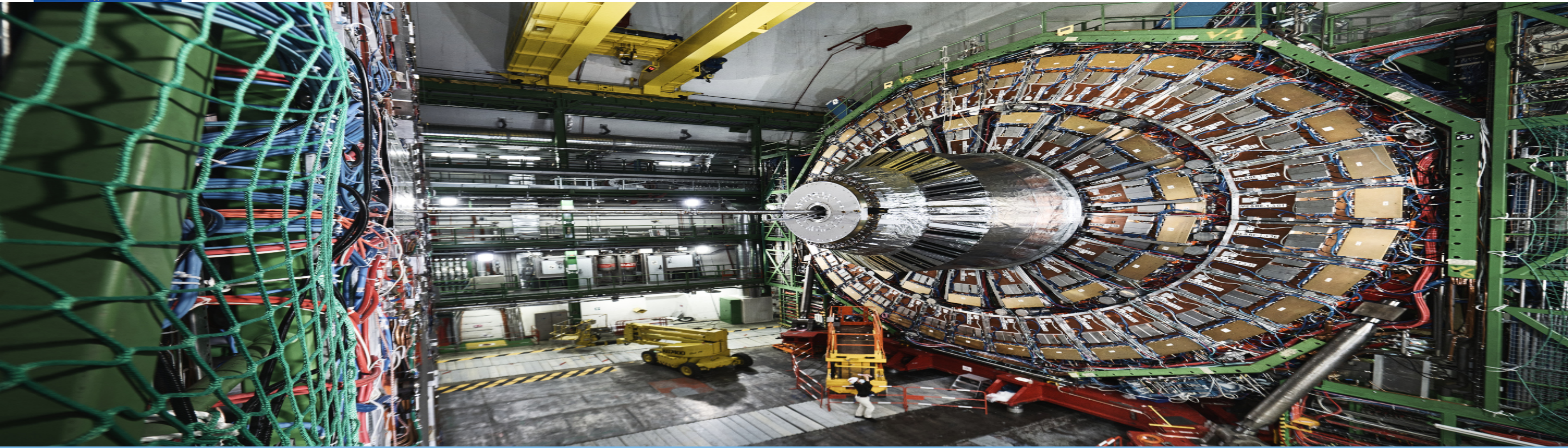

JRA11 – CryoJet: Cryogenically cooled particle streams from nano- to micrometer size for internal targets at accelerators

Alfons Khoukaz (WWU)

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 824093

JRA11/WP29 Objectives

Significantly advance the science and technology of cryogenic target beams for various fields

- Internal targets for accelerator experiments (FAIR, MESA, LEAF, ...)
- Particle-laser interaction (ARCTURUS@HHUD, POLARIS@Jena, …)

Development of advanced diagnostic tools

Special focus:

- Cluster Jet, Microjet, Pellet Beams
- Low-Z elements (H_2, D_2) + heavier gases (N_2, O_2, Ar, Xe)
- Boundary-free targets for hadron physics experiments

Aim: Higher efficiency and performance of targets for future physics facilities

Tasks of JRA11/WP29

Cluster-jet beam studies

- New nozzle production techniques
- Studies on jet beams: highest performance and cluster formation
- Laser-induced particle acceleration (H_2 clusters and heavier gases)

Cryogenic droplet beam target

- Studies on droplet nozzles designs and efficiency
- Measurements on long term stability
- Investigations on high performance

Pellet source studies

- Development and studies with new pellet diagnostic systems
- New nozzle and pellet production techniques

1.) Progress made during the year towards the objectives

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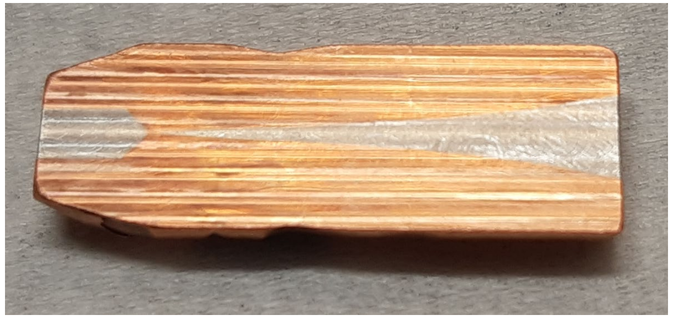
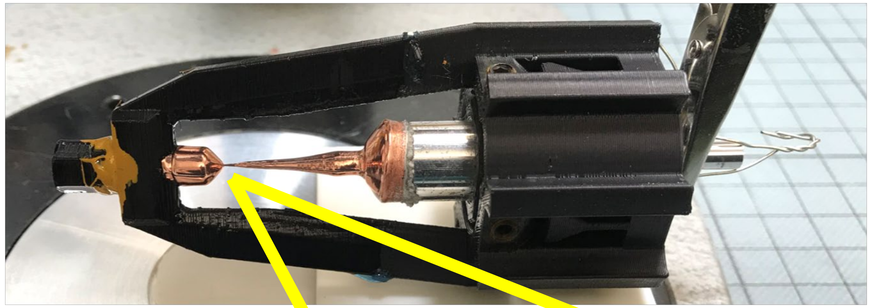
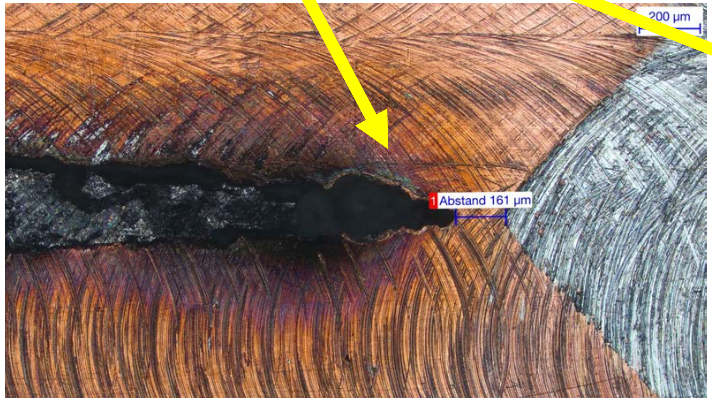


Cluster-Jet Beam Studies

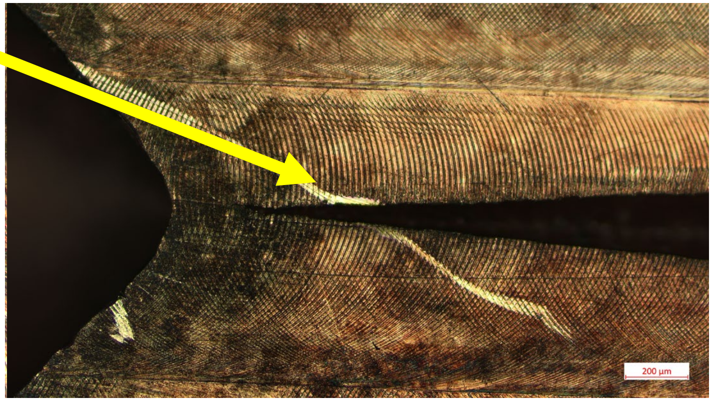
Galvanic production of monolithic copper nozzles significantly improved using ion trajectory simulations (report in progress)



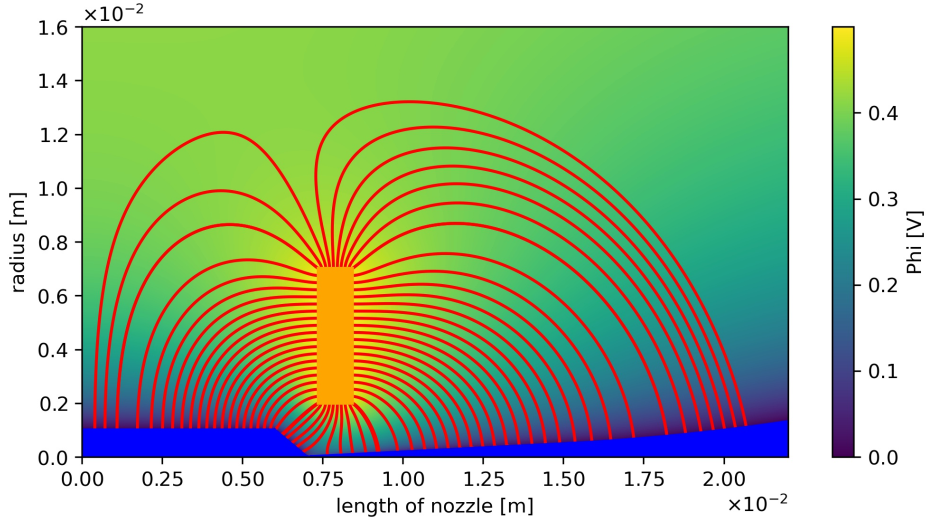
First copper layer after a few hours of galvanization



a) Result using standard procedure

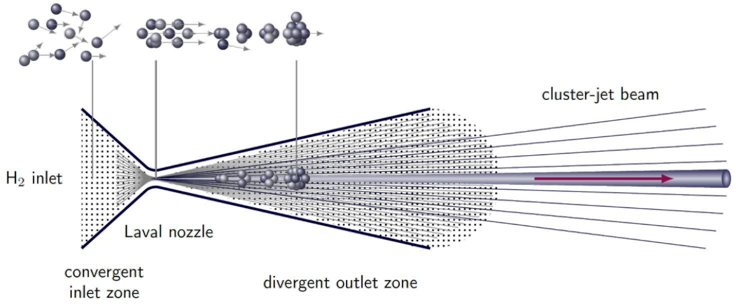


b) Result using optimized electrodes



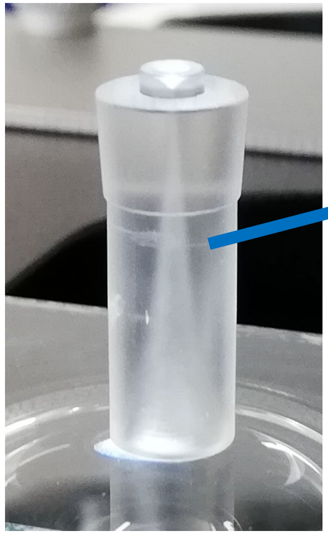
- High quality inner nozzle surface by use of special ring electrodes
- Lower surface roughness will allow for optimized jet beams

