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

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European XFEL

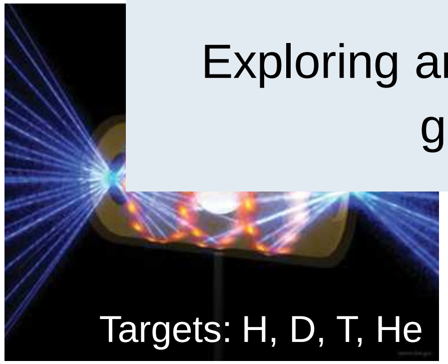
Microfluid workshop, Schenefeld, June15th, 2017

High-Energy Density instrument

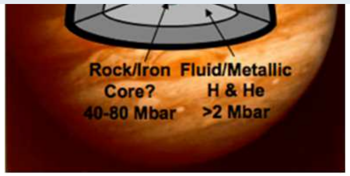
- Ultrafast dynamics and structural properties of matter at extreme states
  - **Highly excited solids→** laser processing, dynamic compression, high B-field
  - **Near-solid density plasmas→** WDM, HDM, rel. laser-matter interaction
- Combination of high excitati… with va…us X… techniques
  - Use of **various pump sources**: … …ds
  - **Various X-ray probe tech…** …, XI, XAS….

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

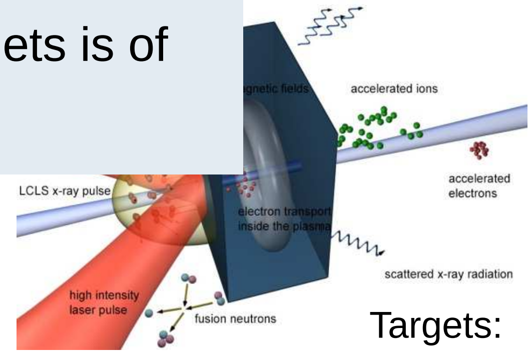
Properties of fusion plasmas



Labora… …y… planetary …ence



…elativistic laser plasmas, Plasma instabilities



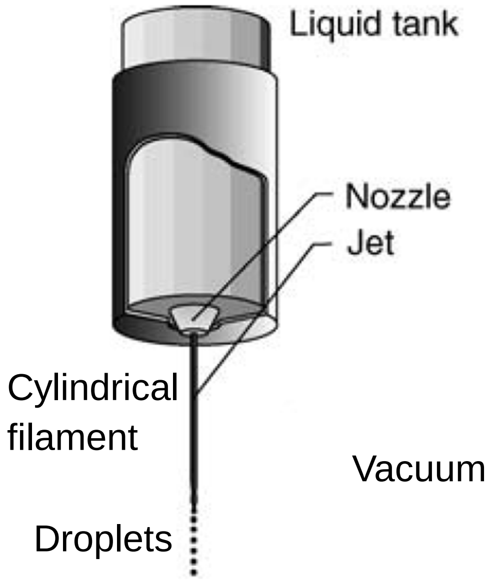
Targets:
H, He, Ne, Ar

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

Outline

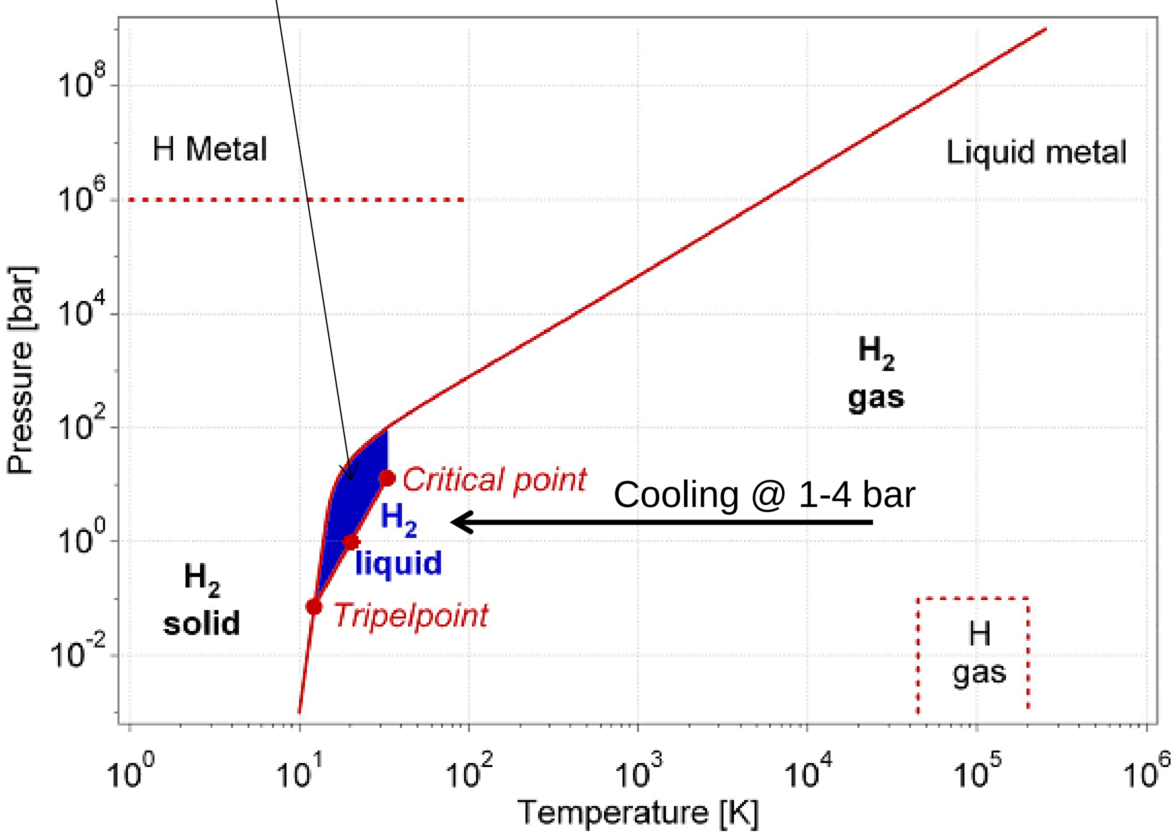
- Introduction into cryogenic liquid jets using Hydrogen
- Experimental plattform for laser experiments with jets
- Experience and results from different laser facilities
- Exploring new cryogenic jet target systems (planar geometry, droplets)
- Oportunities of ultra cold microjets for x-ray crystallography studies

Basic operation principle (exemplary for liquid H_2 jets)



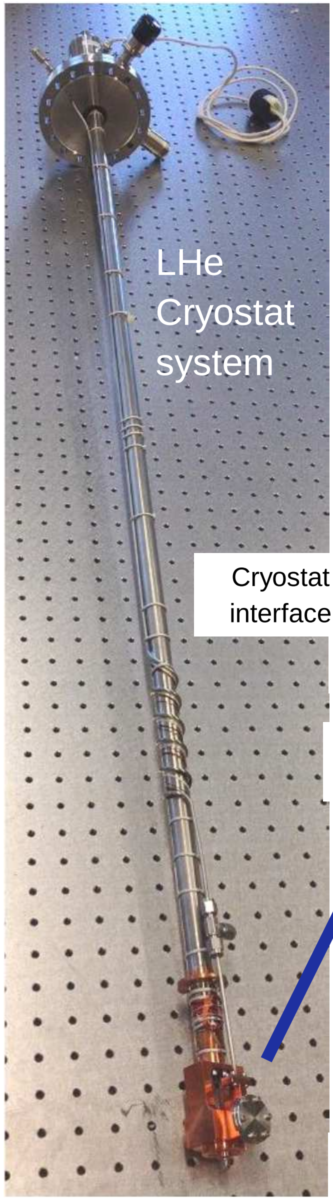
1. Liquid is pressed through a small nozzle into vacuum
2. Continuous liquid jet is formed
3. Plateau-Rayleigh instability leads to breakup of the jet into equidistant droplets
4. Evaporative cooling cause freezing/crystallization

