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The Residual Gas Contribution of Clusters and Pellets in Vacuum

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Overview

- What may be the sources of residual gas inside the accelerator vacuum using a microsphere target?
  - Target source, beam dump backflow, pipe conductance?
- Simulation of microspheres injected into the vacuum
- Comparison of simulation with real jet/ion beam data
- Predictions of gas flows at PANDA using a jet and a pellet target configuration

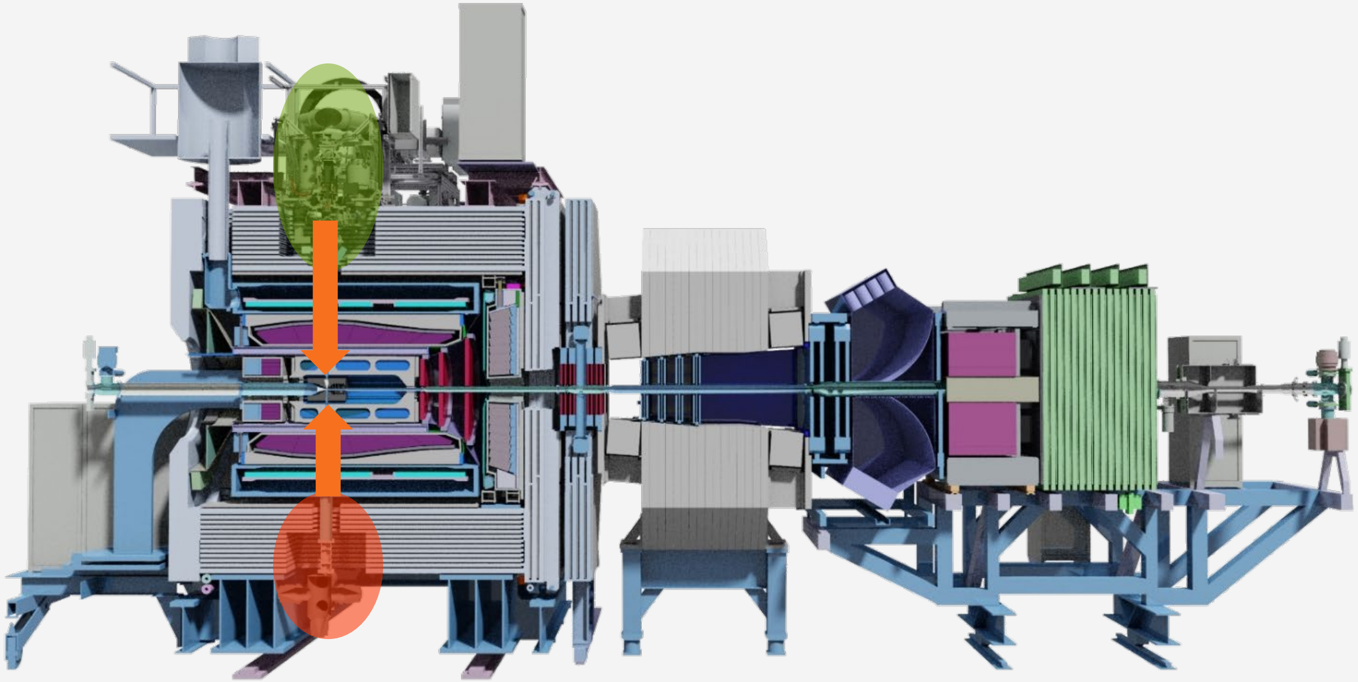
The Residual Gas Contribution of Clusters and Pellets in Vacuum

- Wished by experiments:
  - A thick (›10^{15} atoms/cm^2), localized (≈ some mm width), window-less target without time structure
  - No impact onto the accelerator vacuum (IP: $p \leq 10^{-8}$ mbar)

- Reality:
  - ✓ Thick (10^{15} atoms/cm^2), localized (≈ (1 - 15) mm width) and window-less possible
  - ✓ no time structure possible using a cluster-jet target
  - – Gas flow at IP of O(10^{-4} - 10^{-2} mbar l/s) depending on target thickness

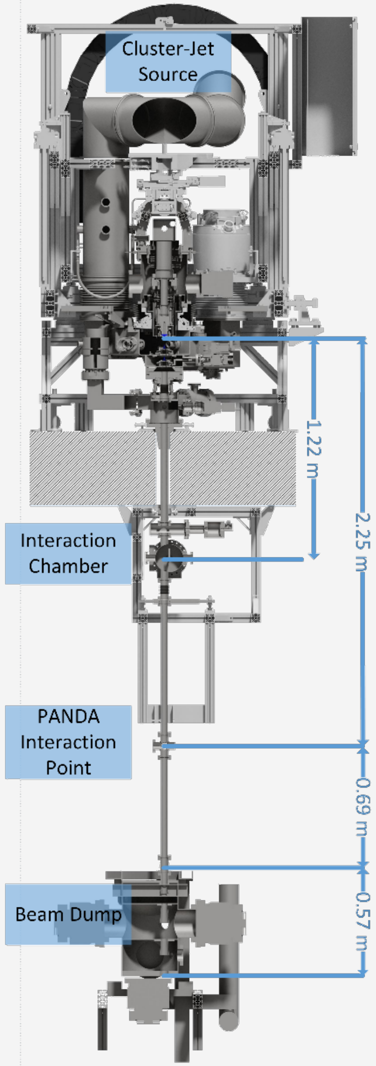
Sources of the Residual Gas Flow

- If the target beam is perfectly aligned and not disturbed by any means, one could simply assume:
  - **Residual gas flow** is dominated by **beam dump** backflow and **target source** residual gas flow



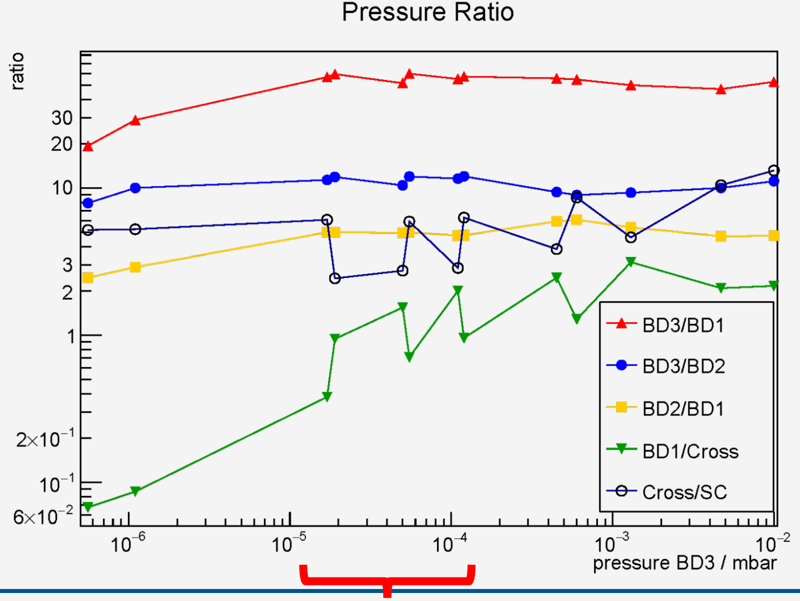
Gas Backflow from the Beam Dump

- Studies of beam dump efficiency done at Münster using
  - PANDA cluster-jet target
  - PANDA beam dump (Genoa dump)
  - Next to PANDA geometry and pumping configuration

