Frontiers of PlasmaPhysics and Technology

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High Energy Density Physics with intense Heavy Ion Beams

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reporting on behalf of

HEDgeHOB

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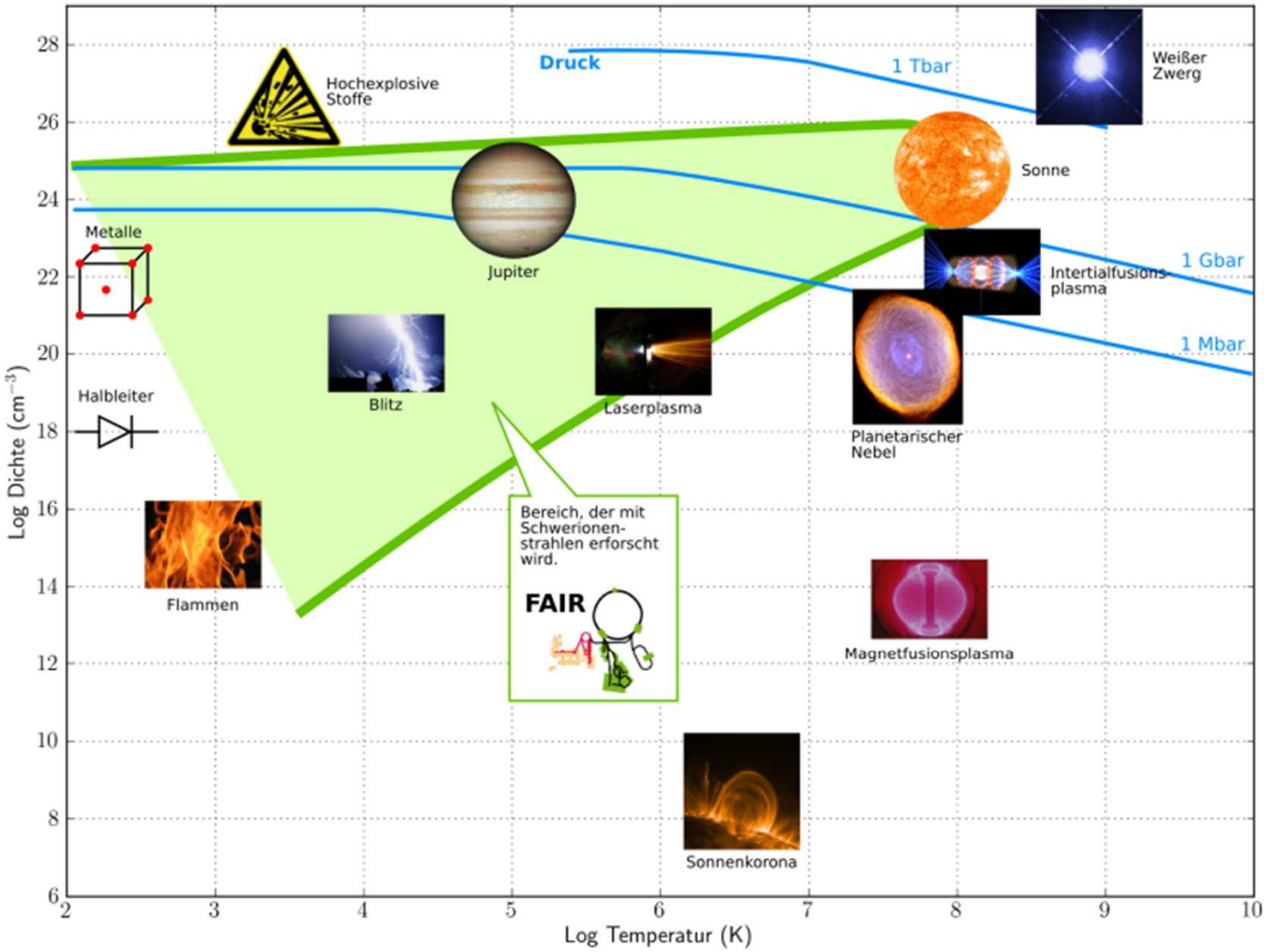
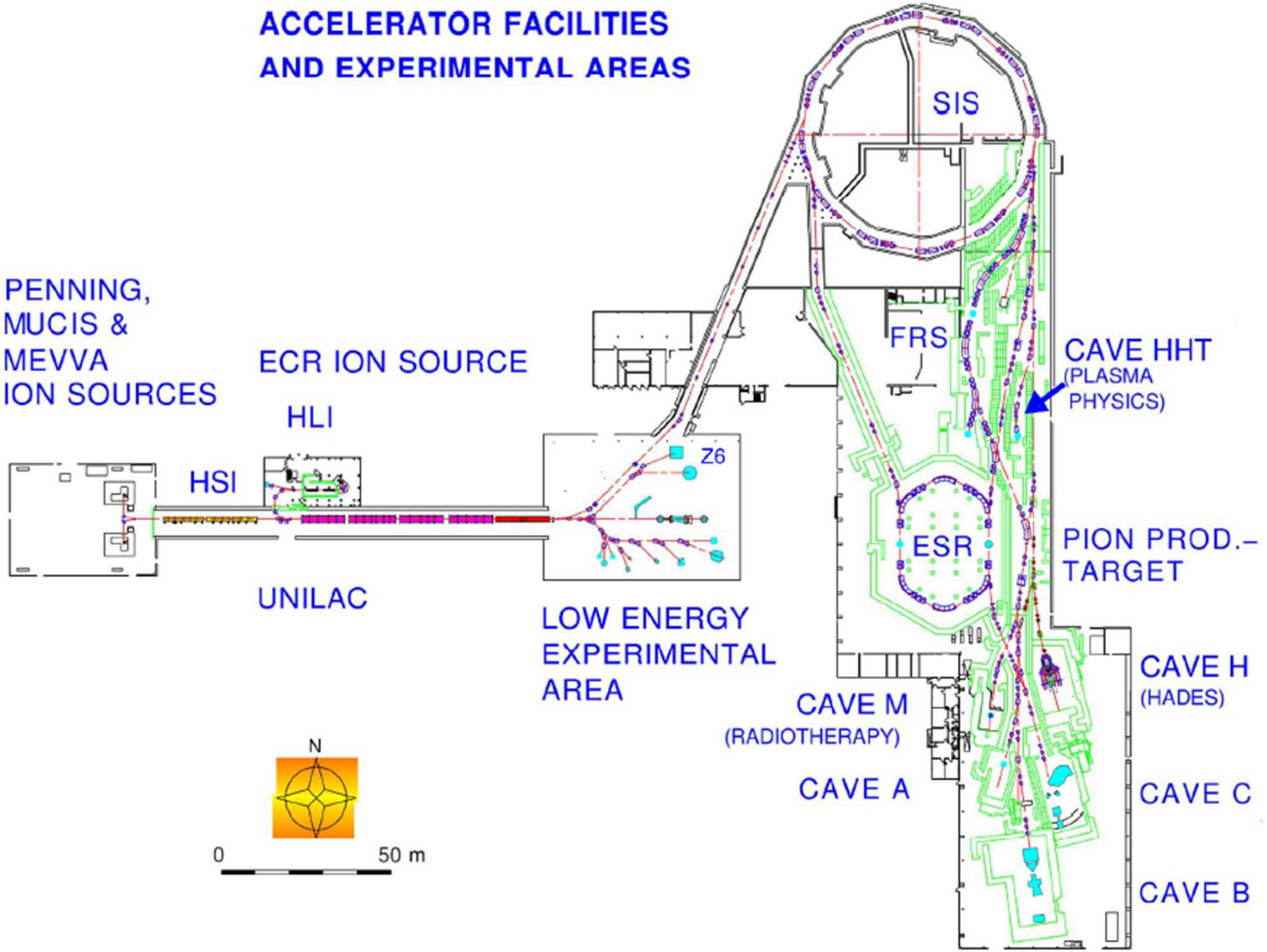
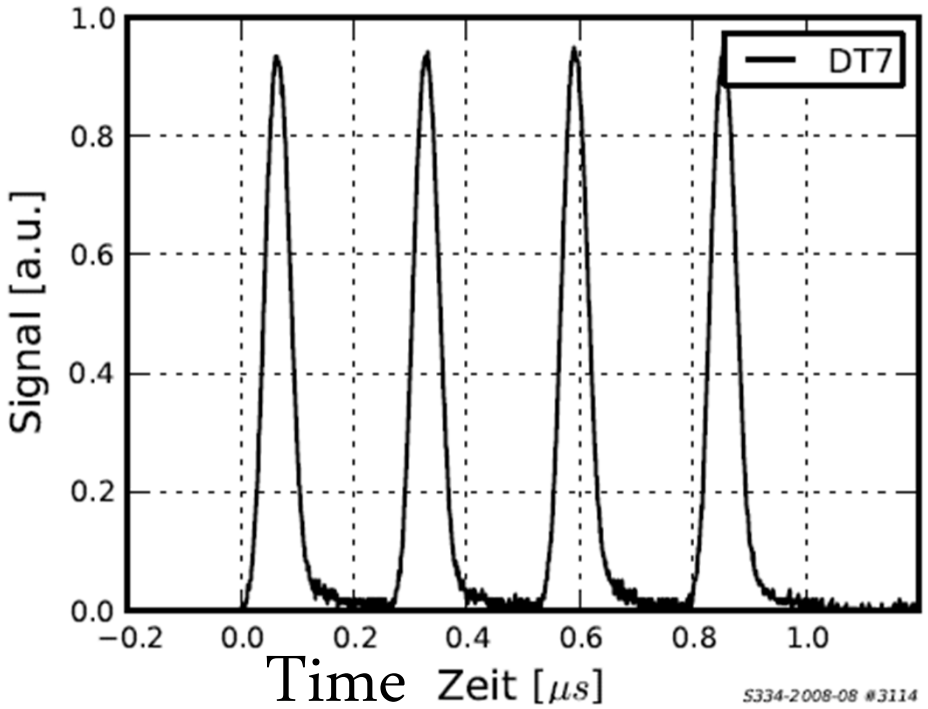
Plasma: Matter at the Extreme



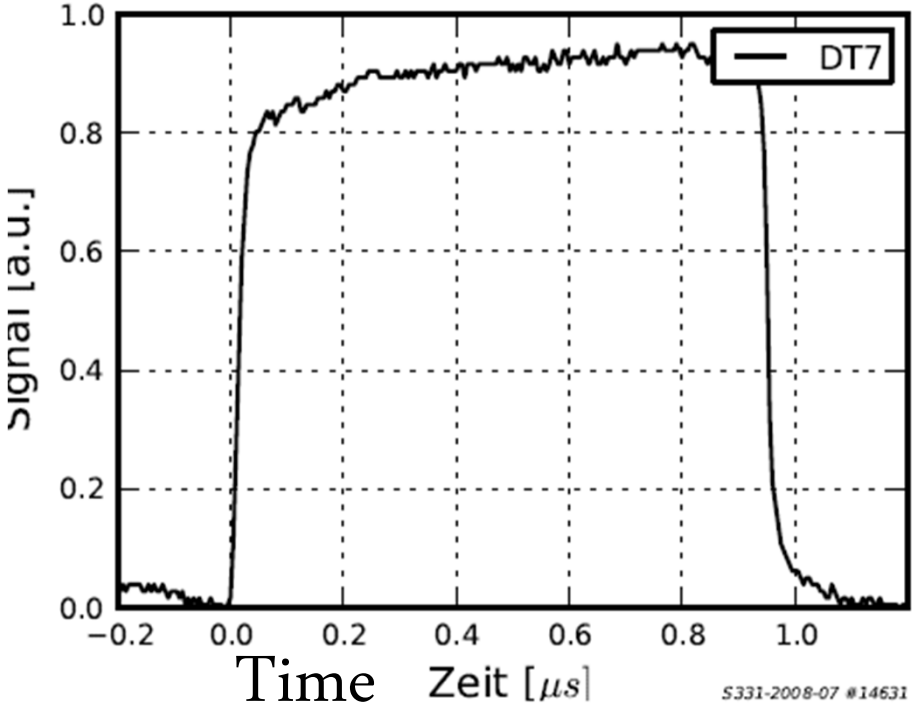
Bildquellen: EFDA-JET, NASA, LLNL, GSI, TUD

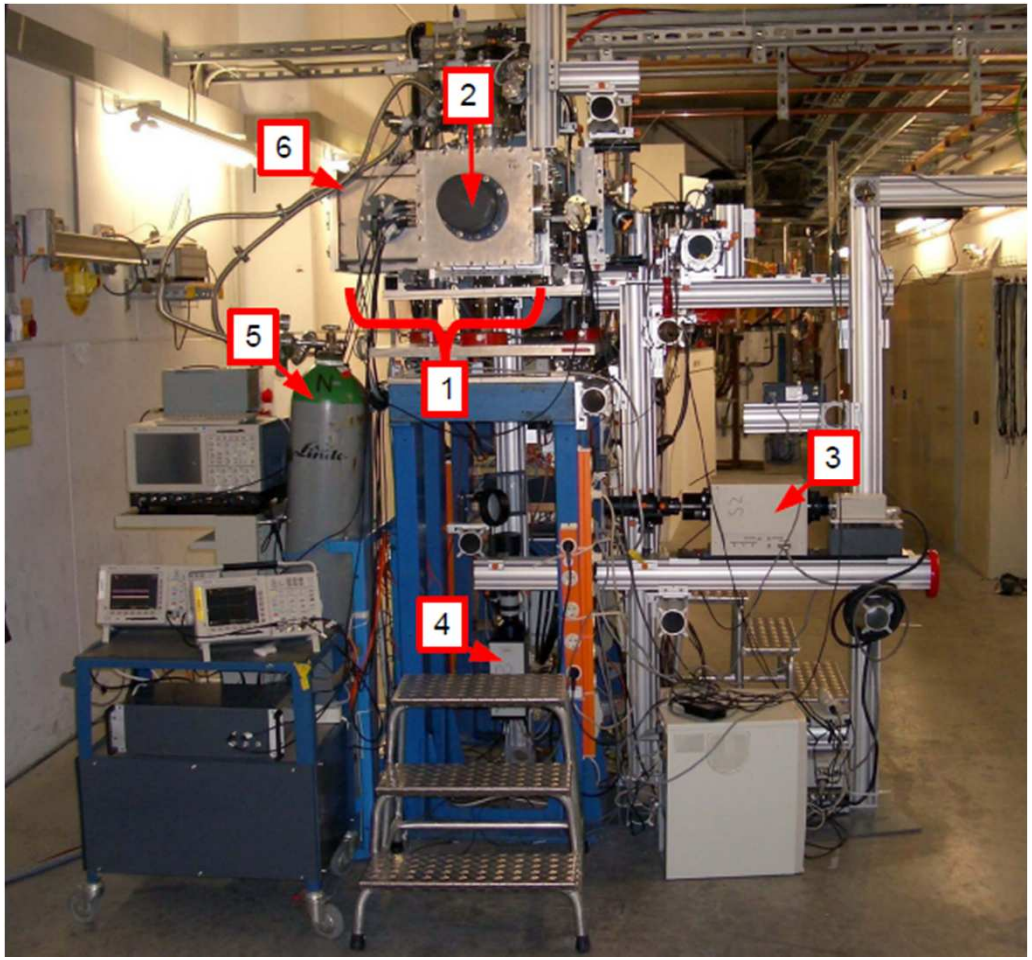

ACCELERATOR FACILITIES
AND EXPERIMENTAL AREAS
SIS
PENNING,
MUCIS &
MEVVA
ION SOURCES
ECR ION SOURCE
HLI
FRS
CAVE HHT
(PLASMA
PHYSICS)
HSI
Z6
ESR
PION PROD.–
TARGET
UNILAC
LOW ENERGY
EXPERIMENTAL
AREA
CAVE M
(RADIOTHERAPY)
CAVE H
(HADES)
CAVE A
CAVE C
CAVE B
N
0
50 m

Pulsed beams



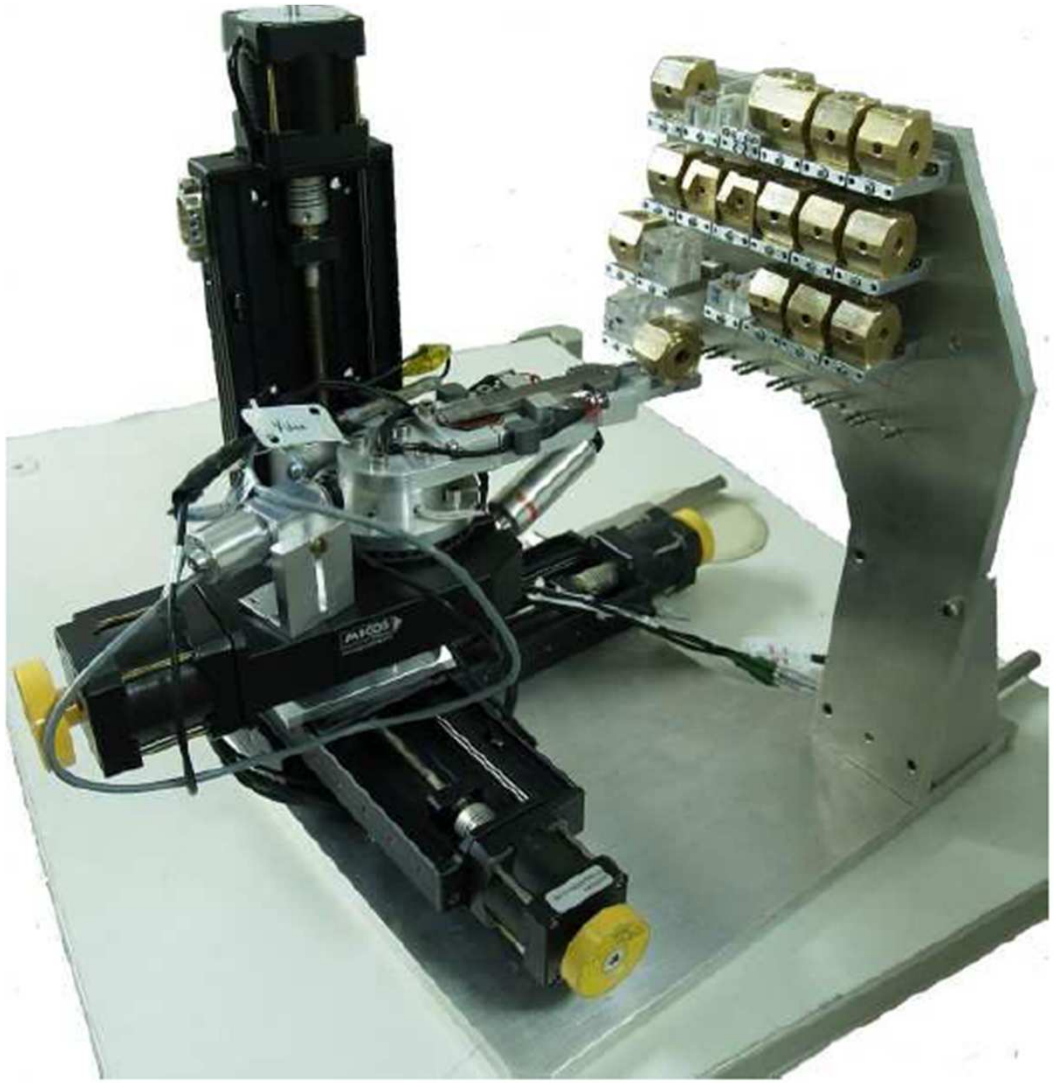
Coasting beam





HHT Messplatz: 1 - Targetkammer; 2 - Beamdump; 3 - Streak–Kamera; 4 - DiCam-Pro Kamera; 5 - Helium- und Argon-Gasflaschen; 6 - Lichtsammelsystem des Pyrometers (in der Targetkammer)

