中國原子能科學研究院
CNNC CHINA INSTITUTE OF ATOMIC ENERGY

Construction of a Proton Radiography Test-stand Based on an 100 MeV Proton Cyclotron

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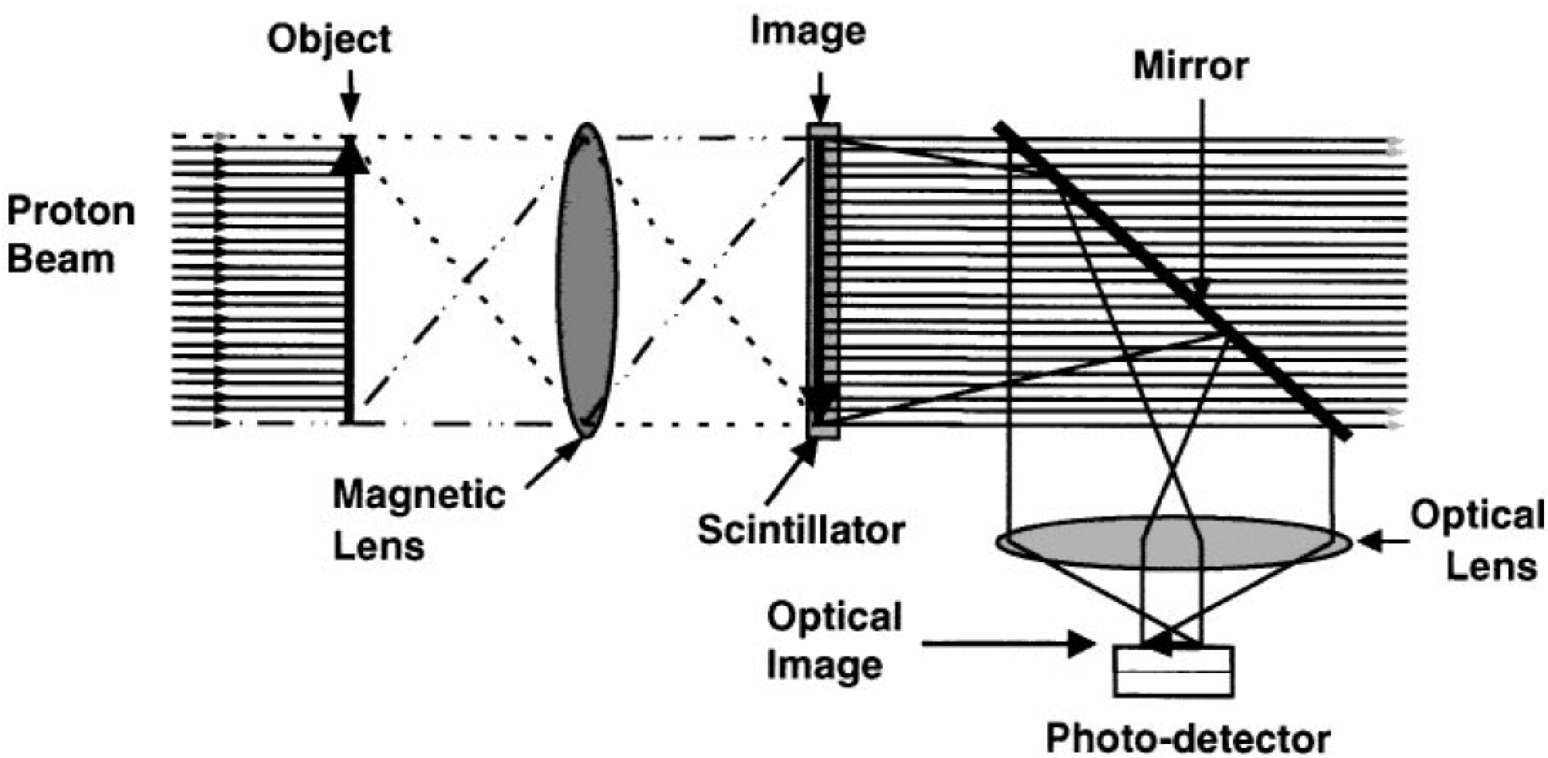
China Institute of Atomic Energy (CIAE)

2016-09-16

CYC2016, Zurich, Switzerland, Sep. 11-16, 2016

What's Proton Radiography?

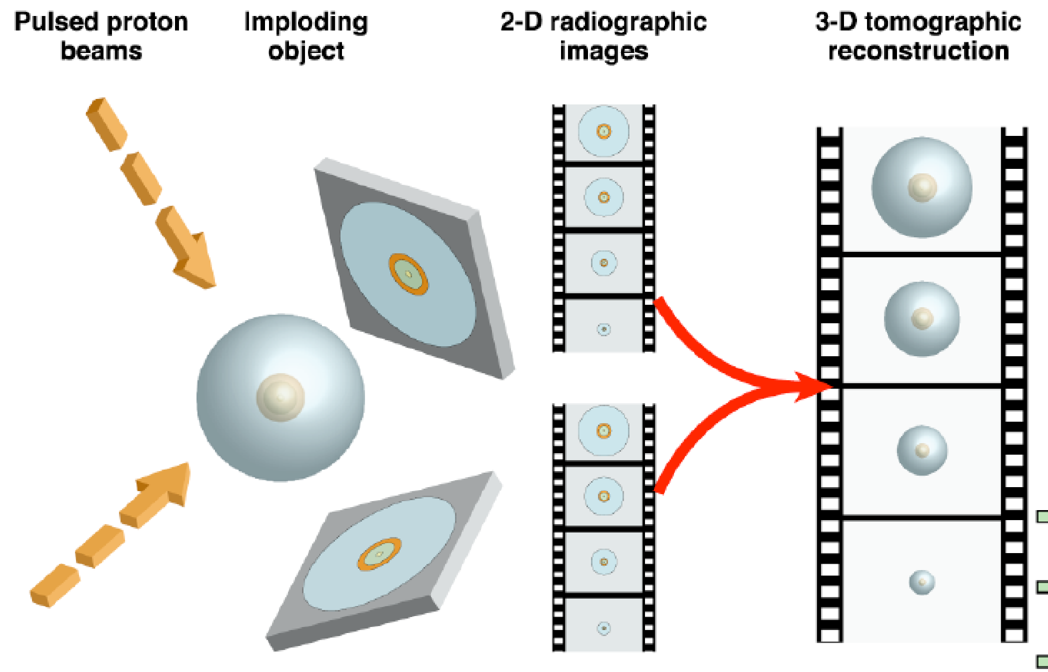
Proton radiography is a new scatheless diagnostic tool providing a potential development direction for advanced hydrotesting.



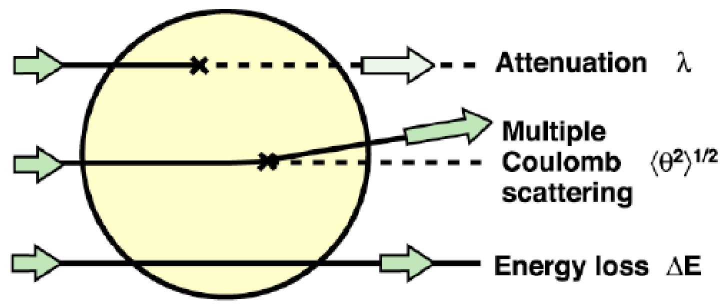
N.S.P. King et al.,, NIMA 424 (1999) 84-91

