Latest results from in-beam W granular target experiments at CERN

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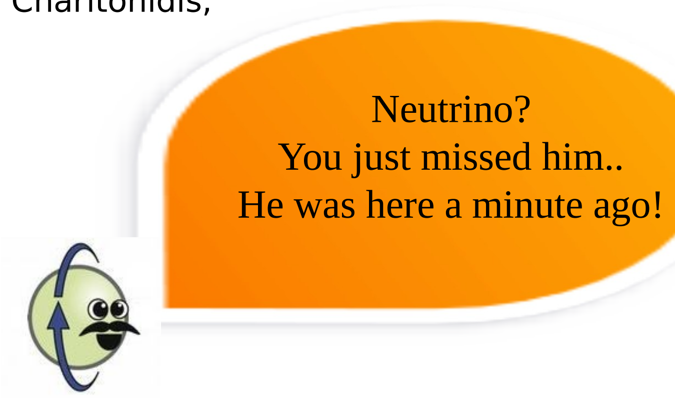


Inputs to High Power Target design envelope

High power proton beam

HP Target

Heat load removal

Stress endurance

Cyclic stresses (fatigue)

Creep

Quasi-static stresses

Dynamic inertial stresses

Disposal

Operational safety

Material props Rad. Damage

Toxicological

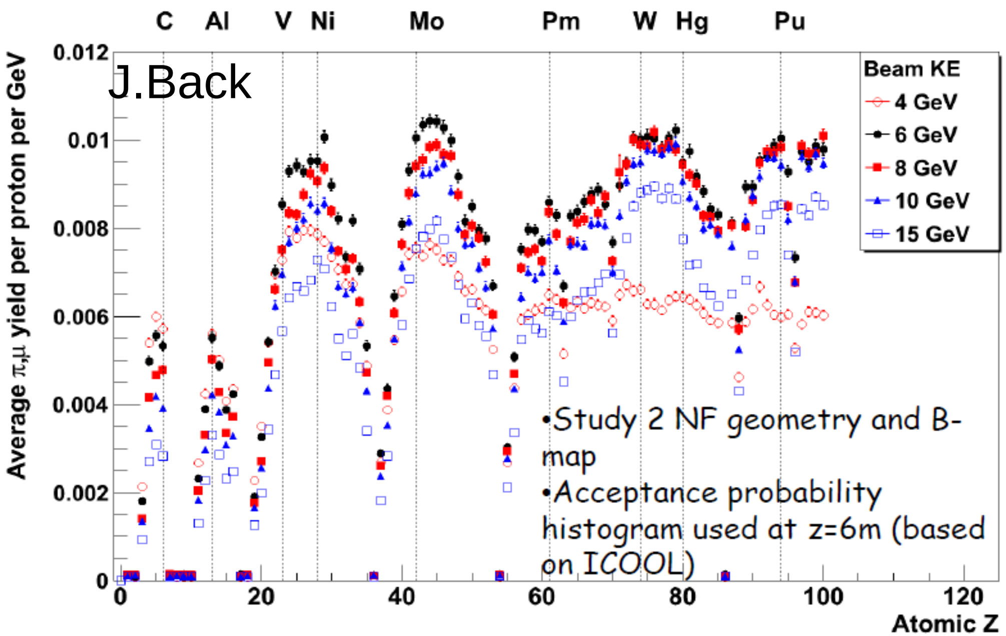
Radiological

Remote handling

Physics performance

Operational reliability

Max particle **Yield** or max particle **Production**?!



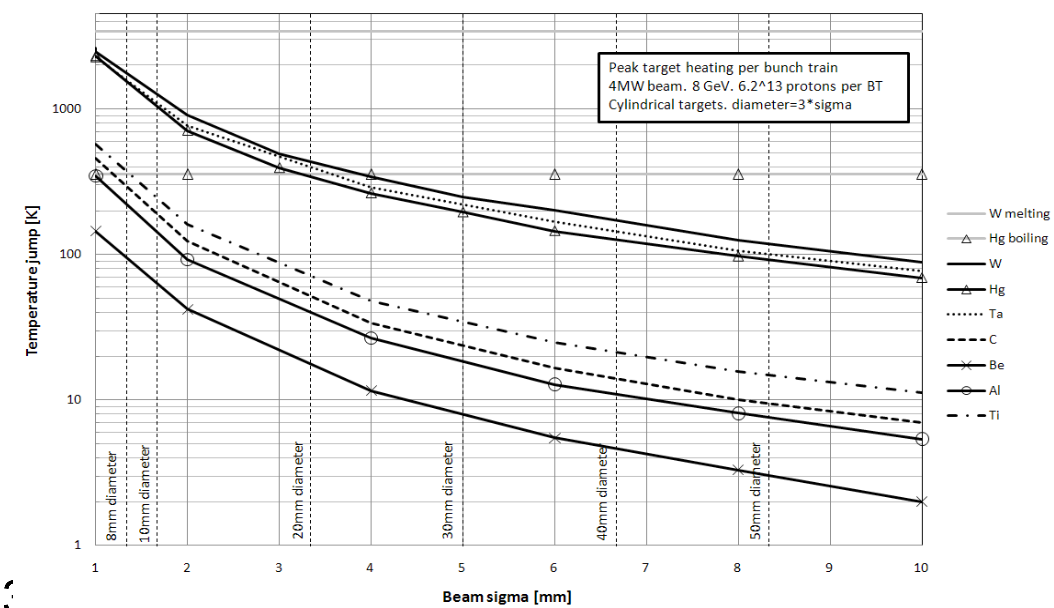
•Study 2 NF geometry and B-map
•Acceptance probability histogram used at z=6m (based on ICOOL)

See NF yield in W with that in C (left) and see respective peak temperature jump (below)

Reliability in engineering

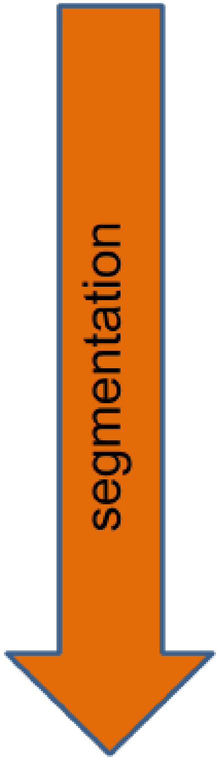
R_{f}= r1*r2*r3*…rn

Where rn<=1 is the reliability of a given component



Heat Removal and Thermal stresses

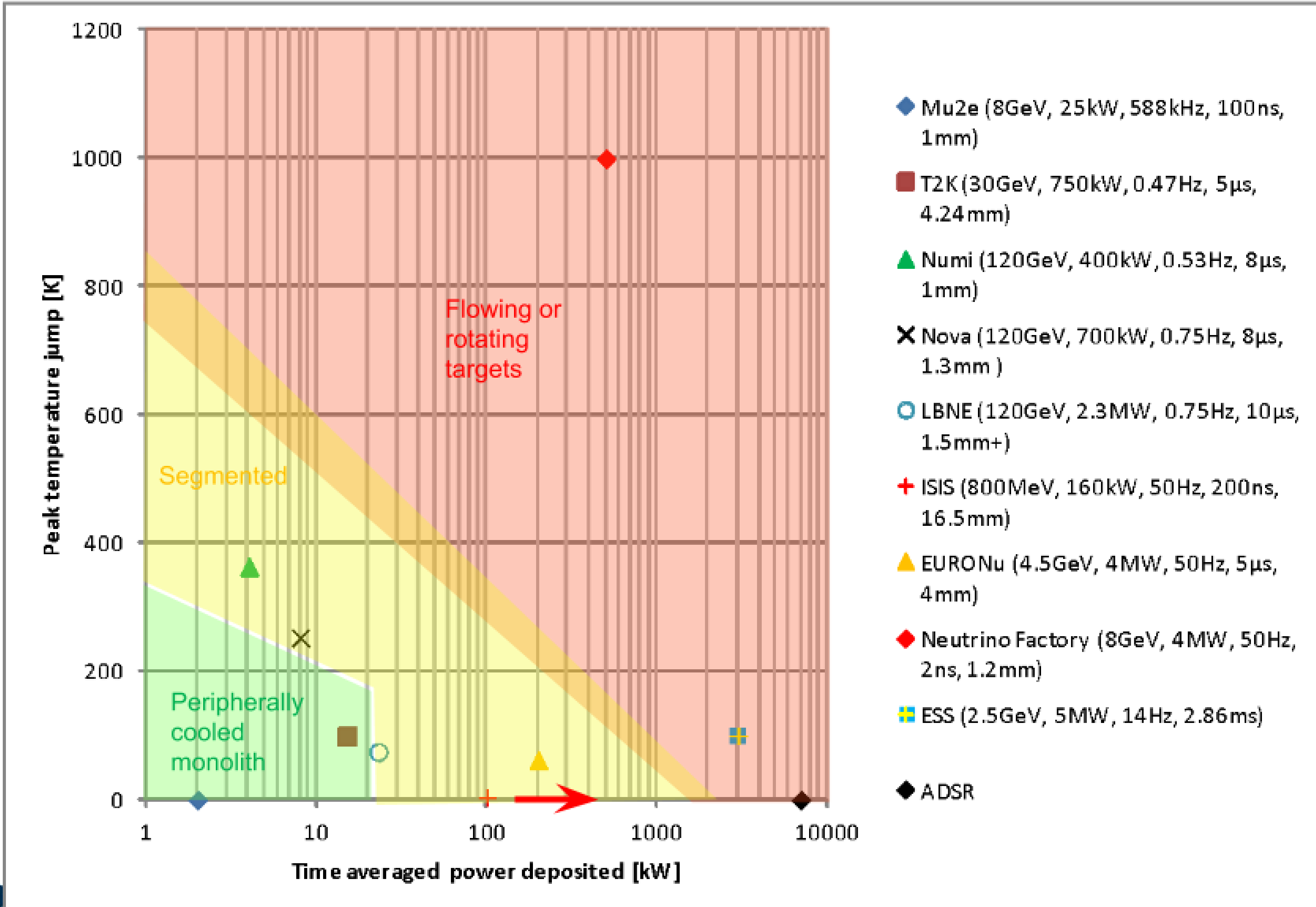
Target	Power Deposited [kW]	Peak Temperature Jump [K]	Existing or proposed solution
Mu2e	2	0.0014	Peripherally cooled cylinder
T2K	15	100	
Numi	4	364	Peripherally cooled segmented
Nova	8	253	
LBNE	23	75+	
ISIS	100	3.8	Segmented with cooling through core
EuroNu	200	62	
Neutrino Factory	500	1000?	Flowing or rotating target
ESS	3000	100	Rotating target with cooling through core of target



T. Davenne

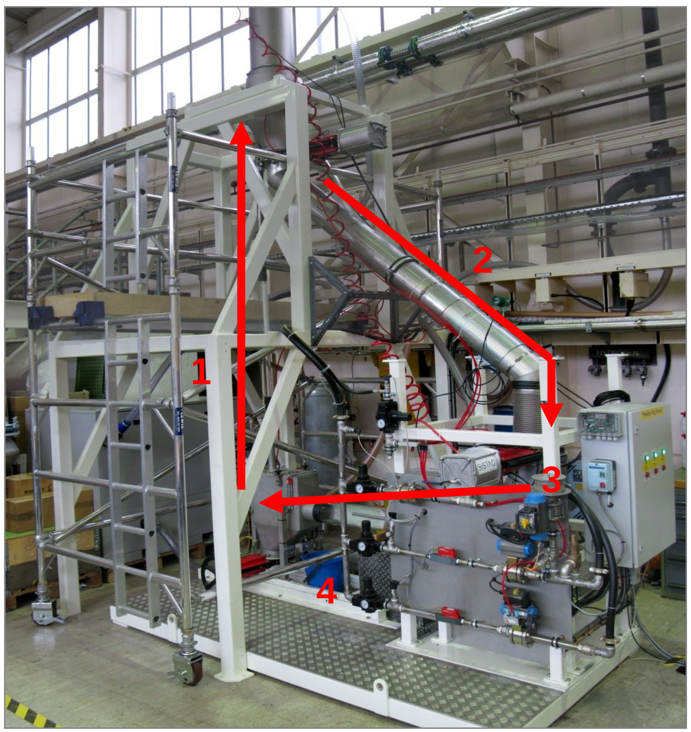
Segmentation is a powerful tool to improve cooling and reduce stresses although there's no such thing as a free ride..

