The Beam Commissioning of BRIF and Future Cyclotron Development at CIAE

Tianjue Zhang for BRIF Project

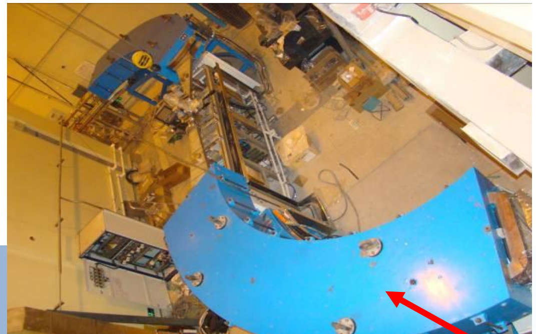
China Institute of Atomic Energy

2014-11-12

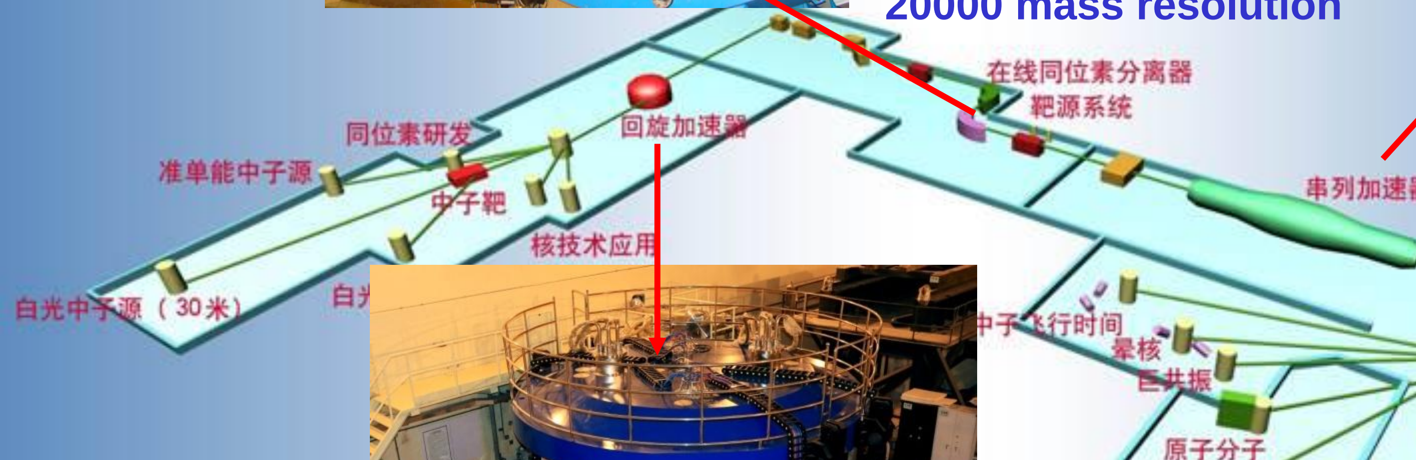
- ☐ **The Beam Commissioning of BRIF**
- ☐ **Future Cyclotron Development at CIAE**

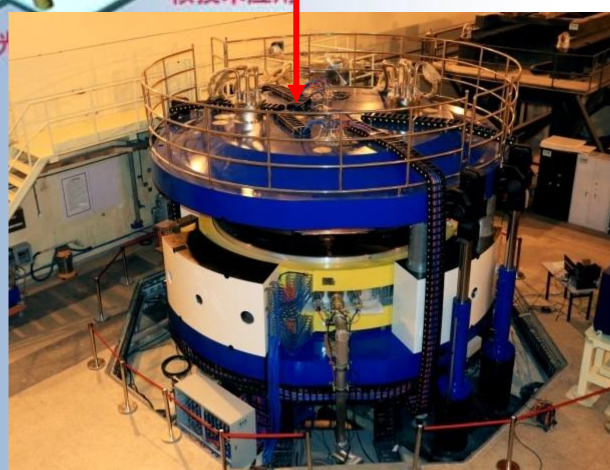
Brief Introduction of BRIF

(Beijing Radioactive Ion-beam Facility)



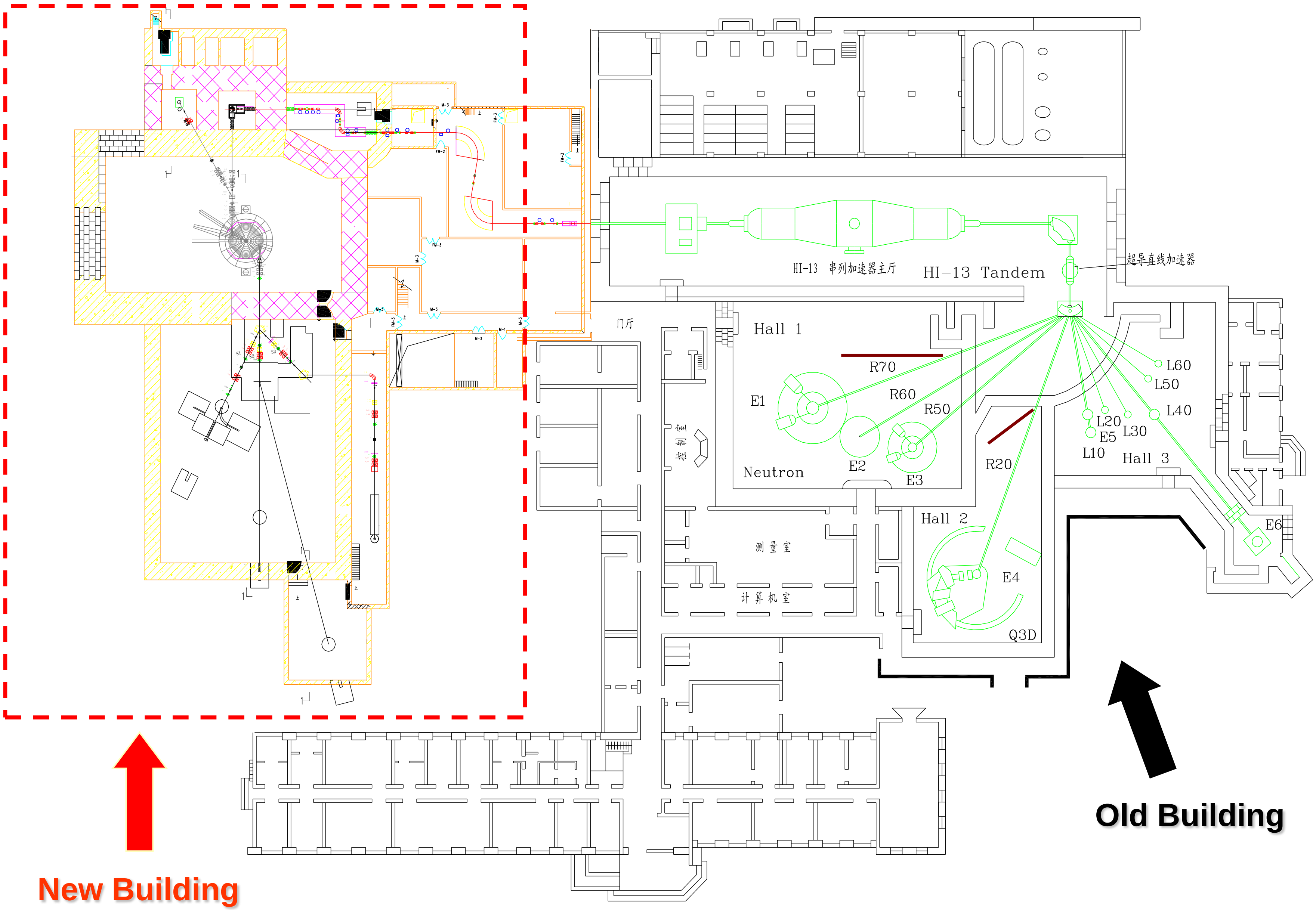
Isotope Separator On-Line
20000 mass resolution

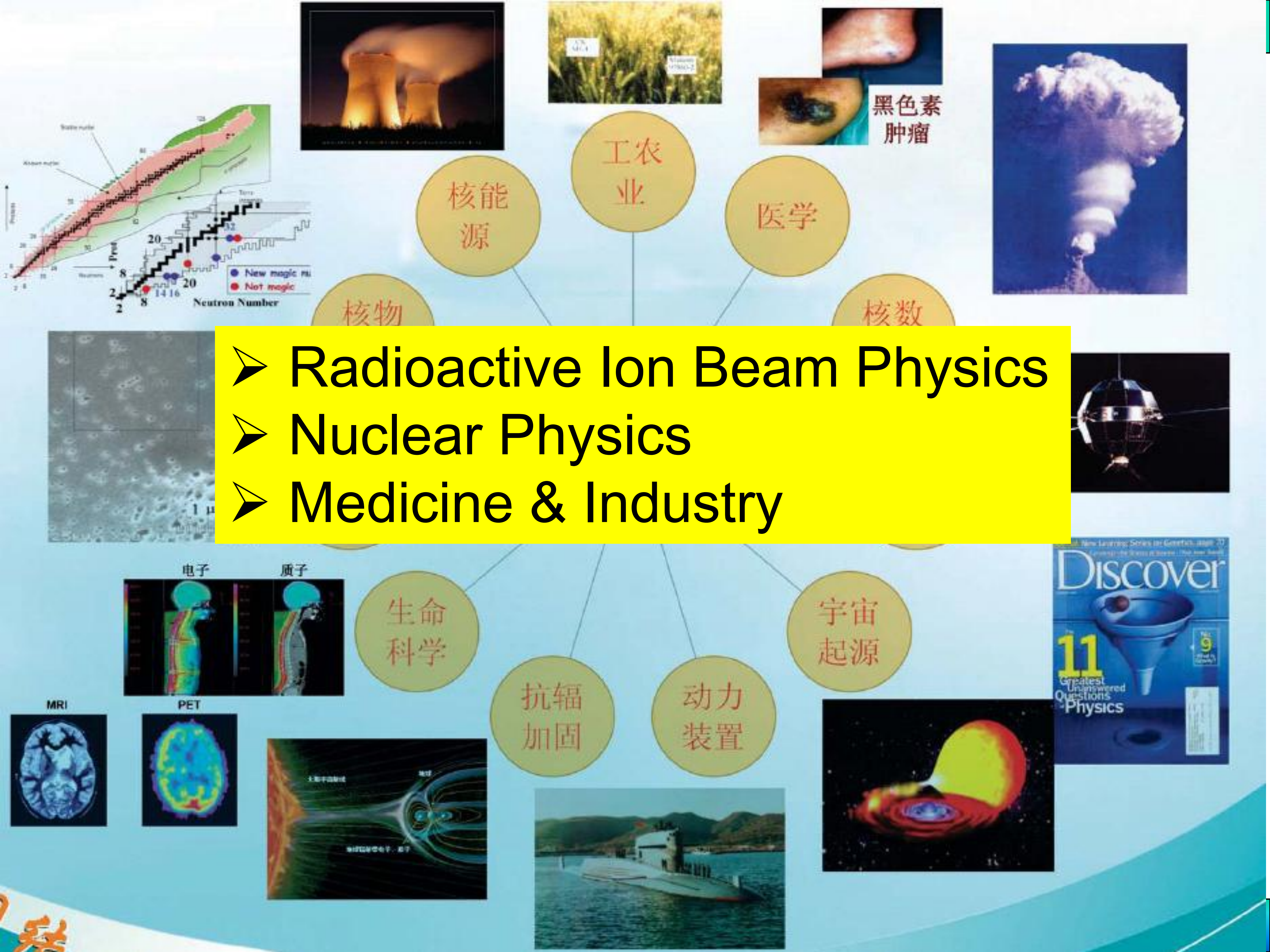




Compact proton cyclotron
100 MeV 200 μA

Superconducting LINAC booster 2 MeV/q


HI-13 串列加速器主厅
HI-13 Tandem
超导直线加速器
门厅
Hall 1
R70
E1
R60
R50
E2
E3
Neutron
控制室
R20
L60
L50
L40
L20
E5
L30
L10
Hall 3
E6
Hall 2
E4
Q3D
测量室
计算机室
Old Building
New Building



