100 MeV H^- Cyclotron Development and 800MeV Proton Cyclotron Proposal

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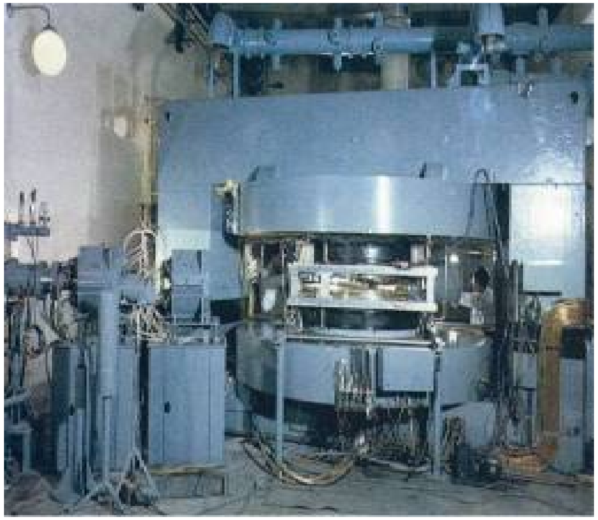
Plan of Talk

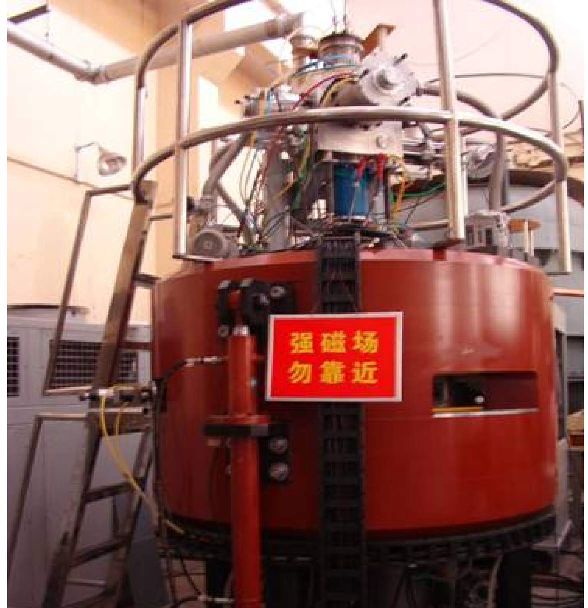
1. Introduction
2. The Beam Commissioning of CYCIAE-100
3. High Power Cyclotron Facility Proposal
4. Other Cyclotron Development

- ***In 1950's , pioneering with hardship and building development basis***
- ***Research reactor and cyclotron***

- ***On June 13, 1958 Reactor reached criticality***
- ***On Sep. 27, 1958 cyclotron provided beams***