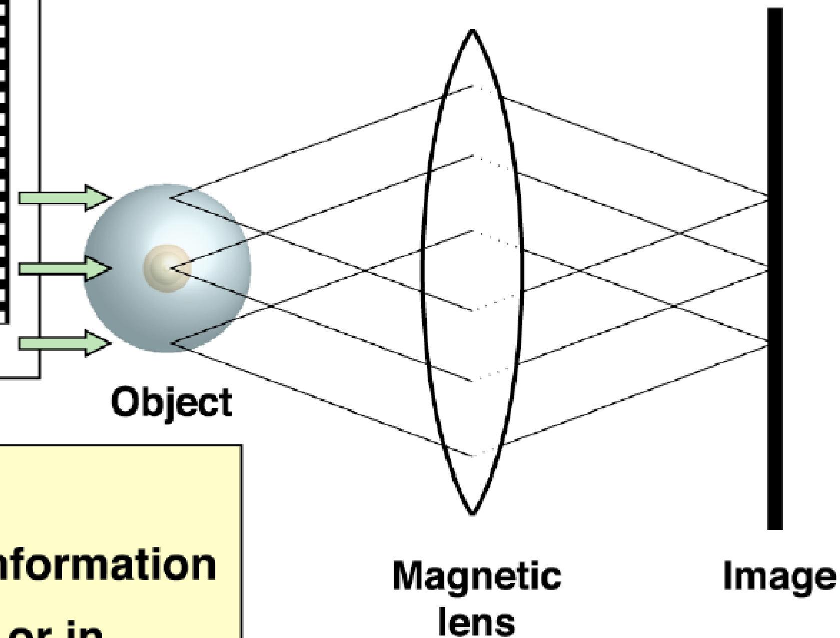
What's Proton Radiography?

3-D Radiographic Imaging



Three Types of Information





- Protons can provide multiple pulses in time
- Protons can provide material identification information
- No issues with conversion — either at target or in detector

Courtesy by Peter D. Barnes

1) Attenuation

$$\frac{N_1}{N_0} = e^{-\sum \frac{l_i}{\lambda_i}}$$

l_i → Thickness of material *i*

λ_i → Mean free path of material *i*

$$\lambda = 1/n\sigma_A$$

n → Number density of the atoms

σ_A → Absorption cross section of strong interaction with a nucleus with mass number A

- Some of the protons are absorbed by nuclear collisions. This is a simple exponential attenuation of the beam.
- Proton radiography technology takes advantage of this effect for image the object onto the detector/film.
- A much lower incident flux of hadrons will produce the same statistical information obtained from a higher flux of high-energy X-rays.

2) Multiple Coulomb Scattering (MCS)

$$\frac{N_2}{N_1} = \frac{1}{2\pi\theta_0^2}\int_0^{\theta_m} e^{-\frac{\theta^2}{2\theta_0^2}}\, d\Omega \cong \left[1 - e^{-\frac{\theta_m^2}{2\theta_0^2}}\right]$$

➢The development and use of magnetic lenses is necessary to compensate for the small angle MCS which otherwise can cause image seriously blurred.

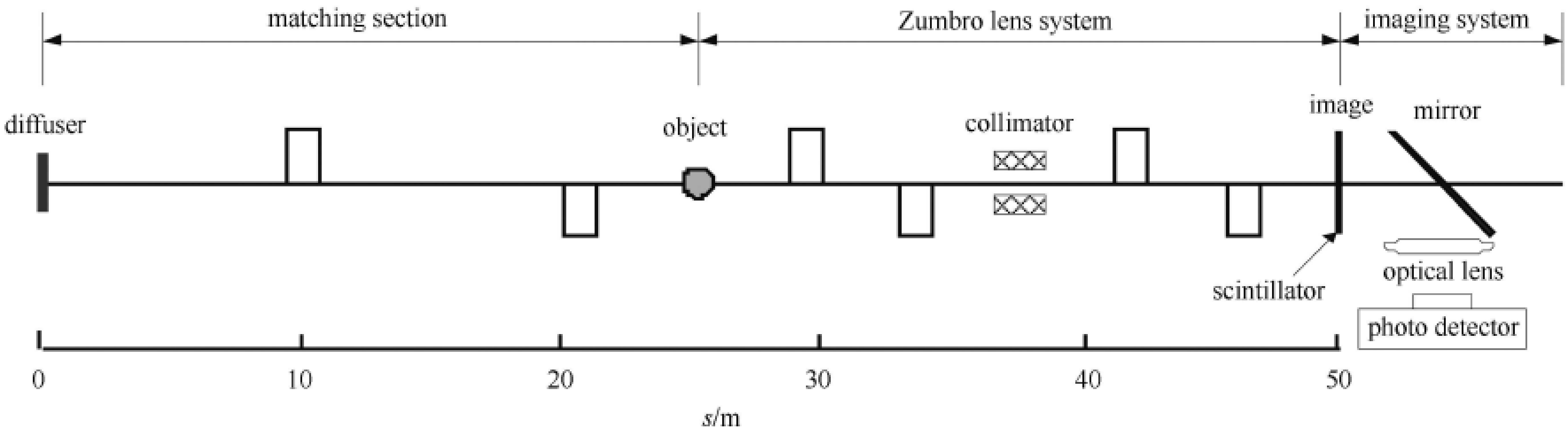
➢The MCS results in additional complexity in forming a radiograph, but can also provide material identification information in the object.

3) Energy losses by ionization process

$$-\frac{dE}{dx} = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left(\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{max}}{I^2} - \beta^2 - \frac{C}{Z} - \frac{\delta}{2} \right)$$

- Protons lose varying amounts of energy as they go through an object from both energy straggling and thickness variations in the object.
- This produces a spread in the momentum of the transmitted protons that blurs the final image due to chromatic aberrations in the lens.

