BRIF: from the First Proton Beam to RIB Production

Tianjue Zhang Baoqun Cui and Yinlong Lv

China Institute of Atomic Energy

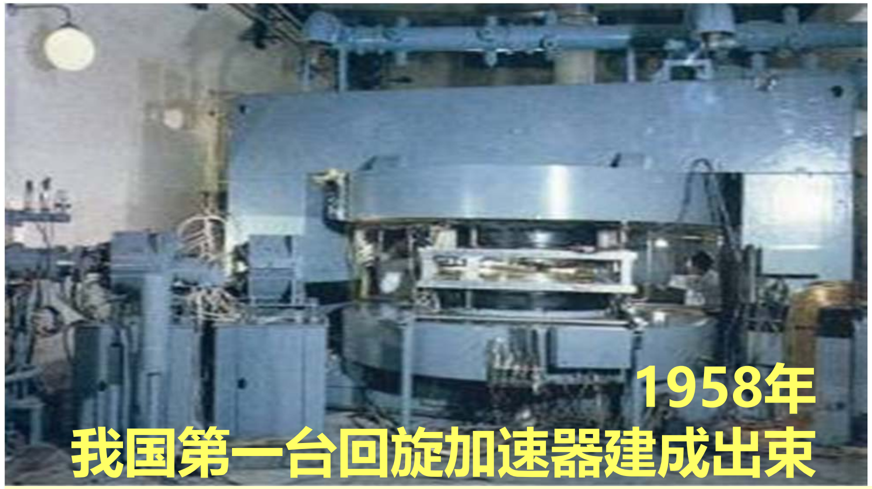
The location of CIAE

CIAE was found in 1950.

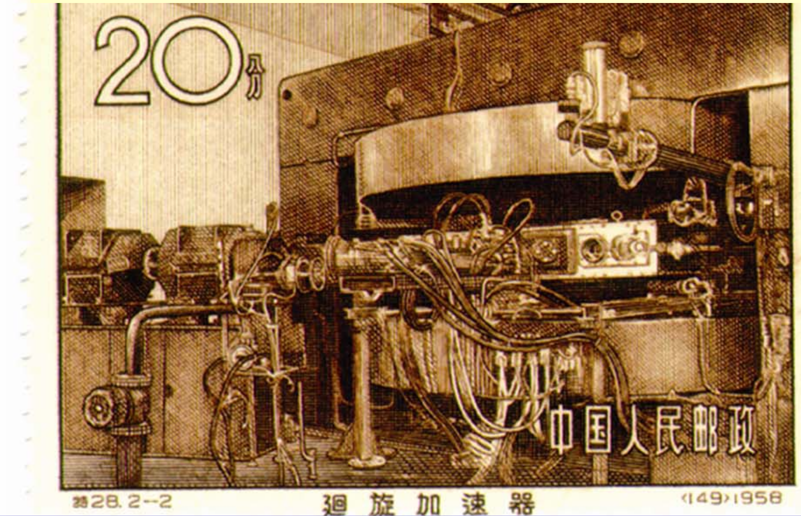

12 Accelerators
6 Reactors
Land:
900 k m²

The International Science and Technology Cooperation Forum for the 60th Anniversary of "First Reactor and First Cyclotron of China"

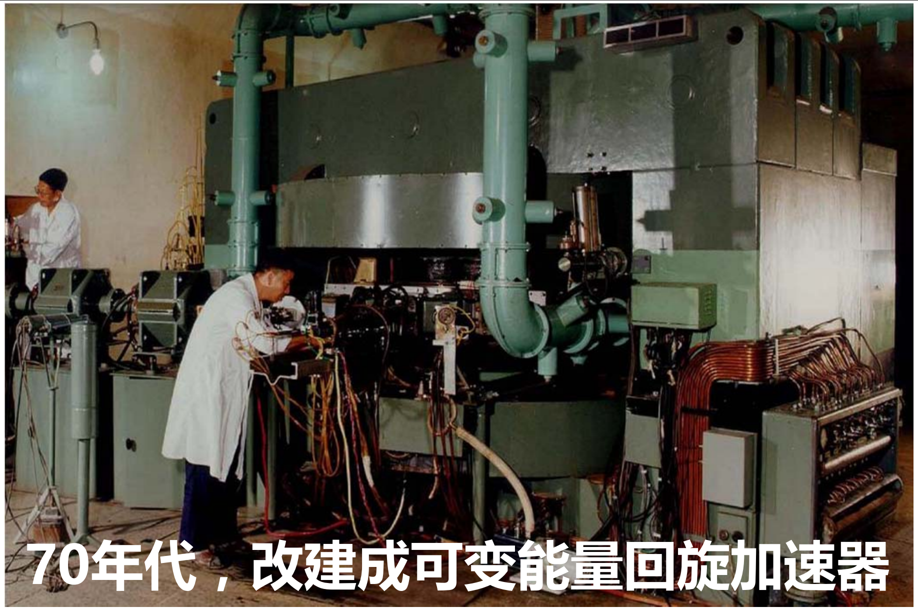
BRIF: from the First Proton Beam to RIB Production



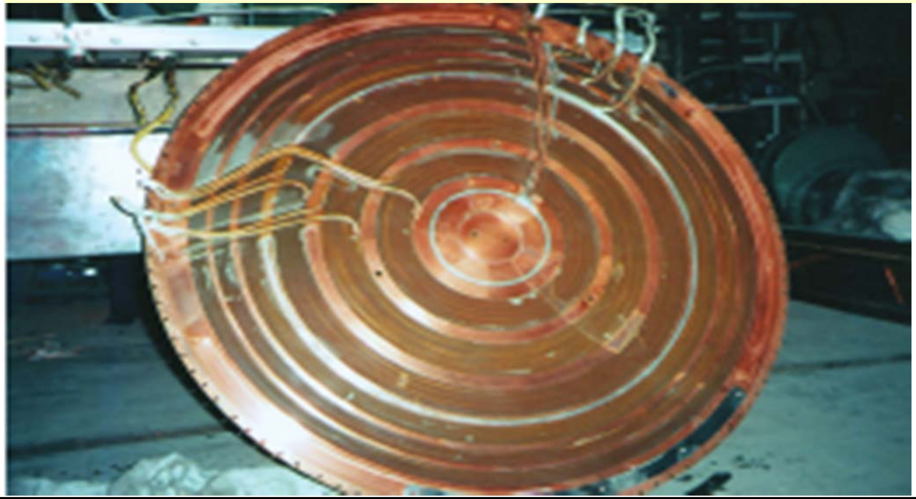
In 1958, the First Cyclotron was put into operation,
Vice Premier Chen Yi cut the ribbon at the ceremony

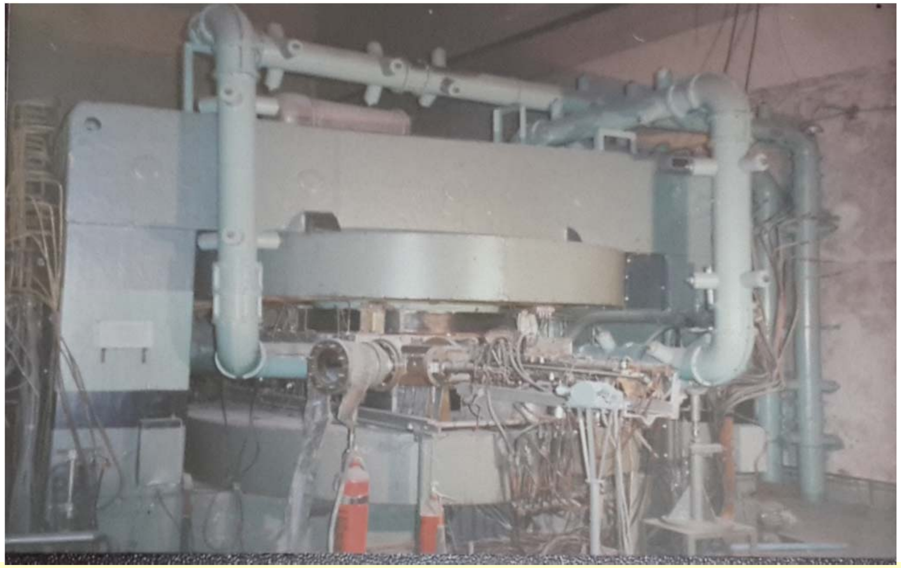


Vice Premier Chen Yi, Nie Rongzhen and other state leaders visited the cyclotron at the Bld. 201



In late 1960s and earlier 1970s, it was upgraded to the varying energy, isochronous cyclotron.





In 1988, the merit cyclotron was shut down after 30 years operation.

Prof. Mike Craddock, TRIUMF&UBC

CYCIAE-30

Refer to IBA original design, CIAE redesigned and constructed a 30 MeV cyclotron CYCIAE-30 for medical isotopes production. 370 uA extracted beam was got at the end of 1994.

For the production of

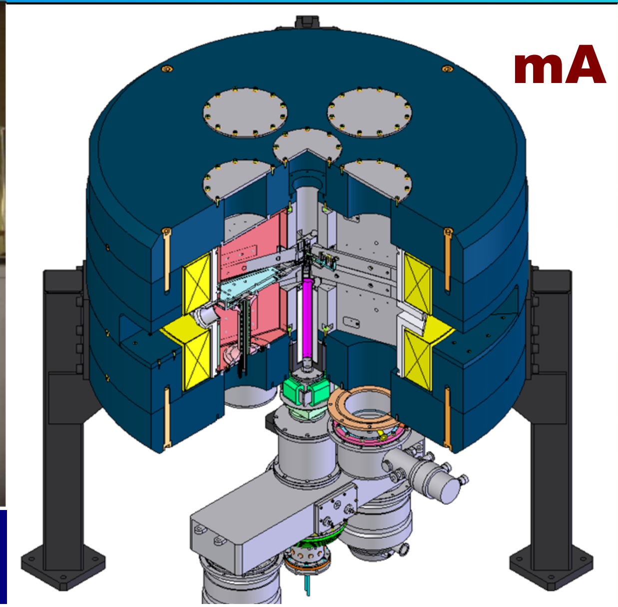
Tl-201	Pd-103
F-18	Ga-67
Co-57	Ge-68
I-123	In-111

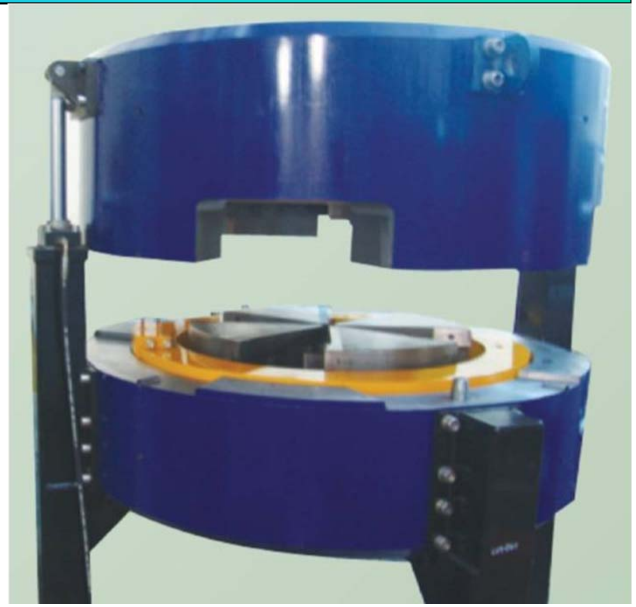
Fan M W, et al. Chinese Sci Bull, 1995, 40(20)1825

370 μA proton beam was extracted from a 30 MeV compact H^- cyclotron CYCIAE-30 at the end of 1994.

BRIF: from the First Proton Beam to RIB Production

10MeV， 430μA



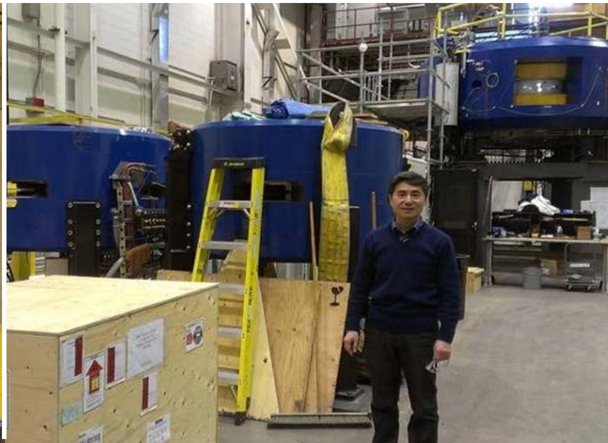


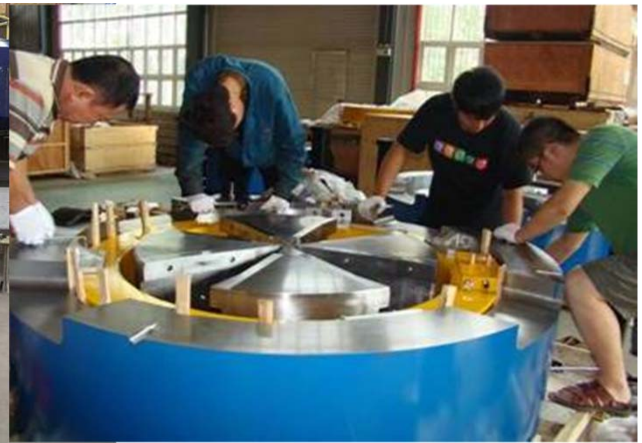
First, Second Small Cyc

10th Small Cyc, under construction for BNCT

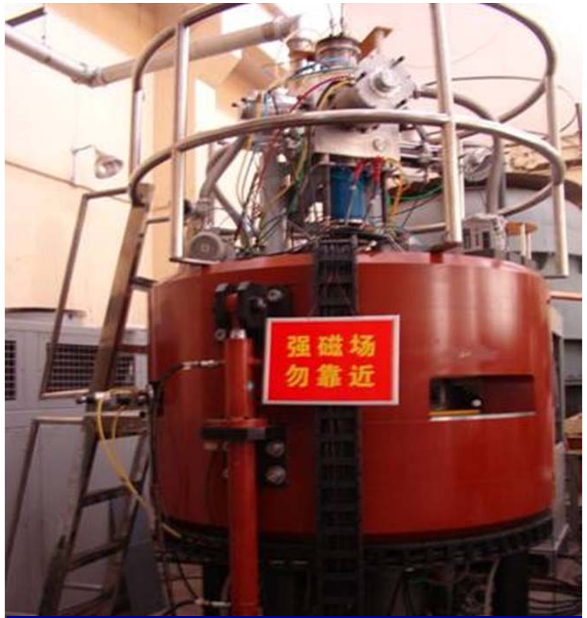
PET Cyclotron, 14 MeV, 450 μA

Main Parts of Small Cyclotron, 14 MeV, 100 μA to 400 μA, for Canada





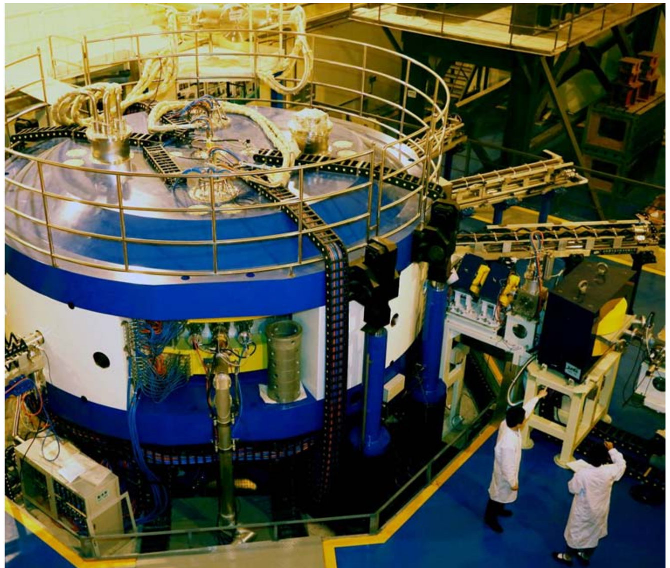
2009 10MeV，430μA



2012, 14MeV，450μA

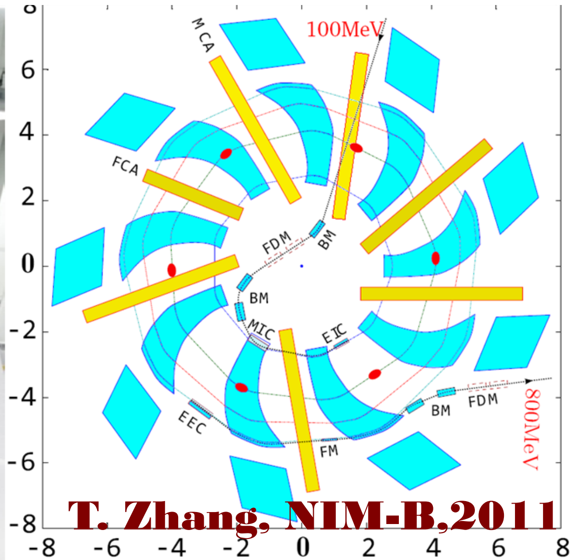
1994, 30MeV，370μA

Development of proton cyclotrons with high intensity at CIAE



100MeV，200-500μA

230MeV，1μA



800MeV，3000μA

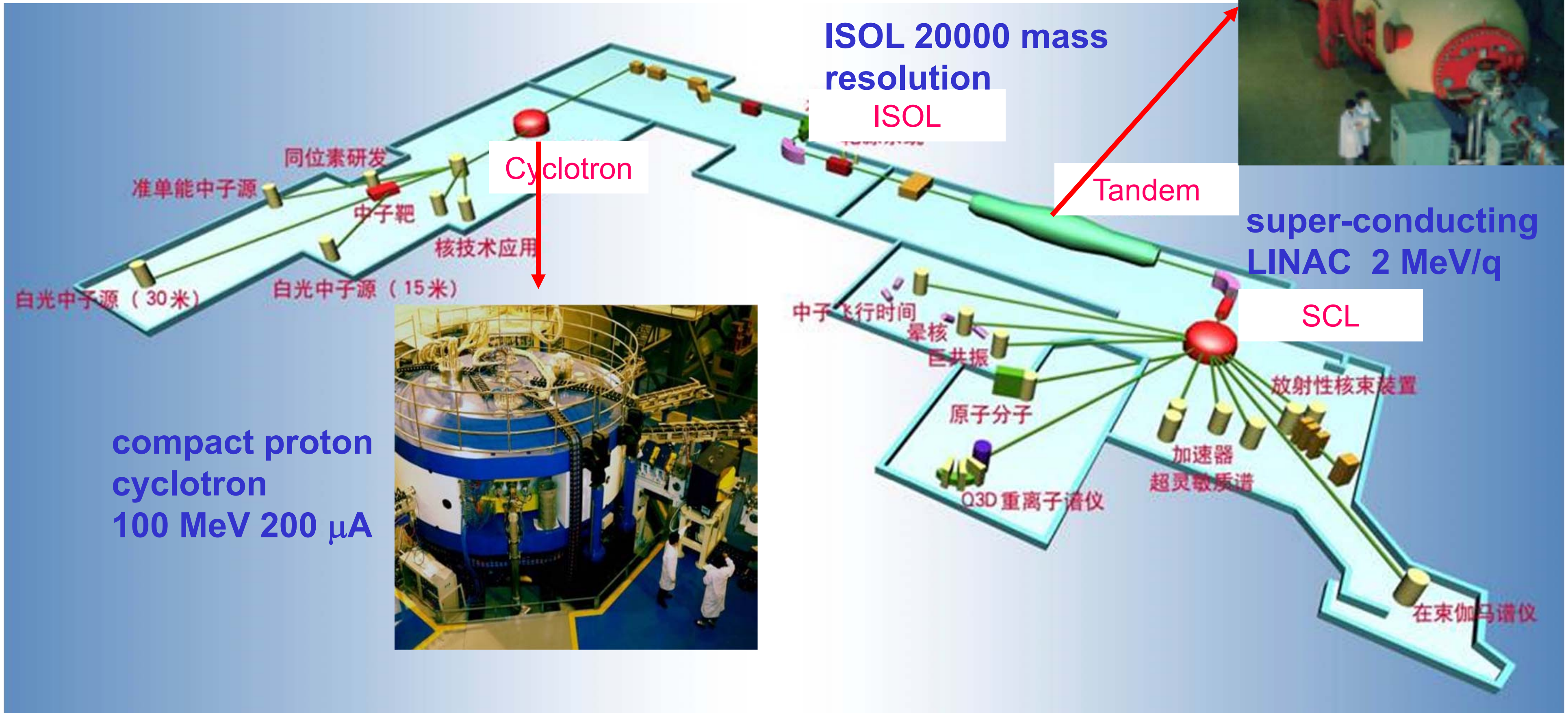
Plan of Talk

a) **BRIF - Beijing Radioactive Ion-beam Facility**
   a) Introduction
   b) First Proton Beam

b) **CYCIAE-100 Beam Development**
   a) Increase Intensity and Improve Stability
   b) mA Acceleration Efforts
   c) Dual Beam Extraction simultaneously

c) **CYCIAE-100 for ISOL and Other Applicati**
   a) Beam lines of CYCIAE-100
   b) ISOL system and Mass Resolution Improvement
   c) RIBs Production and Beam Time Application Opened for User
   d) Proton Irradiation and Other Applications

