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Vacuum studies on the $\overline{\mathrm{P}}$ANDA Target – Flash evaporation and cluster bursting

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Plan for this work

1. Step

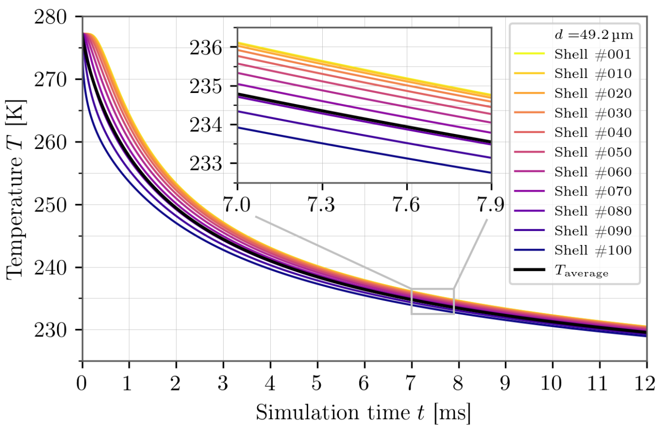
Numerical simulations on flash evaporation

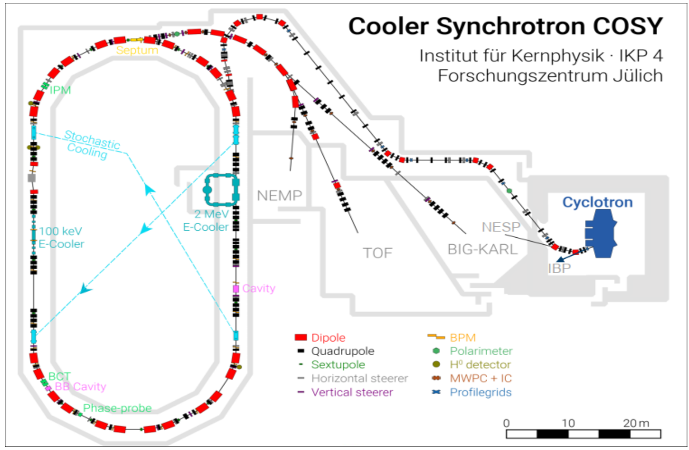
2. Step

Vacuum measurements & beam interaction at COSY

3. Step

Evaporation and cluster bursting as input for vacuum simulations





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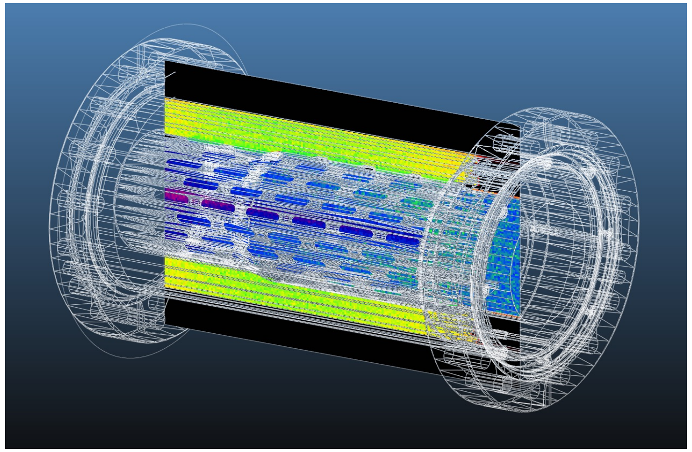

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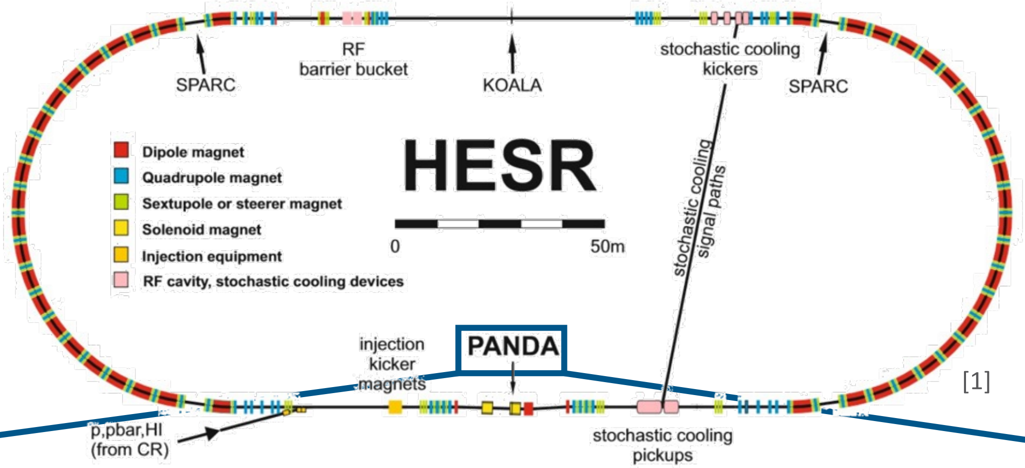
[1] Cern, Molflow+ About, https://molflow.web.cern.ch/node/354 (Lastly visited: 05.06.2023)

[2] R. Modic, A case of Improved Beam Control at COSY Jülich, 2021. https://www.cosylab.com/2021/06/21/a-case-of-improved-beam-control-at-cosy-julich/ (Lastly visited: 10.05.2023)

HESR und $\overline{\mathrm{P}}$ANDA-Detector

Requirements for target

- **Proton target realized by H_2 cluster-jet**
- **Source** and **beam dump in $2.25\ \mathrm{m}$ distance** from **IP**
- **Density** $4\times10^{15}\ \frac{\text{atoms}}{\text{cm}^2}$
- **Low residual gas density** in **beam line**



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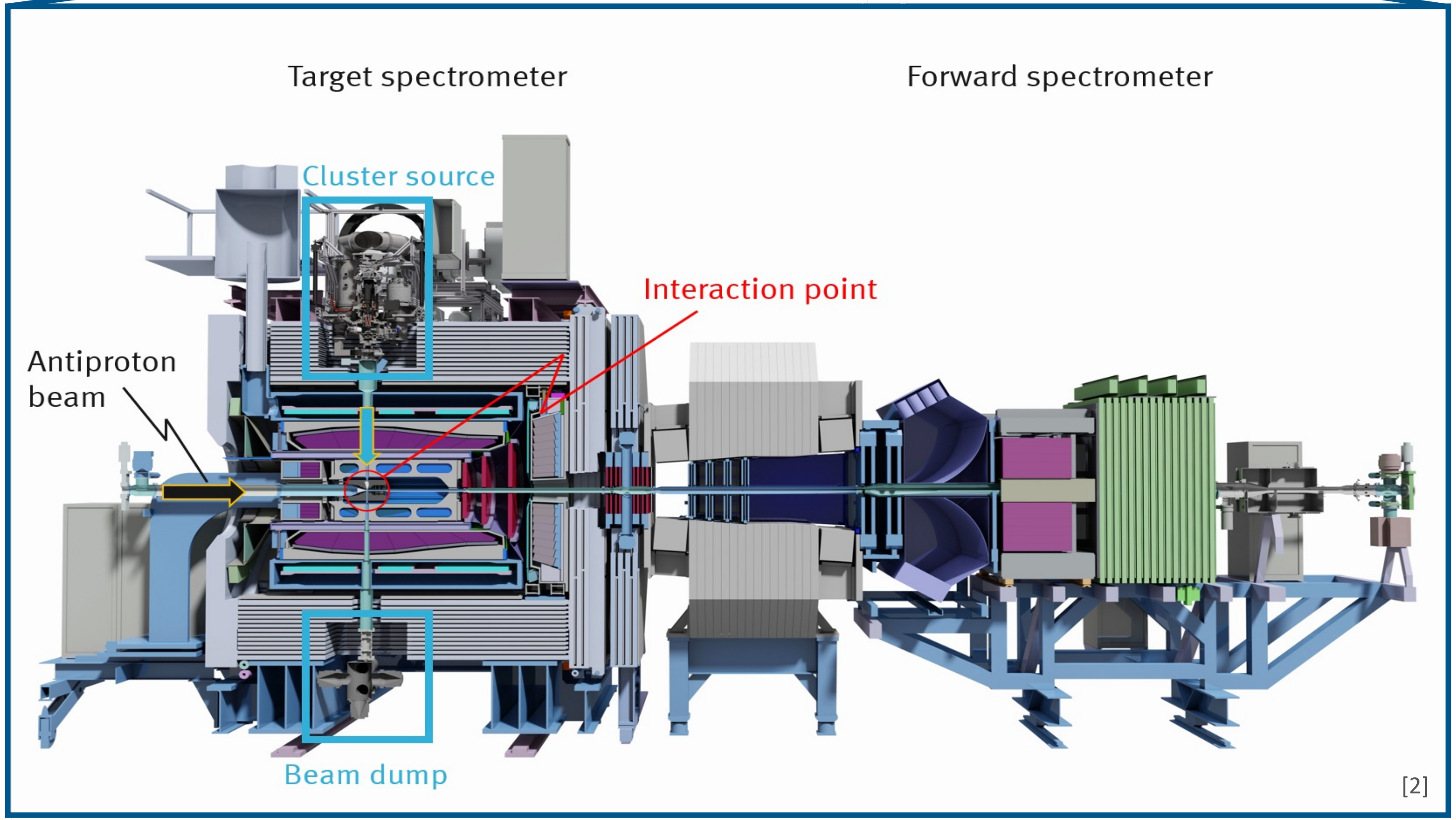

