Prospects and considerations for a fluidized tungsten target for the Muon Collider

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Credits & Collaborations - past, present & future

RAL: Peter Loveridge, Dan Wilcox, Mike Fitton, Otto Caretta, Joe O'Dell, Tristan Davenne

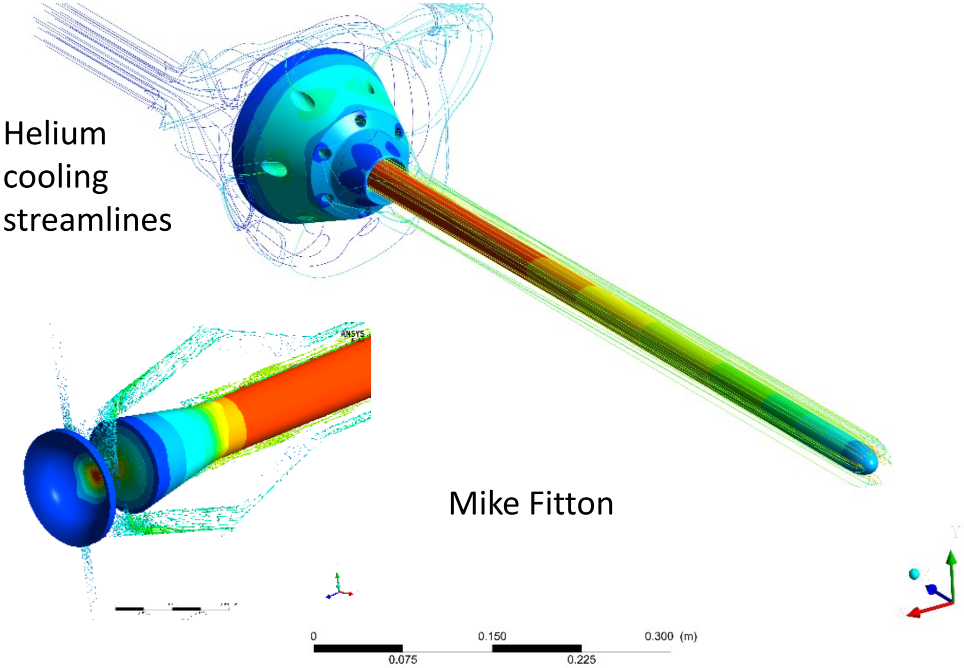
HiRadMat group at CERN: Ilias Efthymiopoulos, Nikos Charitonidis, Adrian Fabich

Transnational access supported by EuCARD-2

Warwick University, UK: John Back, William Bishop (starting October 2023)

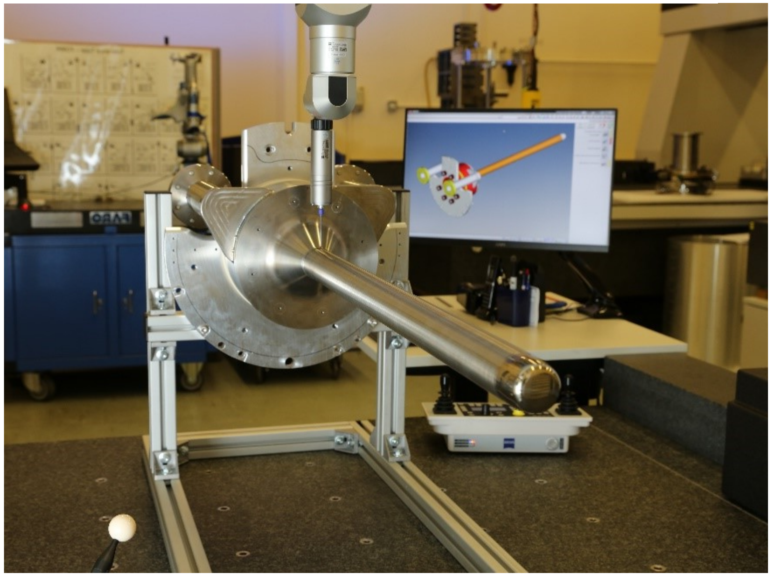
T2K graphite target

- Helium cooled graphite target in titanium alloy vessel & beam windows
- Engineered at RAL as UK in-kind contribution to T2K/HyperK
- Stable operation since 2010, now at 500 kW at 30 GeV
- 1.3 MW prototype constructed and ready for installation for HyperK **(c.2 DPA pa in Ti)**
- **Potential for Muon Collider?**

