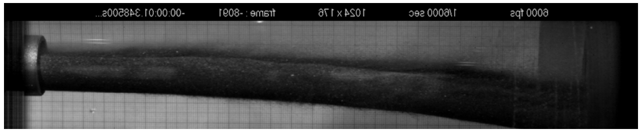
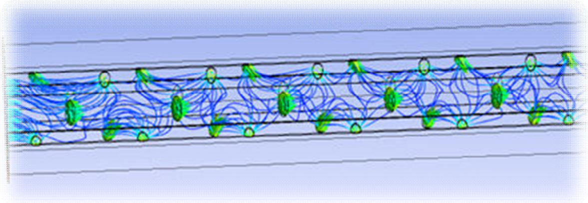
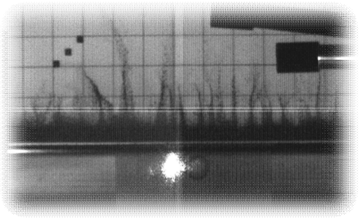
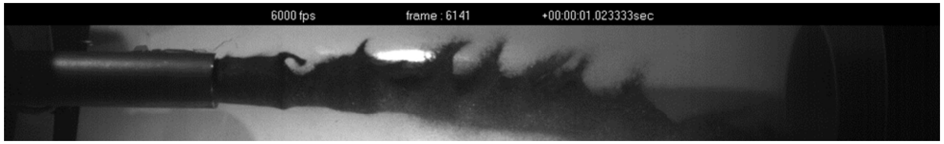




Potential of a Circulating Fluidised Bed (CFB) as a Muon Collider target



Chris Densham

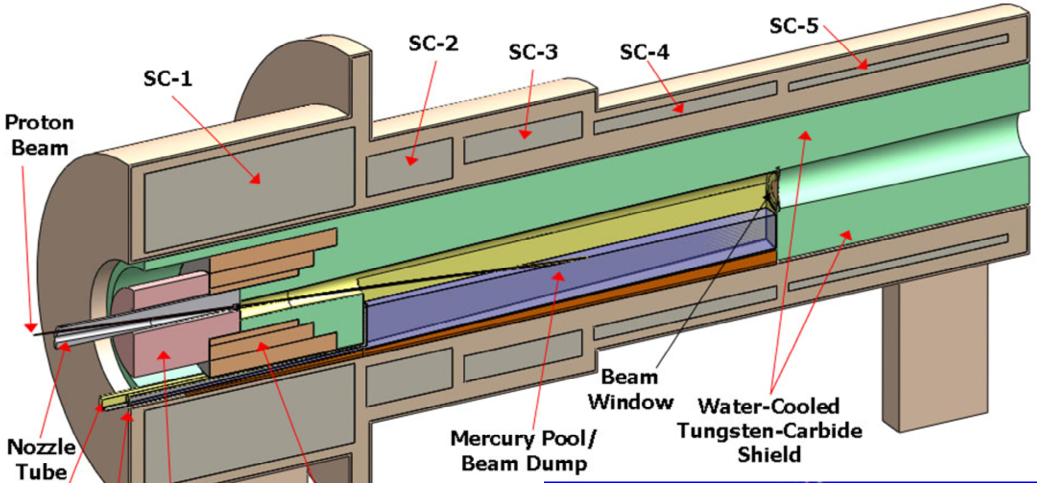
STFC Rutherford Appleton Laboratory, UK

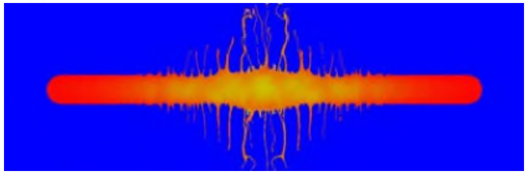
International
MUON Collider
Collaboration

Science & Technology Facilities Council
Rutherford Appleton Laboratory

Previous Muon Collider baseline: free mercury jet

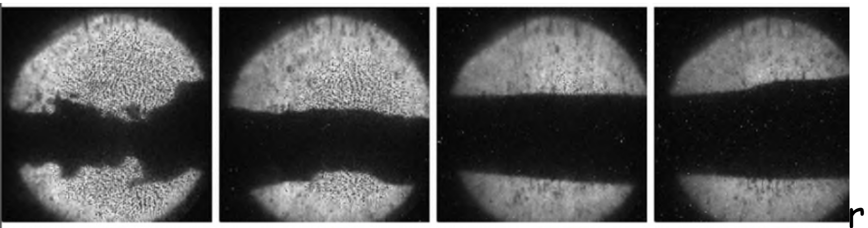
- Baseline liquid mercury target configuration for a Neutrino Factory / Muon Collider
- 20T solenoid captures both signs of pions generated by interaction of proton beam with mercury jet
- Many severe challenges remain, e.g. solenoid, mercury dump, cavitation, radiochemistry, safety, etc