Cluster-Jet Beam Studies

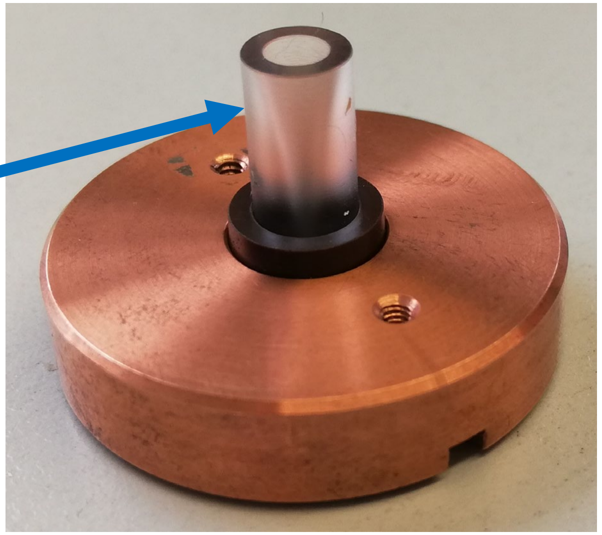


Galvanic production of monolithic glass nozzles using laser-induced etching

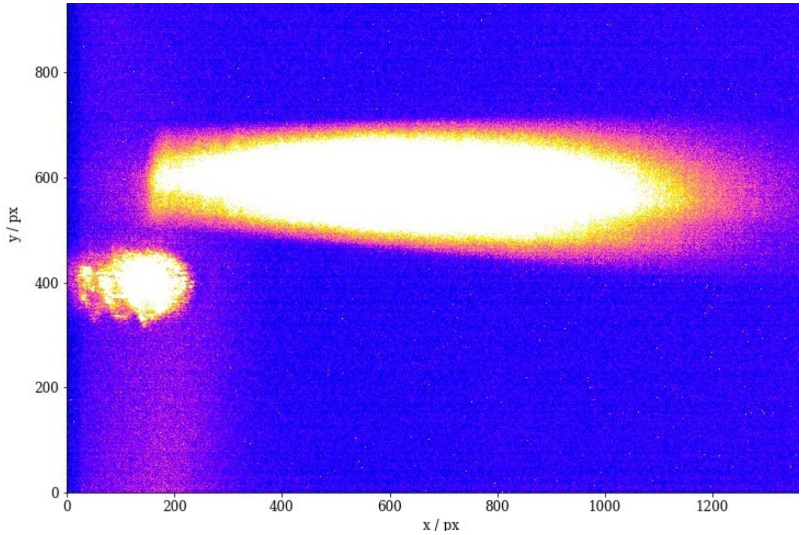
- Nozzles with full length of 18 mm now fabricable due to close contact with LightFab GmbH (Germany)



a) 18 mm monolithic glass nozzle with 30 µm inner opening



b) Completly mounted nozzle



c) Laser-illuminated cluster-jet beam using a new glass nozzle

- Detailed tests on cluster-jet performance in progress
- Effect of additional surface refinement under evaluation

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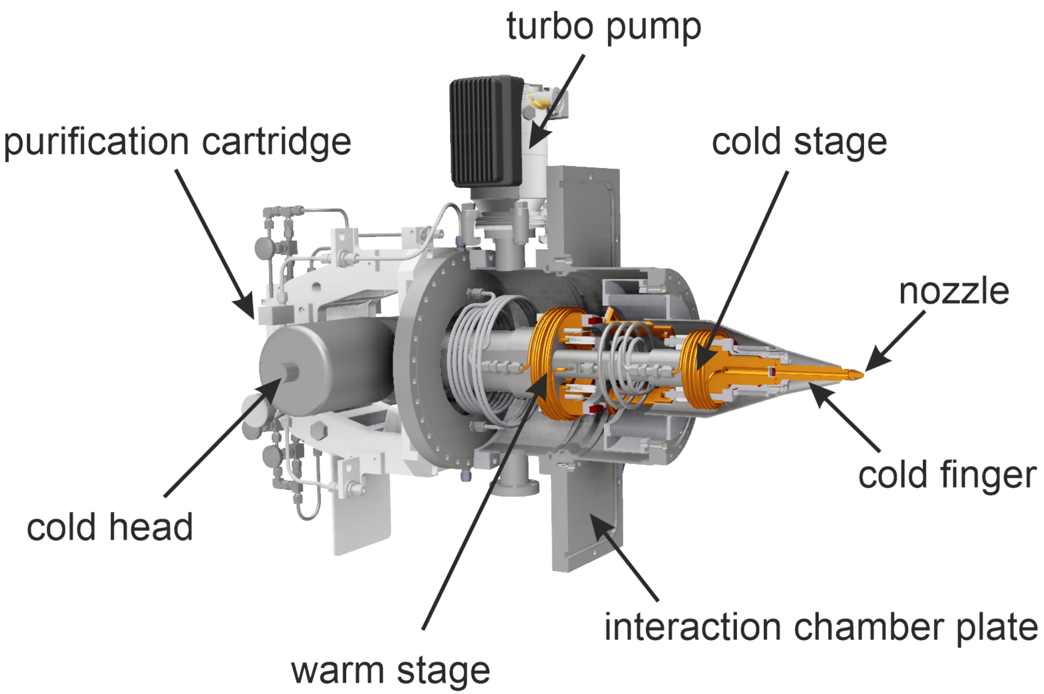
Cluster-Jet Beam Studies



Studies on laser-induced hadron acceleration

- Cluster-jet target at 200 TW ARCTURUS laser (Düsseldorf)
- Experiments using **hydrogen** and **argon** clusters
- Direct optical observation of Coulomb explosions achieved
  - Hydrogen cluster beam, 4 J laser energy, 30 fs laser pulse length
- Large amount of “exploding” clusters visible in each shot
  - high shot-to-shot stability
- Proton energies up to ~MeV observed

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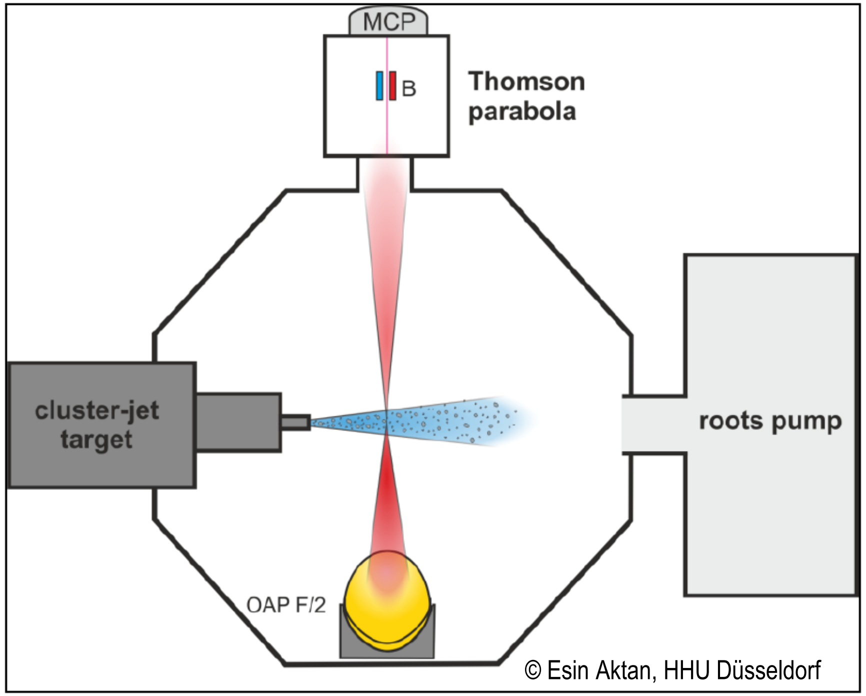