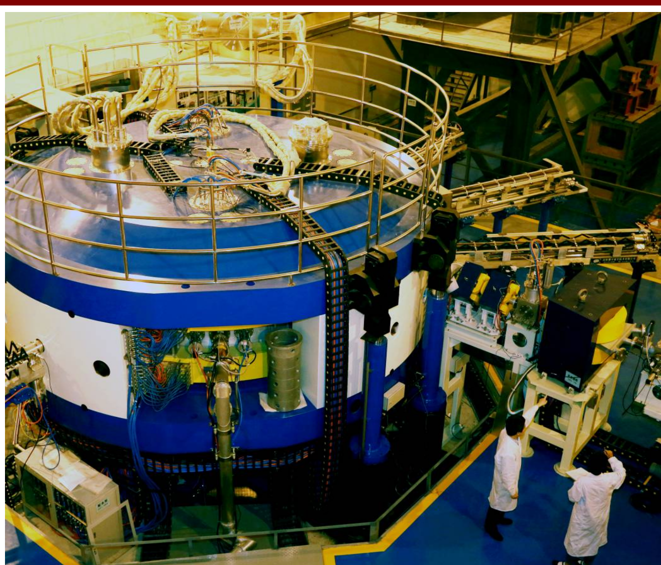
2009 10MeV，430μA



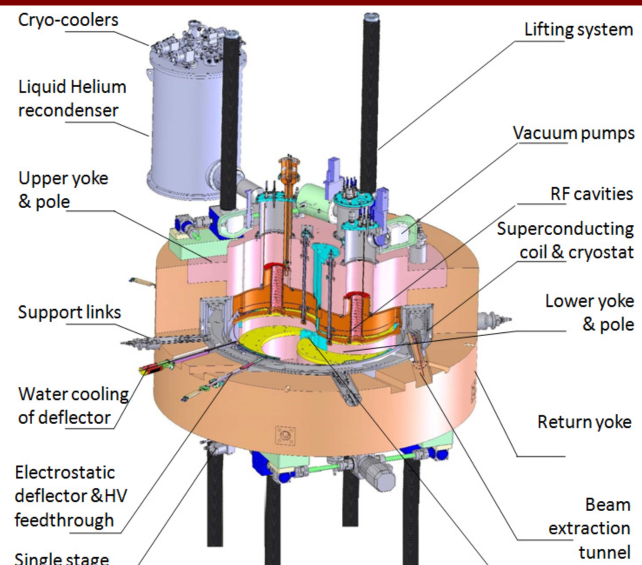
2012, 14MeV，450μA

1994, 30MeV，370μA

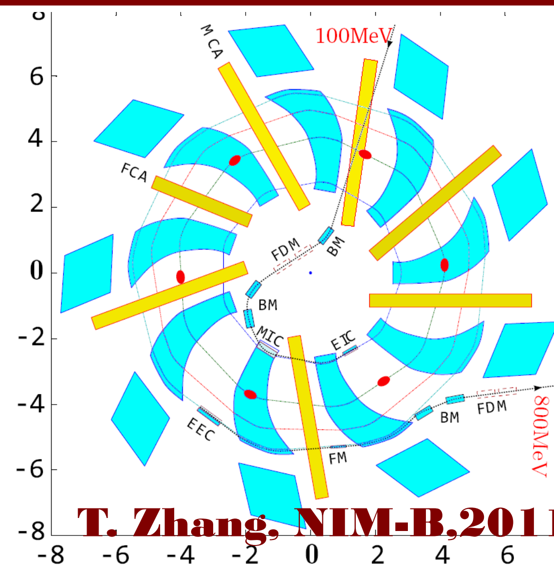
Development of proton cyclotrons with high intensity at CIAE



100MeV，200-1000μA



230MeV，1μA



800MeV，3000μA

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.

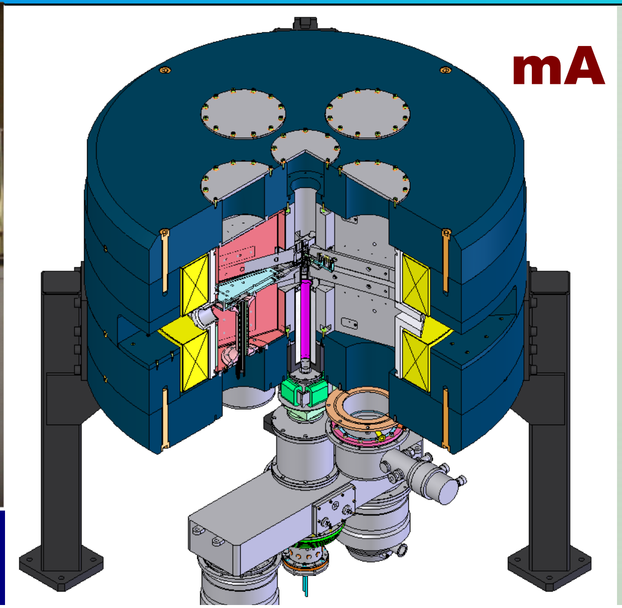
For the production of

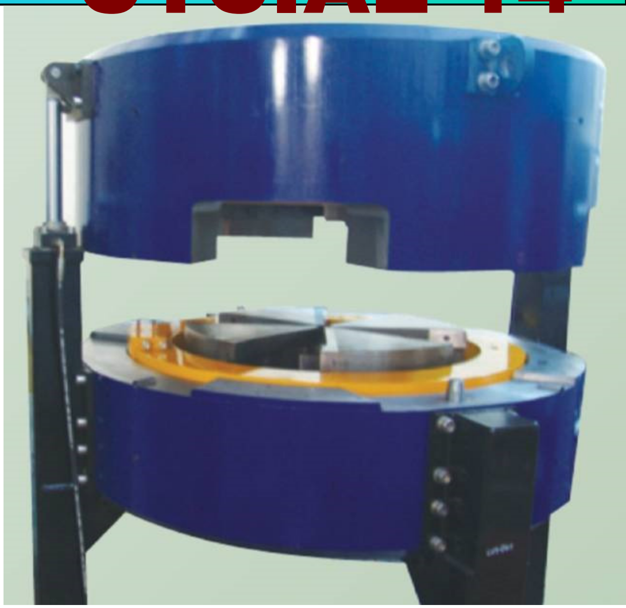
Tl-201	Pd-103
F-18	Ga-67
Co-57	Ge-68
I-123	In-111

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.