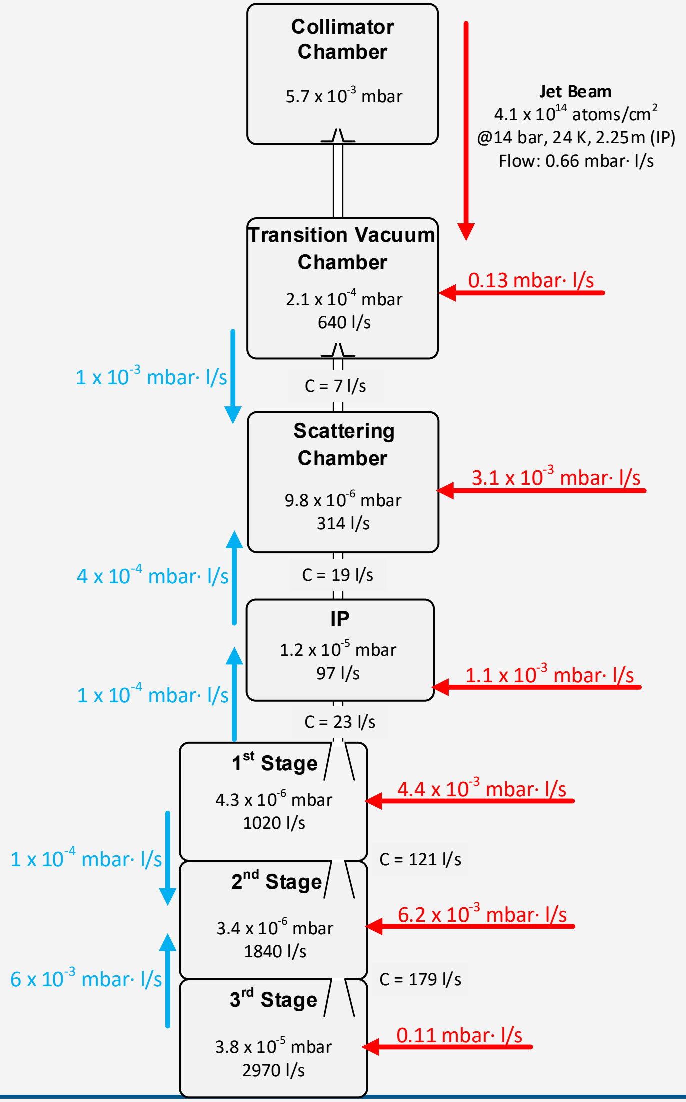


Gas Backflow from the Beam Dump

- Studies of beam dump efficiency done at Münster using
    - PANDA cluster-jet target
    - PANDA beam dump (Genoa dump)
    - Next to PANDA geometry and pumping configuration
- Result:
    - **Beam Dump efficiency of 33 %**
    - **IP gas load cannot be understood by beam dump efficiency and pipe conductance**

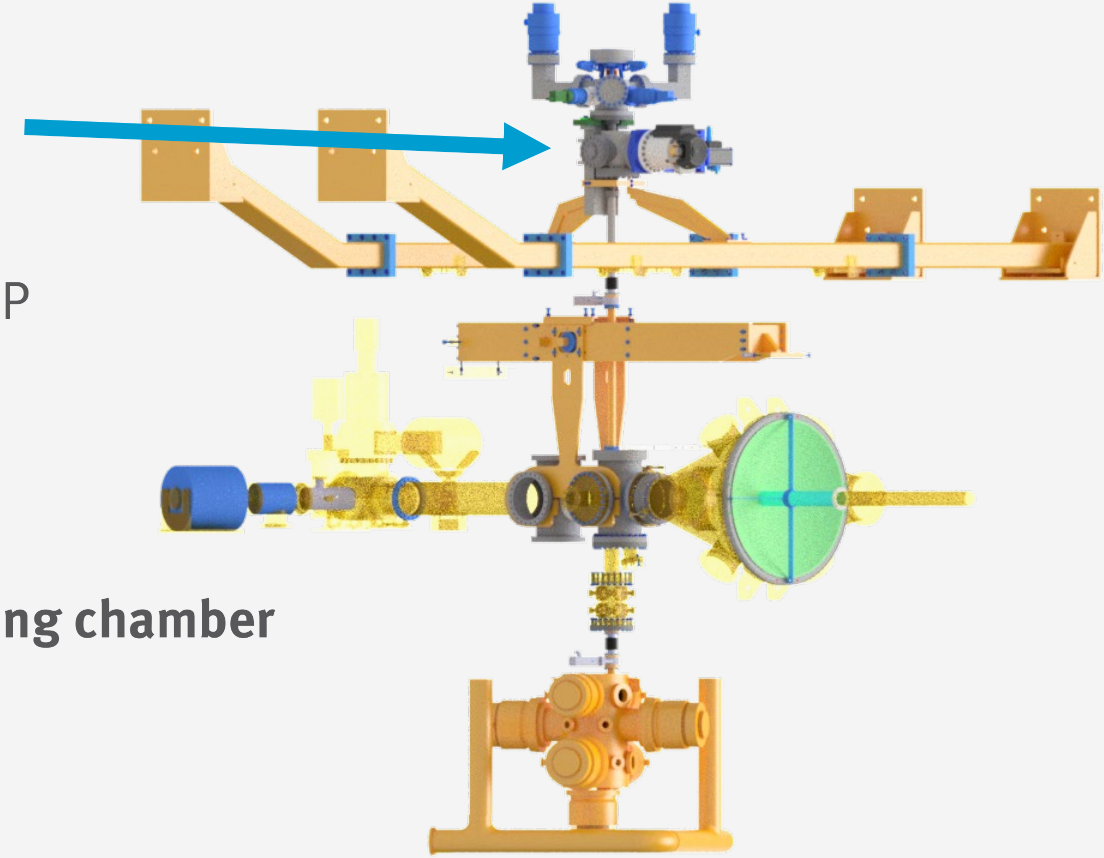


Relevant pressure range



Gas Flow from Target Source

- Studies similar to the beam dump efficiency studies were done at Münster and COSY using the PANDA cluster-jet target
- Added additional differential pumping stage at COSY with separate pump and shutter
- Reduced flow of < 10^{-4} mbar l/s from this chamber to IP



