury jet



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



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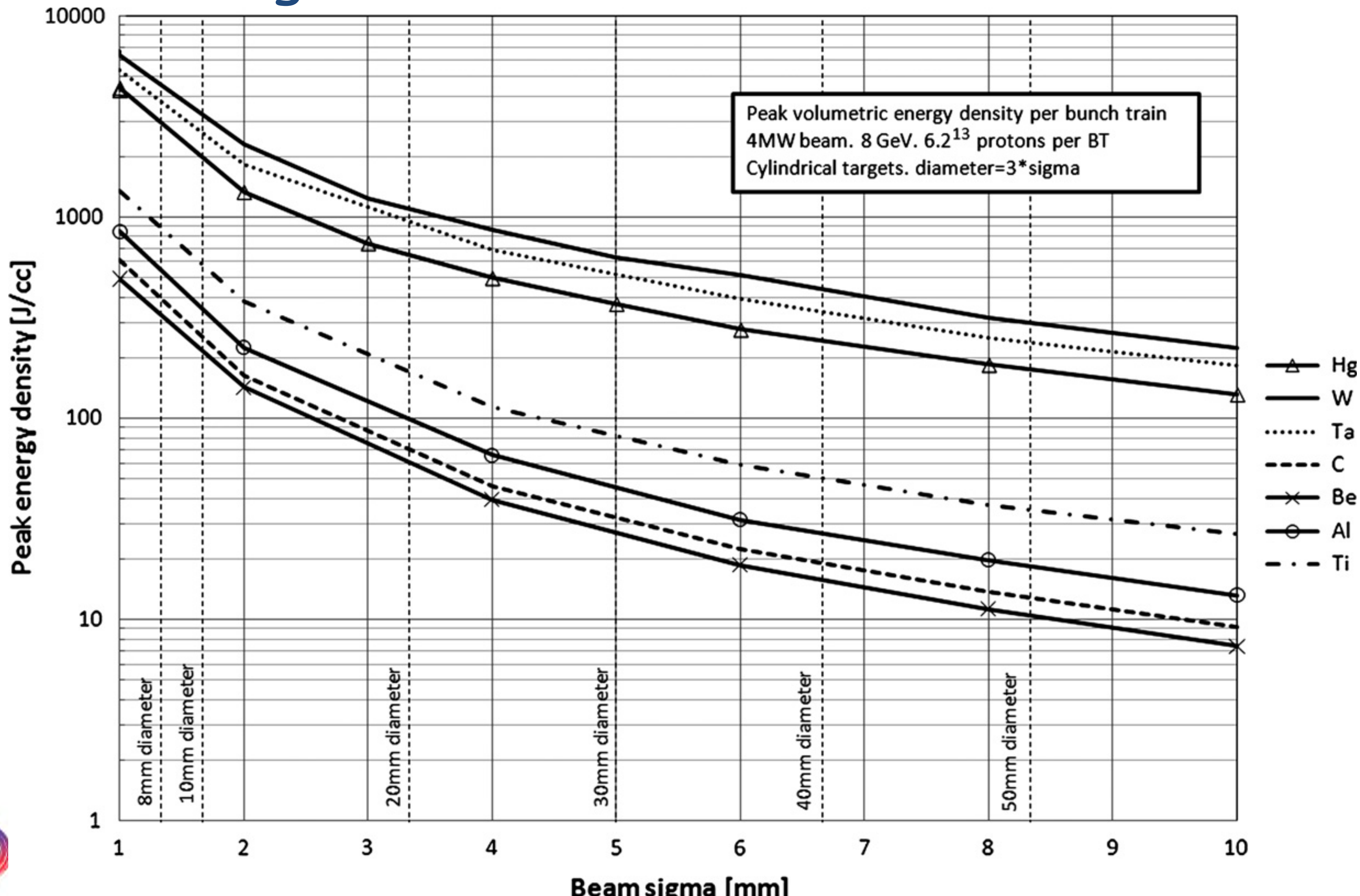
Peak heat load for various target materials & beam sizes



