

Fluidised Tungsten Powder as a Muon Production Target

Dan Wilcox, Chris Densham, Tristan Davenne, Peter Loveridge, Mike Fitton, Joe O'Dell, Robert Bingham

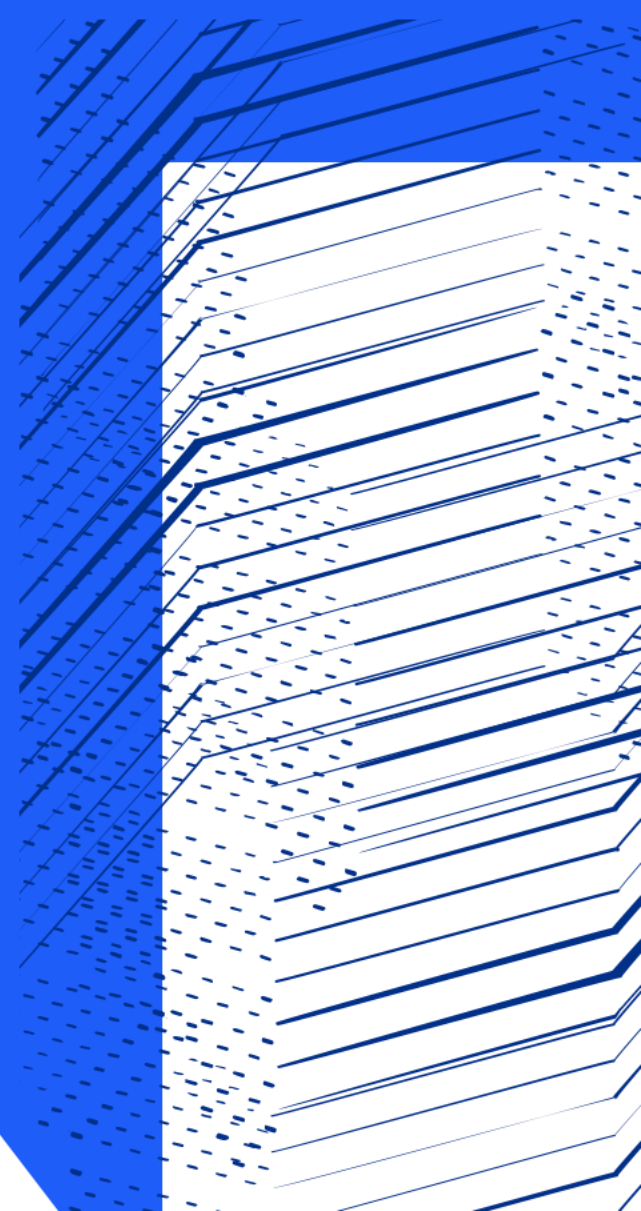
(STFC Rutherford Appleton Laboratory)

Otto Caretta *(CCFE)*

*Workshop on a Future Muon Program At Fermilab
28 March 2023*



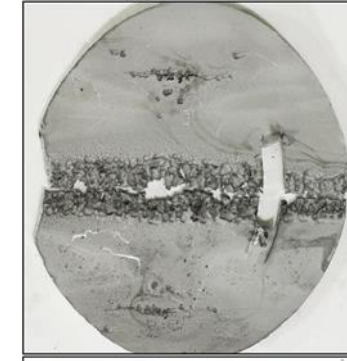
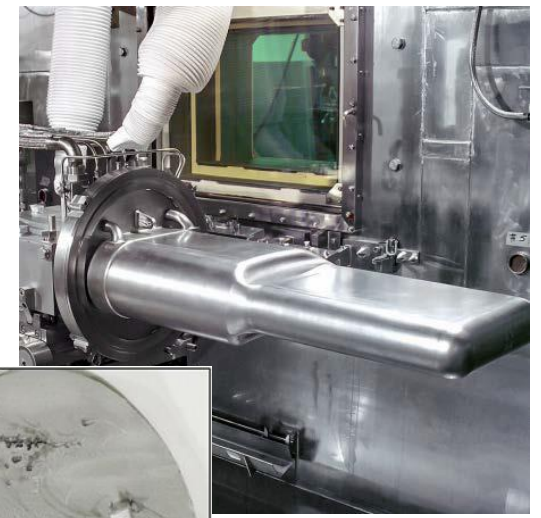
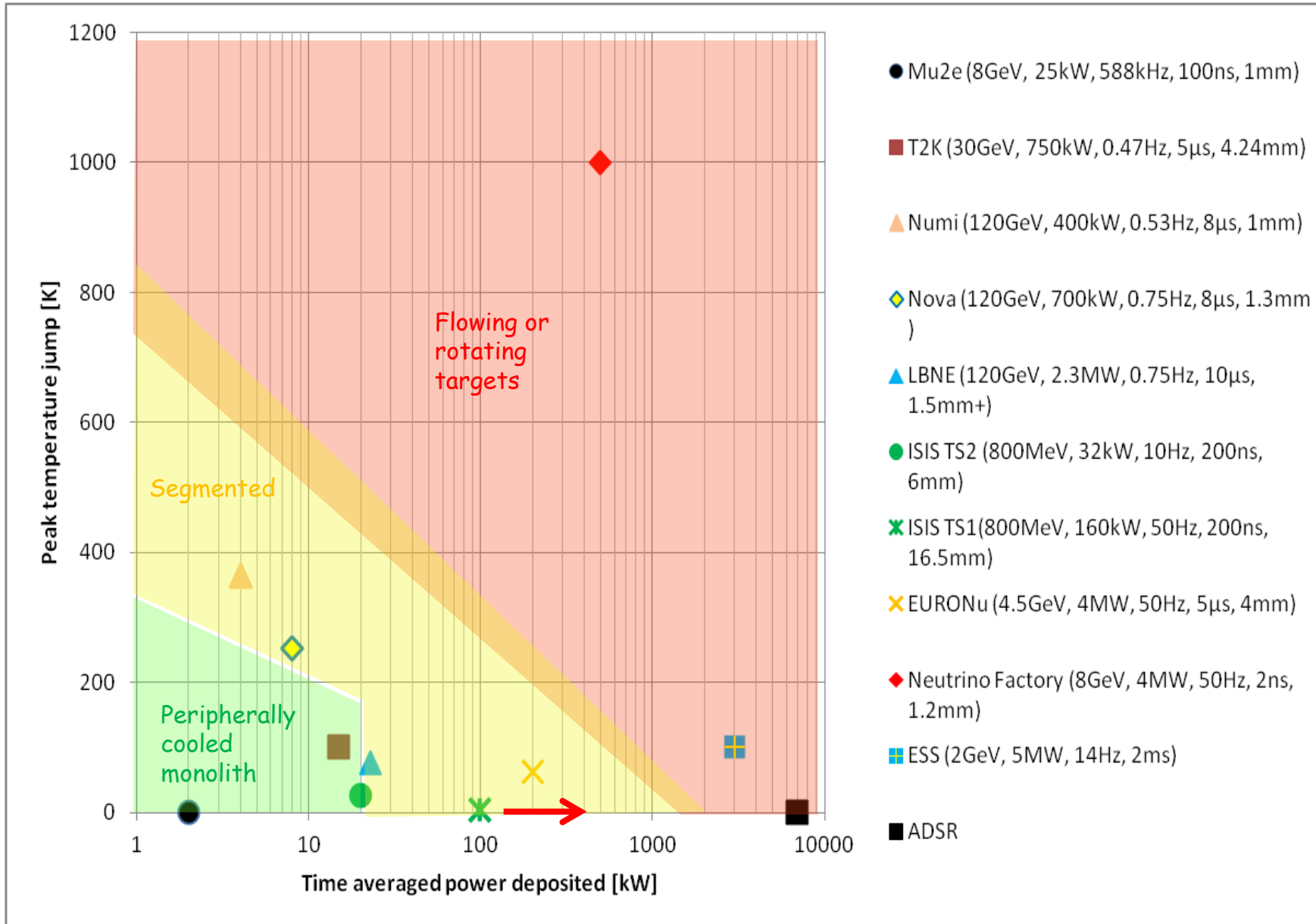
Science and
Technology
Facilities Council



Outline

- ❑ Benefits and Challenges
- ❑ Tungsten Powder Flow Rig at RAL
- ❑ In-Beam Tests at CERN HiRadMat
- ❑ Future Possibilities
- ❑ Conclusions

Limitations of Target Technologies



Cavitation damage on SNS mercury target window



Iridium sample after a single pulse at HiRadMat HRMT27 experiment

Fluidised Tungsten Powder Technology

- ❑ High Z refractory metal – maximal secondary particle production from impinging proton beam
- ❑ Potential solution for applications requiring highest beam powers e.g. as alternative to liquid mercury
- ❑ Pneumatically (e.g. helium) recirculated tungsten powder
- ❑ An innovative generic target system exploiting well-established granular flow technology
- ❑ Test rig developed off-line at RAL
- ❑ 1st in-beam experiment on static mixed crystalline powder sample carried out at HiRadMat facility, CERN in 2012
- ❑ 2nd HiRadMat experiment carried out in 2015

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

Key Benefits

❑ Shock waves

- Material is already broken – intrinsically damage proof
- No cavitation as for liquids
- High power densities can be absorbed without material damage
- Shock waves largely constrained within material grains, c.f. sand bags used to absorb impact of bullets

❑ Heat transfer

- High heat transfer both within bulk material and with pipe walls - so the bed can dissipate high energy densities, high total power, and multiple beam pulses

❑ Quasi-liquid

- Target material continually reformed
- Can be pumped away, cooled externally & re-circulated
- Material easily replenished

❑ Activation

- Majority of radiotoxicity is contained within solid granules (cf mercury)