Cluster-Jet Beam Studies

Cluster-Jet Beam Studies

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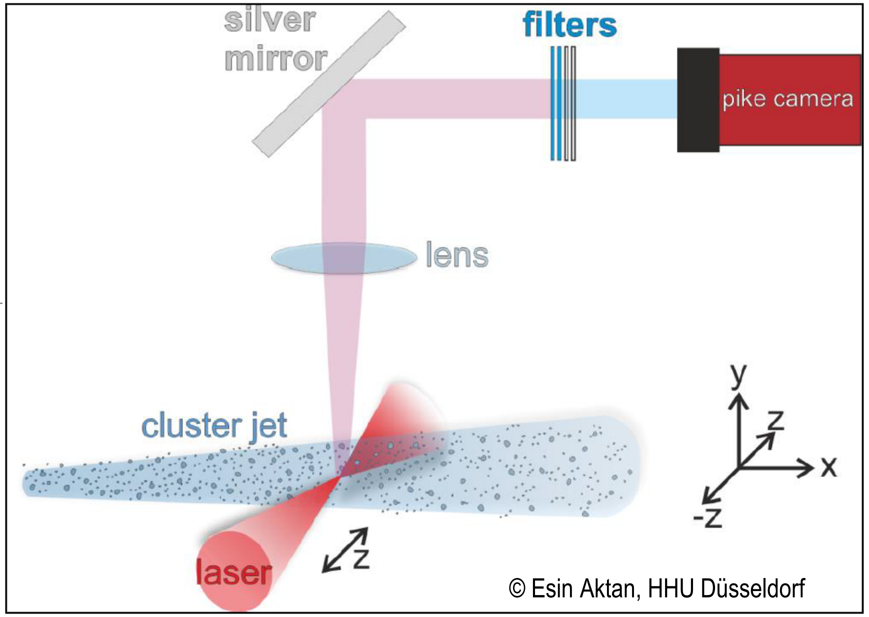
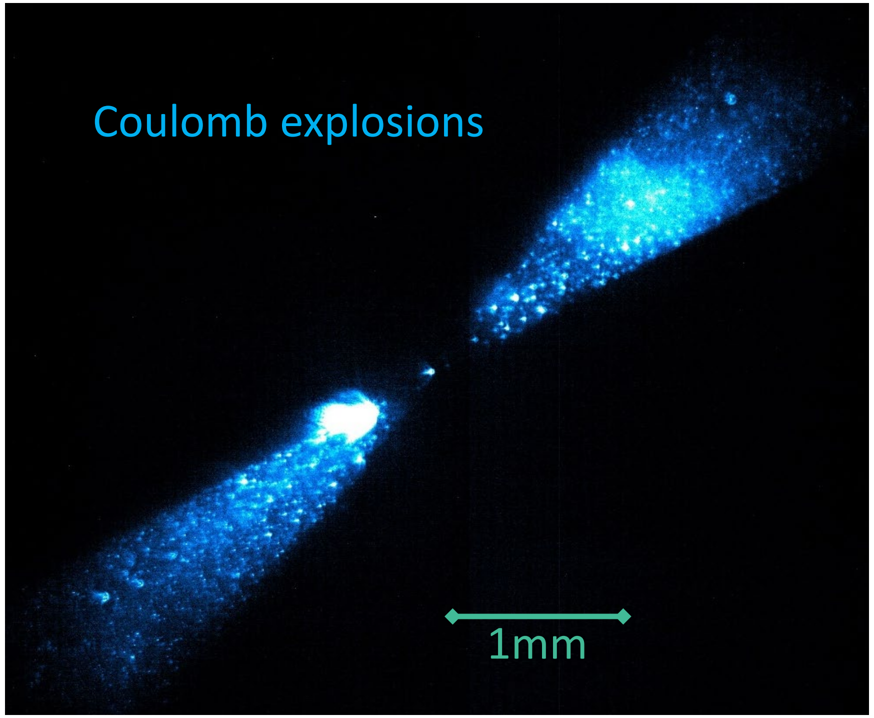
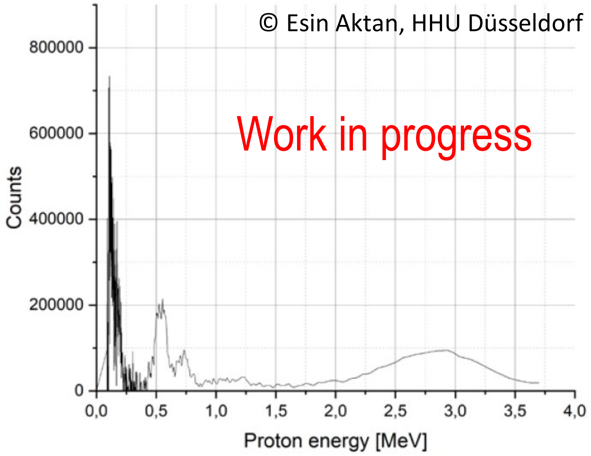
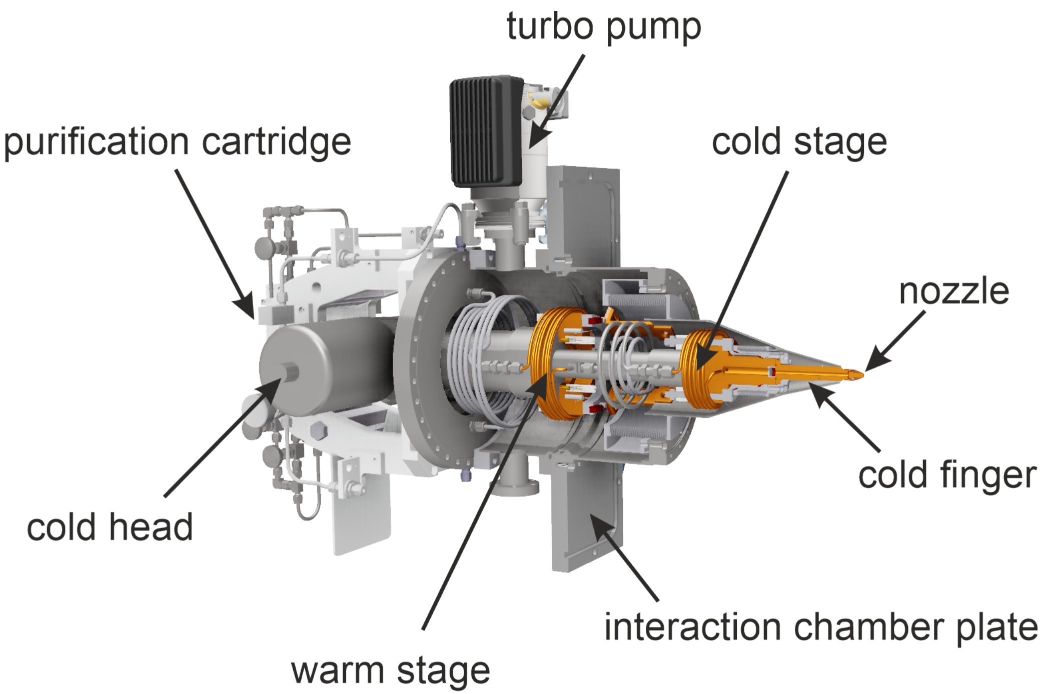






Cluster-Jet Beam Studies



Cluster studies using shadowgraphy

- Investigation of cluster formation
- Determination of mean cluster size and distance

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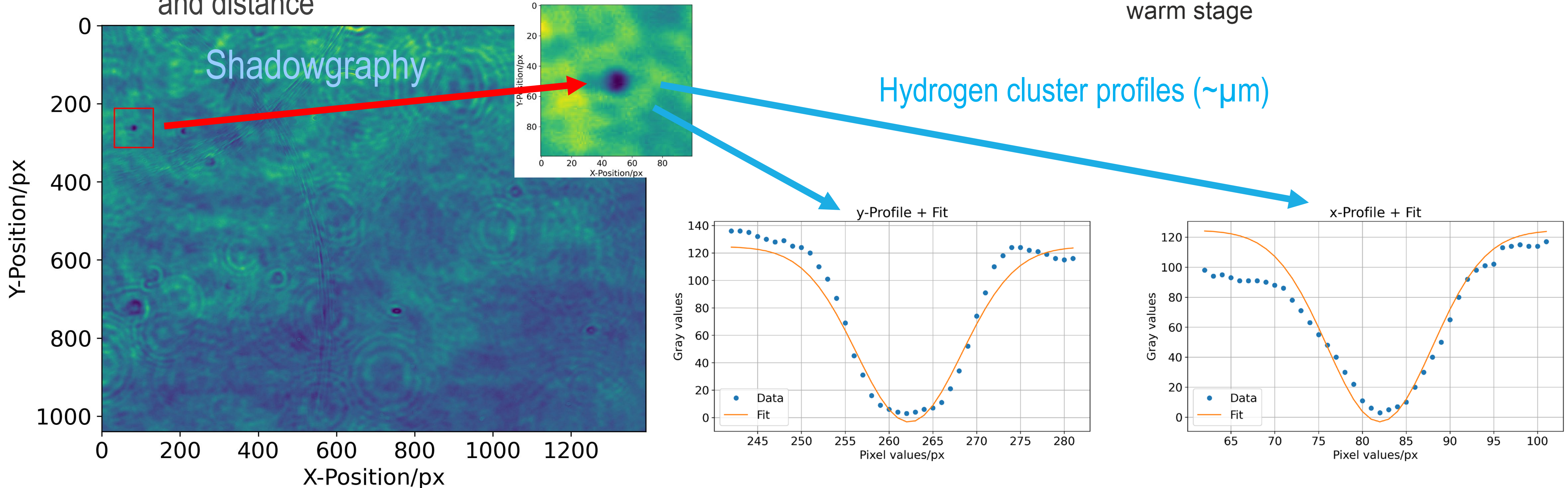
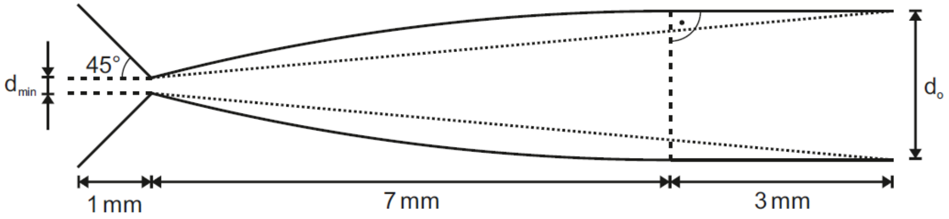


