PRIOR - proton microscope for FAIR
(development and commissioning of PRIOR prototype at GSI)

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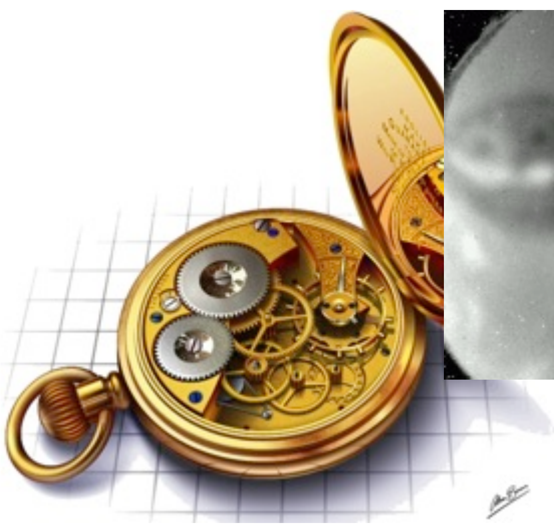
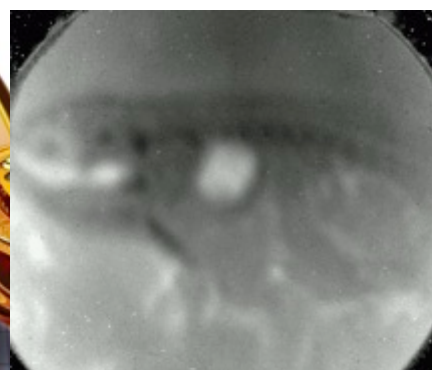
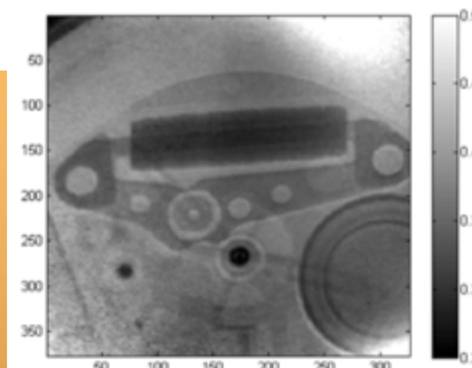
S. Efimov, Ya. E. Krasik, O. Antonov; Technion, Haifa, Israel

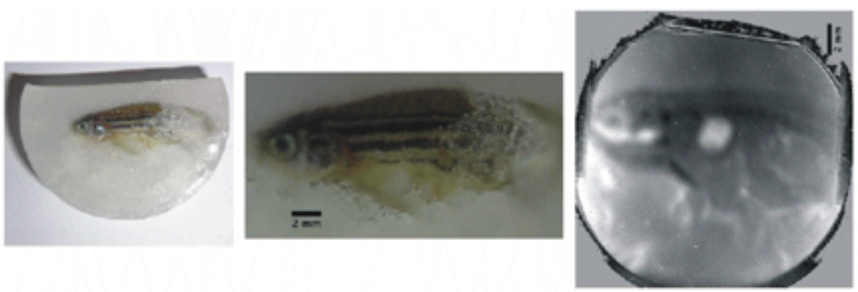


WLIB 2014
(Moscow, 09 December 2014)

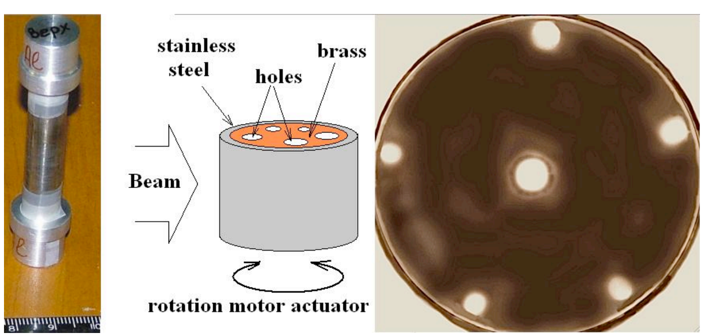
Proton microscopy for high energy density in matter physics, material sciences and beyond

- **materials in extremes** (EOS, dynamic phase transitions, hydrodynamics of HED flows, instabilities, material strength and damage, ...)
- **new materials synthesis and process-aware manufacturing**
- **biophysics, medical applications industrial applications**

Biologically samples

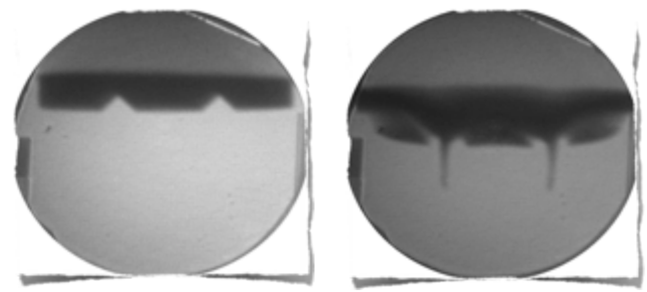


Tomography reconstruction of inner structure of static objects (ITEP)



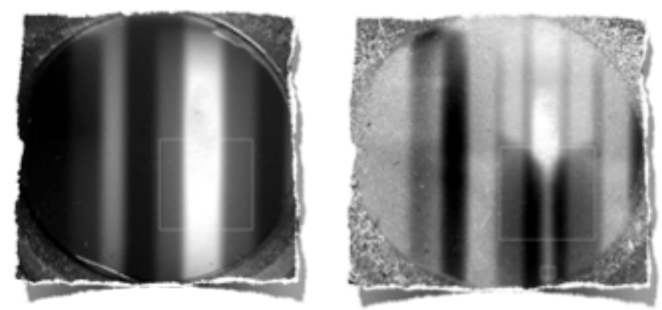
Dynamic fracture and surface ejecta formation in metal under shock loading

Static Dynamic



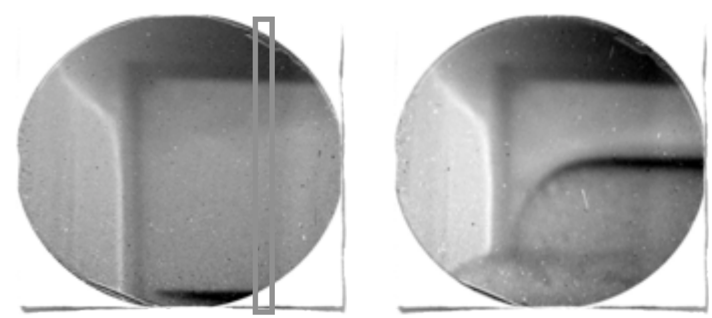
Phase transition of molecular nitrogen (IPCP, ITEP)

Static Dynamic



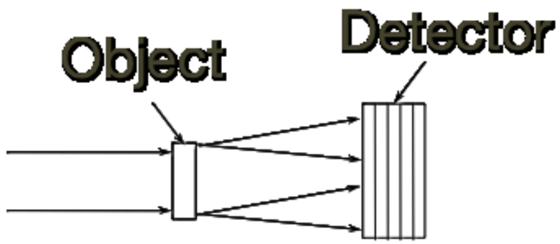
Non ideal plasma of shock compressed noble gas (Xe)

Static Dynamic

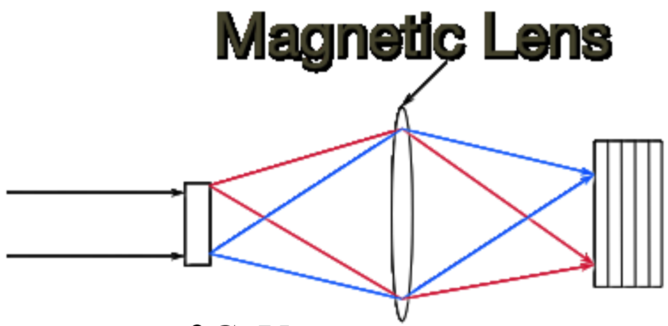


High energy proton radiography

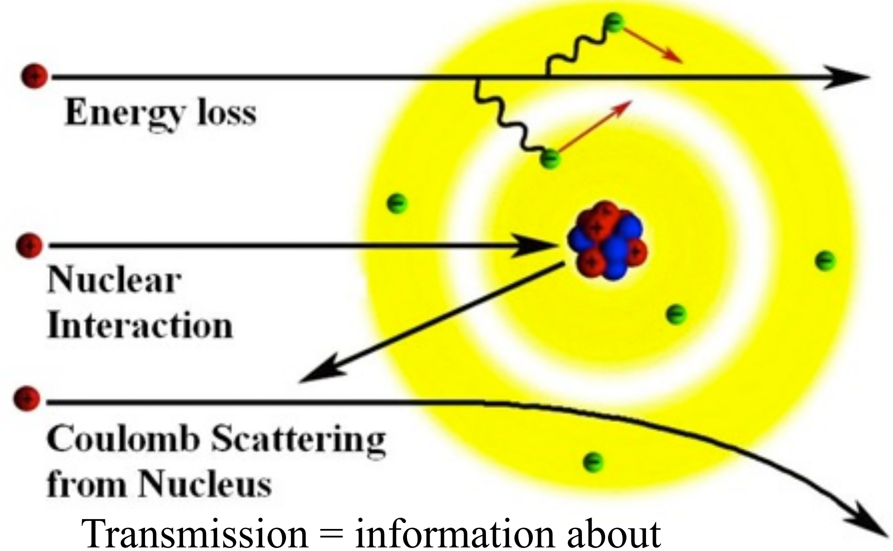
Image at the detector is substantially blurred due to MCS (1968)



Magnetic imaging lens preserves the image in high resolution (LANSCE 1997)