- Result:
  - **No Influence on IP vacuum w/wo additional pumping chamber**
  - **Flow from source negligible**

Sources of the Residual Gas Flow

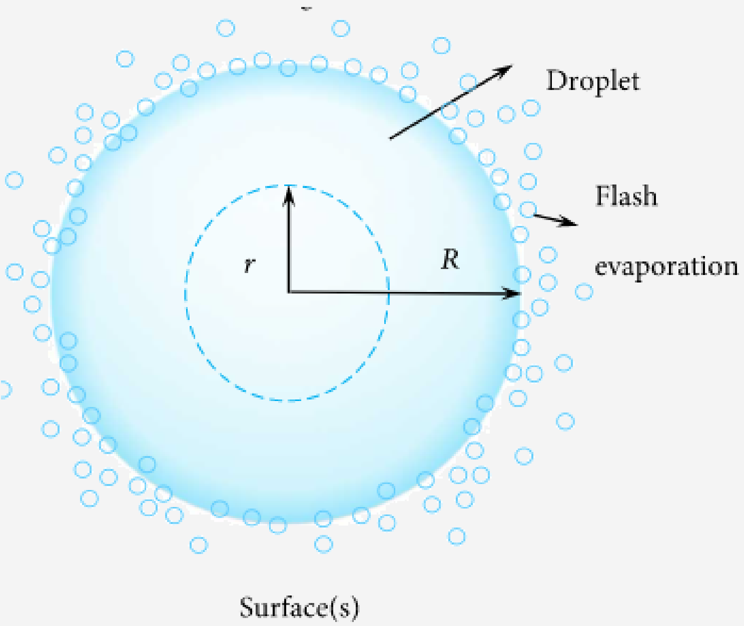
- ~~If the target beam is perfectly aligned and not disturbed by any means, one could simply assume:~~
    - ~~**Residual gas flow** is dominated by **beam dump** backflow and **target source** flow~~

- Only possible explanation:
    - **Some kind of intrinsic flow by the target particles**
    - What happens if a liquid or frozen microsphere (cluster/droplet/pellet) is injected into vacuum?

What happens if a microsphere is inside a vacuum?

- No different physics for big clusters, liquid droplets, solid pellets

- Due to vapour pressure:
  - ▸ Thin Knudsen-Layer of gaseous particles around microsphere surface
  - Mass loss rate: $\dot{m}_{net} = \dot{m}_{in} - \dot{m}_{out}$



What happens if a microsphere is inside a vacuum?

- Mass loss (evaporation) ▸ Surface cooling
  - $Ak\frac{\partial T(r=a)}{\partial r} = \dot{m}\, h_{sup/vap} + \sum \dot{Q}$
    - A: surface area, k: thermal conductance, h: Enthalpy
    - $\sum \dot{Q}$: thermal radiation, convection inside rest gas, …
- Temperature distribution:
  - $\rho C\frac{\partial T}{\partial r} = \frac{1}{r^2}\frac{\partial}{\partial r}(r^2 k\frac{\partial T}{\partial r})$
    - $\frac{\partial T}{\partial r}(0, t) = 0$ (symmetry)
    - T(r=a, t) = T(Surface)

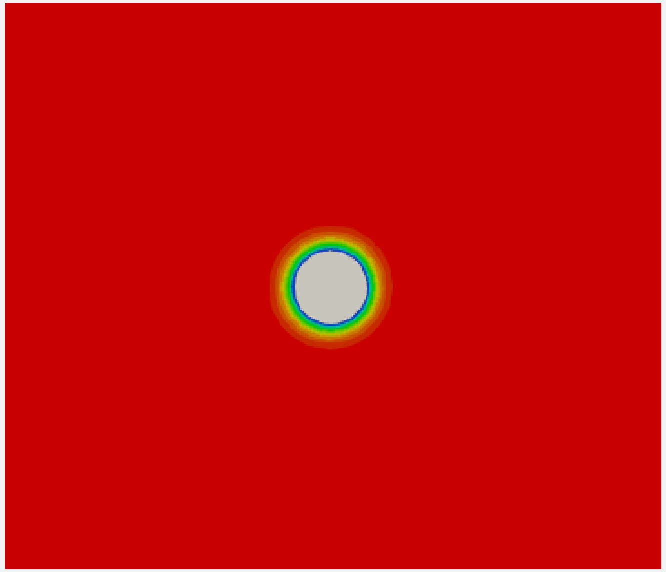
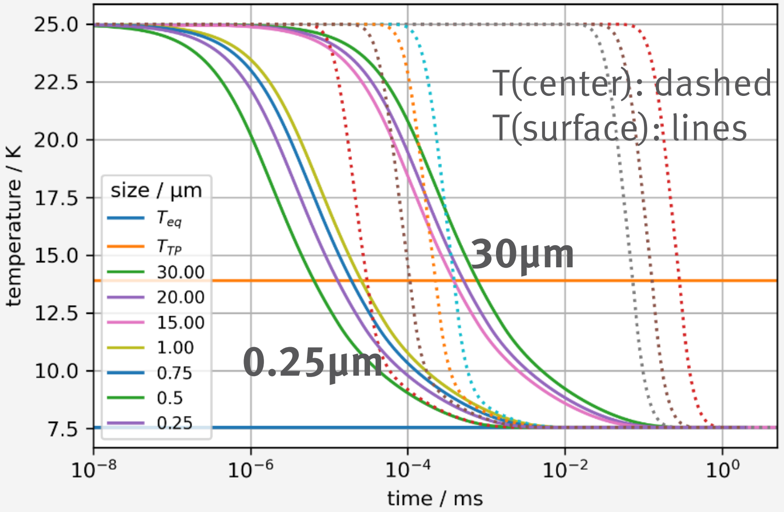
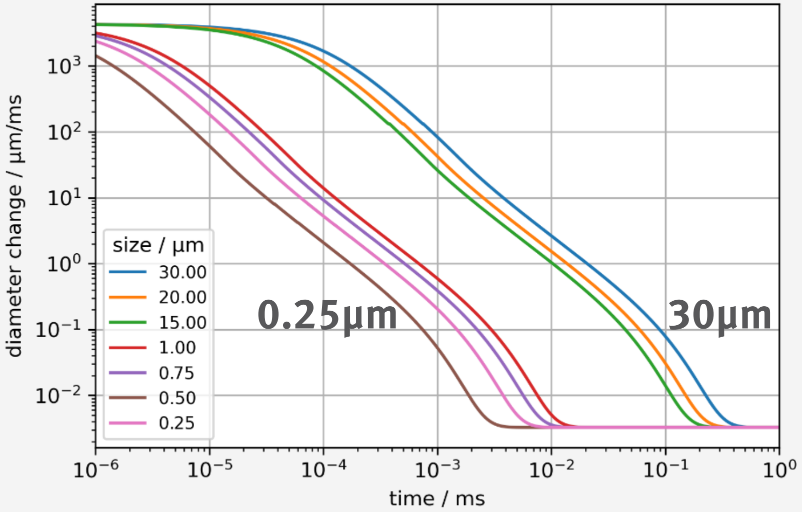
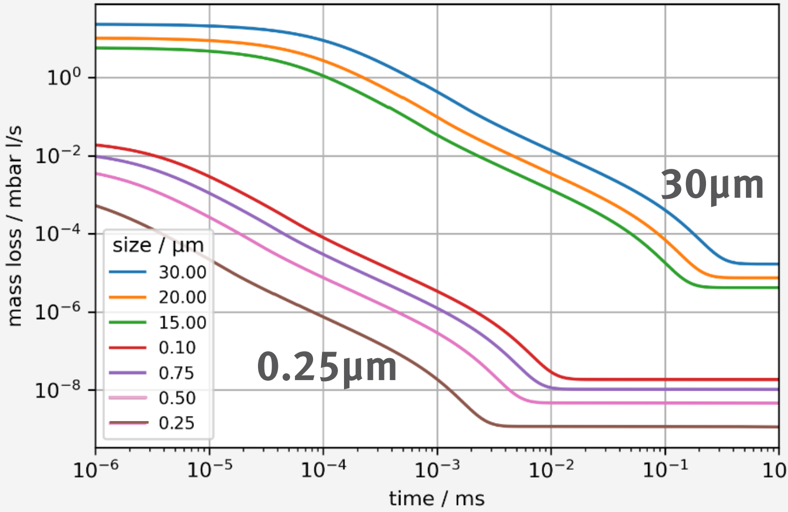