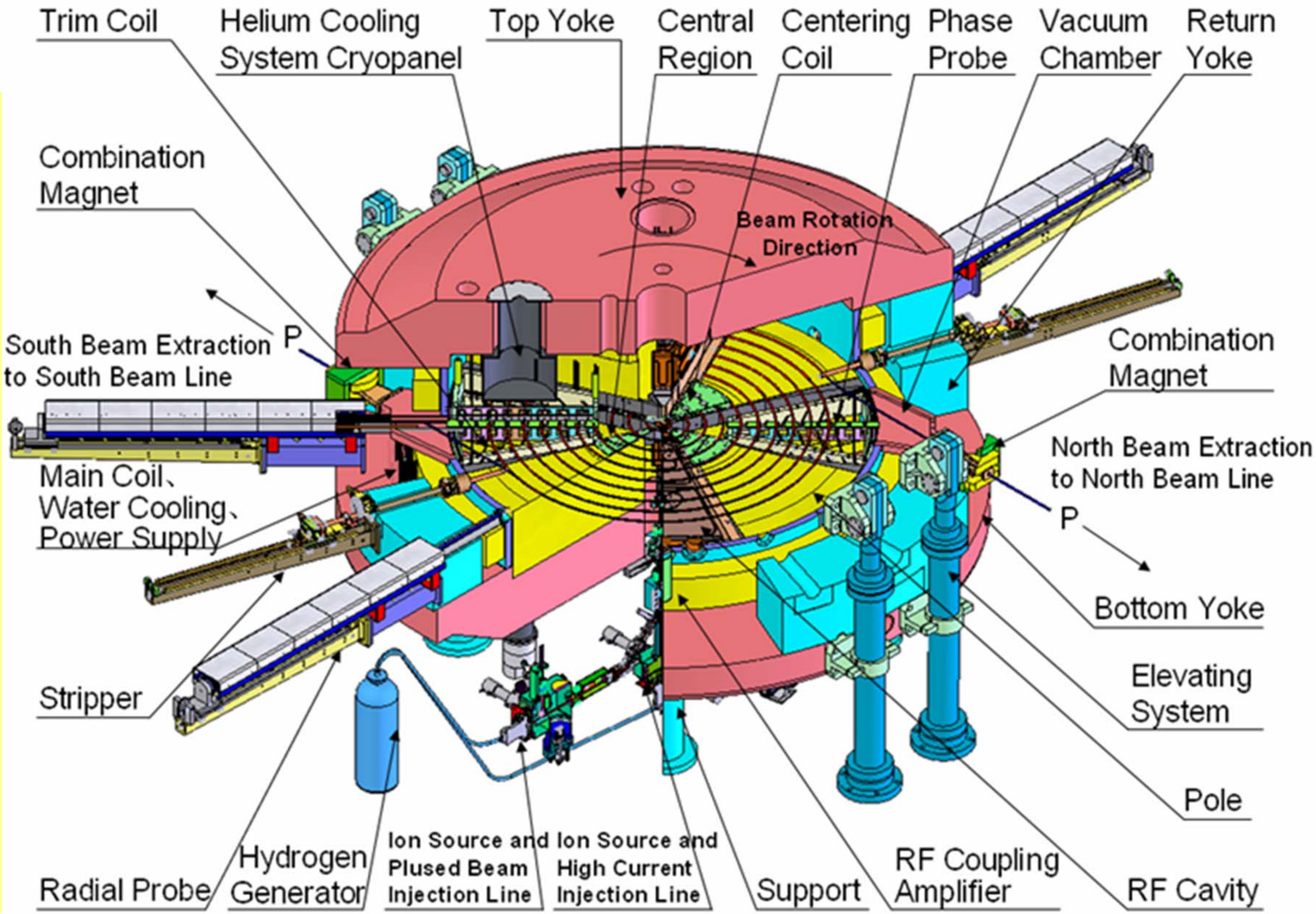
BRIF - **B**eijing **R**adioactive **I**on-beam **F**acility



As one of the main projects at CIAE, the **Beijing Radioactive Ion-beam Facility (BRIF)** have been used in fundamental and applied research such as neutron physics, nuclear structure, material and **life sciences, medical isotope ……**

General View of the 100 MeV Cyclotron

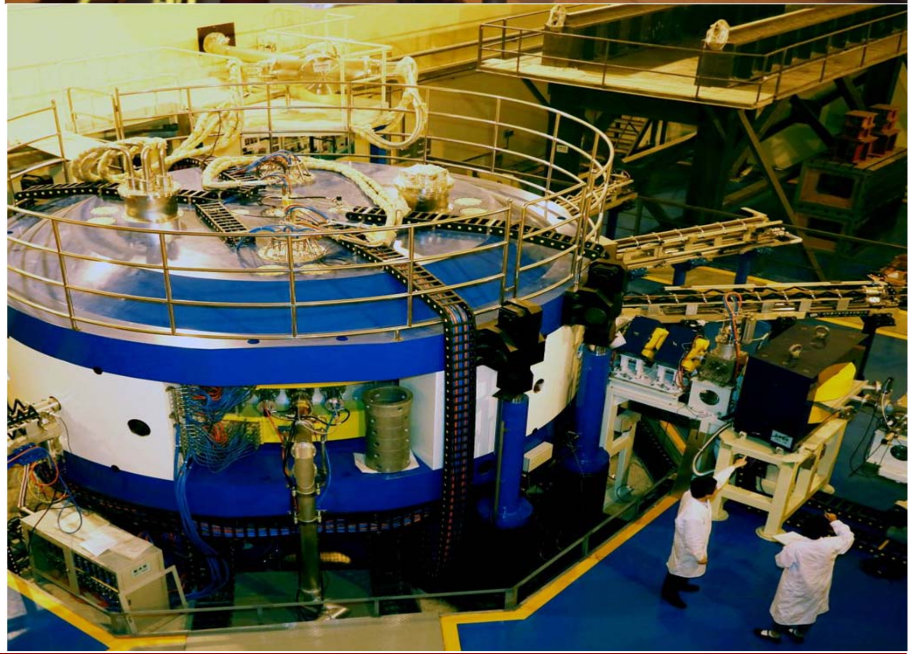
- **CW mode, high current**
- **energy variable;**
- **Dual beam extracted simultaneously;**
- **Low extraction beam losses**



First stage: 70MeV~100MeV, 200~500 μA: 20kW~50kW
Second stage: 30 MeV ~ 100 MeV, 1mA, 100kW.

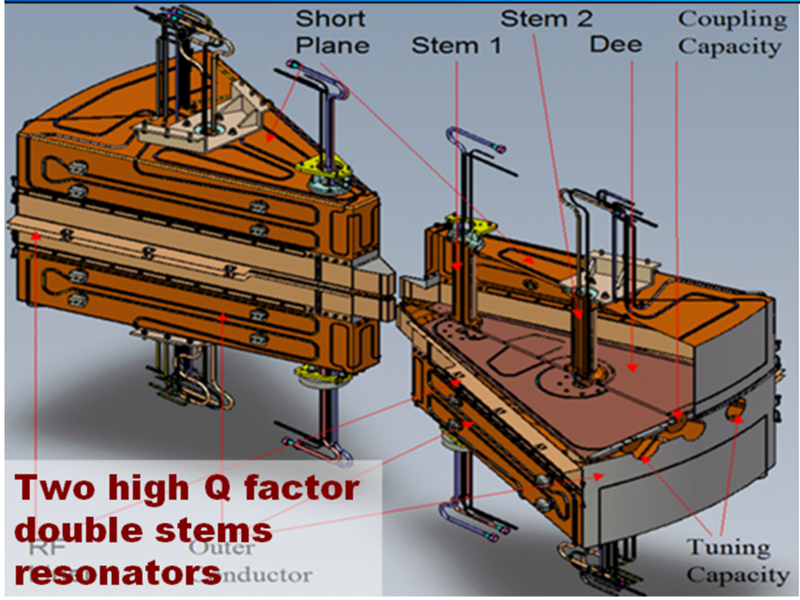
Tolerance Control:

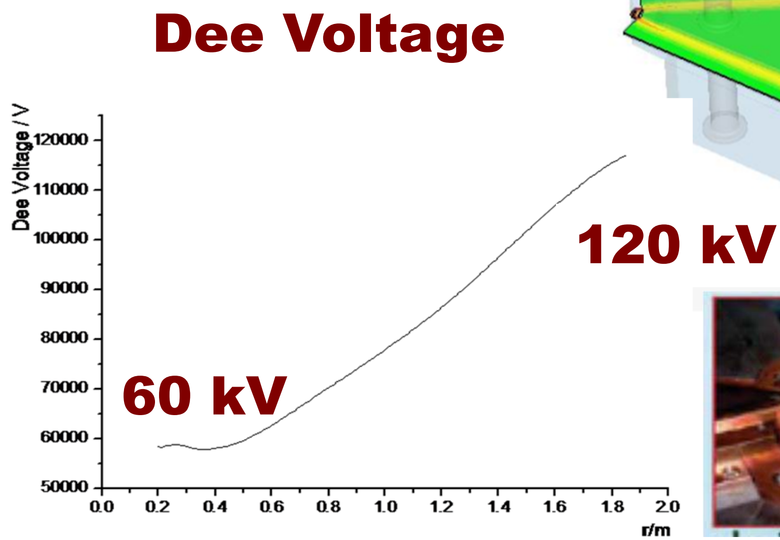
- Hill gap--0.05mm,
- Pole edge--0.1mm,
- others

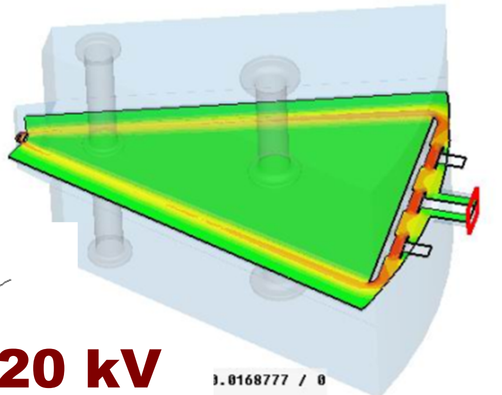


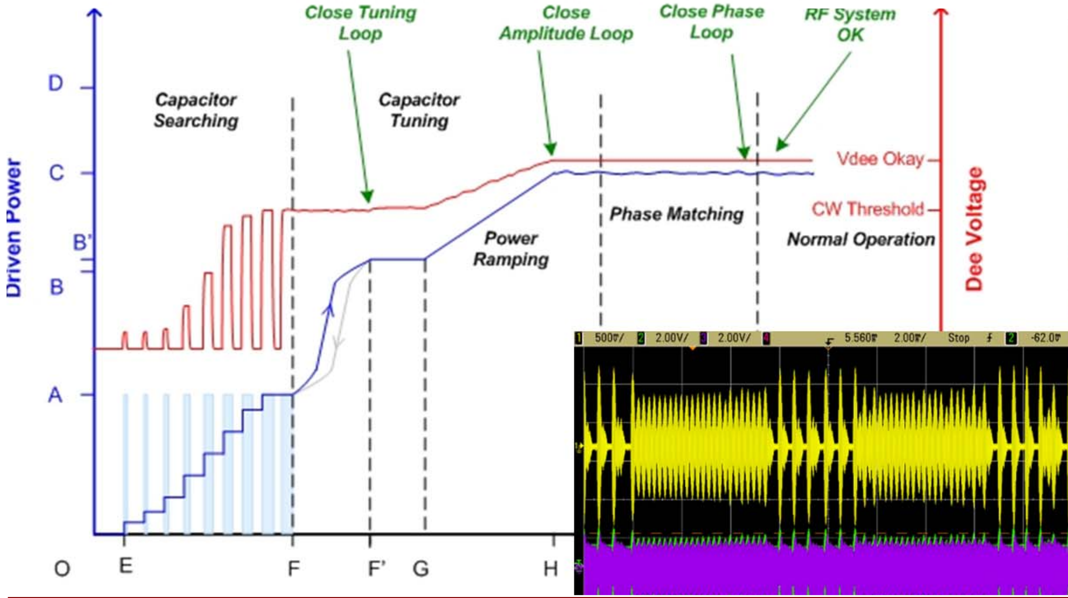
The installation, mapping and shimming of the main magnet system are finished by July, 2013

BRIF: from the First Proton Beam to RIB Production





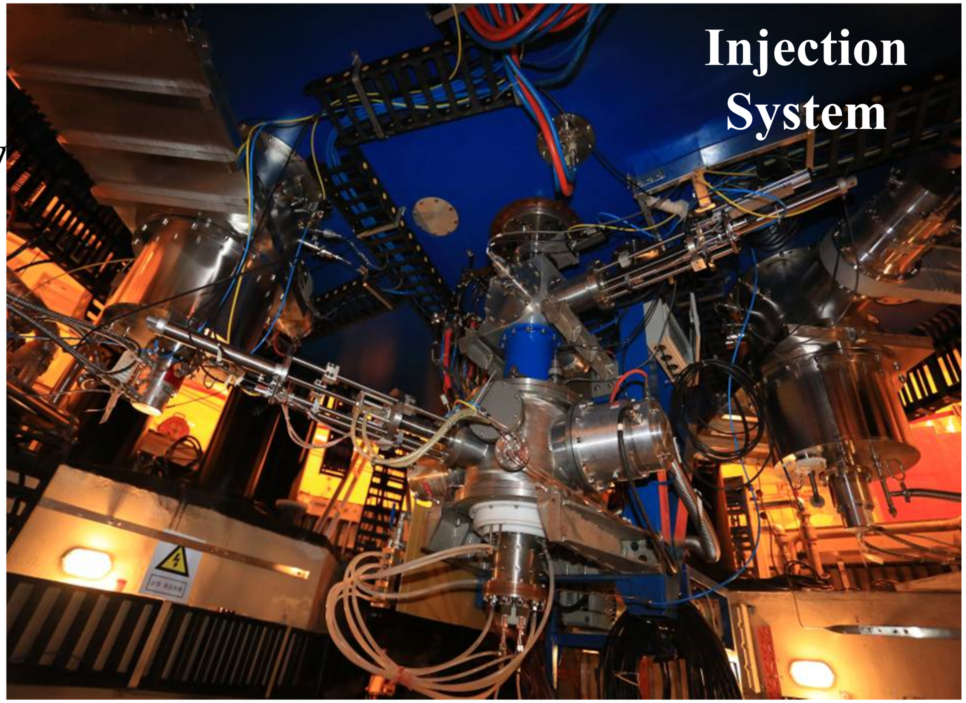




Installation of RF, Vacuum, R-probes, extractors, central region, RF conditioning were finished by the end of 2013

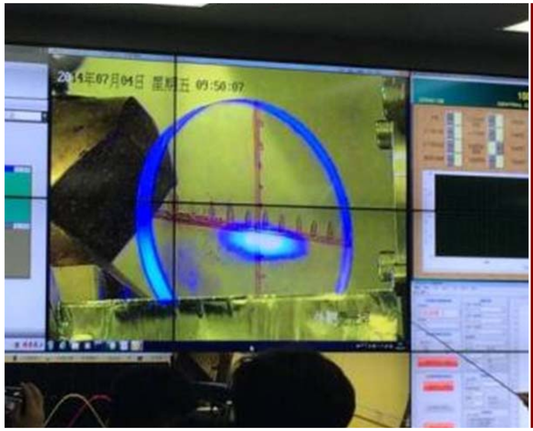
Beam Commissioning

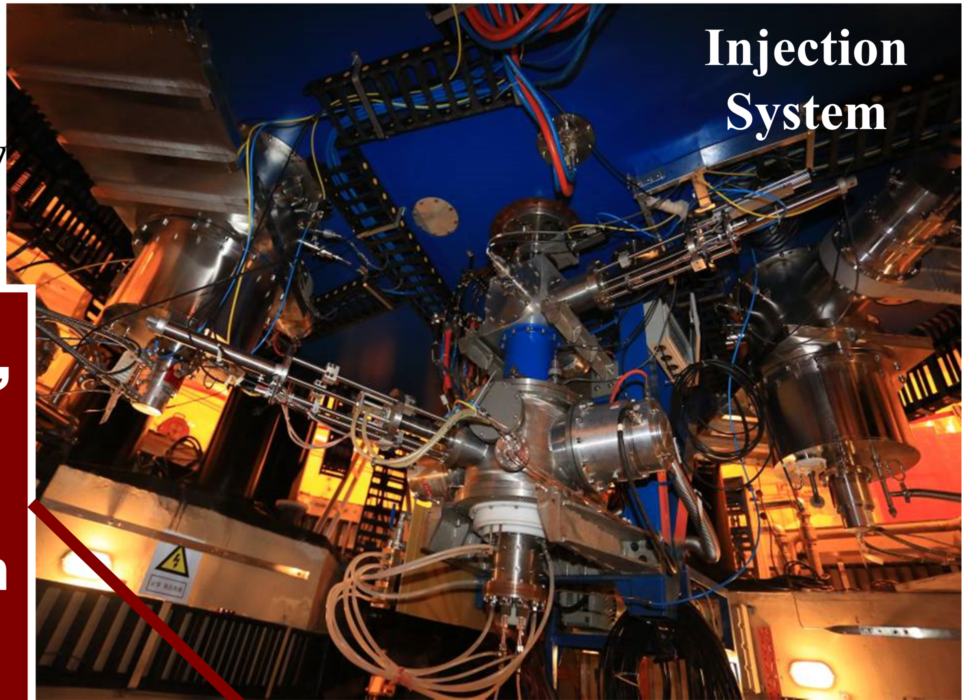
- On December 18 of 2013, we got **320 μA** DC beam on an internal target. The transmission efficiency from the ion source to the exit of inflector is higher than **80%.**



Beam Commissioning

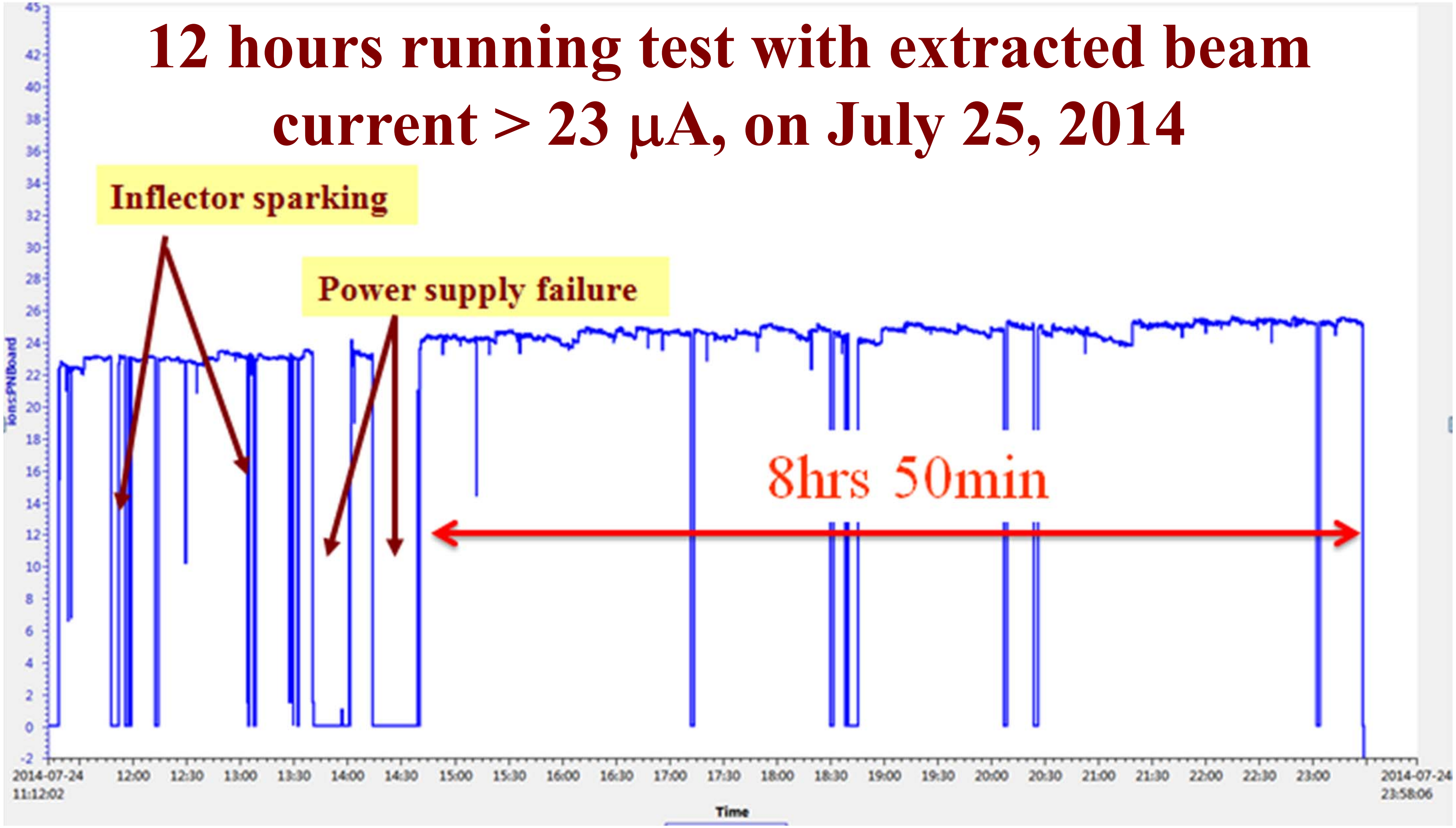
- On December 18 of 2013, we got **320 μA** DC beam on an internal target. The transmission efficiency from the ion source to the exit of inflector is higher than **80%**





July 4, 2014, we got first 100 MeV proton beam Extracted

Beam Commissioning



Plan of Talk

a) **BRIF - Beijing Radioactive Ion-beam Facility**
   a) Introduction
   b) First Proton Beam

b) **CYCIAE-100 Beam Development**
   a) Increase Intensity and Improve Stability
   b) mA Acceleration Efforts
   c) Dual Beam Extraction simultaneously

c) **CYCIAE-100 for ISOL and Other Applicati**
   a) Beam lines of CYCIAE-100
   b) ISOL system and Mass Resolution Improvement
   c) RIBs Production and Beam Time Application Opened for User
   d) Proton Irradiation and Other Applications