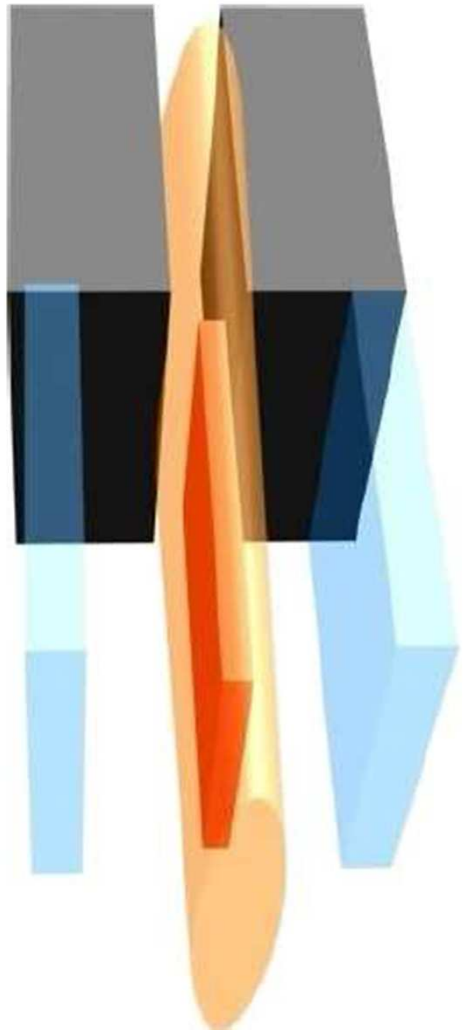
Target Robot and Target Shelf inside the Vacuum Chamber



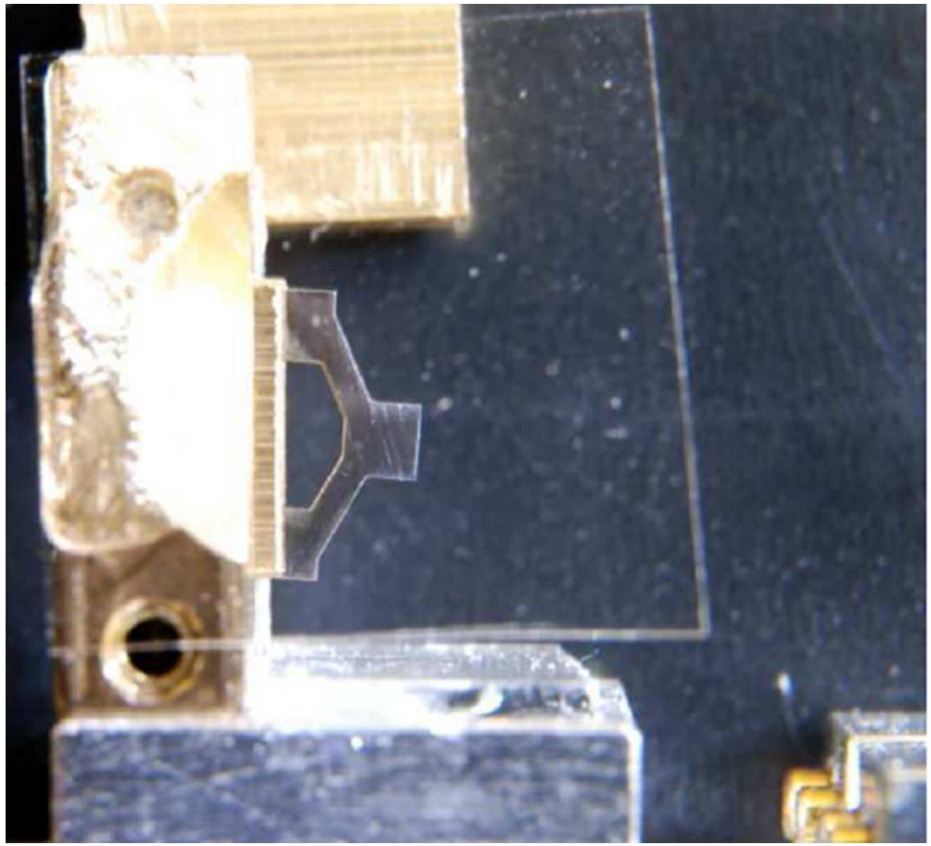
HIHEX-Target

Heavy Ion Heating and Expansion

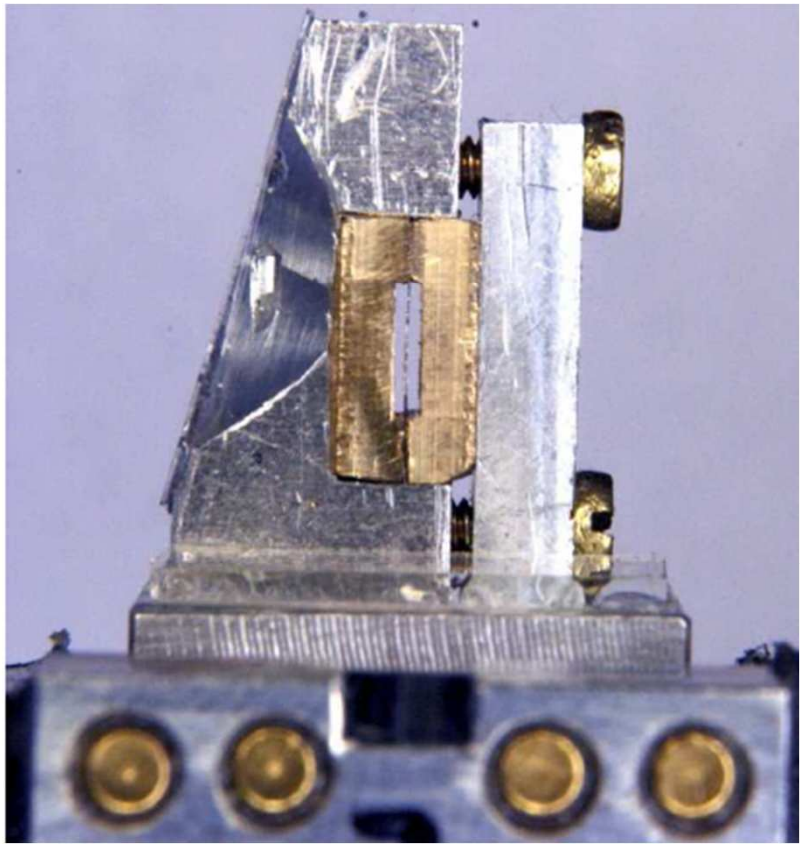
(HEDgeHOB Collaboration)



Target

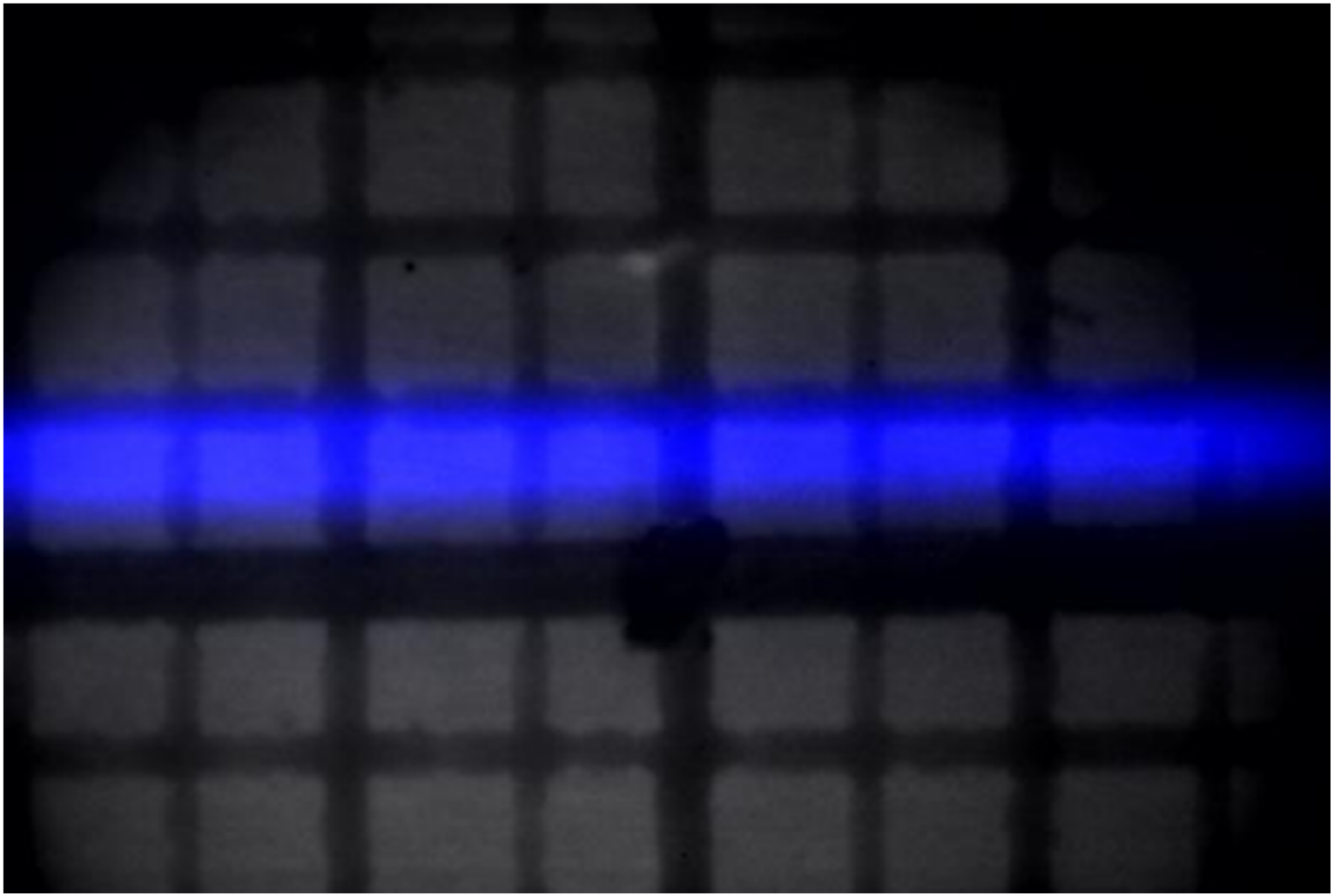


Side view

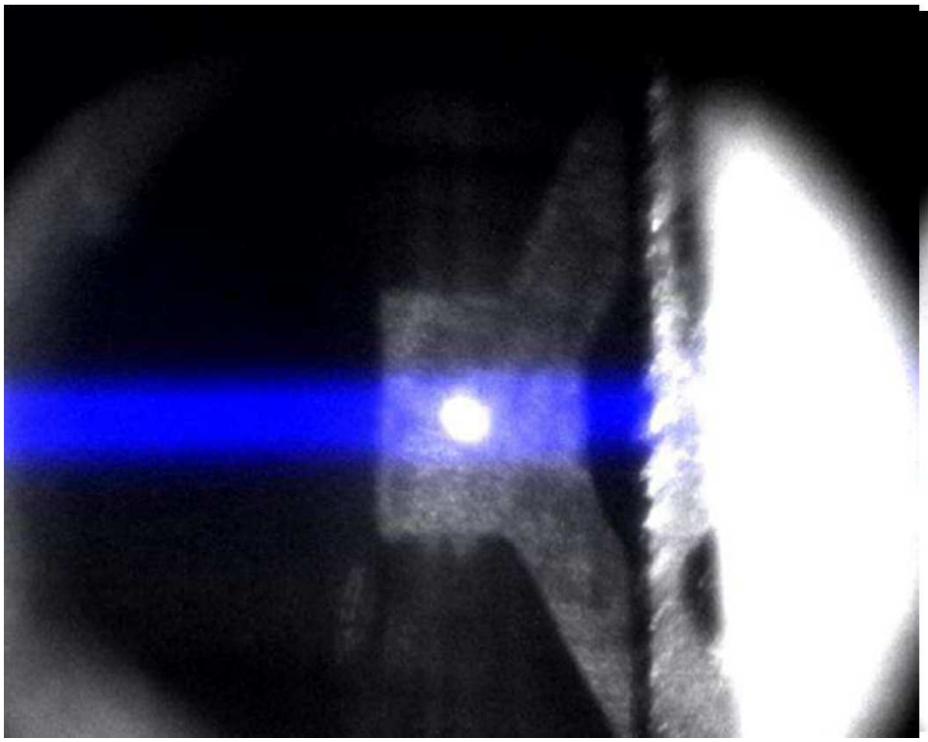


in beam direction

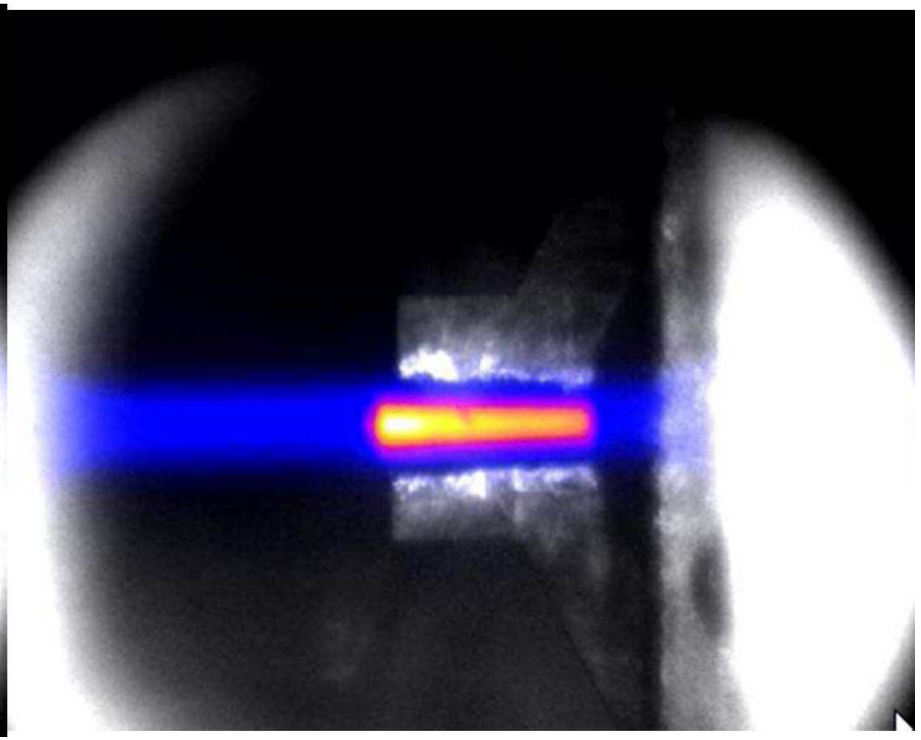
Beam Induced Fluorescence Light Graph Paper



Target



aligned/preshot

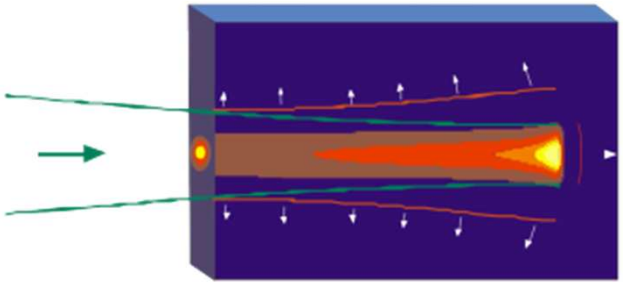


destroyed /postshot

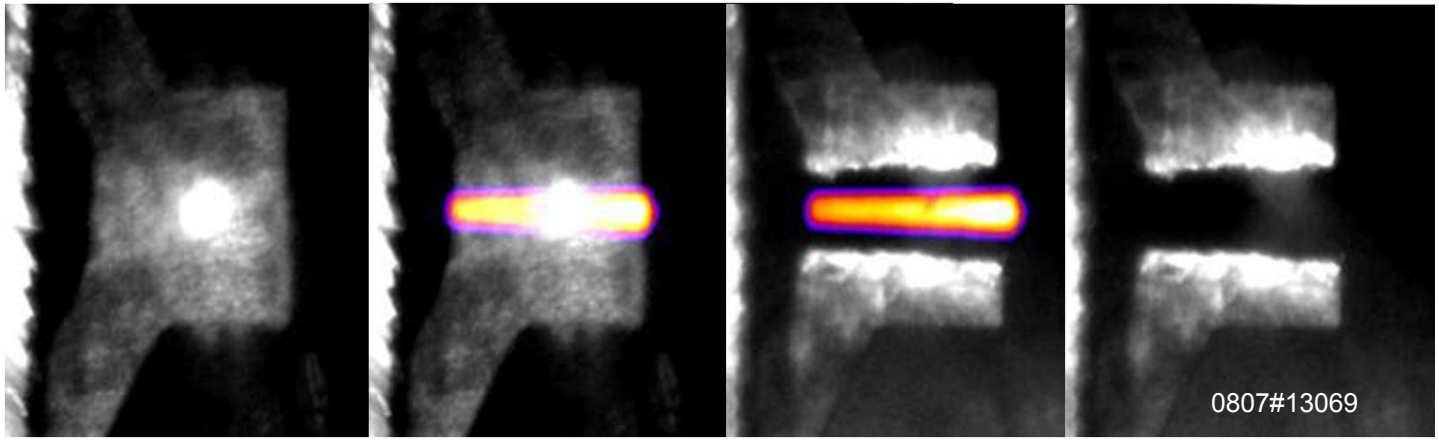
WDM Experiments

An intense heavy ion beam is an excellent tool to generate HED/WDM samples

- Fairly uniform physical conditions
- Large heated volume (mm^3)
- High repetition rate and reproducibility
- Any target material