Heat Removal and Thermal Stress Summary

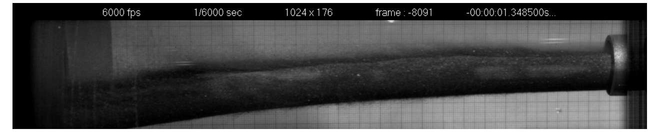


Fragmented high Z flowing target: W powder rig @RAL

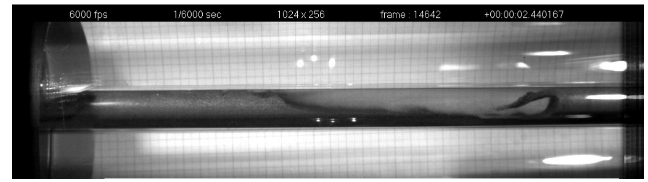
- Offline testing
- Pneumatic conveying
  - (dense-phase and lean-phase)
  - Containment / erosion
  - Heat transfer and cooling of powder



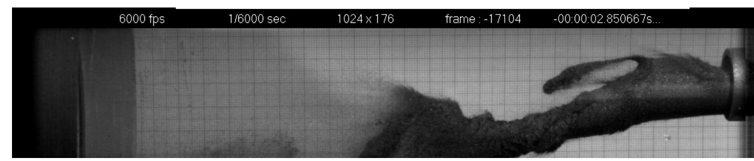
Dense-phase delivery



High speed image: tungsten powder jet

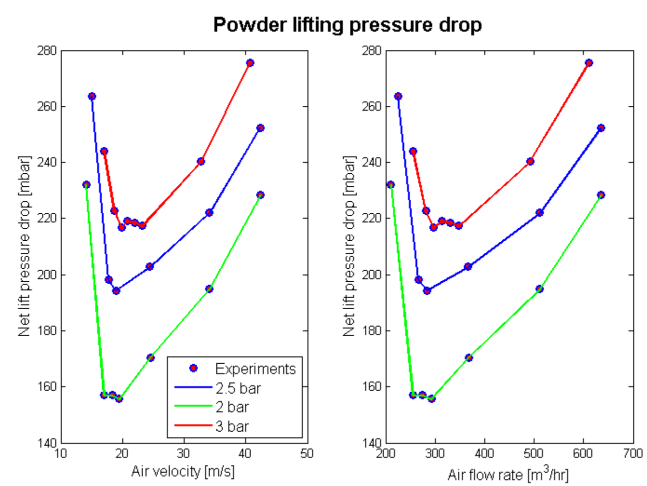


High speed image: tungsten powder flow in a pipe

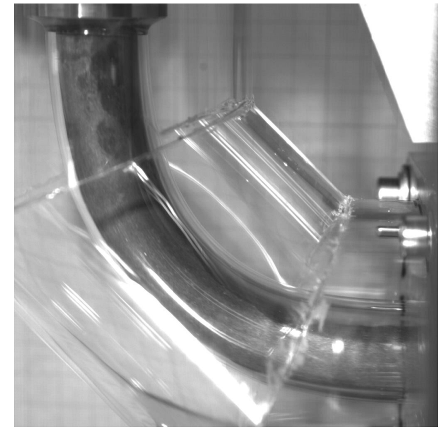


Unstable tungsten powder jet

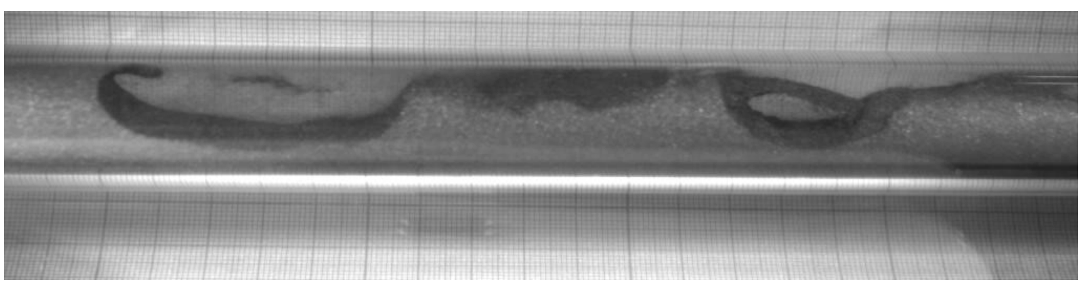
Lean-phase lift

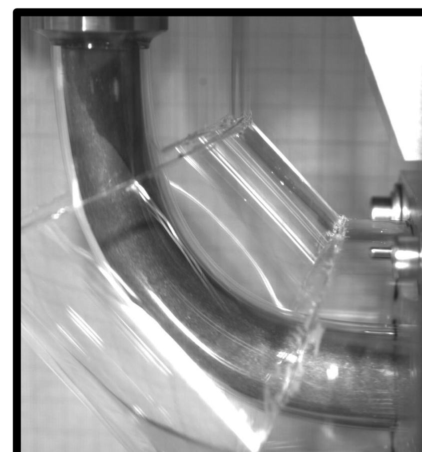


Improving diagnostics to increase the solid fraction



glass parts tube show early stages
of phase separation

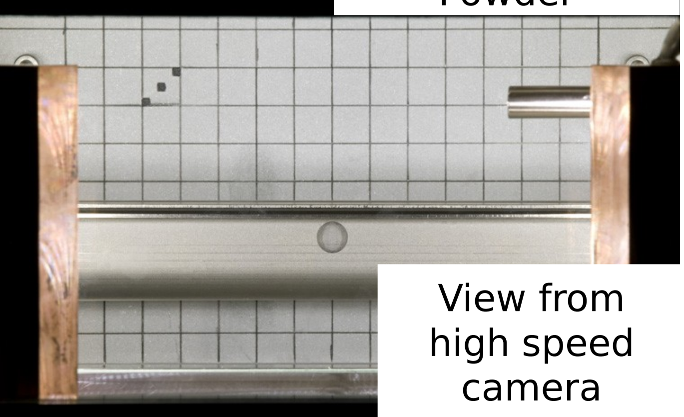


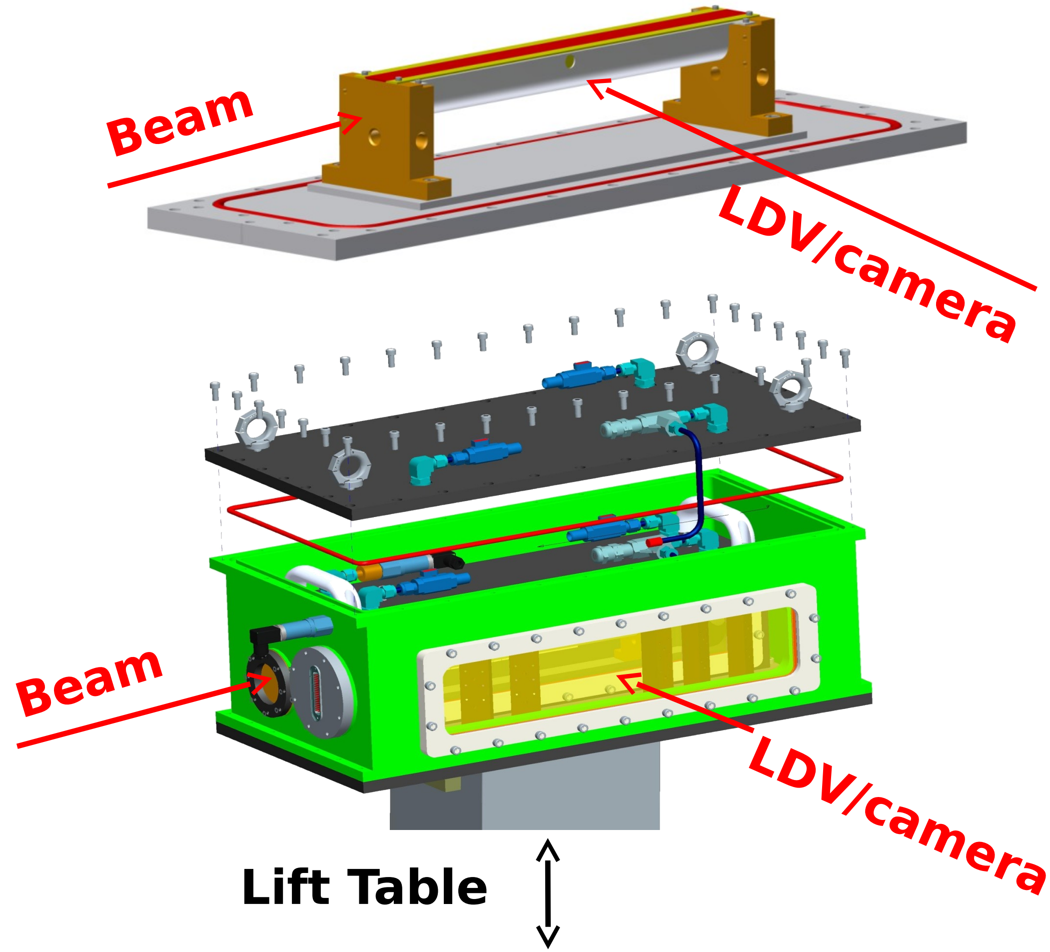


2011 in-beam tests at CERN


Open trough Assembly


Filling with Tungsten Powder

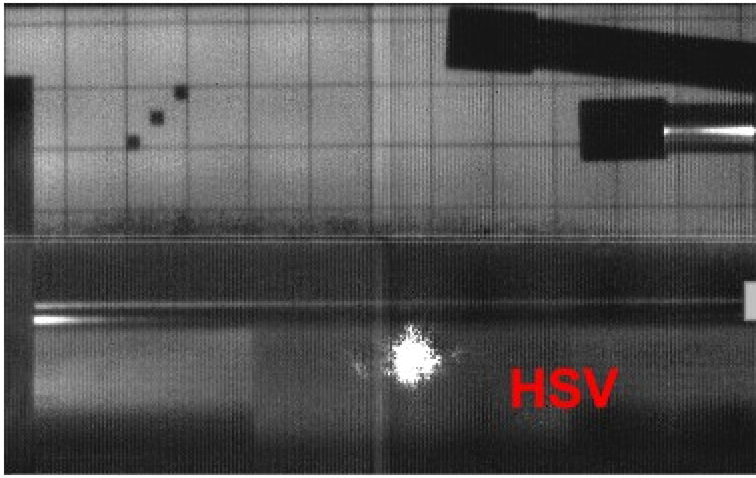

View from high speed camera



- Tungsten powder sample in an open trough configuration
- Helium environment
- Two layers of containment with optical windows to view the sample
- Remote diagnostics via LDV and high-speed camera