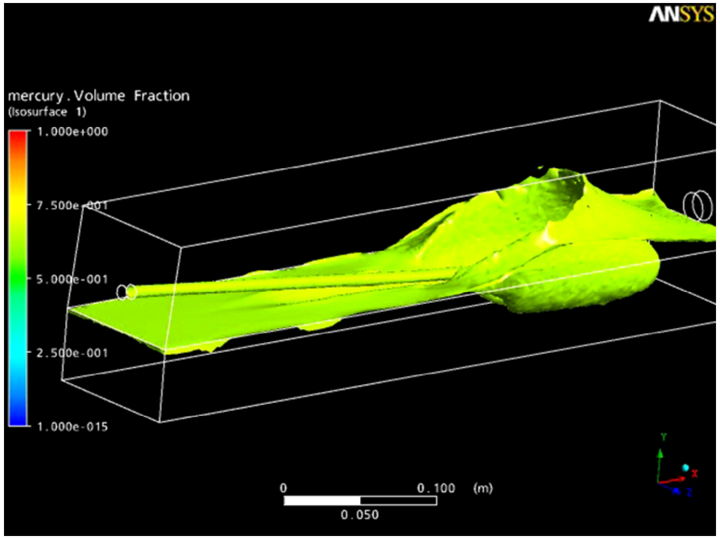


Magnetohydrodynamic simulation of pulsed beam interaction with mercury jet

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

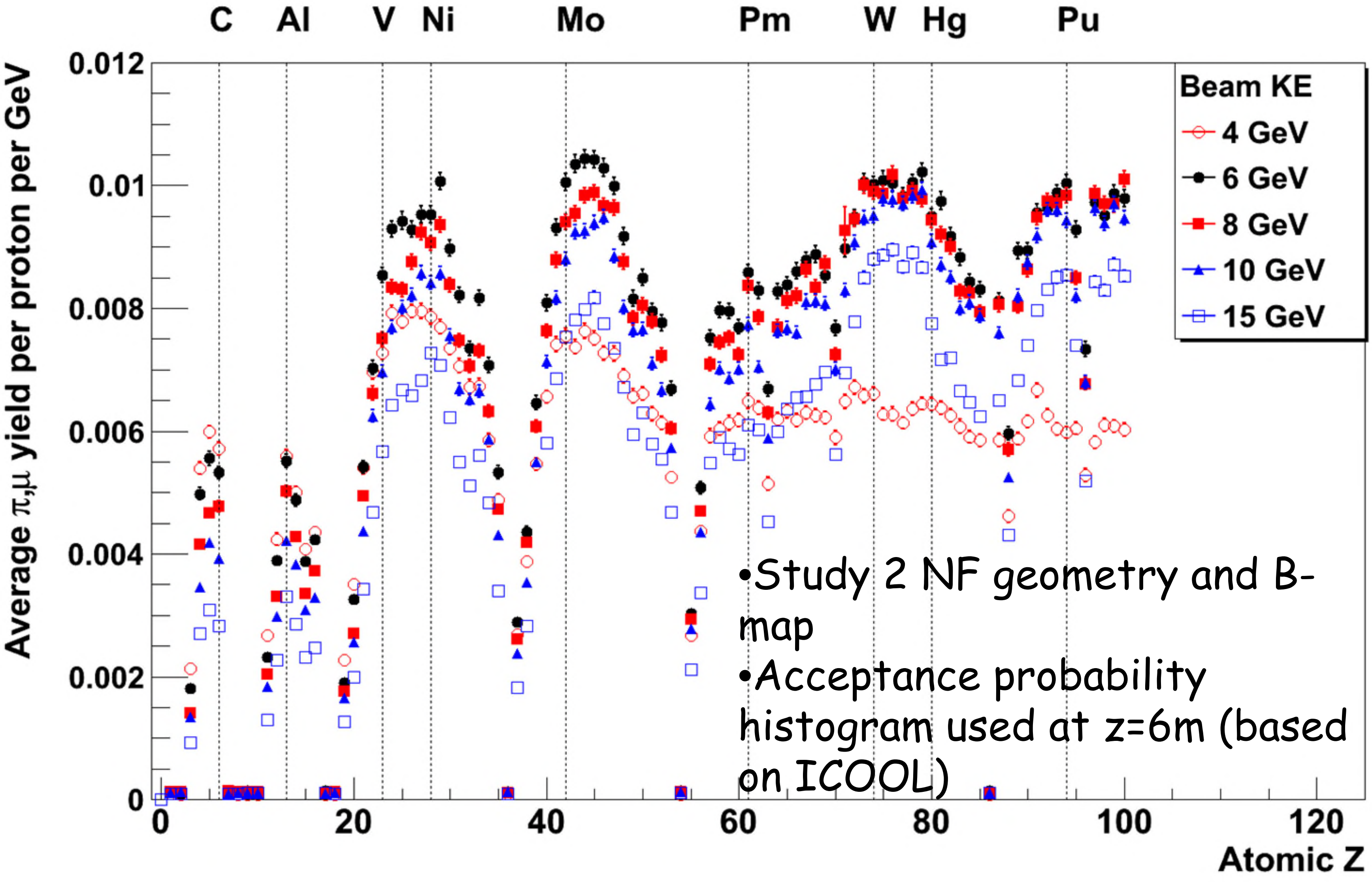


0T 5 T 10 T 15 T



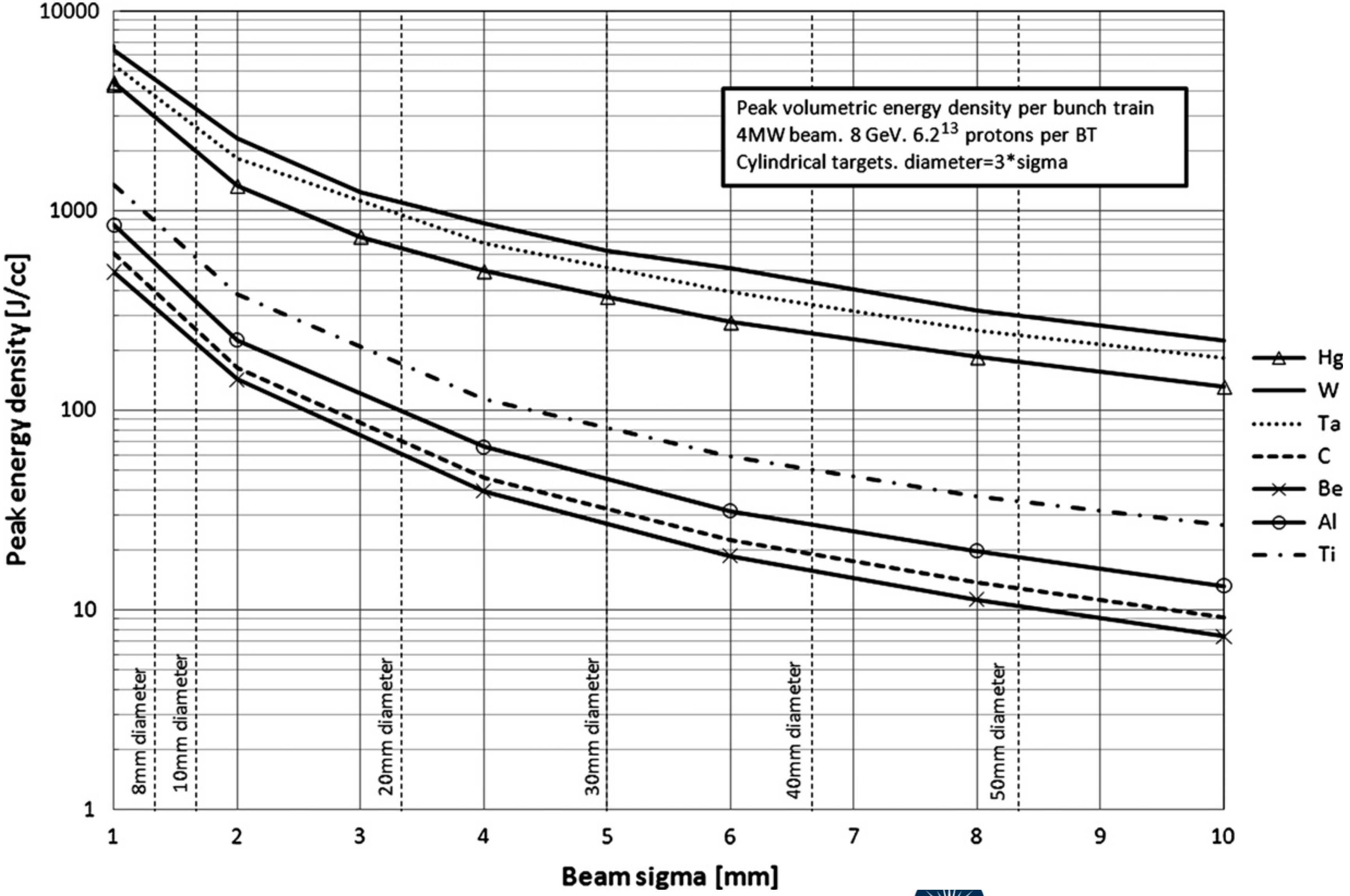
Pion/muon yields for different target Z's and beam energies (J.Back)

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)

Peak heat load for various target materials



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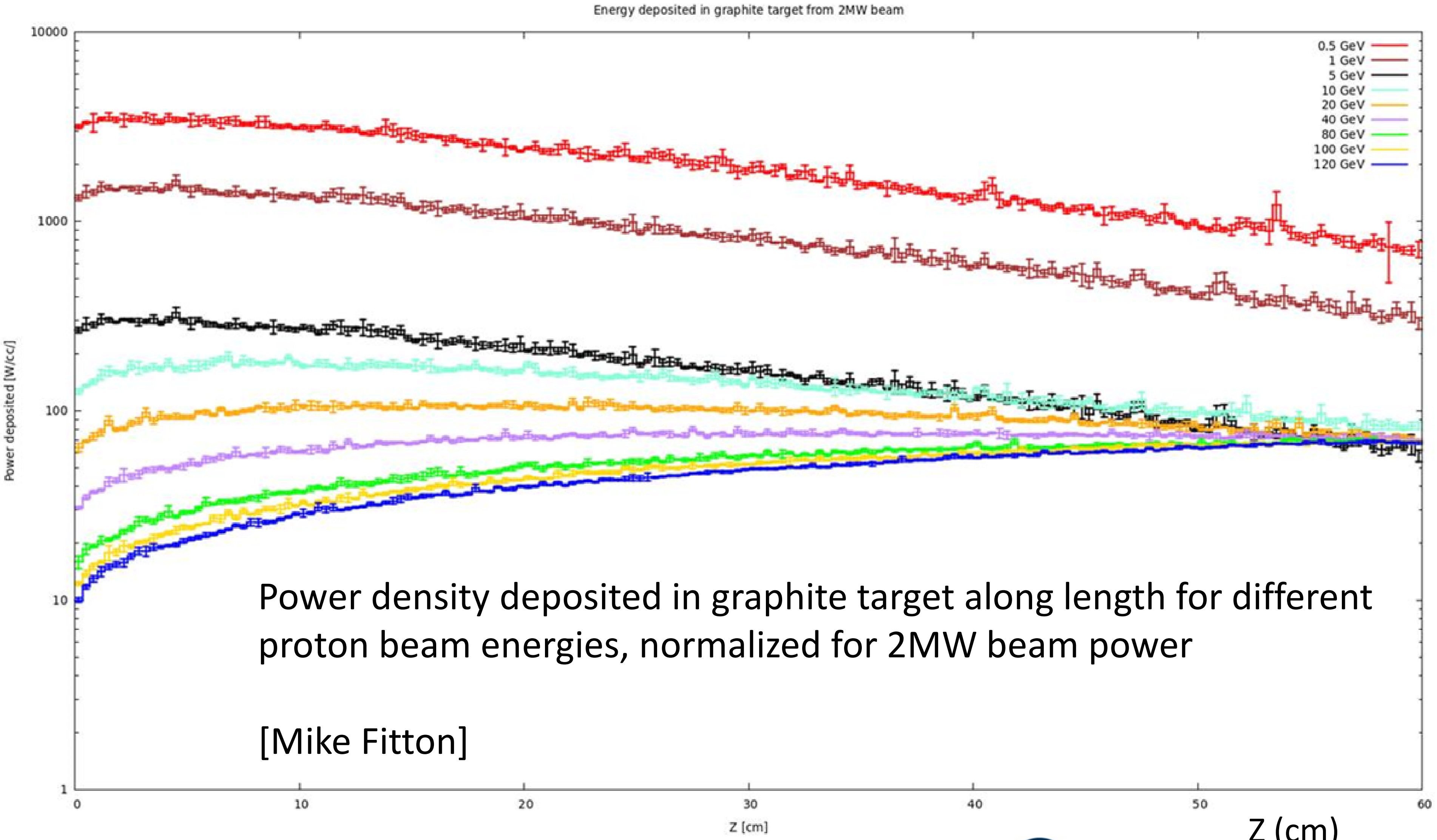
Heat loads in target: Both beam energy and beam power are important



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

[Mike Fitton]

