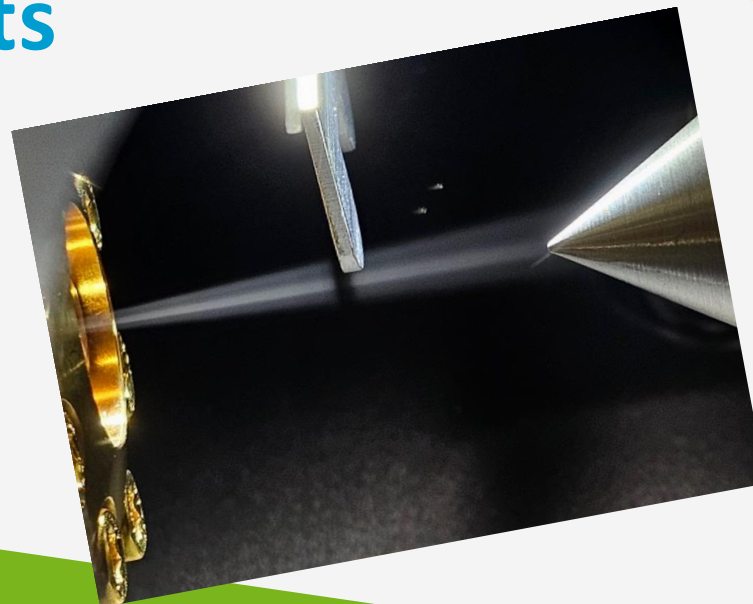


Universität
Münster

Jet Targets for Nuclear and Hadron Physics Experiments

GSI Hadron Physics Seminar
28th October 2026



wissen.leben

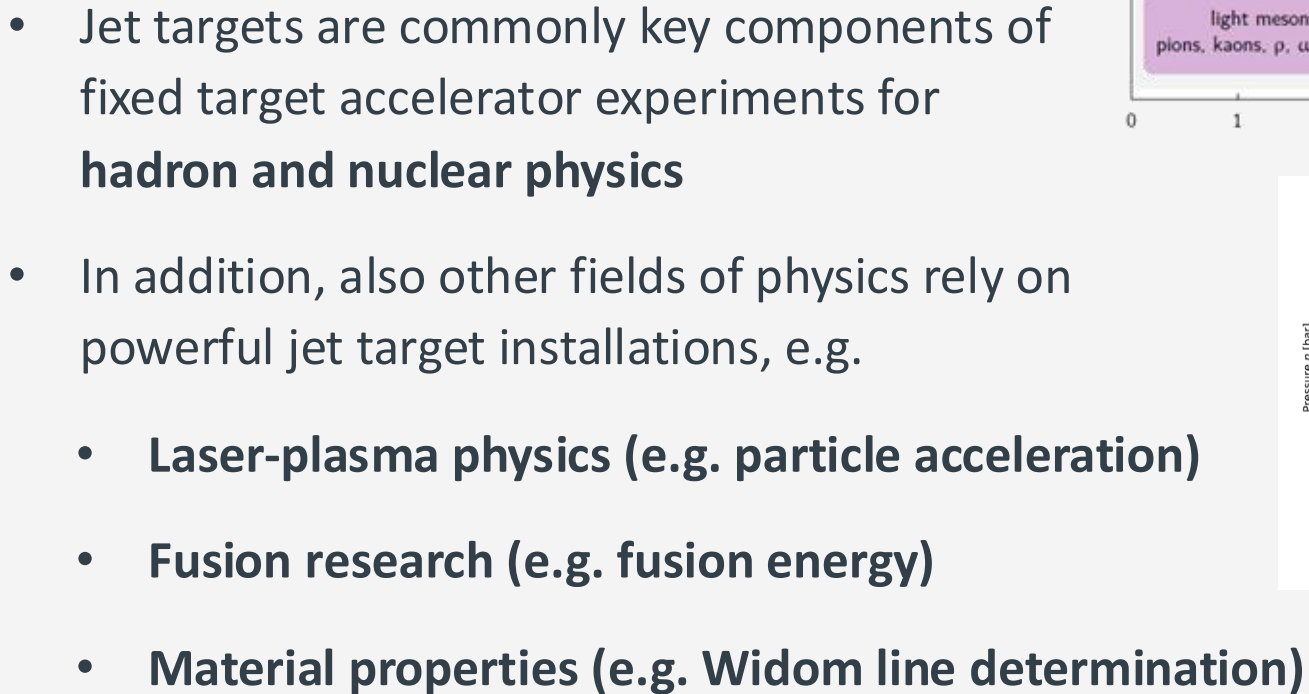
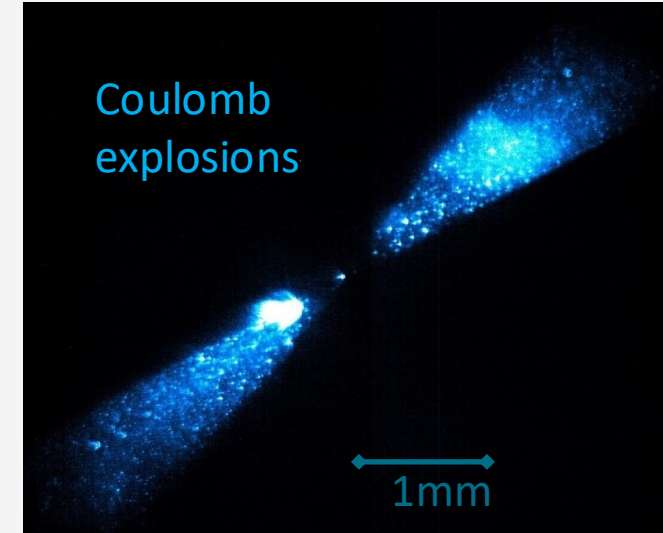
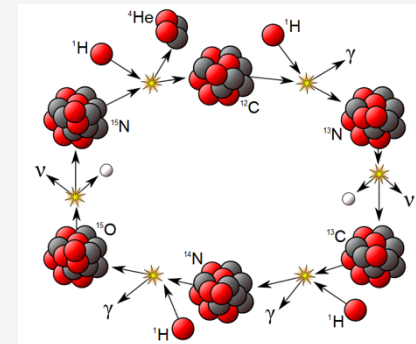
Alfons Khoukaz - Institut für Kernphysik



Bundesministerium
für Forschung, Technologie
und Raumfahrt

NRW-FAIR
Netzwerk





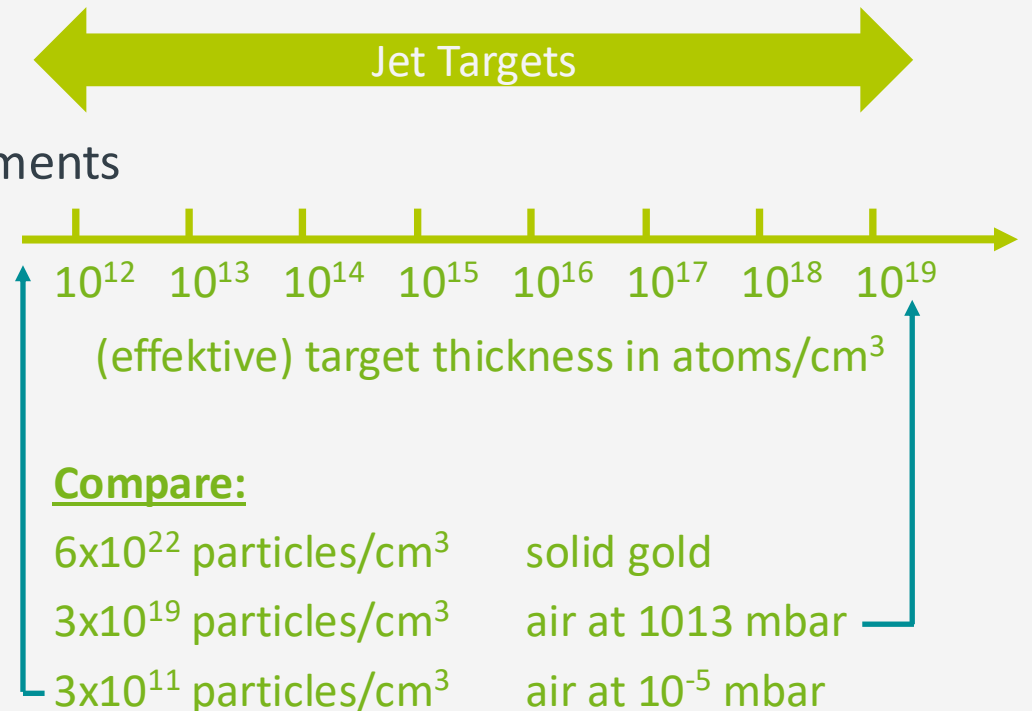
Lets take a closer look at different jet target types and their special properties

Content of this Talk

- Typical Requirements on Jet Targets
- Important Target Types for Nuclear & Hadron Physics Experiments

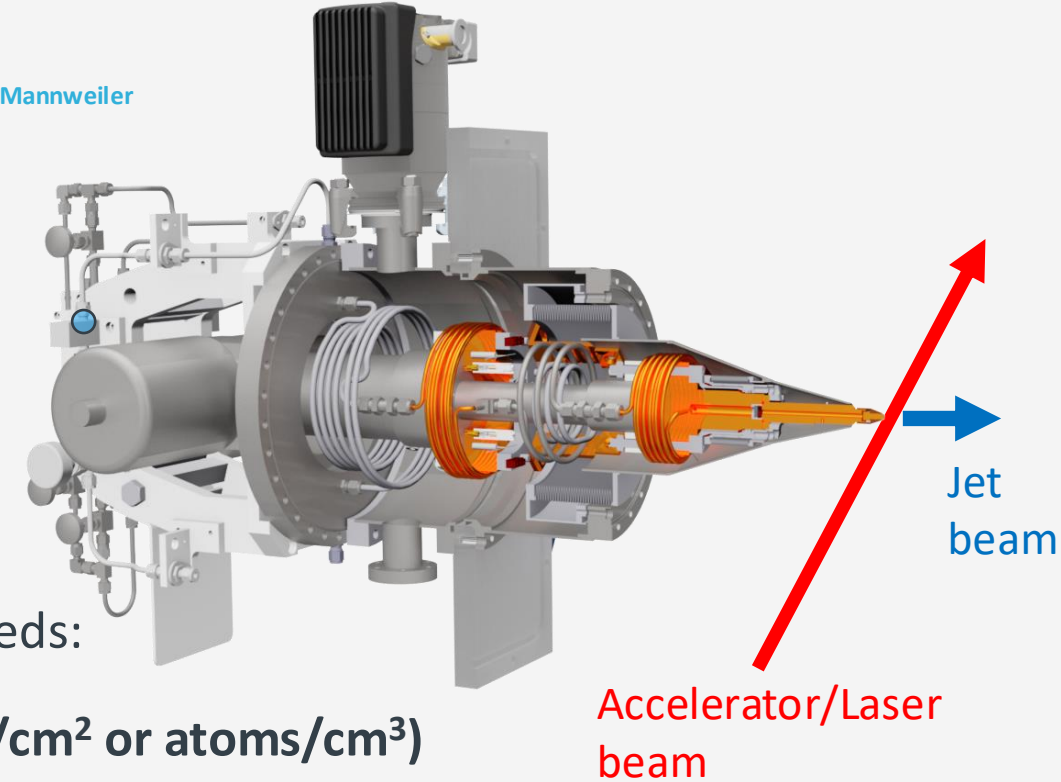
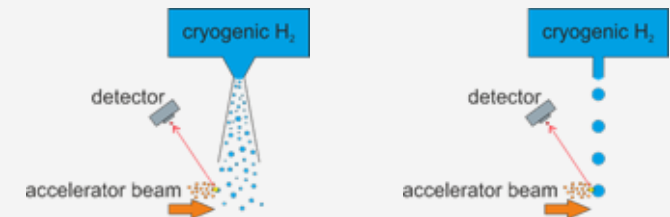
- **Gas-Jet Targets**
- **Cluster-Jet Targets**
- **Pellets/Frozen Filament Targets**

- Diagnostic Tools and Production of μm -Sized Nozzles
- Jet Target Manipulation („Cryobending“, „VapoStab“)
- Upcoming developments: LH_2 targets



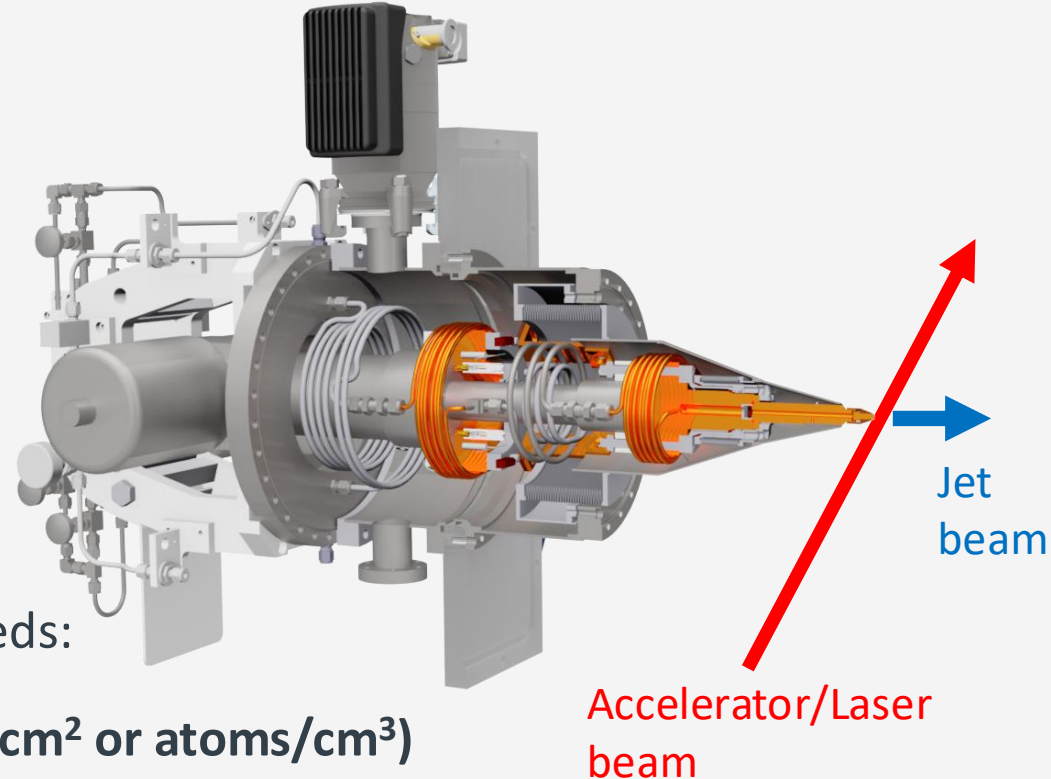
Targets, Nozzles and Jet Beams

- Commonly, the target forms the centerpiece of an experiment
- The choice of the target type is influenced by experimental needs:
 - Luminosity and required target thickness at the IP (atoms/cm^2 or atoms/cm^3)
 - Target particle size distribution (atoms, molecules, small clusters, larger particles of e.g. $20\text{ }\mu\text{m}$, ...)
 - Target material (Hydrogen, Deuterium, ..., Xenon, ...)
 - Distance between the jet generator and the IP (mm, cm, or even meters)
 - Homogeneity and possible time structure in the reaction/event rate
 - Target jet beam size and vacuum situation at the IP
 - ...



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 - **Homogeneity and possible time structure in the reaction/event rate**
 - **Target jet beam size and vacuum situation at the IP**
 - ...



*It would take
hours to discuss
all this!!!*

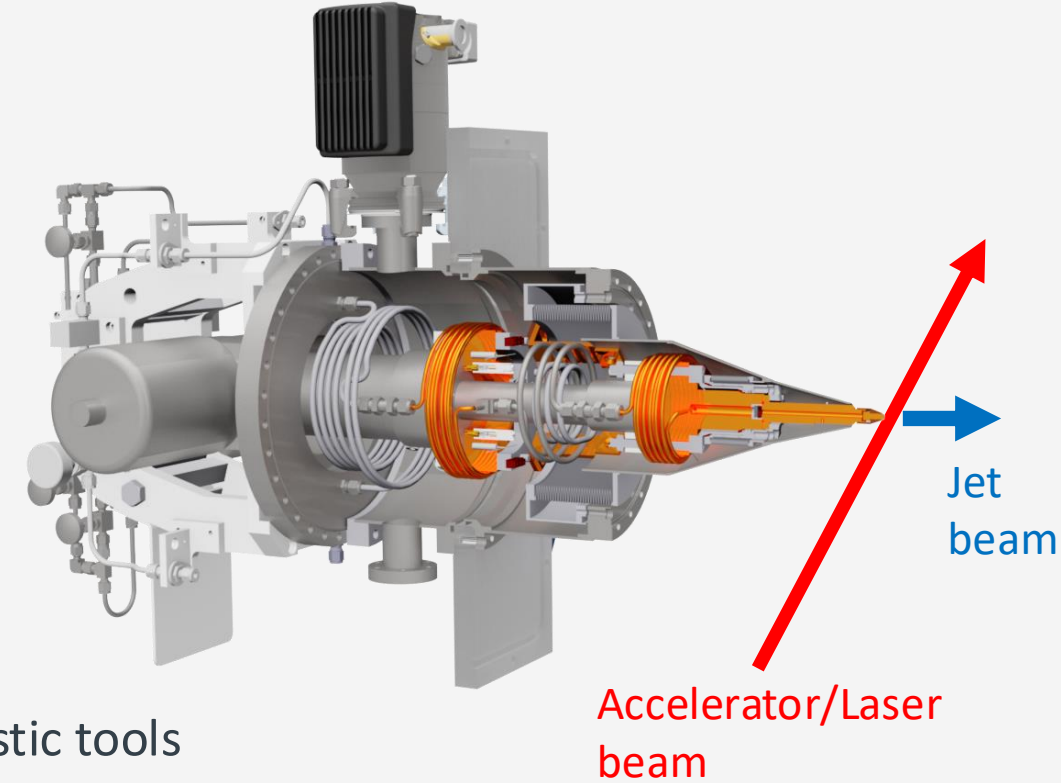
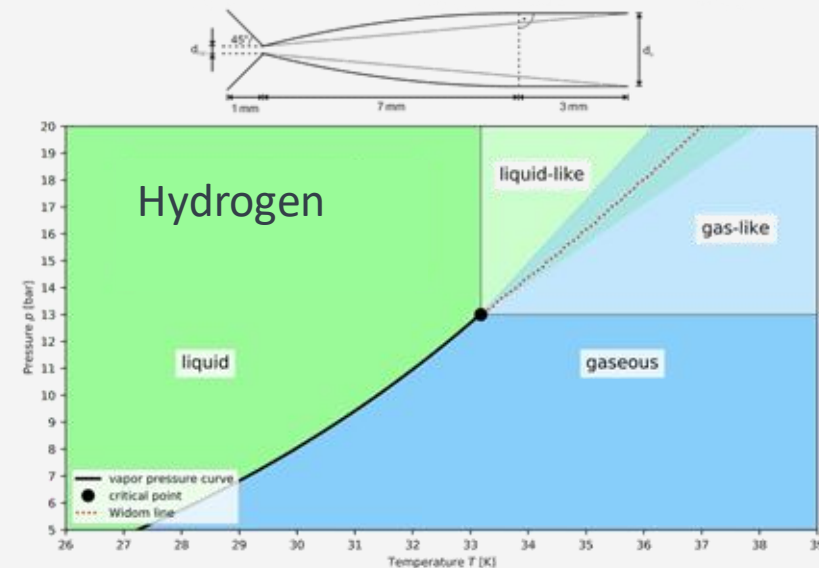
Targets, Nozzles and Jet Beams

This talk

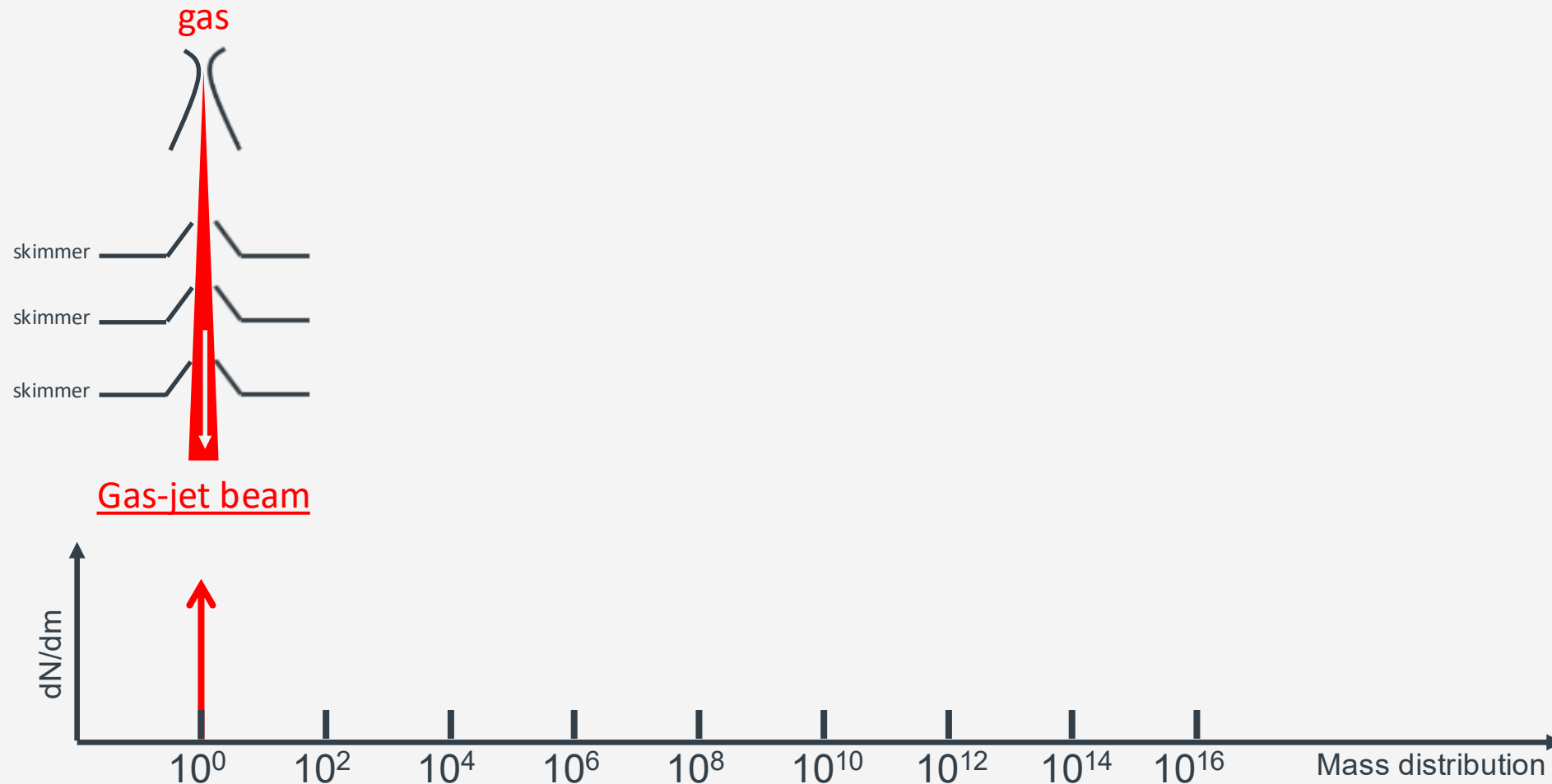
- Recent developments of unpolarized (internal) targets
- Short discussion on the setup, jet beam formation and diagnostic tools

What we will see:

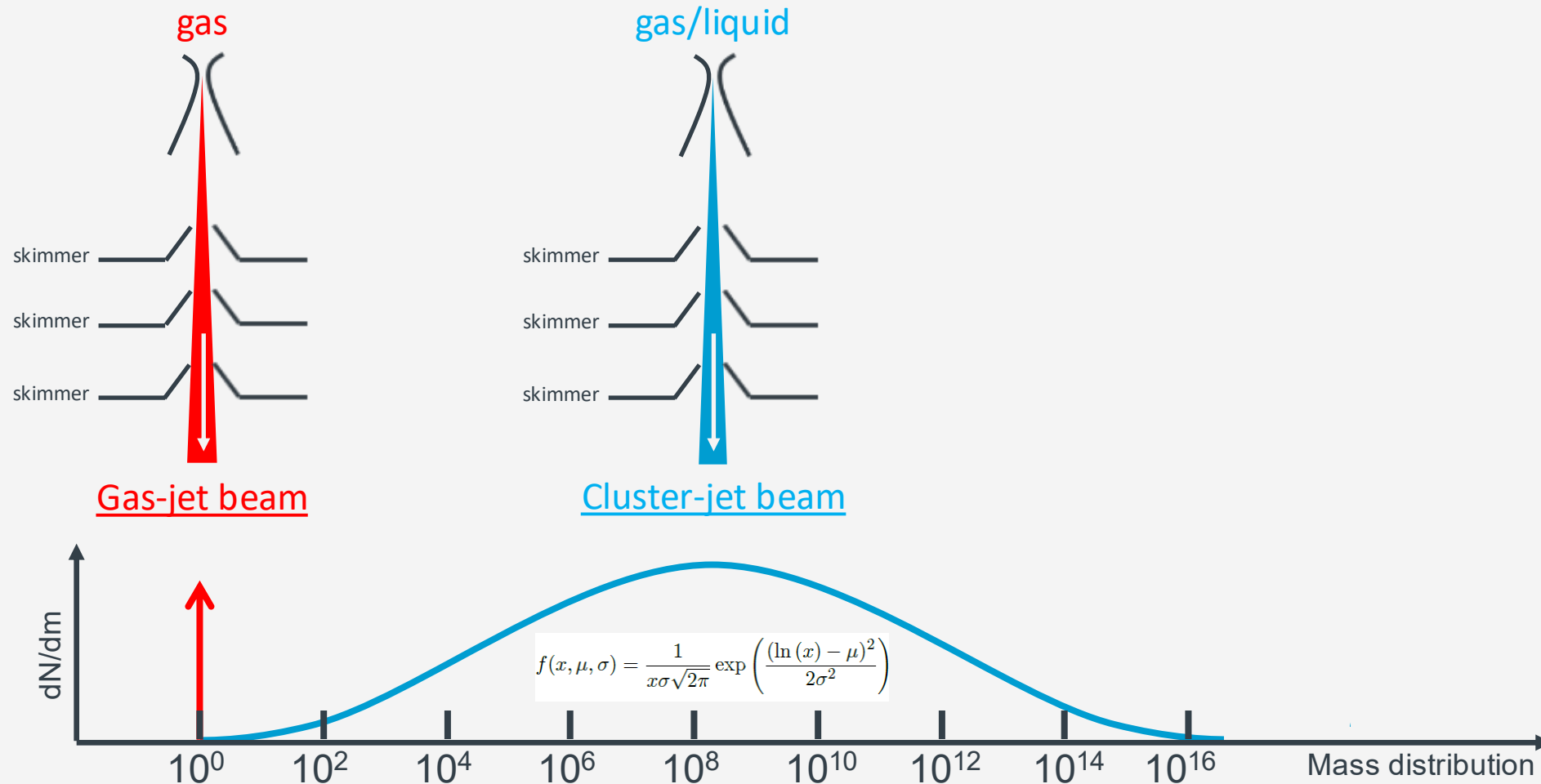
- The choice of the target type is just the beginning
- Even more important:
 - Choice of the right nozzle type/size
 - Choice of the right operating parameters



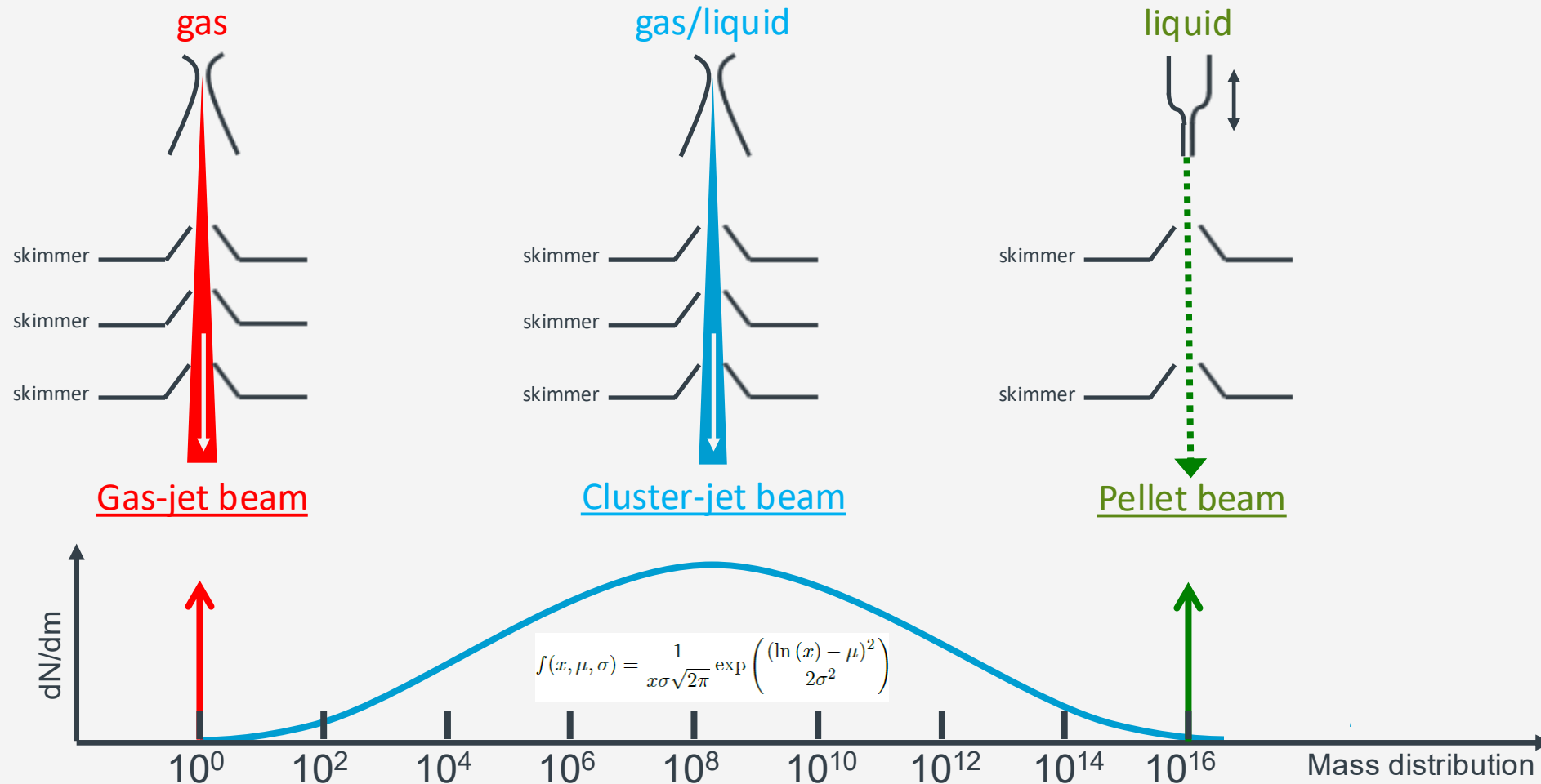
Important Types of Unpolarized Internal Targets