CYCIAE-14





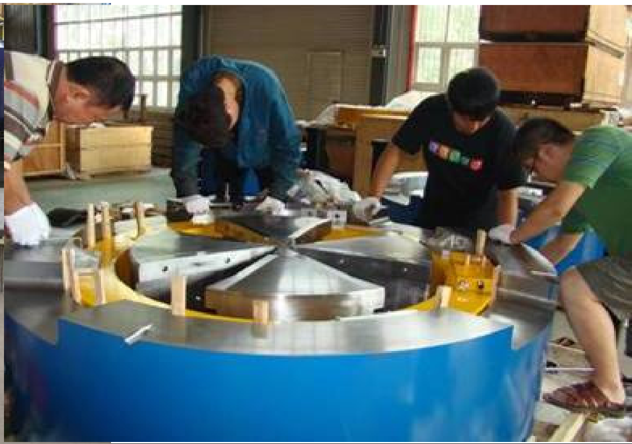
10MeV， 430μA

First, Second Small Cyc

10th Small Cyc, under construction for BNCT

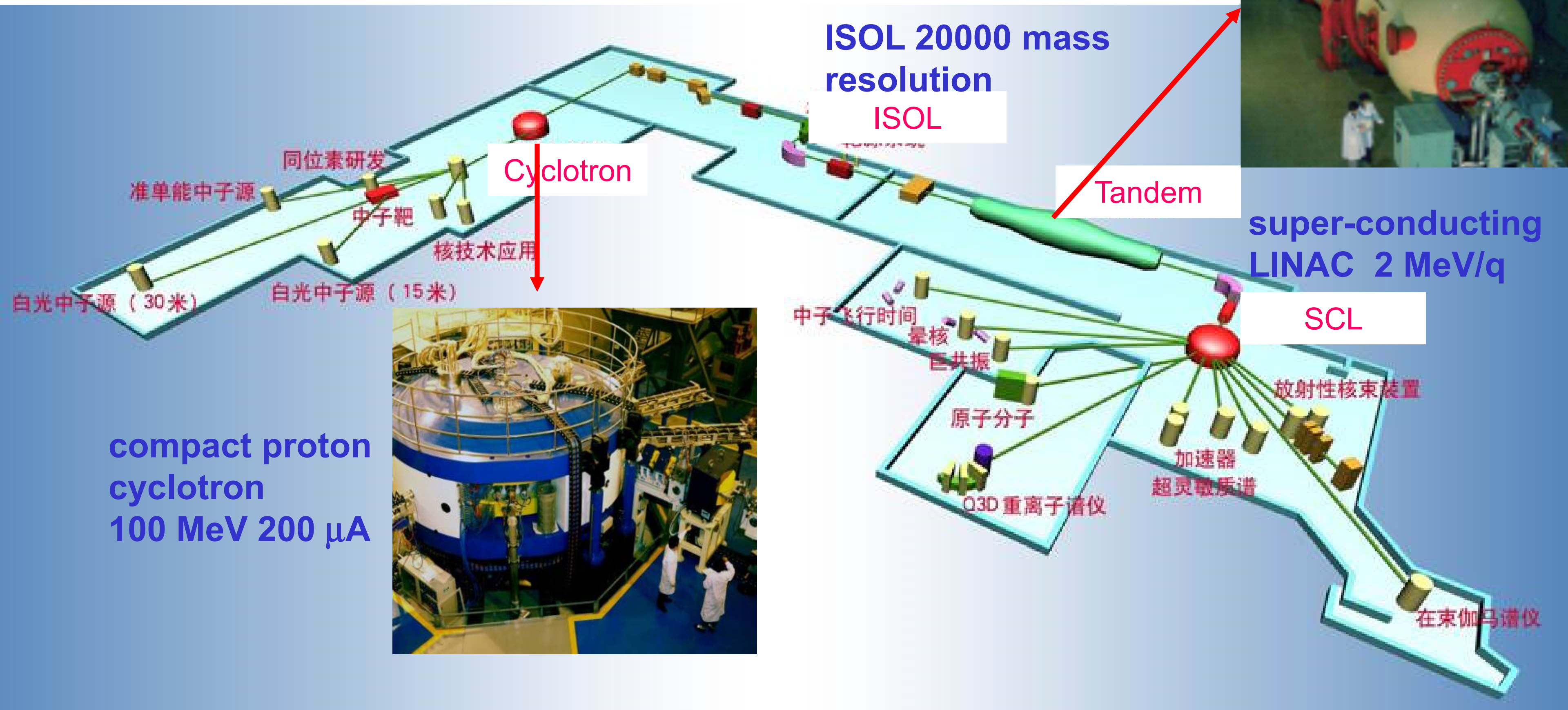
PET Cyclotron, 14 MeV, 450 μA

3rd to 9th Small Cyclotron, 14 MeV, 100 μA to 400 μA, main parts for overseas



CYCIAE-100