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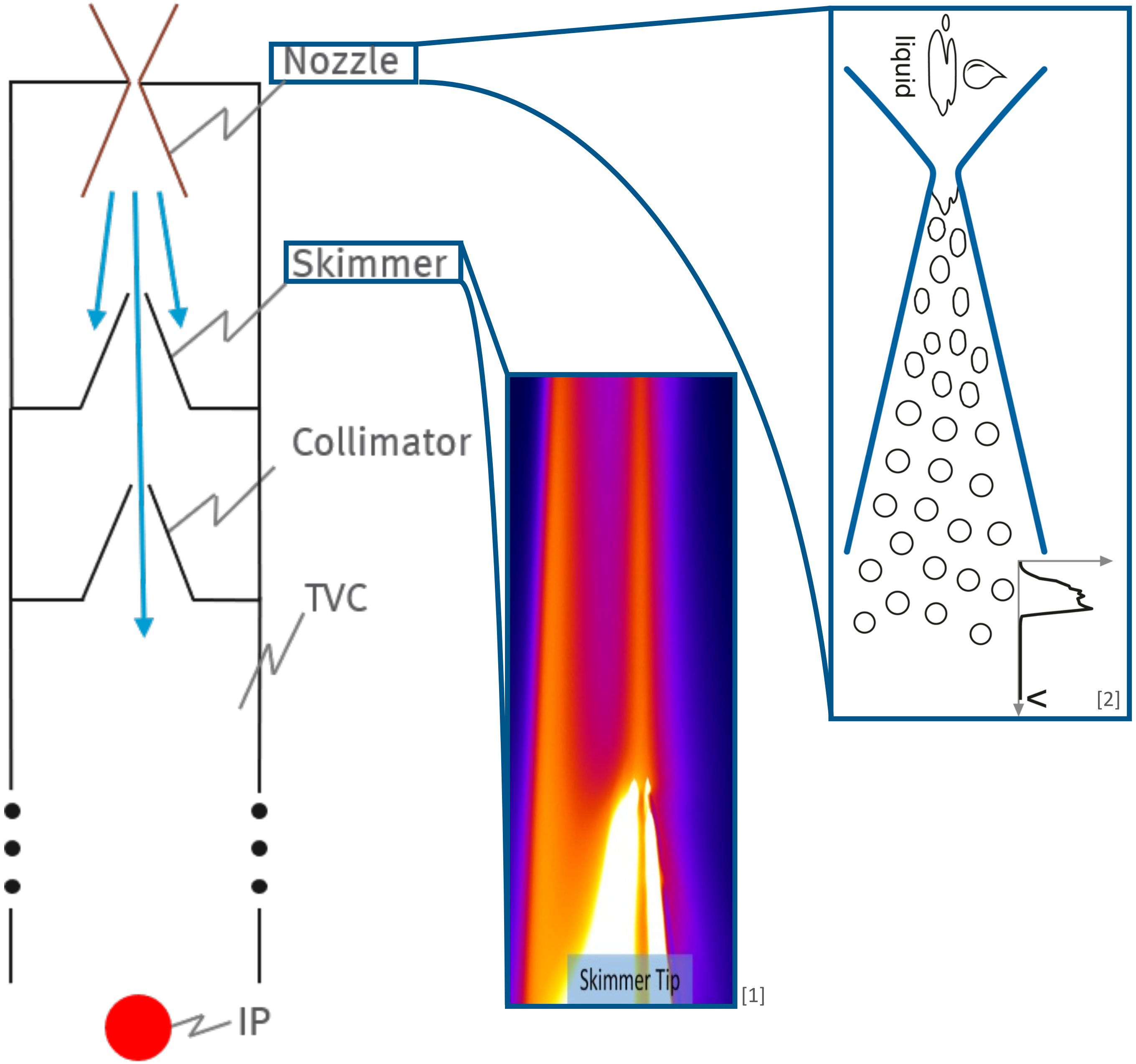
[1] Image rights are held by FAIR/GSI
[2] Created by D. Bonaventura, edited

Cluster Jet-Target

- **Core piece** ist **copper laval nozzle** $(d \approx 30\mathrm{\mu m})$
- **Hydrogen** $\mathbf{H_2}$ with $\boldsymbol{T = 22 - 35\ \mathrm{K}}$ and $\boldsymbol{p} \leq \mathbf{20\ bar}$
- **Cluster velocities** $\boldsymbol{v}_{\mathbf{Cluster}}$ of roughly $200 - 1000\ \mathrm{m/s}$
- Formation of **core beams**, which are **separated** from **residual gas** and **tailored** by **Skimmer & Collimator**
- **After** Transition Vacuum Chamber (**TVC**), a **pipe** leads to **IP**



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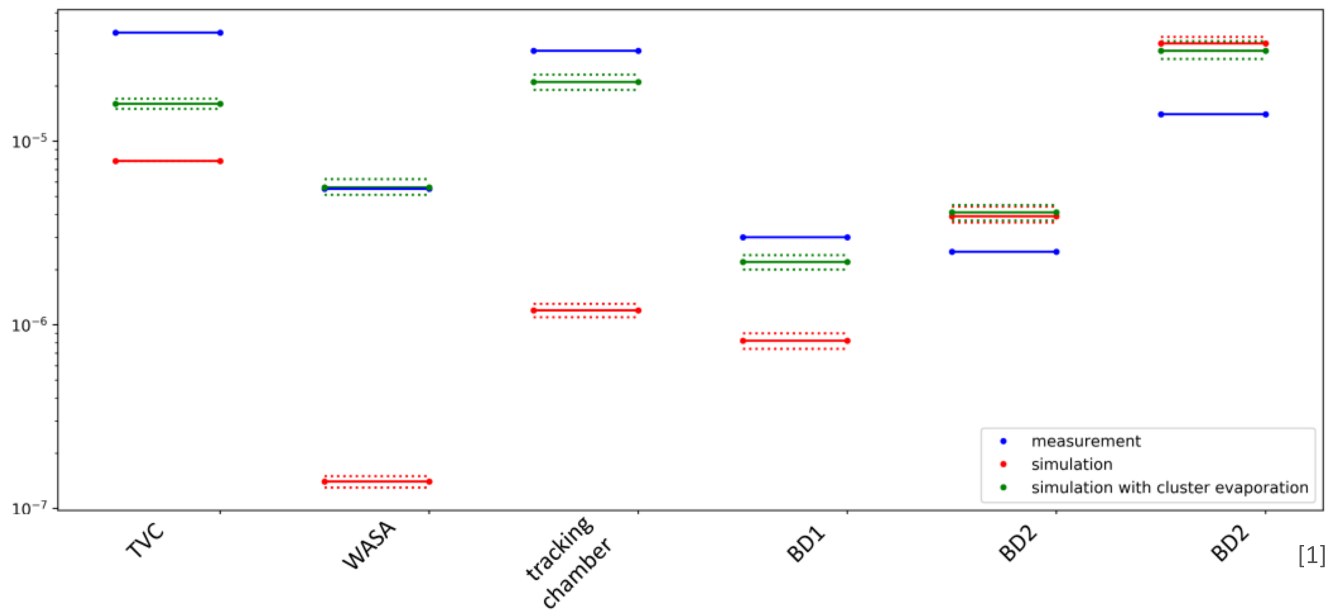
[1] Benjamin Hetz, Construction, implementation, and first beam analysis using the newly developed slow control system of the PANDA cluster-jet target in Münster . Master thesis. Westfälische Wilhelms-Universität Münster. 2017.

[2] Sophia Vestrick, Clara Fischer, Alfons Khoukaz, Crossing the Widom line: Cluster formation as sensitive probe of supercritical fluids, The Journal of Supercritical Fluids, 2022. https://doi.org/10.1016/j.supflu.2022.105686.

Current status

- $\overline{\text{P}}$**ANDA vacuum studies** by D. **Klostermann (2020)**
  - **Density** of $4{\times}10^{15}\ \frac{\text{atoms}}{\text{cm}^2}$ at **IP**
  - **Residual gas originates** only at **IP** → **Flash evaporation not included**
  - **Simulations** in **target pipe differ** from **measurements at COSY** by up to **one order of magnitude**
- **Challenges** for $\overline{\text{P}}$**ANDA**
  - **Large background**
  - **Loss** of **expensive antiprotons,** that are **scattered/annihilated** at **residual gas**