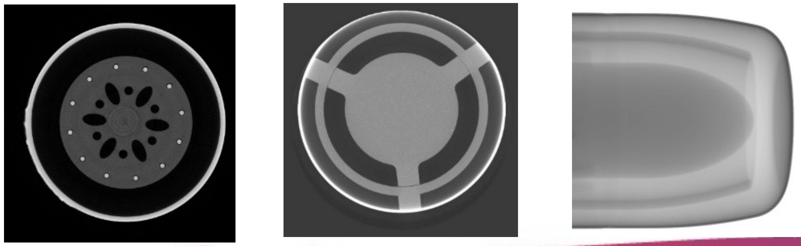


Helium cooling streamlines

Mike Fitton



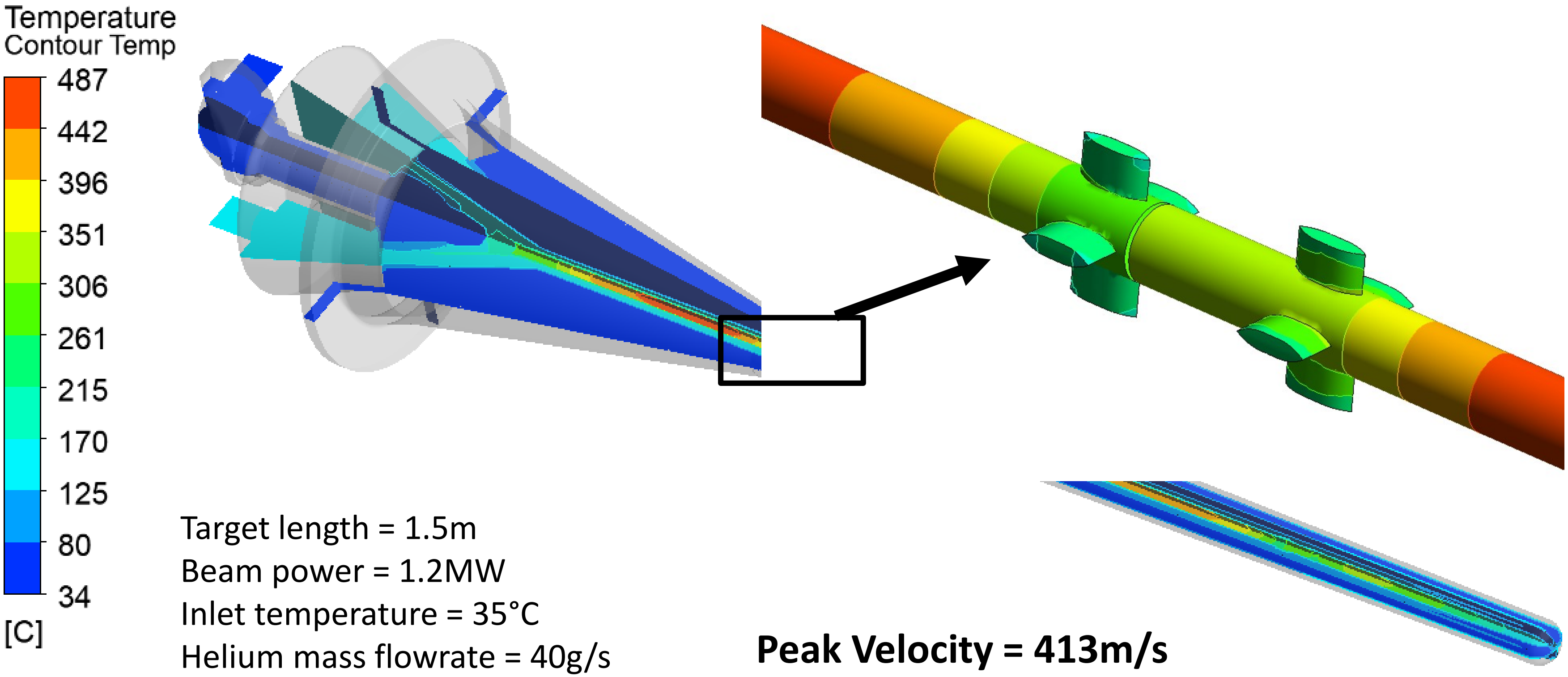
Survey of T2K target using Co-ordinate Measuring Machine (CMM) at RAL.



CT scans of 1.3 MW capable target

LBNF graphite target

- 1.2 MW target beginning construction at RAL as UK IKC to LBNF/DUNE
- Path open towards ACE* upgrade to 2.4 MW (at 120 GeV)



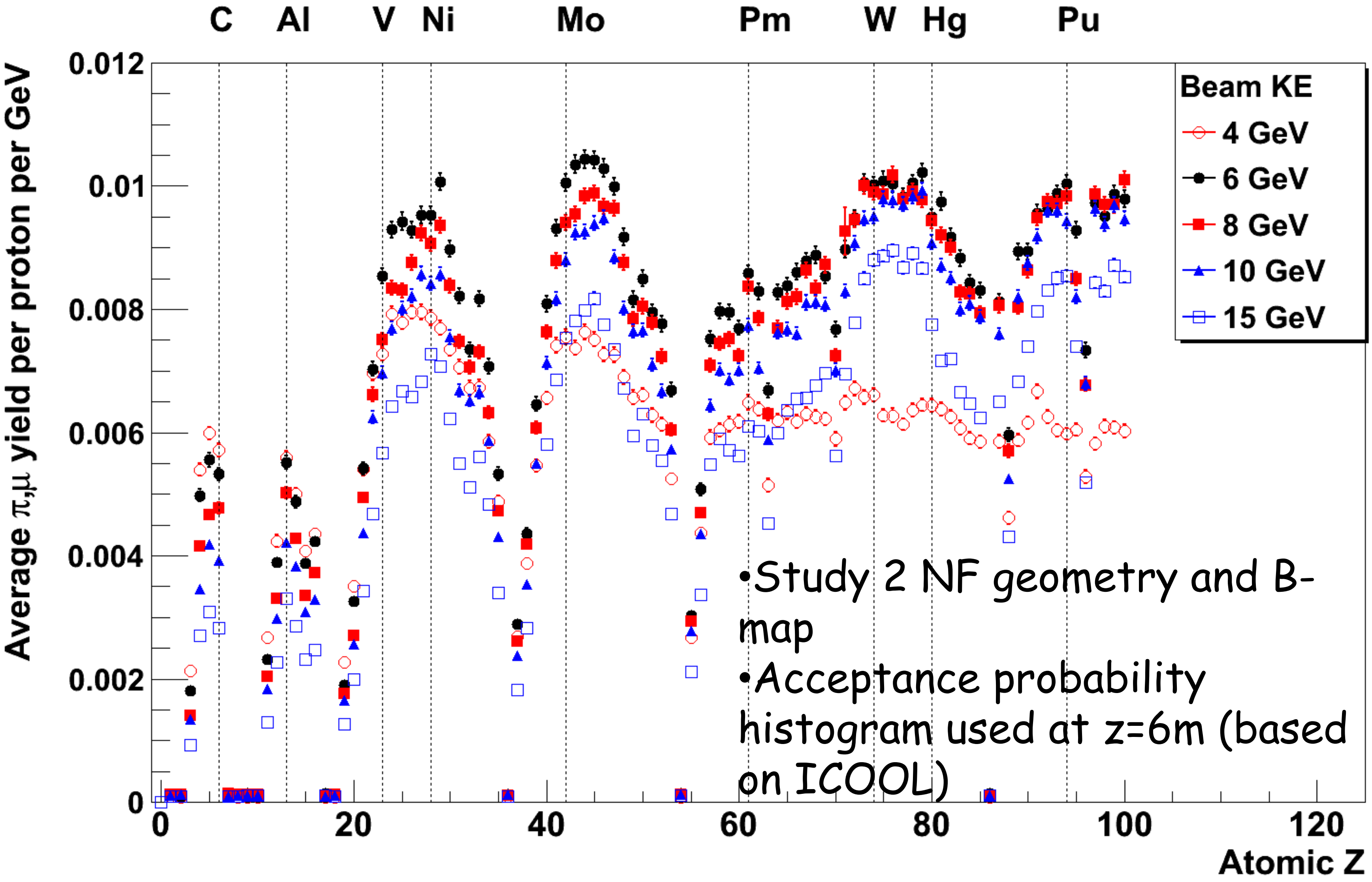
Target length = 1.5m
Beam power = 1.2MW
Inlet temperature = 35°C
Helium mass flowrate = 40g/s
Back-pressure at outlet = 4.5barA