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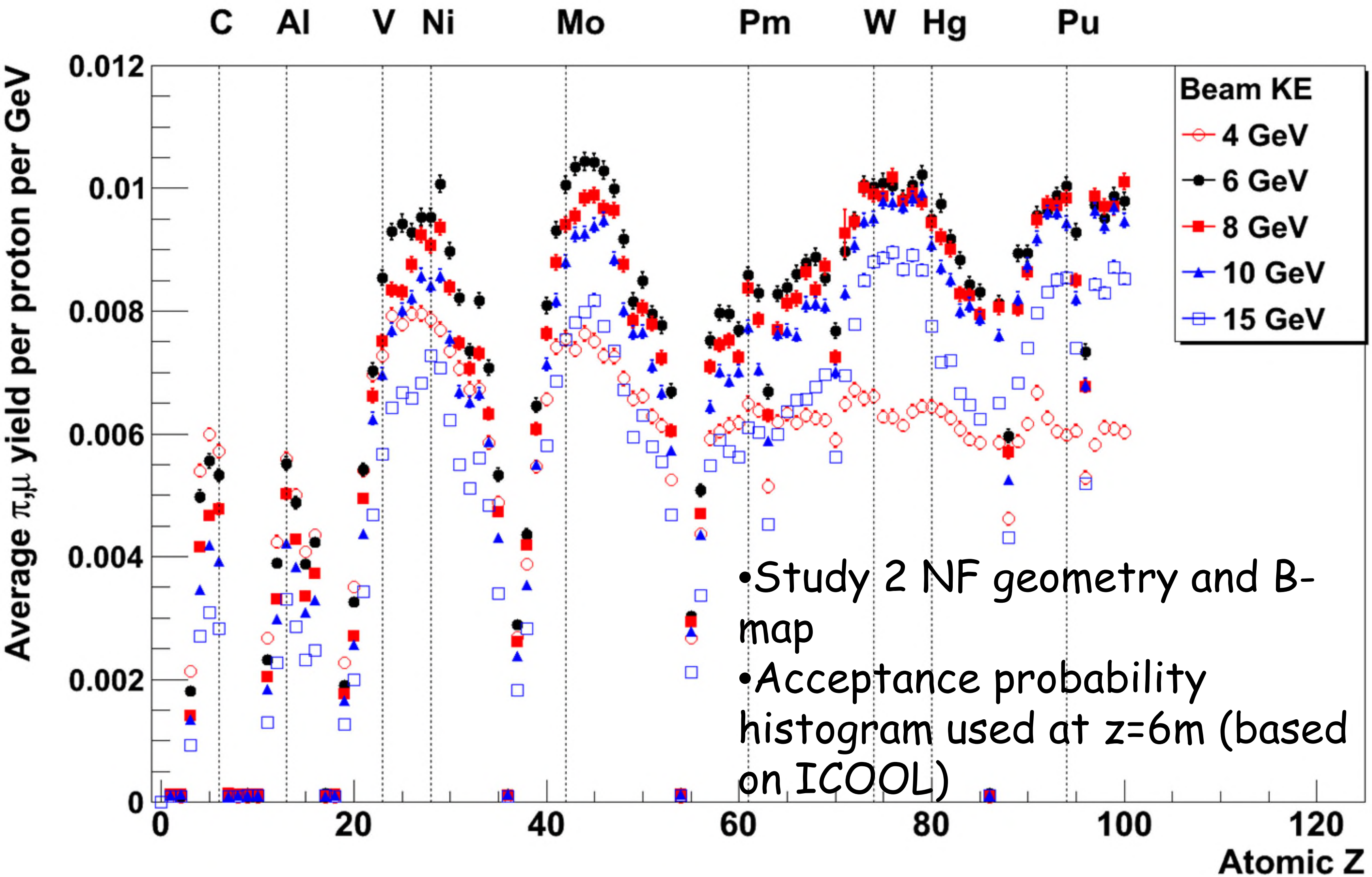
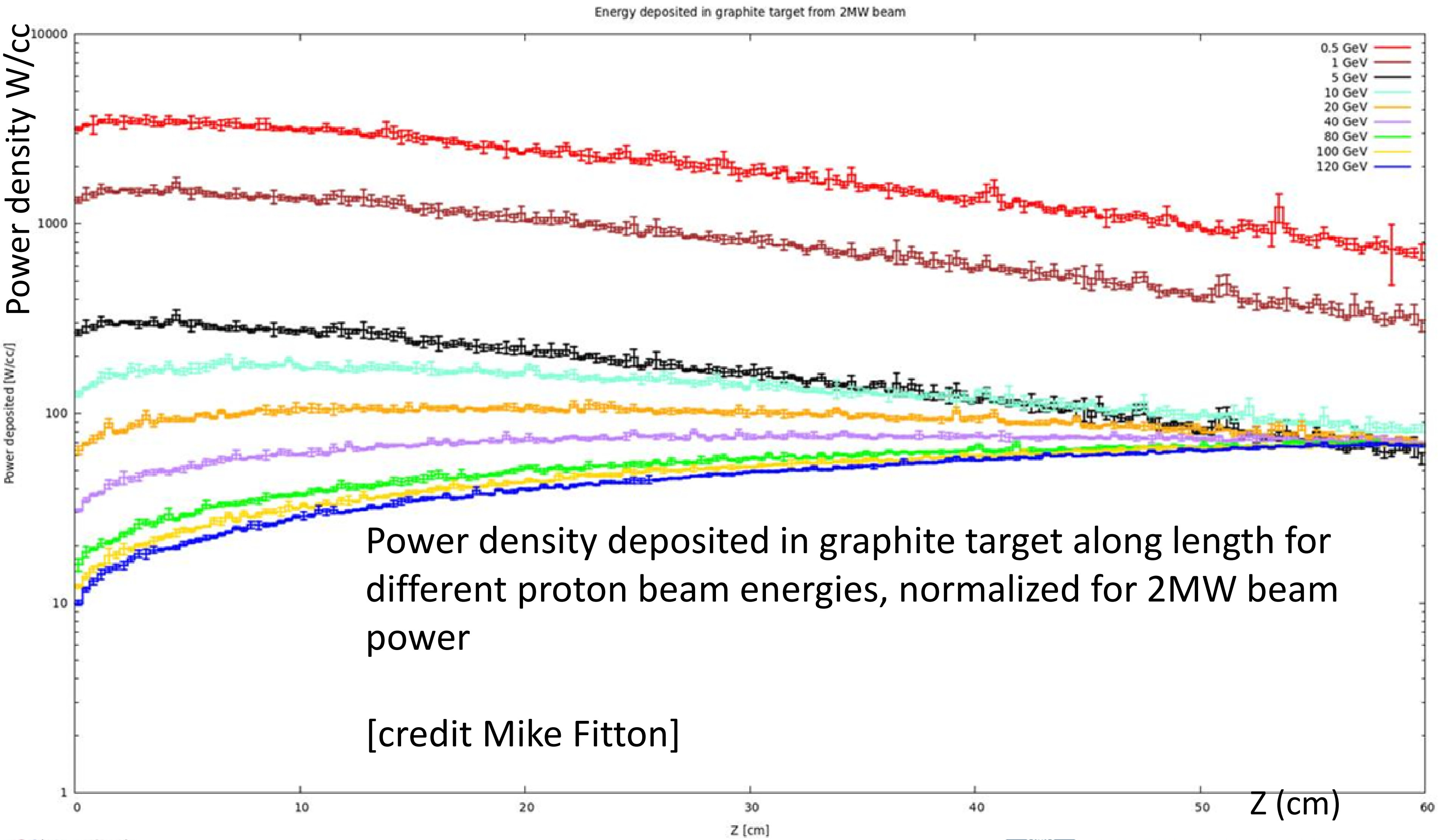
Pion/muon yields for different target Z's and beam energies (J.Back)

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)

Heat load in a graphite target: Both beam energy and power important



Power density deposited in graphite target along length for different proton beam energies, normalized for 2MW beam power

