Cluster Beam Properties and Optimization Studies

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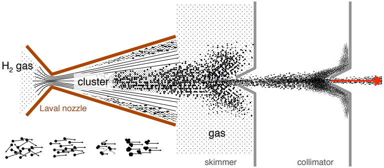
Concept and Objectives

Detailed and systematic studies on:

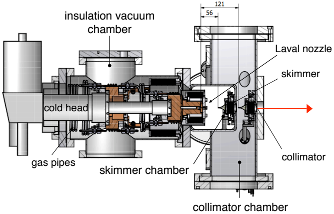
- **Cluster velocity**
- **Target density**
- **Mass distribution**

...in dependence of temperature and pressure settings.

$\Longrightarrow$ Deeper insights into cluster formation process



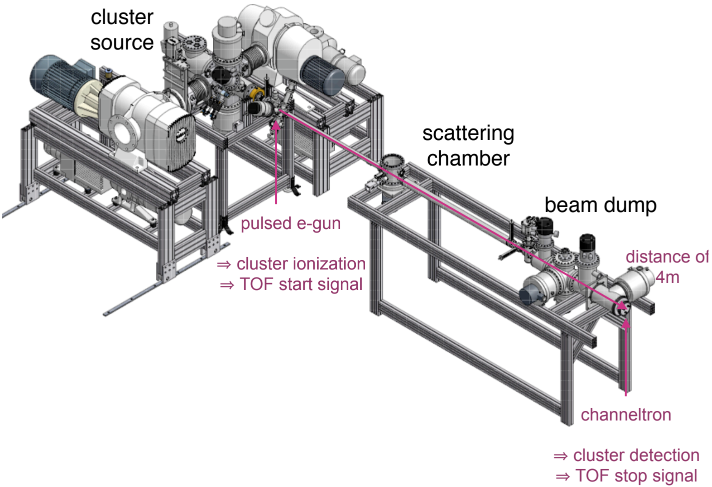
$\Longrightarrow$ Improvement of the cluster source to provide target densities as high as possible



Cluster velocity

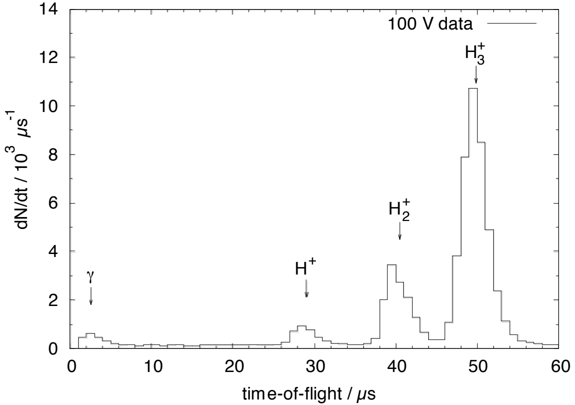
Overview of the high density cluster-jet target for $\overline{\text{P}}$ANDA

- **Complete system installed in $\overline{\text{P}}$ANDA geometry**
  (scattering chamber corresponds to $\overline{\text{P}}$ANDA interaction point)



- Calibration source provides accelerated hydrogen ions (H^+, H_2^+, H_3^+) and photons

$\Longrightarrow$ TOF distribution of different ions (i.e. accelerated through a voltage of $100\,\mathrm{V}$)

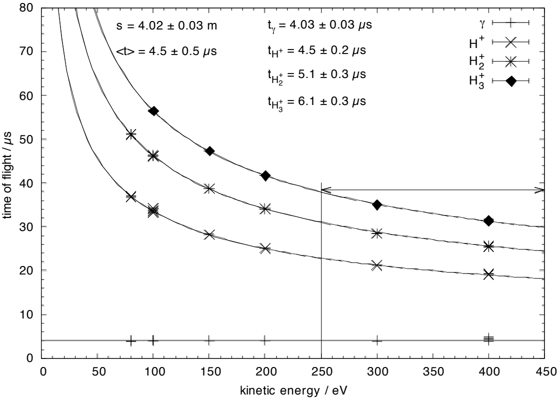


Cluster velocity

TOF Calibration

- Calibration source provides accelerated hydrogen ions (H^+, H_2^+, H_3^+) and photons

$\Longrightarrow$ TOF measurements of different ions and various acceleration voltages



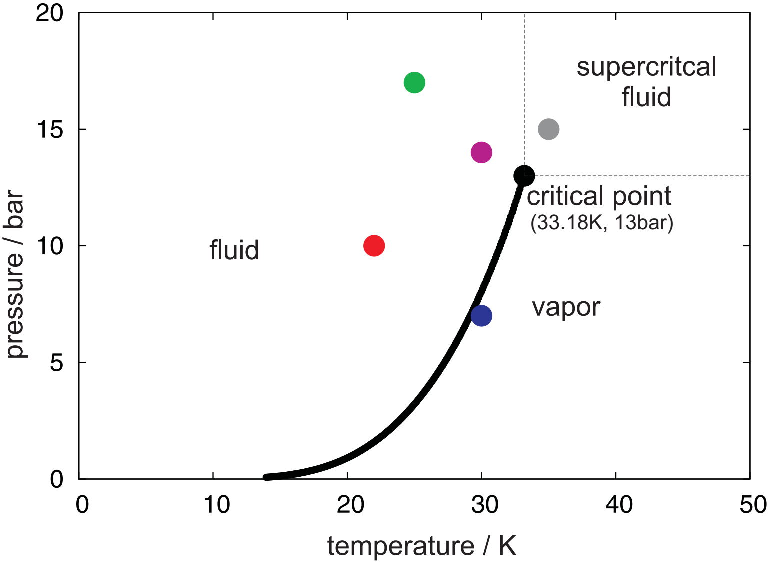
Determination of:

- **Time offset:**
  $\sim \mu s$
- **Flight path:**
  $4.02(3)\,\mathrm{m}$
- **Time resolution:**
  $\approx 3\,\mu s$
  TOF in the range of $20 - 60\,\mu s$ (ions)

  $\approx 20\,\mu s$
  TOF in the range of $0.2 - 10\,\mathrm{ms}$ (cluster)