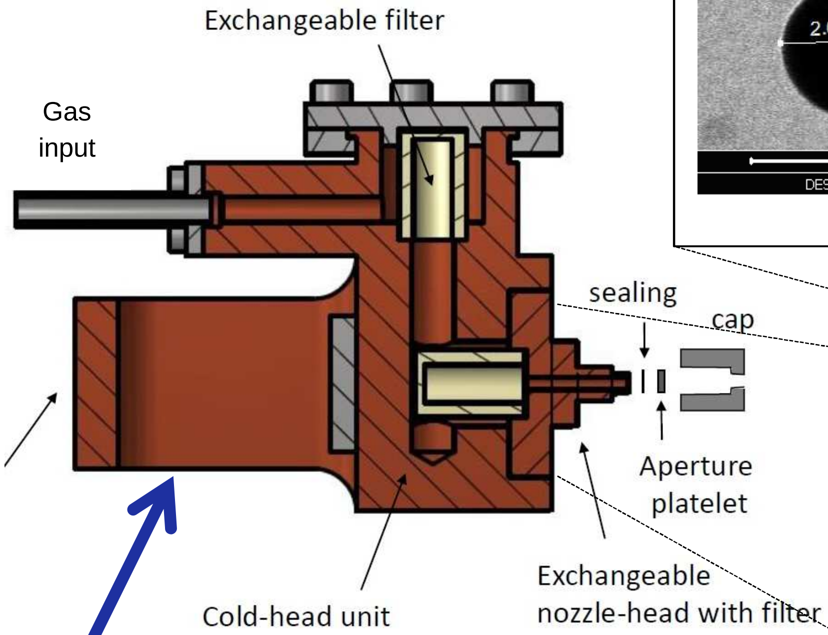
$\Delta T_{solid/liquid}$ @ 2bar = 5K



W. B. Leung and N. H. March H. Motz, “Primitive Phase Diagramm for Hydrogen”, Physics Letters 56A, 6 (1976), pp. 425-426

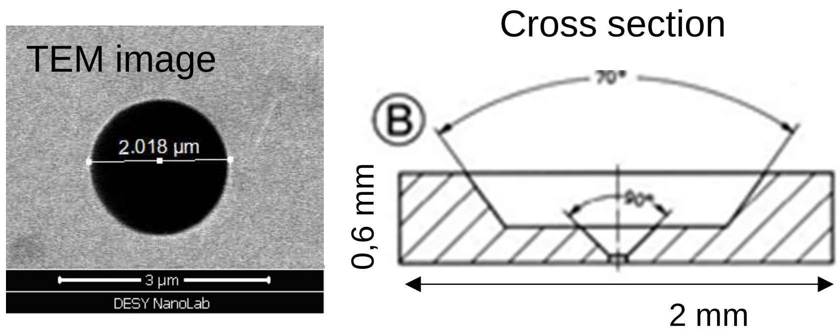
Cryogenic liquid jet source



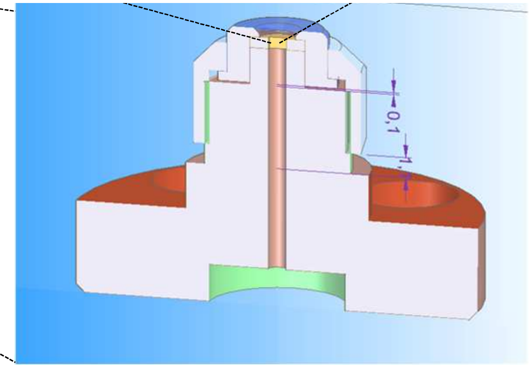


J. Kim, S. Göde and S. Glenzer, Rev. Sci. Instr., (2016)

Aperture plate



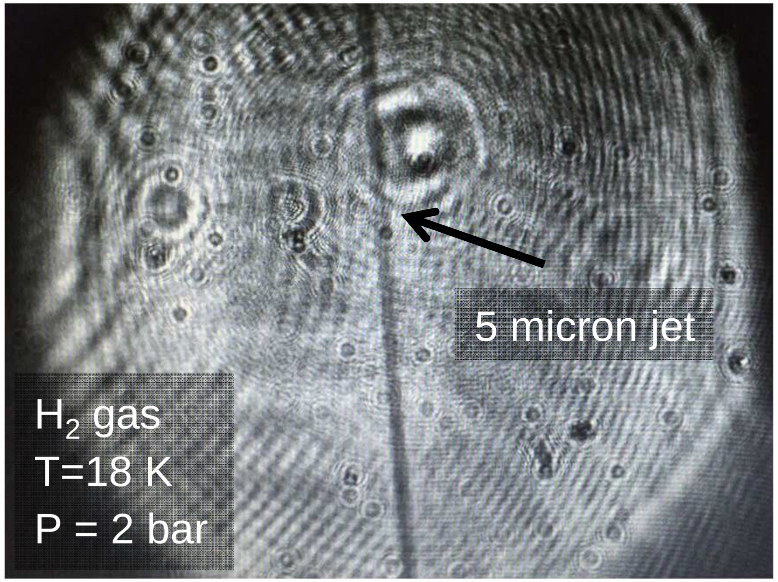
Exchangeable nozzle cap



- Liquid Helium flow cryostat for cooling (5W at 4.2K)
- Vacuum requirements: $p<1x10^{-3}$ 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)