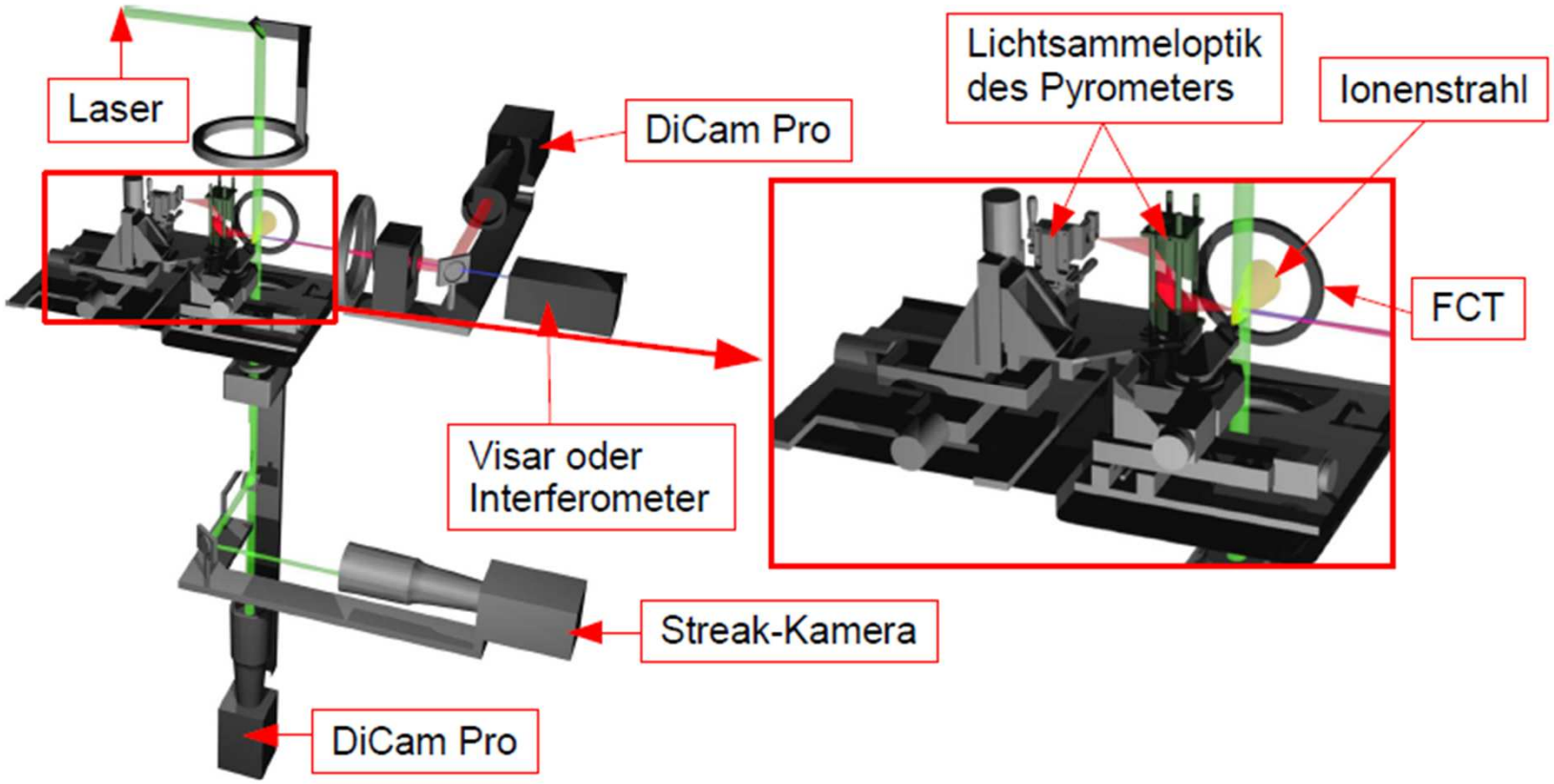
Scheme of ion-beam heated target

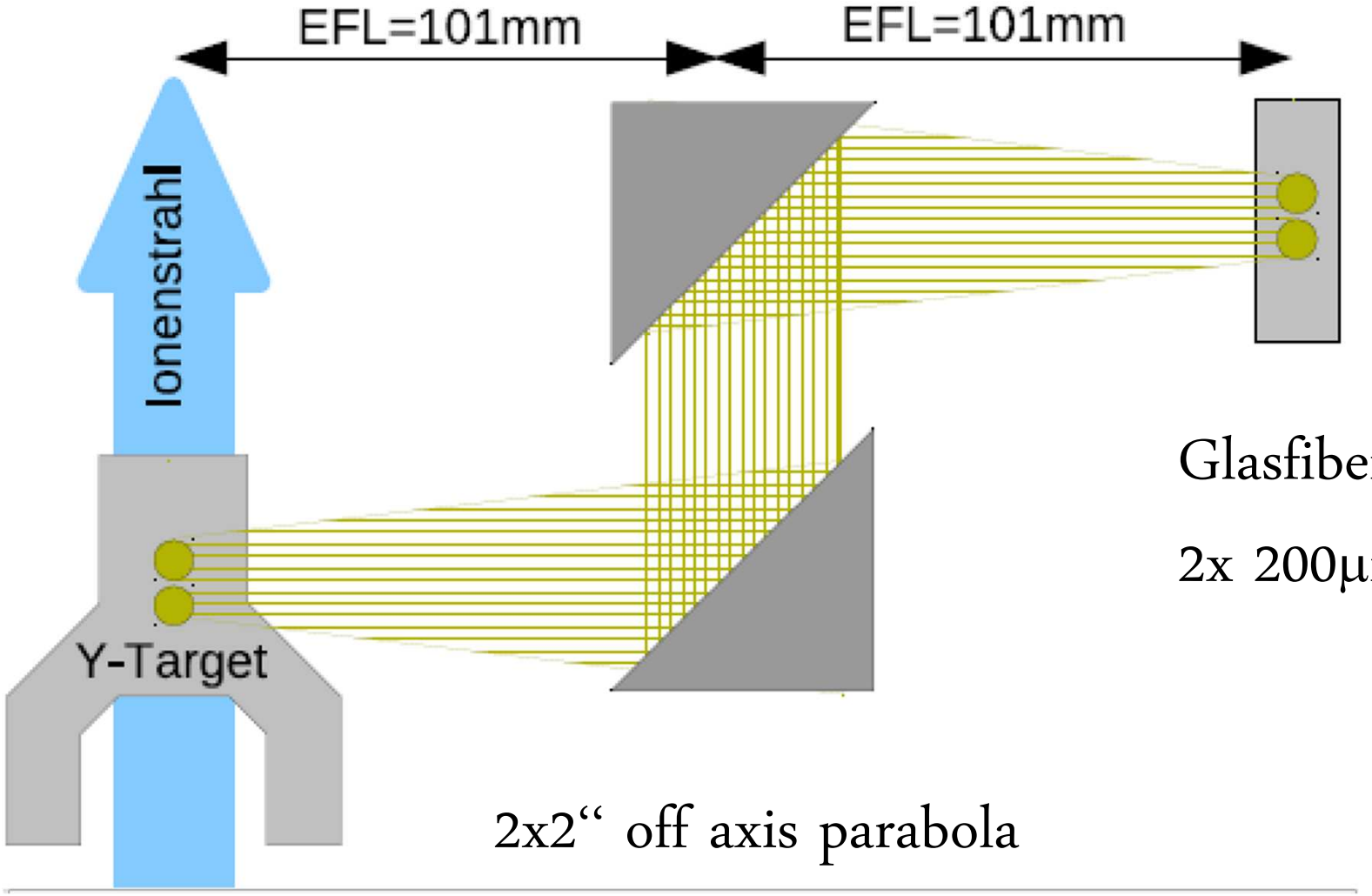


D.Varentsov,

A. Hug

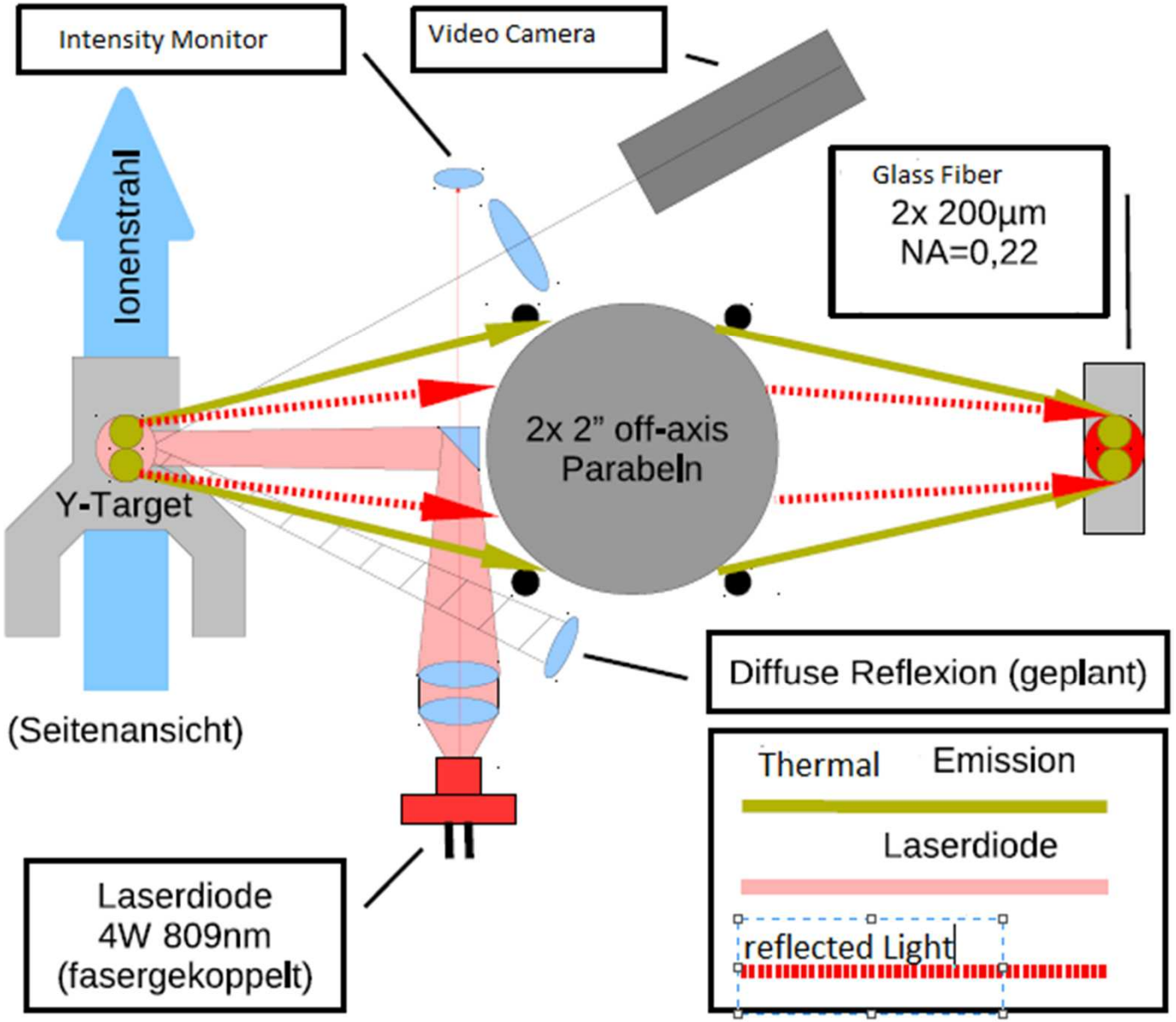
Experimental Set-up



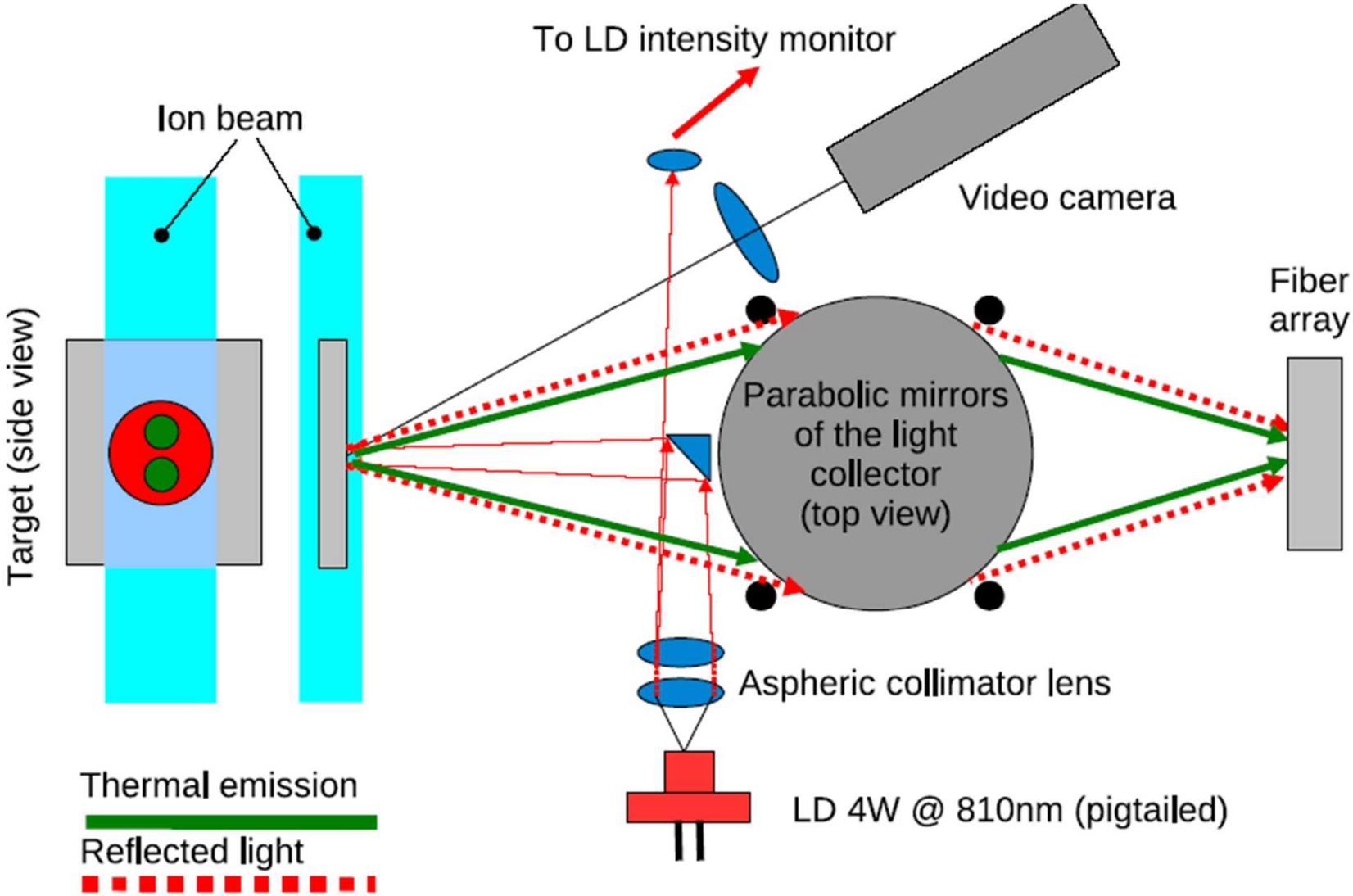

EFL=101mm
EFL=101mm
Ionenstrahl
Y-Target
Glasfibers
2x 200µm
2x2“ off axis parabola

side view

Reflectivity Measurement



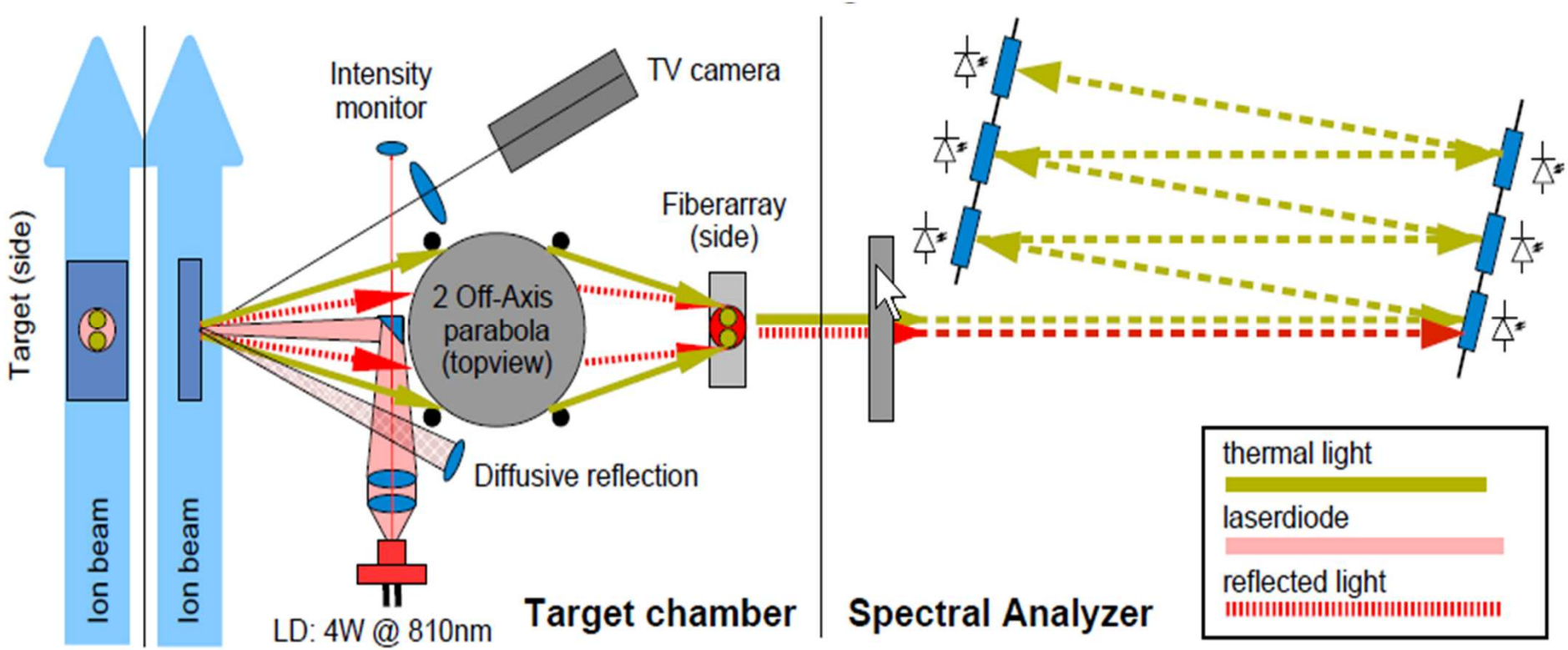
Reflectivity measurements of ion beam heated refractory metals