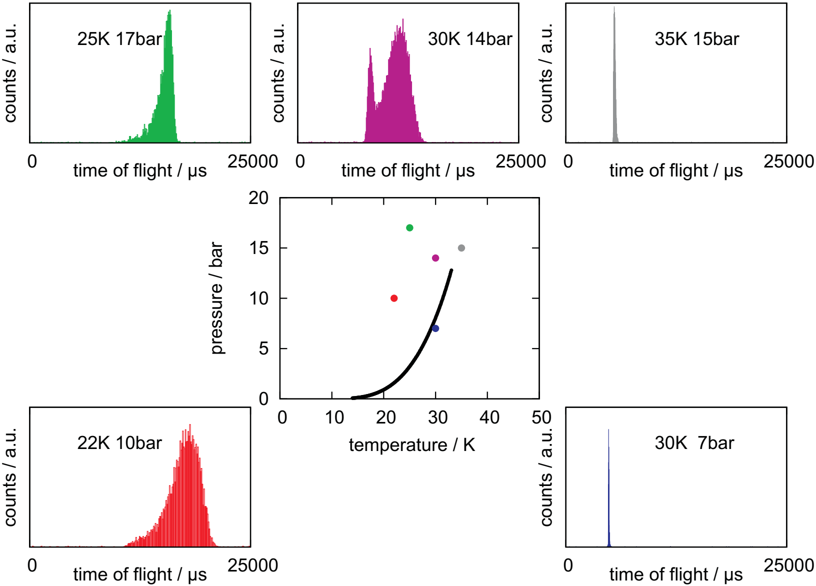
Cluster velocity

Hydrogen vapor pressure curve and TOF cluster measurement



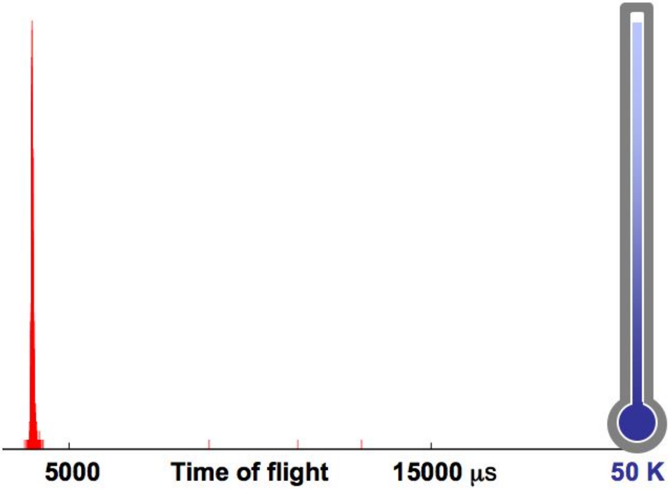
Cluster velocity

Hydrogen vapor pressure curve and TOF cluster measurement



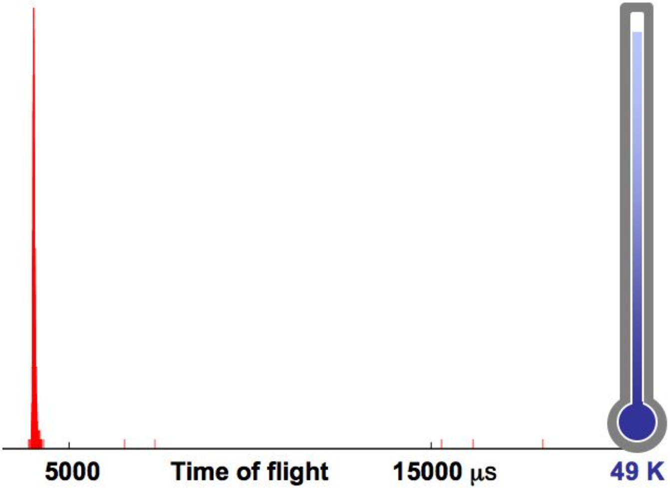
Cluster velocity

TOF cluster measurement at 14 bar, 50 K



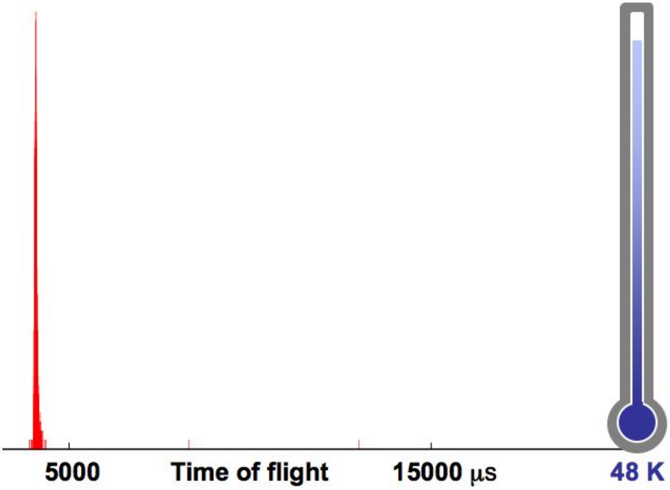
Cluster velocity

TOF cluster measurement at 14 bar, 49 K



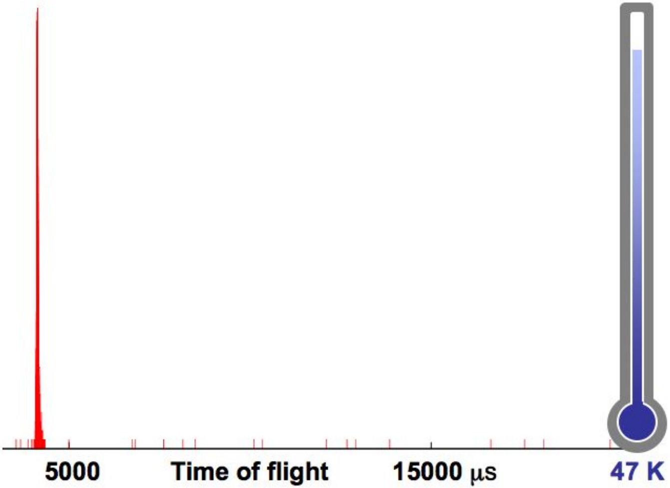
Cluster velocity

TOF cluster measurement at 14 bar, 48 K



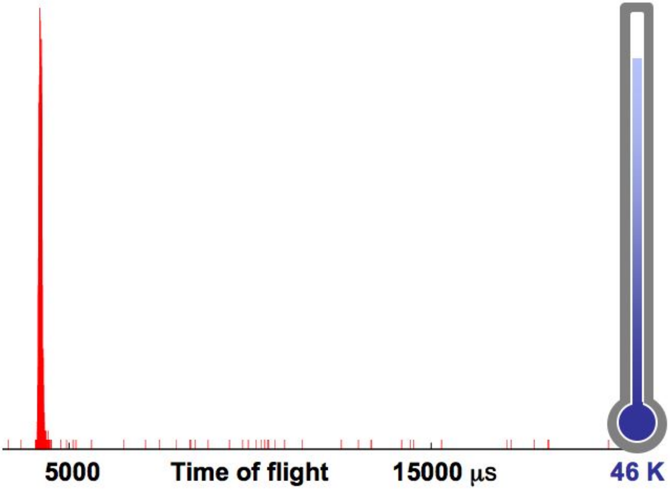
Cluster velocity

TOF cluster measurement at 14 bar, 47 K



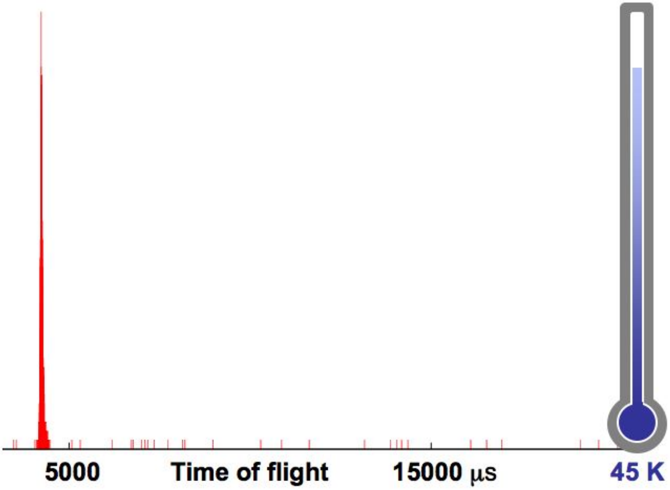
Cluster velocity

TOF cluster measurement at 14 bar, 46 K



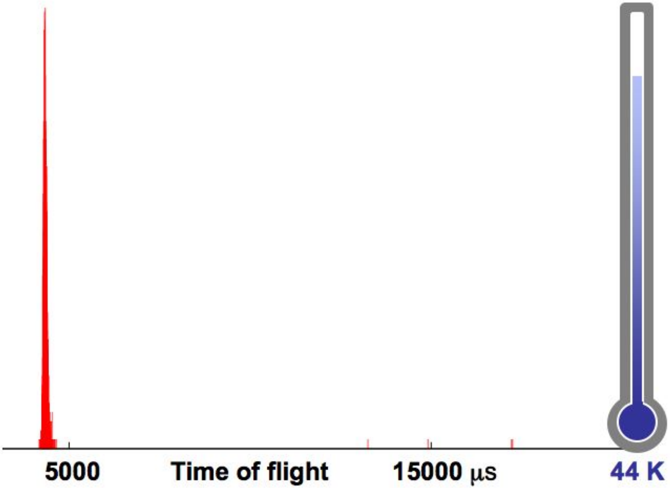
Cluster velocity

TOF cluster measurement at 14 bar, 45 K



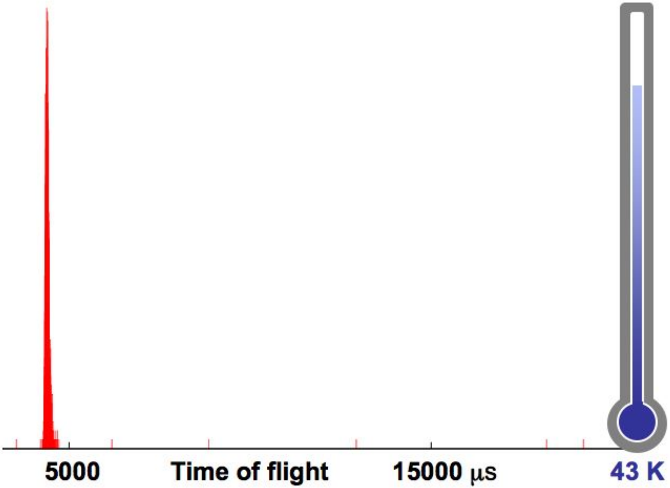
Cluster velocity

TOF cluster measurement at 14 bar, 44 K



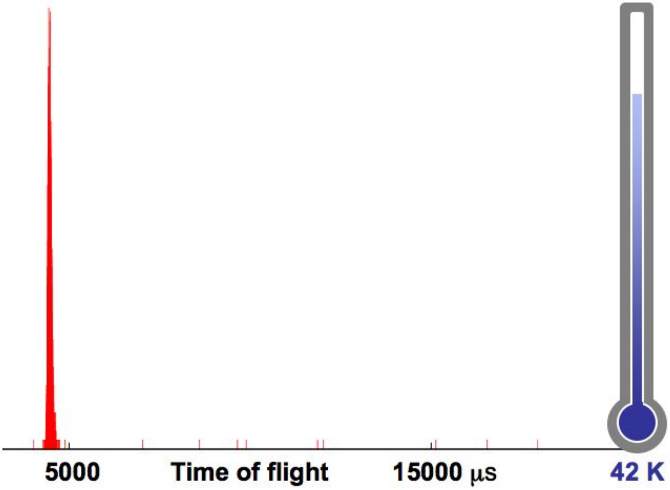
Cluster velocity

TOF cluster measurement at 14 bar, 43 K



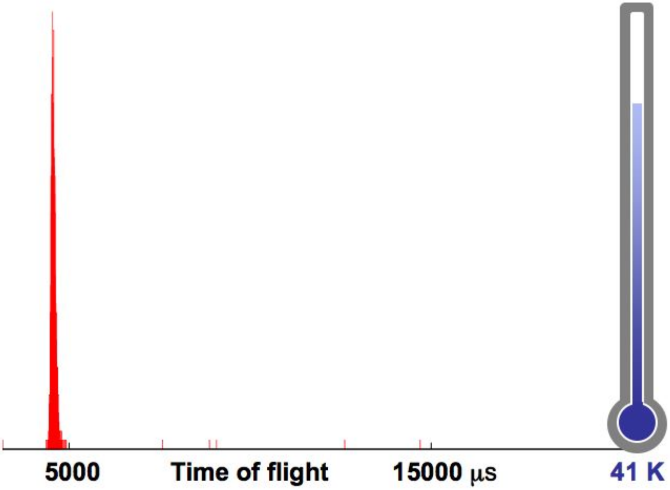
Cluster velocity

TOF cluster measurement at 14 bar, 42 K



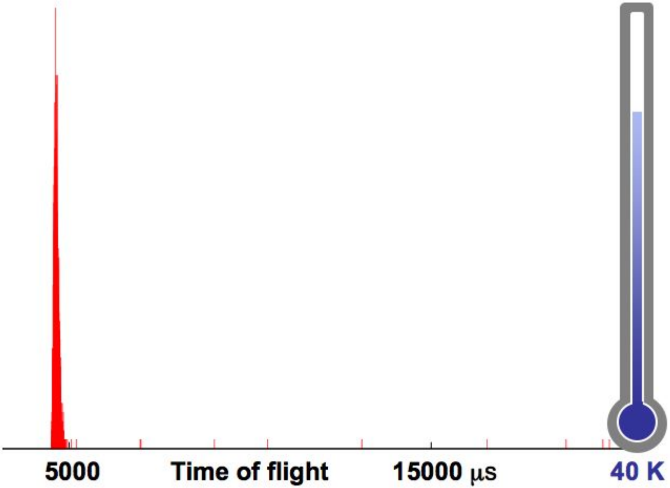
Cluster velocity

TOF cluster measurement at 14 bar, 41 K



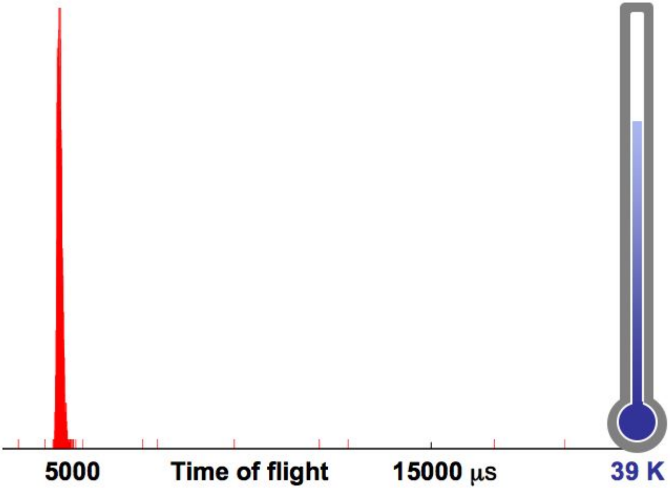
Cluster velocity

TOF cluster measurement at 14 bar, 40 K



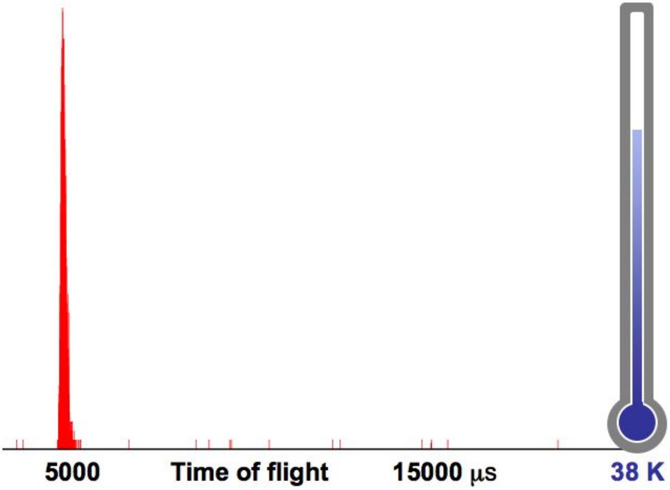
Cluster velocity

TOF cluster measurement at 14 bar, 39 K



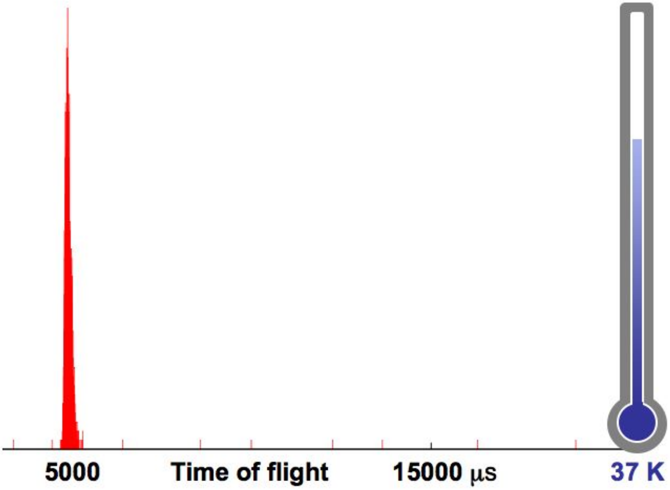
Cluster velocity

TOF cluster measurement at 14 bar, 38 K



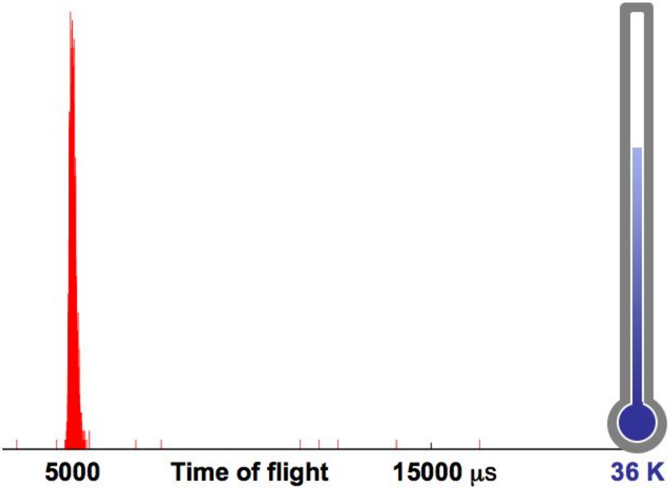
Cluster velocity

TOF cluster measurement at 14 bar, 37 K



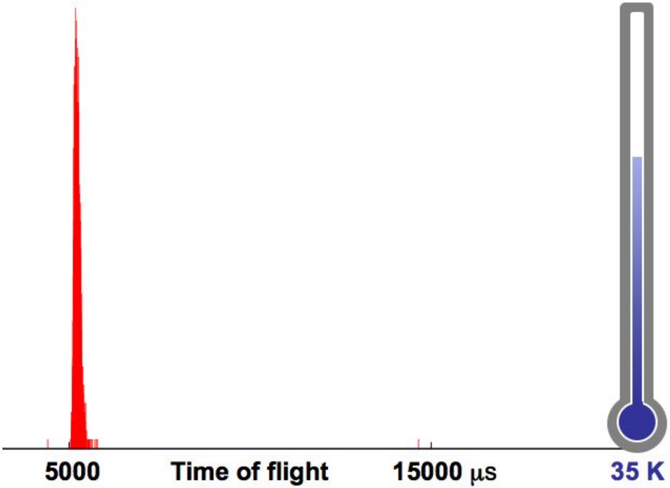
Cluster velocity

TOF cluster measurement at 14 bar, 36 K



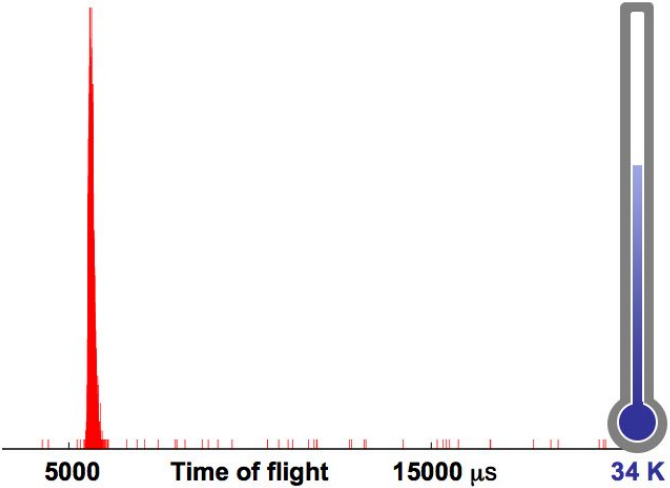
Cluster velocity

TOF cluster measurement at 14 bar, 35 K



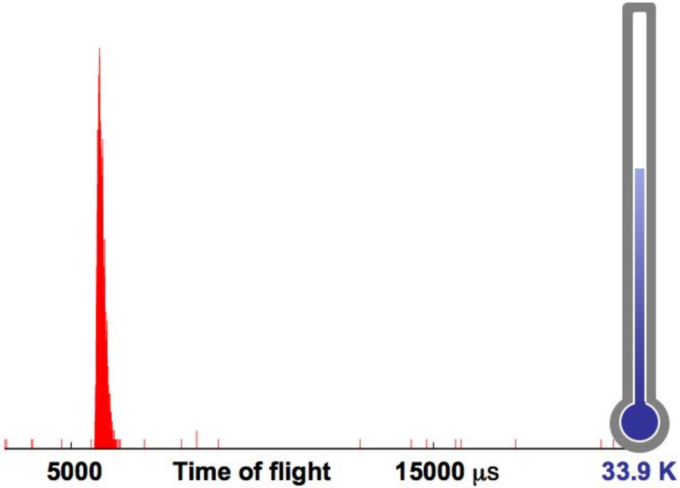
Cluster velocity

TOF cluster measurement at 14 bar, 34 K



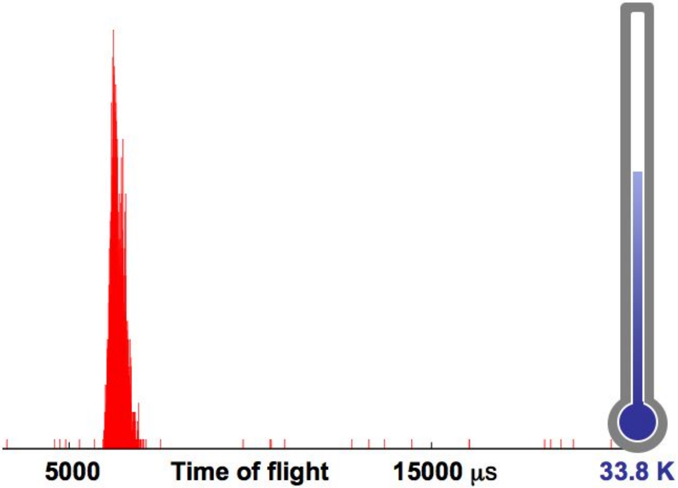
Cluster velocity

TOF cluster measurement at 14 bar, 33.9 K



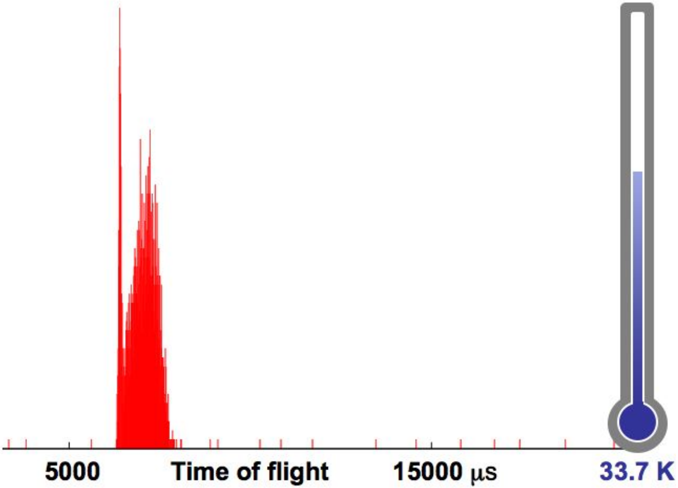
Cluster velocity

TOF cluster measurement at 14 bar, 33.8 K



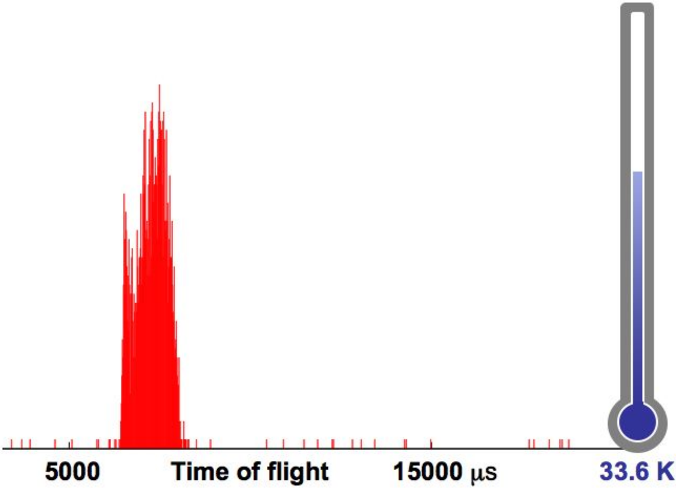
Cluster velocity

TOF cluster measurement at 14 bar, 33.7 K



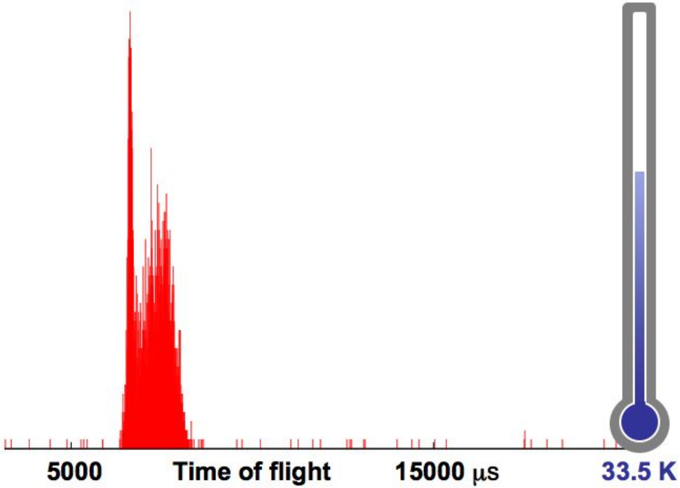
Cluster velocity

TOF cluster measurement at 14 bar, 33.6 K



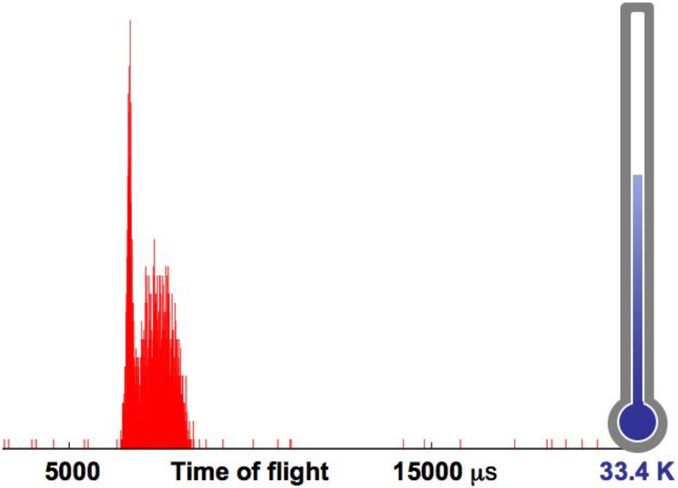
Cluster velocity

TOF cluster measurement at 14 bar, 33.5 K