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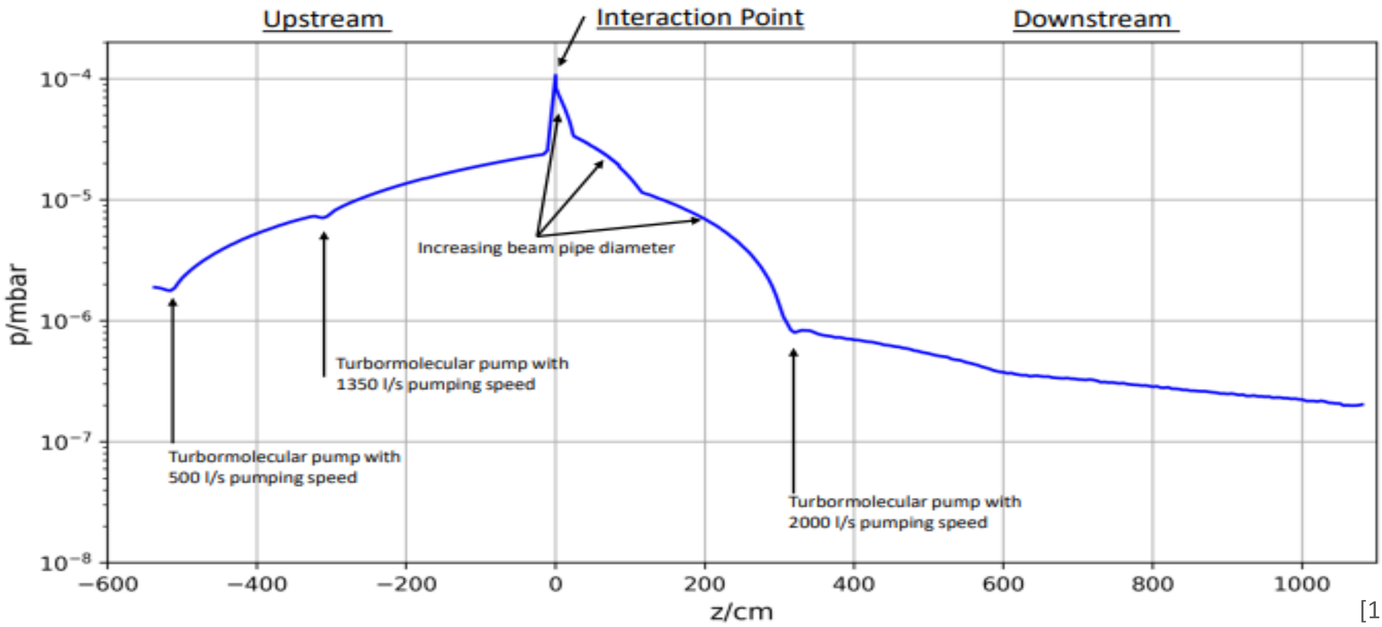
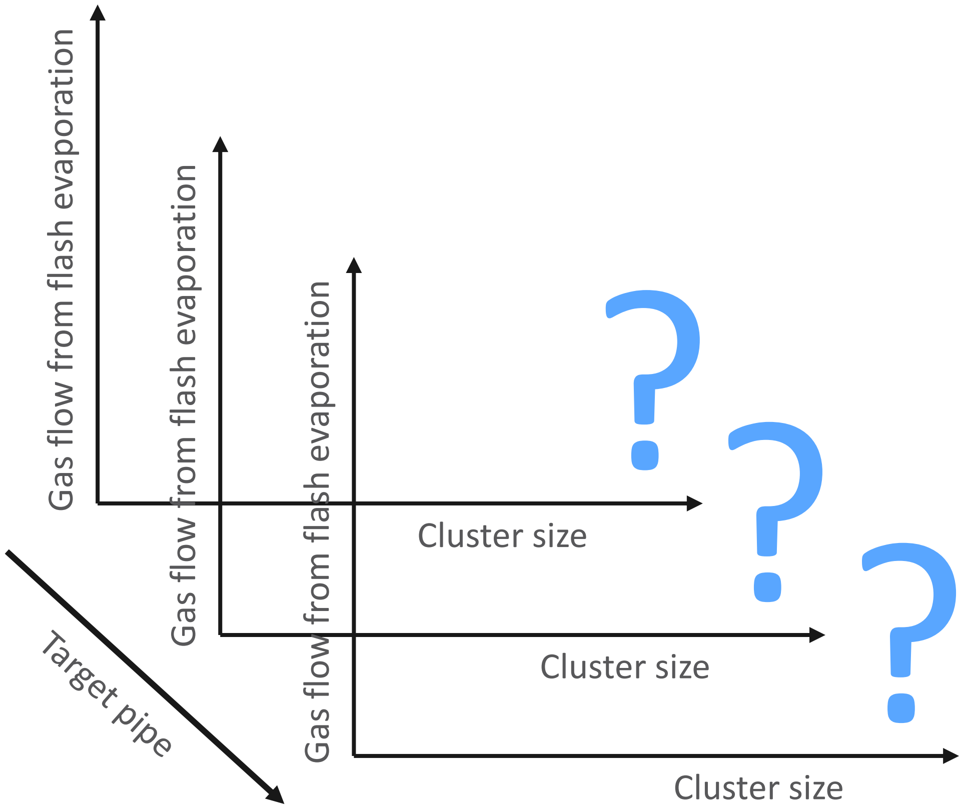


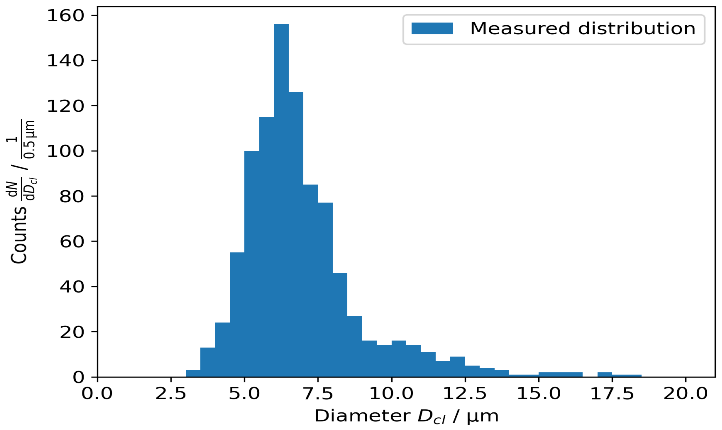
[1]

[1] Daniel Klostermann, Studies on PANDA vacuum conditions using simulations and a cooled beam pipe. Master thesis. Westfälische Wilhelms-Universität Münster. 2020.

Aim of this work

- **Simulations** considering **flash evaporation**
- **Determination** of **gas flow** per **cluster size** along the **target tube**
- **Spatially resolved gas flow rate** through **flash evaporation** determinable by **cluster size distribution**
- Understand **vacuum conditions** at **COSY with simulations** and **measurements** as **comparison**
- **Predict** the **vacuum** at **HESR**





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[1] Hanna Eick, Cluster-jet beams: Size distributions and their effects on a stored accelerator beam. Master thesis. Westfälische Wilhelms-Universität Münster. 2023.

Flash evaporation

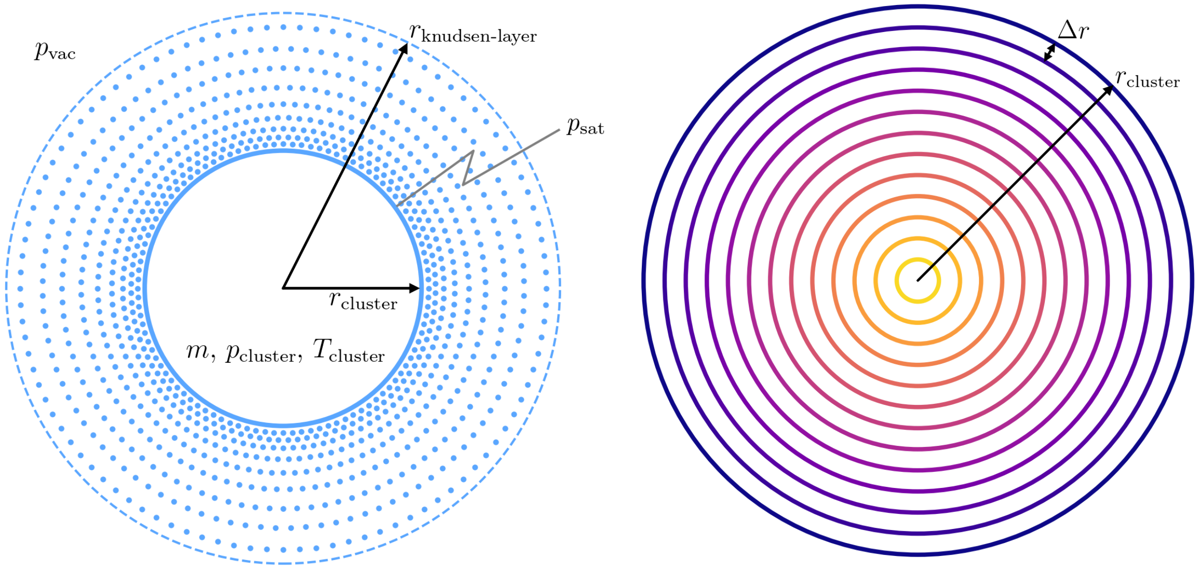
- **Flash evaporation** due to **pressure difference** between **cluster p_{cluster}** and **vacuum p_{vac}**
- **Cluster surface** in **quasi-steady equilibrium** state with its **evaporating gas**

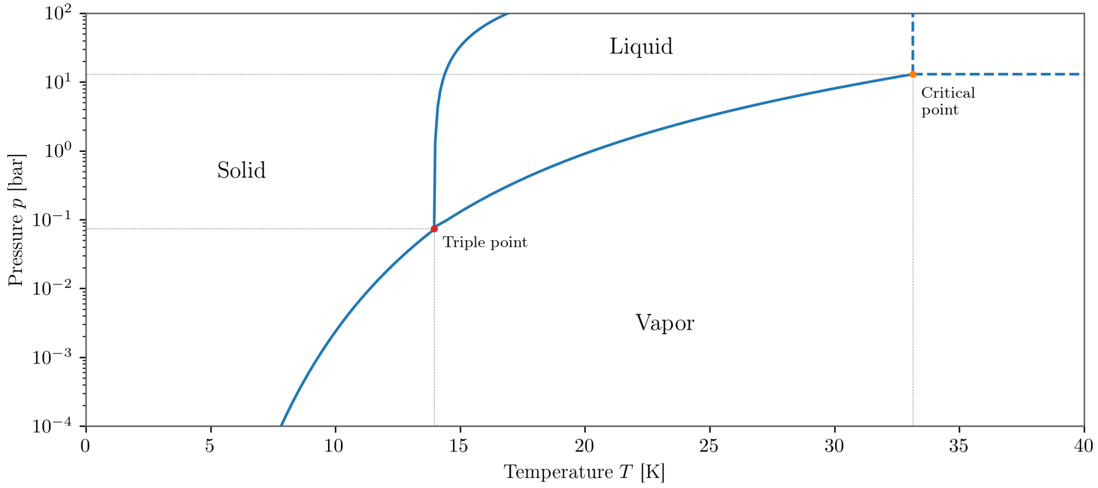
  → **Calculation** along **gaseous saturation line**
- **Phase transition** at **surface results** in:

$$\dot{m} = 1.668 \cdot \underbrace{\boxed{A_{\text{surf}}}}_{\text{Surface}} \cdot \frac{\overbrace{\boxed{p_{\text{sat}} - p_{\text{vac}}}}^{\text{Pressure difference (dominant)}}}{\sqrt{2\pi R_\alpha T}}$$