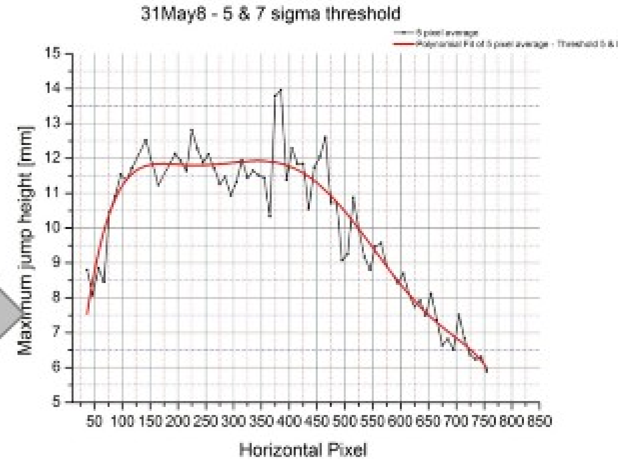
Published PRSTAB: ***"Response of a tungsten powder target to an incident high energy proton beam"***

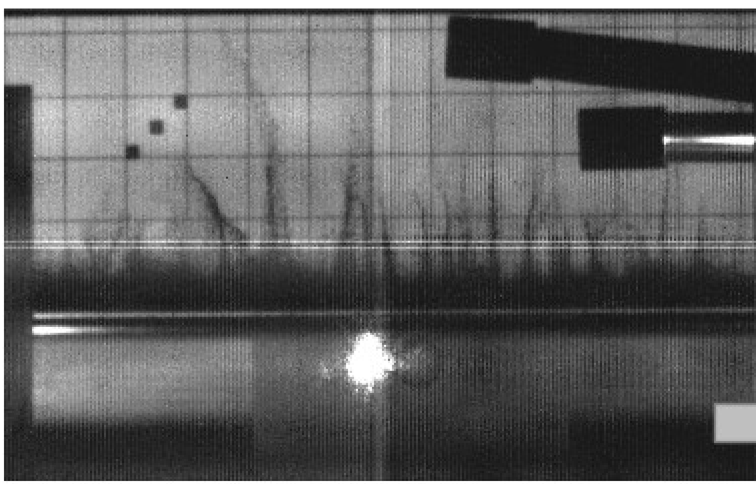
Charitonidis



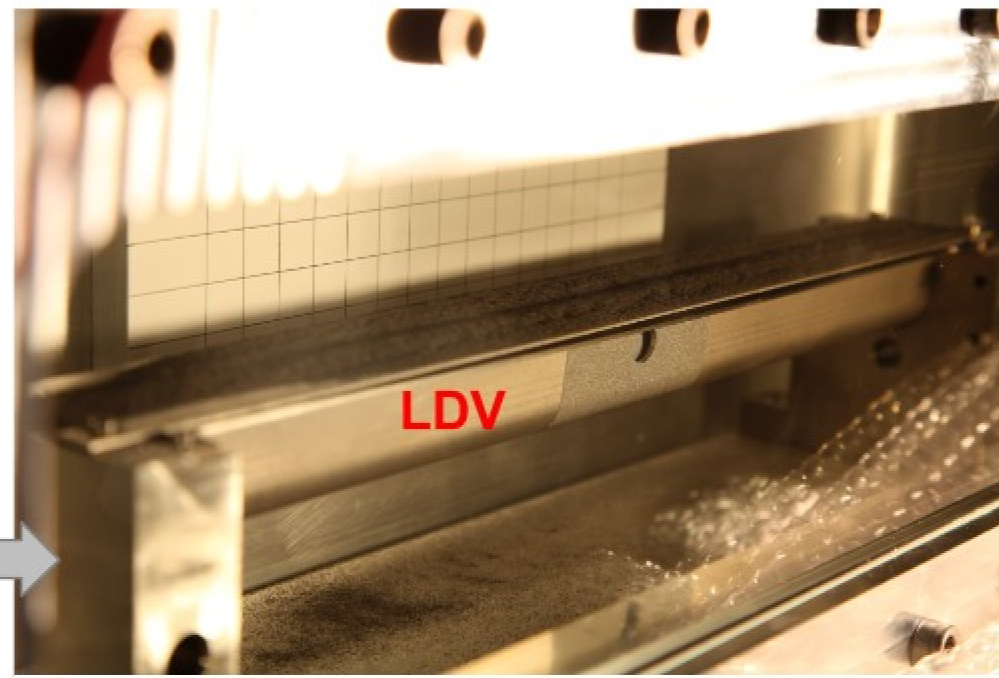
Shot #8, 1.75e11 protons
Note: nice uniform lift

Lift height correlates with deposited energy





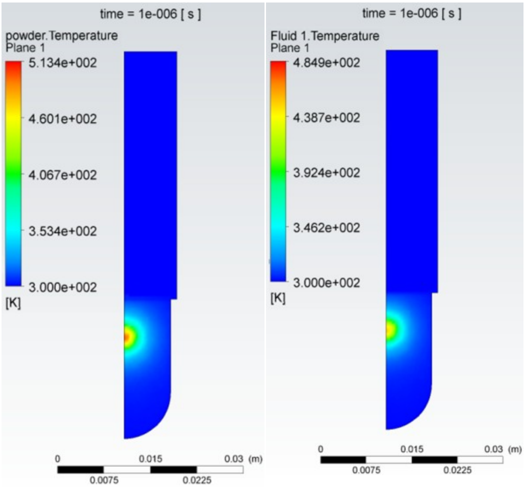
Shot #9, 1.85e11 protons
Note: filaments!

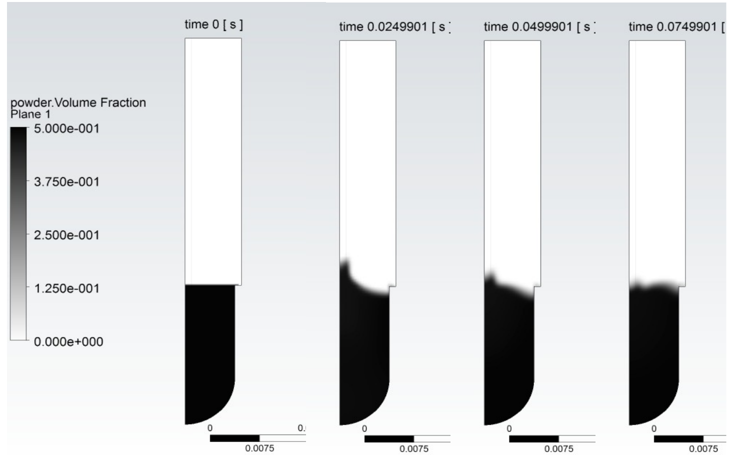


Trough photographed after the experiment.
Note: powder disruption

Davenne: CFD predictions/post fits

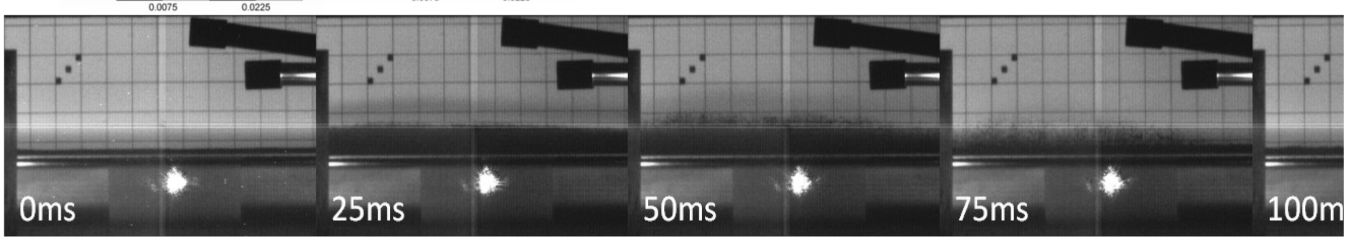
Beam heating





Powder lift was predicted by CFD

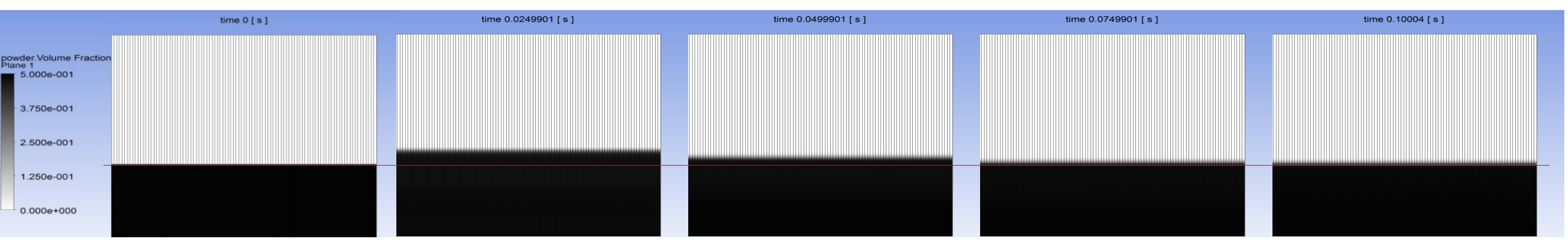
However the energy to lift the powder was found in the experiment to be an order of magnitude smaller than predicted



So is the lift:

- ***aerodynamic?***
- ***stress propagation?***
- ***electrostatic?***

Test Results from Shot #8, 1.75e11 protons, beam sigma 0.75 mm x 1.1 mm



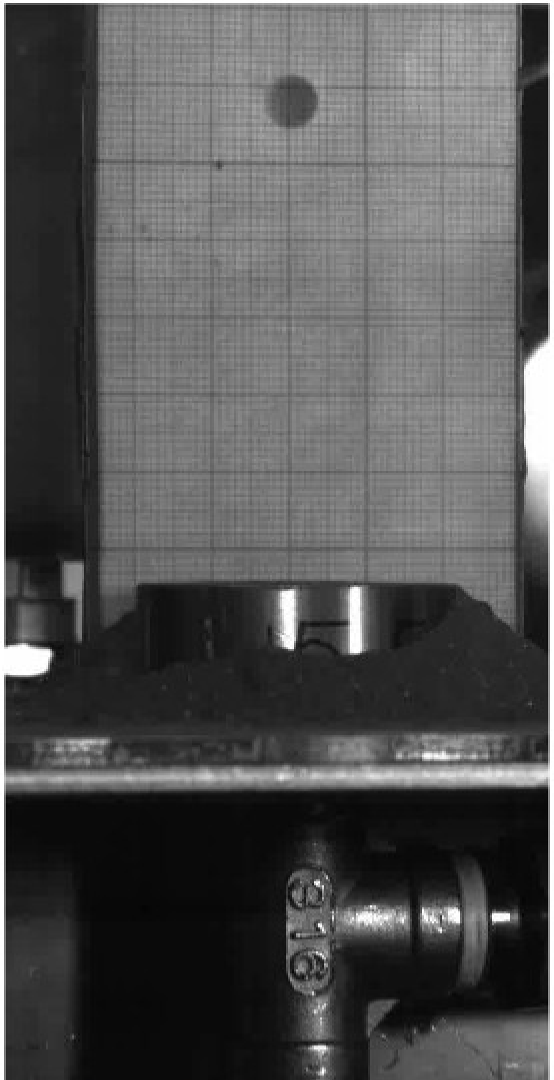
CFD simulation of Shot #8, assuming 1 micron particle size
(n.b. no lift with 25 micron particles at this intensity)

Aerodynamic: tungsten powder puff experiment: understanding the powder lift

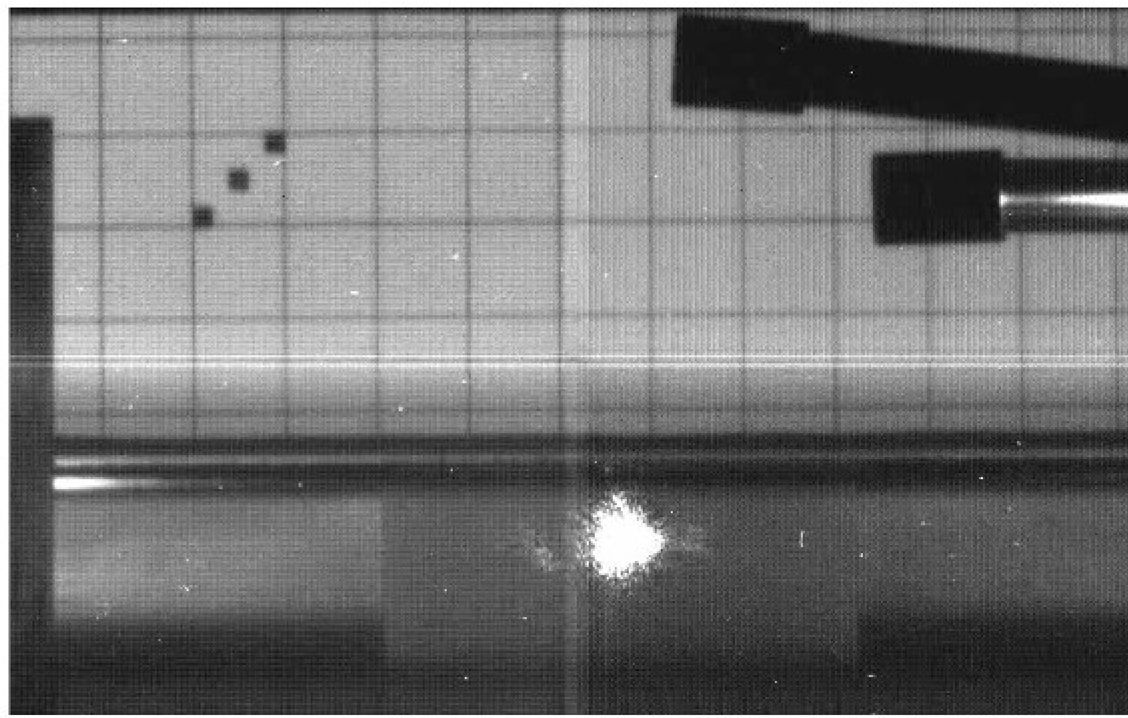
piston

Puff
cell

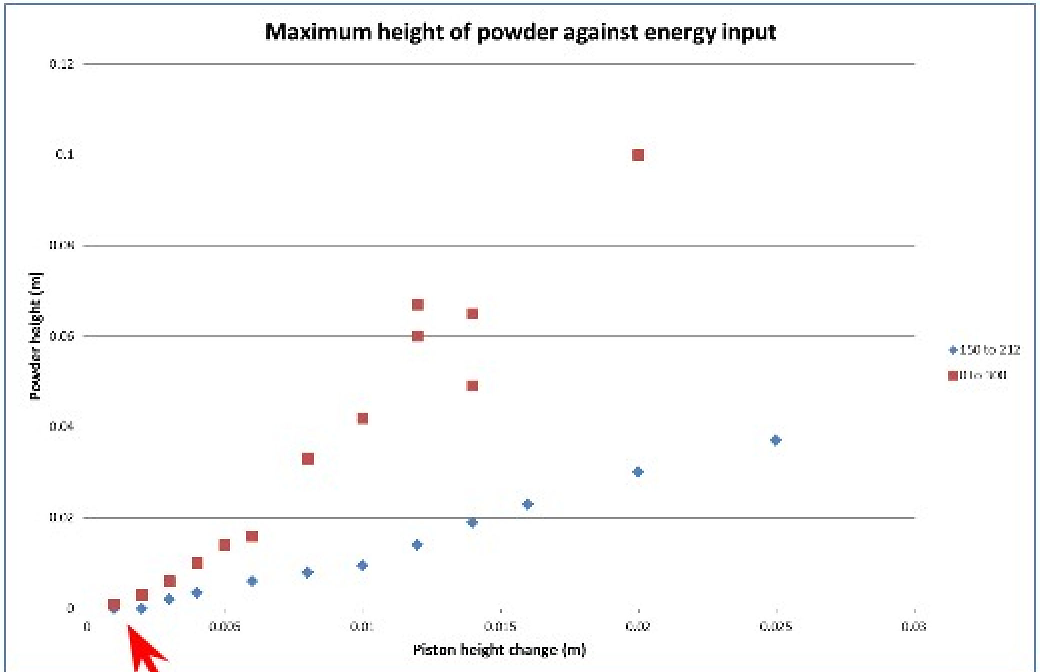
Tungsten powder puff experiment



- Aim: To compare behaviour of Tungsten powder after a short pressure spike against the behaviour in the HiRadMat experiment
- Method: Use a short pressure pulse to lift the powder



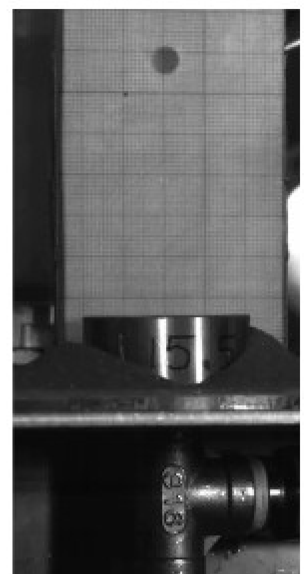
Tungsten powder puff experiment



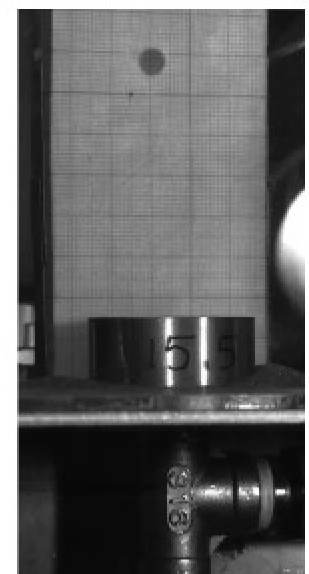
There is a threshold energy which has to be reached before the powder begins to lift. The threshold depends on the depth of the powder

- The maximum height reached by the powder is proportional to the energy put in by the compression of the piston
- The powder sample containing smaller particles was lifted higher than the sample containing only larger particles
- The acceleration is faster that can be captured with 1kHz HSV