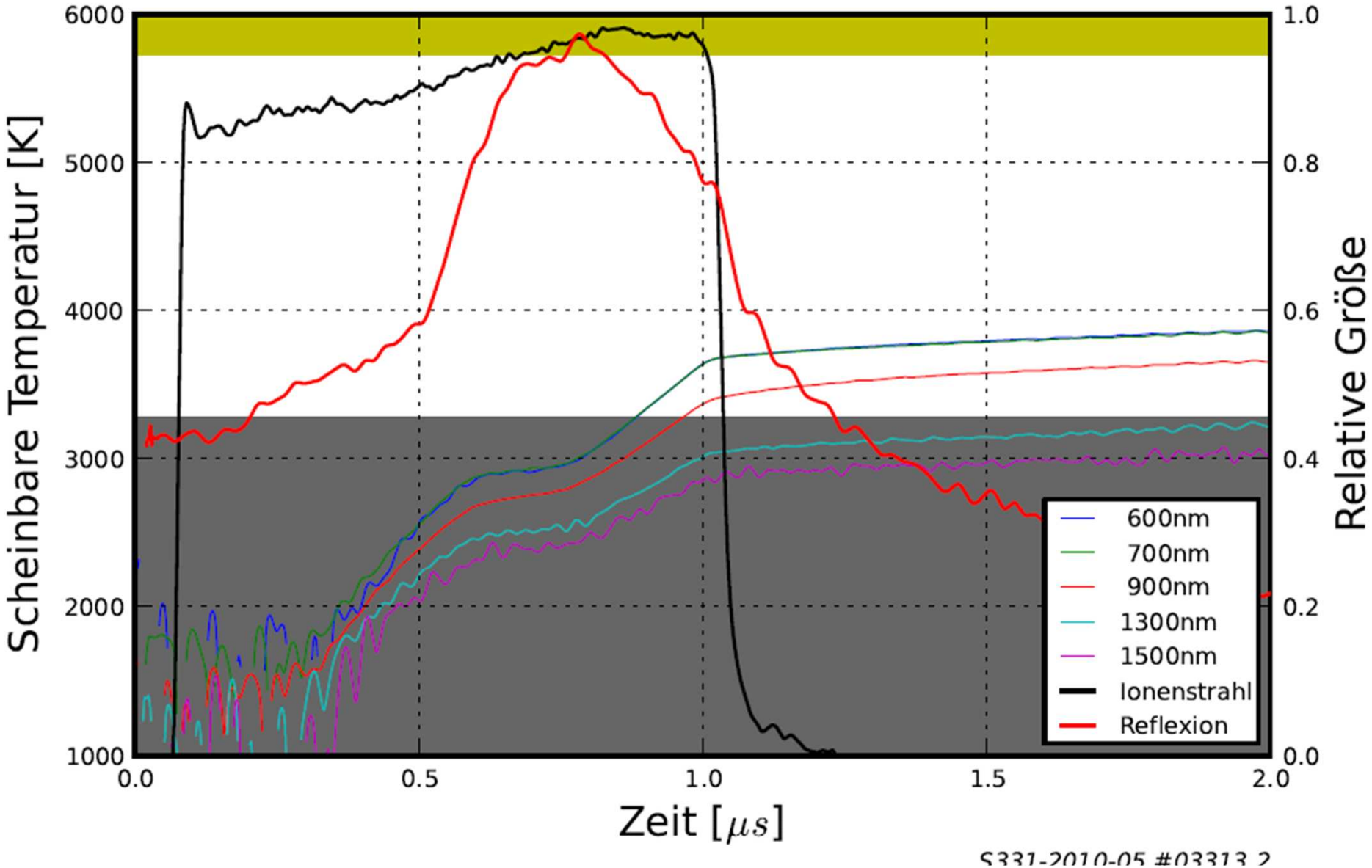
Reflectometer embedded in multi channel pyrometer

Fast multi-channel pyrometer

- Two spectral analyzers with 6 channels each (Vis/NIR)
- Spatial resolution down to 50µm, defined by fiber
- Absolute calibrated
- Embedded reflectometer with diffusive light collector

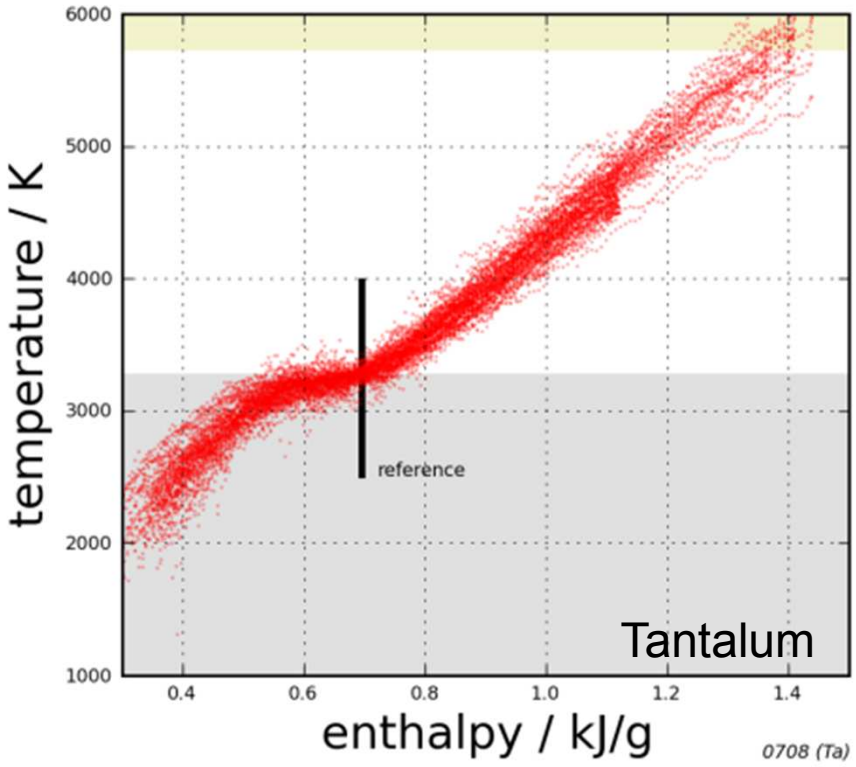


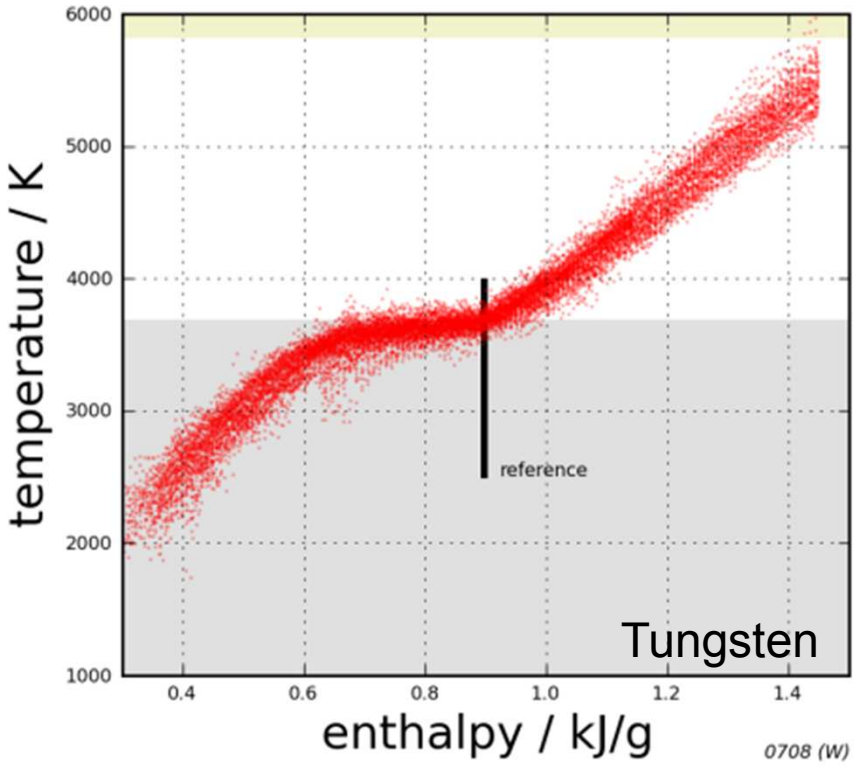
Temperatur Measurement

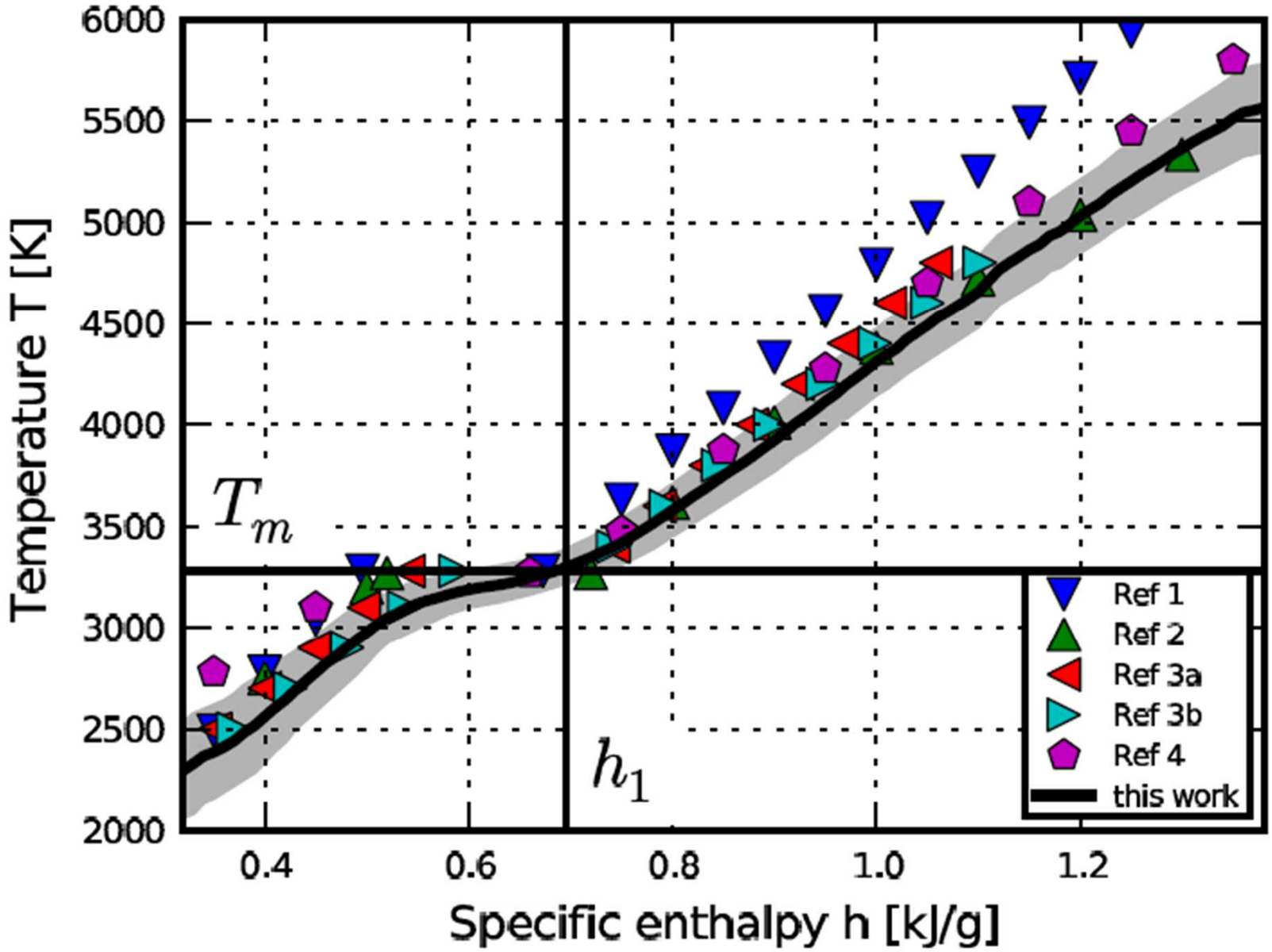


Statistics

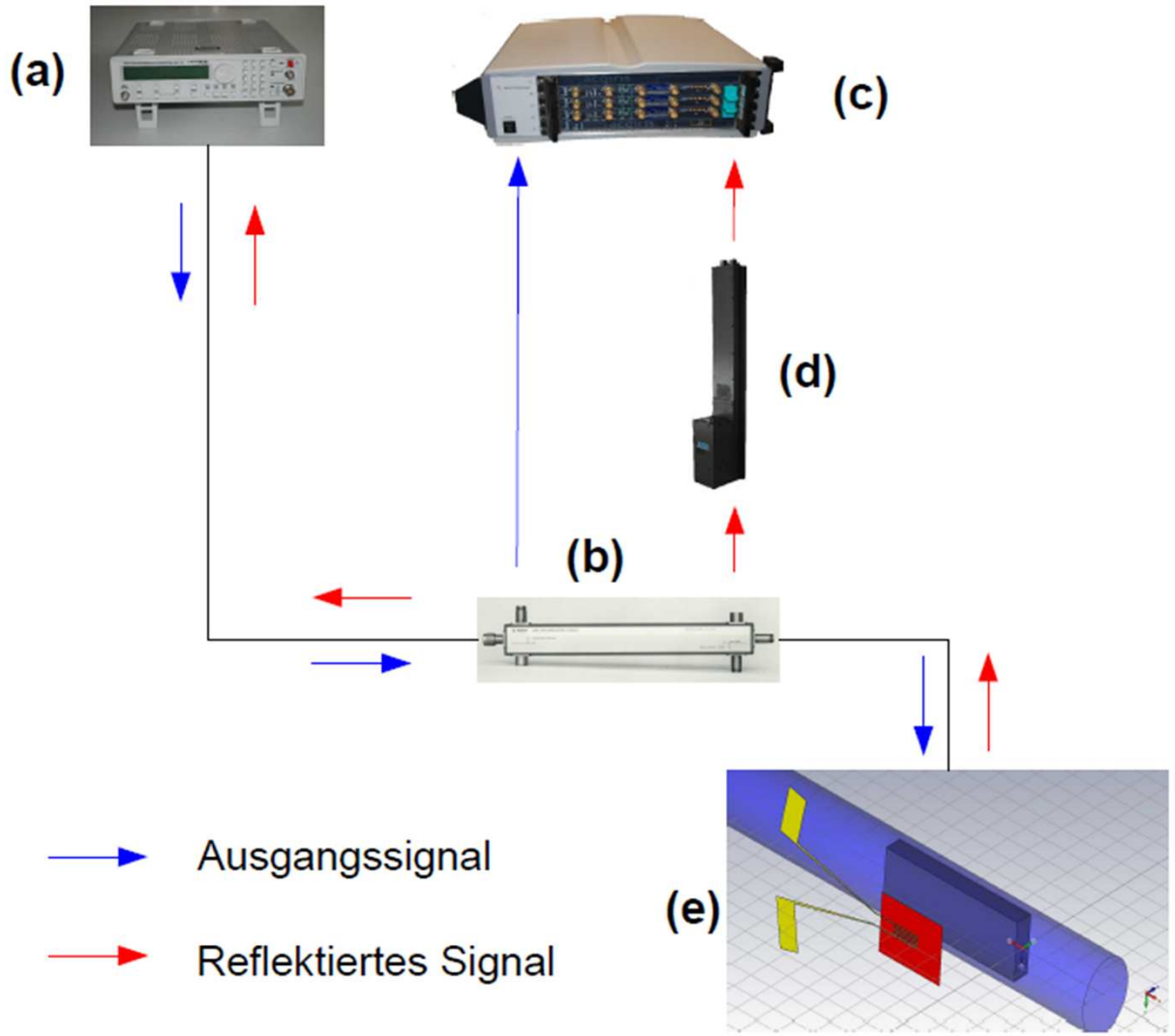
- One experimental campagne
- Accumulating 17 shots on tantalum, 20 shots on tungsten