Increase Intensity and Improve Stability

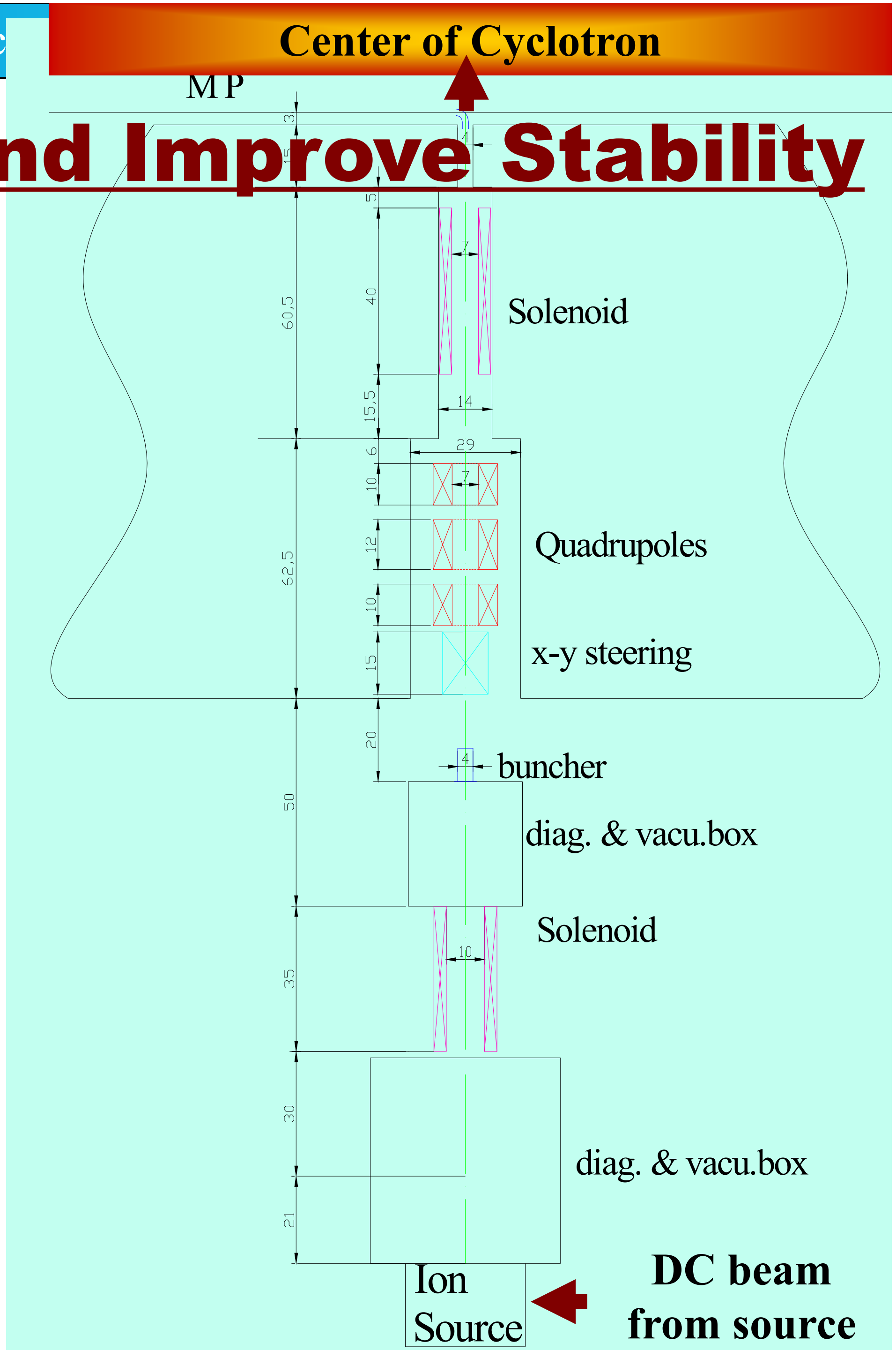
- Matching for injection line:
- S-B-QQQ-S, 2.5m
- 8-10 mA，40keV

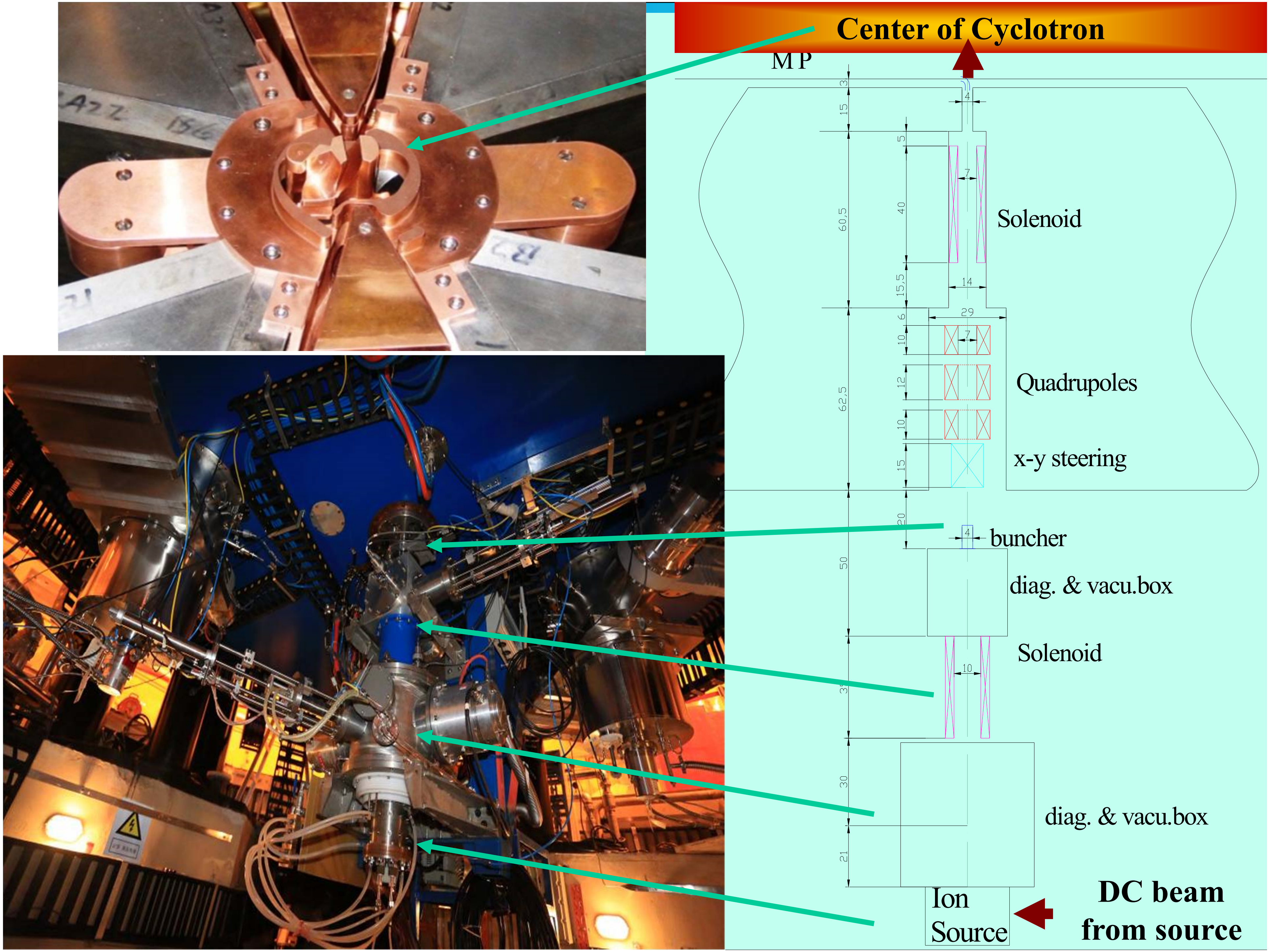
In order to Increase Intensity and Improve Stability, the:

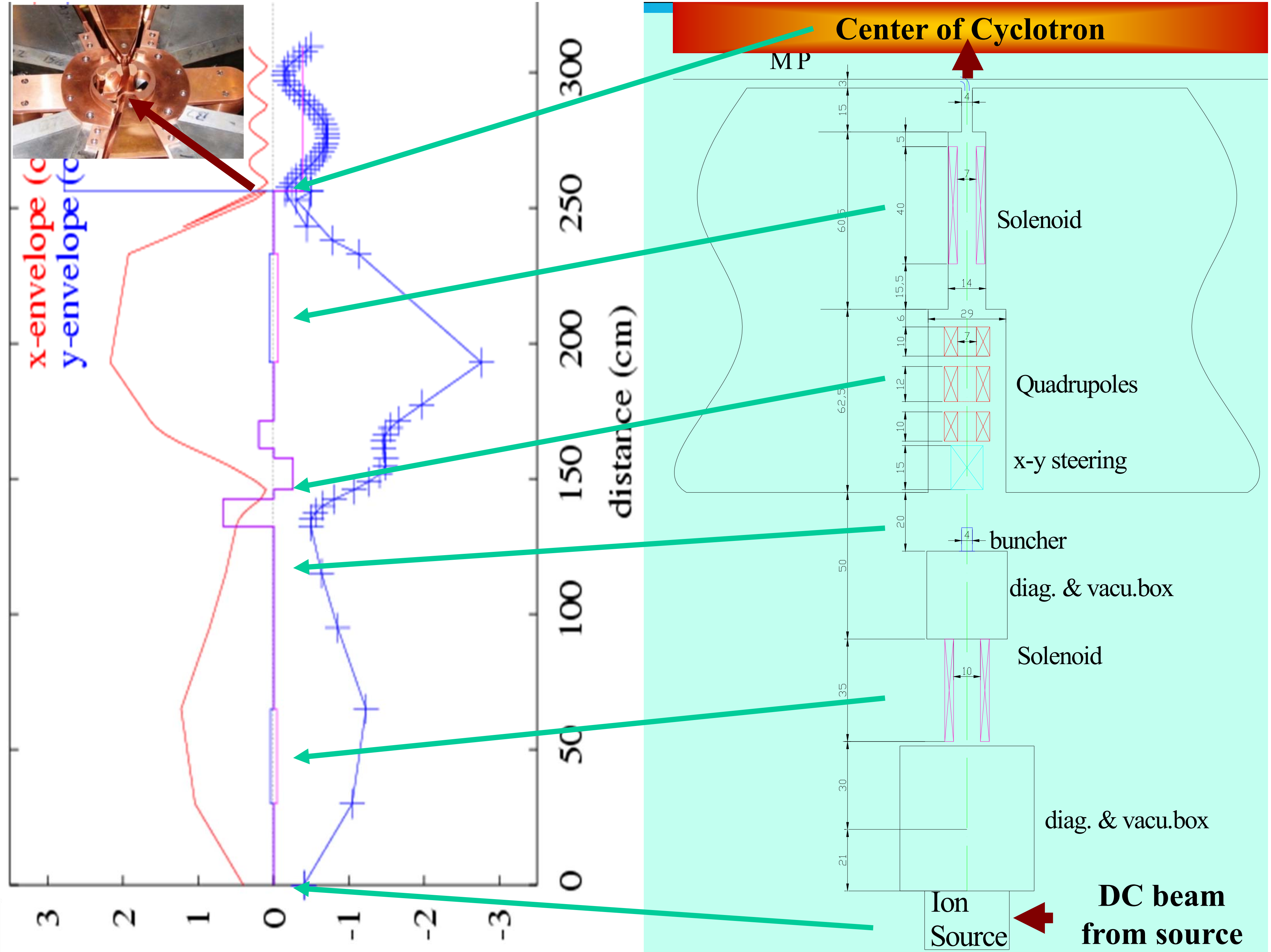
Beam matching from ion source to the central region,

Ion Source,

Water Cool central region etc.



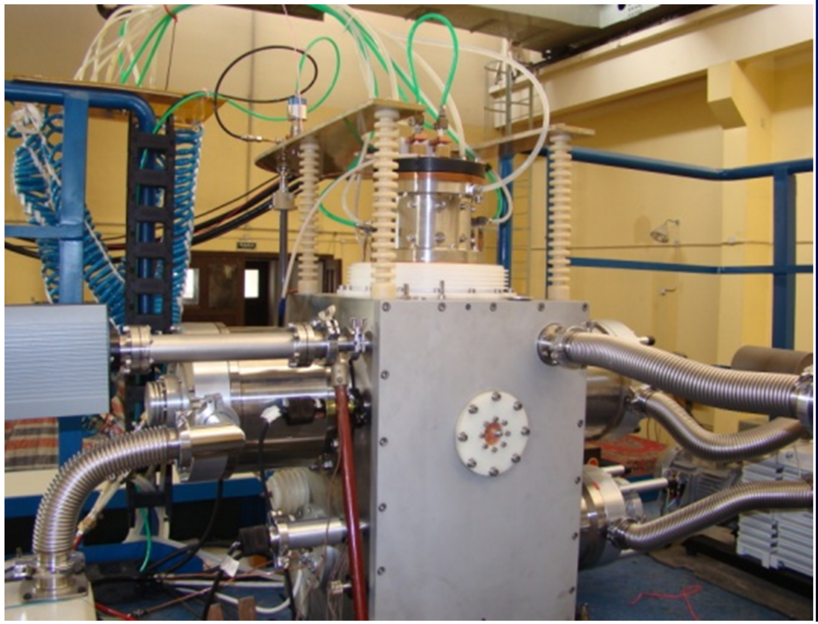

Center of Cyclotron
MP
Solenoid
Quadrupoles
x-y steering
buncher
diag. & vacu.box
Solenoid
diag. & vacu.box
Ion
Source
DC beam
from source

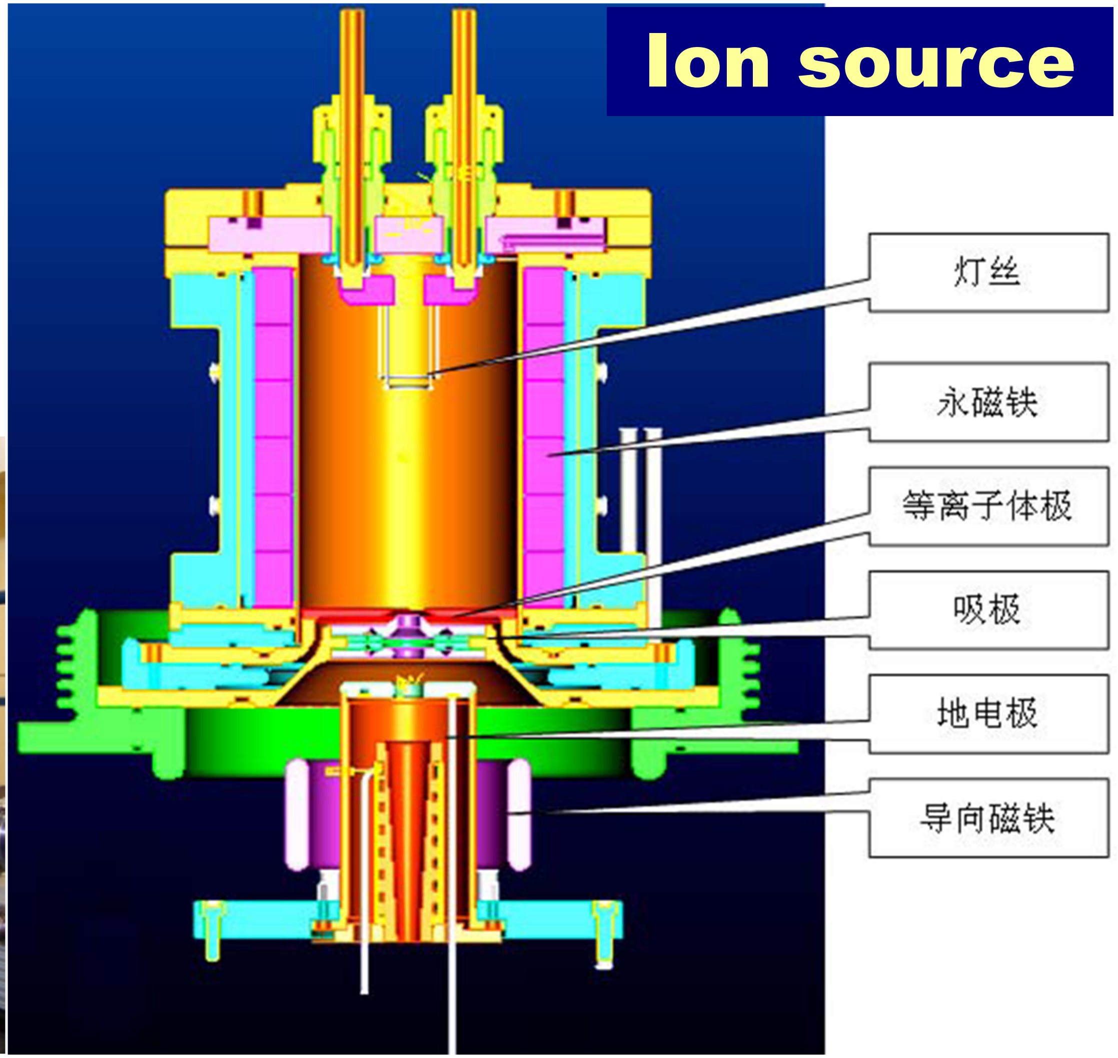


Center of Cyclotron
M P
Solenoid
Quadrupoles
x-y steering
buncher
diag. & vacu.box
Solenoid
diag. & vacu.box
Ion
Source
DC beam
from source
x-envelope (c
y-envelope (c
distance (cm)
0
50
100
150
200
250
300
3
2
1
0
-1
-2
-3

Increase Intensity and Improve Stability

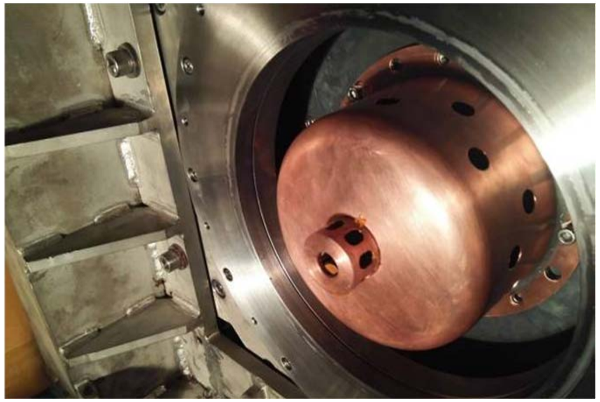
- The multi-cusp ion source on the test stand:
- **18mA, 30 keV**
- → 10mA, 40 keV



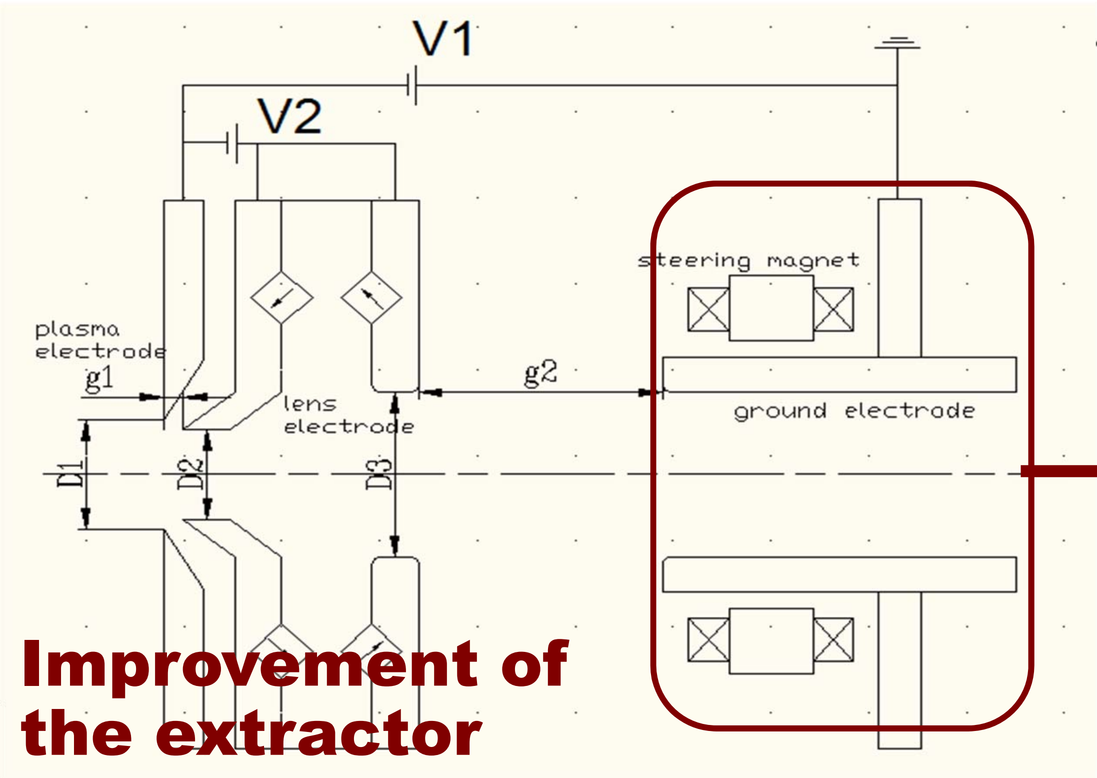


Increase Intensity and Improve Stability

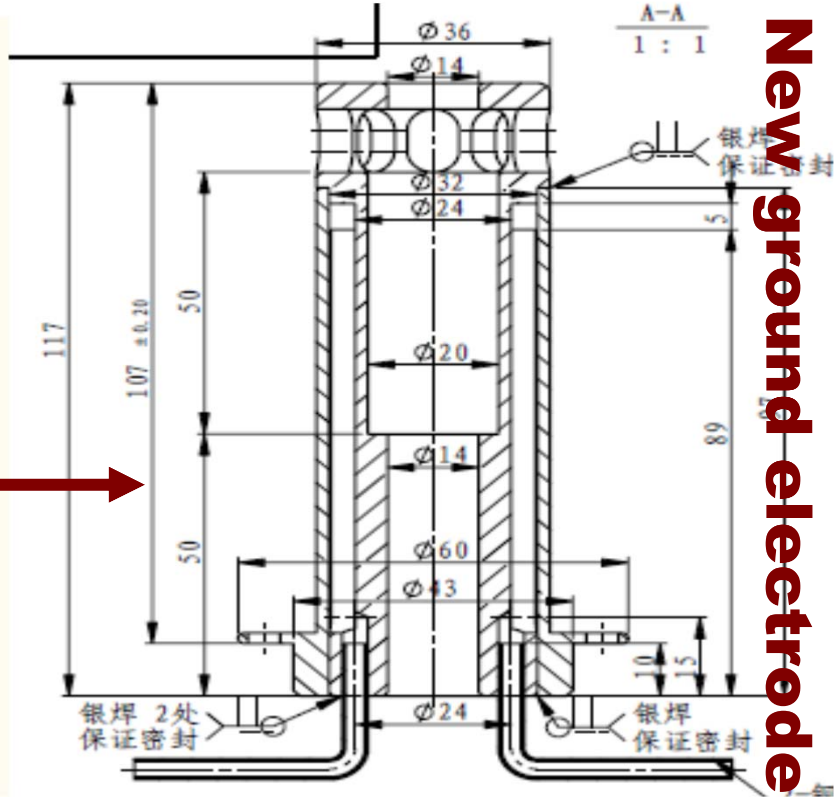
- The multi-cusp ion source on the test stand:
- **18mA, 30 keV**
- → 10mA, 40 keV