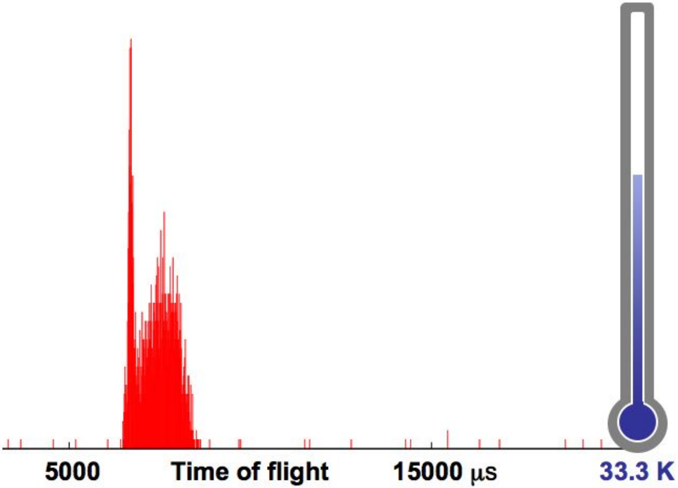
Cluster velocity

TOF cluster measurement at 14 bar, 33.4 K



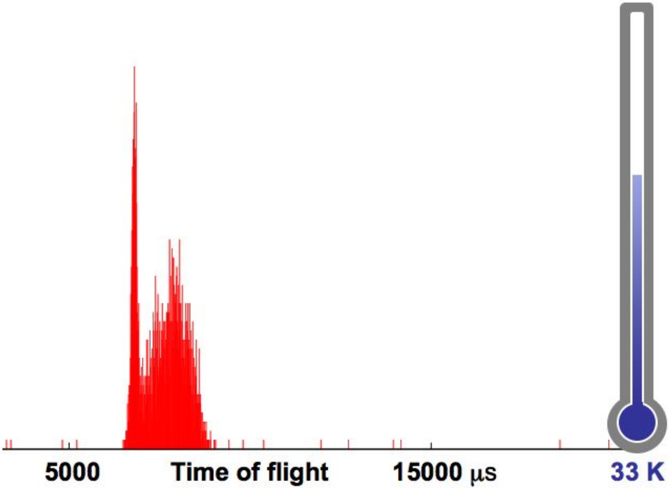
Cluster velocity

TOF cluster measurement at 14 bar, 33.3 K



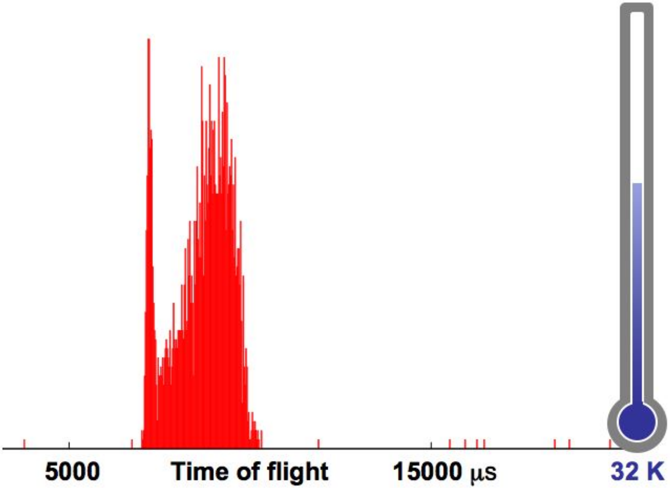
Cluster velocity

TOF cluster measurement at 14 bar, 33 K



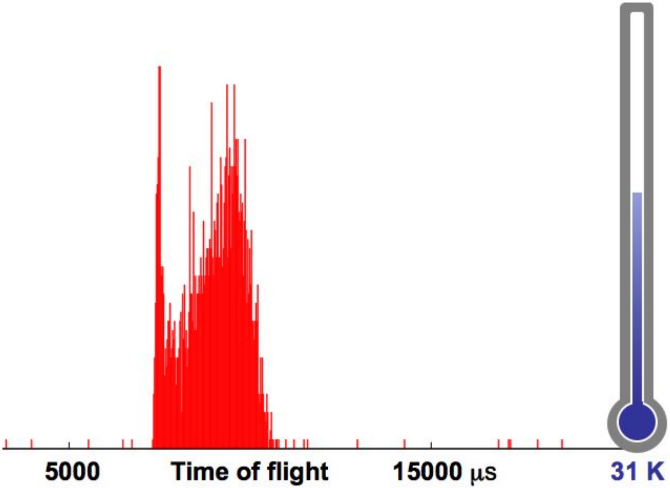
Cluster velocity

TOF cluster measurement at 14 bar, 32 K



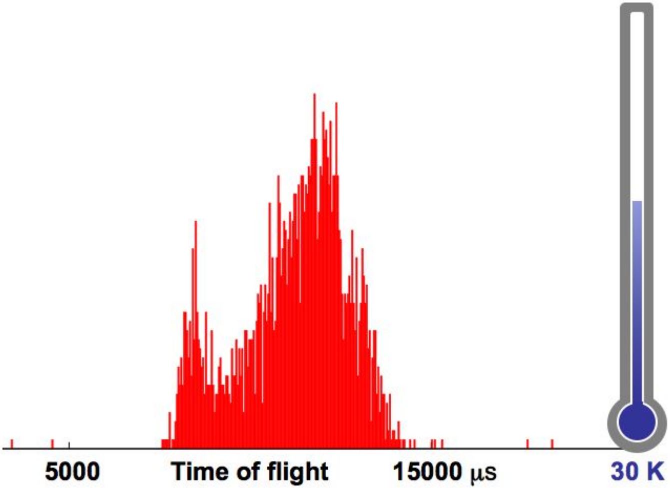
Cluster velocity

TOF cluster measurement at 14 bar, 31 K



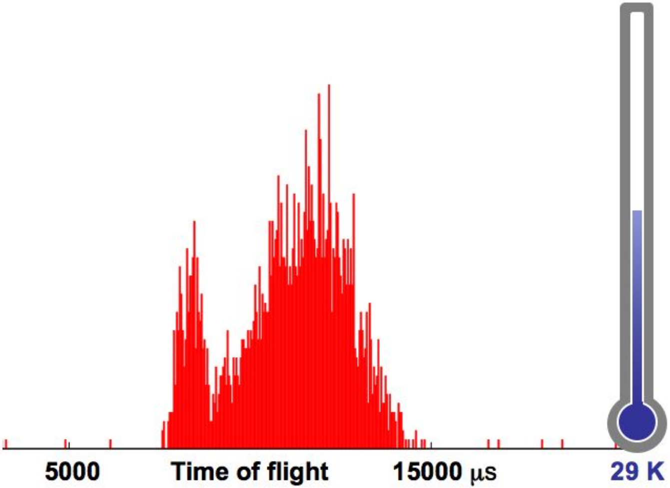
Cluster velocity

TOF cluster measurement at 14 bar, 30 K



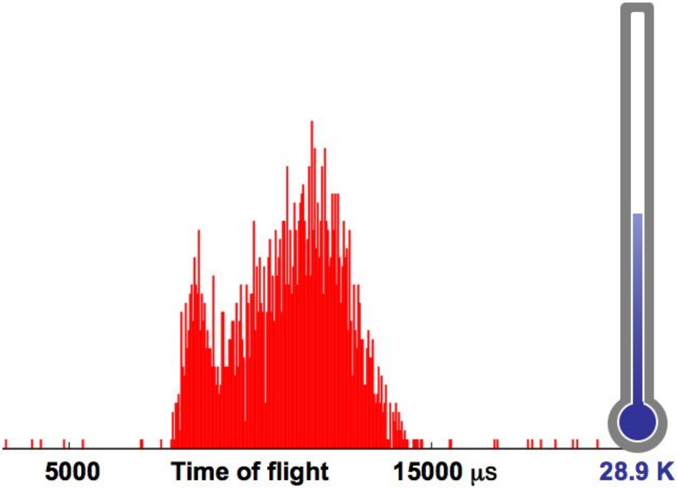
Cluster velocity

TOF cluster measurement at 14 bar, 29 K



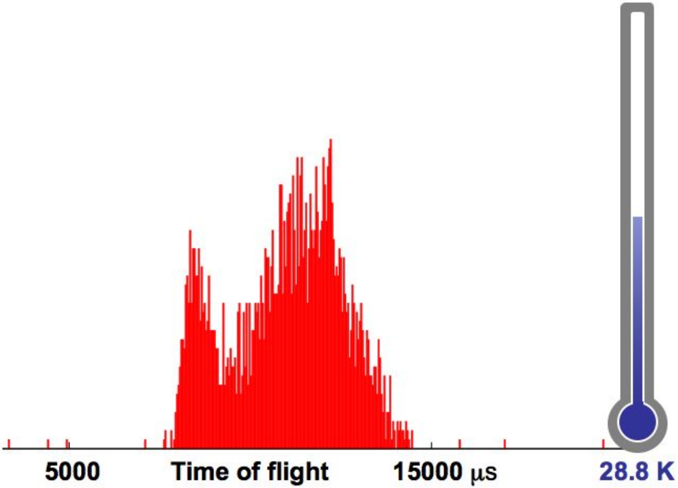
Cluster velocity

TOF cluster measurement at 14 bar, 28.9 K



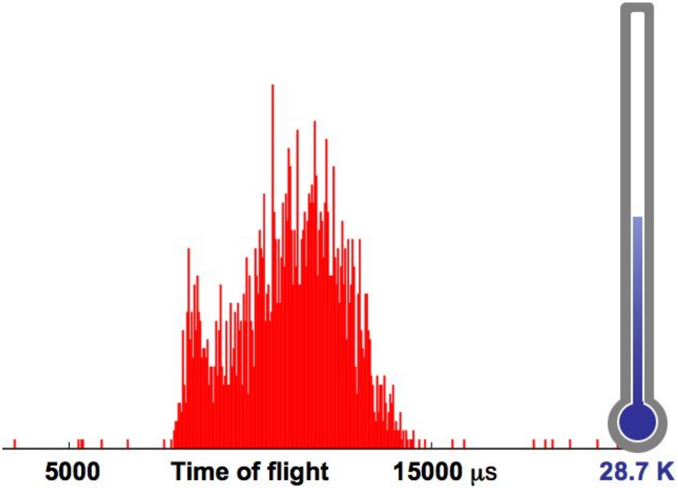
Cluster velocity

TOF cluster measurement at 14 bar, 28.8 K



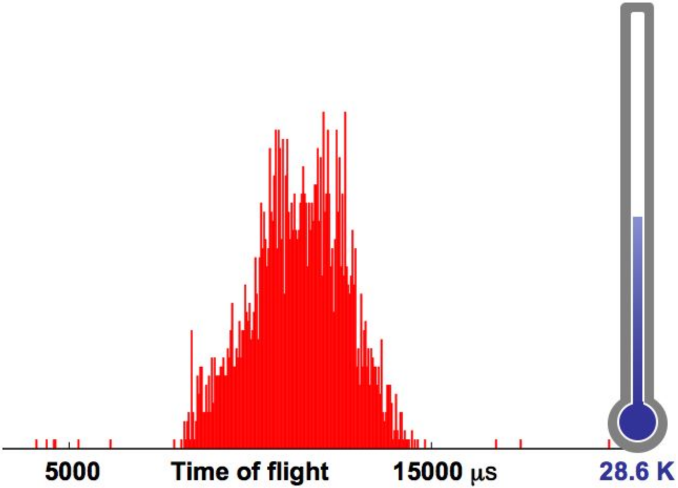
Cluster velocity

TOF cluster measurement at 14 bar, 28.7 K



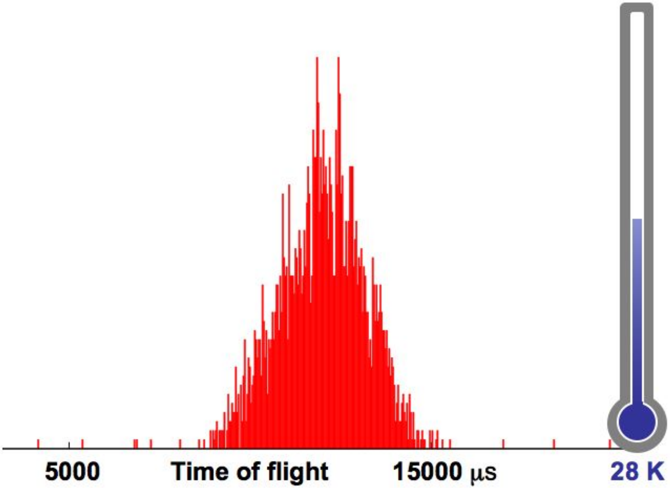
Cluster velocity

TOF cluster measurement at 14 bar, 28.6 K



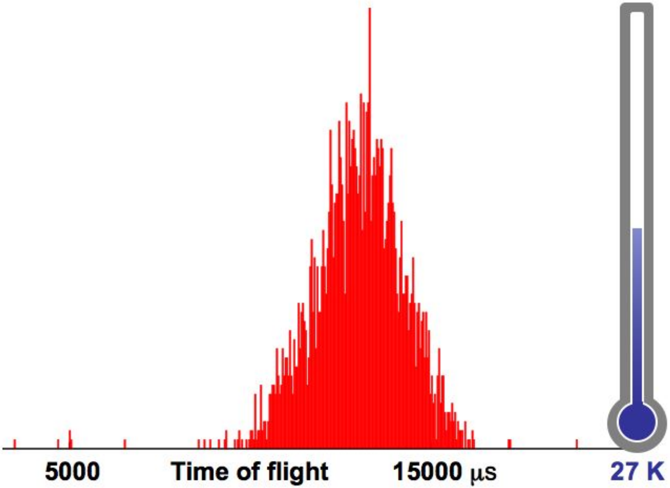
Cluster velocity

TOF cluster measurement at 14 bar, 28 K



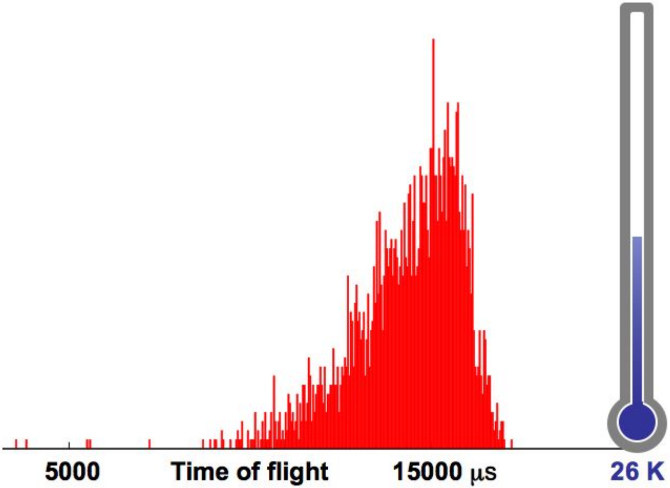
Cluster velocity

TOF cluster measurement at 14 bar, 27 K



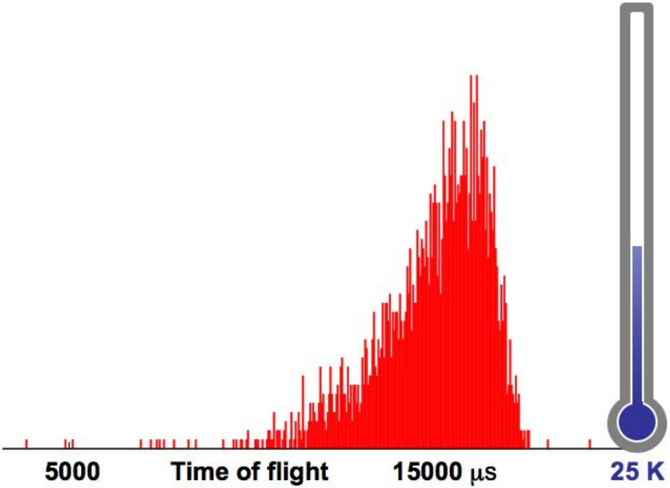
Cluster velocity

TOF cluster measurement at 14 bar, 26 K



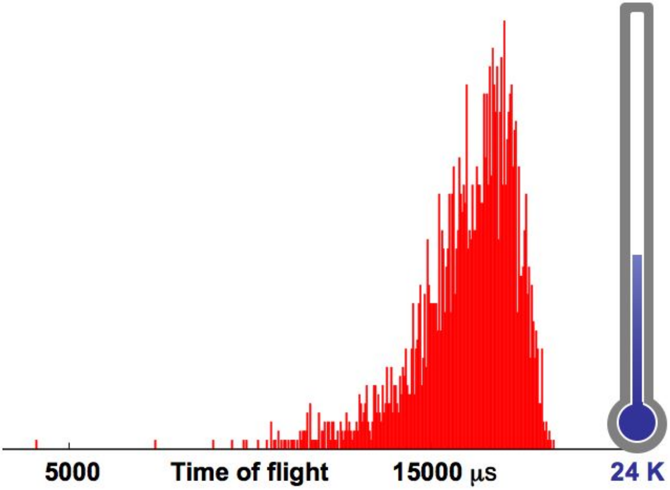
Cluster velocity

TOF cluster measurement at 14 bar, 25 K



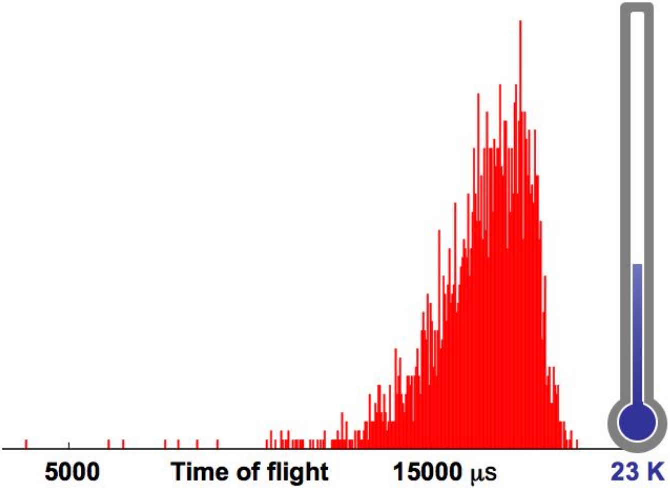
Cluster velocity

TOF cluster measurement at 14 bar, 24 K



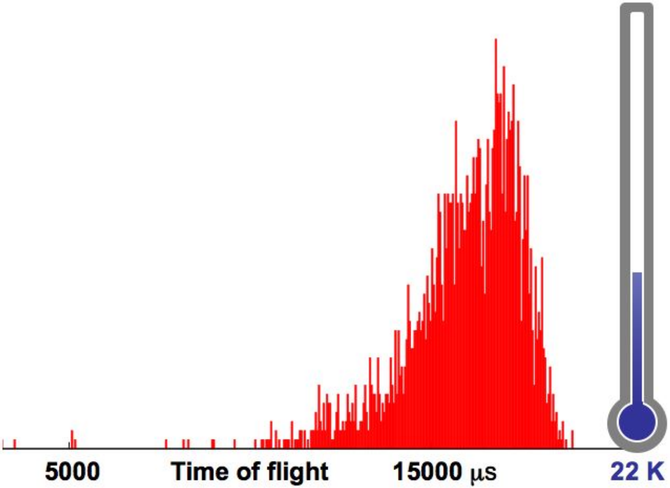
Cluster velocity

TOF cluster measurement at 14 bar, 23 K



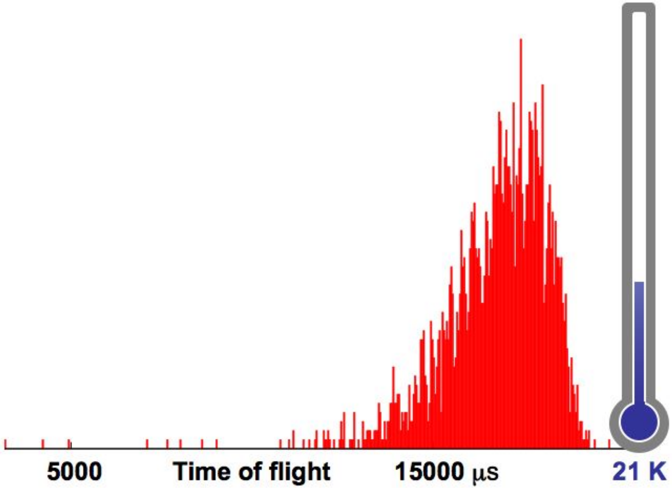
Cluster velocity

TOF cluster measurement at 14 bar, 22 K



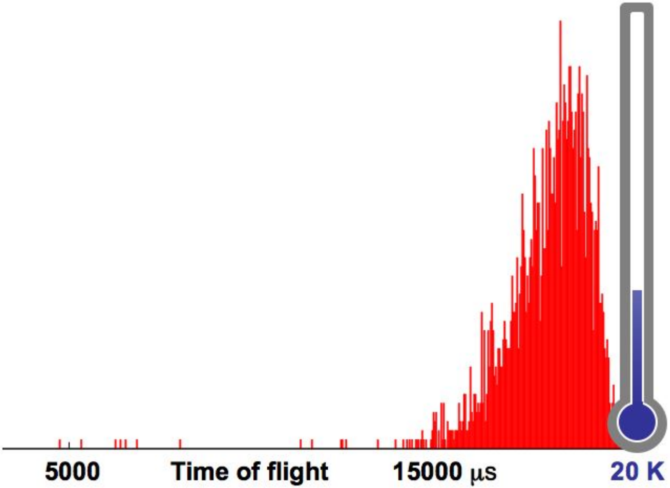
Cluster velocity

TOF cluster measurement at 14 bar, 21 K



Cluster velocity

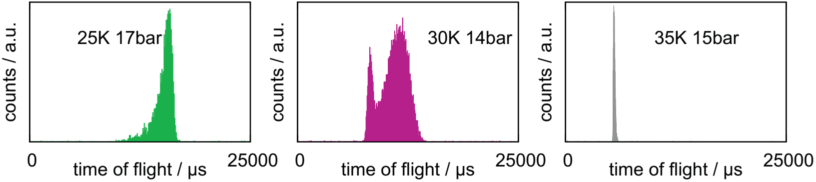
TOF cluster measurement at 14 bar, 20 K



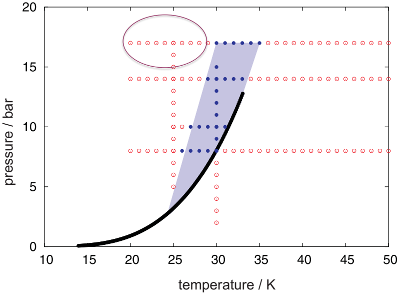
Cluster velocity

TOF cluster measurement

- Observation of different TOF distributions



- Double peak shows up beyond main $\overline{\text{P}}$ANDA working point



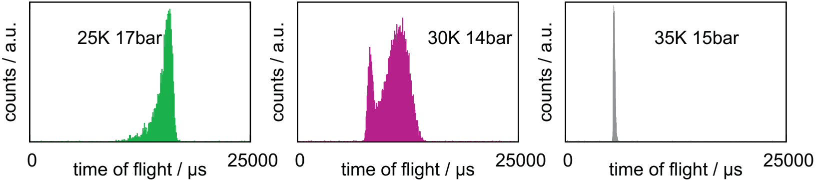
- Evidence for two hydrogen phases and different cluster production processes

  $\Longrightarrow$ **Research on cluster mass and size needed (FP7 HP3)**

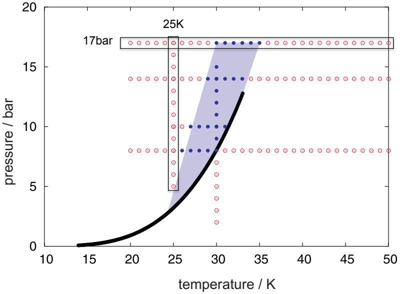