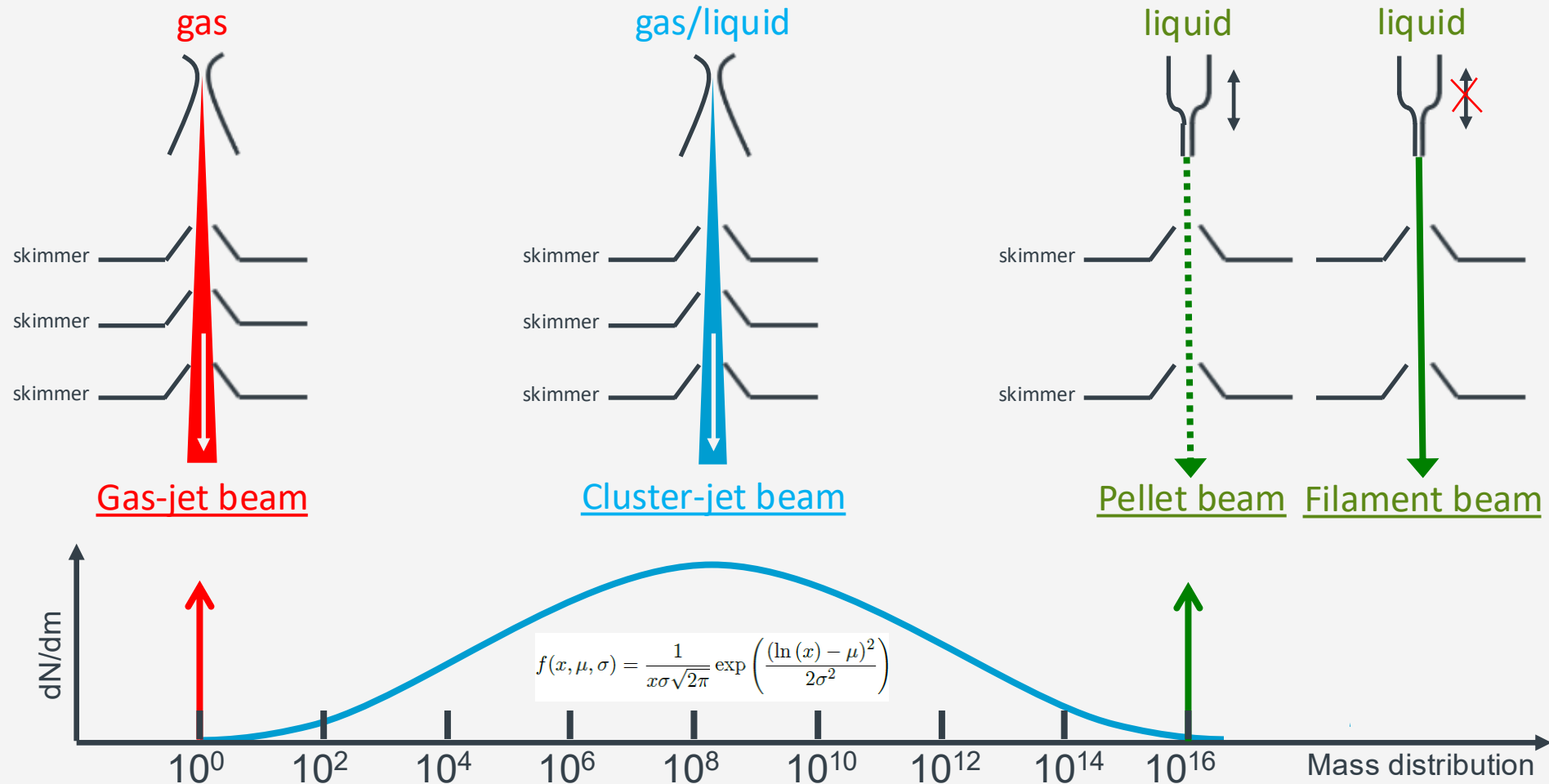
Important Types of Unpolarized Internal Targets



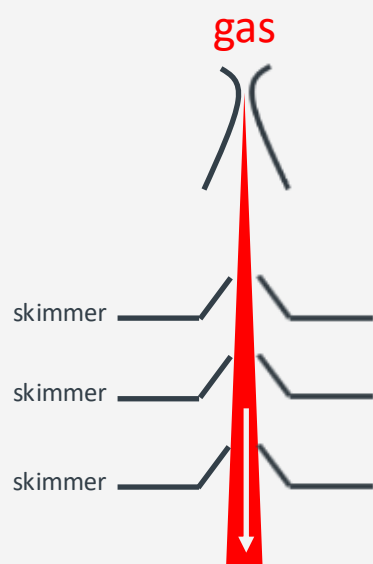
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Important Types of Unpolarized Internal Targets

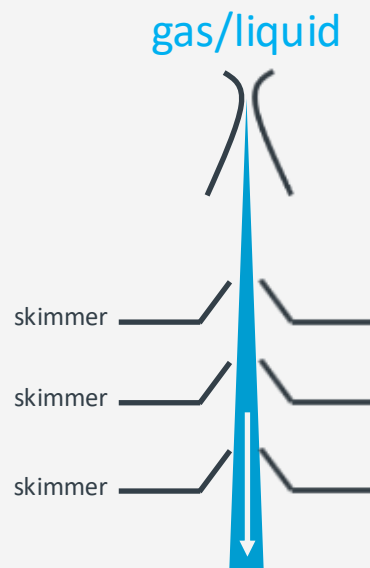


Important Types of Unpolarized Internal Targets



Gas-jet beam

MAGIX target (test runs at MAMI/Mainz)



Cluster-jet beam

COSY-11 target (finished)

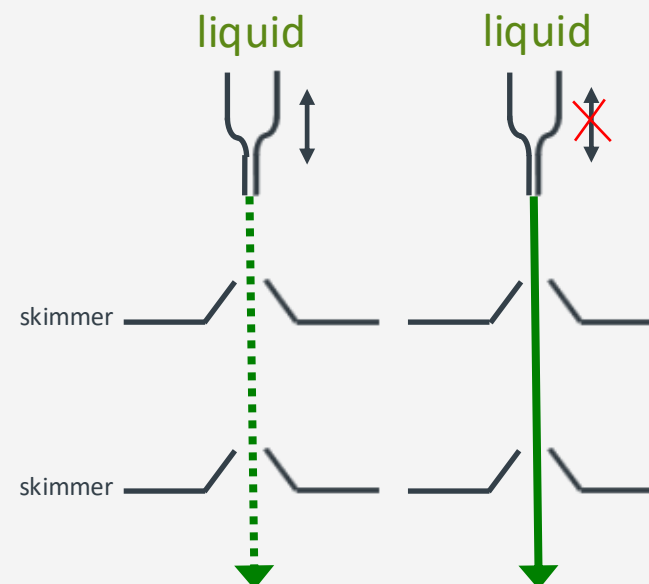
ANKE target (finished)

Prototype target (in operation at Münster)

PANDA target (in operation at COSY)

CryoFlash target (ARCTURUS laser, finished)

KOALA target (in design phase)



Pellet beam

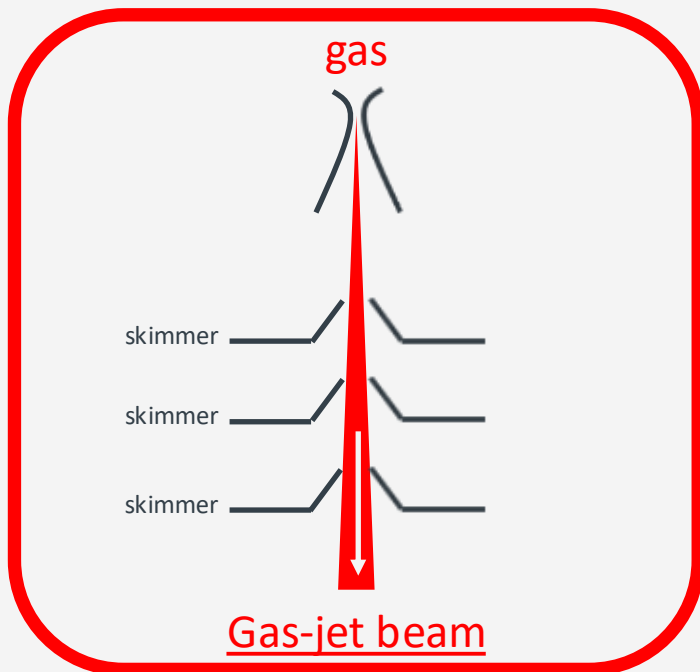
Filament beam

Prototype target (in operation at Münster)

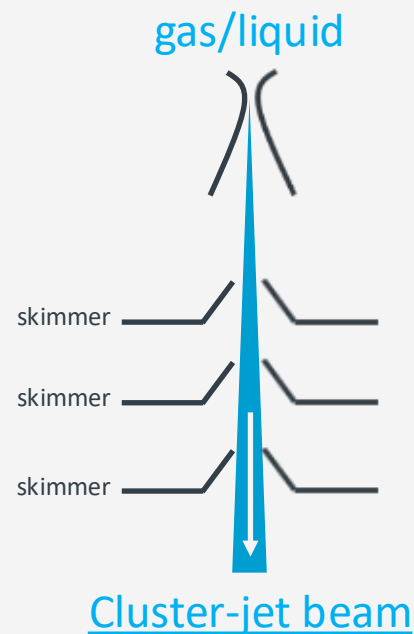
MAGIX target (test runs at MAMI/Mainz)

Münster
target
devices

Important Types of Unpolarized Internal Targets



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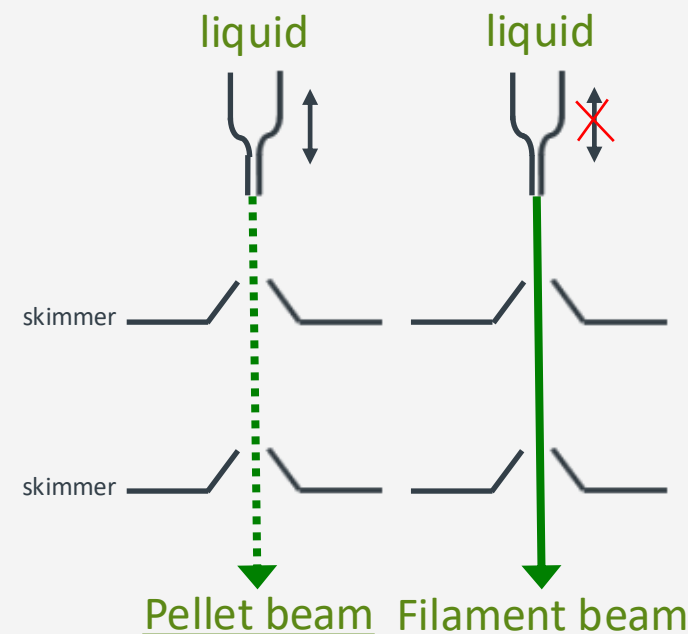
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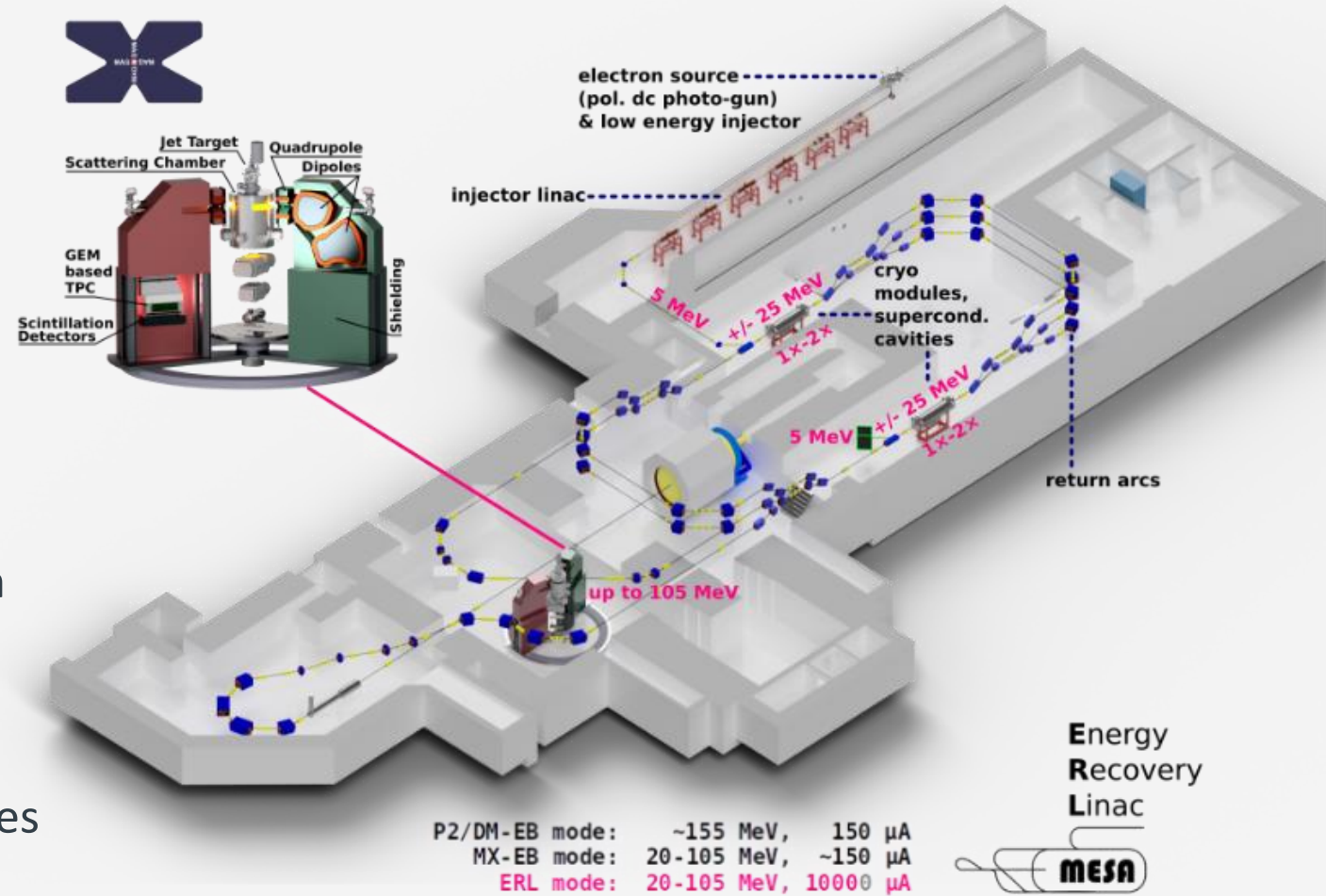
MAGIX target (test runs at MAMI/Mainz)

Münster
target
devices

Gas-Jet Target for MAGIX at MESA

MAGIX at MESA:

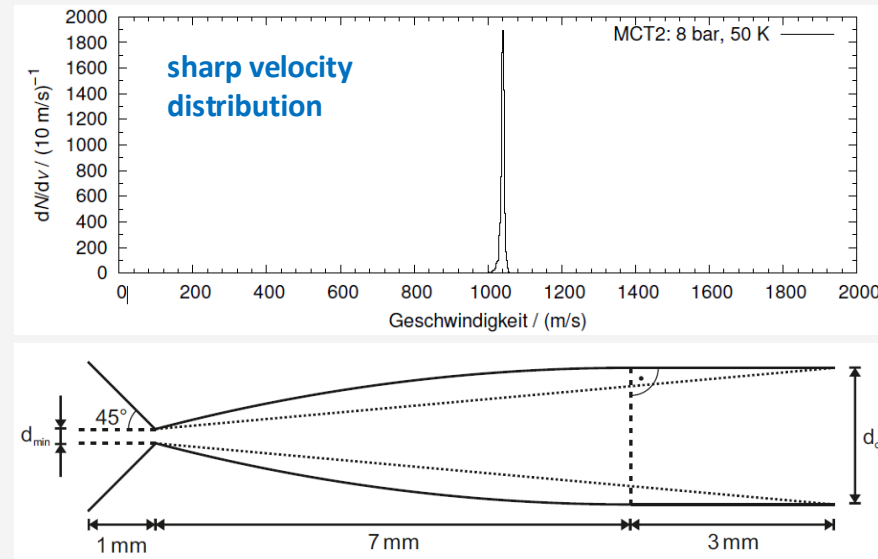
- Broad experimental program of high precision experiments using the high-intense MESA electron beam (up to 10 mA)
- Cryogenic **gas-jet**/cluster-jet target for all types of gases: H₂, D₂, ..., Xe, ...
- Aimed hydrogen target thickness: Up to **10¹⁹ atoms/cm²** for luminosities of **L = 10³⁵ cm⁻²s⁻¹**
- Interaction point: **Very close to the jet nozzle** (mm – cm) possible



Gas-Jet Target for MAGIX at MESA

Considerations on the target design

- Use of convergent-divergent Laval nozzle for supersonic gas jet beams
- High gas jet thickness can be achieved by large gas flows through the jet nozzle
- Target thickness variation over order s of magnitudes: **gas inlet pressure & temperature**



$$Q_{\text{Target}} = \frac{\dot{m}}{v \cdot A_{\text{beam}}}$$

$$\dot{m} = \frac{q_V \cdot M \cdot p_N}{R \cdot T_N}$$

$$q_V = A^* \frac{p_0}{\sqrt{M T_0}} \frac{T_N}{p_N} \left(\frac{2}{\kappa + 1} \right)^{\frac{\kappa + 1}{2(\kappa - 1)}} \sqrt{\kappa R}$$

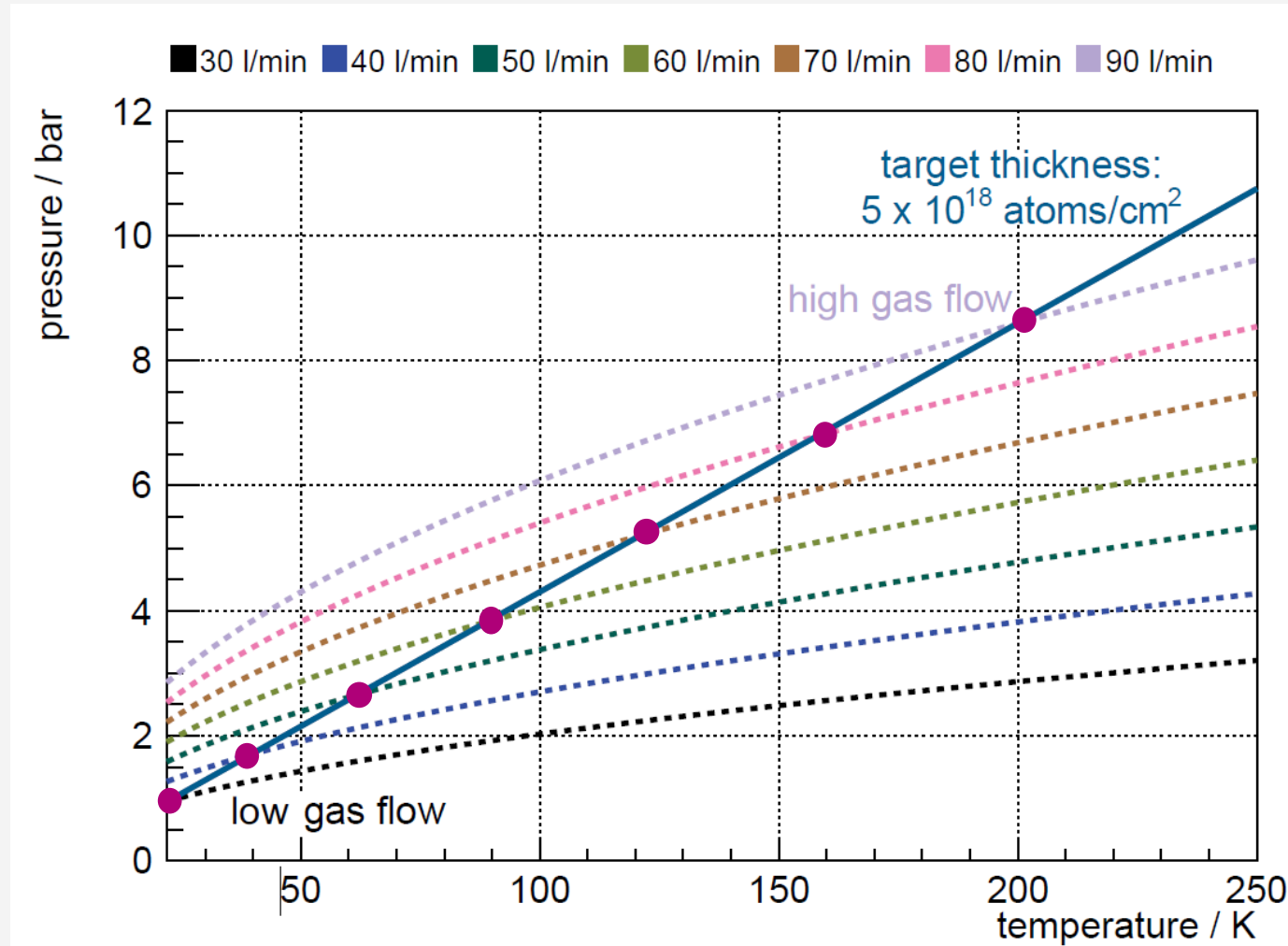
$$v_{\text{max}} = \sqrt{\frac{2\kappa}{\kappa - 1} \cdot \frac{R T_0}{M}}$$

A blue 3D model of the Laval nozzle is shown below the equations. A color scale for velocity (m/s) is provided on the right, ranging from 0.0e+00 to 9.0e+02.

Gas-Jet Target for MAGIX at MESA

Considerations on the target design

- Challenge:**
 High gas flows result in high vacuum pressures and large physical background
- Solution:**
 Use cryogenic gas jets of lowest possible temperature for lower gas flows at same target thickness (for $p > O(10^{17})$ atoms/cm²)

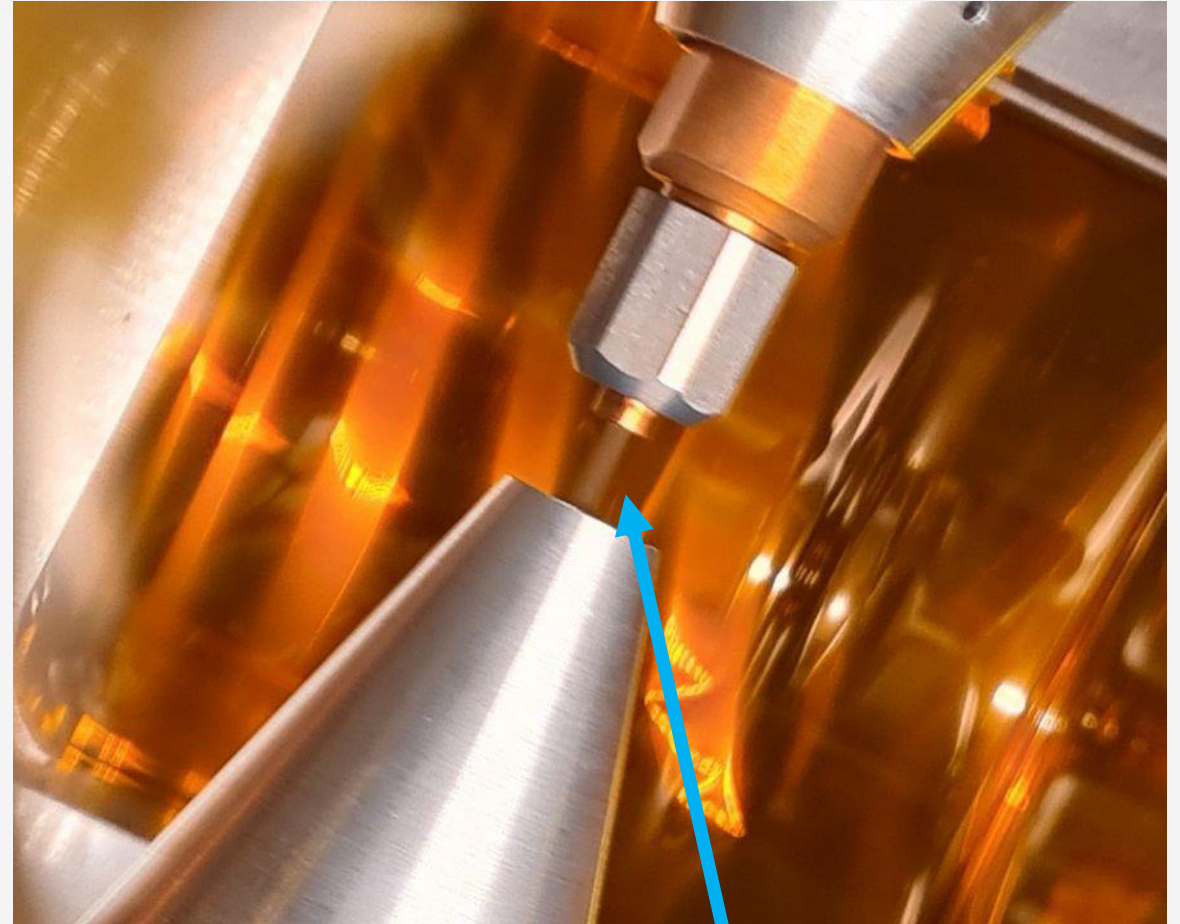


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If the temperature is low enough, the gas might even form cluster (later more)

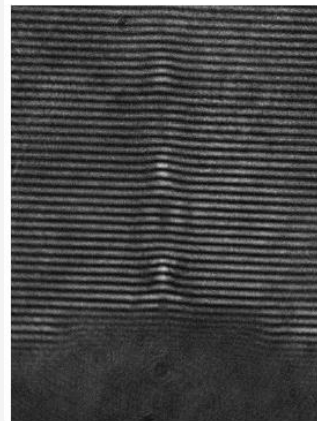
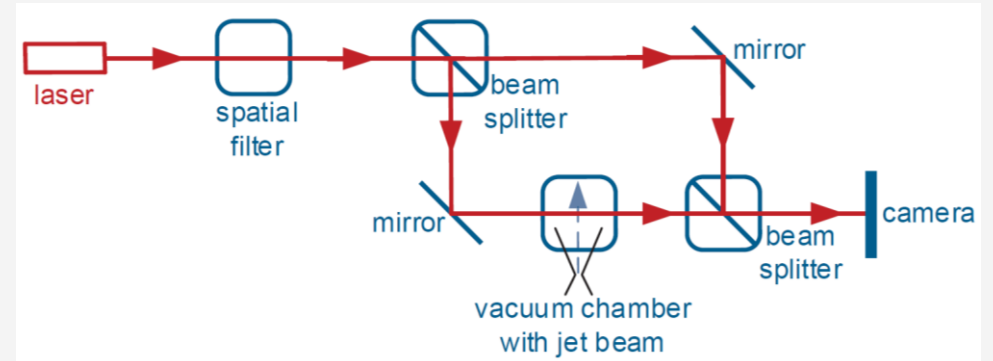
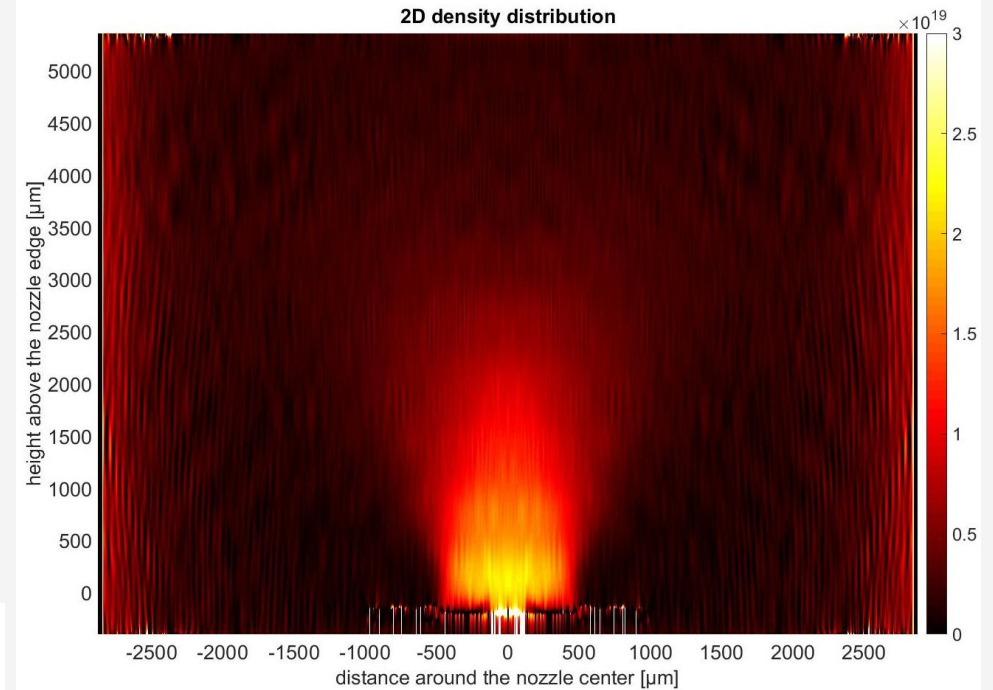
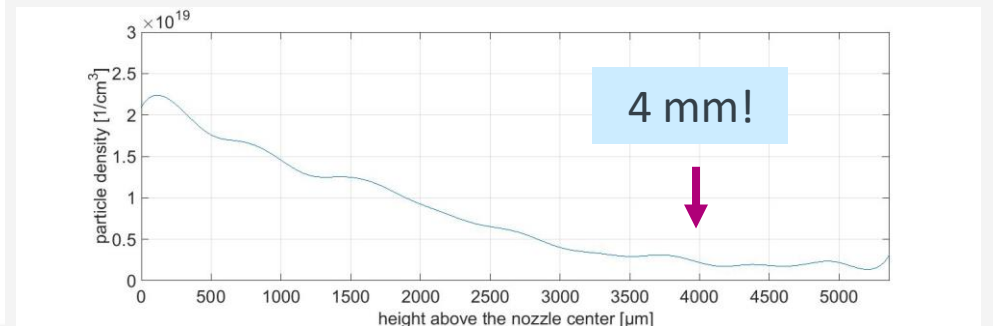