Fig: static microsphere in vacuum

Behaviour of Liquid Microspheres moving inside vacuum

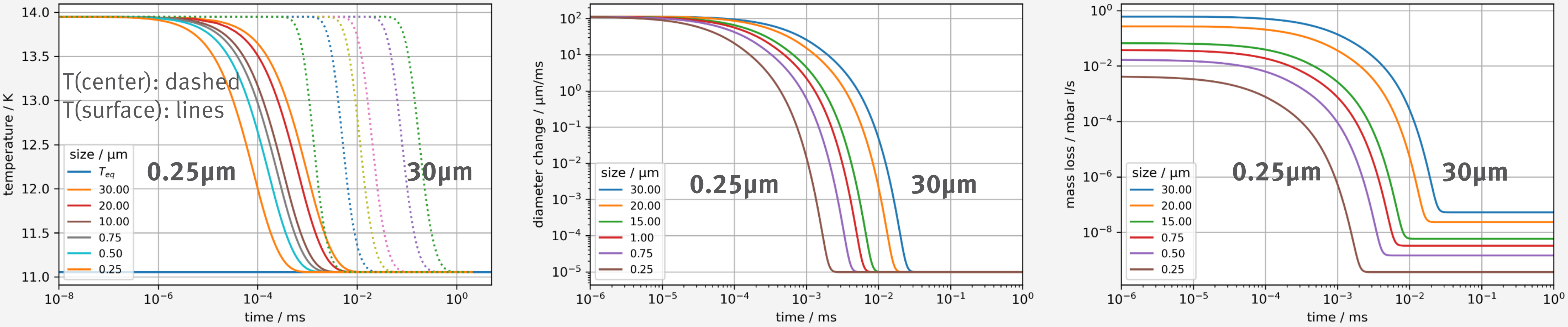






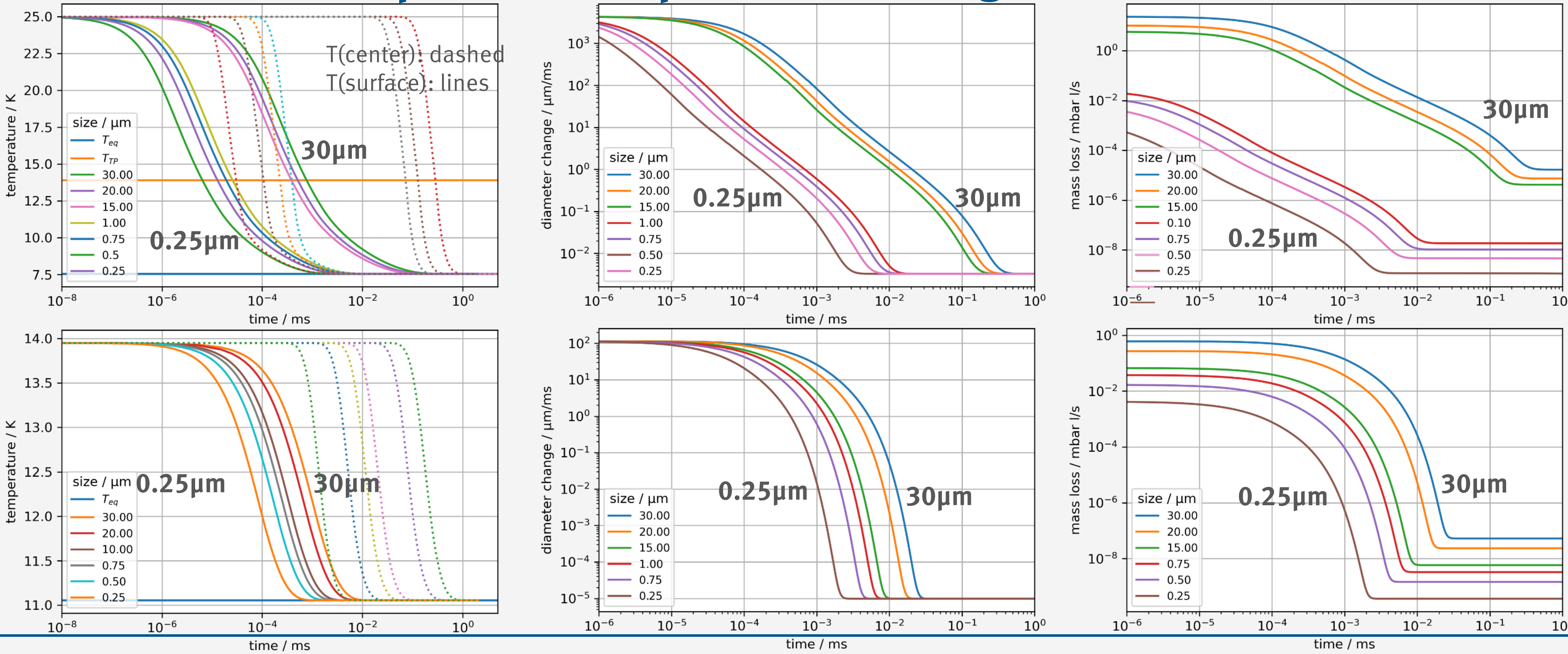
- Microspheres are produced from liquid hydrogen
- **Cluster target production chamber vacuum conditions** assumed
- Assuming supercooling, all microspheres reach same equilibration temperature