Peak Velocity = 413m/s
Peak Mach Number = 0.38
Pressure drop = 0.42bar

* Accelerator Complex Enhancement

Pion/muon yields for different target Z's and beam energies (J.Back c.12 years ago)

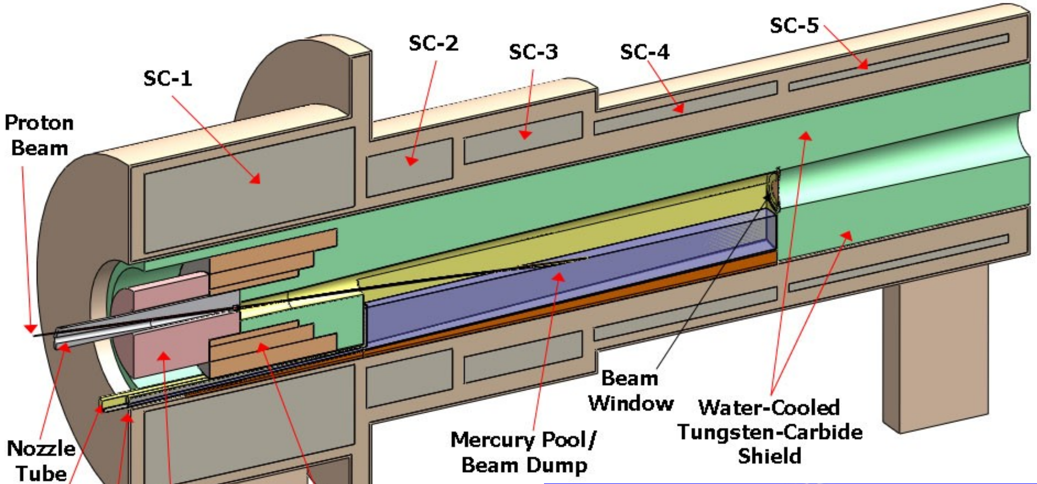
High Z target best at >6 GeV: NB all targets 0.2 m long (Hg jet geometry)

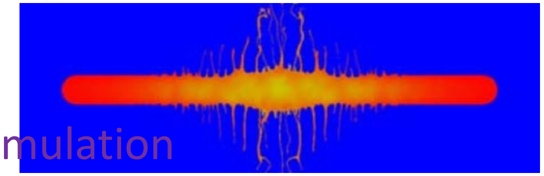


- Study 2 NF geometry and B-map
- Acceptance probability histogram used at z=6m (based on ICOOL)

Previous Muon Collider baseline: free mercury jet

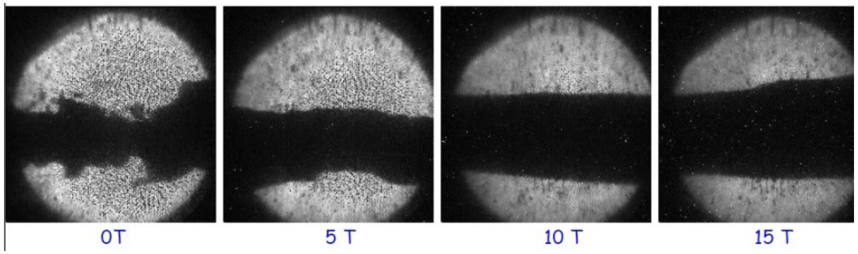
- Baseline liquid mercury target configuration for a Neutrino Factory / Muon Collider
- 20T solenoid captures both signs of pions generated by interaction of proton beam with mercury jet
- Many severe challenges remain, e.g. solenoid, mercury dump, cavitation, radiochemistry, safety, etc
- **Not permissible at CERN (Calviani)**

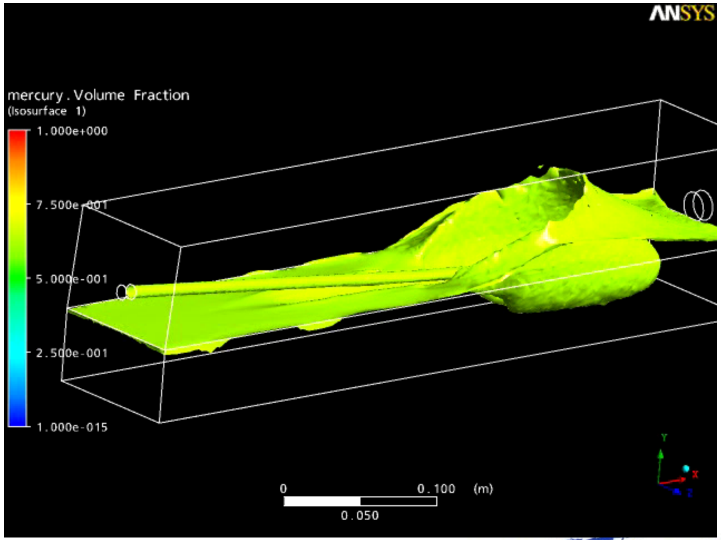




Magnetohydrodynamic simulation of pulsed beam interaction with mercury jet

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





Fluidised Tungsten Powder Technology

☐ Solid (inc. Rotating) Targets

- Poor thermal shock resistance
- Poor heat removal
- No cavitation damage
- No corrosion/radiochemistry

☐ Liquid Metal Targets

- High thermal shock resistance
- Flowing target improves heat removal
- Cavitation damage
- Corrosion/radiochemistry