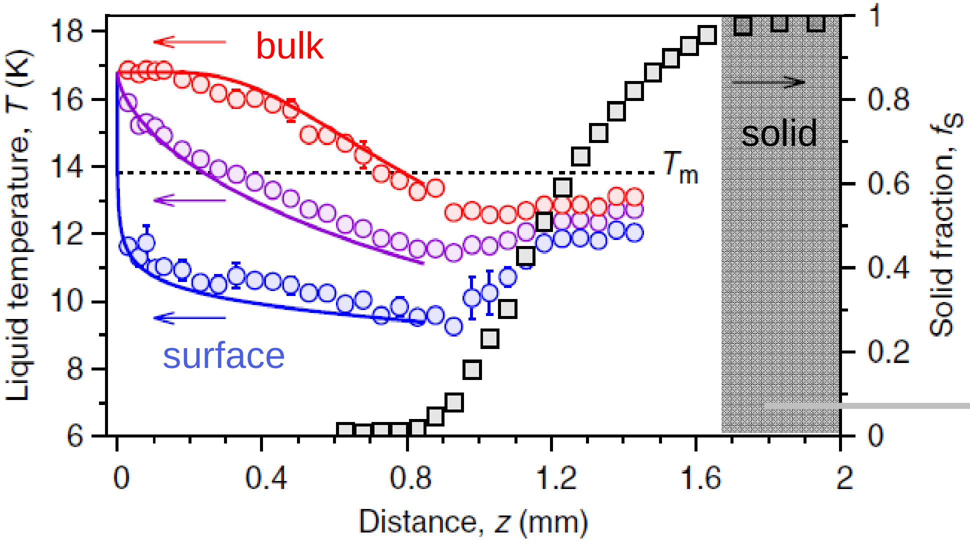


No observation of droplet formation

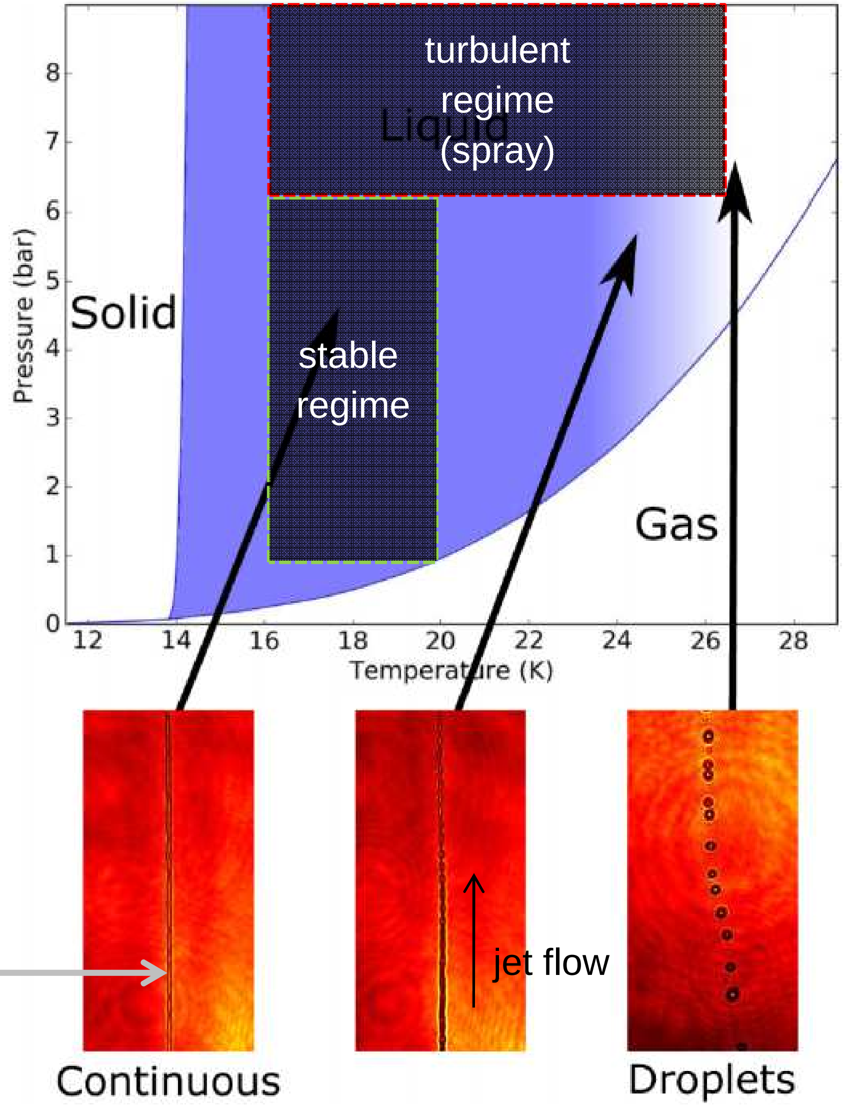
Rayleigh breakup versus crystallization

- Surface ‚evaporative' cooling rate 10^7 K/s
- Fast non-thermal crystallization within first **2 mm** from nozzle
- Droplet formation length $L = 12v\sqrt{\frac{\rho d^3}{\sigma}} = 7\ \text{mm}$

Raman scattering of supercooled liquid hydrogen jet reveal fast crystallization

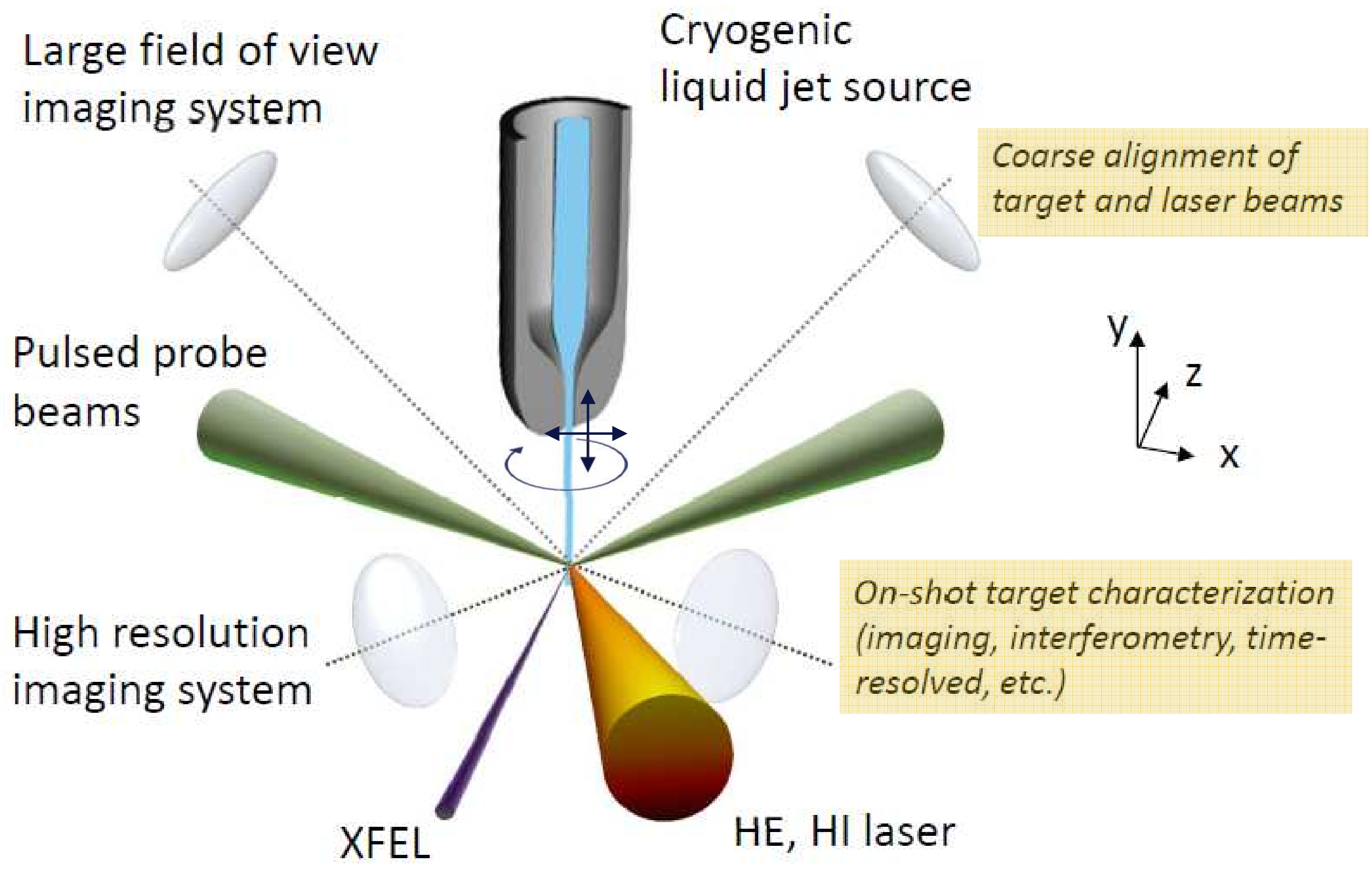


from M. Kühnel et al., Phys. Rev. Lett (2011)