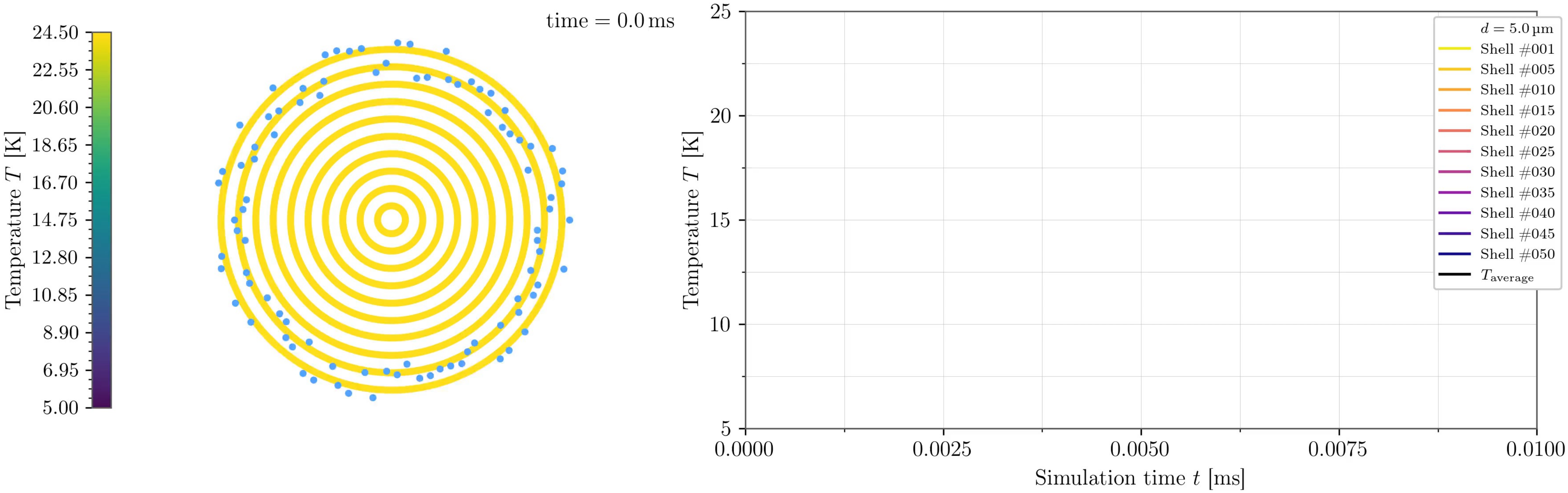
$$\Delta T = \frac{\dot{m} \cdot \overbrace{\boxed{h_{\text{vap}}}}^{\text{Enthalpy of vaporization}} + \dot{Q}}{\underbrace{\boxed{\rho(T) \cdot V(T)}}_{\text{Mass}} \cdot \underbrace{\boxed{c_p(T)}}_{\text{Heat capacity}}} \cdot t$$

- **Discretization** allows to **determine heat flow $\dot{Q}$** and **temperature gradient T_n** by **Fourier's law**



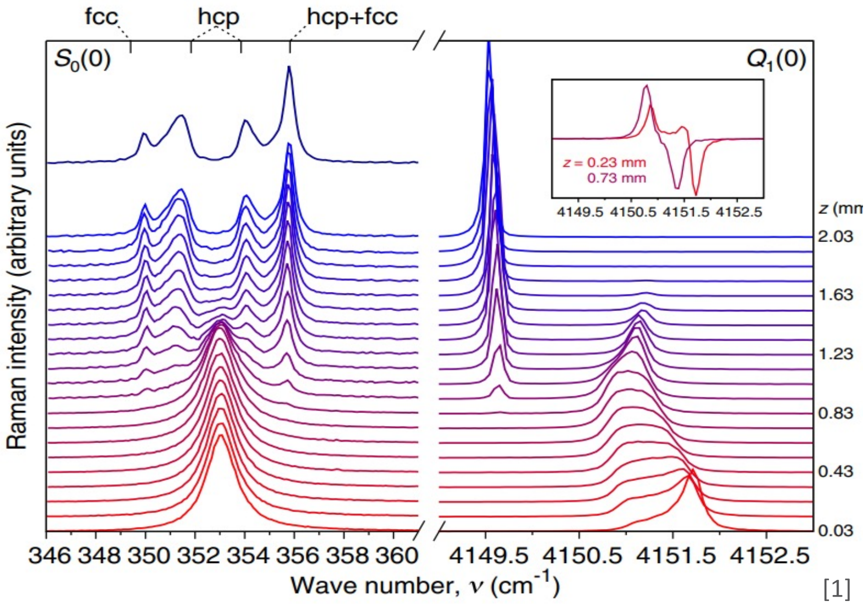


Temperature & clustersize animation (only liquid)



Freeze out

- **Freezing out** of **Para-H_2 observed** (Kühnel, Grisenti et. al)
  - **Recording** of **Raman spectra along** a **cylindrical hydrogen beam**
  - **Temperature gradient** and **moment of freeze out** measured $0.65 \cdot T_m \approx 9\ \mathrm{K} = \mathrm{T_{freeze}}$
  - With **numerical calculations temperature** at **surface** and in the **center** could be **clearly identified**



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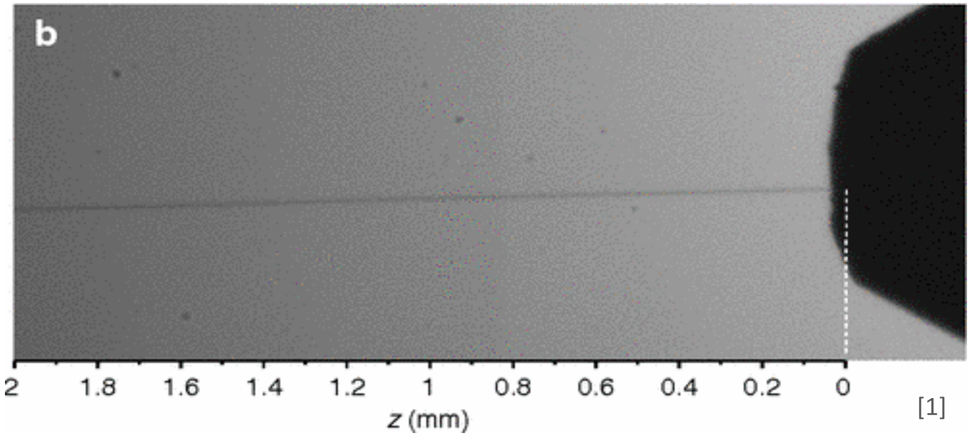

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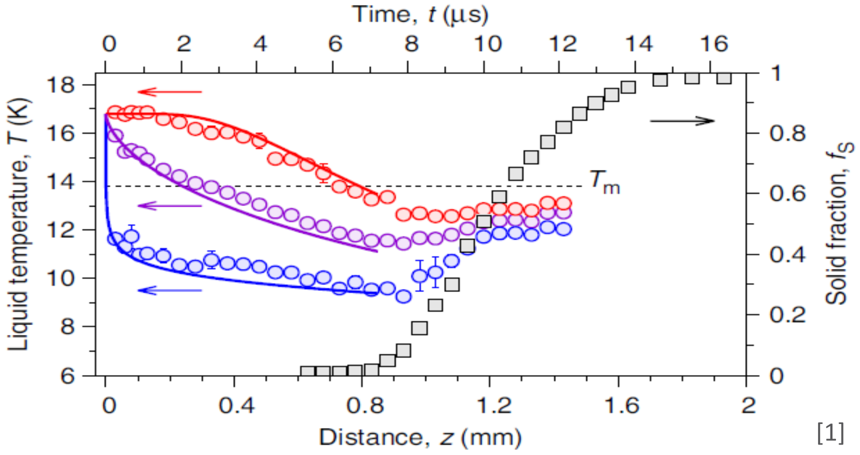

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[1] Kühnel, Matthias; Fernández, José M.; Tejeda, Guzmán; Kalinin, Anton; Montero, Salvador; Grisenti, Robert E. (2011): Time-resolved study of crystallization in deeply cooled liquid parahydrogen. In: *Physical review letters* 106 (24), S. 245301. DOI: 10.1103/PhysRevLett.106.245301.

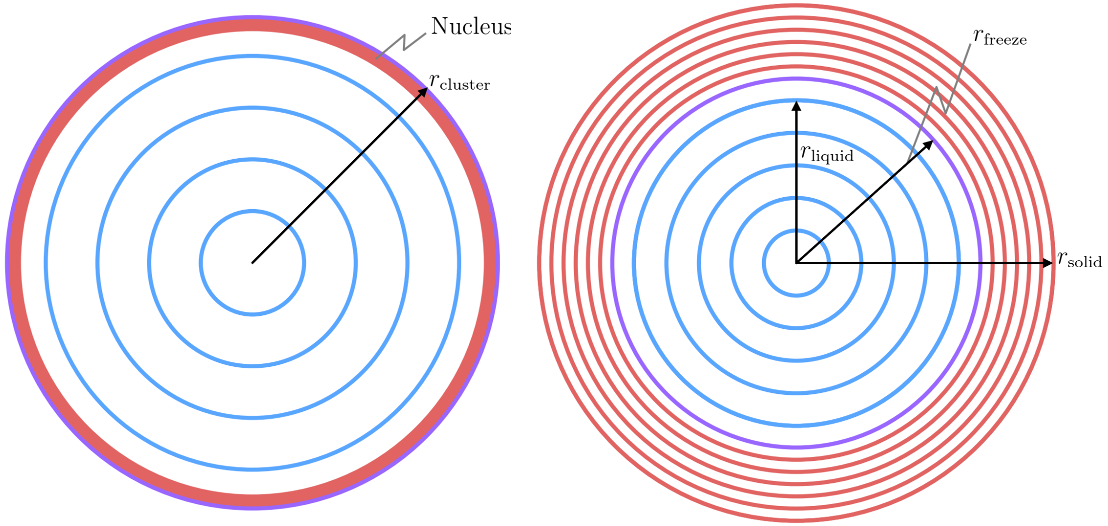
Freeze out shell model

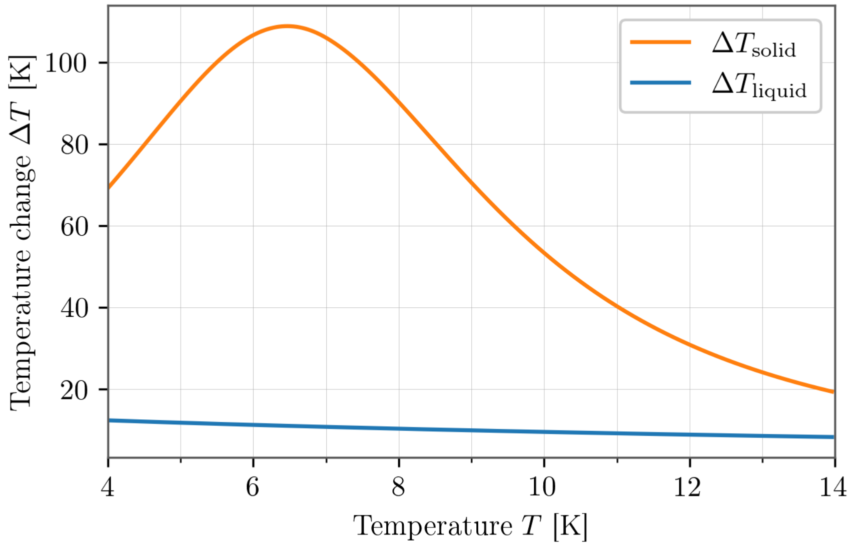
- **Nucleation starts** at **surface** (**radial nucleus** assumed)
- **Freezing out** results in **release** of **heat Q**