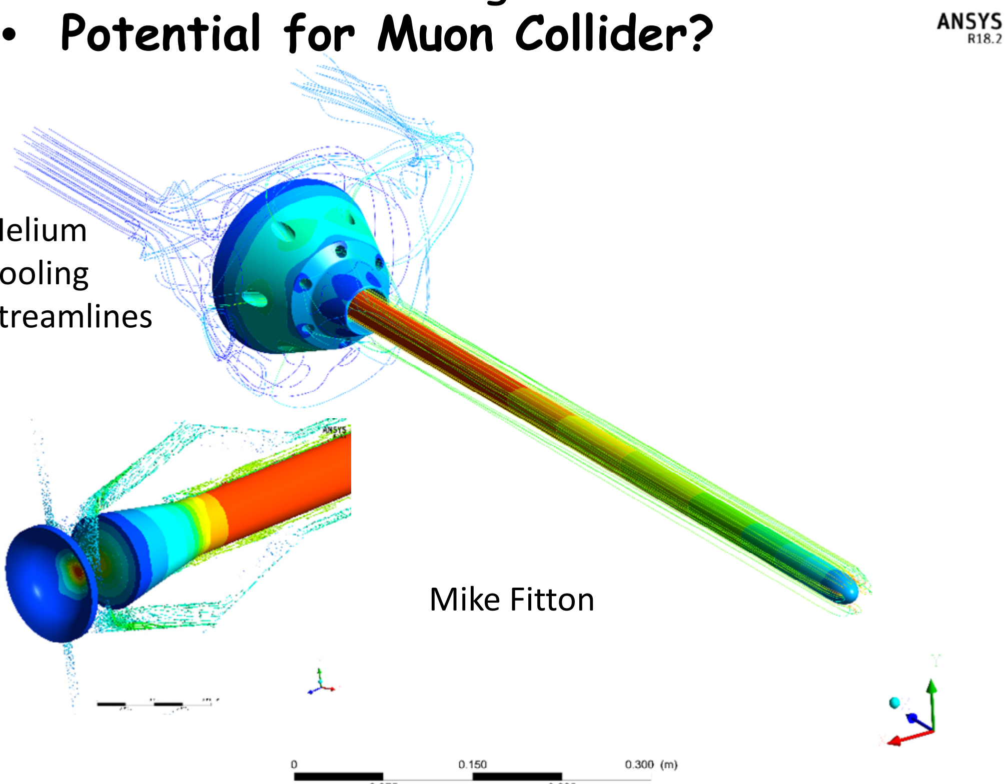
[credit Mike Fitton]

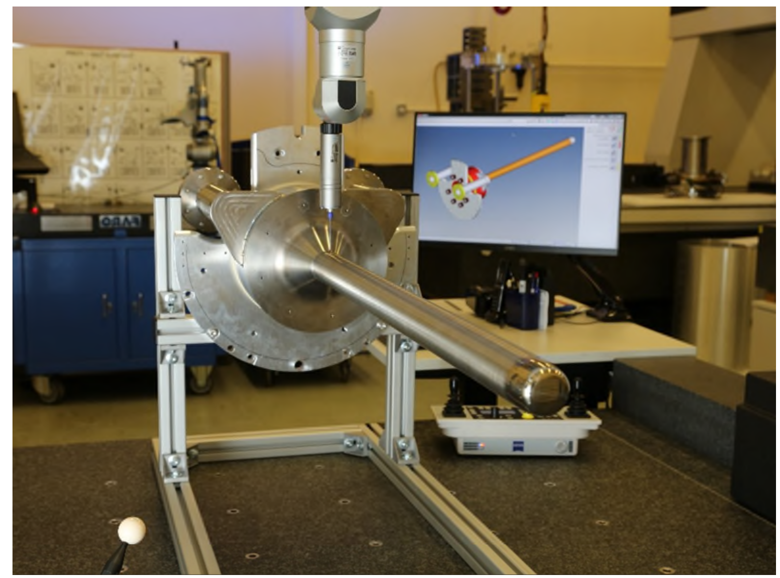
T2K helium cooled graphite target

- 12 years good experience

- Stable operation at 500 kW at 30 GeV
- 1.3 MW prototype constructed and ready for installation
- Basis for LBNF target for 1.2 MW at 120 GeV (2.4 MW upgrade planned)
- **Potential for Muon Collider?**

Helium cooling streamlines

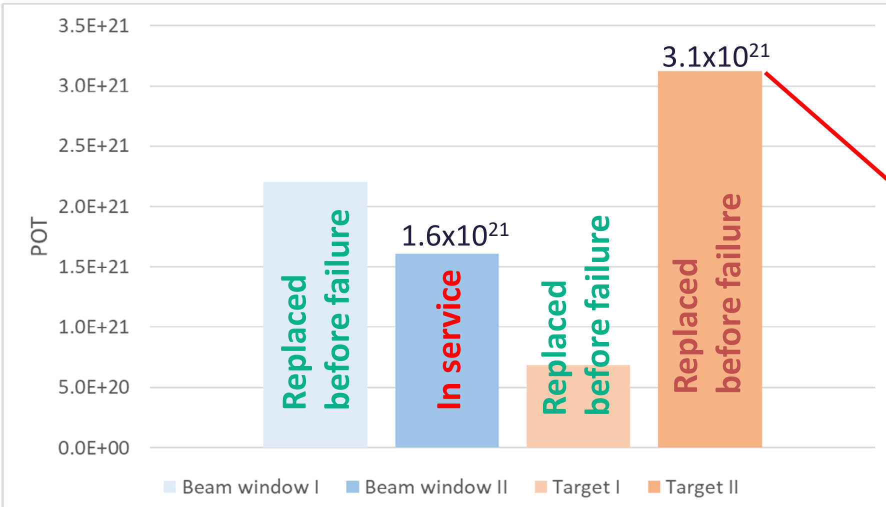




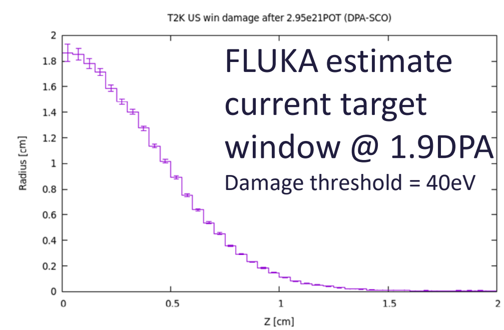
Survey of T2K target using Co-ordinate Measuring Machine (CMM) at RAL.