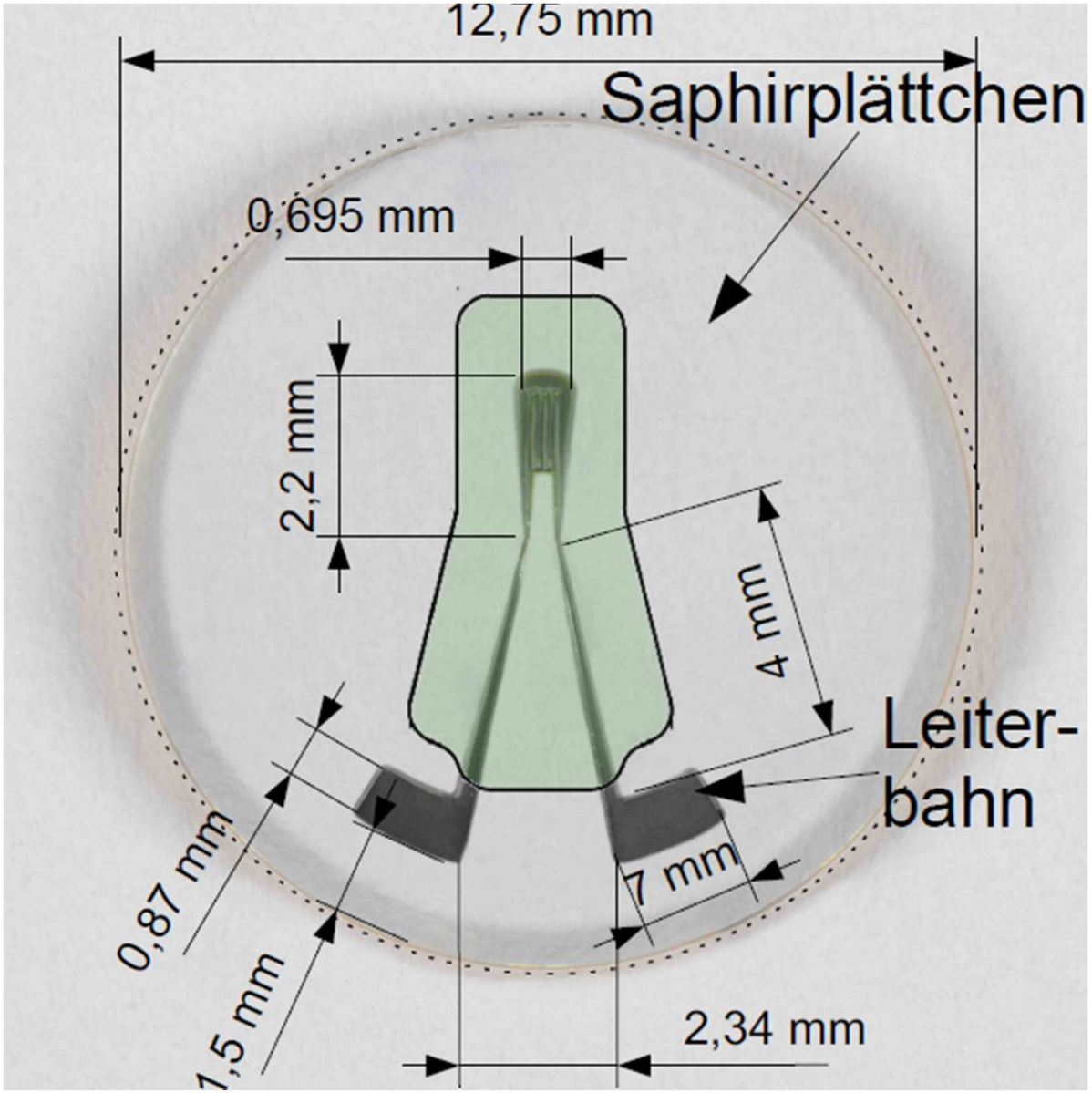


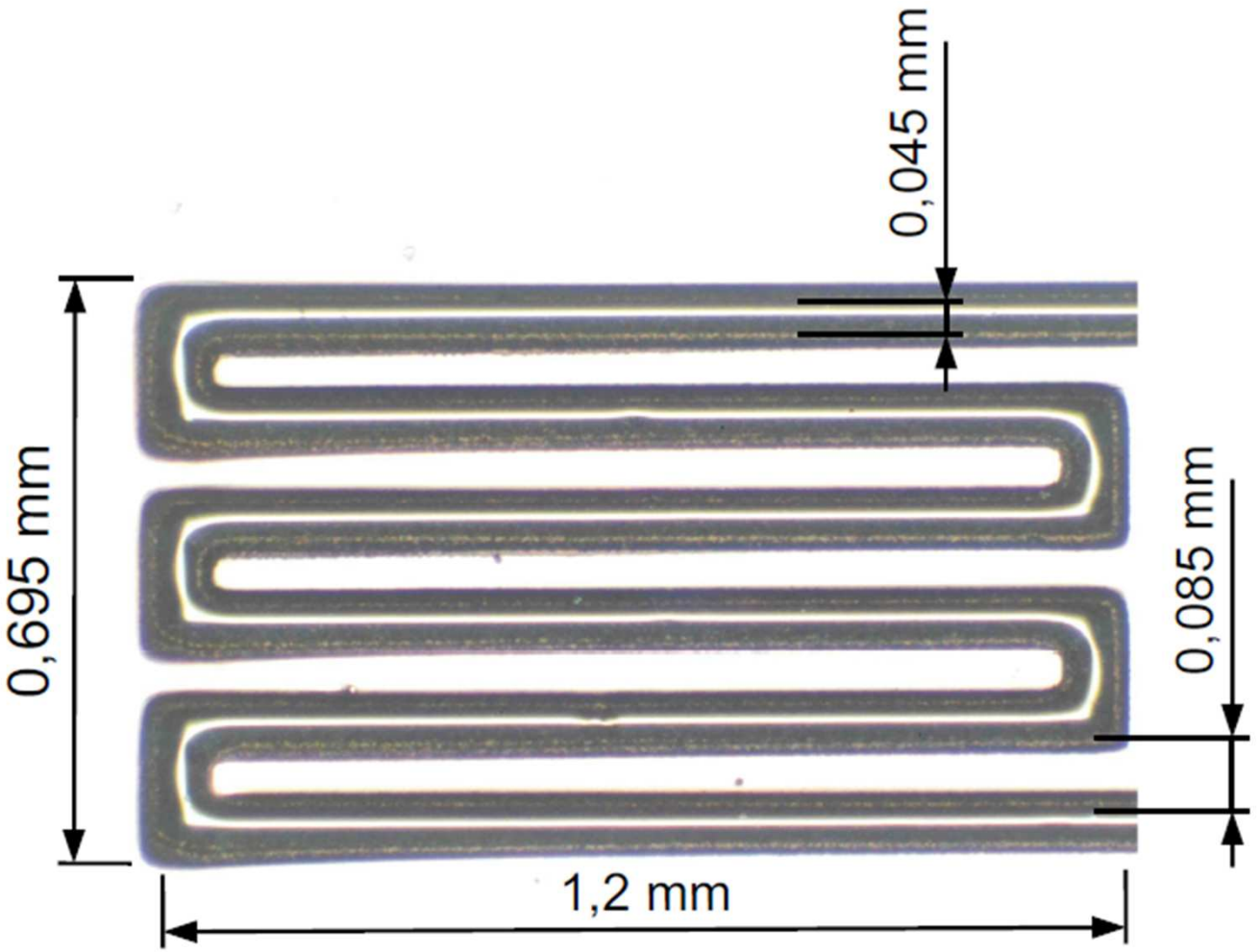



6000
5500
5000
4500
4000
3500
3000
2500
2000
Temperature T [K]
0.4
0.6
0.8
1.0
1.2
Specific enthalpy h [kJ/g]
T_m
h_1
Ref 1
Ref 2
Ref 3a
Ref 3b
Ref 4
this work

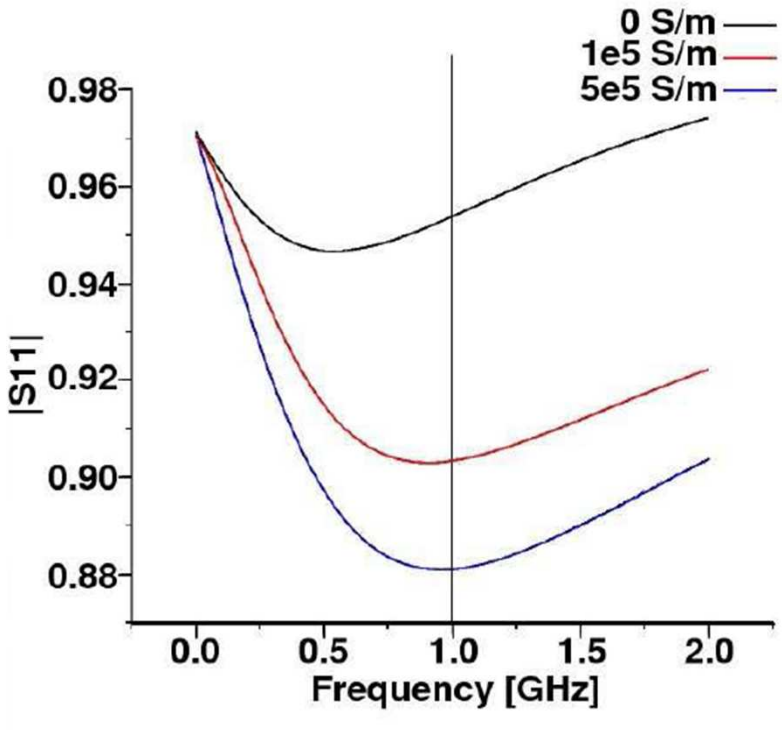
Electrical Conductivity – Non Contact Measurement

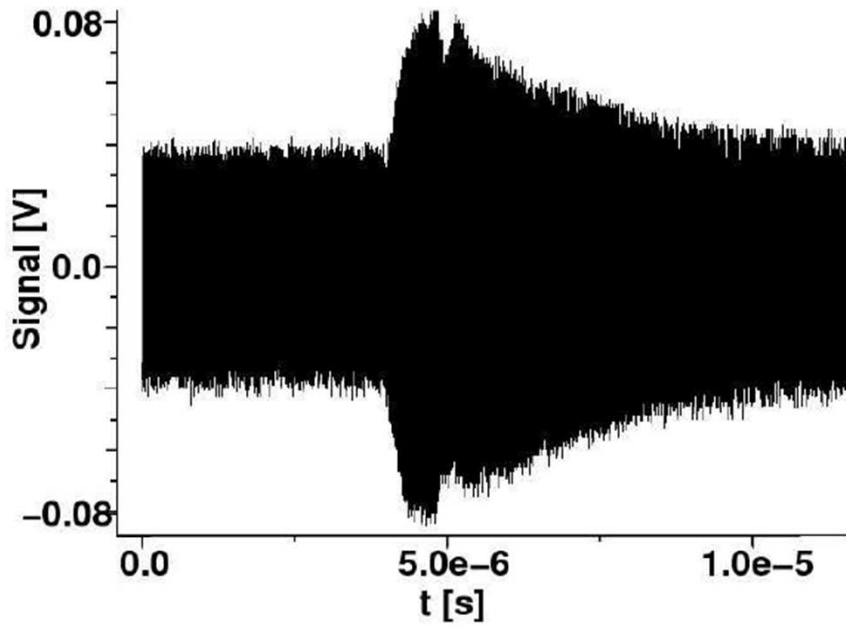



12,75 mm
Saphirplättchen
0,695 mm
2,2 mm
4 mm
Leiter-
bahn
0,87 mm
7 mm
2,34 mm



Mäanderförmige Struktur des Sensorkopfes. Die Leiterbahnen haben eine Breite von 45 m und eine Dicke von 9 m.

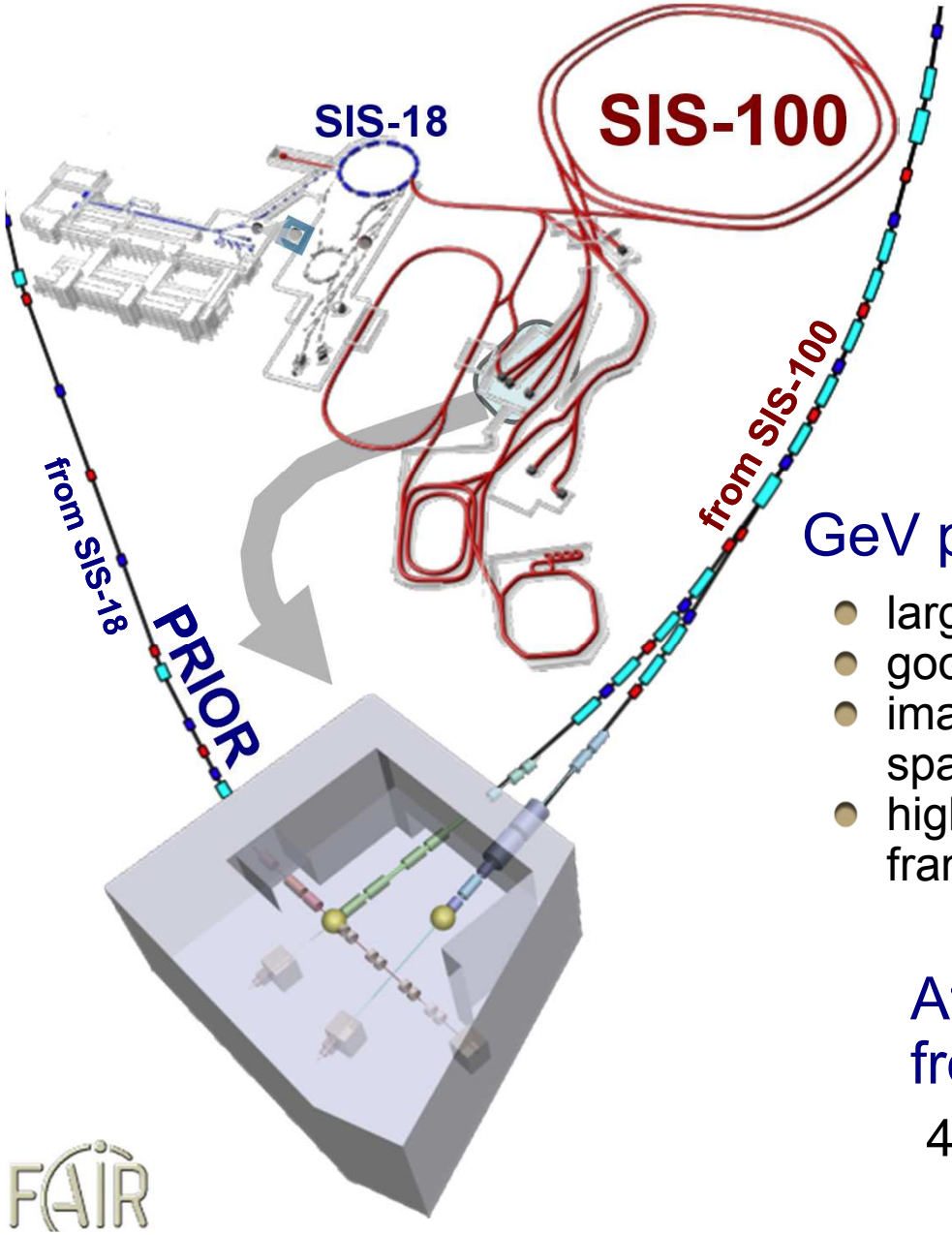

0 S/m
1e5 S/m
5e5 S/m
0.98
0.96
0.94
0.92
0.90
0.88
|S11|
0.0
0.5
1.0
1.5
2.0
Frequency [GHz]


0.08
0.0
−0.08
Signal [V]
0.0
5.0e−6
1.0e−5
t [s]

PRIOR

Proton Microscope for FAIR

PRIOR – Proton Radiography at FAIR



Challenging requirements for density measurements in dynamic HEDP experiments:

- up to ~20 g/cm^2 (Fe, Pb, Au, etc.)
- ≤10 µm spatial resolution
- 10 ns time resolution (multi-frame)
- sub-percent density resolution

GeV protons:

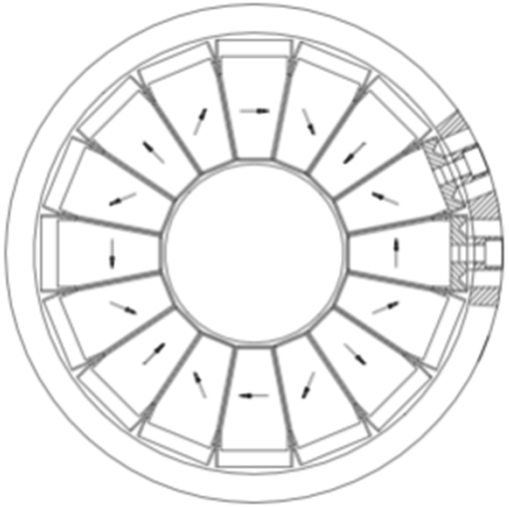
- large penetrating depth (high ρx)
- good detection efficiency (S/N)
- imaging, aberrations correction by magnetshigh spatial resolution (microscopy)
- high density resolution and dynamic rangemulti-frame capability for fast dynamic events

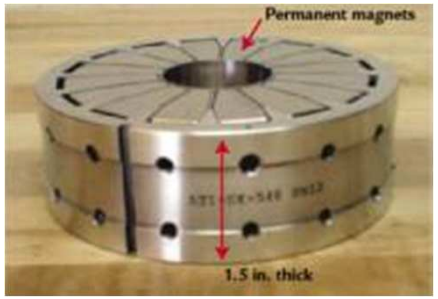
At FAIR: a dedicated beam line from SIS-18 for radiography

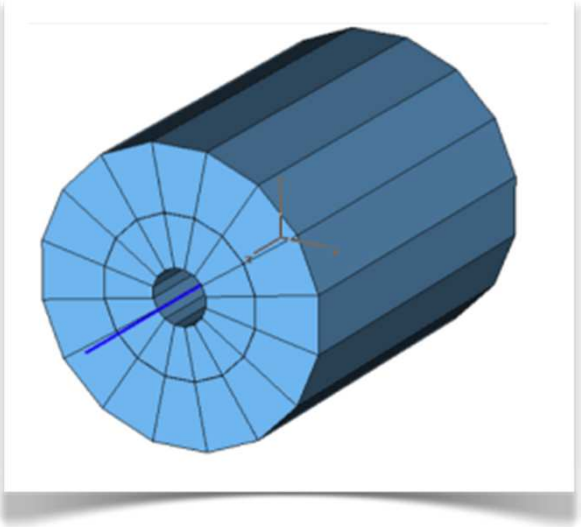
4.5 GeV, 5·10^{12} protons

Permanent Magnetic Quadrupoles (PMQ) – design

High Gradient Split-Pole Quadrupole

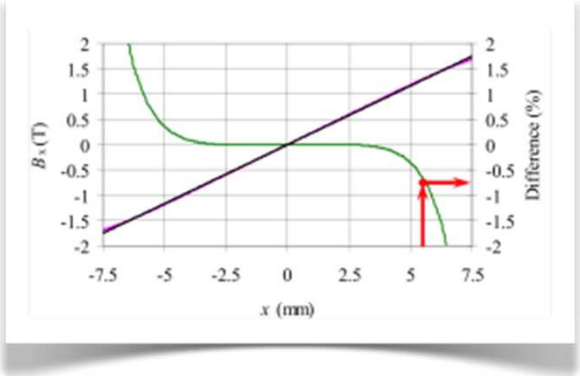


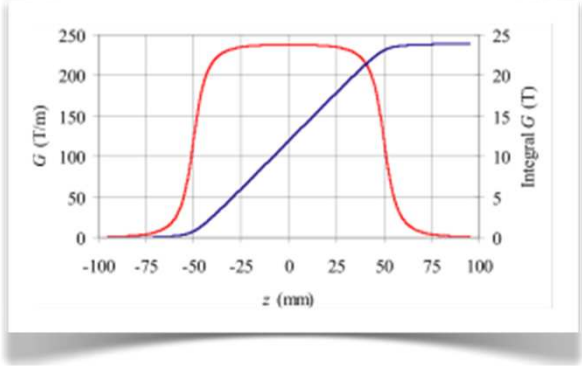




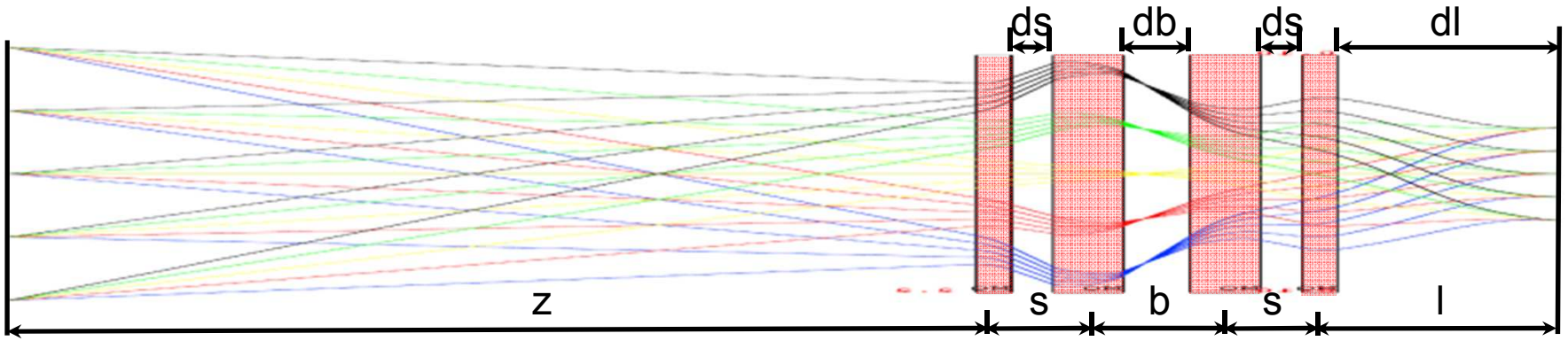
- Extremely High-Level **Gradient** - Maximal Demagnetization Factor
- Flexible Choice of the REPM **Coercivity** on Magnetization
- Minimal Demagnetization in Median Planes (in Critical Spaces)
- Gradient – Fixed

