Extreme States of Matter by Intense Heavy Ion Beams

Presented by:

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Extreme states of matter:

(don't take the limits too strict)

- T ~ 0.1 to 50 eV (melting of Fe ≈ 0.16 eV)
- ρ ~ 0.1 to 100 g/cm^3 (1 g/cm^3 for usual Water)
- p ~ kbar, Mbar, ...
- E > 1 kJ/g

Getting a feeling

Strongest man

$p_0 - p_1 \approx 25$ mbar
$A = 1\ m^2$

1 Gbar: the pressure on the tip of your thumb holding 10 fully loaded aircraft carriers

Courtesy D. Varentsov, GSI

1 kJ/g is approximately needed to heat and melt for instance Fe or Al, starting at room temperature.

What about storage?

(of 1 kJ for or as a result of pulsed power experiments)

Three examples

Capacitive	Motion	Inductive
45 kV @ 1 µF	1.4 km/s @ 10^{-3} kg	1.4 kA @ 1 mH

Plasma physics, atomic physics, thermophysics
fundamental properties of matter in unexplored regions of the phase diagram: equation-of-state, exotic phase transitions, transport and optical properties, effects of strong inter-particle interaction, ...

Astrophysics and planetary sciences
brown dwarfs, pulsars, supernova explosions, structure of the earth and sun interior, giant and extra-solar planets

Energy research and inertial confinement fusion
fusion energy, portable nuclear and MHD reactors, safety of power plants

Technologies
material research, pulsed and high-temperature technologies, dynamic syntesis of new materials, space technologies, defence applications

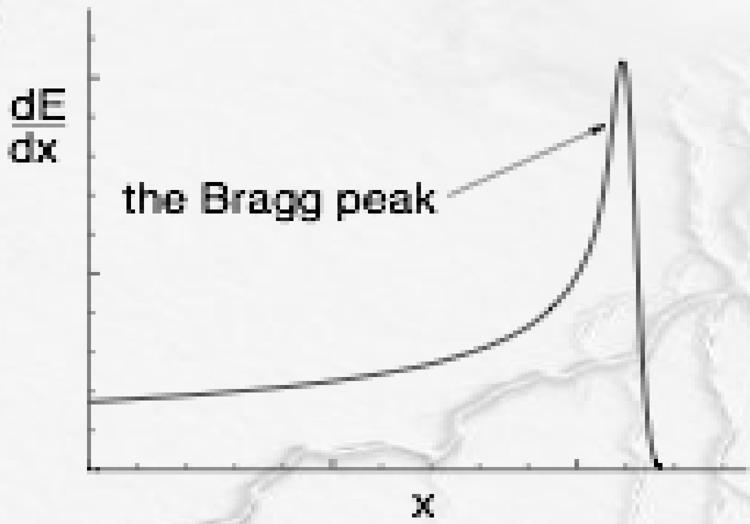
Drivers to generate extreme matter states

- **Solid state (NIF, LULI, PHELIX, ...) and free electron lasers (FLASH)**
- **High explosives**
- **Particle accelerators (GSI, TWAC, NDCX)**
- **Rail guns**
- **Electromagnetic discharges (Z-Machine, ANGARA-5)**

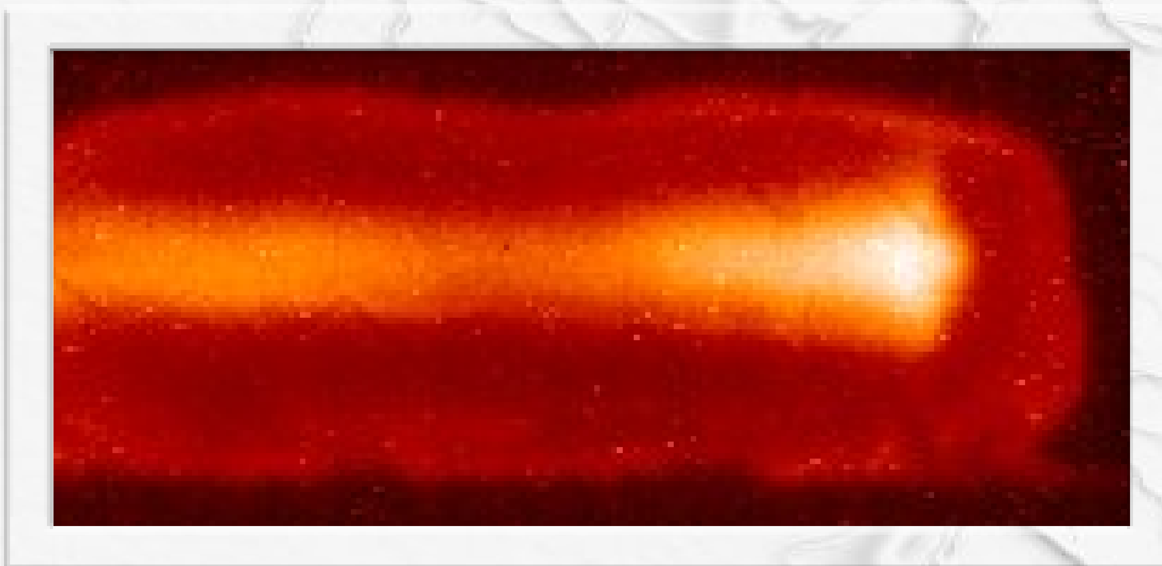
Highly versatile:

- Direct heating and expansion (HIHEX)
- Shock wave generation
- Strong, low entropy compression (LAPLAS)

Heavy ions: energy deposition

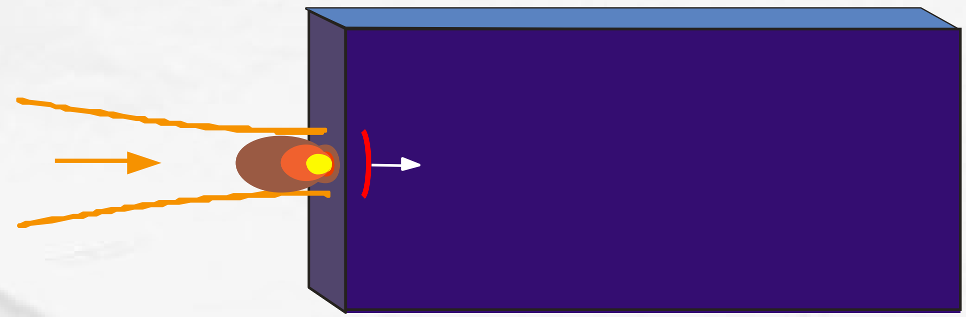


$$E_s \propto \frac{1}{\rho} \cdot \frac{dE}{dx} \cdot \frac{N}{r_b^2}$$



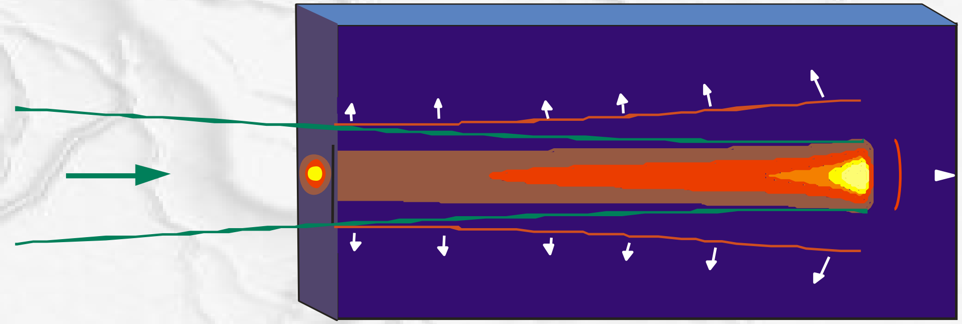
Heavy ion vs. laser beams

Powerful lasers[1]:
energy is absorbed at the target surface (critical density)
=> shock wave, high gradients



1 - VUV, X-ray lasers or indirect heating allow for reduced gradients.

Intense ion beams:
energy is deposited in the bulk of the target
=> quasi-isochoric heating



Beam parameters, whishlist

- High Z, since $dE/dx \sim Z^2$, $Z_U = 92$

- Ion energy 50 – 1500 MeV/u

- maximum beam intensity (number of ions per pulse) $N \sim 10^9 - 10^{12}$

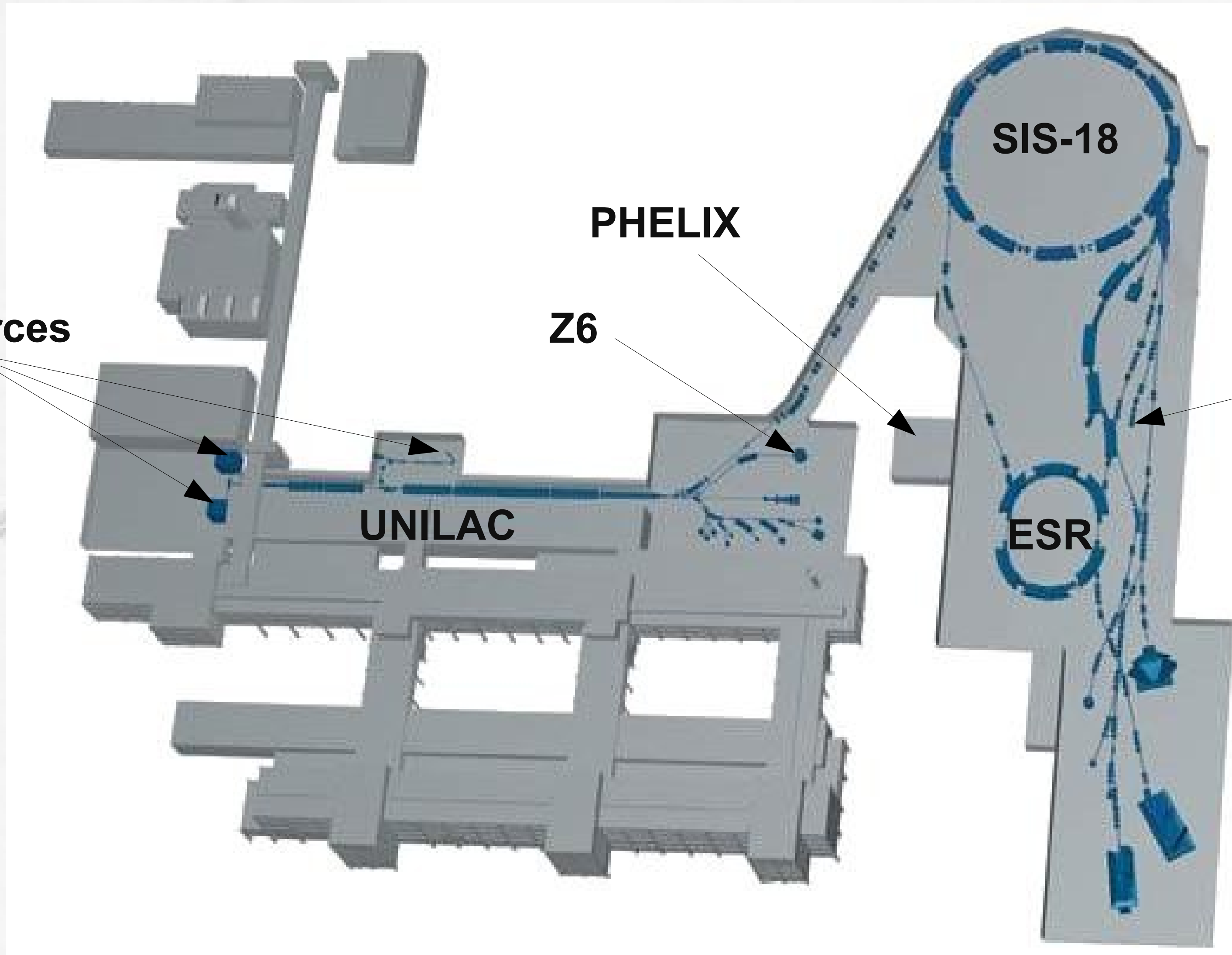
- minimum pulse duration $\tau \sim 50 - 100$ ns => bunch compression