Cluster-Jet Beam Studies

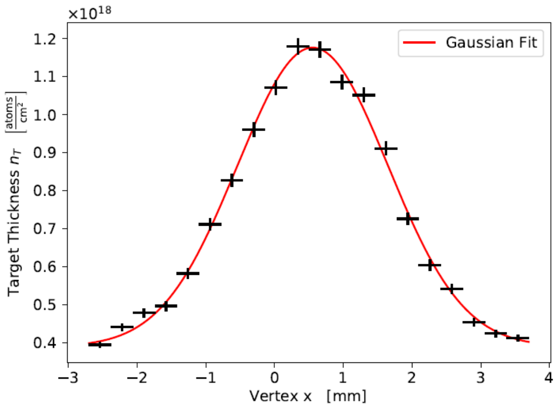
Numerical simulations on gas expansion in Laval nozzles

- Identification of an optimized nozzle design for gas-jet beams



Comparison of simulation results with experimental data obtained at MAMI (A1)

- Hydrogen target beams
  - Thickness $\rho > 10^{18}$ atoms/cm^2
  - Beam width σ = 1mm



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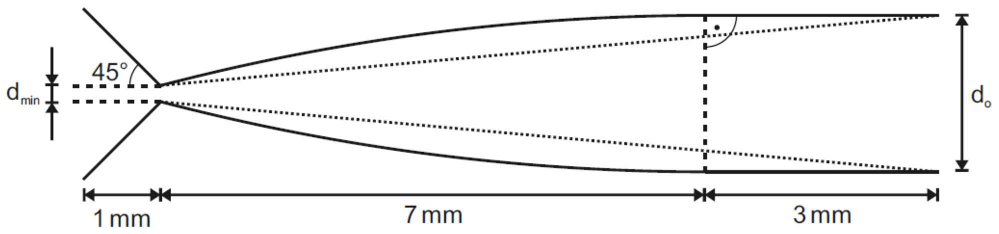
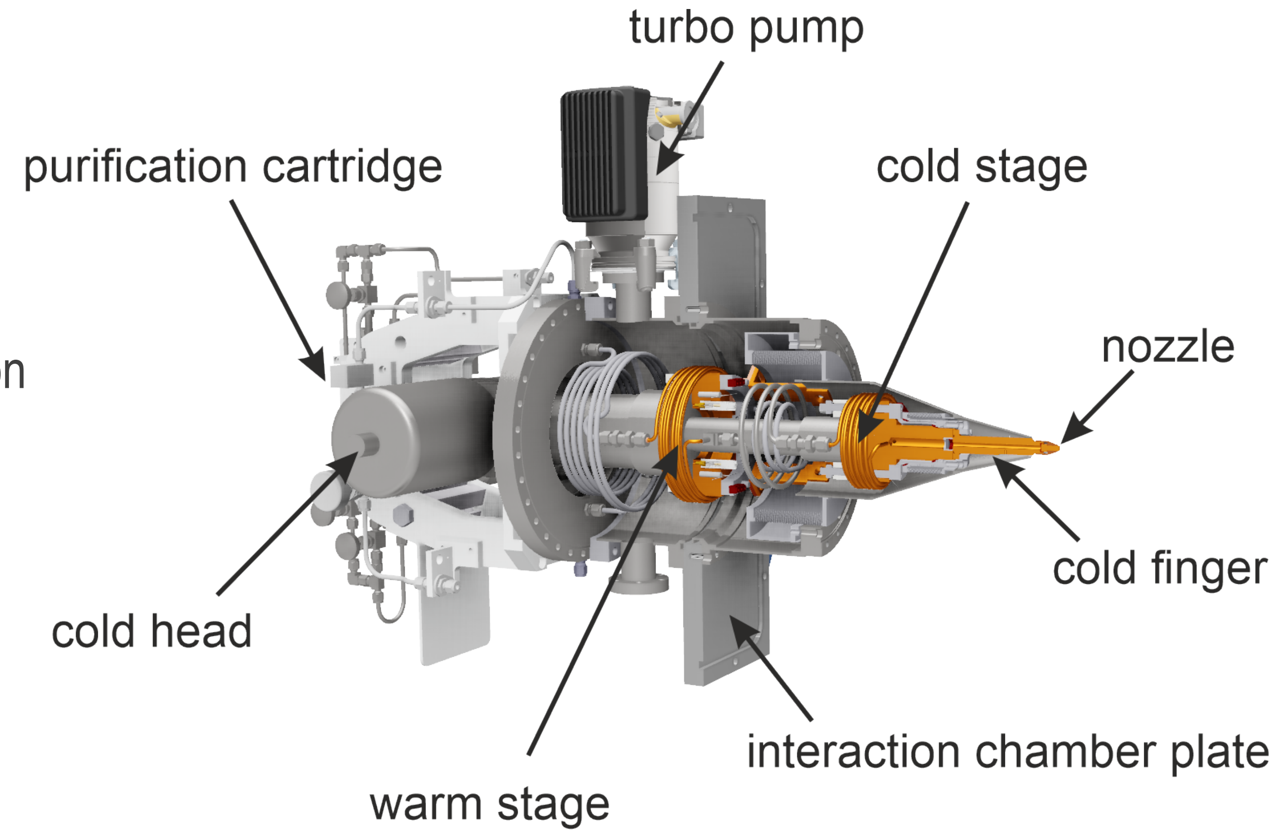
Cluster-Jet Beam Studies

Jet beams from heavier gases: Argon

- Gas beam simulations for an optimum Argon jet beam
- Identification of nozzle shape and diameter
- Galvanic jet nozzle production based on simulation results:





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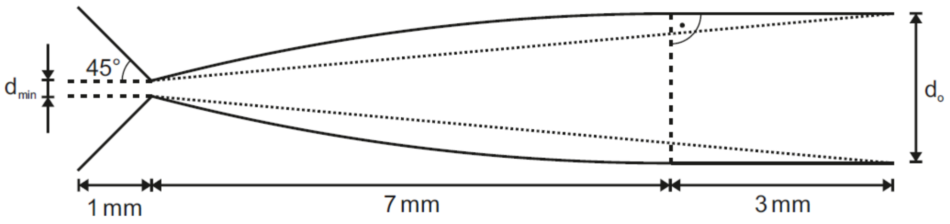
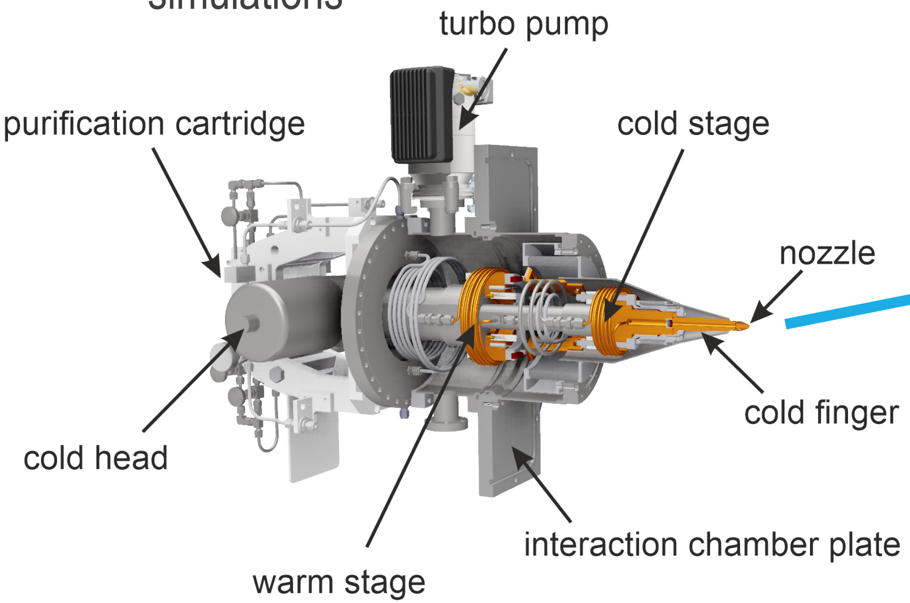
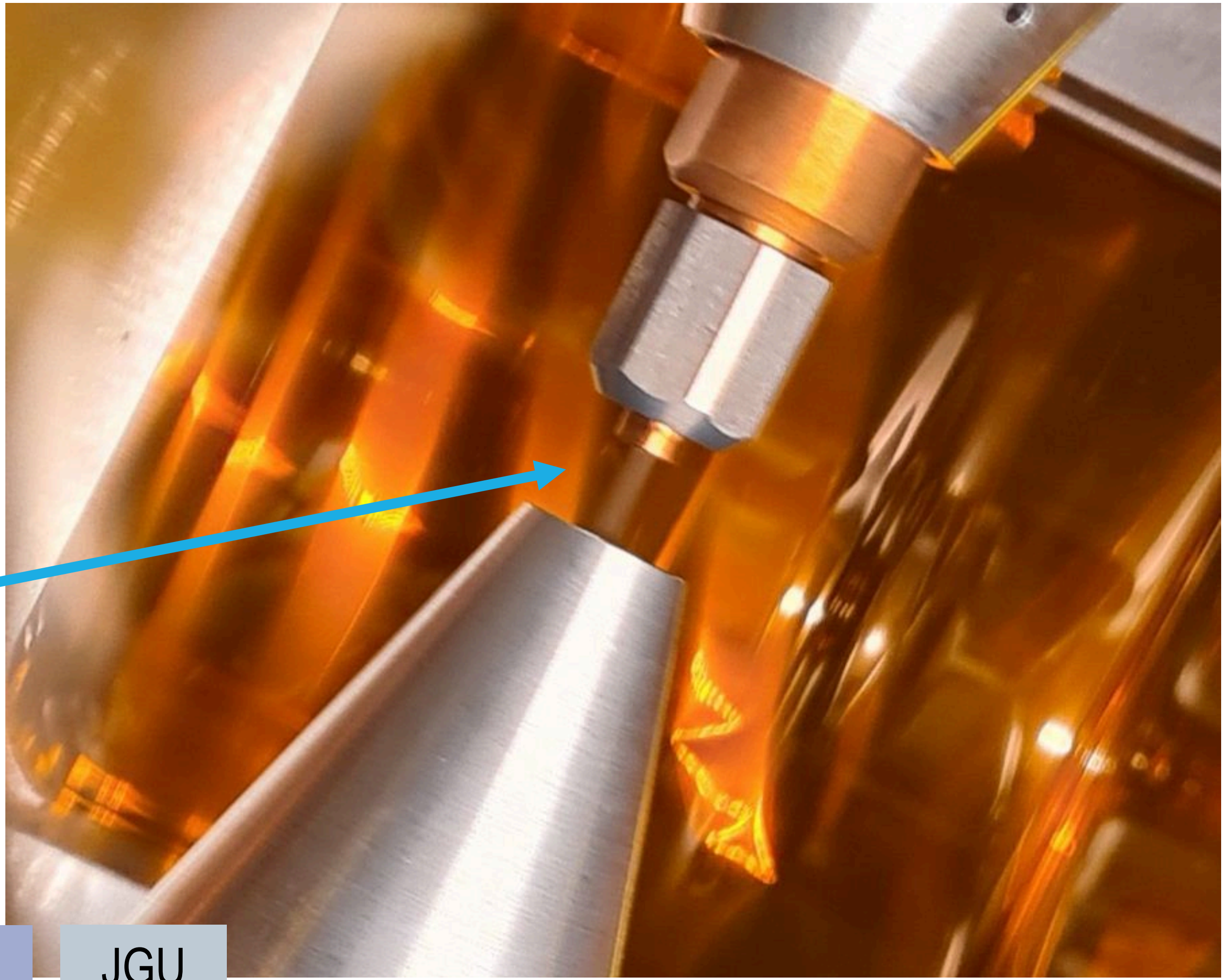
Cluster-Jet Beam Studies



Jet beams from heavier gases: Argon

- Argon jet beam
  - Directly visible due to high thickness
  - Very low beam divergence, in accordance with simulations





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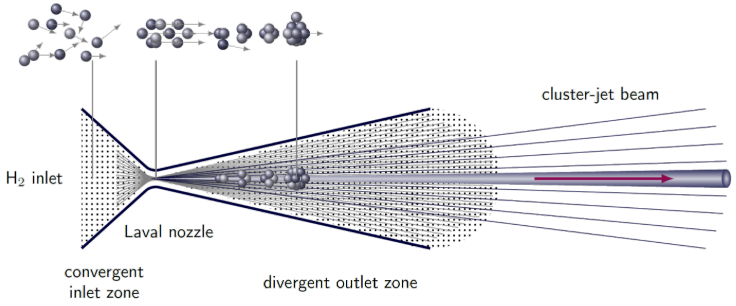
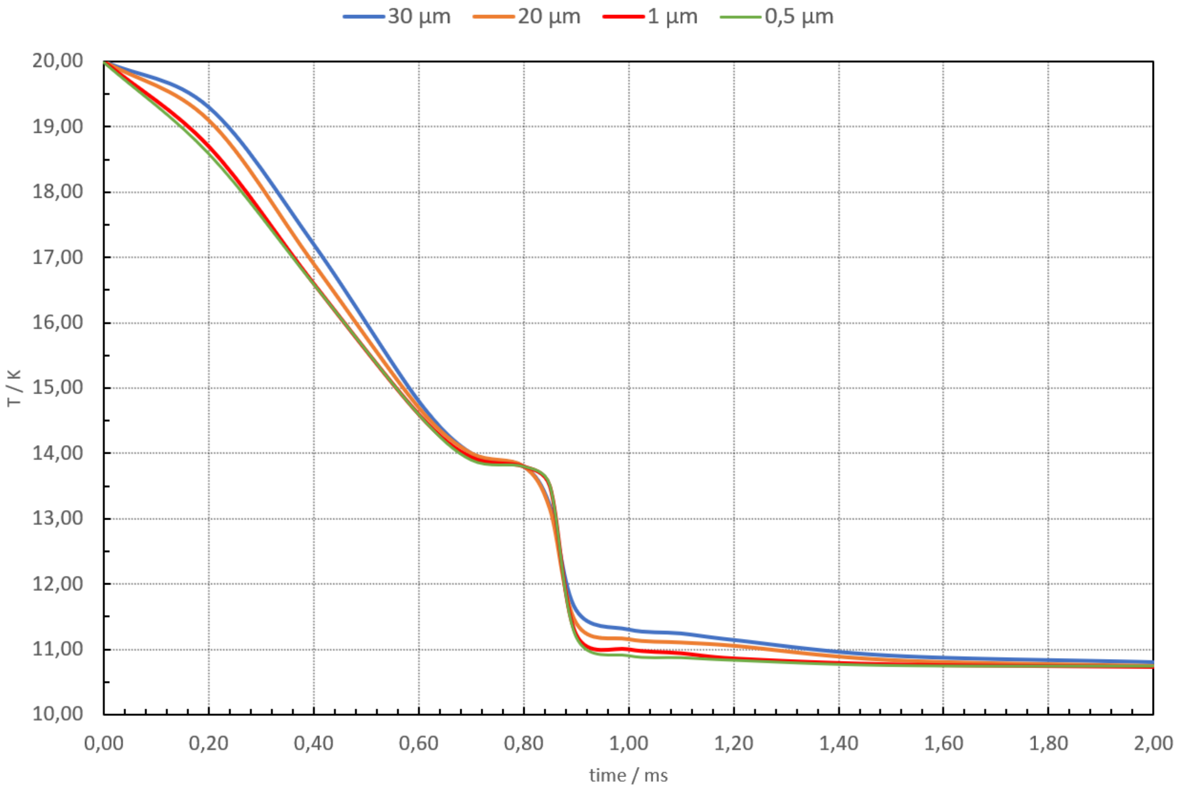
Cluster-Jet Beam Studies



Numerical simulations on droplet/cluster/pellet evaporation in vacuum well advanced



- Evaporation studies essential for advanced vacuum situation in case of experiments using
  - Liquid droplet beams
  - Pellet beams produced by droplet streams
  - Cluster beams produced using cryogenic liquids in front of the nozzle
- Original droplet diameter is of minor relevance for time of freeze-out
- Freeze-out position inside of the vacuum chamber (O(0.3 m)) depends on the
  - Droplet velocity
  - Stagnation condition