Cluster velocity

TOF cluster measurement

- Observation of different TOF distributions



- Double peak shows up beyond main $\overline{\text{P}}$ANDA working point

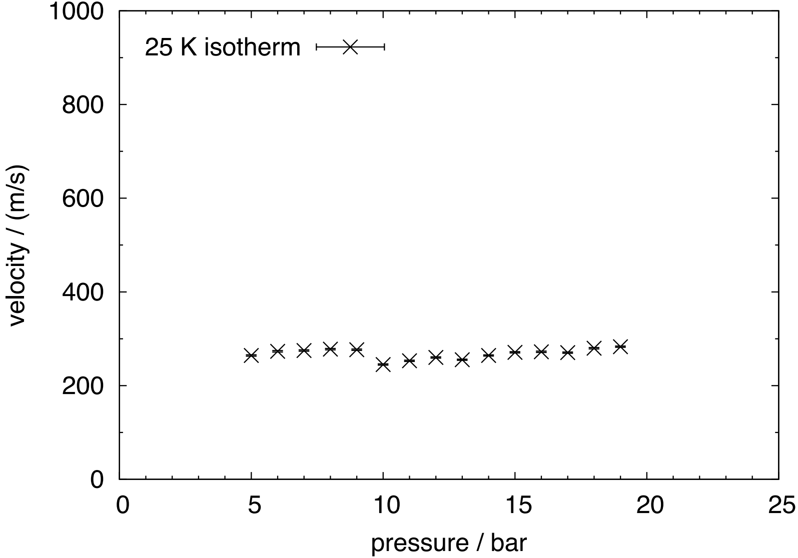


- Evidence for two hydrogen phases and different cluster production processes

  $\Longrightarrow$ **Research on cluster mass and size needed (FP7 HP3)**

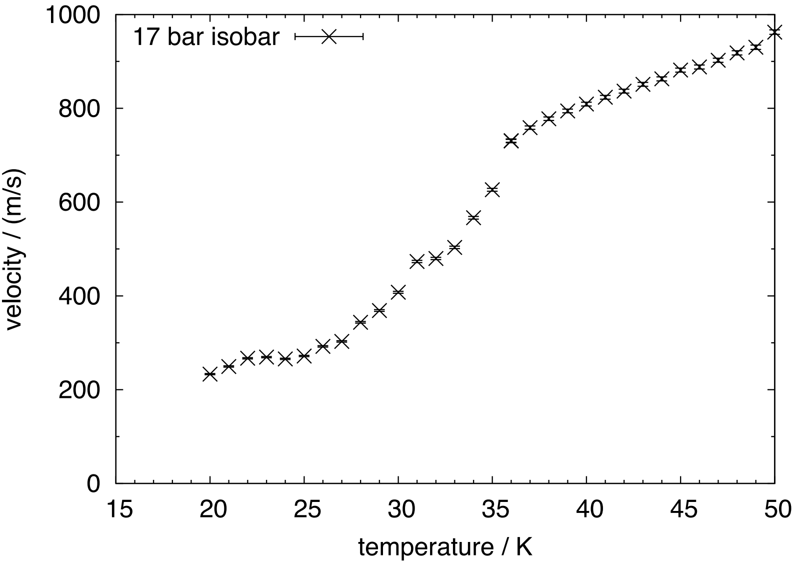
Cluster velocity

25 K isotherm



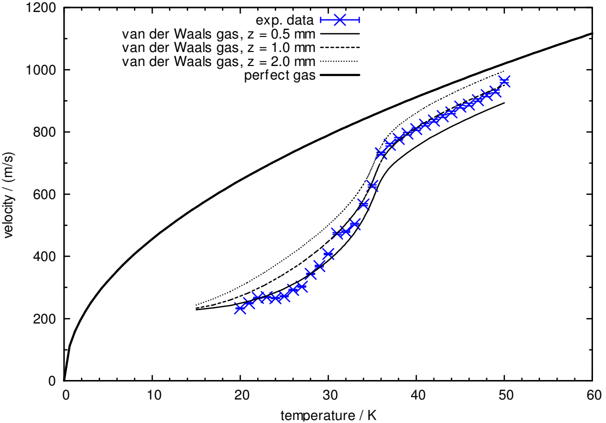
Cluster velocity

17 bar isobar



Cluster velocity

17 bar isobare

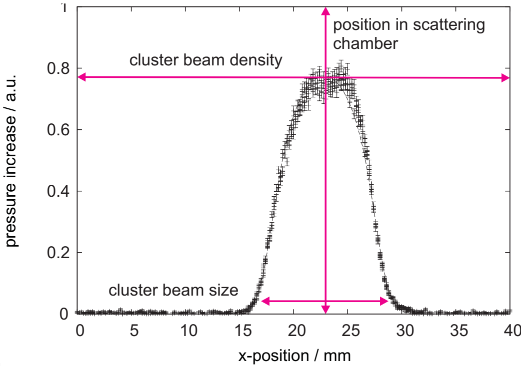


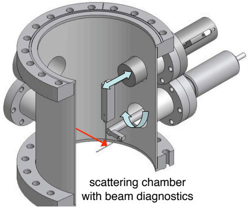
- Observed velocity: $\approx 200 - 1000\,\mathrm{m/s}$
- Strong discrepancy from perfect gas
- Good agreement with van der Waals gas (small variations)
- **Freezeout position** z of the cluster velocity at 0.5 and 1 mm from the narrowest point

  $\Longrightarrow$ important for nozzle production

Target density

Beam profile





$$\rho_T \sim \frac{p_{sc}}{v_c}$$

ρ_T: Target density

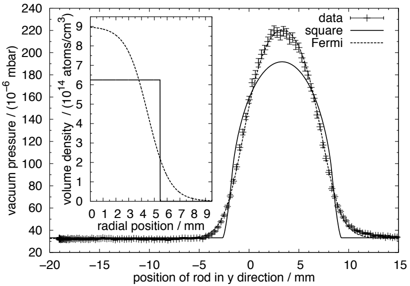
p_{sc}: Pressure increase

v_c: Cluster velocity

$(200 - 1000\,\mathrm{m/s})$

Target density

Beam profile



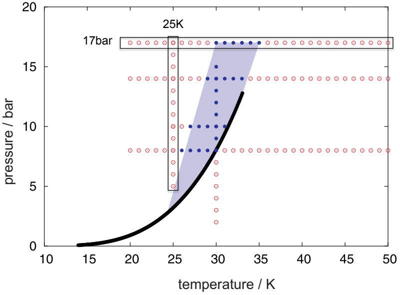
- Solid line: fit assuming a homogeneous radial volume density (with sharp boundaries) $\rho_{square}(r) = \begin{cases} \rho_0 & \text{for } r \leq R \\ 0 & \text{for } r > R \end{cases}$
- Dashed line: Fermi-like density (with smooth boundaries)

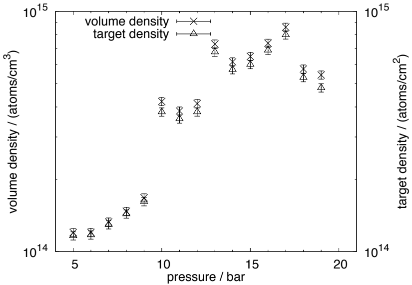
$$\rho_{Fermi}(r) = \rho_0 \left(\exp\left(\frac{-R}{s}\right) + 1\right) / \left(\exp\left(\frac{r-R}{s}\right) + 1\right)$$

ρ_0: maximal volume density
R: beam radius
s: smearing factor

Target density

...at 25 K

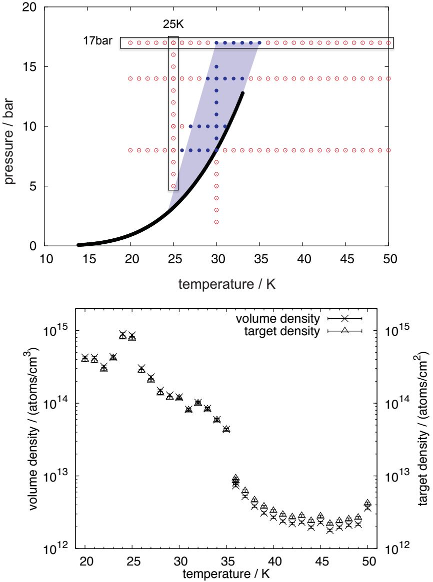




- Target density easy to vary over **one order of magnitude** (T constant, p variable)
- **Increase** of target density with increasing pressure up to 17 bar (with small variations)
- **Decreasing** target density above 17 bar

Target density

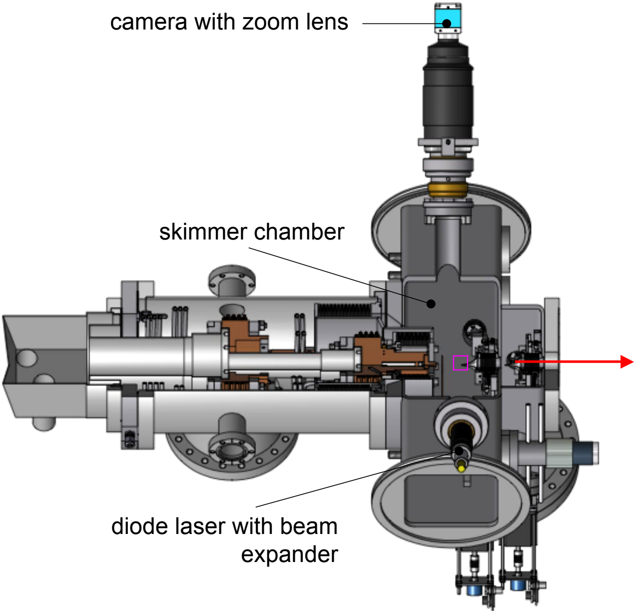
...at 17 bar, above critical point (33.18 K, 13 bar)



- Target density easy to vary over **several orders of magnitude** (T variable, p constant)
- **Increase** of target density with decreasing temperature up to 24 K (8×10^{14} atoms/cm^2) (with small variations)
- **Drop** because of different hydrogen phases at formation of clusters (supercritical fluid $\longrightarrow$ fluid)
- **Decreasing** target density below 24 K