Behaviour of Liquid Microspheres moving inside vacuum



- Microspheres are produced from liquid hydrogen
- **Droplet production chamber vacuum conditions** assumed (triple point conditions)
- Assuming supercooling, all microspheres reach same equilibration temperature

Behaviour of Liquid Microspheres moving inside vacuum

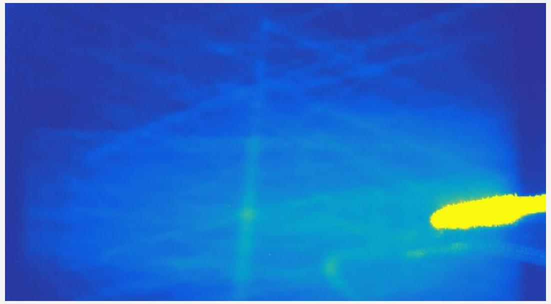


Is supercooling of microspheres happening?

- Yes, it happens!

PANDA cluster-jet target

Cluster jet hits the skimmer.
No bouncing clusters visible,
cluster must be liquid.

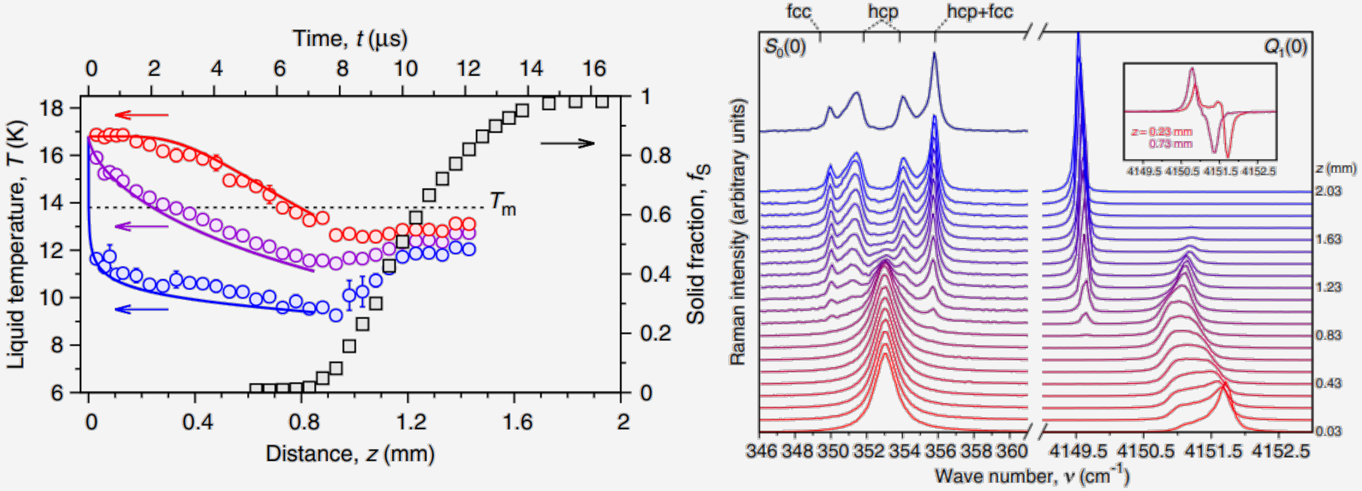


Cluster jet hits doped with impurities
as nucleation seeds.
Bouncing clusters visible.

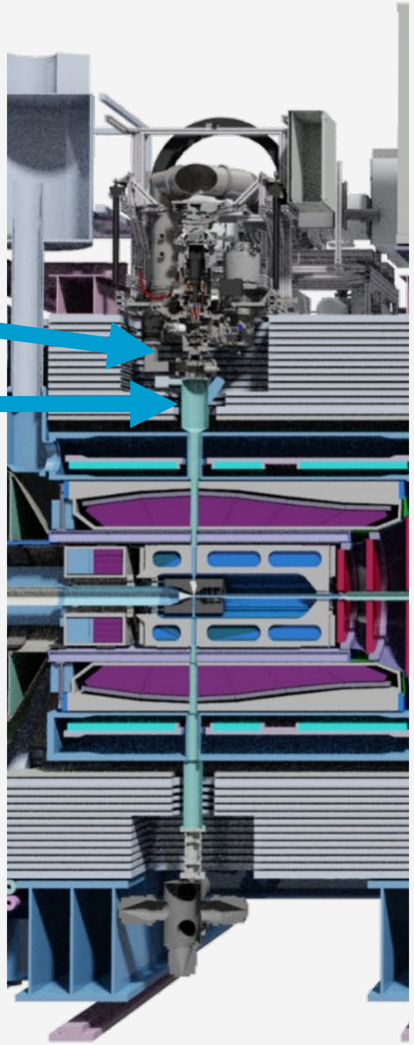
5 cm ▸ 0.2 ms ToF ▸ 8 K microsphere temperature

Direct observation of supercooling with a 5 µm hydrogen filament target using Raman spectroscopy.

Grisenti et al, Time-Resolved Study of Crystallization in Deeply Cooled Liquid Hydrogen
DOI: 10.1103/PhysRevLett.106.245301



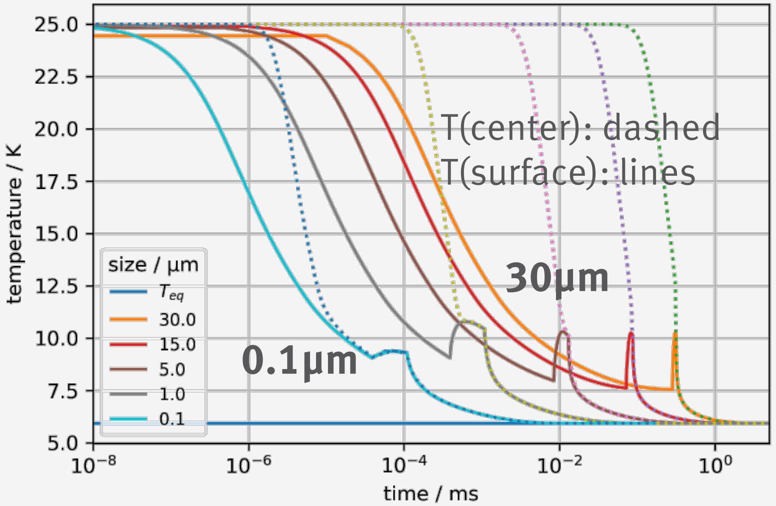
Evolution of the supercooled microspheres