Interaction of proton with matter

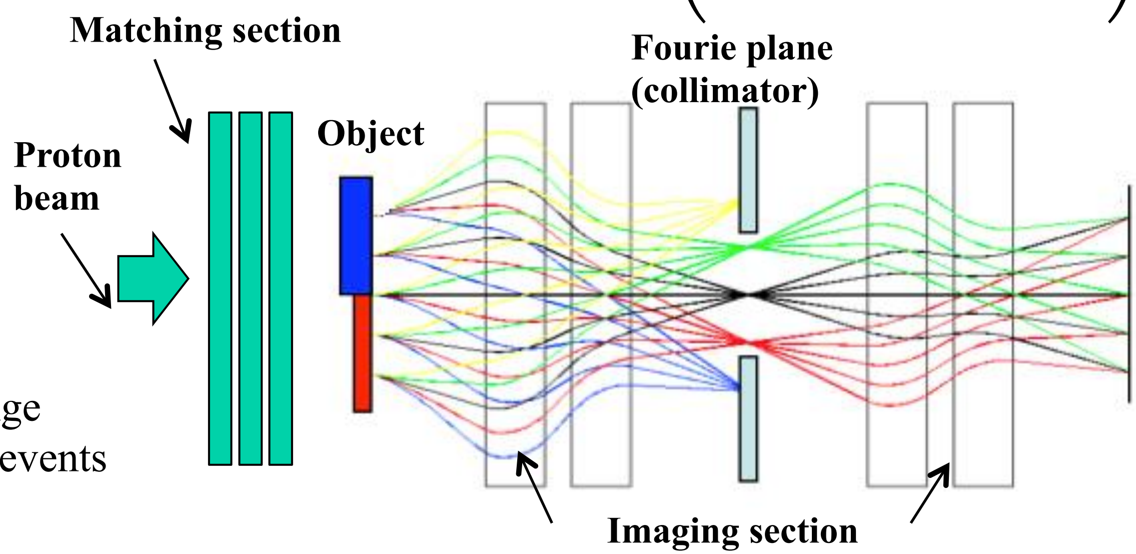


Transmission = information about density distribution

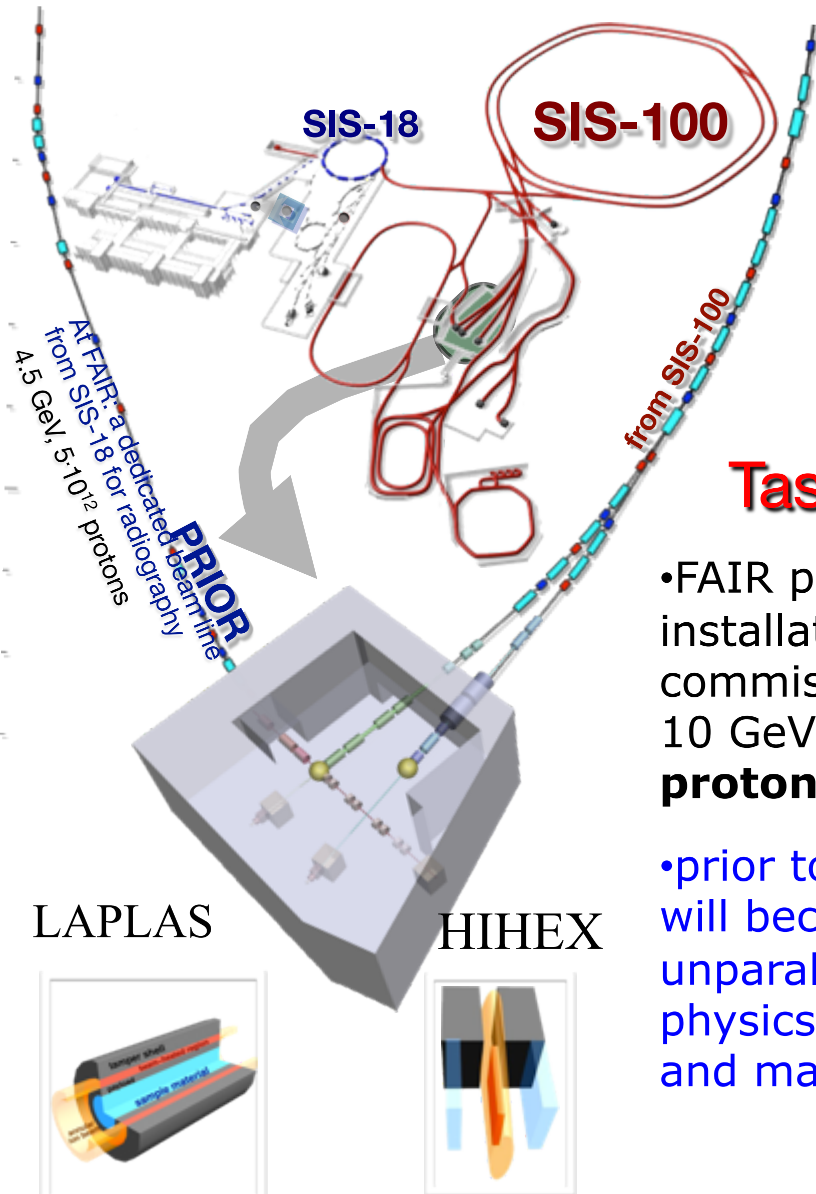
$$T = T_{mcs}T_{nuc} = e^{-x/\lambda_c}\left(1 - e^{-\left(\frac{\theta_c p\beta c}{13.6}\right)^2 \frac{x_0}{2x}}\right)$$

Advantages of GeV protons:

- large penetrating depth (eight times more than X-Ray (4 MeV))
- aberrations correction by magnets
- high spatial resolution (microscopy)
- high density resolution and dynamic range
- multi-frame capability for fast dynamic events



PRIOR – density diagnostic tool for high energy density in matter experiments of HEDgeHOB collaboration:



Challenging requirements for density measurements in dynamic HEDP experiments (HIHEX, LAPLAS):

- up to ~20 g/cm2 (
- Fe, Pb, Au, etc. ≤10 μm spatial resolution
- 10 ns time resolution (multi-frame) sub-percent density resolution

Tasks for PRIOR :

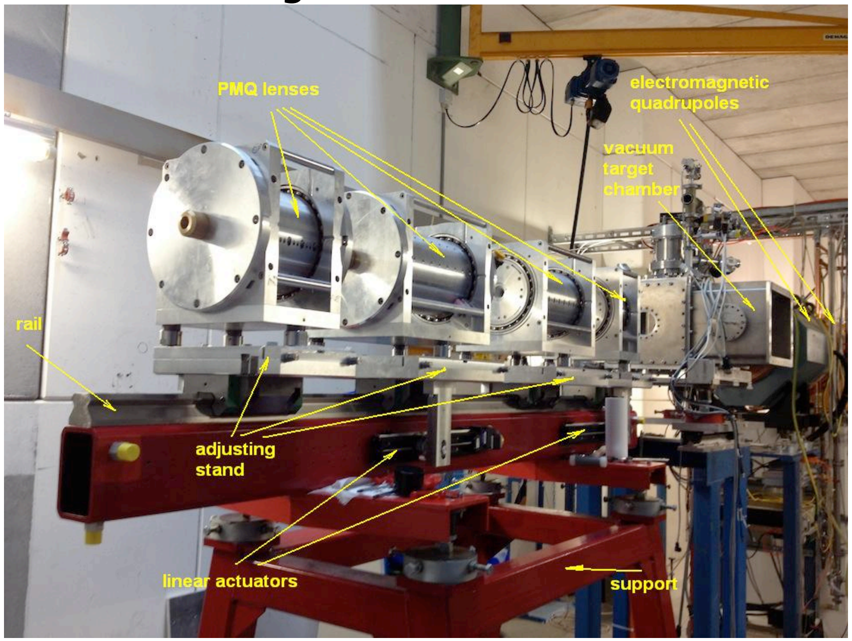
•FAIR proton radiography system which a core FAIR installation will be designed, constructed and commissioned in full-scale dynamic experiments with 10 GeV proton beam from SIS–100 **or with 4.5 GeV proton beam from SIS–18**

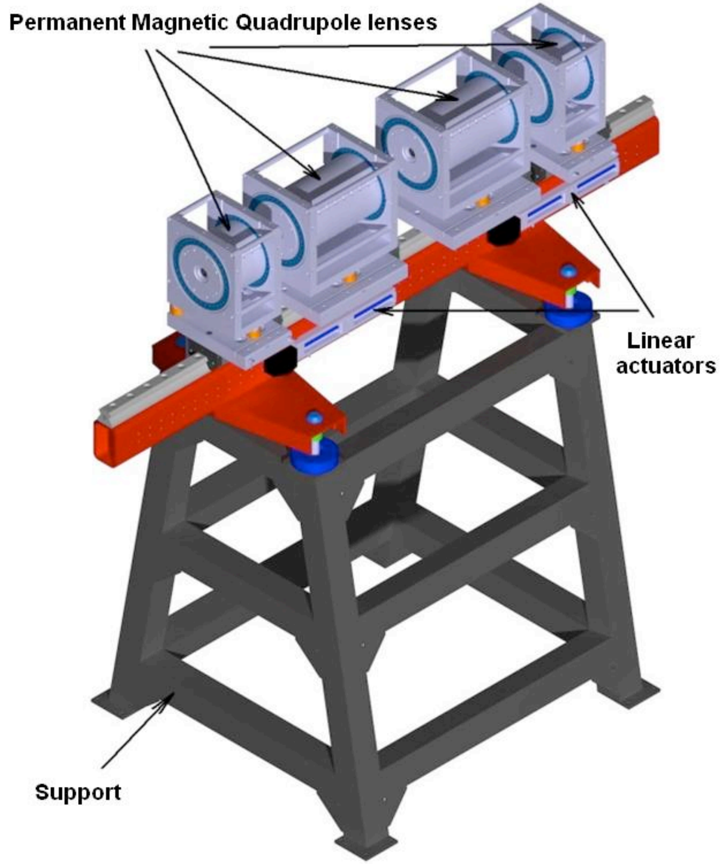
•prior to FAIR, a worldwide unique radiographic facility will become operational at GSI providing a capability for unparalleled high-precision experiments in plasma physics, high energy density (HED) physics, biophysics, and materials research

PRIOR (Proton microscope for FAIR)

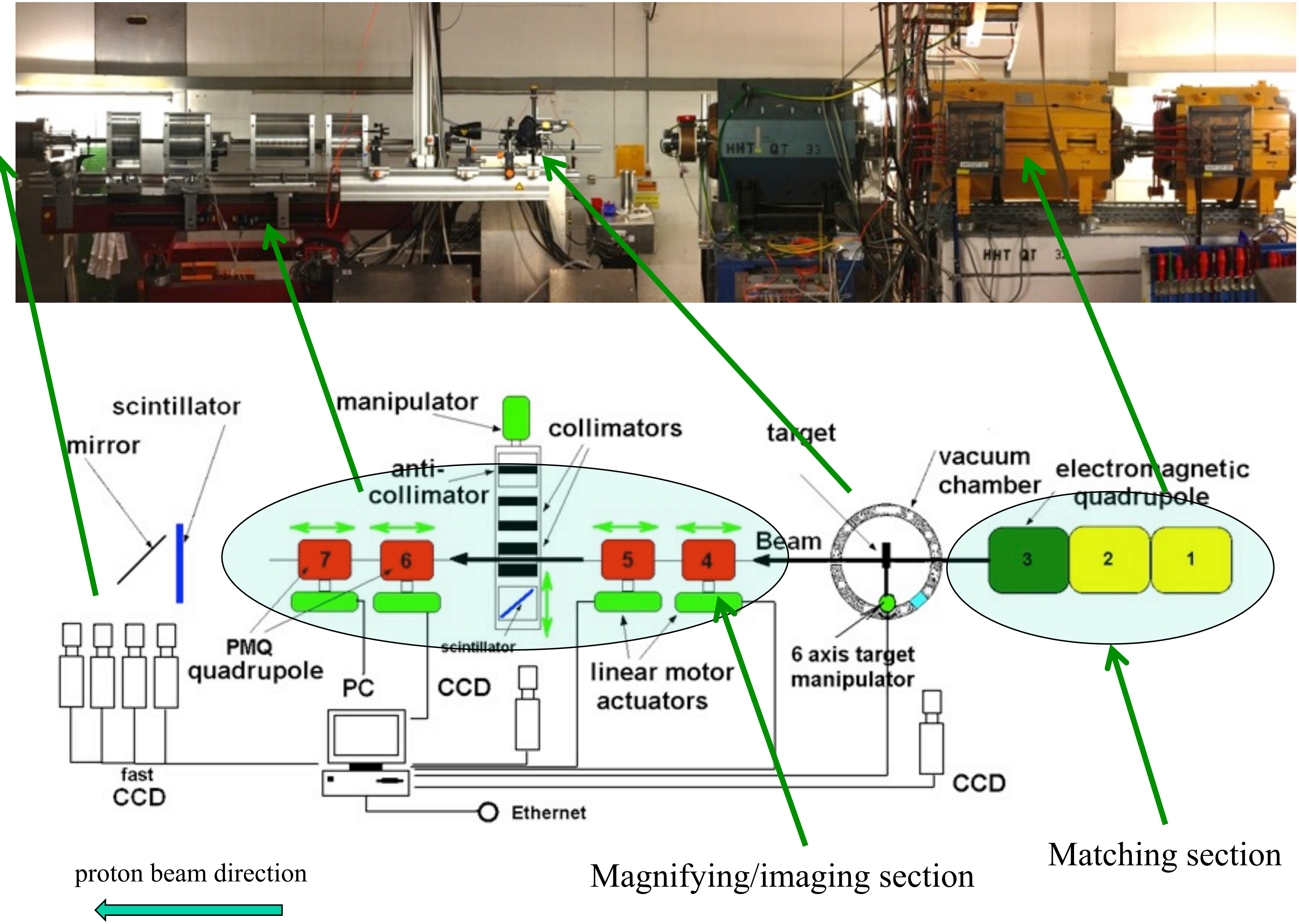
Main parameters:

- proton energy: up to **4.5 GeV (at GSI),** up to 10 GeV (at FAIR) ;
- areal density of target: up to **100 g/cm²**;
- areal density reconstruction: sub-percent level;
- spatial resolution: less than **10 μm**;
- temporal resolution: **10 ns**;
- multi-framing capability: up to **4** frames per dynamic event (at GSI), 16 frames at FAIR ;
- field of view: 10 – **15** mm;
- length of setup ~ **25 m**
- proton beam intensity: **$5*10^{10}$** (at GSI), $2.5*10^{13}$ (at FAIR)
- chromatic length: ~**3** m

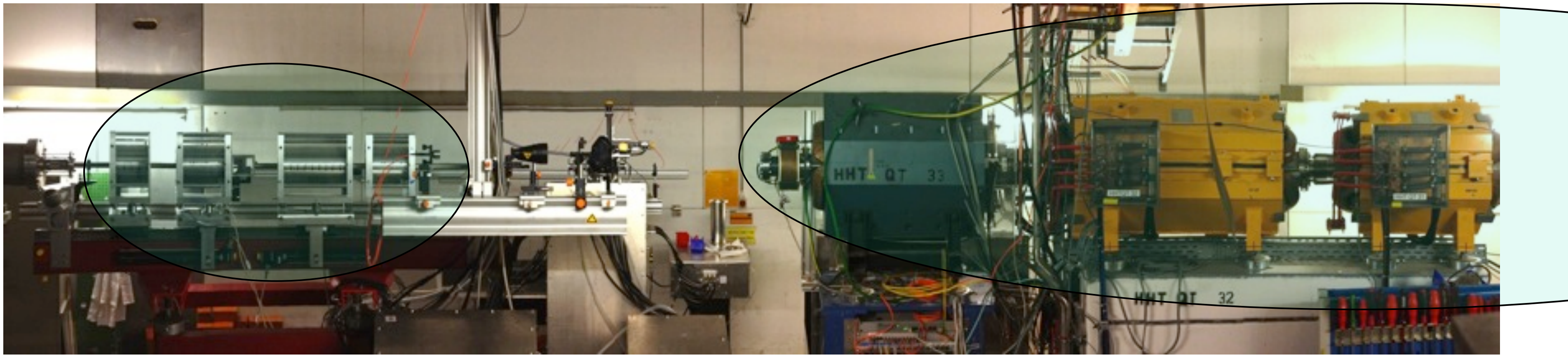




Prototype of PRIOR at HHT experimental area at GSI

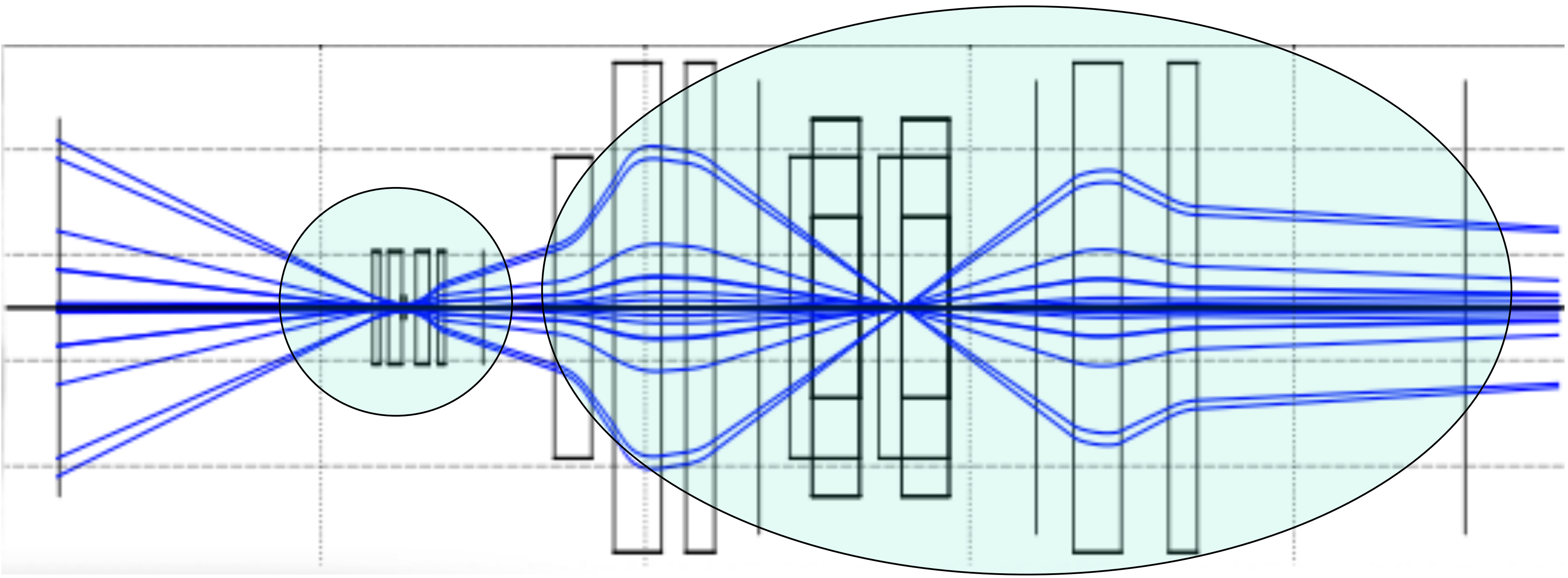


Prototype of PRIOR at HHT experimental area at GSI



Magnifying/imaging section

Matching section



proton beam direction

Dmitry Varentsov, GSI (Darmstadt, Germany)

Prototype of PRIOR at HHT experimental area at GSI

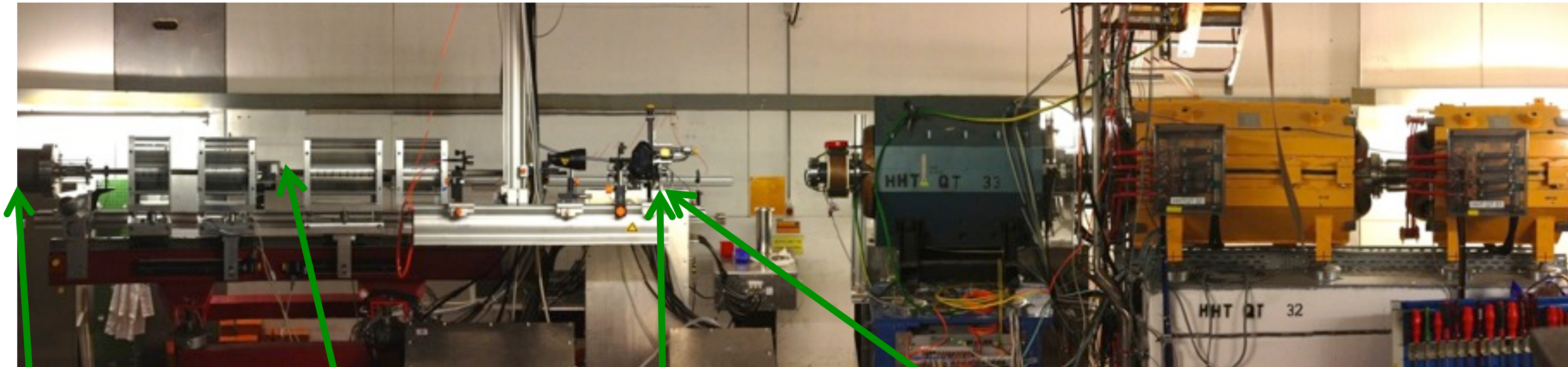
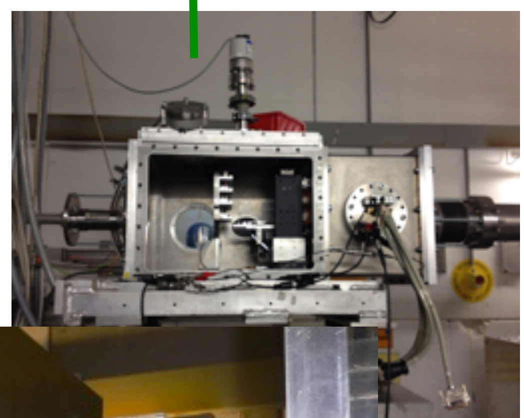
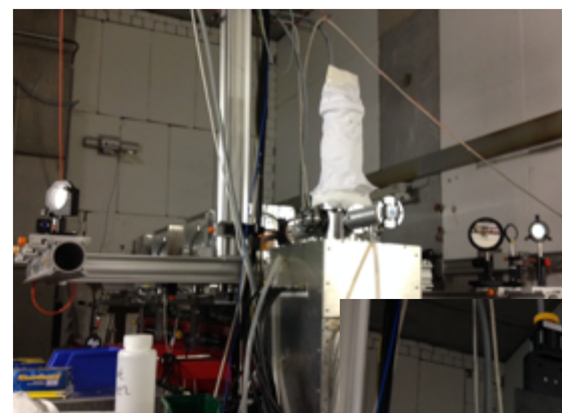


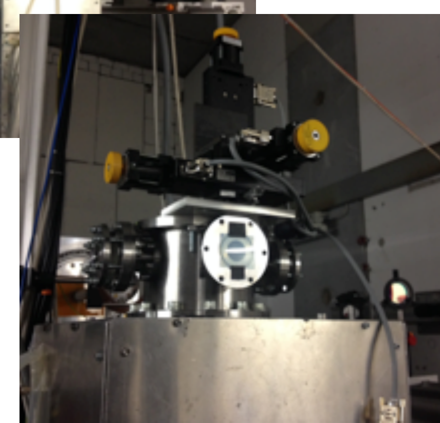
Image registration system PCO DicamPro + PCO DiMax

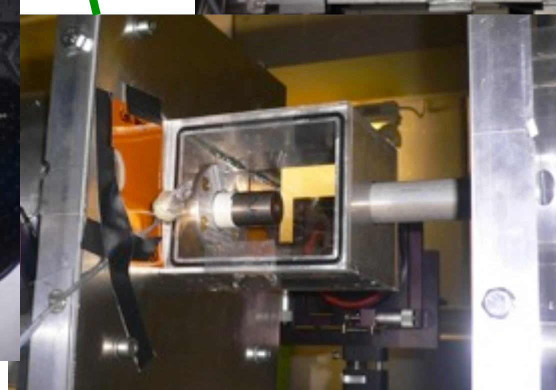
Static targets in vacuum



Dynamic target (Underwater electrical wire explosion)