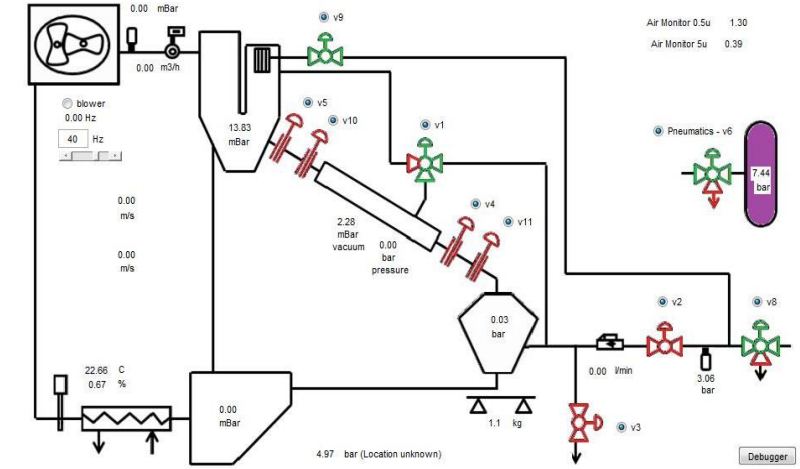
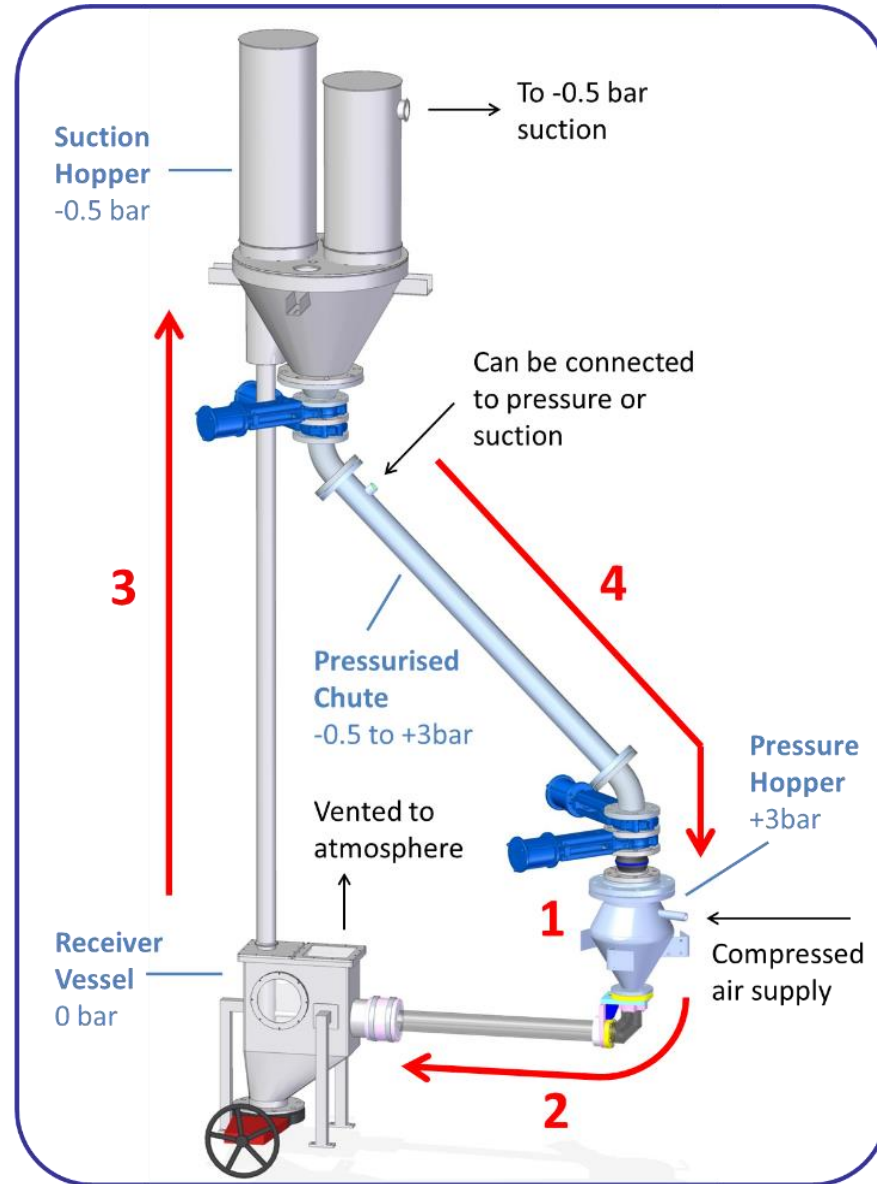
❑ Other

- Can exclude moving parts from beam interaction area
- Fluidised beds are a mature technology
- **Most issues of concern can be tested off-line -> experimental programme**

Challenges

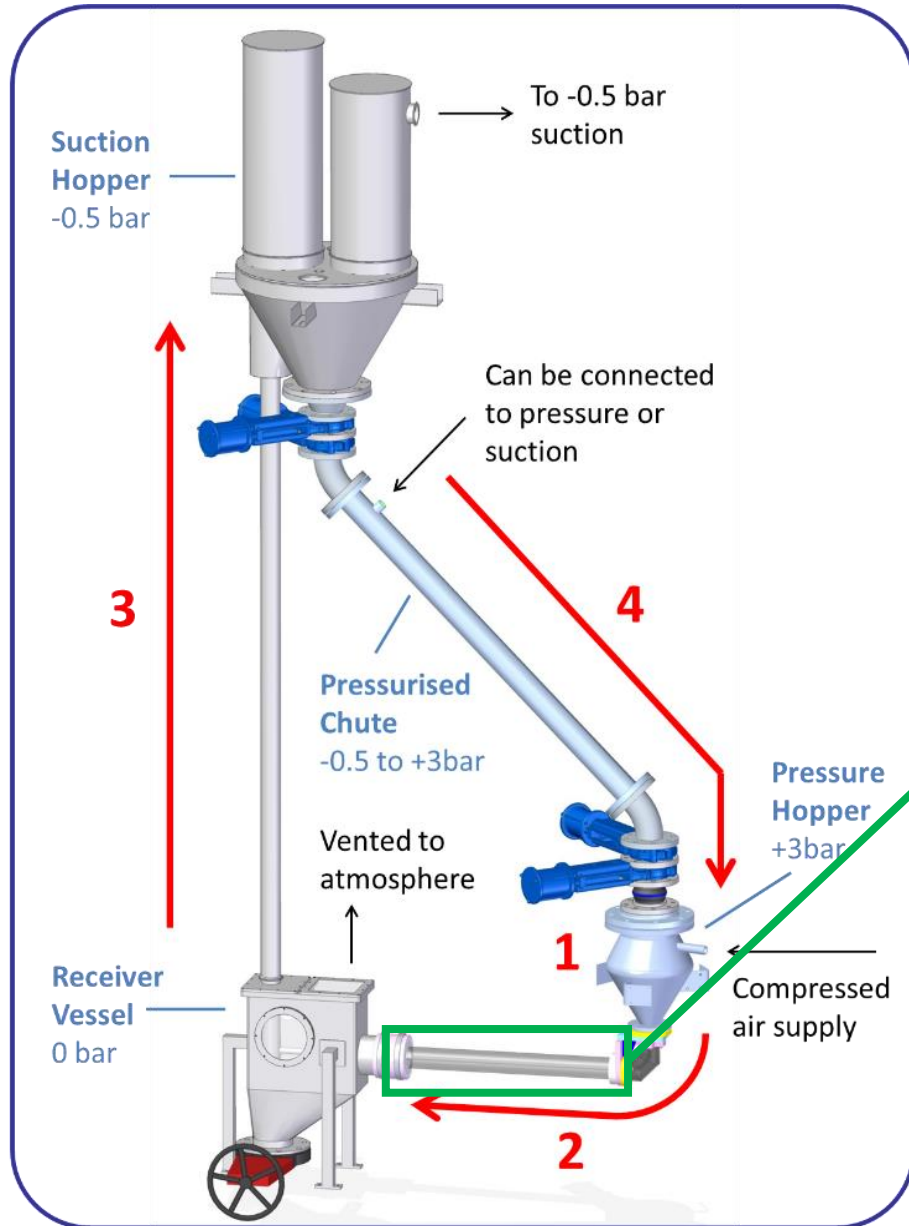
- ❑ Erosion of material surfaces, e.g. nozzles
- ❑ Difficult to avoid moving parts in circuit (e.g. valves)
- ❑ Activated dust on circuit walls
- ❑ Activation of carrier gas circuit
- ❑ Achieving high material density – typically maximum 50% bulk material fraction
- ❑ Secondary heating of pipe walls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

Tungsten Powder Flow Rig Development at RAL

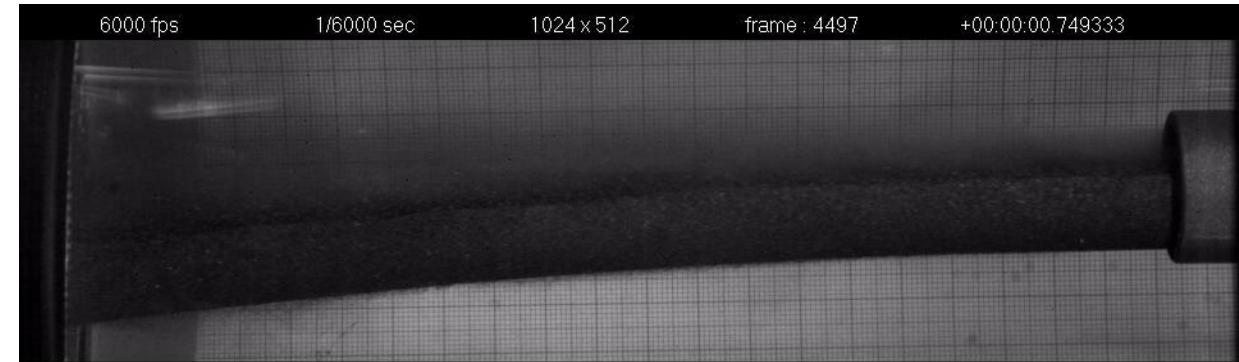


1. Pressurised powder hopper
2. Ejection of dense phase powder ("Target" section)
3. Suction lift of lean phase powder
4. Gravity chute refills powder hopper

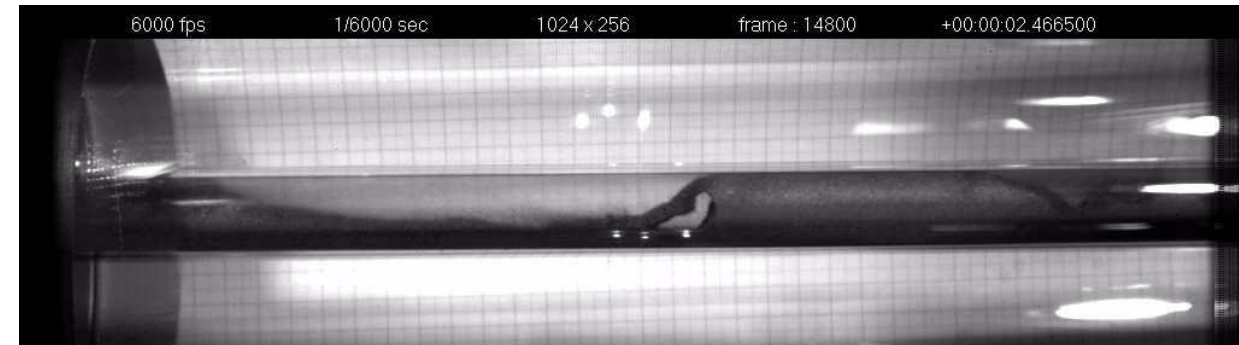
Target Section Development



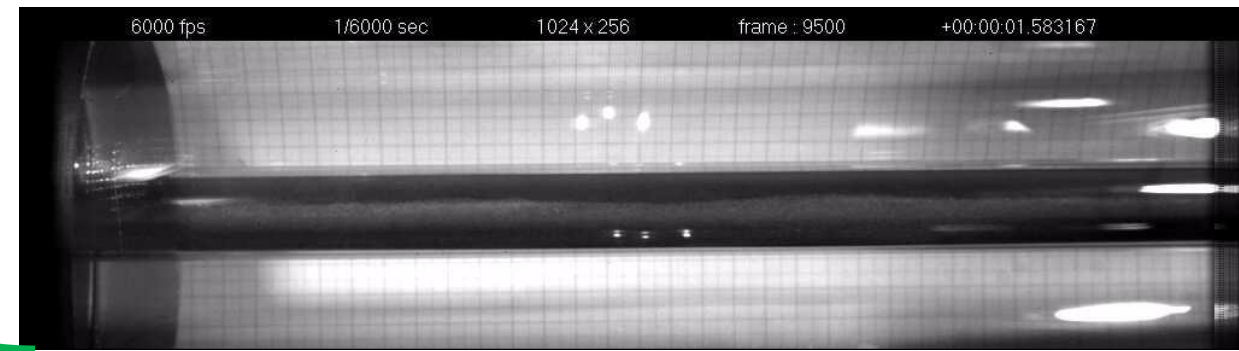
Open jet (~40% bulk density):