0 to 300 um

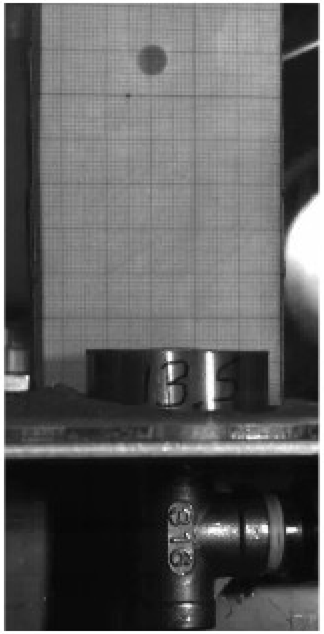


150 to 212 um

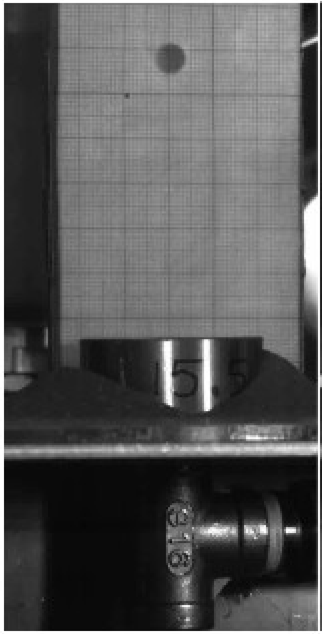


Tungsten powder puff experiment

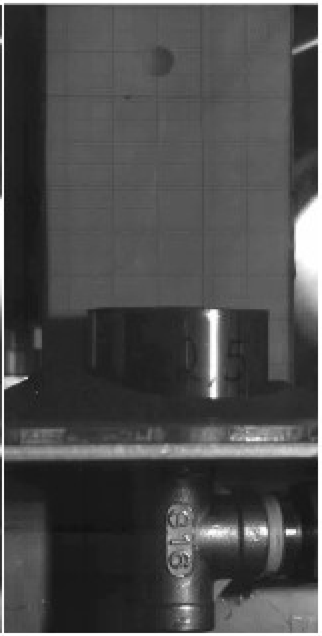
Powder depth = 13.5mm



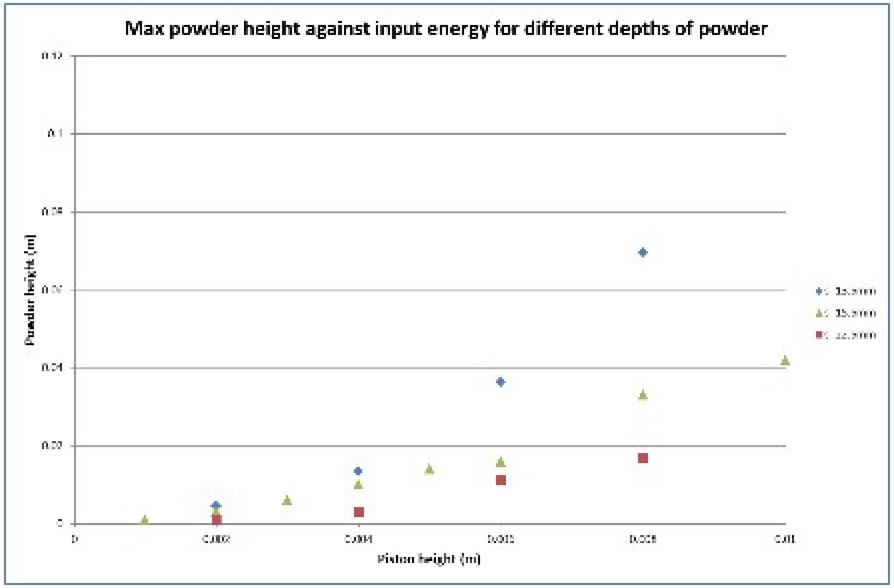
Powder depth = 15.5mm

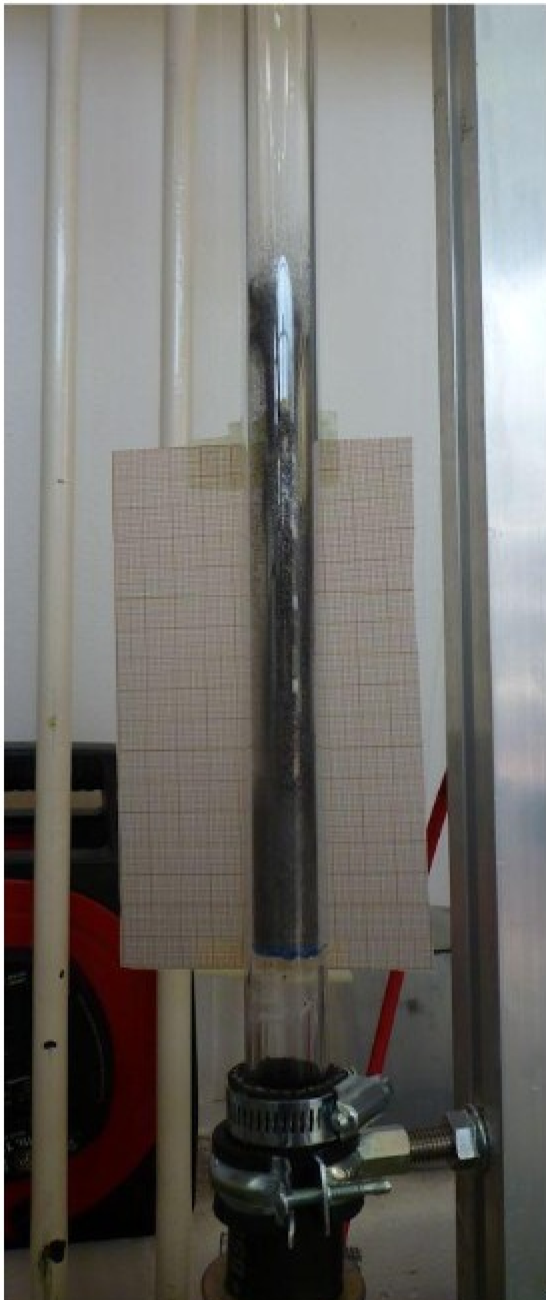


Powder depth = 22.5mm



- The smaller the depth of powder, the larger the maximum powder height reached





Understanding powder lift

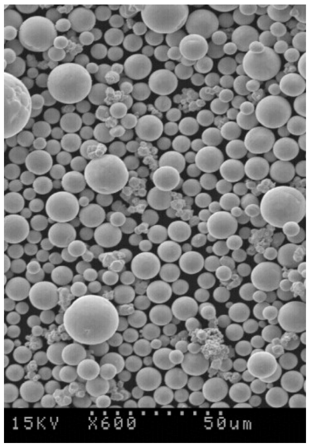
Pressure drop for air flowing through a bed of powder

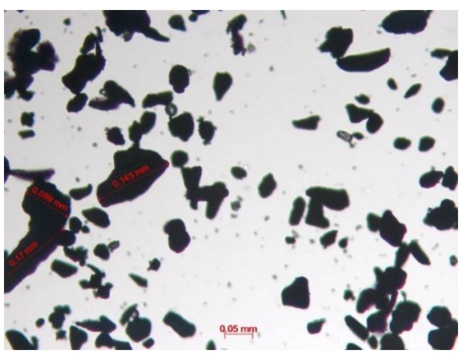
Atherton, Davenne

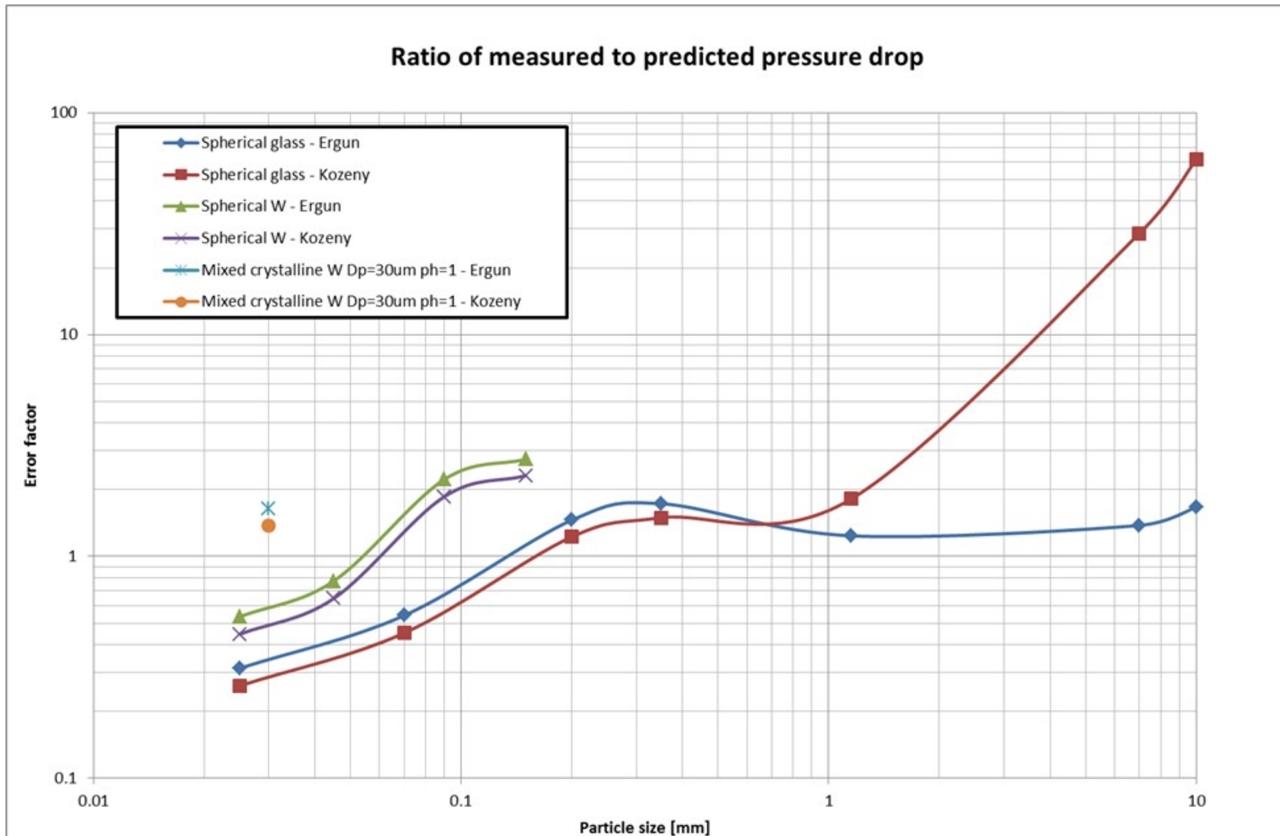
Packed bed experiment

Experimental pressure drop measured across a packed bed of W powder is in line with the analytical pressure drop given by Ergun (employed by CFX)

$$\frac{\Delta P}{h} = \rho_g U^2 \left[\frac{150(1-\varepsilon)}{\mathrm{Re}_d \psi} + \frac{7}{4}\right] \frac{1-\varepsilon}{\psi\, d_p\, \varepsilon^3}$$



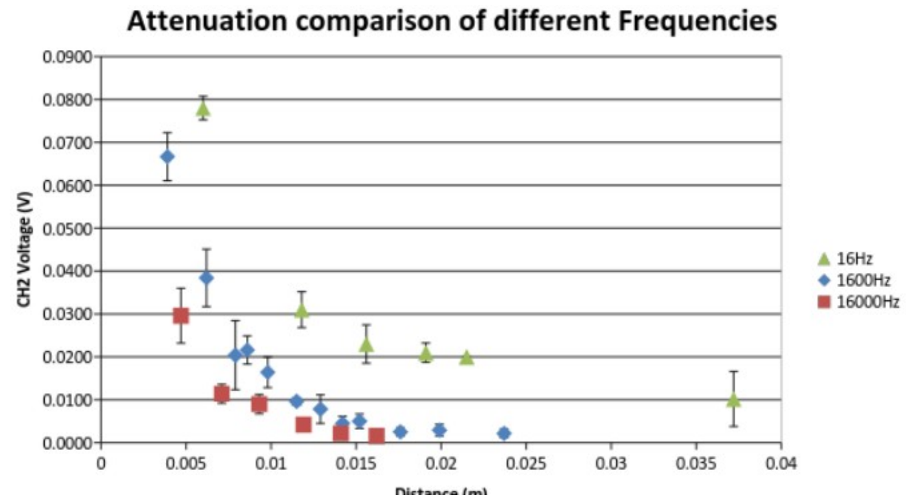


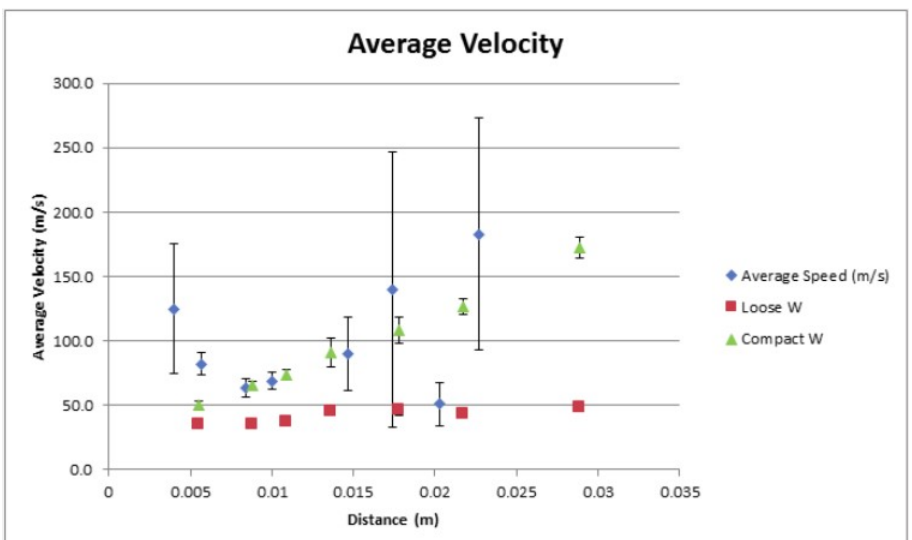


Stress propagation/dissipation in powder

Piezo-powder-piezo sandwich

- Exponential decay of stress propagation.
- Slow sound speed in powder
- Sound wave attenuates quicker in smaller spheres
- Sound speed is faster in larger spheres