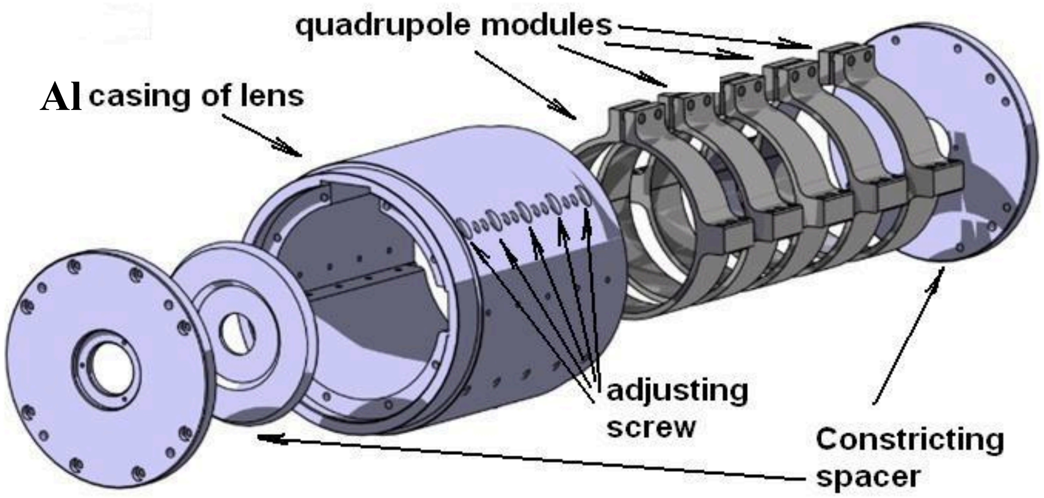


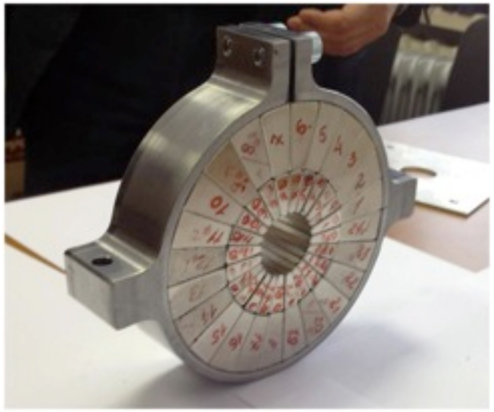




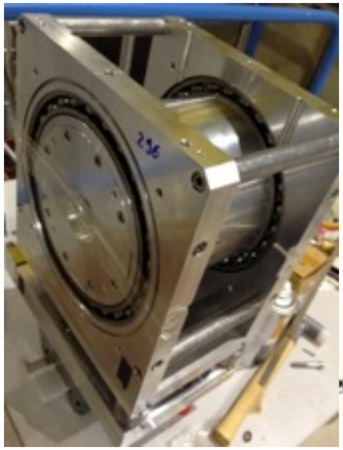
W collimator (2 mrad,)

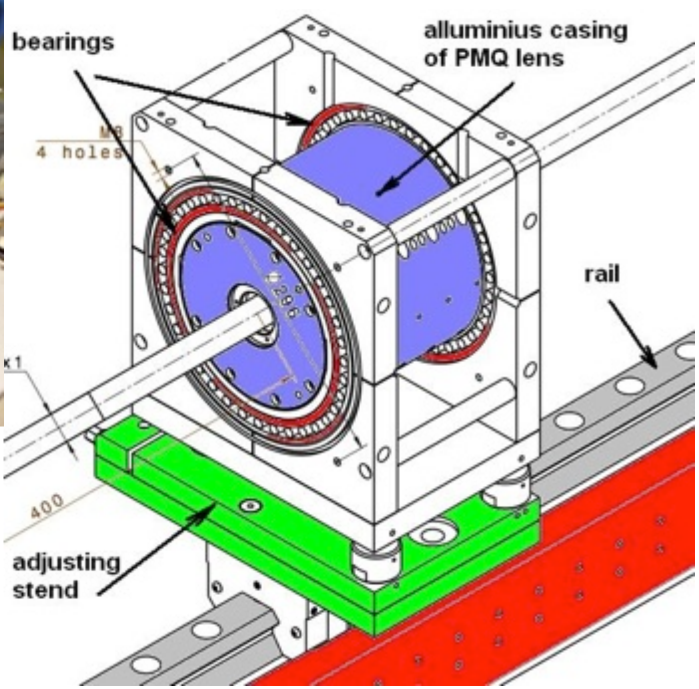
Permanent magnet quadrupole lenses (PMQ)





One quadrupole module
in metal case





Main parameters of PMQ lenses:

PMQ quantity: 4
Pole tip field: 1.83 T
Field gradient: 122 T/m
Nonlinearity: <0.9%
Two layer structure with trapezoidal sectors
Magnetic element material: NdFeB
Aperture diameter: 30 mm ;Outer diam. 210 mm
PMQ Length: 180mm (144 mm) (4 modules+1 dummy)
360mm (288 mm) (8 modules +2 dummy)

Possibility to use same lenses at FAIR (10 GeV proton beam) with addition modules

3D magnetic field reconstruction

3D field model [3] (FB Bridge code) will be used for calculation of all component of magnetic field at all points inside aperture of PMQ

$$B_r = -\sum_{k=1}^{\infty}\sum_{n=0}^{\infty} R_{kn}\left(A_{kn}^{\cos}\cos n\varphi + A_{kn}^{\sin}\sin n\varphi\right)\sin\frac{\pi k(z-z_0)}{l}$$

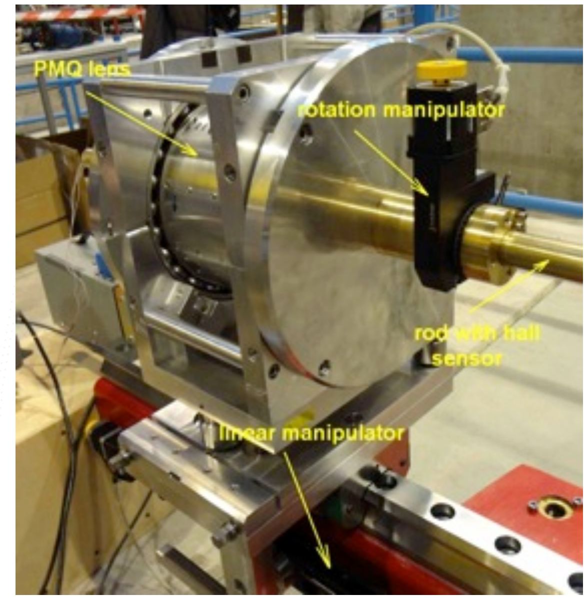
$$B_\varphi = -\sum_{k=1}^{\infty}\sum_{n=0}^{\infty} \frac{n}{r}\frac{I_n\left(\frac{\pi k r}{l}\right)}{I_n\left(\frac{\pi k r_0}{l}\right)}\left(-A_{kn}^{\cos}\sin n\varphi + A_{kn}^{\sin}\cos n\varphi\right)\sin\frac{\pi k(z-z_0)}{l}$$

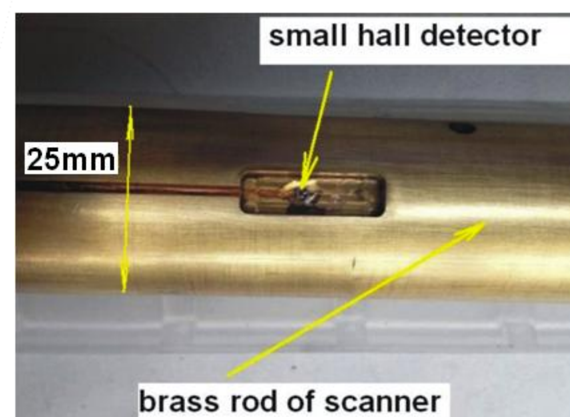
$$B_z = -\sum_{k=1}^{\infty}\sum_{n=0}^{\infty} \frac{\pi k}{l}\frac{I_n\left(\frac{\pi k r}{l}\right)}{I_n\left(\frac{\pi k r_0}{l}\right)}\left(A_{kn}^{\cos}\cos n\varphi + A_{kn}^{\sin}\sin n\varphi\right)\cos\frac{\pi k(z-z_0)}{l}$$

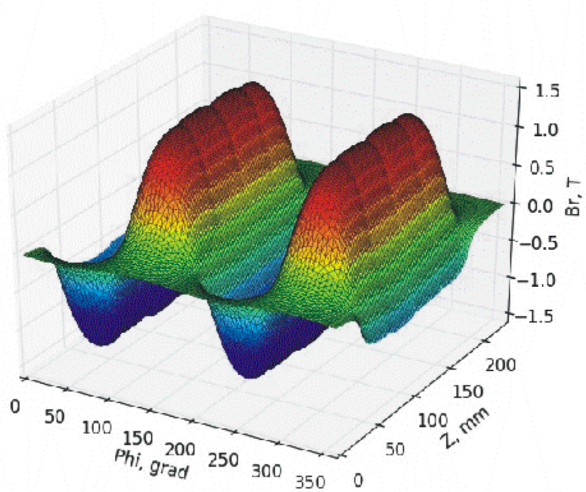
$$R_{kn}(r) = \frac{\frac{n}{r}I_n\left(\frac{\pi k r}{l}\right) + \frac{\pi k}{l}I_{n+1}\left(\frac{\pi k r}{l}\right)}{I_n\left(\frac{\pi k r_0}{l}\right)}$$

I_n – Bessel function

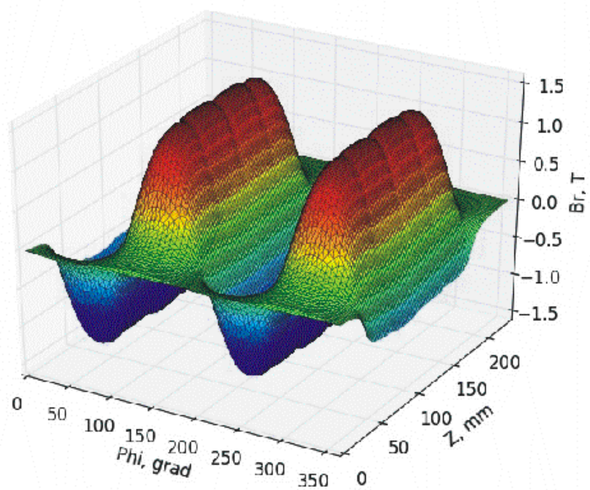
Scanner for radial component of magnetic field of PMQ





