“Development and characterization of cryogenically cooled liquid droplet internal target beams”

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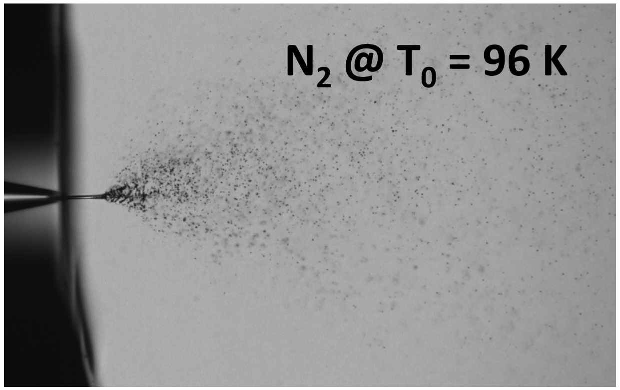
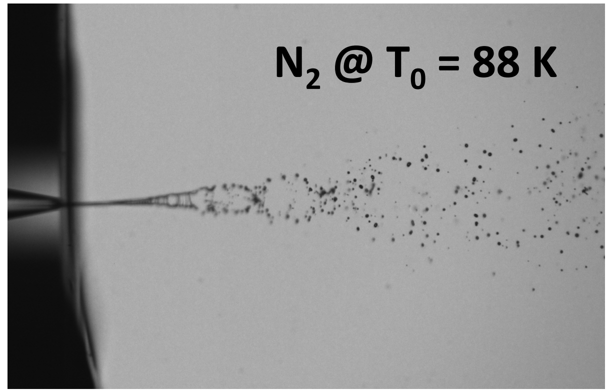
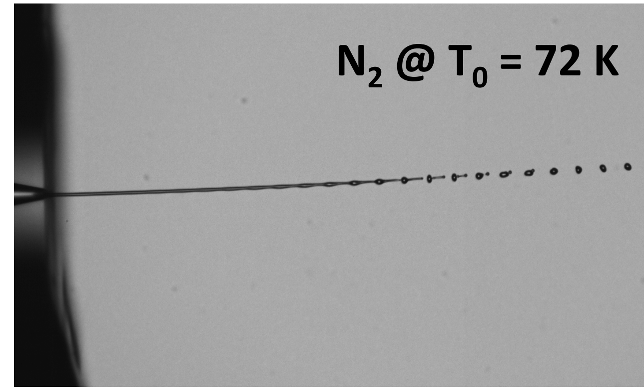
Simple idea to increase the target density



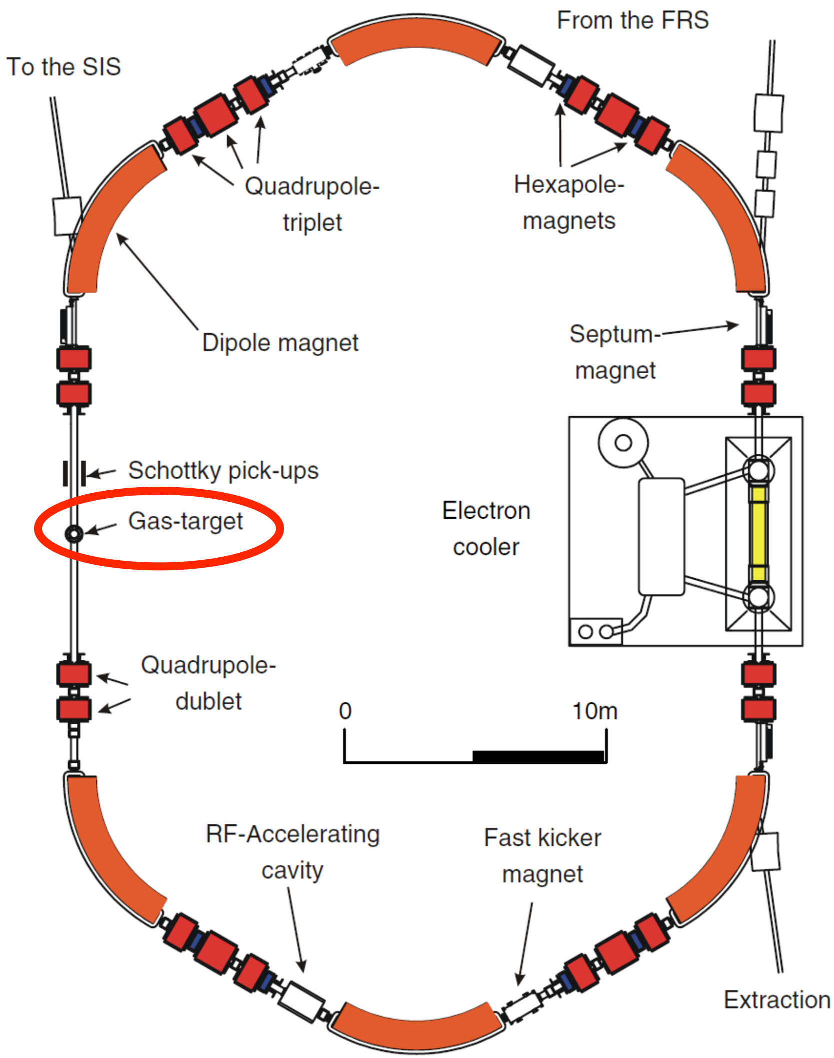


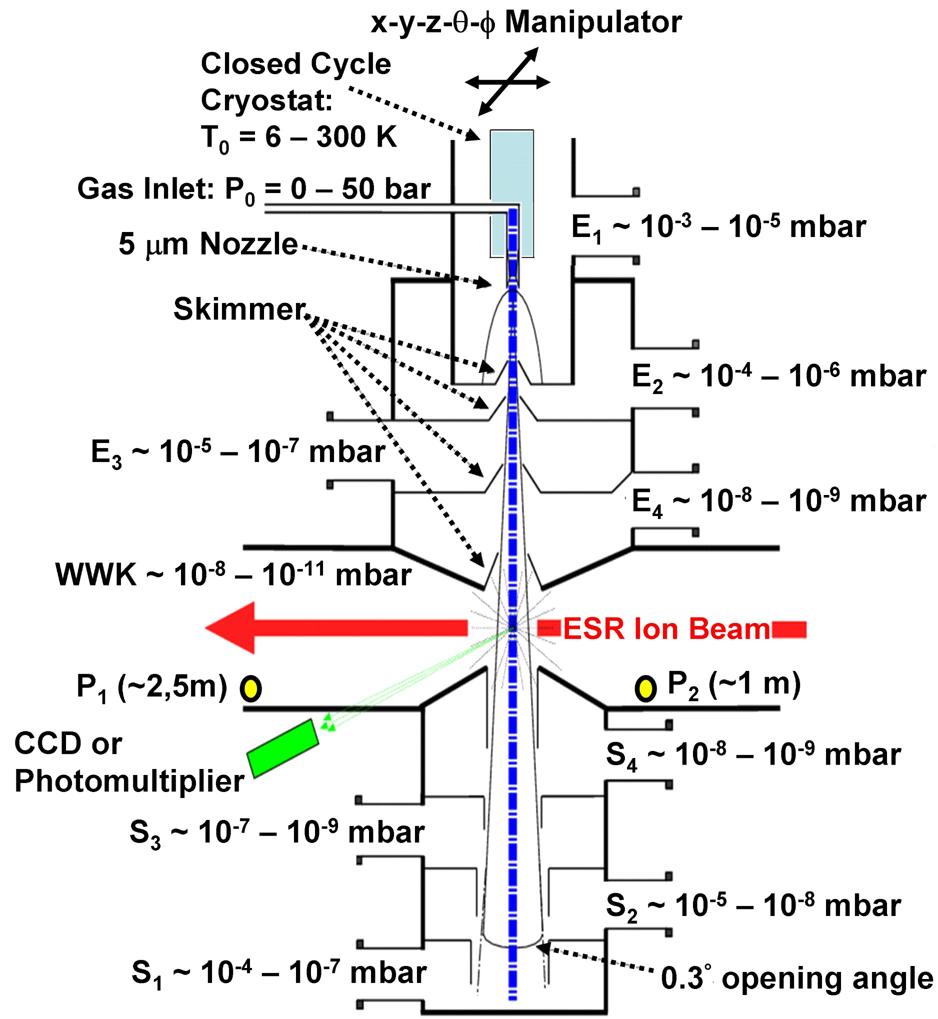


- By changing the source parameters (pressure and/or temperature) a fragmentizing **liquid** droplet beam with decreasing divergence can be produced

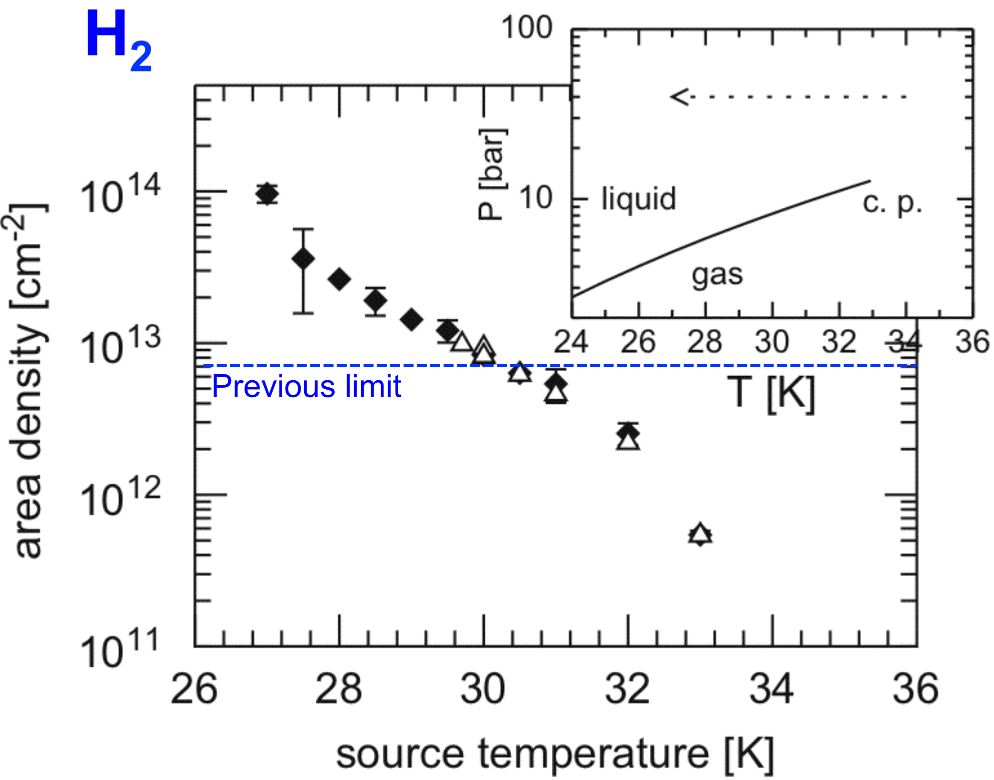
- Mass conservation leads to a significant increase of the target density in the interaction region

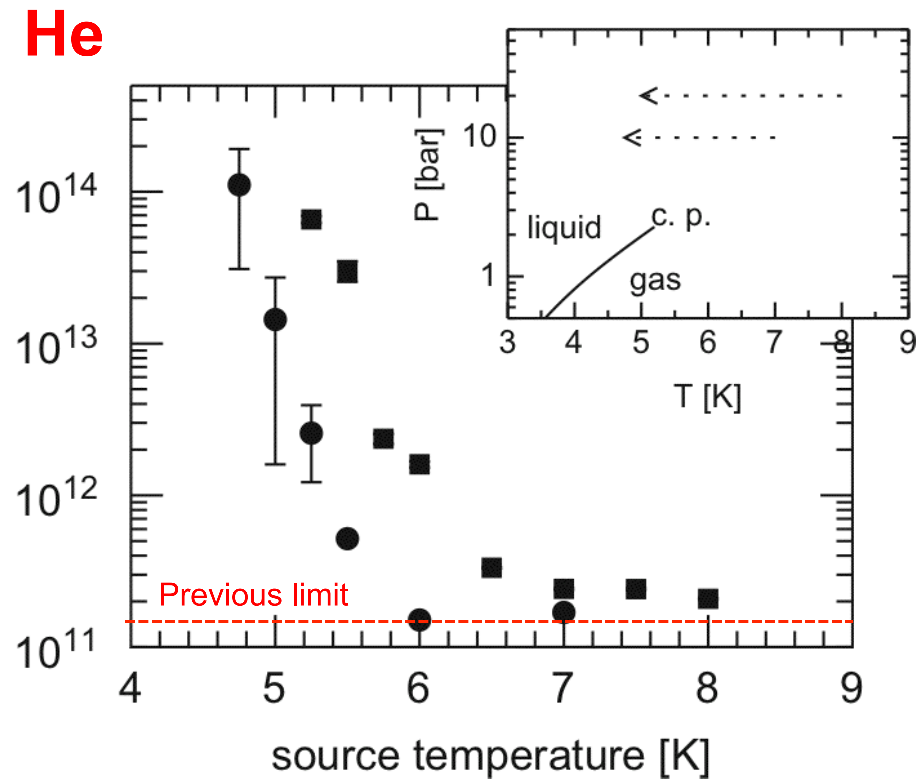
The internal target station at the ESR





Test this simple idea: H_2 and He targets at the ESR





Many open questions

- Does the very high **droplet local density (≈ 10^{22} cm^{-3})** has any important effect, e.g., for ion cooling?