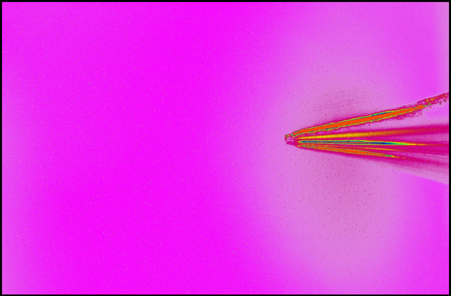
Target density

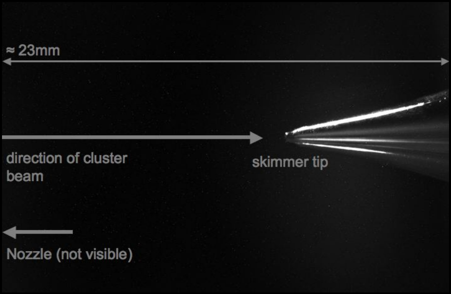
Cluster source overview



Target density

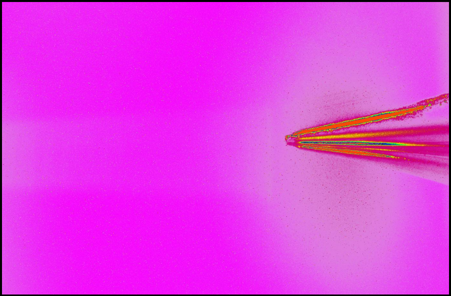
50-40 K, 18.5 bar

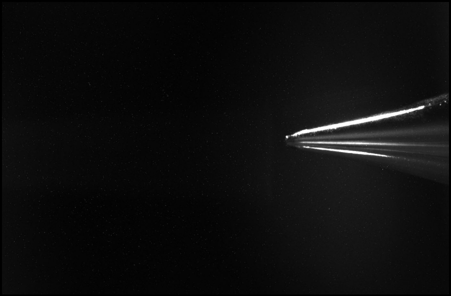




Target density

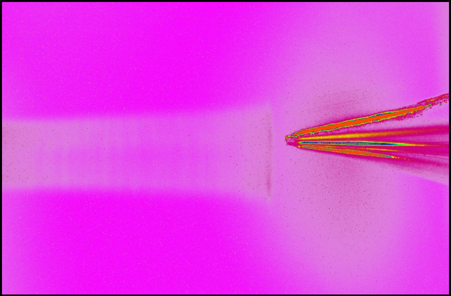
39 K, 18.5 bar

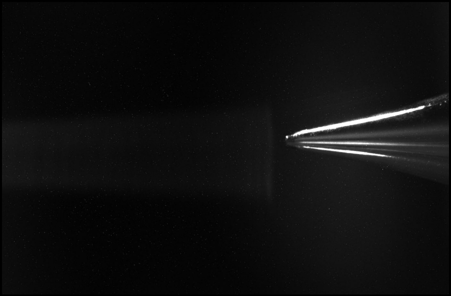




Target density

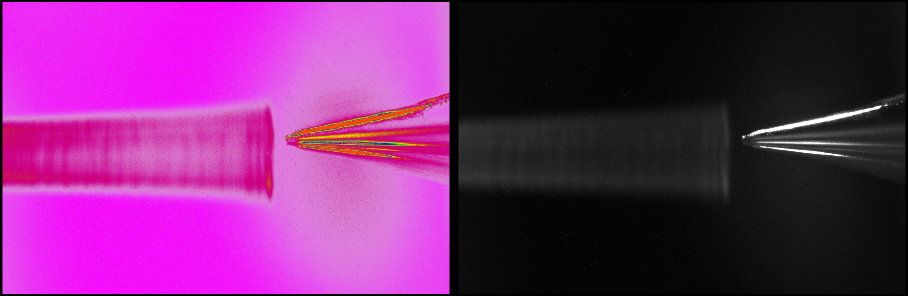
38 K, 18.5 bar





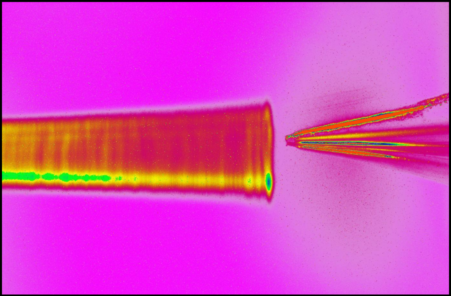
Target density

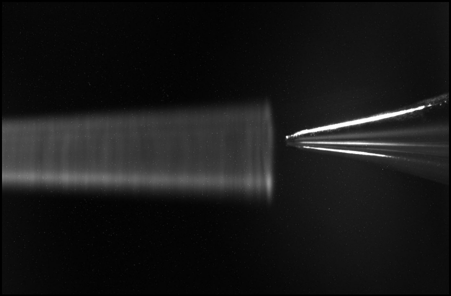
37 K, 18.5 bar



Target density

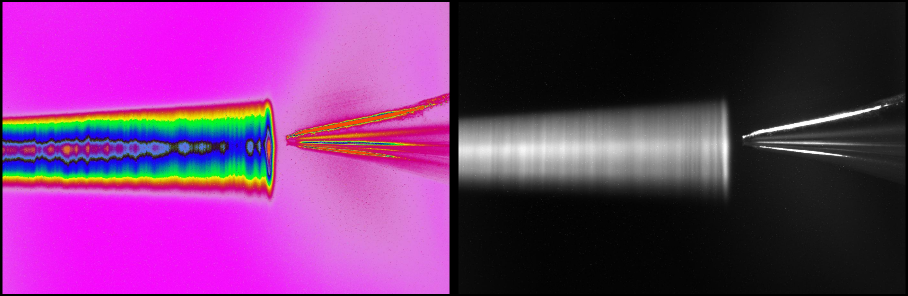
36 K, 18.5 bar





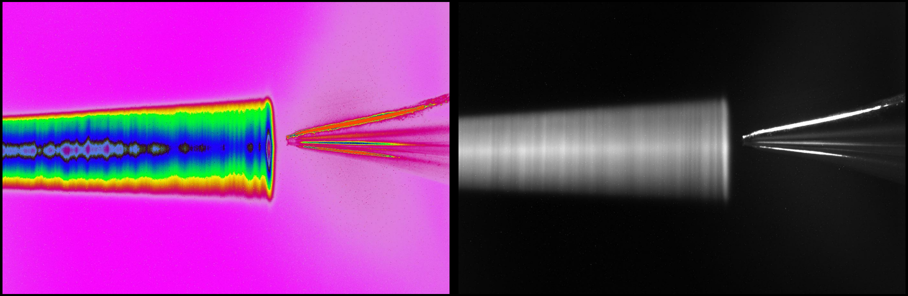
Target density

35 K, 18.5 bar



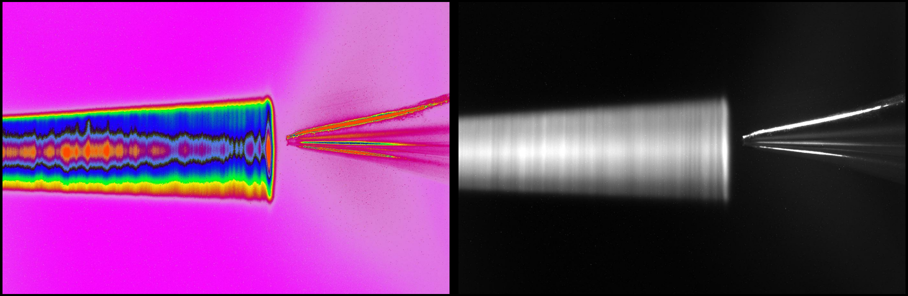
Target density

34 K, 18.5 bar



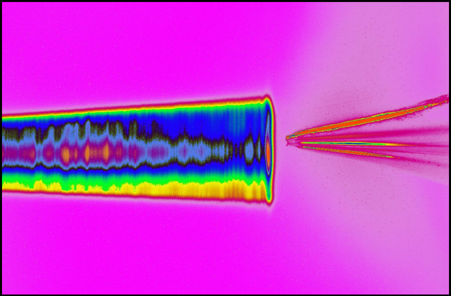
Target density

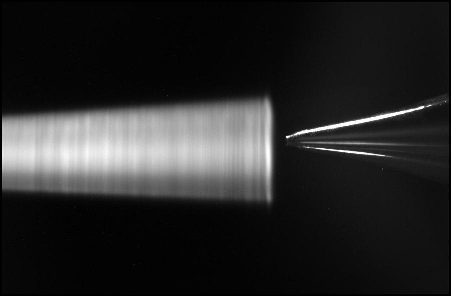
33 K, 18.5 bar



Target density

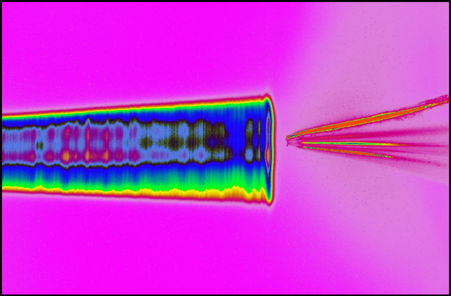
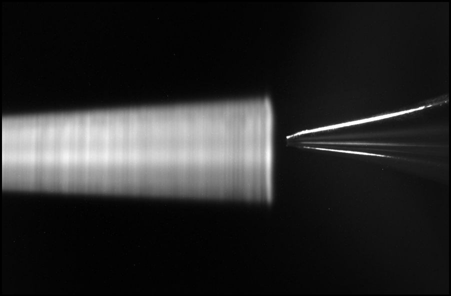
32 K, 18.5 bar