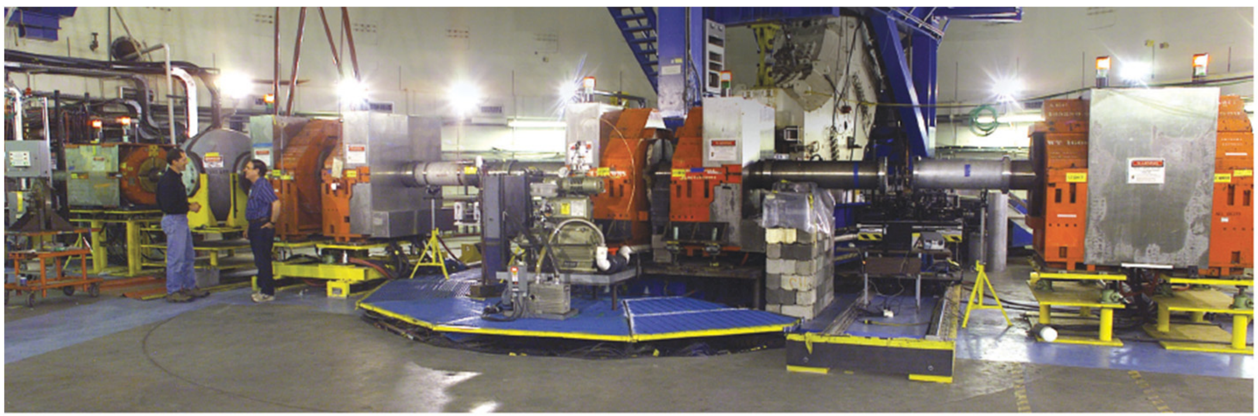
Schematic Layout

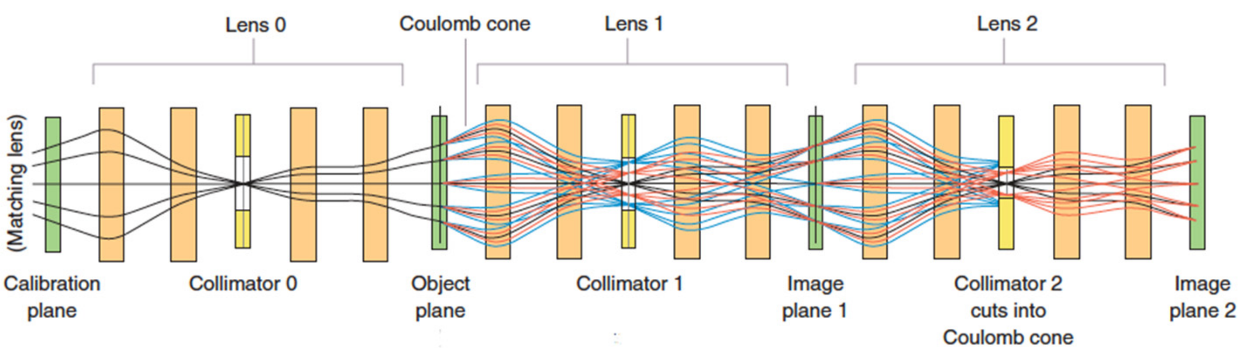


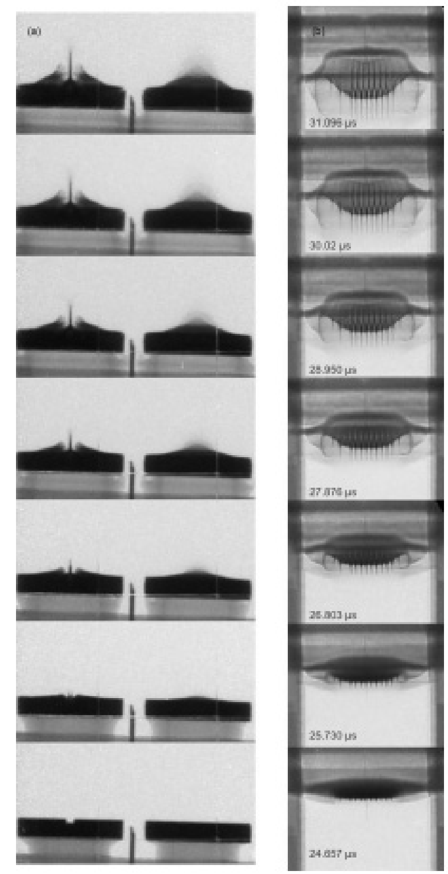
T. Wei et al., *Chinese Physics C, 2012, 36(8): 792-796*

pRad with 800MeV Linac @ LANL

The technique of proton radiography was firstly developed at LANL to utilize 800 MeV proton beam as a radiographic probe for the diagnosis of hydrotesting research.