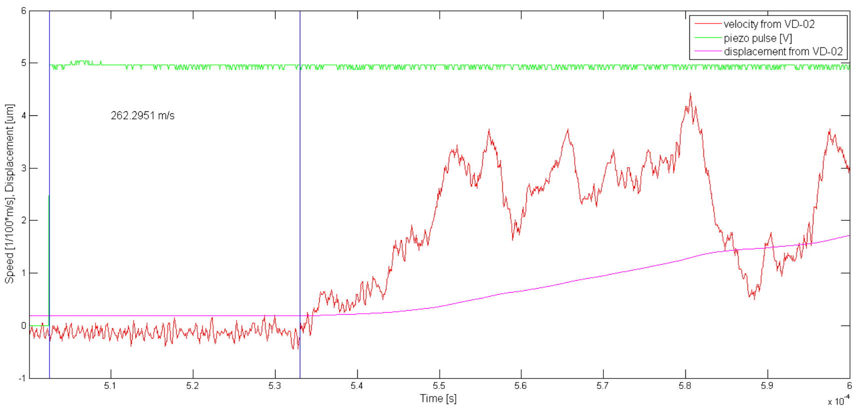
Stress propagation/dissipation in powder

Hiradmat-like setup:
Piezo crystal – powder – LDV diaphragm

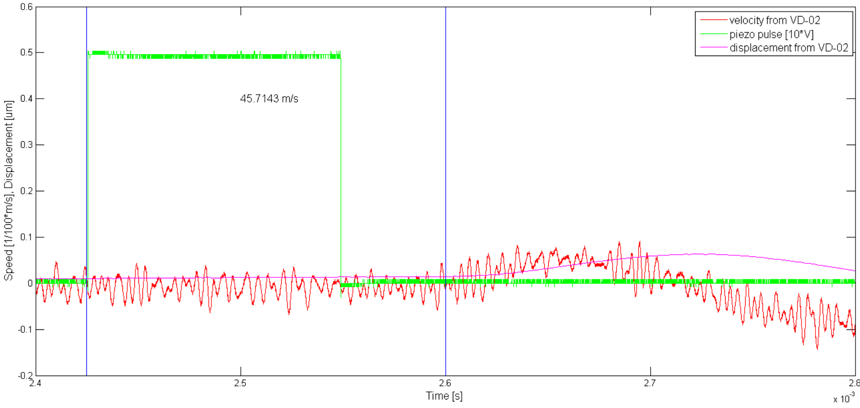
Piezo produces 2um rapid displacement. 1cm powder. 30um thin diaphragm

- Shows quick attenuation of sound wave.
- Confirms sound low speed in the granular media

3mm spheres



150um spheres



Electrostatic Effects on powder

Showed a response of the powder to electrostatic charge.

Brave engineer, volunteered to be zapped with 10kV!

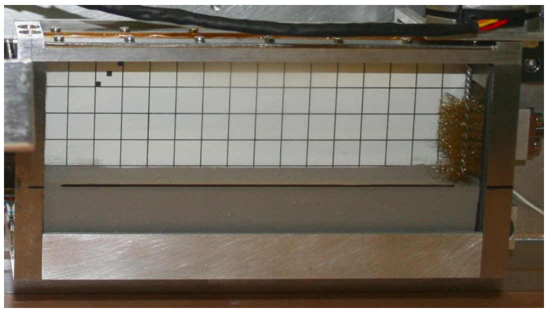
W powder in glass container

Van der Graaf generator

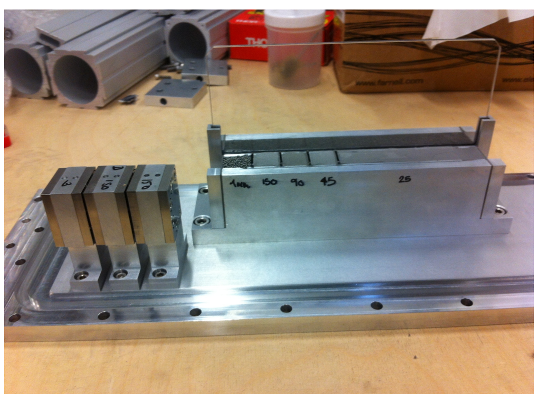
Recent in-beam experiments: Hiradmat 2015

3 open top troughs and 3 packed bed samples with different grain sizes
Experiments repeated in vacuum and He atmosphere

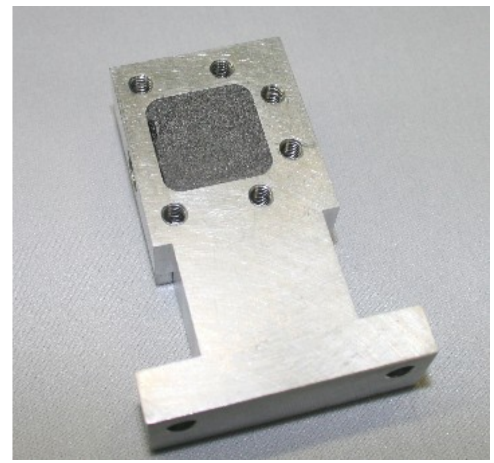
1- Resettable trough with 45um grains

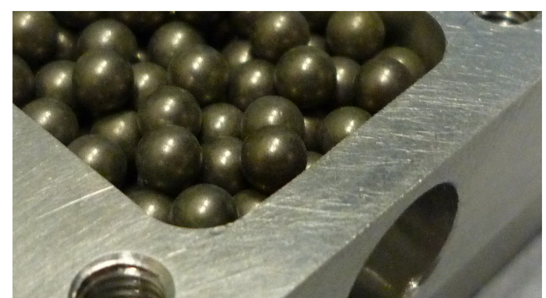


2- Mixed powder (60mesh) trough
3- Trough with separated sizes



Packed bed samples
3mm spheres and 150um spheres

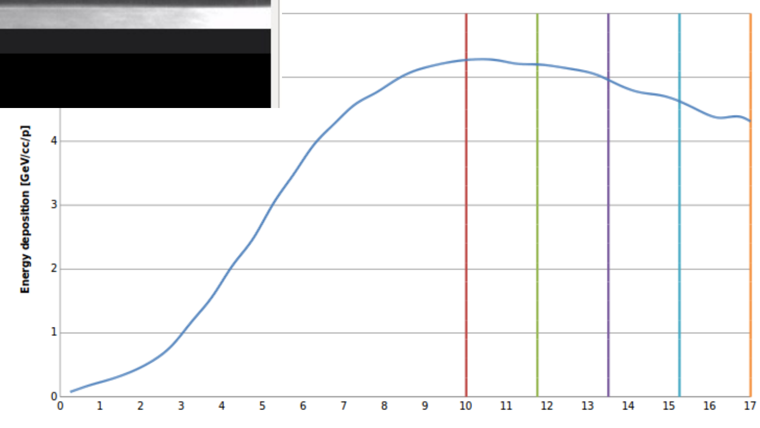




Recent In Beam experiments: preliminary observations

- The powder lifts in mechanical vacuum (i.e. where no aerodynamic effects are expected). So the lift is either stress induced or induced by particle charge
- The lift height appears proportional to the energy deposition (e.g. the number of PoT and shower along the trough lenght)

- Shot 1-24
- 45um powder
- 1.2e11 PoT
- ~30J/g peak eDep



Recent In Beam experiments: preliminary observations

- Higher response for higher PoT

- Shot 1-26
- 45um powder
- 3.3e11 PoT

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Recent In Beam experiments: preliminary observations

- Powder adhering to the glass drops at beam shot (perhaps discharged?!)

- Shot 1-27
- 45um powder
- 2.2e11 PoT

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Recent In Beam experiments: preliminary observations

- This shot shows the beam effect on samples of W spheres of different size separated by septa
- Smaller spheres have a bigger response suggesting that the lift is probably charge induced as opposed to stress induced

- Shot 1-28
- Several sizes
- 2e11 PoT

1mm

150um

90um

45um

25um

Large lift for small grains.
Negligible or no lift for larger particles

Recent In Beam experiments: preliminary observations

- This shot was taken on the trough containing 60 mesh (i.e. smaller than 250um), mixed size crystalline powder
- The parameters are thought to be similar to those of the 2011 experiment, except for this shot was in vacuum (as opposed to a He atmosphere in 2011)
- The response seems more dramatic than in the previous experiment suggesting that the He atmosphere might somehow have damped the powder response

- Shot 2-26
- Several sizes
- 2e11 PoT

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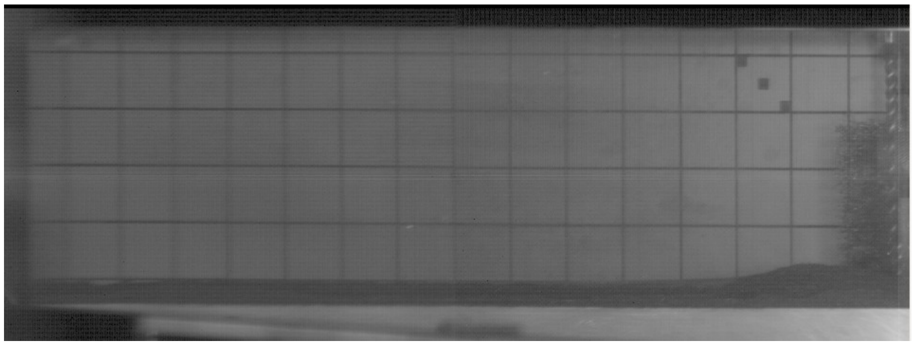
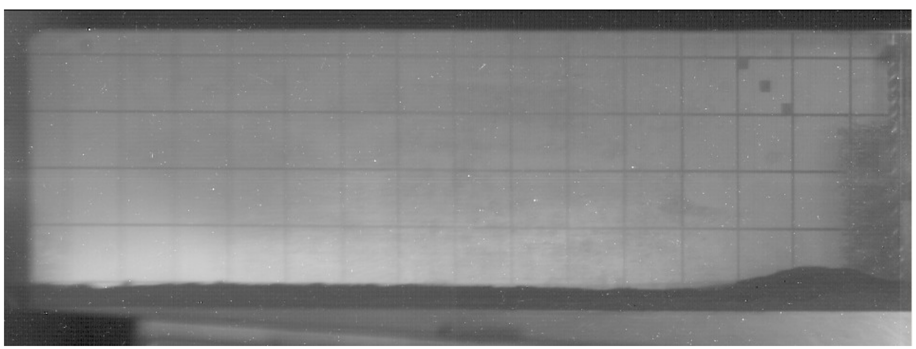
Recent In Beam experiments: preliminary observations

- Luminescent flash noticed at beam impact (i.e. before the powder response)

Before beam impact



At/after beam impact



- Shot 2-43
- 45um
- 2e12 PoT

Recent In Beam experiments: preliminary observations

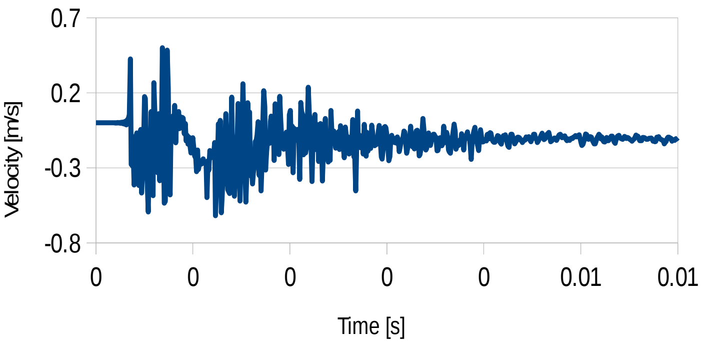
- At ~NUFACT peak energy deposition (~130J/g) the 45um spheres (which have an average size distribution ~20um) lift with a velocity of approx 3m/s
- Notice that at this energy deposition the whole rig (rather heavy and stiffly supported) seems to shudder!