- minimum focal spot size at the target r_b
  - reducing transverse emittance – electron cooling
  - special final focusing system

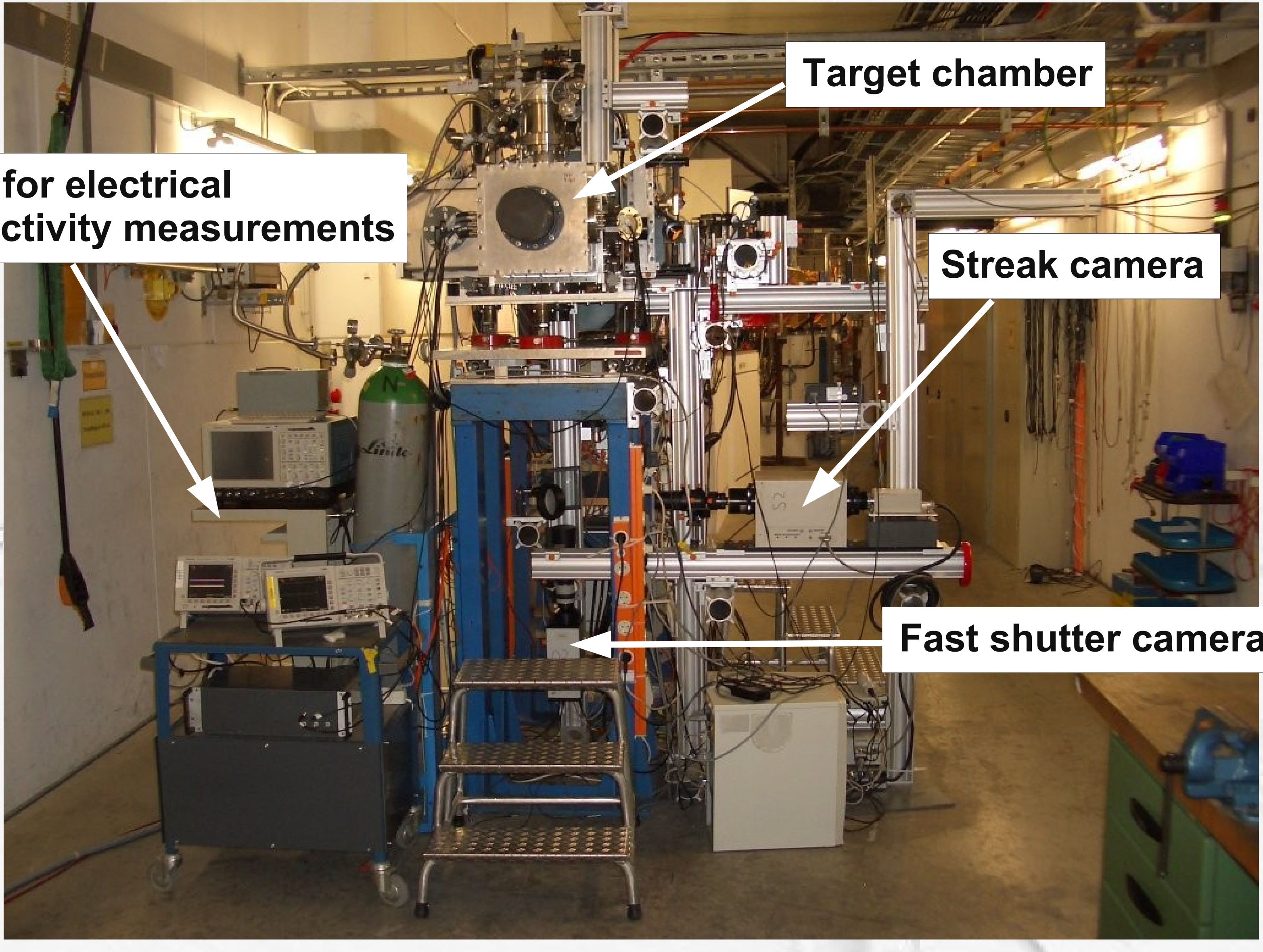
Beam parameters, present and future

	GSI	FAIR
E_0	0.4 AGeV	2.7 AGeV
N	$5\cdot10^9$	10^{12}
E	0.06 kJ	38 kJ
τ	100 ns	50 ns
P	0.5 GW	750 GW
S	<1 mm^2	1 mm^2
E/Pb	1 kJ/g	300 kJ/g
P/Pb	5 GW/g	6 TW/g