- Interaction studies between micrometer-sized hydrogen pellets and relativistic protons have been reported, but the situation is expected to change dramatically for HCI since energy losses scale with the square of the charge number.

The Schottky-pickup diagnostics: energy losses

- The Schottky provides the revolution frequency spectrum of the circulating ions, characterized by a mean revolution frequency f_0, which is directly related to the longitudinal ion momentum.

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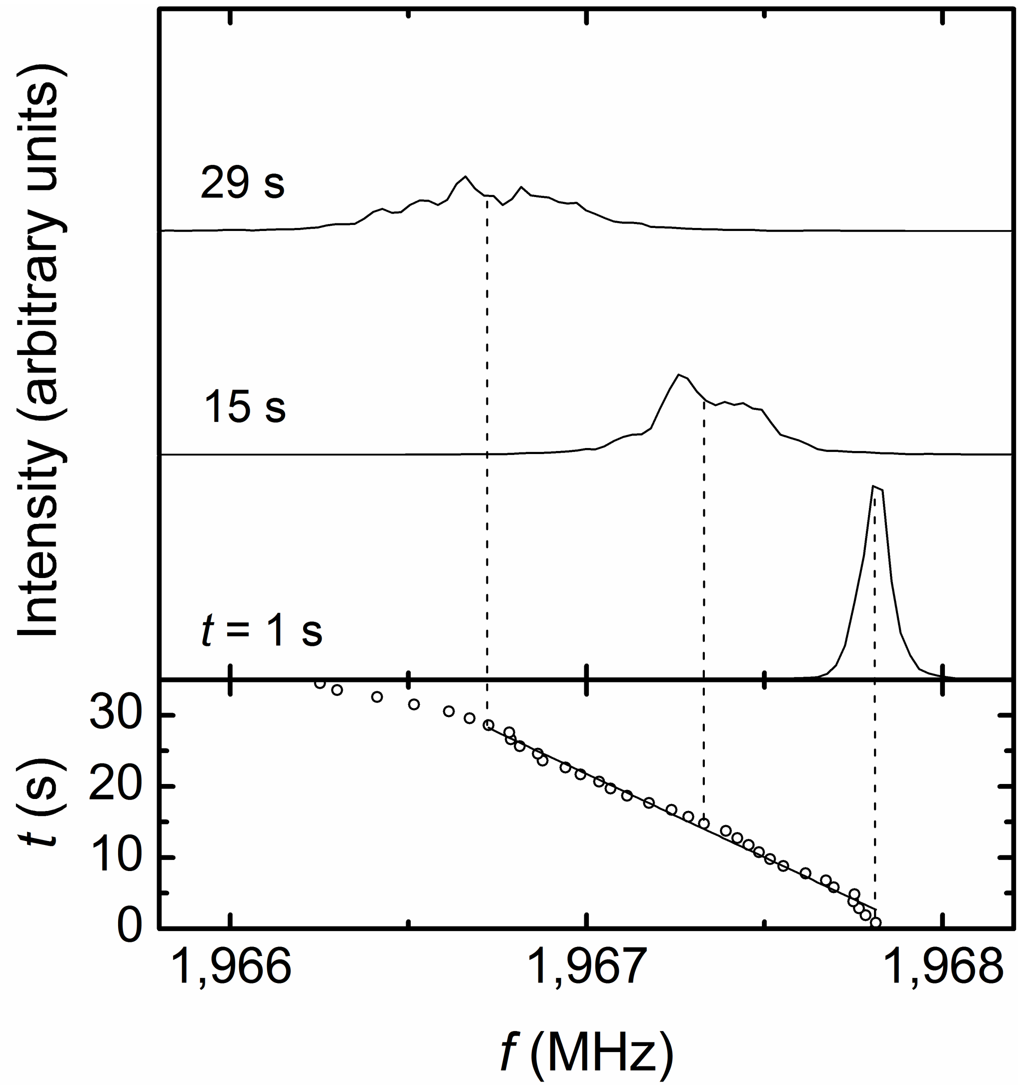
- Once the electron cooler has been turned off, the revolution frequency decreases (linearly in time) due to energy losses.



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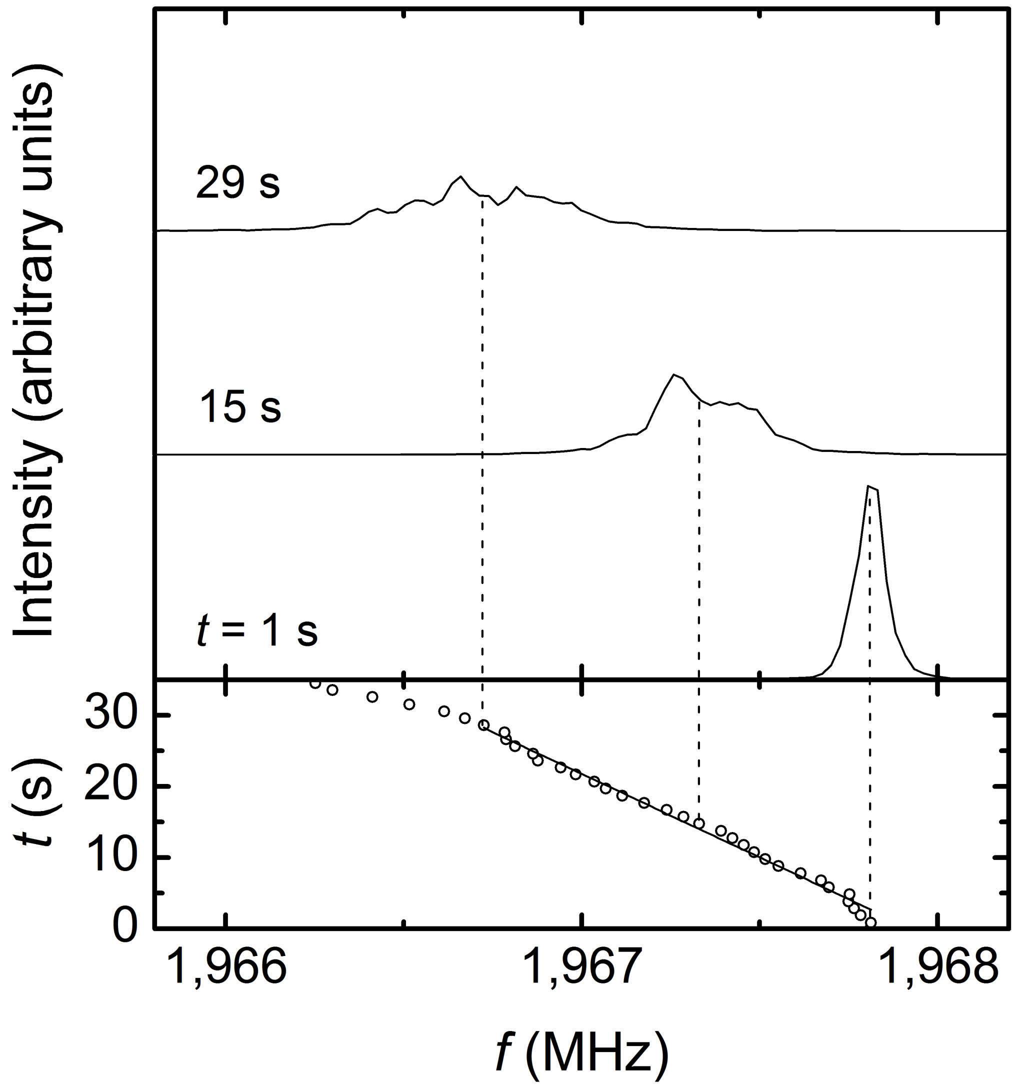
- Once the electron cooler has been turned off, the revolution frequency decreases (linearly in time) due to energy losses.
- The ion beam energy loss (per turn) can be determined from the frequency shift rate f' as

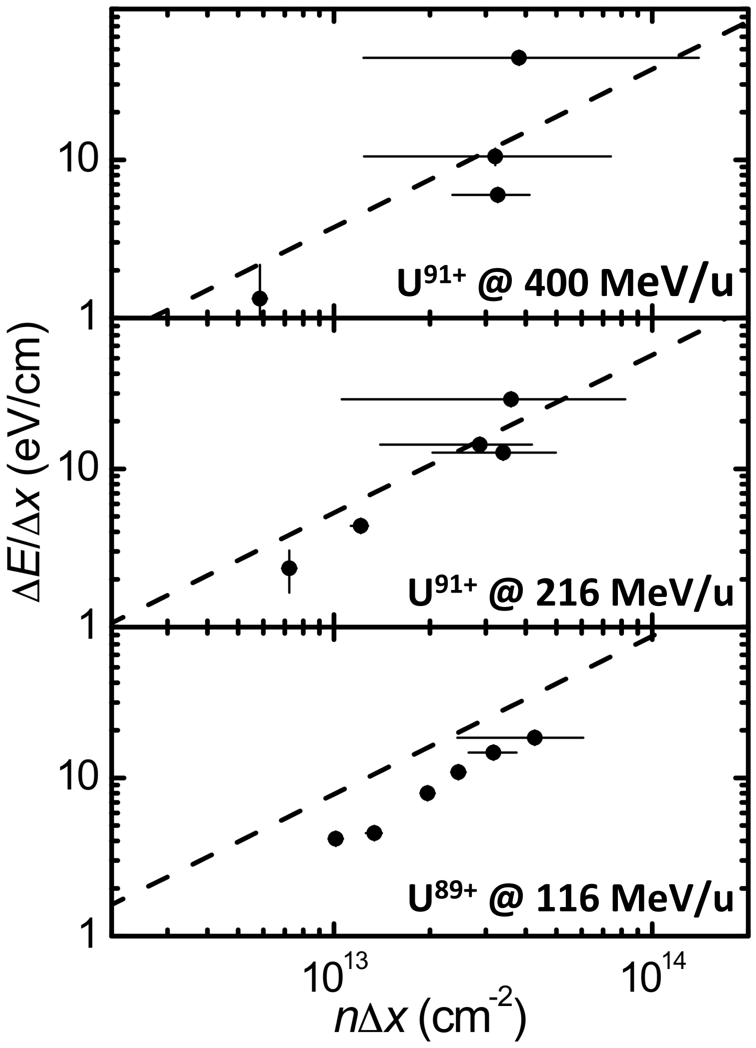
$$\Delta E = \left(\frac{1+\gamma_0}{\gamma_0}\right)\frac{1}{\eta}\frac{E_0}{f_0^2} f'$$



The Schottky-pickup diagnostics: energy losses

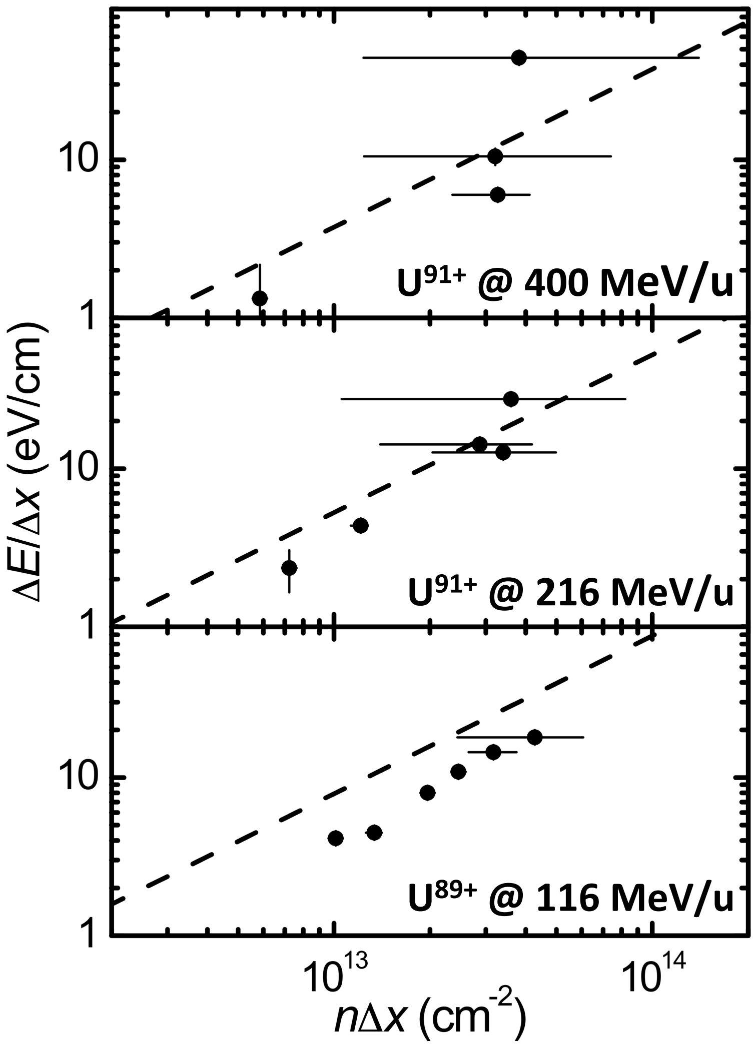
- The measured Ion energy-losses are in reasonable agreement with predictions based on the Bethe-Bloch formula for a uniform target density corresponding to our measured mean $n\Delta x$.