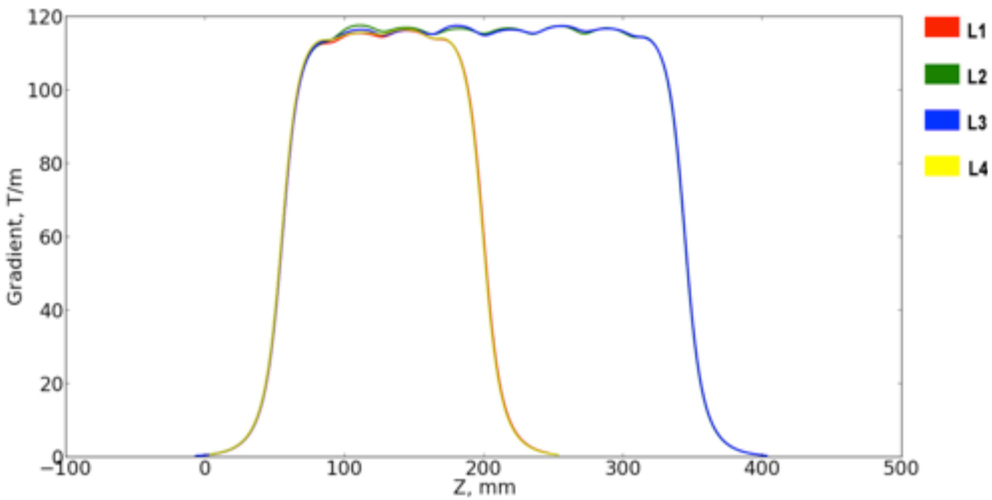


Results of first scan of Br components of field

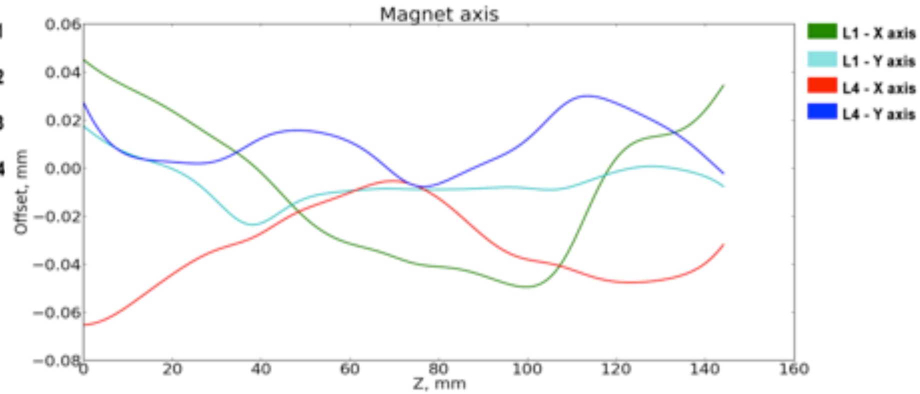


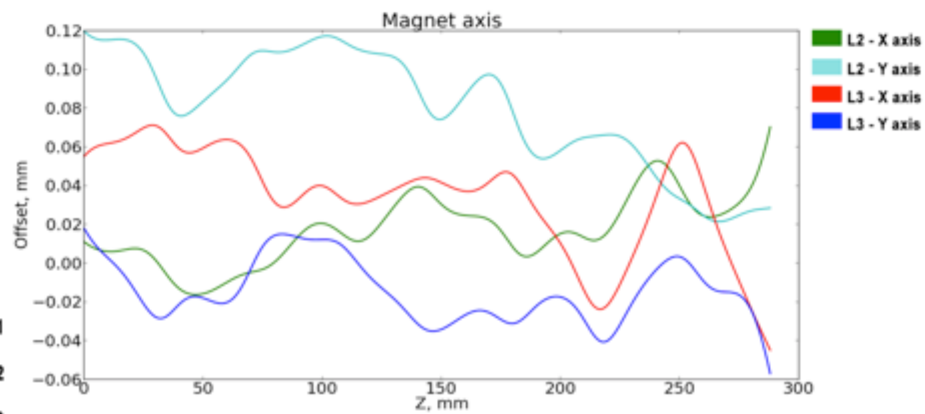
Br component reconstruction by FB Bridge code

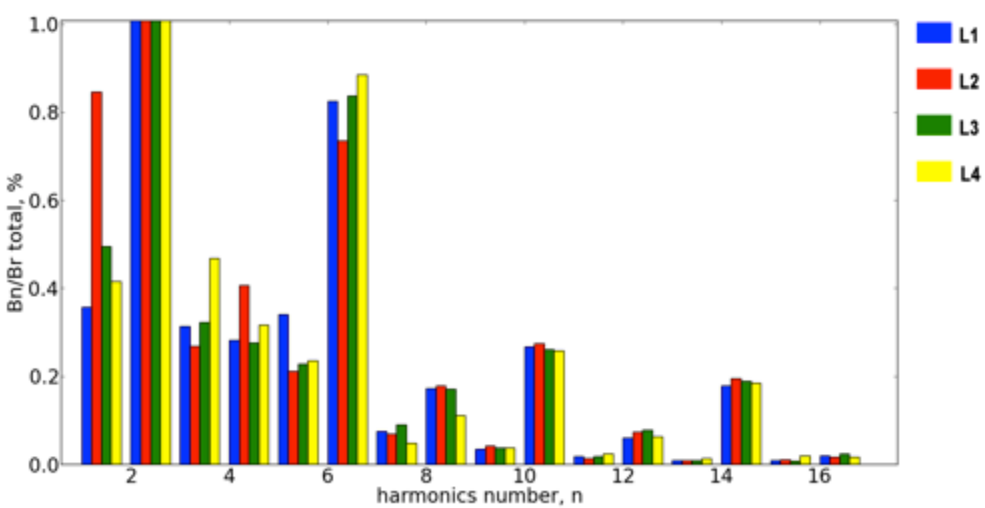
Measured parameters of magnetic field of PMQ



Field gradient.
Integral of gradient: L1 = 16.96 T, L2 = 33.90 T, L3 = 33.88 T, L4 = 17.01 T





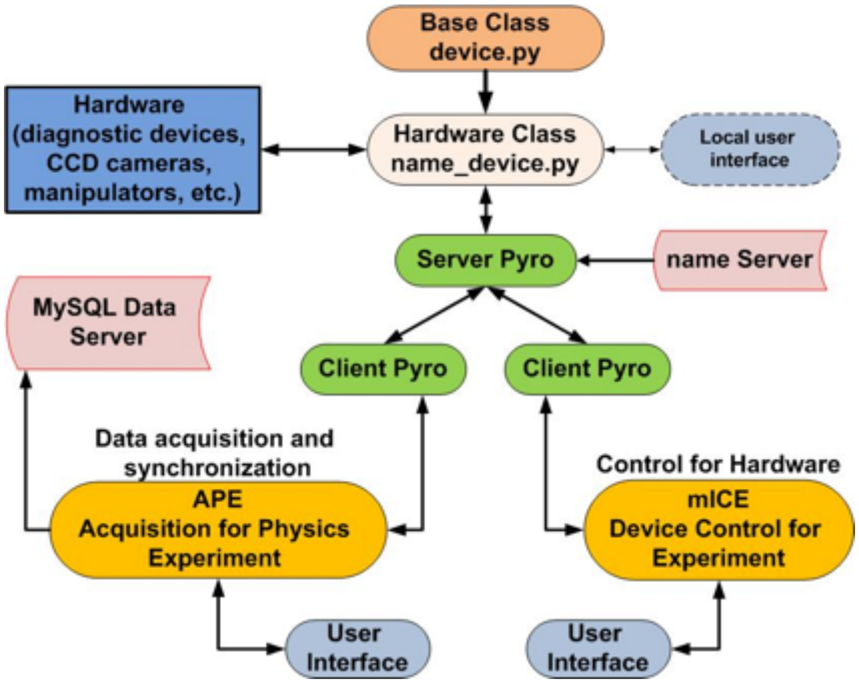


High order harmonics.

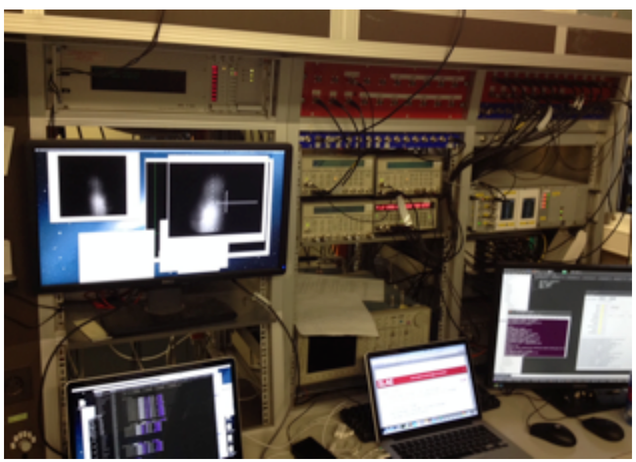
Accuracy of magnetic axis position : ±30 μm

Nonlinearity of magnetic field: less then 1 %

Data acquisition and control system for PRIOR



Data acquisition and control system is based on the individual software modules, united by local Ethernet network. Basic programming language for writing of software elements of system – is Python. To transfer the data (as the control commands and the transfer of all the experimental data - waveforms, images, etc.) between the modules of the system uses client-server oriented module Pyro (includes RCP (remote calling procedure) technology).



Main control panel

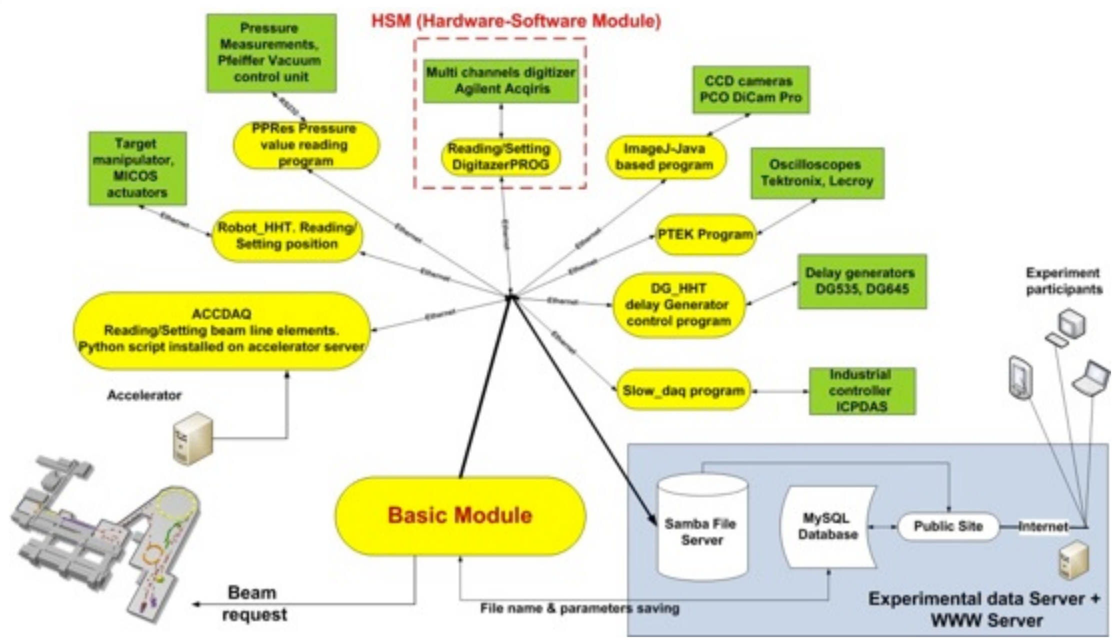
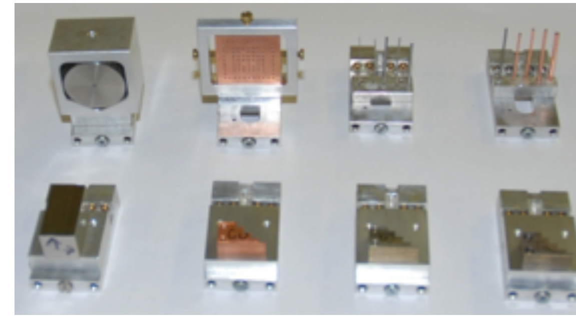


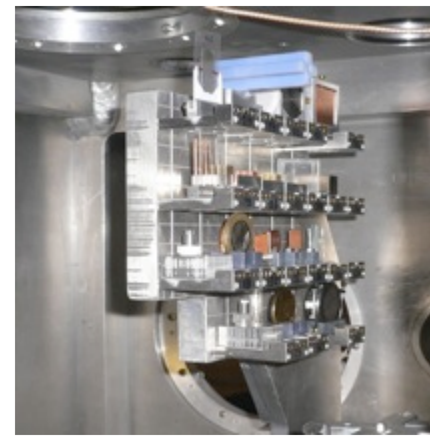
Diagram of operation of data acquisition system

<u>Static commissioning of PRIOR</u>

(April 2014, GSI, SIS-18, proton beam energy 3.6 GeV)