$$Q_{\text{released}} = h_{\text{fus}} \cdot m_{\text{freeze}} \quad Q_{\text{absorb}} = m_{\text{absorb}} \cdot c_p \cdot \Delta T$$

$$\Rightarrow \Delta T = \frac{h_{\text{fus}}}{c_p}$$

- If a shell **absorbs** its **complete released heat Q instantaneously**, it would **apply** $T_{\text{shell}} \gg T_{\text{M}}$ ↯
- **Dividing** the **shells** in **three** parts (**liquid**, **solid** & **freezing**)
- **Shells freeze** with **constant mass increment Δm**
- **Duration** of **freezing process** determined by **crystal growth rate u**





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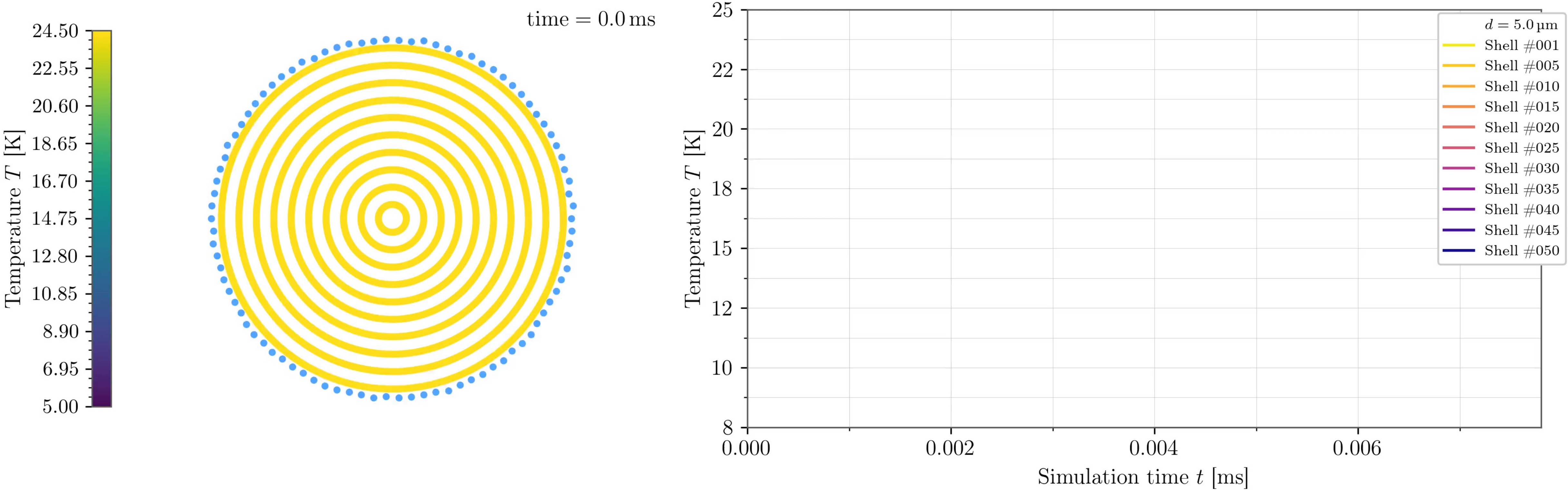
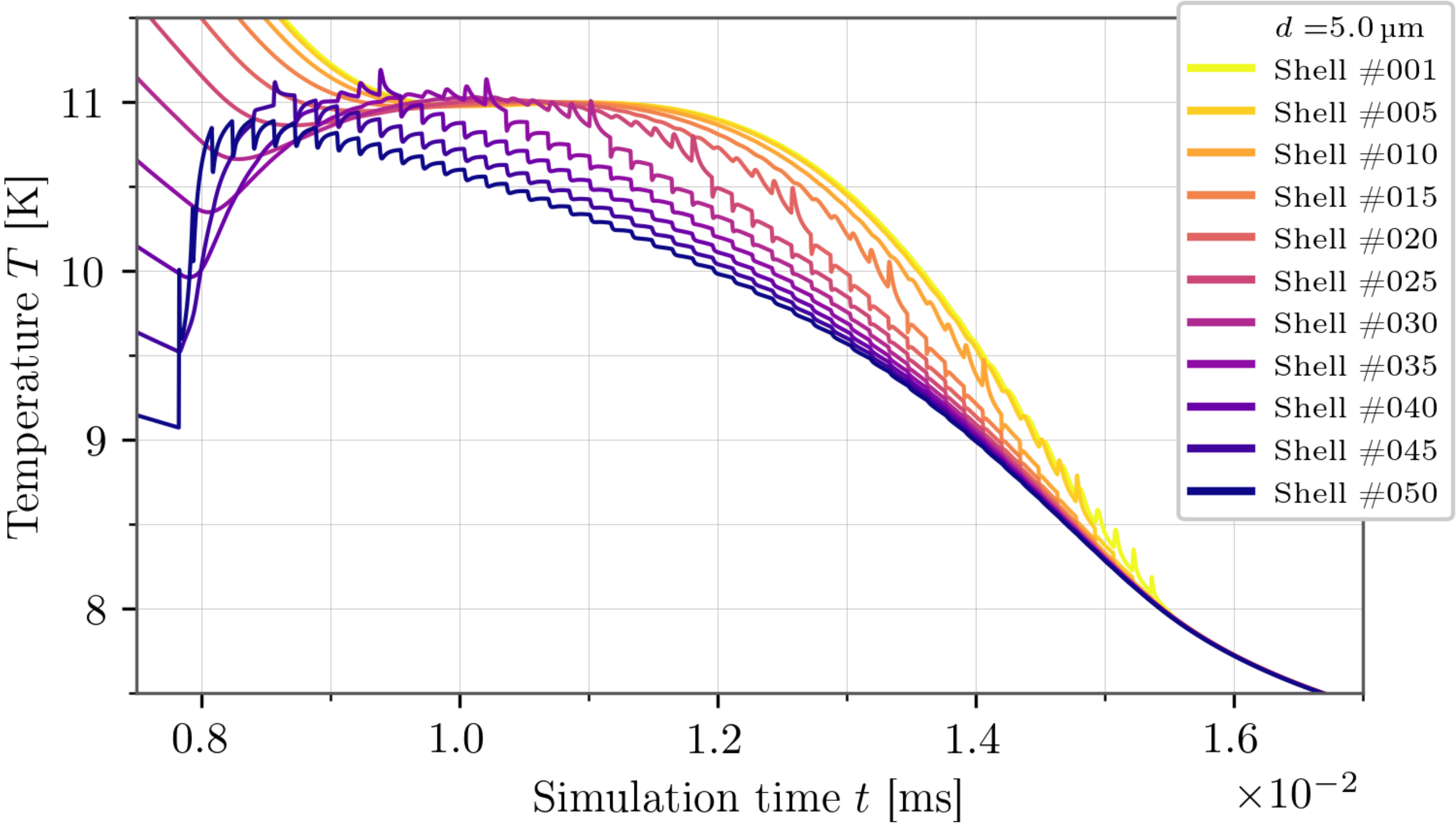
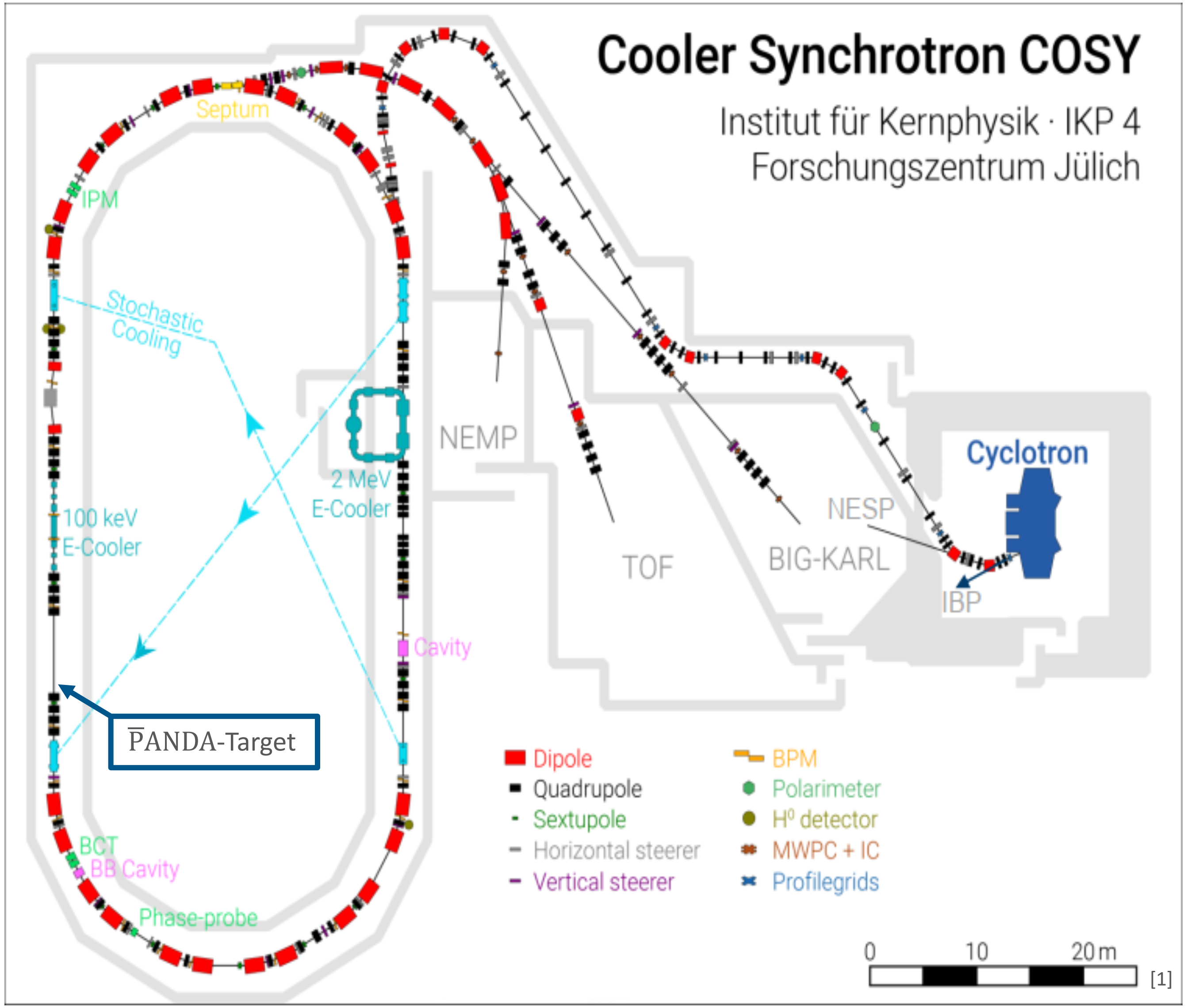