- Shot 2-43
- 45um
- 3.1e12 PoT

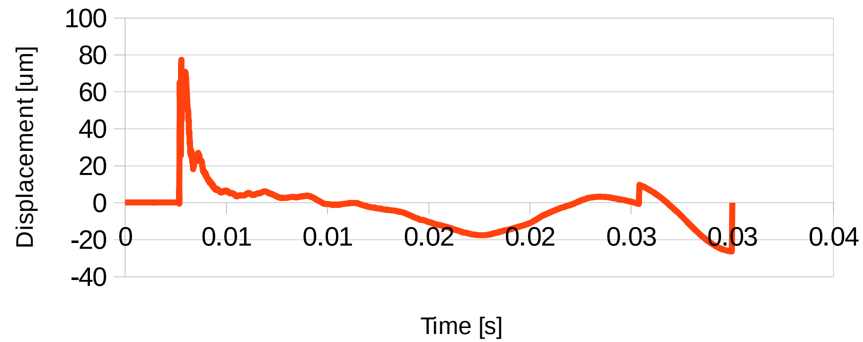
Recent In Beam experiments: preliminary observations

- Several Laser doppler vibrometer (LDV) measurements were taken on thin windows in contact with the powder in the trough and in the packed bed samples

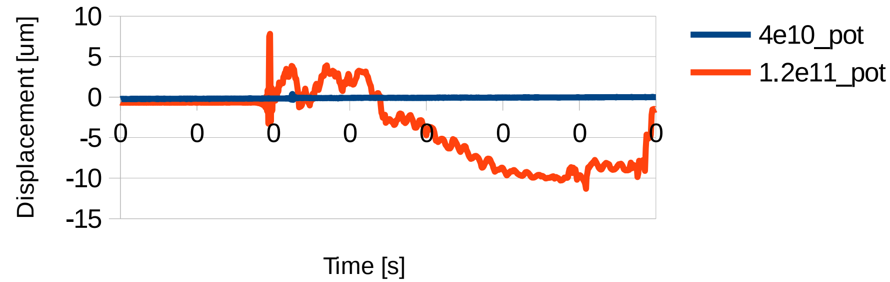
Velocity of 25um Ti window
in contact with
packed bed of 150umm tungsten speres (LDVp3_02_41)
BEAM: 2mm sigma, 450GeV, 3.1e12 pot
~250J/g as NUFACT IDS, approx dT 1500K



Displacement of 25um Ti window
in contact with
packed bed of 150mm tungsten speres (LDVp3_02_41)
BEAM: 2mm sigma, 450GeV, 3.1e12 pot
~250J/g as NUFACT IDS, approx dT 1500K



Displacement of 25um Ti window
in contact with
packed bed of 3m tungsten speres (LDV5_02_14&16)
BEAM: 2mm sigma, 450GeV

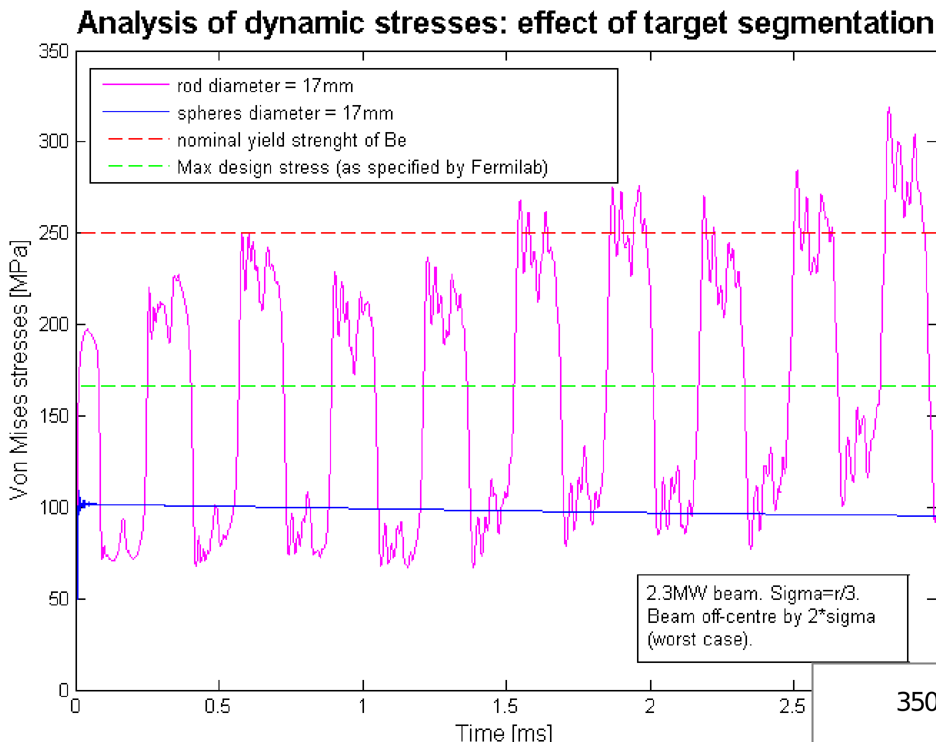


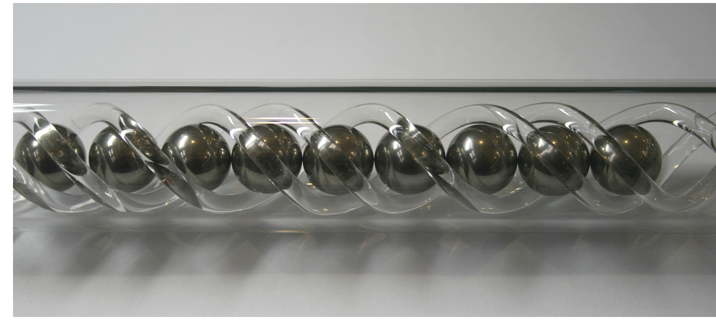
Lukasz Jerzy Lacny and
Michael Guinchard

Plans for future work on granular targets

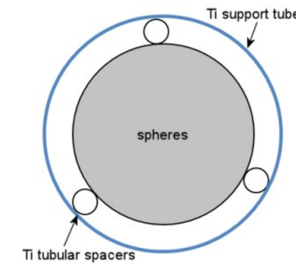
- **Analysis of data recorded during the 2015 hiradmat experiment**
  - HSV analysis to determine correlation between powder lift/speed and energy deposition
  - LDV analysis to determine peak displacements of containing windows and relative stresses
  - LDV study to validate speed of sound in granular material
- **Analytical studies and bench top experiments to unravel electrostatic powder lift**
- **W powder rig:**
  - Heat transfer studies
  - Work to improve solid dense phase fraction in the delivery nozzle
- **Studies on heating and stress propagation in packed beds**

Segmented target: LBNF



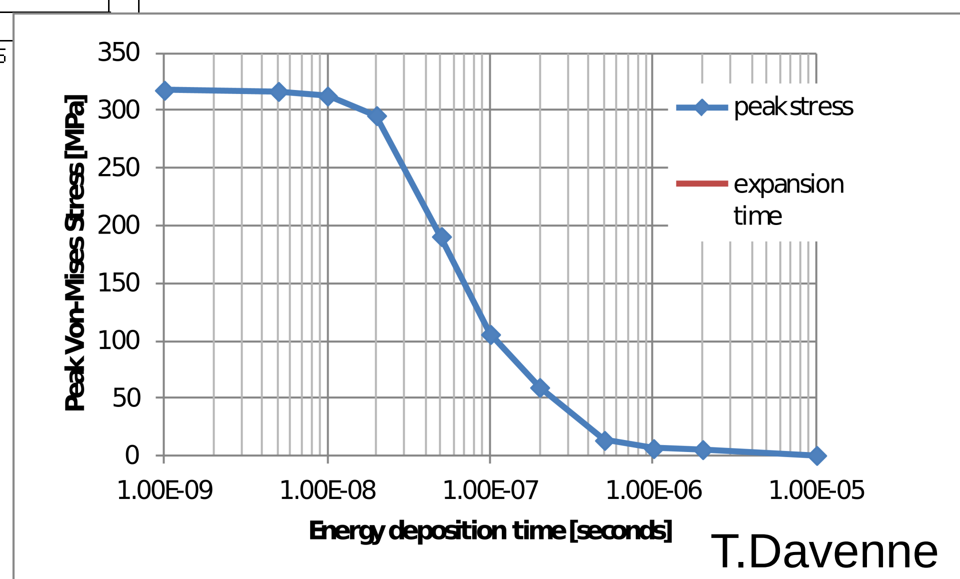


Dynamic stresses in beryllium cylinder compared to beryllium spheres as a result of LBNF 2.3MW beam