- However, they are of up to **three orders of magnitude smaller** than those expected on the basis of the Bethe-Bloch formula for a sub-micron hydrogen droplet with a local density of $\approx 10^{22}$ cm^{-3} (of the order of 10^4 eV).



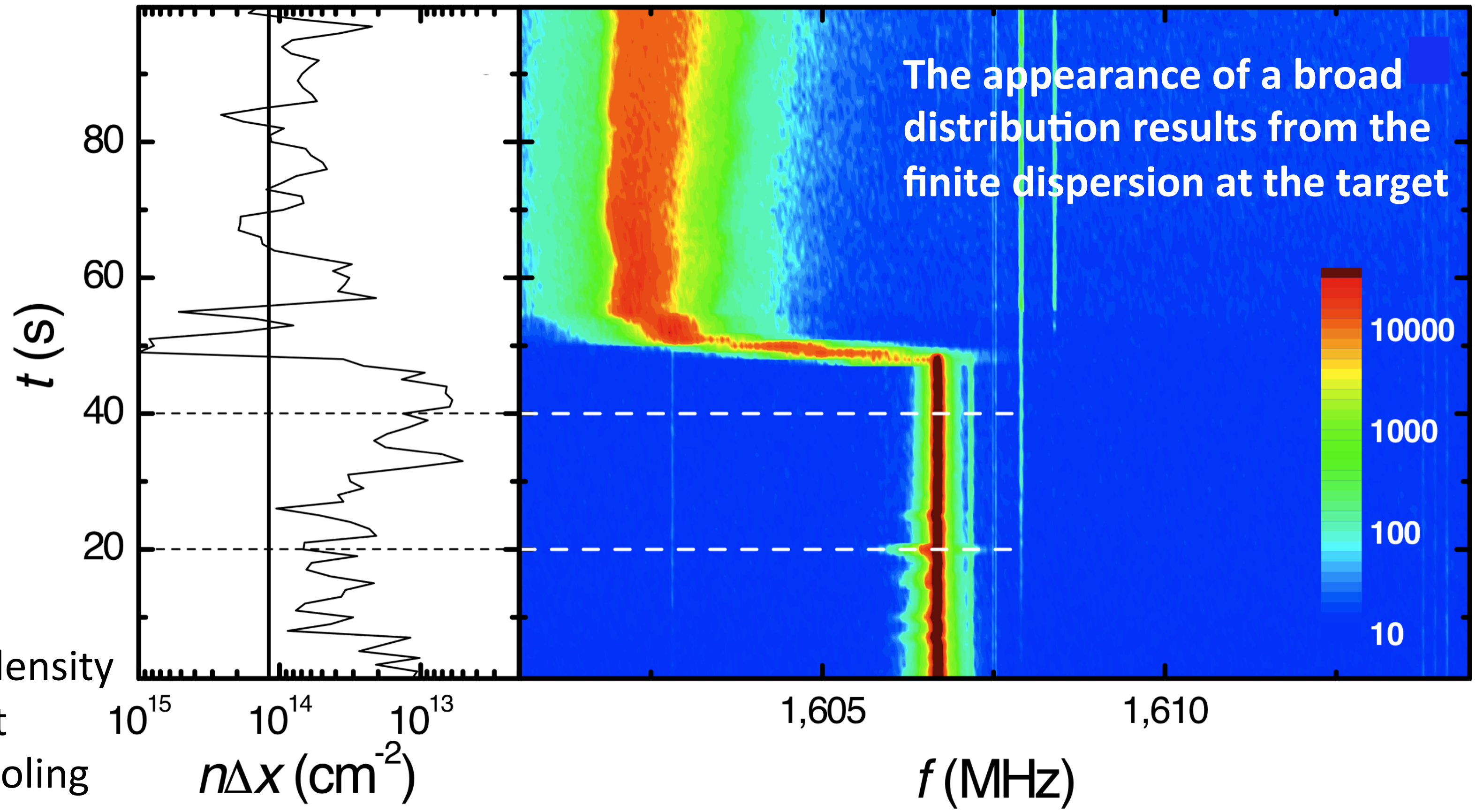
Interpretation of the energy losses

- A small fraction (estimated to be 10^{-4} per turn) of the HCIs undergoes direct collisions with the target beam droplets
- After a single collision event the droplet probably disintegrates, producing both neutral and ionized atoms and larger fragments.
- Since this fragmentation process occurs on the picosecond time scale, the experimentally measured energy losses are likely primarily dominated by the interaction of the HCIs with the nearly spatially uniform target consisting of the fragmentation products.



Dramatic cooling effects

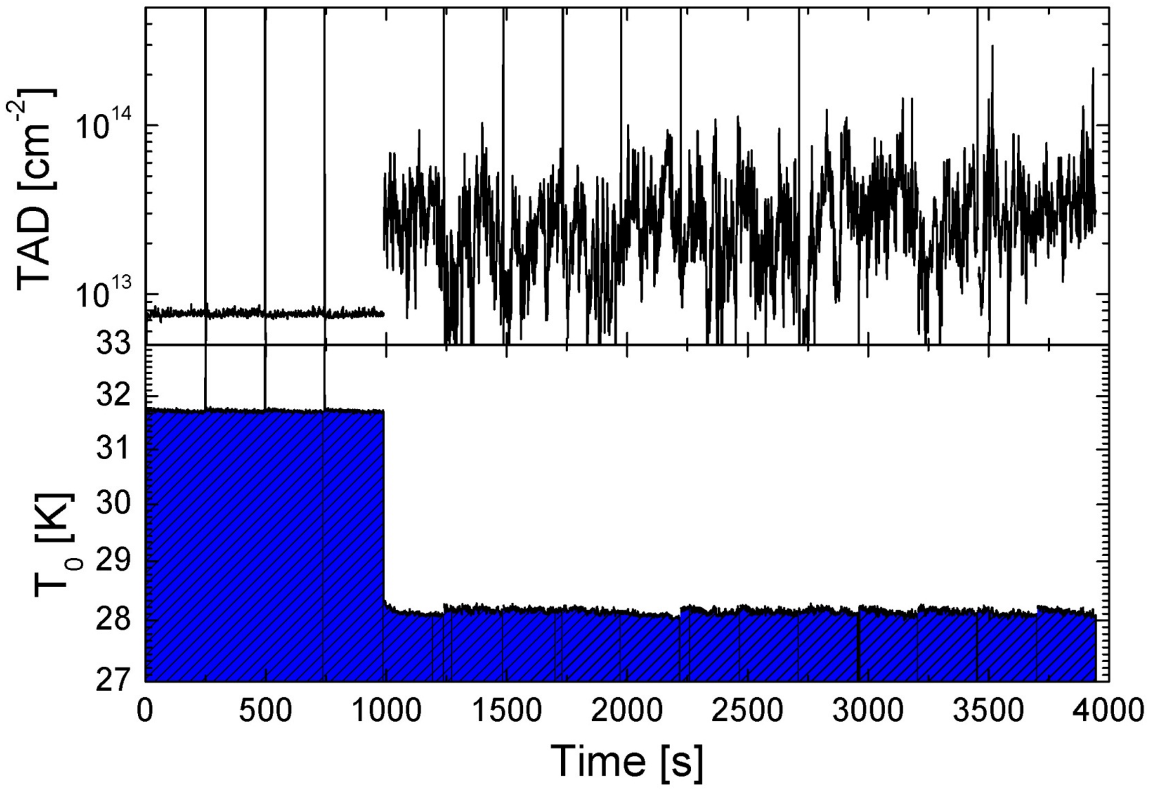
- The achieved high densities provides the most direct evidence so far for a dramatic energy loss event during interaction with a H_2 target that cannot be balanced by the electron cooler



Theoretical threshold density for efficient electron cooling

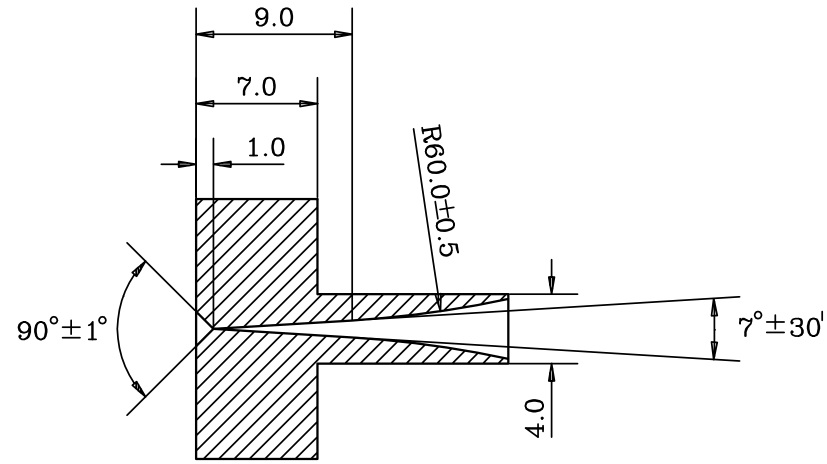
Major drawback: target beam instability

- However, **serious target beam instabilities make the use of the droplet target beam for normal user operation presently unreliable**



Solution: CERN nozzle for optimal user operation

- The use of a CERN-type nozzle (**kindly provided by A. Khoukaz for the PANDA collaboration**) provides high target densities **for both the low-*Z* (H_2) and the high-*Z* gases (Ar, Xe)**



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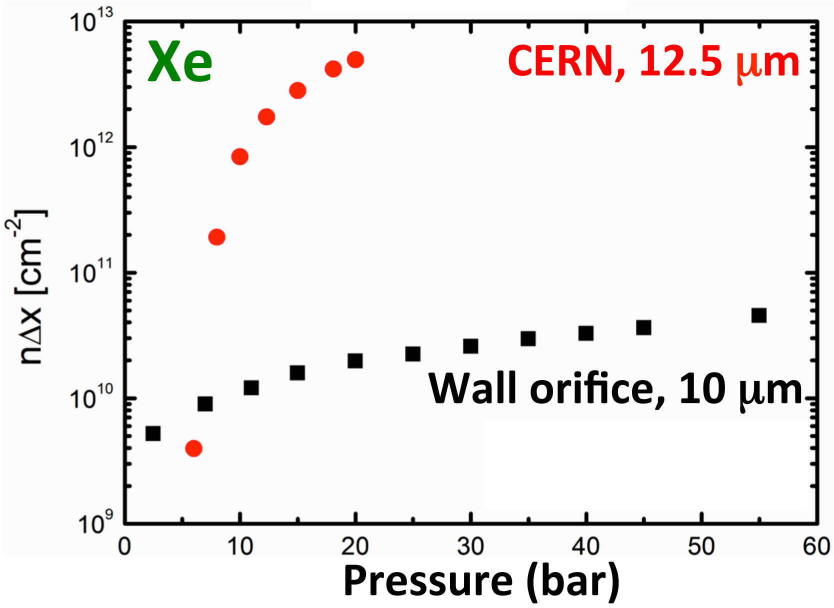

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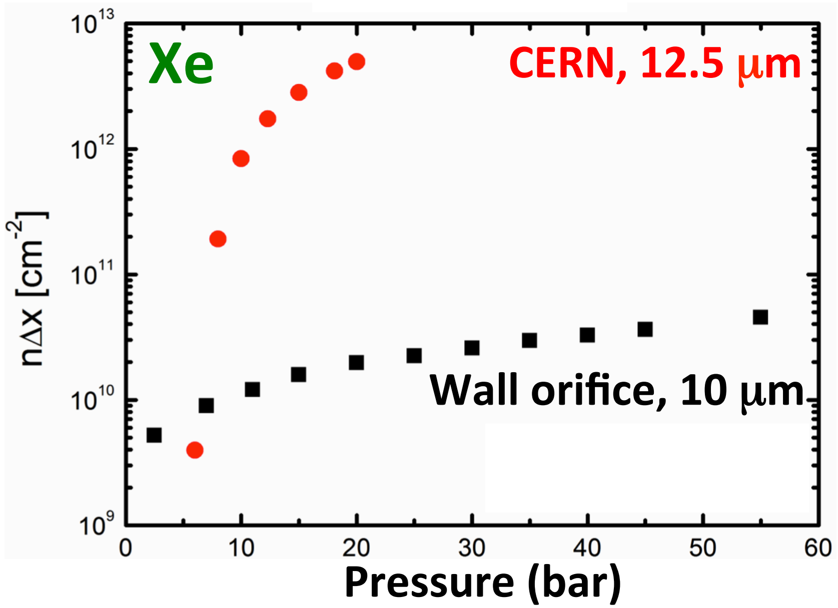