CT scans of prototype 1.3 MW target

Titanium beam windows:
Good experience so far on T2K at 500 kW

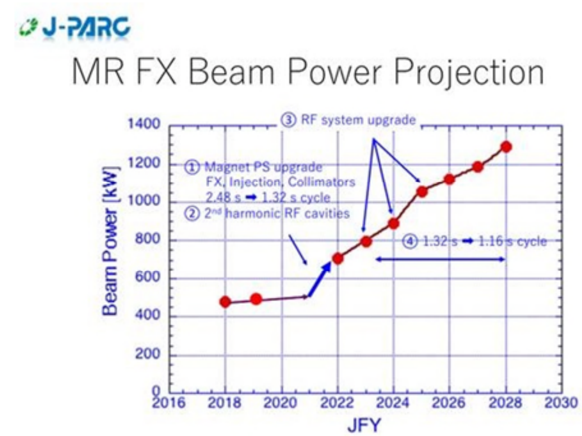


- How long will a Ti-6Al-4V window/target last?
- Target currently has highest POT ~3 x 10^{21} POT
- C.2 DPA – c.10x BLIP sample data so far(c.0.24 DPA)

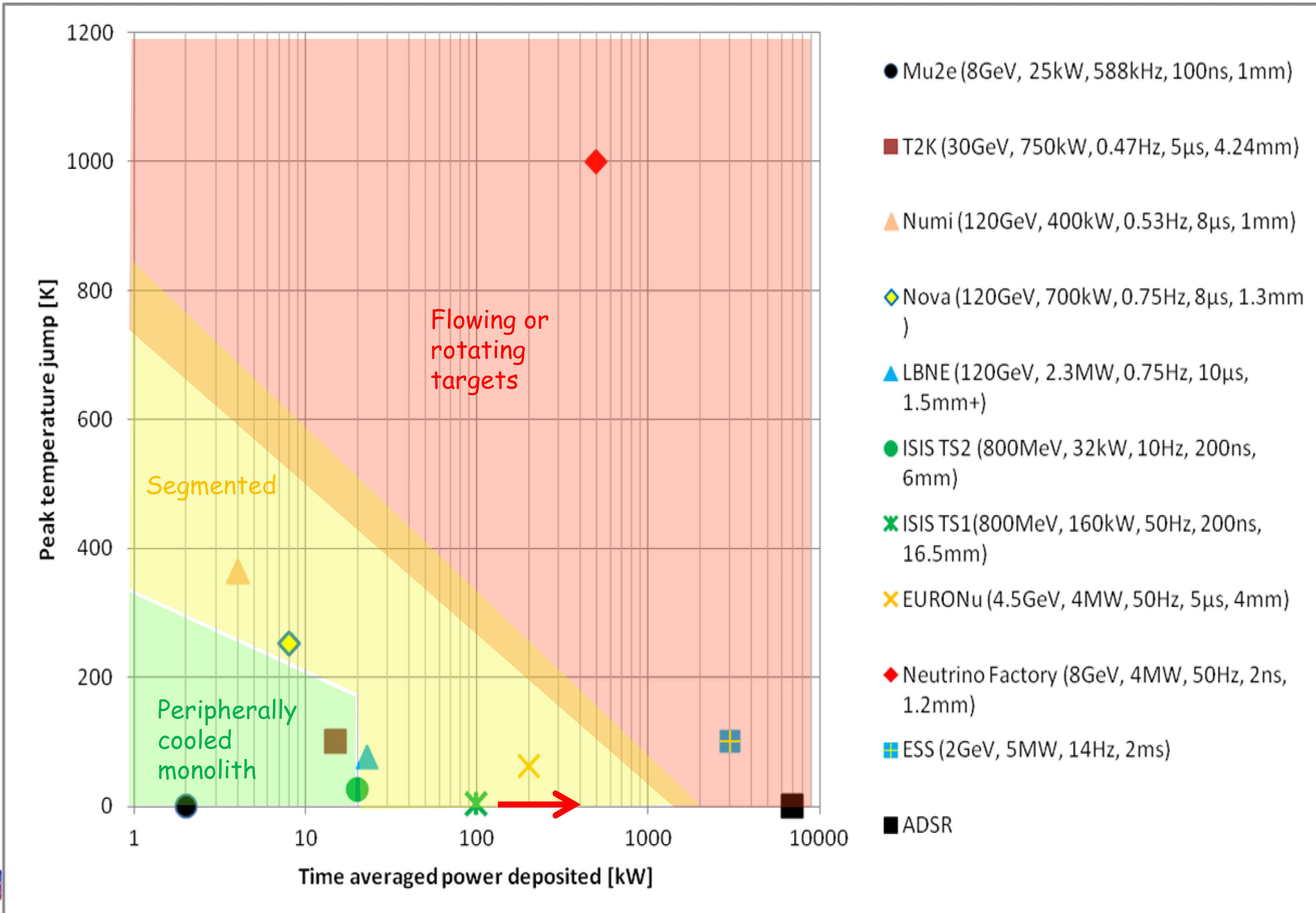


Future plans	PPP	rep rate	current (A)	Beam power (kW)	Run time (mths)	POT/yr
2021	2.64E+14	2.48	1.71E-05	512	4	7.28E+20
2022	2.20E+14	1.32	2.67E-05	801	3	8.55E+20
2023	2.48E+14	1.32	3.01E-05	903	4	1.29E+21
2024	2.24E+14	1.16	3.09E-05	928	4	1.32E+21
2025	2.80E+14	1.16	3.87E-05	1160	2	8.26E+20
2026	2.96E+14	1.16	4.09E-05	1227	4	1.75E+21
HK	3.20E+14	1.16	4.42E-05	1326	6	2.83E+21