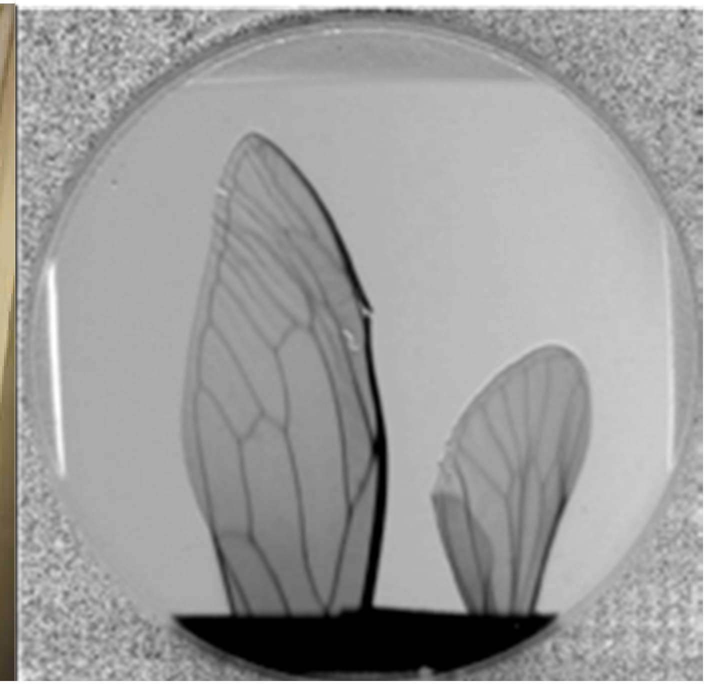


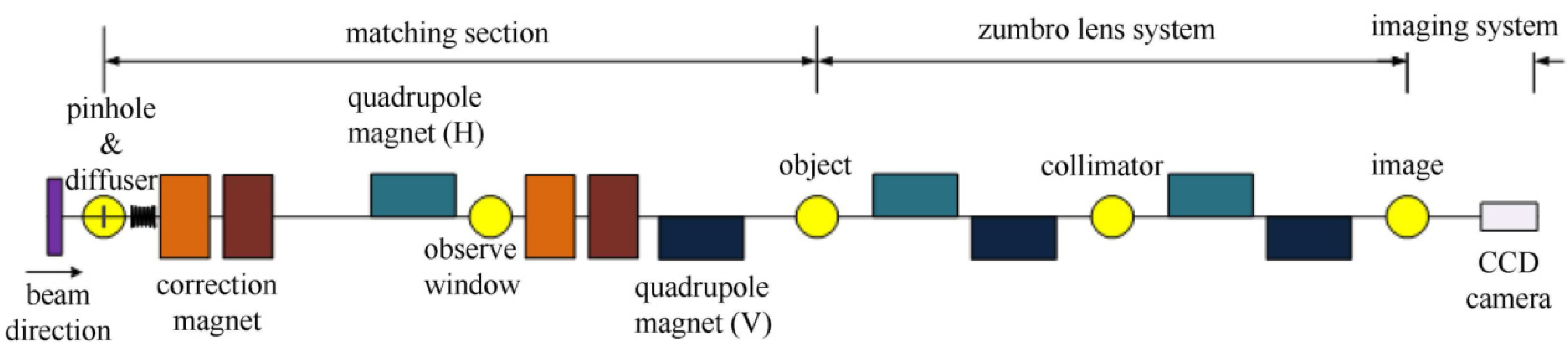




Courtesy by S. Gregory

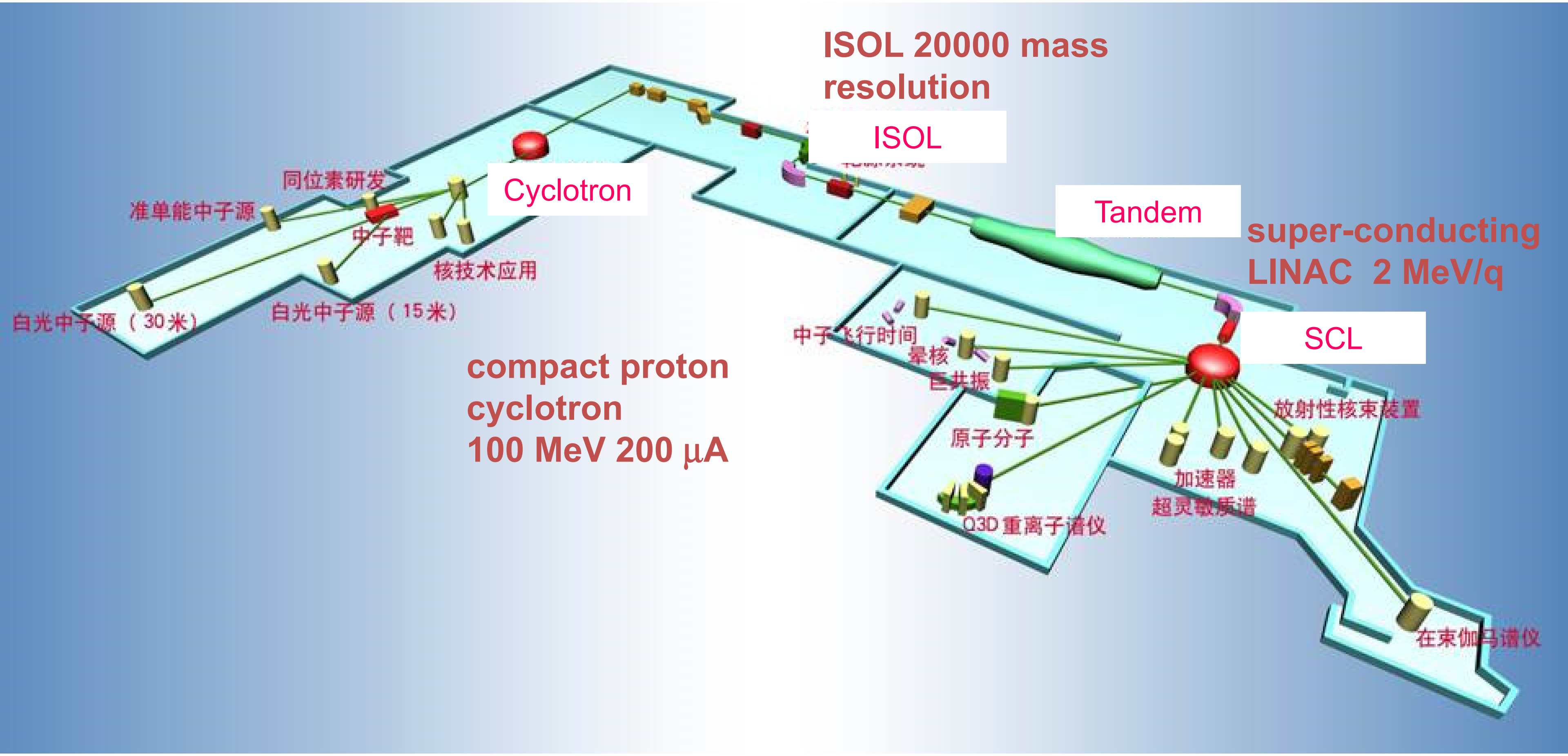
pRad with a 11MeV cyclotron @ CAEP





T. Wei et al., *Chinese Physics C,* Vol. 38, No. 8 (2014) 087003

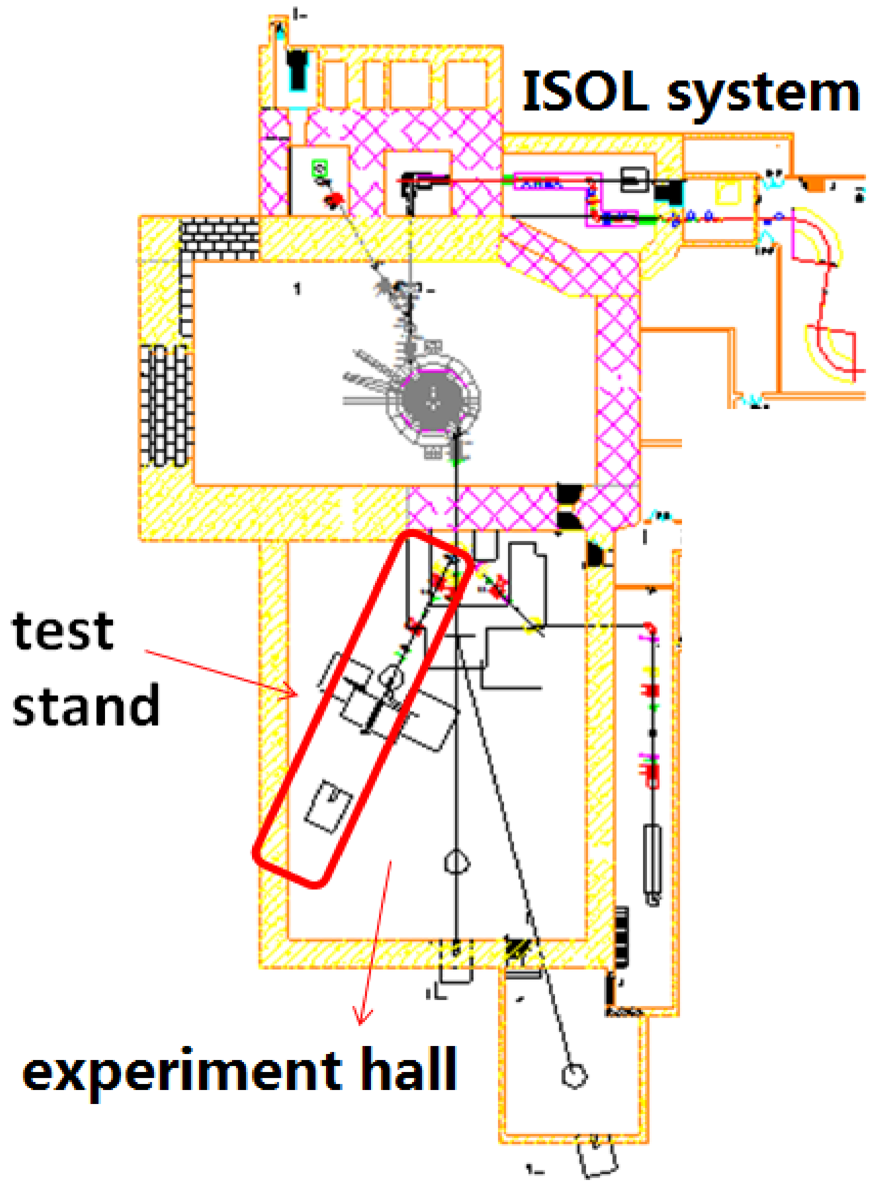
BRIF - Beijing Radioactive Ion-beam Facility



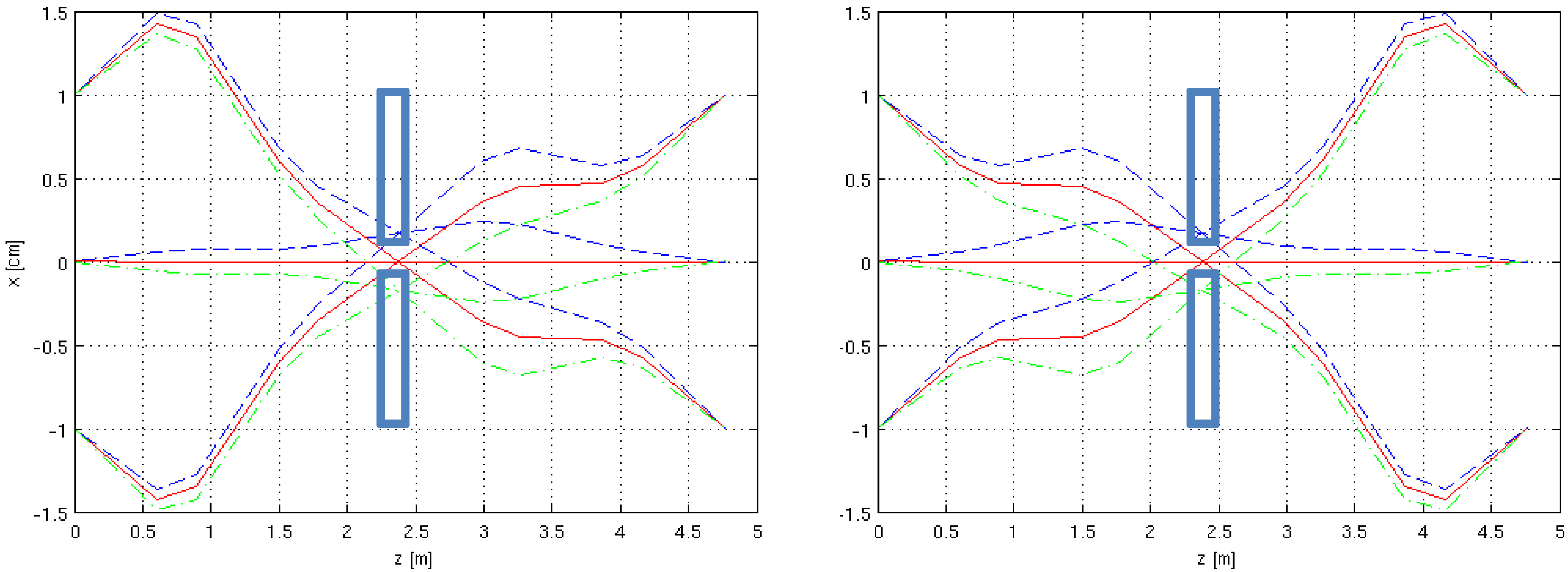
As one of the main projects at CIAE, the Beijing Radioactive Ion-beam Facility (BRIF) will be used in fundamental and applied research, such as neutron physics, nuclear structure and medical isotope production.