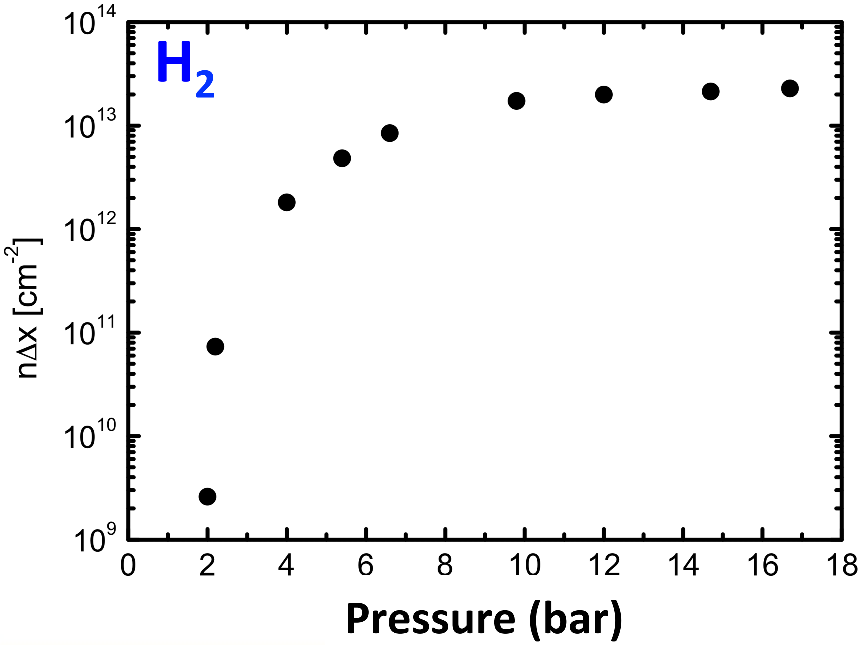

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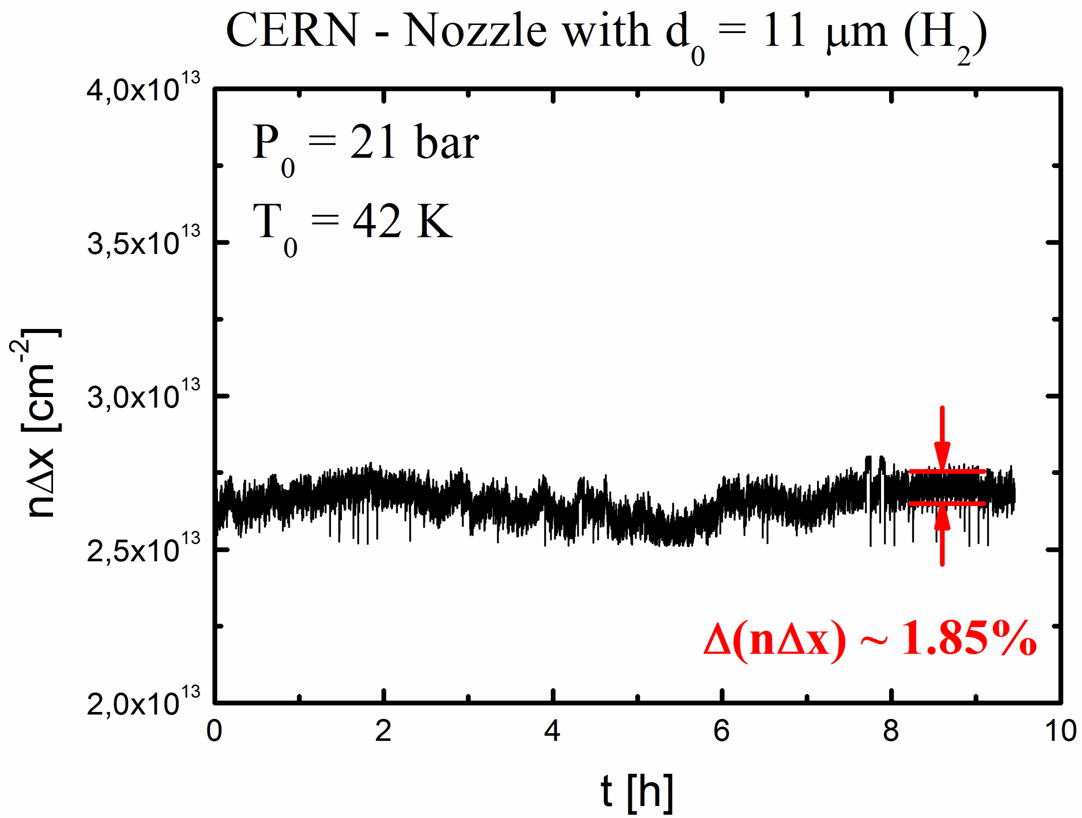
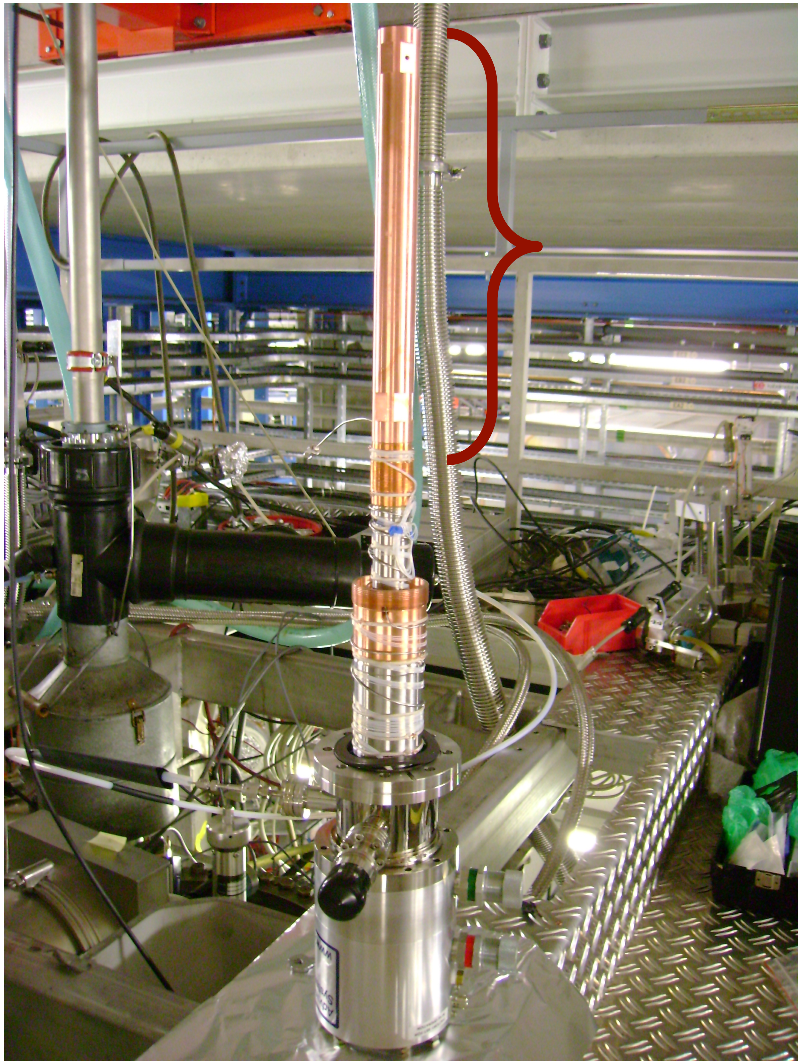


- Long term stability of better than 2%

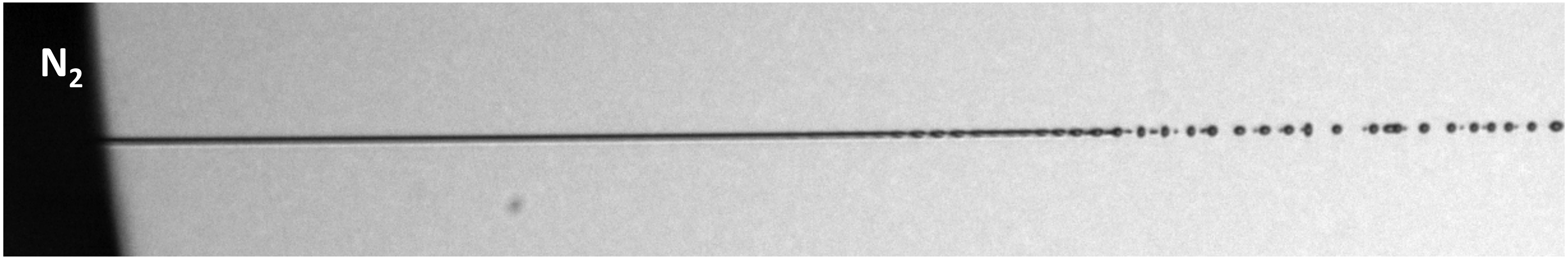
Present maximum values limited by the geometry

- The maximum target densities, especially for the light targets, are currently set by the target beam inlet geometry, which severely limits the source cooling capacity of the closed cycle cryostat



Cryogenic liquid jets as mass-limited targets

- Cryogenic liquids expanding in vacuum represent **the ideal realization of a mass-limited target** ideally suited for relativistic laser-plasma generation



- The droplets
  - ✓ are truly “free-standing”
  - ✓ are replenished at MHz repetition rates, thus eliminating the problem of target replacement after each laser shot

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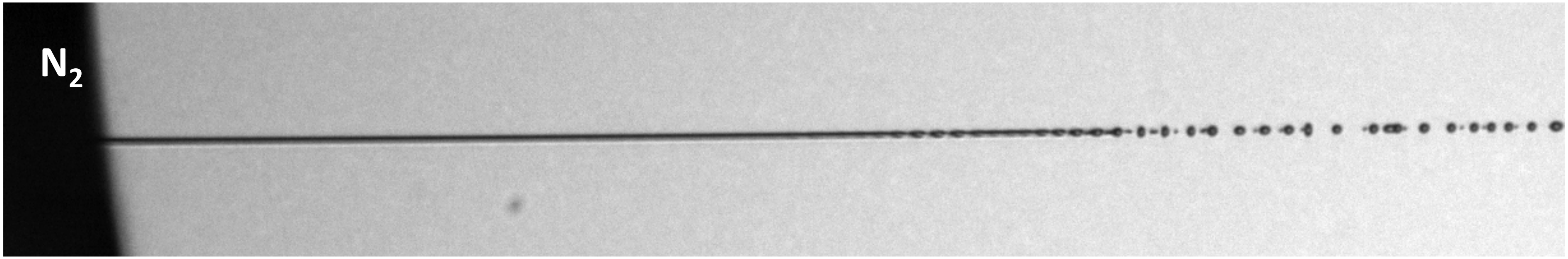
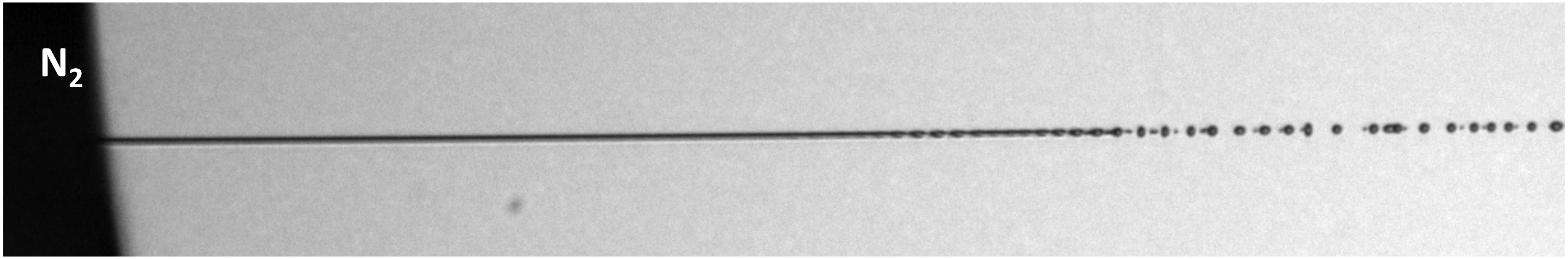


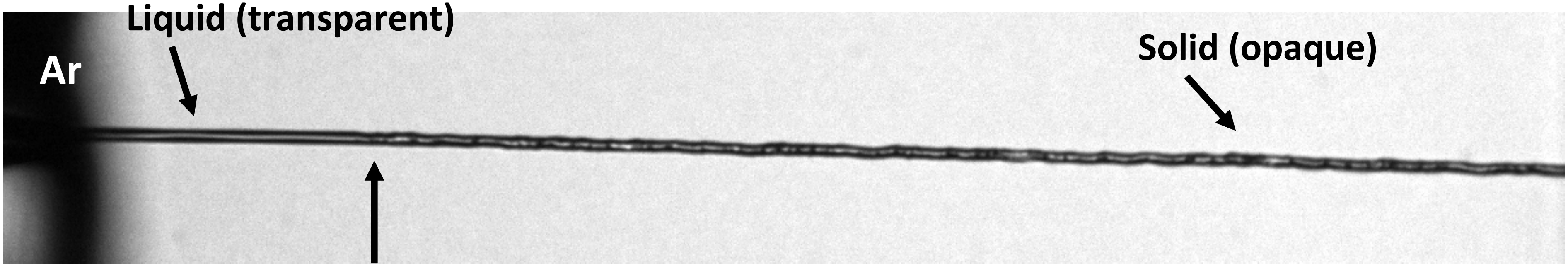
✓ For laser-driven acceleration hydrogen droplets are the most appealing

✓ For WDM studies droplets of the heavy cryogenic gases (e.g., argon) are required

Critical issue with cryogenic liquid jets: freezing

- However, Cryogenic liquids of interest rapidly cool by surface evaporation and start freezing before breakup occurs