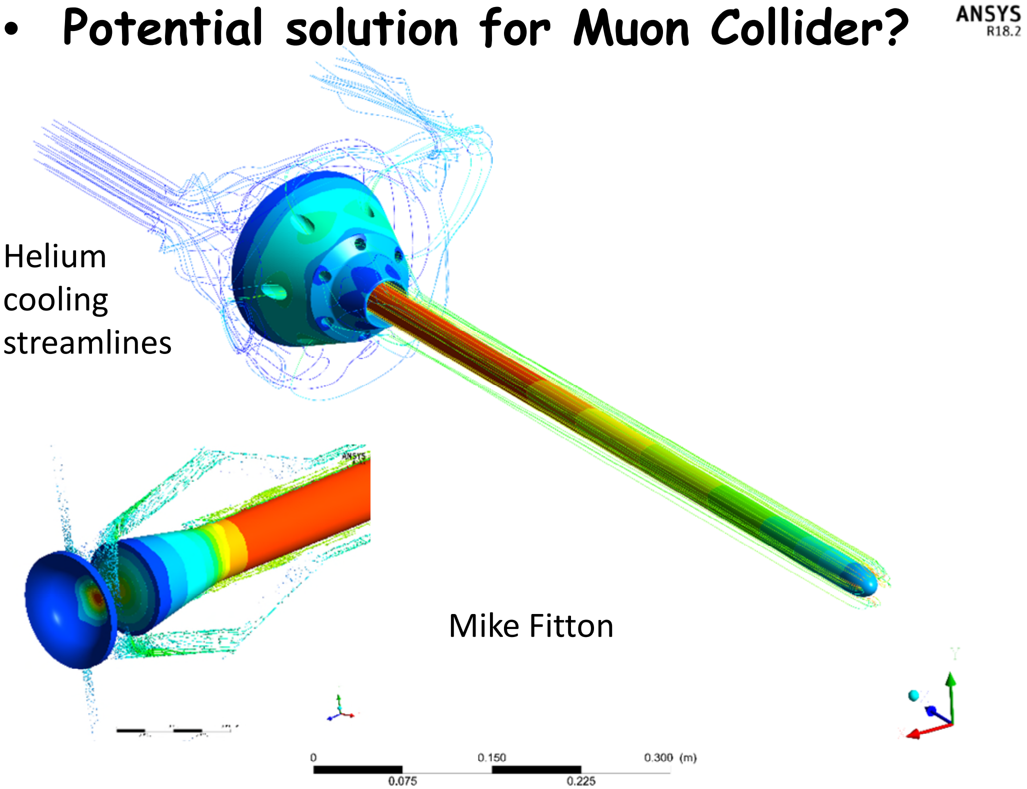
Z (cm)

Chris Densham

Science & Technology Facilities Council
Rutherford Appleton Laboratory

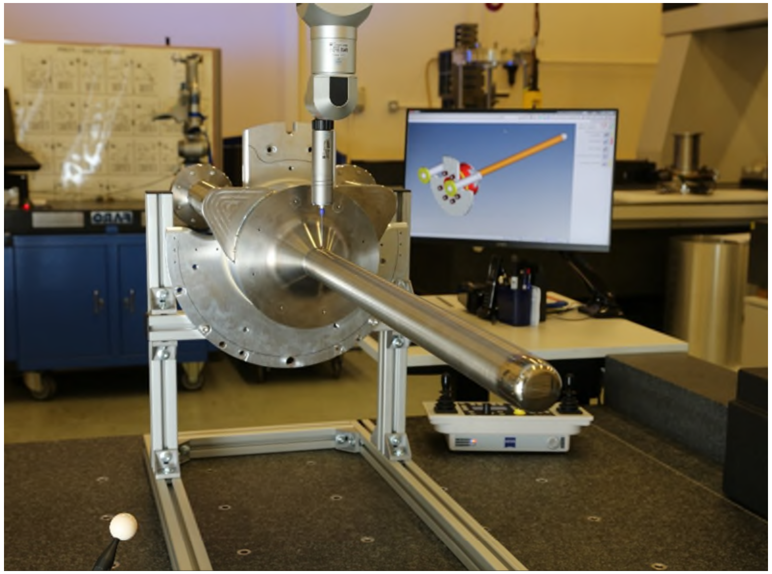
T2K graphite target – 10+ years experience

- Stable operation at 500 kW at 30 GeV
- 1.3 MW prototype constructed at RAL – UK contribution to T2K/HyperK
- Basis for LBNF target for 1.2 MW at 120 GeV (2.4 MW upgrade planned)
- **Potential solution for Muon Collider?**

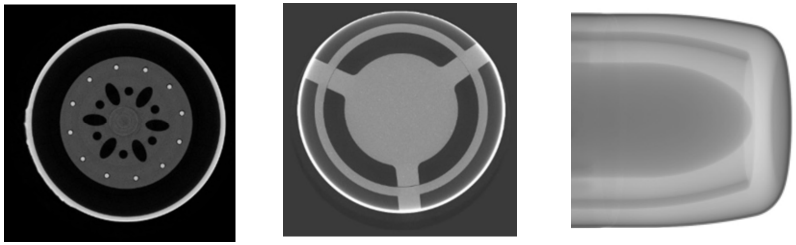


Helium cooling streamlines

Mike Fitton



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



CT scans of new target

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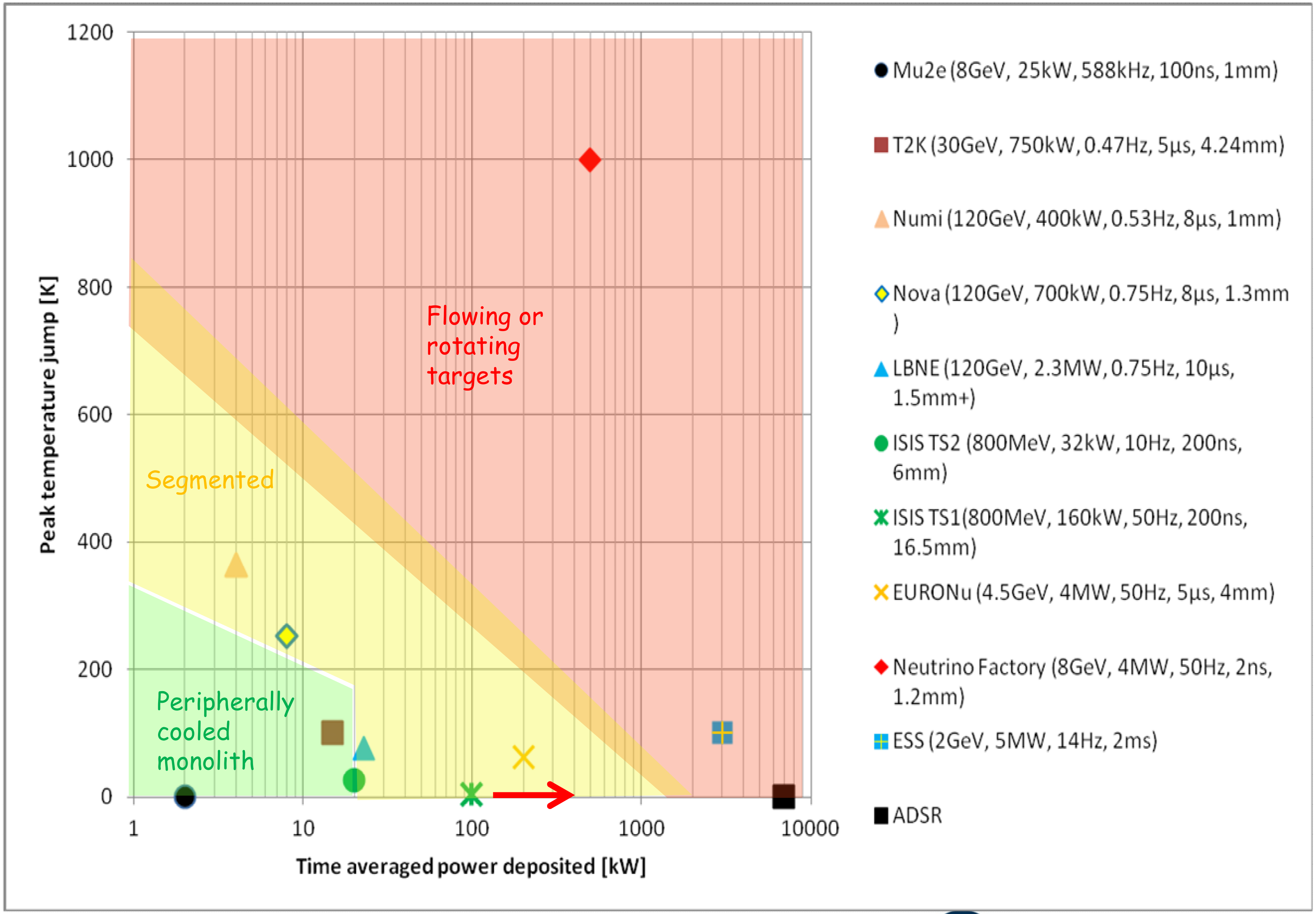
Limitations of target technologies