Gas-Jet Target for MAGIX at MESA

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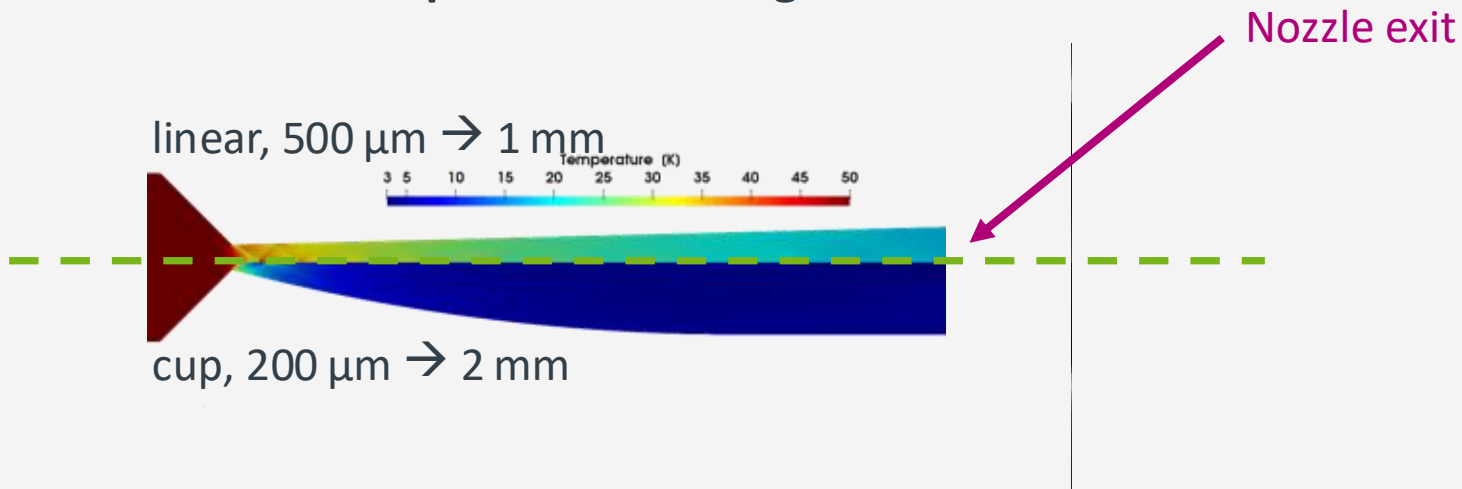
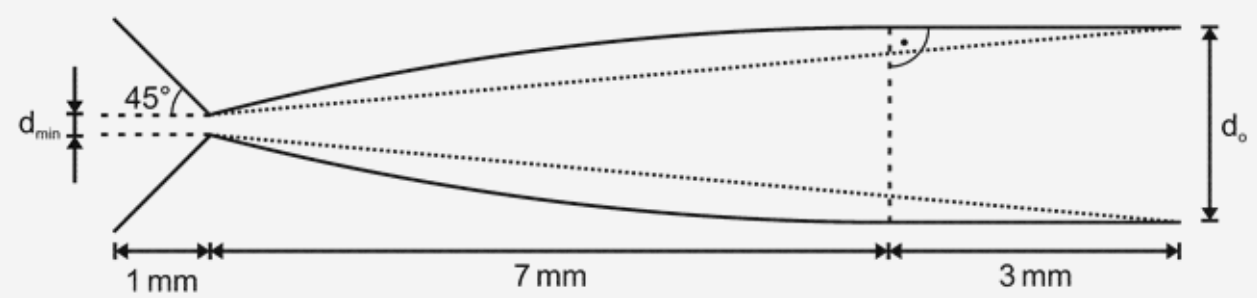
- **Useful diagnostic tool:**
Mach-Zehnder Interferometer
- **Challenge:**
Intense gas jet beam „disappears“ within a few mm behind the nozzle
- **Solution:**
Choose interaction point as close as possible to the jet nozzle

Argon (293 K, 17 bar)
 Nozzle: $d_{\min} = 0.5 \text{ mm}$
 $d_{\text{out}} = 1.0 \text{ mm}$



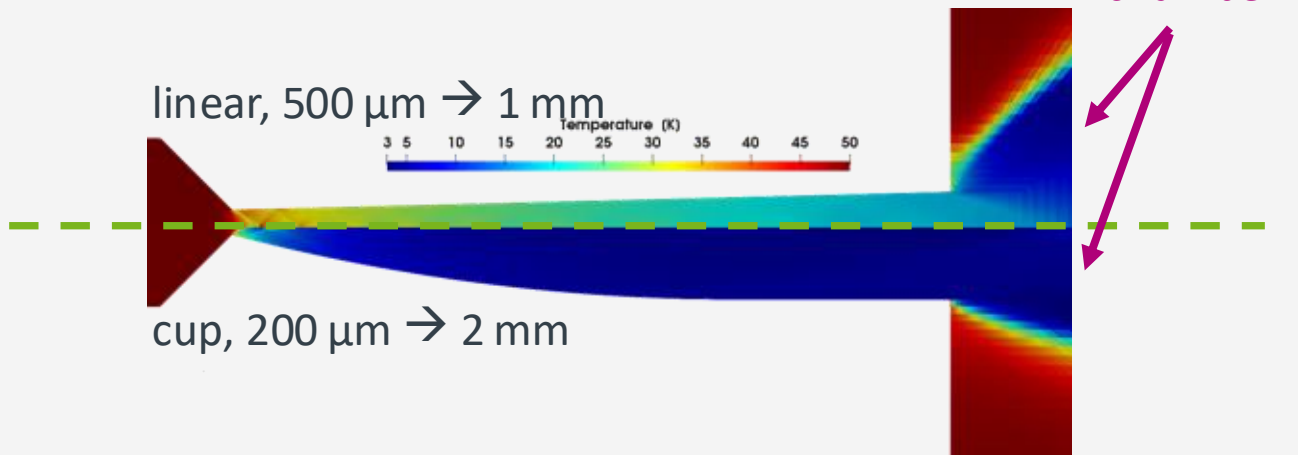
Activities Towards MESA

- Numerical simulations (e.g., OpenFOAM) on
 - **optimized jet nozzles geometries**
 - Inner/outer diameter
 - Inner shape and total length

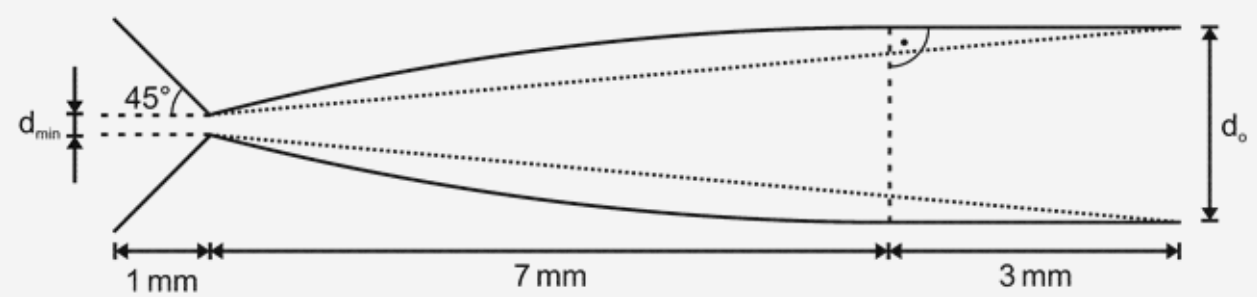
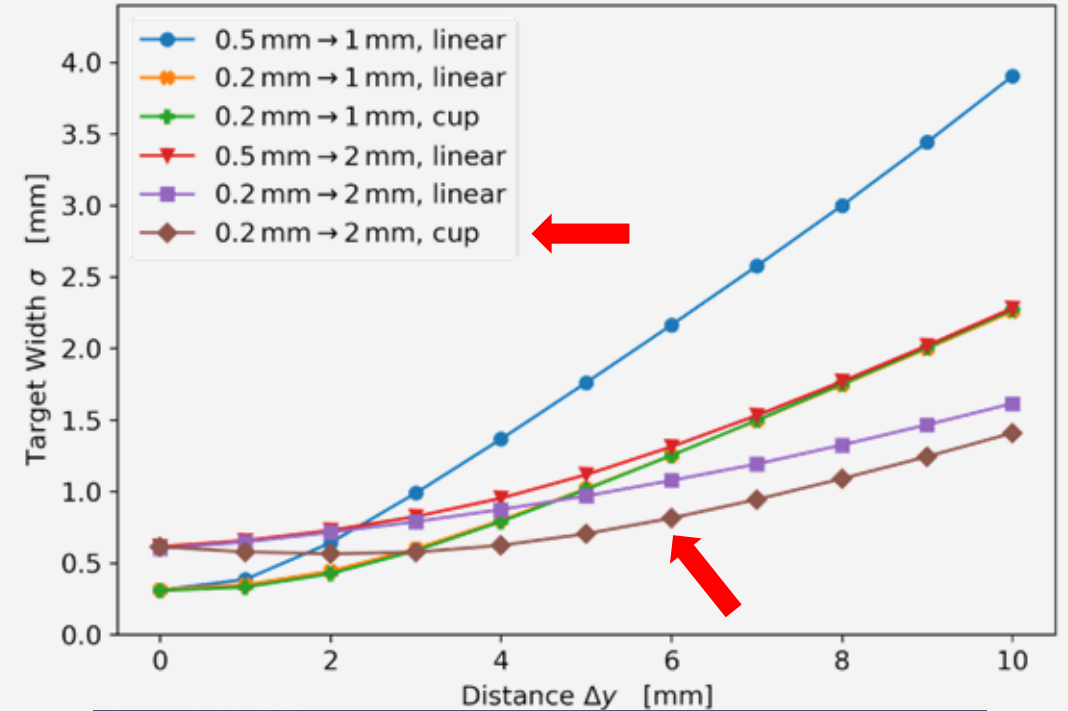
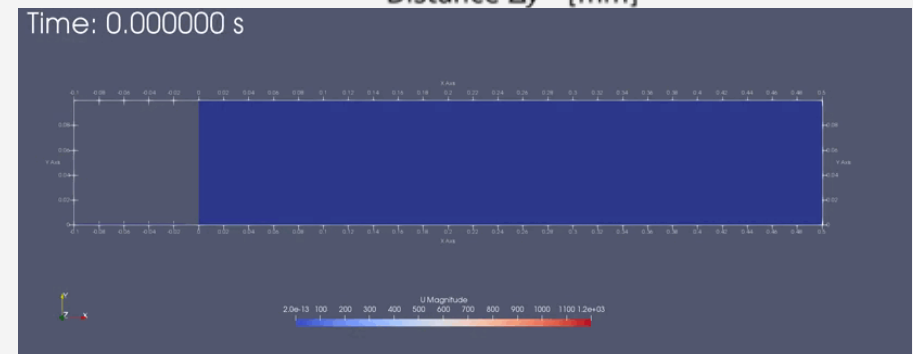


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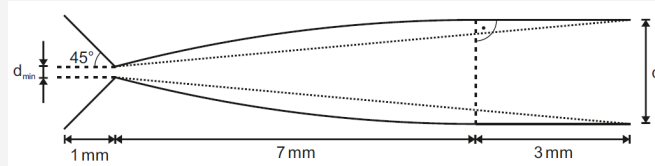
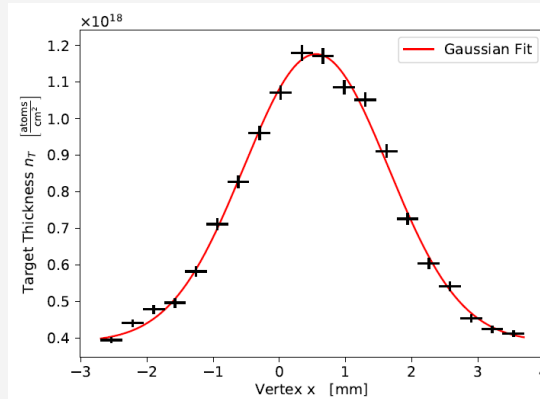
Philipp Brand (UMs)



Gas-Jet Target for MAGIX

Jet nozzle fabrication in Münster

- Numerical simulations on gas expansion in Laval nozzles (e.g., OpenFOAM)
- **Identification of an optimized nozzle design for gas-jet beams**
- Comparison of simulation results with data obtained at MAMI (A1)
 - **Hydrogen target beams**
 - Thickness $\rho > 10^{18}$ atoms/cm²
 - Beam width $\sigma = 1$ mm



Gas-Jet Target for MAGIX: Test Run at MAMI for Proton Radius Measurements

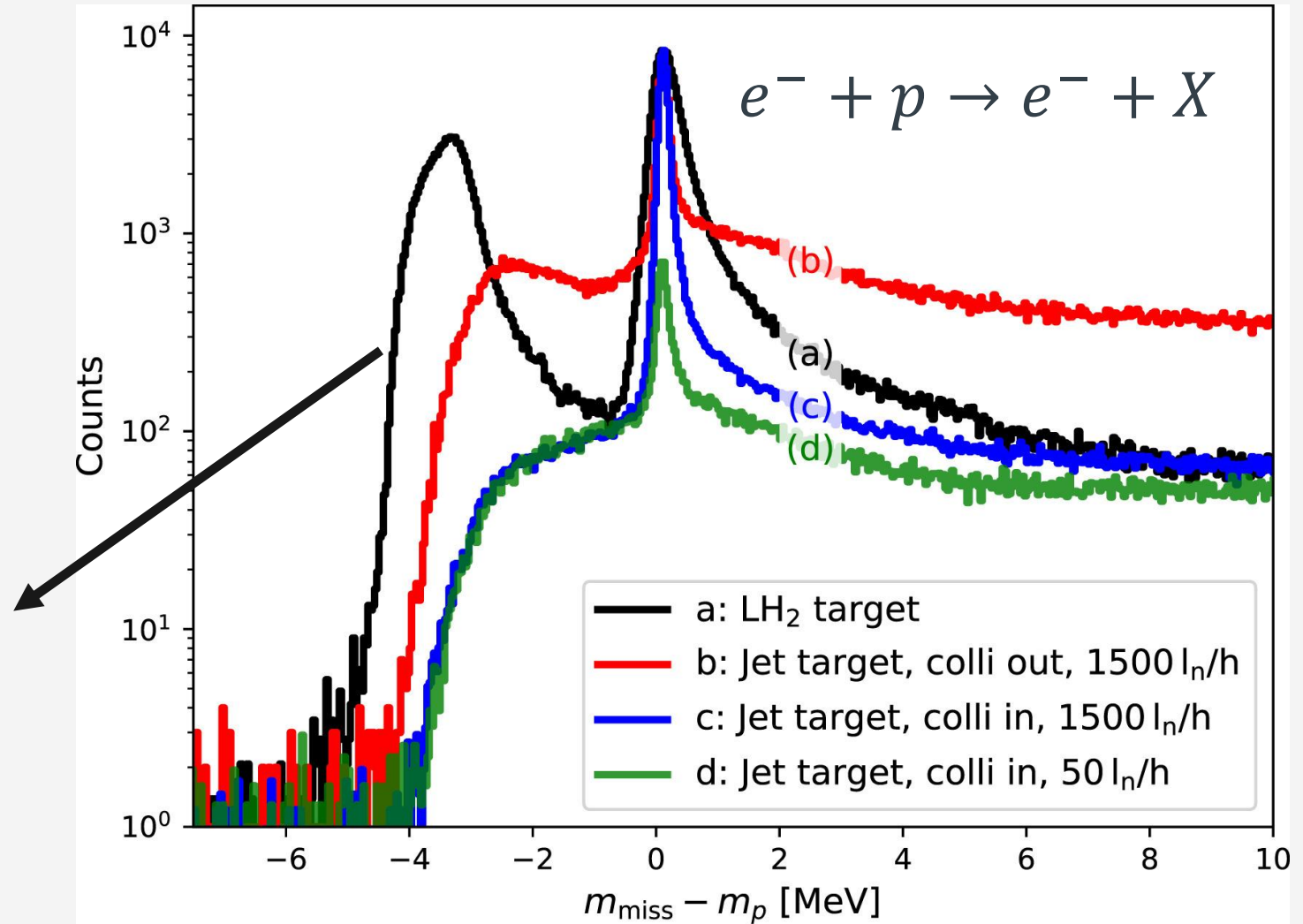
Advantages at MAGIX@MESA

- Access to very low Q^2 values
- Drastically reduced background
- Excellent momentum resolution

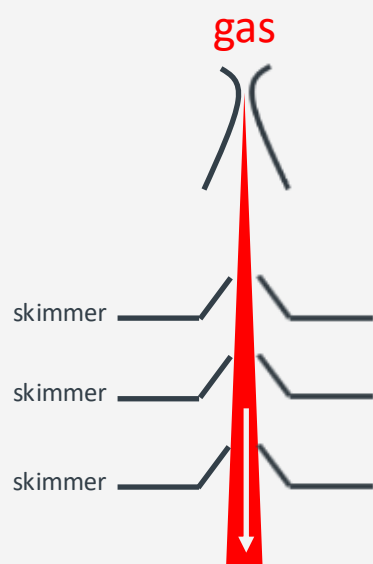
Target Cell used before at MAMI



Thomas Pospischil, 2000 (PhD U Mainz)

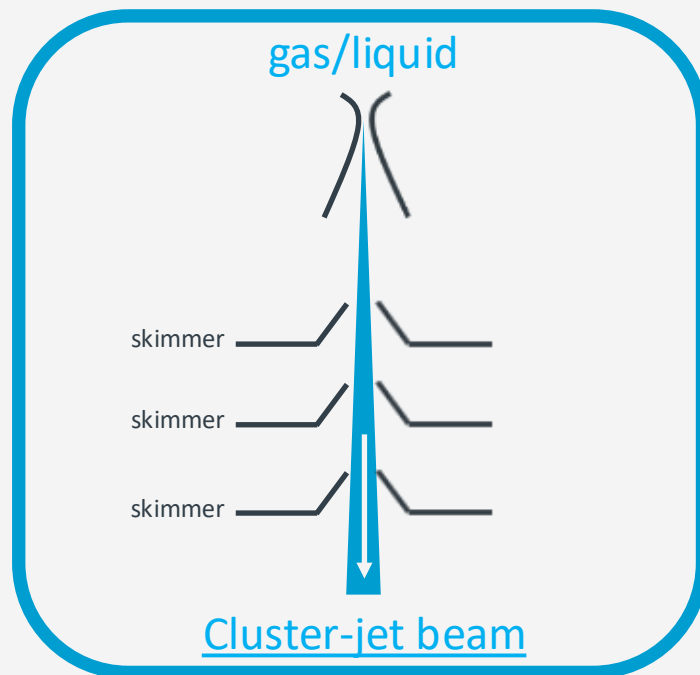


Important Types of Unpolarized Internal Targets



Gas-jet beam

MAGIX target (test runs at MAMI/Mainz)



Cluster-jet beam

COSY-11 target (finished)

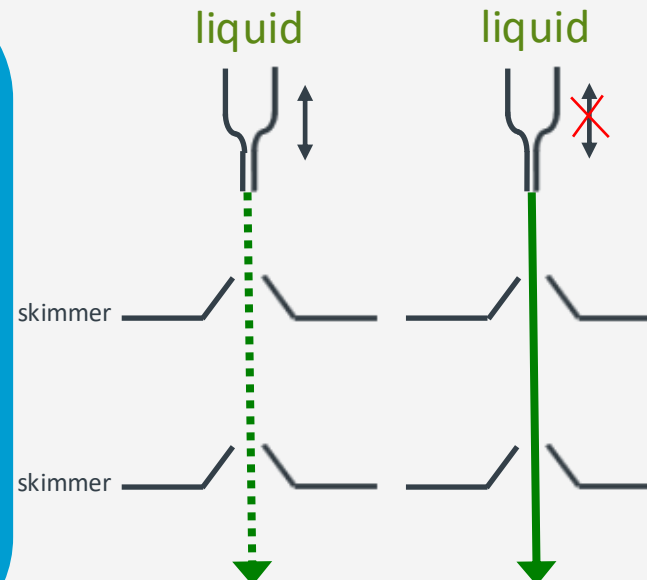
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Prototype target (in operation at Münster)

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KOALA target (in design phase)



Pellet beam

Filament beam

Prototype target (in operation at Münster)

MAGIX target (test runs at MAMI/Mainz)

Münster
target
devices

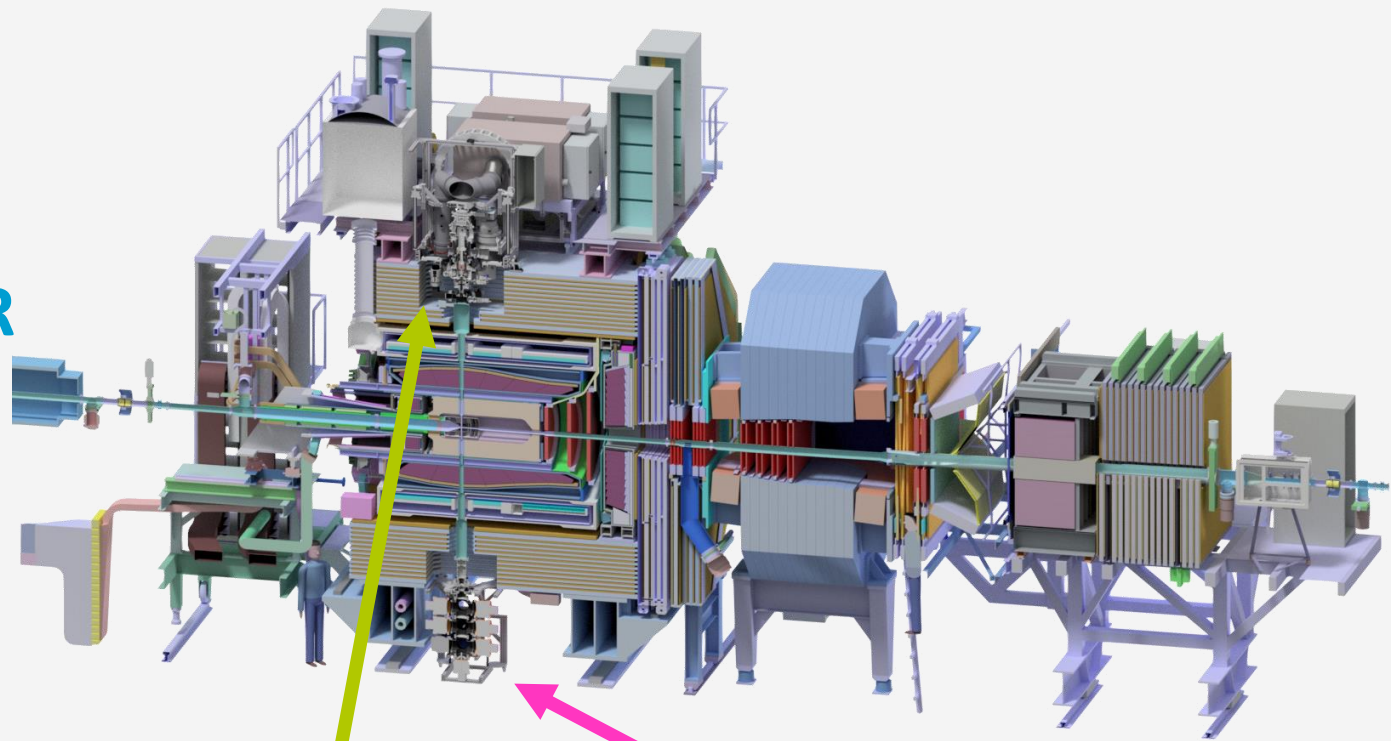
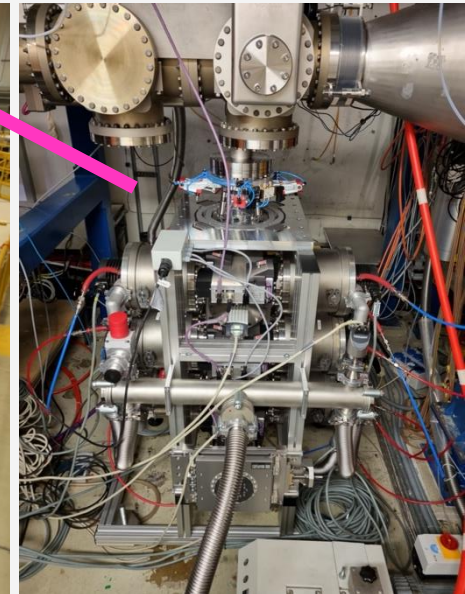
Cluster-Jet Target for PANDA at FAIR

PANDA at HESR:

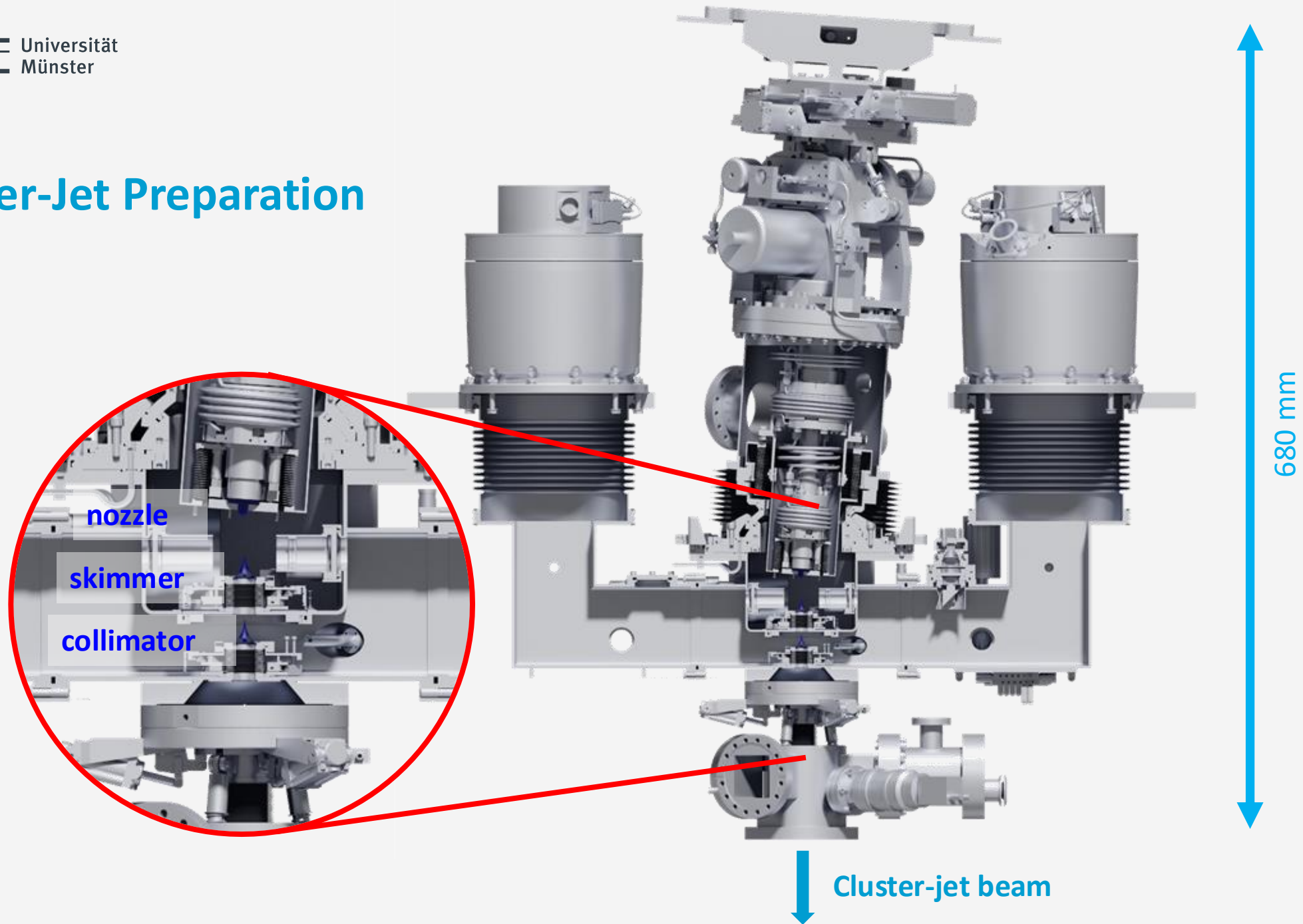
- Broad planned hadron physics program using antiproton beams with $p = 1.5 - 15 \text{ GeV}/c$
- Cluster-jet target for all types of gases: H_2 , D_2 , ...
- Luminosity up to $L = 2 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$
- Interaction point: **> 2 m behind the jet nozzle !!!**