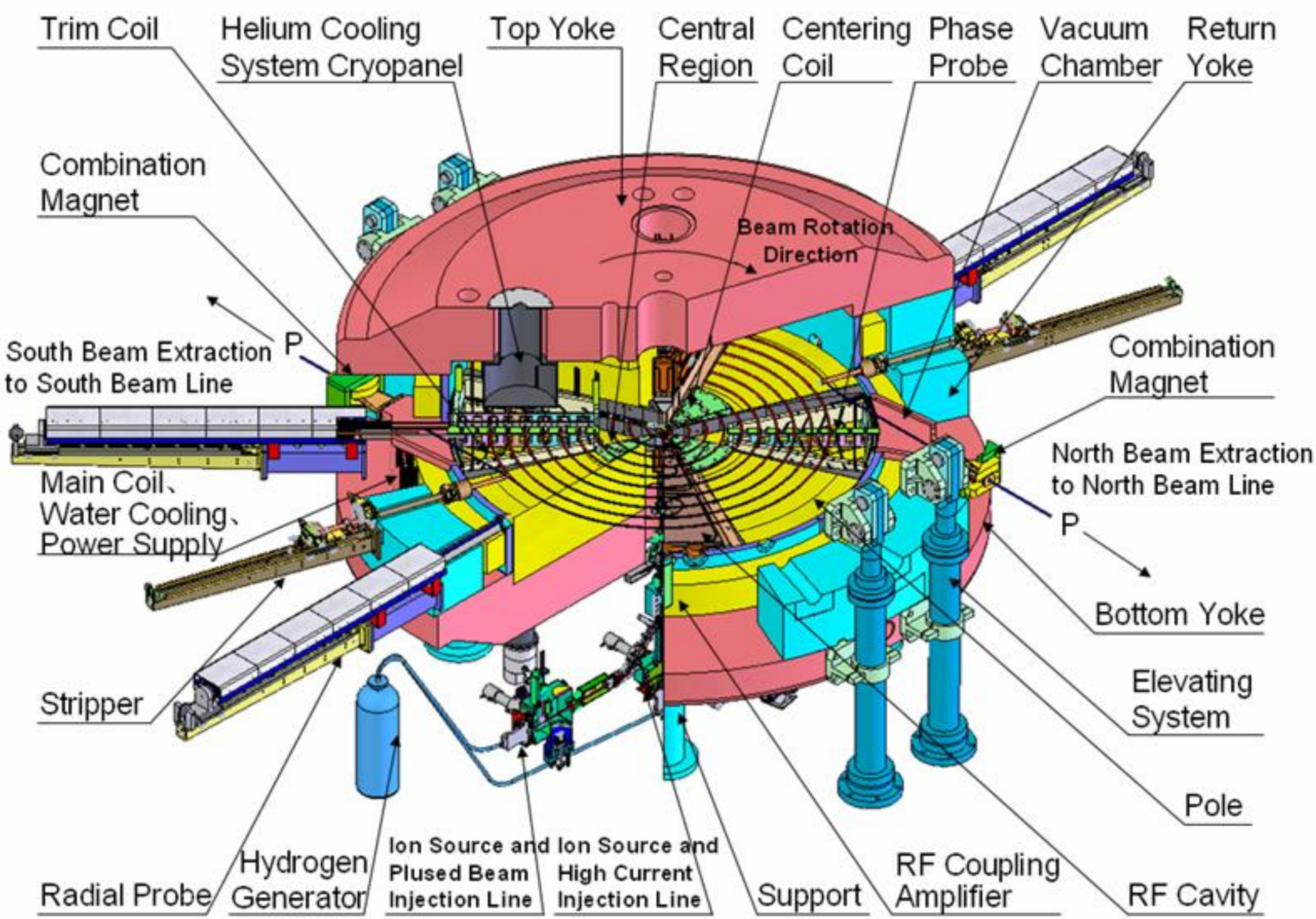
- Radioactive Ion Beam Physics
- Nuclear Physics
- Medicine & Industry

Commence building on 2011-4-28

2012-1-16

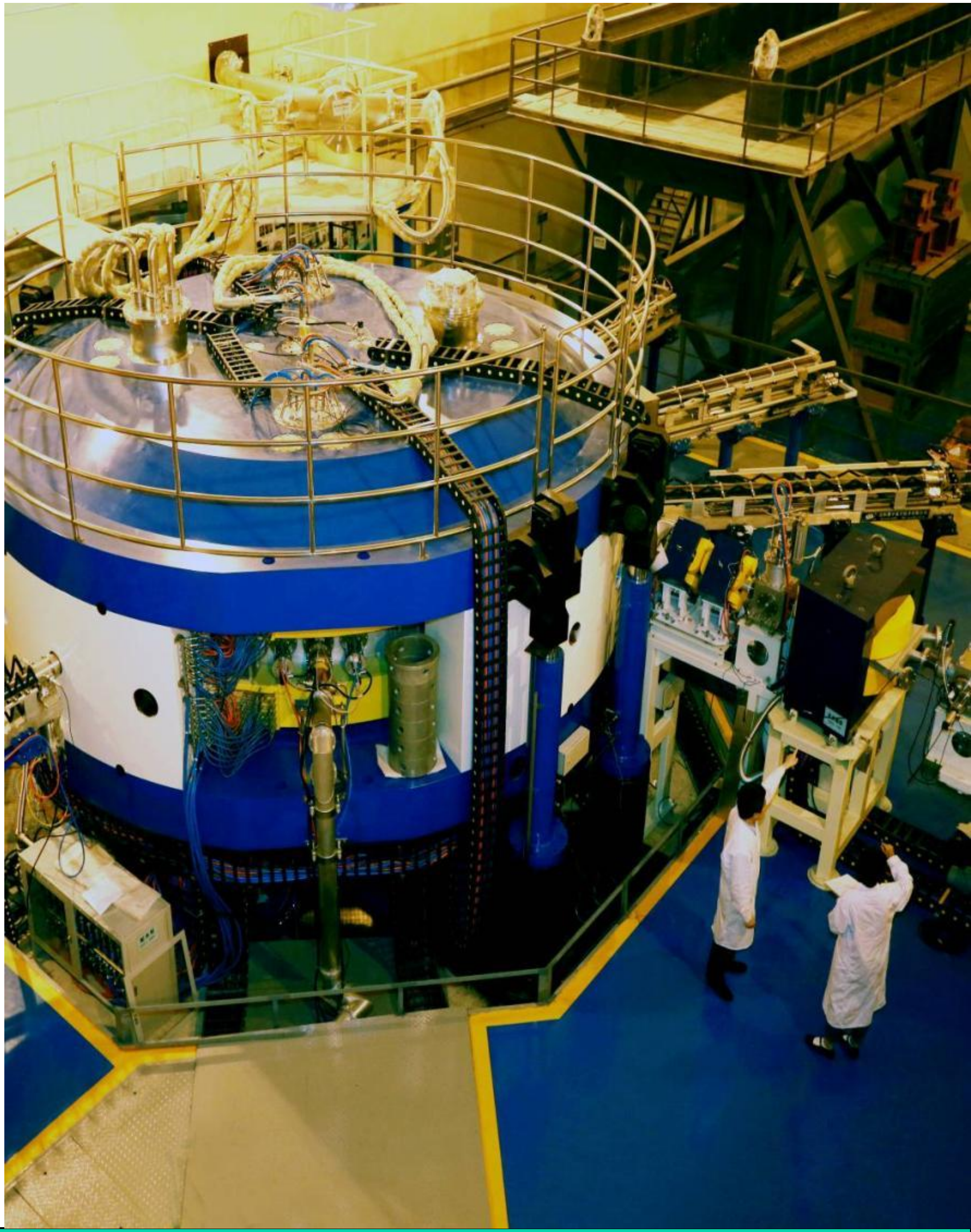
Now

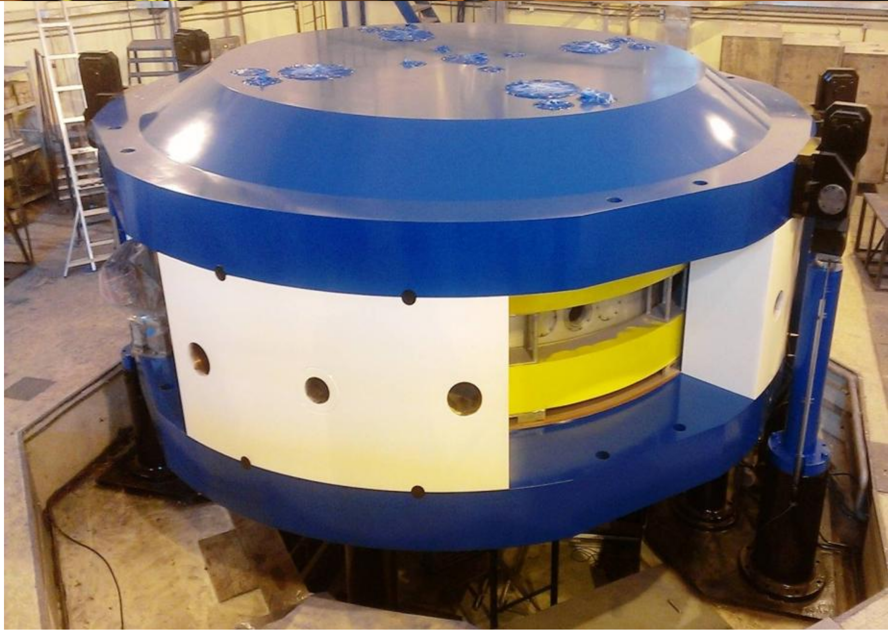
General View of the 100 MeV Cyclotron



Characteristics：

- Compact structure;
- CW mode, high beam current；
- High electric power conversion rate;
- 70-100MeV energy variable;
- Dual beam extracted simultaneously;
- Low extraction beam losses.

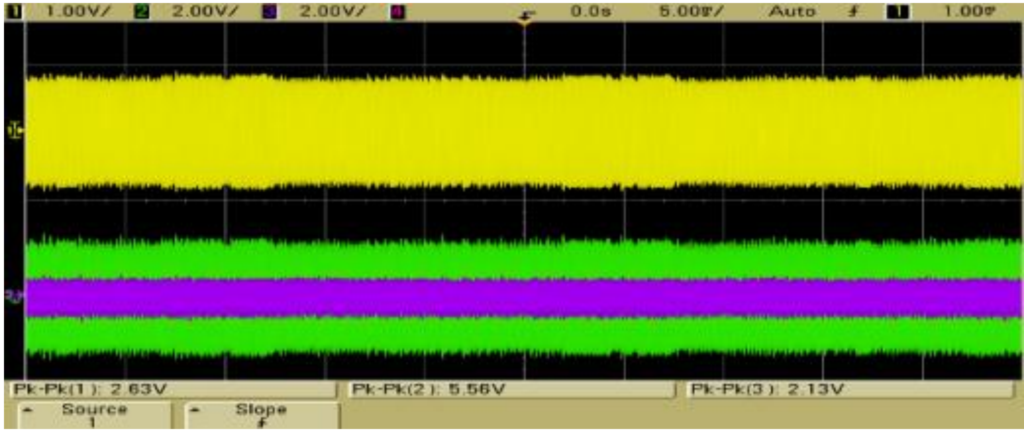




The installation, mapping and shimming of the main magnet system are finished by July, 2013, total weight is 436 tons

RF system

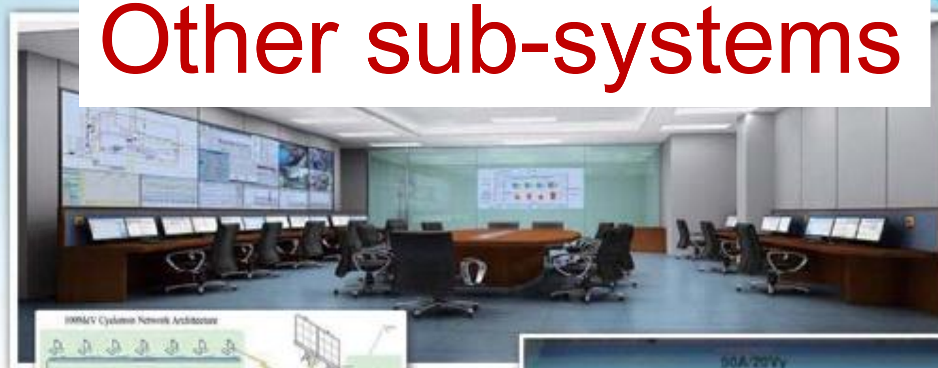
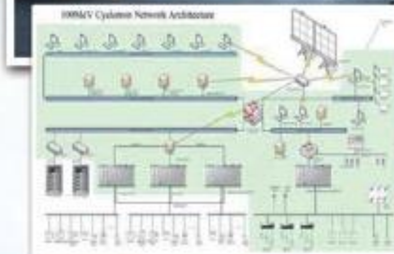
The measured Q factor reaches 9500， world record of the compact cyclotron