Discretization effect during freeze out



Cooler Synchrotron – COSY

- H^-**-ions** accelerated in **Cyclotron**
- At **injection point** H^-**-ions fly** through **carbon-foile**
  → **Stripping** off the **electrons**
- **Beam** can be **focused** with **electron** and **stochastic cooling**
- **Proton beam** with impulse $\leq 3{,}5\ \mathrm{GeV/c}$
- **Beam** can be **guided** to the **right, center** and **left** of **target beam** by **steerer magnets**
  → **Sweeping over target beam possible**



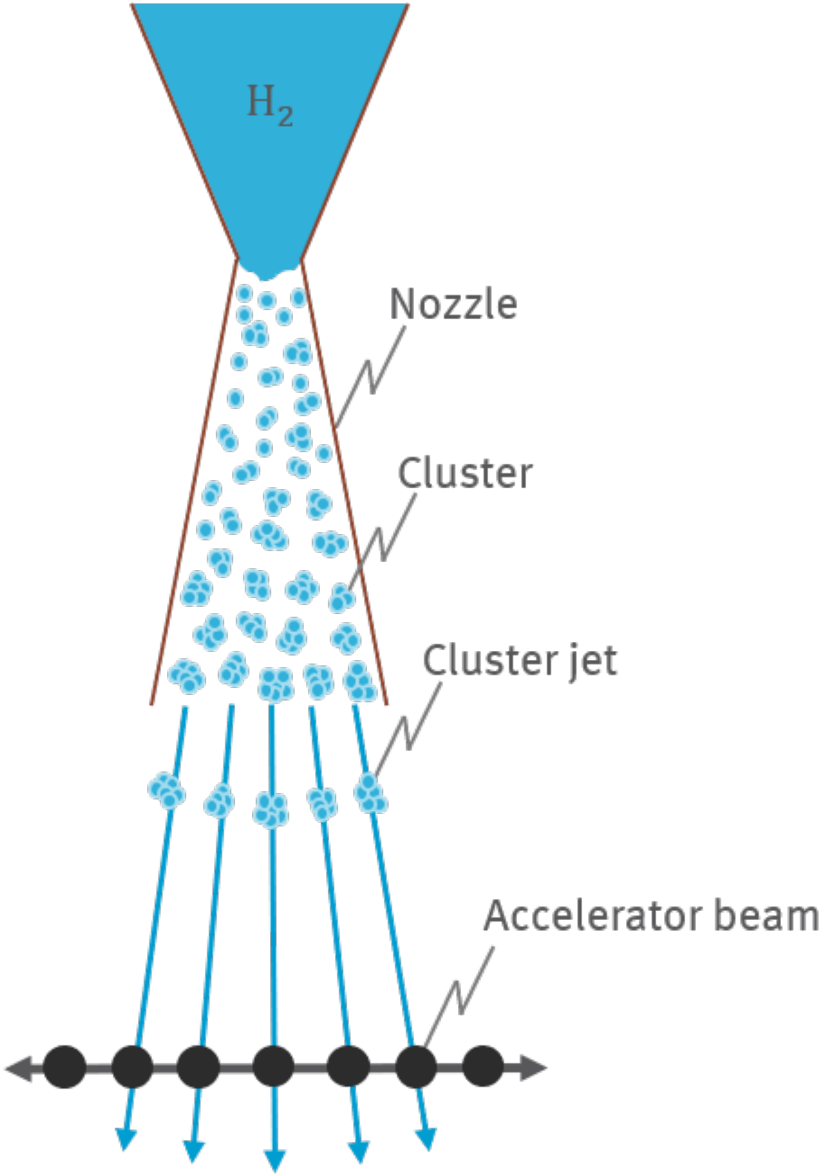
$\overline{\text{P}}$ANDA-Target

[1]

[1] R. Modic, A case of Improved Beam Control at COSY Jülich, 2021. https://www.cosylab.com/2021/06/21/a-case-of-improved-beam-control-at-cosy-julich/ (Lastly visited: 10.05.2023)

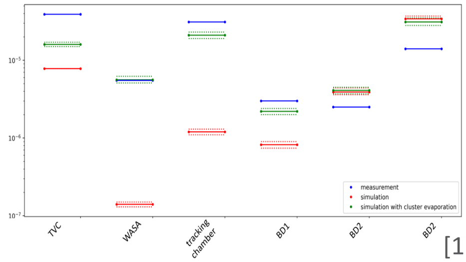
COSY beam time measurements

- **Aim** is to **measure gas load** due to **bursting** of **clusters** during **beam interaction**
  → **Sweeping** the **accelerator** beam over the **cluster beam**
- **Multiple measurements** at different **densities**
- At very **high densities, pressure increase** is **not measurable** due to **large background**
- Start at **low densities** to **determine extrapolation function** for **high densities**
- **Verification** by **energy transfer** to **cluster** and **its binding energy** possible



Summary

- **Vacuum simulations not** yet **complete**
- **Aim:** Determine **spatially resolved gas flow rate** by **flash evaporation**
- **Theory** on **flash evaporation** and **freezing out**
- Final **adjustments required** in **numerical simulations**
- **Models** for **Molflow+** already **exist**
- **COSY measurement plan** is **prepared**



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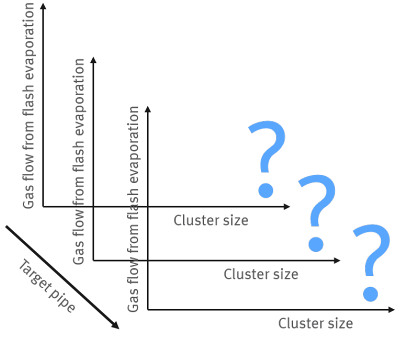

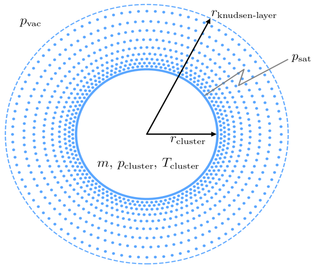

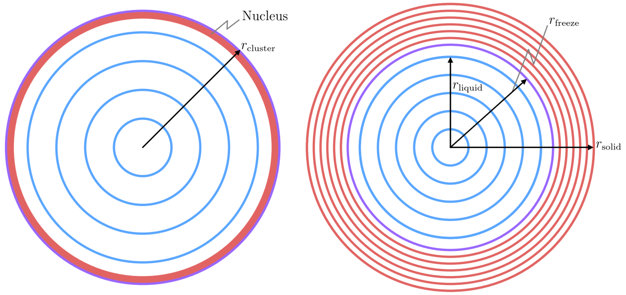

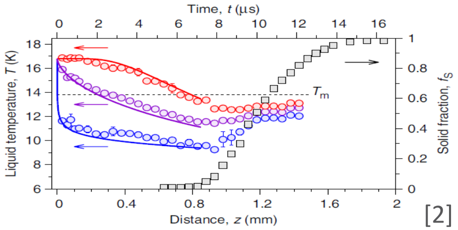

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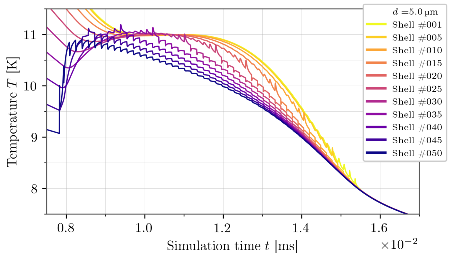

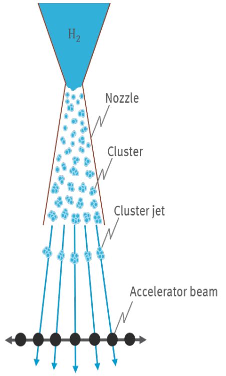

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[3] Anenja Vihara, http://anenja-vihara.org/vortrag-samstag-den-25-1/ (Lastly visited: 10.05.2023)

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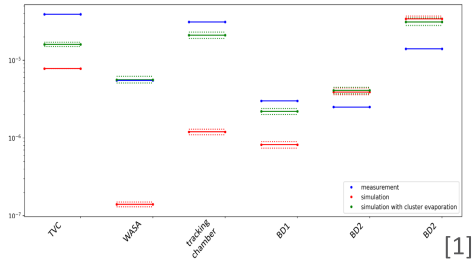