Status PANDA cluster-jet target:

- Ready and routinely in operation (now: at COSY)
- Achieved target thickness: $2 \times 10^{15} \text{ atoms/cm}^2$ (H_2)



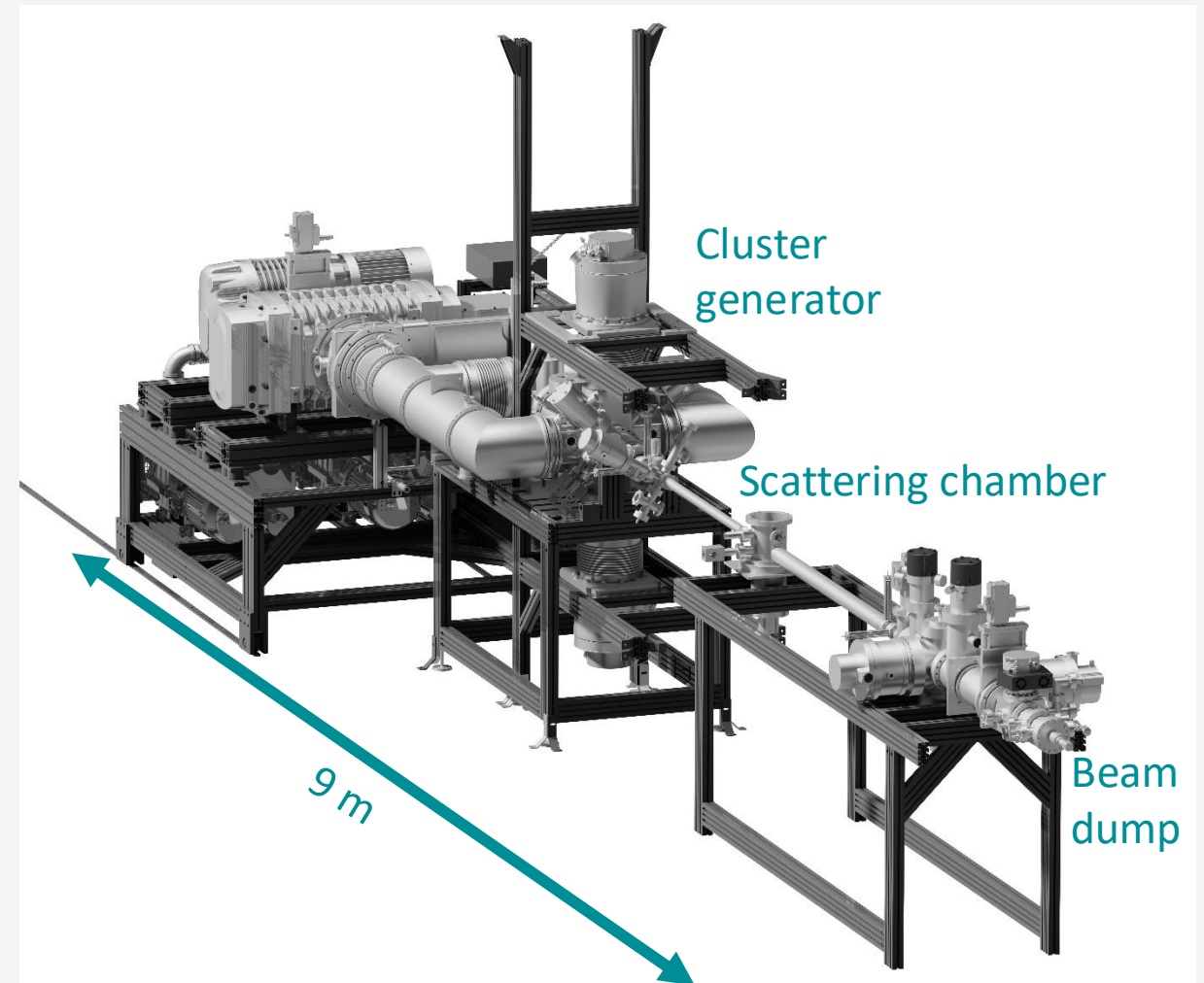
Cluster-Jet Preparation



PANDA Prototype Target

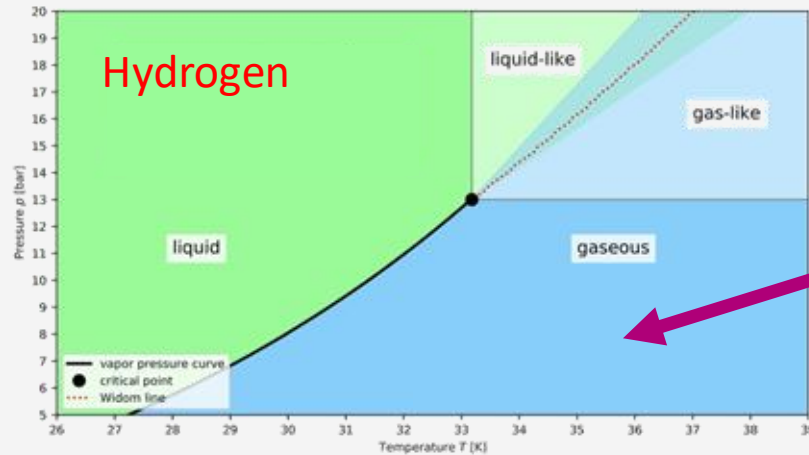
Prototype target in close to PANDA geometry

- Development and test of new PANDA target components
- Studies on cluster production
 - **Cluster properties (size, velocity, thickness, ...)**
- Development of new target technologies
 - **Diagnostic tools**
 - **Nozzle developments**
 - **Physics experiments (e.g., studies on Widom line)**



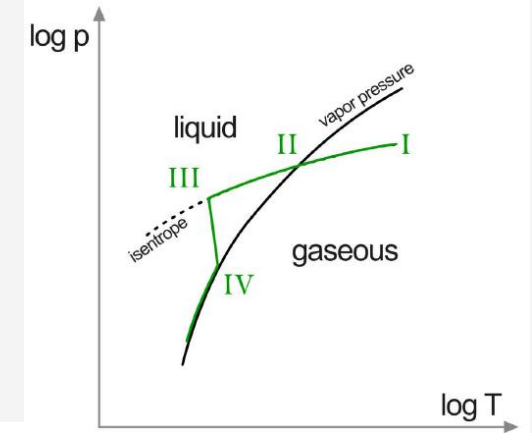
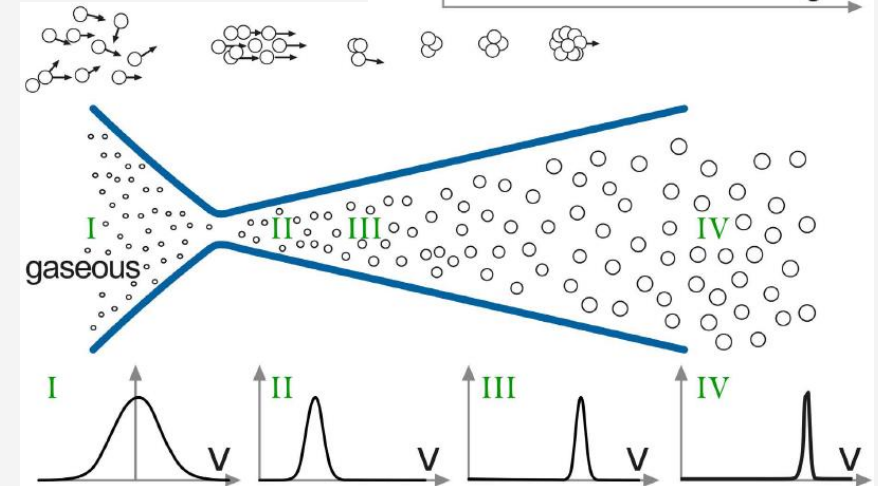
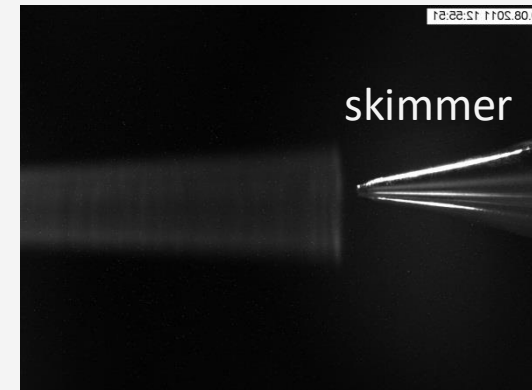
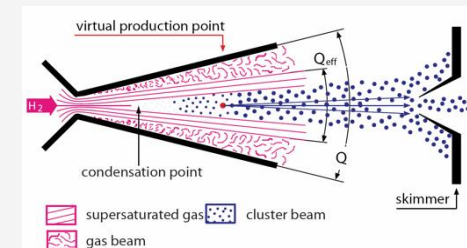
Production of Cluster-Jet Beams

- Typically, cluster-jet targets operate with gaseous phase



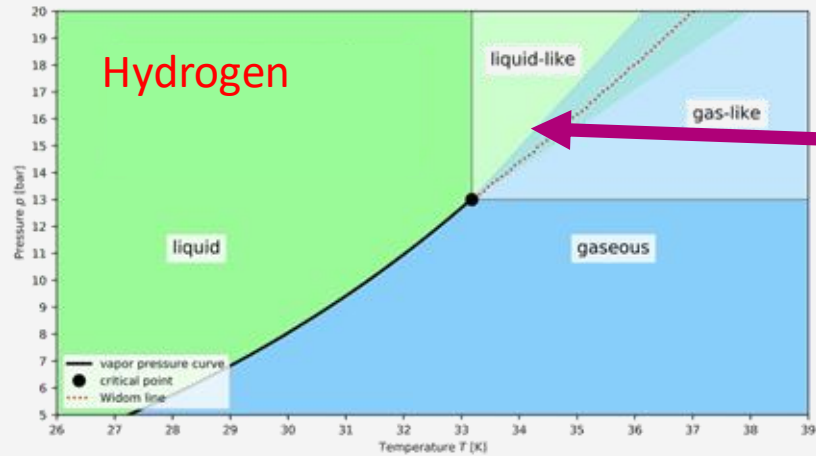
- Small clusters ($\ll 1\mu\text{m}$)
- Sharp velocity distribution (see gas beams)
- „Low“ target thickness, e.g., 10^{13} - 10^{14} atoms/cm² at 1 m

Sophia Vestrick (UM)

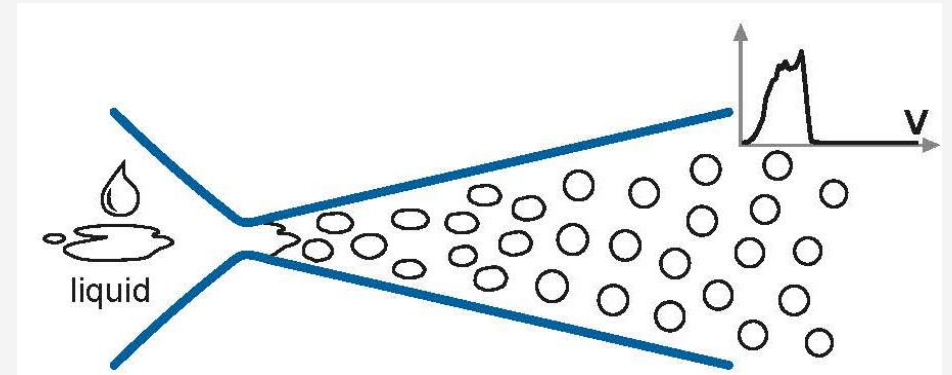
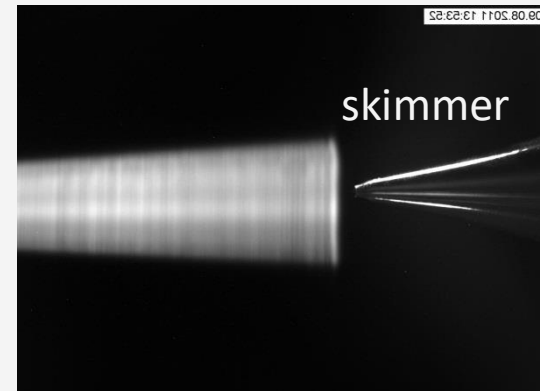


Production of Cluster-Jet Beams

- **But:** Why not operating them at the liquid phase?

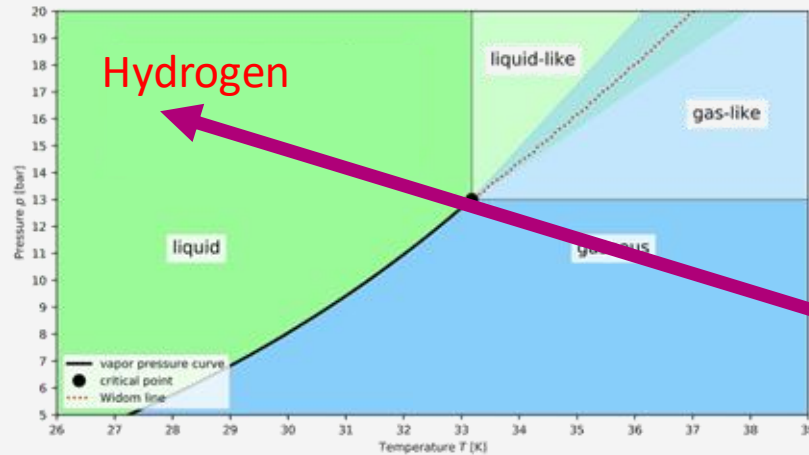


- Larger target particles (nm - μm)
- Broad velocity distribution $\rightarrow$ atomization of the liquid

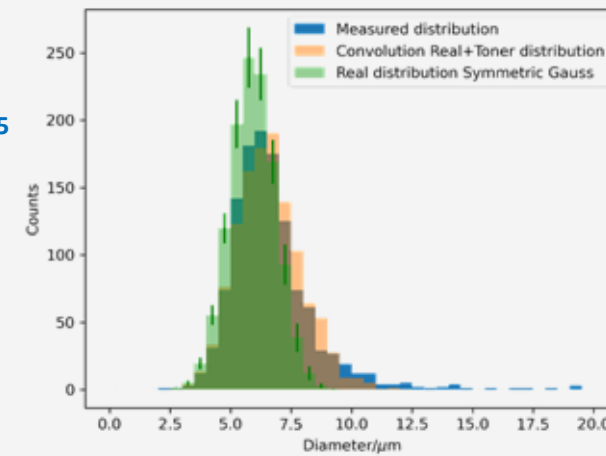
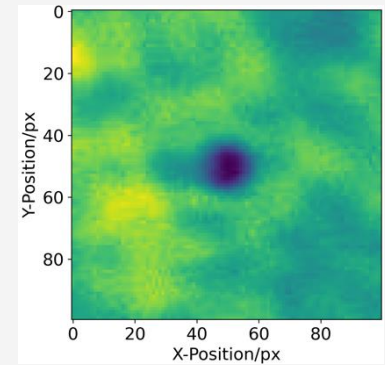


Production of Cluster-Jet Beams

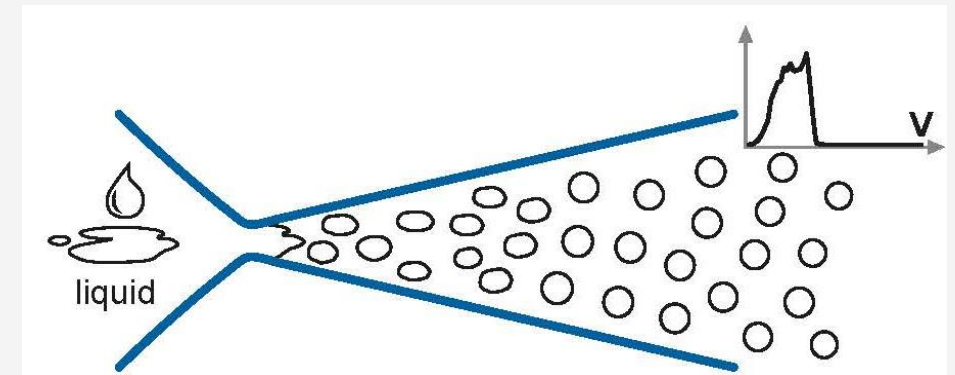
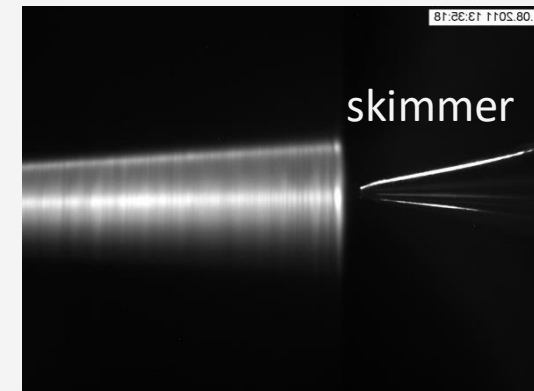
- **But:** Why not operating them at the liquid phase?



- Larger target particles (nm - μm)
- Broad velocity distribution $\rightarrow$ atomization of the liquid
- High target thickness of, e.g., $2 \cdot 10^{15}$ atoms/cm² at 2 m

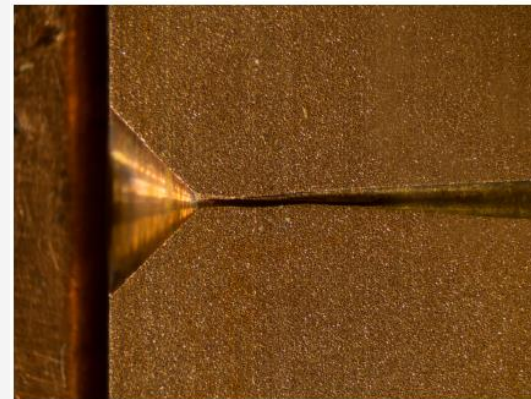
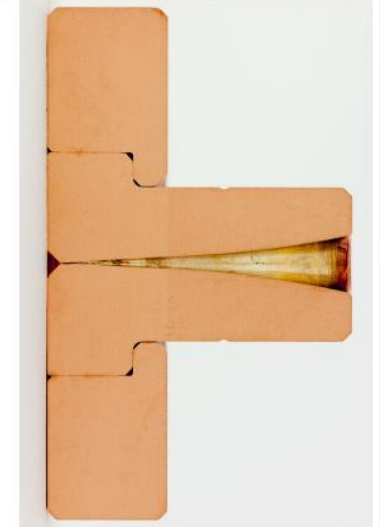


Laser pulse length: 30 fs



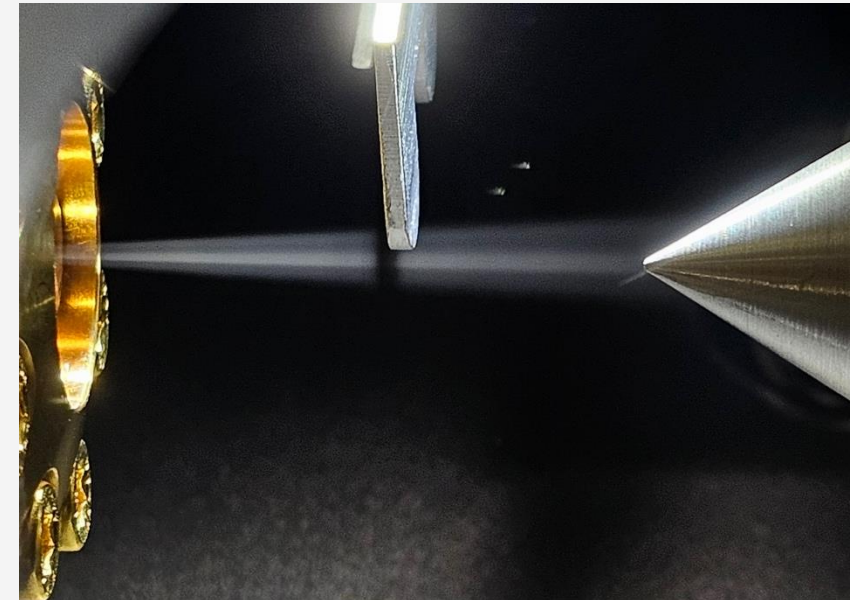
Laval Nozzle Production at Münster

- Convergent-divergent nozzle shape
- Narrowest inner diameter e.g. $\approx 30 \mu\text{m}$, total length of 18 mm (i.e., $l=600 \cdot d$)
- Multi-step production process (completely in-house):
 - **Galvanize nozzle outlet negative**
 - **Lathe outer geometry**
 - **Drill convergent inlet**
 - **Drill narrowest diameter in multiple steps**
 - **Remove outlet negative chemically**



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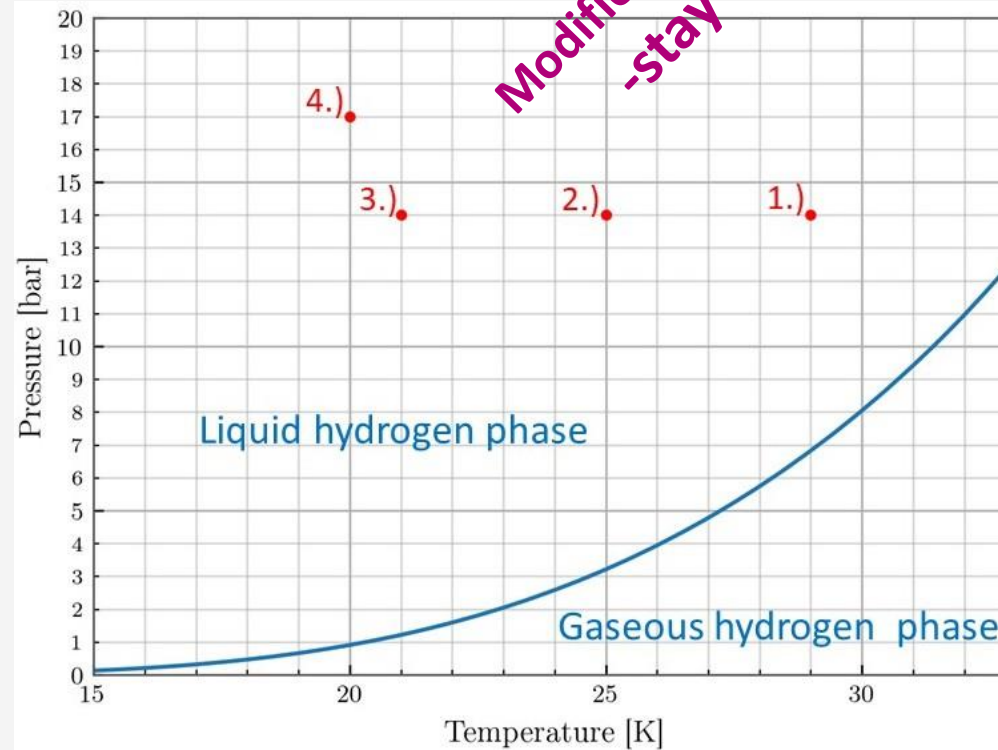
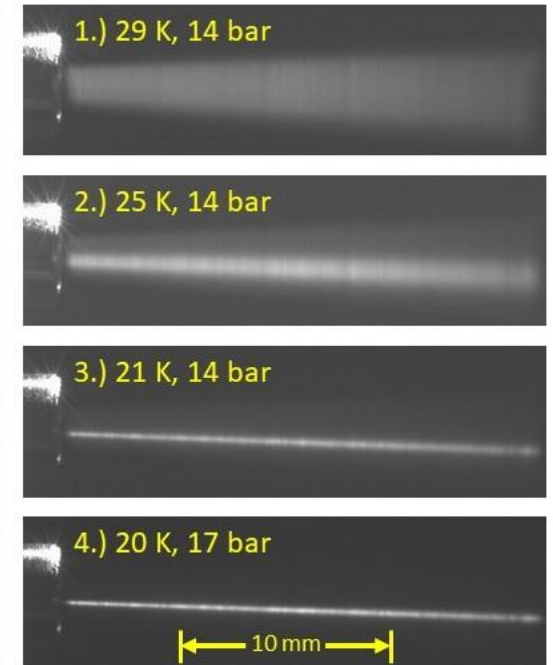


New Nozzle Design

The all-rounder for

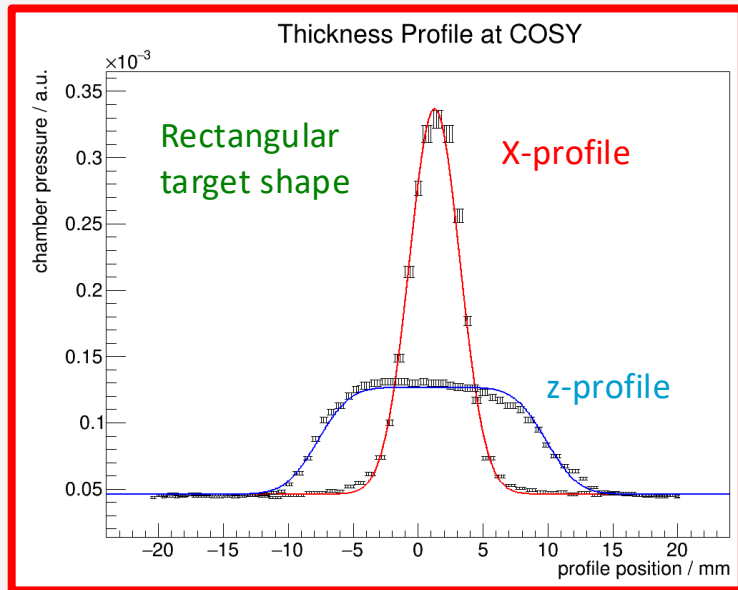
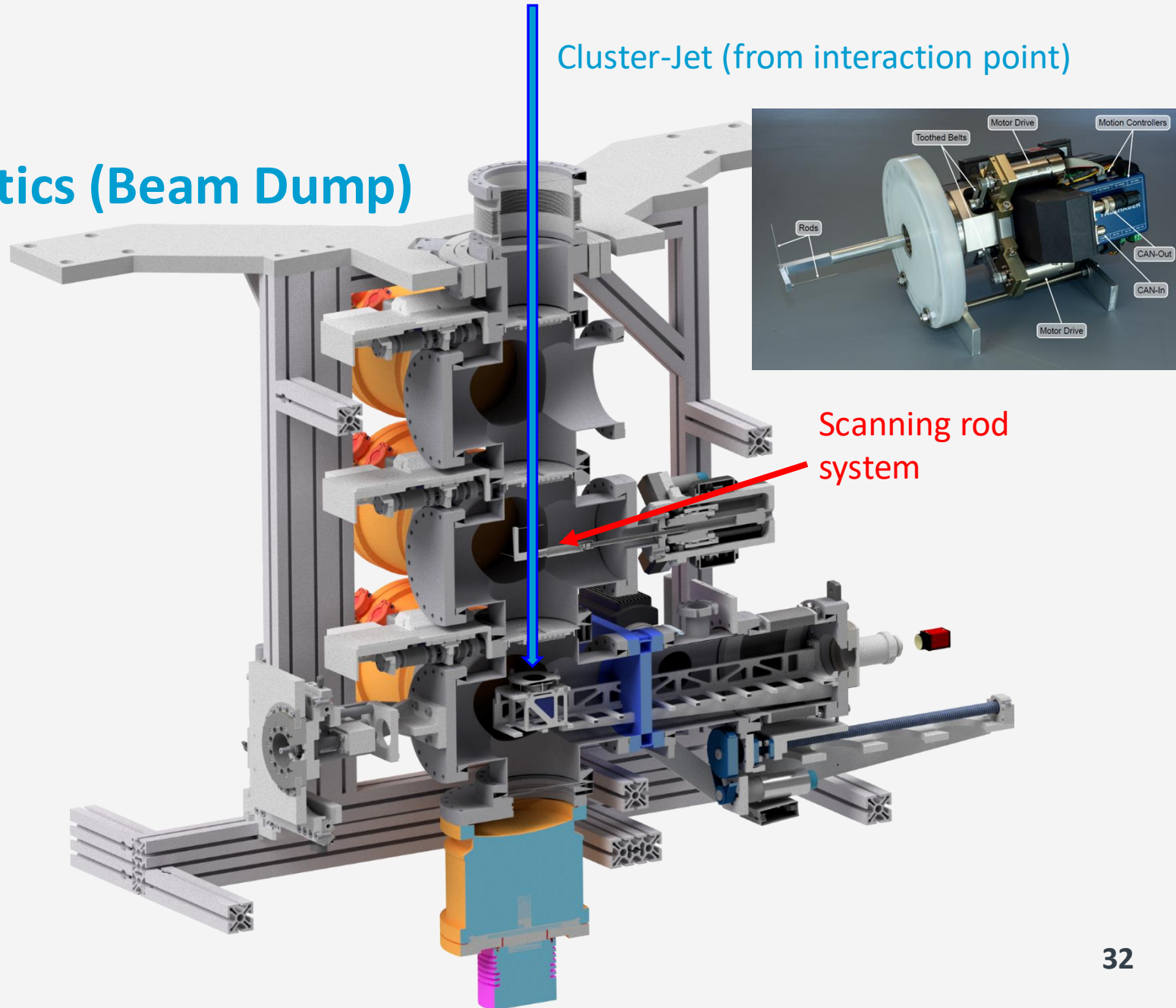
- Gas-jets,
- Cluster-jets
 - **record thickness:**
 $\sim 10^{16}$ atoms/cm² at ~ 2 m
behind the nozzle
- Droplets/pellets
- and probably also frozen filaments