注入、引出、真空、控制、液压、电源等系统

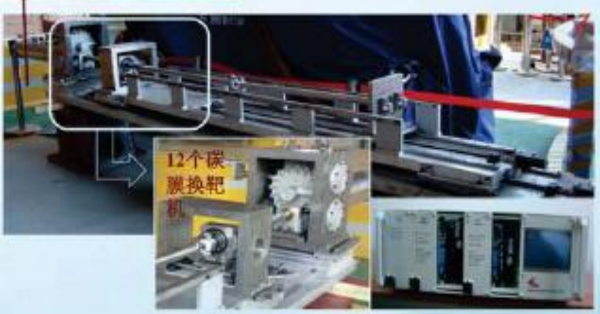
Other sub-systems


负氢离子源：18mA, 40keV

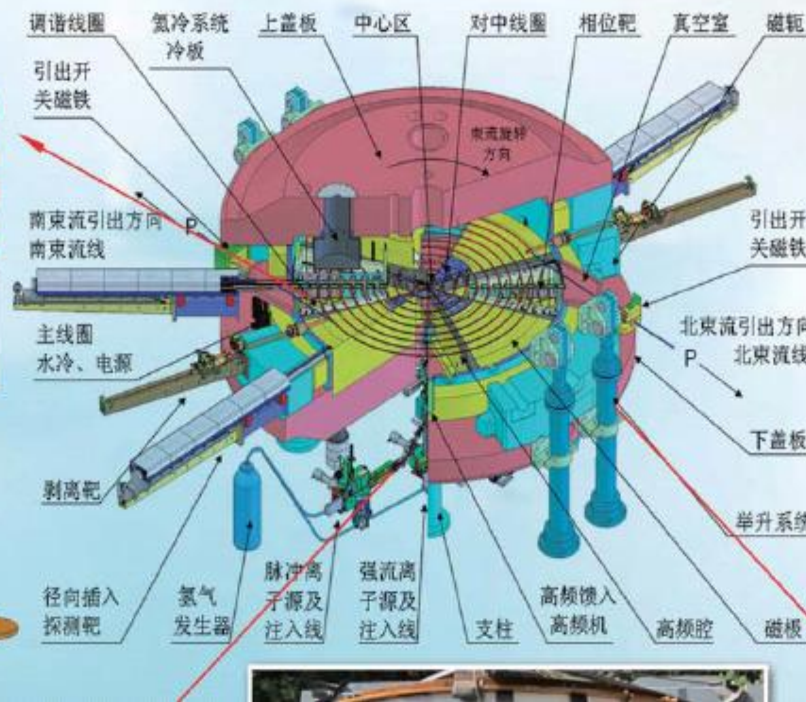




控制系统

75-100MeV可变能量引出开关磁铁

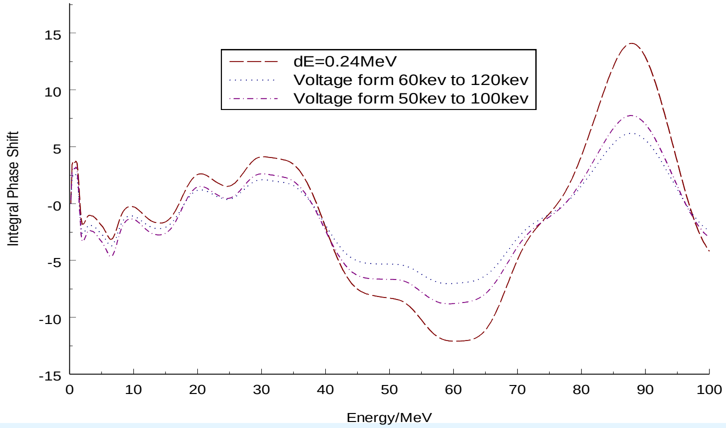


剥离引出系统

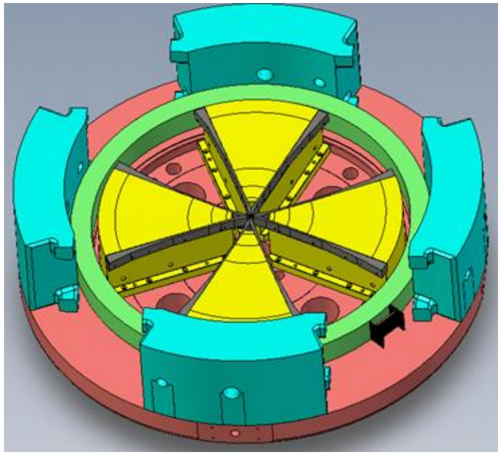


电源系统


中心区与注入偏转板

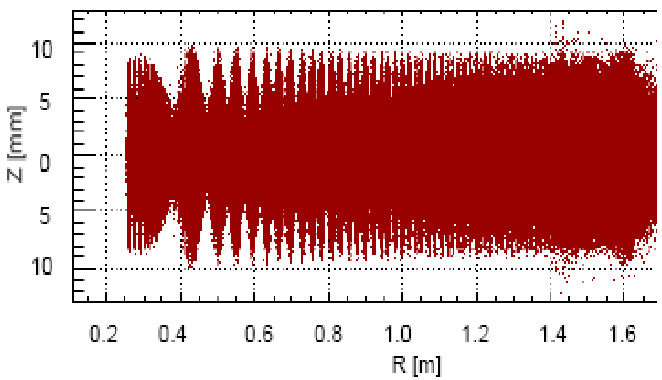


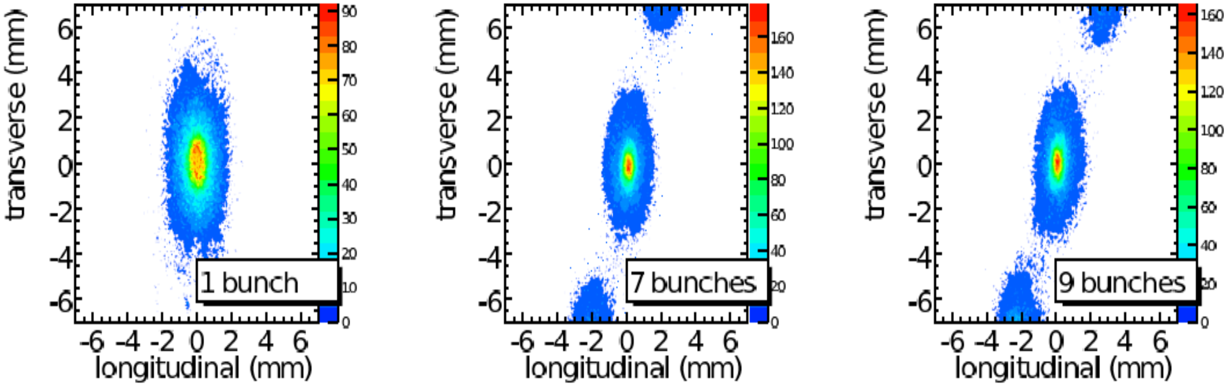
First compact cyclotron with straight sector pole for energy beyond 70 MeV in the world



Technical Innovations

Field map is measured in the vacuum for the first time in the world, the final phase slop less than ±10°





Developing a parallel computation code, which is implemented in 6 institutes to study space charge effects and multi-pacting effects.

Beam Commissioning

- The multi-cusp ion source was tuned up and could provide 5mA, 38 keV H^- beam.
- On December 18 of 2013, we got 320 μA DC beam on an internal target. The transmission efficiency from the ion source to the exit of inflector is higher than 60%.
- On June 16 of 2014, the internal target is moved to 1 MeV region and successfully catch 109 μA beam under the condition of 20% rf duty cycle, corresponding to an injection efficiency of more than 10%.
- we gradually increased the duty cycle and reached CW mode operation.



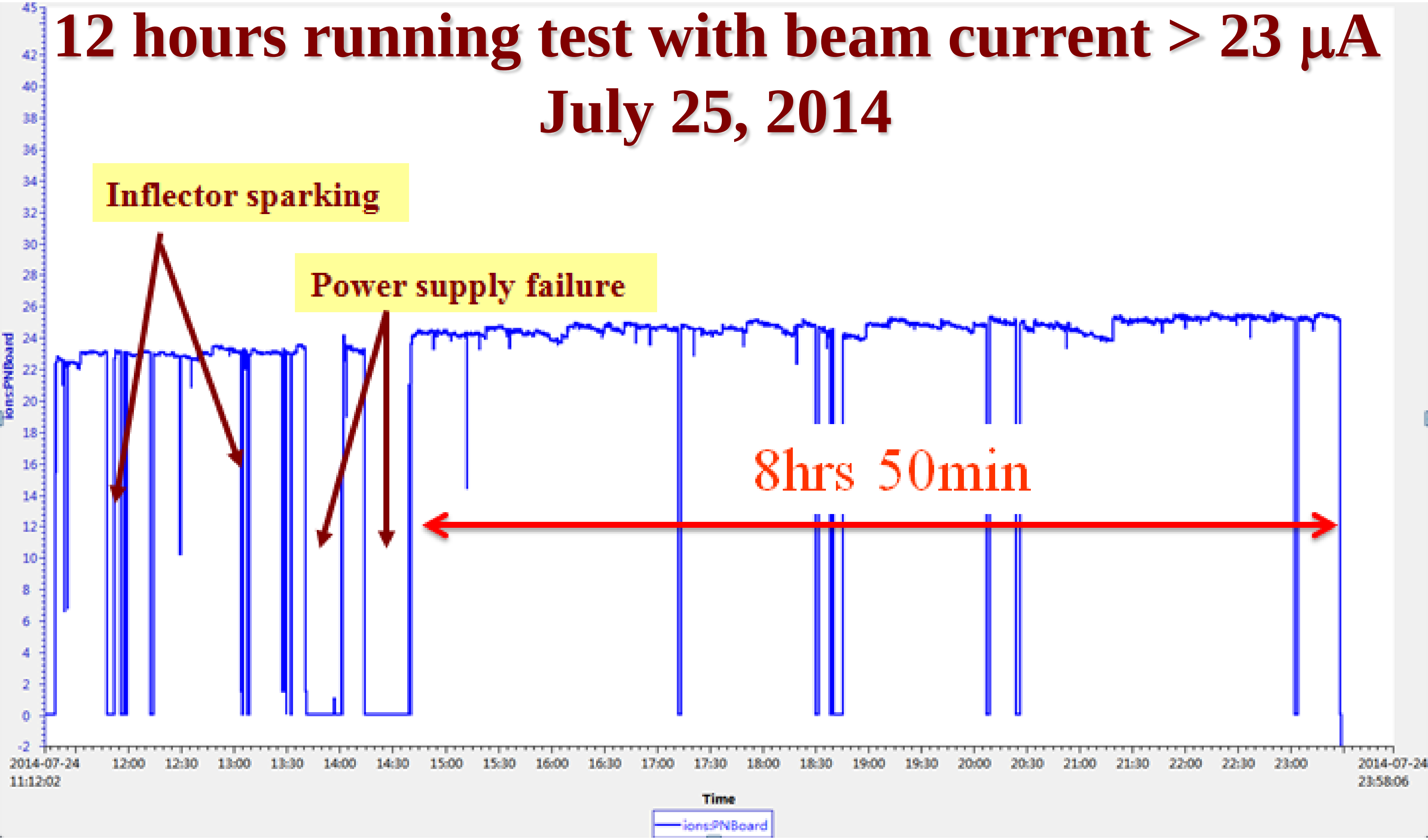


加速器外荧光
靶上束斑




July 4, 2014, First 100 MeV Proton Beam Witness

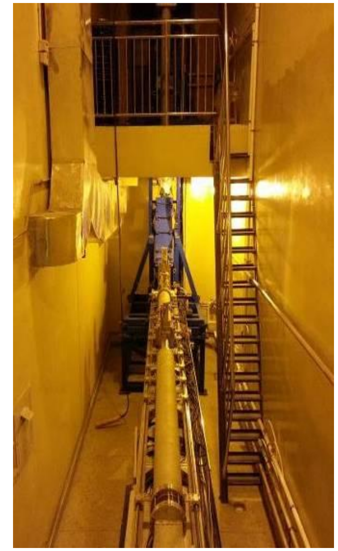
12 hours running test with beam current > 23 μA
July 25, 2014