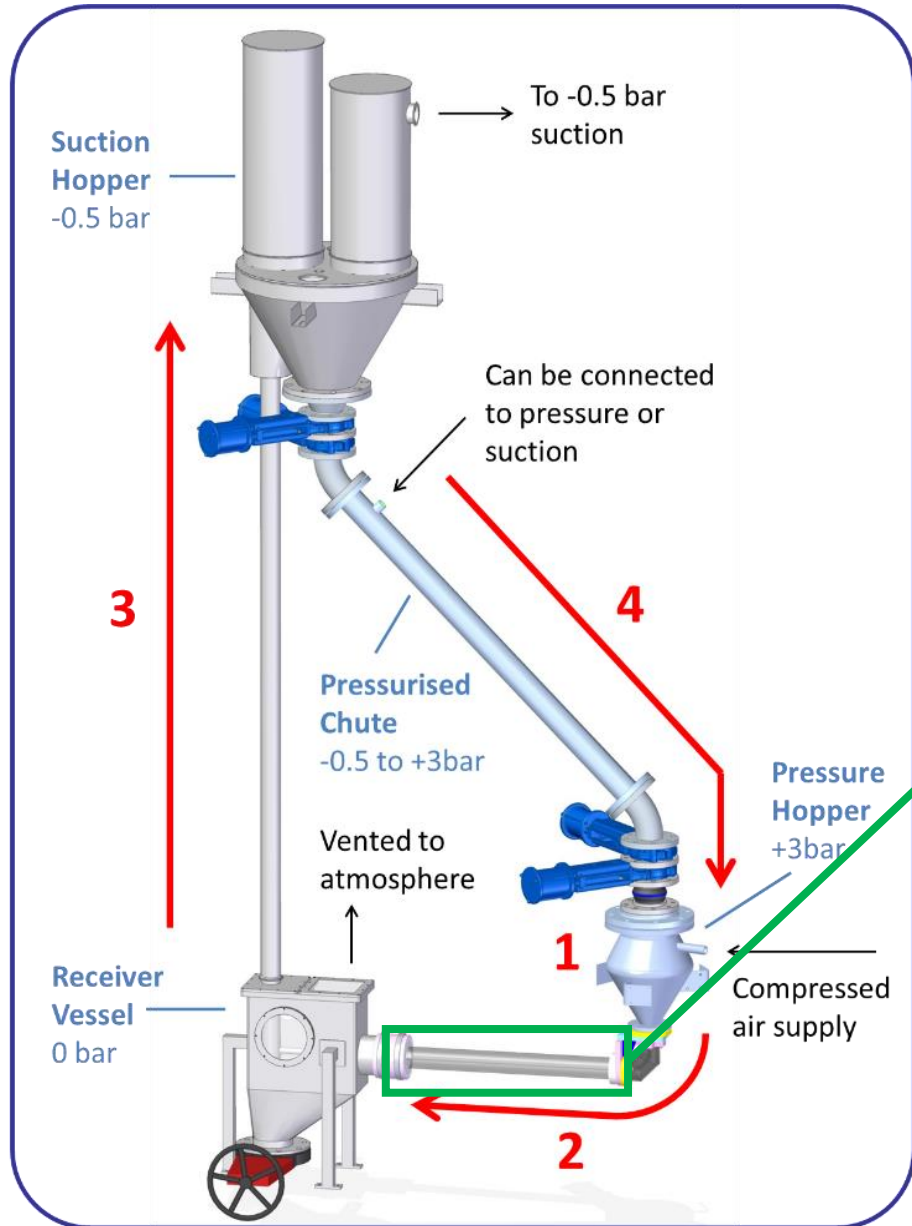
Contained discontinuous dense phase:



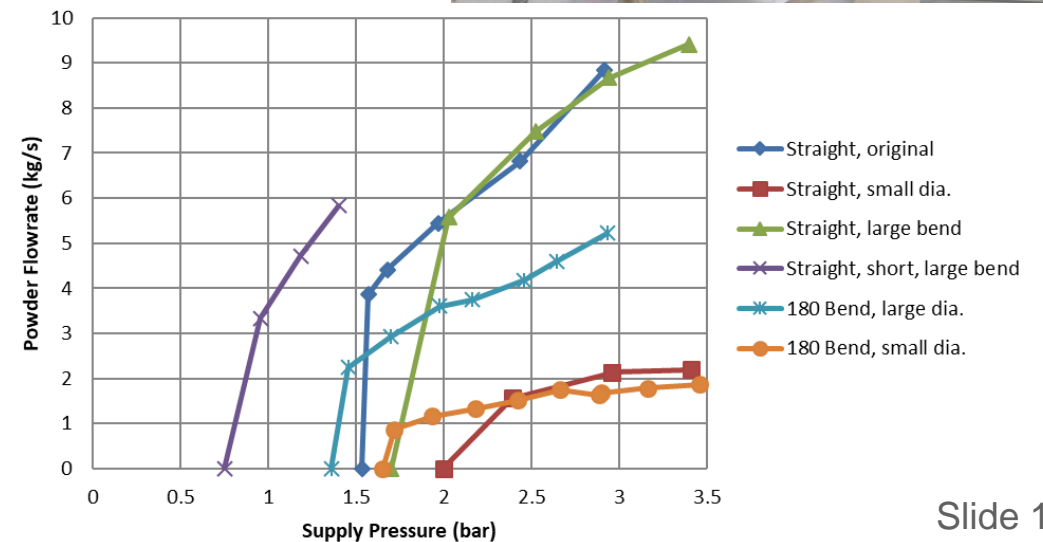
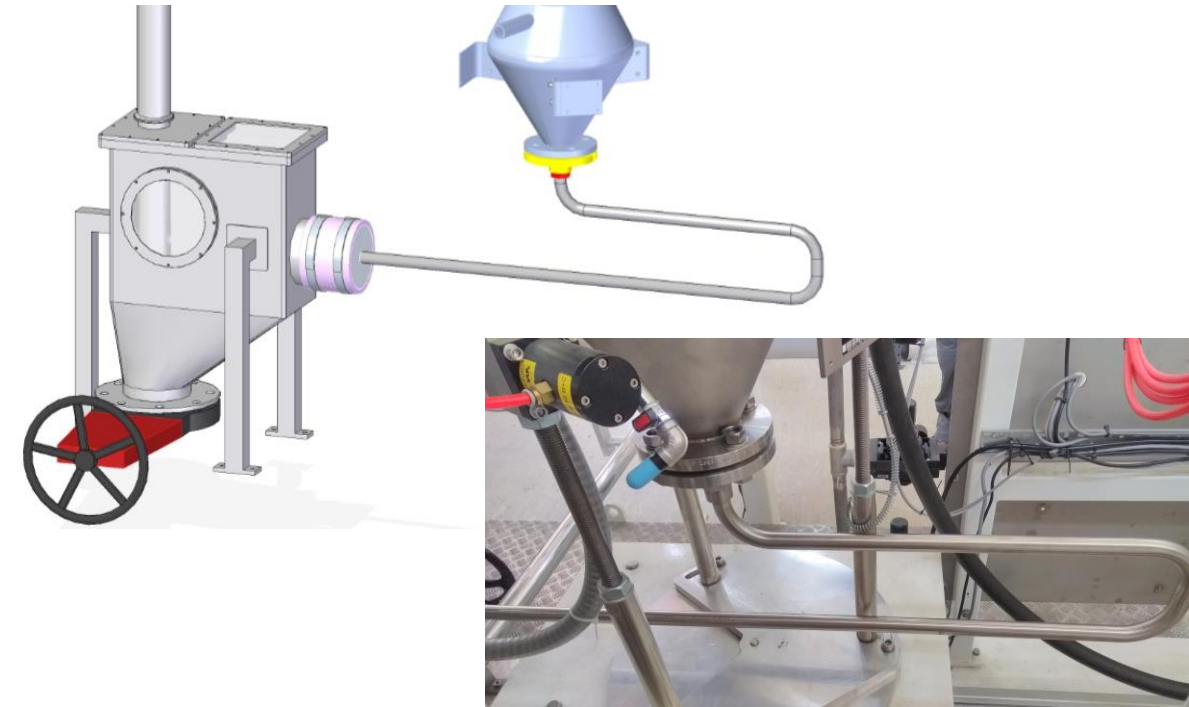
Contained (partially) continuous dense phase (~50% bulk density):

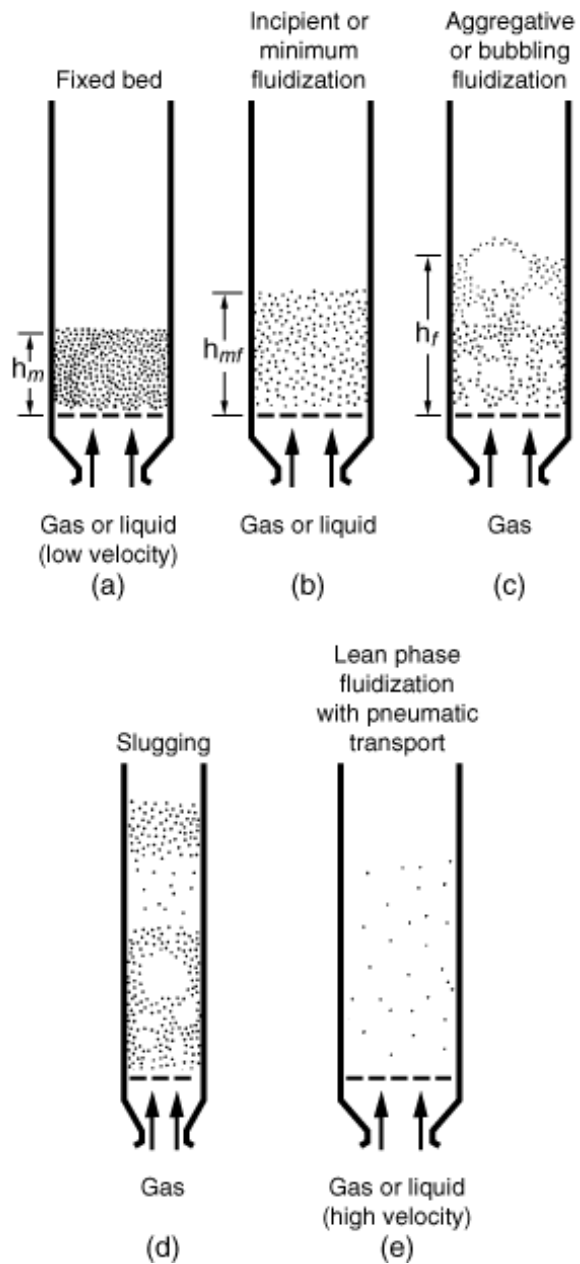


Target Section Development

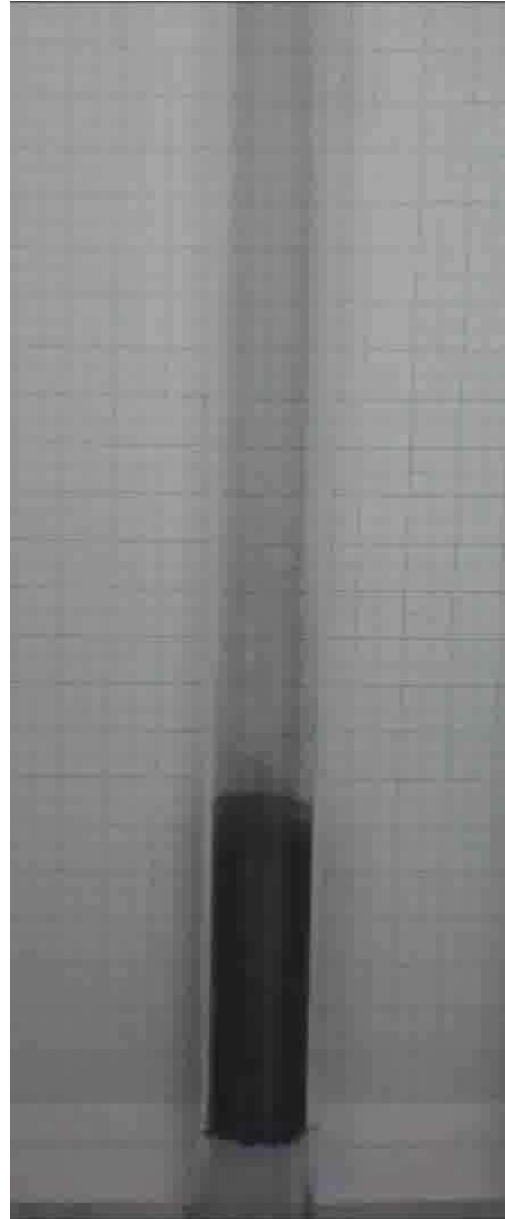


Turnaround section: one plausible geometry to deliver a flowing powder target inside a solenoid