NEW
Modified nozzle design
-stay tuned-



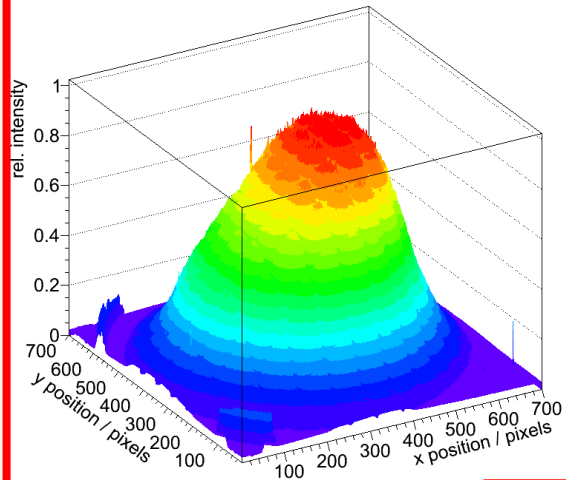
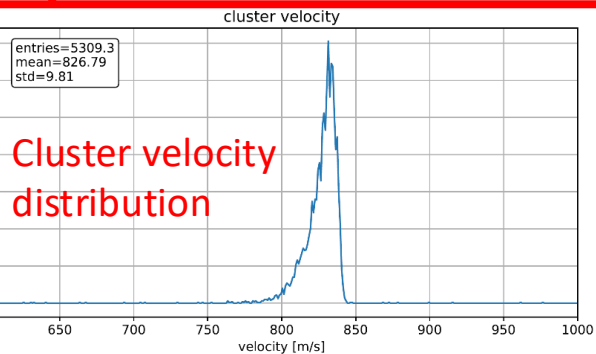
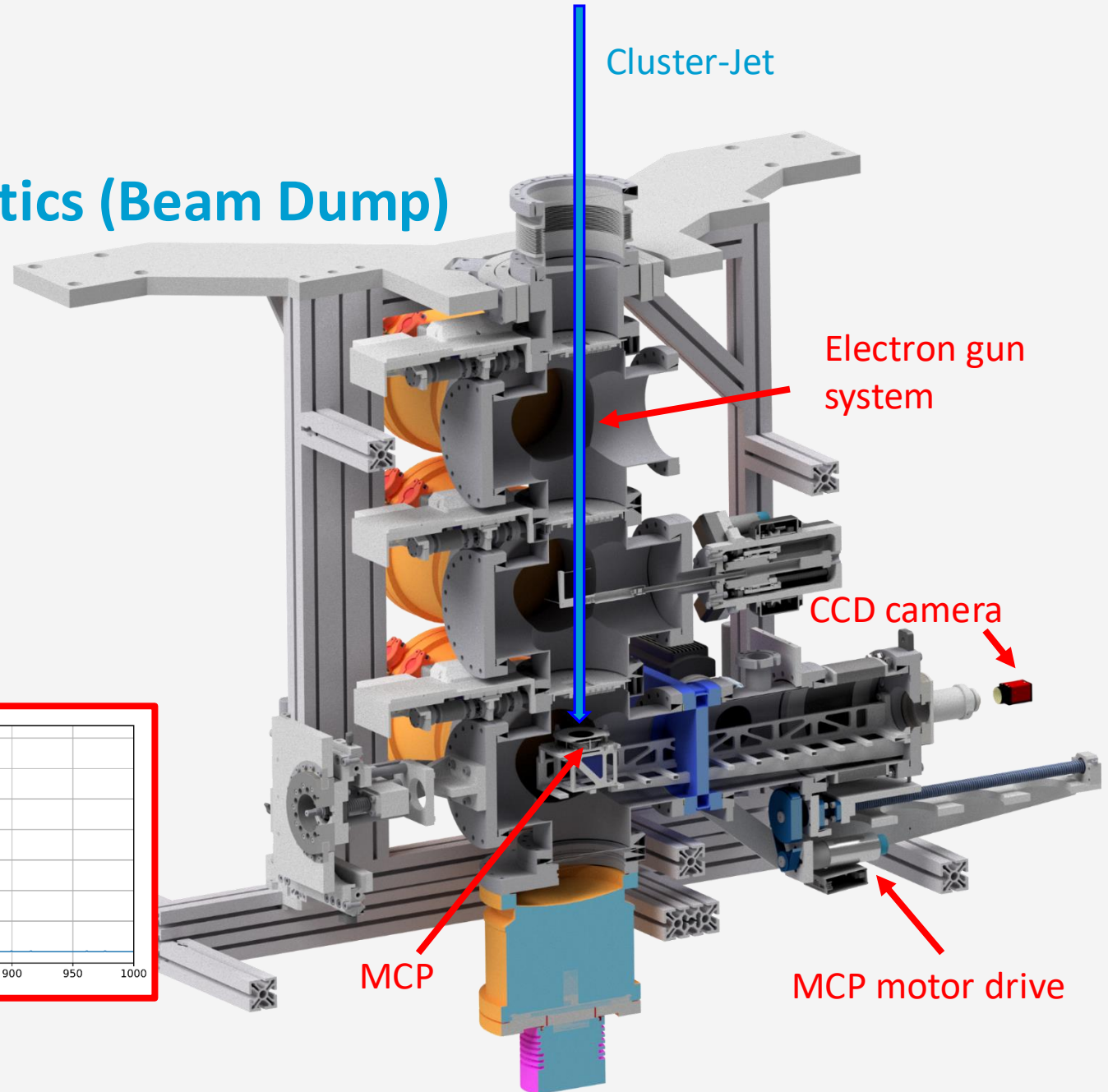
Michael Weide (UMs)

PANDA Cluster Beam Diagnostics (Beam Dump)



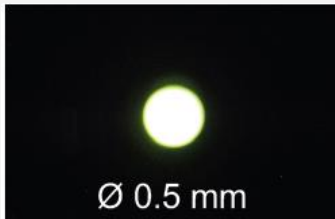
PANDA Cluster Beam Diagnostics (Beam Dump)

Thickness distribution

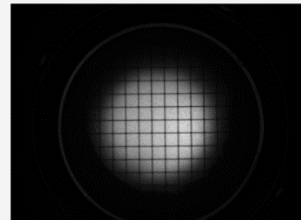
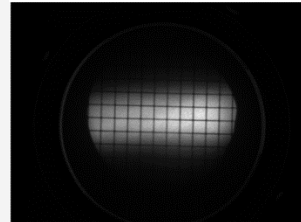
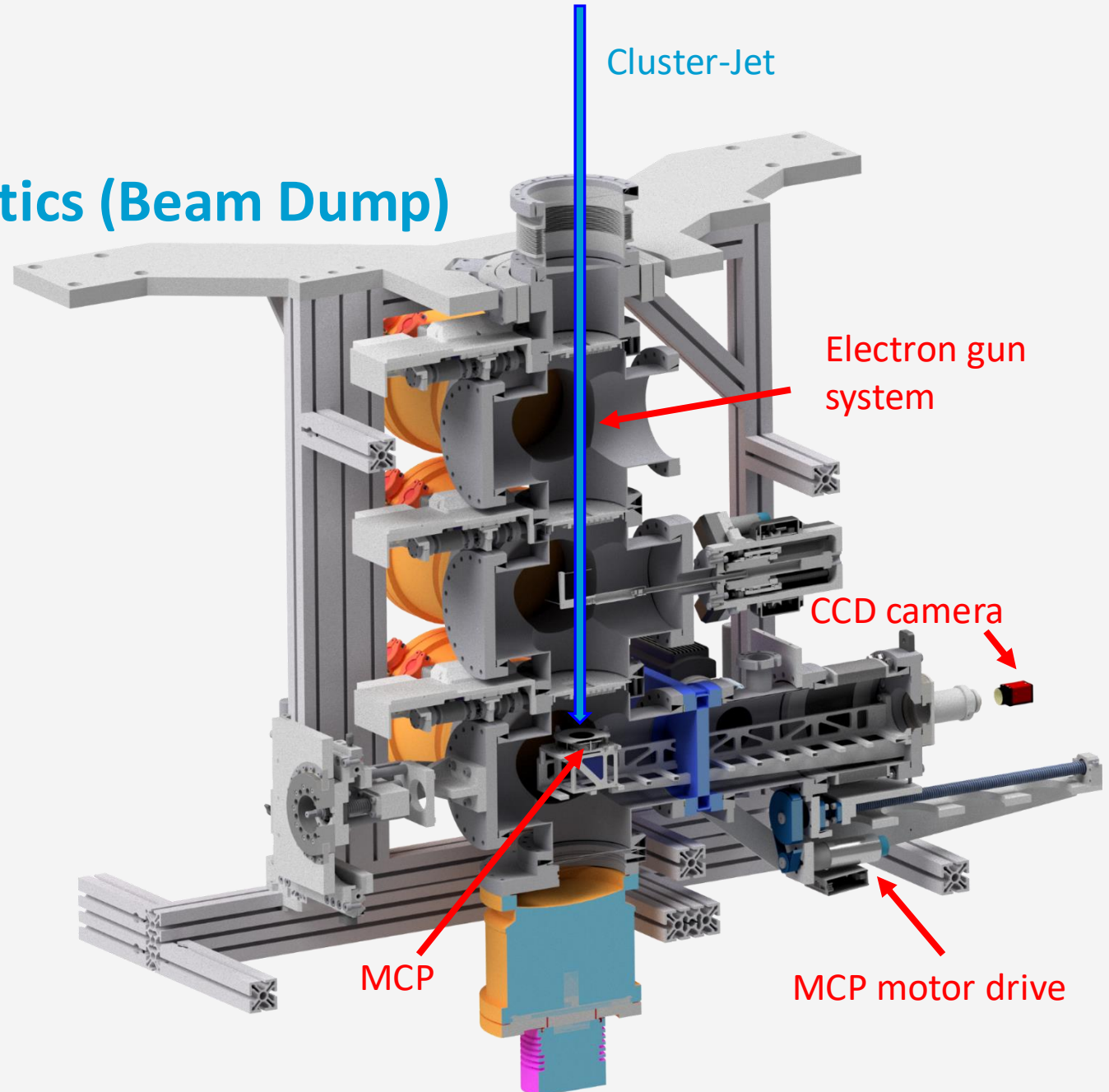


PANDA Cluster Beam Diagnostics (Beam Dump)

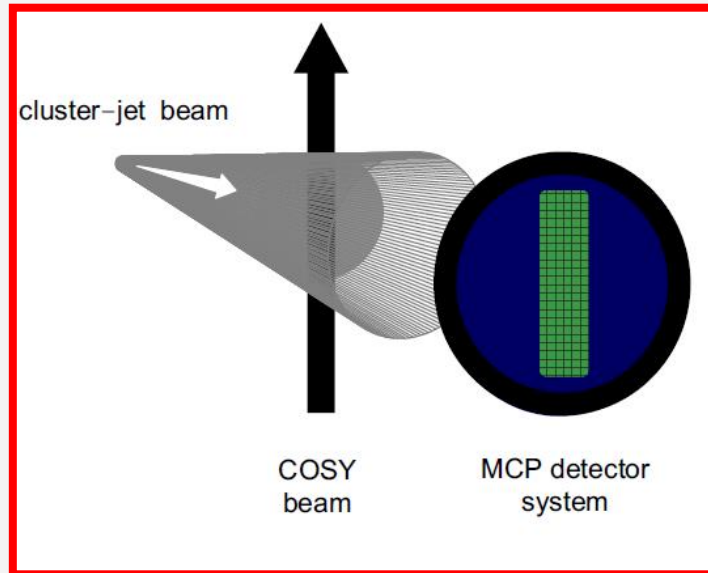
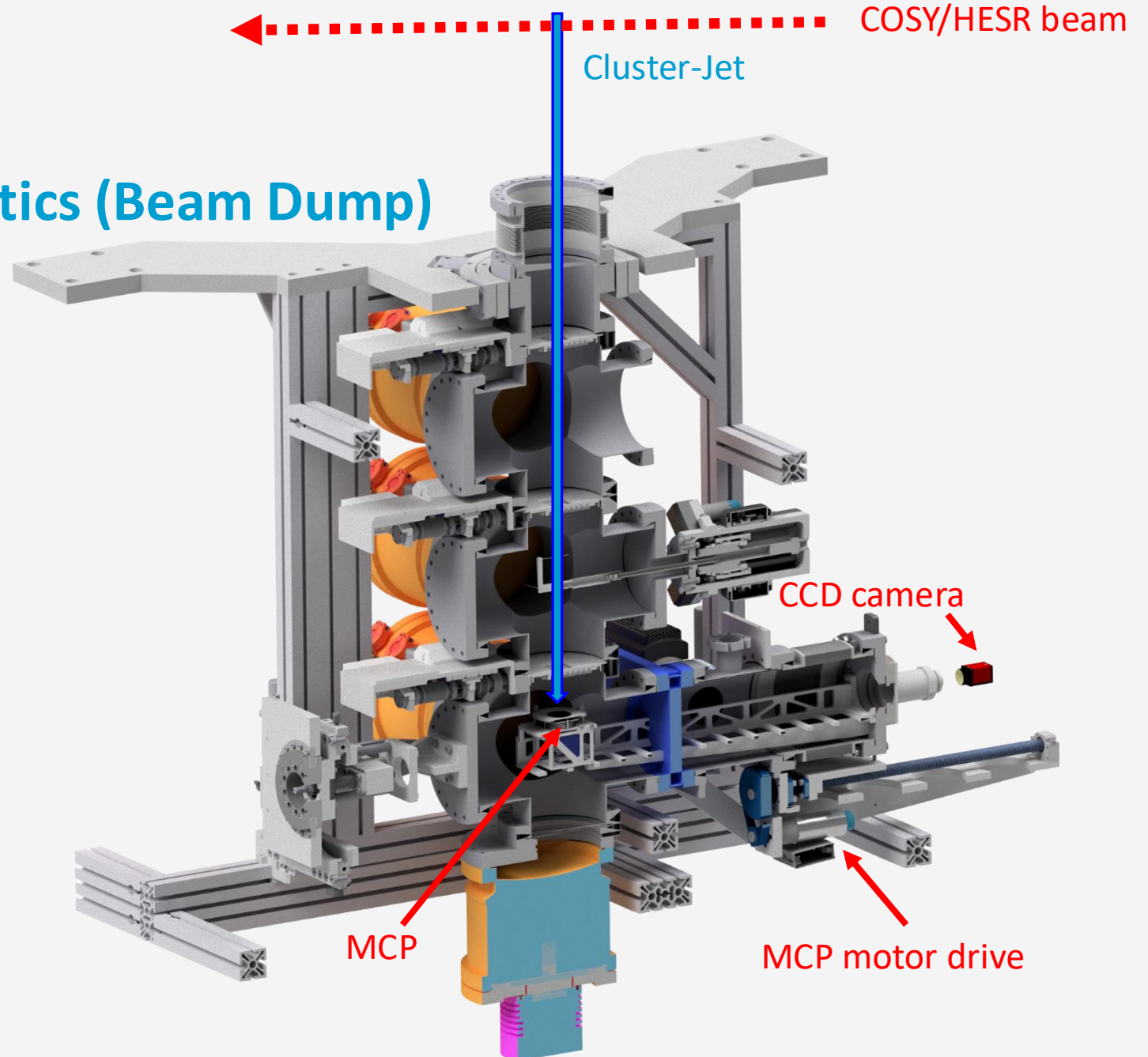
Collimator,
installed shortly
behind the nozzle



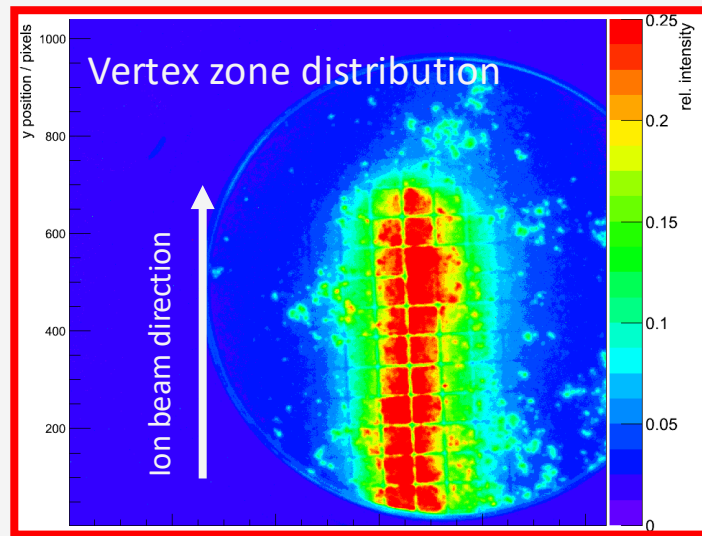
MCP picture in the
beam dump after
5 m!!!



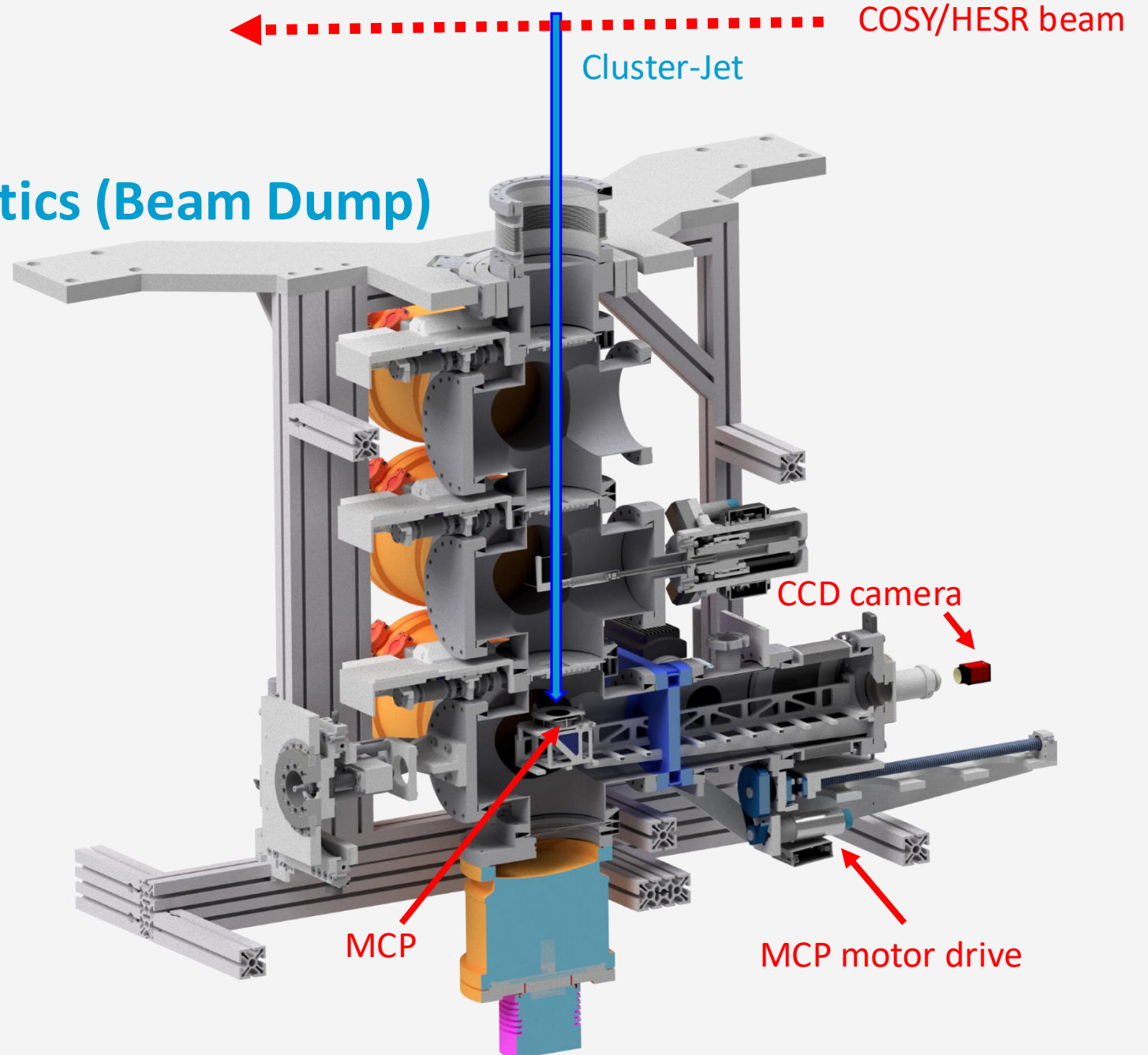
PANDA Cluster Beam Diagnostics (Beam Dump)



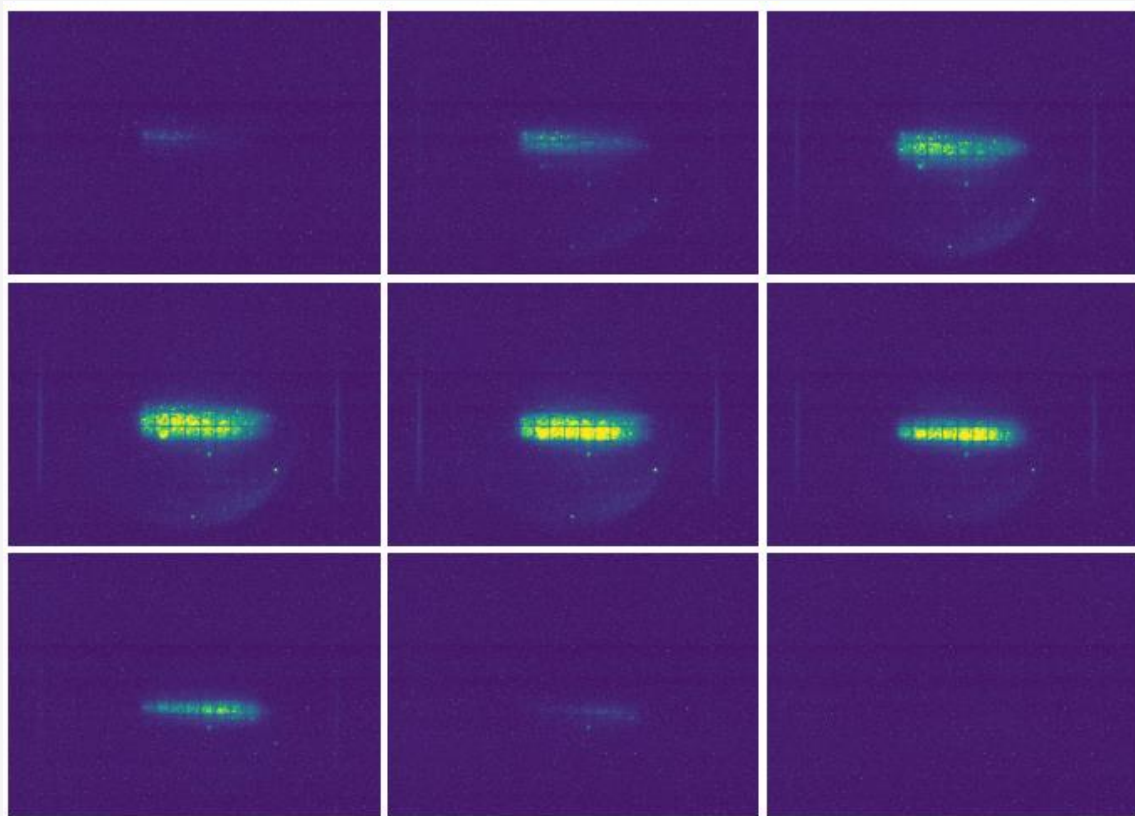
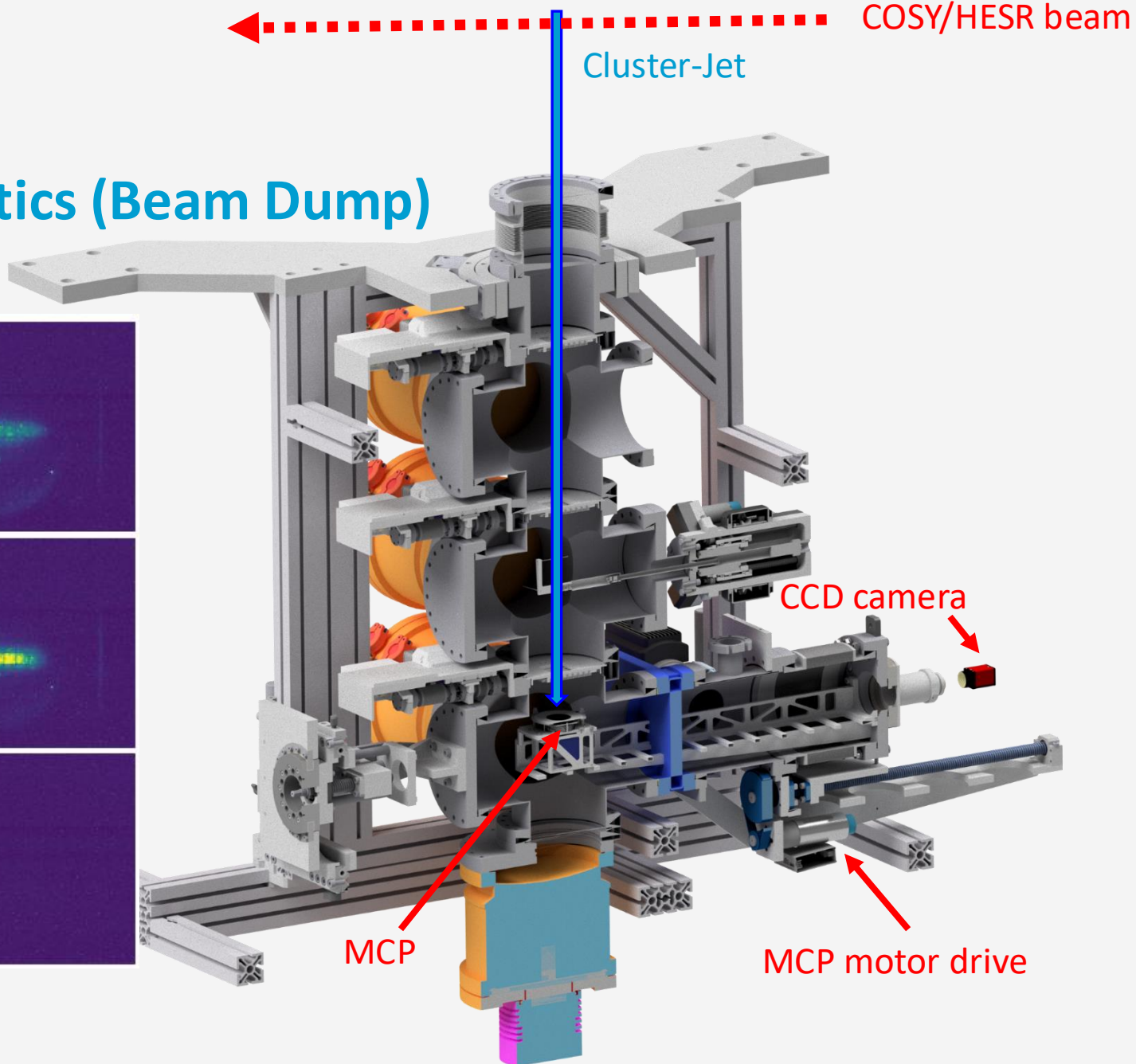
PANDA Cluster Beam Diagnostics (Beam Dump)