☐ Fluidised Powder Targets

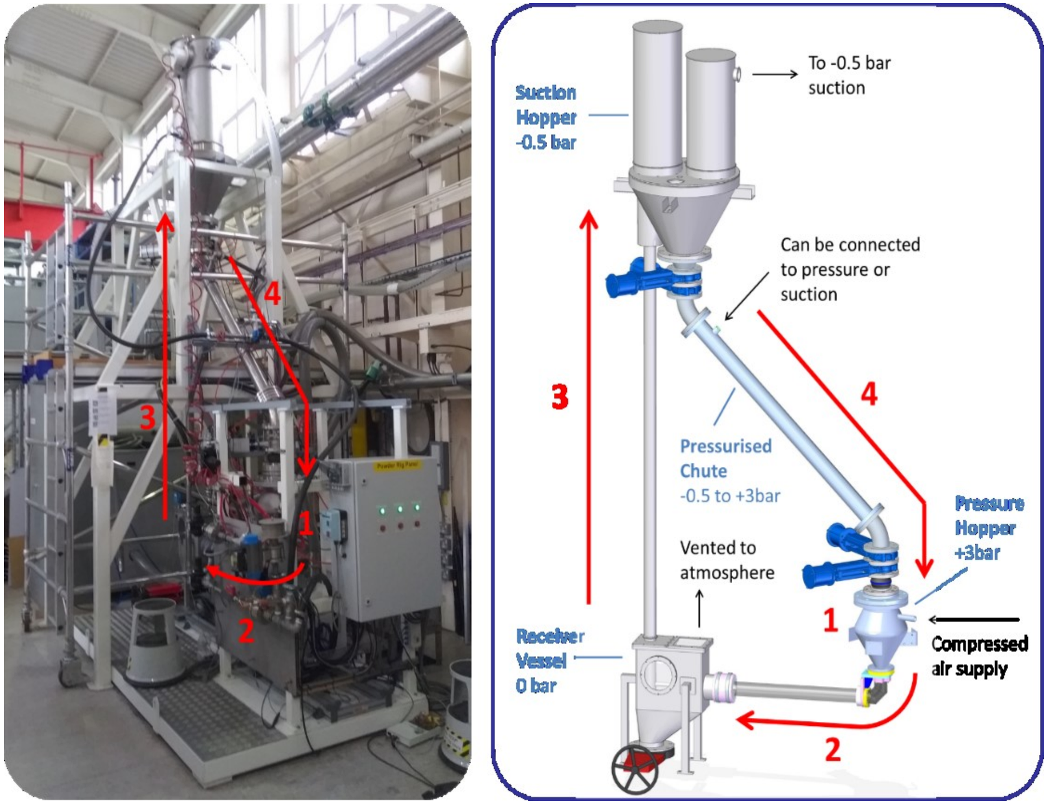
- Combines main benefits of solid and liquid targets
- Poses new challenges e.g. erosion management and powder handling
- These challenges can be addressed with cost effective off-line testing

Fluidised tungsten powder technology

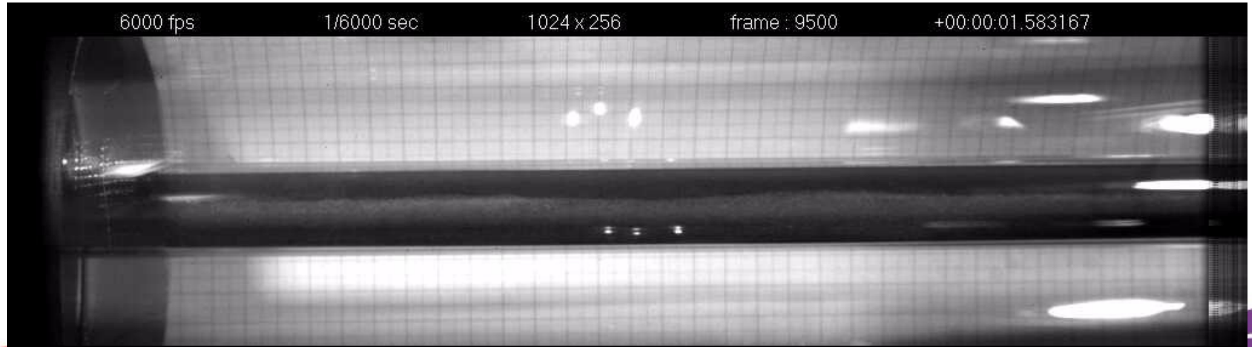
- High Z refractory metal – maximal production of pions
- Alternative to Muon Collider previous baseline of liquid mercury jet, or if graphite or lead not feasible
- Pneumatically (helium) recirculated tungsten powder
- An innovative generic target system exploiting well-established granular flow technology
- Demonstrated off-line at RAL, UK
- 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)

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



Key components of RAL fluidised powder rig

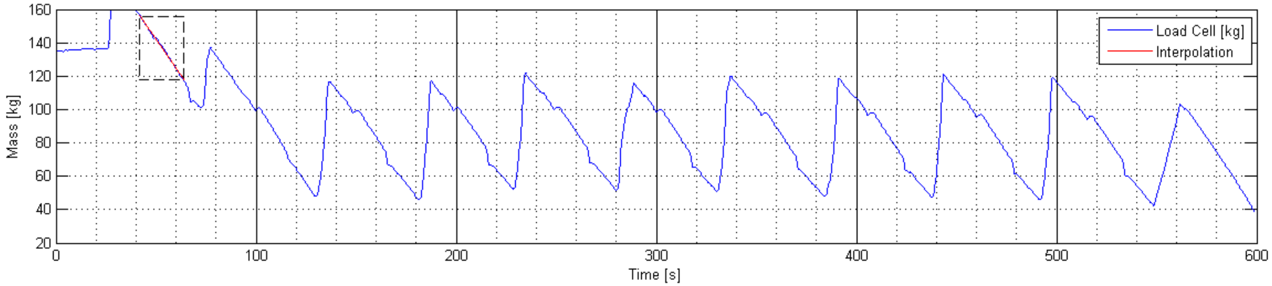


[1] O. Caretta, C. J. Densham, T. W. Davies and R. Woods, "Preliminary Experiments on a Fluidised Powder Target," in Proceedings of EPAC08, WEPP161, Genoa, Italy, 2008.