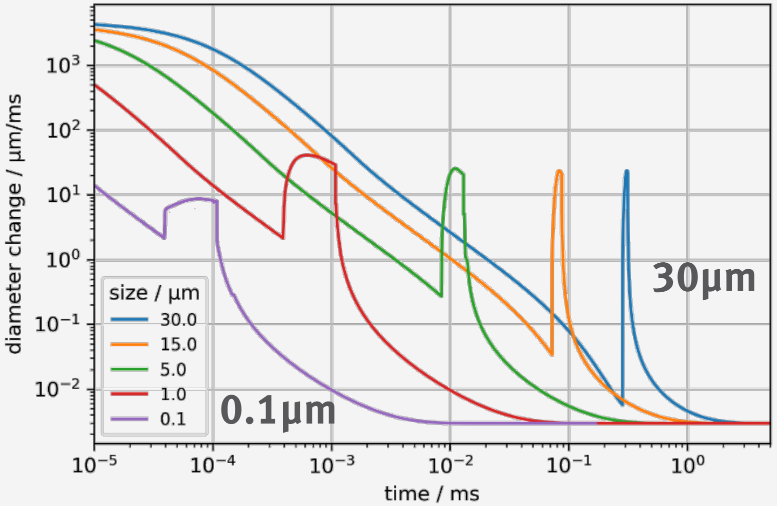


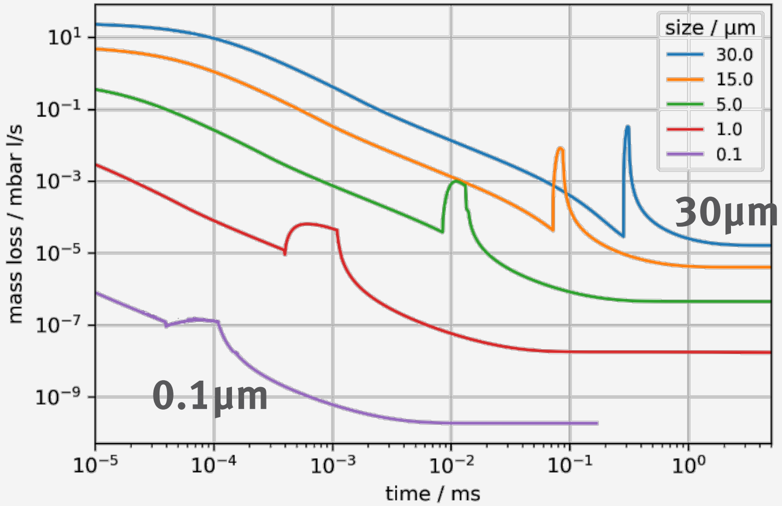
- After a ToF of 1 ms the spheres are here (≈30 cm behind the nozzle)
- The moment they enter the accelerator vacuum, the vacuum is about $p \leq 10^{-5}$ mbar
- Same vacuum conditions for cluster and pellets for the last ≈20 ms ToF to dump

➢ At some point the supercooled microspheres freeze out

Microsphere Freeze Out

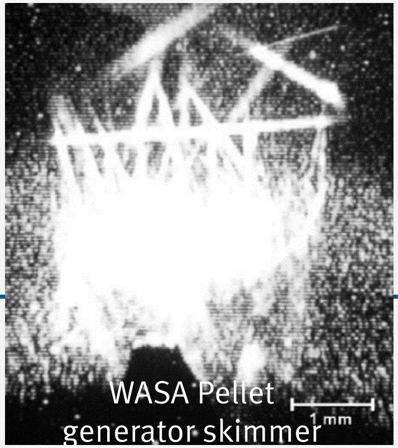






- Plots show freeze out happening at most likely supercooled T assuming a Lennard-Jones-potential [1]
- 5 µm sphere freeze out in agreement with the measured 5 µm filament stream data [2]
- Relevant microsphere sizes freeze out inside target generators

➢ There is a constant residual gas flow from microspheres per length unit inside the accelerator vacuum



WASA Pellet generator skimmer

[1] Seidel, Williams, et al, Supercooling of liquid hydrogen, DOI: 10.1103/PhysRevLett.56.2380

[2] Grisenti et al, Time-Resolved Study of Crystallization in Deeply Cooled Liquid Hydrogen, DOI: 10.1103/PhysRevLett.106.245301

Concrete Microsphere Freeze Out Time

- Measurements and Models:

  [1] Grisenti et al, Time-Resolved Study of Crystallization in Deeply Cooled Liquid Hydrogen, DOI: 10.1103/PhysRevLett.106.245301

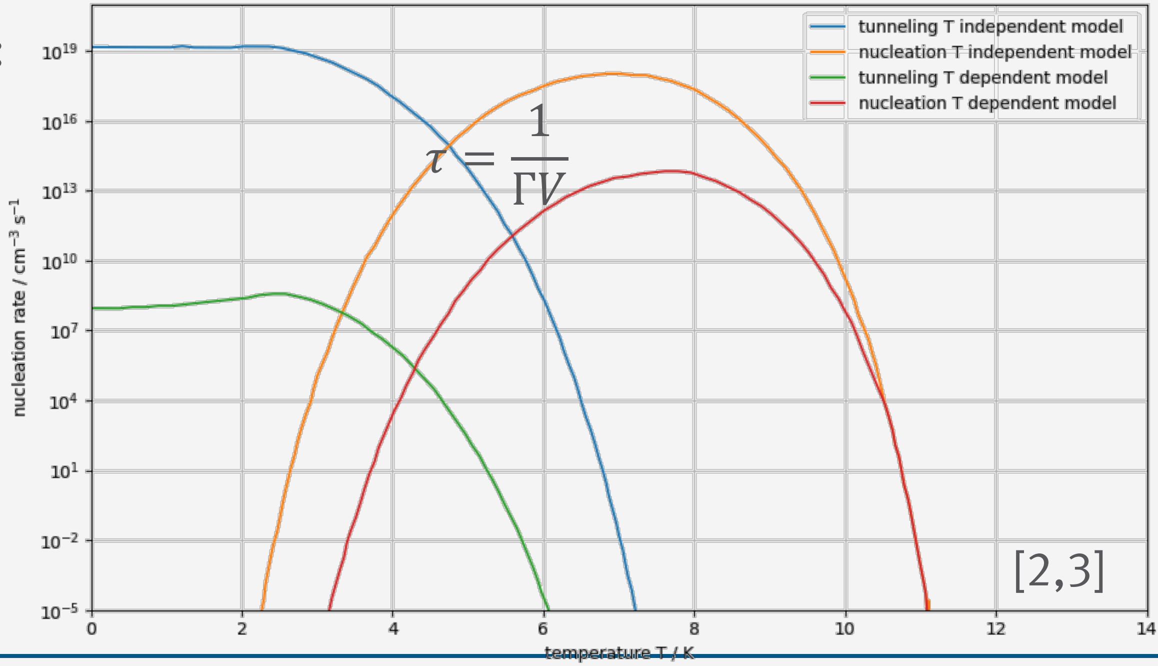
  [2] Seidel, Williams, et al, Supercooling of liquid hydrogen, DOI: 10.1103/PhysRevLett.56.2380