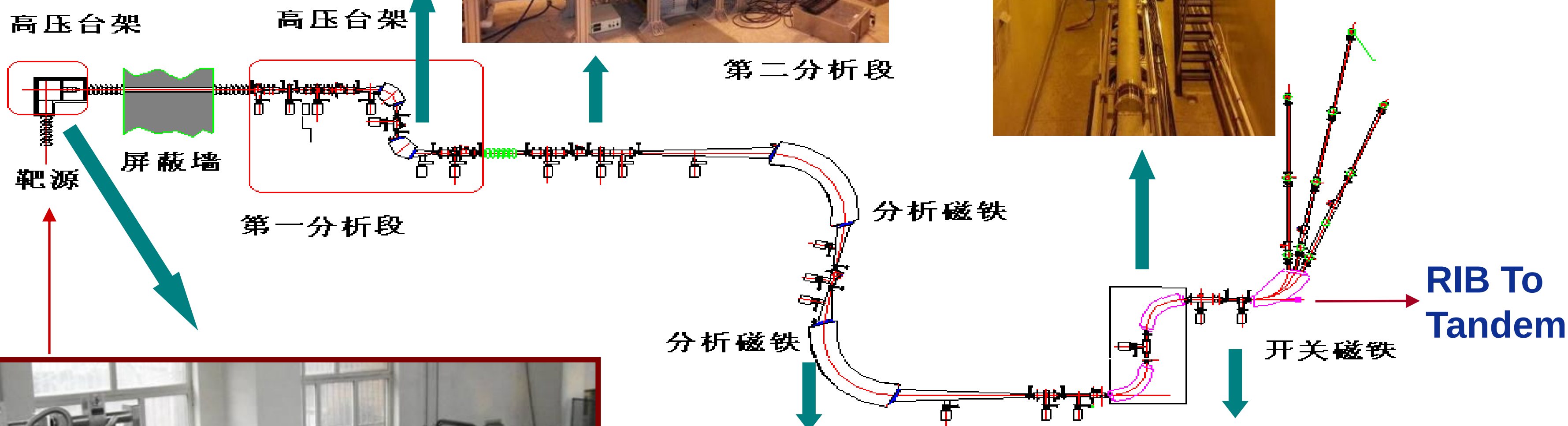


CCTV、新华社、中国新闻社、人民网、凤凰网、《科技日报》、《光明日报》《经济日报》、《中国科学报》、《中国军工报》、《中国核工业报》、《健康报》和北京电视台等多家地方电视台和网络媒体陆续报道。

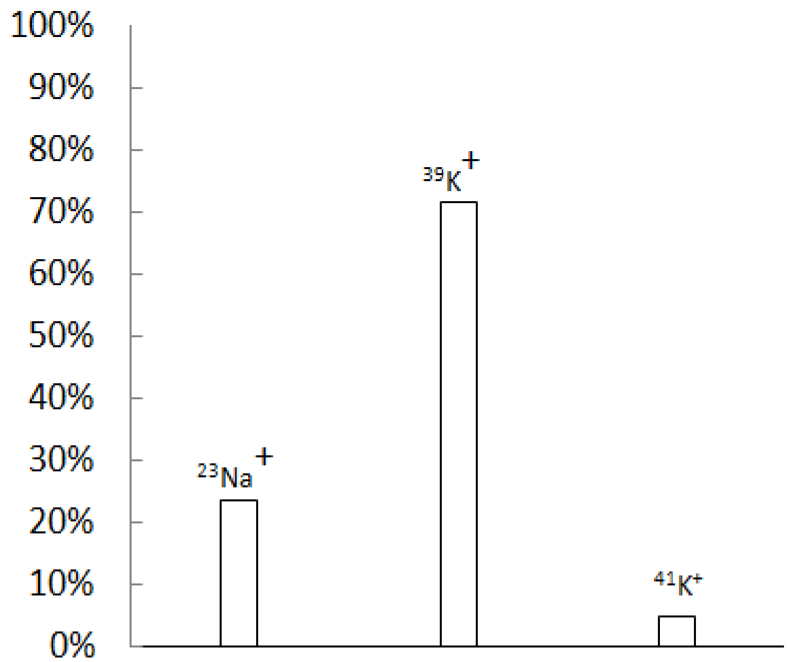
Media Reports

The ISOL System





The ISOL System



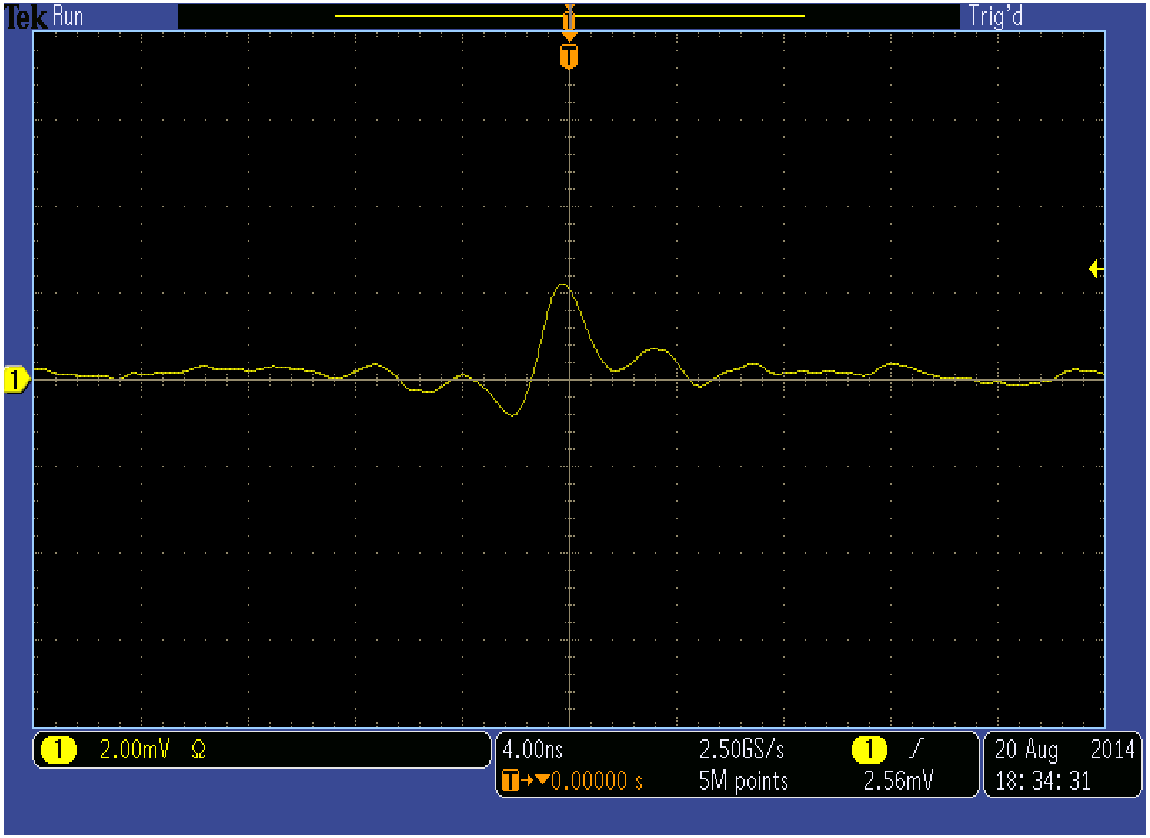
- In May of 2014, the stable ^{39}K beam is tested for commissioning and is successfully transported to the front of the HI-13 tandem.
- The mass resolution is better than 10000. The transmission efficiency is higher than 70% under the high mass resolution condition.

Superconducting Booster

- In March of 2014, The sputtering experiment for the first QWR cavity is done and the measured quality factor is about 3×10^8.
- During low-temperature test, the power is successfully fed into the cavity and the measured accelerating gradient is 2.5MV/m.
- the procedure of low-temperature rf conditioning is established and the functionalities of the low-level rf control system were debugged in detail.

The QWR cavity before and after the sputtering process

Superconducting Booster

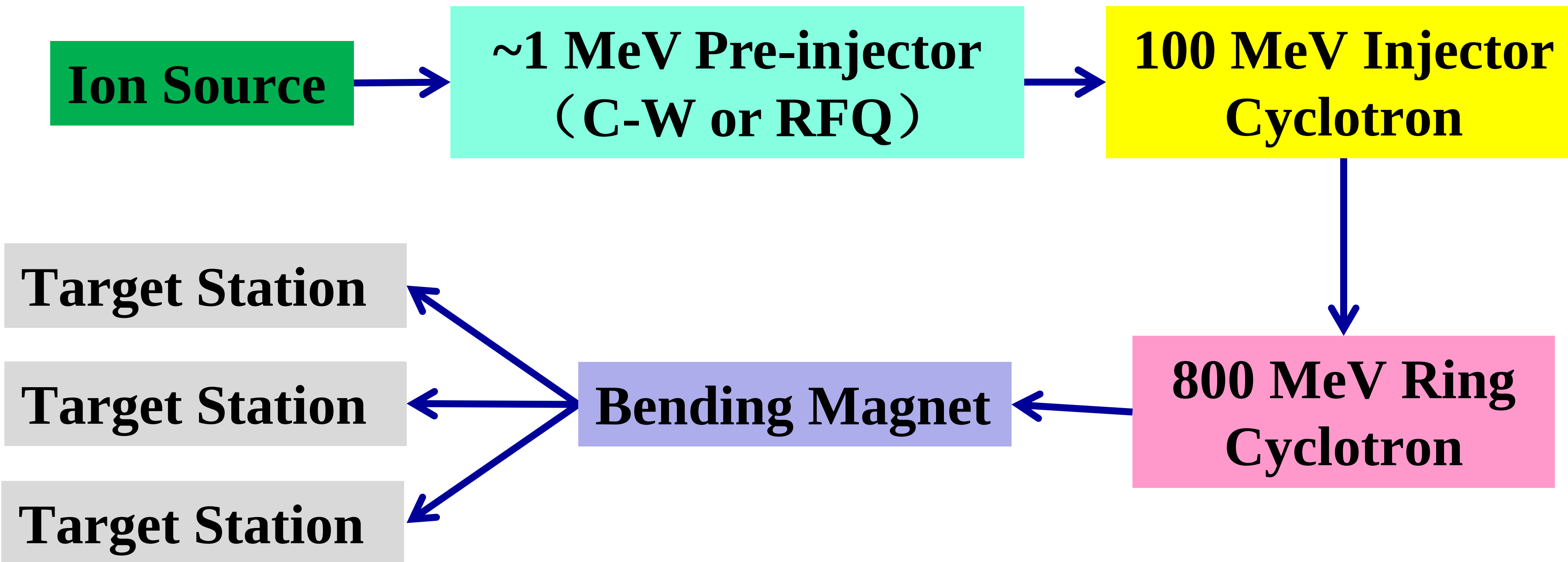


The measured wave profile of the pulsed beam by using the capacitive ring (FWHM of beam length is 2 ns)

- The beam-loading experiment of the pulsing system is carried out for 2 times.
- The pulsing equipment results agreed well with the designing. We tested the chopper and buncher by using the oxygen beam.

- ☐ The Beam Commissioning of BRIF
- ☐ **Future Cyclotron Development at CIAE**

CIAE High Power Cyclotron Proposal



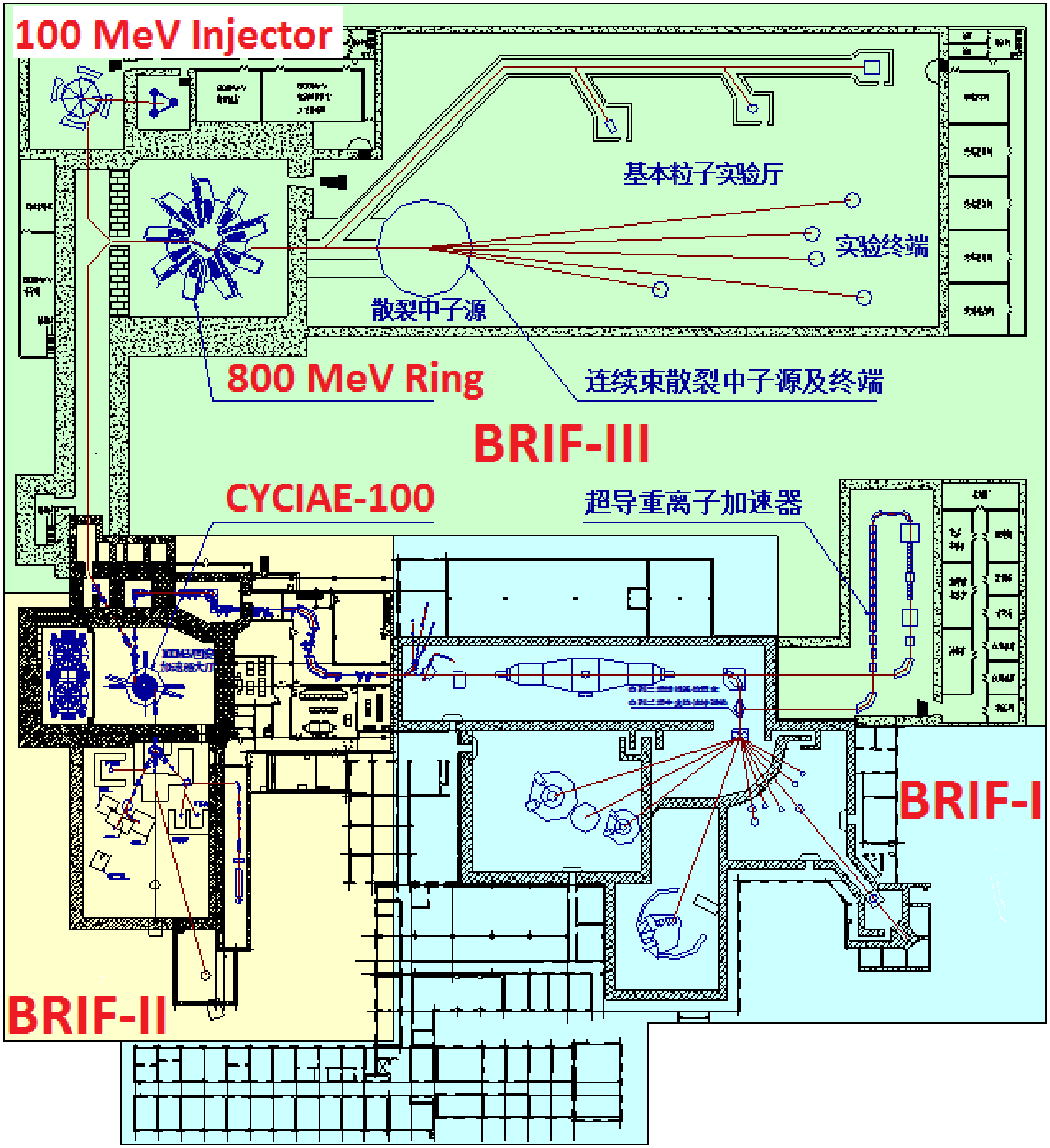
Our option: p

(rather than H_2^+)