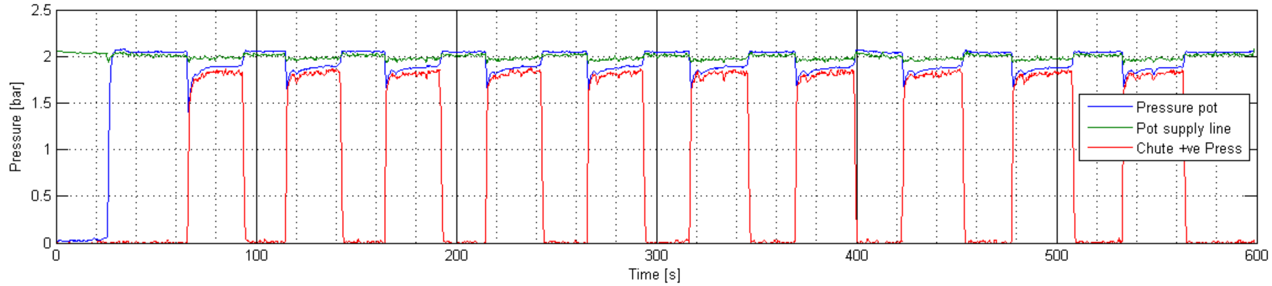
[2] C. J. Densham, O. Caretta and P. Loveridge, "The potential of fluidised powder target technology in high power accelerator facilities," in Proceedings of PAC09, WE1GRC04, Vancouver, BC, Canada, 2009.

[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.

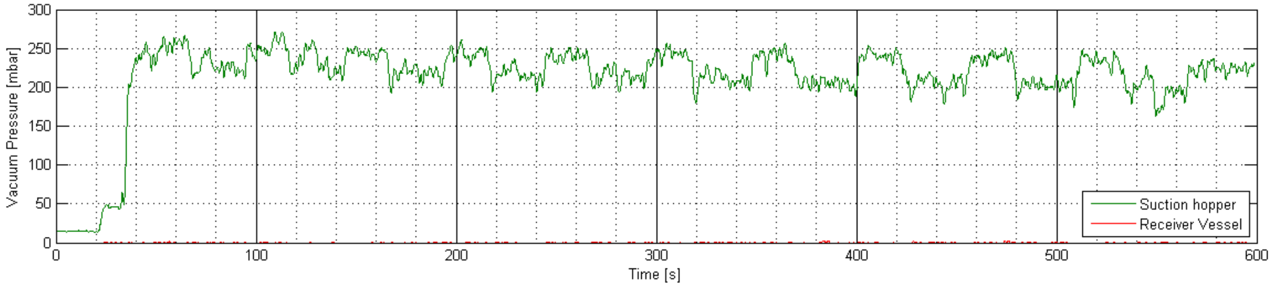
Continuous recirculating flow demonstrated (batch mode)



Mass in pressurised discharge hopper



Pressure cycling of chute and discharge hopper



Suction line pressure variation during recycling

Circulating Fluidized Bed technology

- Literature may indicate future technology path for a Muon Collider target

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Research Article

Wall-to-Suspension Heat Transfer in a CFB Downcomer

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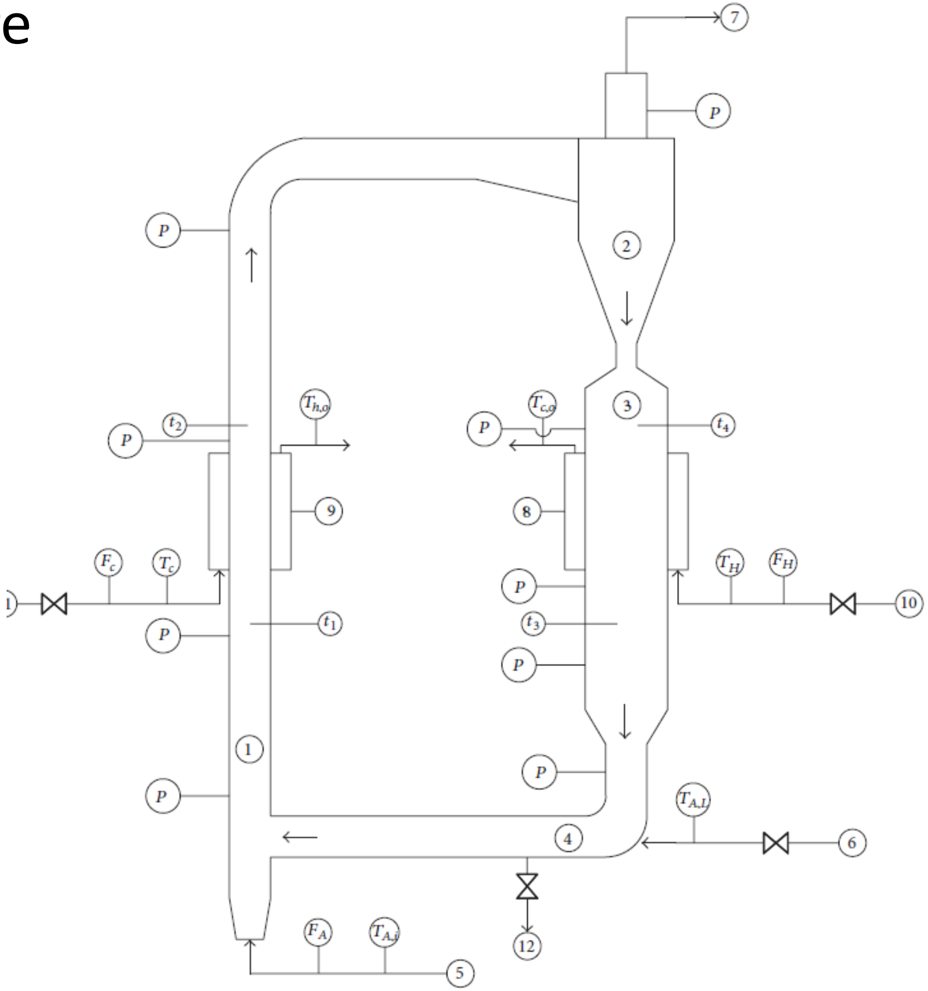
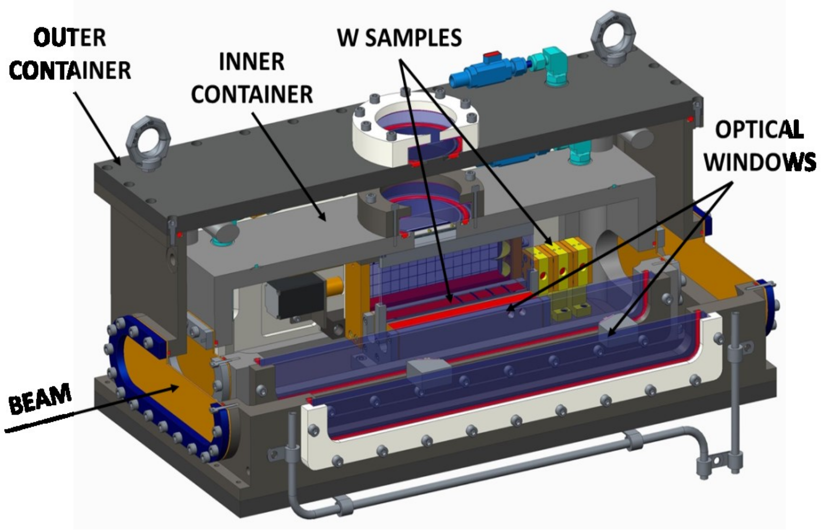
With the development of circulating fluidized beds (CFB) and dense upflow bubbling fluidized beds (UBFB) as chemical reactors, or in the capture and storage of solar or waste heat, the associated downcomer has been proposed as an additional heat transfer system. Whereas fundamental and applied research 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.