AK et al., NIM A 735 (2014) 12-18

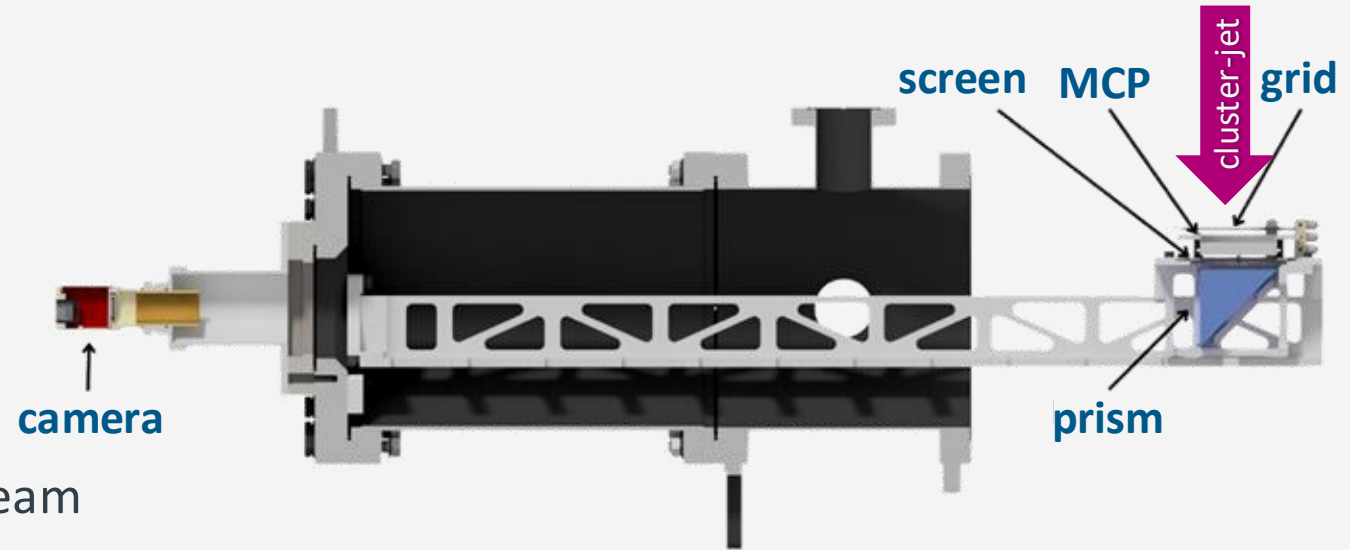
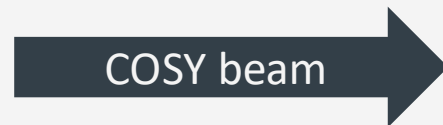
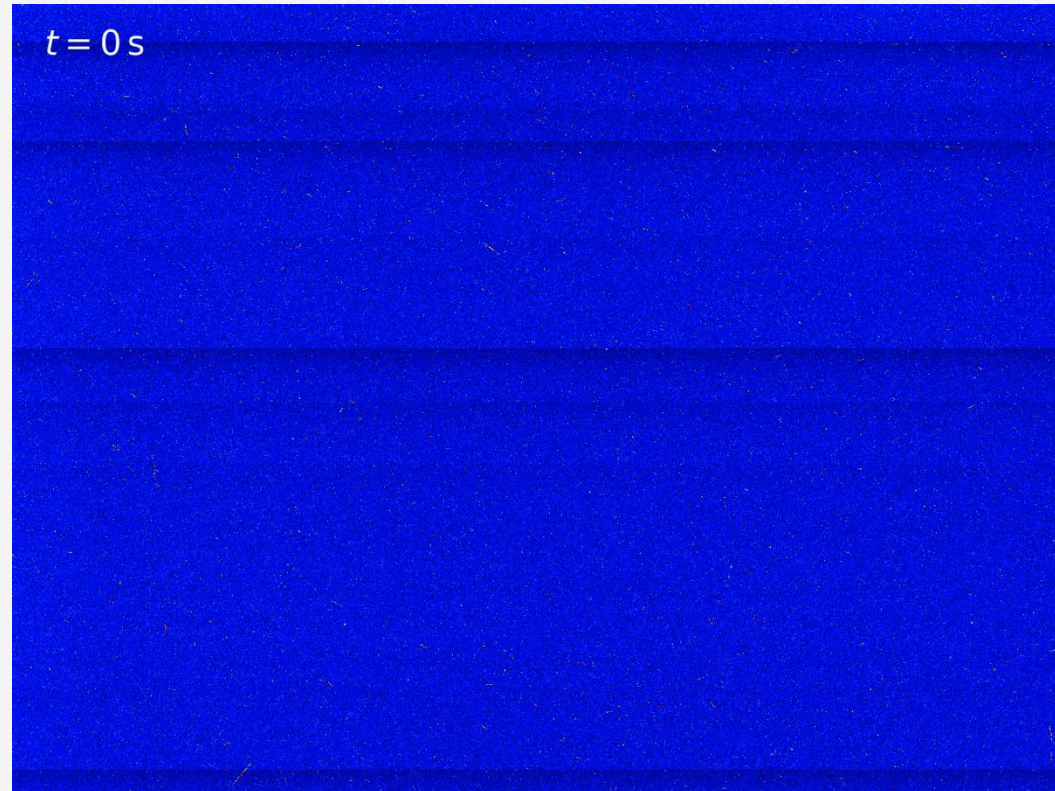


PANDA Cluster Beam Diagnostics (Beam Dump)



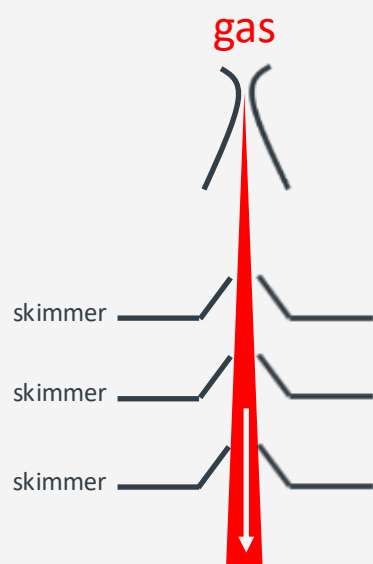
IP Observation in Realtime

- Visualization of an ionized cluster beam
- Ionization of the clusters by accelerator beam (here: COSY) while sweeping over the target



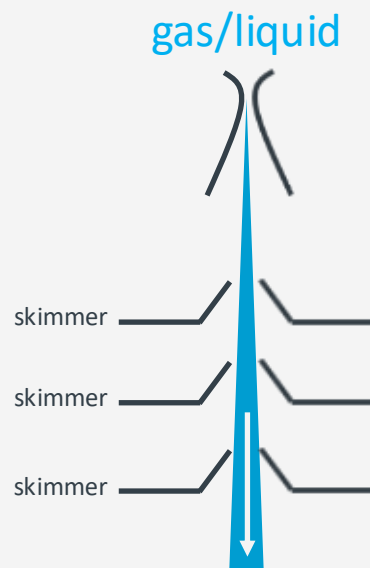
Video:
 Cluster-jet beam
 moves out of
 the plane

Important Types of Unpolarized Internal Targets



Gas-jet beam

MAGIX target (test runs at MAMI/Mainz)



Cluster-jet beam

COSY-11 target (finished)

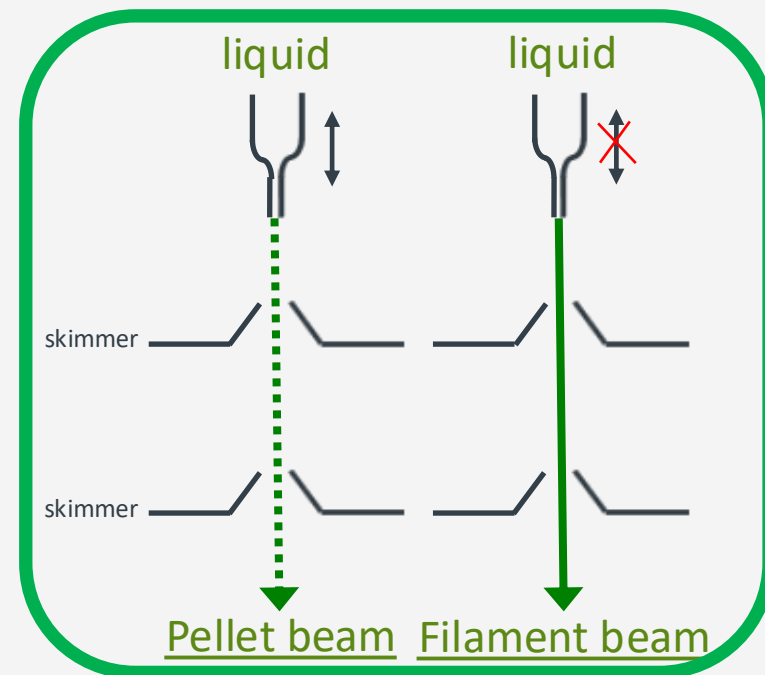
ANKE target (finished)

Prototype target (in operation at Münster)

PANDA target (in operation at COSY)

CryoFlash target (ARCTURUS laser, finished)

KOALA target (in design phase)



Pellet beam Filament beam

Prototype target (in operation at Münster)

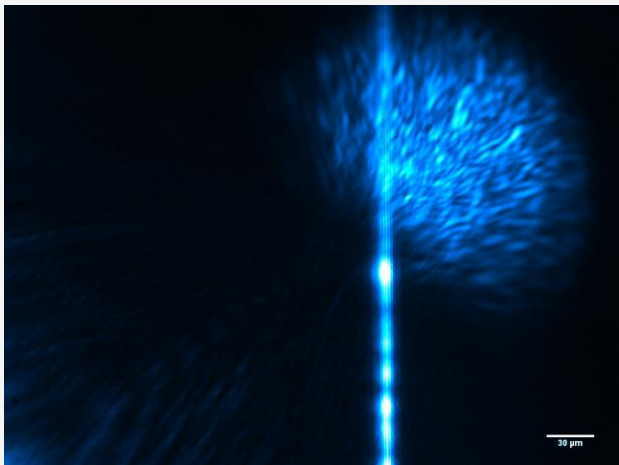
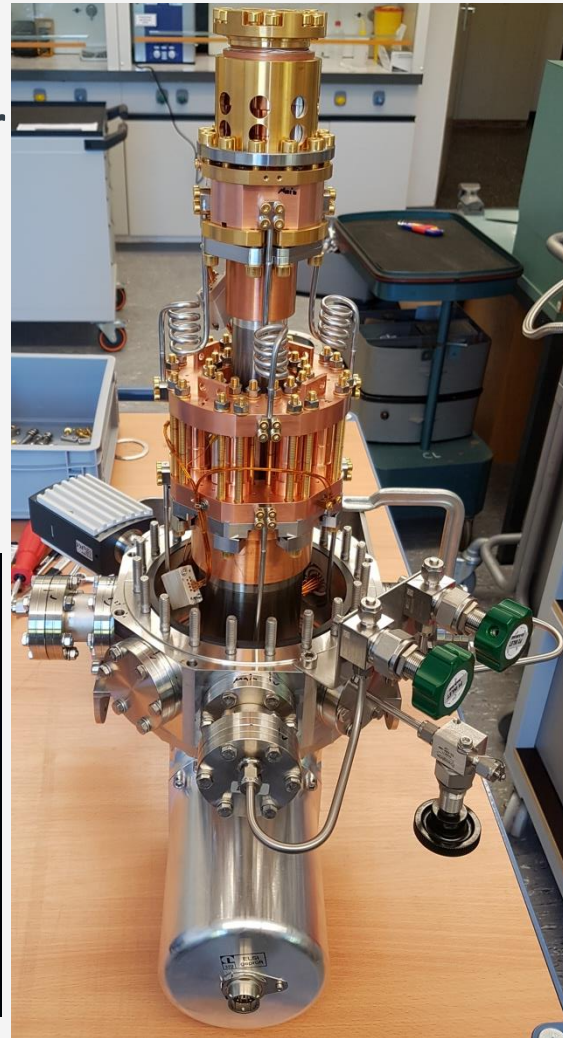
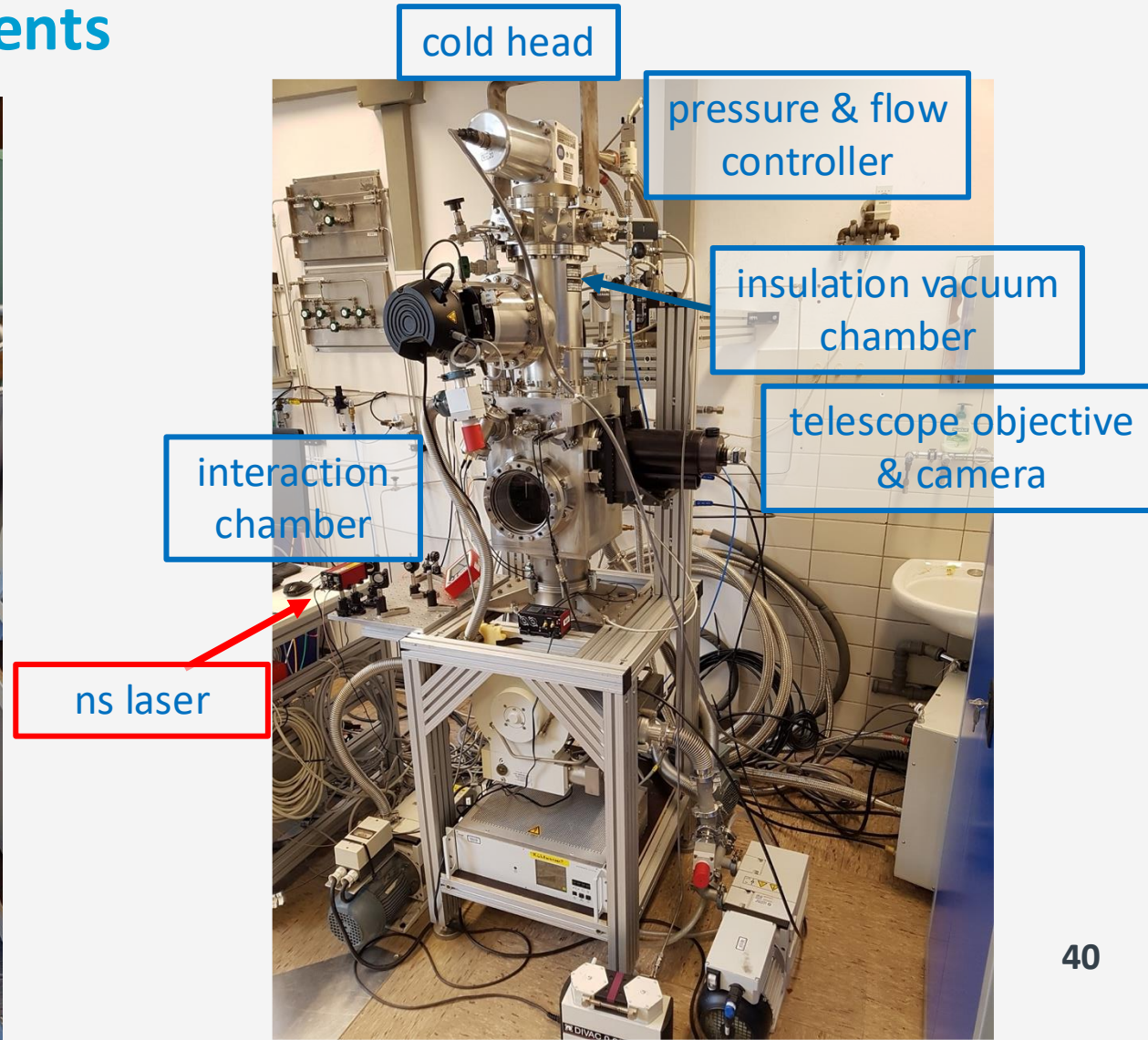
MAGIX target (test runs at MAMI/Mainz)

Münster
target
devices

Droplet/Pellet Target and Frozen Filaments

New target setup at Münster

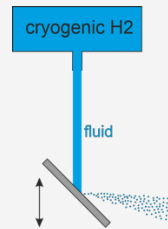
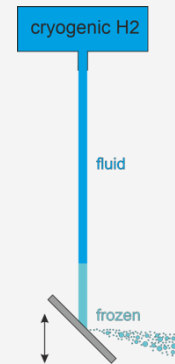
- Generation of droplets, pellets and frozen hydrogen fibers



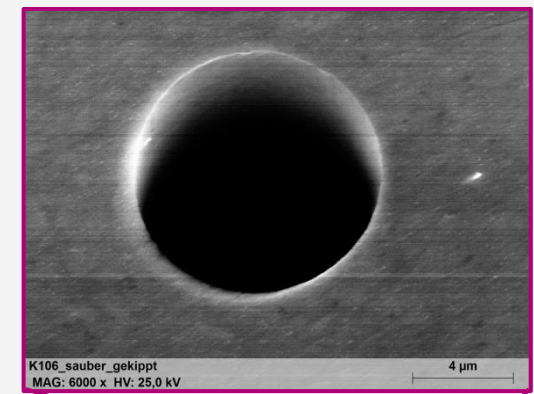
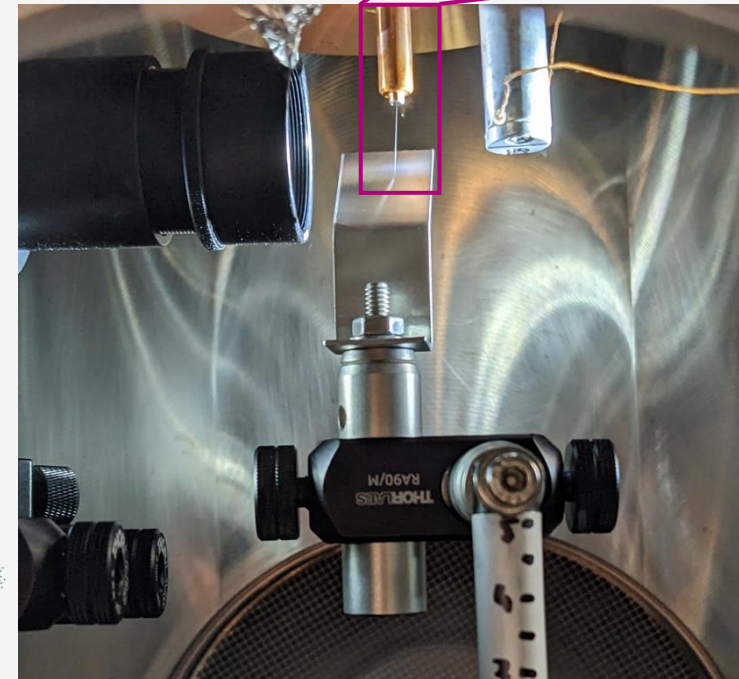
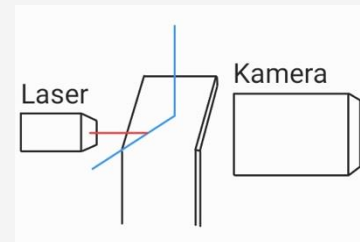
Droplet/Pellet Beam Studies

Preparation and test of new droplet/filament generator at Münster

- Optimized setup with improved heat exchanger design
- Hydrogen filament target now routinely in operation
- Stable beam in 100 h continuous operation
- Excellent beam quality achieved
- Studies on freeze-out of hydrogen jets
- Study droplet beam reflections at different distances from the droplet nozzle



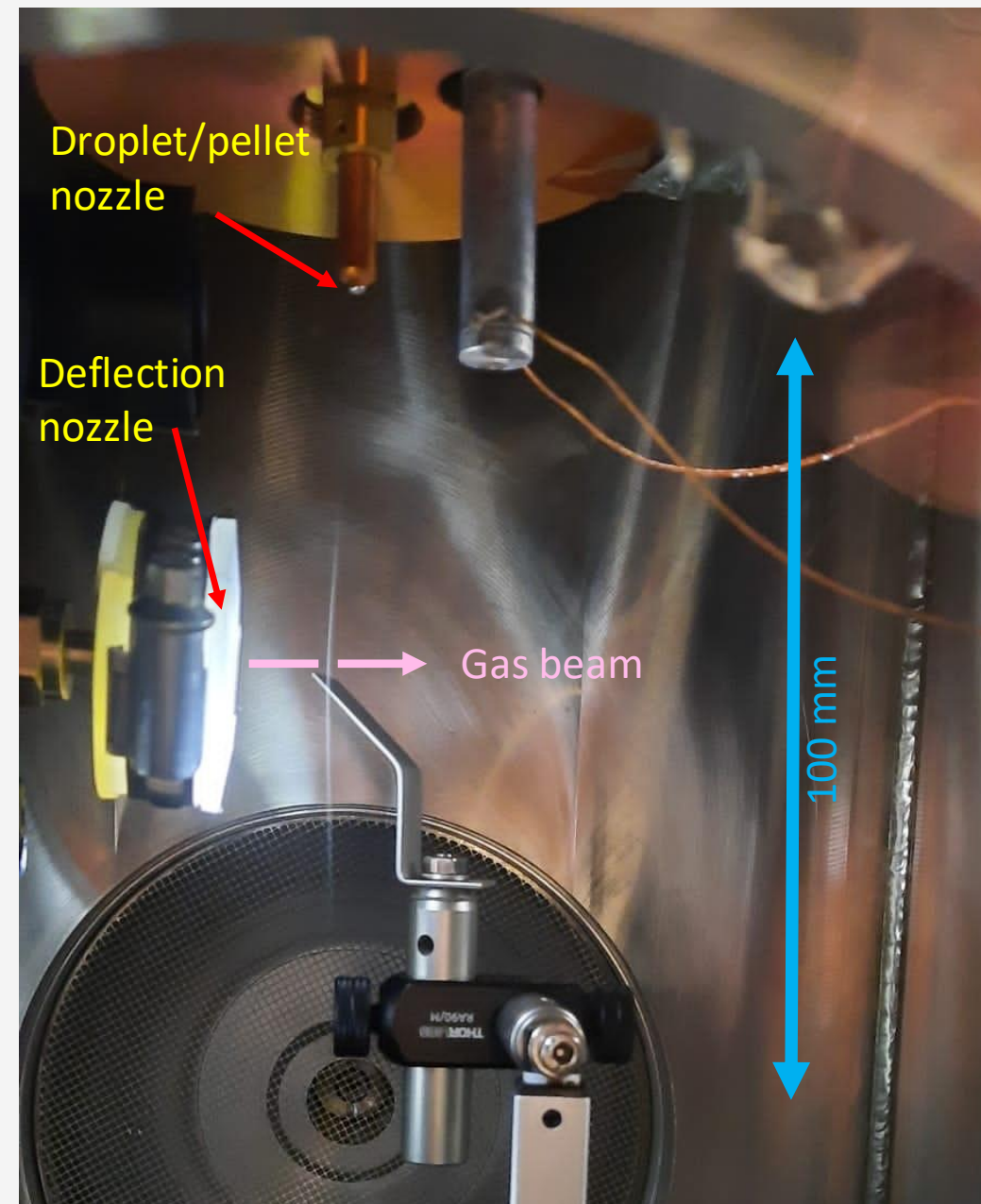
Nozzle opening:
10 μm



Start of Extensive Experimental Program

Studies on jet properties and freeze-out position

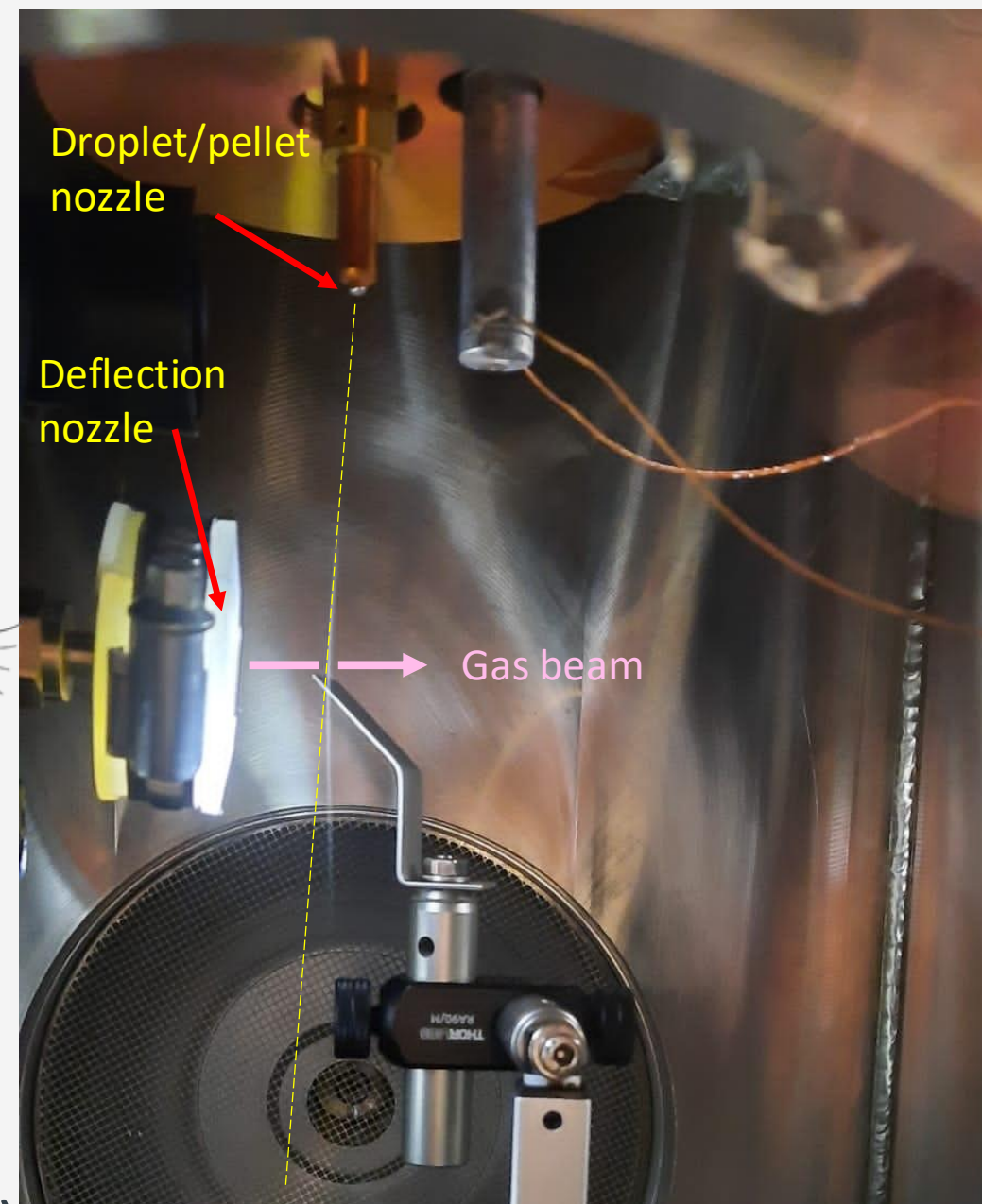
- Process gas: Hydrogen
- Nozzle diameter(s) = **10 μm** & 20 μm
- Liquid/frozen hydrogen filament with high local thickness ($\text{O}(10^{19} \text{ atoms/cm}^2)$) (also at large distances from the nozzle)
- Possible application: PANDA, MAGIX, ...