Similar DPA/year for LBNF at 1.2 MW



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**

Gas cooling (helium/nitrogen) 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 for engineering (static, easier)

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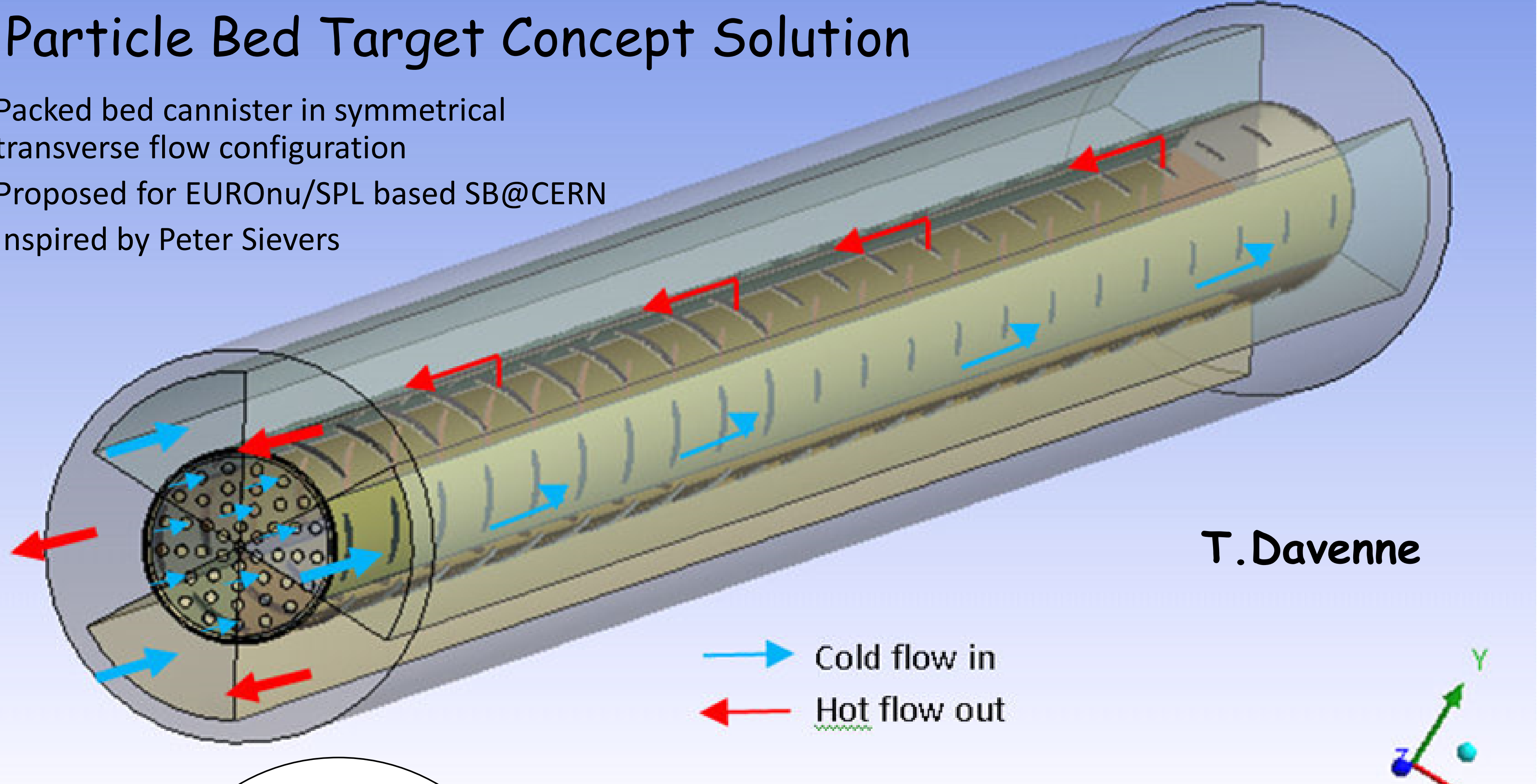
Particle Bed Target Concept Solution

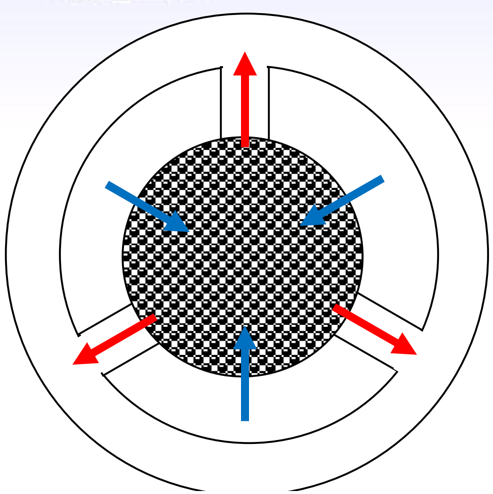
Packed bed cannister in symmetrical transverse flow configuration

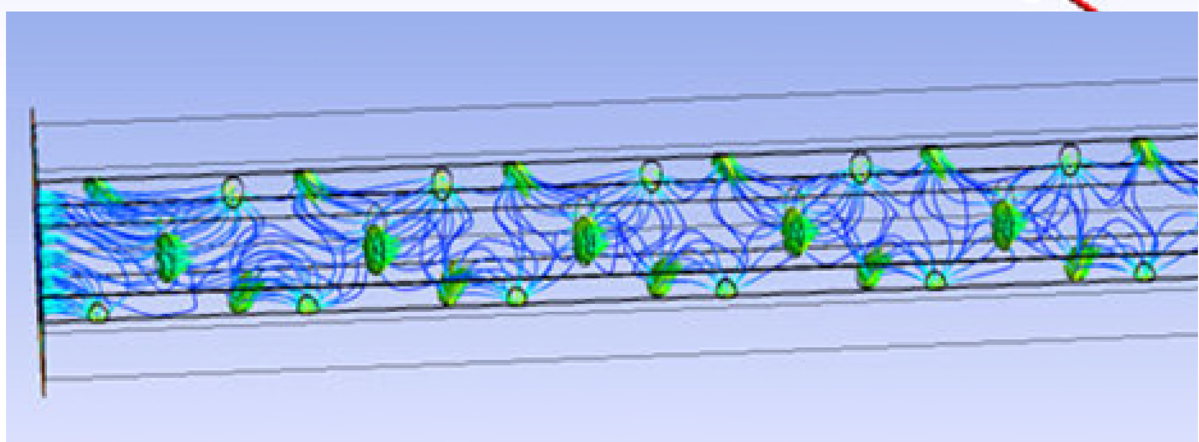
Proposed for EUROnu/SPL based SB@CERN

Inspired by Peter Sievers



T.Davenne





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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