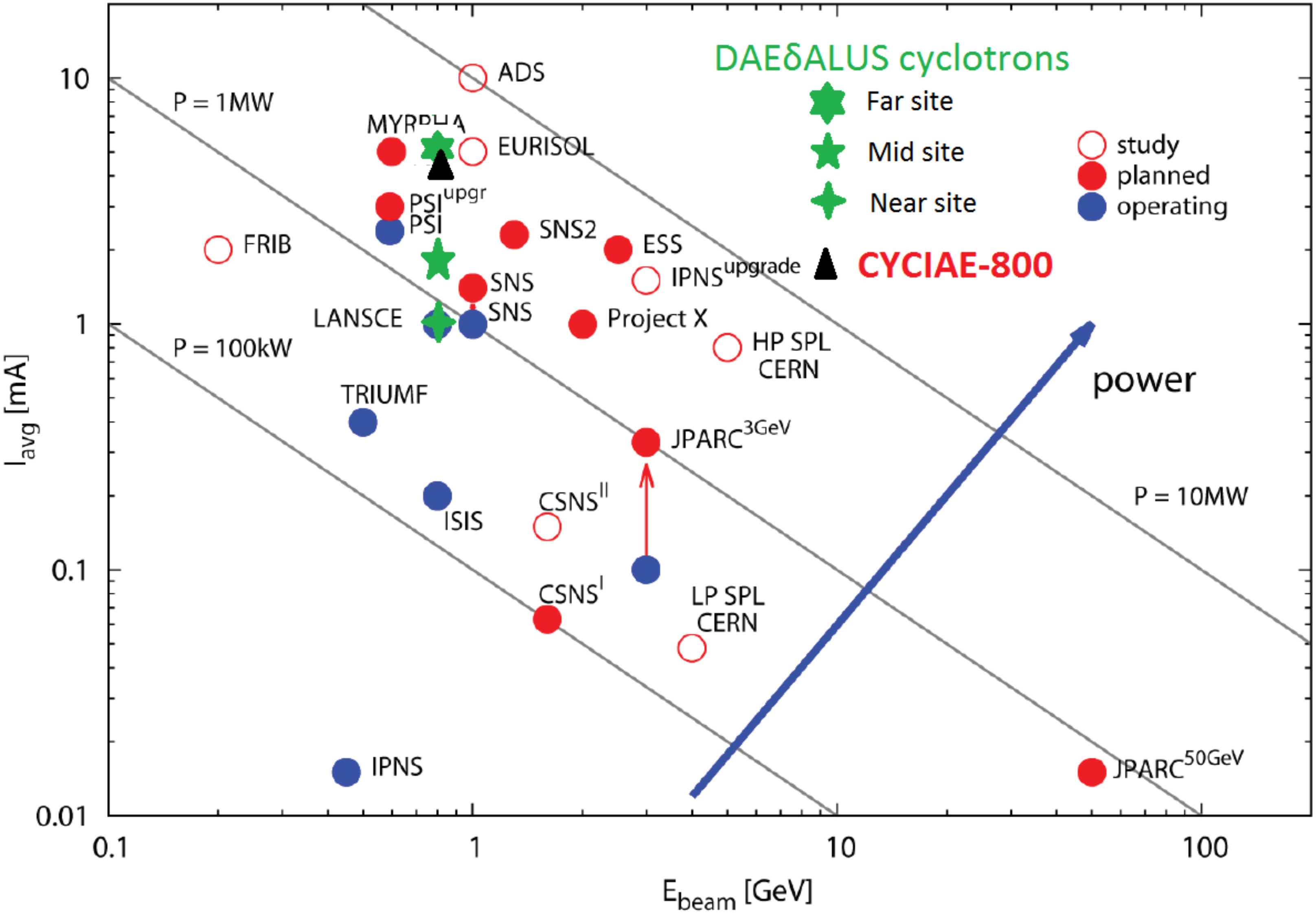
- Better extracted beam quality
- Mature technology
- Lower engineering risk

CIAE Proposal

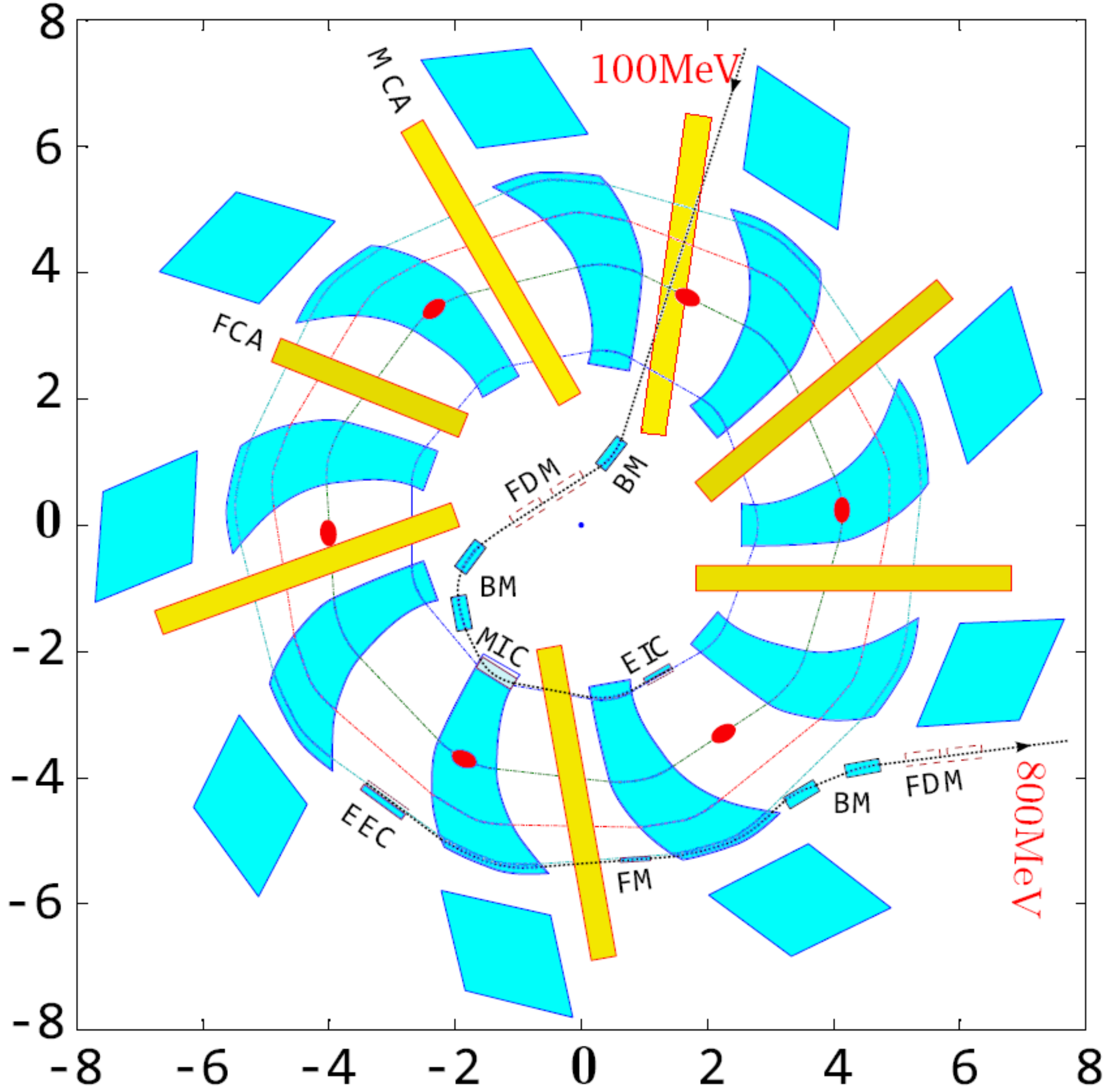
We proposed an 800 MeV high power proton cyclotron complex to provide high power proton beam for ADS, neutron science, proton radiography, radioactive ion production and other high power applications.



Top proton beam power accelerators



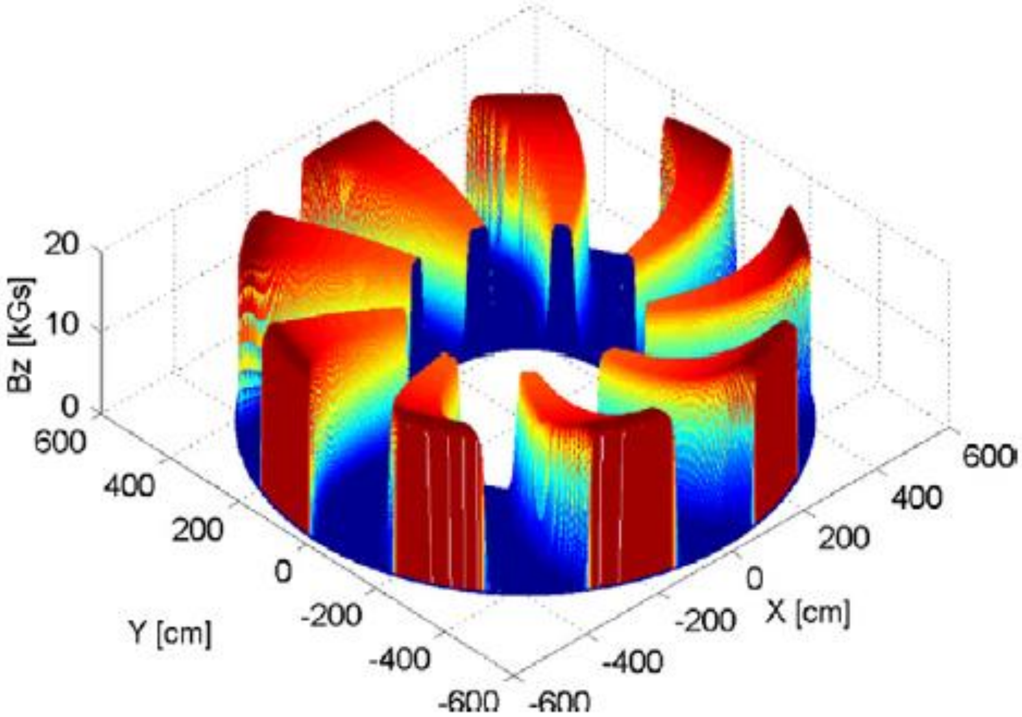
Layout of the 800MeV cyclotron



pole number	**9**
kinetic energy (MeV)	**100-800**
magnetic rigidity (T·m)	**1.48-4.88**
average orbit radius (m)	**2.76-5.42**
cyclotron radius (m)	**8.0**
RF frequency(MHz)	**44.37**
harmonic number	
main cavity number	**5**
flat-top cavity number	**1 or 2**
Q_r / Q_z at extraction	**1.55/1.40**
Q_r max/min	**1.85/1.10**
Q_z max/min	**1.40/1.05**
dR/dn at extraction (mm)	**7 (centering injection)**
dR/dn max/min (mm)	**35/6**