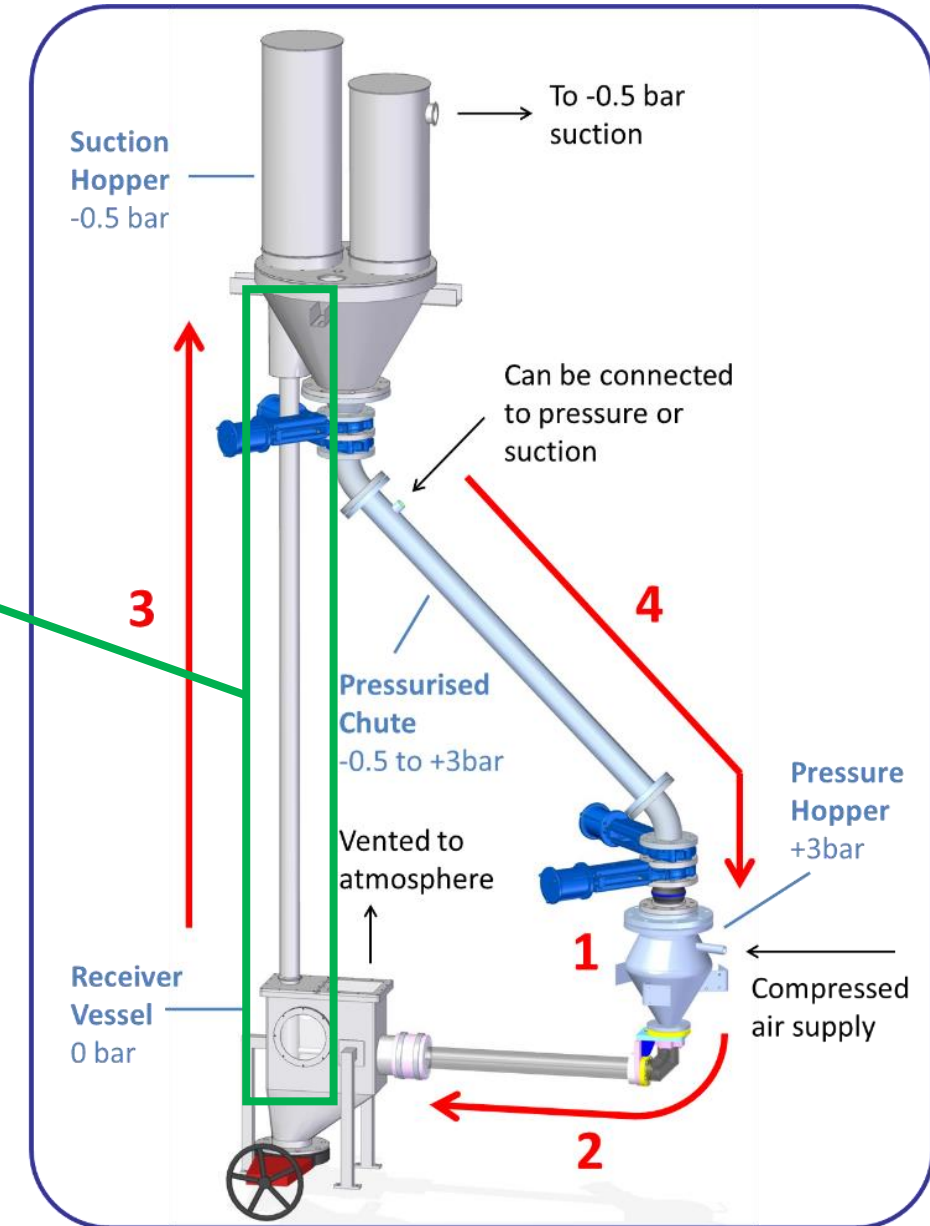




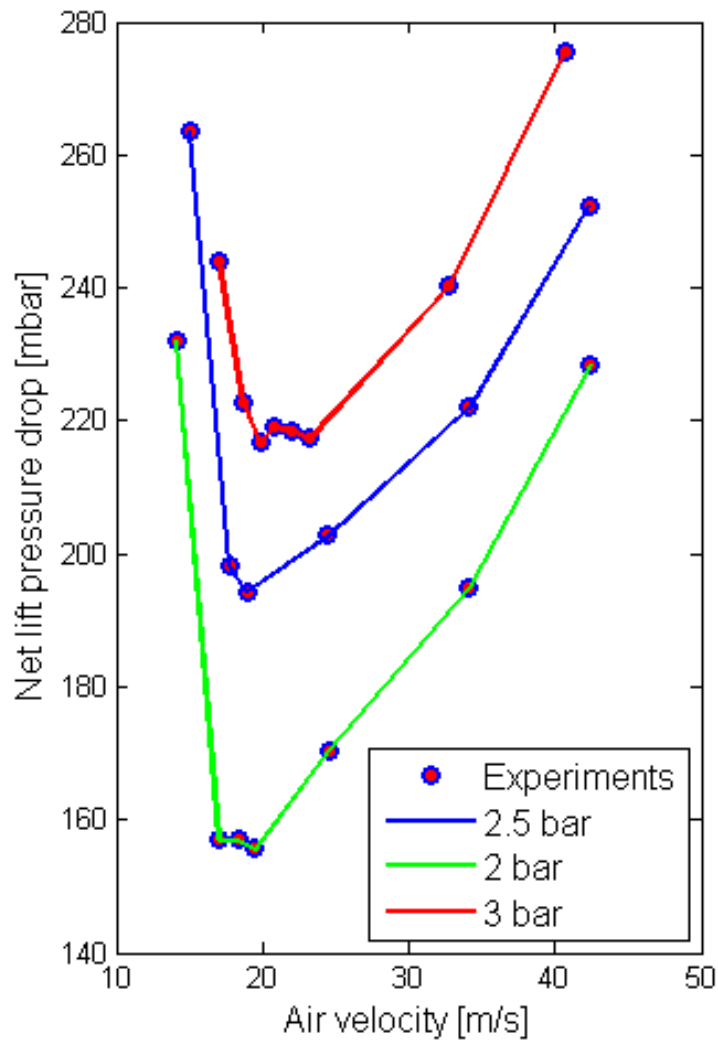
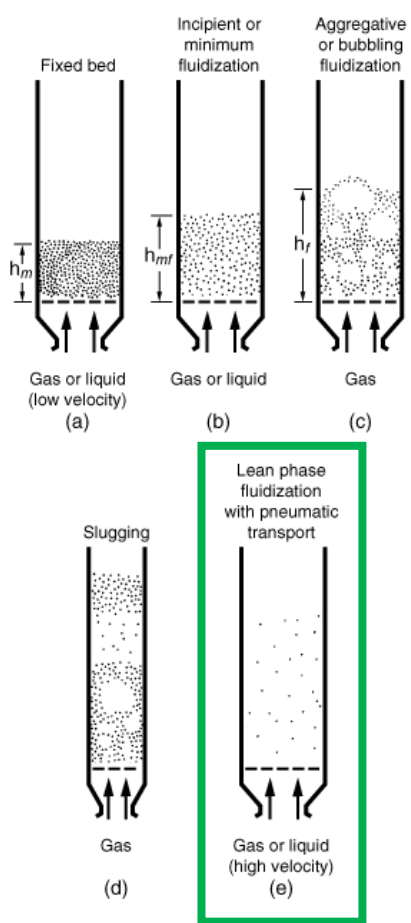
Pressure drop for air flowing through a bed of powder:



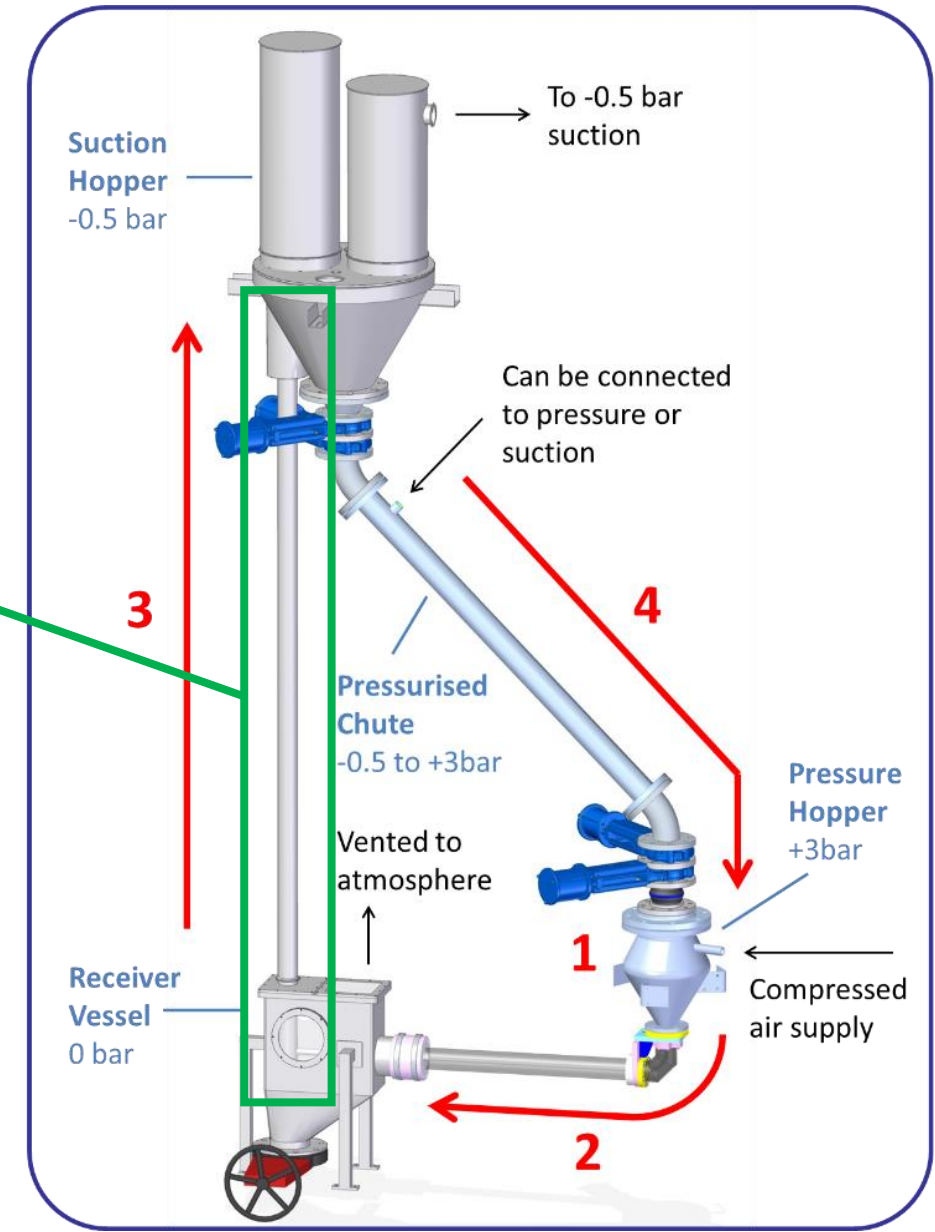
Suction Lift Development



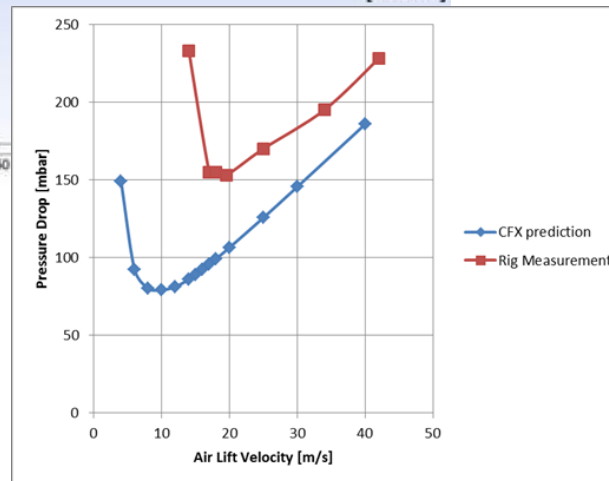
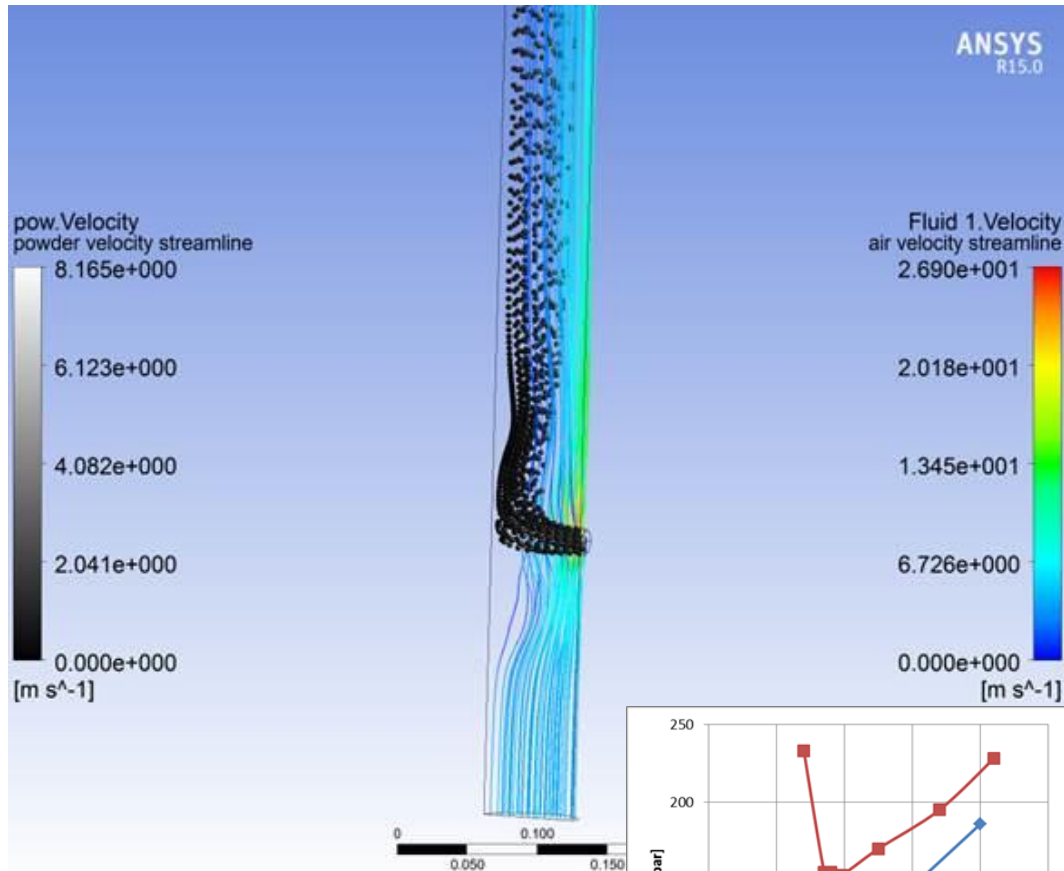
- Objective: Minimise gas lift pressure drop, flowrate (and lift velocity) before flow chokes and stalls.