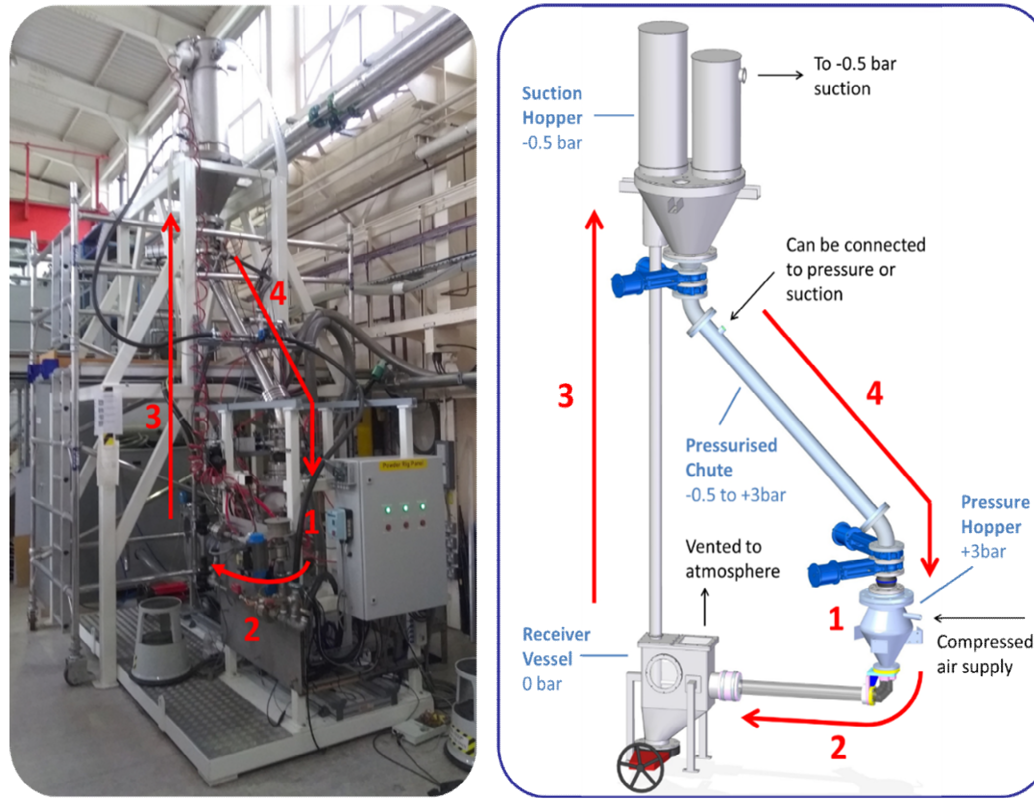
Fluidised tungsten powder technology

- 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

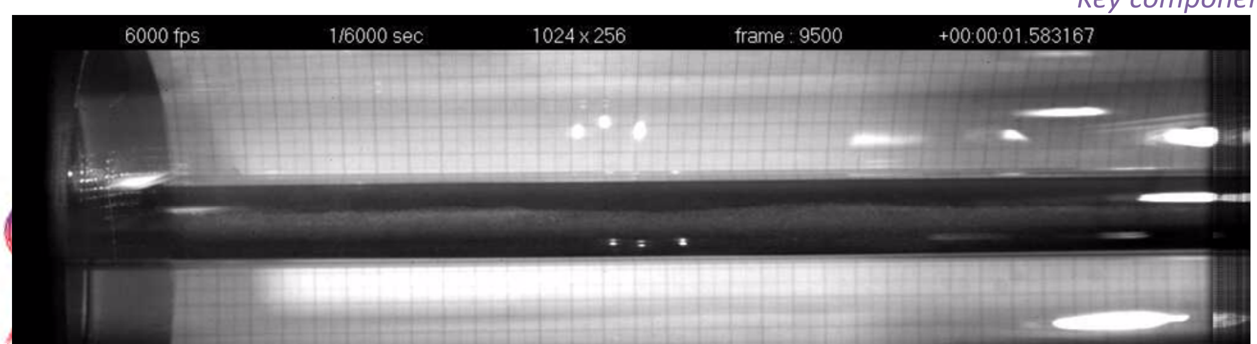
[1] O. Caretta, C. J. Densham, T. W. Davies and R. Woods, "Preliminary Experiments on a Fluidised Powder Target," in Proceedings of EPAC08, WEPP161, Genoa, Italy, 2008.
[2] C. J. Densham, O. Caretta and P. Loveridge, "The potential of fluidised powder target technology in high power accelerator facilities,"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

Fluidised Tungsten Powder Experiments (Offline)

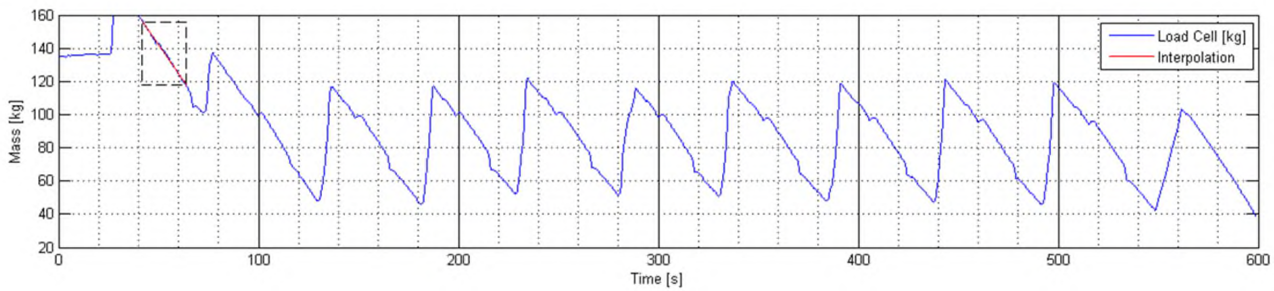
- Test rig built and operated at Rutherford Appleton Laboratory from 2009-2018
- Demonstrated key powder handling processes:
  - Suction lift of powder (lean phase fluidisation)
  - Pneumatic conveying of dense phase powder (~50% volume fraction)
  - Ejection of powder as a dense fluidised jet (~40%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