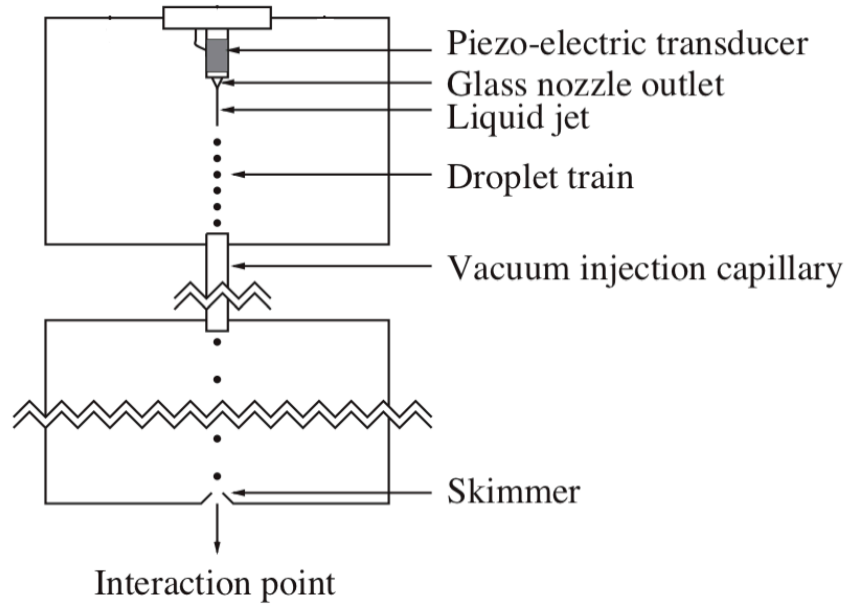




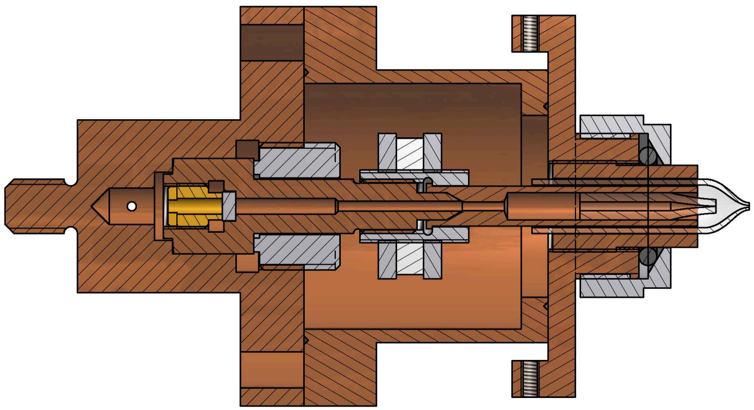
Avoiding freezing for droplet production

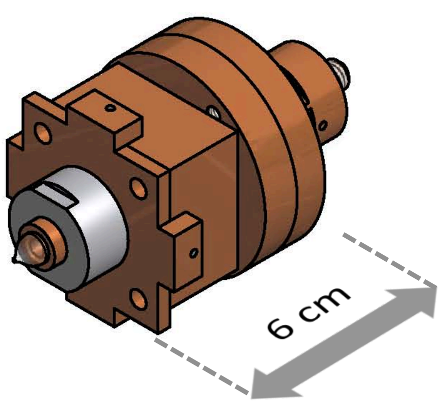
- Simple solution: to avoid freezing expand the liquid jet in a gas kept close to triple-point (TP) conditions
- The production of large hydrogen droplets by injecting the liquid into a TP chamber has been demonstrated within the PANDA collaboration
- However, the considerable dimensions of the droplet inlet system and the droplet beam divergence preclude its use for laser-plasma applications
  - **One has to deliver droplets synchronized temporally with the laser pulse with a spatial stability better than half the laser focus (≈ 5 μm)**

Schema of the prototype droplet inlet system for PANDA (Uppsala University)



Two-fluid stream droplet beam source





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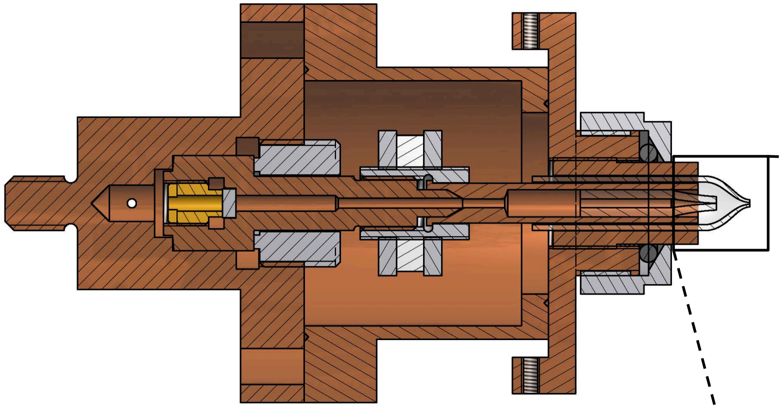

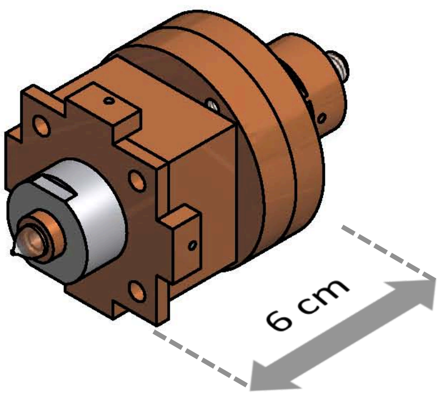

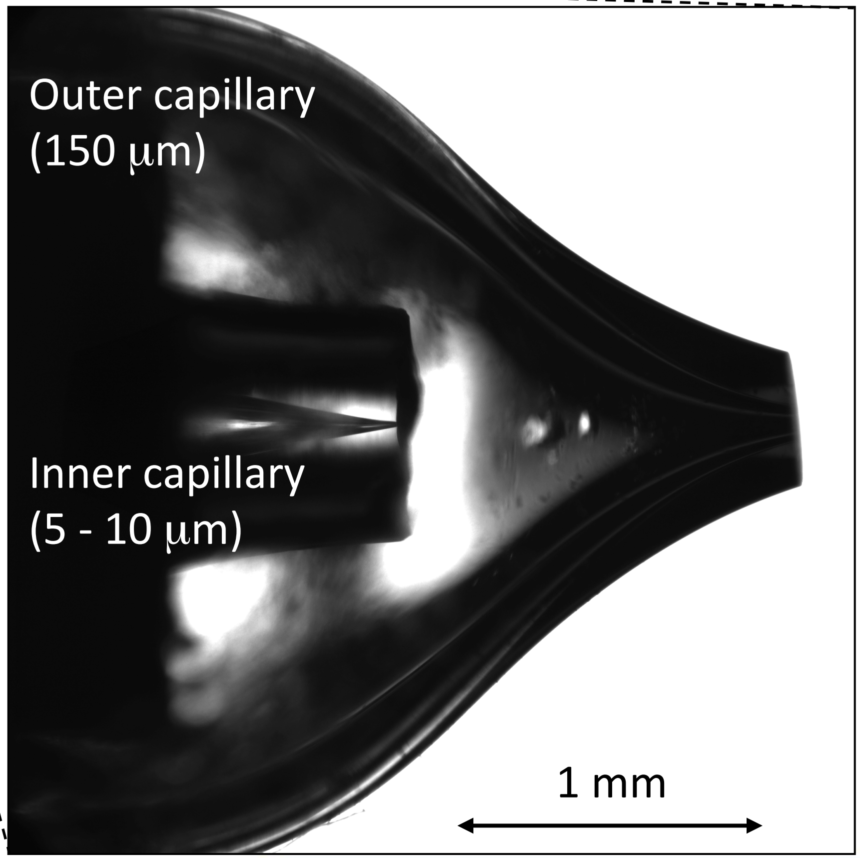

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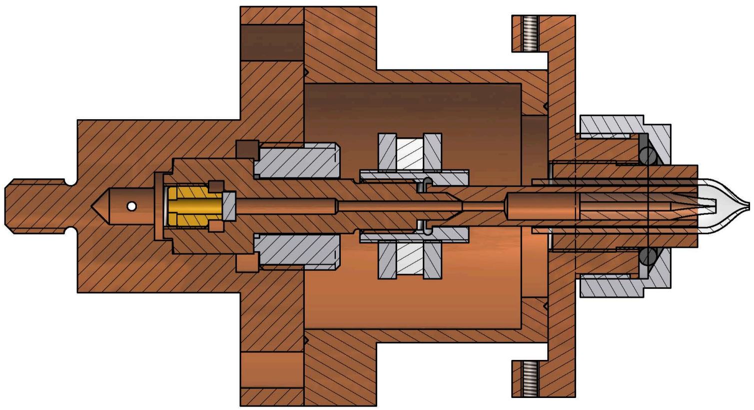
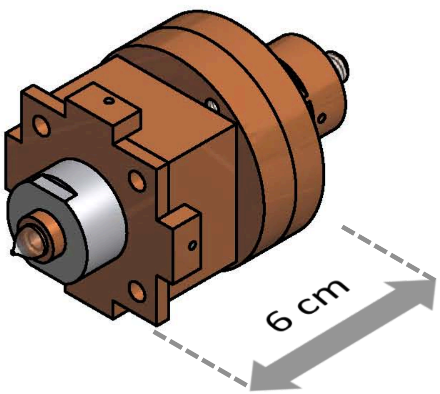
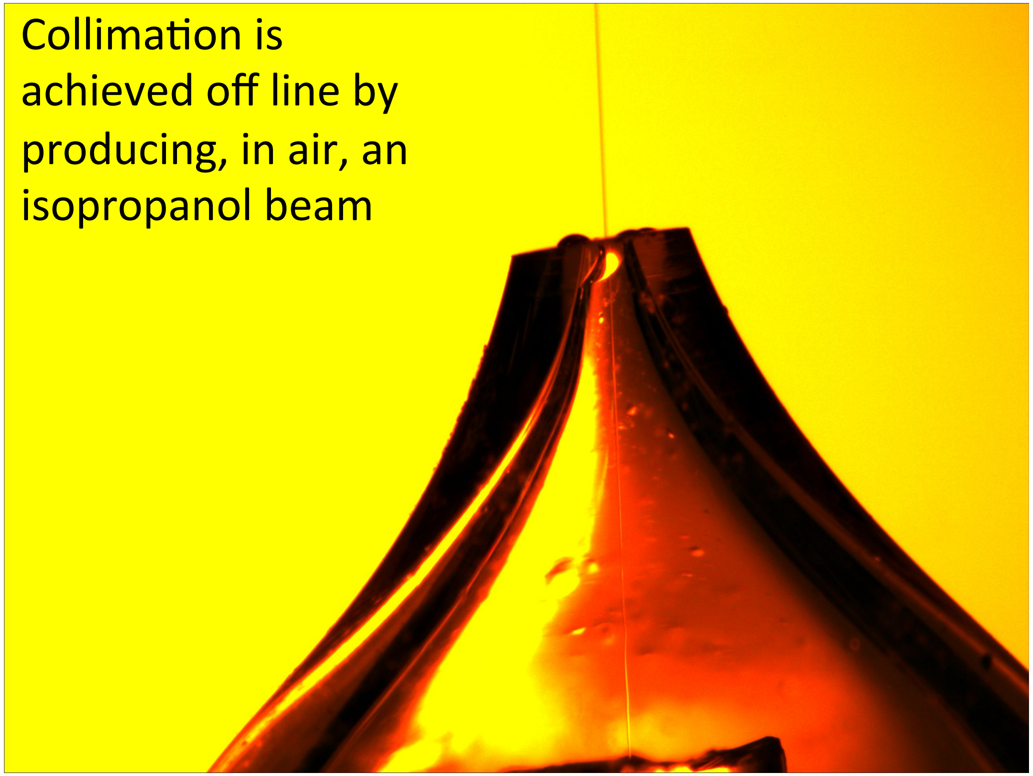
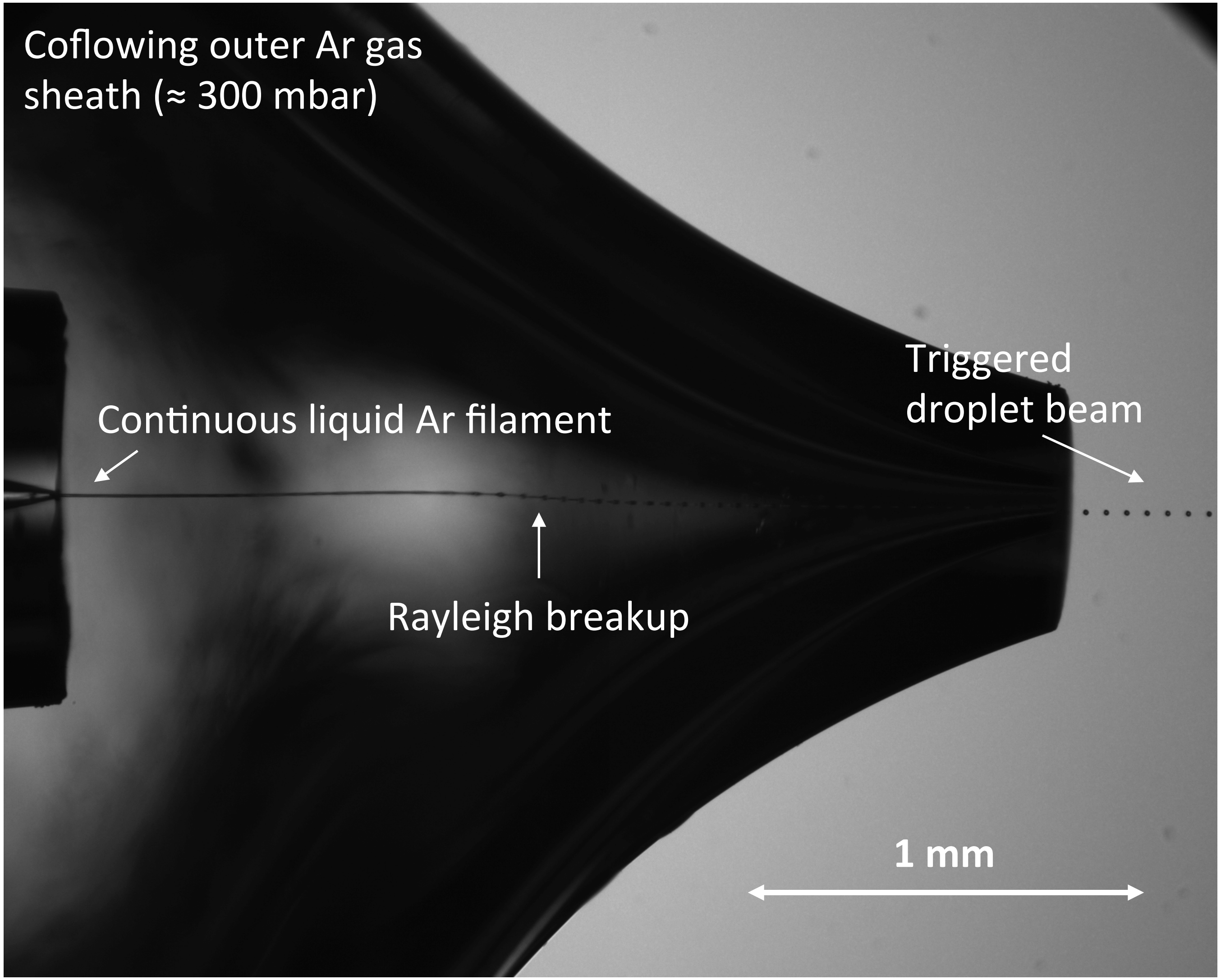