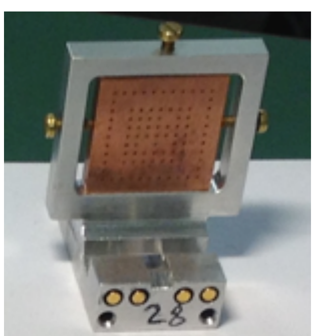
Static targets



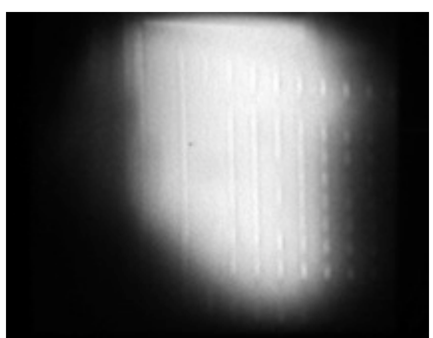
Proton beam parameters

Energy: 3.6 GeV

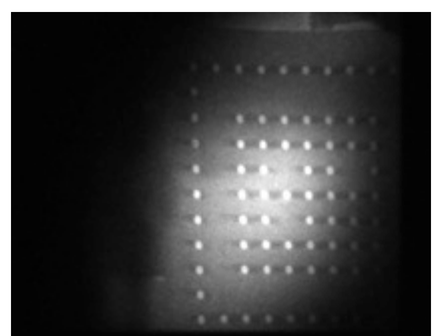
Intensity: $<5*10^9$ protons



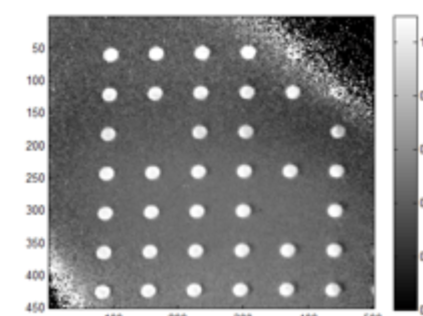
Target 5 mm Cu



4.5 GeV



3.6 GeV

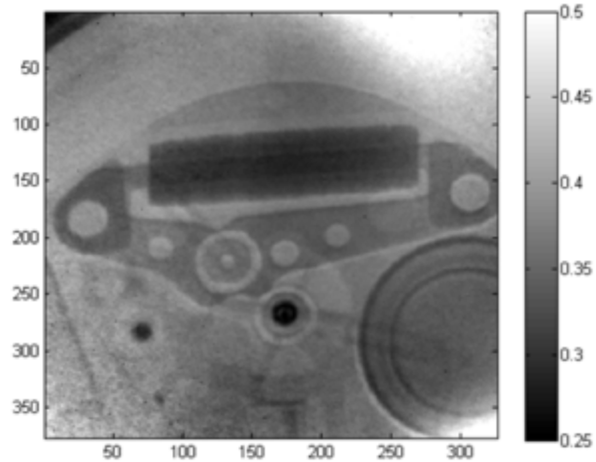


tuned

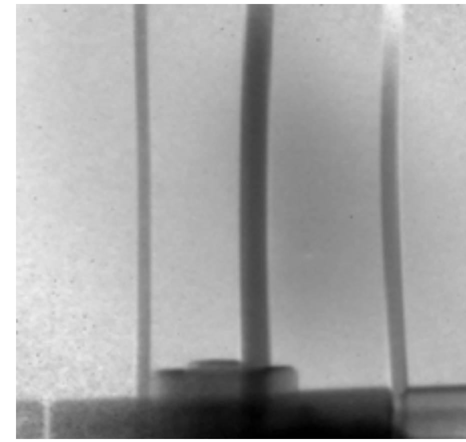
Static commissioning of PRIOR

(April 2014, GSI, SIS-18, proton beam energy 3.6 GeV)

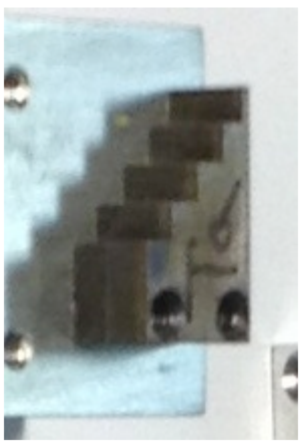
Quartz watch

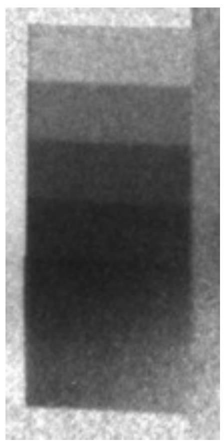


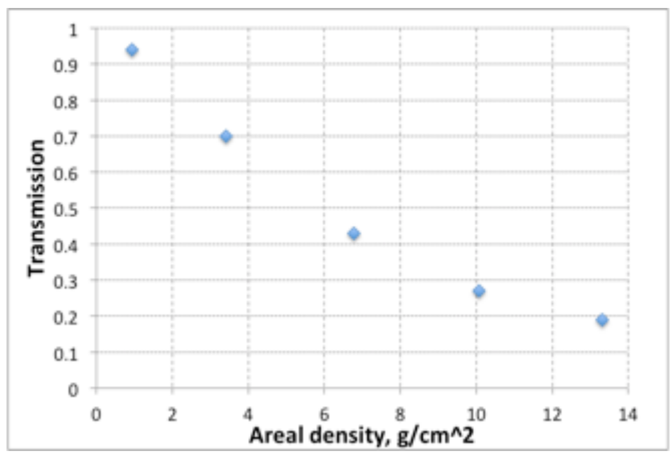
Ta wire 0.8 mm at vacuum

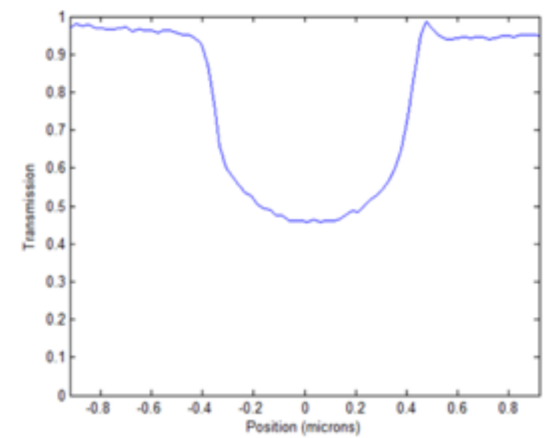


Thickness of Ta steps (0.56 mm, 2.06 mm, 4.07 mm and 6.05 mm)





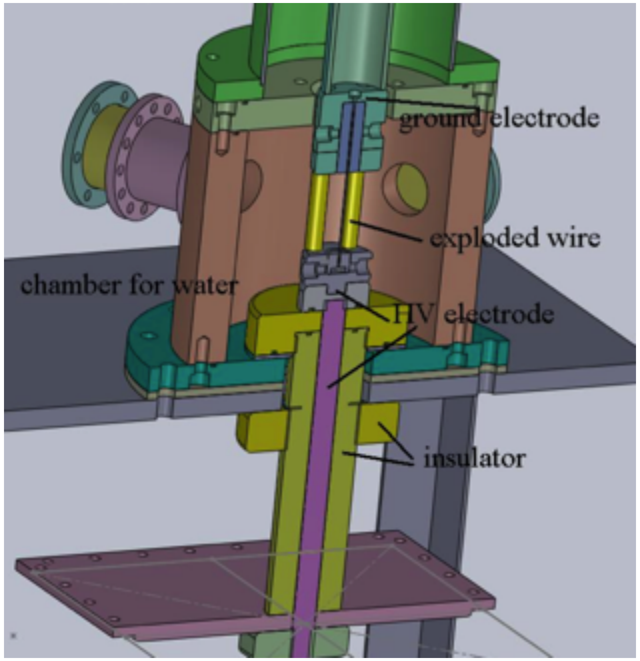


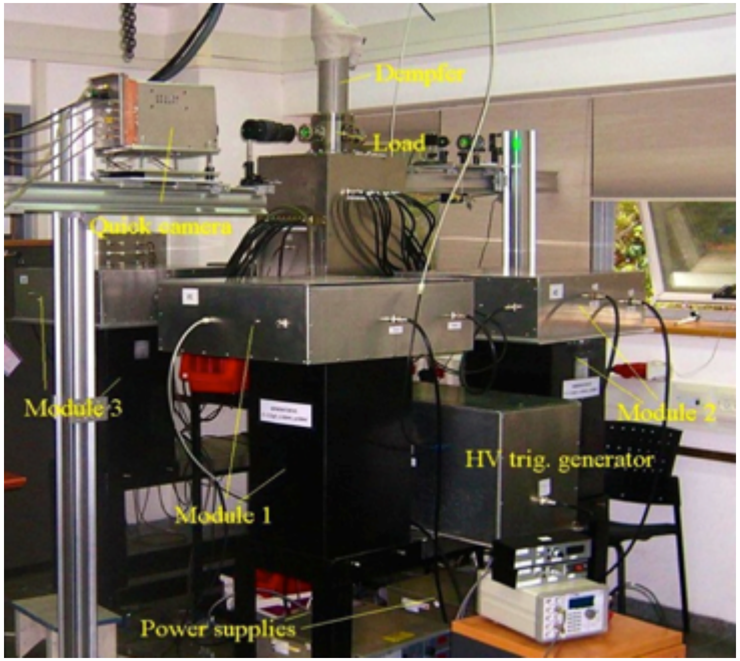


Best spatial resolution of **30 µm** was obtained with target - tungsten rolled edge with a radius of 500 mm

Dynamic commissioning of PRIOR
(underwater electrical wire explosion target)

Pulse power generator:
- 50 kV, 10 μF, 150 nH
- 250 kA,
- 2.5 μs (rise time)
- 12.5 kJ stored
- Wire: 0.1-1 mm diam.,
  4-5 cm long
  (Ta, Cu, W ..)
- T ~ few eV
- ε ~ up to 50 kJ/g