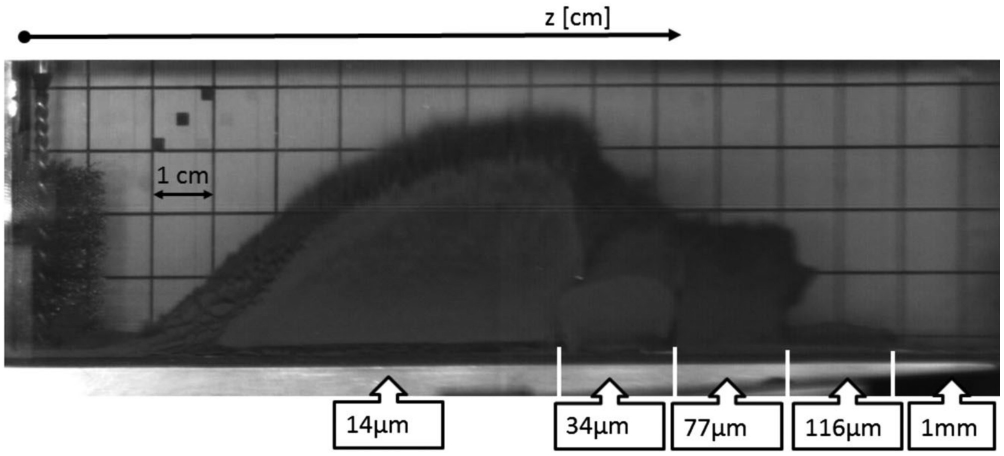
Chris Densham

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 experiment could investigate powder contained in tube**



HiRadMat Experiment Container



Response of various size spherical tungsten particles to 2E11 protons

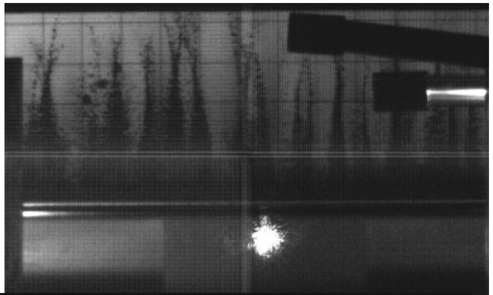
[1] O. Caretta, T. Davenne et al., “Response of a tungsten powder target to an incident high energy proton beam,” Physical review special topics - accelerators and beams, vol. 17, no. 10, DOI: 10.1103/PhysRevSTAB.17.101005, 2014.

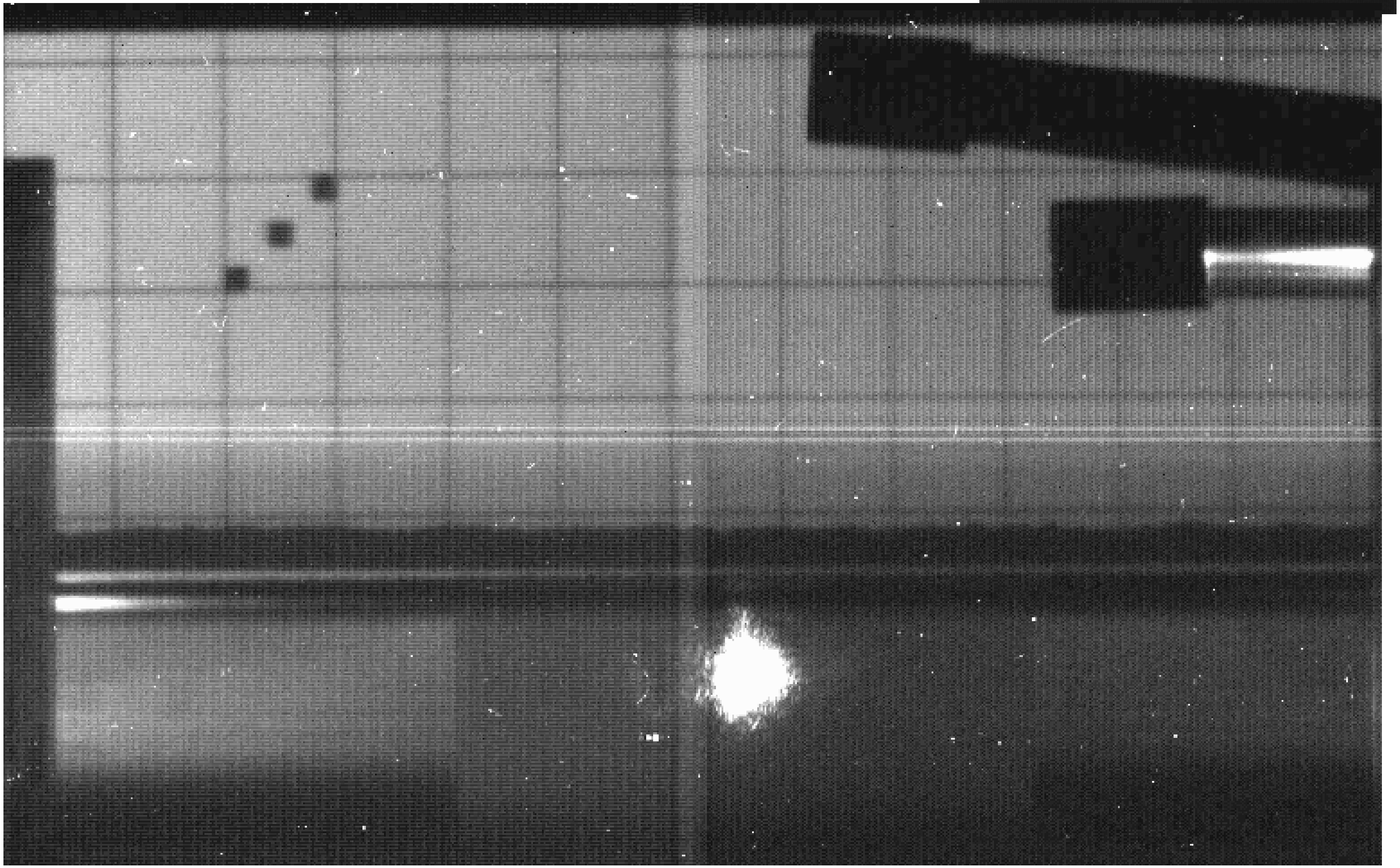
[2] O.Caretta, P.Loveridge et al., “Proton beam induced dynamics of tungsten granules,” Physical Review Accelerators and Beams, vol. 21, no. 3, DOI: 10.1103/PhysRevAccelBeams.21.033401, 2018.