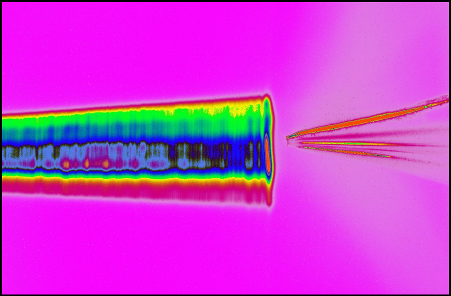
Target density

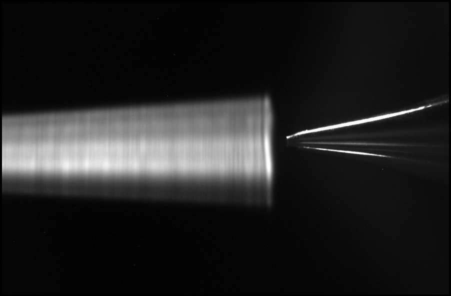
31 K, 18.5 bar

Target density

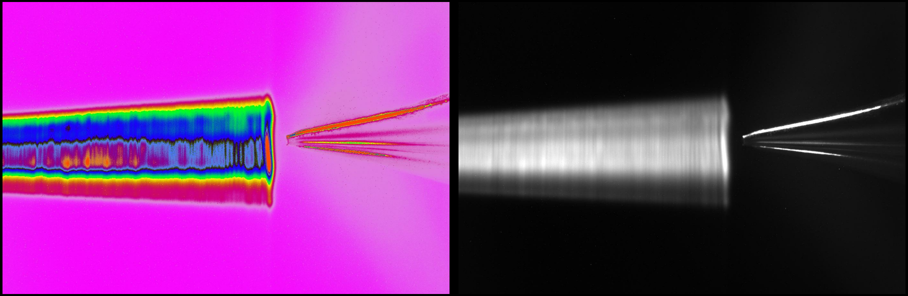
30 K, 18.5 bar





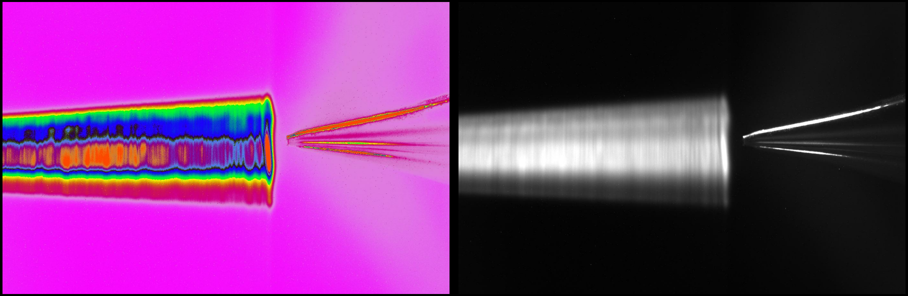
Target density

29 K, 18.5 bar



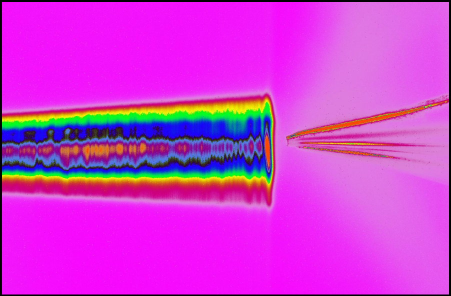
Target density

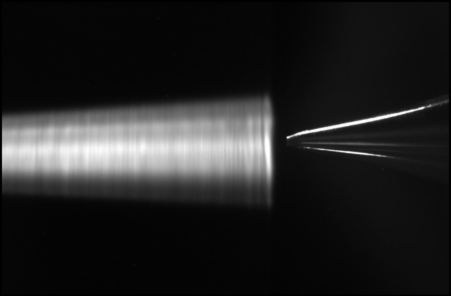
28 K, 18.5 bar



Target density

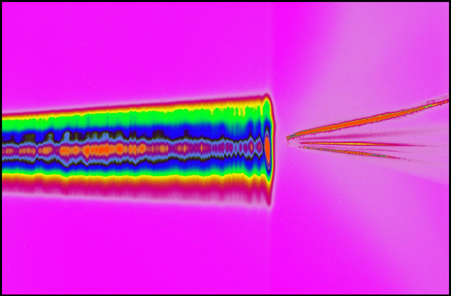
27 K, 18.5 bar

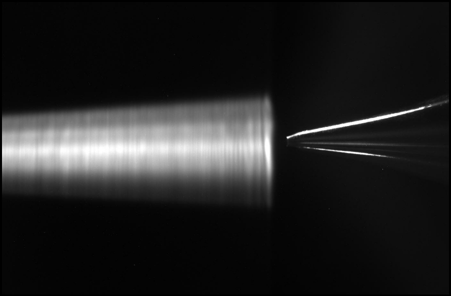




Target density

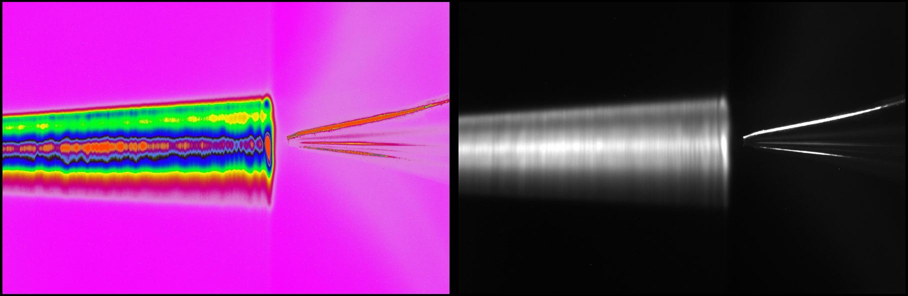
26 K, 18.5 bar





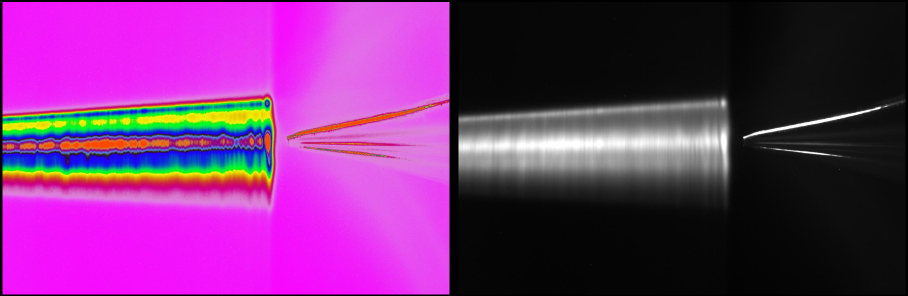
Target density

25 K, 18.5 bar



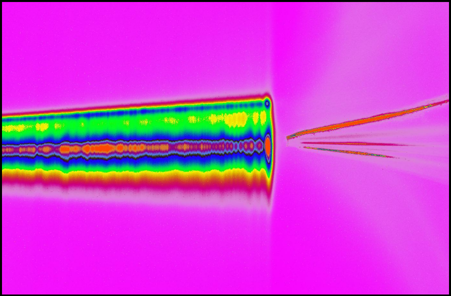
Target density

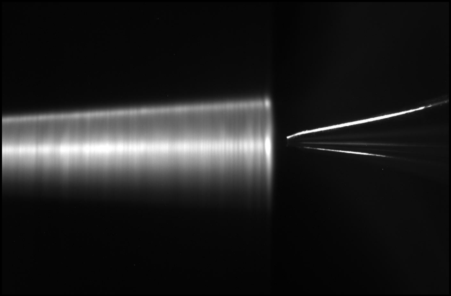
24 K, 18.5 bar



Target density

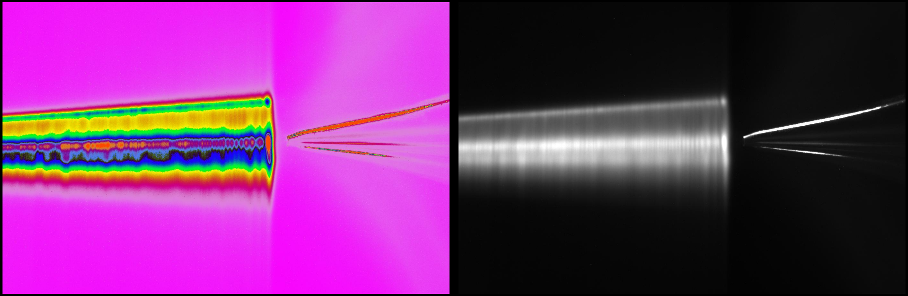
23 K, 18.5 bar





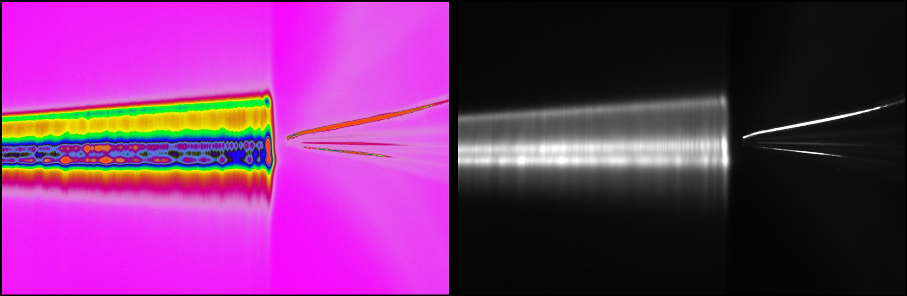
Target density

22 K, 18.5 bar



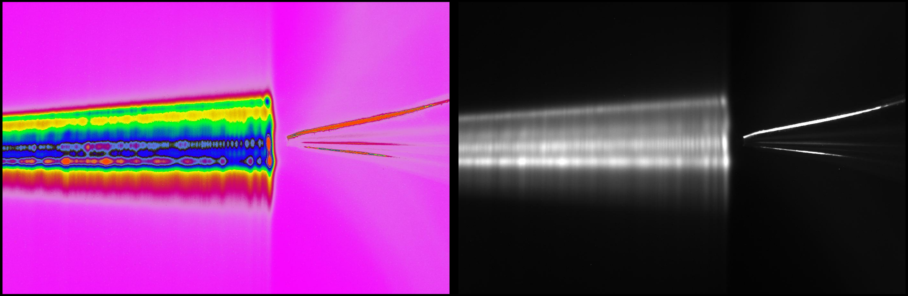
Target density

21 K, 18.5 bar



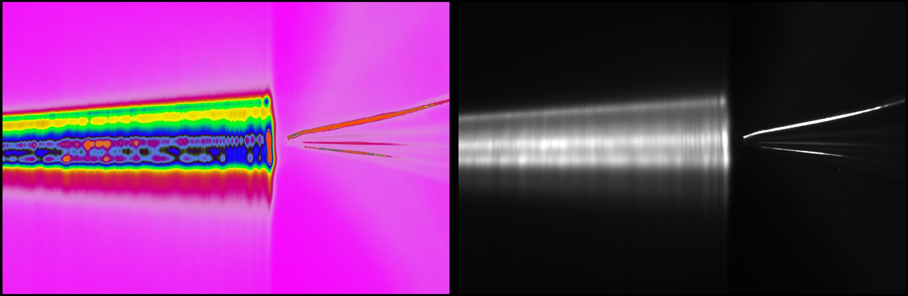
Target density

20 K, 18.5 bar



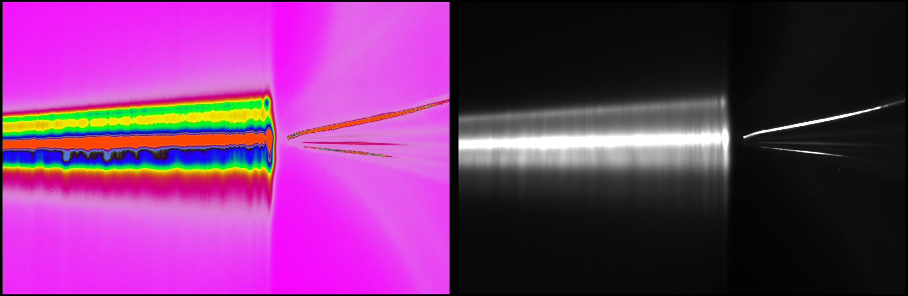
Target density

19 K, 18.5 bar



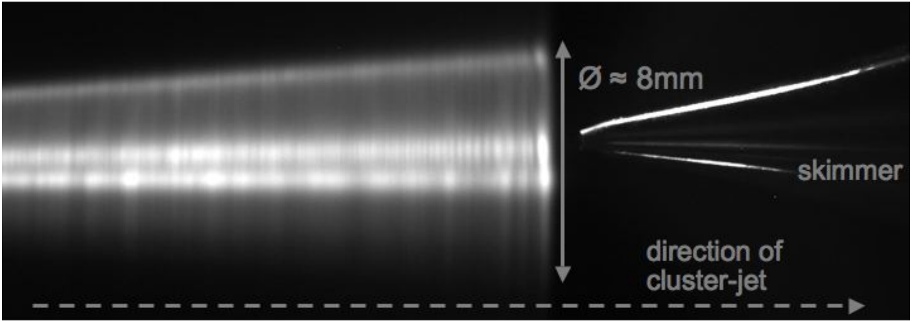
Target density

18.3 K, 18.5 bar



Target density

Cluster beam in skimmer chamber

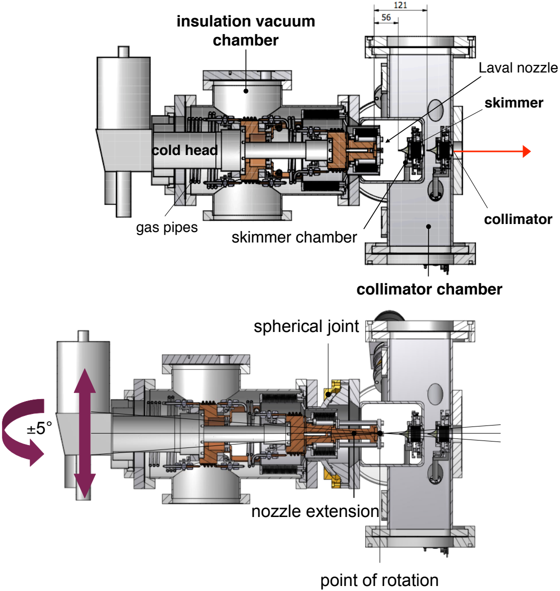


- Inhomogeneous cluster beam in skimmer chamber
- Density still constant in scattering chamber
  ($\overline{\text{P}}$ANDA interaction point) $\longrightarrow$ extracted beam is homogeneous
- Brighter area = higher density ?