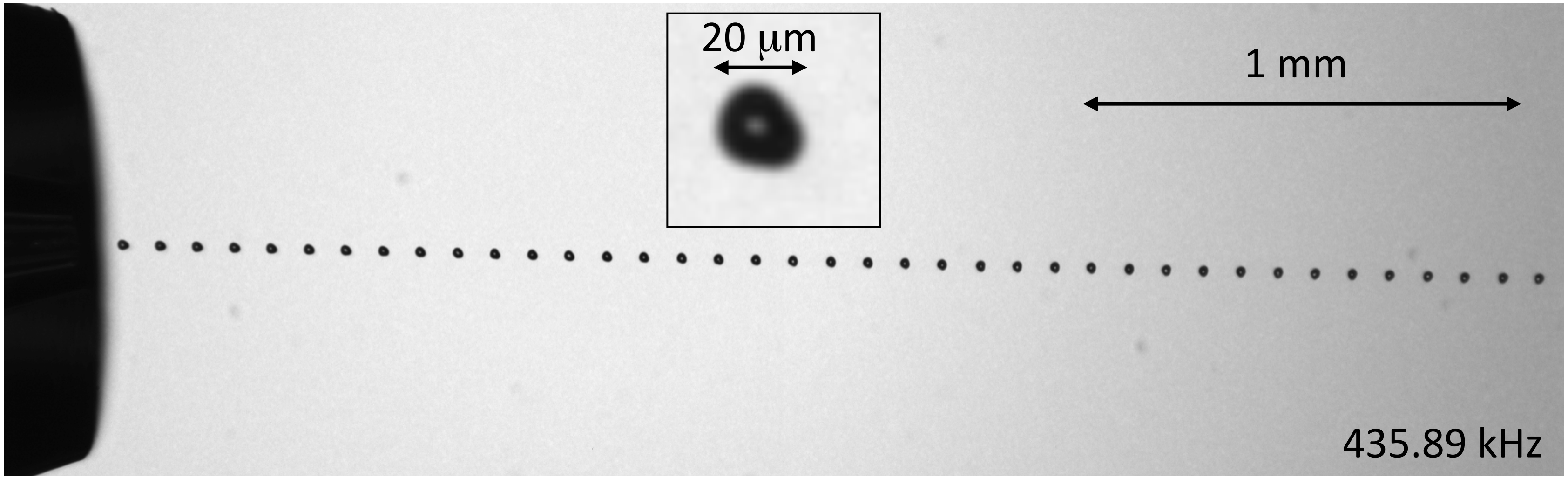
Collimation is achieved off line by producing, in air, an isopropanol beam



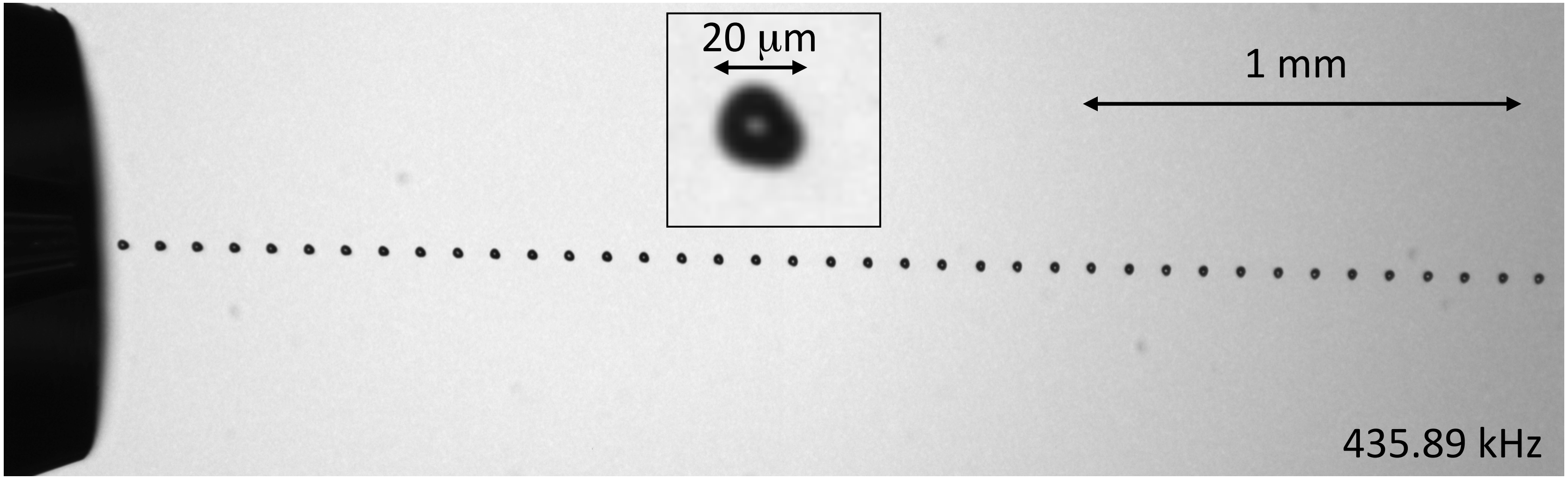
Two-fluid stream droplet beam source

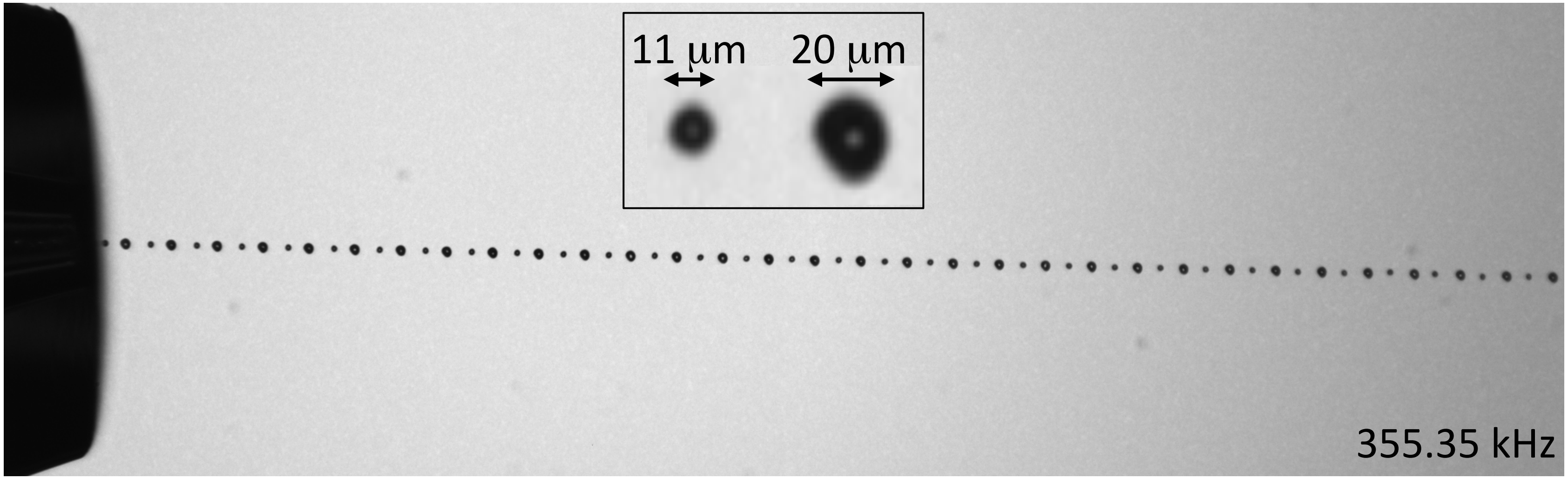


Two-fluid stream droplet beam source: argon

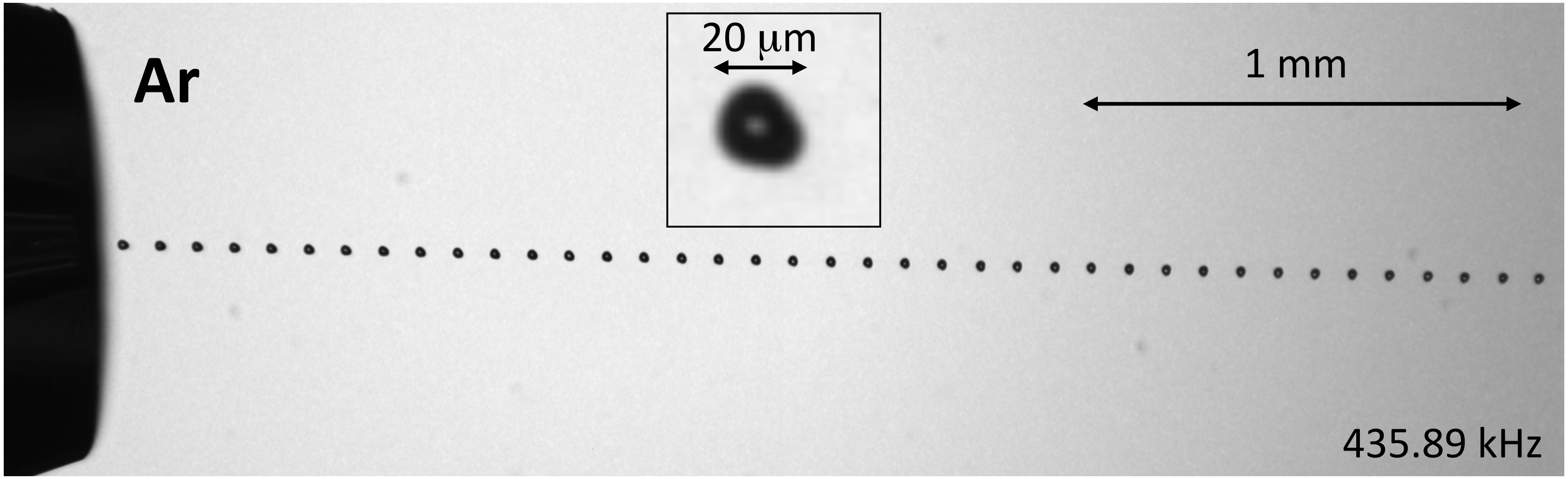


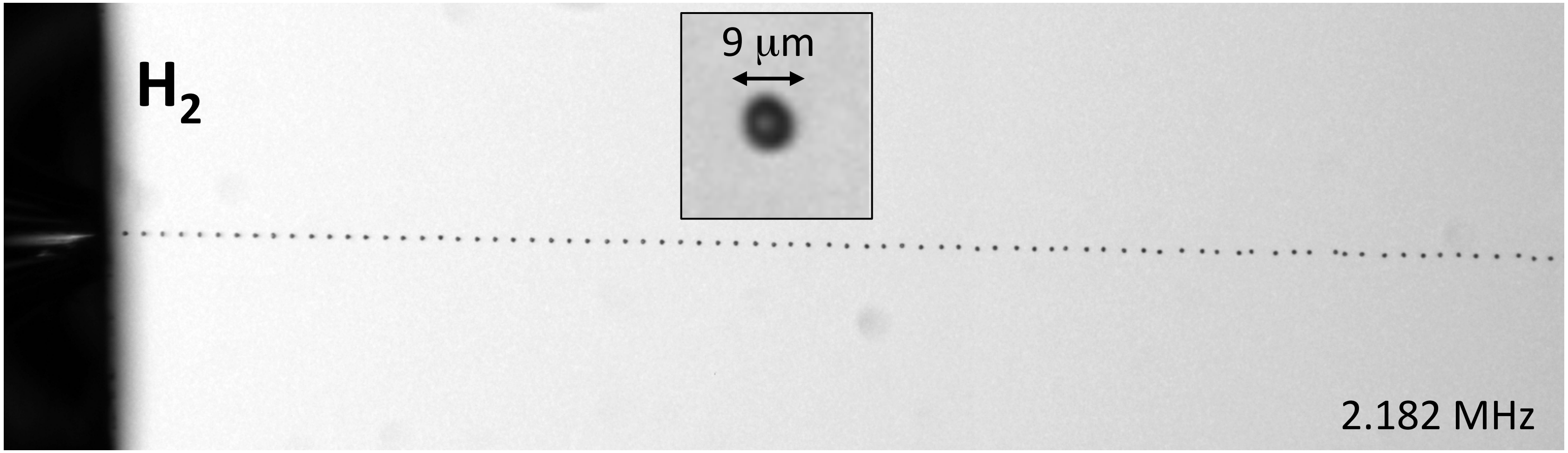
Two-fluid stream droplet beam source: argon