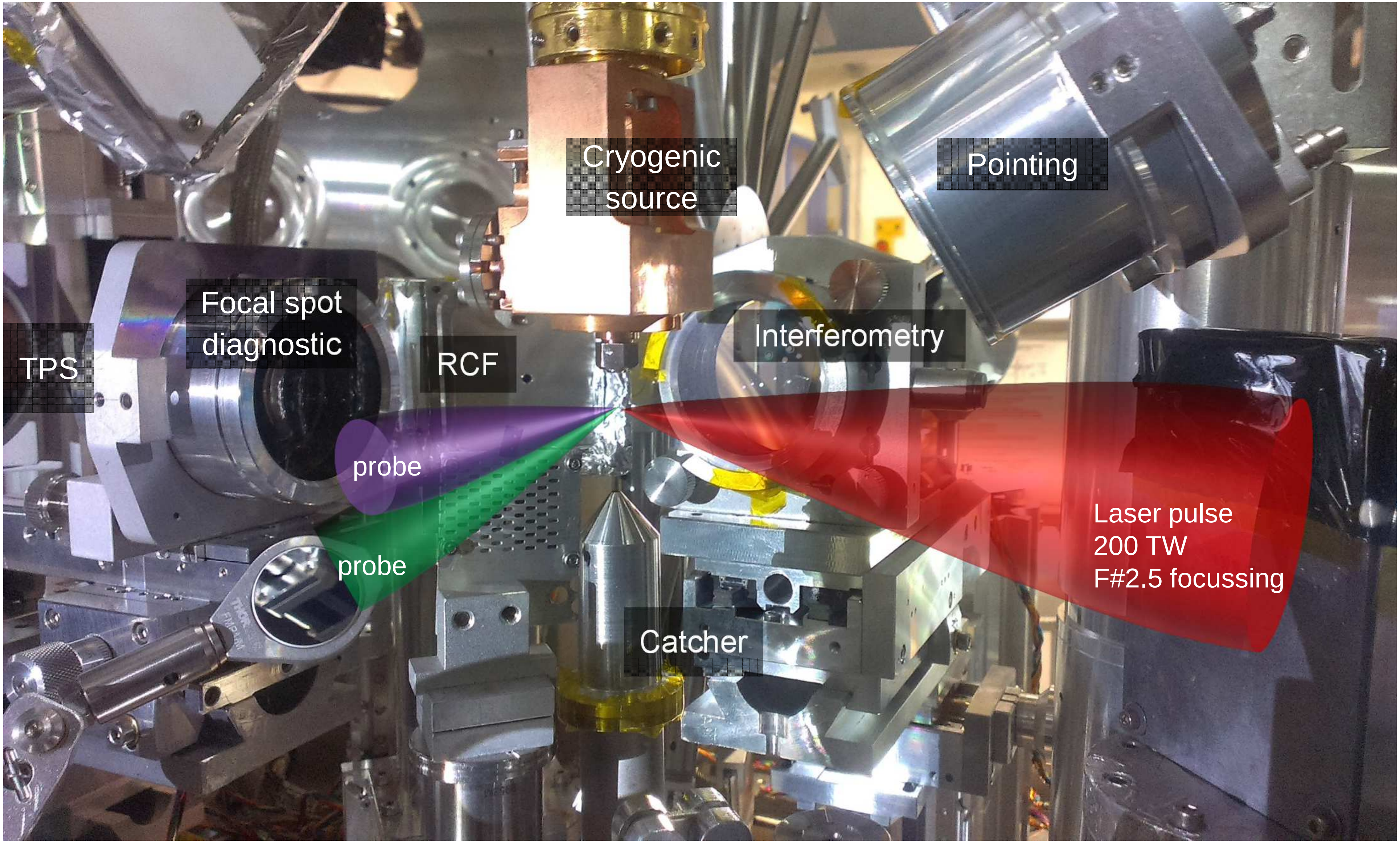


J. Kim, S. Göde and S. Glenzer, Rev. Sci. Instr., (2016)

Liquid jets in a full-scale laser experiment



View into the experimental chamber at DRACO (HZDR)

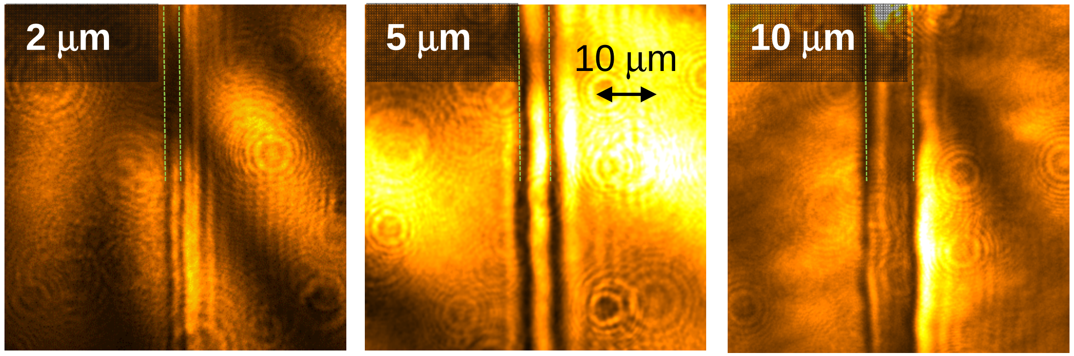


Operation conditions for various jet sizes

Experimental parameters:

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

Demonstration of 3 different jet diameters



Gas load increase significant with diameter:

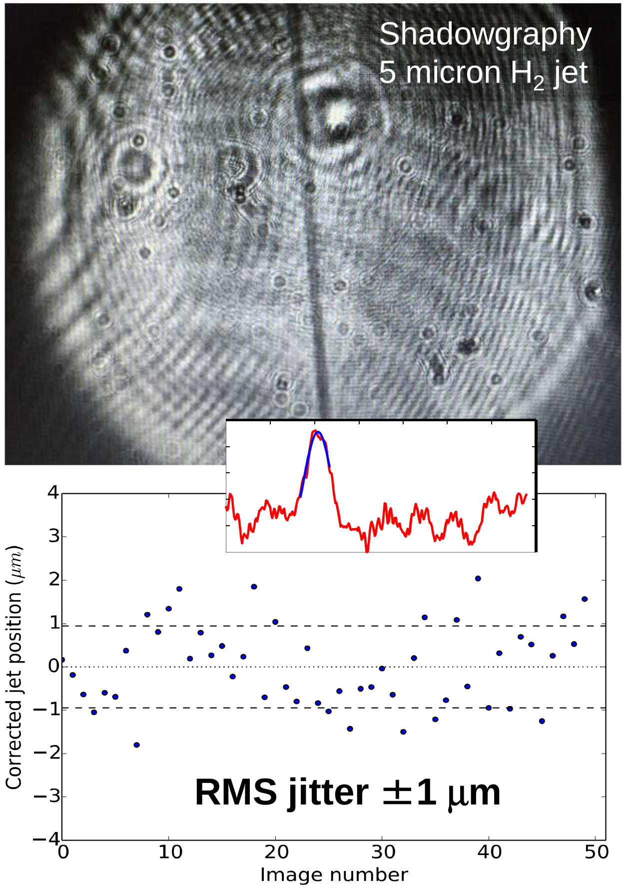
Jet diameter [µm]	2	5	10	20
Cross section [μm^2]	13	79	314	1257
Gas flow [SCCM]	12	75	300	1200
Vac. pressure [mbar]	5E-05	3E-04	1E-03	5E-03

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

Catcher reduces chamber pressure by factor ~10

Jet pointing stability

MEC-LCLS (SLAC)

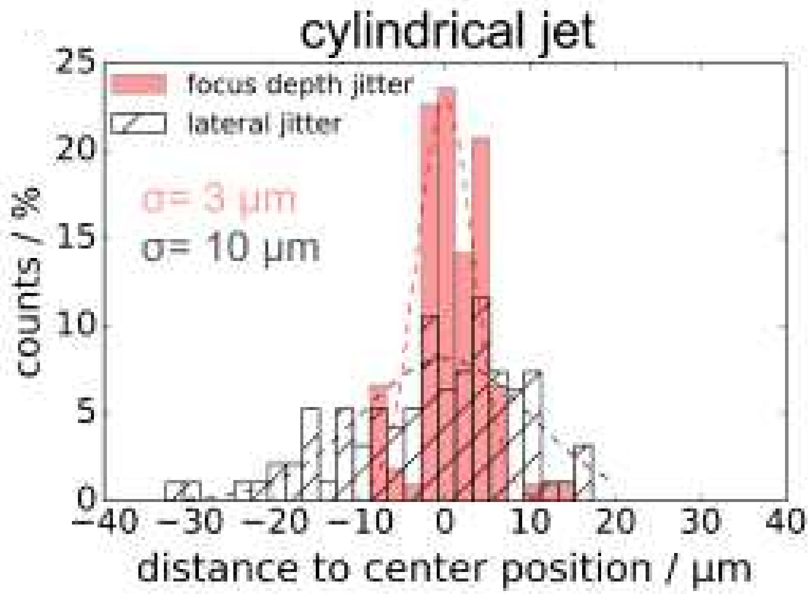


J. Kim, S. Göde and S. Glenzer, Rev. Sci. Instr., (2016)
L. Obst, S. Göde, et al. submitted

Potential source for spatial jitter:

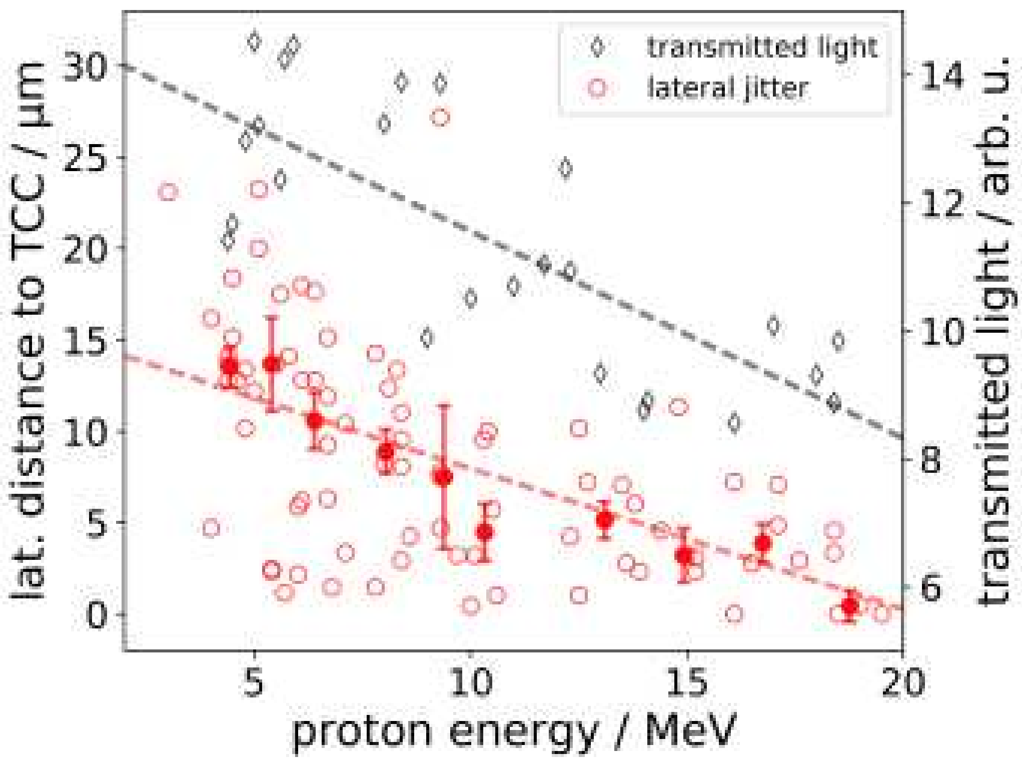
- Mechanical vibration from vacuum chamber
- Aperture surface quality (dents and spikes can cause asymmetric jitter)
- Fluid dynamics depend on P and T

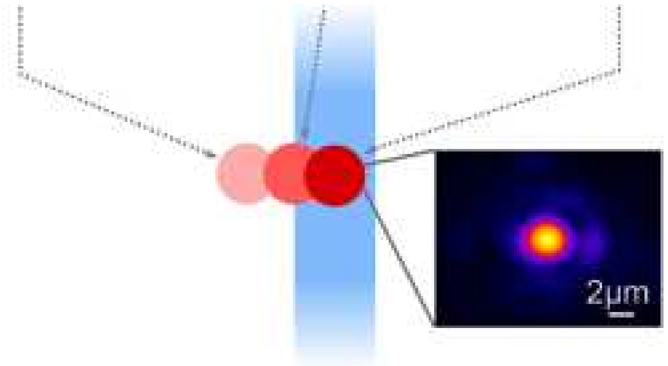
DRACO (HZDR)



On-shot characterization – target position

Proton acceleration in relativistic laser fields at DRACO laser





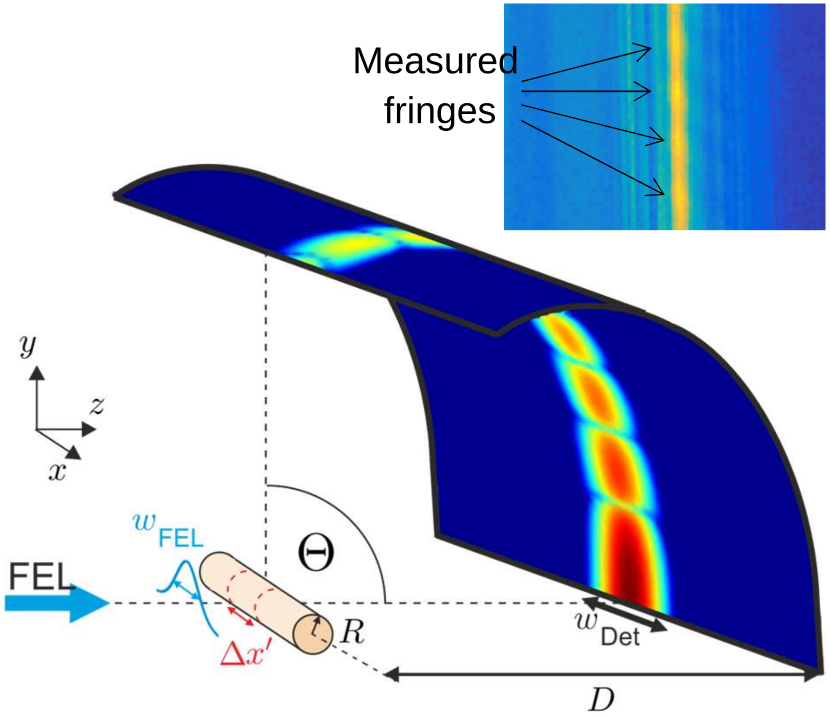
Laser focus
E=3J, τ=30fs
I=5x10^{20} W/cm^2

Highest proton beam energies for central hits

L. Obst, S. Göde, et al., submitted

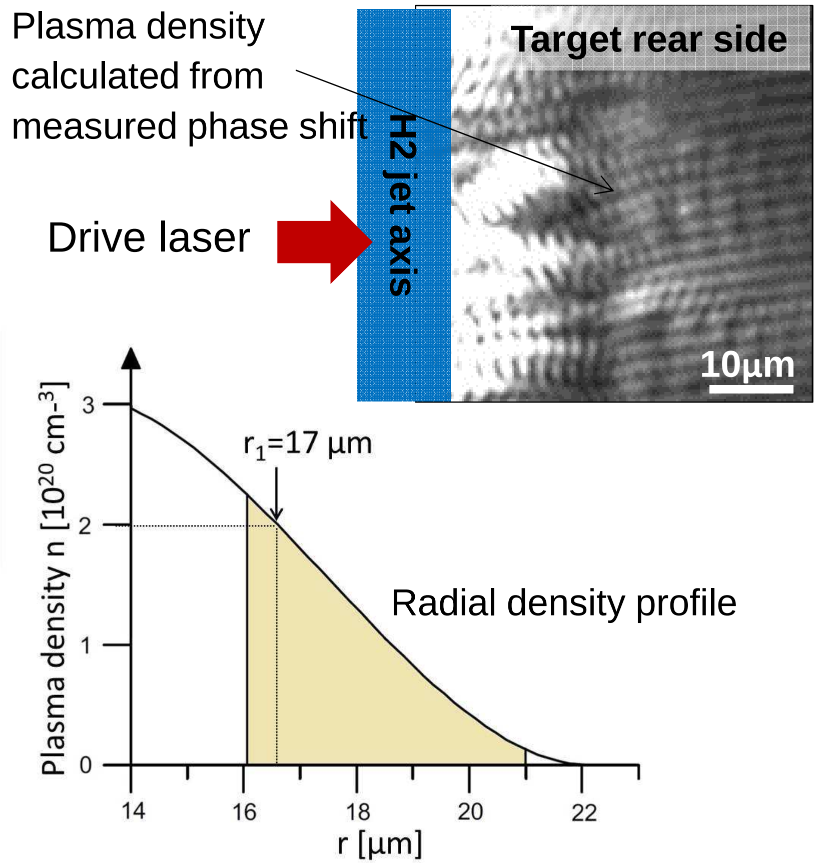
On-shot characterization – target properties

Coherent scattering (Mie-scattering)



Determination of jet size and surface modulations

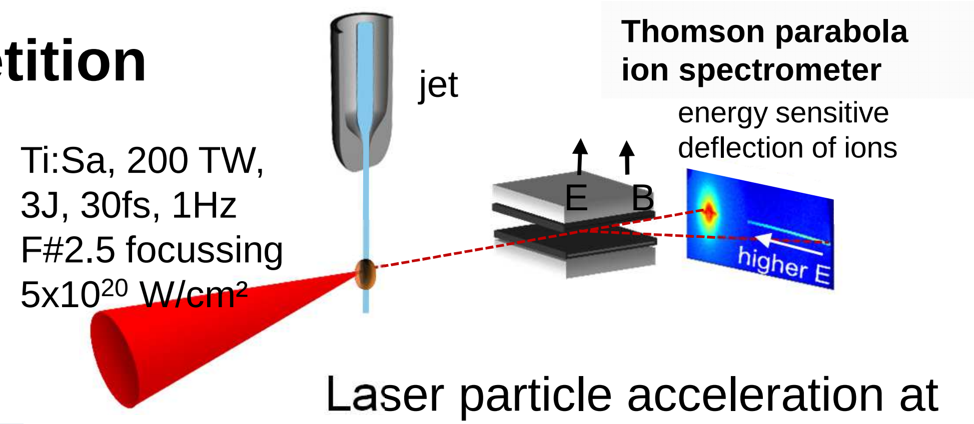
Interferometry (e.g. Nomarski)