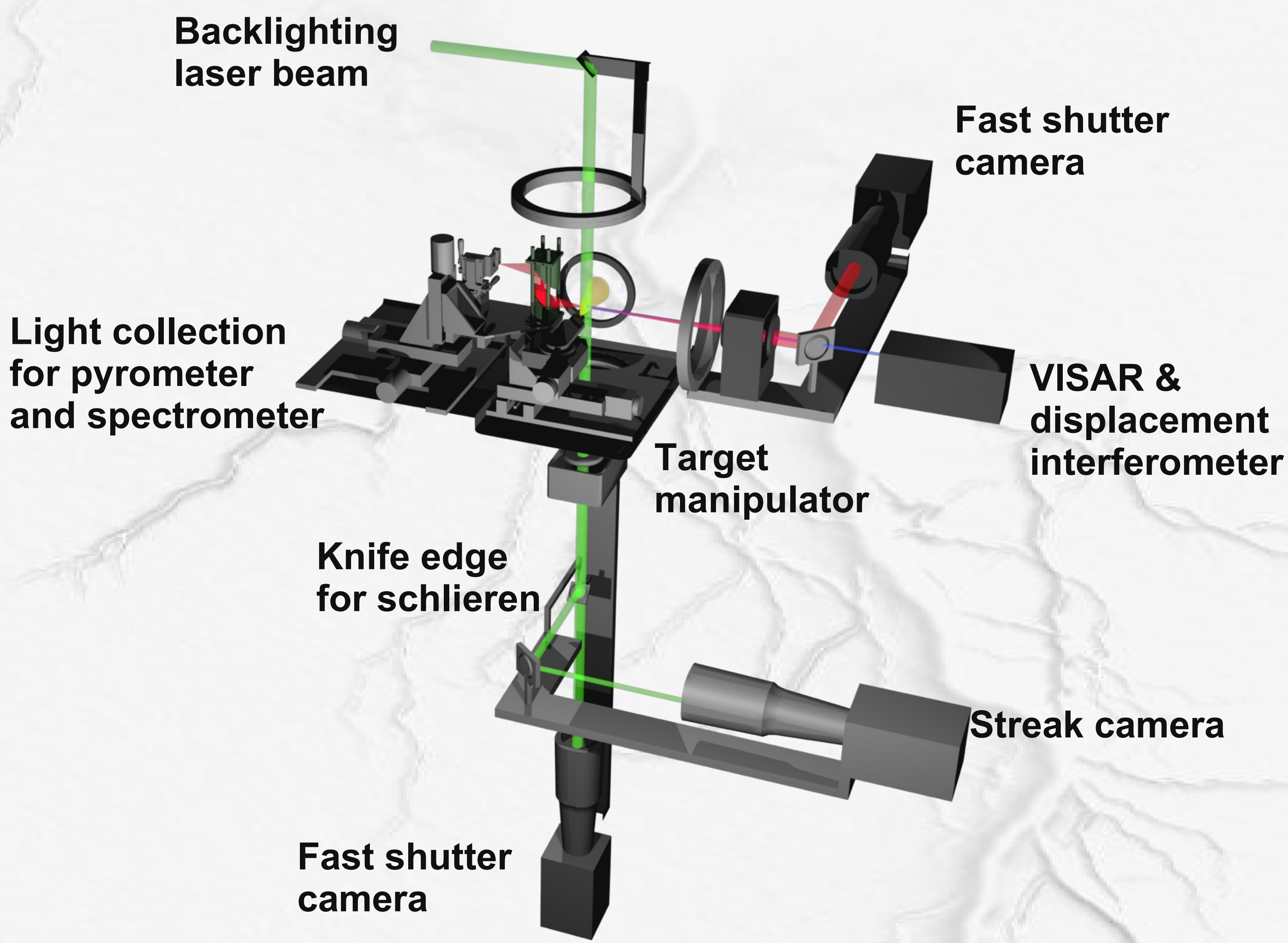
The GSI accelerator facilities

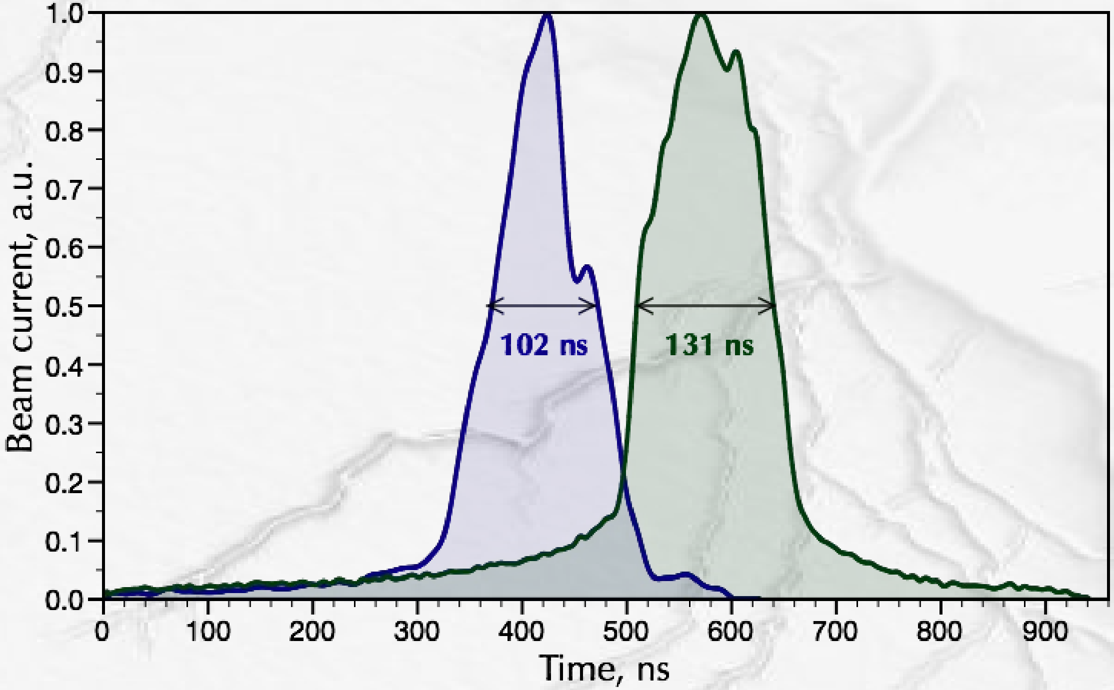


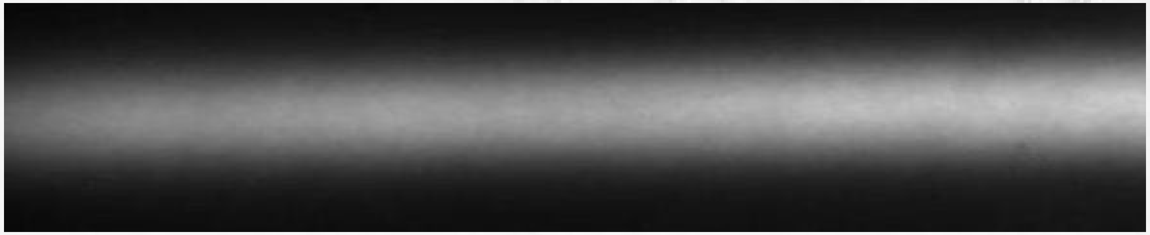
The HHT cave

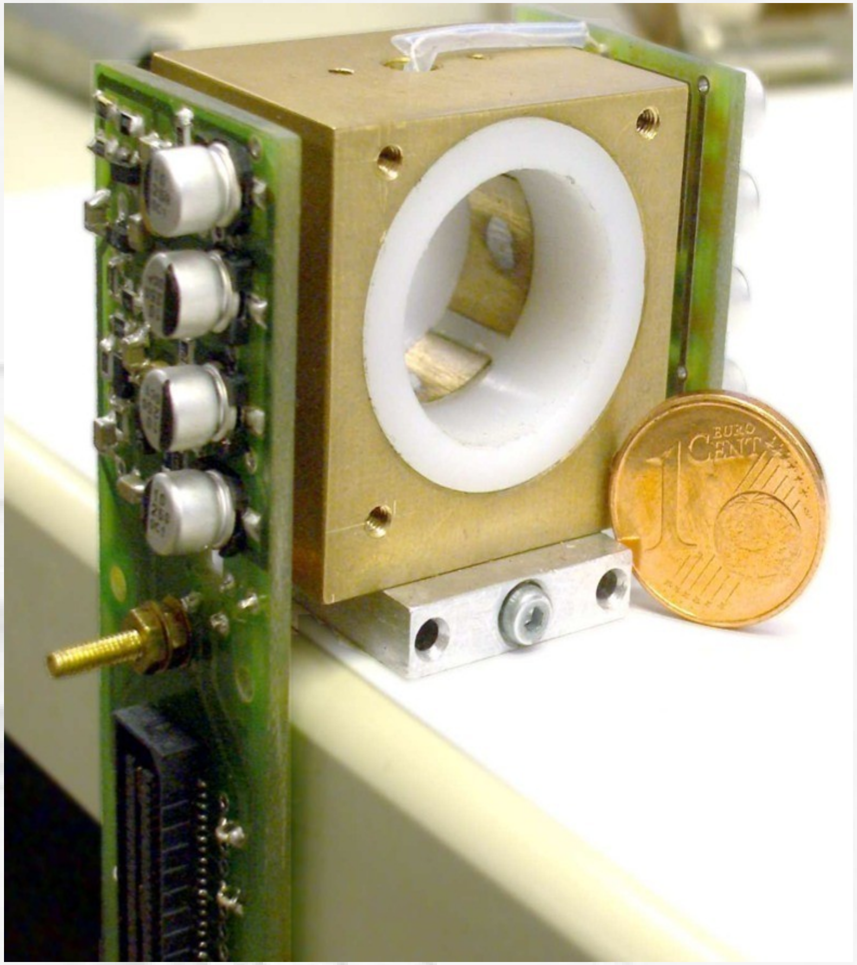

Target chamber
Setup for electrical conductivity measurements
Streak camera
Fast shutter camera

Typical experimental setup

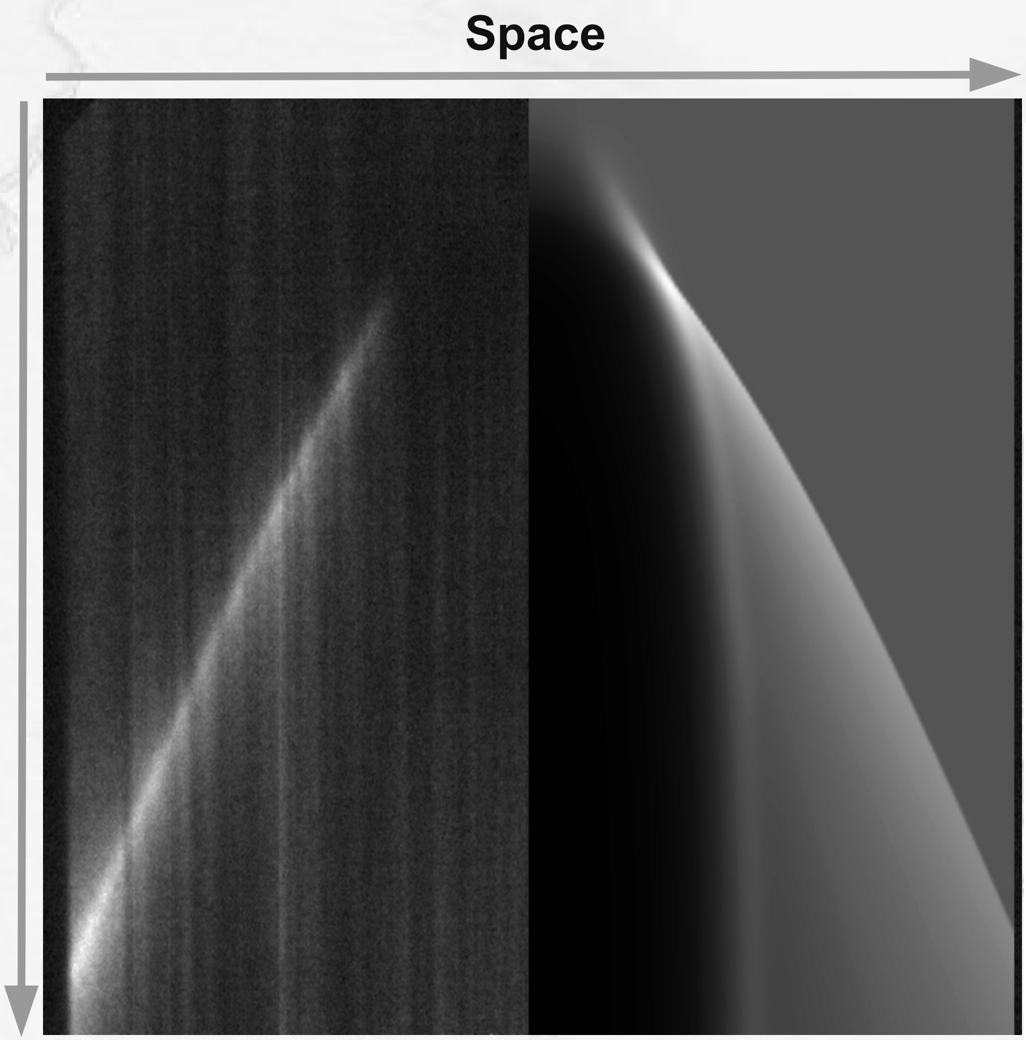



Beam current, a.u.
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
100
200
300
400
500
600
700
800
900
Time, ns
102 ns
131 ns