[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.

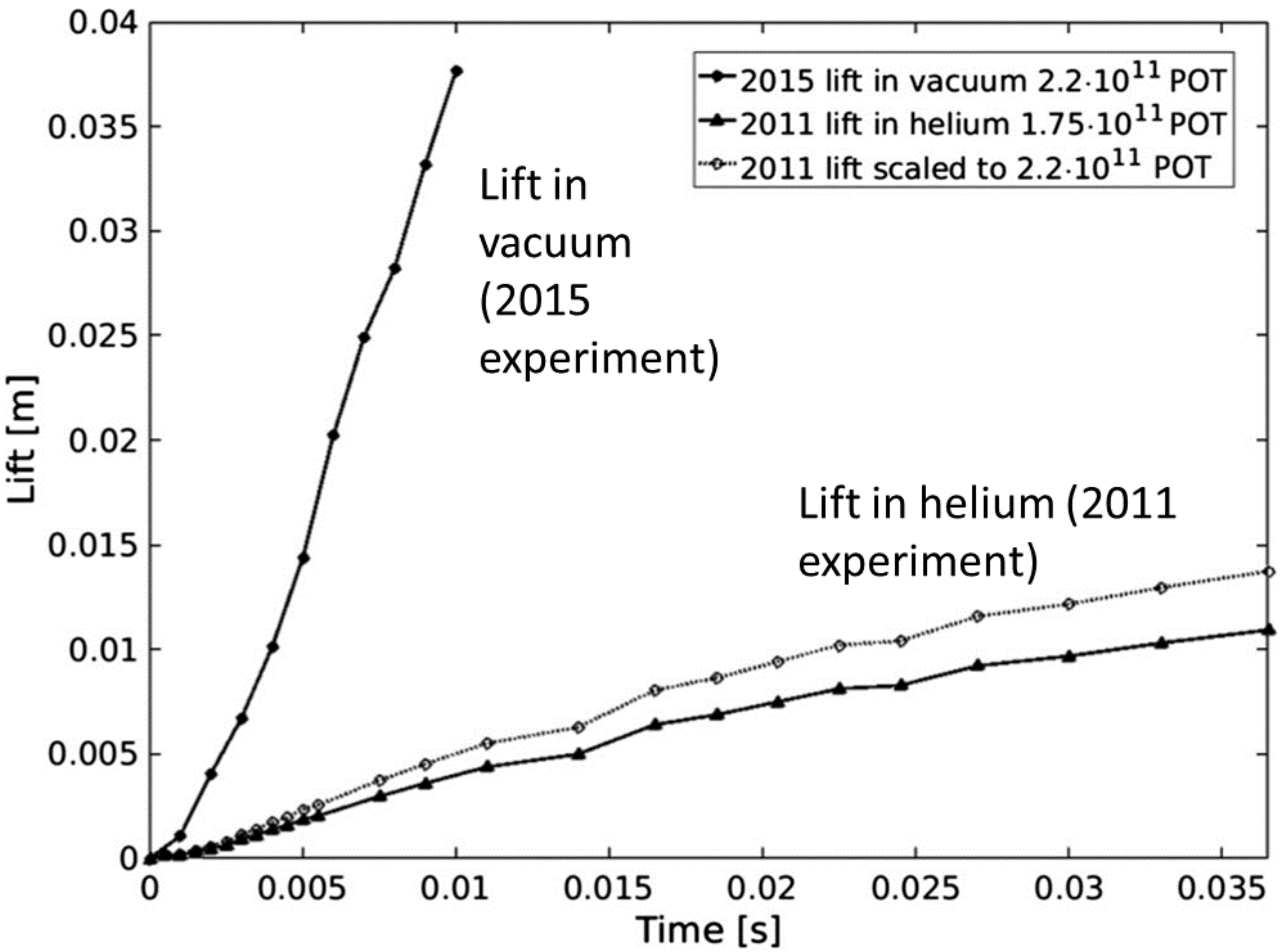
1st experiment on HiRadMat at CERN

3E+11 protons on tungsten powder in helium atmosphere
(ΔT=365°C in 7μs)