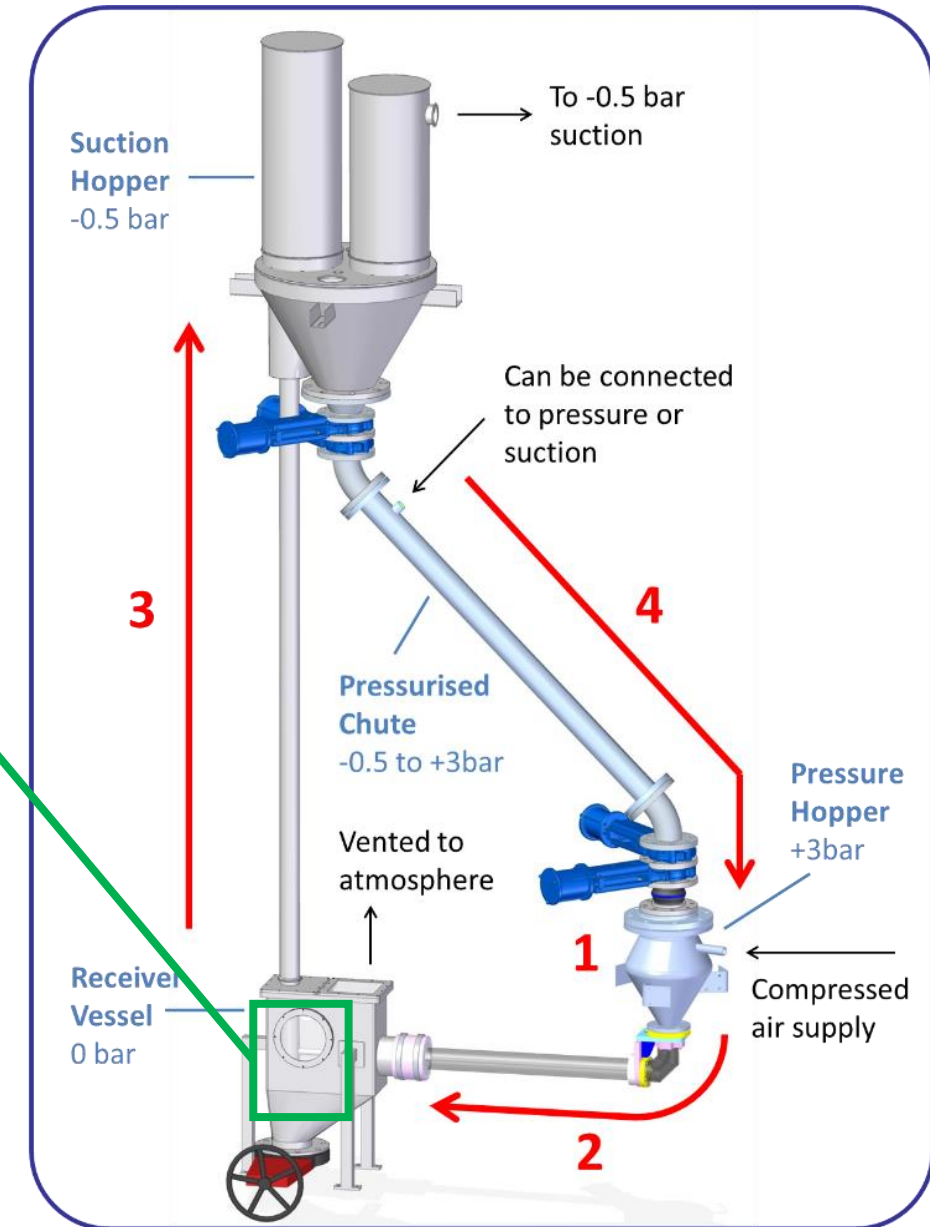
Suction Lift Development



CFX simulation of powder lift by Tristan Davenne

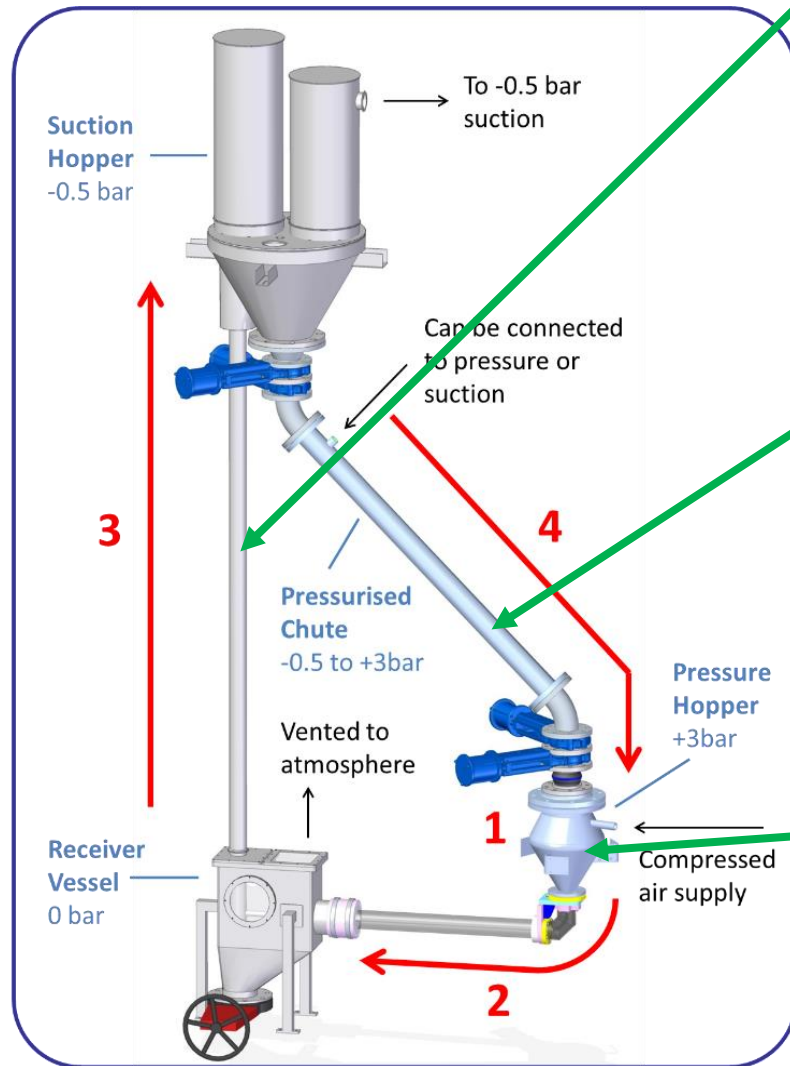


Suction Lift Development

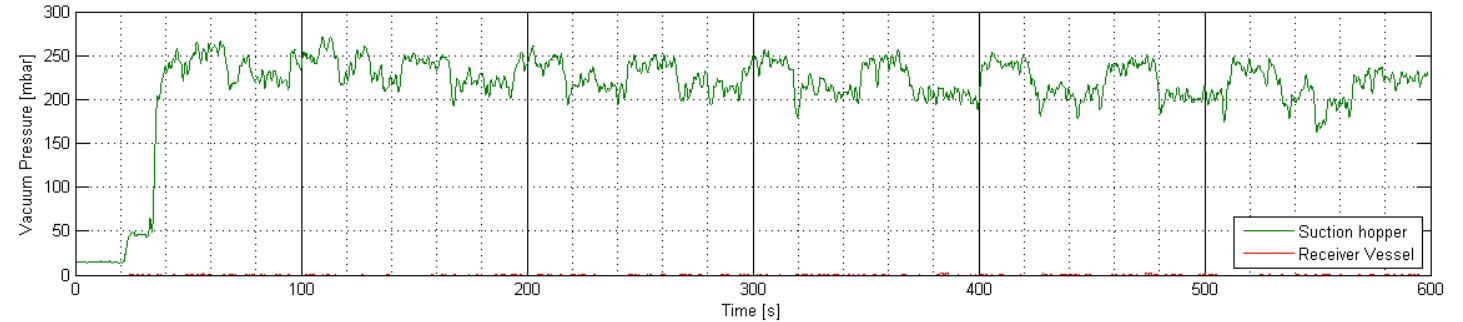


- Gidaspow interphase drag correlation
- Spherical tungsten, 100 micron dia.
- Injection volume fraction = 0.5

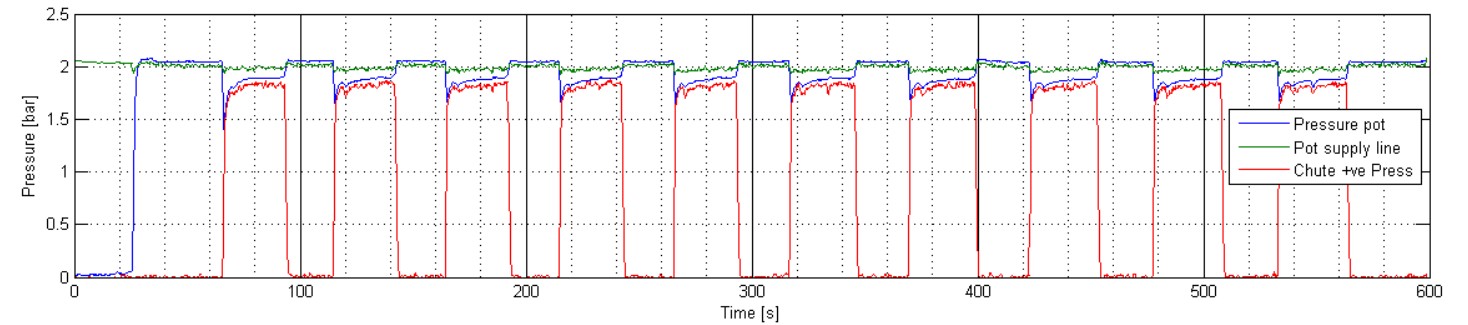
Continuous Flow Development



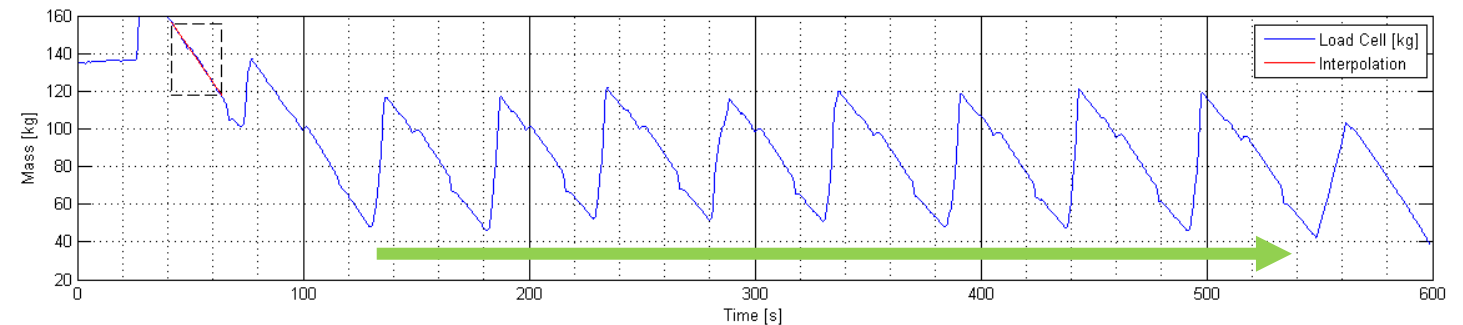
Suction line pressure variation during recycling:



Pressure cycling of chute and discharge hopper:



Mass in pressurised discharge hopper:



Sustainable continuous flow

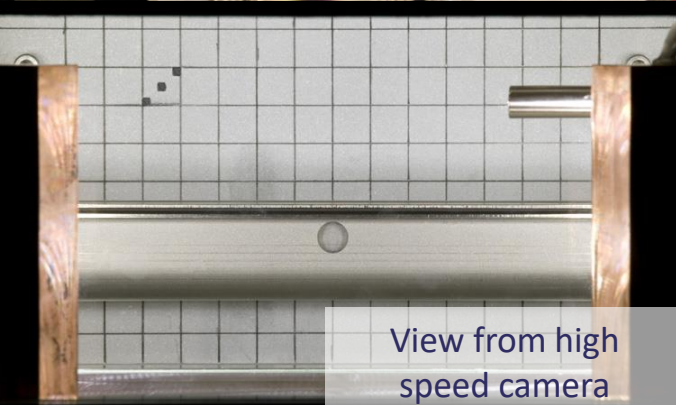
Tungsten powder experiments at CERN HiRadMat



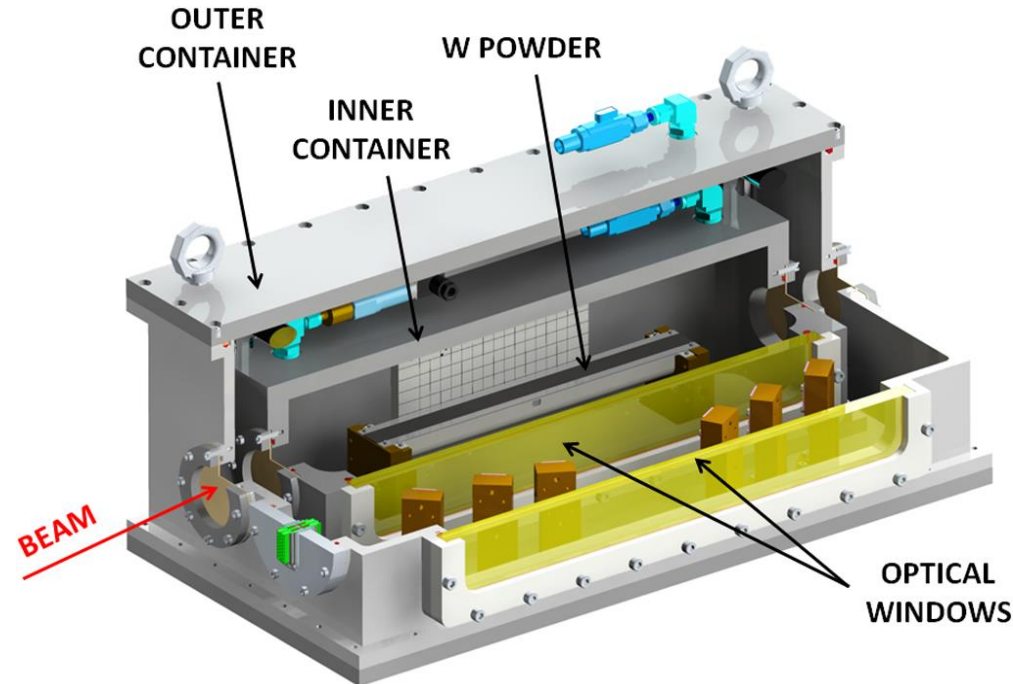
Open trough Assembly



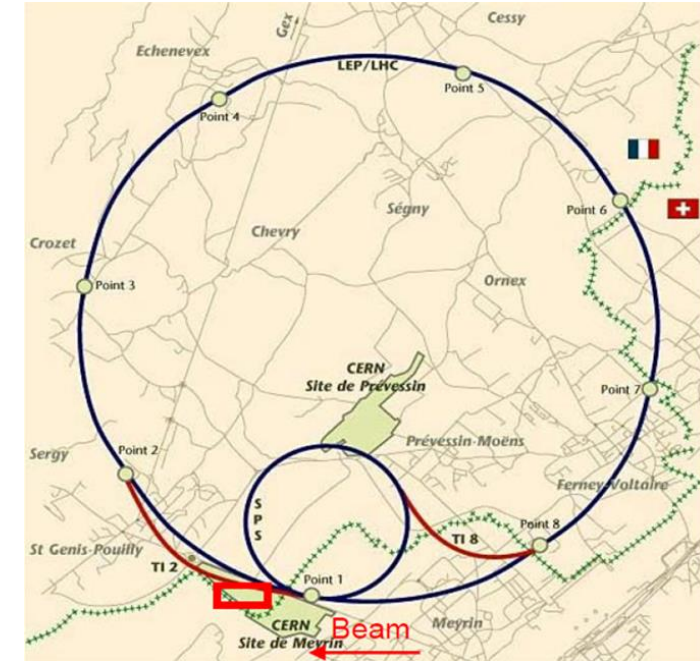
Filling with Tungsten Powder



View from high speed camera



- ❑ Tungsten powder sample in an double-walled open trough
- ❑ Helium environment
- ❑ Remote diagnostics via:
 - High-speed camera
 - Laser Doppler Vibrometer to measure vibrations of inner and outer container
 - to differentiate between effect of powder on wall and secondary heating effects



High-intensity proton beam pulses from LHC injector directed to the HiRadMat facility in parasitic mode.

Beam Energy 440 GeV

Maximum pulse intensity 4.9×10^{13} protons

Pulse length 7.2 μ s

Beam size at target variable around 1 mm²

Installation and Remote Diagnostics

Fast camera and Laser Doppler Vibrometer in shielded bunker
35 m from interaction point



Response of Tungsten Powder to Proton Beam



Proton
beam

Response of Tungsten Powder to Proton Beam

- ❑ 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

1 mm

150μm

90μm

45um

25um

Particle diameter

Explanation for Particle Lift?