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'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:

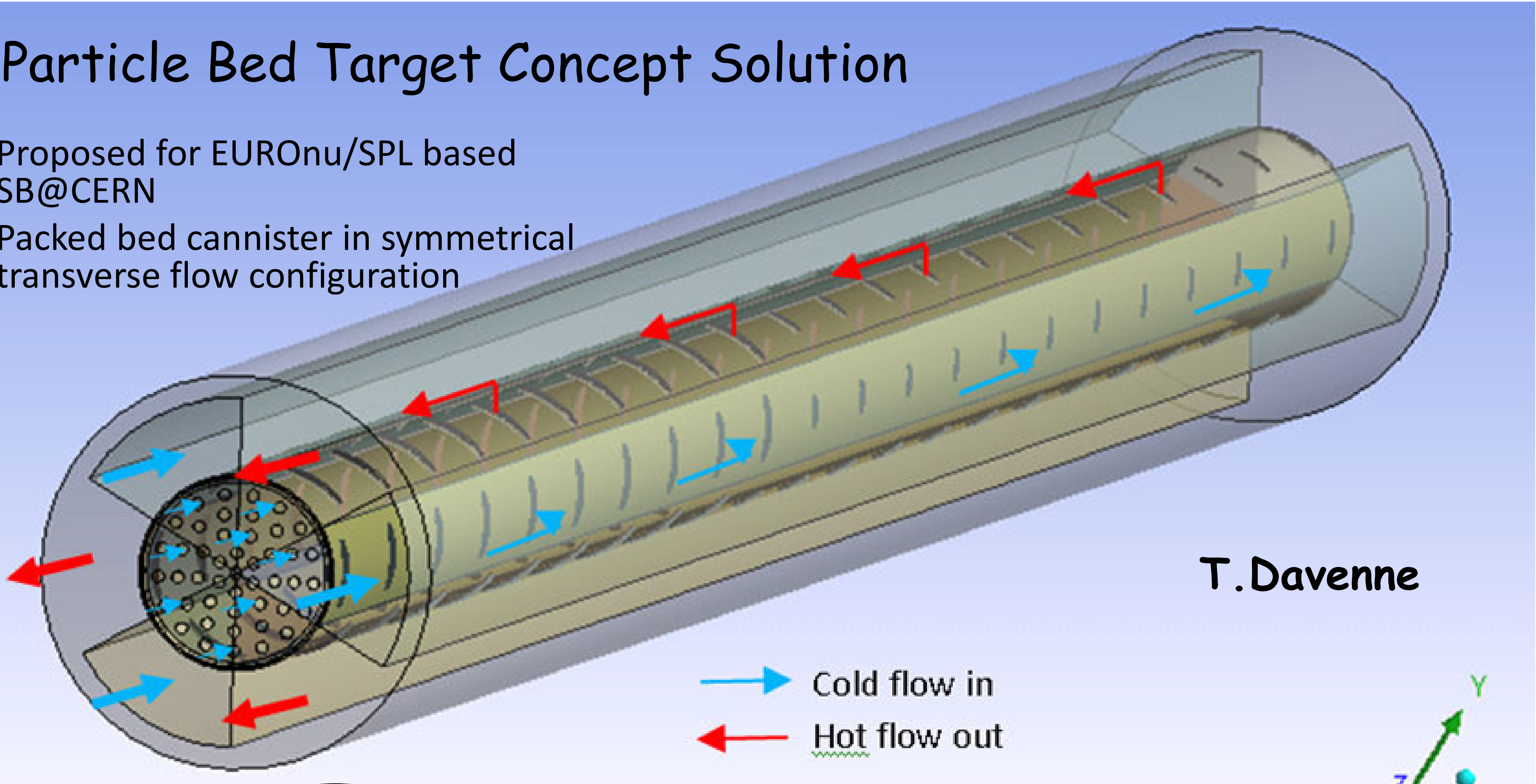
- No 'water hammer' or cavitation effects from pulsed beams
- Lower coolant activation, no radiolysis
- Negligible pion absorption – coolant can be within beam footprint
- For graphite, higher temperatures anneal radiation damage

Low-Z target concepts preferred (static, easier)

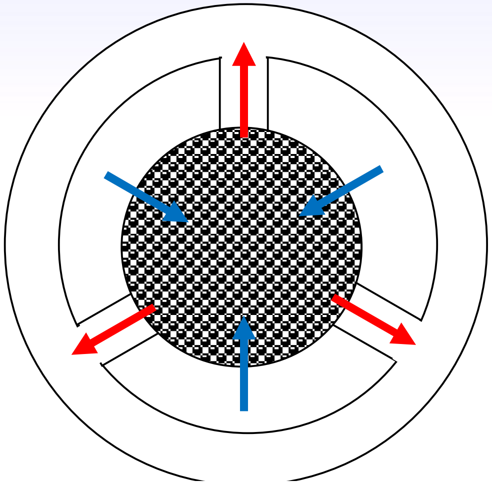
Particle Bed Target Concept Solution

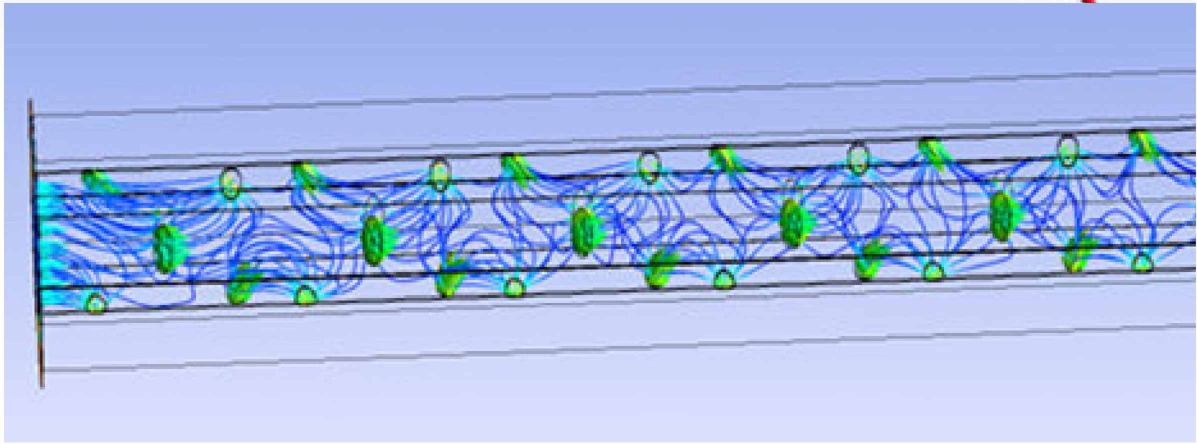
Proposed for EUROnu/SPL based SB@CERN

Packed bed cannister in symmetrical transverse flow configuration



T.Davenne

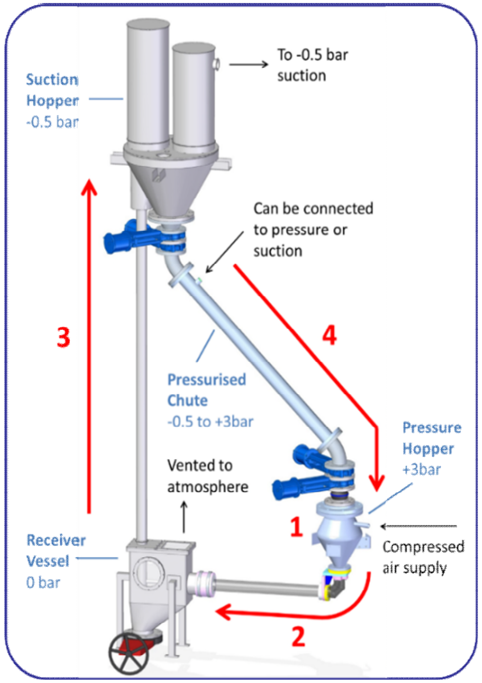




Fluidised tungsten powder technology

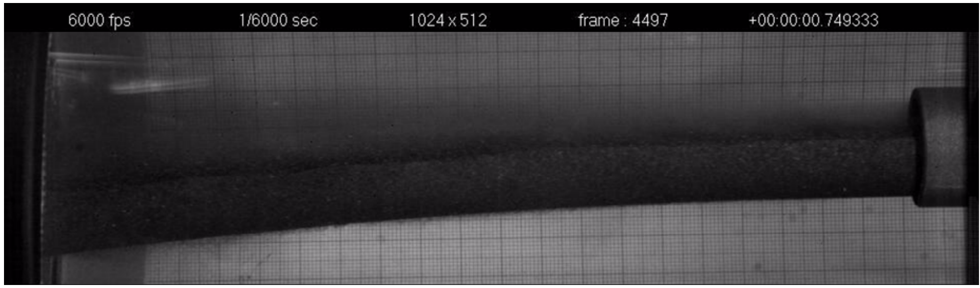
- High Z refractory metal – maximal production of pions
- Alternative to Muon Collider liquid mercury jet
- Pneumatically (helium) recirculated tungsten powder
- An innovative generic target system exploiting well-established granular flow technology
- Demonstrated off-line at RAL
- 1st in-beam experiment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