Determination of plasma scale length in rel. laser plasma interaction

S. Göde, et al. Phys. Rev. Lett. 118, 194801 (2017)

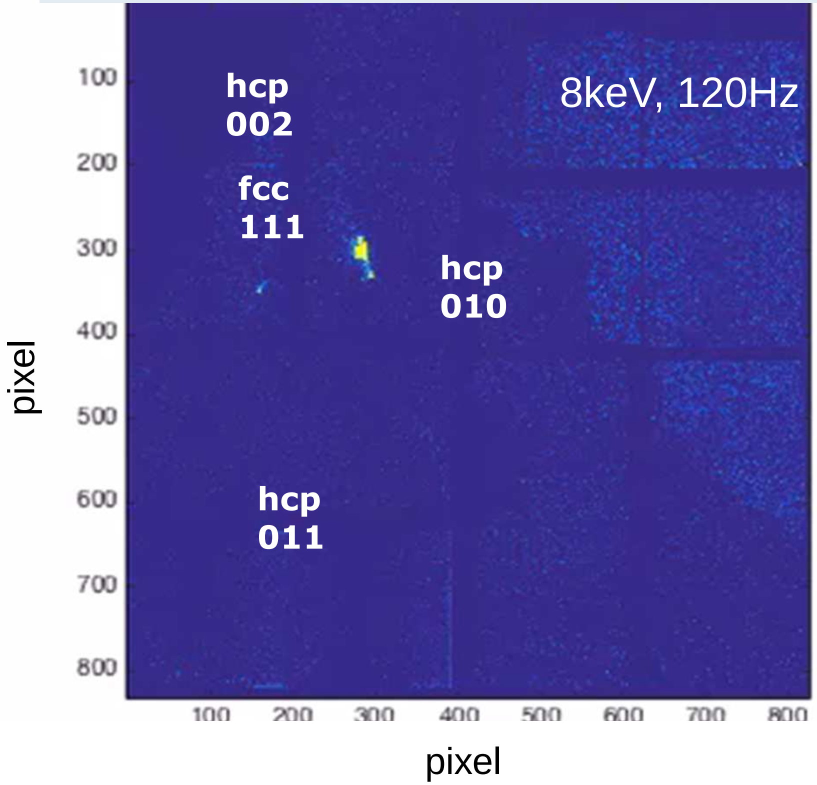
Demonstration of high repetition rate performance



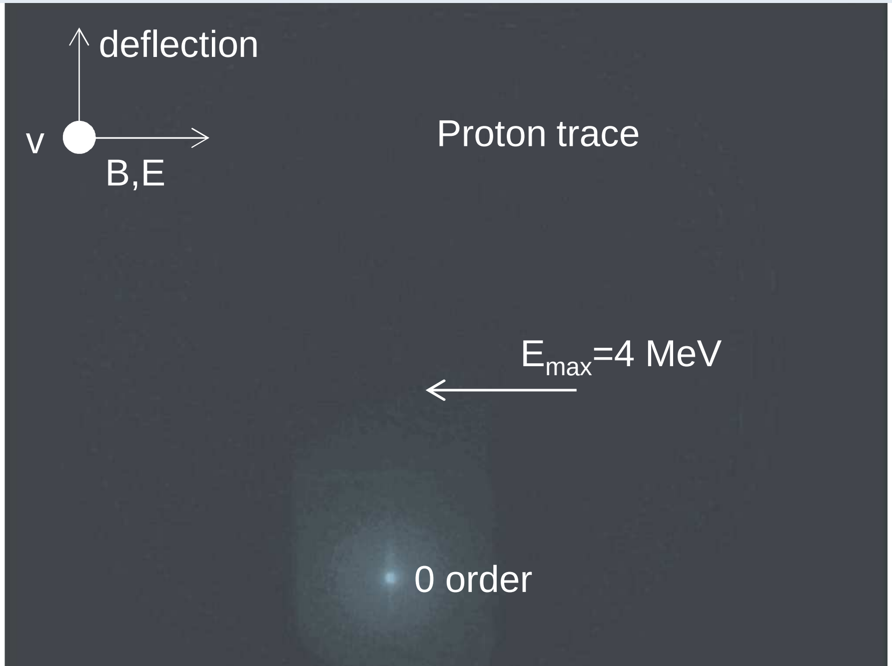
X-ray diffraction with x-ray FEL at MEC-LCLS

Laser particle acceleration at the DRACO laser (HZDR)

Crystallization of supercooled hydrogen jets



Generation of energetic proton beams with 1Hz*

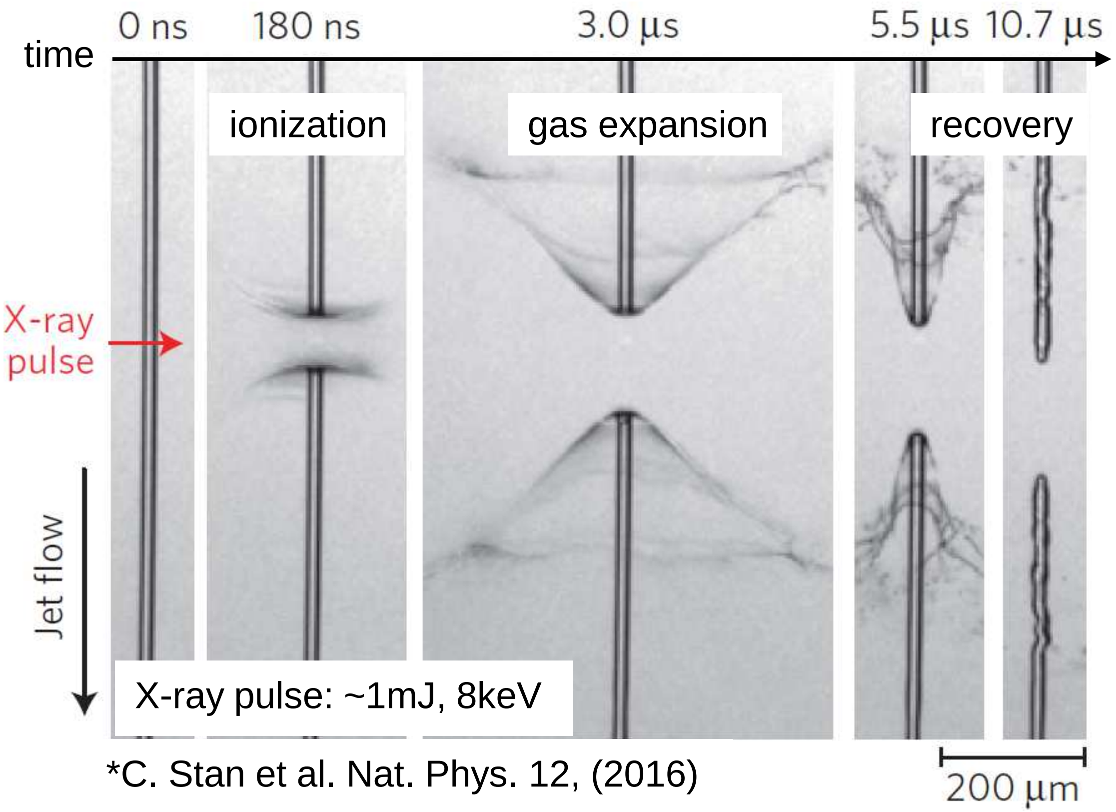


*M. Gauthier, C. Curry, S. Göde et al. in preparation

Limitation for high repetition rate experiments

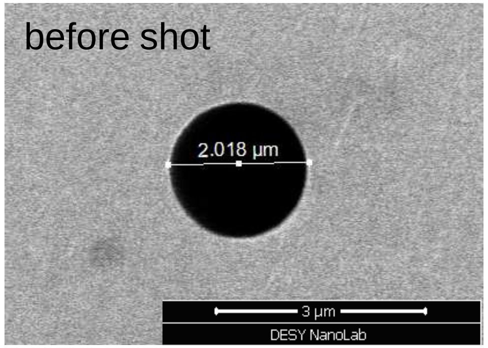
Shock explosion in liquid jet

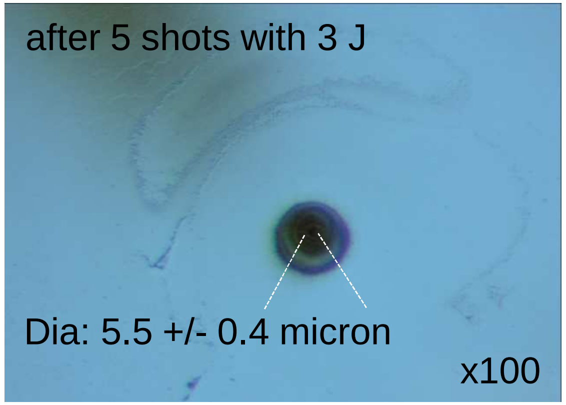
- Principle repetition rate of 4.5 MHz seems possible (assuming <20 µm focal spot size and 100 m/s jet velocity)
- Recovery times of about 1 ms after shock explosion limiting repetition rate to about 1 kHz*