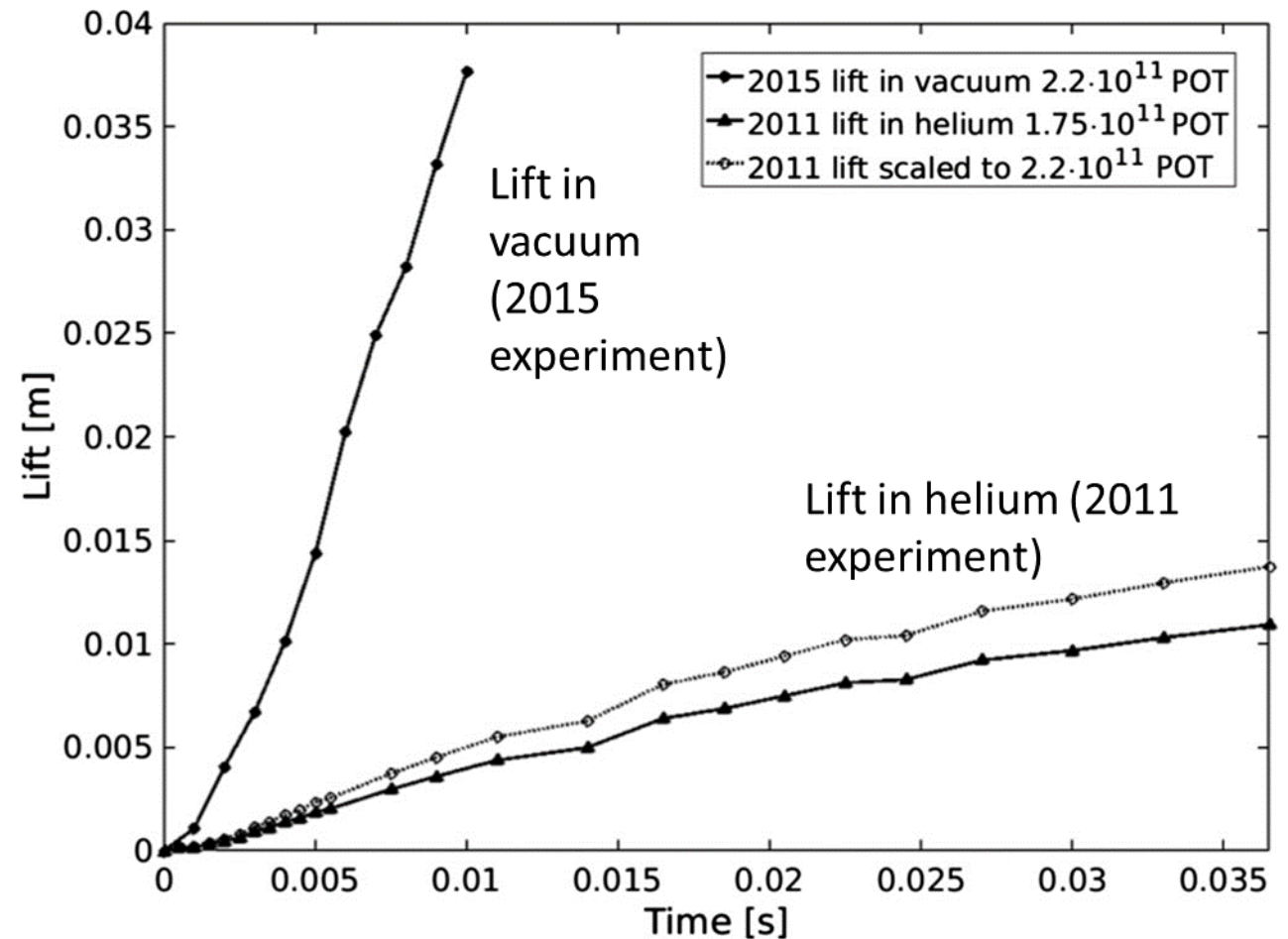
□ Possible Explanations:

- **Aerodynamic lift?** – Observed lift is higher in vacuum than air
- **Force chains?** – Small particles lift higher than large ones
 - Offline experiments also failed to produce force chain effects
- **Electrostatic effect?** – Plausible explanation from experiments and calculations



1mm
150um
90um
45um
25um
Particle diameter

Proton beam

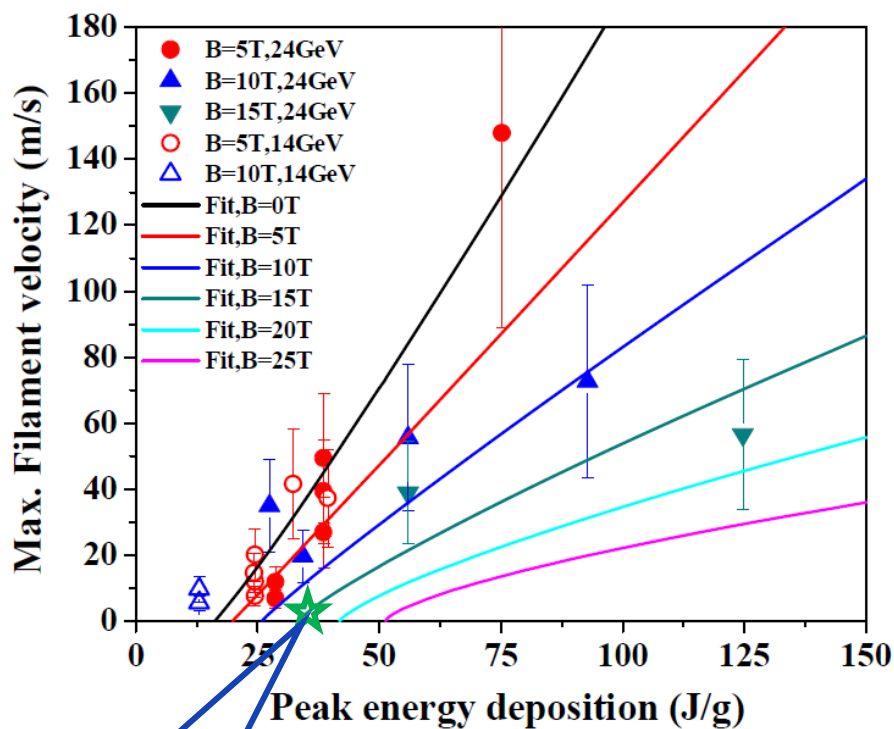


For full details see:

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, 2018.

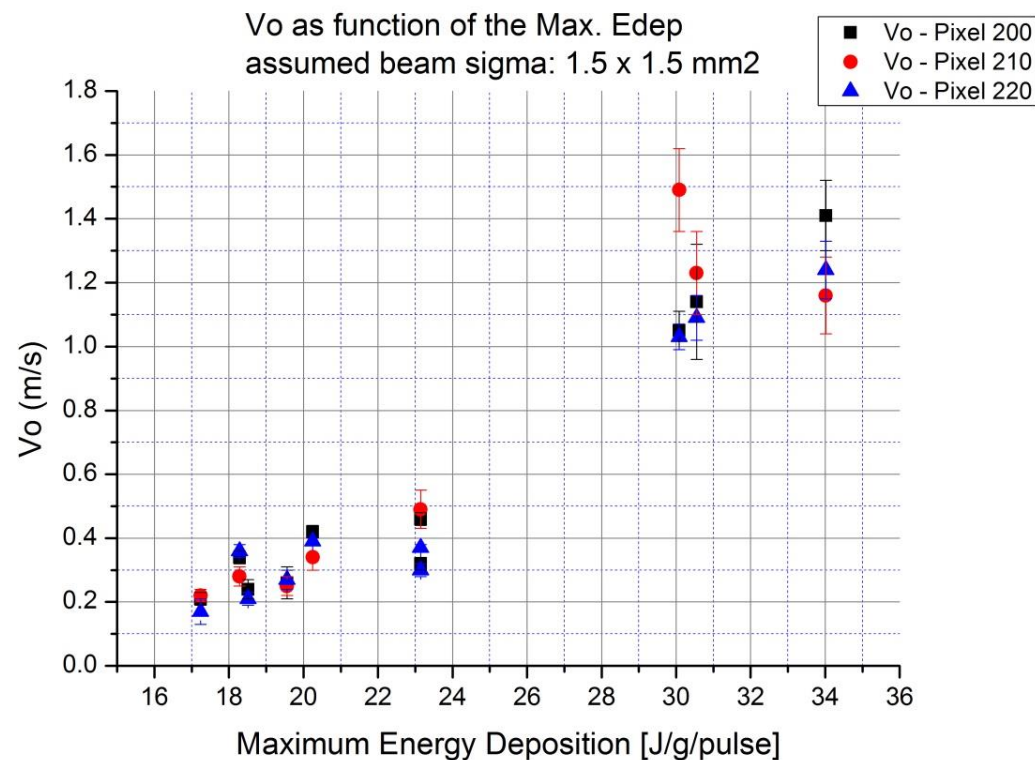
Comparison with Liquid Mercury

MERIT results



Tungsten powder

Tungsten powder results



Interim analysis by N. Charitonidis.
Need simulations for different parameters for each beam shot.

Simulations vs Observations

Prompt energy deposition/radiation
(FLUKA Monte Carlo Code)

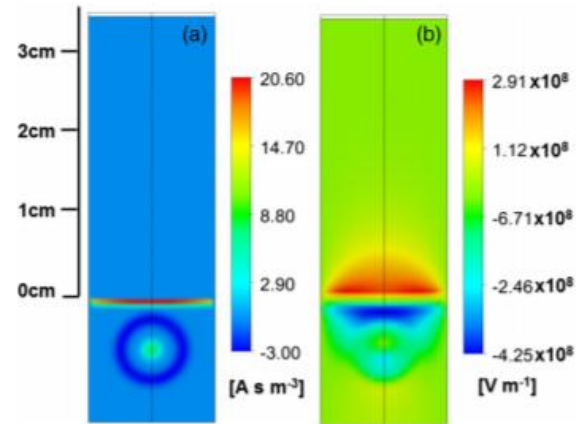
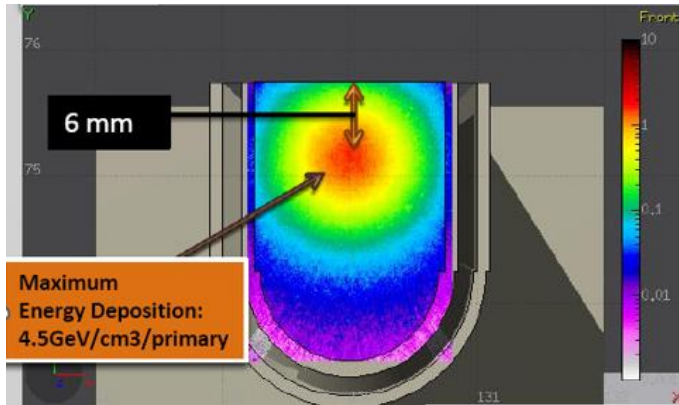


FIG. 16. Simulated deposited charge density on the solid powder phase (a) and resultant vertical electric field (b) immediately following a beam pulse of 3×10^{12} protons.