$\Longrightarrow$ **Movable nozzle required**

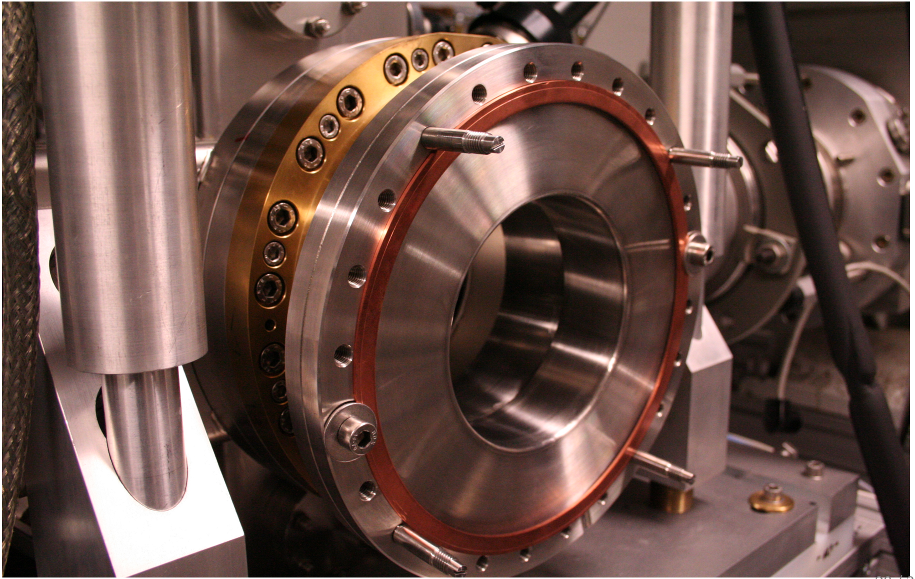
Target density

Movable nozzle

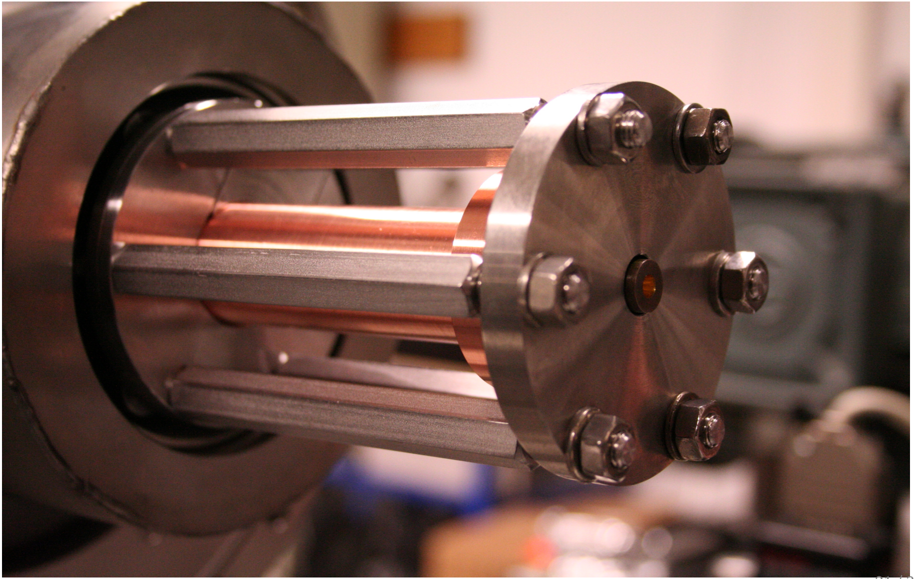


Target density

Spherical joint

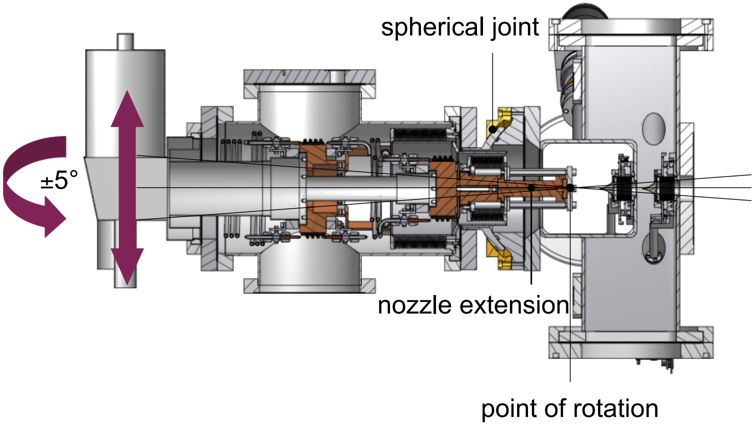


Target density
Nozzle extension



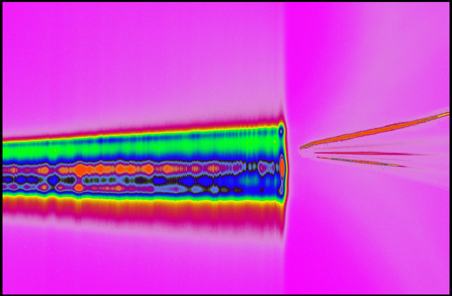
Target density

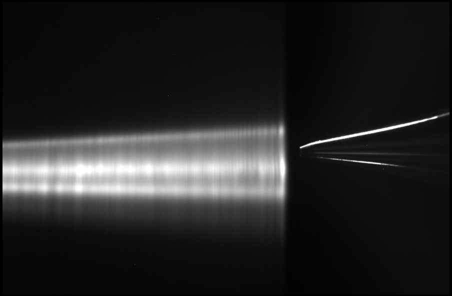
Movable nozzle

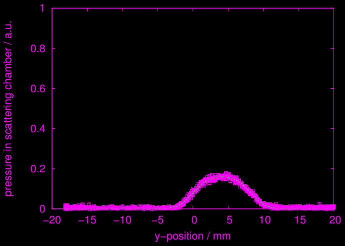


Target density

19 K, 18.5 bar

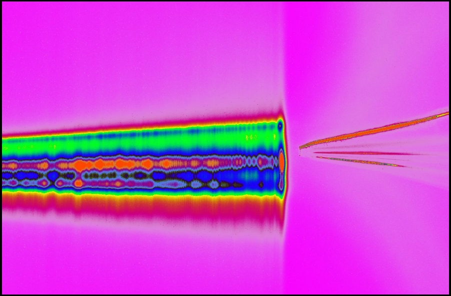


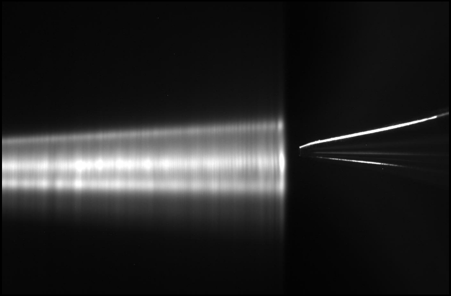


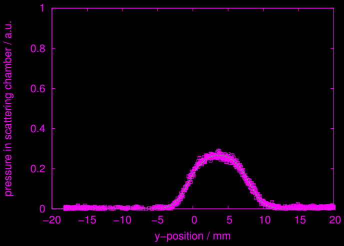


Target density

19 K, 18.5 bar

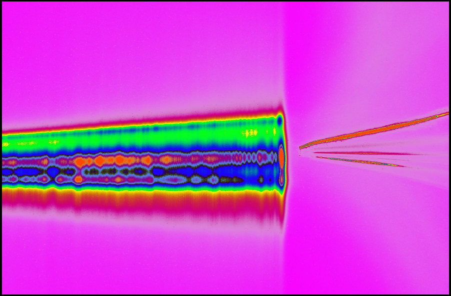


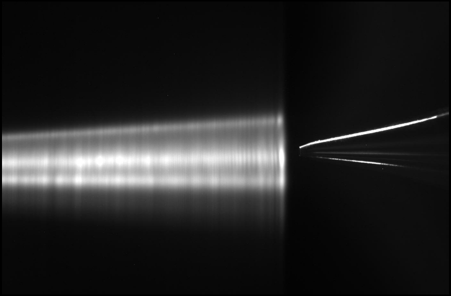


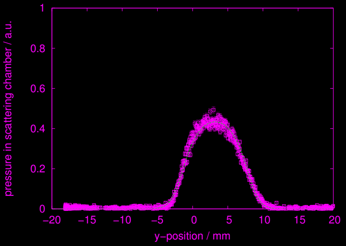


Target density

19 K, 18.5 bar

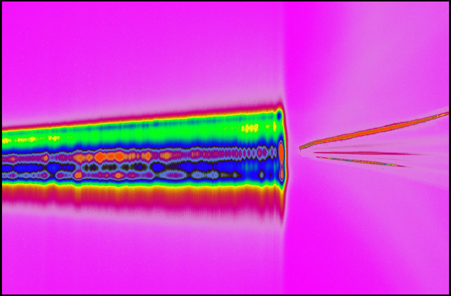


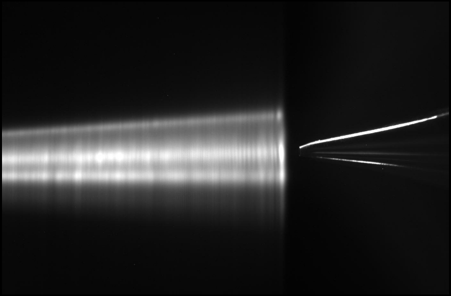


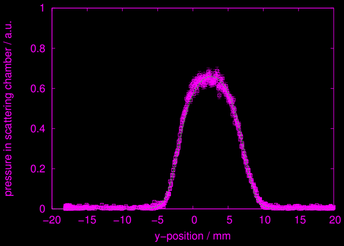


Target density

19 K, 18.5 bar

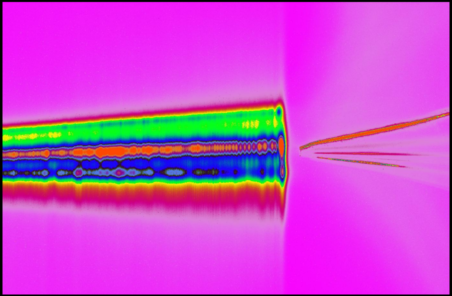


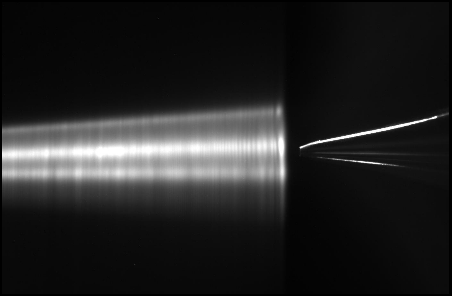


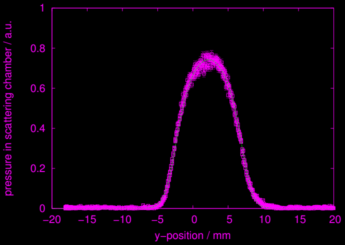


Target density

19 K, 18.5 bar

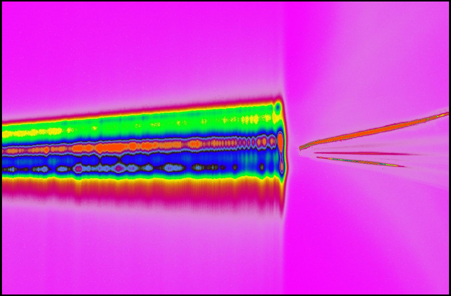


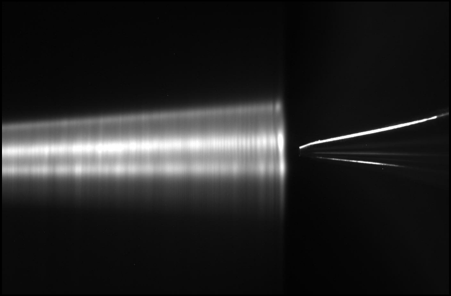


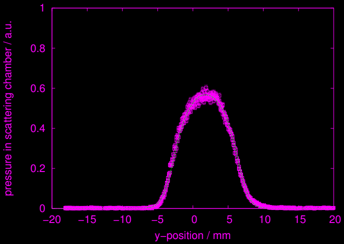


Target density

19 K, 18.5 bar

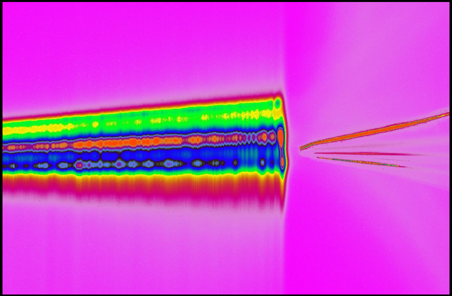


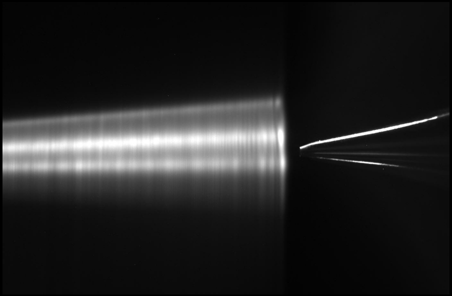


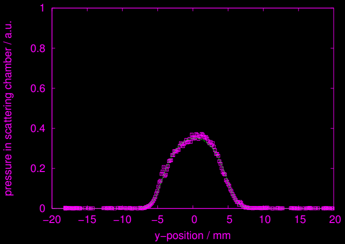


Target density

19 K, 18.5 bar

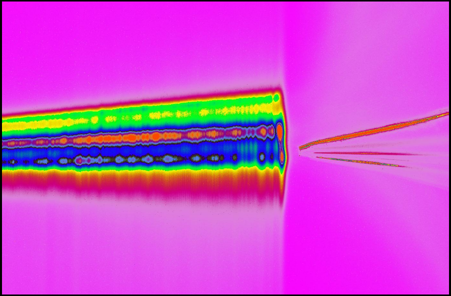


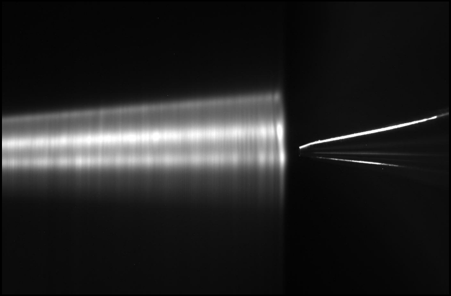


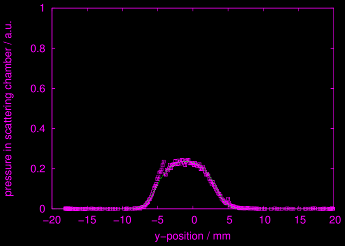


Target density

19 K, 18.5 bar

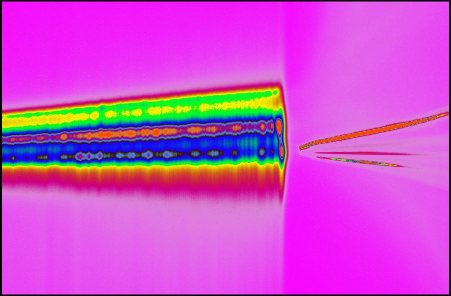


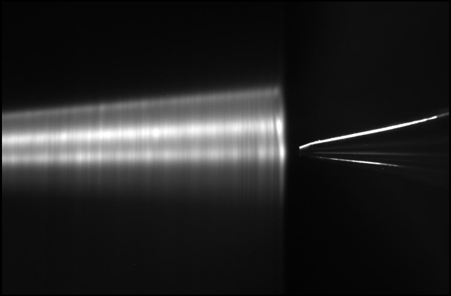


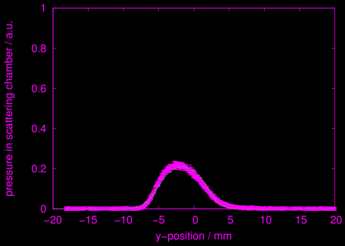


Target density

19 K, 18.5 bar

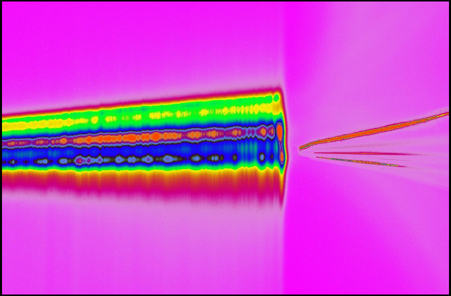


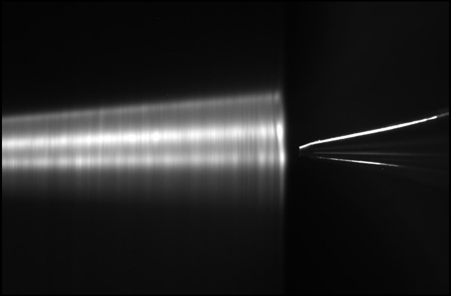


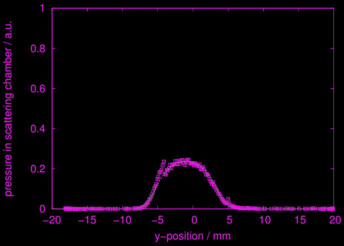


Target density

19 K, 18.5 bar

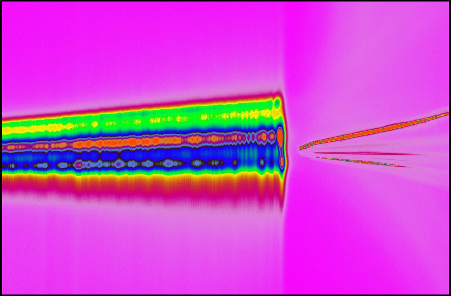


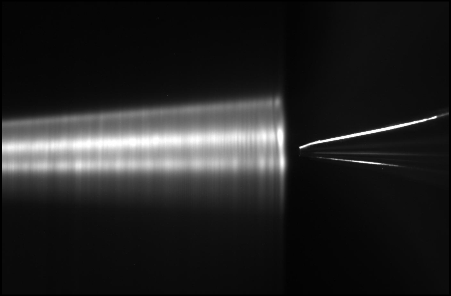


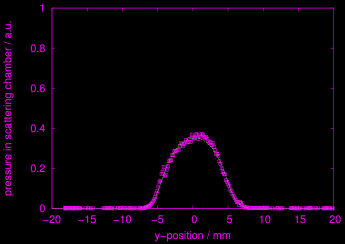


Target density

19 K, 18.5 bar

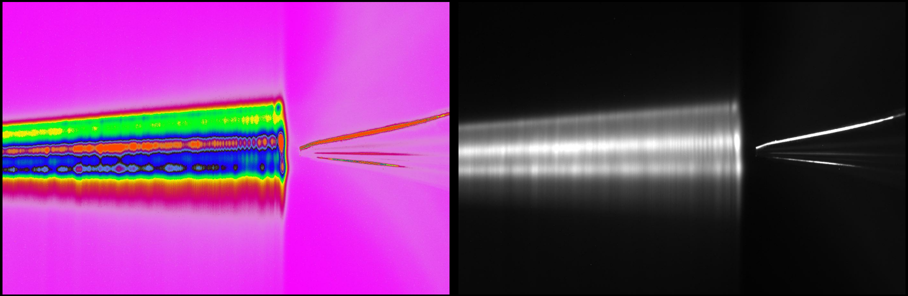


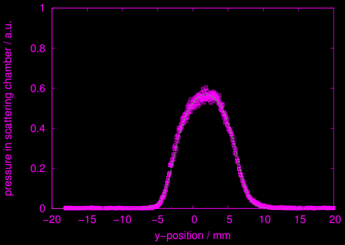




Target density

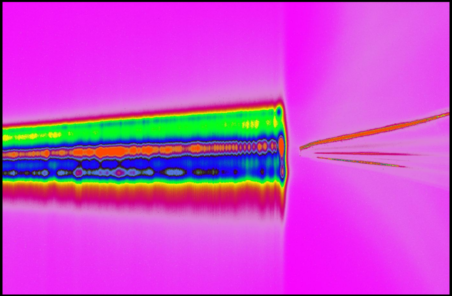
19 K, 18.5 bar

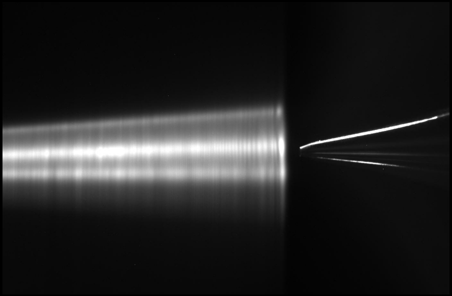


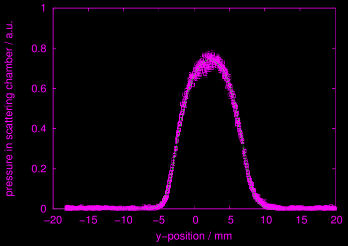


Target density

19 K, 18.5 bar

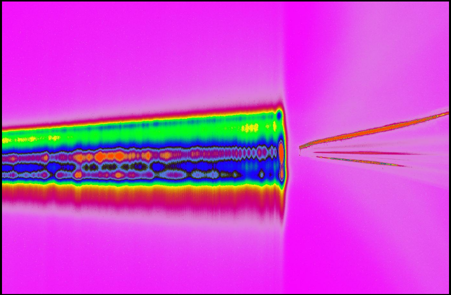


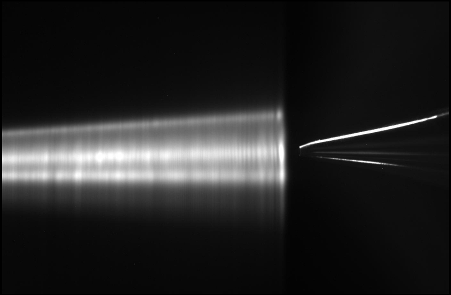


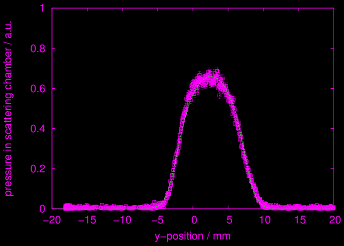


Target density

19 K, 18.5 bar

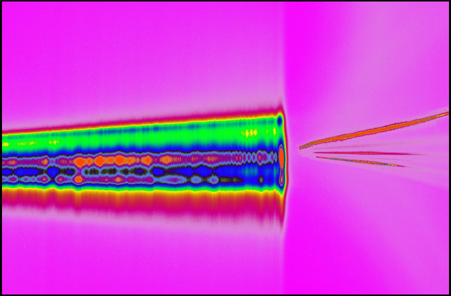


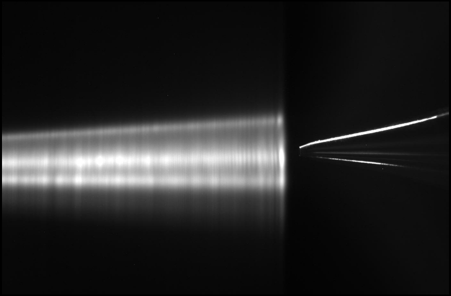


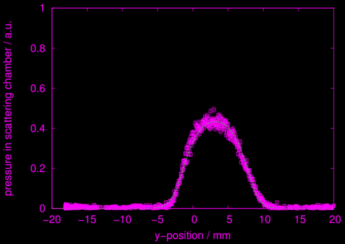


Target density

19 K, 18.5 bar

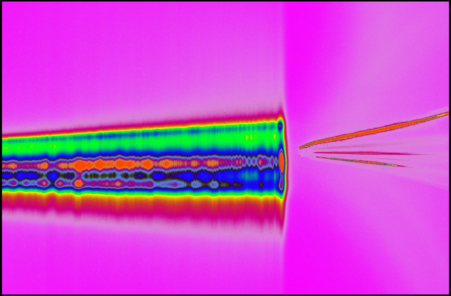


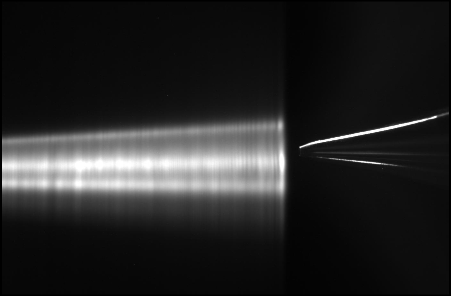


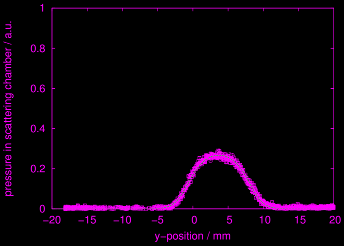


Target density

19 K, 18.5 bar

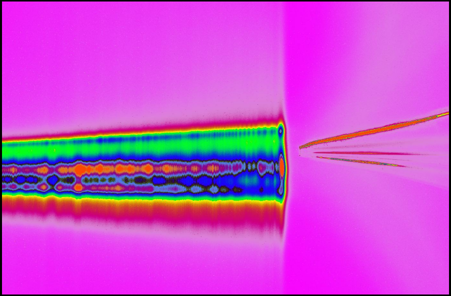


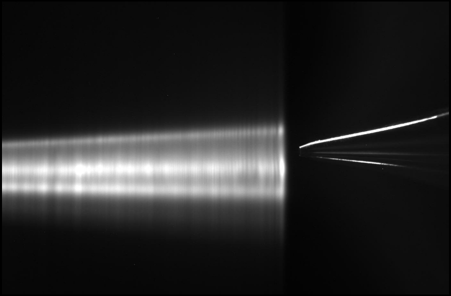


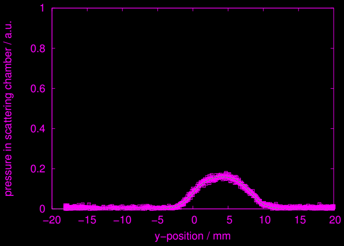


Target density

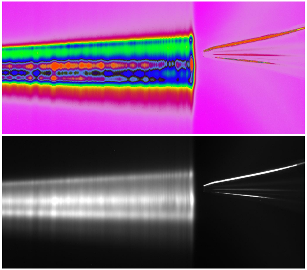
19 K, 18.5 bar

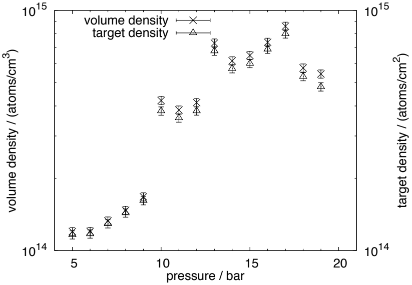


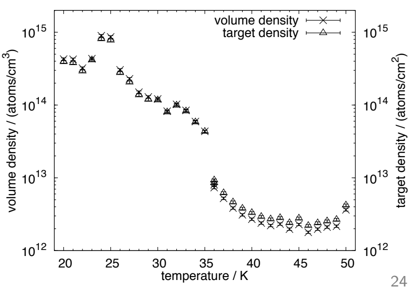




- Brighter area = higher density !
- Structures responsible for
  - variations
  - decreasing density