PMQ parameter	**Value**
Inner aperture, $2 \cdot R_i$	15 mm
Outer dimensions, $2 \cdot Ro$ x L	79 x 100 mm
Internal ring magnetization	1.16 T
External ring magnetization	1.19 T
Pole tip field	1.7 T





PRIOR magnetic lens design: thin lens approximation



$$\begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} = \begin{pmatrix} 1 & z \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ \frac{-1}{df+f} & 1 \end{pmatrix} \begin{pmatrix} 1 & s \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ \frac{k}{df+f} & 1 \end{pmatrix} \begin{pmatrix} 1 & b \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ \frac{-k}{df+f} & 1 \end{pmatrix} \begin{pmatrix} 1 & s \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ \frac{1}{df+f} & 1 \end{pmatrix} \begin{pmatrix} 1 & l \\ 0 & 1 \end{pmatrix} = \begin{pmatrix} -m & 0 \\ M_{21} & \frac{-1}{m} \end{pmatrix}$$

Total length: $x = z + 2 \cdot s + b + l$

Quad focal length: $f = \sqrt{\frac{k^2 m s^2}{km - m + k - 1} - \frac{k^2 s^2}{km - m + k - 1} + \frac{2k^2 lms}{km - m + k - 1} - \frac{2klms}{km - m + k - 1}}$

Last Quad to detector: $z = \frac{(km - k)\, s + (k - 1)\, lm}{k - 1}$

Distance 2d to 3d Quad: $b = \frac{(km - k)\, s^2 + (2k - 2)\, lms}{(k^2 - k)\, ms + (k^2 - 2k + 1)\, lm}$

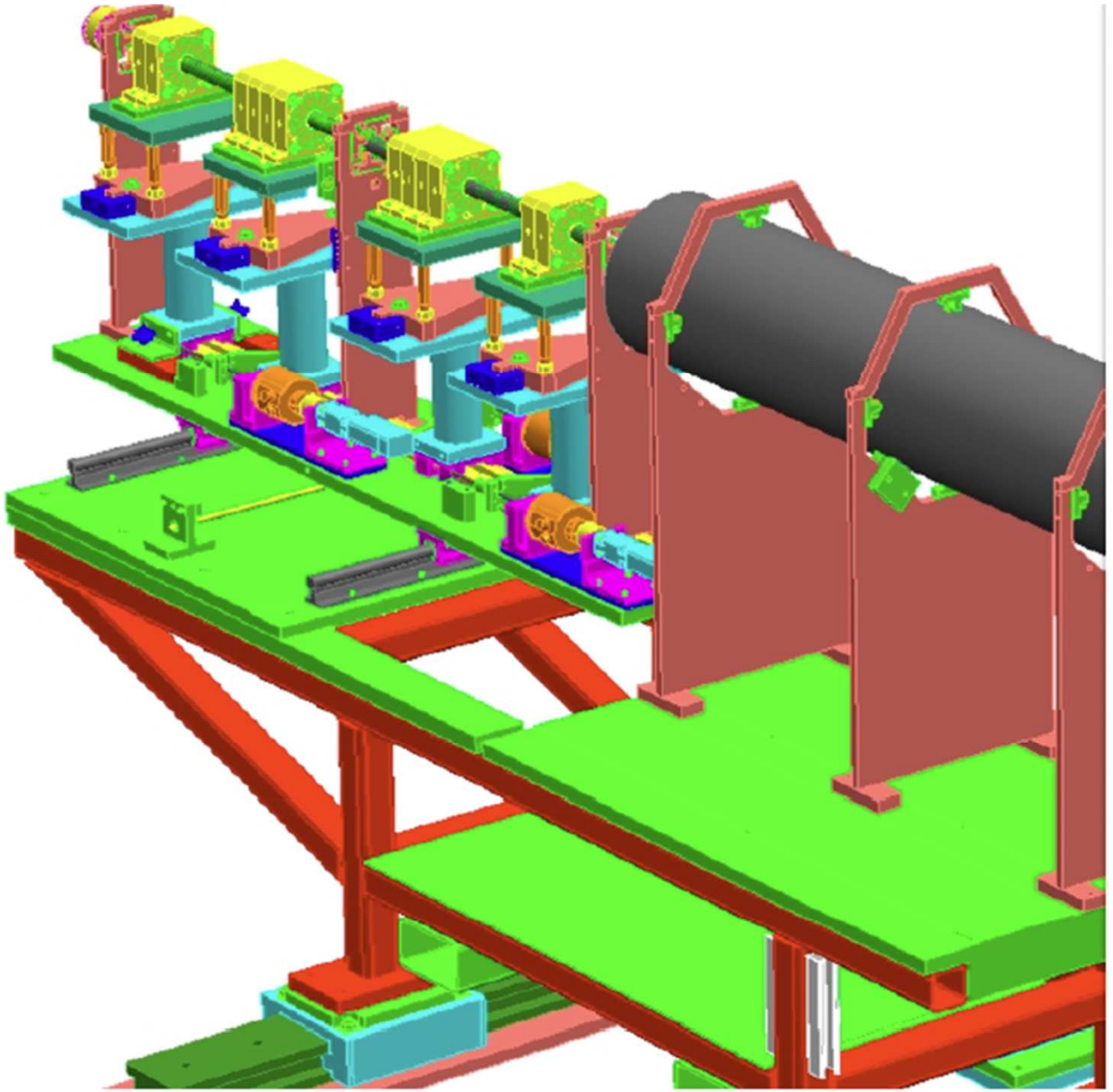
Chromatic length - complicated function of lens spaces:

$$M_{126} = \frac{-4bk^2ls^2z}{f^4} + \frac{3bk^2s^2z}{f^3} + \frac{4lsz}{f^2} + \frac{2bk^2sz}{f^2} - \frac{2sz}{f} + \frac{2bk^2lz}{f^2} - \frac{4bklz}{f^2} + \frac{2blz}{f^2} + \frac{bkz}{f} - \frac{bz}{f} - \frac{3bk^2ls^2}{f^3} + \frac{2bk^2s^2}{f^2} + \frac{2bk^2ls}{f^2} + \frac{2ls}{f} - \frac{bkl}{f} + \frac{bl}{f}$$

$$M_{346} = \frac{-4bk^2ls^2z}{f^4} - \frac{3bk^2s^2z}{f^3} + \frac{4lsz}{f^2} + \frac{2bk^2sz}{f^2} + \frac{2sz}{f} + \frac{2bk^2lz}{f^2} - \frac{4bklz}{f^2} + \frac{2blz}{f^2} - \frac{bkz}{f} + \frac{bz}{f} + \frac{3bk^2ls^2}{f^3} + \frac{2bk^2s^2}{f^2} + \frac{2bk^2ls}{f^2} - \frac{2ls}{f} + \frac{bkl}{f} - \frac{bl}{f}$$

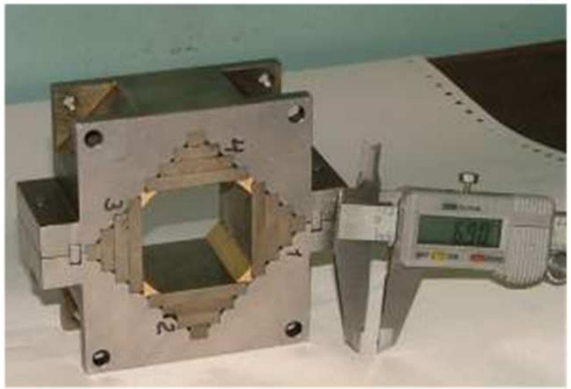
Chromatic blur: $x_0 - \frac{x_i}{M_{11}} = \frac{M_{126}\theta_A\delta}{M_{11}}; y_0 - \frac{y_i}{M_{33}} = \frac{M_{346}\theta_A\delta}{M_{33}}$ - for properly matched beam

(characterize spatial resolution)

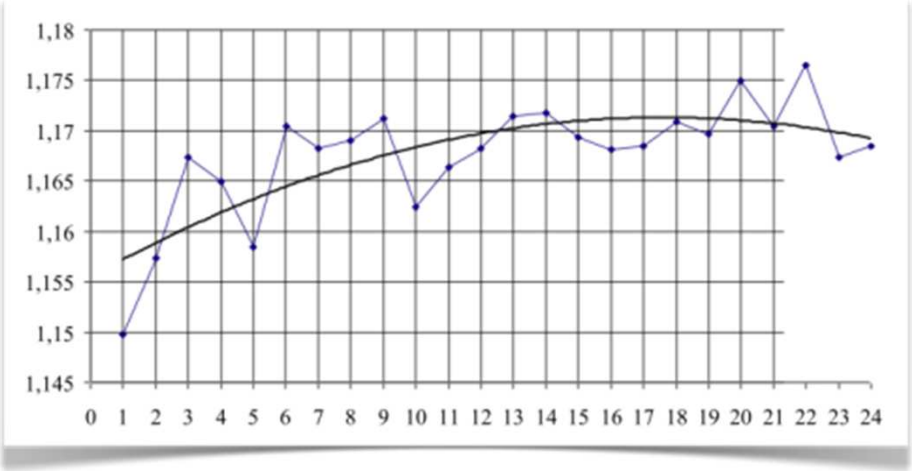


Permanent Magnetic Quadrupoles (PMQ) – manufacturing

Quasi-Sheet Multipole (QSM)



ITEP microscope



series PMQ modules production:
correction of 1.5% field variation

- field gradients up to 240 T/m
- 0.75% or better field linearity
- design and measured PMQ parameters agrees to measurement accuracy
- REPM: Sm-Co vs Nd-Fe-B
- first off-line measurements of the PRIOR 16-sector high gradient split-pole PMQ prototypes has been started at ITEP

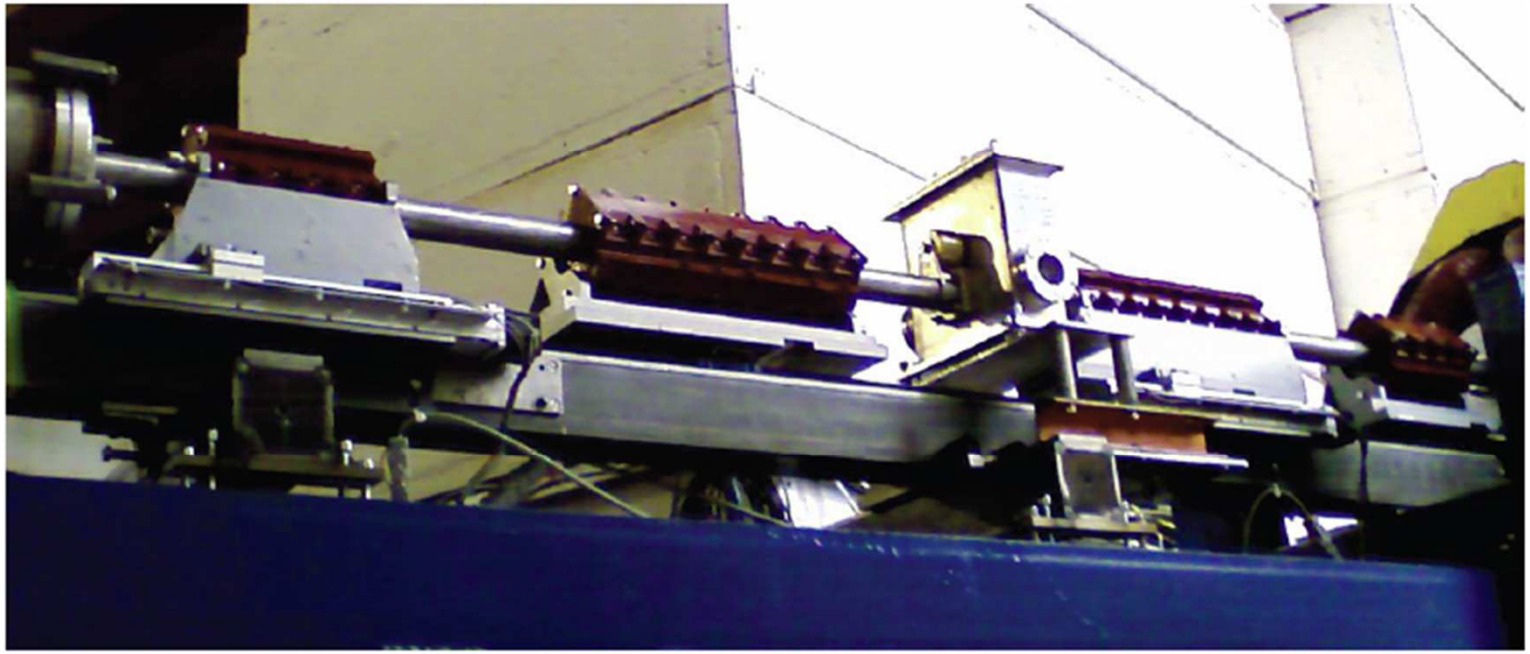
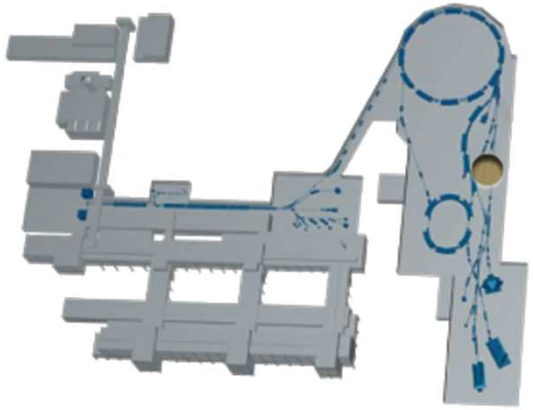
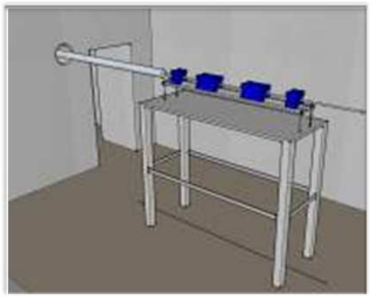
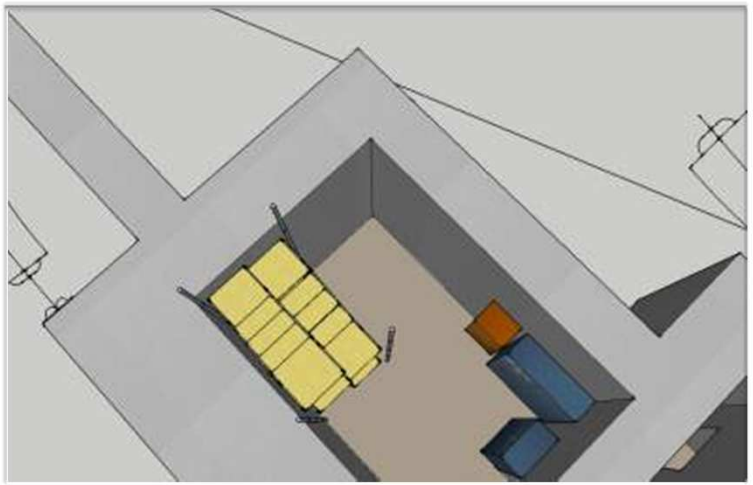


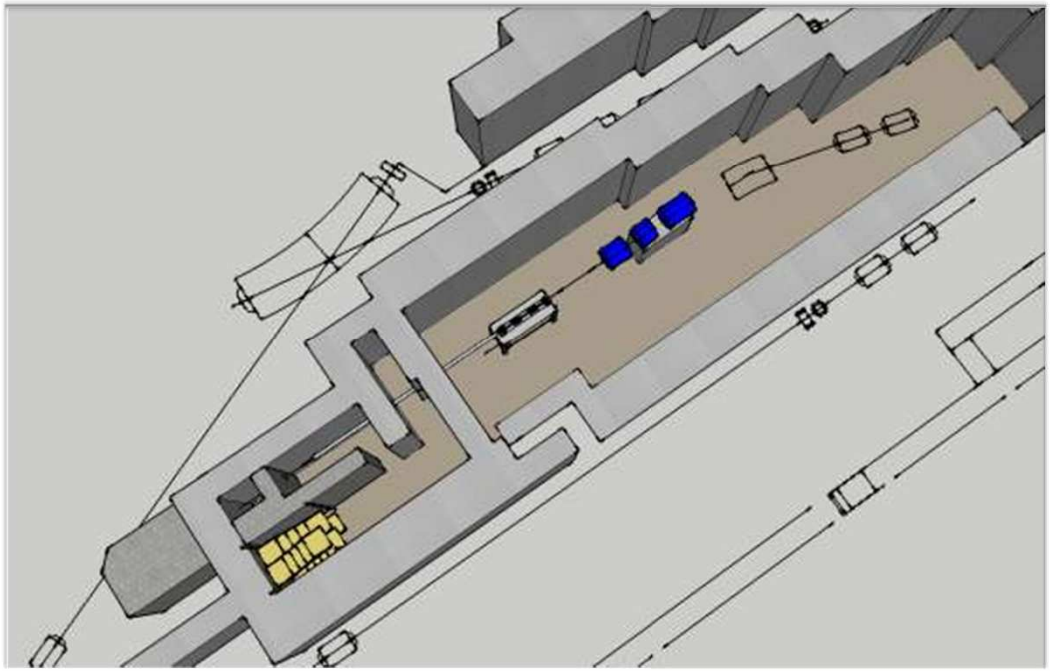
Figure 4: Mechanical construction of the 0.8 GeV ITEP proton microscope.