Beam Line Design

- The design philosophy of the test-stand is fully using the existing devices and equipments and minimize the additional required ones.
- The test-stand is consisted of a beam-matching section, experimental object, a magnetic lens section and an imaging system.



Point-to-Point Imaging

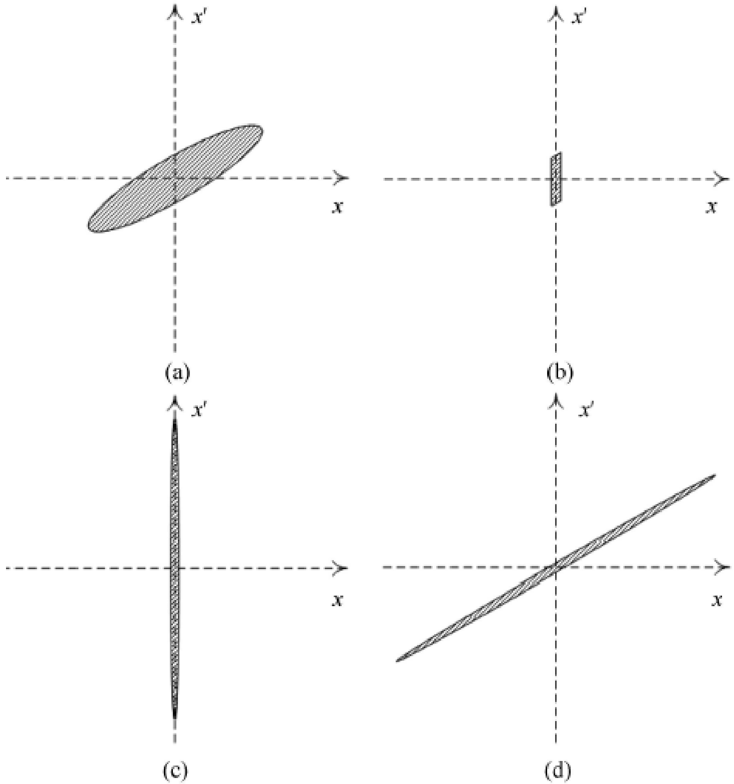


- Point-to-point imaging means $R_{12} = R_{34} = 0$, so the final position is independent of the initial angle.
- The Zumbro magnetic has a Fourier plane, where the position of a particle is determined by its initial angle only and is independent of its initial position (angle sorting).
- The particles of large MCS angle in a matched beam can be removed through a transverse collimator at the Fourier plane and thus the blur of the image can be diminished.

Matched Beam Preparation

The initial horizontal distribution from an accelerator

The beam distribution after a pinhole collimator



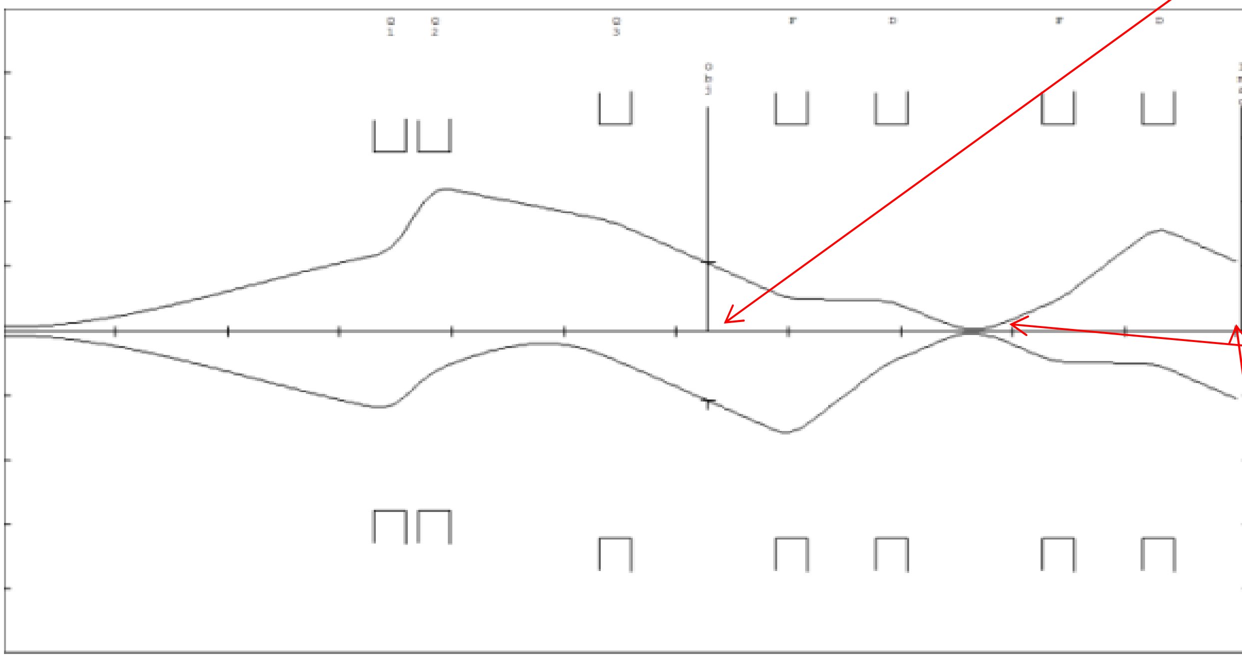
The beam distribution after a diffuser

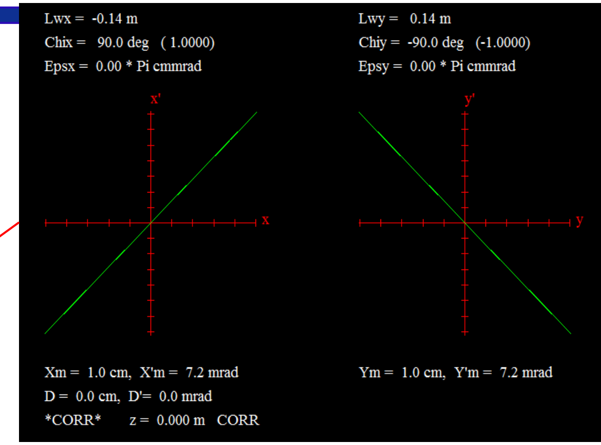
The beam distribution at the object position

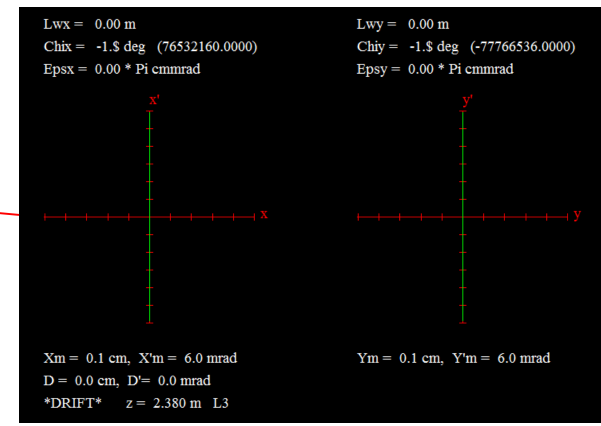
- The chromatic aberration coefficients define the final position errors for particles off the design momentum.
- If $\omega = -R11'/R12' = T_{116}/T_{126}$ $x_{image} = -x_{object} + R12'\varphi\Delta$, all position dependent chromatic aberrations vanish. The remaining chromatic aberration depends only on the deviation angle φ.