Start of Extensive Experimental Program

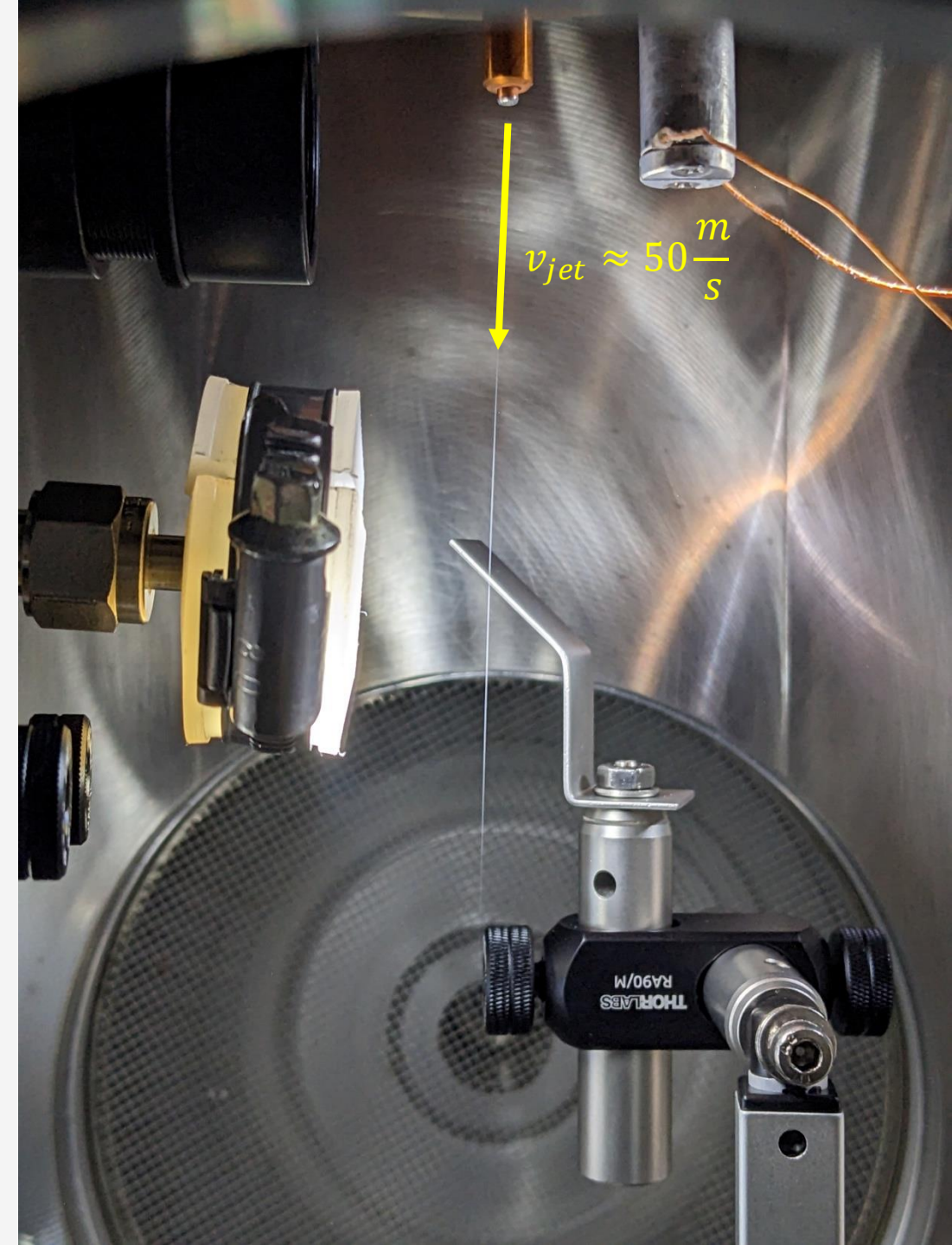
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- Liquid/frozen hydrogen filament with high local thickness ($\text{O}(10^{19} \text{ atoms/cm}^2)$) (also at large distances from the nozzle)
- **Possible application: PANDA, MAGIX, ...**
- Deflection in real-time easily possible by transversal gas jet
- **Highly interesting for IP at large distances, e.g. several meters from the nozzle (large 4π experiments)**



Real-time Jet Beam Adjustment

He pressure at deflection nozzle (100 μm diameter): 0 bar



Real-time Jet Beam Adjustment

He pressure at deflection nozzle (100 μm diameter): 1 bar



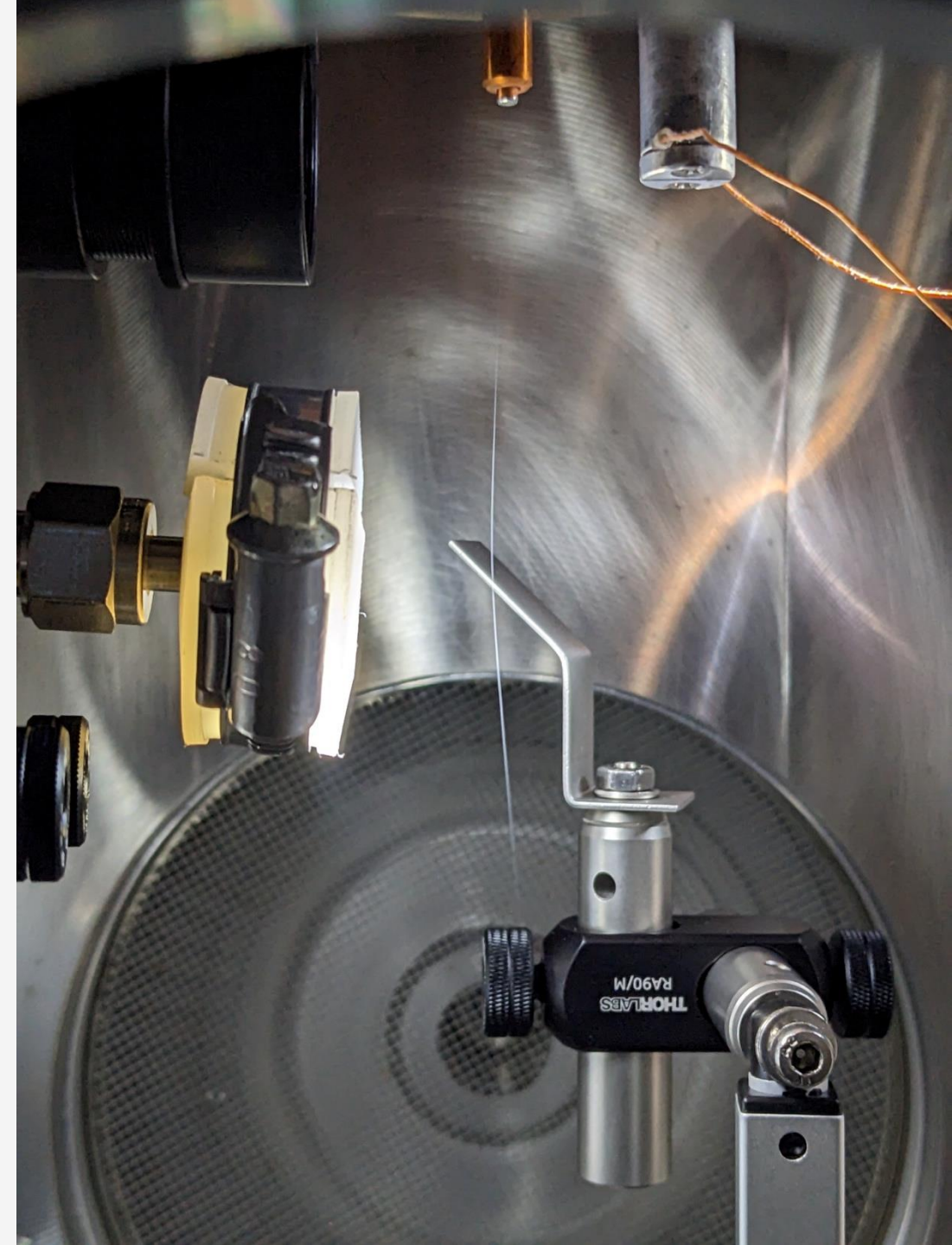
Real-time Jet Beam Adjustment

He pressure at deflection nozzle (100 μm diameter): 2 bar



Real-time Jet Beam Adjustment

He pressure at deflection nozzle (100 μm diameter): 3 bar



Real-time Jet Beam Adjustment

He pressure at deflection nozzle (100 μm diameter): 4 bar



Real-time Jet Beam Adjustment

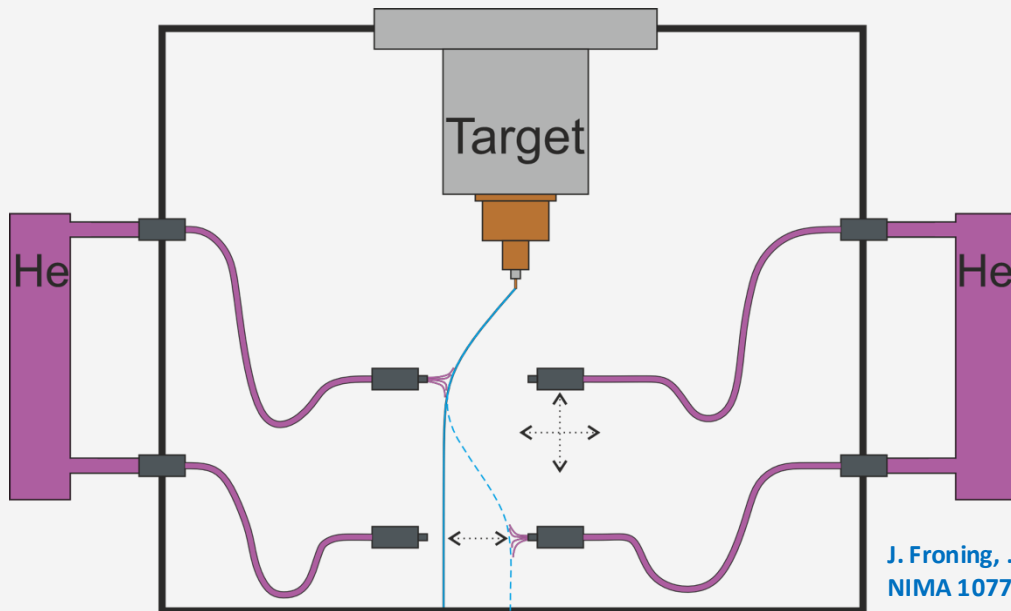
He pressure at deflection nozzle (100 μm diameter): 5 bar



Real-time Jet Beam Adjustment

He pressure at deflection nozzle (100 μm diameter): 6 bar

**Proof of principle for a new method to manipulate/adjust
in real-time a frozen filament or a pellet stream!!!**

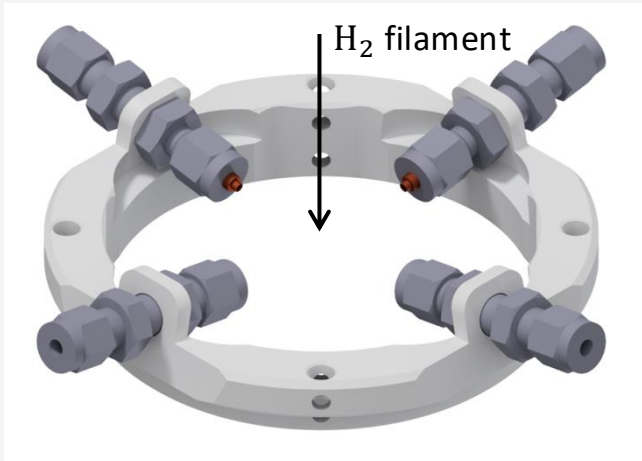
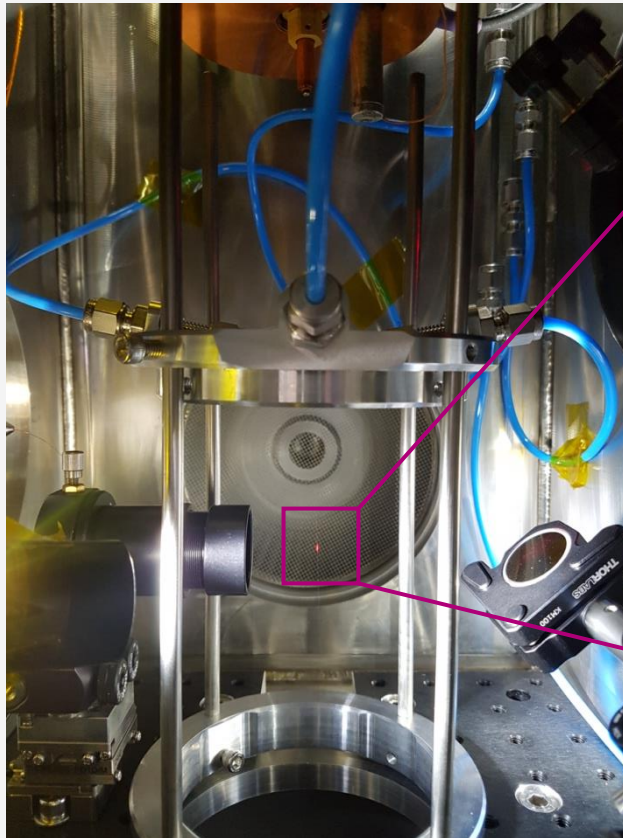
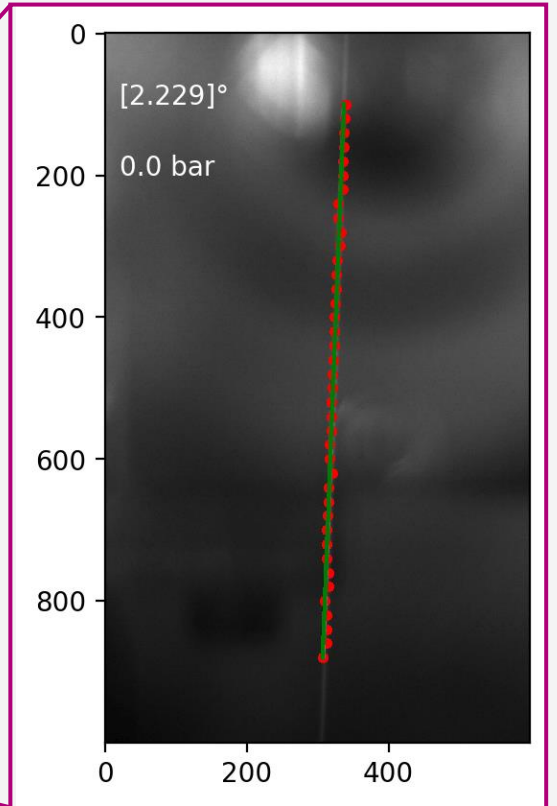


J. Froning, ..., AK
NIMA 1077 (2025) 170526



Cryobending – Ring of Nozzles

- Circular arranged nozzles, connected to individual pressure controller
- Use two rings in the future
- Automatic beam detection/bending



Preparation of Frozen Filaments in Large Setups

- New setup for experiments at large distances
- **>4.3 m flight path** between nozzle and beam dump
- Studies on pellets and frozen filaments
- Broad experimental programm...

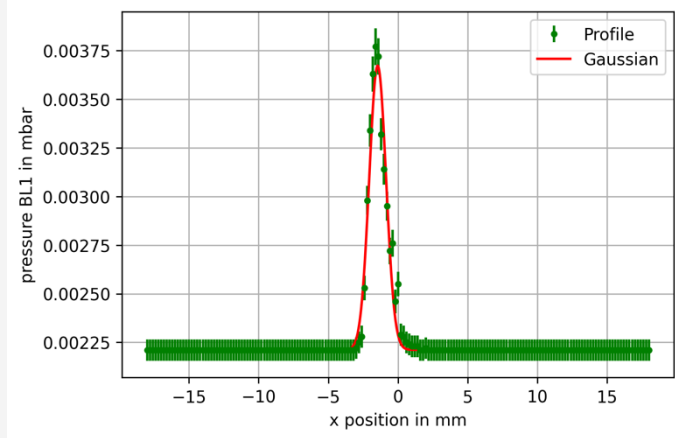


Jet flight path to the lab in the lower floor

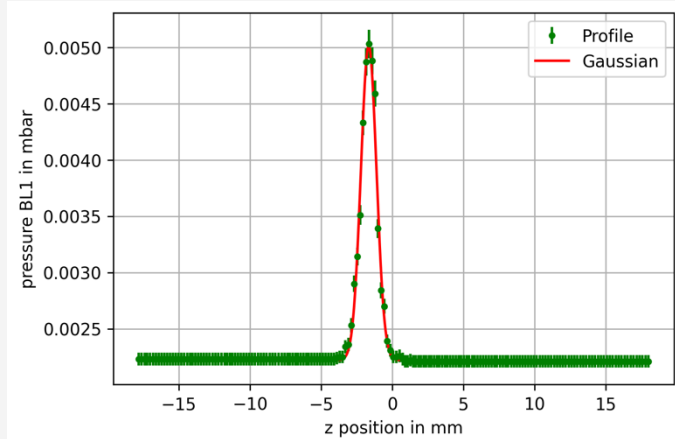
Jet flight path from the lab in the upper floor



Scanning Rod System



$$\sigma_x = (0.60 \pm 0.01) \text{ mm}$$

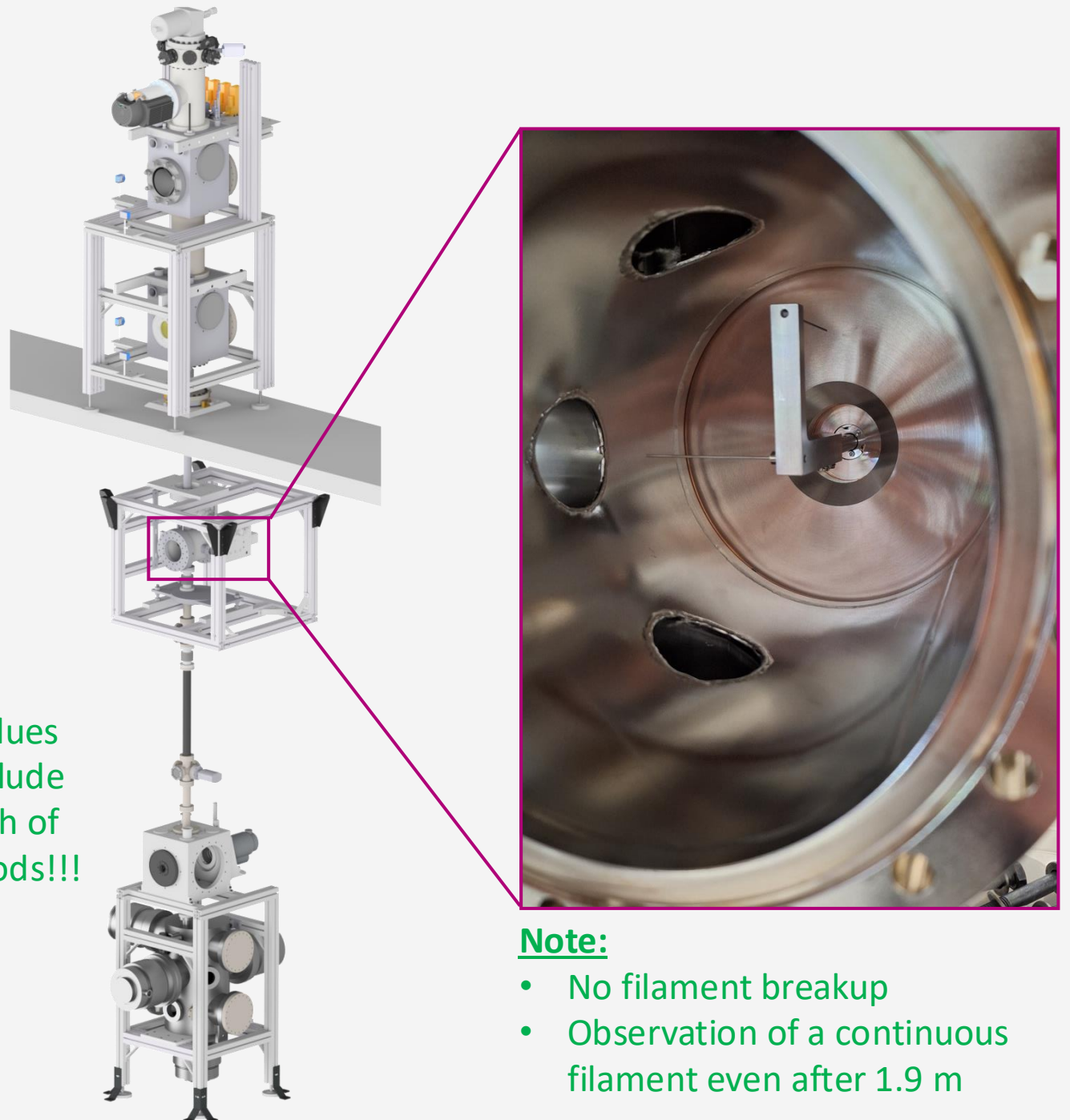


$$\sigma_z = (0.55 \pm 0.01) \text{ mm}$$

~ 1.9 m

Note:

The given σ values after 1.9 m include the 1 mm width of the scanning rods!!!

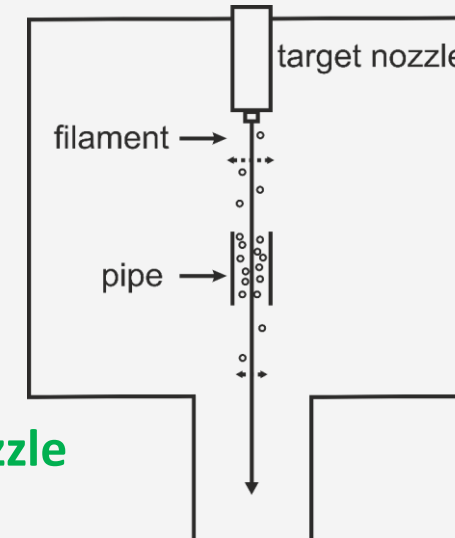


Note:

- No filament breakup
- Observation of a continuous filament even after 1.9 m

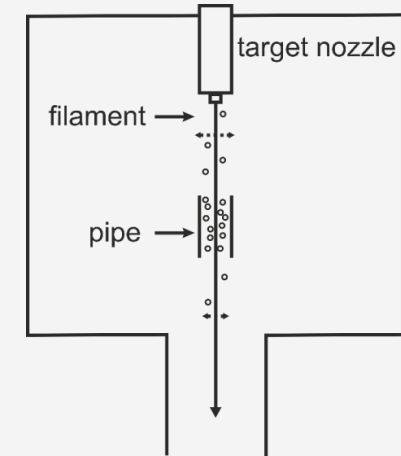
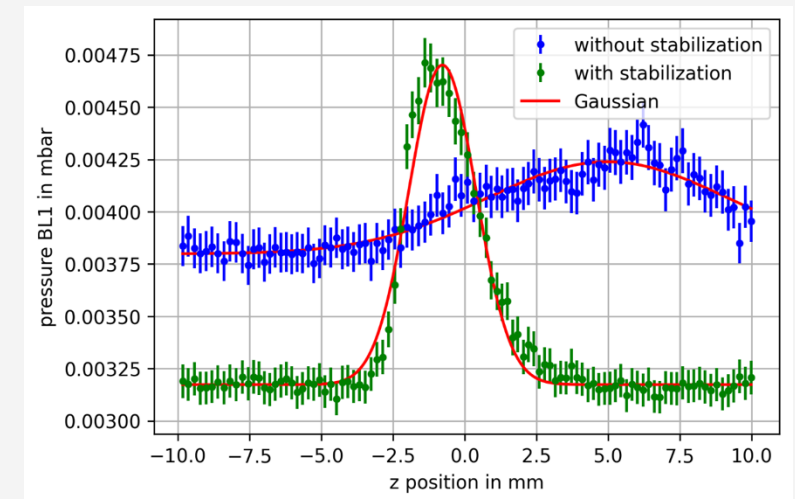
New Method: Stabilisation and Manipulation of Frozen Filament Beams

- Development of a novel method for **contact-free** filament beam stabilisation and manipulation ([Patent application DE 10 2026 124 275.8](#))
- Experiment:
 - Frozen hydrogen filament of 10 μm diameter
 - New device close to the filament nozzle
 - Position measurement of the filament: **1.9 m behind the nozzle**



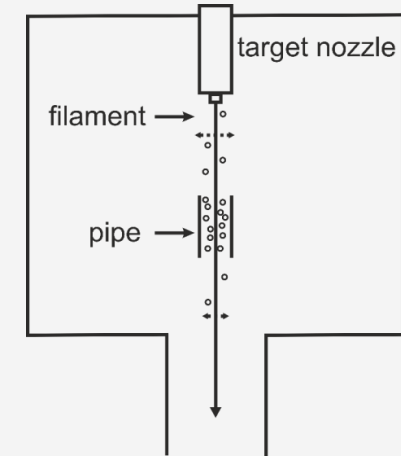
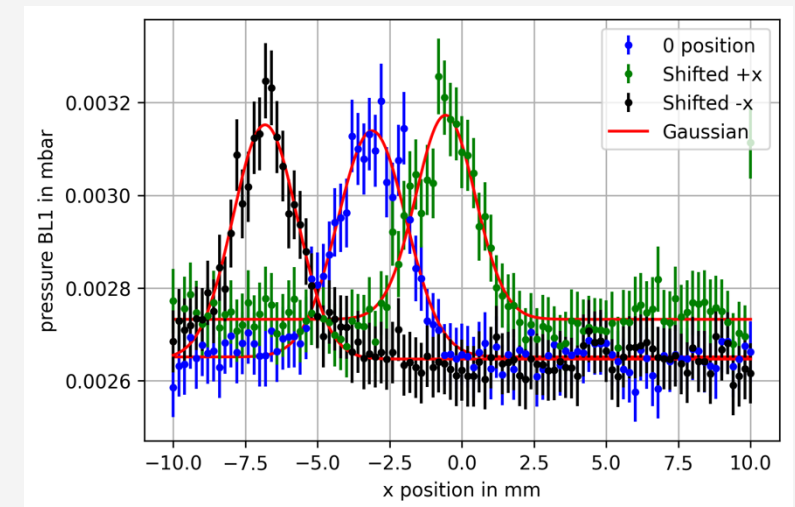
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- Results:
 - Reduction of the filament spread from $\sigma \approx 4 \text{ mm} \rightarrow \sigma \approx 1 \text{ mm}$



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- Results:
 - Reduction of the filament spread from $\sigma \approx 4 \text{ mm} \rightarrow \sigma \approx 1 \text{ mm}$
 - Easy and stable filament manipulation by, e.g., several mm



Towards High Precision Measurements at MAGIX/MESA: Filament Beams

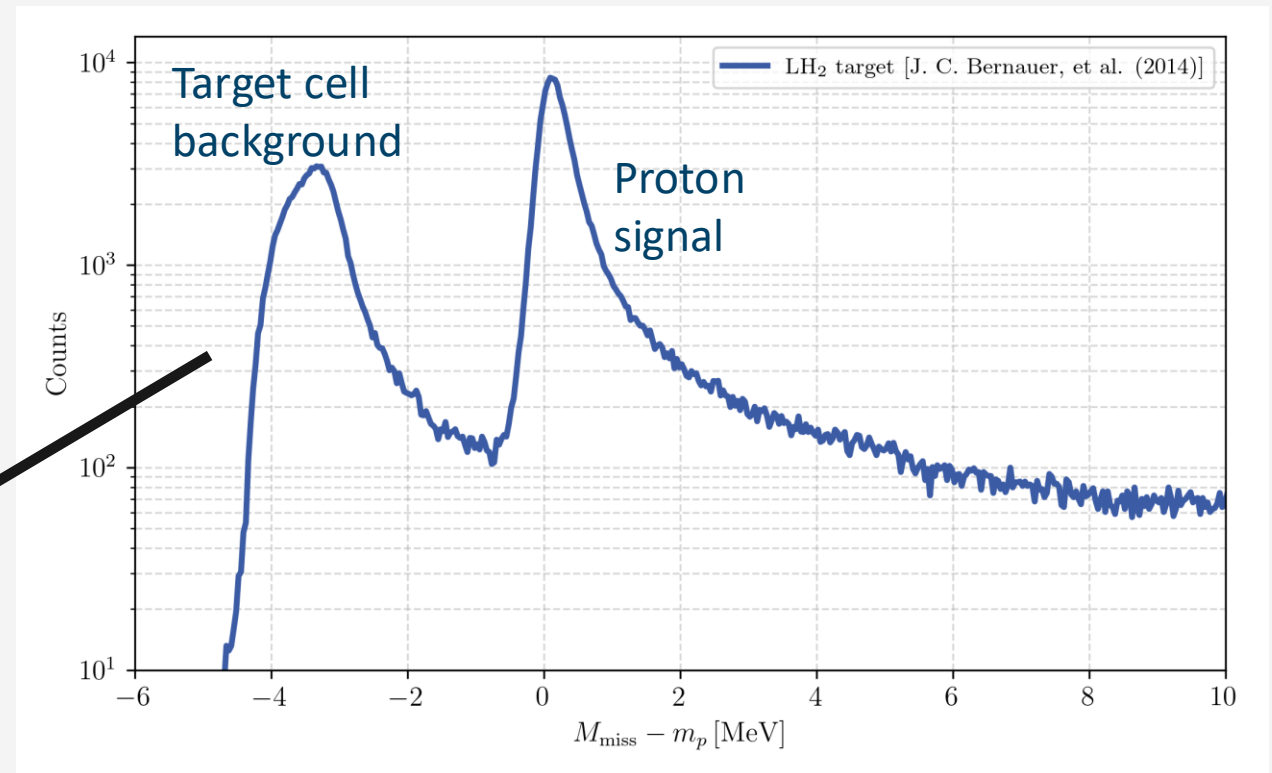
Electron-proton scattering data at MAMI

- Past: Use of a liquid hydrogen cell for proton radius measurements
- **Good mass resolution, but large background from wall material**

Target Cell used before at MAMI



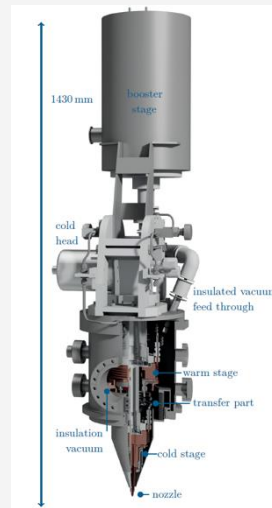
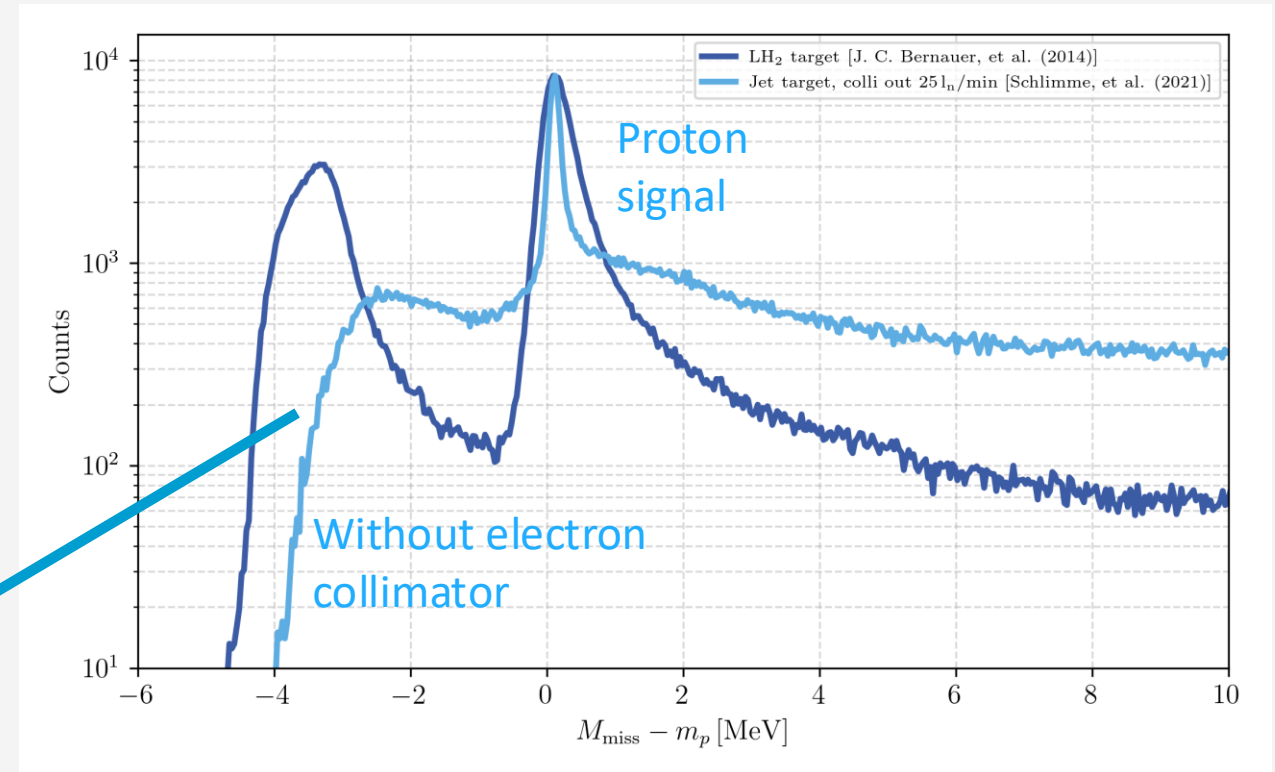
Thomas Pospischil, 2000 (PhD U Mainz)