BRIF - Beijing Radioactive Ion-beam Facility

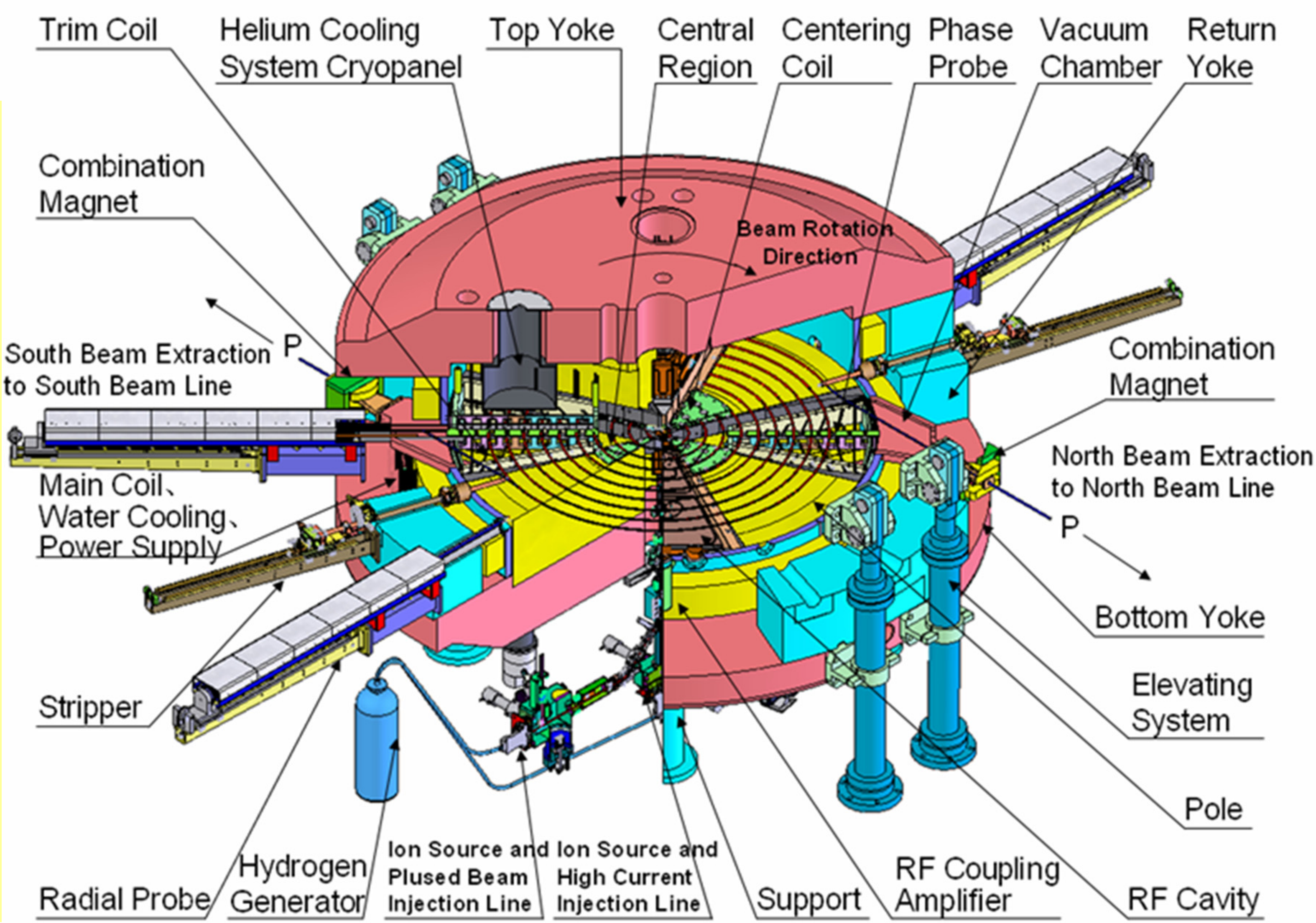


As one of the main projects at CIAE, the Beijing Radioactive Ion-beam Facility (BRIF) will be used in fundamental and applied research such as neutron physics, nuclear structure, material and life sciences, medical isotope production.

CYCIAE-100