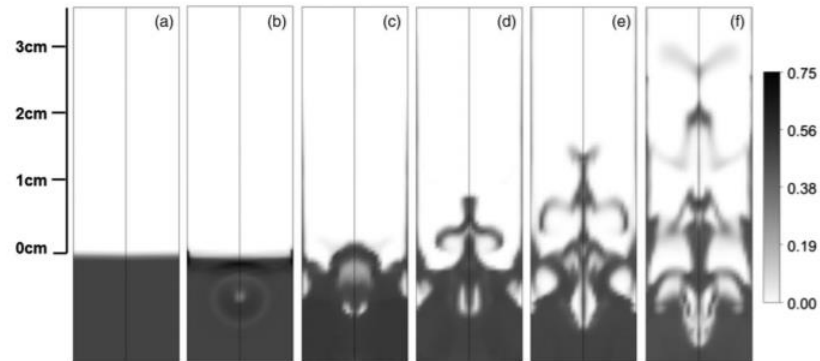


FIG. 17. Simulation of charge induced lift of 34 micron diameter tungsten particles, tungsten volume fraction at plane AA at indicated time intervals after a beam pulse with 3×10^{12} protons; $a = 1 \mu\text{s}$, $b = 0.1 \text{ ms}$, $c = 1 \text{ ms}$, $d = 2 \text{ ms}$, $e = 3 \text{ ms}$, and $f = 5 \text{ ms}$.

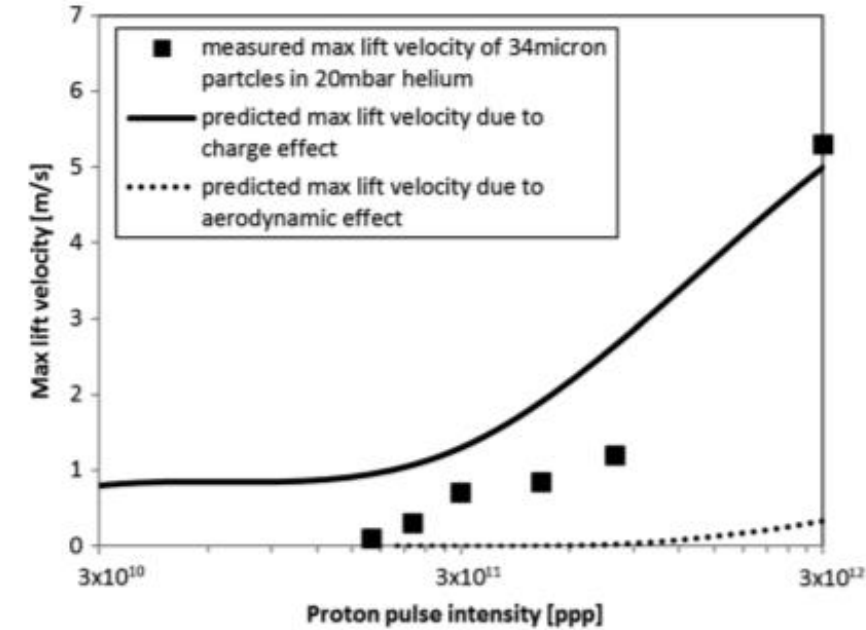


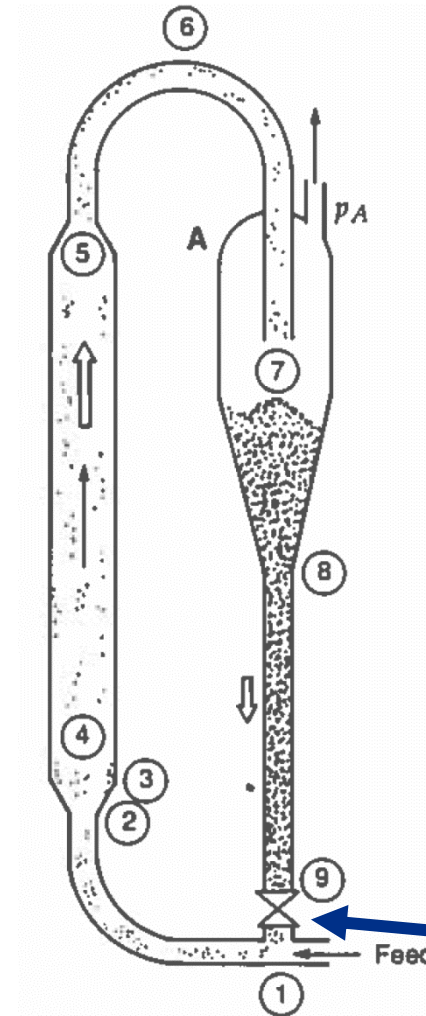
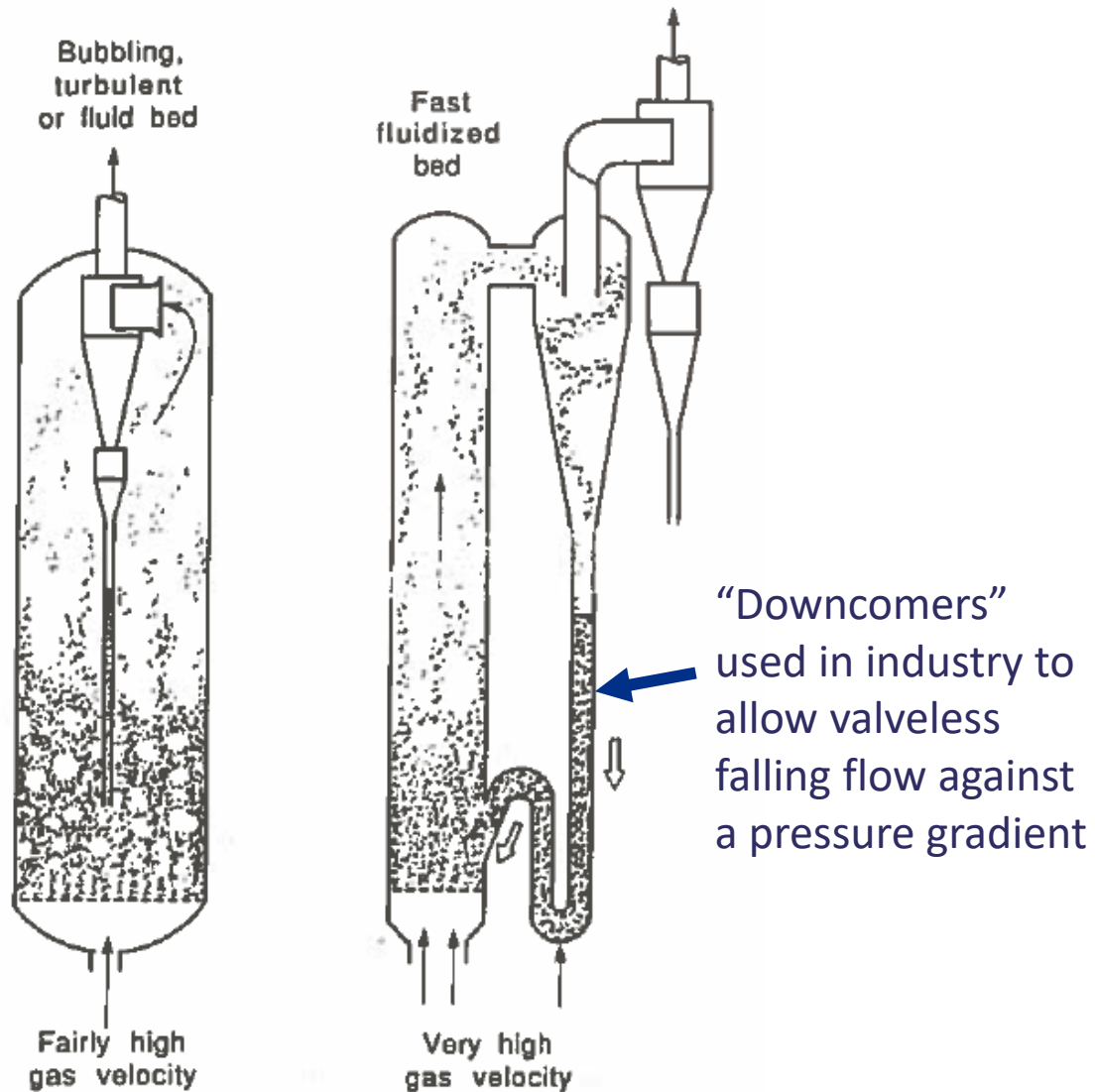
FIG. 21. Maximum lift velocity, comparing measurements with predictions from charge and aerodynamic models; helium pressure = 20 mbar; mean particle diameter = $34 \mu\text{m}$.

**Reasonable agreement
between charge induced lift
simulations and observations**

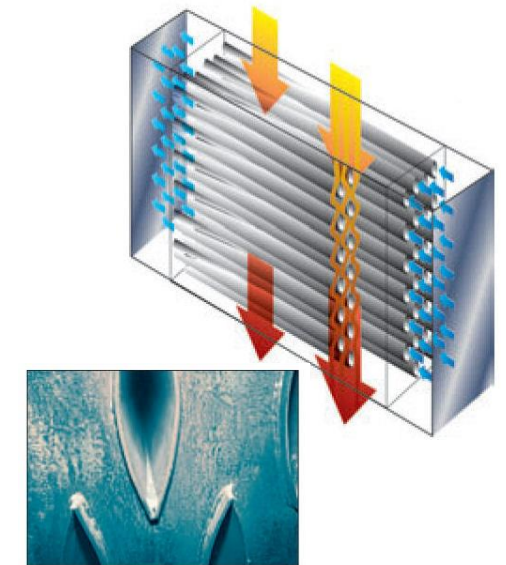
Fluidised Tungsten Powder – Future R+D

- ❑ Measurement of erosion rates, and development of improved components to mitigate erosion risk
- ❑ Development of powder circuit design to minimise or eliminate the need to have moving parts such as slide valves in contact with the powder
- ❑ Measurement of heat transfer to and from flowing tungsten powder
- ❑ Development of improved diagnostics for automated operation and fault detection
- ❑ Investigate the use of spherical powder to improve flow characteristics

Circulating Fluidised Beds from Literature



Powder heat exchangers available commercially, but not yet tested with tungsten



Designs with valves could be modified to position the valves away from the irradiated target section

Fluidised Tungsten Powder as a Muon Production Target

Fluidised Tungsten Powder – Summary

❑ Advantages:

- Can withstand extremely high energy density
- Fluidised powder handling technology is well-established in industry
- Lower eruption velocity than liquid mercury, and no cavitation damage

❑ Challenges:

- More R+D required to mitigate erosion of containment during long term operation
- Tungsten is much more dense than materials handled in industry; existing flow equations and plant designs may need to be modified
- Diagnostics and process control must be developed to ensure reliable long-term operation

❑ These challenges can be addressed with cost effective off-line testing

Publications

Fluidised powder flow:

- O. Caretta, C. J. Densham, T. W. Davies and R. Woods, “Preliminary Experiments on a Fluidised Powder Target,” *Proceedings of EPAC08, WEPP161*, Genoa, Italy, 2008.
- C.J.Densham, O.Caretta and P.Loveridge, “The potential of fluidised powder target technology in high power accelerator facilities,” *Proceedings of PAC09, WE1GRC04*, Vancouver, BC, Canada, 2009.
- 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.

In-beam testing:

- 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*, p. DOI: 10.1103/PhysRevSTAB.17.101005, 08 2014.
- O.Caretta, P.Loveridge et al., “Proton beam induced dynamics of tungsten granules,” *Physical Review Accelerators and Beams*, vol. 21, 2018.
- 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, 2018.



Science and
Technology
Facilities Council

The background features a large blue rectangle on the right side, which is partially overlaid by a series of blue lines forming a complex, abstract geometric pattern. This pattern includes several nested, right-angled shapes and lines that create a sense of depth and movement. The overall color scheme is dominated by orange and blue.

Questions?