*C. Stan et al. Nat. Phys. 12, (2016)

High power laser damage to nozzle





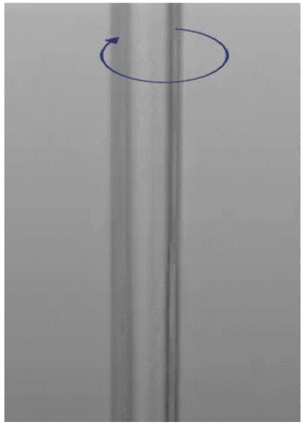
Physical nozzle damage after plasma discharge along the jet axis

Jets with planar geometries

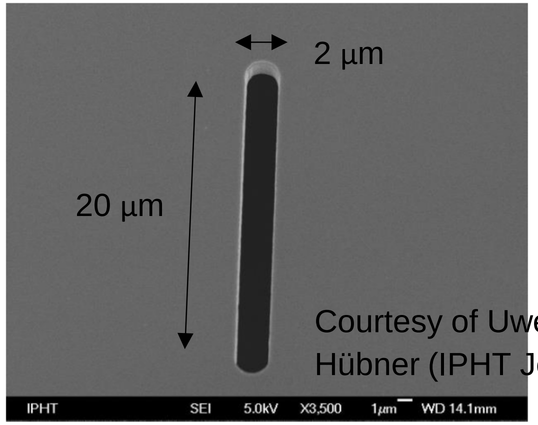
Working principle:

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

Planar jet

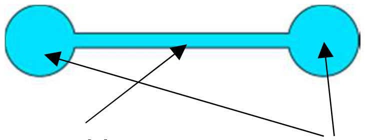


Slit aperture TEM image

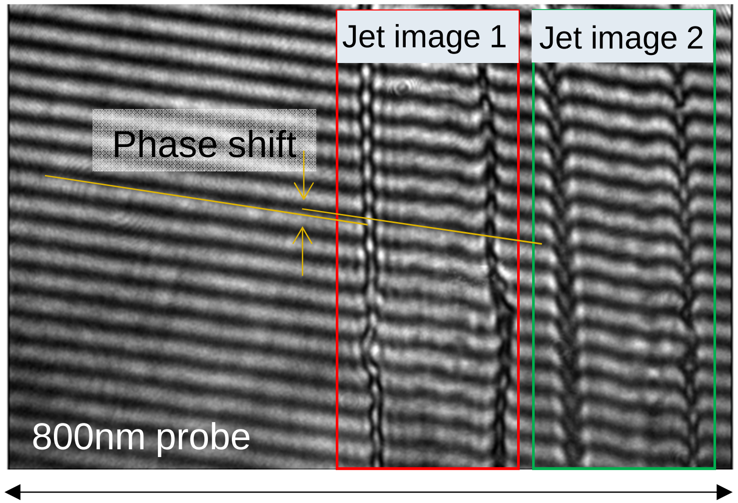


Courtesy of Uwe Hübner (IPHT Jena)