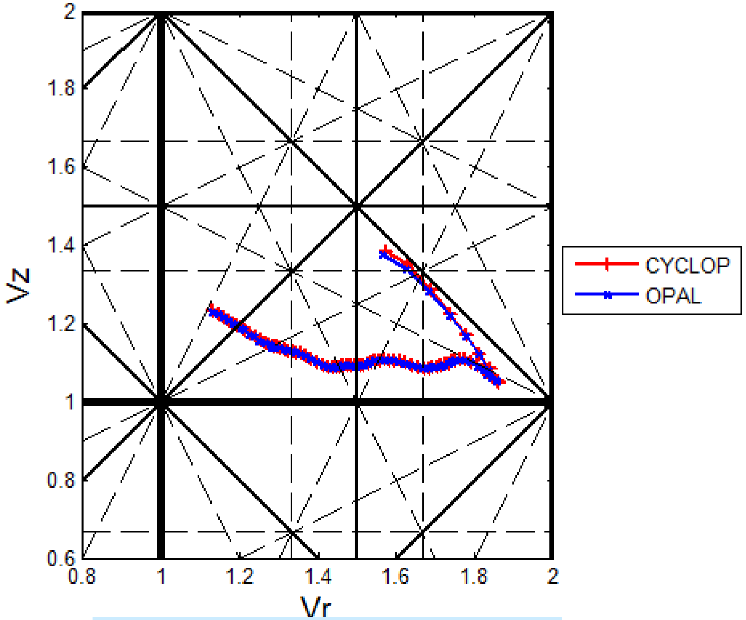
[T.J. Zhang et al., NIM-B,2011]

Ideal Field Map

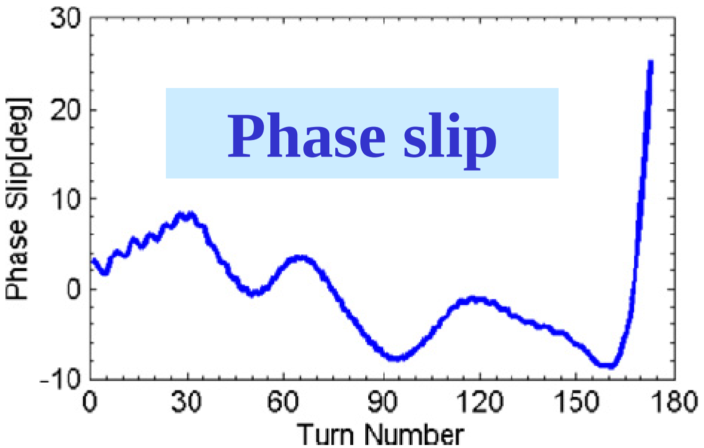


$$r = \beta \frac{c}{\omega_0}, \quad \bar{B}_0(r) = \gamma(r) \cdot B_{\text{center}},$$

$$B_z(r,x) = B_s(r)\left(1 + \exp\sum_{i=0}^{5} c_i x^i\right)^{-1},$$

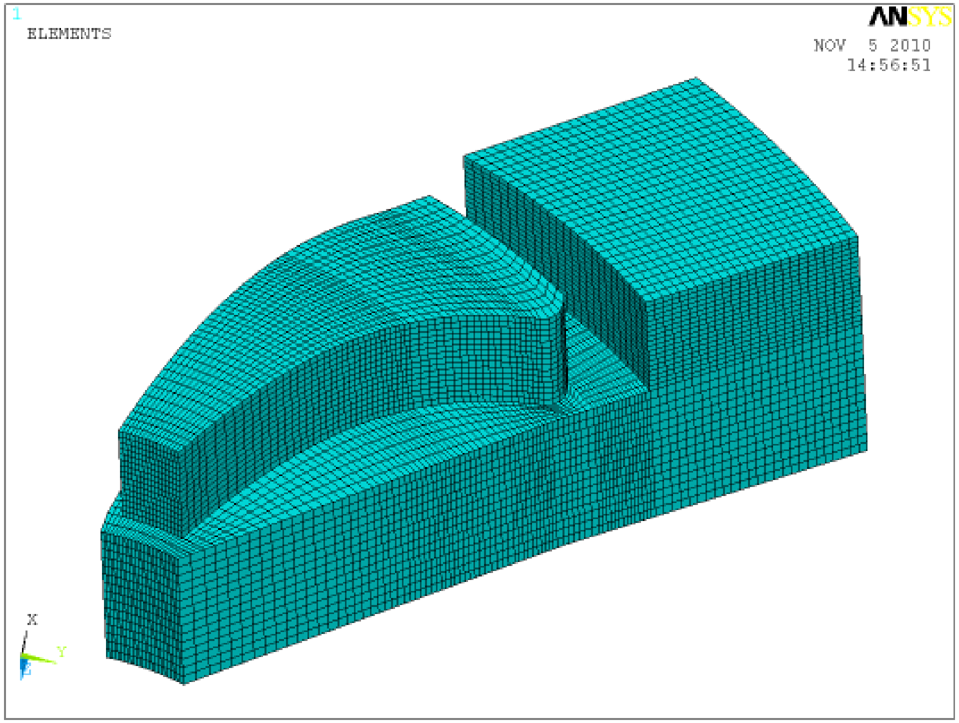


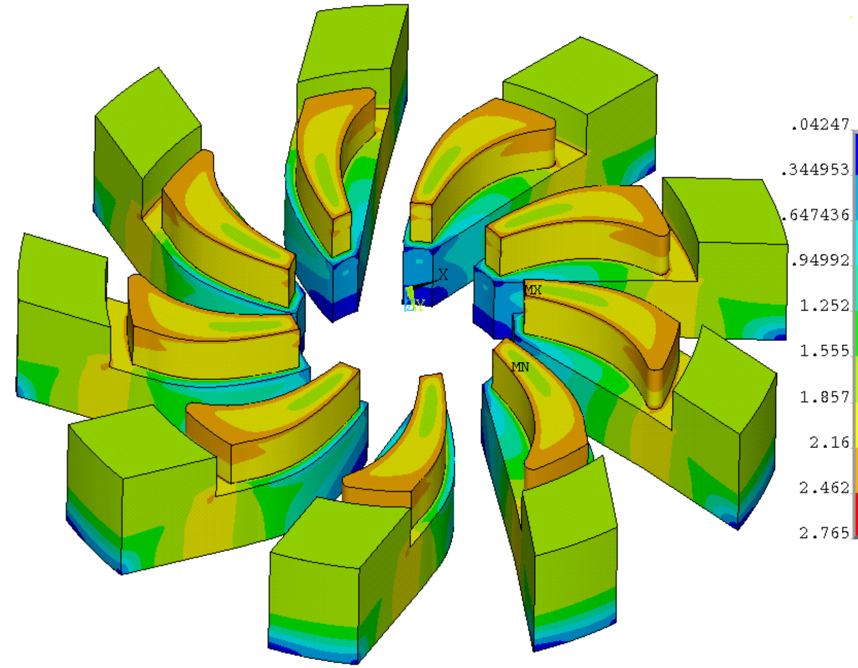
Tune diagram



Phase slip

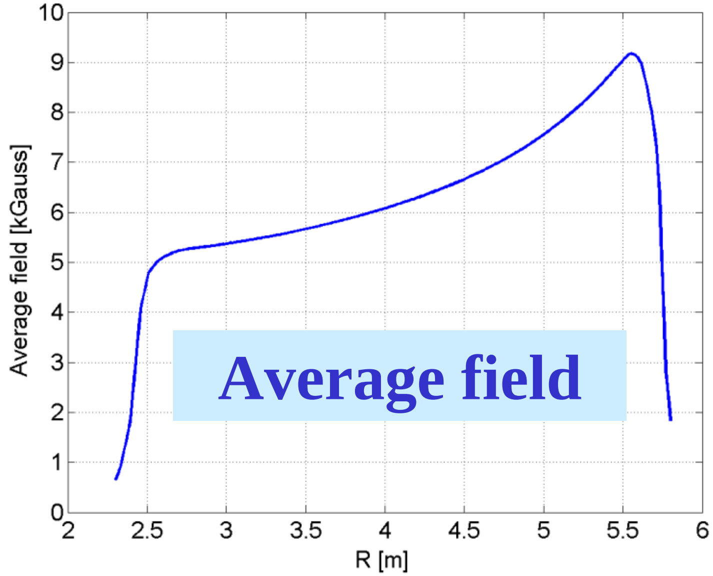
3D Magnet Design

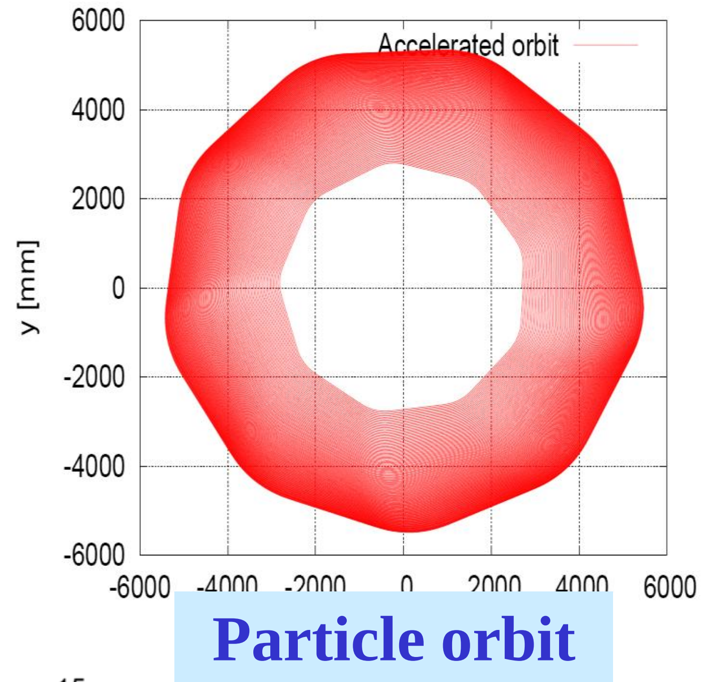


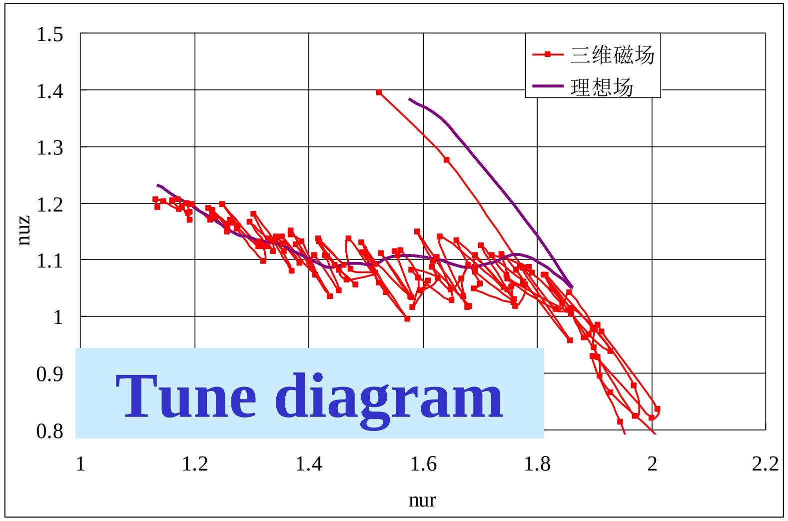


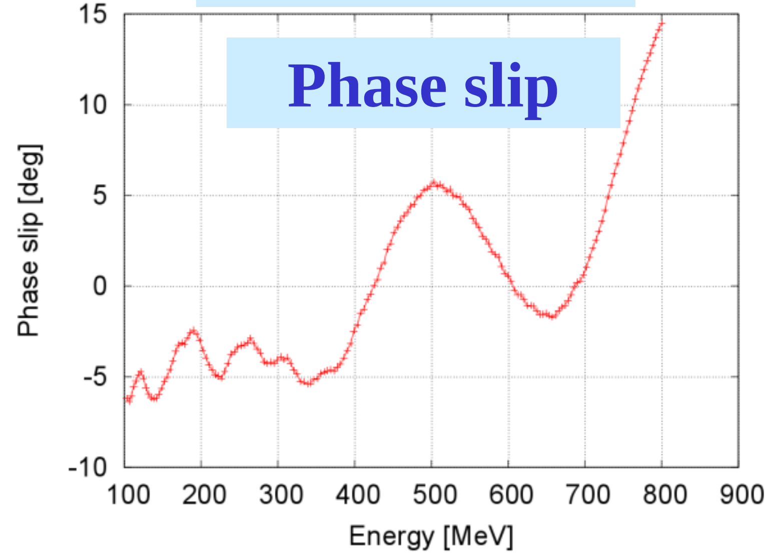
- 3D FEM magnet model is built
- Good isochronous magnetic field is found
- The design of normal ring conducting coil is straightforward