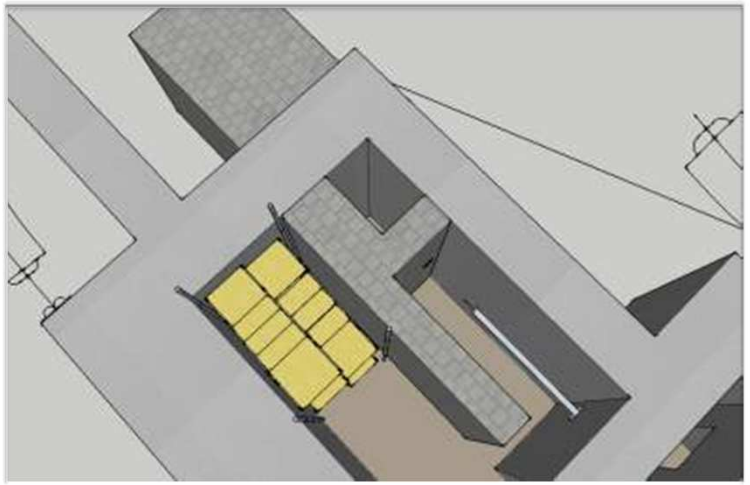
Fielding at GSI – a minor reconstruction of the HHT cave



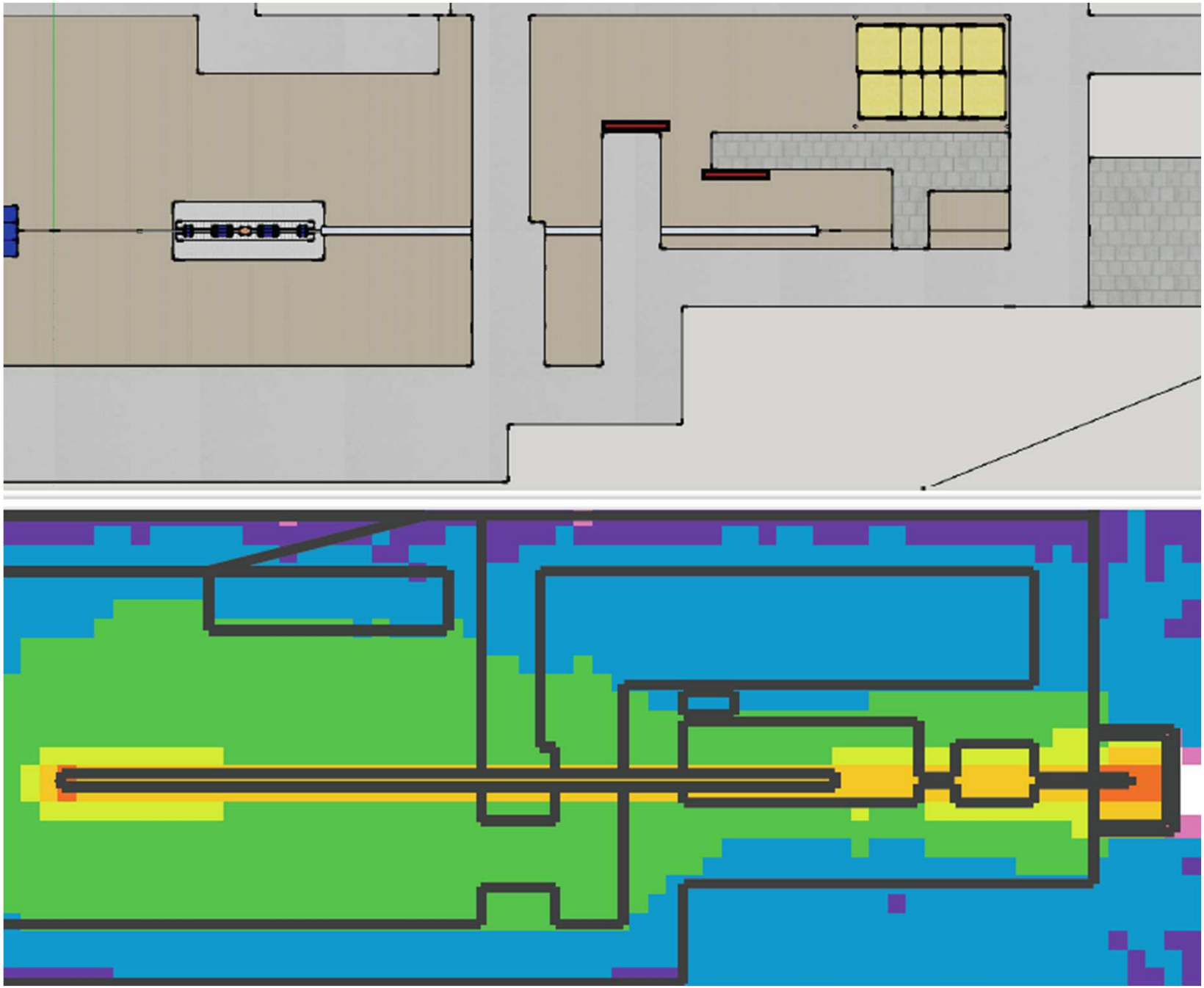








- a compact system but long drift is needed for the microscope



Technical specifications and resolution scalings

Spatial resolution scalings with proton energy:

- object scattering

$$\sigma_o \propto \frac{\ell_t^{\frac{3}{2}}}{p}$$

- chromatic aberrations

$$\sigma_c \propto \frac{\ell_t^{\frac{1}{2}}}{p^{\frac{3}{2}}}$$

- detector blur

$$\sigma_d \propto \frac{\ell_s \ell_t^{\frac{1}{2}}}{p}$$

PRIOR technical specifications (for FAIR experiments):

- proton energy: 4.5 GeV
- spatial resolution: ≤10 μm
- temporal resolution: 10 ns
- multi-framing capability: 1 – 4 frames within 1 μs
- target characteristics: up to 20 g/cm^2
- areal density reconstruction: sub-percent level field of view: 10 – 15 mm
- stand-off distance: 1 – 1.5 mproton illumination spot size: 3 – 15 mm
- total length after object plane: less than 15 m
- using permanent magnets or/and existing electromagnets

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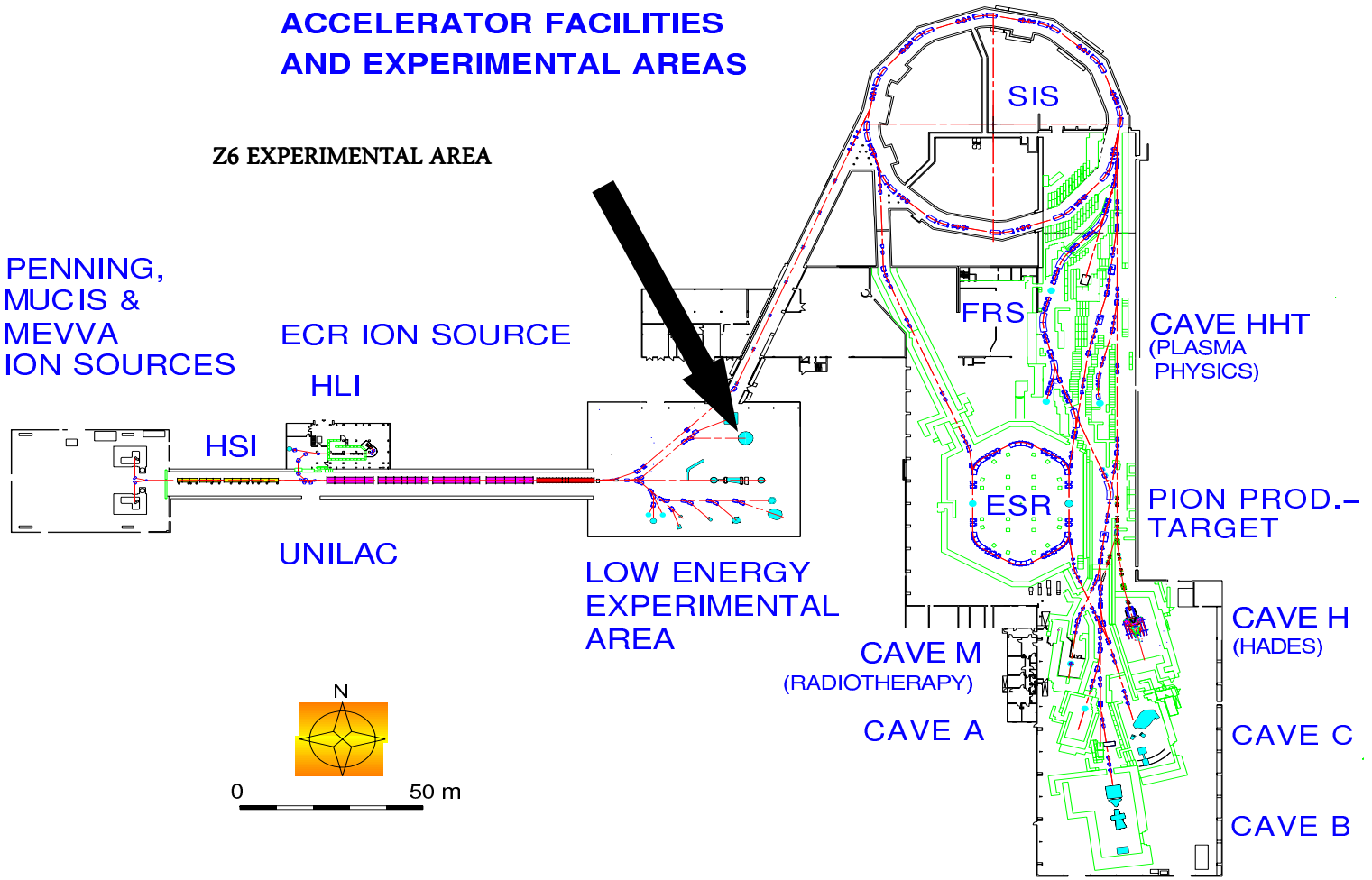
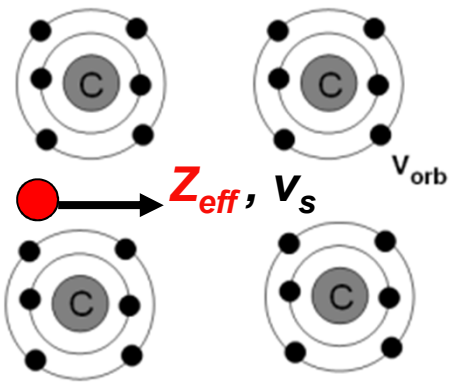


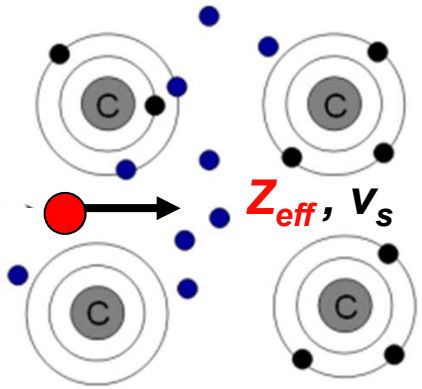
Heavy ion stopping in ionized matter

Heavy ion interaction with laser produced plasma:



Increased energy transfer from the projectile ion to free plasma electrons

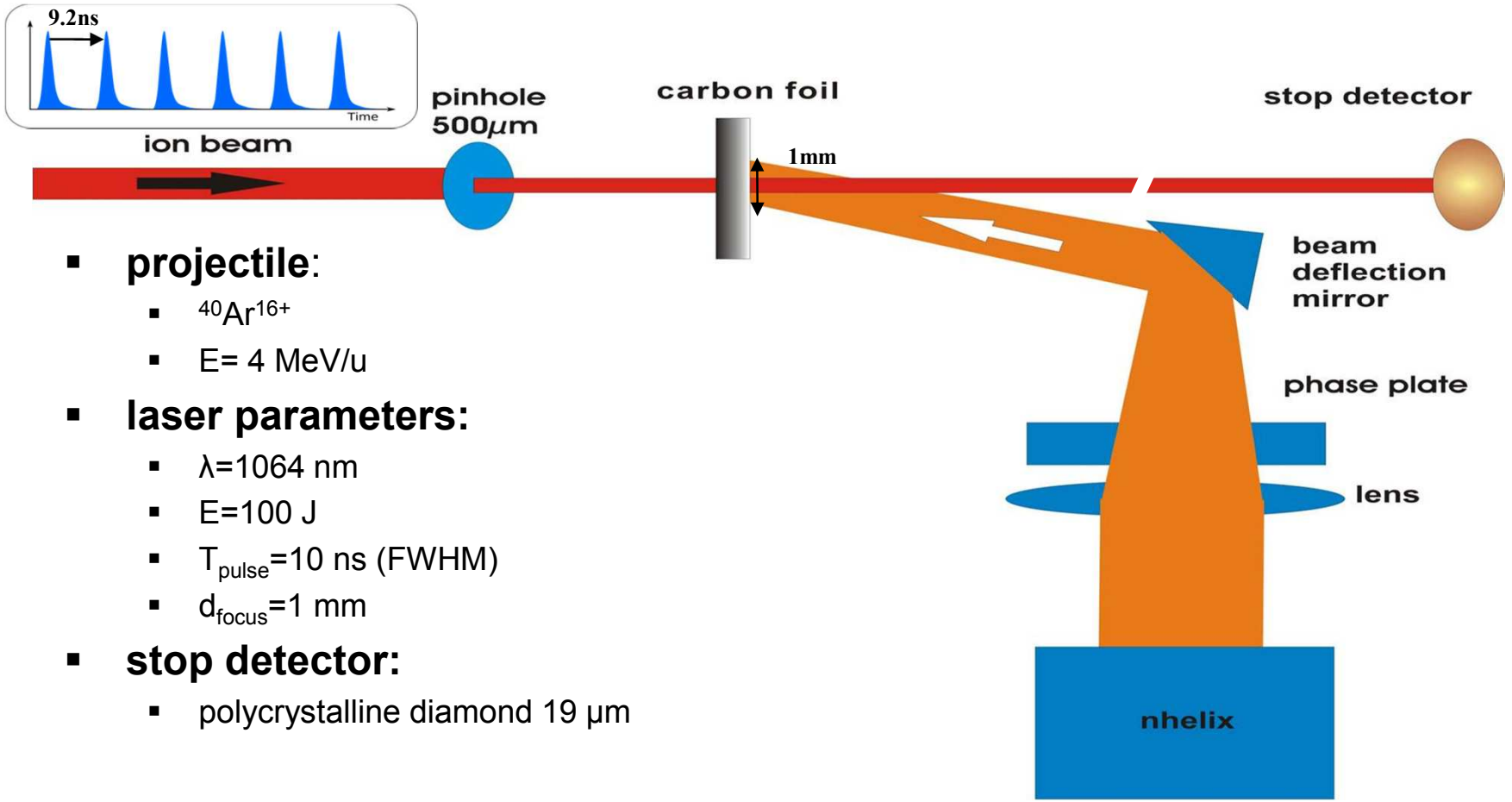
Higher projectile ion charge in plasma



Projectile energy loss in partially ionized matter

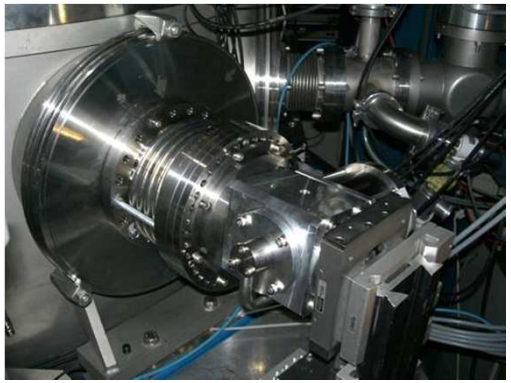
$$-\frac{dE_S}{dz} = \frac{16\pi a_0^2 I_H^2 Z_{eff}^2}{m_e v_S^2}\left[\underbrace{\sum_{Z=0}^{Z_K}(Z_K - Z)\ln\left(\frac{2m_e v_S^2}{I_Z}\right)}_{\text{bound electrons}} + \underbrace{\ln\left(\frac{2m_e v_S^2}{\hbar\omega_p}\right)}_{\text{free electrons}}\right]$$

Experimental Setup of Ion Energy Loss Measurements in Laser Plasmas



- **projectile**:
  - $^{40}Ar^{16+}$
  - E= 4 MeV/u
- **laser parameters:**
  - λ=1064 nm
  - E=100 J
  - T_{pulse}=10 ns (FWHM)
  - d_{focus}=1 mm
- **stop detector:**
  - polycrystalline diamond 19 μm

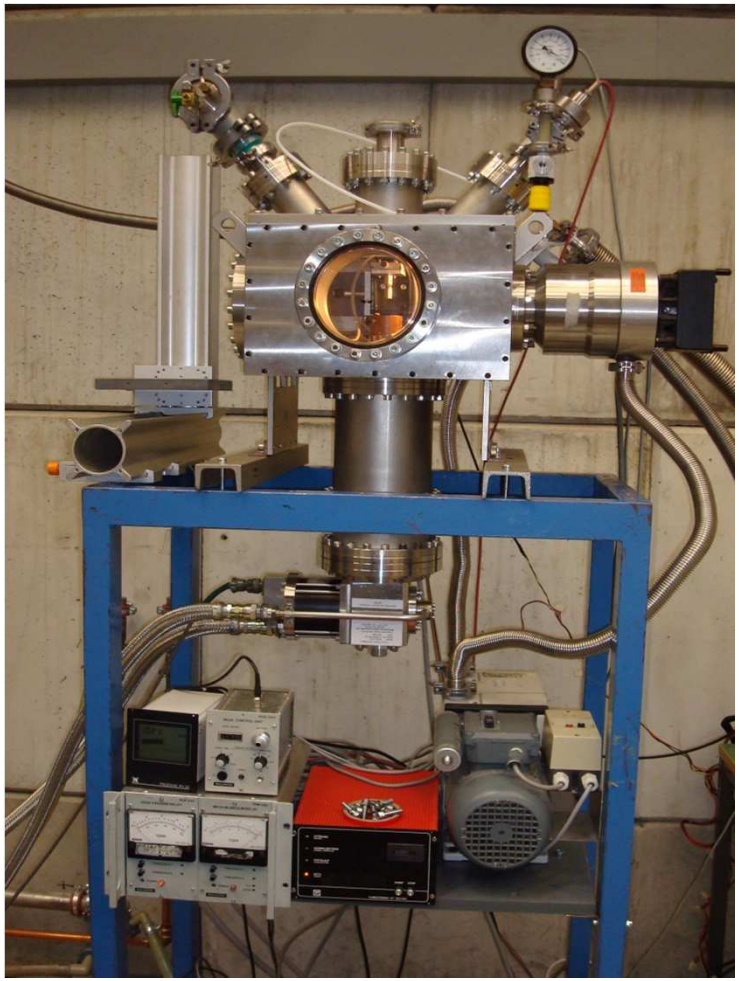
Cryo test setup



4K cryo system

cooling capacity: 1.5Watts @ 4.2K

cooldown time: 60min

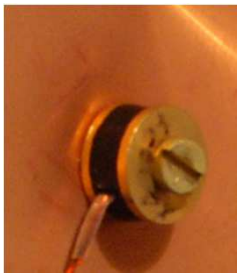


Cernox temperatur sensors

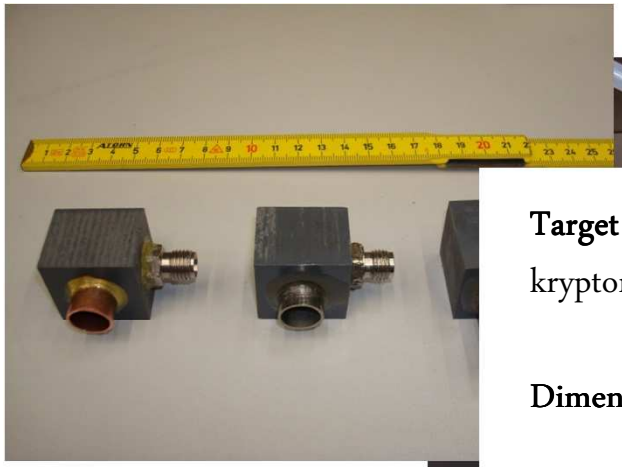
calibrated accuracy: 5 mK @ 4.2K

temperture range: 1.5-300K

dimensions: 8x4.5mm



Cryo target production

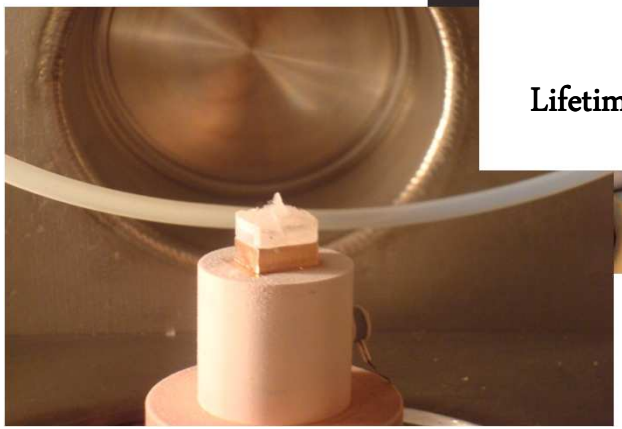


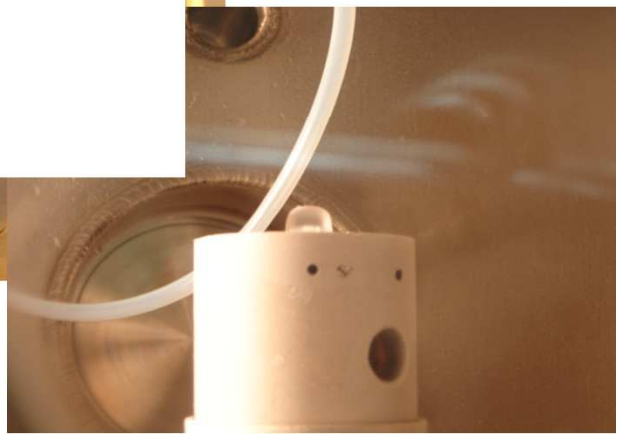
Target materials: nitrogen, argon, neon, krypton, hydrogen, deuterium