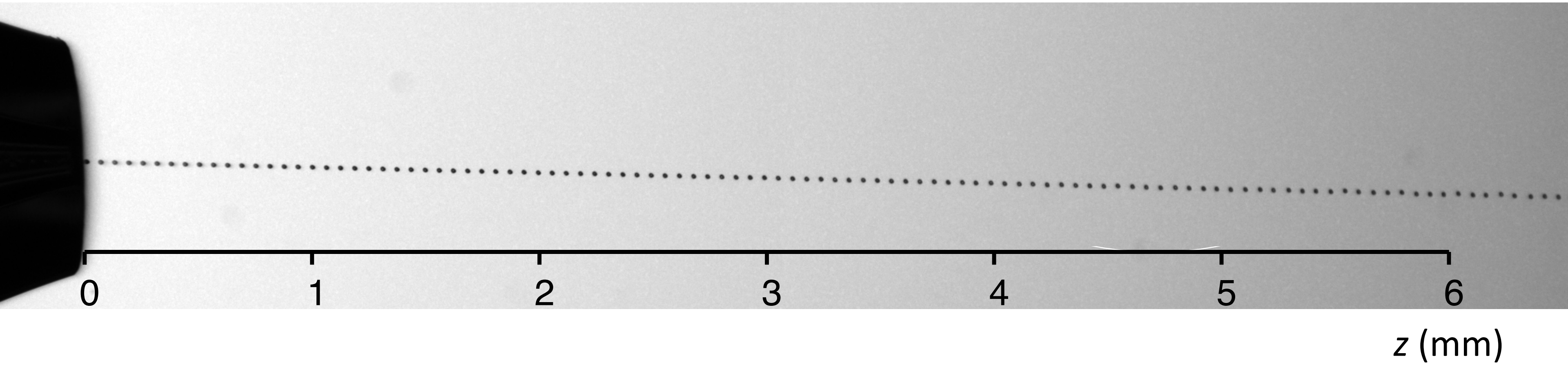
Two-fluid stream droplet beam source





Spatial stability analysis

- Single shot



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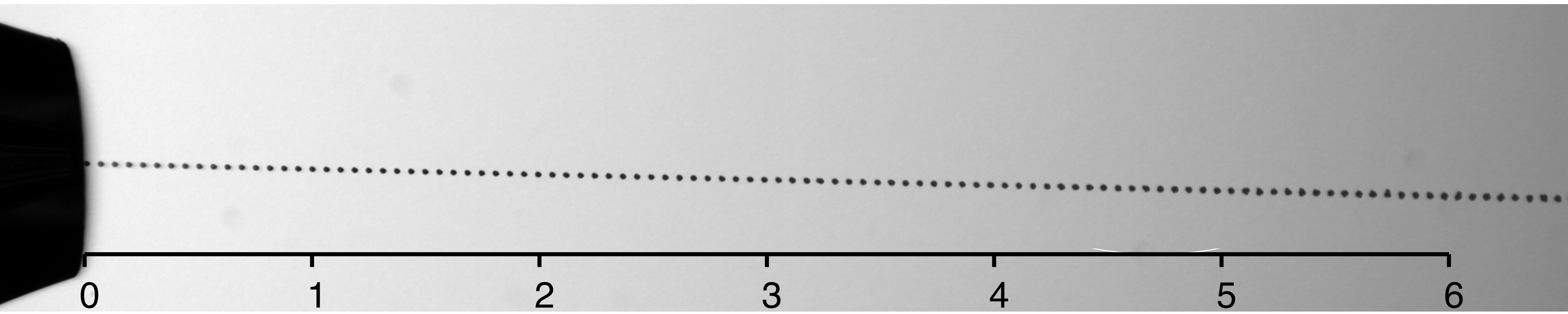
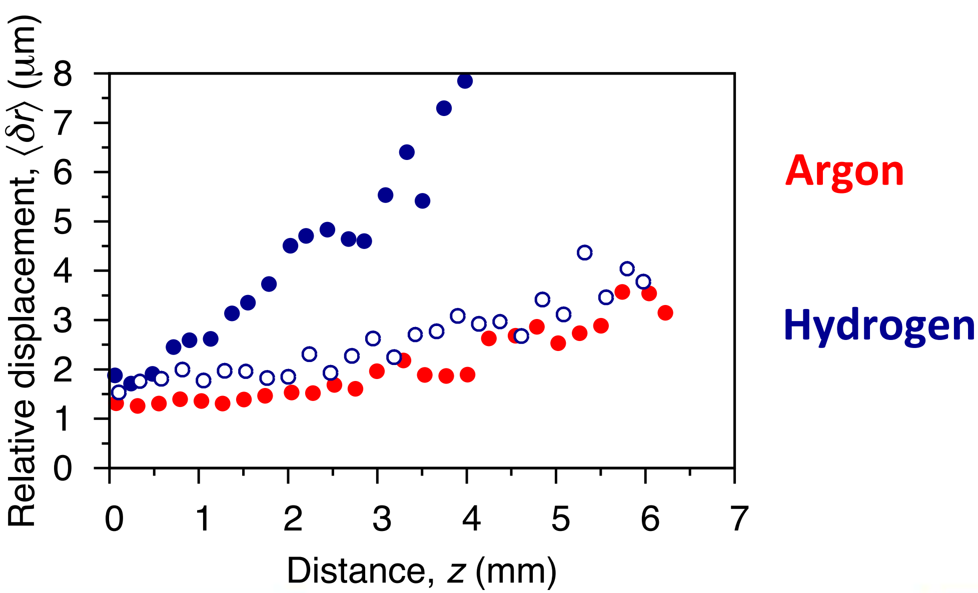
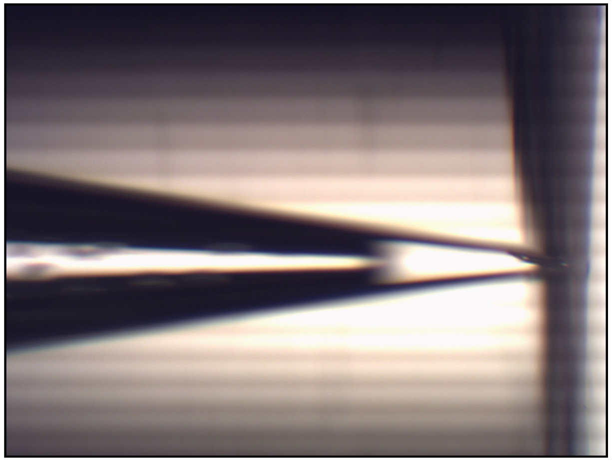
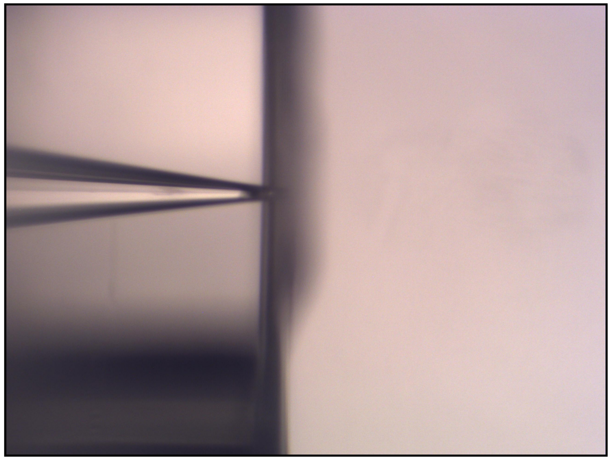
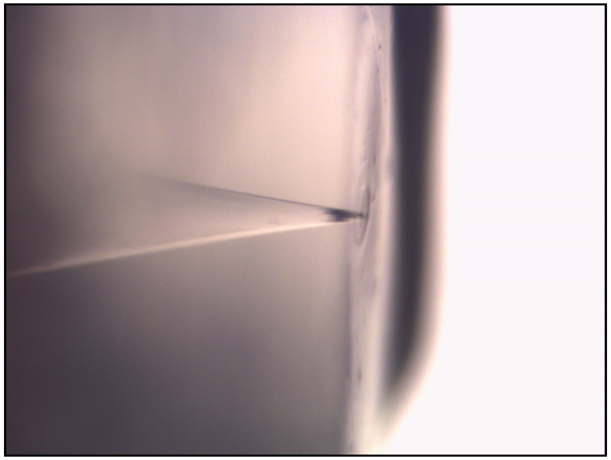


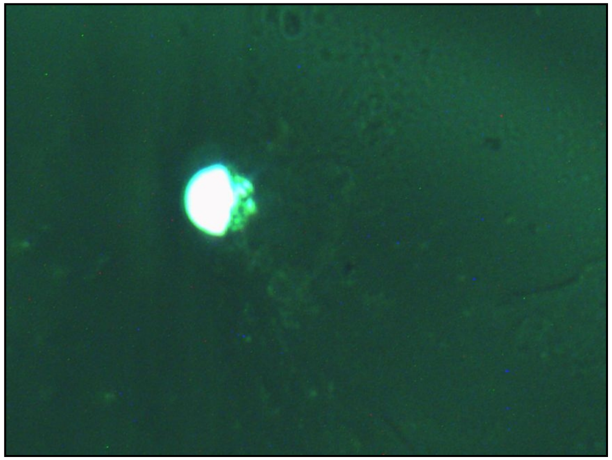


Annoying capillary clogging problem

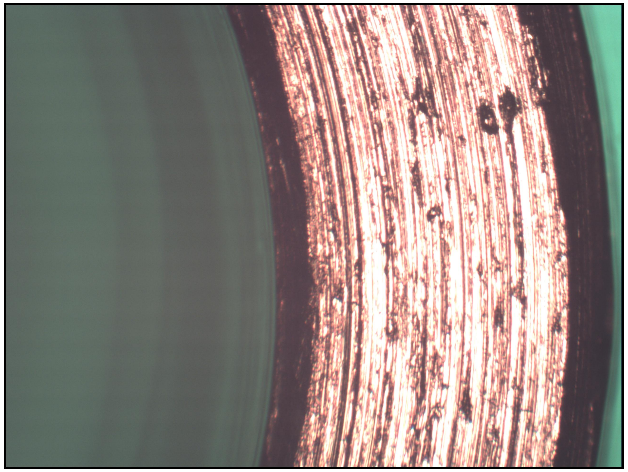


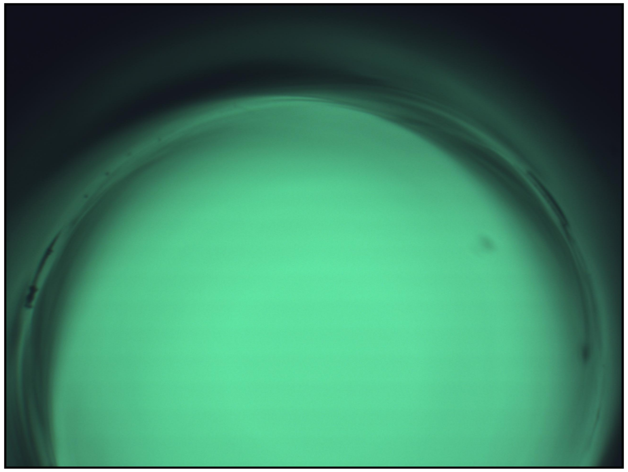


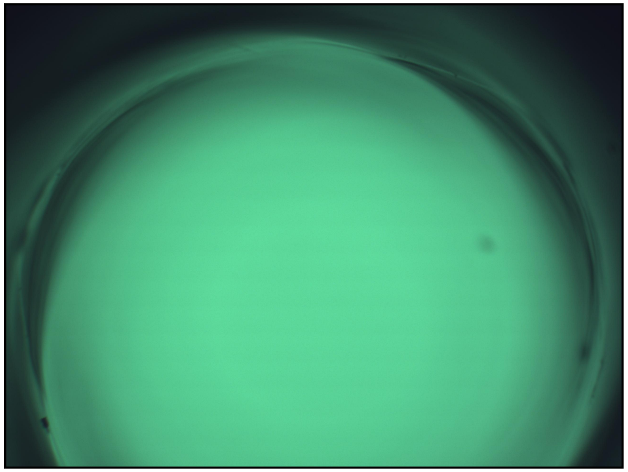




Annoying clogging problem: copper clog?