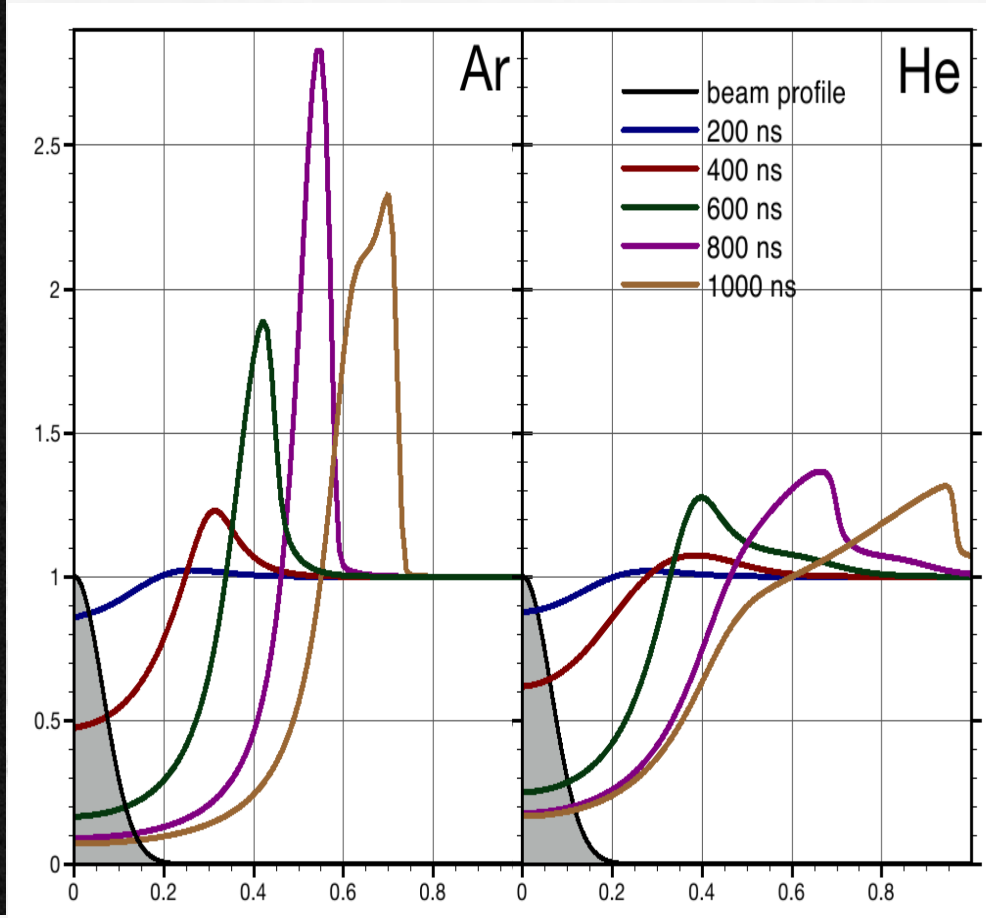




Gas dynamics



Streak image by schlieren optics and simulation

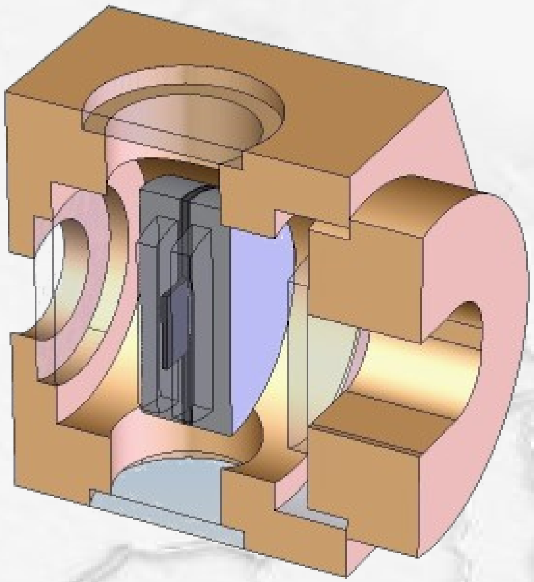


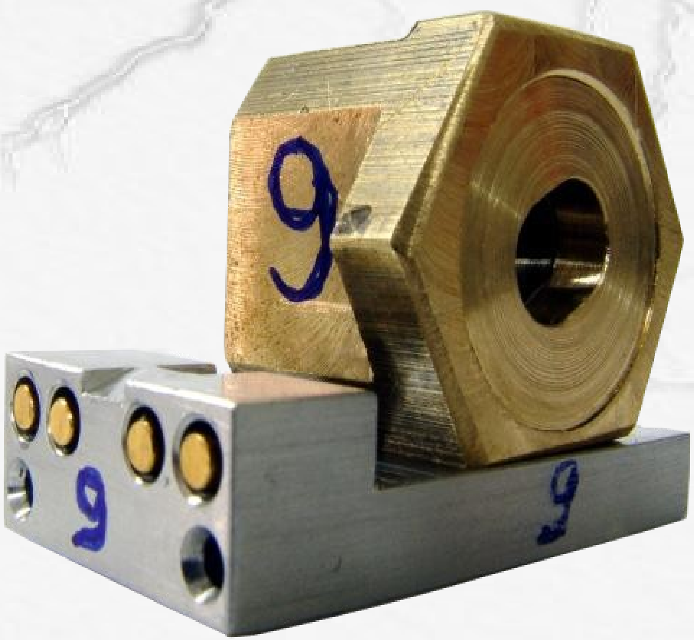
Density profiles from simulation

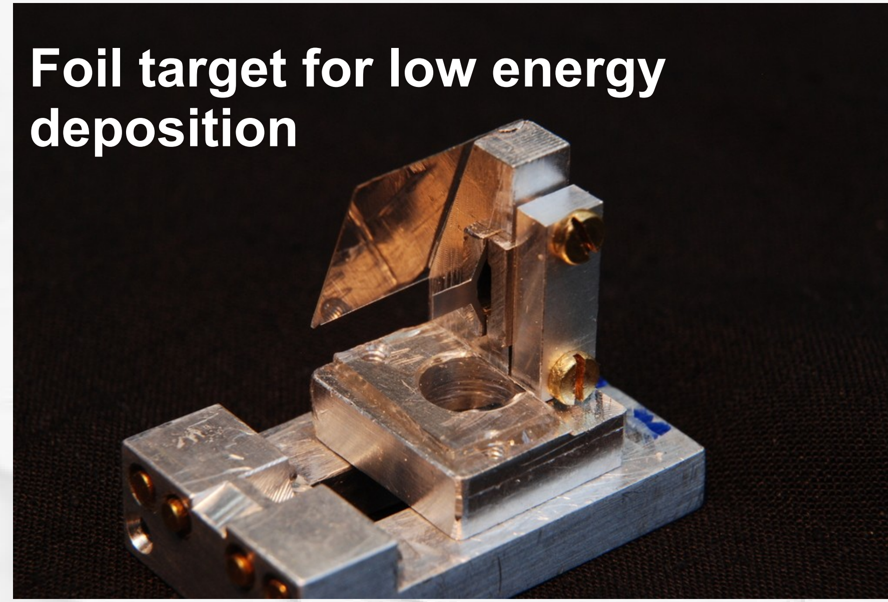
TUD

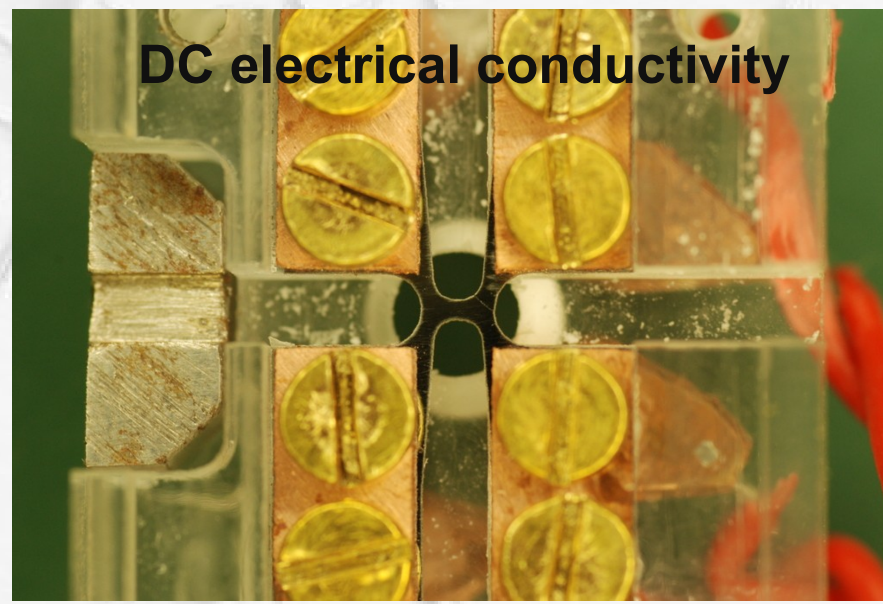
Target designs

Foil target for high energy deposition

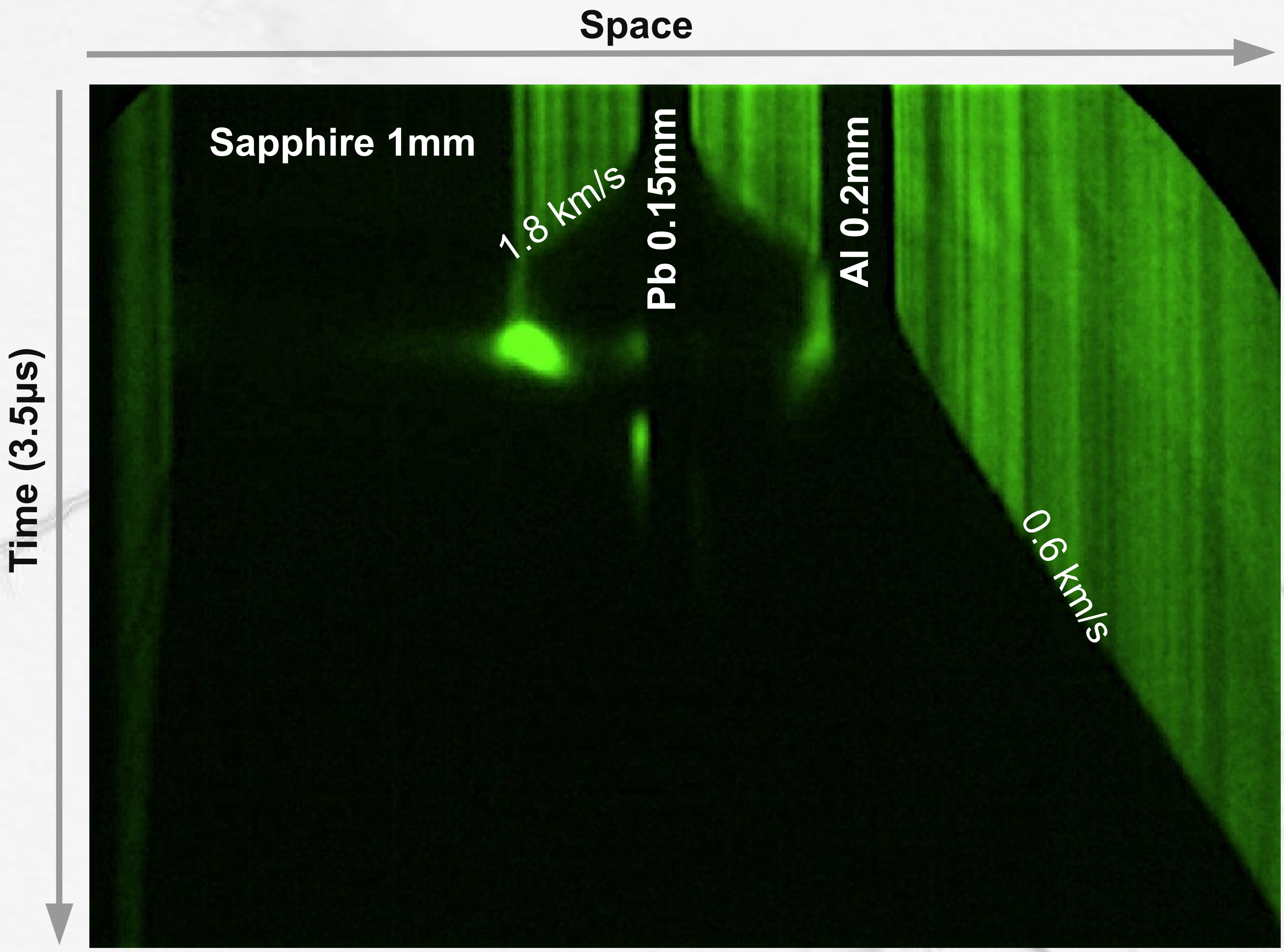




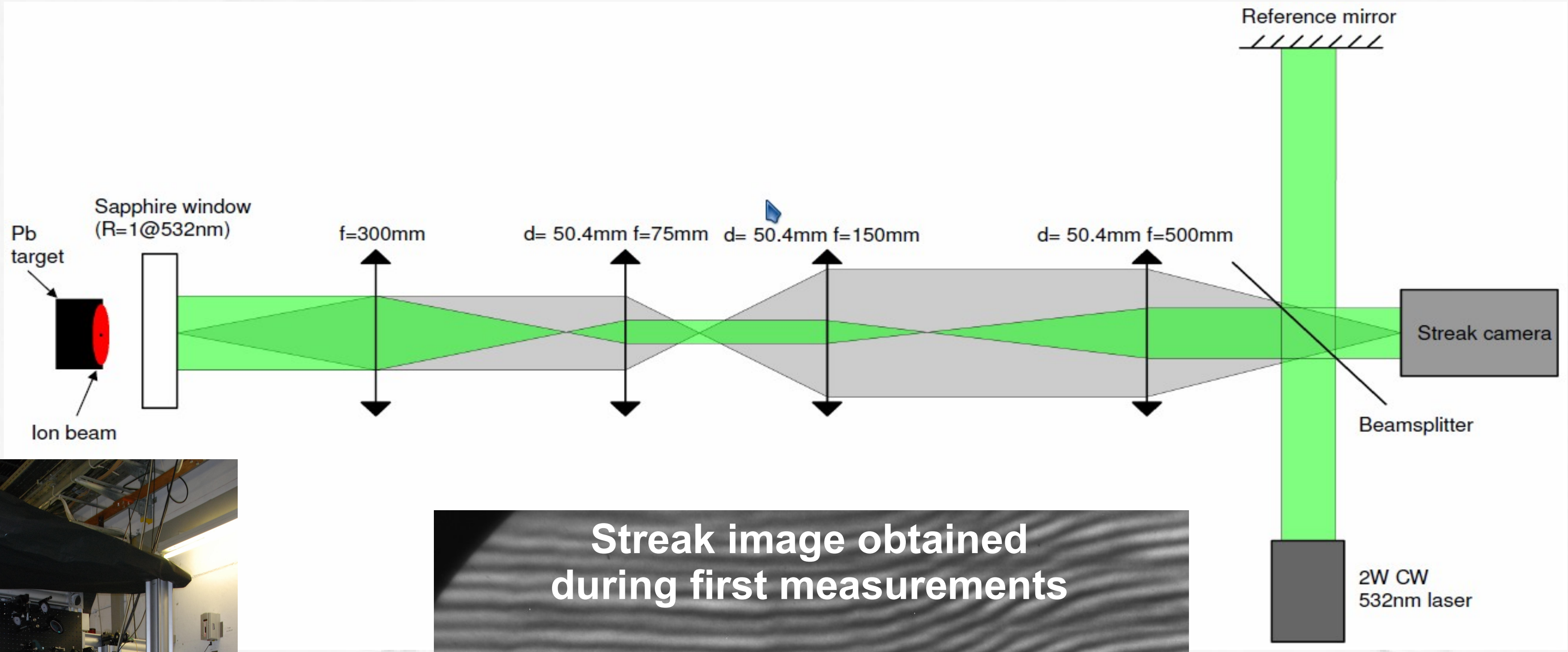