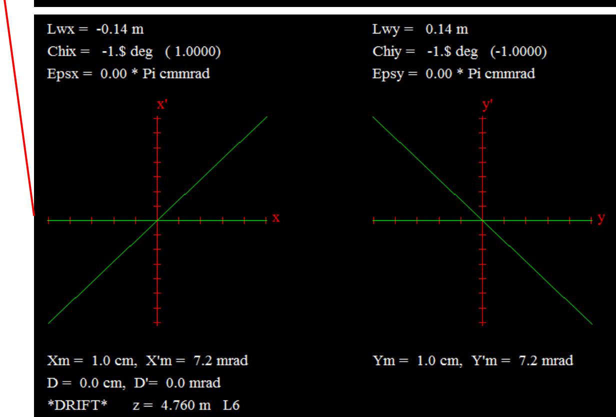
Beam Line Design

Beam optics design

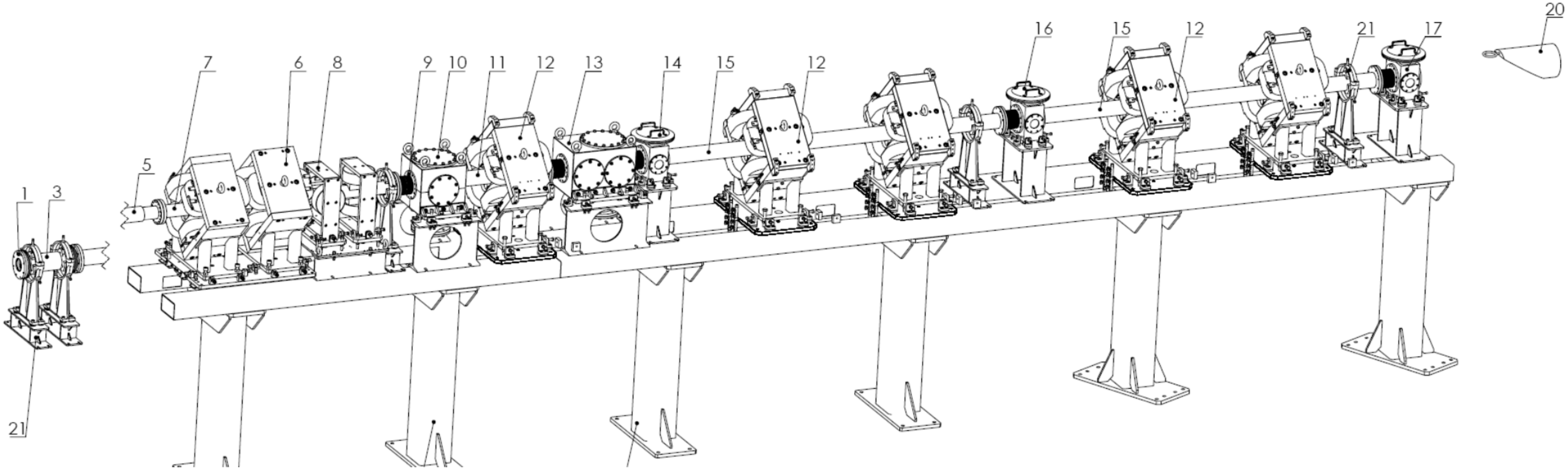






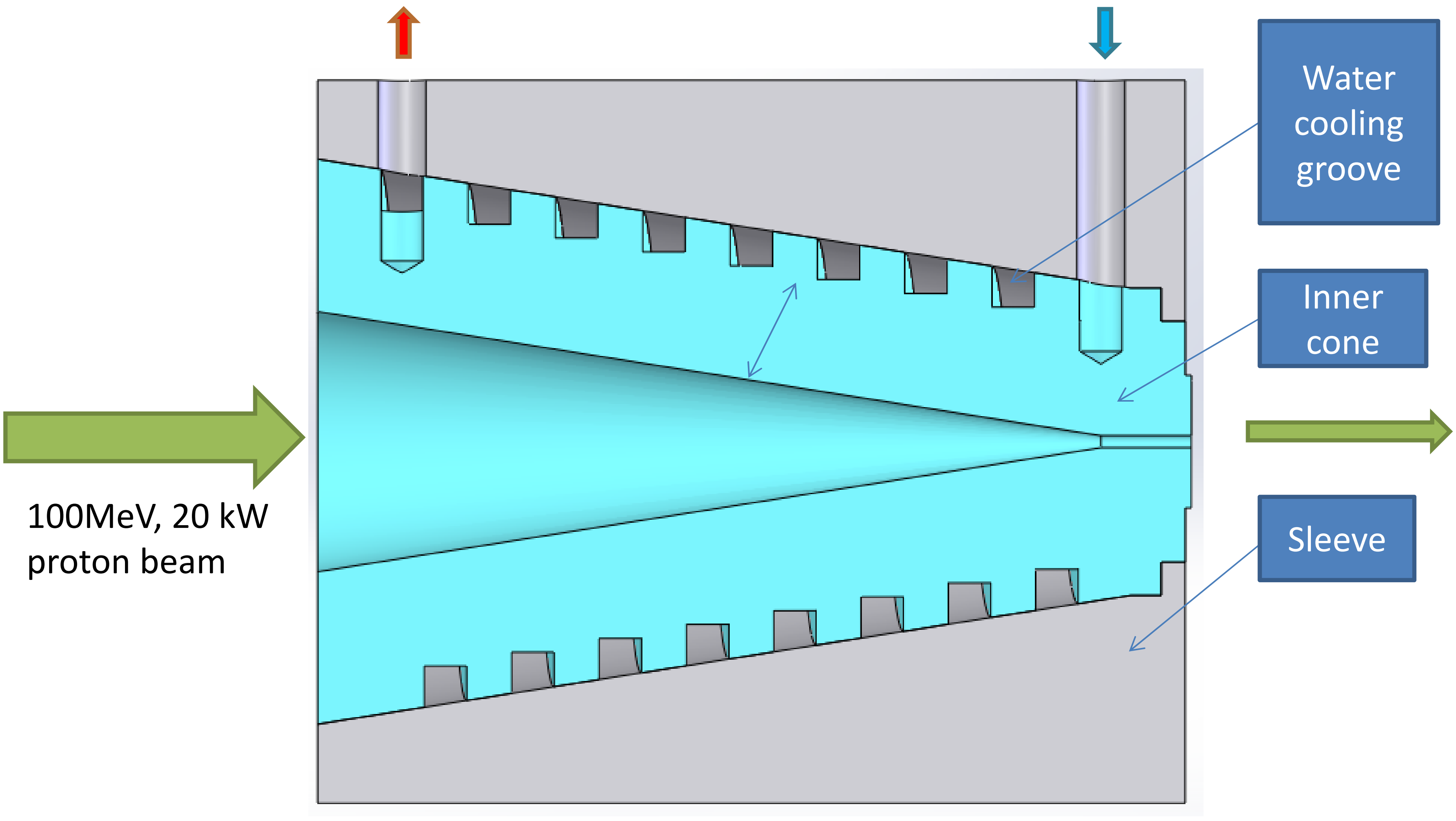


Mechanical Drawings

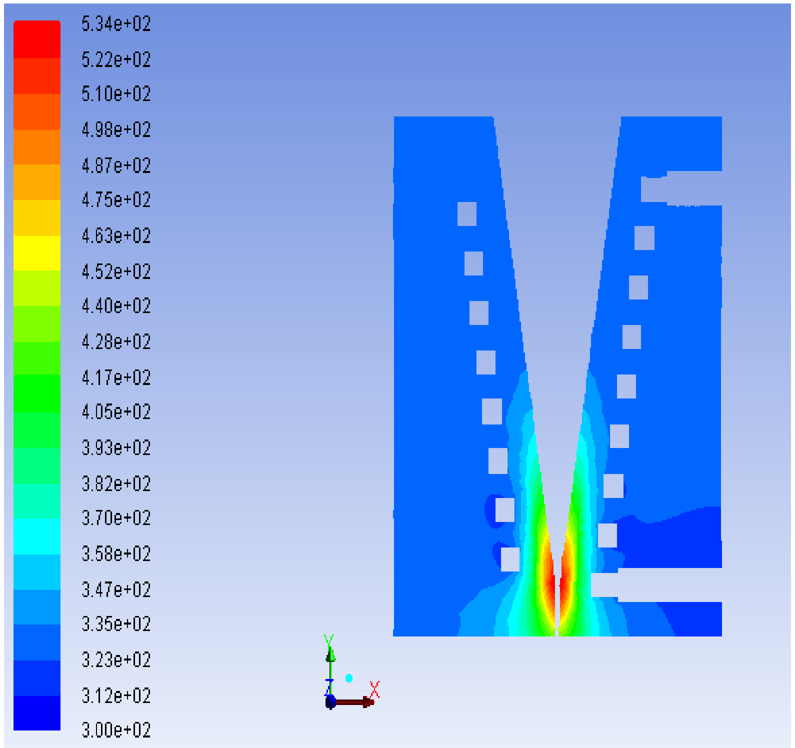


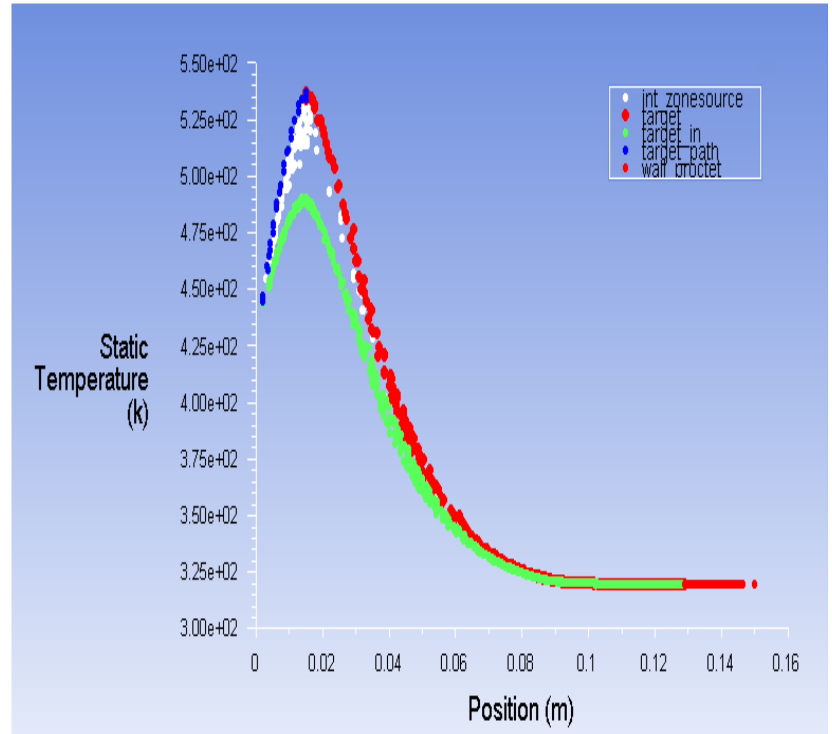