New XY steering magnet



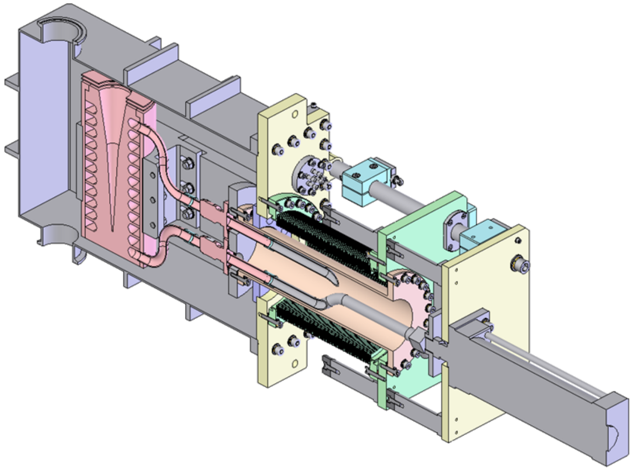
Improvement of the extractor

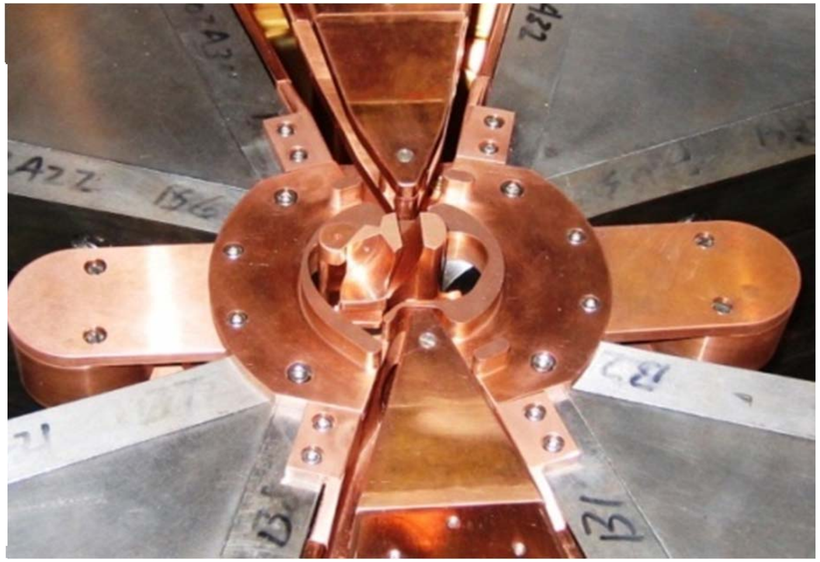


New ground electrode

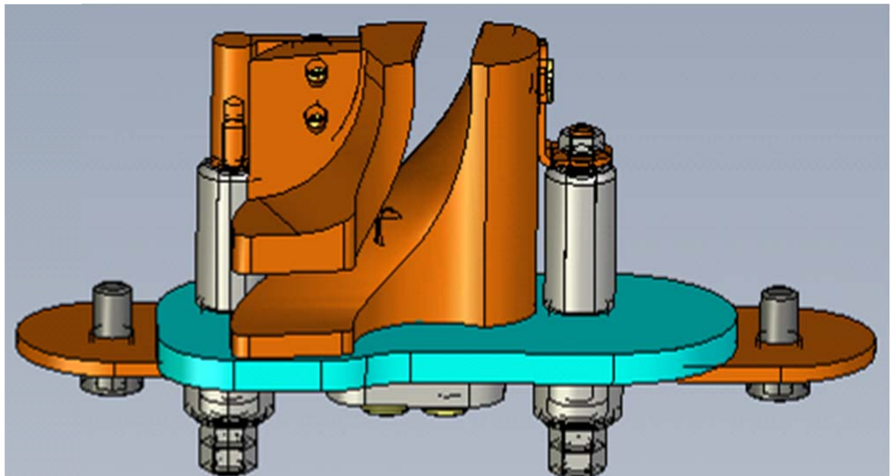
Increase Intensity and Improve Stability

High Power Beam Dump

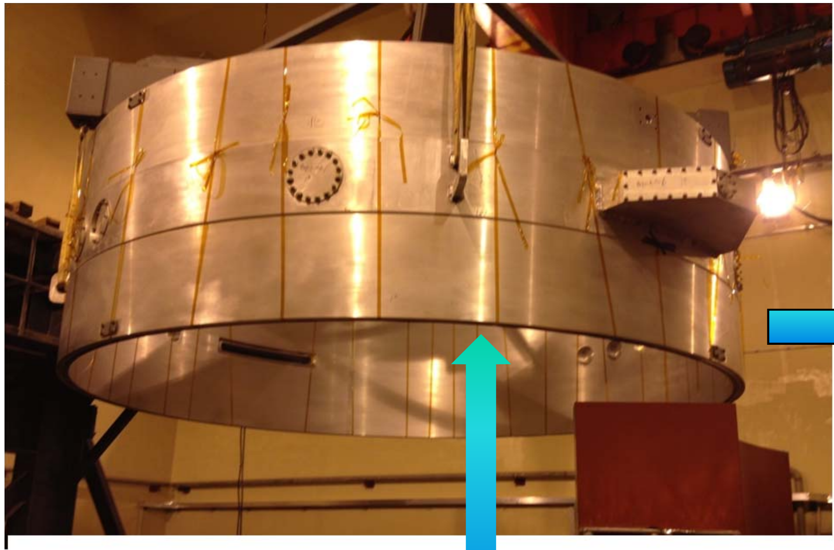


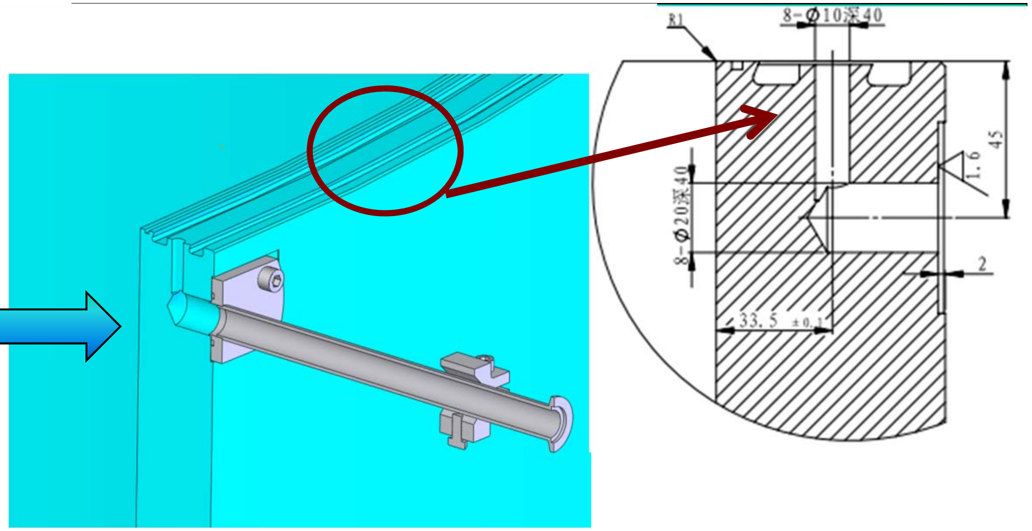


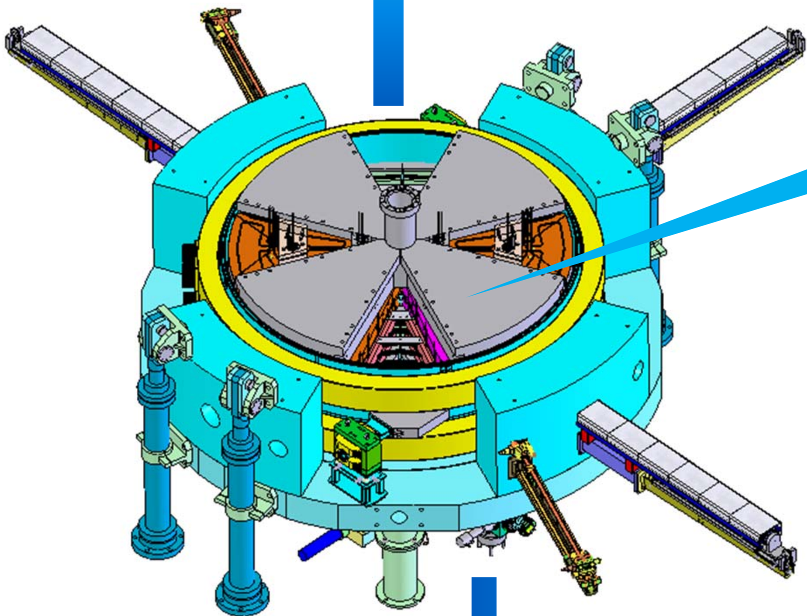
- For 100 MeV extracted beam
- 200 μA



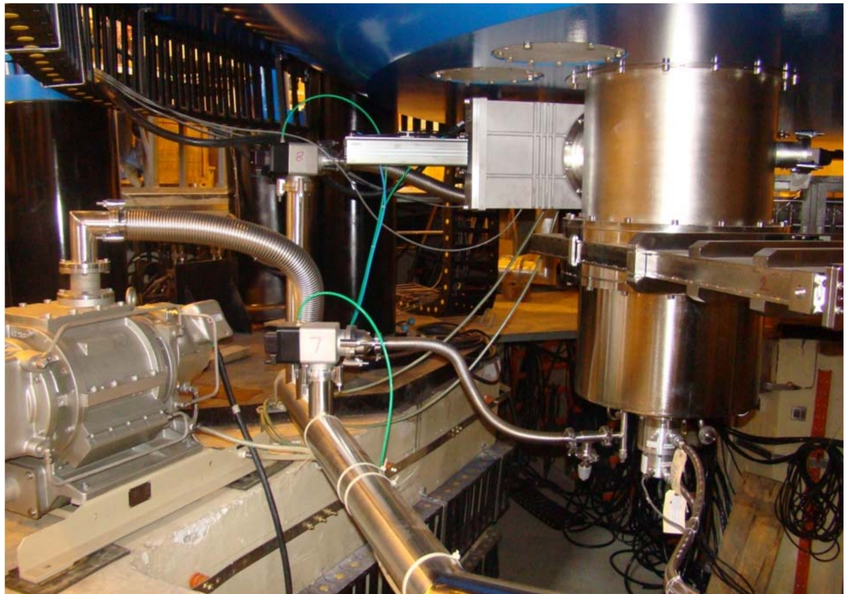
Water cool Central region





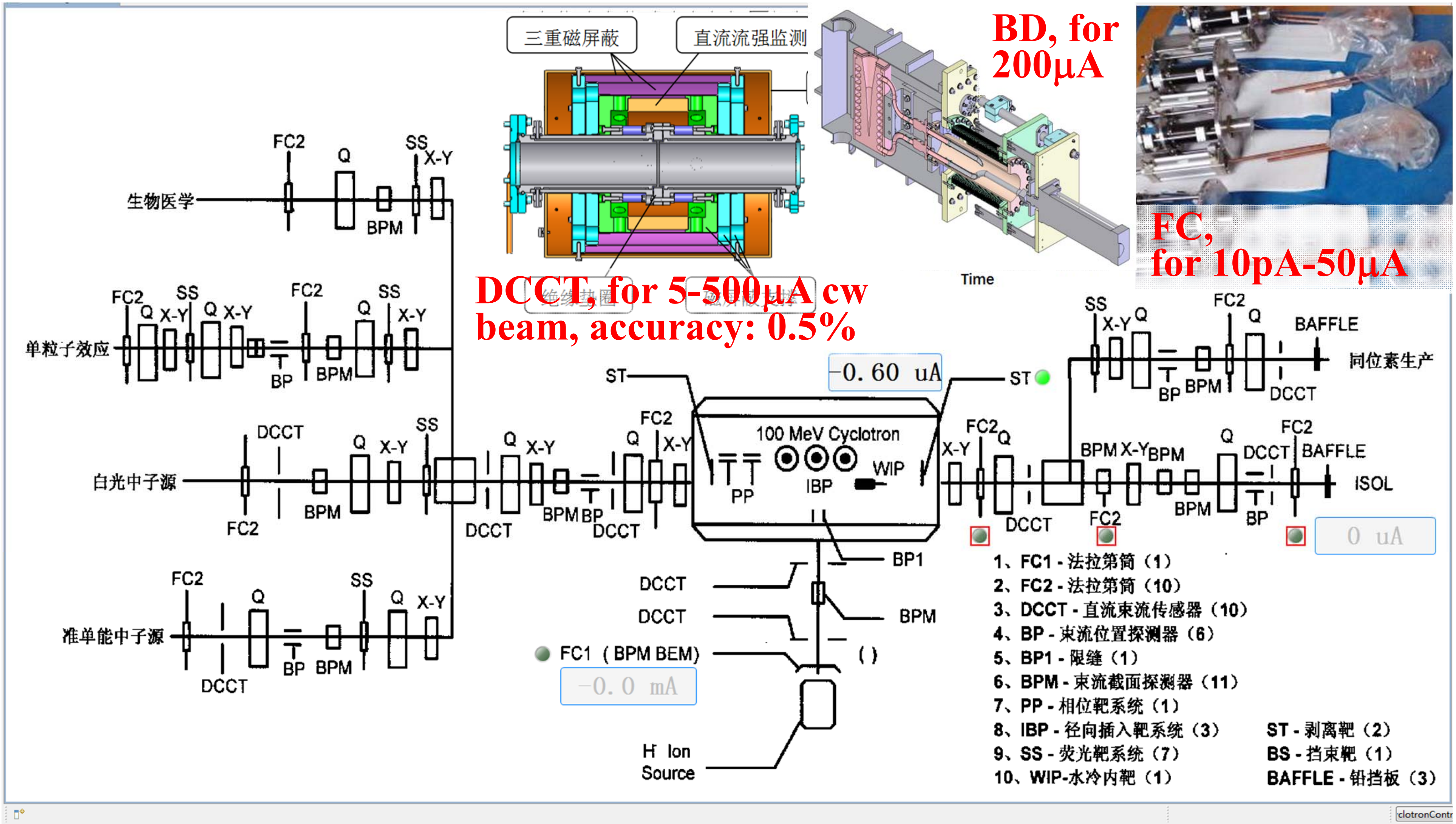


Vacuum Dissociation, H- Beam Losses

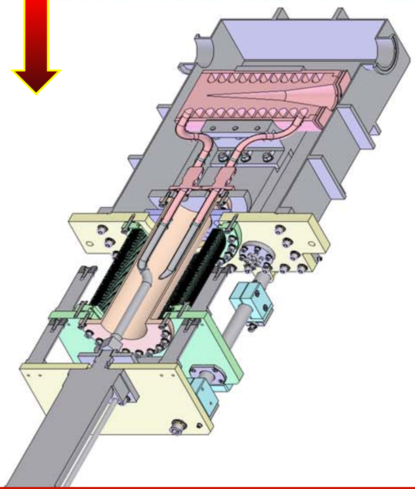


Double layer pumping system for main vacuum improvement

Increase Intensity and Improve Stability

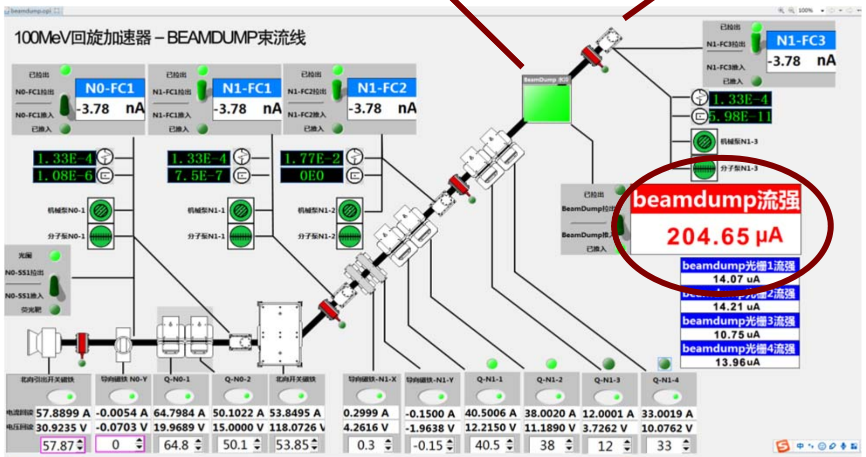


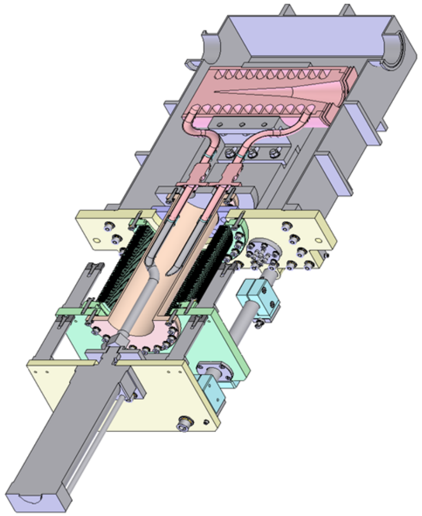
Beam Diagnostics for CYCIAE-100



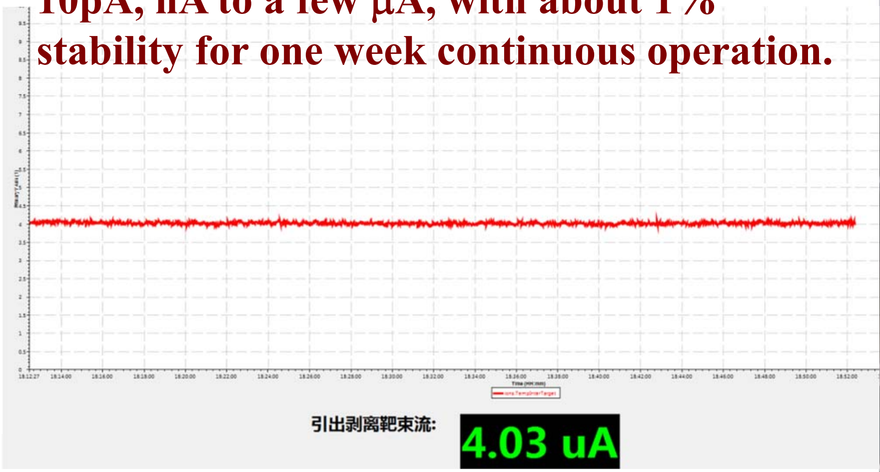
Beam Dump

High Power Beam Dump **Isotope Production**

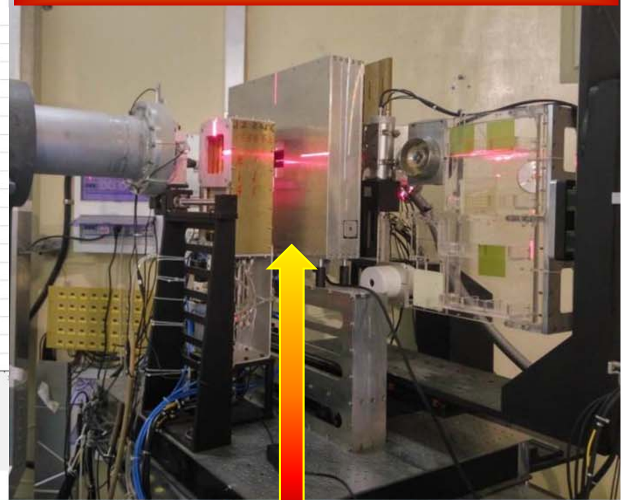




Beam Intensity can be fine adjustable from 10pA, nA to a few μA, with about 1% stability for one week continuous operation.