  [3] Seidel, Williams et al, Seidel, Williams, et al, Supercooling of liquid H2 and the possible production of superfluid H2, DOI: 10.1007/BF00683224

- Mean supercooled lifetime τ:

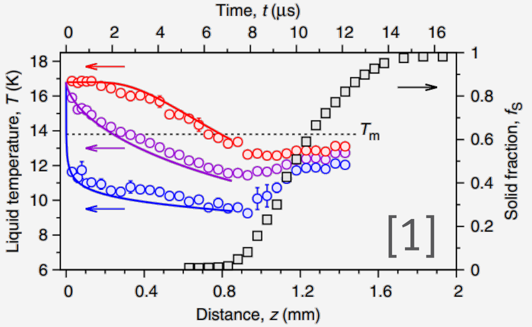
Γ: nucleation rate
V: microsphere volume

0.1 µm: $(1 - 10^{3})$ ms
1.0 µm: $(10^{-3} - 1)$ ms
10.0 µm: $(10^{-6} - 10^{-2})$ ms



$$\tau = \frac{1}{\Gamma V}$$

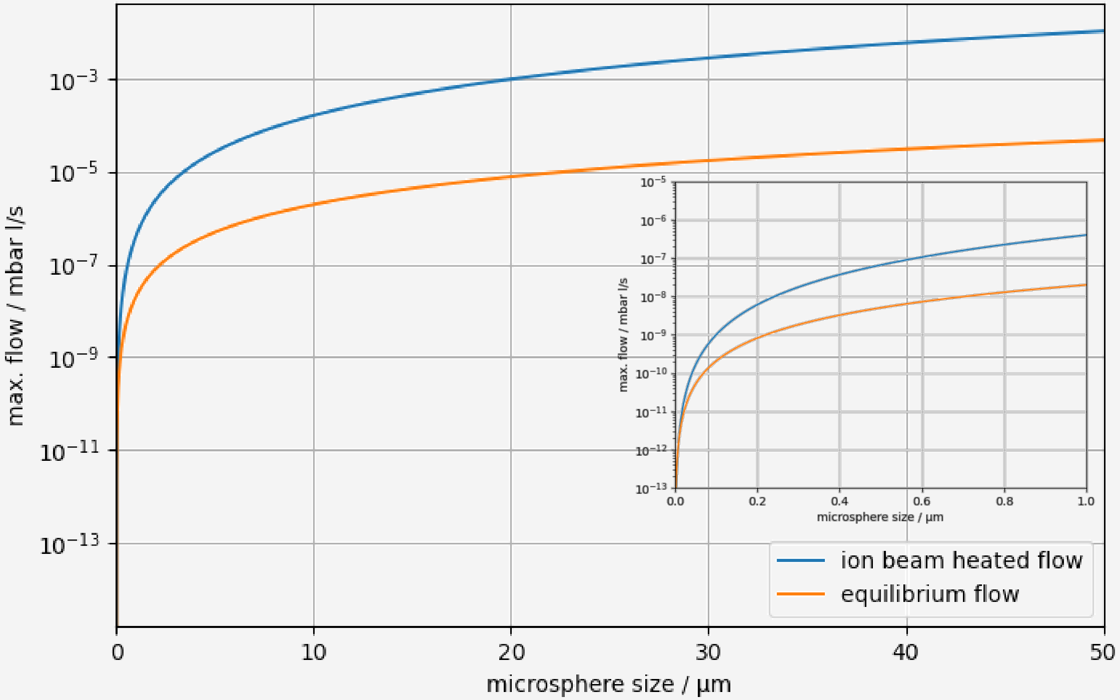
[2,3]



[1]

Effect of the Ion Beam onto the Microspheres

- $Ak\frac{\partial T(r=a)}{\partial r} = \dot{m}\, h_{sup/vap} + \sum \dot{Q}$, additional $\dot{Q} = \rho f \eta S r^2 \cdot\ \mathrm{rect}(vt \in \mathrm{IP})$
  for ion beam heating at IP with target thickness ρ, frequency f and stopping power S
- Simulation shown for PANDA HL mode
- **Maximal flow is not the net IP flow!**
  - Microspheres fly with (50 – 300) m/s,
    Ion beam passing time (1 – 100) µs,
    One must include movement of spheres and pipe conductance!
- Microsphere heating up by ≈ 4 K
  ▸ ≈11 K sphere temperature!