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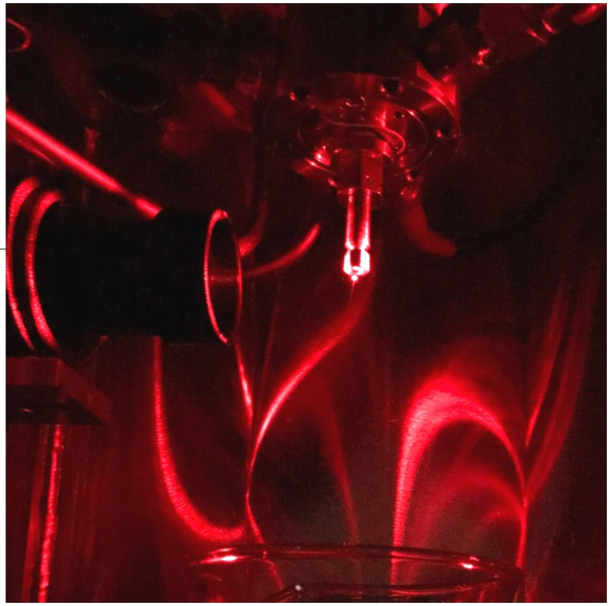
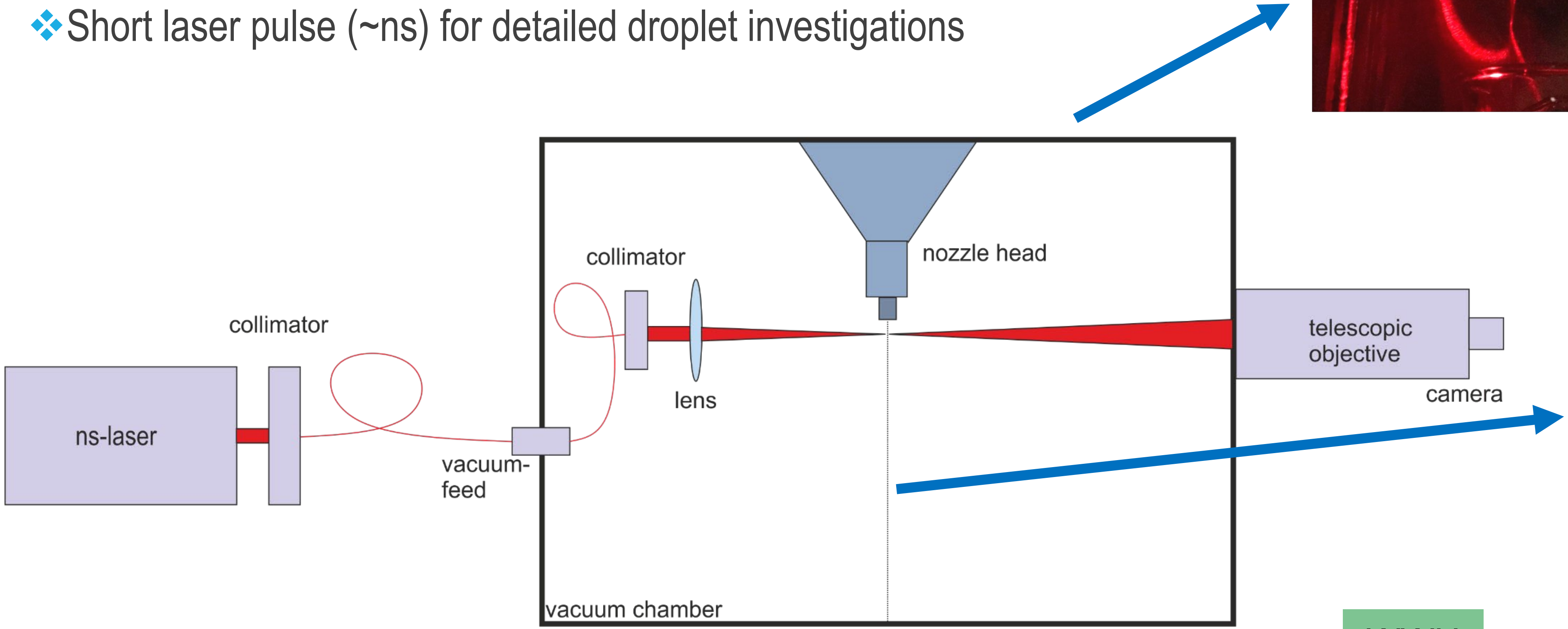
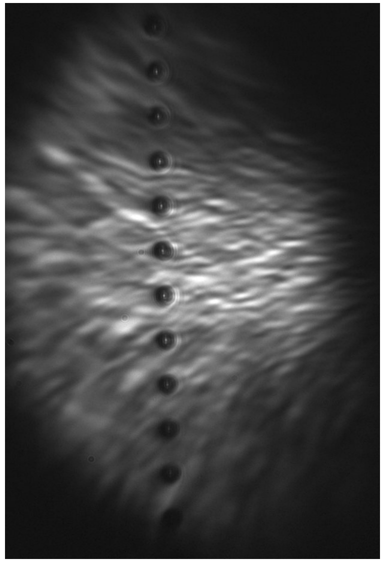
Cryogenic Droplet Beam Target

Preparation of an optical diagnostic system for a new droplet generator

- Stroboscopic and single-shot operation possible
- Short laser pulse (~ns) for detailed droplet investigations







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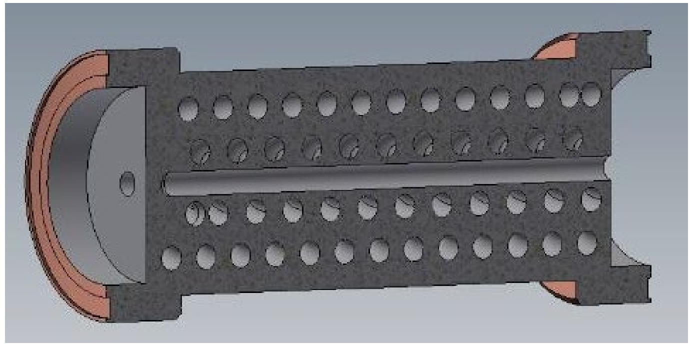
Cryogenic Droplet Beam Target

Setup of new droplet generator in progress

- Improved cooling power
- Less mechanical vibration
- Novel 3D printed heat exchangers



- New laser diagnosis system

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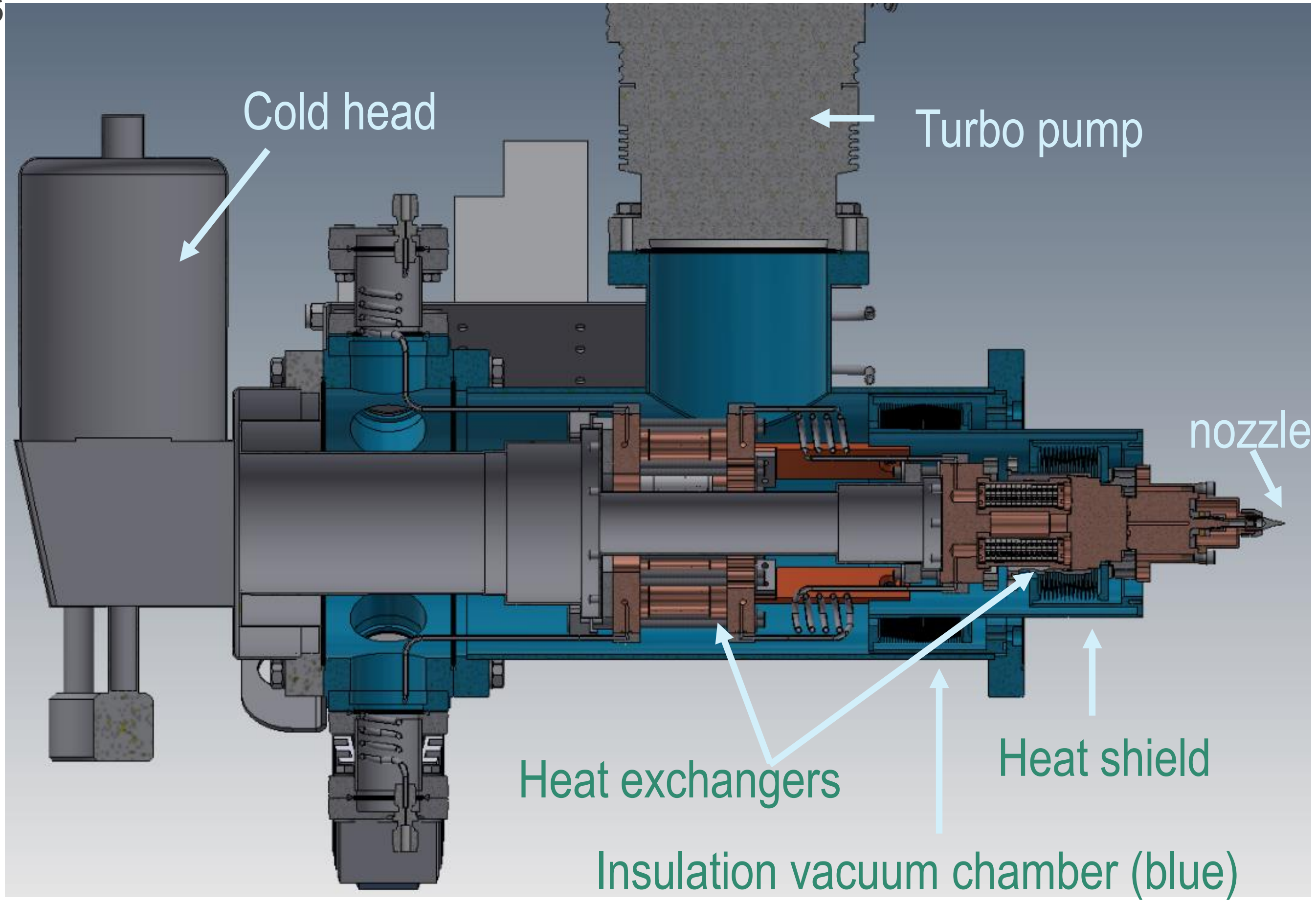
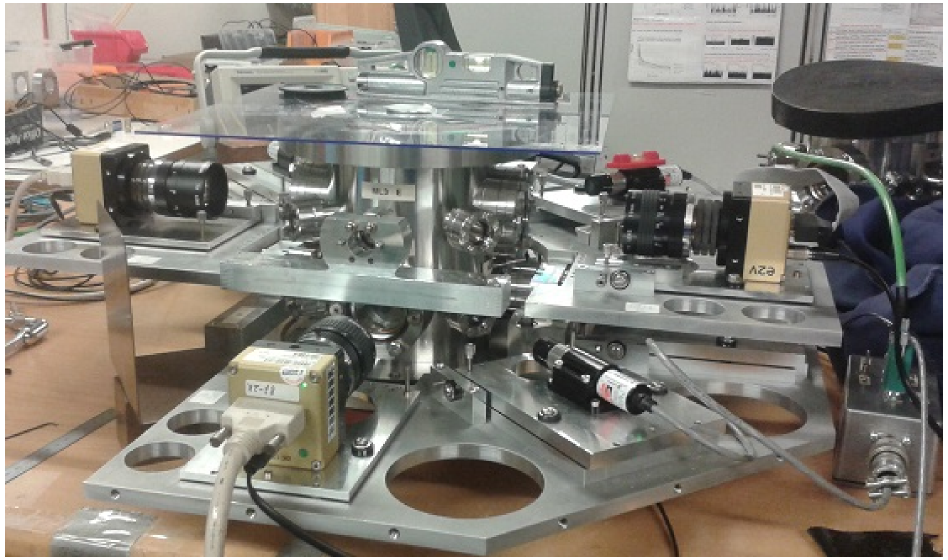
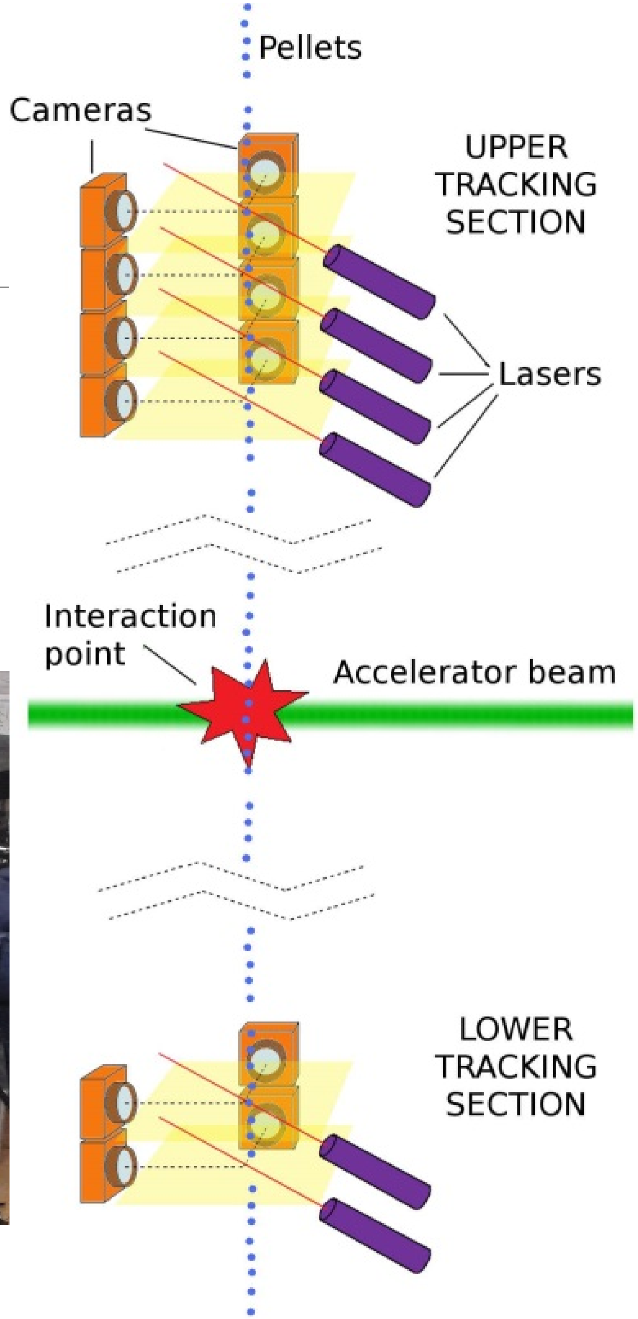