Schematic cross section of planar jets

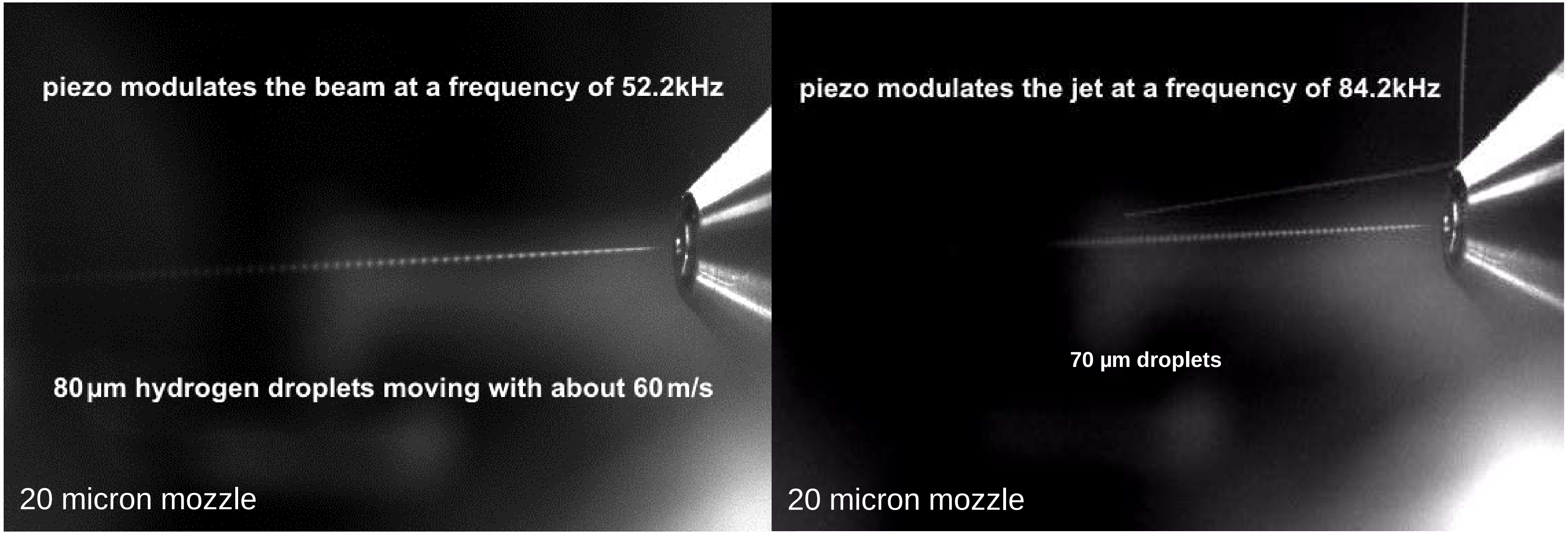


Nomarski interferogram of planar jet



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

Controlled droplet formation



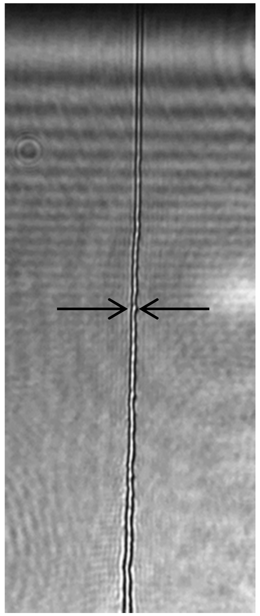
Measured at FLASH

Measured pellet speed of 62 m/s

A catalogue of available cryogenic liquid jets

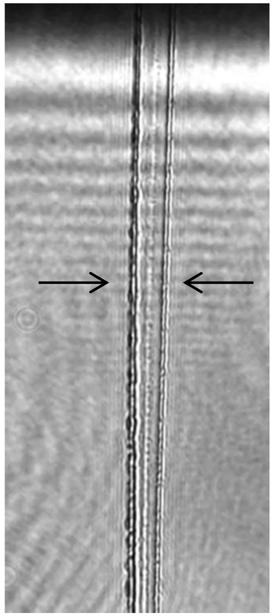
Cylindrical Jet

2 -10 µm diameter



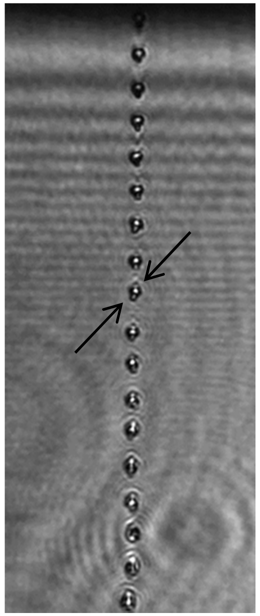
Planar Jet

20 - 50 µm width, 0.3 - 4 µm thick



Spherical Droplet Jet

10 - 19 µm diameter

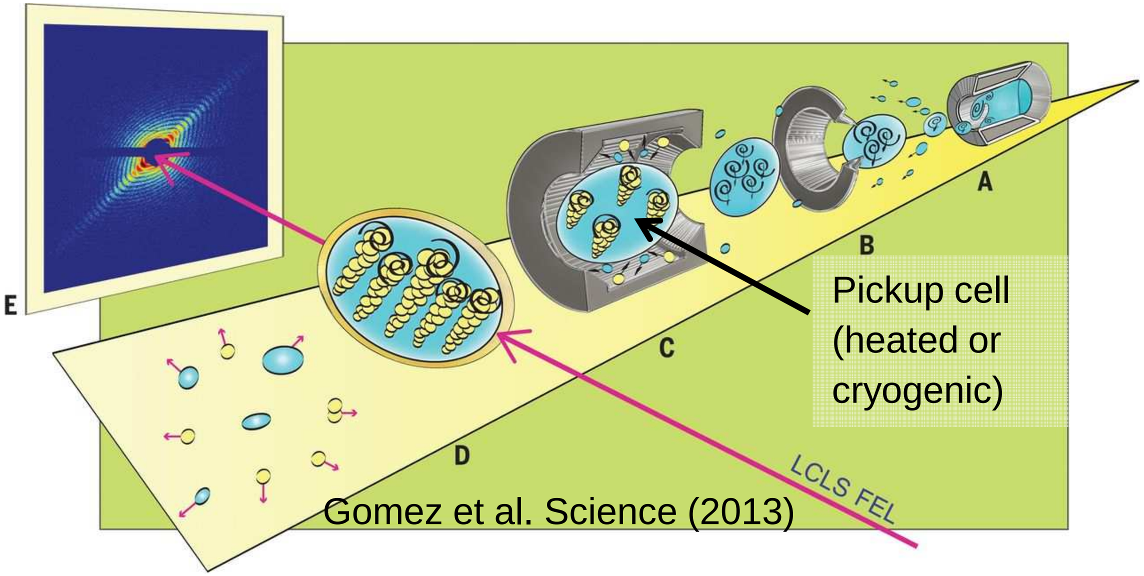


Courtesy of J. Kim (SLAC)

Performance of cylindrical jets using Deuterium, Methane (CH_4) and Argon successfully demonstrated

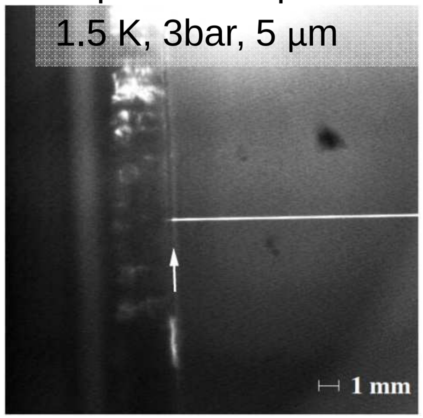
Science fiction: Doping of cryogenic droplet jets

Superfluid helium nano-droplets has been used to prepare and probe alligned Xenon aggregates



Gomez et al. Science (2013)

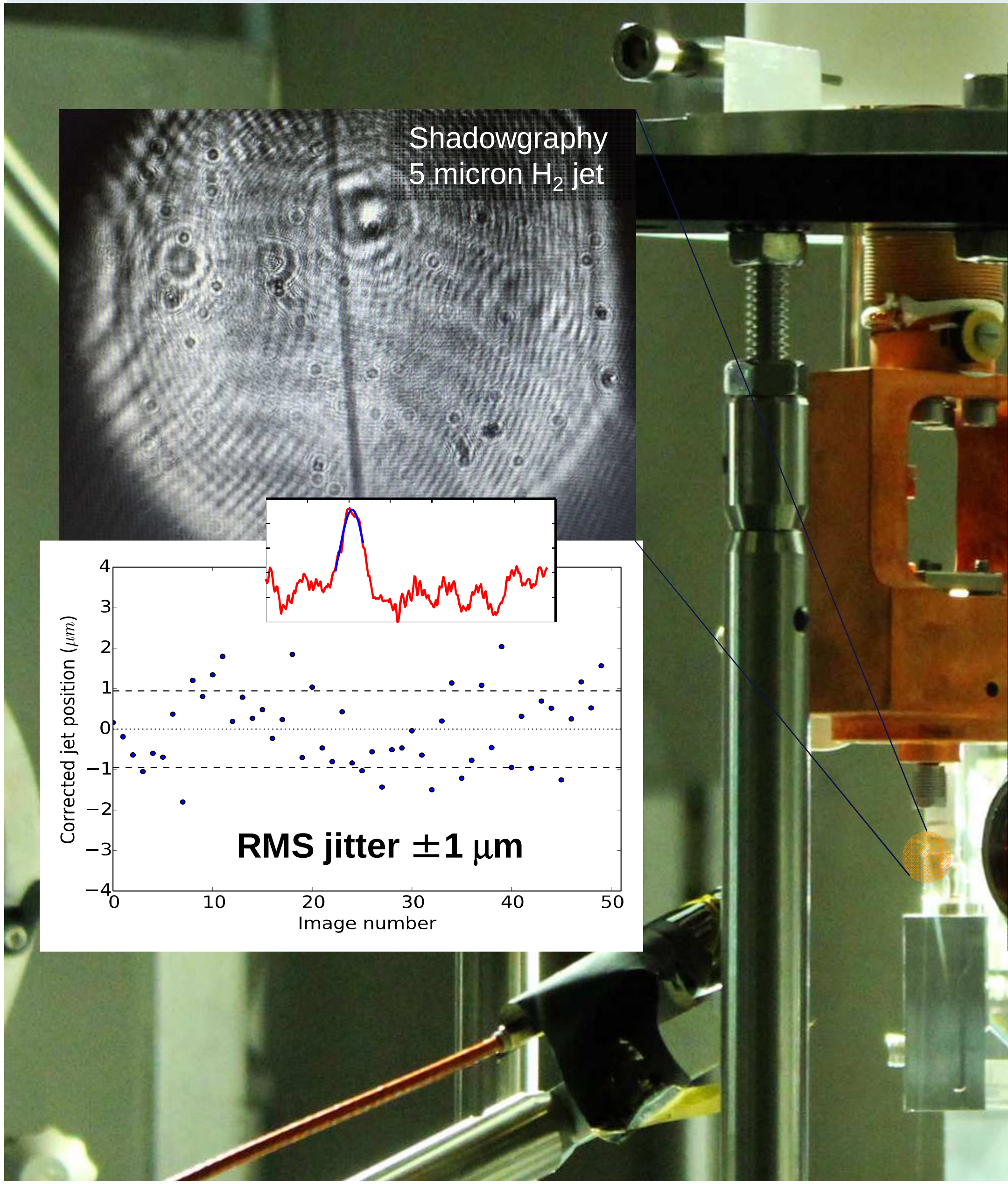
Liquid He droplet beam
1.5 K, 3bar, 5 µm



Grisenti et al. Phys. Rev. Lett. (2003)

- Low Z host matrix provide 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: H_2, D_2, He, 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

<u>Hydrogen jet target</u>:

S. Göde, J.Kim, C. Rödel, M. Gauthier, W. Schumaker, M. MacDonald, S. Glenzer
HED Science Dept., SLAC National Accelerator Laboratory

<u>Draco laser:</u>

K. Zeil, L. Obst, M. Rehwald, F. Brack, R. Gebhardt, U. Helbig,
J. Metzkes, H.-P. Schlenvoigt, P. Sommer, T. Cowan, U. Schramm
Helmholtz-Zentrum Dresden-Rossendorf and TU Dresden, Germany

<u>Theory:</u>

R. Mishra, C. Ruyer, F. Fiuza
Plasma Theory, SLAC National Accelerator Laboratory, Stanford University

SLAC NATIONAL ACCELERATOR LABORATORY

U.S. DEPARTMENT OF ENERGY Office of Science

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