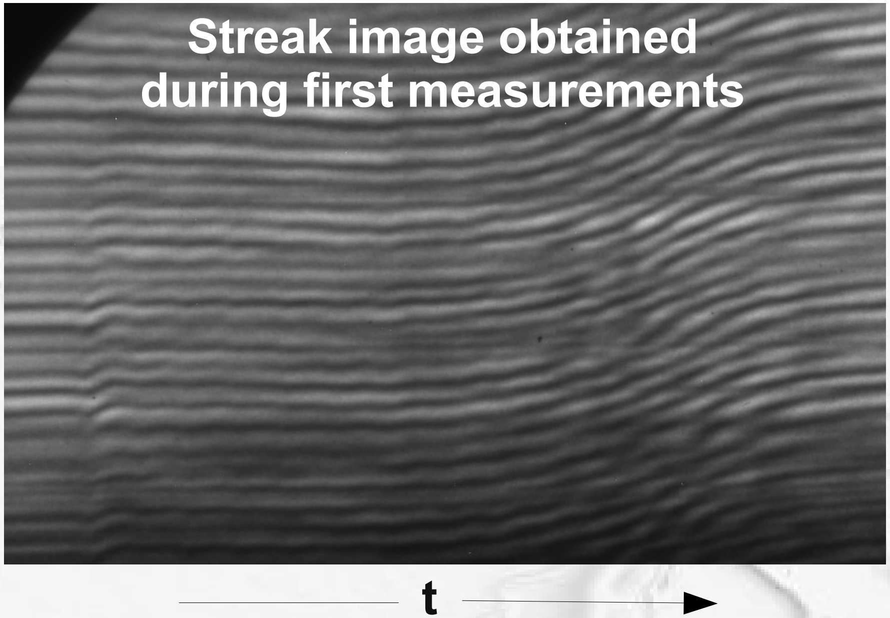


Streak image of target dynamics



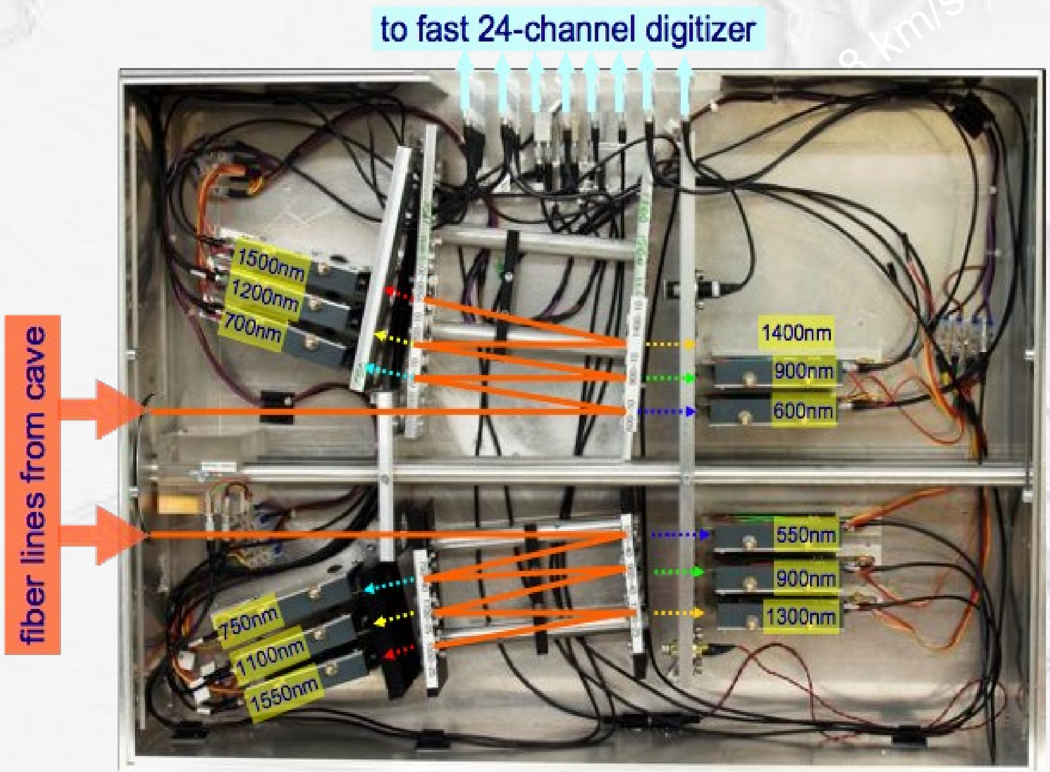
Displacement interferometer

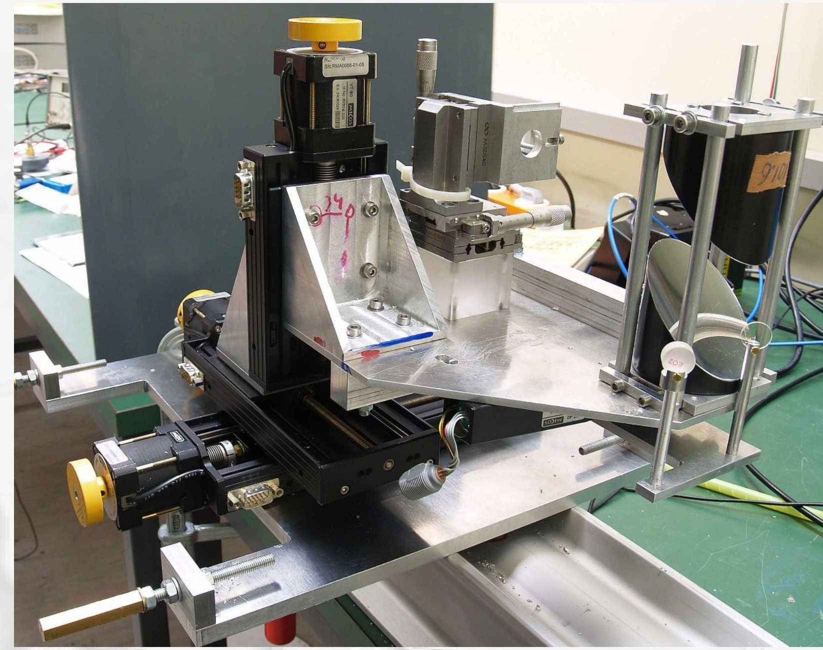


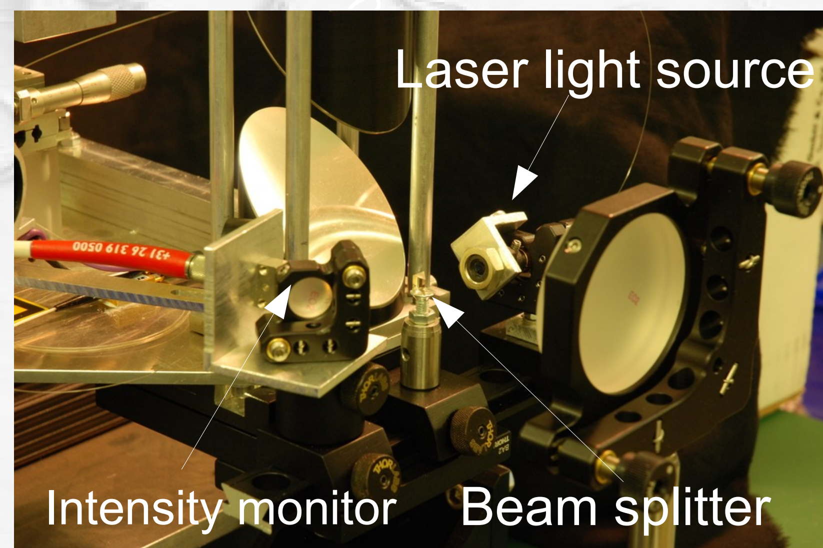


B. Ionita (GSI/TUD)

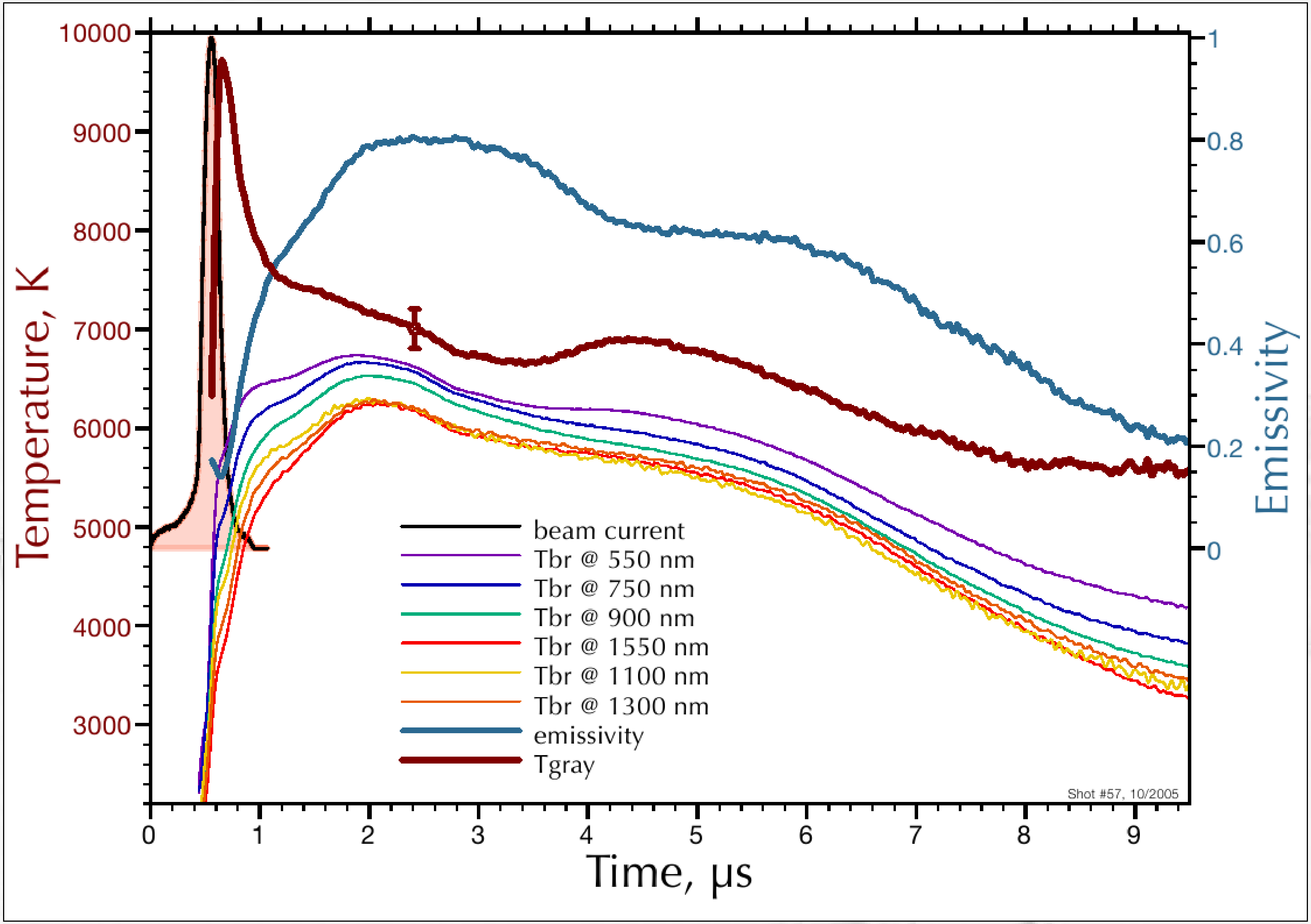
The pyrometer and reflectometry setups



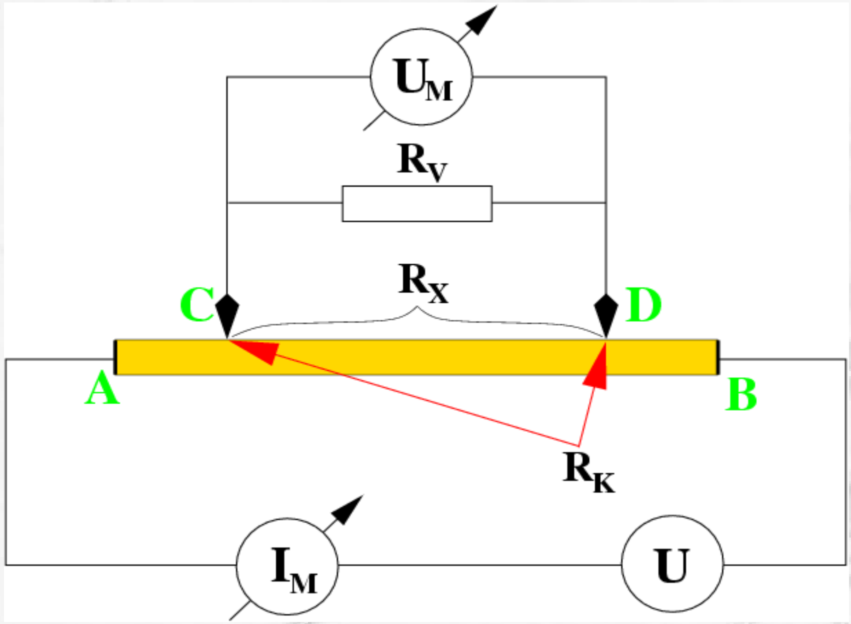




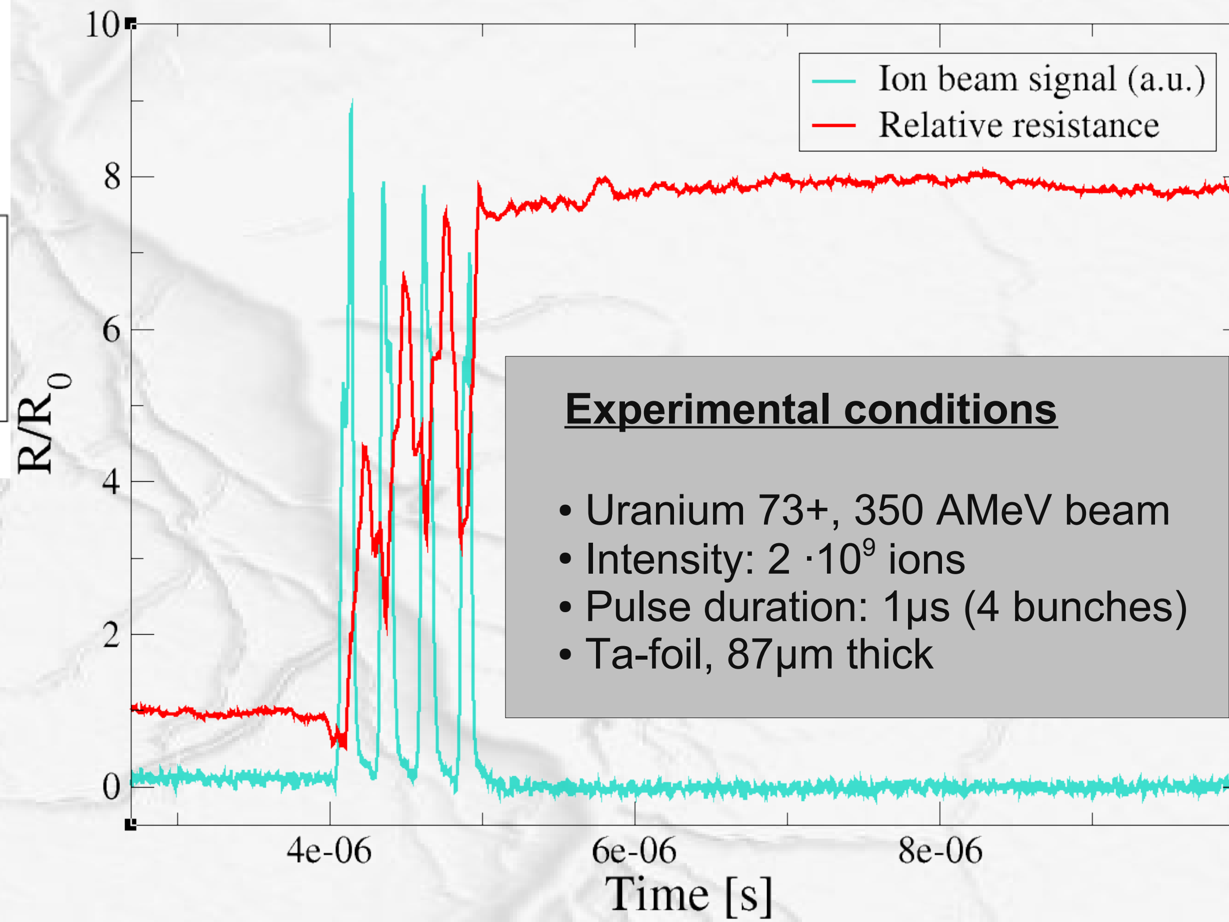
Temperature measurement