- The length of imaging lens section is 4.76 m and the total length of the beam line is 11.04 m.

Pinhole Collimator Design



Temperature calculation

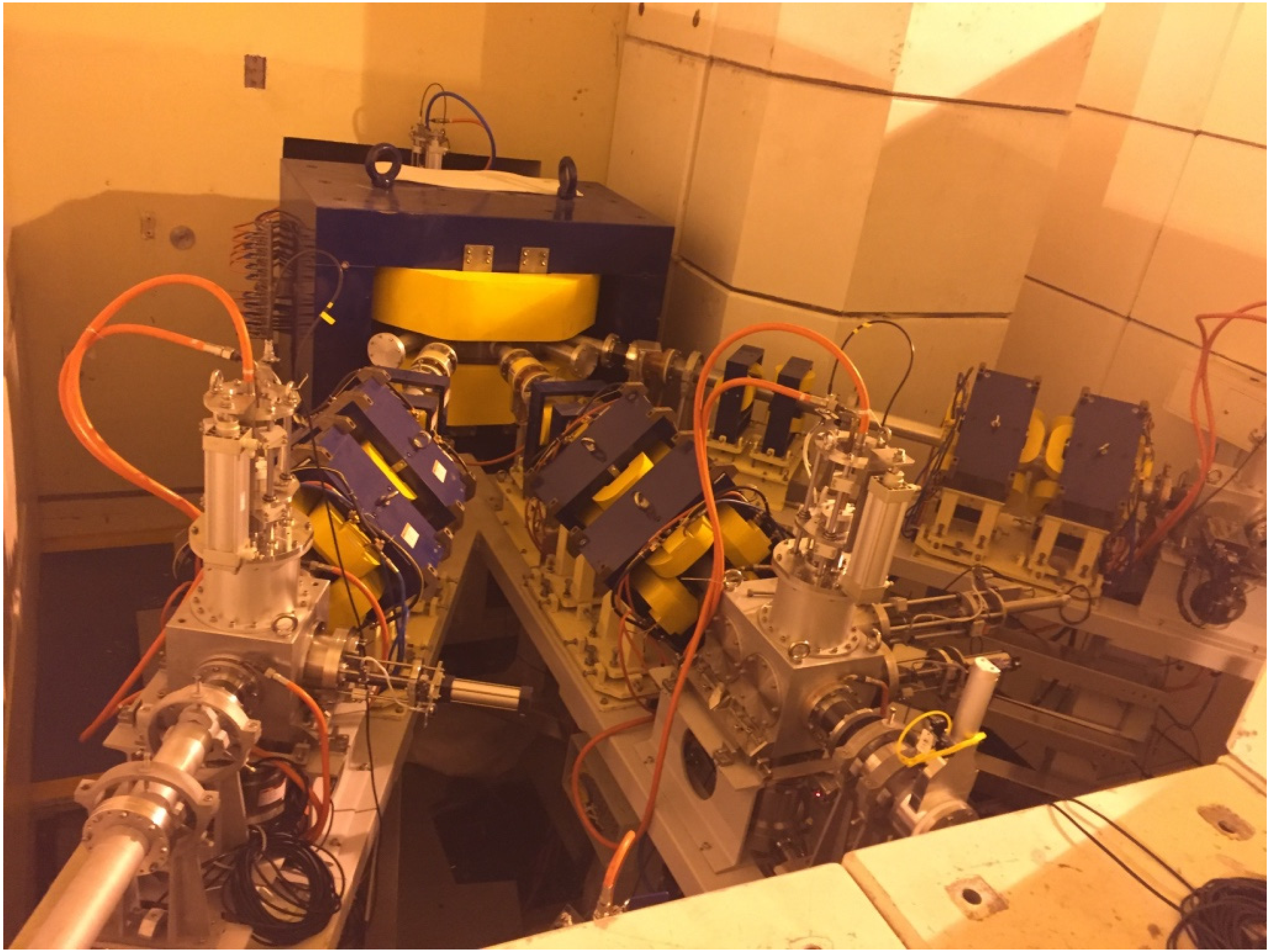




The maximal temperature is 260℃ under the condition of the flow rate of 2 m/s, lower than melting point of Copper