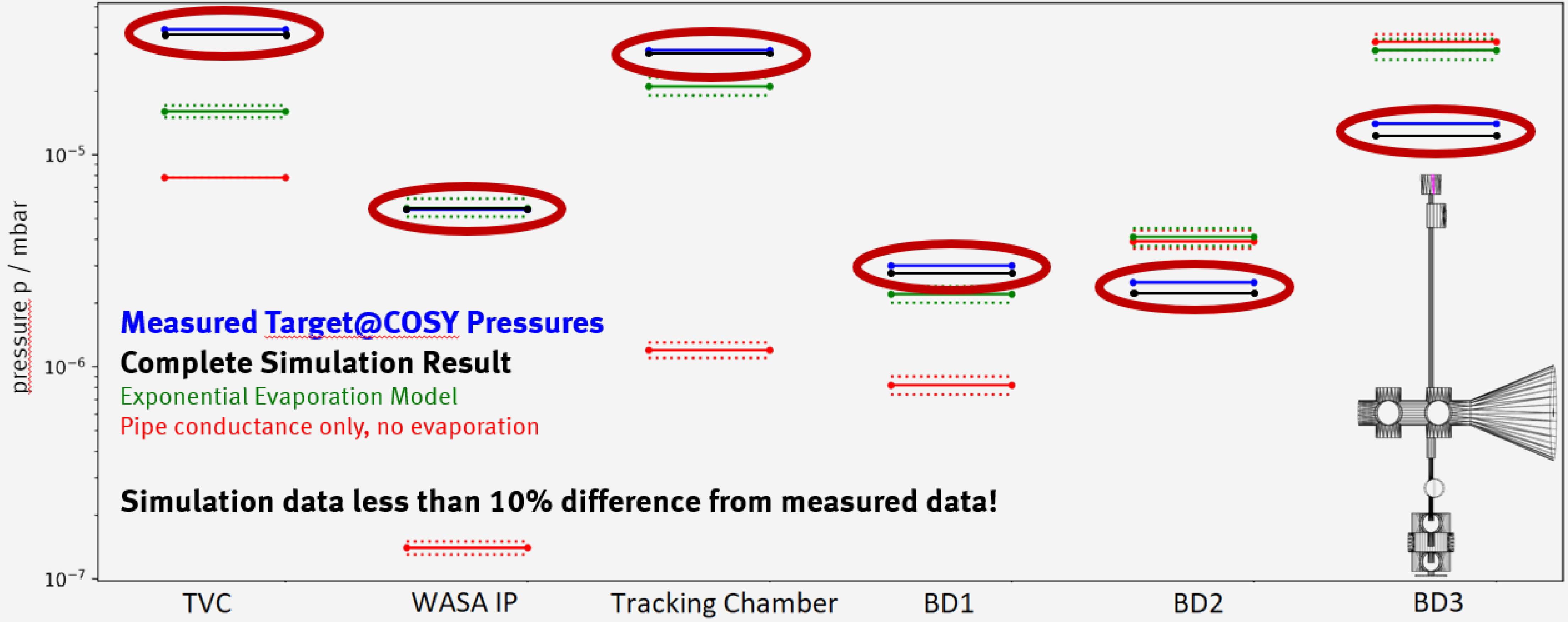


Vacuum Predictions and Measurements of the Cluster-Jet Target

- Sphere evaporation inside the target beam pipe is simulated with:
    - (Super-)cooling and freezing with mean supercooled liquid lifetime from literature,
    - Ion beam heating at IP,
    - Monte Carlo vacuum conduction simulations using MolFlow+ and realistic experiment geometries,

  and the results are compared with cluster-jet and ion beam measurements at COSY.

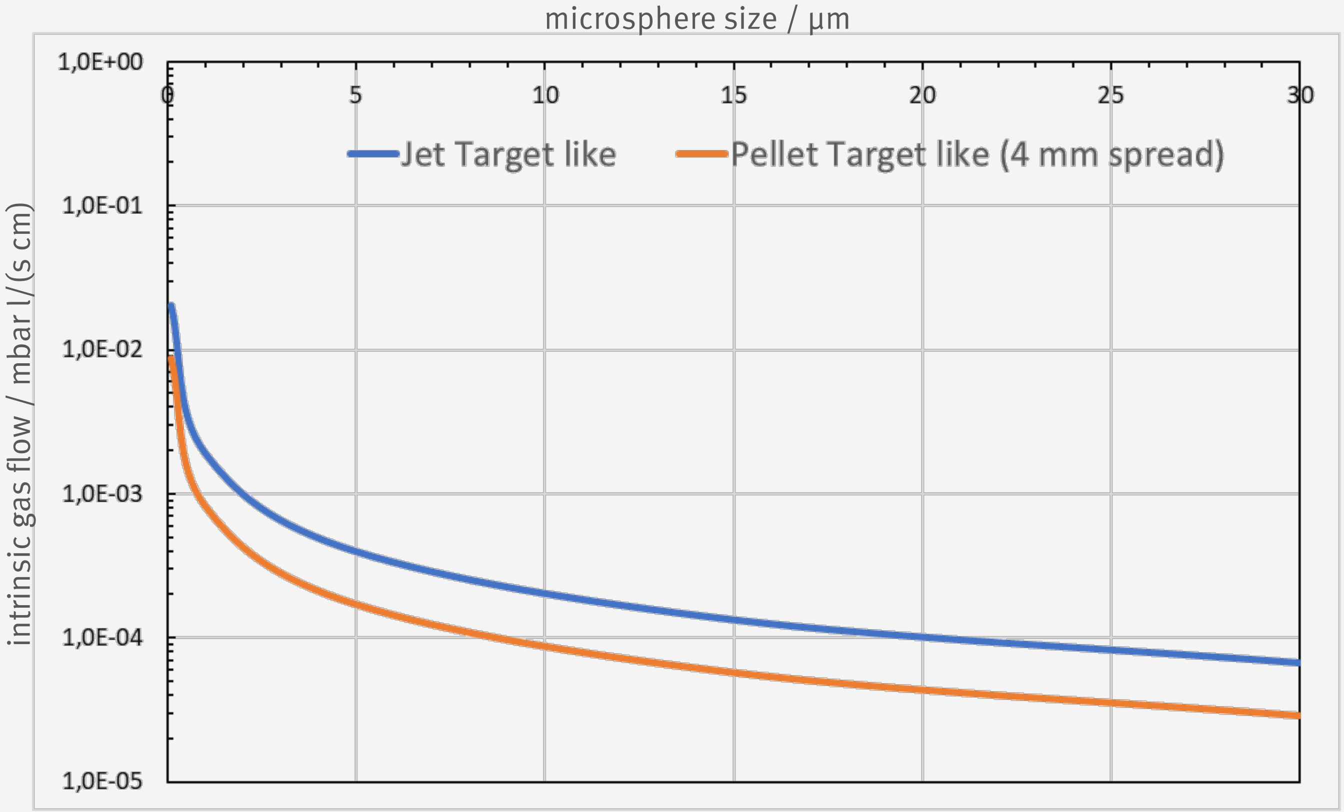
Vacuum Predictions and Measurements of the Cluster-Jet Target



Simulation data less than 10% difference from measured data!

Vacuum Predictions of Microsphere Targets

- Predictions of residual gas flows with realistic target dimensions
- Plot:
  - 2×10^{15} atoms/cm^2 target thickness
  - Target point dimensions:
    - PANDA jet target like: (1x15)mm^2
    - WASA pellet target like: 4 mm spread
- **Residual gas differs only by a factor of 2.3!**



Summary

- The most residual gas at PANDA will **not** be induced by means of conductance effects from source/dump
- Clusters/droplets and pellets **evaporate** inside vacuum and induce the main residual gas load
- Supercooled microspheres have very **different lifetimes before freezing**, measurements needed
- Simulations of gas load are in **perfect agreement** with measurements at Münster and COSY using the PANDA cluster-jet target and an ion beam
- **Vacuum predictions** for different kinds of targets can be made with high precision and arbitrary vacuum chamber/pipe configurations
- There will be only a factor of **2.3 difference concerning vacuum** conditions of cluster-jet and pellet target operation, pellet vacuum measurements would be welcome

Thank you for your attention!

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