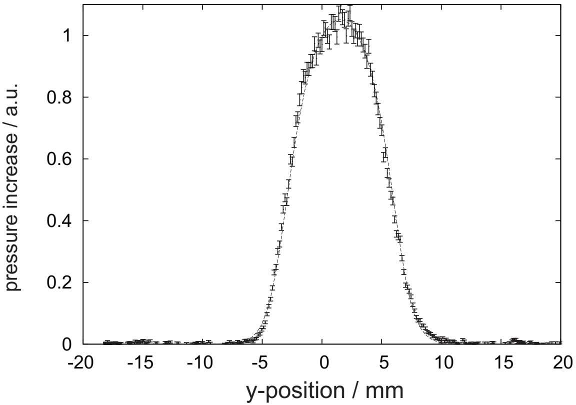




Target density

First tests with tilting system

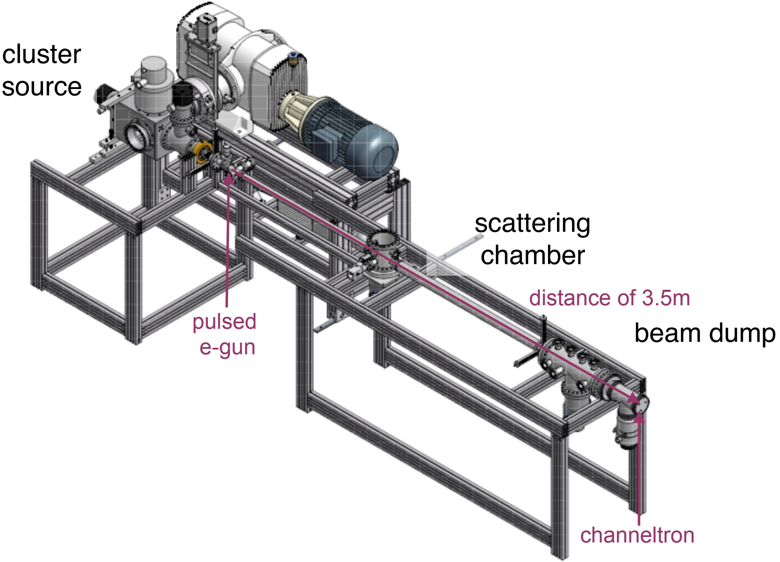
- temperature:
  19 K
- pressure:
  18.5 bar
- diameter:
  10.3 mm
- velocity:
  $\approx 250\,\mathrm{m/s}$



- Volume density:
  $$\mathbf{1.9 \times 10^{15}}\,\mathrm{atoms/cm^3}$$
  $\Longrightarrow$ **Systematic studies (FP7 HP3)**

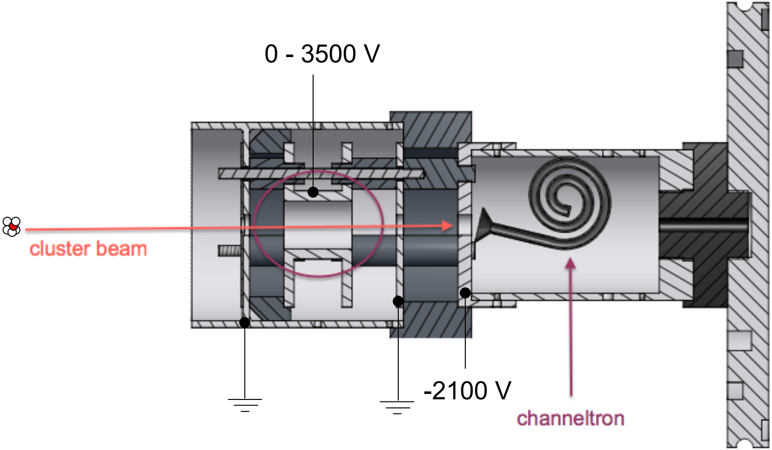
Mass distribution

Overview of the MCT1 cluster-jet target



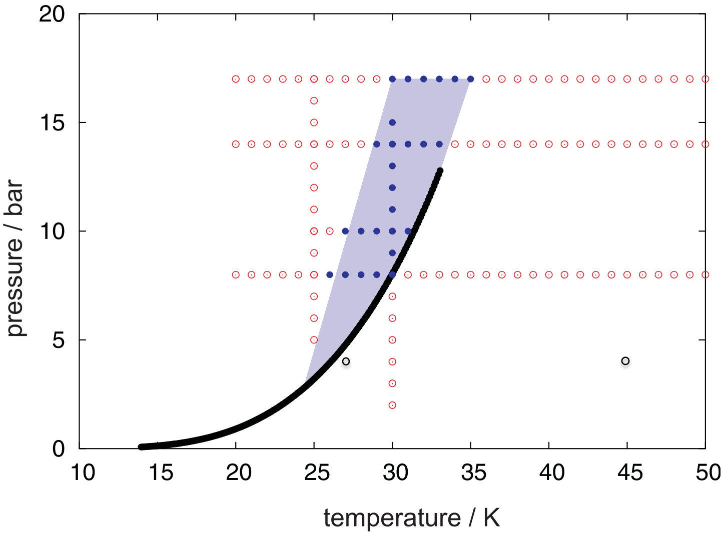
Mass distribution

Opposing electrical field



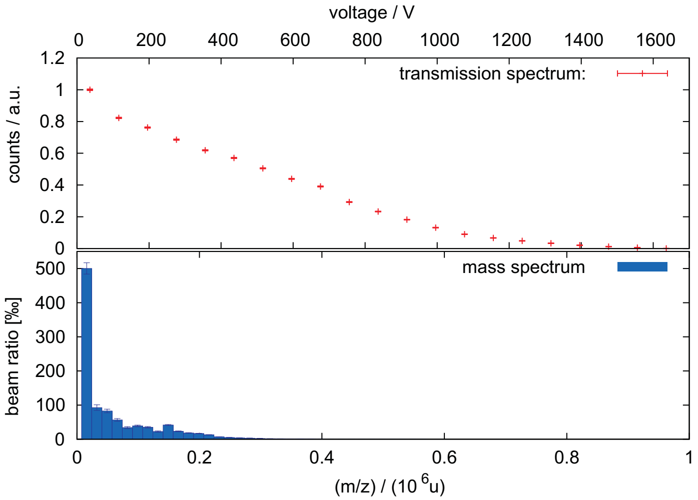
Mass distribution

...measurements at 4 bar (MCT1)



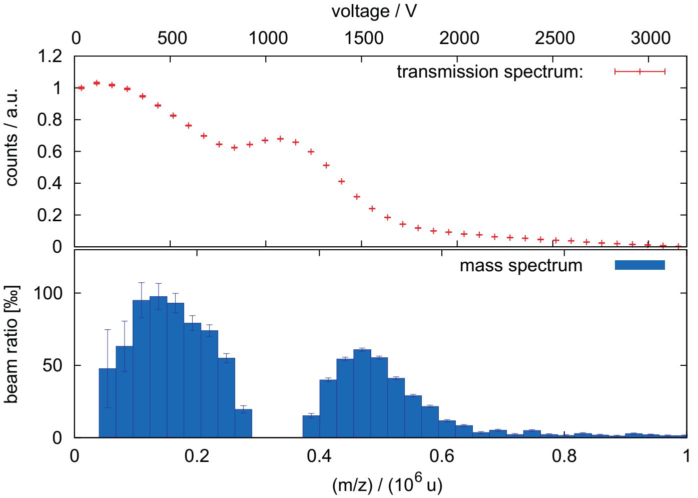
Mass distribution

45 K, 4 bar (MCT1)



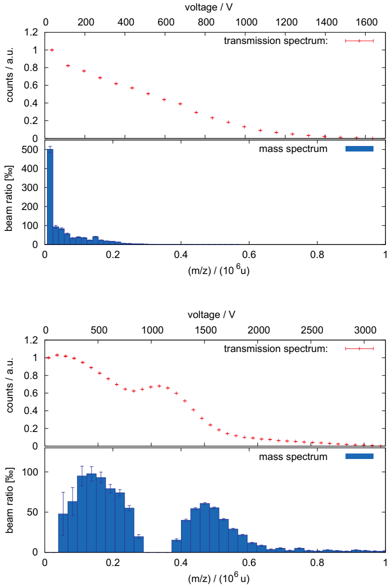
Mass distribution

27 K, 4 bar (MCT1)



Mass distribution

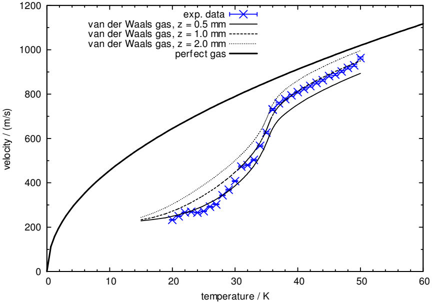
45 and 27 K at 4 bar (MCT1)



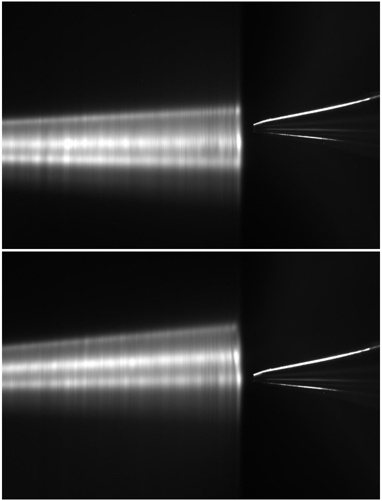
- Increase of cluster mass with decreasing temperature
- Measured clusters consist of up to 500 000 molecules (at 26.5 K, 4 bar)
- Indication of two different cluster masses at the same T/p settings (near vapor pressure curve)

  $\Longrightarrow$ Associated with measured TOF double peak ?

- Extended velocity measurements with tilting system

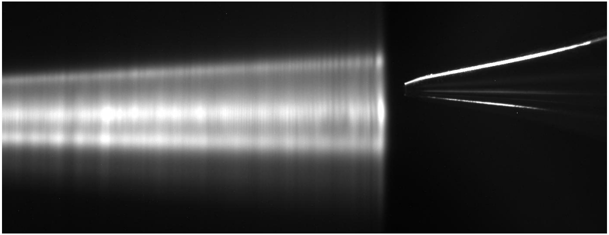


- Systematic measurements:
  - Brighter area = higher density ! = lower velocity ?
  - Variations because of beam structure ?



Future concept and objectives (FP7 HP3)

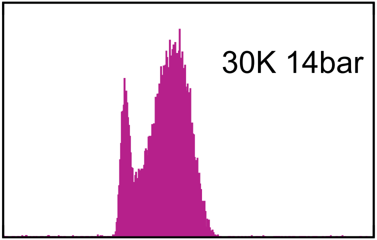
Target density

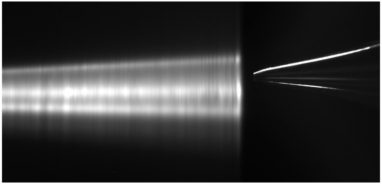


- Systematic measurements:
  - Search for the T/p settings with the highest density (in combination with tilting system)
  - Stability measurements
  - Reproducibility of cluster beam $\longrightarrow$ impacts on adjustment
  - Feasibility studies on density adjustments in real time
    - variation of pressure settings
    - modification of vacuum conditions in skimmer chamber
    - inception of plates/wires at cluster beam

Future concept and objectives (FP7 HP3)

Mass distribution

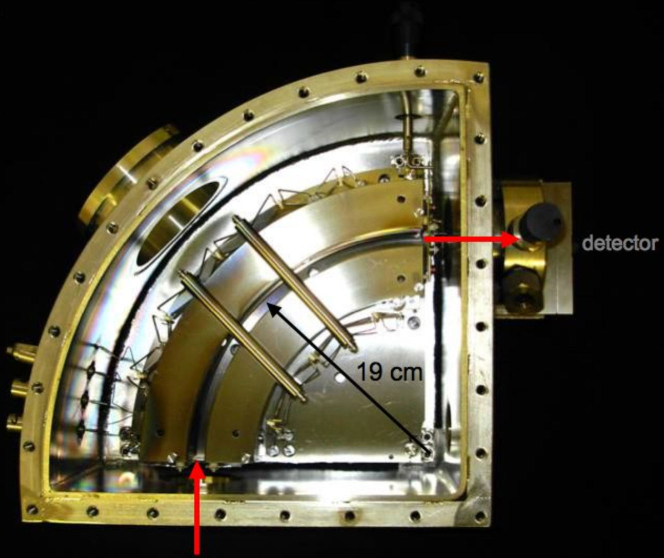




- Extended mass measurements with tilting system (MCT2)
- Systematic measurements:
    - TOF double peak because of two different cluster masses ?
    - Brighter area = higher density = higher masses ?
    - Cluster production with liquid hydrogen ?

Future concept and objectives (FP7 HP3)

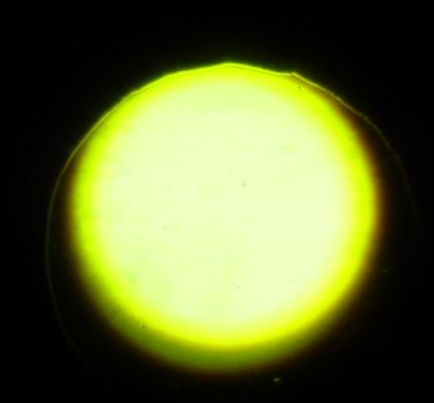
Mass distribution with new mass spectrometer



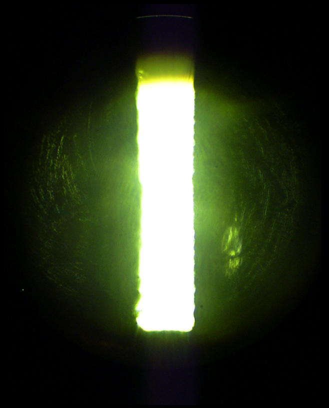
Future concept and objectives (FP7 HP3)

Beam shape

LM-Micrograph of a collimator with round opening and slit



$\varnothing = 0.7\,\mathrm{mm}$

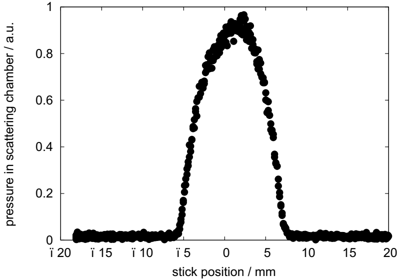


$150 \times 860\,\mu\mathrm{m}$

Future concept and objectives (FP7 HP3)

Beam shape

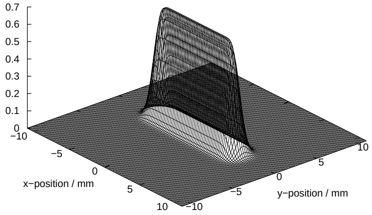
Round shaped cluster beam vs. line formed cluster beam

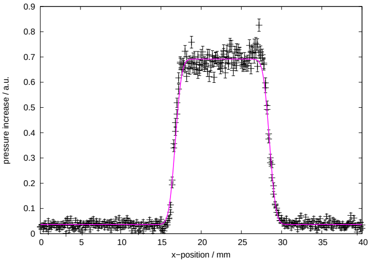


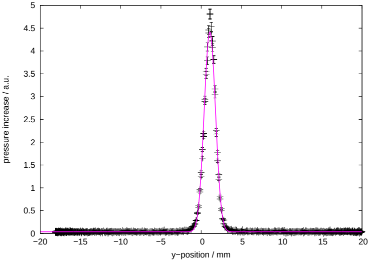
- First measurements: cluster beam is easy to shape with an orifice

Future concept and objectives (FP7 HP3)

Beam shape







- Density distribution: $\rho(x,y) = \rho_0$

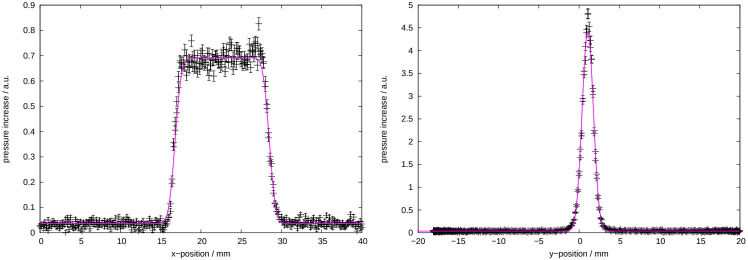
$$\cdot \frac{\left(\mathrm{erf}\left(\frac{\frac{b_x}{2}-x}{s}\right) - \mathrm{erf}\left(\frac{\frac{-b_x}{2}-x}{s}\right)\right)}{2}$$

$$\cdot \frac{\left(\mathrm{erf}\left(\frac{\frac{b_y}{2}-y}{s}\right) - \mathrm{erf}\left(\frac{\frac{-b_y}{2}-y}{s}\right)\right)}{2}$$

ρ_0: maximal volume density
$b_{x,y}$: total width
s: smearing factor

Future concept and objectives (FP7 HP3)

Beam shape



- Systematic measurements:
  - Influence on the vacuum conditions ?
  - Influence on target density ?
  - Search for the best size
  - 2-dim image with use of a micro channel plates

Thank you for your attention!

Westfälische Wilhelms-Universität Münster

Bundesministerium für Bildung und Forschung