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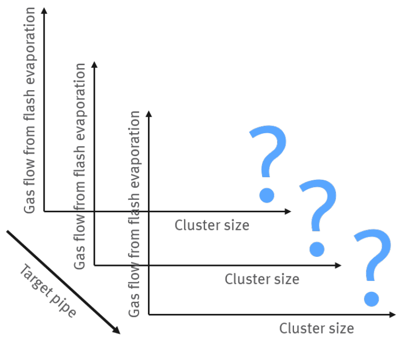

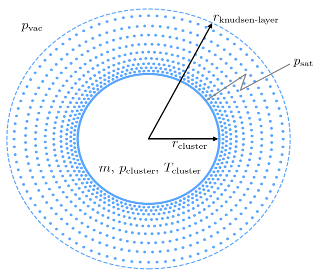

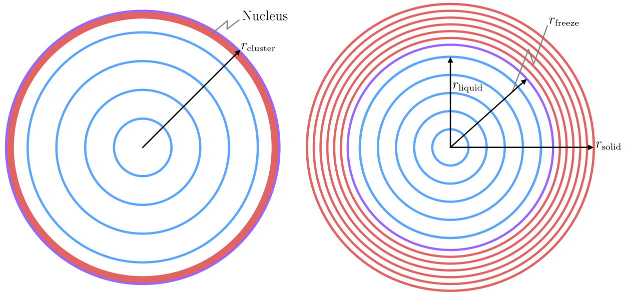

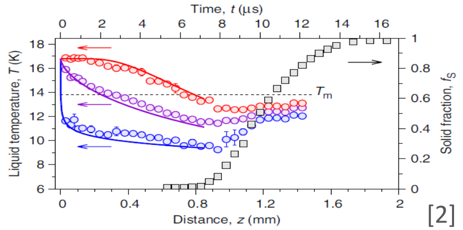

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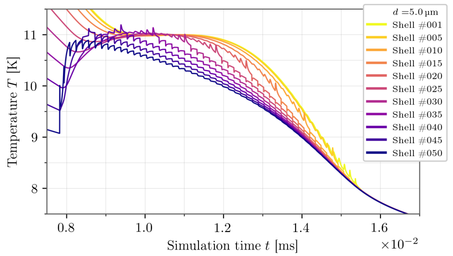

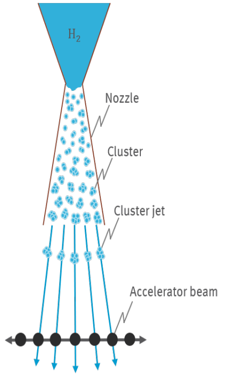

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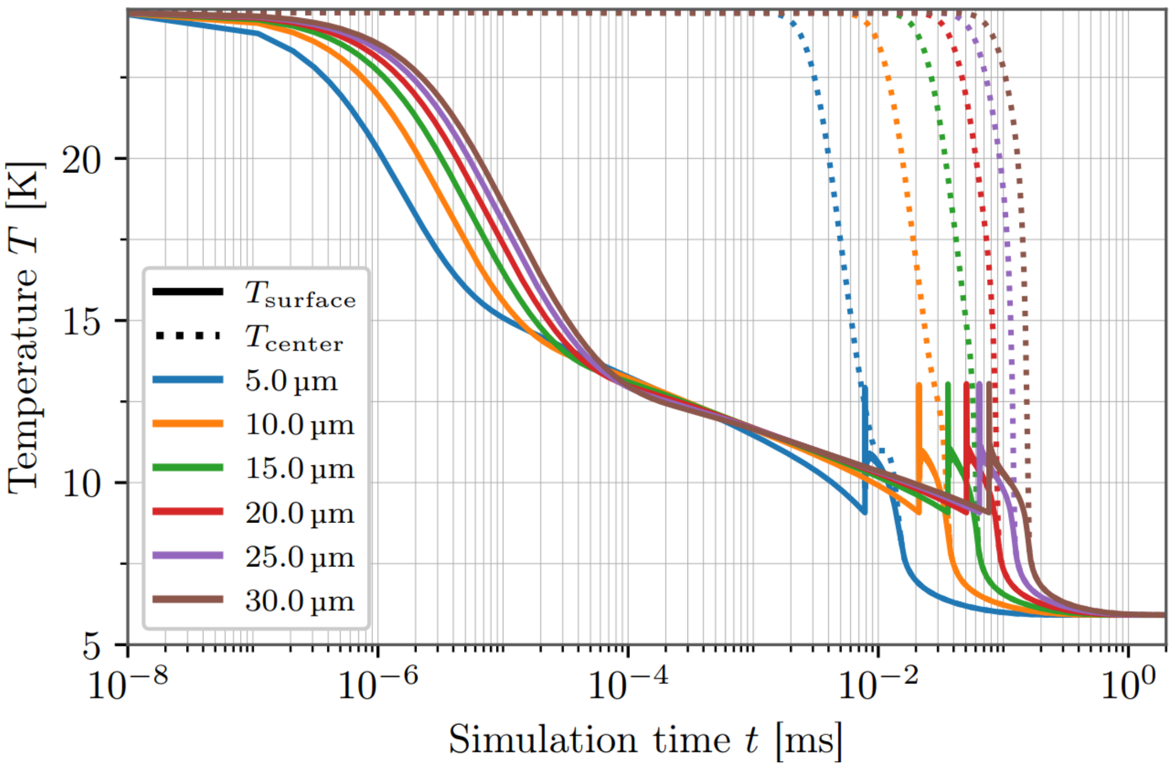
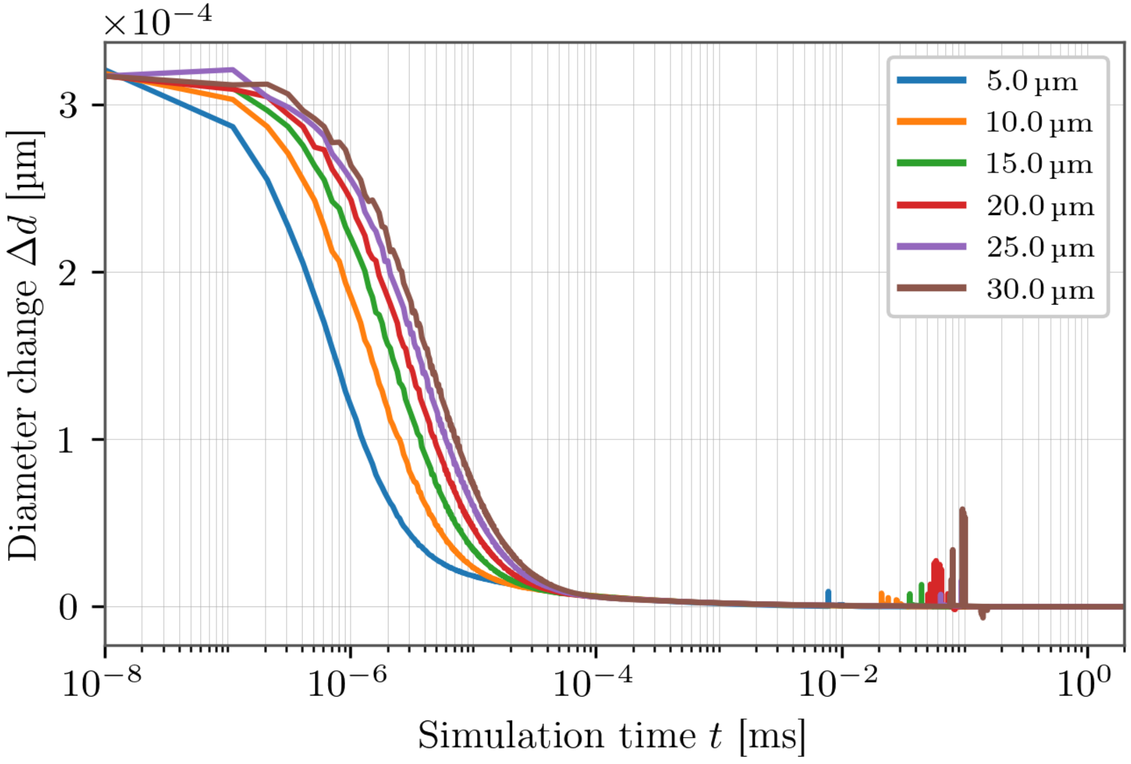
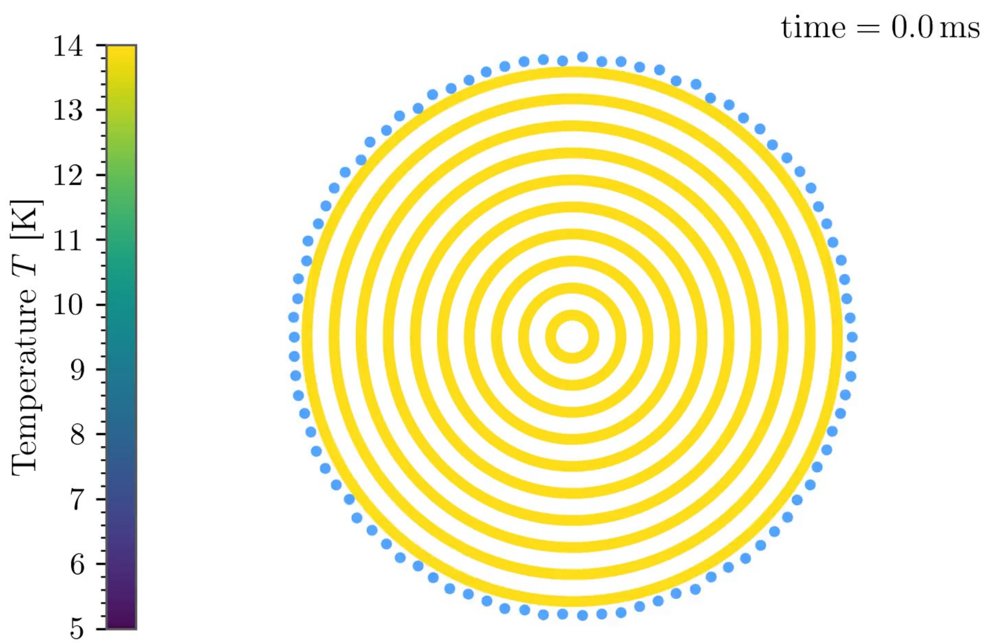
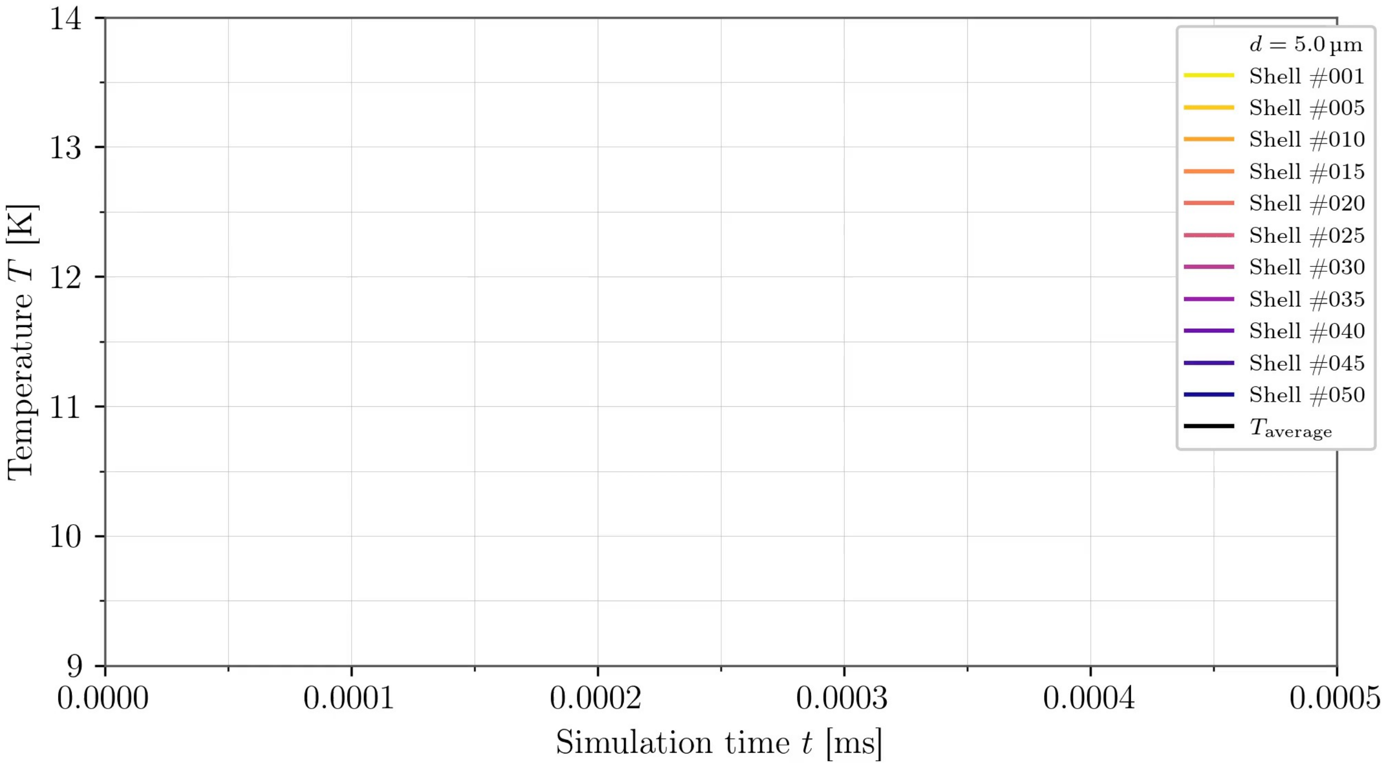
Backup slides – Plots with different cluster sizes