Proton Irradiation

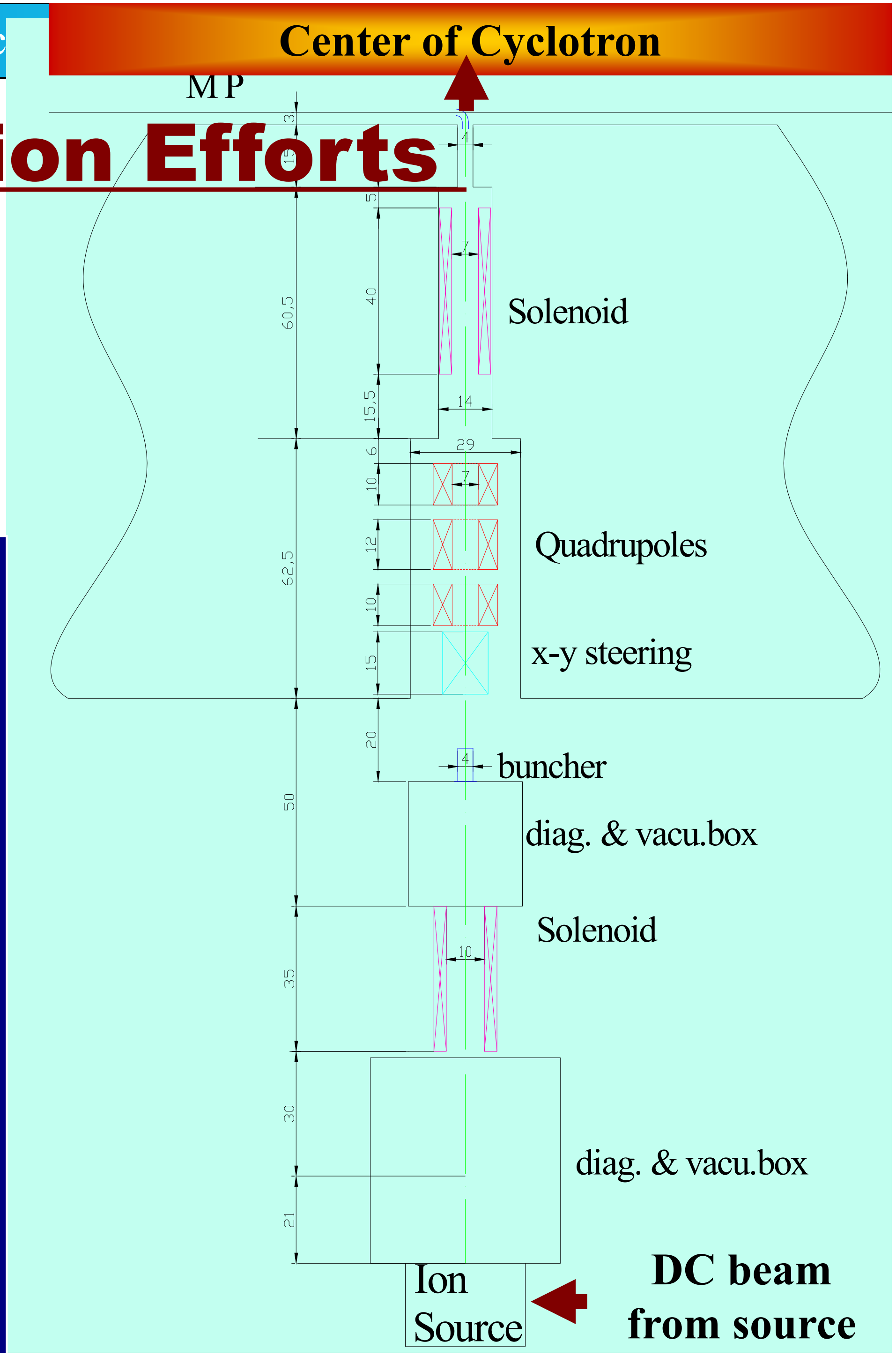


Proton Radiography Principle Experiment

mA Beam Acceleration Efforts

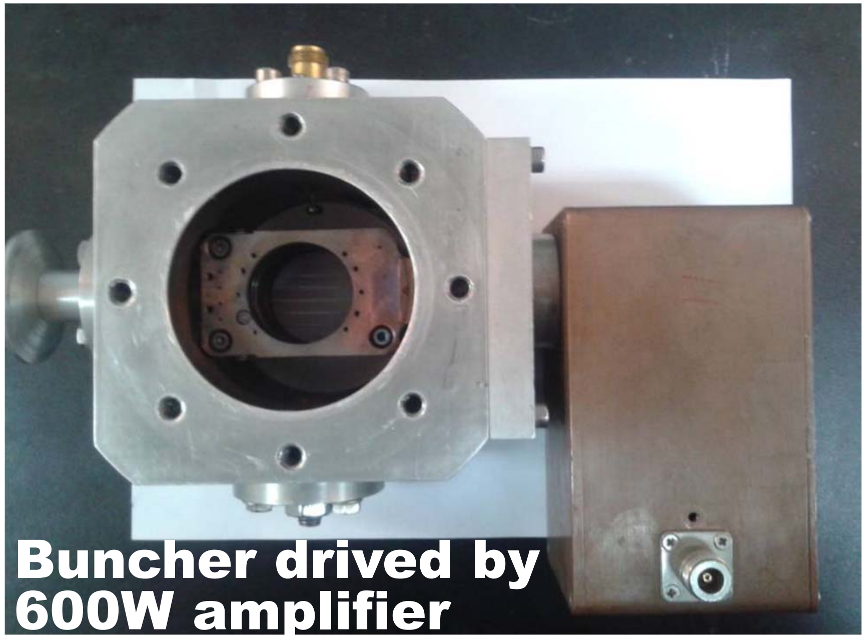
- Matching for injection line:
- S-B-QQQ-S, 2.5m
- 8-10 mA， 40keV

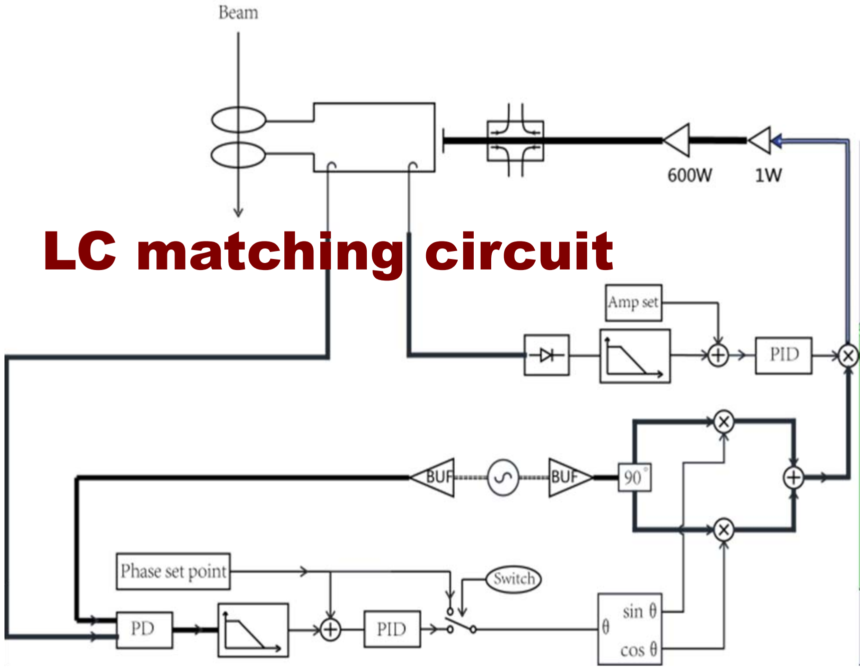
In order to get mA level acceleration beam, several aspects are improved, Besides the ion source , beam matching from ion source to the central region, Also the buncher system, beam loading of the RF system, space charge effects limit, etc.

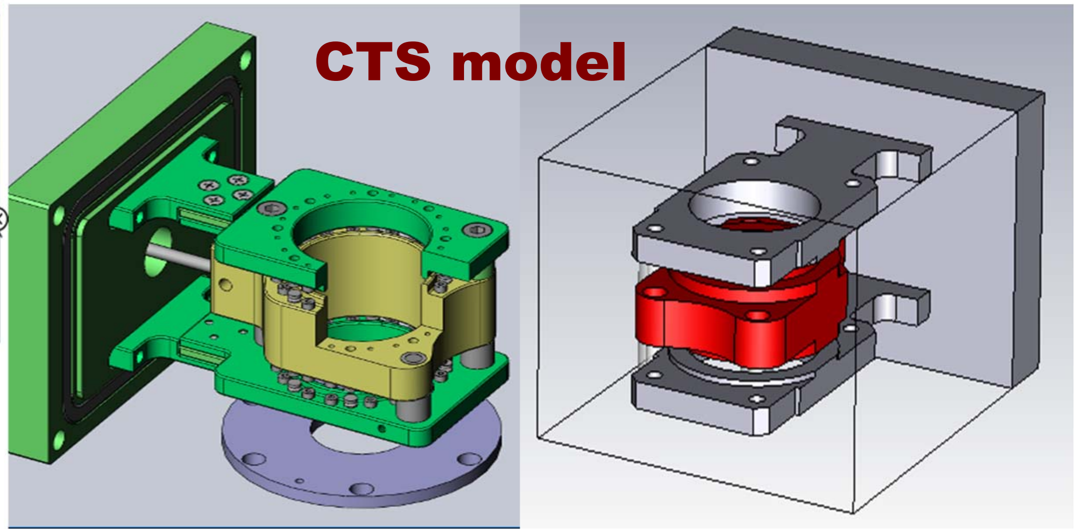


mA Beam Acceleration Efforts — Buncher

- Non-intercepting 2-gap buncher
- Between the first solenoid and the triplet, ~1.1m away from the inflector.
- Gap=5 mm and D=0.5βγ instead of 1.5βγ at TRIUMF







mA Beam Acceleration Efforts

Buncher

In June, 2016, we got accelerated beam > mA

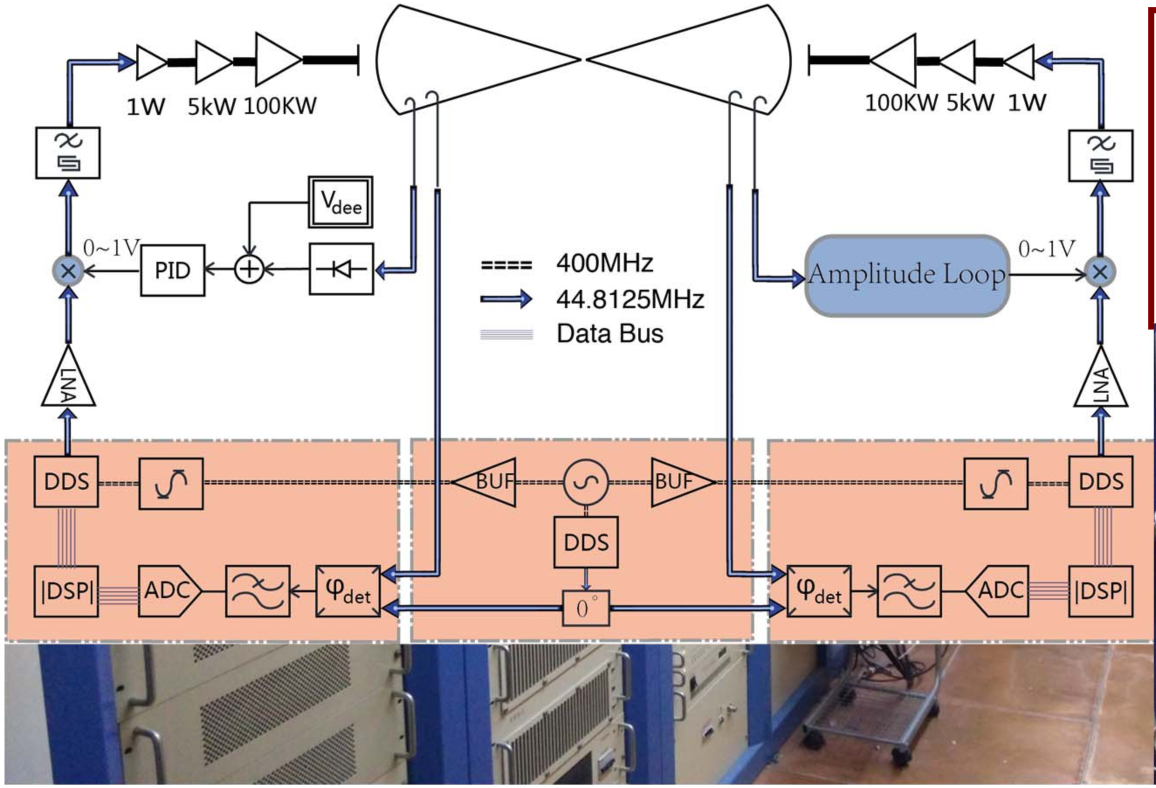
1073μA

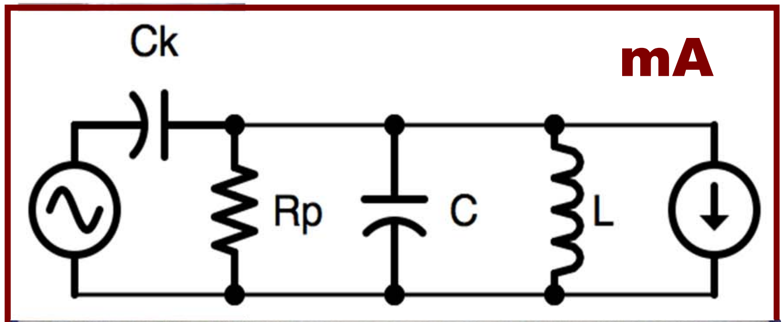
Ion source (mA)	Without Buncher (μA)	With Buncher (μA)	Bunching efficiency	Acceleration efficiency (%)
1.33	100	201	2.01	15.1
1.91	145	310	2.14	16.2
3.25	201	399	1.99	12.3
4.27	258	490	1.90	11.5
4.71	410	633	1.54	13.4
6.43	542	740	1.37	11.5
8.69	610	950	1.56	10.9
9.52	**636**	**1073**	**1.68**	**11.2**

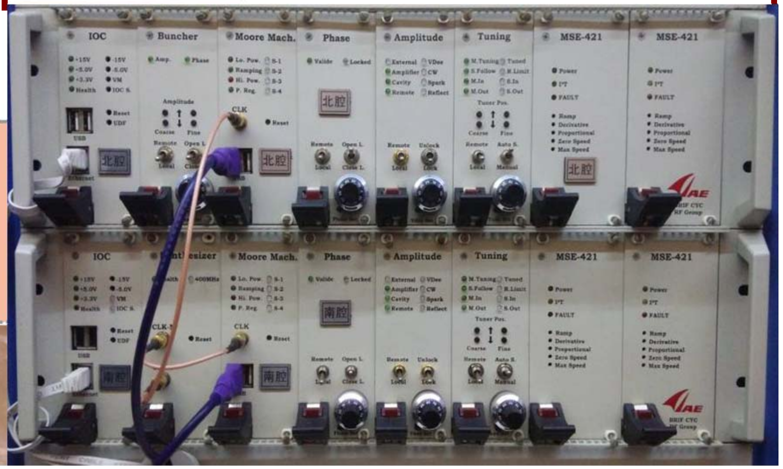
mA Beam Acceleration Efforts

LLRF

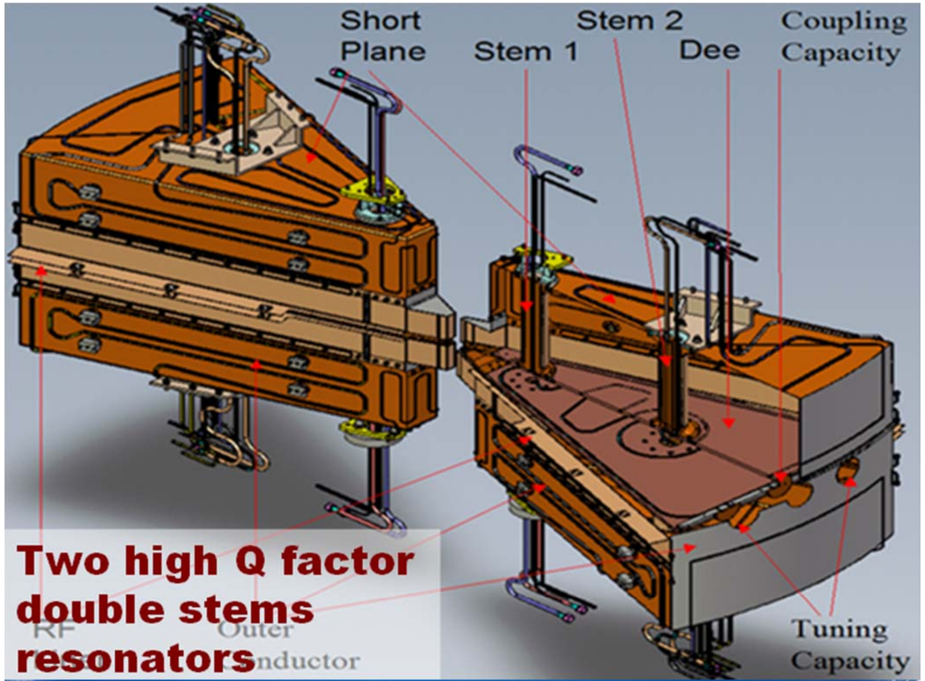
- The mA level beam is a heavy load for the RF system and may cause an open-loop condition for the Dee voltage regulation.
- To achieve an accurate amplitude control, the LLRF adopts a self-adaptation strategy to ensure the control loop is always closed, unless the power requirement exceeds 120% of nominal value.

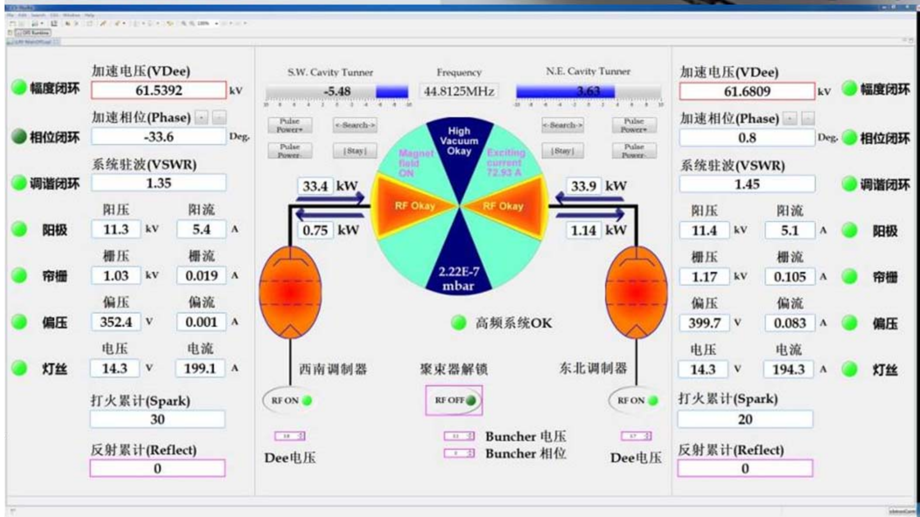






mA Beam Acceleration Efforts RF Cavity





- The tuner of the cavity consists of a fine capacitor and a coarse capacitor drived by two DC motors.
- Based on the thermal situation after some operation of the cavities,
- the fine tuner was changed to a smaller one to achieve more precise tuning of the RF cavity. **The residual tuning errors are reduced to less than 3 degrees for both cavities.**

mA Beam Acceleration Eff

mA Beam Acceleration

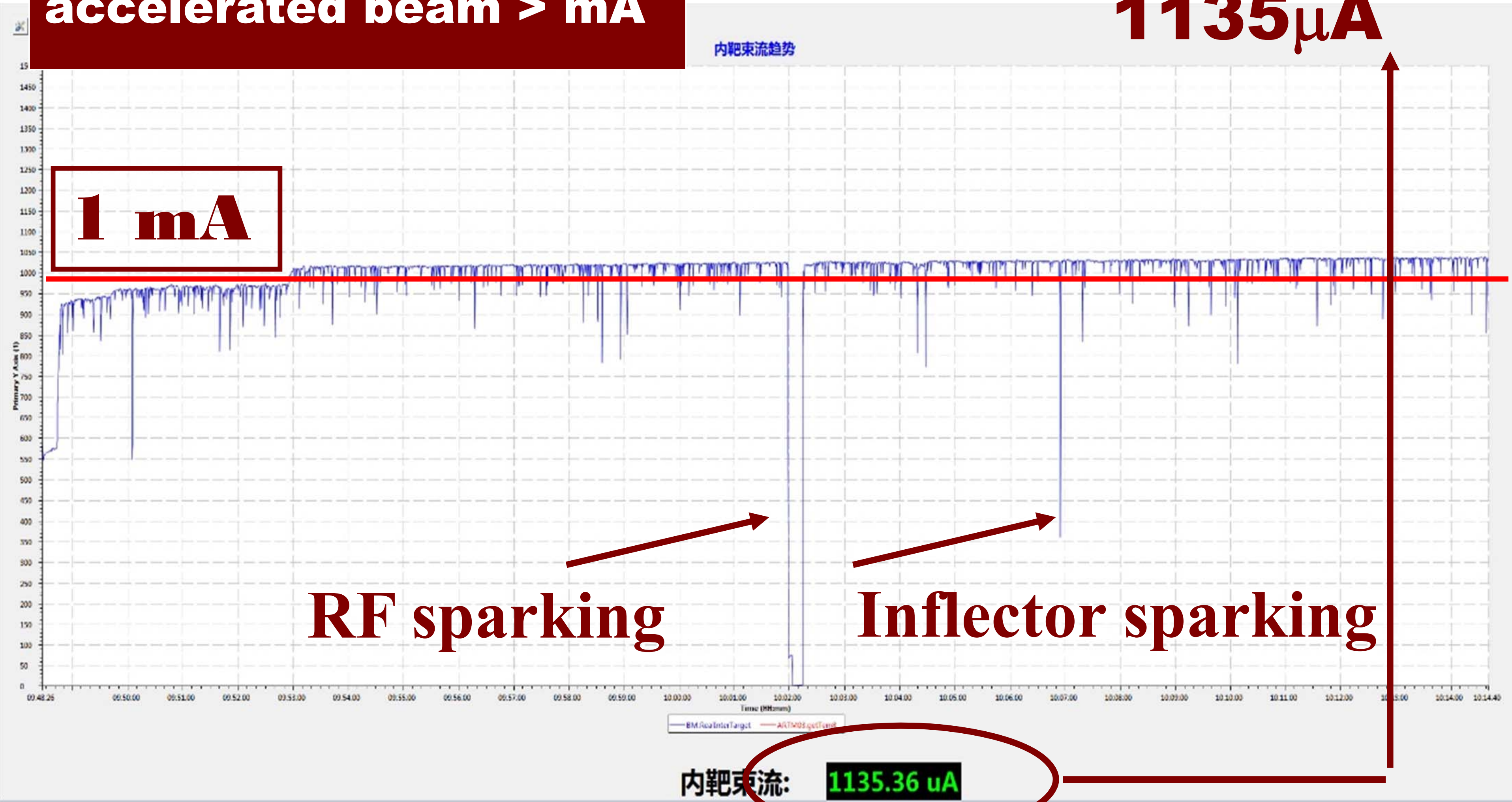
In June, 2016, we got accelerated beam > mA