Fluidised tungsten powder test rig at RAL

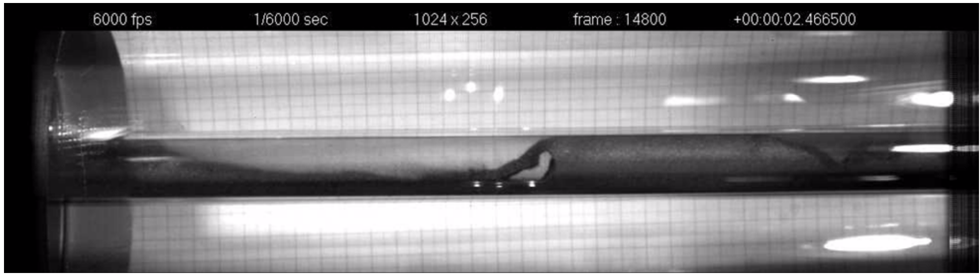


1. Suction / Lift
2. Load Hopper
3. Pressurise Hopper
4. Powder Ejection and Observation

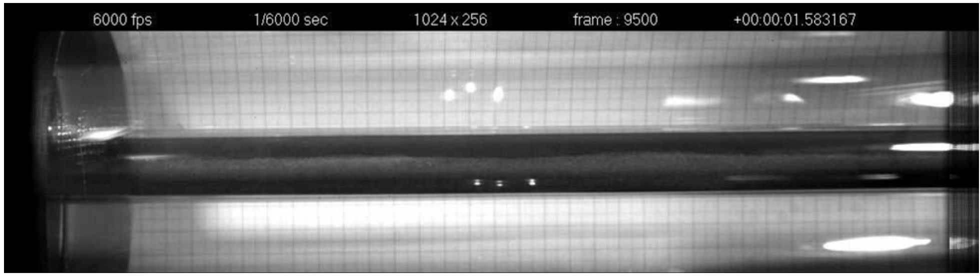
Open jet:



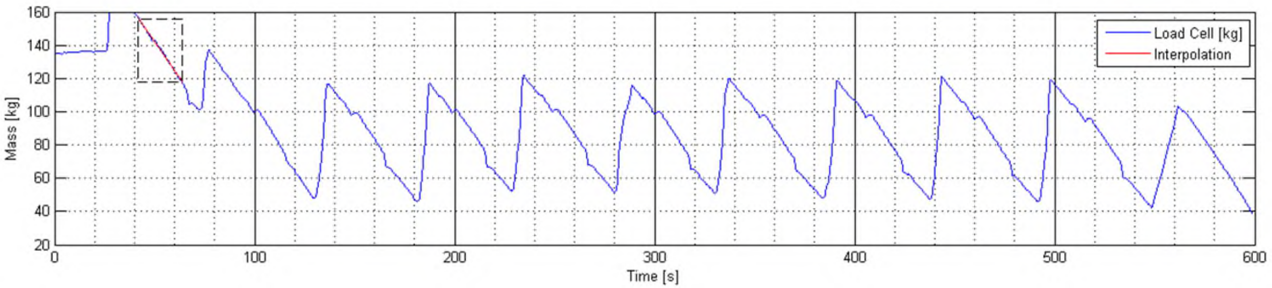
Contained discontinuous dense phase:



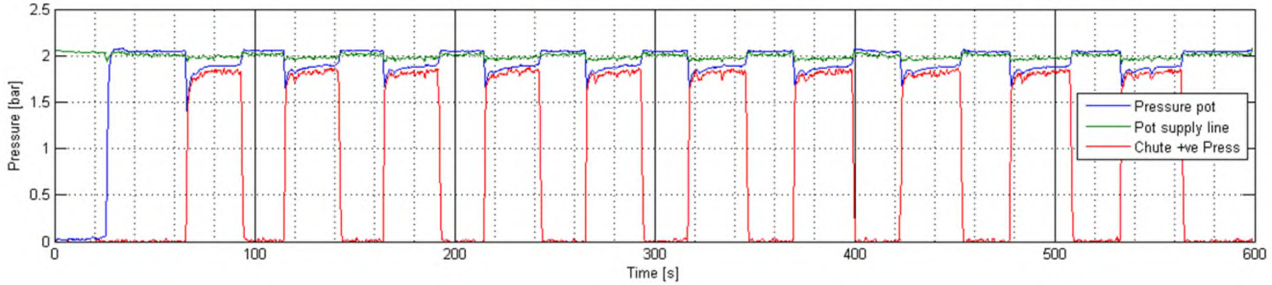
Contained continuous dense phase:



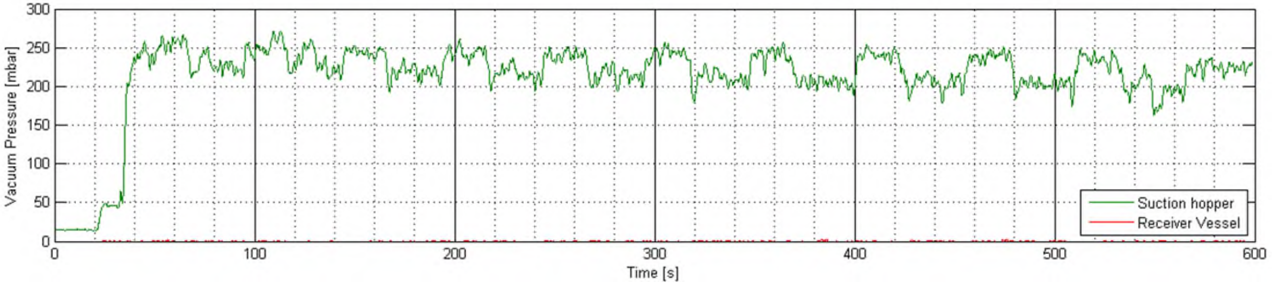
Continuous flow demonstrated (batch mode)



Mass in pressurised discharge hopper



Pressure cycling of chute and discharge hopper

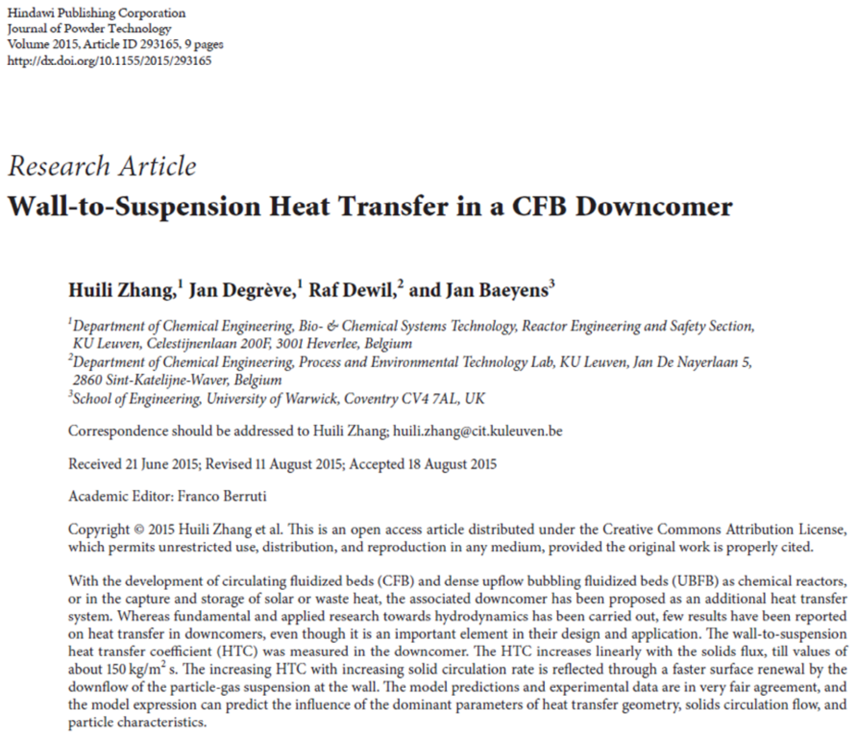


Suction line pressure variation during recycling

Credit: Dan Wilcox, Peter Loveridge

Circulating Fluidized Bed technology

- Circulating fluidized bed (CFB) from literature
- In-line process valves eliminated by a ‘downcomer’
  - flow falls against pressure gradient
  - excellent heat transfer