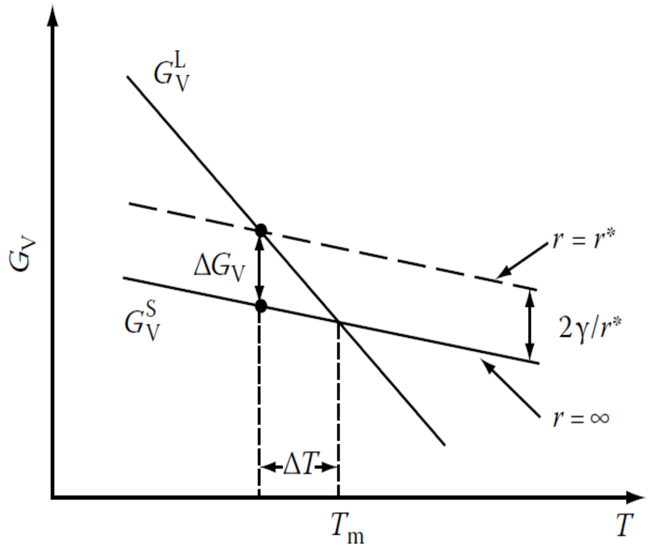
Backup slides – Temperature- & clustersize-animation (Only solid)





Backup slides – Theory on freeze out

- **Nucleation** is **statistical process** driven **by free energy reduction** ΔG_V
  - **Atoms/molecules combine randomly** to form a **nucleus**
  - If **energy** of the **nucleus ΔG^* is greater** than **interfacial energy, it is preserved**
  - **Grows radially** with **growth rate $\boldsymbol{u}$**
- **Differentiation** between **homogeneous** and **heterogeneous nucleation**
  - **Homogeneous: Formation** of a **spherical nucleus** **Heterogeneous: Spherical nucleus** forms on **foreign atoms** or **surface** → **Reduction** of the **interfacial energy**



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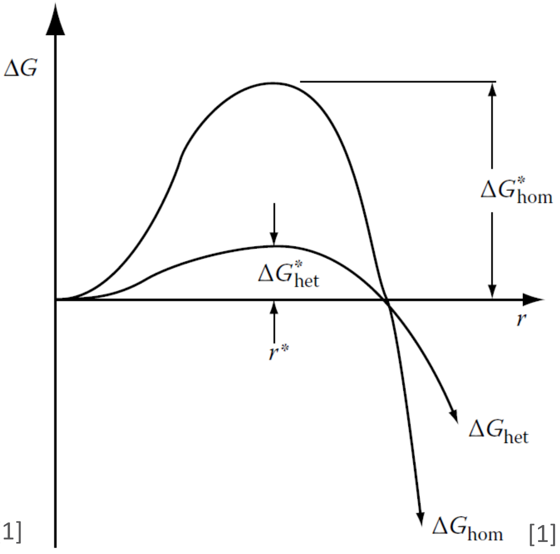

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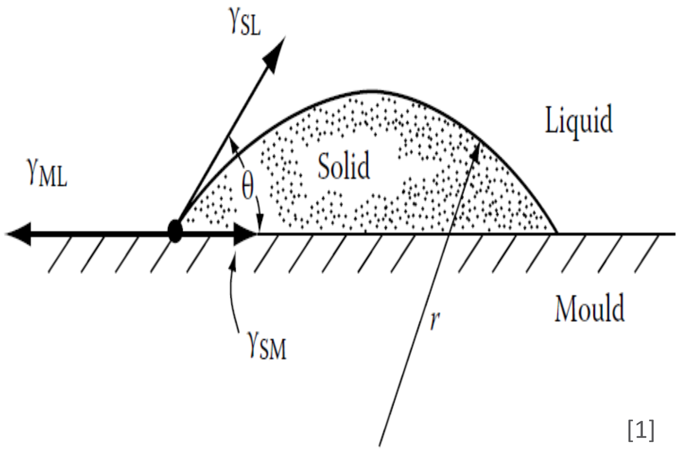

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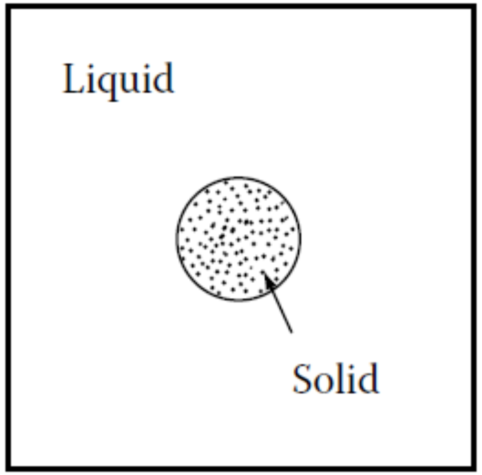
Heterogeneous nucleation



[1]

Homogeneous nucleation

[1] Porter, David A.; Easterling, Kenneth E.; Y, Sherif Mohamed (2009): Phase transformations in metals and alloys. 3rd ed. Boca Raton: CRC Press.

Backup slides – Crystal growth rate

- **Crystal growth rate u**

Enthalpy of fusion

Difference in free energy

Average thermal velocity

$$u = f \cdot u_0 \cdot exp\left(-\frac{m \cdot h_{\mathrm{fus}}}{k_{\mathrm{B}} \mathrm{T_m}}\right)\left(1 - \exp\left(-\frac{\mathrm{m} \cdot \Delta \mathrm{g}}{k_{\mathrm{B}} T}\right)\right)$$

Fraction of active sites contributing to growth

- **Free energy Δg** is **determined through heat capacity c_p**

$$\mathrm{g}^{\mathrm{L,S}} = \underbrace{\mathrm{h}^{\mathrm{L,S}}}_{h_0^{L,S}(T_M) - \int_T^{T_{\mathrm{M}}} c_p^{L,S}(T')dT'} - \underbrace{\mathrm{T} \cdot s^{L,S}}_{T s_0^{L,S}(T_M) - T \int_T^{T_{\mathrm{M}}} \frac{c_p^{L,S}(T')}{T'} dT'}$$

- $f = 0.01$ for **Para-H$_2$** observed (Kühnel, Grisenti et. al)
  - $f = 0.0025$ for **n-H$_2$** rather agrees with research