DC electrical conductivity measurements

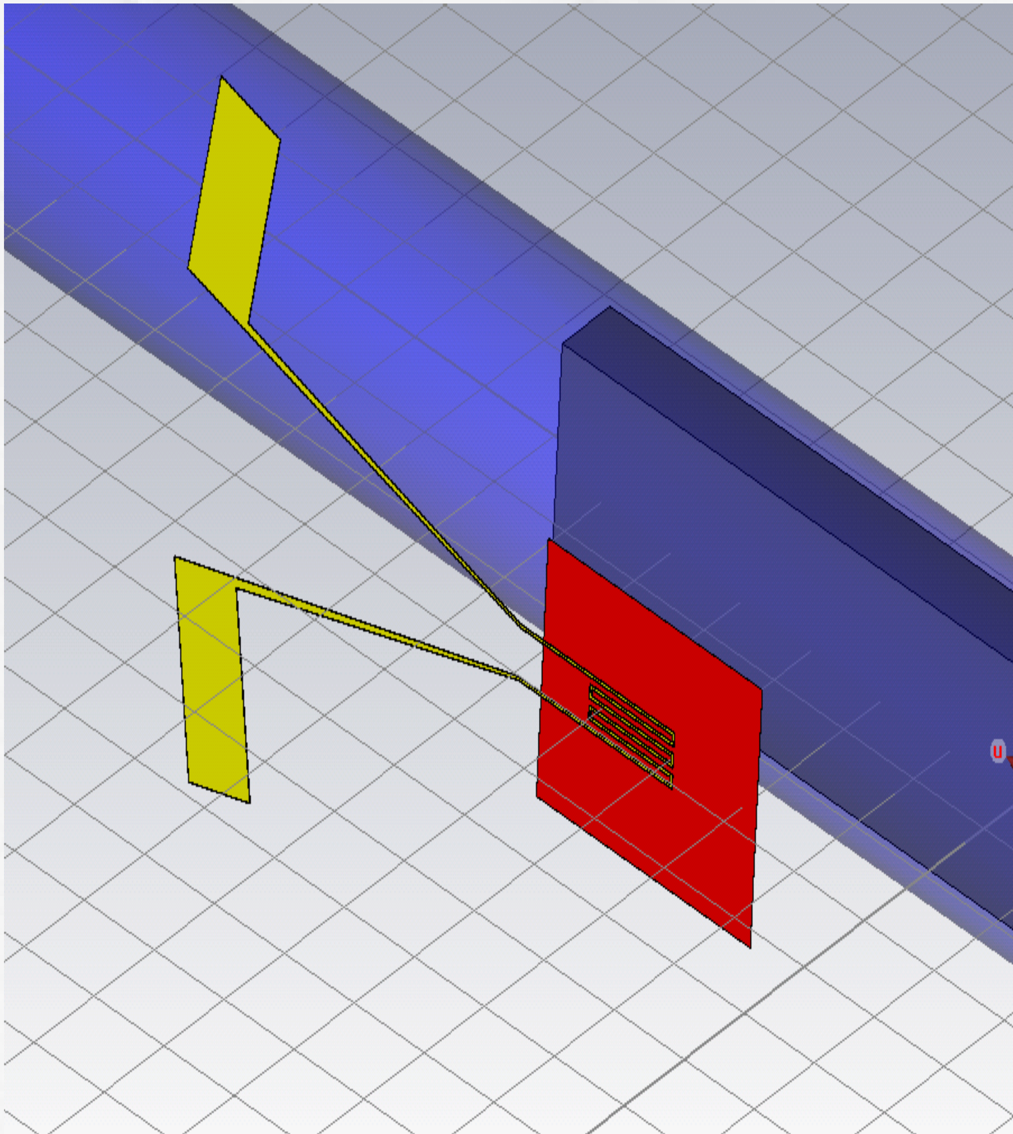


$$R_X = \frac{U_M \cdot (1 + \frac{R_K}{R_V})}{I_M - \frac{U_M}{R_V}}$$

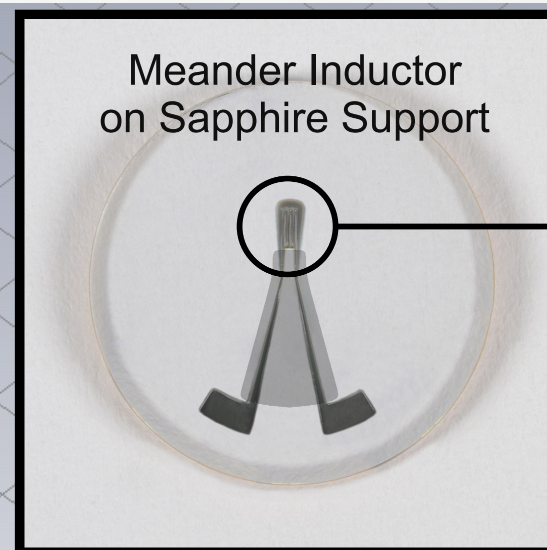


RF, non-contact conductivity setup

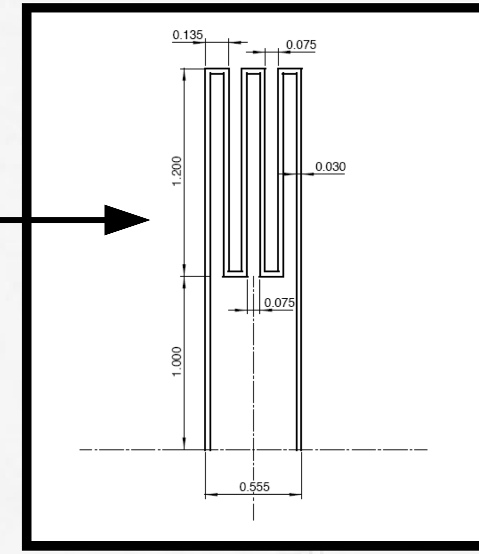
New target setup



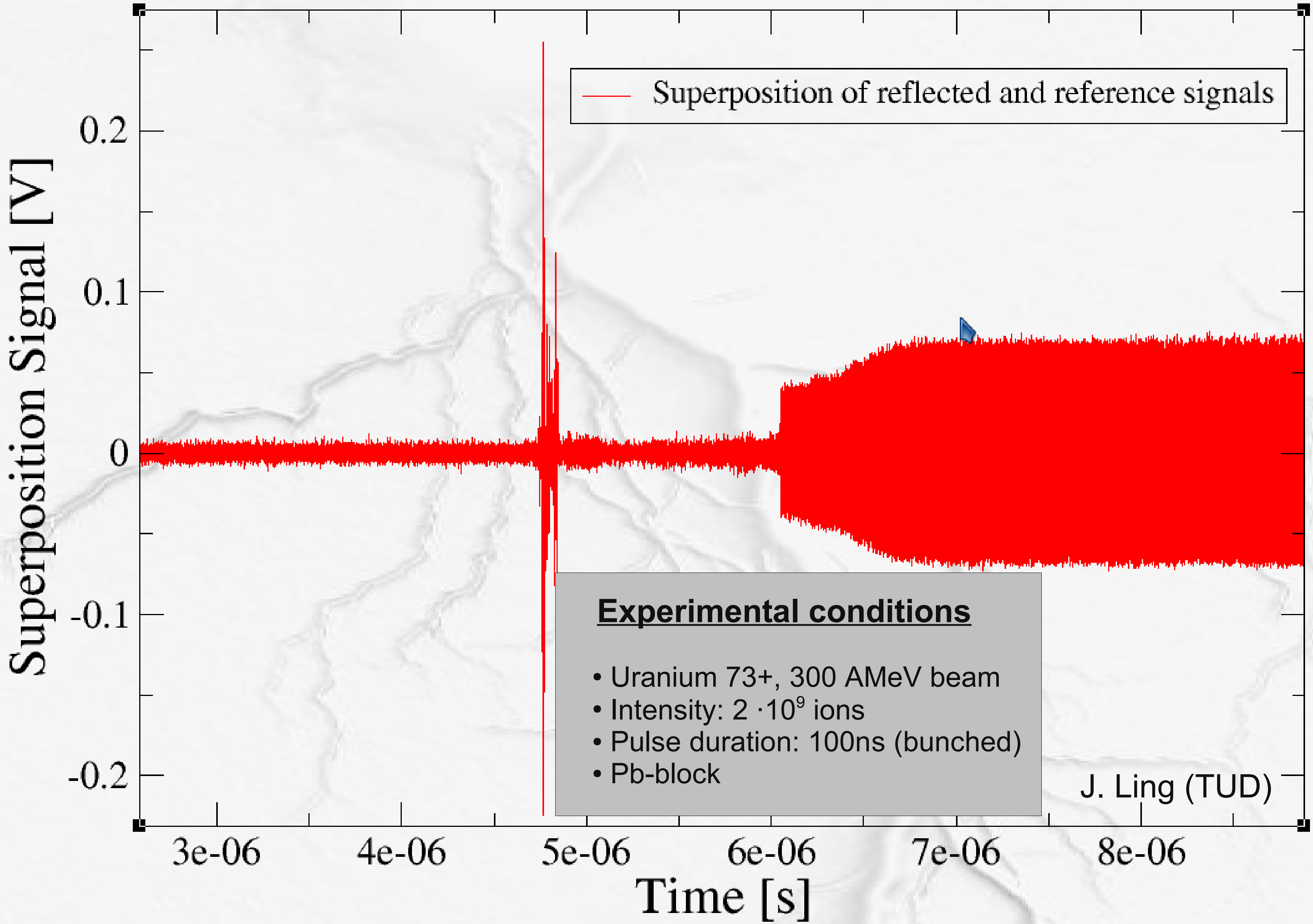
Sensor



Sensor Details



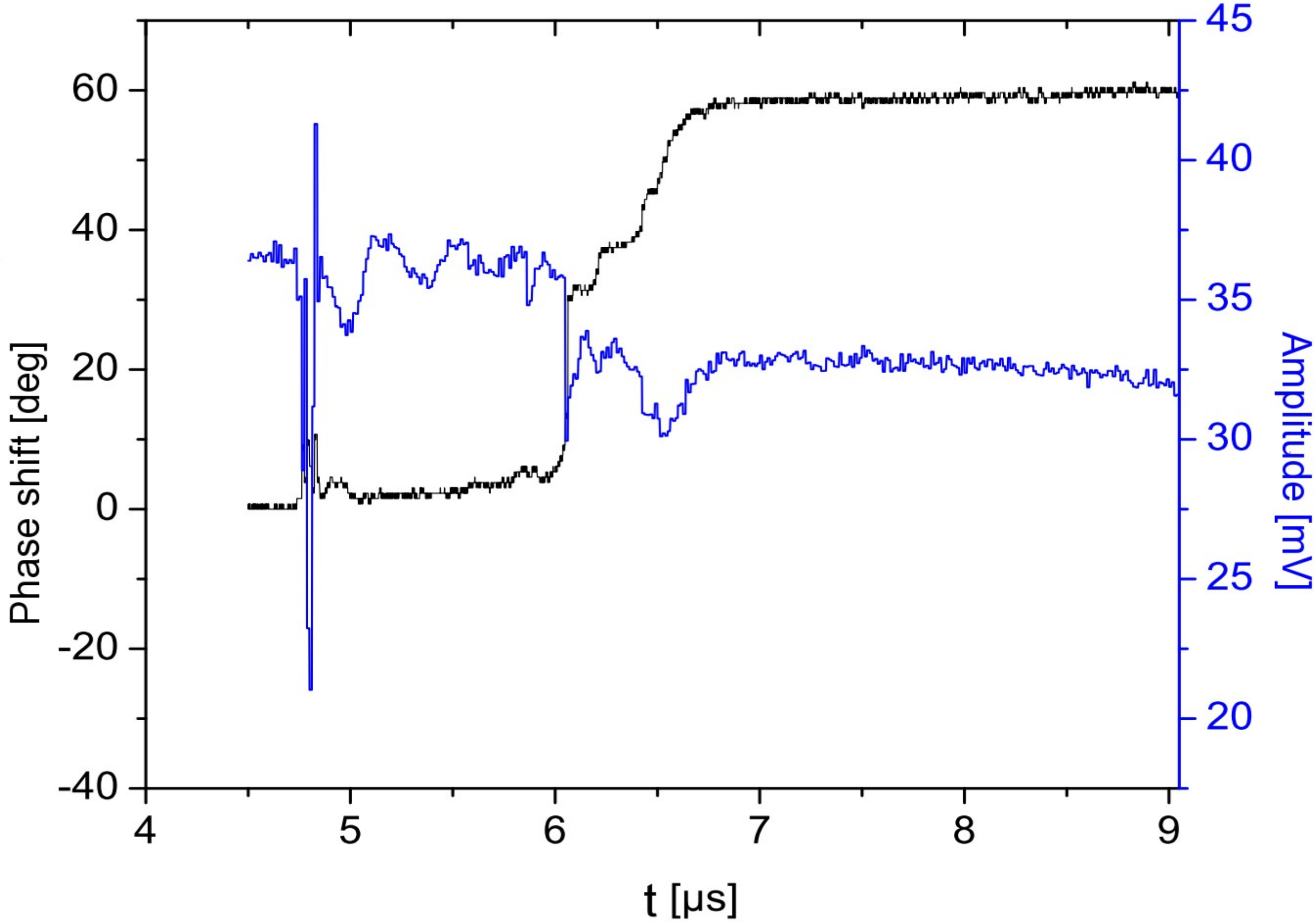
TUD RF, non-contact conductivity measurements



Experimental conditions