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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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[2] *Department of Chemical Engineering, Process and Environmental Technology Lab, KU Leuven, Jan De Nayerlaan 5, 2860 Sint-Katelijne-Waver, Belgium*
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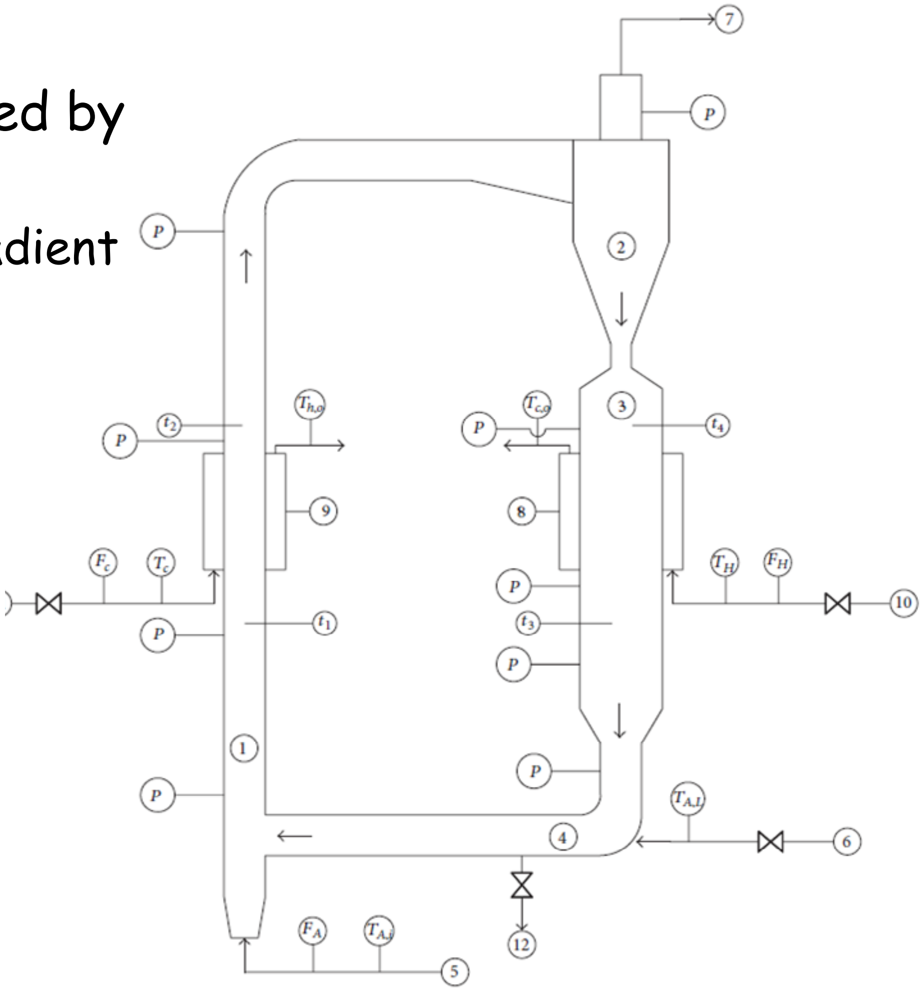
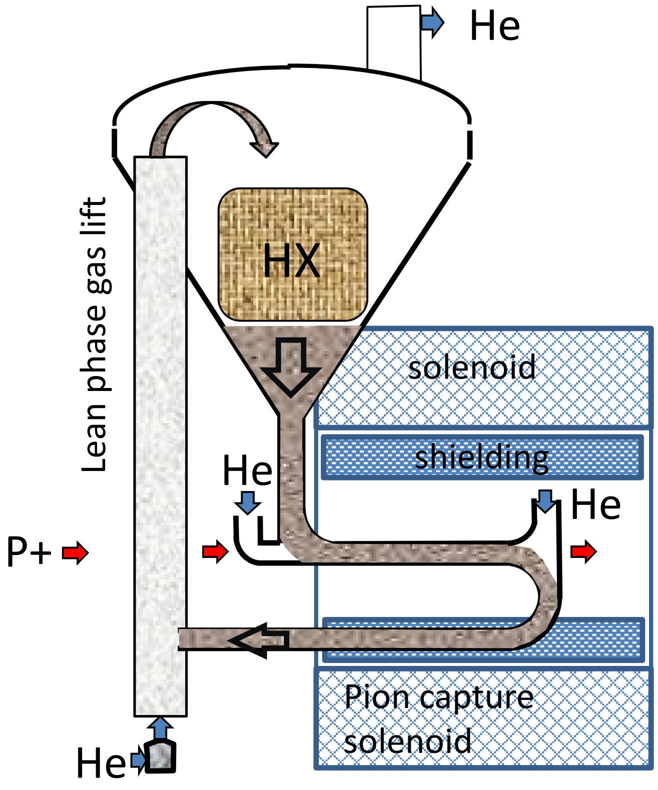
Academic Editor: Franco Berruti

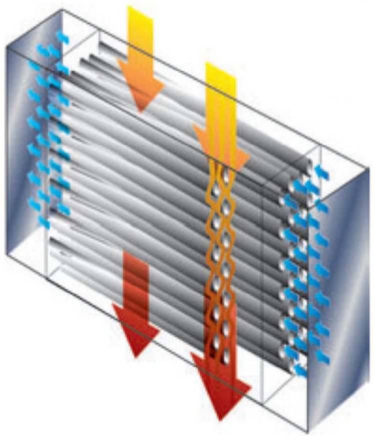
With the development of circulating fluidized beds (CFB) and dense upflow bubbling fluidized beds (UBFB) as chemical reactors, or in the capture and storage of solar or waste heat, the associated downcomer has been proposed as an additional heat transfer system. Whereas fundamental and applied research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



Cartoon suggestion of muon collider target schematic – feasible?

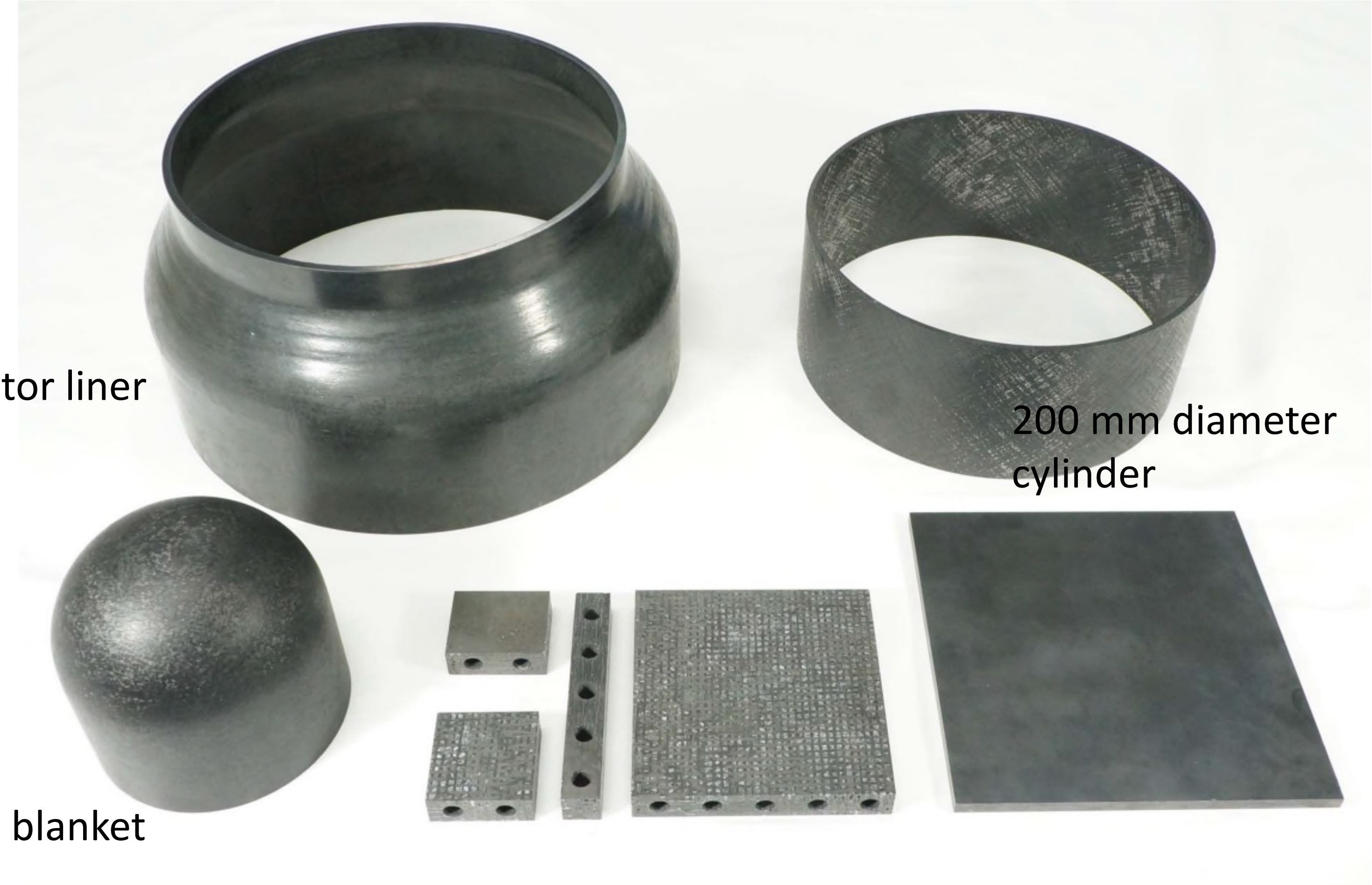
- Circulating Fluidized Bed
  - Dense phase ‘downcomer’
- Gas flow injected at beam entry window and beam exit window to fluidize tungsten powder
- Low velocity dense phase injected into high velocity, high conductance lean phase gas lift
- John Back (Warwick) consulting Prof. Peter Thomas head of Fluid Dynamics Research Centre at Warwick **today**