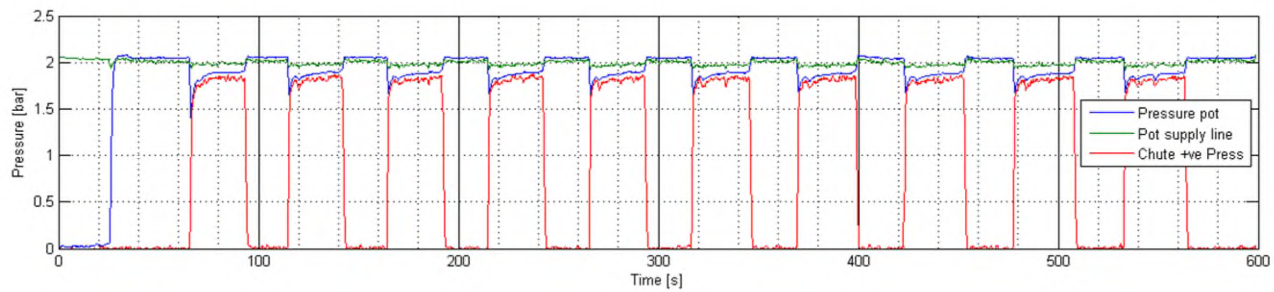
Key components of RAL fluidised powder rig



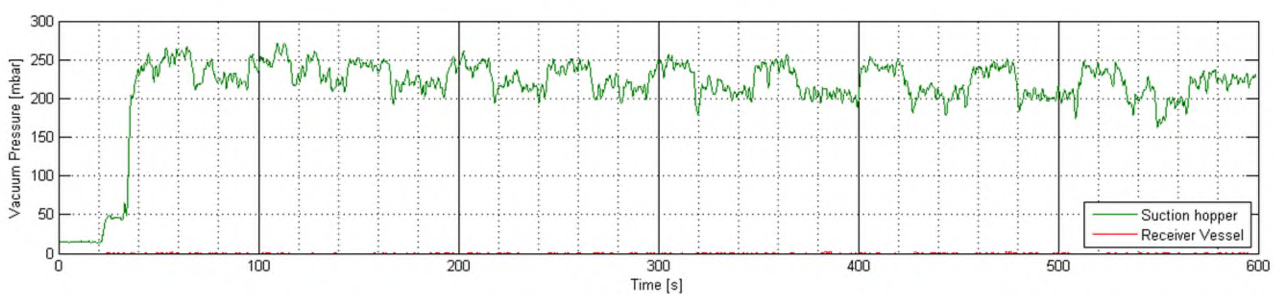
Continuous flow demonstrated (batch mode)



Mass in pressurised discharge hopper



Pressure cycling of chute and discharge hopper



Suction line pressure variation during recycling

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Circulating Fluidized Bed technology

- Plan to read the literature & re-imagine for a MC

Hindawi Publishing Corporation
Journal of Powder Technology
Volume 2015, Article ID 293165, 9 pages
http://dx.doi.org/10.1155/2015/293165

Research Article

Wall-to-Suspension Heat Transfer in a CFB Downcomer

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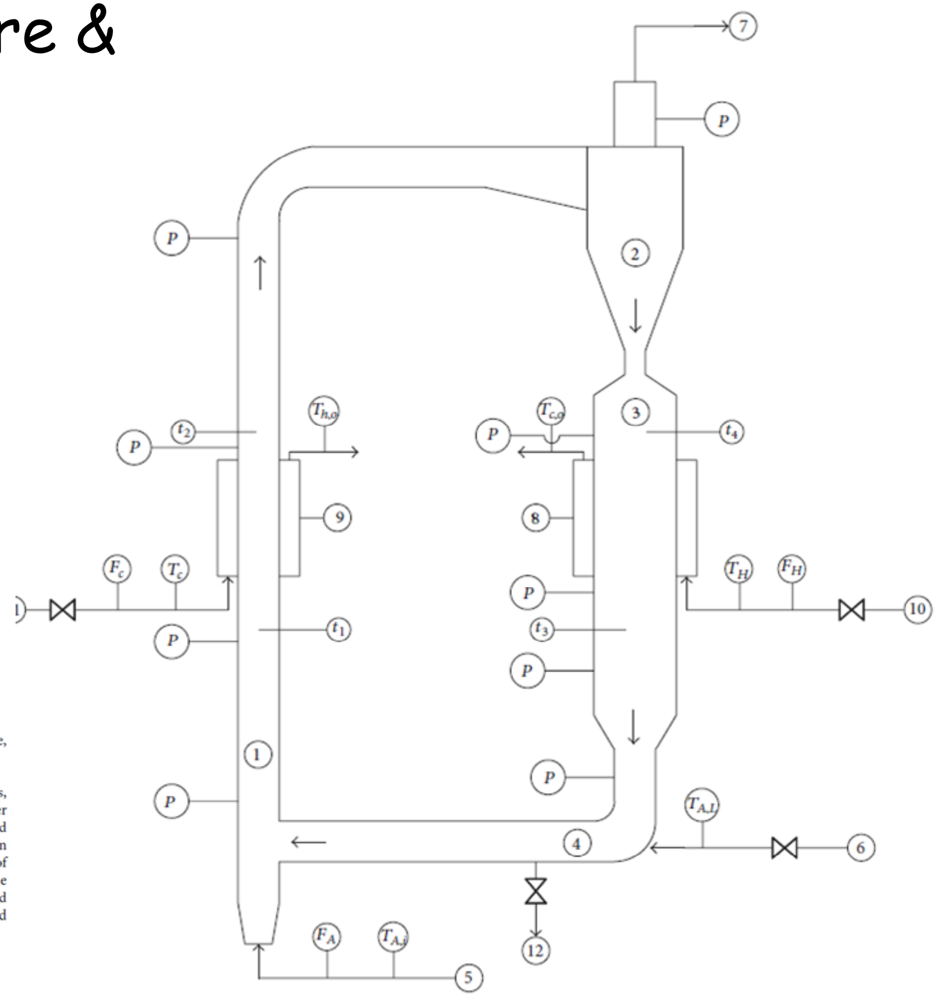
Received 21 June 2015; Revised 11 August 2015; Accepted 18 August 2015