Pellet Source Studies

Real-time pellet tracking system

- Goal: pellet reconstruction with O(100μm) precision
- Overall design of a pellet tracking system in progress
- Possible applications
  - Hadron physics accelerators
  - Laser-induced particle acceleration
- Two fully equipped measurement levels prepared, sufficient for first realistic prototype test
- Dummy target for bench alignment being prepared





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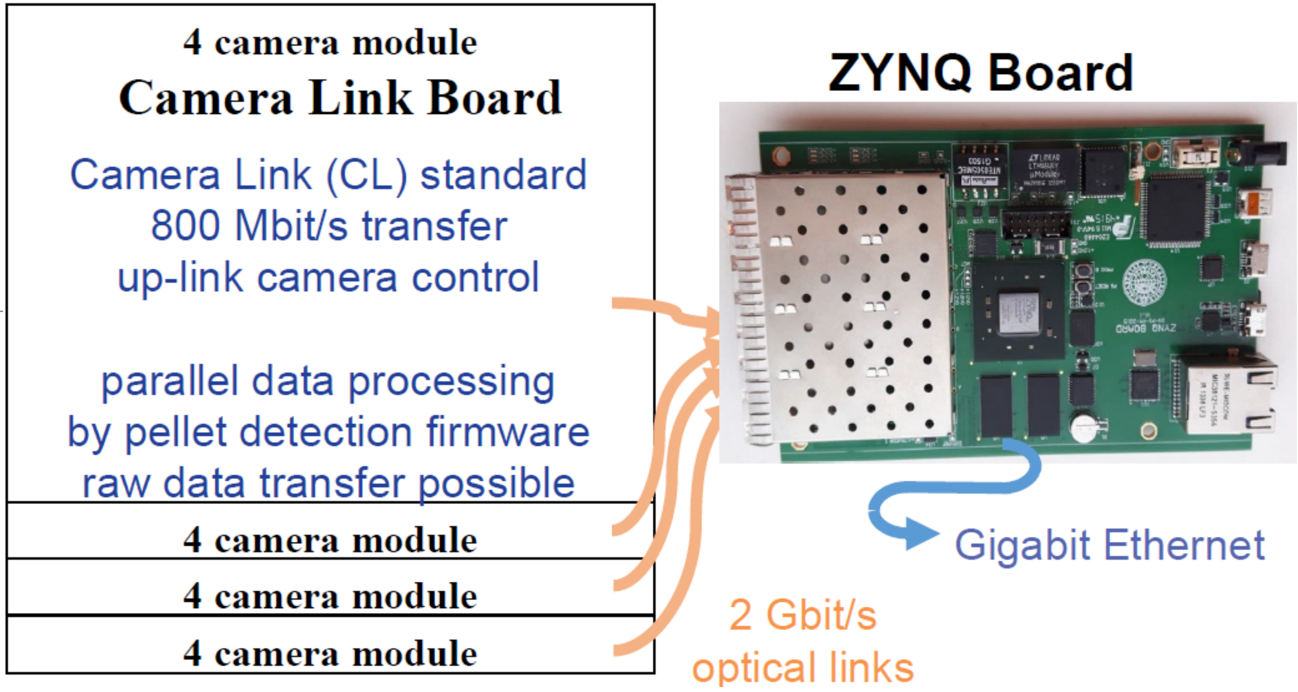
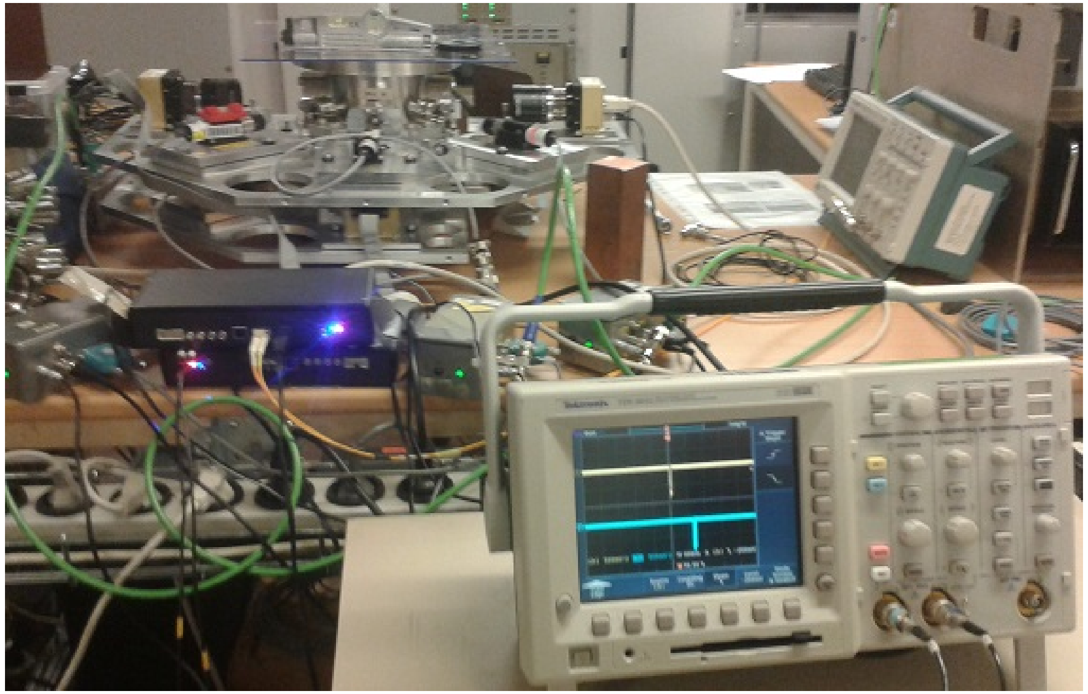
Pellet Source Studies