1073μA

mA Beam Acceleration Eff

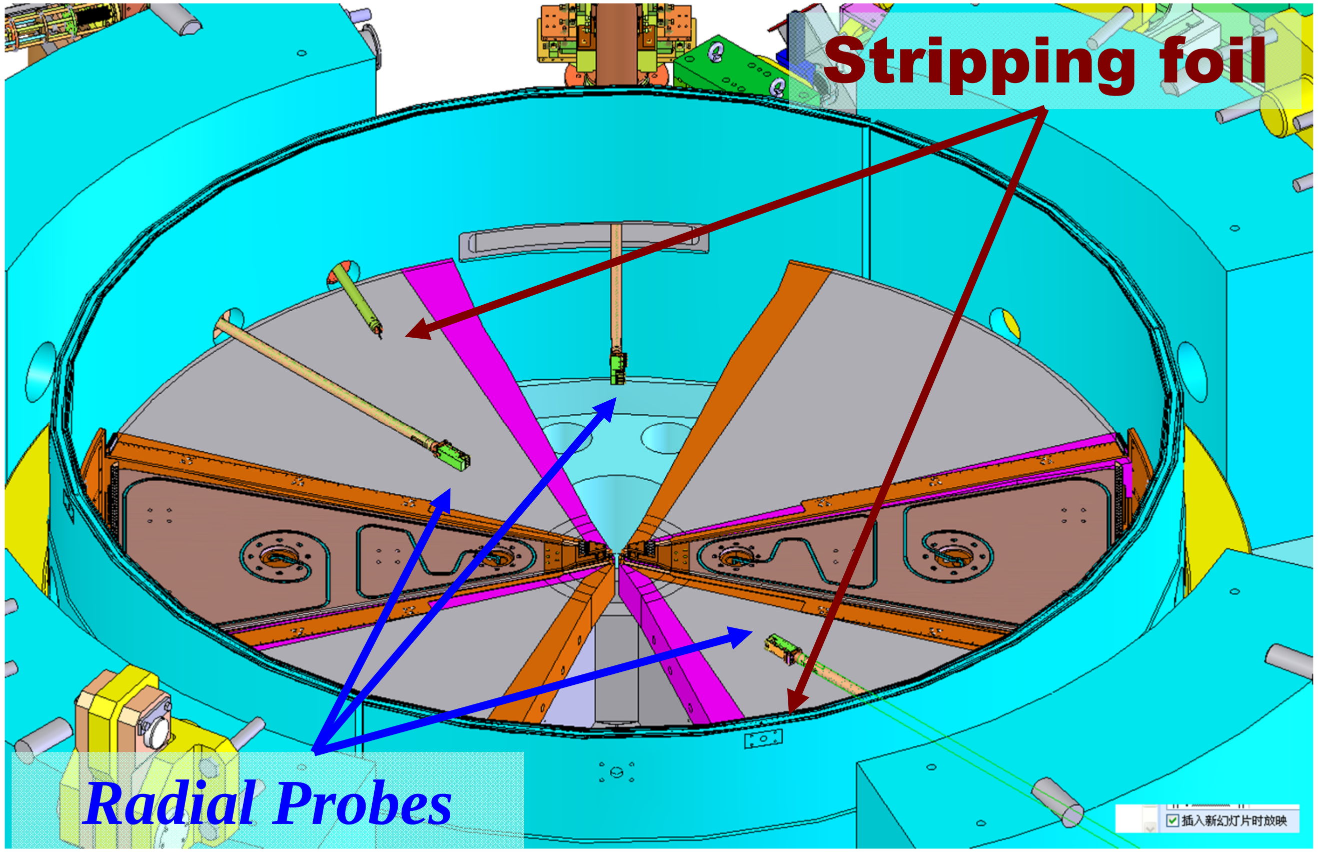
mA Beam Acceleration

In June, 2016, we got accelerated beam > mA



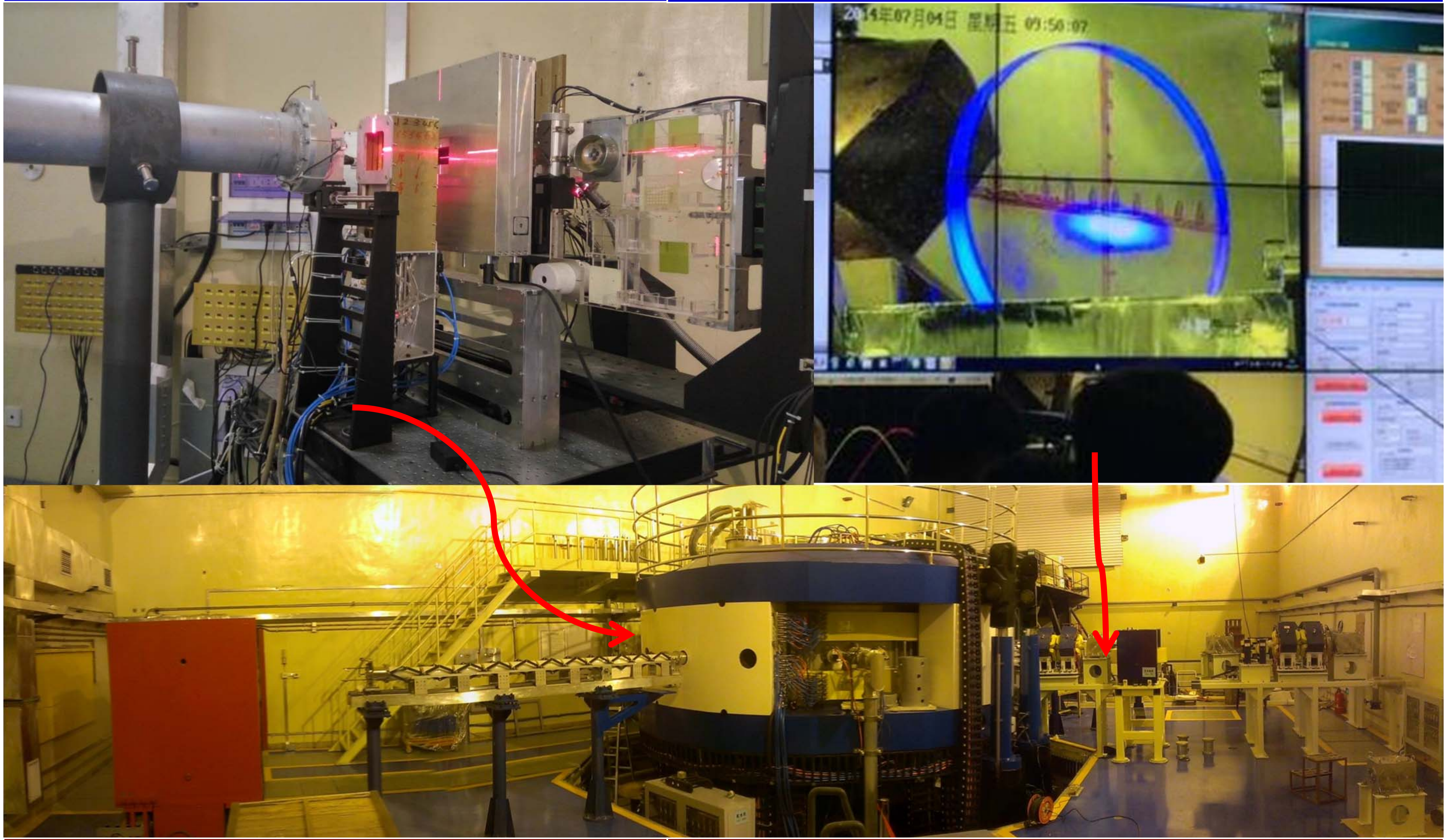
Dual Beam Extraction simultaneously

- Fine adjustments of the two stripping foils
  1. The positions = Energy,
  2. Orientations = Beam Optics



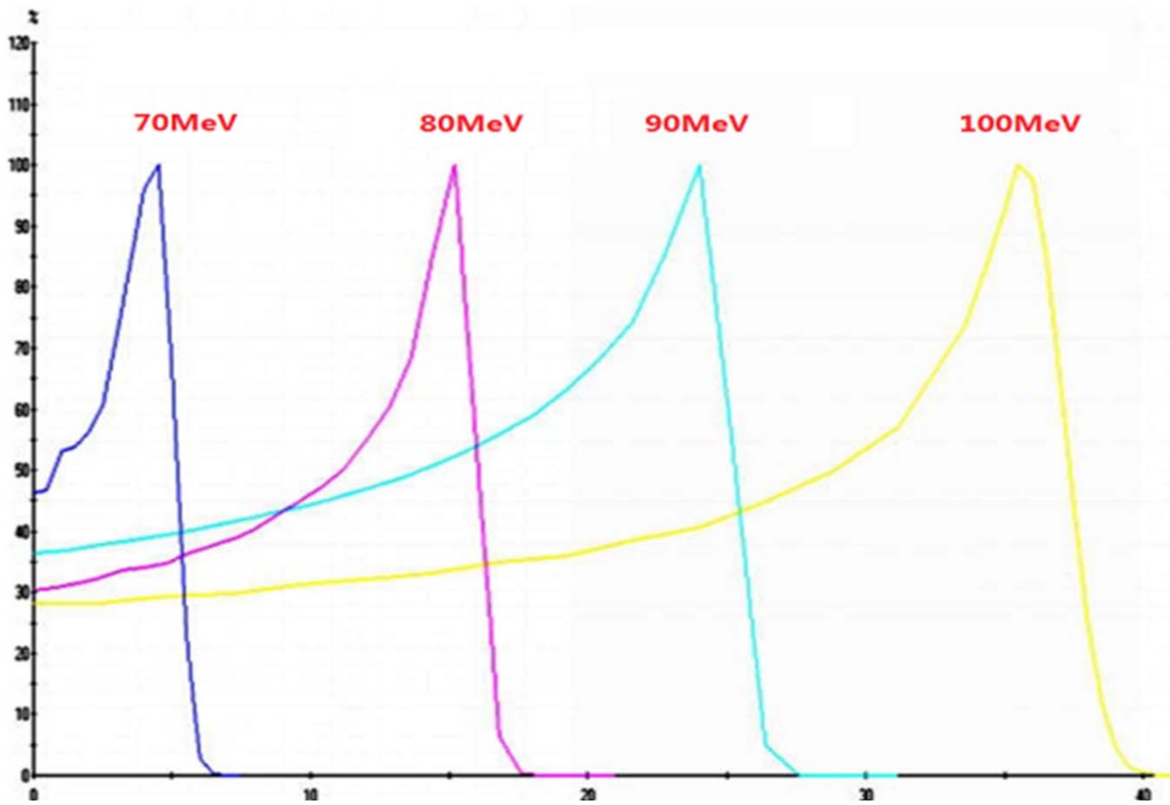
BRIF: from the First Proton Beam to RIB Production

S1: 1-5μA, S2: 50-200μA, S3: 10pA -10nA	N1 : 300nA – 200μA, N2: 5-10μA (potential intensity of 200μA, **ISOL**)



South Extracted Beam	**North Extracted Beam**

Dual Beam Extraction simultaneously



The proton beams have been extracted in dual opposite directions by charge exchange stripping devices at the same time, from CYCIAE-100.

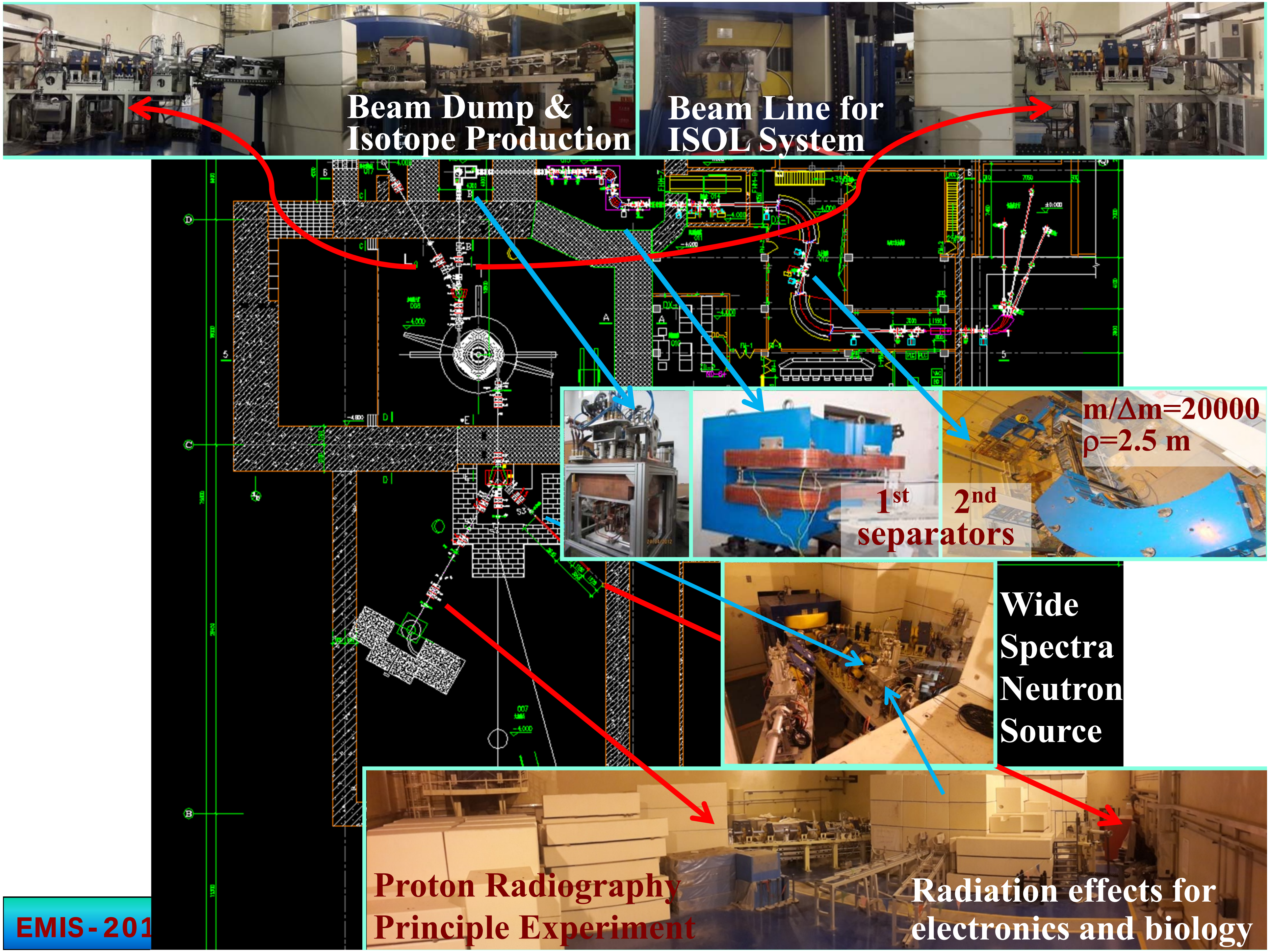
The extracted proton beam energy can be adjusted continuously between 70 MeV and 100 MeV.

Plan of Talk

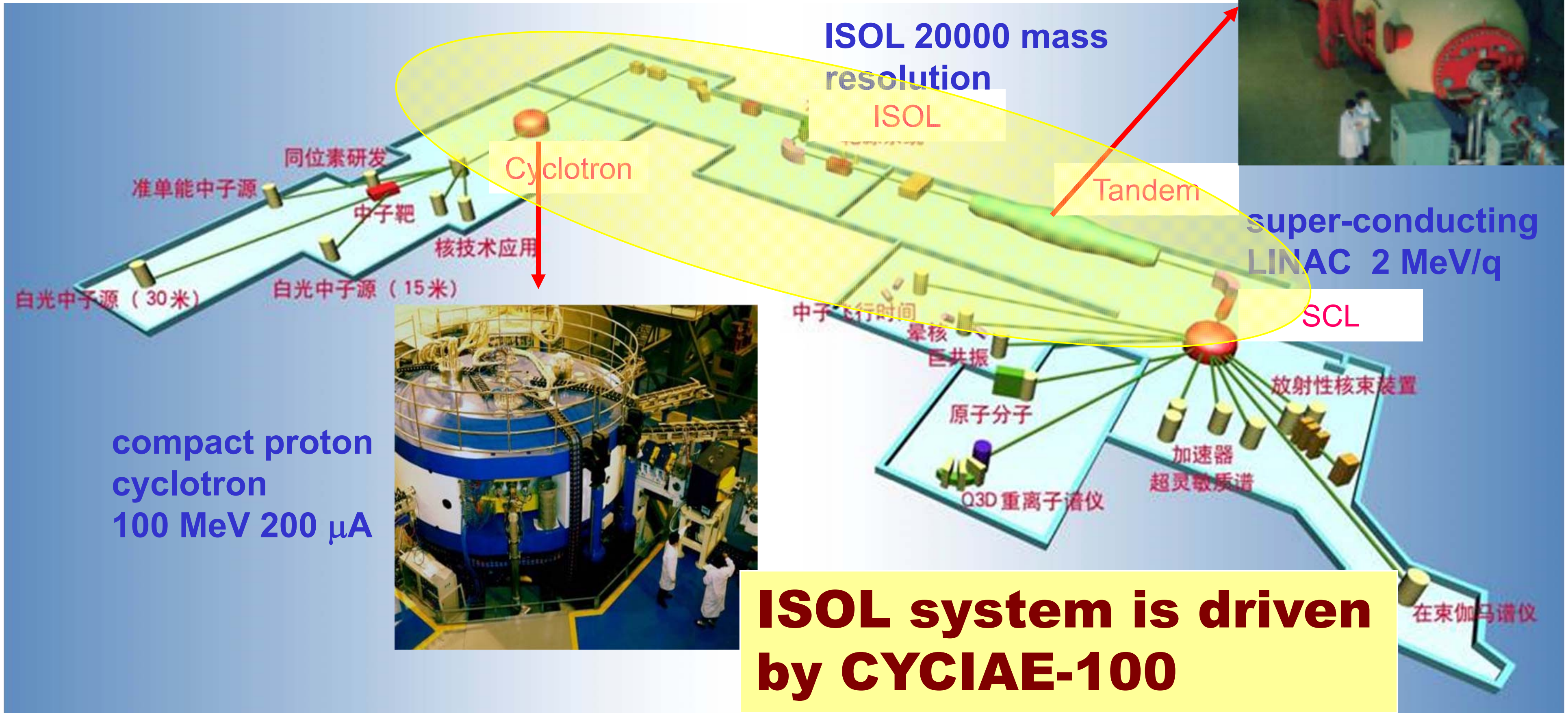
a) **BRIF - Beijing Radioactive Ion-beam Facility**
   a) Introduction
   b) First Proton Beam

b) **CYCIAE-100 Beam Development**
   a) Increase Intensity and Improve Stability
   b) mA Acceleration Efforts
   c) Dual Beam Extraction simultaneously

c) **CYCIAE-100 for ISOL and Other Applicati**
   a) Beam lines of CYCIAE-100
   b) ISOL system and Mass Resolution Improvement
   c) RIBs Production and Beam Time Application Opened for User
   d) Proton Irradiation and Other Applications


Beam Dump &
Isotope Production
Beam Line for
ISOL System
m/Δm=20000
ρ=2.5 m
1st 2nd
separators
Wide
Spectra
Neutron
Source
Proton Radiography
Principle Experiment
Radiation effects for
electronics and biology