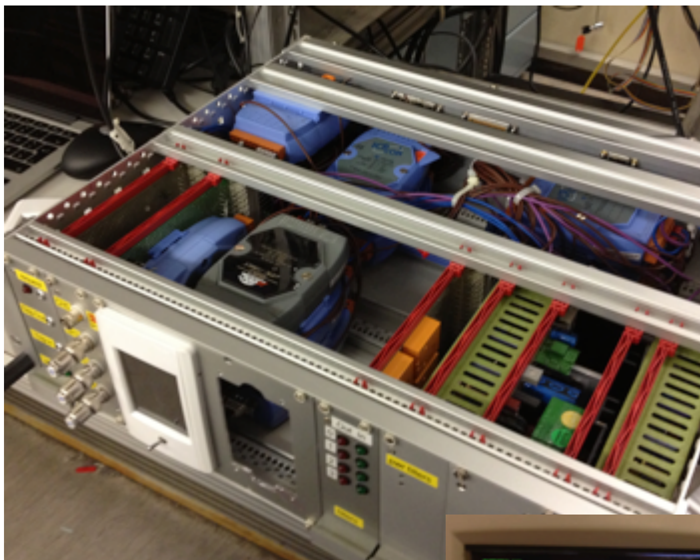




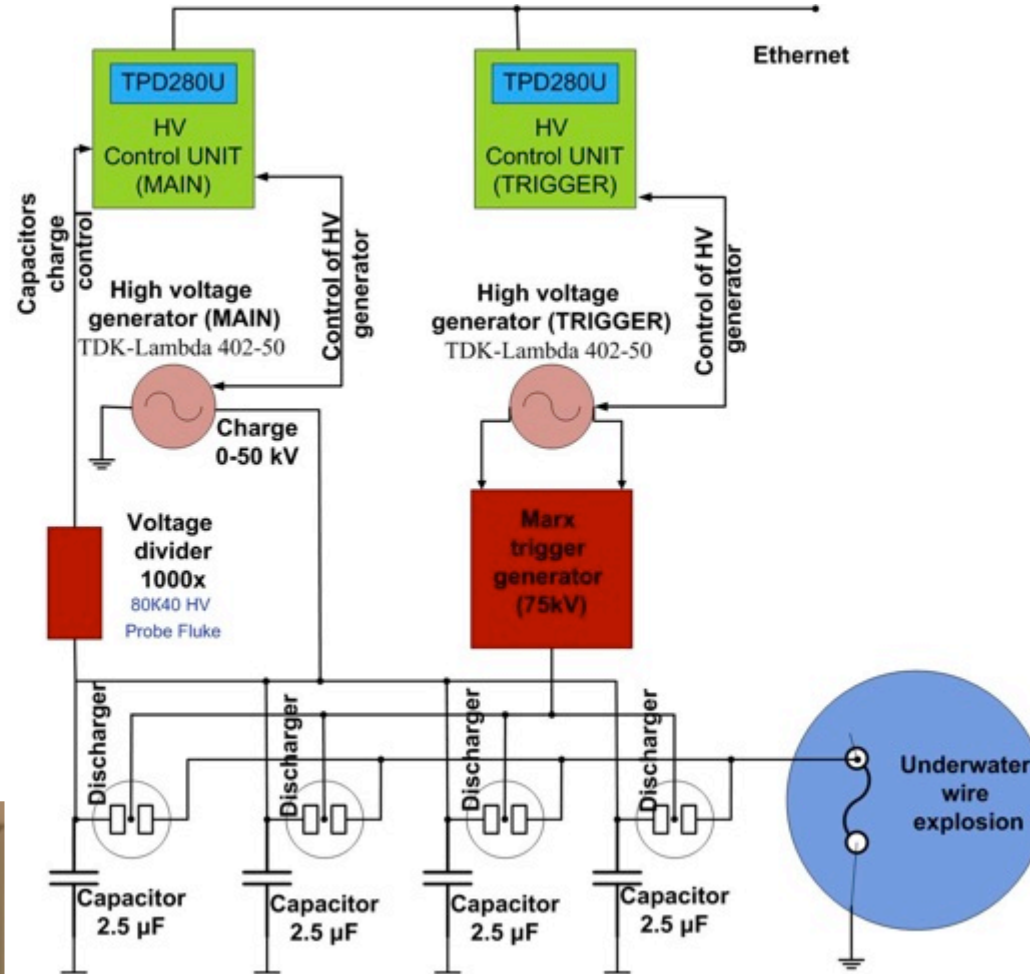
Advantages of the Underwater Electrical Wire Explosion:
- Shunting of the discharge is prevented due to:
  - High breakdown voltage of the water medium (>300 kV/cm).
  - High pressure of the adjacent water layer (>10 kBar) increases breakdown voltage.
- Increase in the temperature of the wire plasma is achieved by:
  - High resistance of the water to compression limits the wire expansion and leads to the increase in the current density.
  - Substantial decrease in the energy loss to the shunting channel and to radiation (water "bath" effect)

Yakov Krasik, Technion (Haifa, Israel)

Dynamic commissioning of PRIOR
(underwater electrical wire explosion target UEWE)

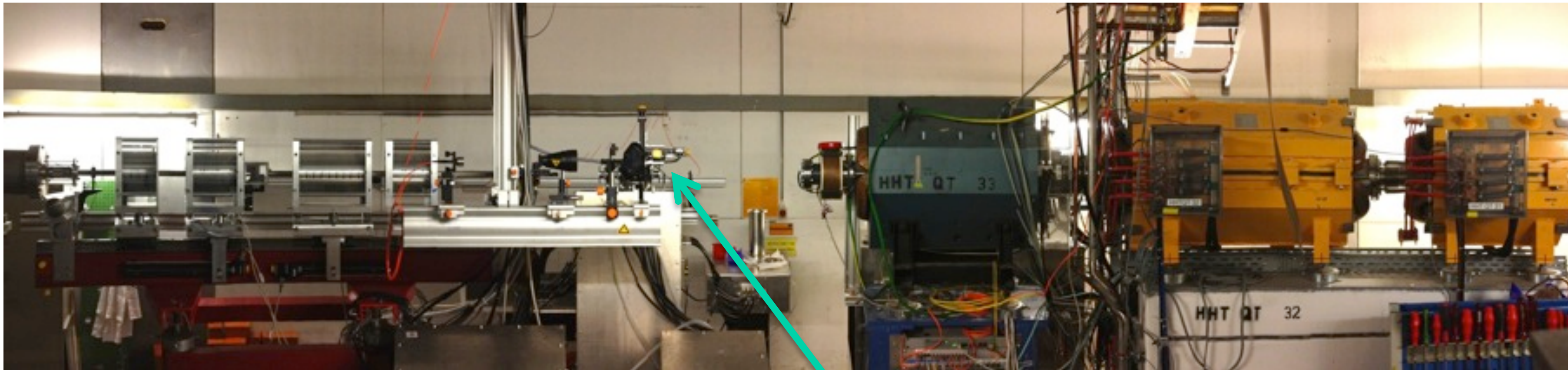


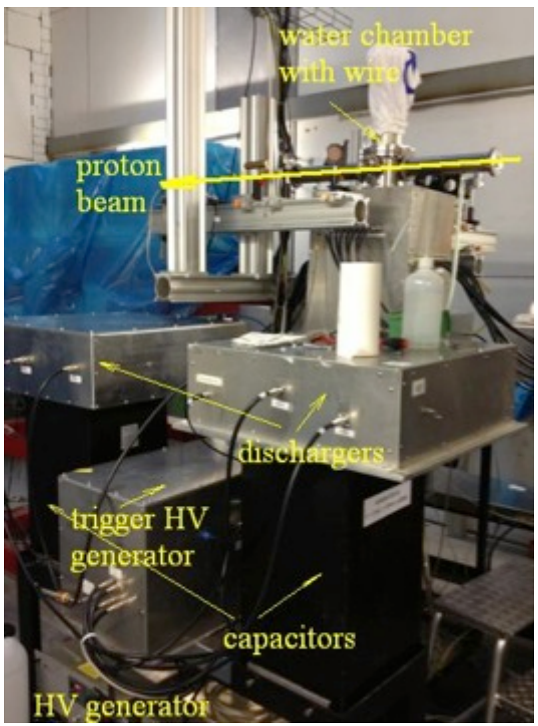
Control system for HV generators of UEWE dynamic target

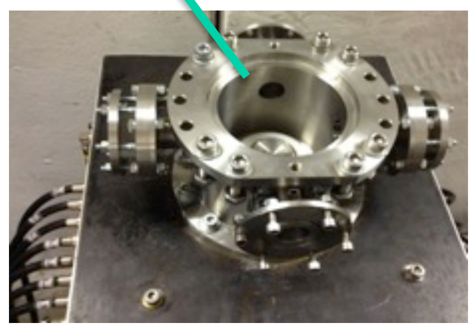


Scheme of control system (based on ICPDAS modules)

Dynamic commissioning of PRIOR

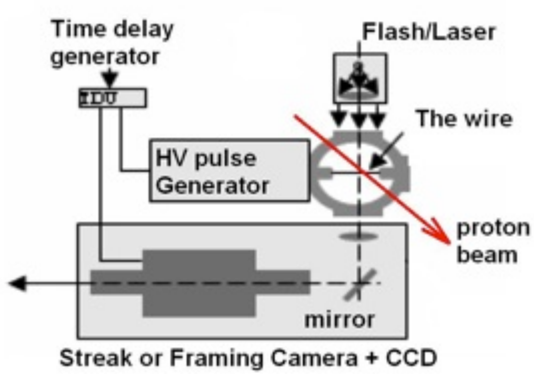


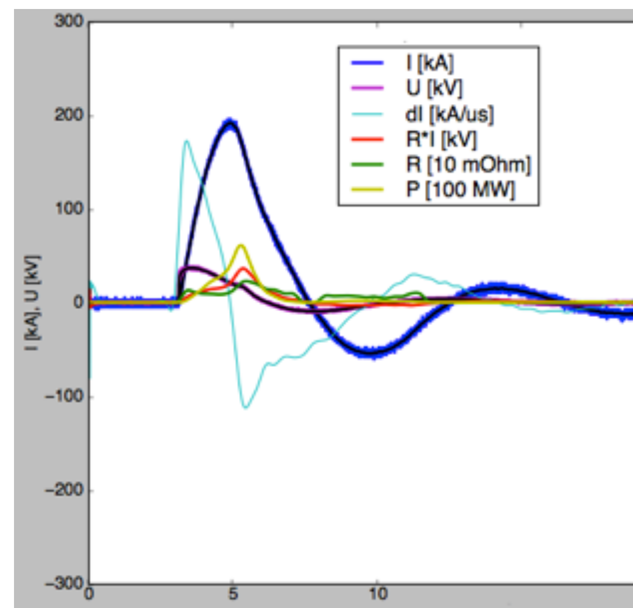




Water filled target chamber

Main goal: measure density distribution of internal structure of expanding Ta wire





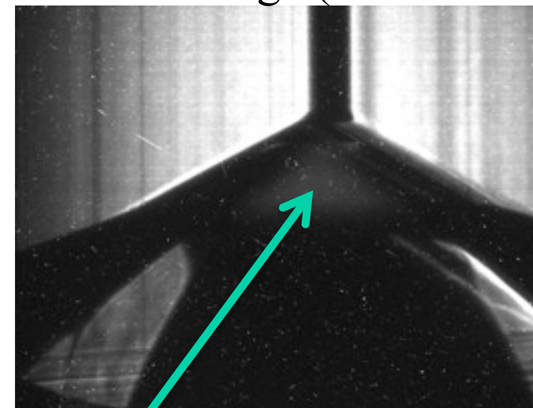
Electrical signals

Dynamic commissioning of PRIOR

(August 2014, GSI, SIS-18, proton beam energy 3.65 GeV)

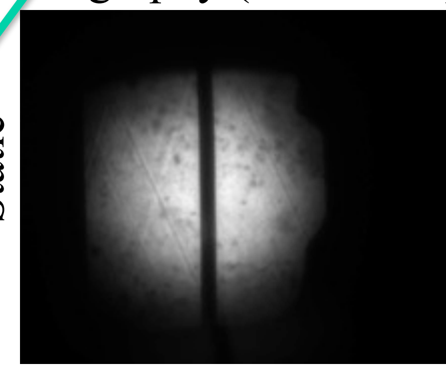
- Ta wire: diameter - 0.8 mm, length - 50 mm
- HV pulse: voltage 35 kV
  amp. of current: 200 кA (2.5 ms - rise time)
- Energy deposition: ~10 kJ/g
- Current density is about 40 MA/cm^2
- ~2 eV

Streak camera image (5 us/frame)

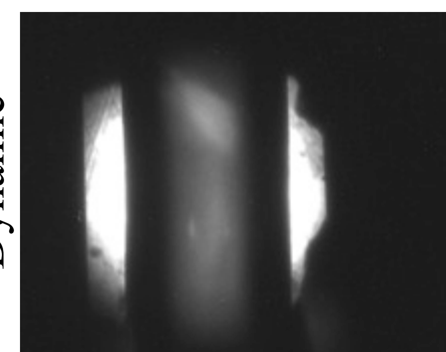


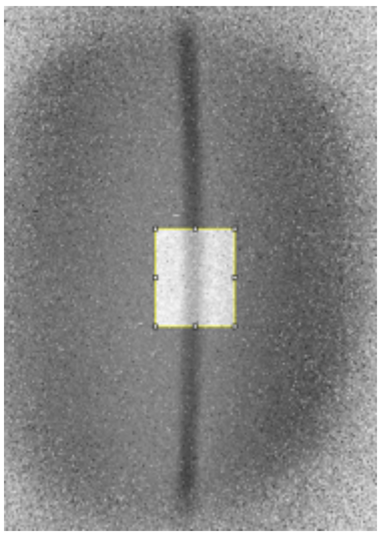
Shadowgraphy (DicamPro)