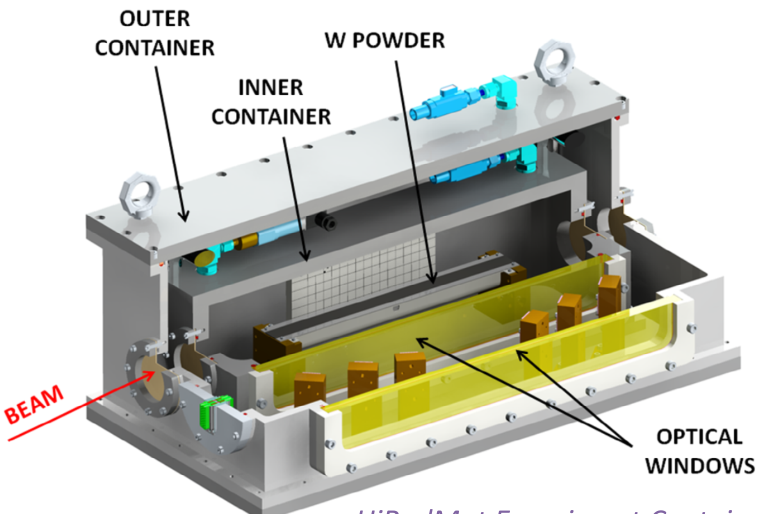
Academic Editor: Franco Berruti

With the development of circulating fluidized beds (CFB) and dense upflow bubbling fluidized beds (UBFB) as chemical reactors, or in the capture and storage of solar or waste heat, the associated downcomer has been proposed as an additional heat transfer system. Whereas fundamental and applied research towards hydrodynamics has been carried out, few results have been reported on heat transfer in downcomers, even though it is an important element in their design and application. The wall-to-suspension heat transfer coefficient (HTC) was measured in the downcomer. The HTC increases linearly with the solids flux, till values of about 150 kg/m^2 s. The increasing HTC with increasing solid circulation rate is reflected through a faster surface renewal by the downflow of the particle-gas suspension at the wall. The model predictions and experimental data are in very fair agreement, and the model expression can predict the influence of the dominant parameters of heat transfer geometry, solids circulation flow, and particle characteristics.

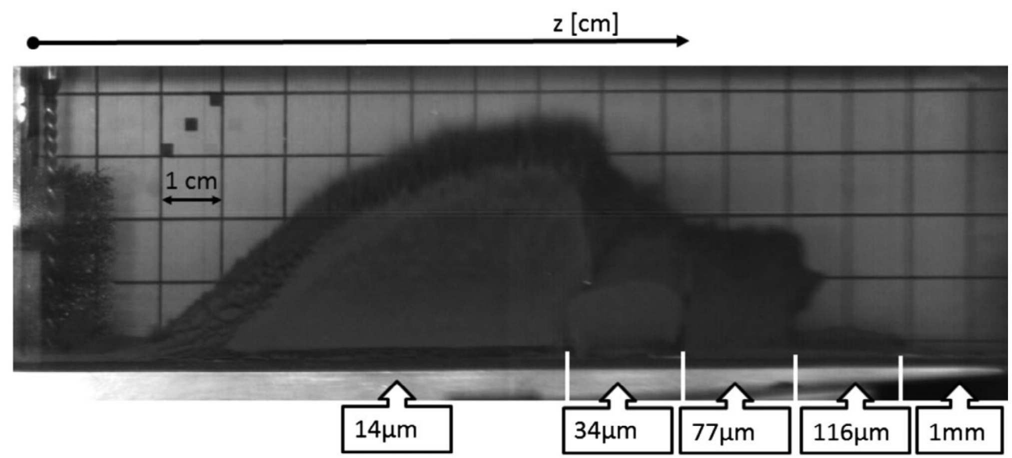


Tungsten Powder Experiments (Online)

- 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
  - Future experiments needed for powder contained in tube



HiRadMat Experiment Container



Response of various size spherical tungsten particles to 2E11 protons

[1] O. Caretta 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 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 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.

Disruption of granular tungsten in vacuum

Fluidized bed targets: some potential challenges

- Erosion of material surfaces, e.g. nozzles
- Challenge to avoid moving parts in circuit (e.g. valves)
- Activated dust on circuit walls
- Activation of carrier gas circuit
- Achieving high material density – typically maximum 50% bulk material fraction
- Secondary heating of pipe walls
- Still need a beam window somewhere

Circulating Fluidized Bed of Tungsten Powder Future R+D

- Circuit conceptual design to incorporate into capture solenoid system including beam dump
- Development of circulating fluidised bed design to minimise or *eliminate* moving parts
- Selection of container materials (SiC-SiC composite?)
- Measurement of erosion rates, and development of improved components to mitigate erosion risk
- Measurement of heat transfer between flowing tungsten powder and container wall
- Development of diagnostics for automated operation and fault detection
- Investigate the use of spherical powder to improve flow characteristics

Pragmatic plan for target technology

- 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 & heat load on SC solenoid)
- Graphite has an excellent pedigree as a target material – well worth pursuing for a MC – ref Franqueira talk
  - 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…

Chris Densham