Beam Line Construction

Beam Line Construction



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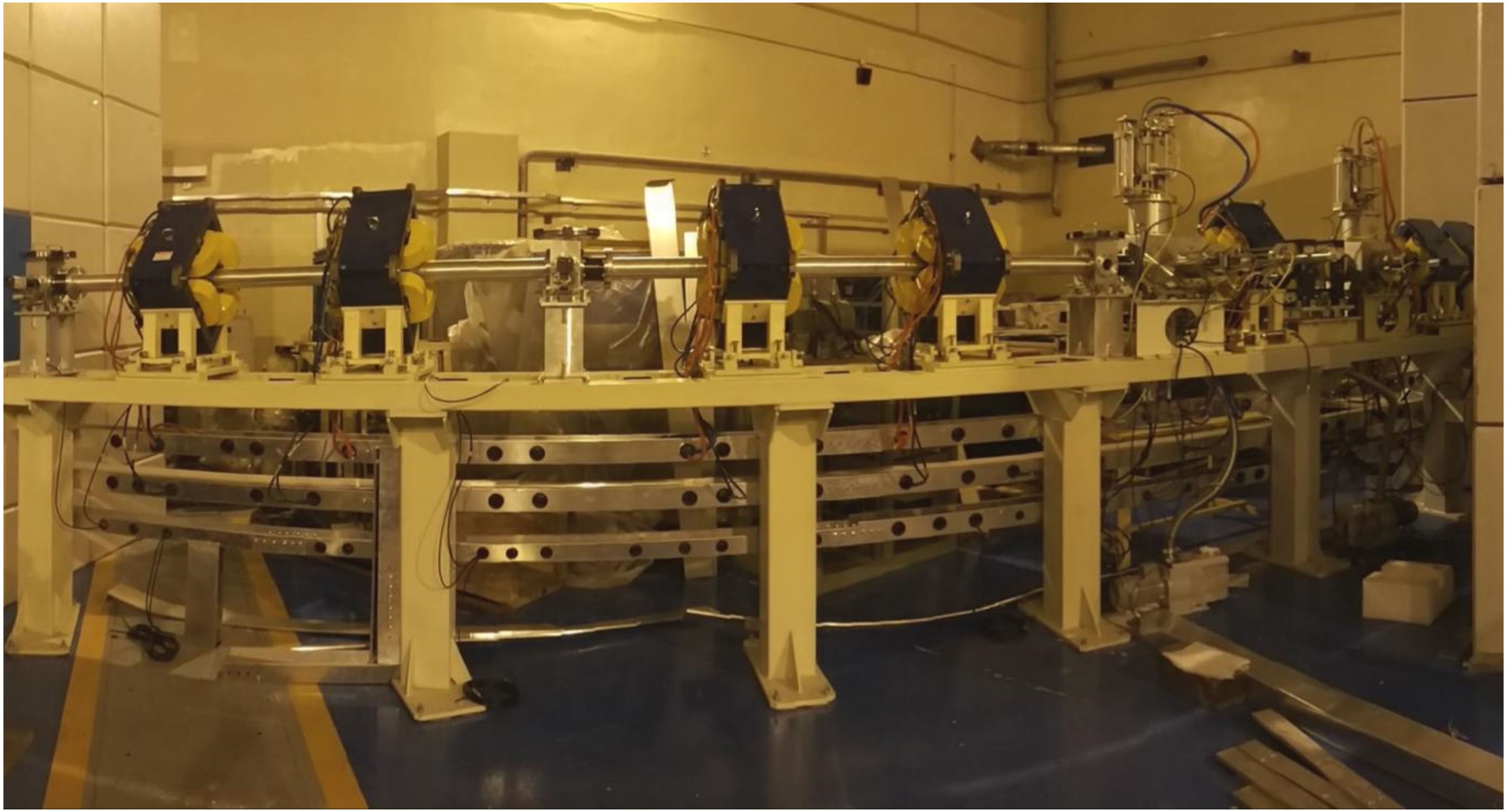

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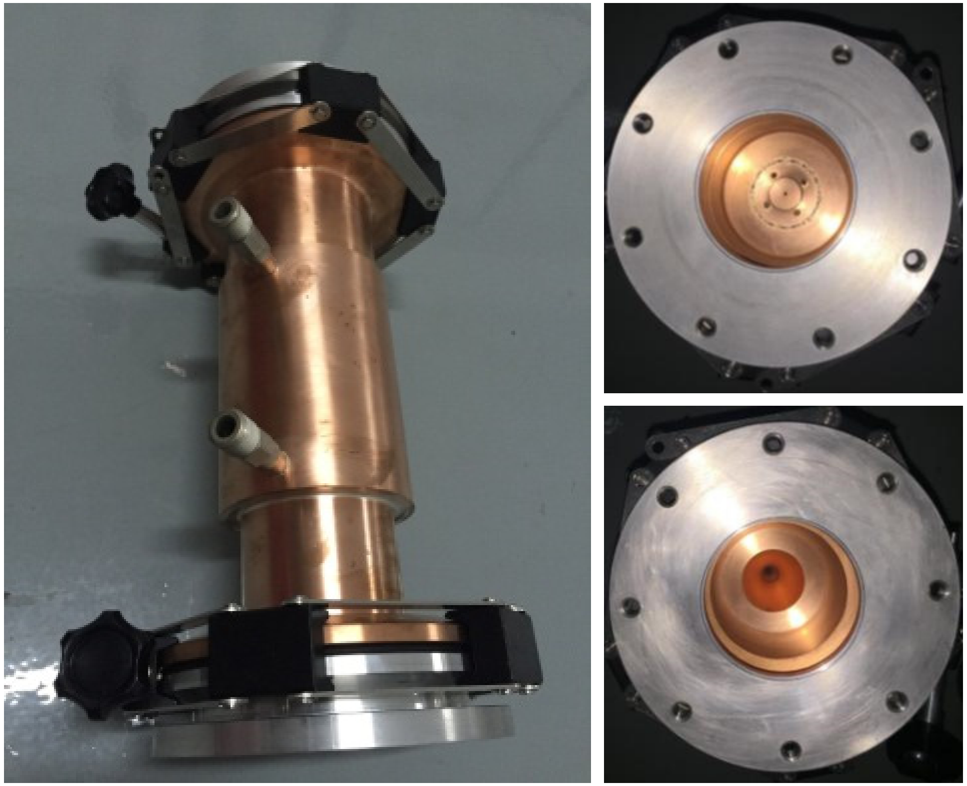
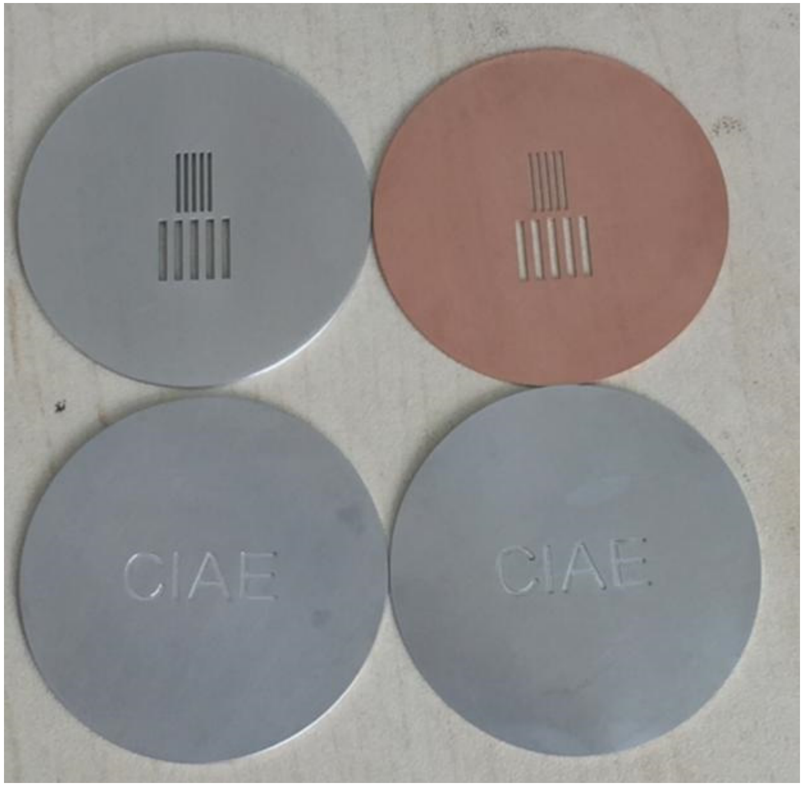


Pinhole collimator



Object sample

Summary & Outlook

- The test-stand is now ready for beam commissioning. The proton radiography experiment on a static, thin, mental object is scheduled in next month.
- The pulsed beam will be provided by using a suppressor on the injection of the cyclotron to take radiography on dynamic process.
- In long term, once the proposed 800 MeV cyclotron CYCIAE-800 is constructed, we can carriy out proton radiography on much more thick object.

Thanks !