Static

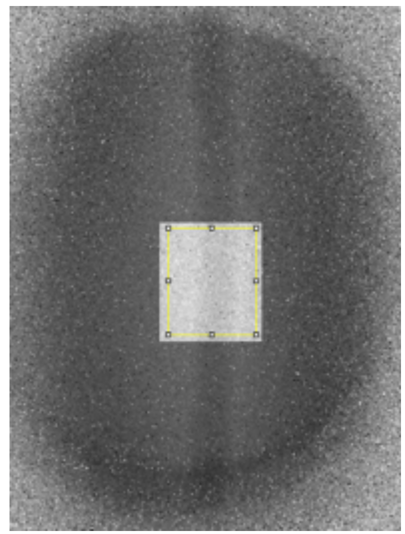


Dynamic

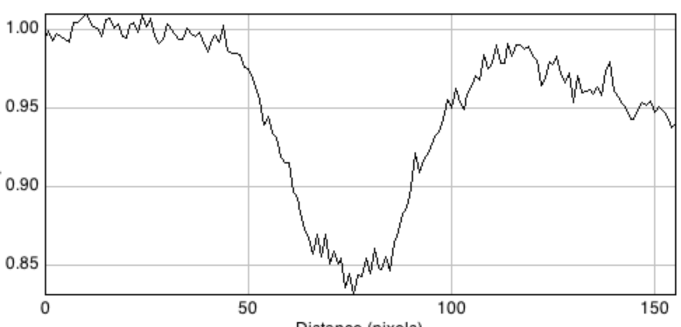


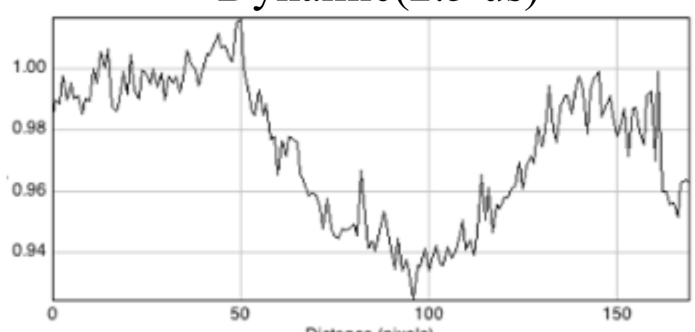


Static

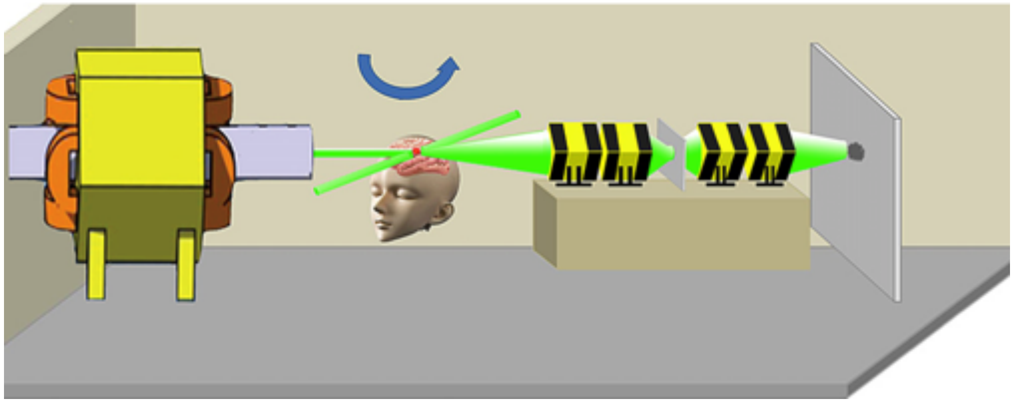


Dynamic(2.5 us)





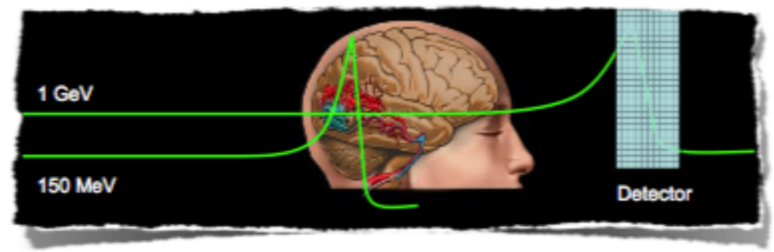
Experiment PaNTERA – ProtoN ThErapy and Radiography (image-guided stereotactic particle radiosurgery IGSpRS)

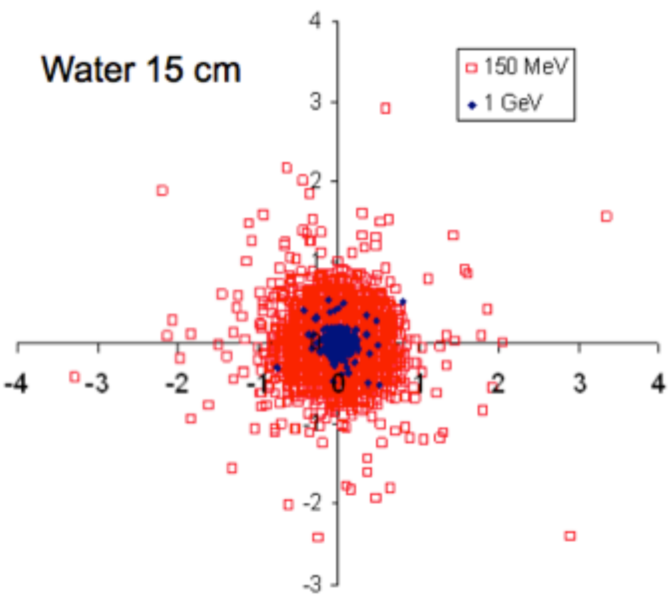


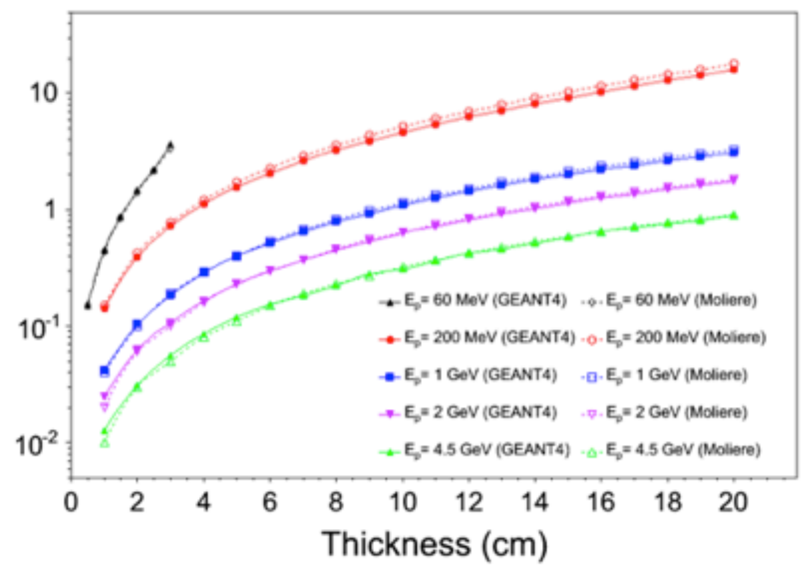
Lateral scattering for high energy protons

Advantages with high energy protons and proton radiography:

Online imaging and low lateral scattering allow reduction of margins, treatment of moving targets and dose escalation

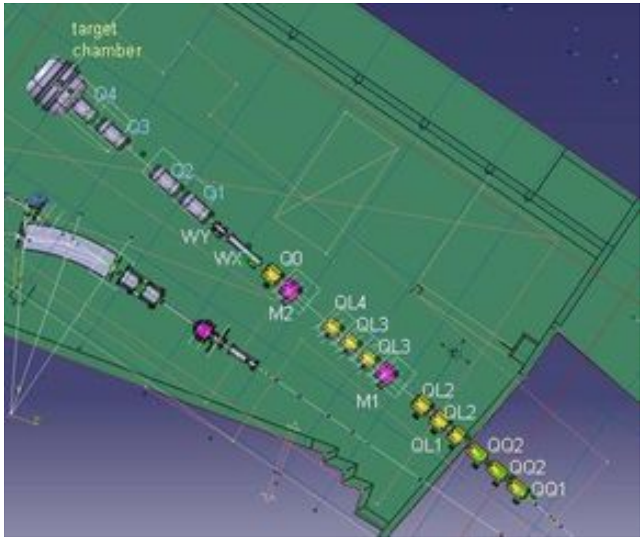






Plans

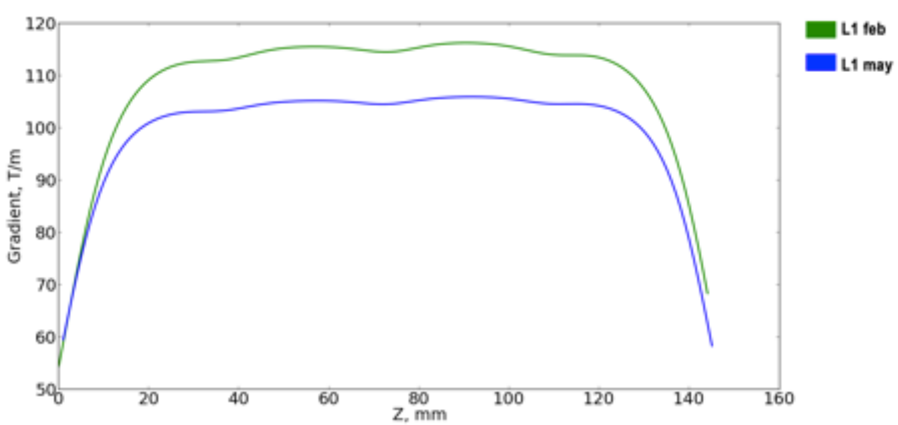
Experimental data processing in progress…

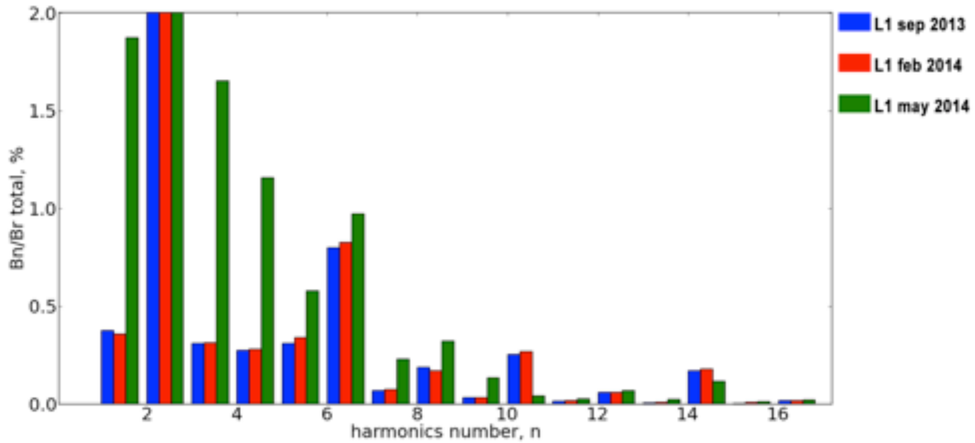


PRIOR at FAIR:

- x500 beam intensity
- x2 proton energy
- SC or PMQ imager options
- probably the first HEDgeHOB experiment at FAIR

Radiation damage of magnetic material – NdFeB:





Need for demagnetization of NdFeB

This work was supported by Young FAIR Groups Leaders Contest of FRRC

Thank you for attention!