Example gravity fed granular flow heat exchanger

SiC-SiC composite products – potential wall material



Combustor liner

200 mm diameter cylinder

Fusion blanket

SiC, SiC fiber and SiC/SiC

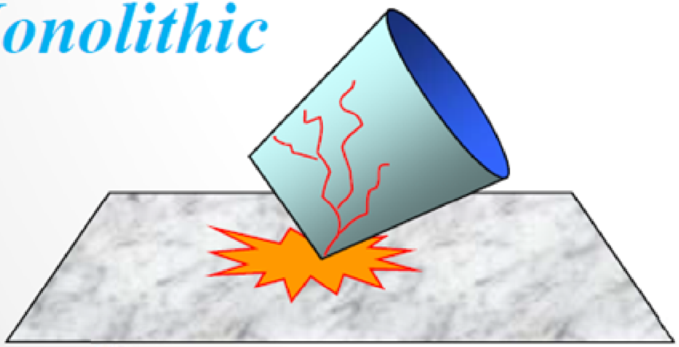
Silicon Carbide (SiC)

- Low specific weight
- High heat resistance
- High strength at high temperature
- High chemical stability
- Low thermal expansion
- Low induced radioactivity …etc
- But, Monolithic SiC is brittle

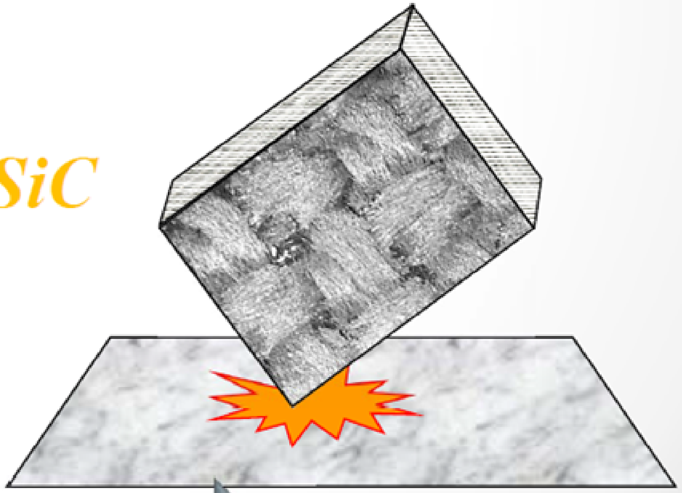
Continuous SiC fiber-reinforced SiC matrix (SiC/SiC) composites

: Attractive as structural materials & components under sever environments including high temperature & high energy neutron bombardment

Monolithic



SiC/SiC

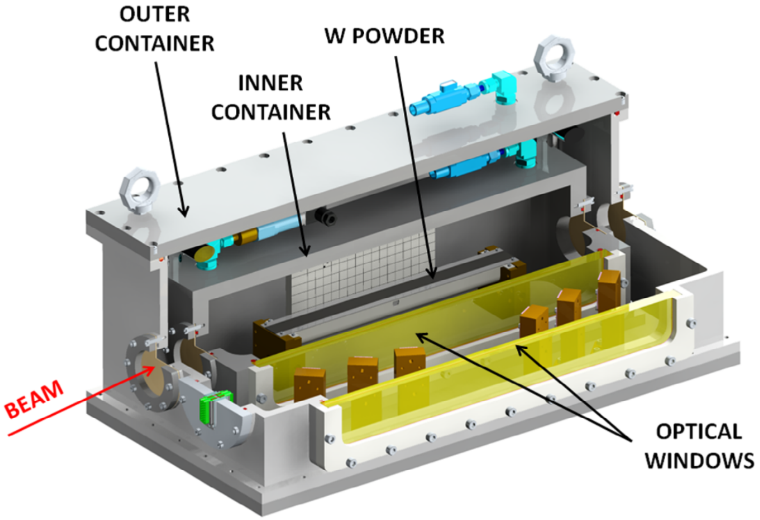


Improvement in fracture resistance

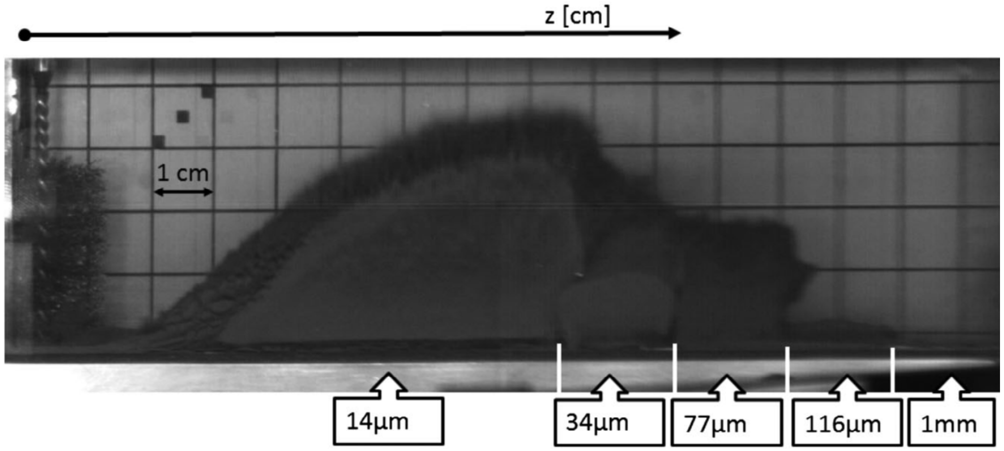
(Continuous SiC Fiber reinforcement)

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, 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.

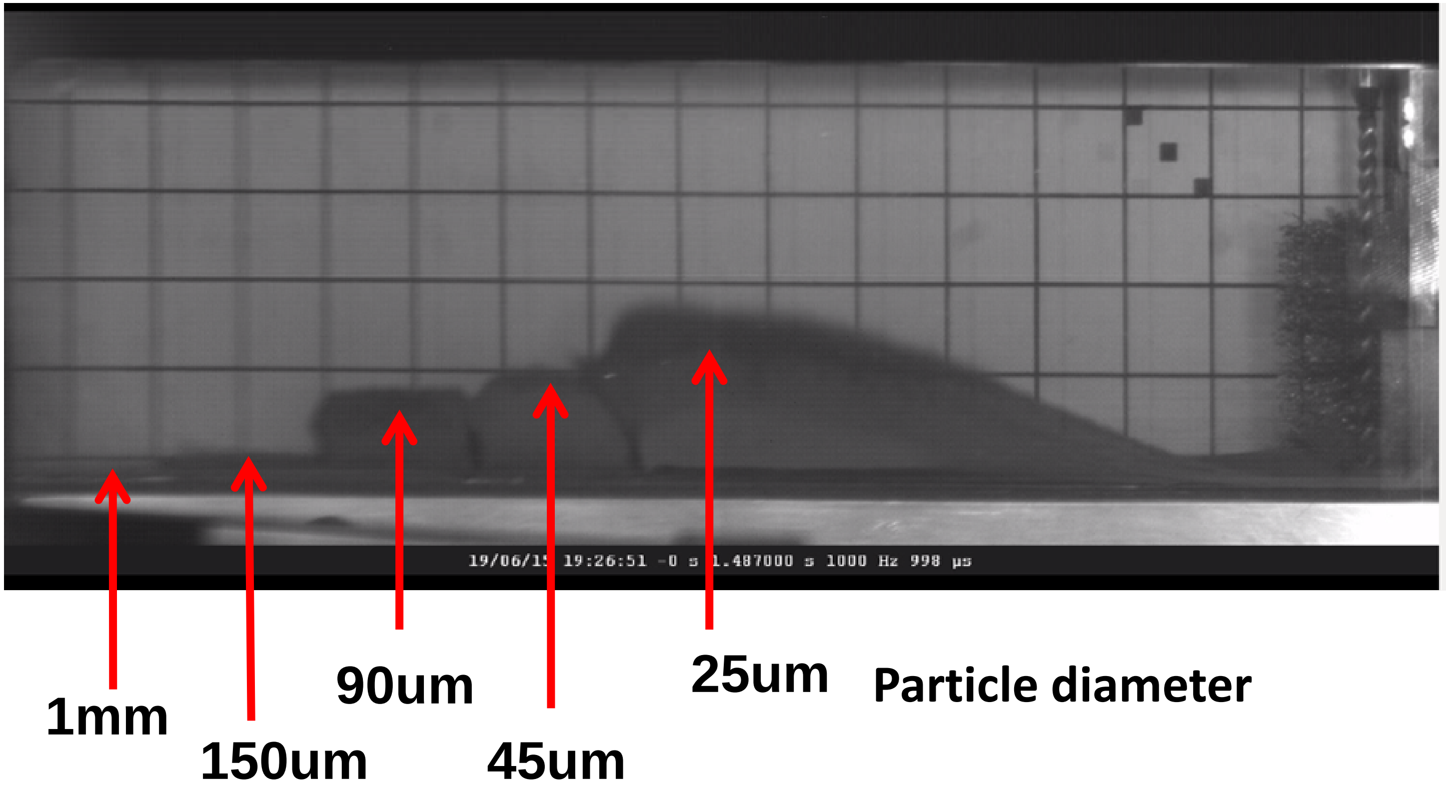
[2] O.Caretta, P.Loveridge et al., "Proton beam induced dynamics of tungsten granules," Physical Review Accelerators and Beams, vol. 21, no. 3, DOI: 10.1103/PhysRevAccelBeams.21.033401, 2018.