Real-time pellet tracking system

- Test of prototype system performance
- Development of a readout and DAQ system
- Synchronisation of line-scan cameras:
  - Real-time trigger signals from two cameras in coincidence → sufficient for first realistic prototype test
  - Extension to arbitrary number of cameras
  - Readout, data transfer from CamLink to ATLB and VME
  - Planned: readout, data transfer from CamLink to ZynqBoard





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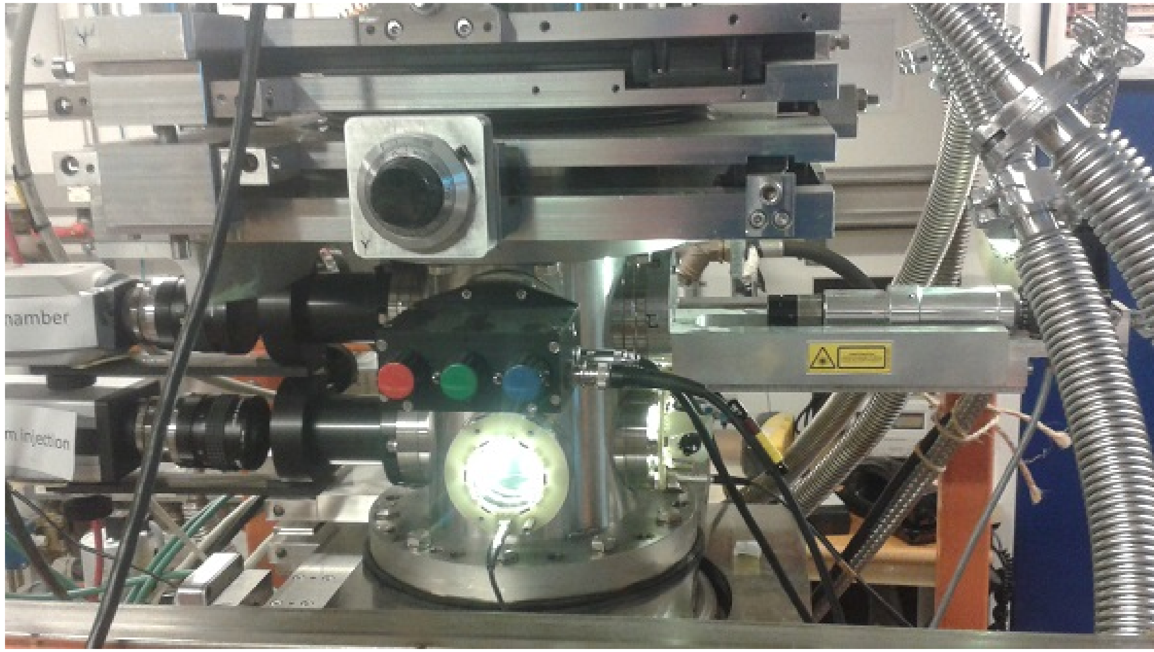
Pellet Source Studies

Pellet beams

- Droplet/pellet formation occurs commonly via
  - Spontaneous Rayleigh breakup
  - Vibration induced breakup using piezo excitation
- Novel idea: stimulated breakup by pulsed laser beams
  - infrastructure in preparation
  - laser installed at test station
  - pellet generator prepared for initial measurements (tested 04/2021)
  - preparations to illuminate different regions of pellet formation
  - Synchronized pulsed laser operation during following test run



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Pellet Source Studies

Studies towards frozen fiber target beams

- Observation of frozen hydrogen fibers in vacuum
  - length ~1.5 m
  - Lateral stability within millimeters for hours
- First step during following test runs:
  - reproduce (non-standard) conditions
- Next test run: Oct. 25-29, 2021

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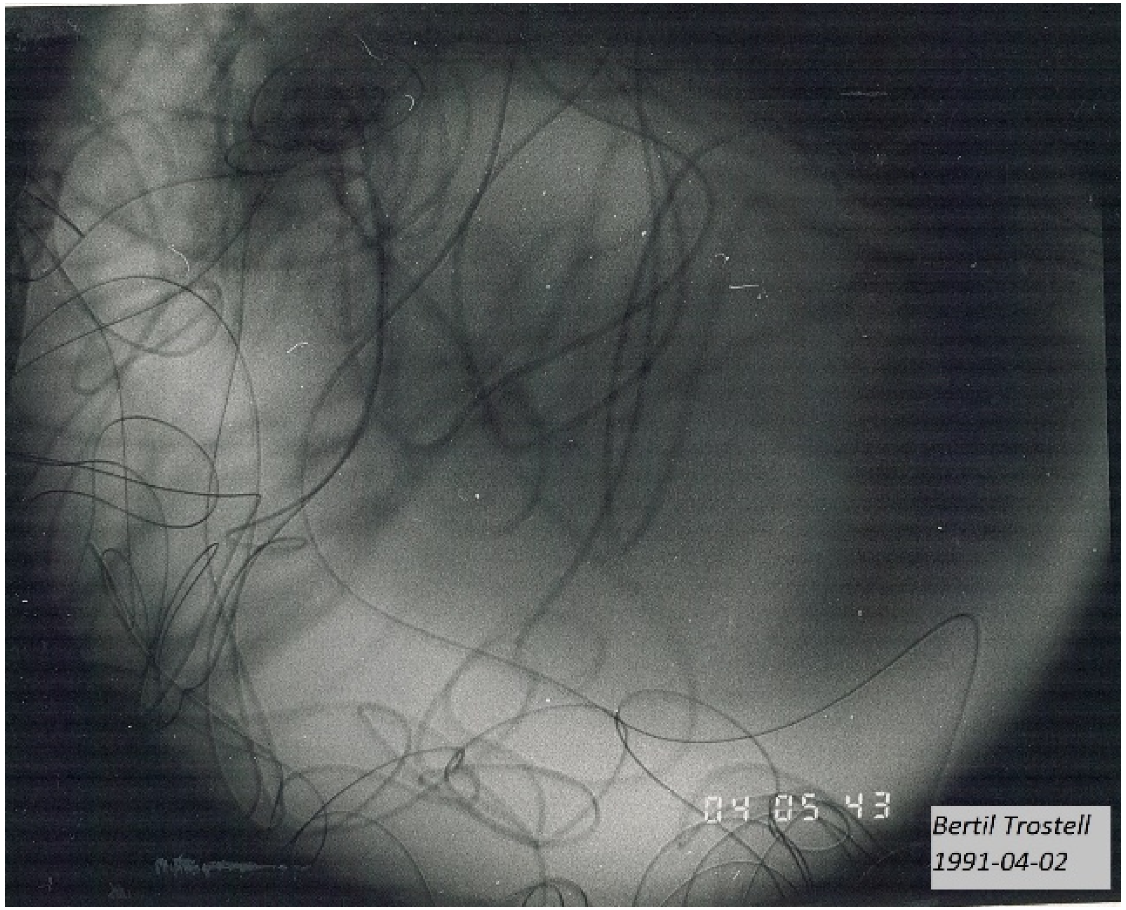

frozen hydrogen fibers bumping up and down in the beam dump (B.Trostell, 1991)

2.) Deviations from planned objectives and tasks, and their impact on the progress of the Work Package

- Up to now there are no deviations with respect to the objectives and tasks

3.) Deliverables and milestones

Tasks, Deliverables and Milestones

Work package number	29
Work package acronym	CryoJet
Work package title	JRA11-Cryogenically cooled particle streams from nano-to micrometer size for internal targets at accelerators

TASKS/Subtasks	Year 1				Year 2				Year 3				Year 4			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
1. Cluster-Jet Beam Studies																
1.1 New nozzle production techniques								1								
1.2 Studies on jet beams: highest performance and cluster formation																
1.3 Laser-induced particle acceleration (H_2 clusters and heavier gases)																
2. Cryogenic droplet beam target																
2.1 Studies on droplet nozzles designs and efficiency				2												
2.2 Measurements on long term stability																
2.3 Investigations on high performance																
3. Pellet Source Studies																
3.1 Development and studies with new pellet diagnostic systems																
3.2 New nozzle and pellet production techniques								3								

Tasks, Deliverables and Milestones

Deliverables

- No deliverables are due before the end of October 2021

Milestone number	Milestone title	Due Date (in months)	Means of verification	Comments
MS67	New production techniques for cluster nozzles identified	24	Successful production of new nozzles. Measurements will be performed	Delivered in month 24 ✓
MS68	Setup of a droplet test device	12	Successful operation of the droplet generator	Delivered in month 4 ✓
MS69	Improved pellet nozzle production avoiding nozzle blocking	24	Laboratory prototypes prepared and tested	Delayed (due to Cov-19), expected for 12/2021 (✓)

Summary

- Despite of the working restrictions caused by Cov-19, the Cryojet project is going very well
- Experiments are successfully performed at
  - the local laboratories of WWU Münster, UU Uppsala and GSI Darmstadt
  - the TW ARCTURUS Laser of the University Düsseldorf
  - the electron accelerator MAMI at Mainz
  - the proton synchrotron COSY at FZ Jülich
  - ITEP in Moscow
- Close contact to companies to establish new production lines
- It is expected that all deliverables and milestones will be reached