Towards High Precision Measurements at MAGIX/MESA: Filament Beams

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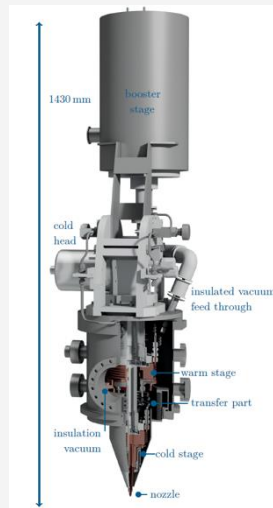
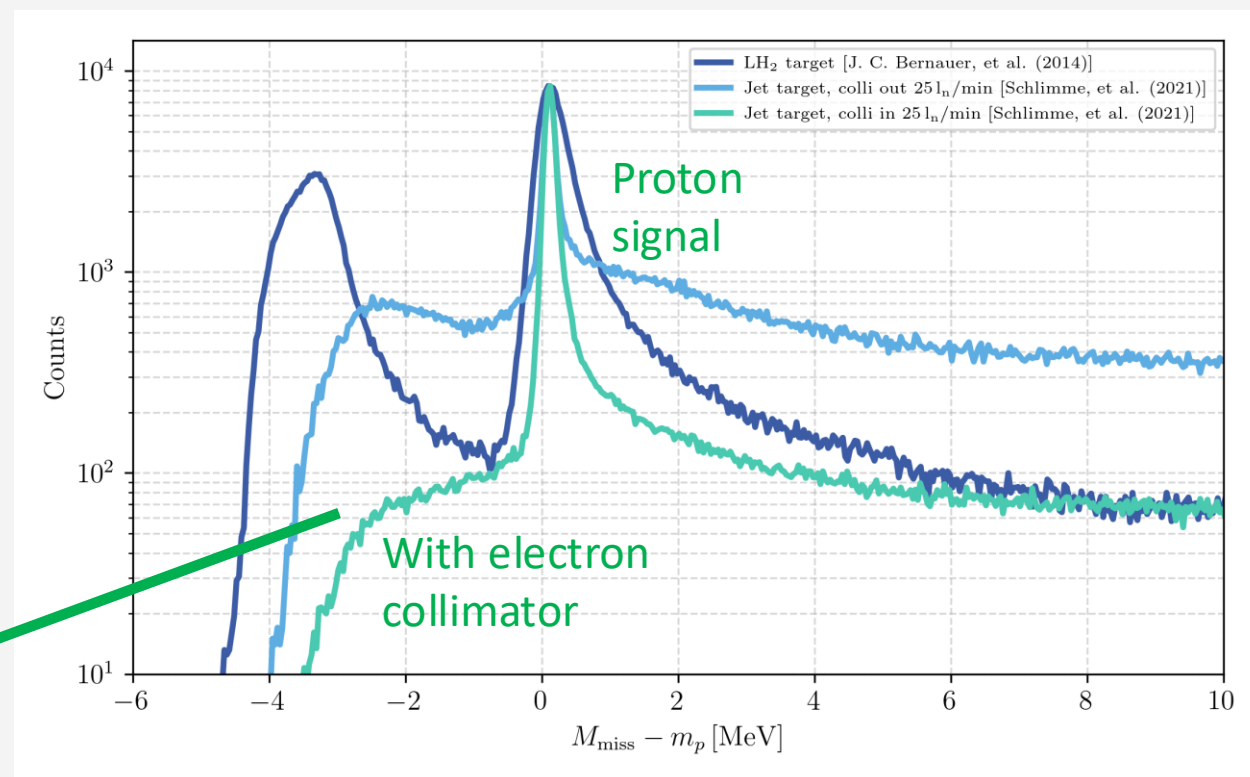
- Pilot measurements with Münster gas-jet target
- Improved mass resolution, reduced background



Towards High Precision Measurements at MAGIX/MESA: Filament Beams

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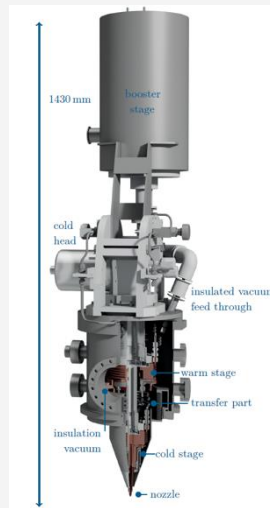
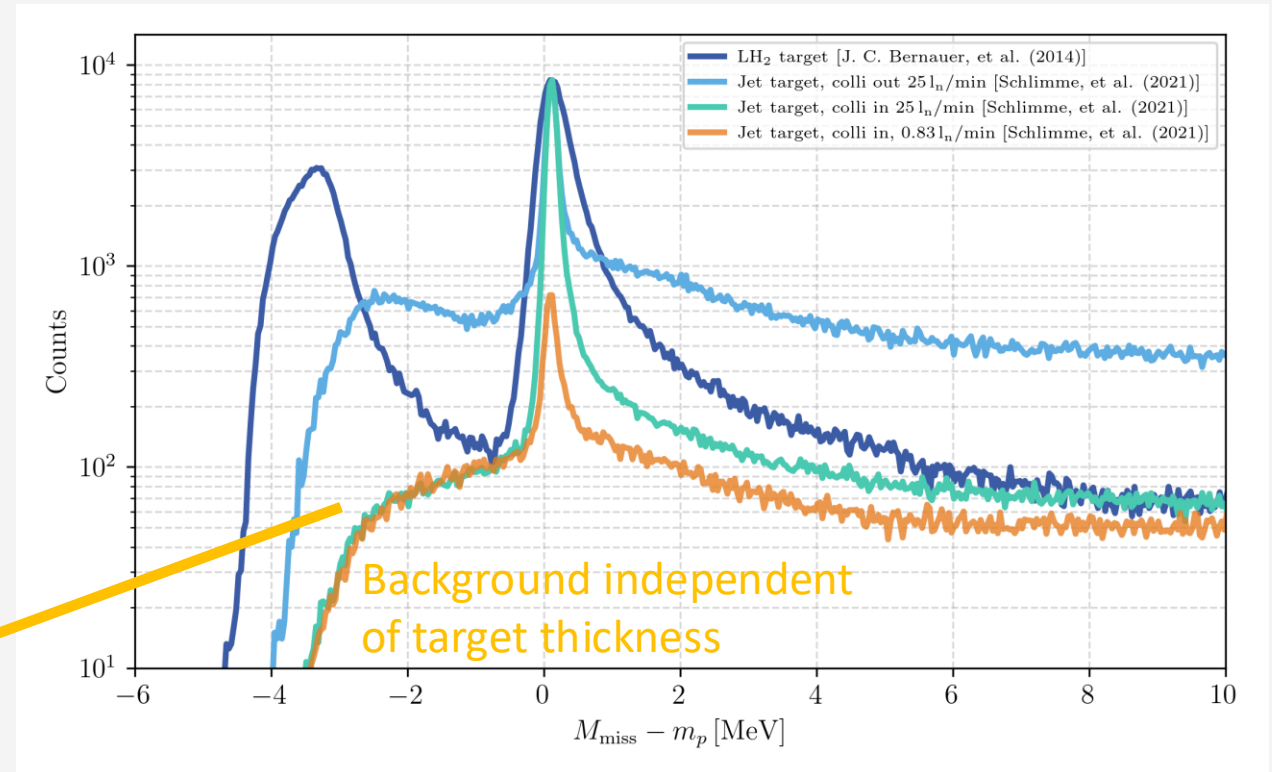
- Pilot measurements with Münster gas-jet target
- **Drastically reduced background use of electron beam collimator**



Towards High Precision Measurements at MAGIX/MESA: Filament Beams

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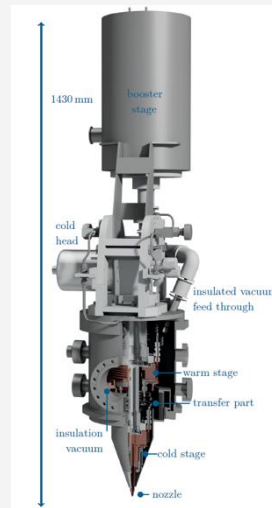
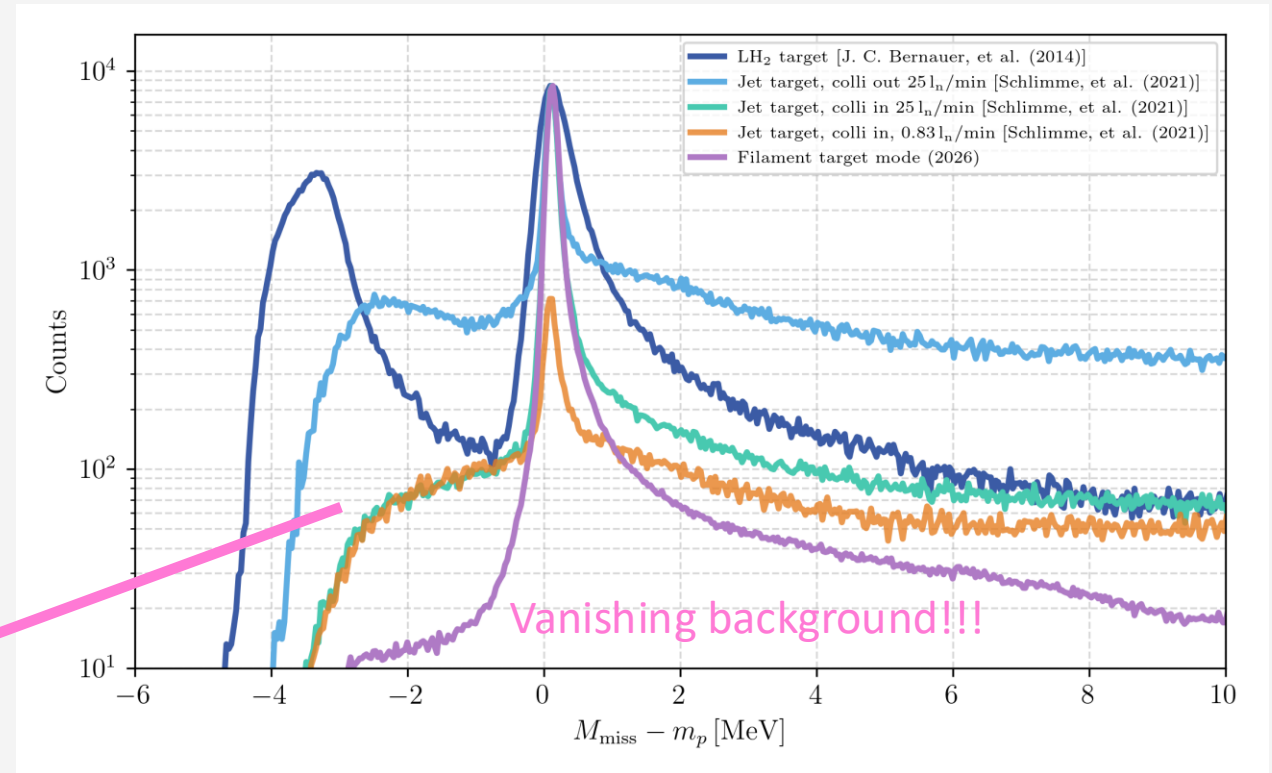
- Pilot measurements with Münster gas-jet target
- **Drastically reduced background** use of electron beam collimator



Towards High Precision Measurements at MAGIX/MESA: Filament Beams

Electron-proton scattering data at MAMI

- Münster gas-jet target operated in filament mode
- Excellent mass resolution and essentially no background
- $S/N = 1000:1$

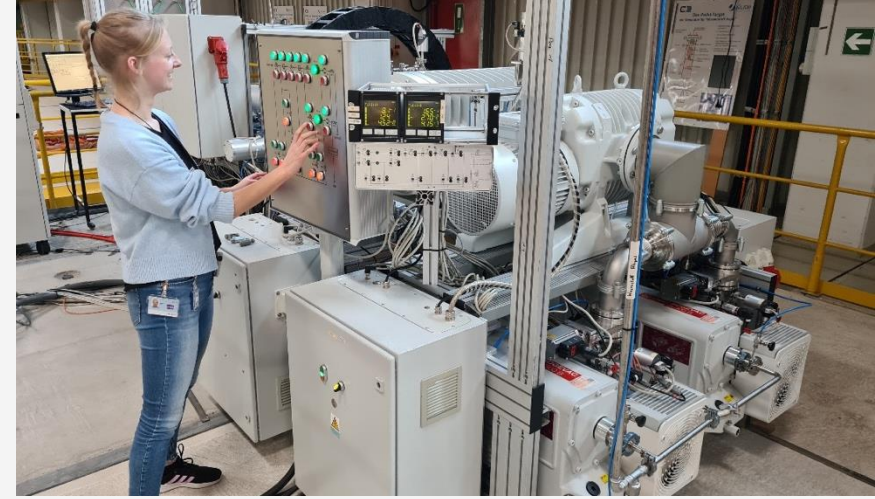
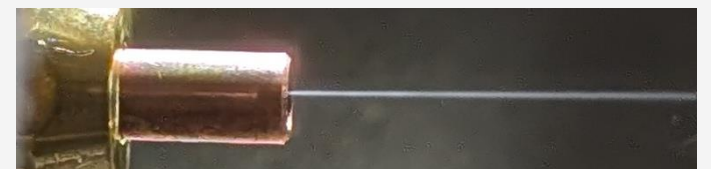


Summary

- Gas-jet, cluster-jet and pellet/filament targets are important target types for hadron physics experiments
- Modern experiments require
 - **a further development of these target types itself**
 - **a further development of diagnostic tools**
 - **innovative target beam manipulation methods**
- The jet nozzles are the key components of these devices

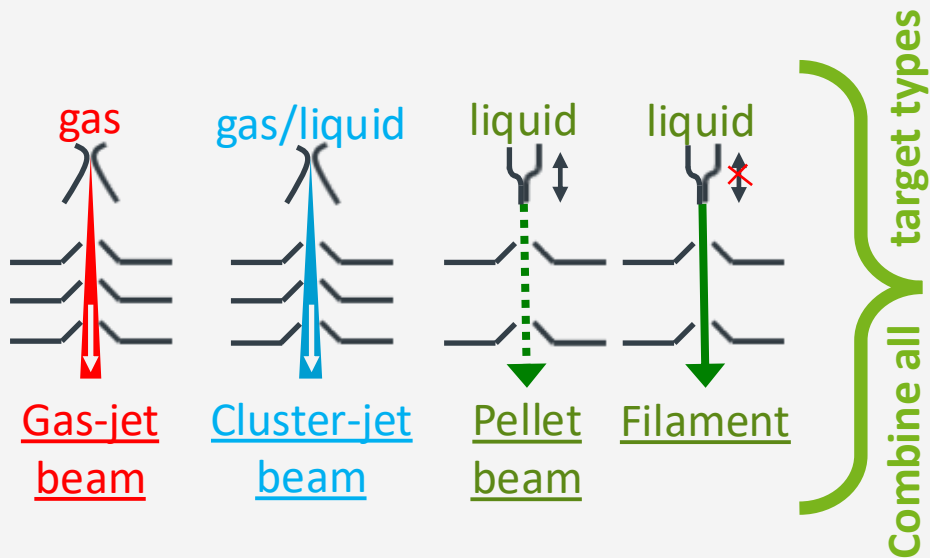
Note:

- The type of the jet nozzle (simple orifice, convergent-divergent, ...) and the nozzle size/geometry are only two aspects to consider
- Of same importance are the right operational parameters
 - **Gas input pressure/temperature**
 - **Nozzle material**

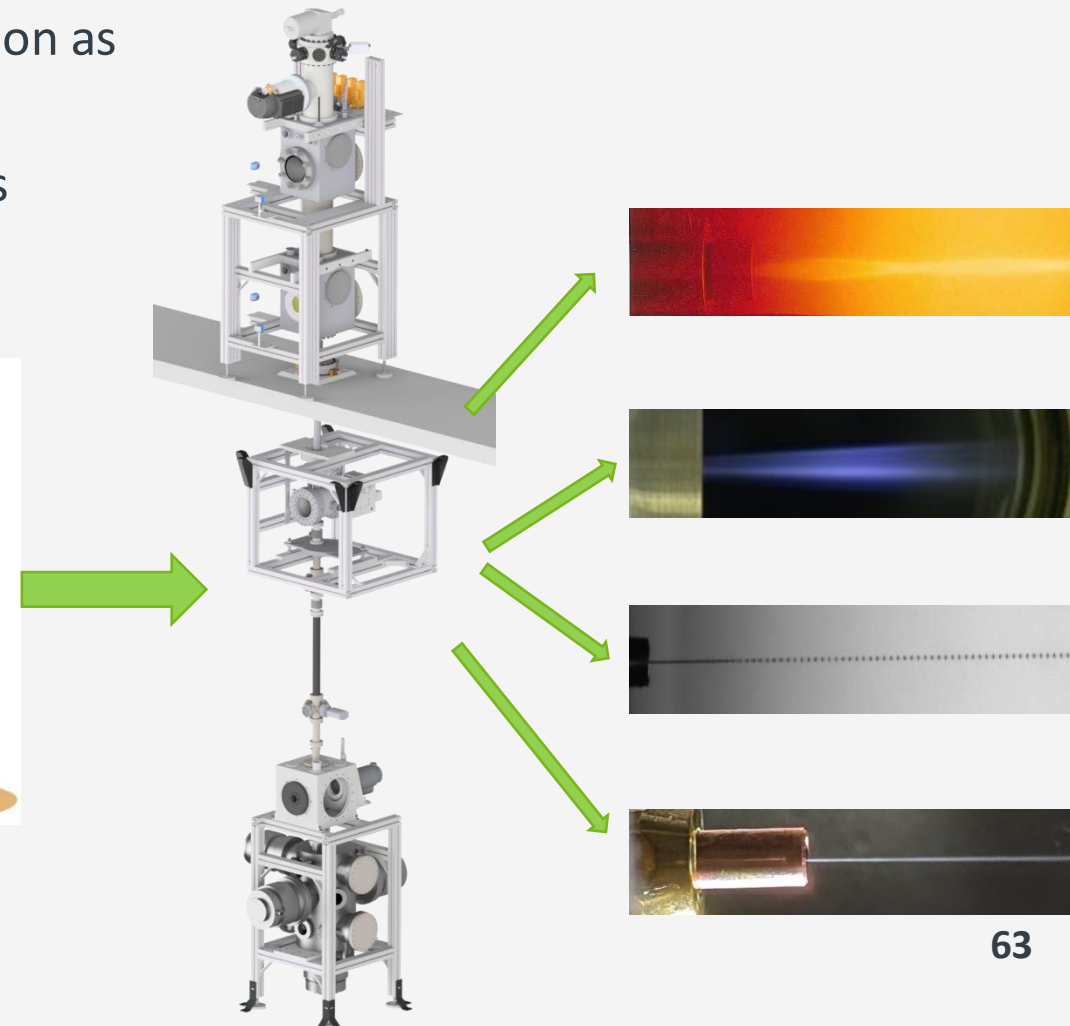


Outlook

- Studies towards a **general target design** which allows operation as gas-jet, cluster-jet and pellet/filament target
- Design of **advanced jet nozzles** for different operation modes (depending on properties of incoming fluid)



Designed by Freepik

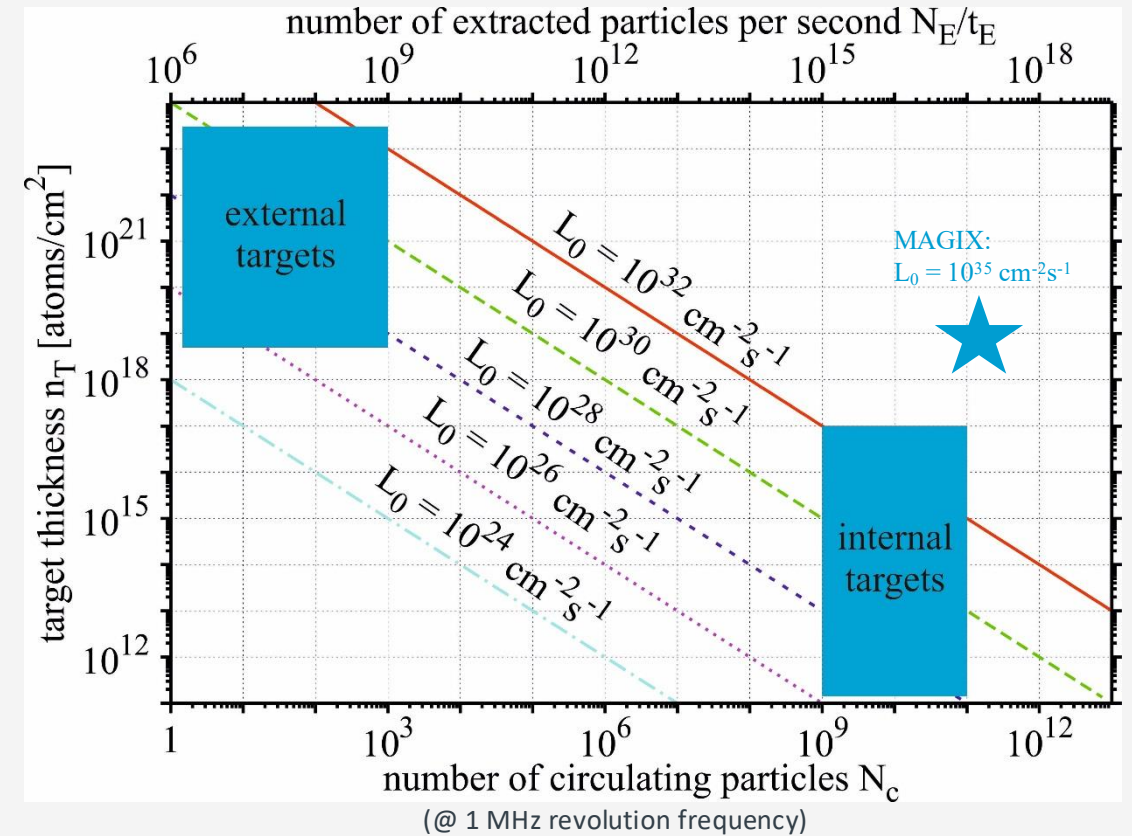


Thank you for your attention ...



A Few Words on How to Reach a Certain Luminosity

- External beam experiments require typically massive targets (e.g. foils, liquids) in order to achieve a certain luminosity
- In contrast, internal beam experiments at storage rings use thin targets (e.g. gas jets / cluster jets) to reach the same luminosity
- Such thin jet targets introduce certain challenges in the preparation, but offer several interesting possibilities
 - **Beam and IP diagnostics, highest purities, absence of secondary reactions, ...**



Outlook (2): Studies Towards LH₂ Targets for FAIR

Interesting properties and facts

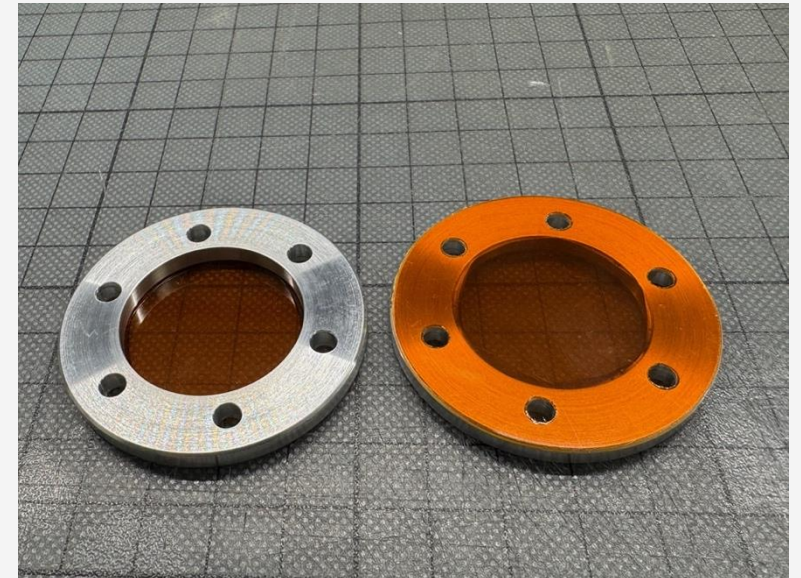
- Density of liquid hydrogen at 18 K and 1 bar: $\rho = 71 \text{ mg/cm}^3$
- LH₂ target thickness per mm cell length: $\rho_T = 4.18 \cdot 10^{21} \text{ atoms/cm}^2$

Example of a target cell with Kapton windows (C₂₂H₁₀N₂O₅)

- Assume a cell length of $l = 20 \text{ mm}$
- LH₂ pressure = 1 bar absolut; outside: vacuum
- 50 μm Kapton windows for stress safety factor 3
- Center deflection of Kapton windows: ca. 2x 3.3mm
→ Total effective target cell length: $l = 27 \text{ mm}$
→ Total target thickness: $\rho_T = 1.1 \cdot 10^{23} \text{ atoms/cm}^2$



Cell tests in Münster (AG Khoukaz)



Outlook (2): Studies Towards LH₂ Targets for FAIR

Interesting properties and facts

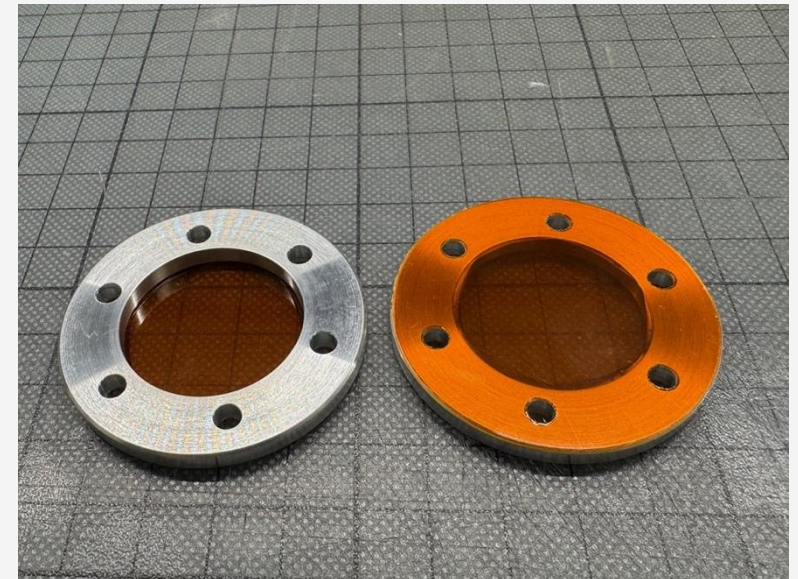
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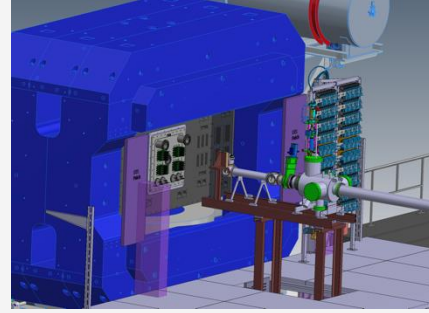
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 - Total effective target cell length: $l = 27 \text{ mm}$
 - Total target thickness: $\rho_T = 1.1 \cdot 10^{23} \text{ atoms/cm}^2$
- Background due to kapton window (50 μm):
C: 1:13,000 **N:** 1:140,000 **O:** 1:55,000



Cell tests in Münster (AG Khoukaz)



Studies Towards a LH2 Target for CBM



Total and inelastic cross sections, luminosity and reaction rates at CBM

- SIS100:
 - Momentum: 29 GeV/c
 - Beam intensity: $2 \cdot 10^{13}$ protons/cycle
 - Slow extraction: 10 s
- CBM: beam intensity of $\dot{N}_{SIS100} = 10^{11}$ protons/s discussed
- Proton-proton interaction cross sections:
 - Total cross section: $\sigma_{total} = 50$ mb
 - Inelastic cross section: $\sigma_{inel.} = 32$ mb
- Reaction rates:
 - $\dot{N}_{inel,CBM} = L \cdot \sigma_{inel.} = \dot{N}_{SIS100} \cdot \rho_T \cdot \sigma_{inel.} = 357$ MHz
 - Extraction rate for $\dot{N}_{inel,CBM} = 10$ MHz: $\dot{N}_{SIS100} = 3 \cdot 10^9$ protons/s

} maximum
10¹² protons/s possible
(assume less)



Cell tests in Münster (AG Khoukaz)



KOALA @ Cave C: Development and Optimization of Targets for FAIR

The planned KOALA at Cave C setup will allow for important developments for the FAIR pillars

- **NUSTAR & APPA:**
Test of optimized new jet nozzles for the jet targets at CRYRING & ESR
- **PANDA:**
Optimization and further development of targets: cluster-jet / pellet / filament
- **CBM (first idea!):**
Possibility to perform test measurements using a LH_2 target