Beam Dynamic Design



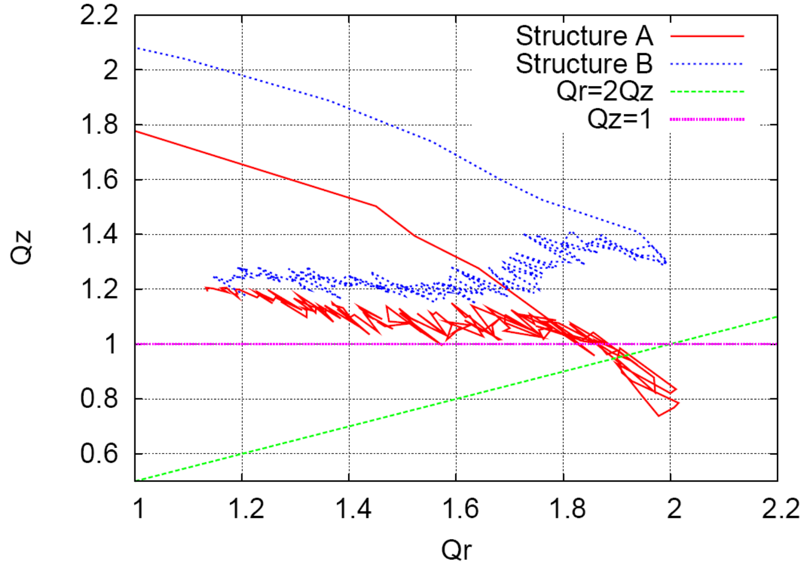


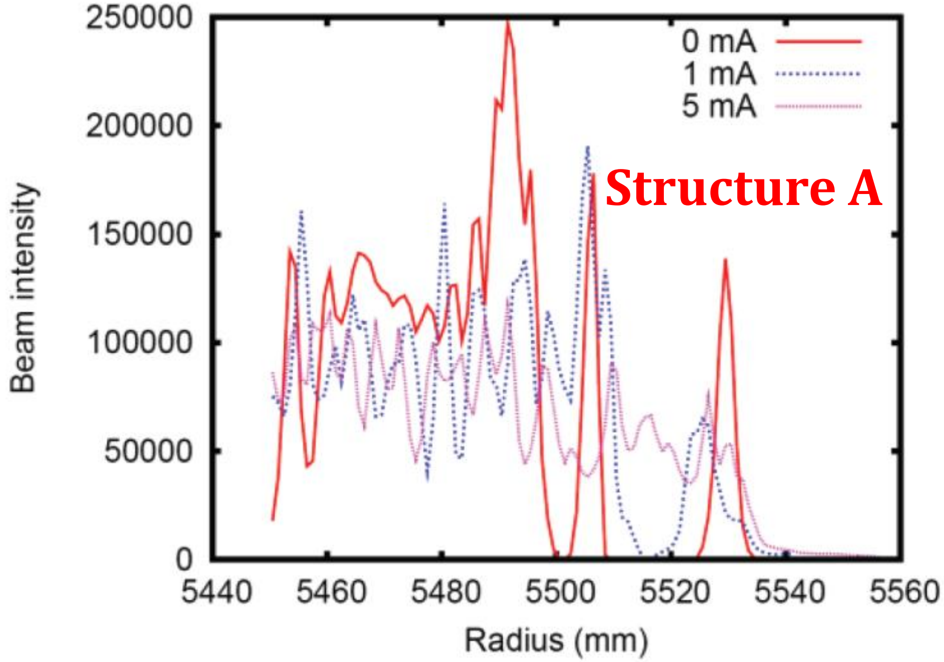


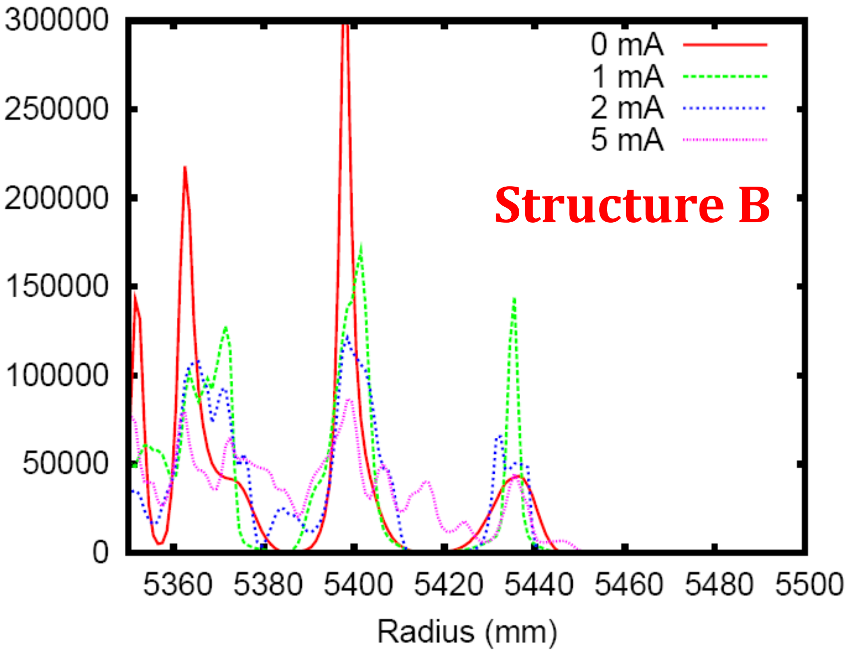


Space charge simulation by OPAL-cycl

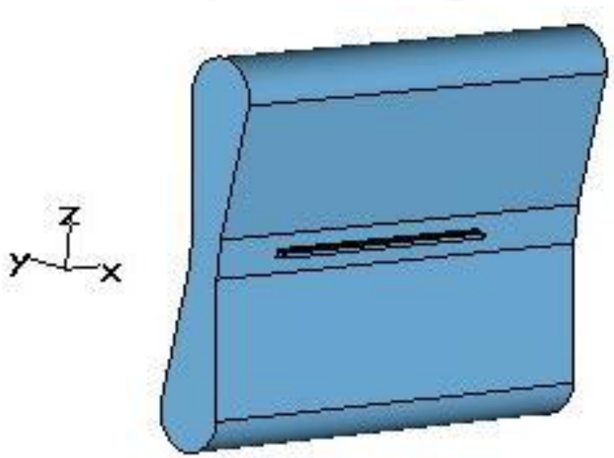
The space-charge-limited beam current is increased to 2 mA by avoiding the crossing of $Q_r=1$ and $Q_r=2Q_z$ resonance. More work need to further increase beam current.



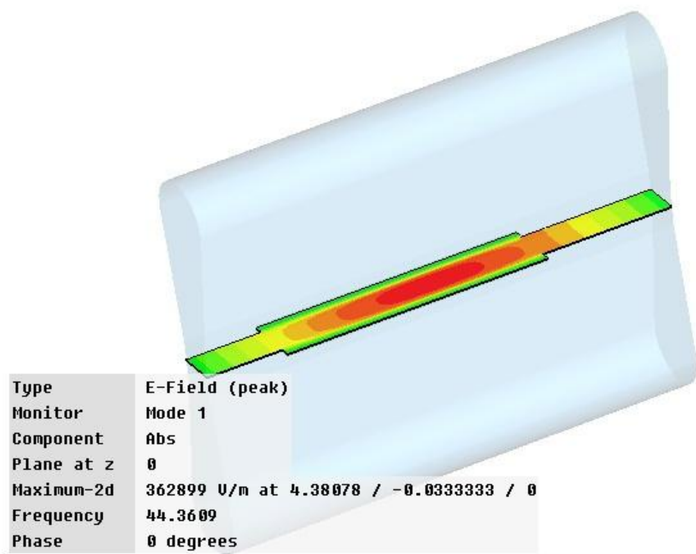


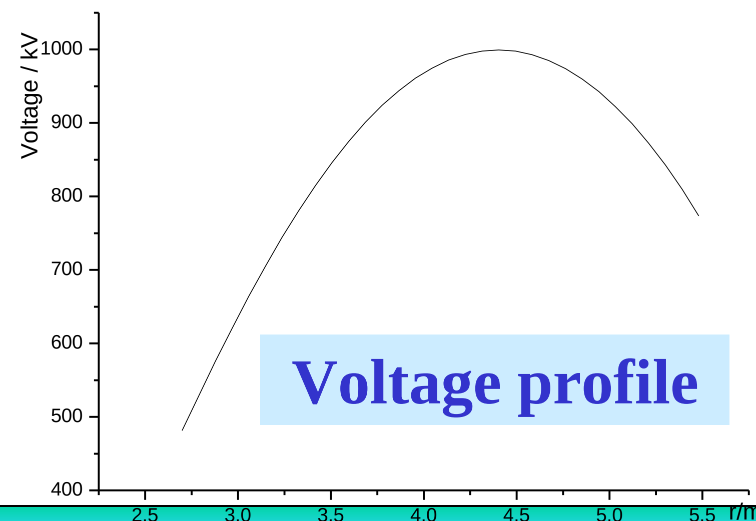


RF cavity design

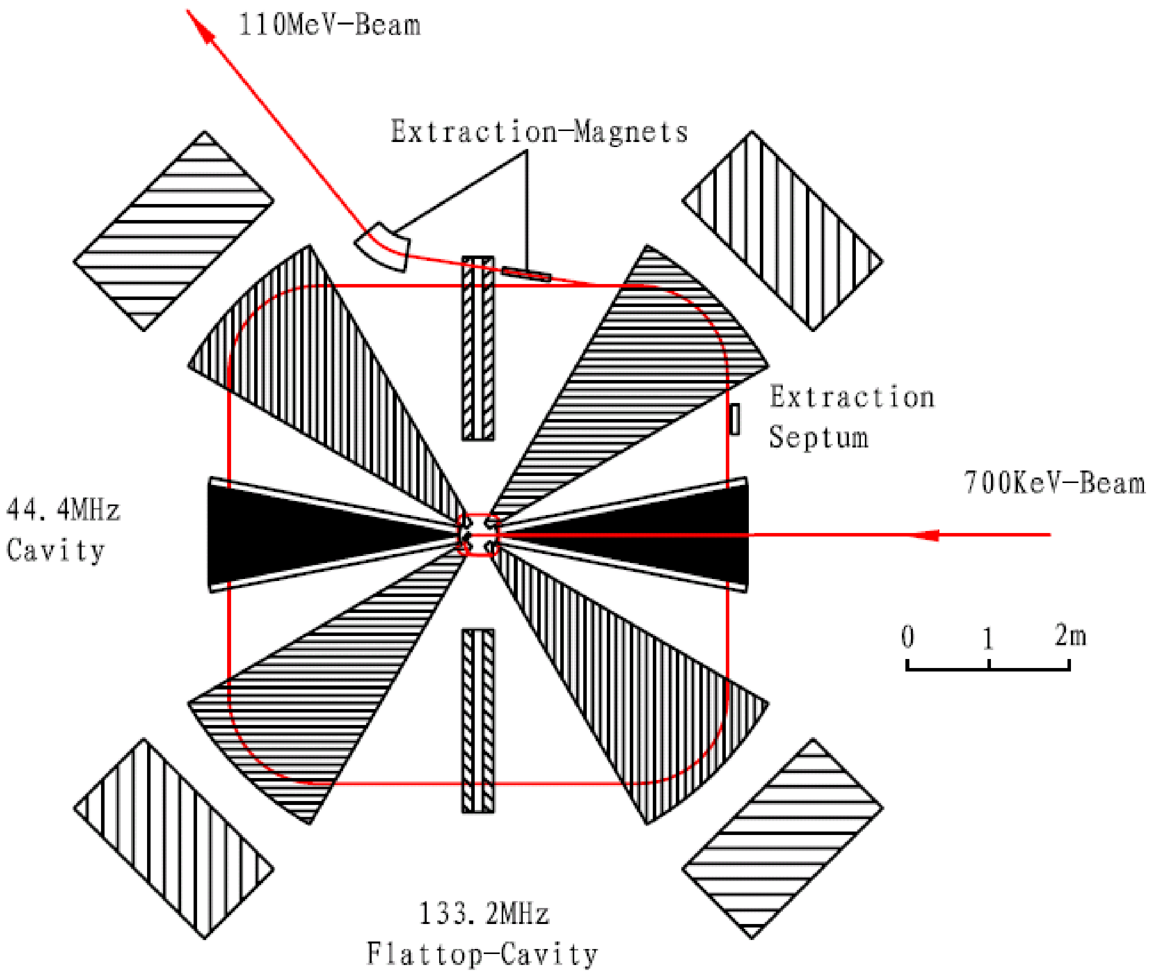


cavity number	**5**
peak voltage (MV)	**1.0**
frequency (MHz)	**44.37**
length (m)	**5.0**
height (m)	**3.63**
cavity center (m)	**4.4**
inner radius (m)	**1.9**
outer radius (m)	**6.9**
cavity width (m)	**0.4**
cavity azimuth (°)	**25.0**
cavity rotation angle (°)	**15.0**





Layout of the Injector



Magnet

pole type	**straight sector**
pole number	**4**
hill field (T)	**1.15**
average field (T)	**0.36-0.41**
pole radius (mm)	**4134**
Azimuth width (°)	**22-30**
hill gap (mm)	**40**
yoke inner radius (mm)	**4300**
yoke outer radius (mm)	**6100**

