Cryogenic jet targets for high repetition rate experiments at FEL and high power laser facilities

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High-Energy Density instrument

- Ultrafast dynamics and structural properties of matter at extreme states
  - Highly excited solids → laser processing, dynamic compression, high B-field
  - Near-solid density plasmas → WDM, HDM, rel. laser-matter interaction

- Combination of high excitation with various X-ray techniques
  - Use of various pump sources: optical laser, XFEL, B-fields
  - Various X-ray probe techniques: XRD, SAXS, XRTS, hrIXS, XI, XAS...

- Properties of fusion plasmas
- Laboratory astrophysics, planetary science
- Plasma instabilities

European XFEL
10Hz repetition rate
4.5 MHz intra-bunch train

Exploring and employing of cryogenic targets is of great interest in HED science

Targets: H, D, T, He

European XFEL
Outline

- Introduction into cryogenic liquid jets using Hydrogen
- Experimental platform for laser experiments with jets
- Experience and results from different laser facilities
- Exploring new cryogenic jet target systems (planar geometry, droplets)
- Opportunities of ultra cold microjets for x-ray crystallography studies
Basic operation principle (exemplary for liquid H$_2$ jets)

1. Liquid is pressed through a small nozzle into vacuum
2. Continuous liquid jet is formed
3. Plateau-Rayleigh instability leads to breakup of the jet into equidistant droplets
4. Evaporative cooling cause freezing/crystallization

Cryogenic liquid jet source

- Liquid Helium flow cryostat for cooling (5W at 4.2K)
- Vacuum requirements: $p < 1 \times 10^{-3}$ mbar during operation
- Source assembly from high purity OFHC copper
- Commercially available circular apertures (1-50 micron)
- Source compatible for many gases, e.g. $H_2$, $D_2$, $CH_4$, Ar, …
Liquid Hydrogen jet

Shadow image using pulsed illumination source (Ti:Sa laser)

No observation of droplet formation
Rayleigh breakup versus crystallization

- Surface 'evaporative' cooling rate $10^7$ K/s
- Fast non-thermal crystallization within first 2 mm from nozzle
- Droplet formation length $L = 12v\sqrt{\frac{\rho d^2}{\sigma}} = 7$ mm

Raman scattering of supercooled liquid hydrogen jet reveal fast crystallization

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Liquid jets in a full-scale laser experiment

- Large field of view imaging system
- Cryogenic liquid jet source
- Pulsed probe beams
- High resolution imaging system
- X-FEL
- HE, HI laser

Coarse alignment of target and laser beams

On-shot target characterization (imaging, interferometry, time-resolved, etc.)
View into the experimental chamber at DRACO (HZDR)
Operation conditions for various jet sizes

Experimental parameters:
- Source: $T=18$ K, $P=2$ bar
- Jet velocity: $v \sim 100$ m/s
- Pumping speed: $dV/dt=4000$ l/s

Demonstration of 3 different jet diameters

Gas load increase significant with diameter:

<table>
<thead>
<tr>
<th>Jet diameter [$\mu$m]</th>
<th>2</th>
<th>5</th>
<th>10</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross section [$\mu$m$^2$]</td>
<td>13</td>
<td>79</td>
<td>314</td>
<td>1257</td>
</tr>
<tr>
<td>Gas flow [SCCM]</td>
<td>12</td>
<td>75</td>
<td>300</td>
<td>1200</td>
</tr>
<tr>
<td>Vac. pressure [mbar]</td>
<td>5E-05</td>
<td>3E-04</td>
<td>1E-03</td>
<td>5E-03</td>
</tr>
</tbody>
</table>

Heat conduction impacts cooling for $p_{\text{max}}>10^{-3}$ mbar

Catcher reduces chamber pressure by factor $\sim10$
Jet pointing stability

MEC-LCLS (SLAC)

Potential source for spatial jitter:
- Mechanical vibration from vacuum chamber
- Aperture surface quality (dents and spikes can cause asymmetric jitter)
- Fluid dynamics depend on P and T

DRACO (HZDR)

L. Obst, S. Göde, et al. submitted
On-shot characterization – target position

Proton acceleration in relativistic laser fields at DRACO laser

L. Obst, S. Göde, et al., submitted

- Laser focus
  \( E=3\text{J} \), \( \tau=30\text{fs} \)
  \( I=5\times10^{20} \text{ W/cm}^2 \)

Highest proton beam energies for central hits
On-shot characterization – target properties

Coherent scattering (Mie-scattering)

Interferometry (e.g. Nomarski)

Plasma density calculated from measured phase shift

Determination of jet size and surface modulations

Determination of plasma scale length in rel. laser plasma interaction

Demonstration of high repetition rate performance

X-ray diffraction with x-ray FEL at MEC-LCLS

Crystallization of supercooled hydrogen jets

Thomson parabola ion spectrometer

Generation of energetic proton beams with 1Hz*

*M. Gauthier, C. Curry, S. Göde et al. in preparation
Limitation for high repetition rate experiments

Shock explosion in liquid jet

- Principle repetition rate of 4.5 MHz seems possible (assuming <20 μm focal spot size and 100 m/s jet velocity)
- Recovery times of about 1 ms after shock explosion limiting repetition rate to about 1 kHz*


High power laser damage to nozzle

Dia: 5.5 +/- 0.4 micron

Physical nozzle damage after plasma discharge along the jet axis
Jets with planar geometries

Working principle:

1) Liquid expands into vacuum and persit shape of aperture

2) Jet contraction is qenched due to rapid crystallization

3) Final target has 'dump bell' shape

Schematic cross section of planar jets

- flat sheet with tunable width and thickness
- cylindrical rims (dia ~2-4 micron)

Work in progress: Characterization by high resolution imaging and interferometry (Collaboration between European XFEL, SLAC, HZDR and IPHT)
Controlled droplet formation

piezo modulates the beam at a frequency of 52.2kHz

80 µm hydrogen droplets moving with about 60 m/s

20 micron nozzle

piezo modulates the jet at a frequency of 84.2kHz

70 µm droplets

20 micron nozzle

Measured at FLASH

Measured pellet speed of 62 m/s
A catalogue of available cryogenic liquid jets

Cylindrical Jet

- Diameter: 2 - 10 µm
- Width: 20 - 50 µm
- Thickness: 0.3 - 4 µm

Planar Jet

- Diameter: 10 - 19 µm

Spherical Droplet Jet

- Diameter: 10 - 19 µm

Performance of cylindrical jets using Deuterium, Methane (CH₄) and Argon successfully demonstrated

Courtesy of J. Kim (SLAC)
Science fiction: Doping of cryogenic droplet jets

Superfluid helium nano-droplets have been used to prepare and probe aligned Xenon aggregates.

- Low Z host matrix provides orders of magnitude reduced background from x-ray scattering compared to e.g. water.
- Molecules are stabilized at ultra low temperatures in vibrational and rotational ground states.
- He is transparent in optical and UV range (pump-probe experiments).


Summary – Cryogenic liquid Jets

- Exploring new target systems for HED science: $\text{H}_2$, $\text{D}_2$, He, $\text{CH}_4$, CO, CO$_2$
- Providing renewable and high repetition rate samples
- Tunable target size, shape and geometry
- Embedding molecules in low z-material jets allow low background x-ray scattering experiments
Collaborators

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