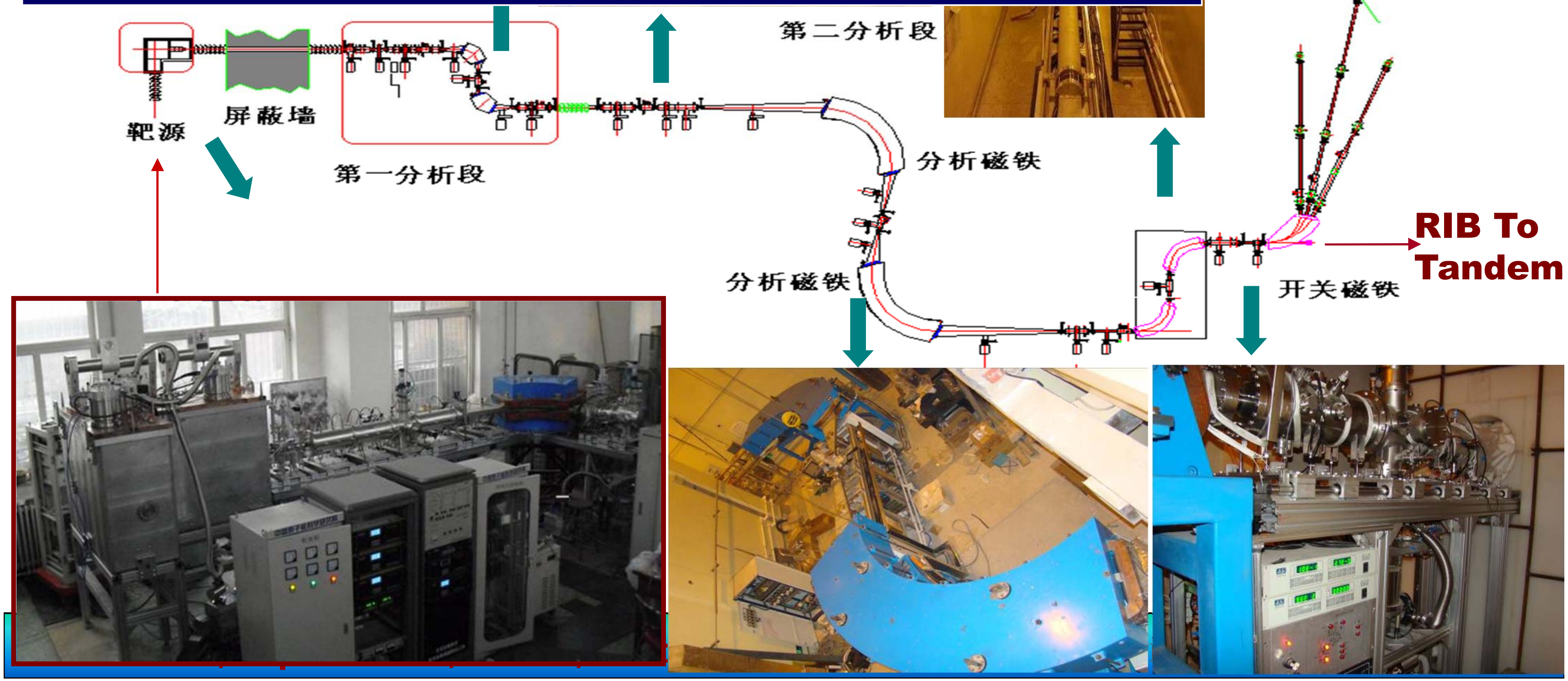
BRIF - Beijing Radioactive Ion-beam Facility



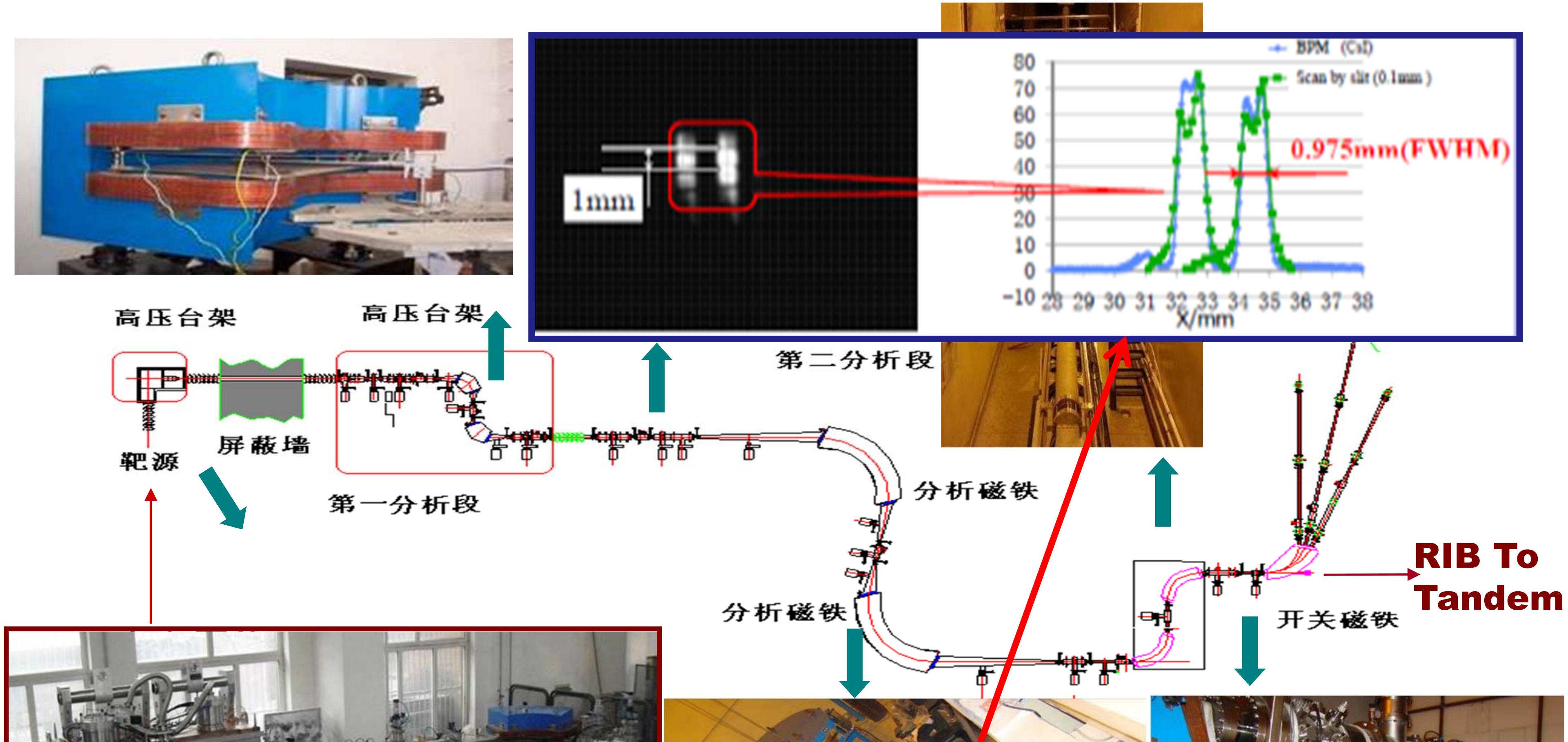
As one of the main projects at CIAE, the Beijing Radioactive Ion-beam Facility (BRIF) will be used in fundamental and applied research such as neutron physics, nuclear structure, material and **life sciences, medical isotope production**.

ISOL system, Mass Resolution Improvement & RIBs Production

1. In May of 2014, the stable ^{39}K beam
2. The mass resolution: ~10000.
3. The transmission efficiency is higher than 70% under the high mass resolution condition.

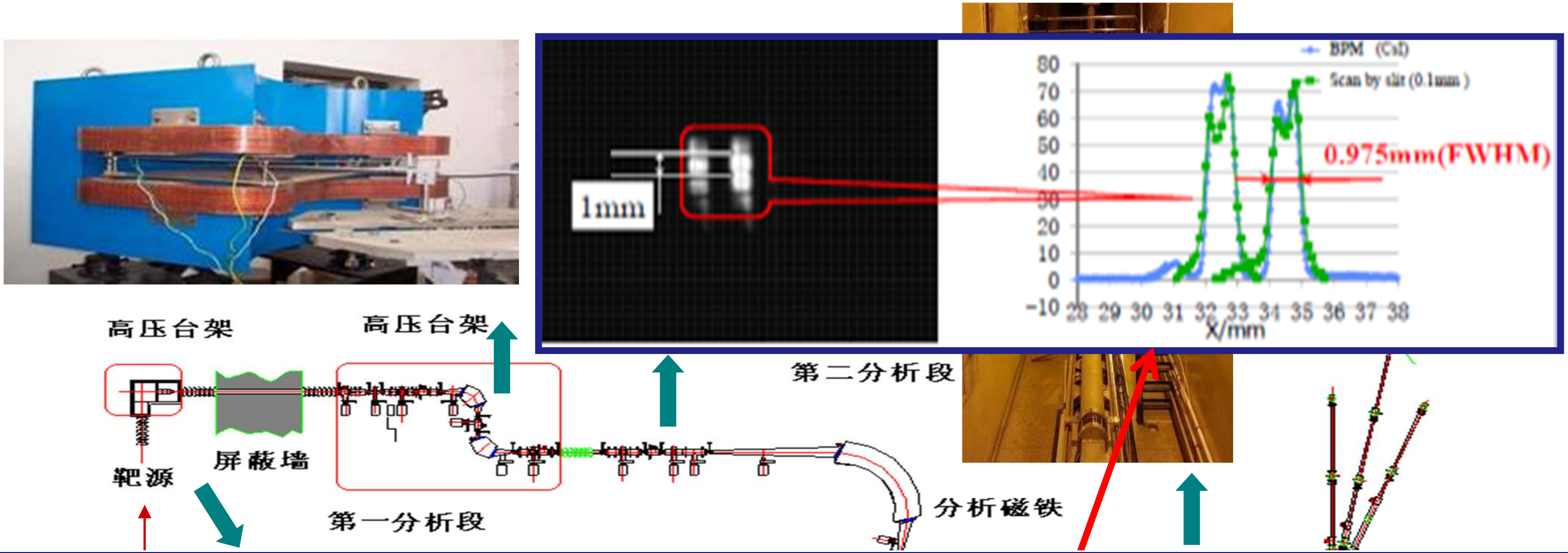


ISOL system, Mass Resolution Improvement & RIBs Production



1. On Oct 20, 2014, the stable beam, produced by ISOL system, was tested and accelerated by Tandem.
2. The mass resolution: 14385

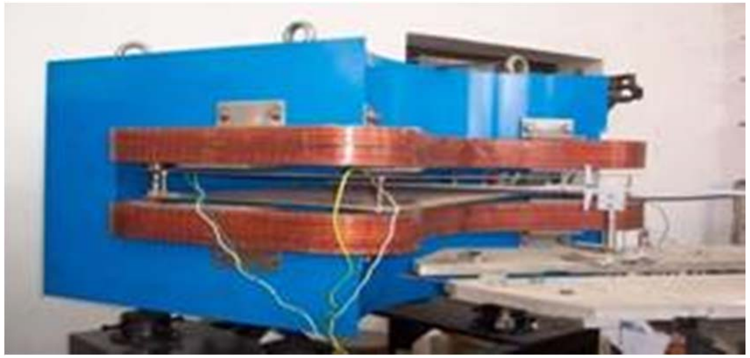
ISOL system, Mass Resolution Improvement & RIBs Production



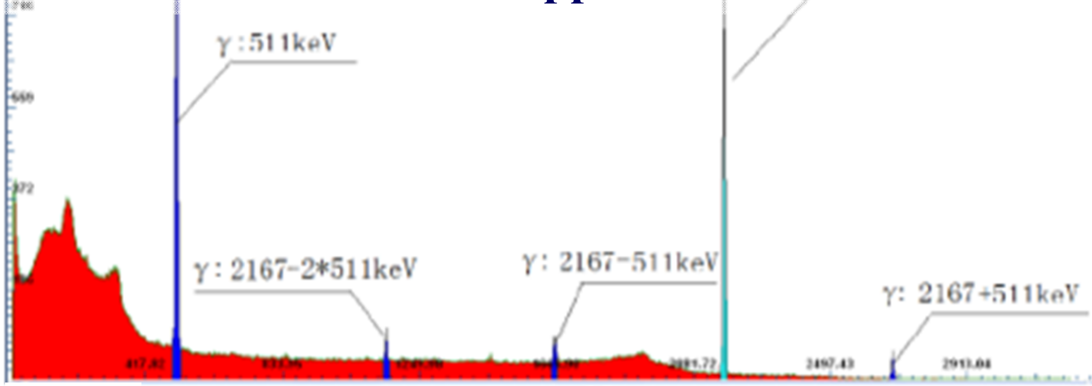
1. On Oct 20, 2014, the stable beam, produced by ISOL system, was tested and accelerated by Tandem.
2. The mass resolution: 14385

3. On May 26, 2017, the mass resolution: 24460
4. The transmission efficiency is higher than 90% for the 2nd stage of separators.

ISOL system, Mass & RIBs Production

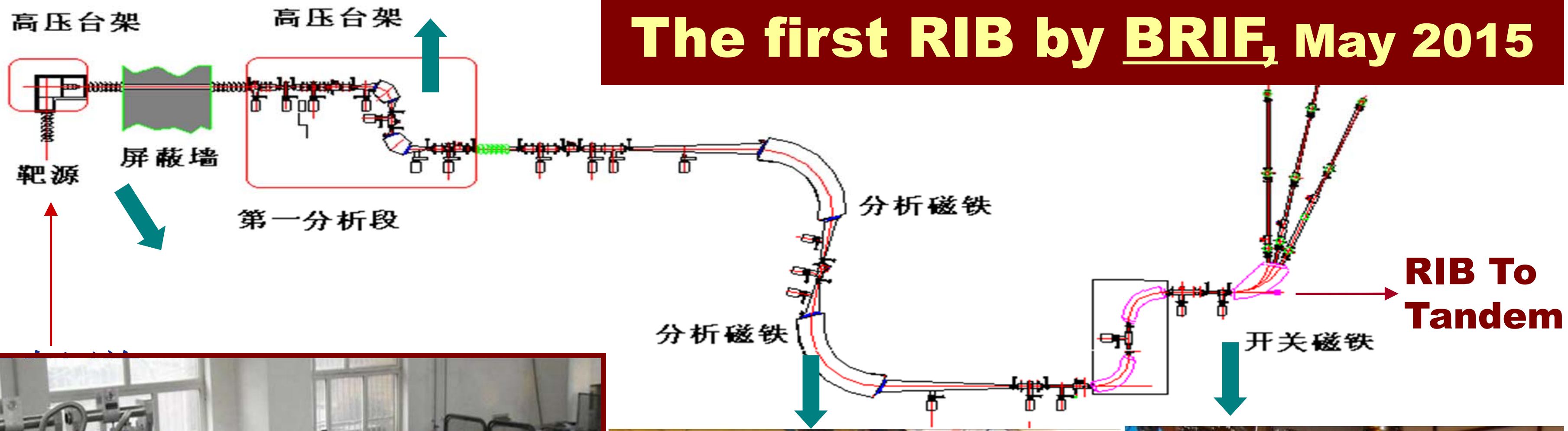


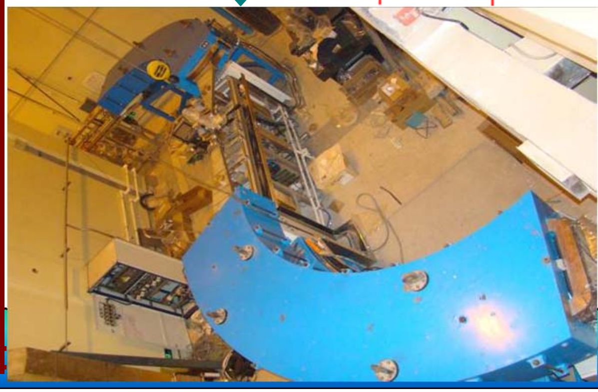
100 MeV proton beam on CaO target
Production of $^{38}K^{+}$: 1×10^{6} pps



The gamma spectra of ^{38}K after separator

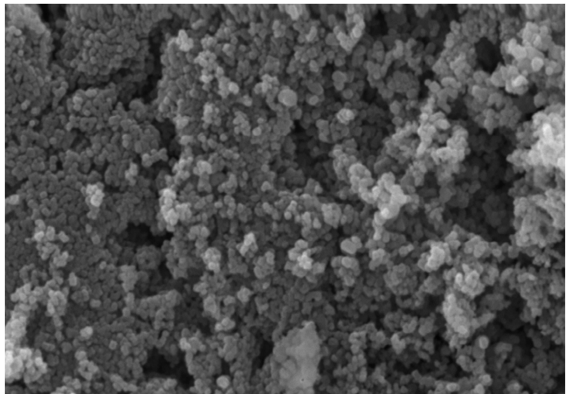
The first RIB by BRIF, May 2015



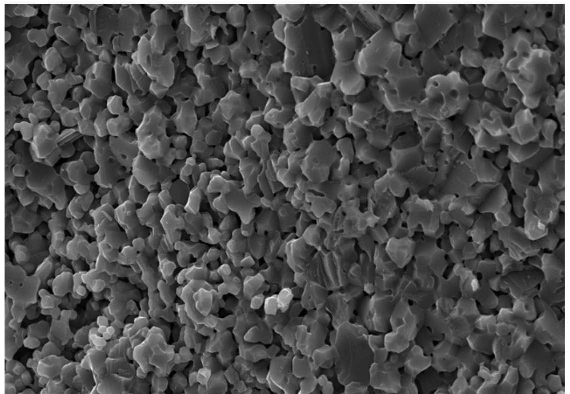


ISOL system, Mass Resolution Improvement & RIBs Production

In 2017, the RIB ^{20}Na has been generated for decay data measurement. **MgO is selected for the production of ^{20}Na.** The discs of MgO targets were prepared by hot-pressing sintering process at 1200℃, density of the targets is 1.2g/cm^3. The significant contraction (~20%) of MgO targets was observed in the heating experiment at 1600℃ for 4 hours. And the density of the target after shrinkage is about 2.4 g/cm^3.



SEM of MgO
before shrinkage



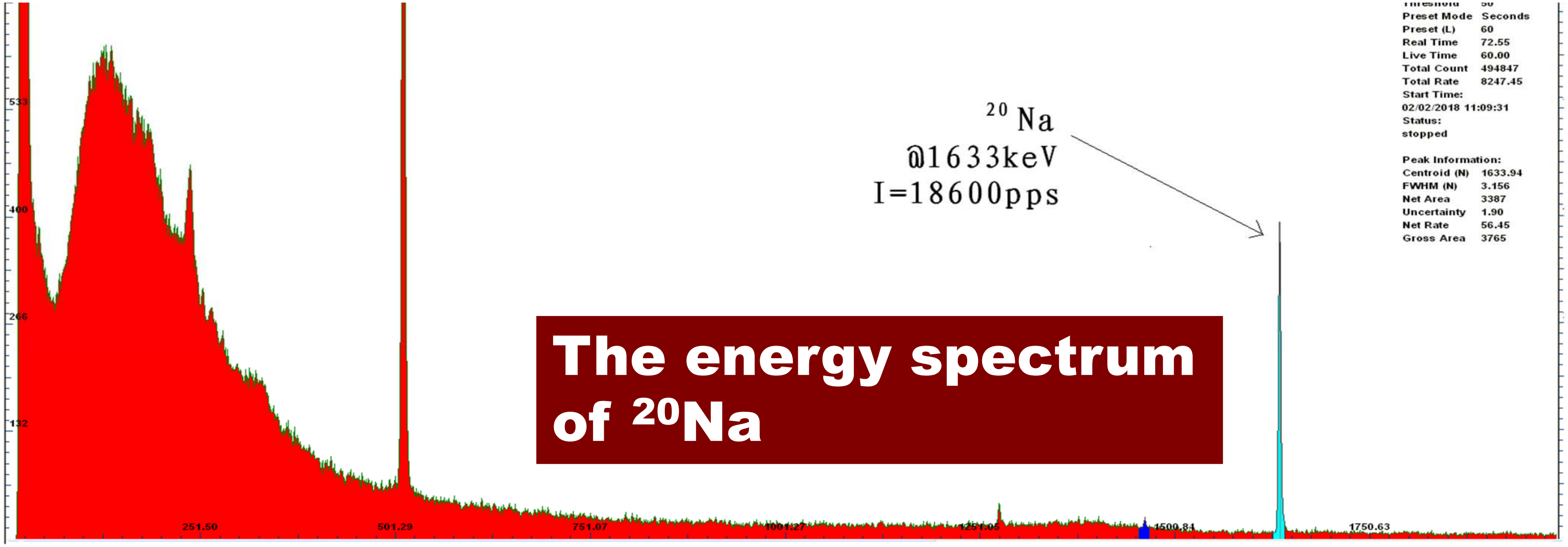
SEM of MgO
after shrinkage

MgO discs in the
target tube

Because the MgO discs shrinks obviously, to prevent the beam from passing through the target tube directly, the MgO target fragments were filled into the gap between the discs and the target tube

ISOL system, Mass Resolution Improvement & RIBs Production

In the first On-line experiments, the ^{20}Na beam wobbles after passing through the main dipole magnet since the instability of proton beam. The beam fluctuation is reduced by the better stability of proton beam and high voltage platform. The experiment for the decay data measurement of ^{20}Na was successfully completed.



When the proton beam is 10μA, the yield of ^{20}Na at the experimental terminal can **reach 1.35E+05 PPS**. The ^{20}Na beam has been delivering to target for more than **230 hours**.