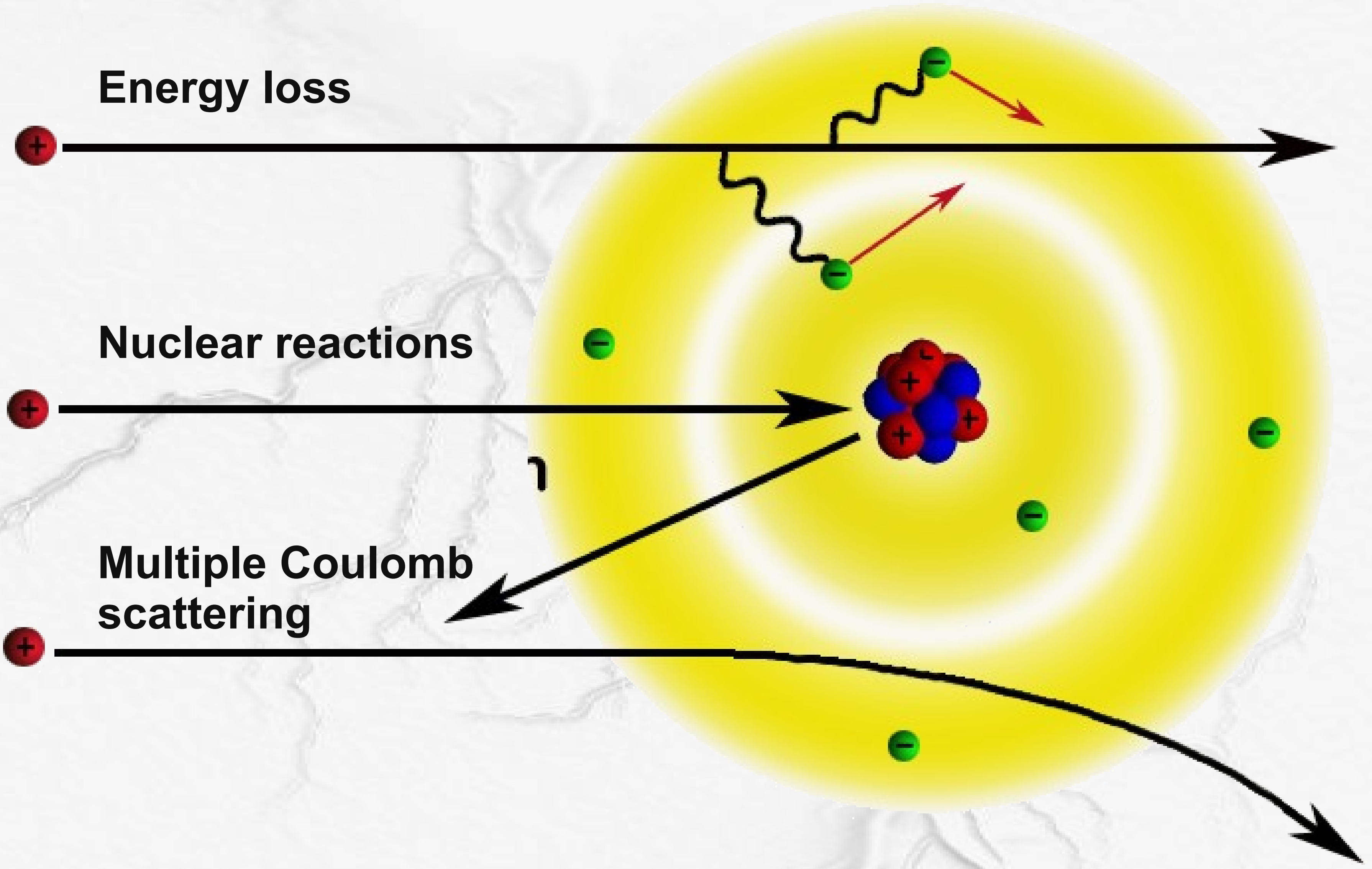
- Uranium 73+, 300 AMeV beam
- Intensity: $2 \cdot 10^9$ ions
- Pulse duration: 100ns (bunched)
- Pb-block

TUD RF, non-contact conductivity measurements



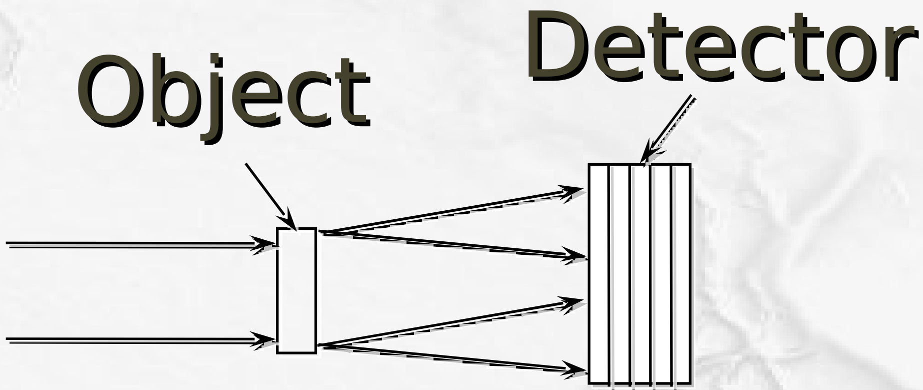
J. Ling (TUD)

Proton radiography: basic interactions



TUD

Proton radiography principles



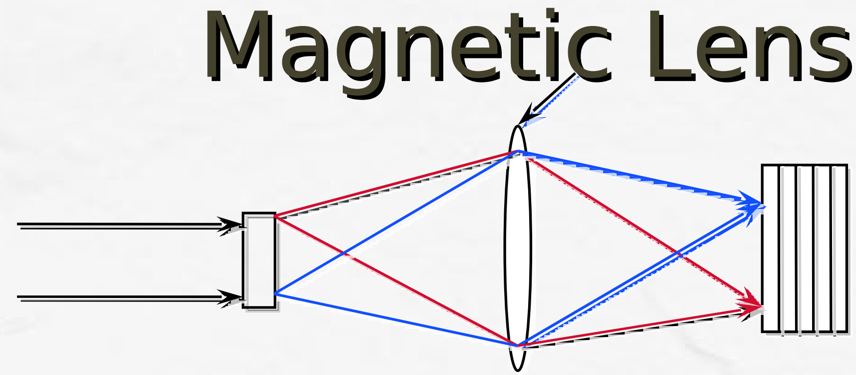
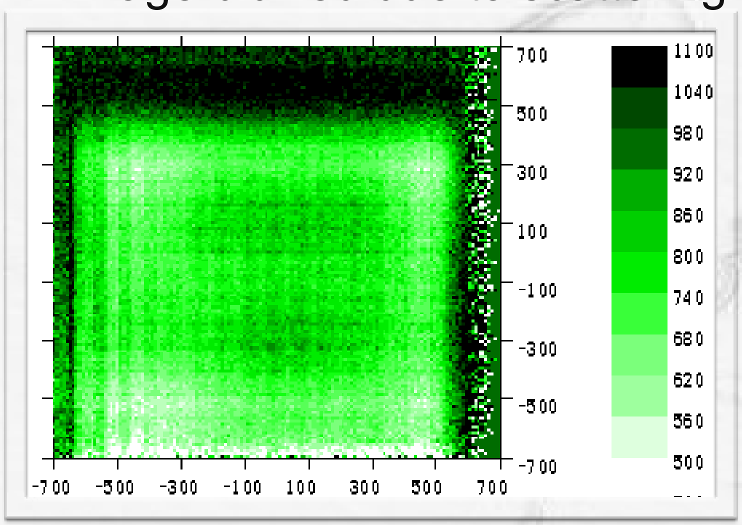
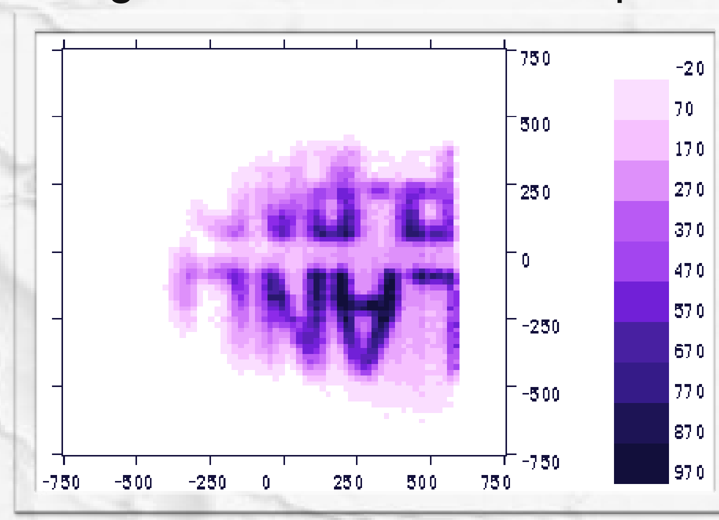