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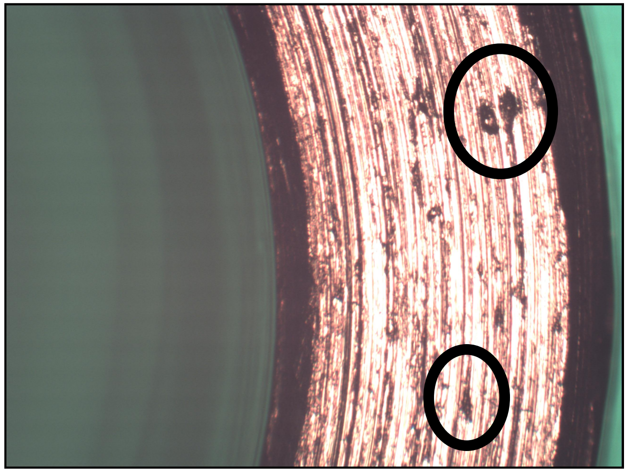

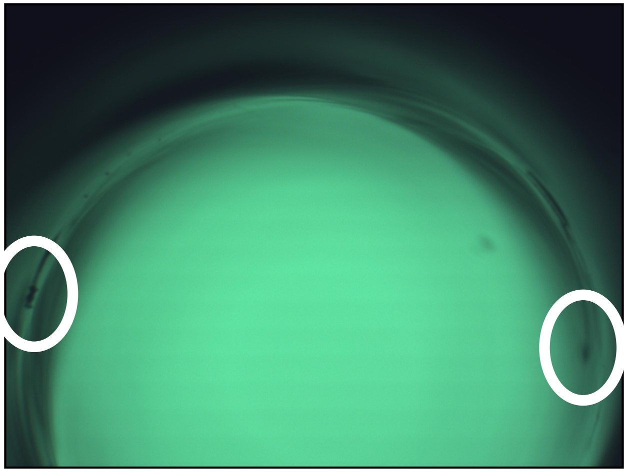

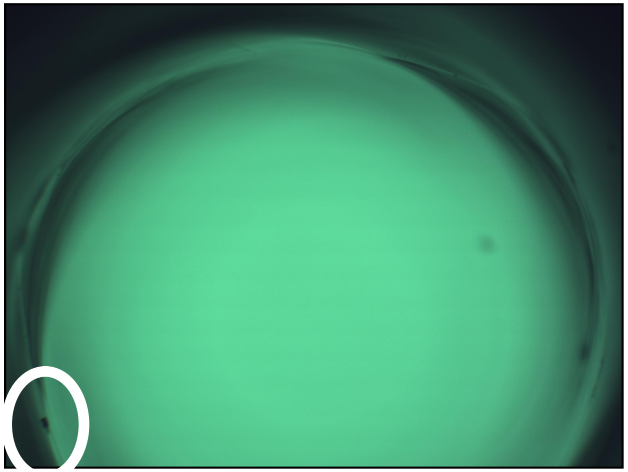

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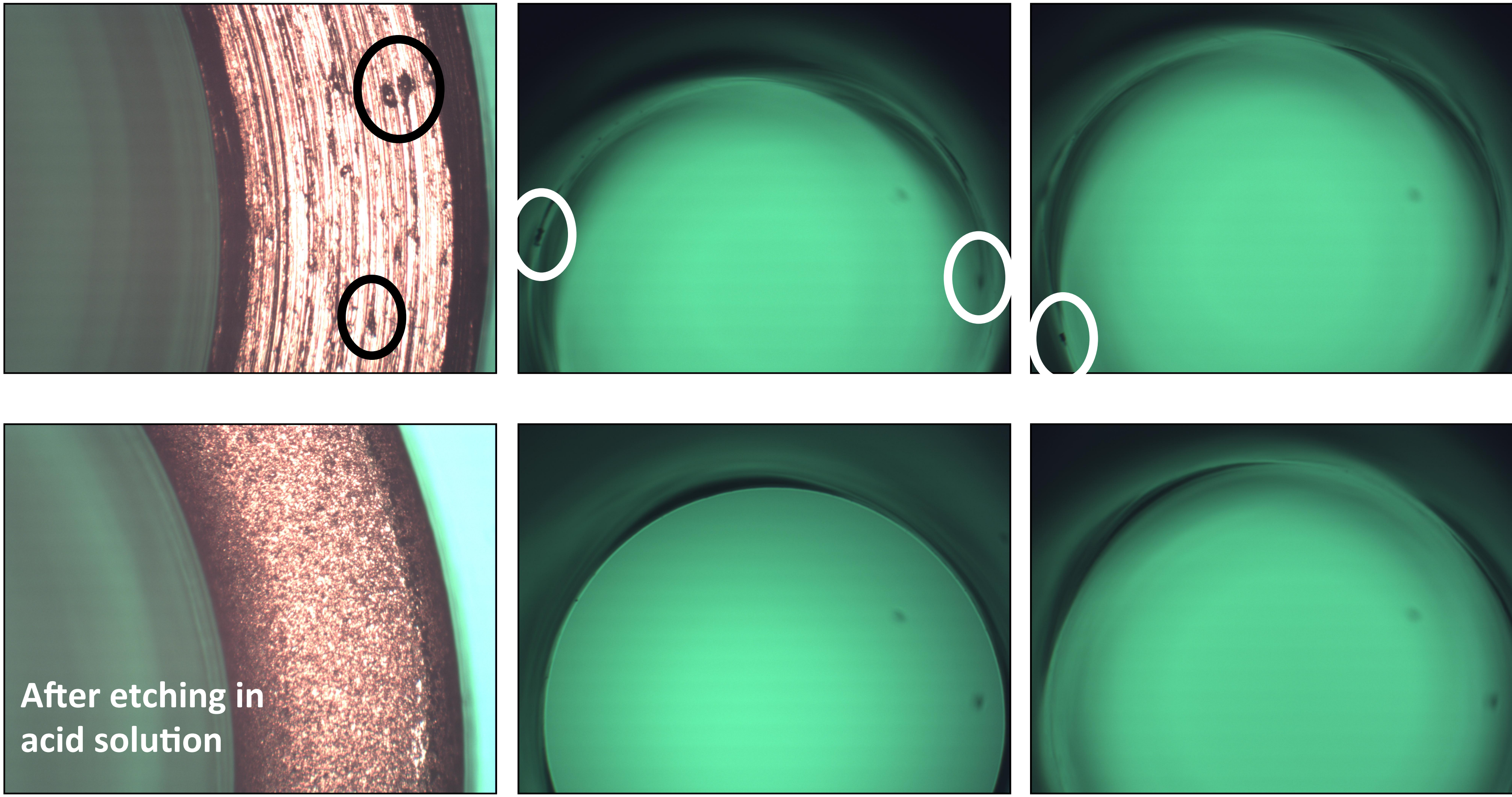
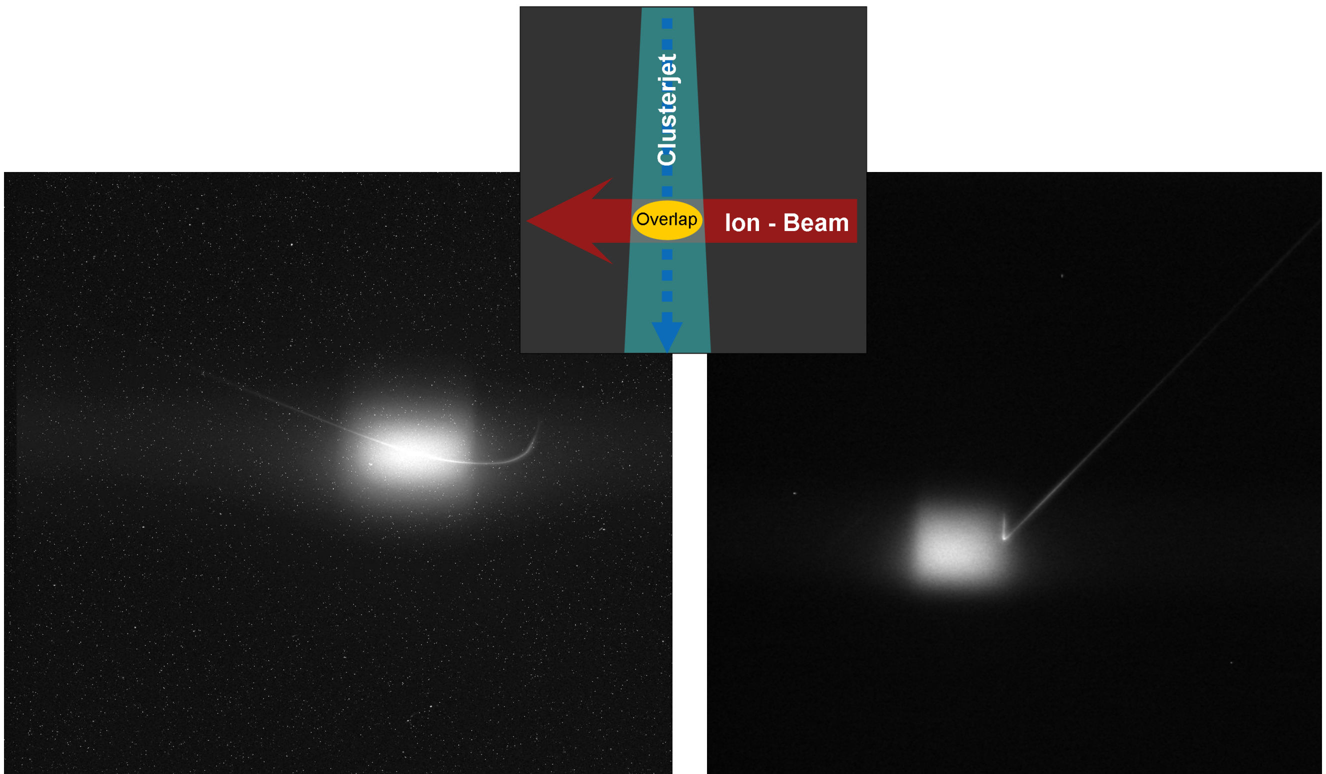


Outlook

- Strong experimental evidence for **non trivial** relativistic highly-charged ion – droplet beam interaction.

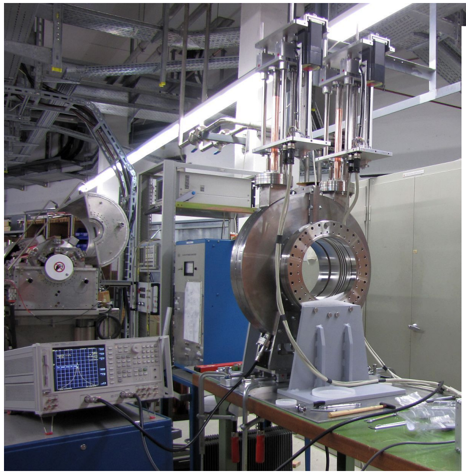
- However, so far **non-ideal** experimental conditions and theoretical description of the underlying processes **extremely difficult**



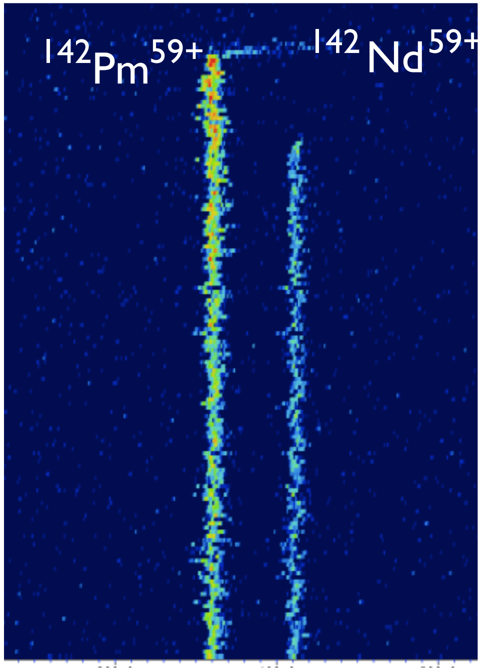
„Comet"-like events observed during several beamtimes employing droplet beams

Outlook

- Strong experimental evidence for **non trivial** relativistic highly-charged ion – droplet beam interaction.
- However, so far **non-ideal** experimental conditions and theoretical description of the underlying processes **extremely difficult**
- Exploit the possible combination of newly developed storage-ring diagnostic techniques with microscopic droplet beams to provide **nearly ideal conditions**



New resonator cavity at the ESR for single-ion analysis (2010)



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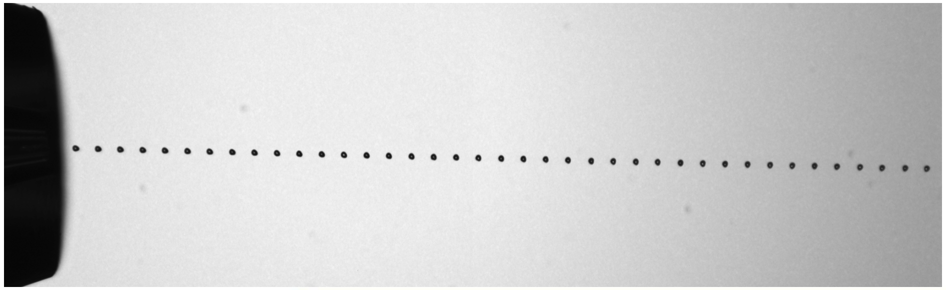

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- These experiments might offer unprecedented possibilities for novel investigations of light – matter interaction