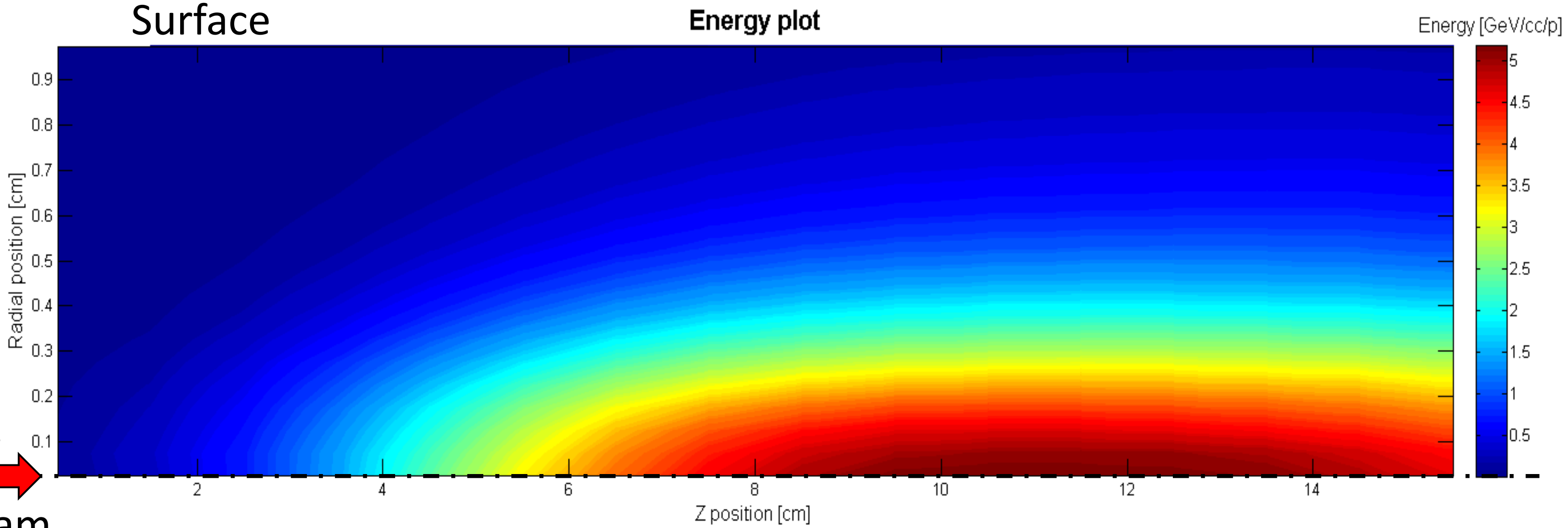


Powder lift in vacuum vs helium



Energy and charge deposition in 50% v/v W

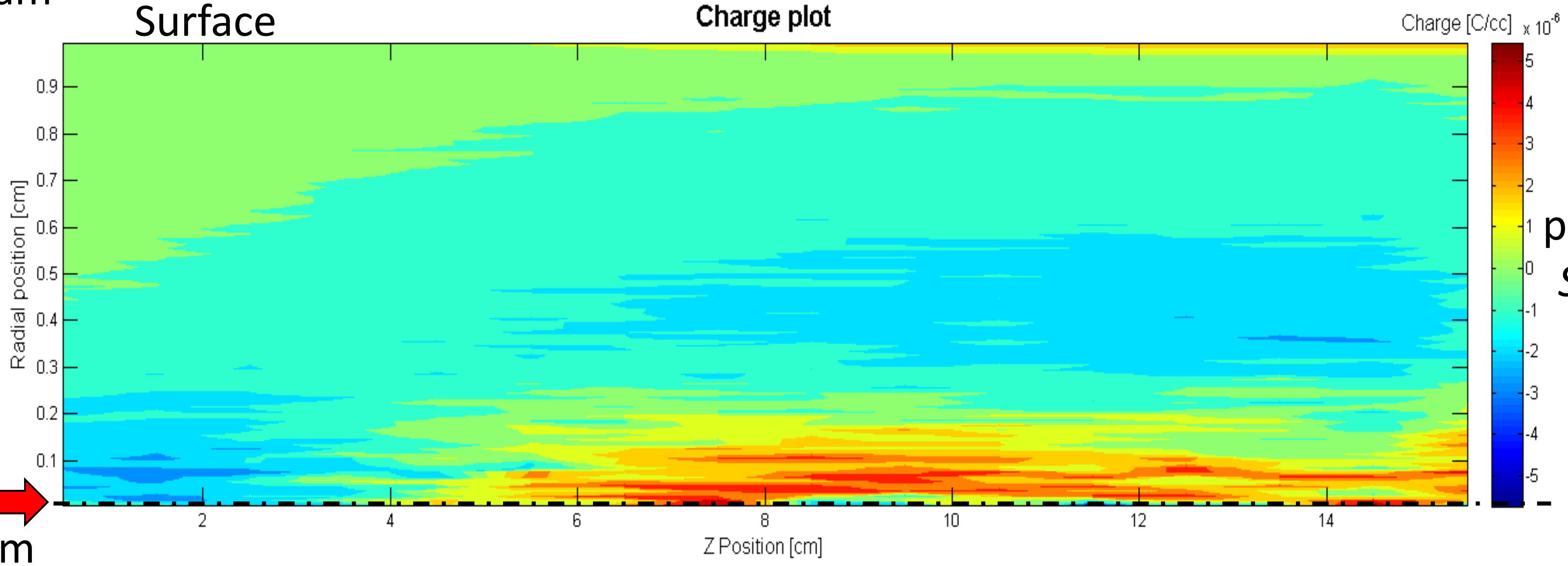
Surface



C/L

Beam

Surface



C/L

Beam

C/cc x10^{-6} after 3.1×10^{12} proton pulse *Sufficient to provide lift mechanism*

Interim conclusions

- Granular tungsten can be effectively pneumatically conveyed in the dense phase (c.50% v/v) and recirculated in the lean phase.
- Granular tungsten is perturbed by intense pulsed particle beams in vacuum, with a lift velocity proportional to the beam intensity.
- Helium environment damps the pulsed beam lift, with a greater damping effect for mixed crystalline powder than for 45 μm spheres.
- Smaller particles demonstrated a greater response than larger ones.
- Lift behaviour consistent with beam induced charge in sample (e.g. ‘coulombic explosion’)

MuCol work plan

- Write paper on fluidized (tungsten) powder test rig
- PhD at Warwick University/RAL starting Oct 2023
  - Physics studies - implement fluidized target & solenoid/horn geometry into BDSIM & FLUKA
  - Consideration of other granular materials e.g. Ni?
- Design of next generation test rig to study outstanding questions/challenges
  - Eliminate moving parts in full circuit design?
  - Select and test container materials (e.g. SiC-SiC?)
- Possible future HiRadMat experiment in more realistic configuration to study interactions with pipe wall