Dimensons: mm, cm

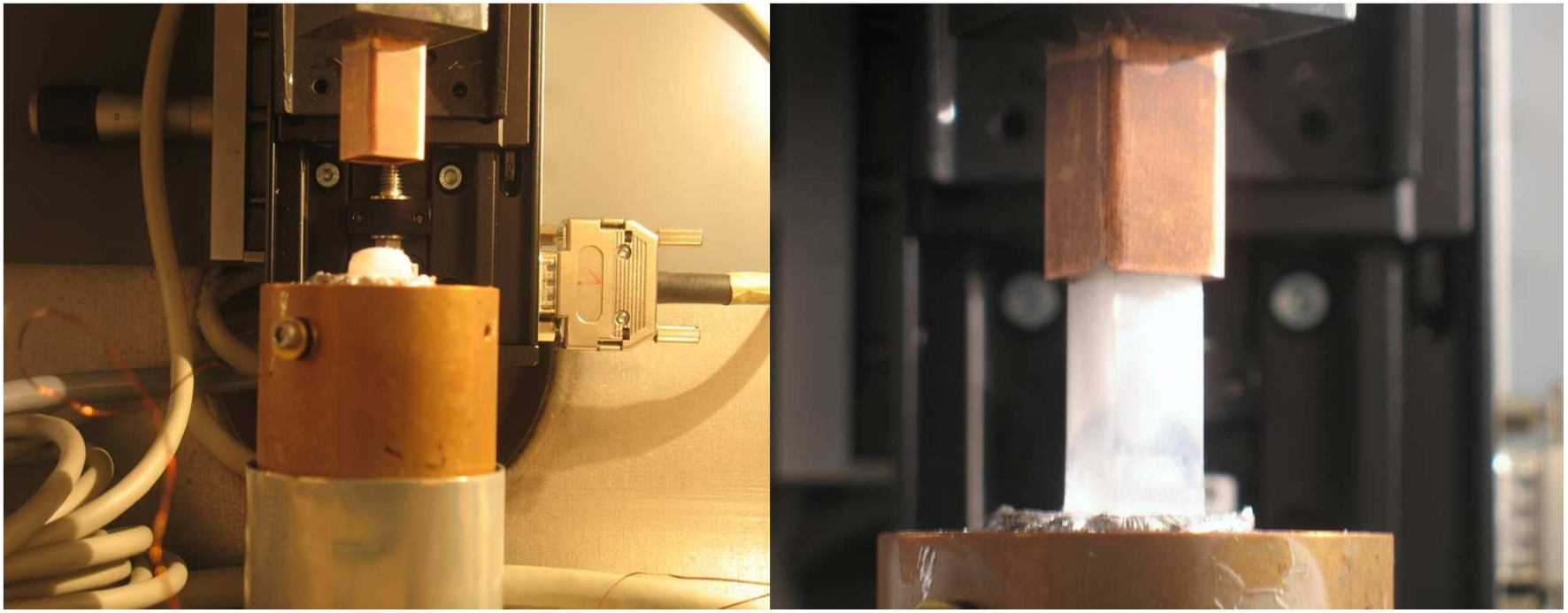
Growing time: 10-40min

Lifetime: 30min and longer



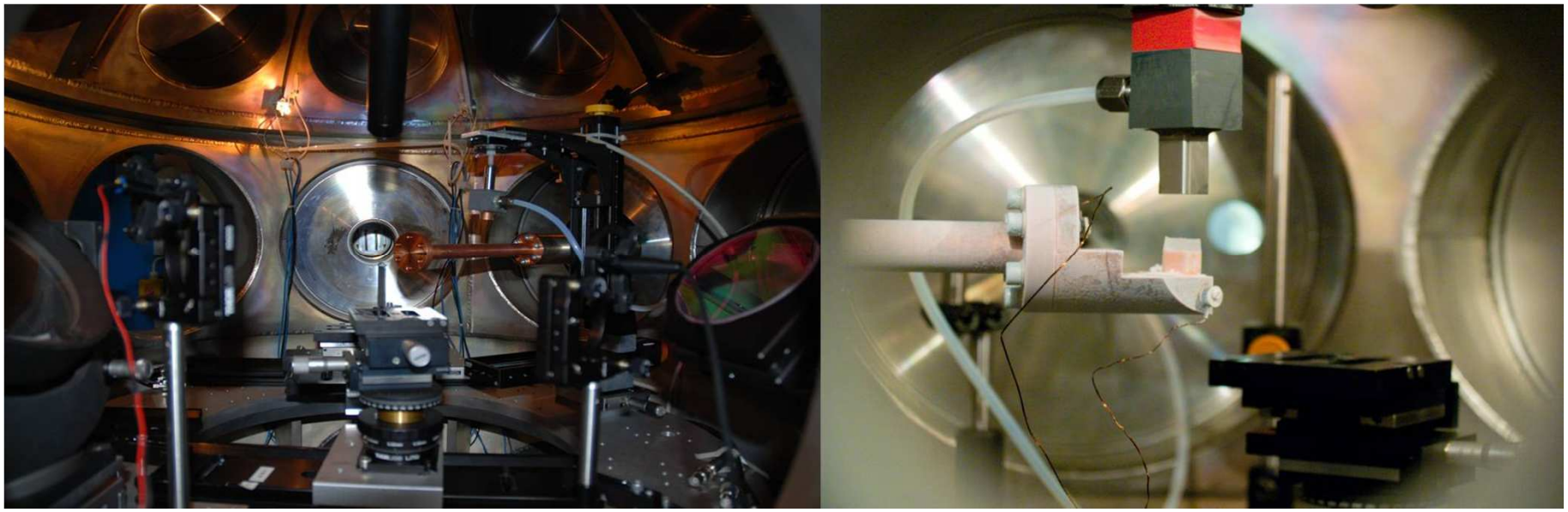


Gas precool system



The quality of cryo crystals can be improved by using precooled gas.
This decreases growing time; tall crystals of height 4 cm are possible.

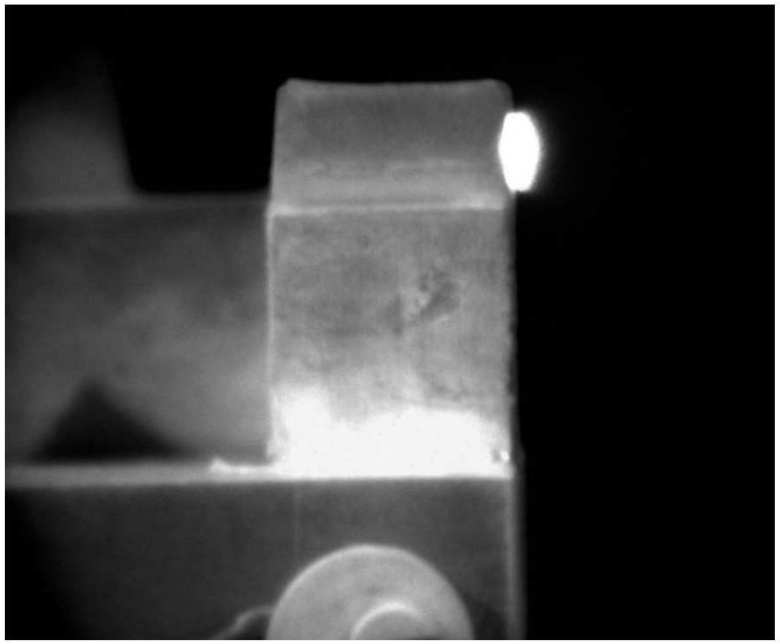
Laser plasma produced out of a solid nitrogen target

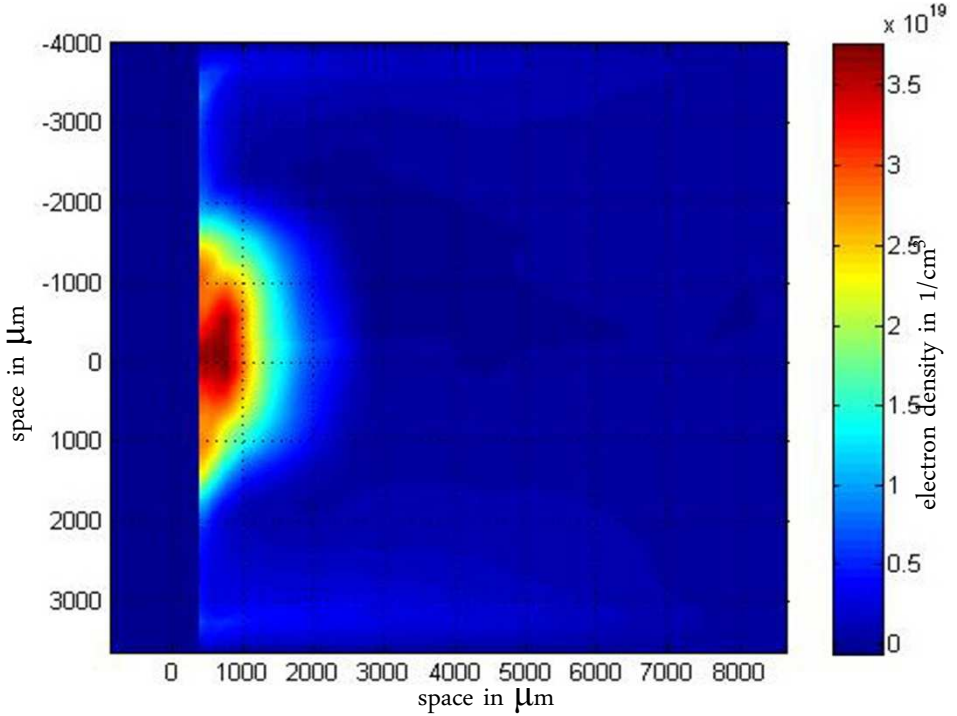


additional components:

- Adjustable mounting of cryo cooler
- Remote control of the growing chamber
- Copper extension of cryo cooler
- Target support for the cryo target

Laser plasma produced out of a solid nitrogen target





solid nitrogen target:

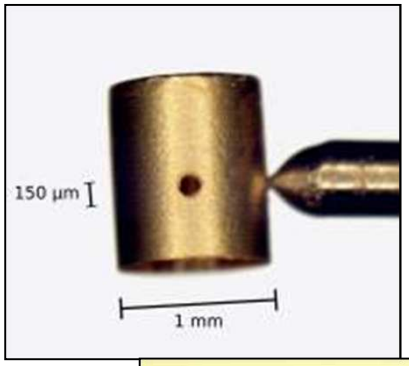
- dimensions: 10x10x4mm
- growing time: 20min
- growing pressure: 300mbar
- temperature: 10K

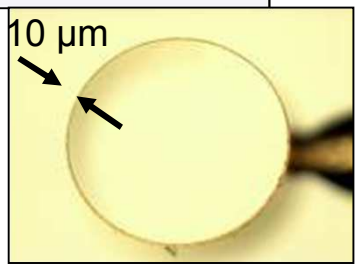
diagnostics:

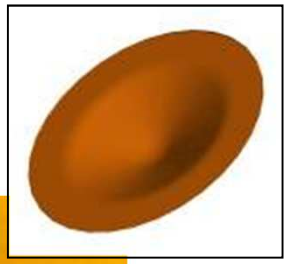
- streak camera
- fast shutter camera
- X-ray pinhole camera
- Wollaston interferometer (λ=355nm)

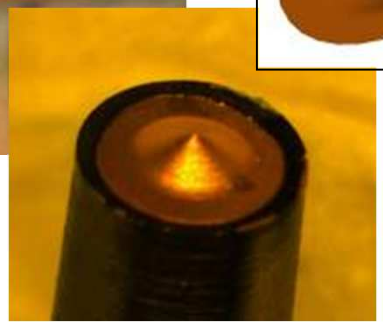
Target fabrication at TU-Darmstadt: Hohlraum targets, Cones, Hemi-Spheres

sphere:
Ø 750 µm
port:
Ø 150 µm
350 µm









Target Fabrication at TU-Darmstadt

- 100 m² clean room (10.000) & Flow Boxes (<1000)

- Wet chemical processing
  - Ultra pure deionized water installation.
  - Equipment to handle acids (including hydrofluoric acid).
  - Electroplating for gold, nickel & copper

- Photolithography (proximity & projection)
  - 3D photo resist

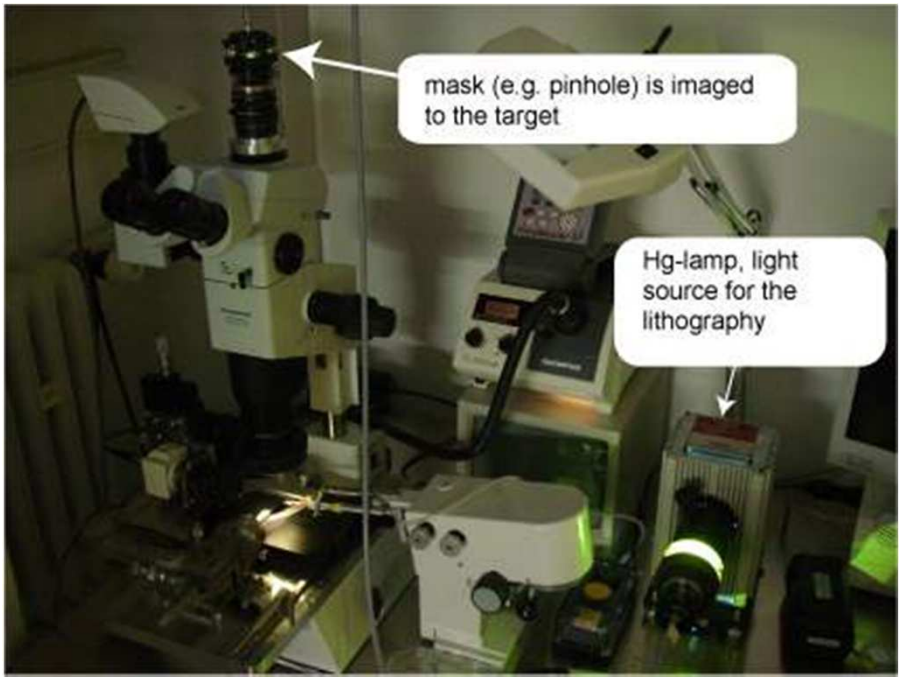
- Thermal evaporation plants (access to sputter plant, e-beam evaporation, etc.).

- Process gases, like nitrogen, oxygen, hydrogen and argon.
  Equipment to handle & store targets under inert gas atmosphere.

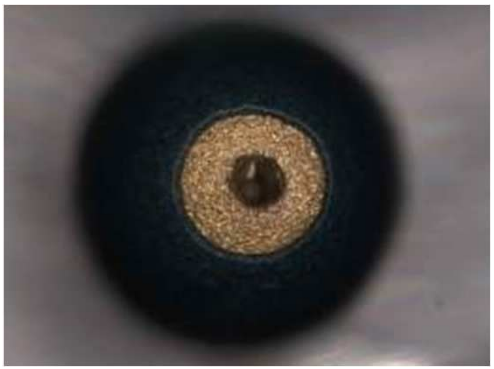
Target Fabrication at TU-Darmstadt

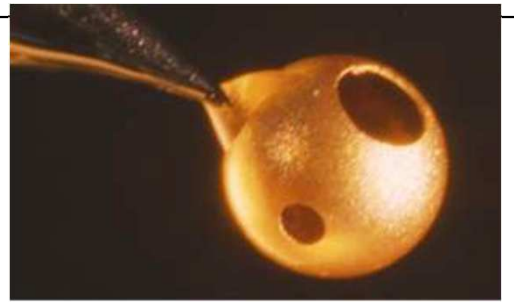
- Film thickness measurement by means of alpha particle energy loss rating (Americium 241).
- Optical microscopy, manual assembly station, glue dispenser, …
- Precision micro machining (lathe).
- Bonding equipment.
- Access to Ti:Sa-laser (in house). Laser machining and 3D-two photon lithography under development.
- Cryogenic target development (hydrogen & deuterium targets).
- … and “unlimited” man power in terms of master & PhD students …

Hohlraum manufacturing



- Positive form (e.g. bras or stainless steel ball)
- Contact the ball with a 50µm wire
- Cleaning procedure
- Electroplate (cyanide based Au)
- Apply the 3D positive photo resist
- Expose, e.g. laser entrance hole
- Etch the gold
- Etch the massive brass body
- Glue the hollow sphere to a target support.






TECHNISCHE
UNIVERSITÄT
DARMSTADT
TU-Darmstadt
Target Laboratory
1mm
Probably not the most precise
Hohlraum Targets in the World
-- but at least the most friendly ones -