[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.

Disruption of granular tungsten in vacuum

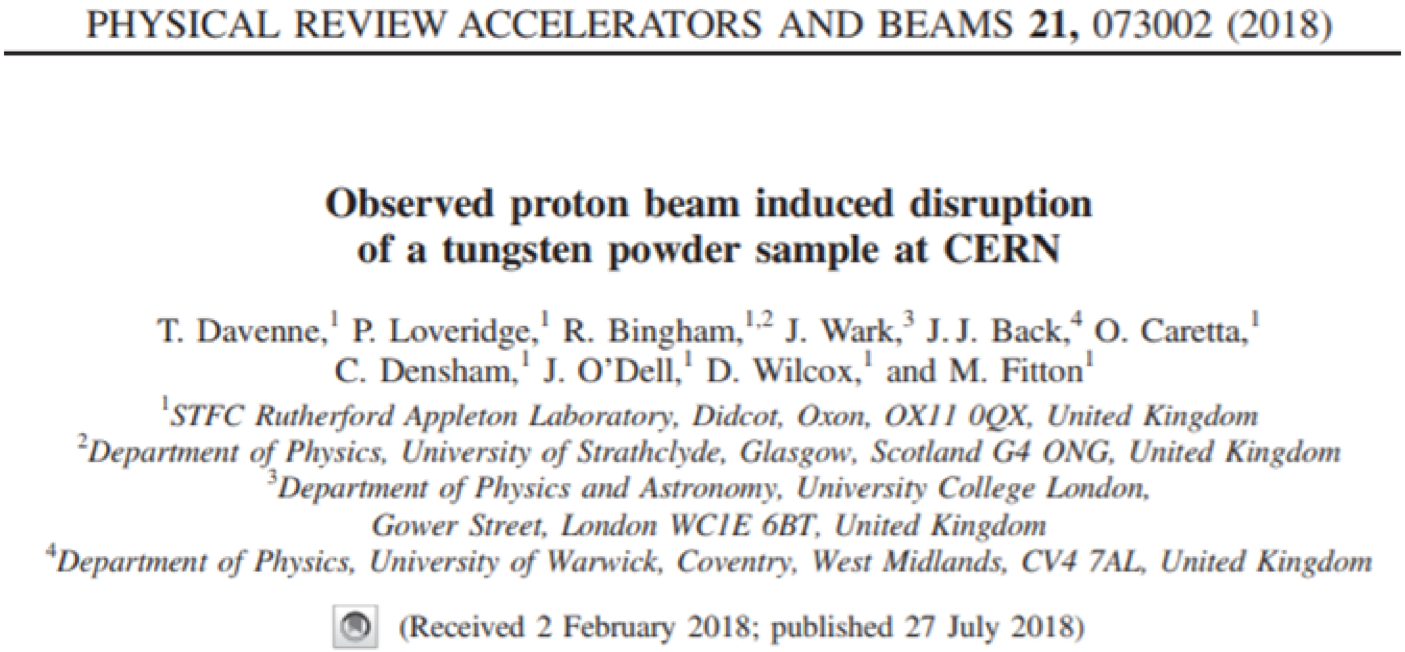
Response of different spherical particle sizes

- Pulsed beam effect on samples of W spheres of various diameters
- Single shot experiment in vacuum
- Larger lift observed for smaller grains



- **2e11 proton pulse**

Proton beam



PHYSICAL REVIEW ACCELERATORS AND BEAMS **21,** 073002 (2018)

Observed proton beam induced disruption of a tungsten powder sample at CERN

T. Davenne,[1] P. Loveridge,[1] R. Bingham,[1,2] J. Wark,[3] J. J. Back,[4] O. Caretta,[1]
C. Densham,[1] J. O'Dell,[1] D. Wilcox,[1] and M. Fitton[1]
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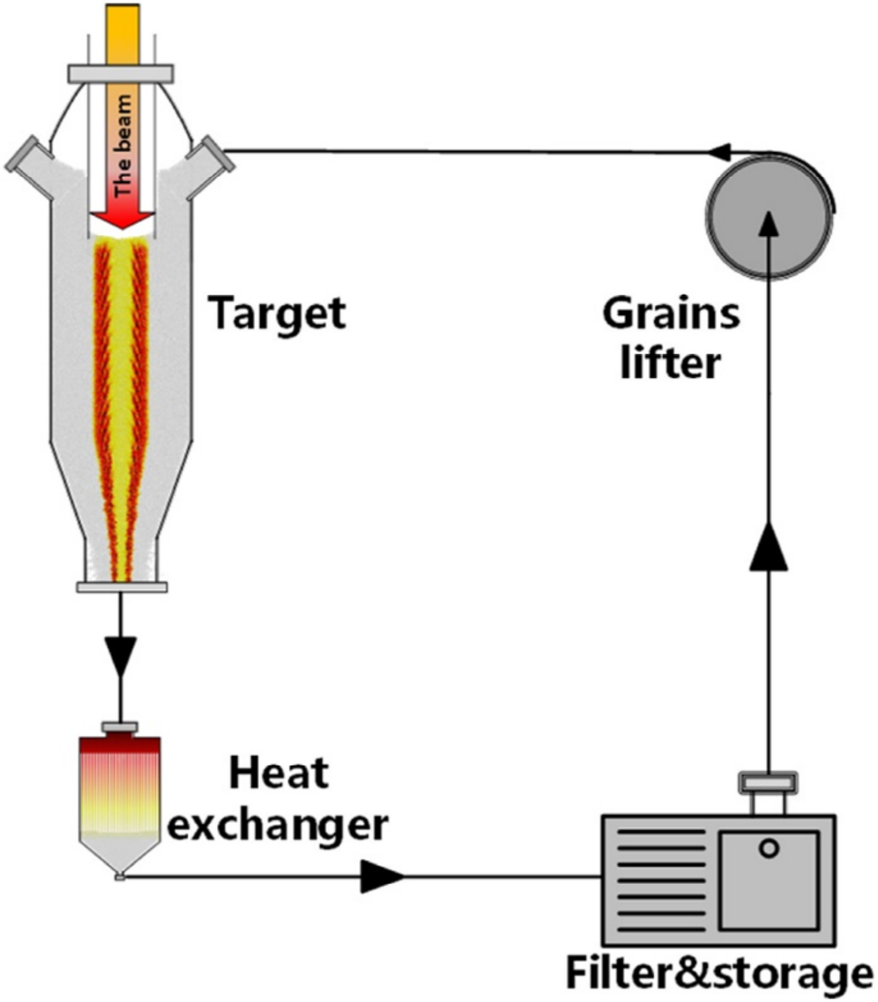
(Received 2 February 2018; published 27 July 2018)

- Aim: explain the physics behind the tungsten powder eruptions we observed at CERN HiRadMat experiments
- Considered three possible mechanisms –
- 1. Aerodynamic lift (no)
- 2. Knock on thermal expansion (no)
- 3. Charge induced lift (yes)

Fluidized bed targets: some potential challenges – and plans

- Erosion of material surfaces, e.g. nozzles, beam windows
  - 3rd year undergraduate project underway (Suitters at Sheffield University)
- Challenge to avoid moving parts in circuit (e.g. valves)
  - study CFB – collaboration between RAL, Warwick (and IMPCAS?)
- Heat transfer – inc. secondary heating of pipe walls
  - Part of Warwick study
- Activated dust on circuit walls
- Activation of carrier gas circuit
- Achieving consistent stable flow with high material density – typically maximum 50% bulk material fraction
  - Potential future test rig? (lab space available at RAL)
  - Just needs people & money

Dense granular flow target - recent R&D for CiADS



- Large effort (c.100 staff) and vast computing resources utilized to study windowless dense granular target
- Experimental program recently discontinued (LBE solution chosen as more mature technology)
- Meetings held with IMP CAS colleagues earlier this week
    - requested collaboration with us
    - possibility for Warwick PhD (Bishop) to access GPU farm and multiphase codes being investigated

Pragmatic plan for target technology

- Previous MC baseline of high-Z liquid metal target best avoided (liquid Hg likely excluded at CERN (& don't mention LBE!))
- Low-Z more feasible than High-Z
  - (Plus lower neutron & heat load on SC solenoid)
- Graphite has an excellent pedigree as a target material e.g. T2K – well worth pursuing for a MC (ref CERN MC effort)
  - 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…