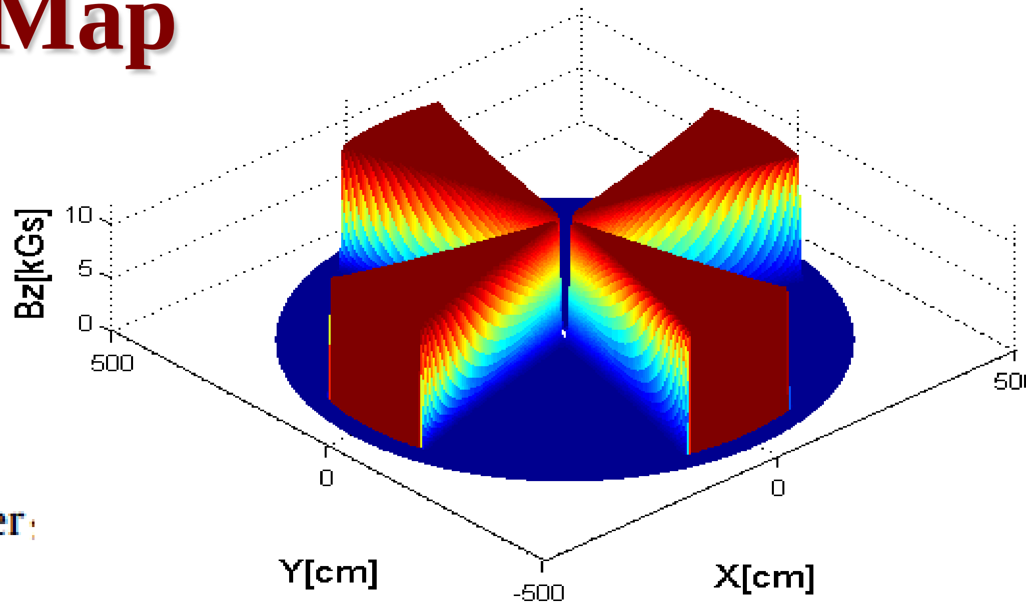
Cavity

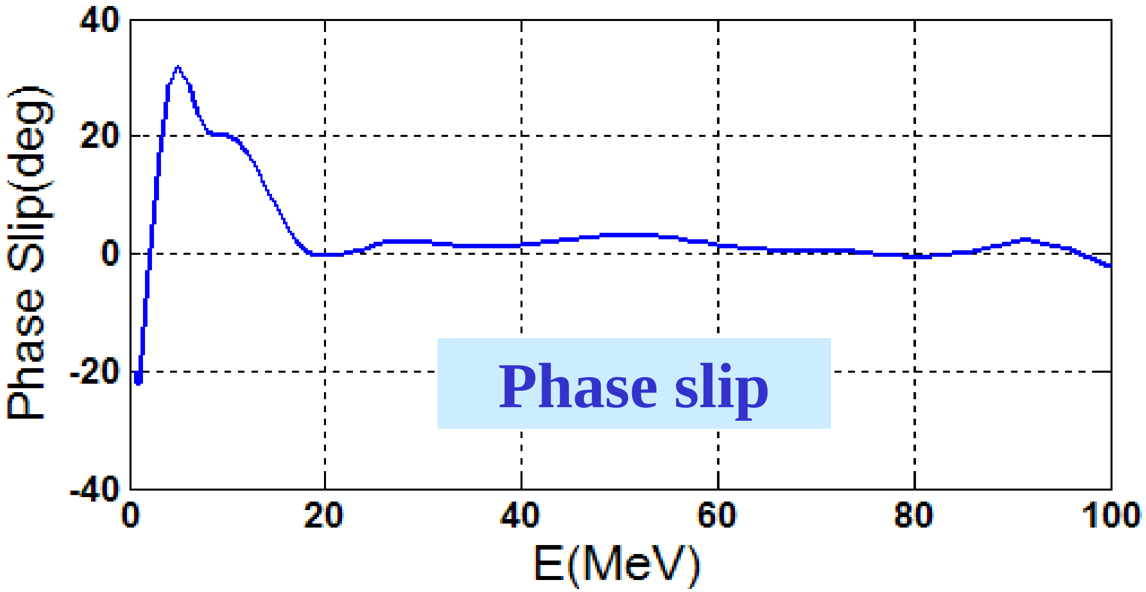
cavity number	**2**
cavity type	**double-gap**
outer radius (mm)	**3900**
Dee angle (°)	**22.5**
peak voltage (kV)	**500**

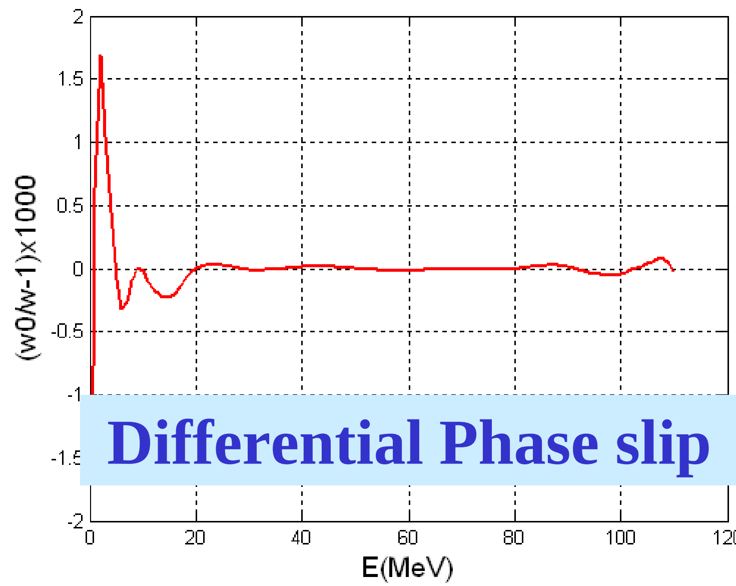
Injector: Ideal Field Map

$$B_z(r,x) = B_s(r)\left(1 + \exp\sum_{i=0}^{5} c_i x^i\right)^{-1},$$

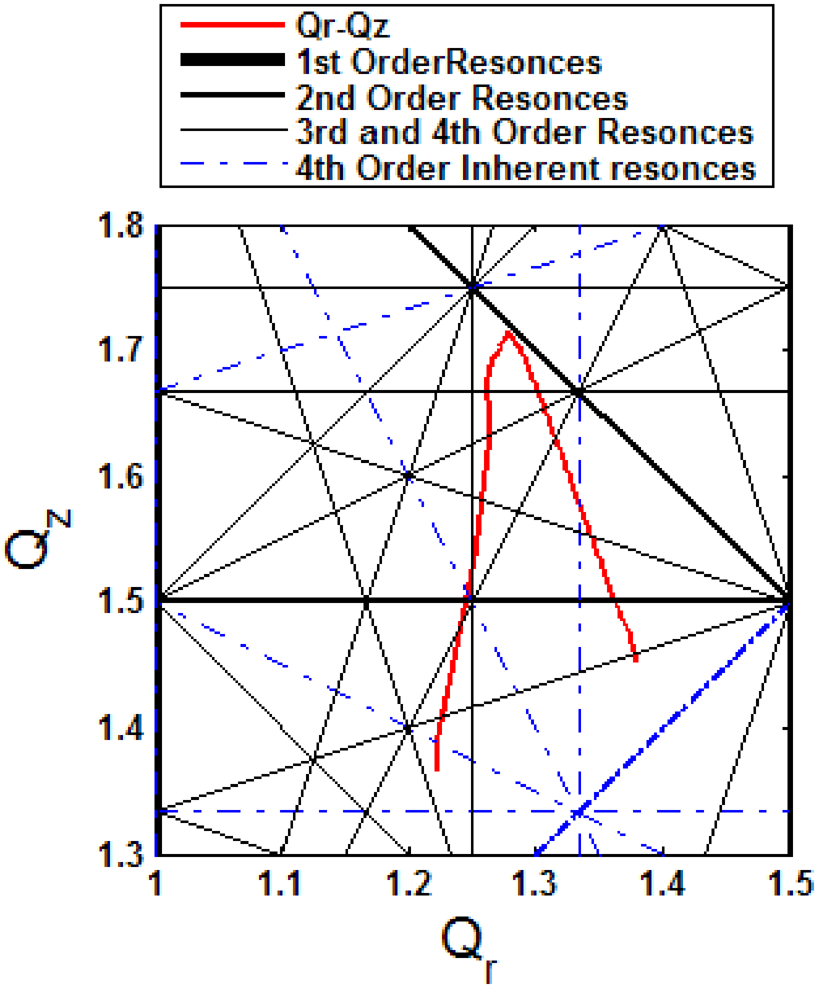
$$r = \beta\frac{c}{\omega_0}, \quad \bar{B}_0(r) = \gamma(r)\cdot B_{center}$$

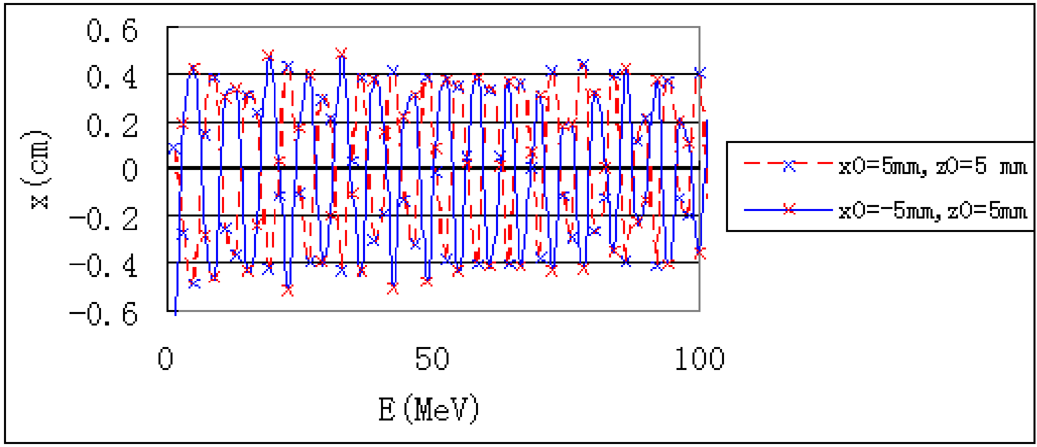


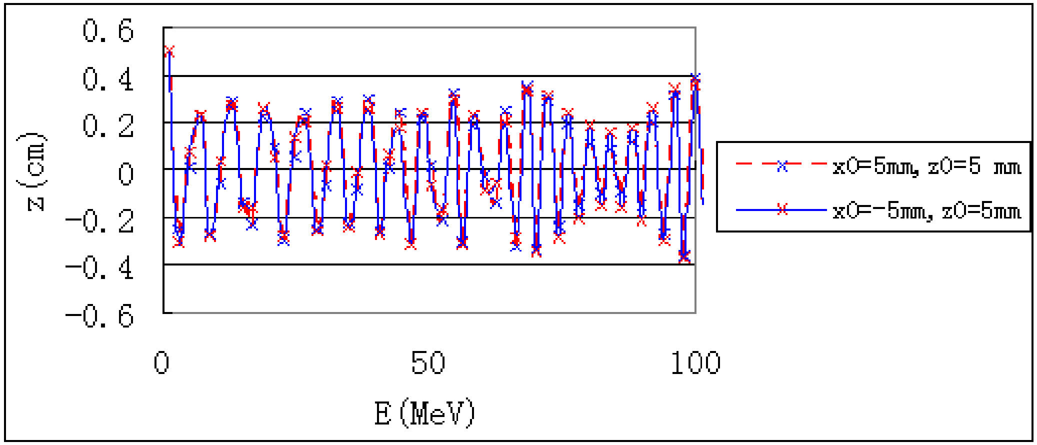




Injector: Betatron Tune and Resonance







Conclusion: the resonance-crossing will not bring evident influence on the beam’s quality.

Summary

- The beam commissioning of the three sub-systems of the BRIF project is in progress. The results show that the driver of 100 MeV cyclotron will be able to provide 200-500 μA proton beam in the coming years. The joint commissioning of the three sub-systems for RIB production is expected to start soon.
- From the pre-study of an 800 MeV high power cyclotron complex, it is confirmed that a 3-4 MW cw proton machine should be feasible based on our existing technologies. We are eagerly expecting extensive international collaborations.

Acknowledgement

- We would like to thank the people from the project team, e.g. Dr Baoqun Cui, Dr Zhaohua Peng, Mr Hui Yi et. al. to provide the materials.

- We also would like to extend our cordial gratitude to experts from **TRIUMF**, **PSI**, **INFN-LNS** and the international cyclotron community for their long-term support on the project.