Relationship between peak dynamic stress and energy deposition time for a sphere

Expansion time vs target size

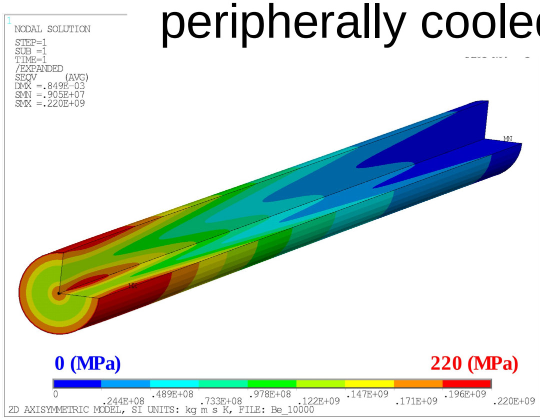


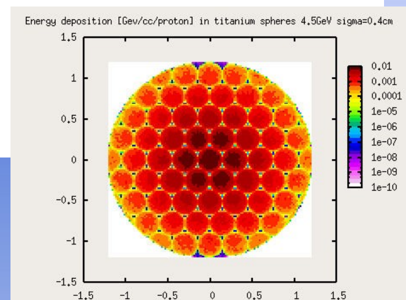
T.Davenne

Science & Technology Facilities Council
Rutherford Appleton Laboratory

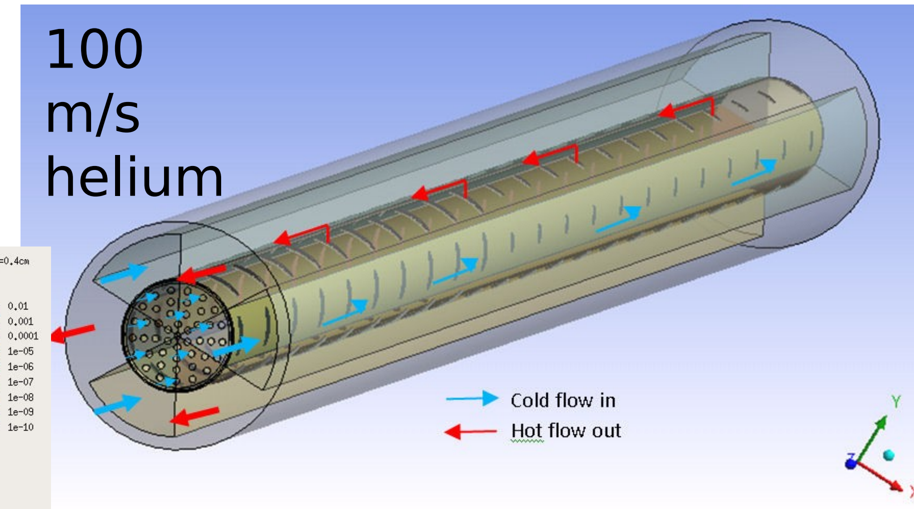
Segmented Target: EURONu

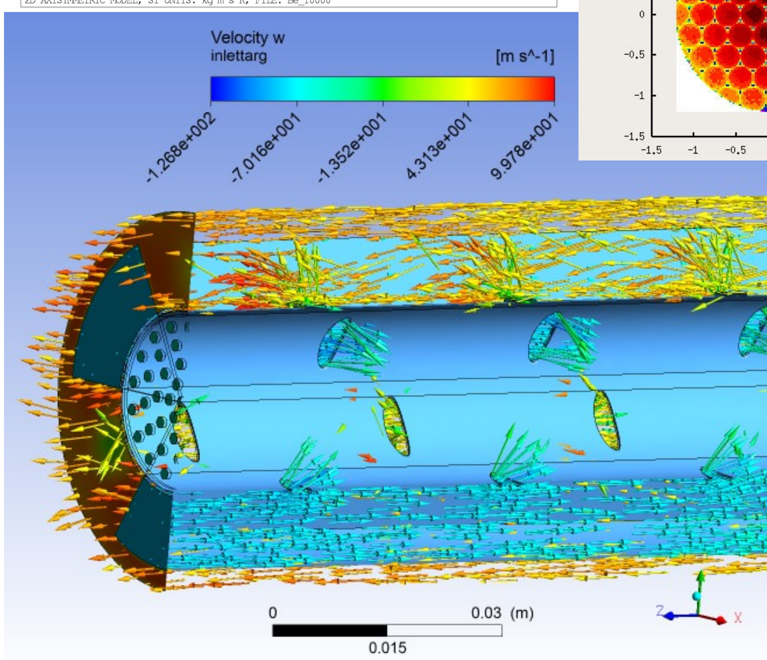
Stress limit reached for solid peripherally cooled target



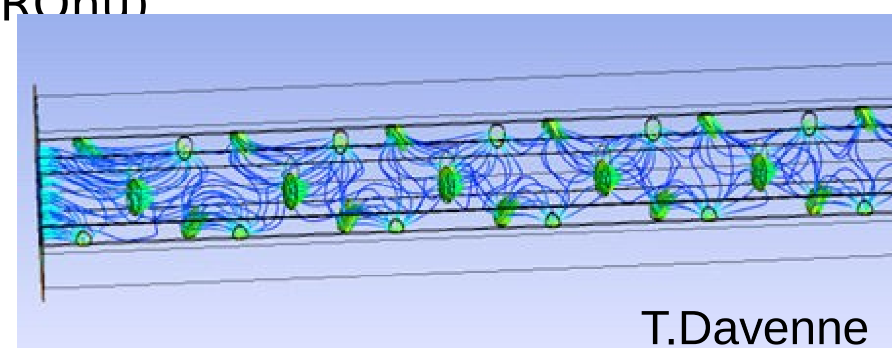


Increased surface area. Coolant reaching maximum energy deposition region



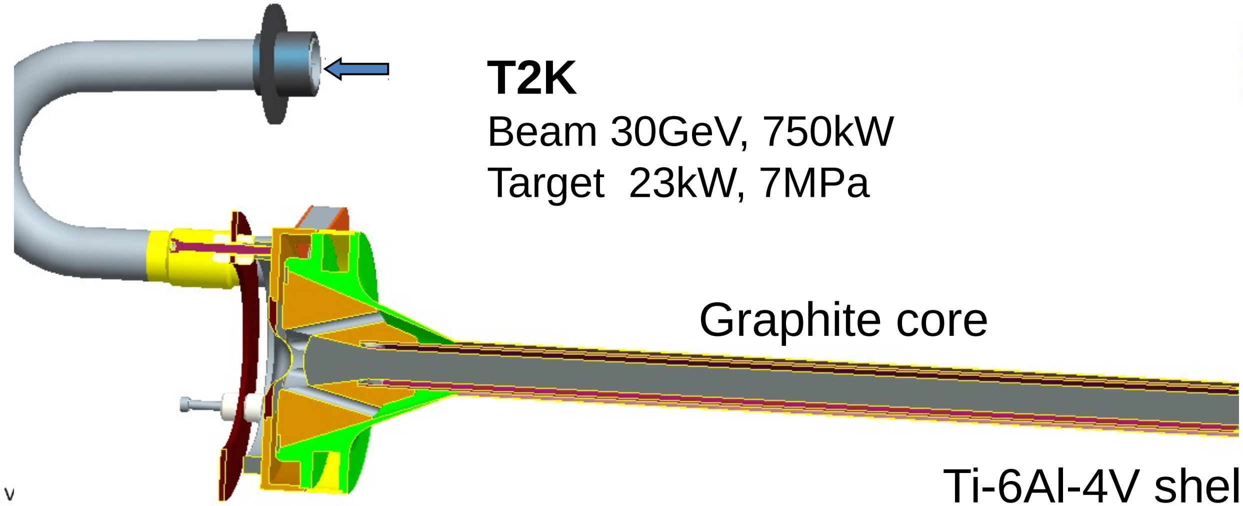


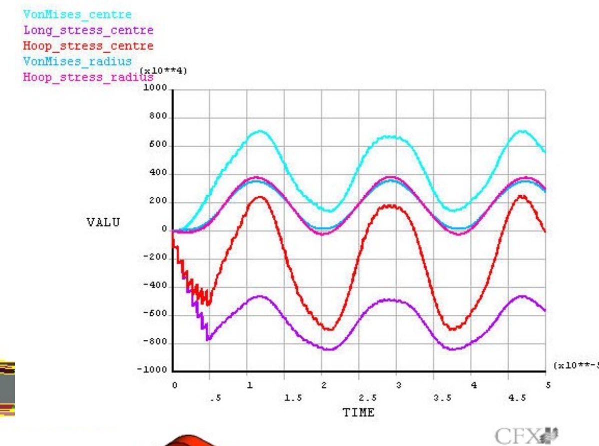
Packed bed target concept for 4 MW Neutrino Superbeam study (EUROnu)

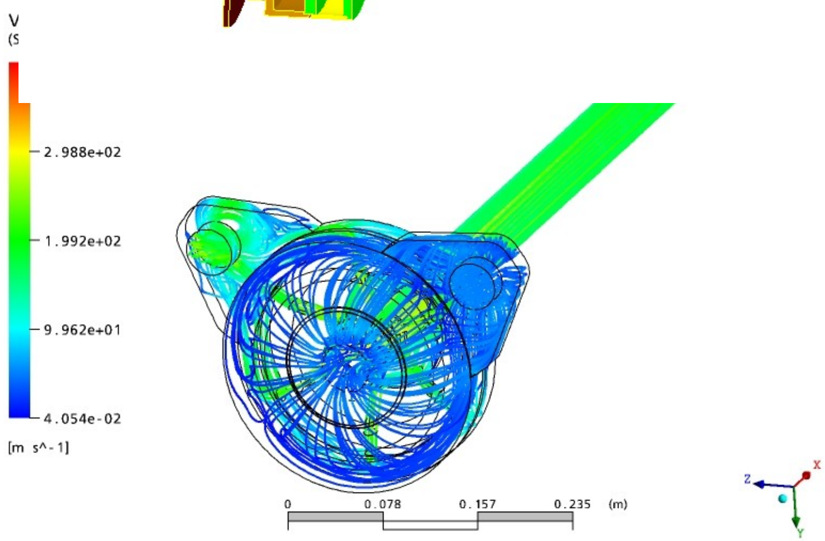


Monolithic (peripherally cooled) target: T2K

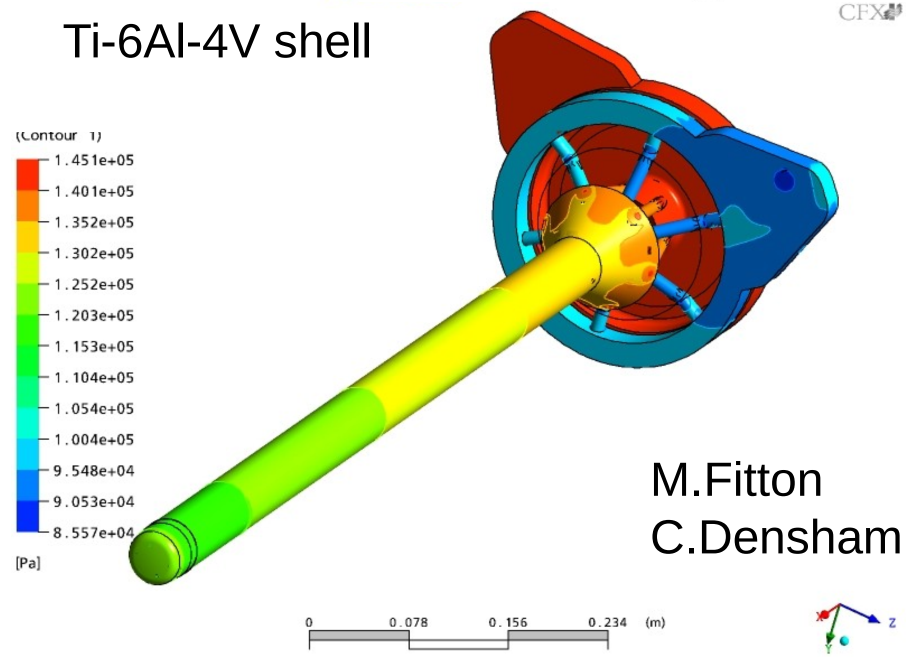
T2K
Beam 30GeV, 750kW
Target 23kW, 7MPa







Helium cooling velocity streamlines
Maximum velocity = 398 m/s



M.Fitton
C.Densham

Pressures (gauge)
Pressure drop = 0.792 bar

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