Image blurred due to scattering

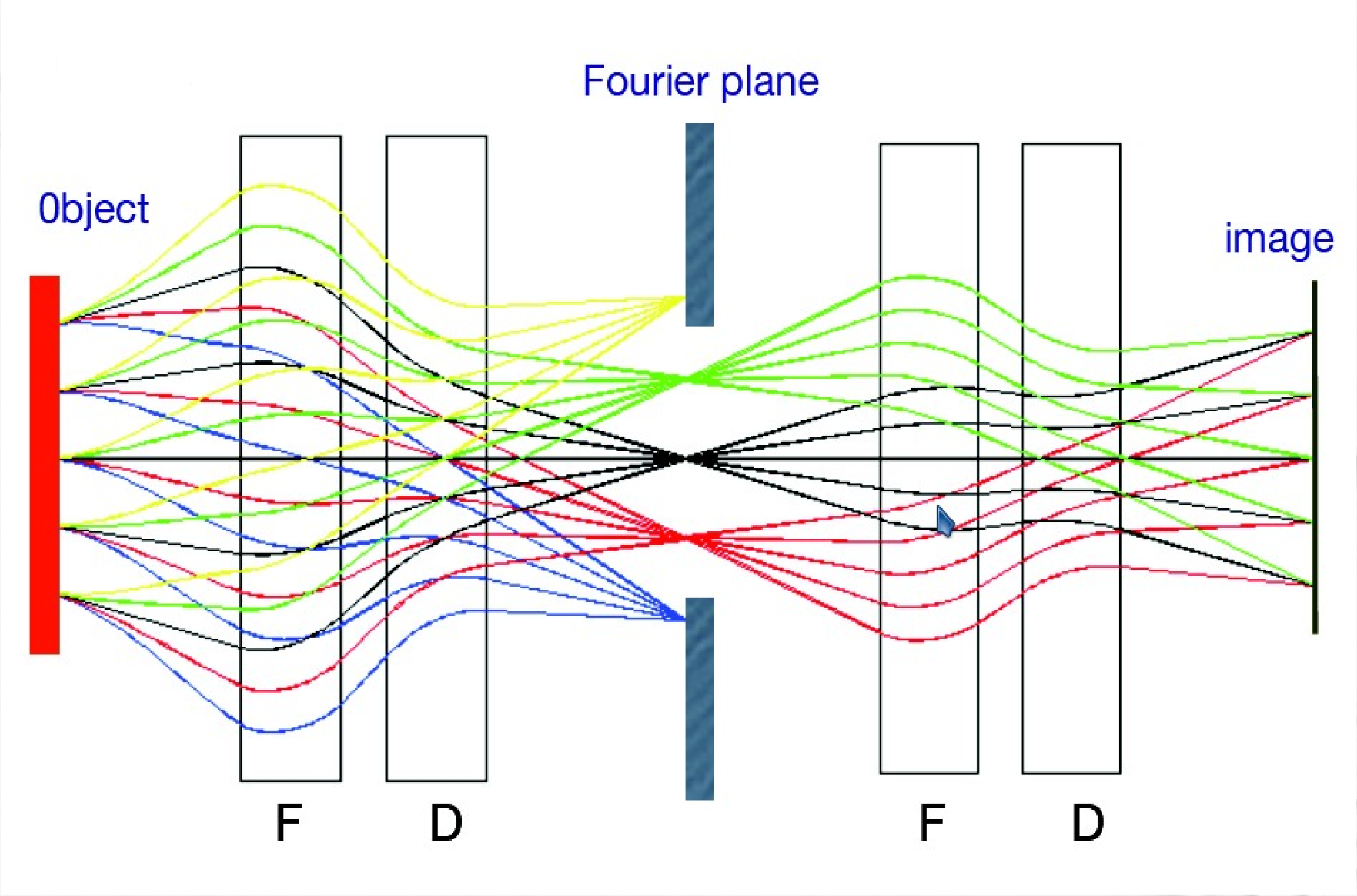
Magnetic lens creates sharp image





Transmission radiography with magnetic lenses has been developed at LANL (1995)

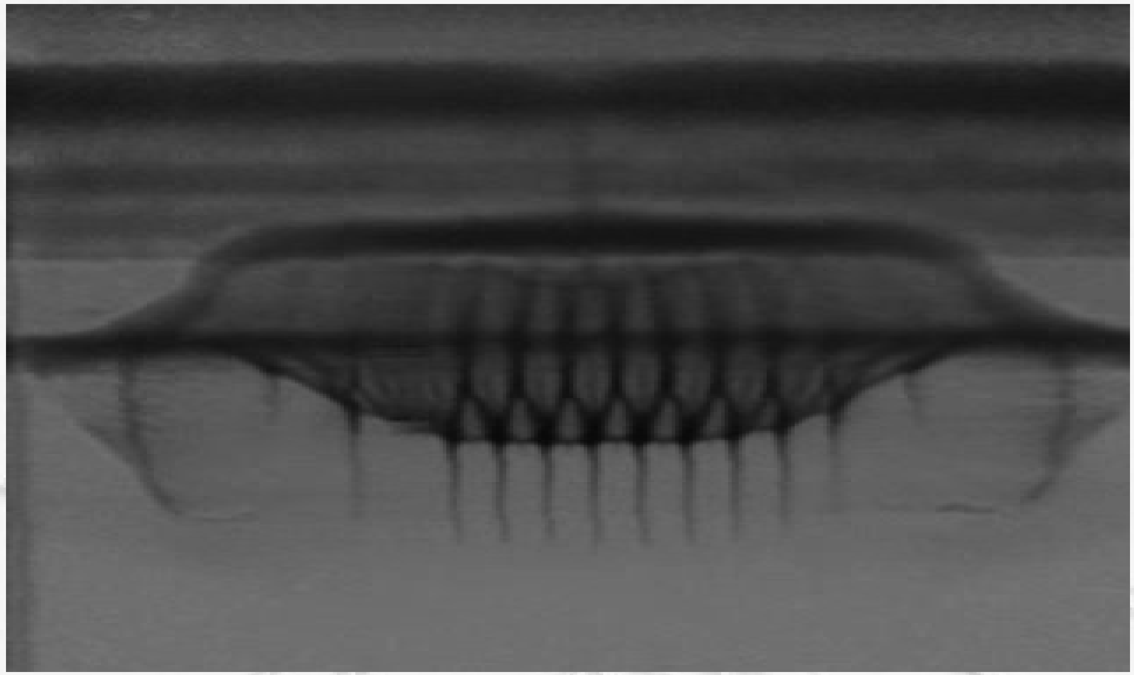
Working principle of the magnetic lense

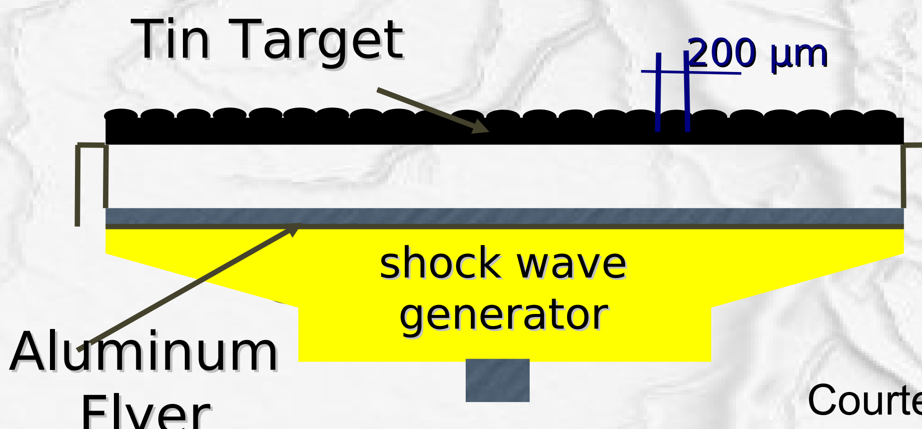


- stigmatic imaging lens
- initial beam is matched to have certain position-angle correlation
- same position-angle correlation which forms a Fourier plane at the center of the lens also cancels second order chromatic terms

Courtesy D. Varentsov (GSI)

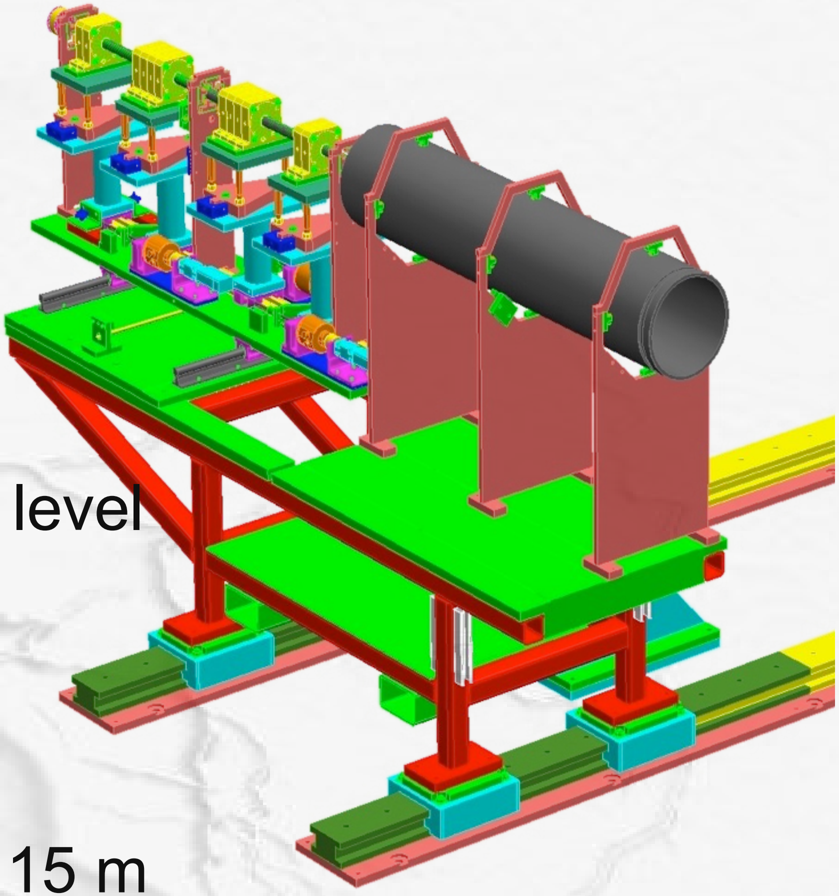
Proton radiography measurement





Courtesy Frank Merrill (LANL)

PRIOR @ HHT



Proton energy: 4.5 GeV

Spatial resolution: ≤10 μm

Temporal resolution: 10 – 20 ns

Multi-framing: 1 – 4 frames within 1 μs

Target characteristics: up to 20 g/cm2

Areal density measurement: sub-percent level

Field of view: 10 – 15 mm

Stand-off distance: 1 – 1.5 m

Proton illumination spot size: 3 – 15 mm

Total length after object plane: less than 15 m

Collaboration: GSI, TUD, ITEP Moscow, IPCP Chernogolovka, Los Alamos

Summary

- intense heavy ion beams presently available at GSI as well as those to be provided at FAIR offer unique capabilities for the research of extreme matter states
- essential instruments and diagnostic methods are being developed and commissioned at HHT
- new accelerator facilities and experimental areas are needed
- the international community shall be further developed; young talented researches are wanted!