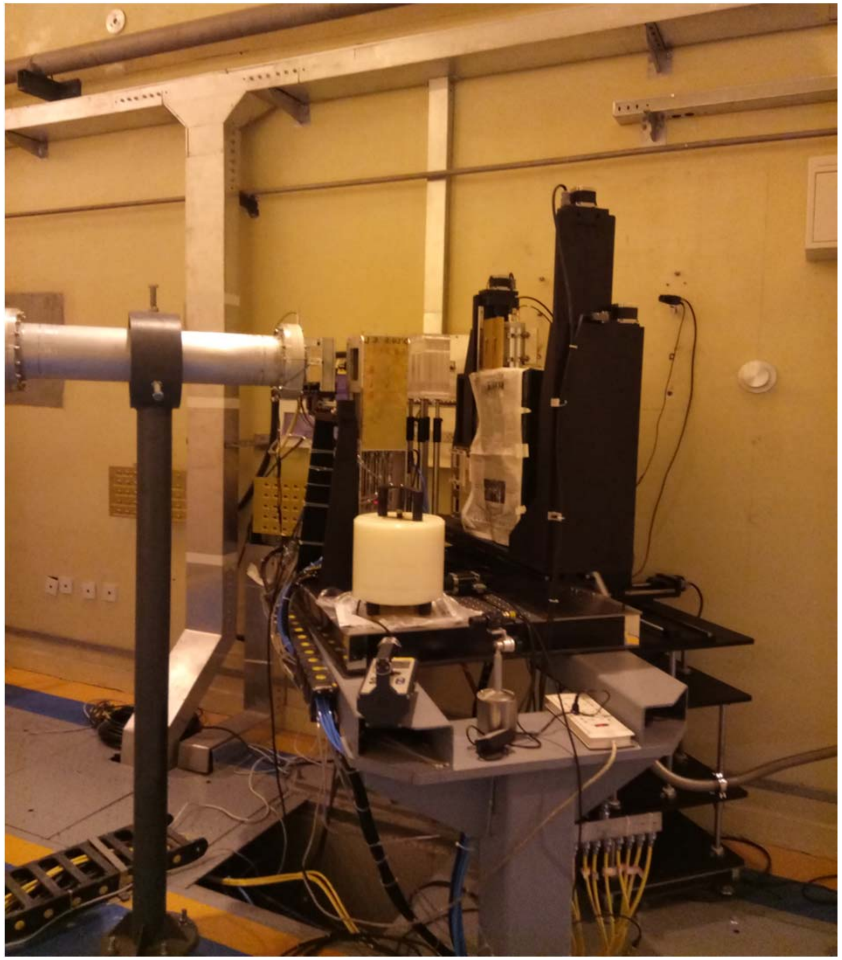
Proton Irradiation and Other Applications

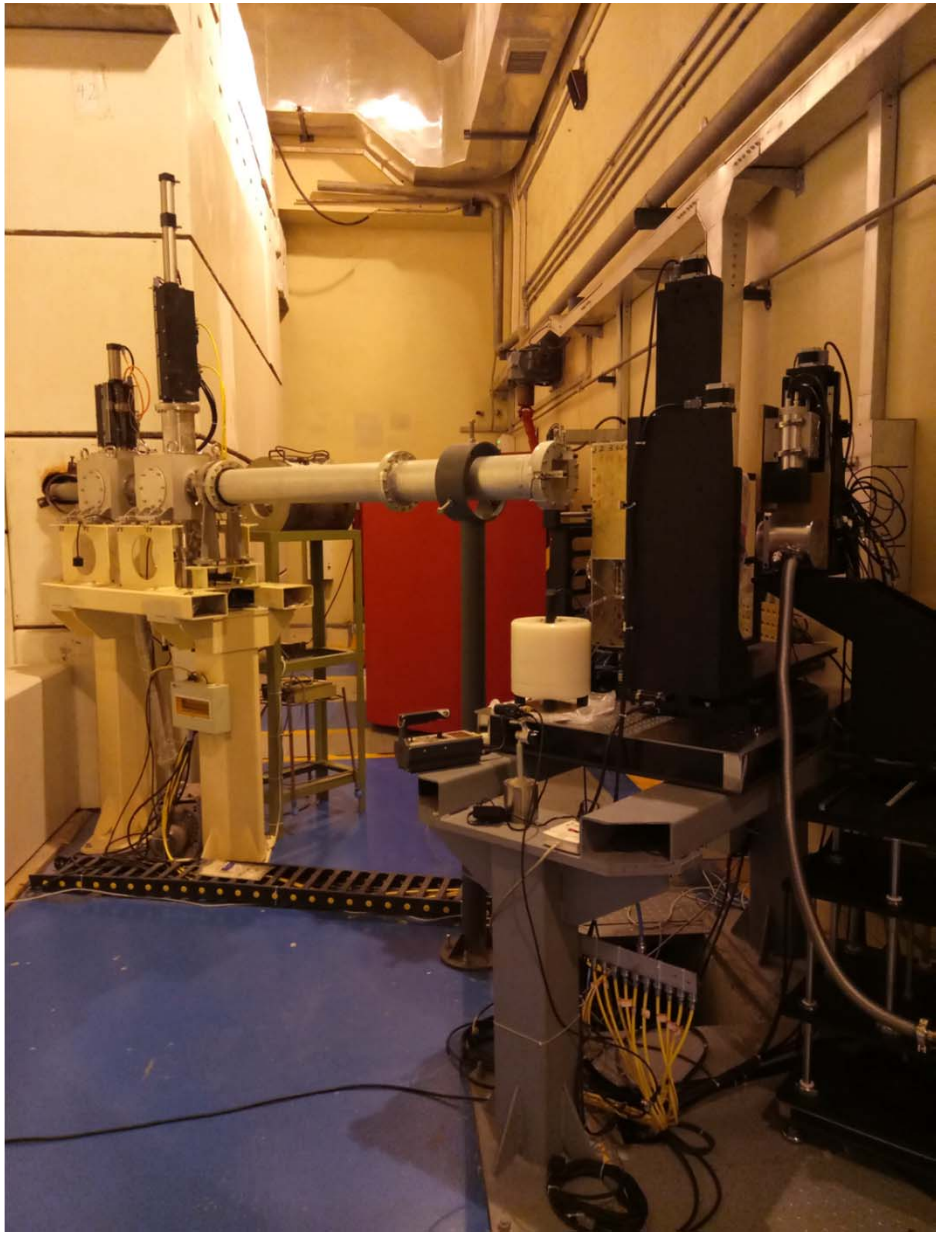
In Oct 2016, the White light neutron source installed, and shielded.

Target for White light neutron production

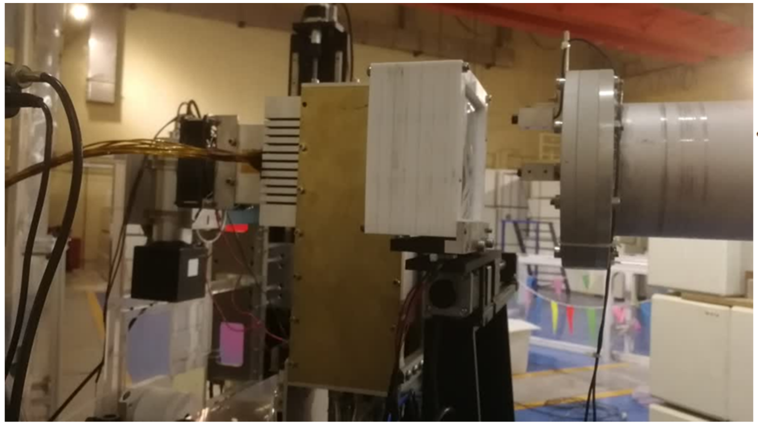
Proton Irradiation and Other Applications

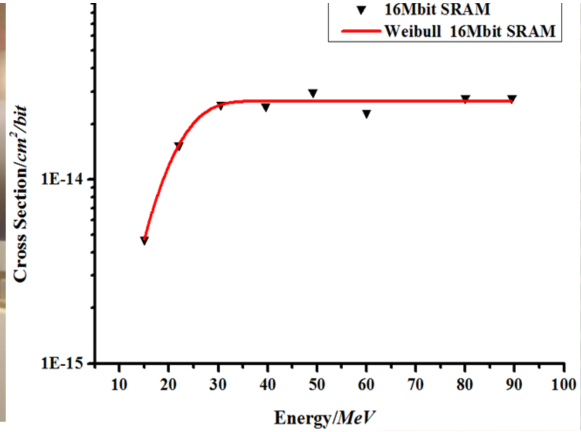
In Nov 2016,
the PIF installed,
n flux tested

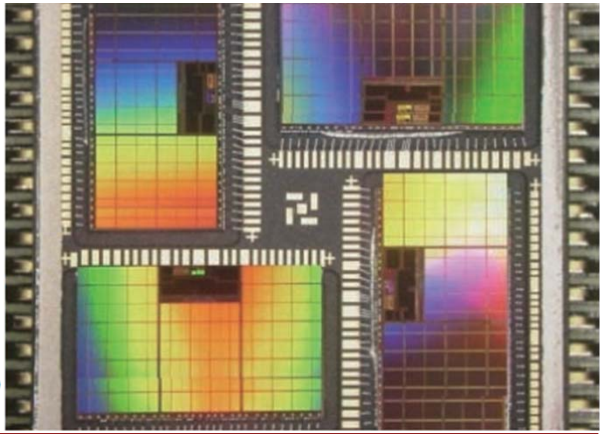




Proton Irradiation and Other Applications







Proton irradiation of single crystal diamond module; Radiation protection effect of typical materials for manned spacecraft

0.25μm 8×512k×8bits CMOS SRAM

香港科技大學
HONG KONG UNIVERSITY OF SCIENCE & TECHNOLOGY

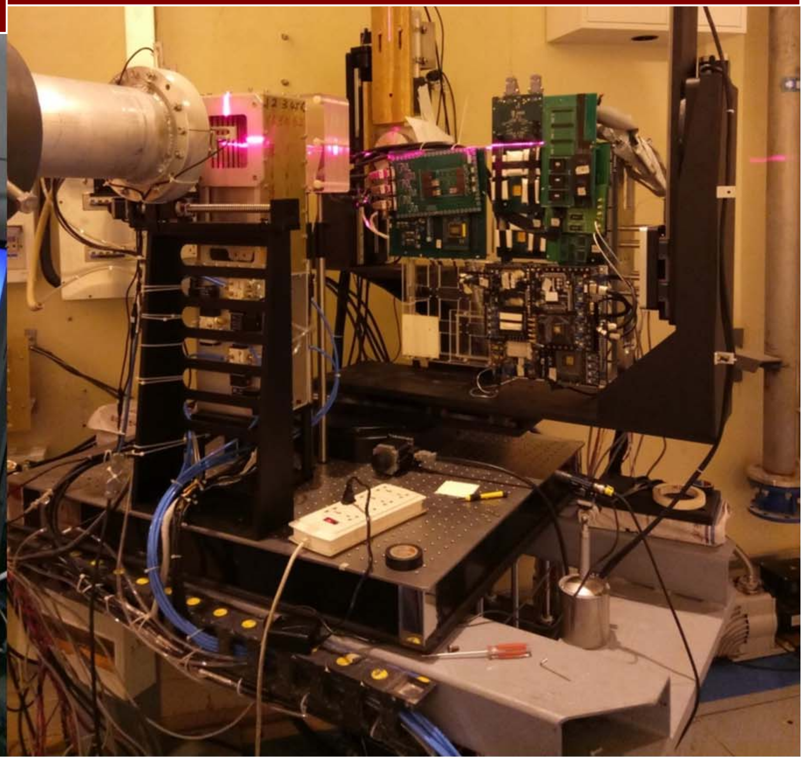
中国航天 中国空间技术研究院
China Academy of Space Technology

南京大學

CETC 中国电科

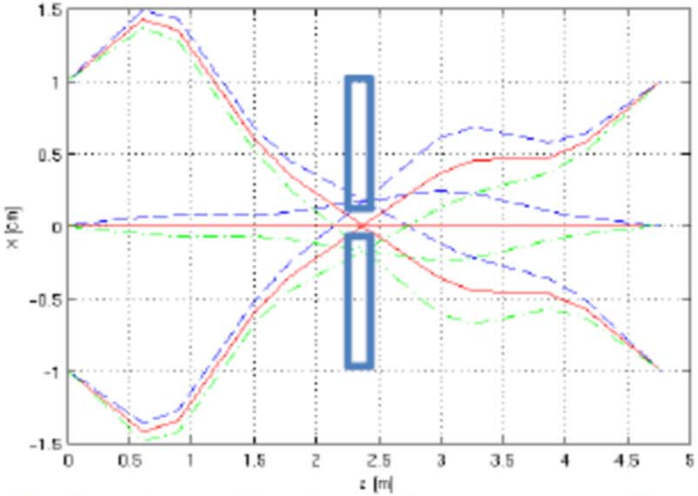
XTIPC

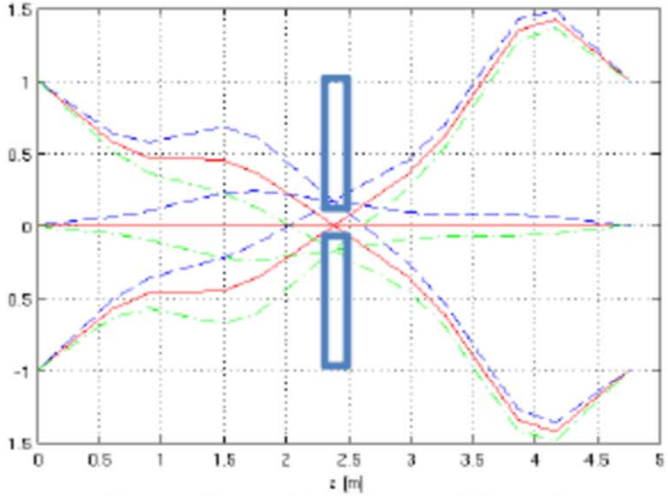
國防科學技術大學
National University of Defense Technology



Proton Irradiation and Other Applications

Proton radiography experiment





Pinhole collimator

- 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).

Proton Irradiation and Other Applications

Medical isotope production

Medicine

Isotope

Strontium-82, parent of rubidium-82

Germanium-68, positron emitter

Copper-67, research isotope

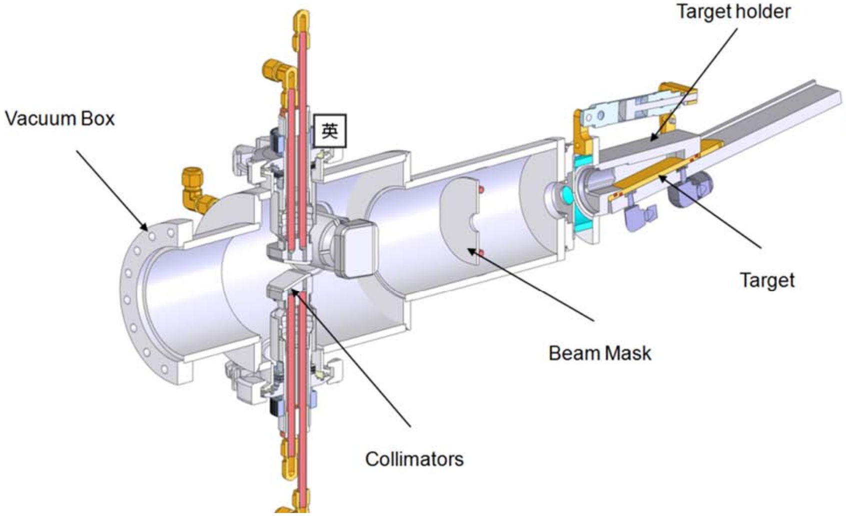
Rhenium-186, research isotope

Arsenic-72, research isotope

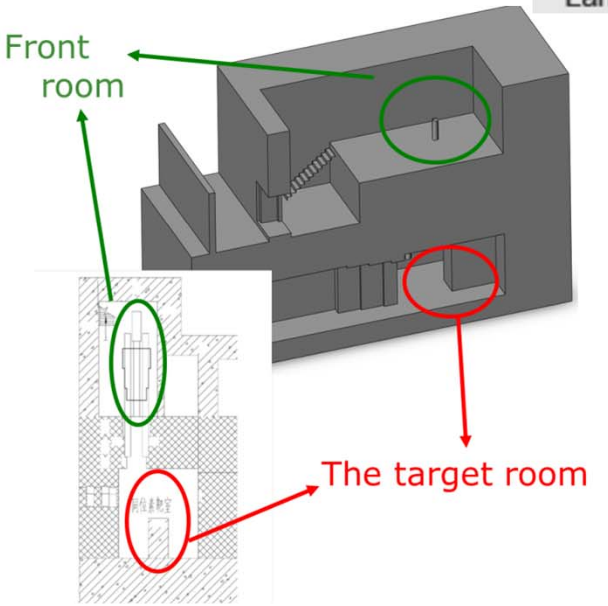
Arsenic-76, research isotope

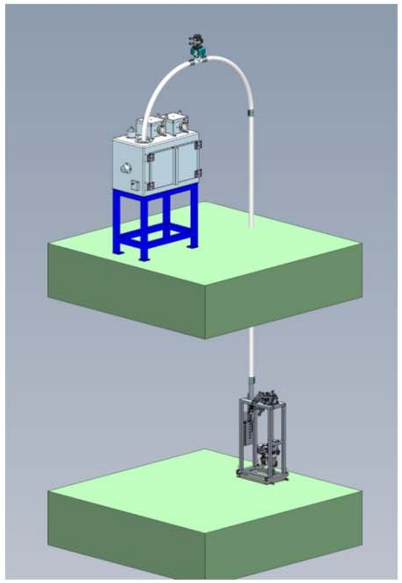
Bromine-77, one of the halogen isotop

Lanthanide isotopes, research isotope



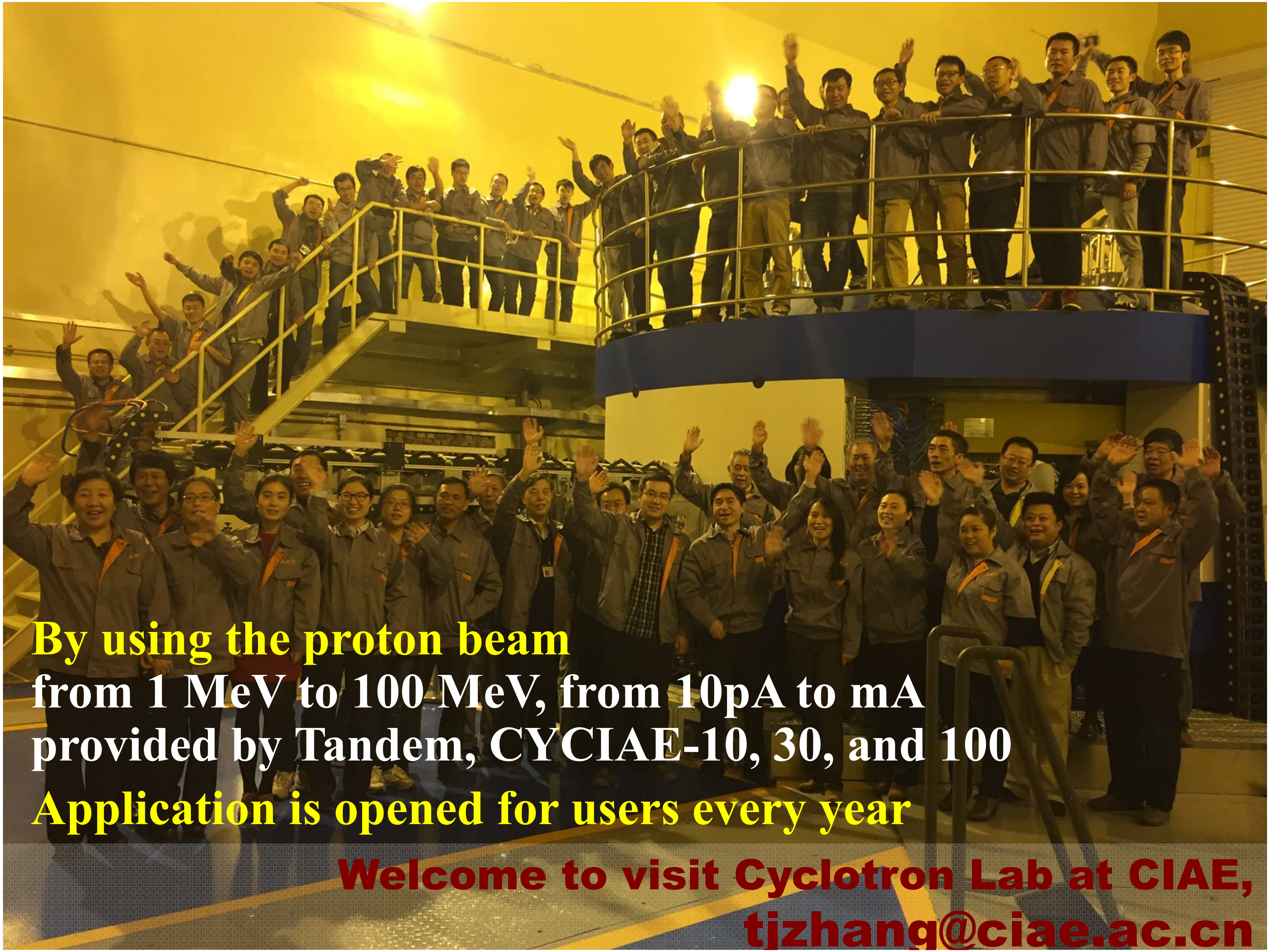
Target Irradiation System Cross-Section





Summary

- The beam commissioning on the CYCIAE-100 is completed. We got **the first 100 MeV proton beam on July 4 2014, and the first RIB on May 4, 2015,** 1mA proton beam on internal target in June, 2016. The 100 MeV cyclotron is able to provide 200 μA proton beam, dual beam extraction simultaneously. It has been put into routine operation since 2017.
- It is confirmed that 10pA to a few nA proton beam is also be provided stably by the high current machine CYCIAE-100 after we deliver beam for more than 10 users for the studies of radiation damage etc.
- After the first RIB production, the mass resolution of ISOL system is improved, better than 20000 with the transmission efficiency higher than 90% for the 2nd stage of separators. More RIBs was produced, e.g. ^{20}Na last year.


By using the proton beam
from 1 MeV to 100 MeV, from 10pA to mA
provided by Tandem, CYCIAE-10, 30, and 100
Application is opened for users every year
Welcome to visit Cyclotron Lab at CIAE,
tjzhang@ciae.ac.cn