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.**

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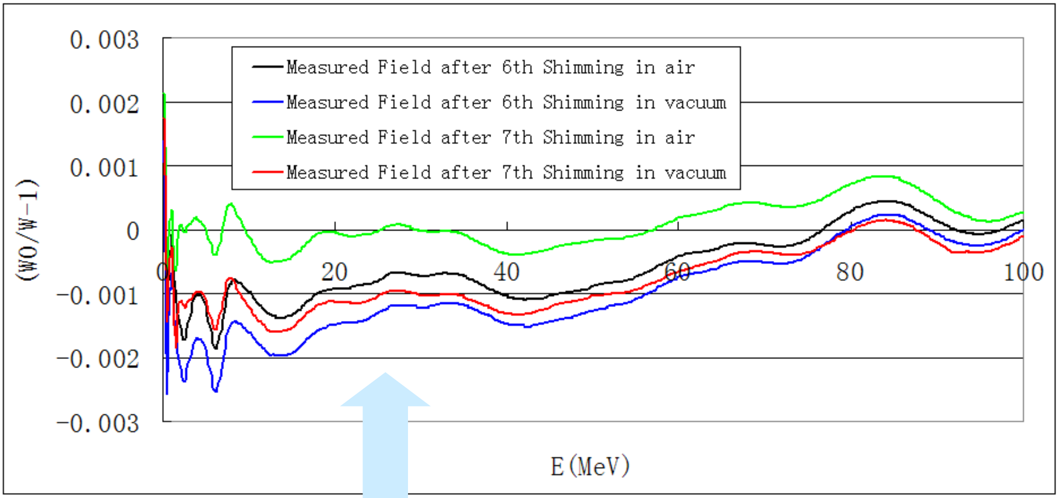
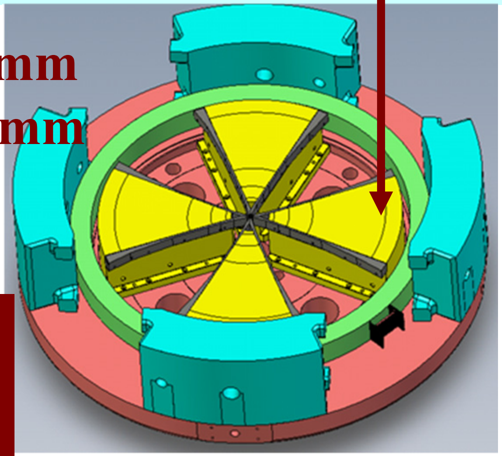


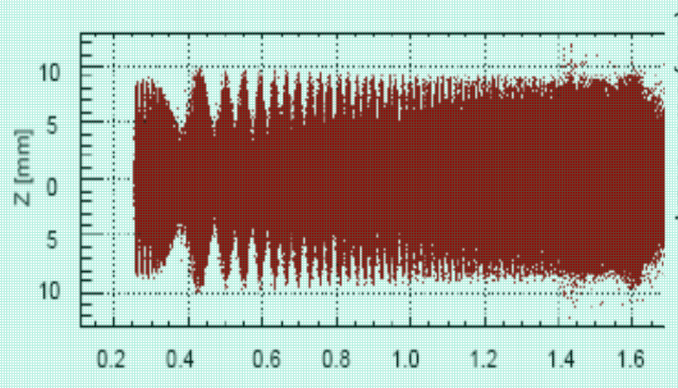
First compact cyclotron with straight sector pole for energy beyond 70 MeV.

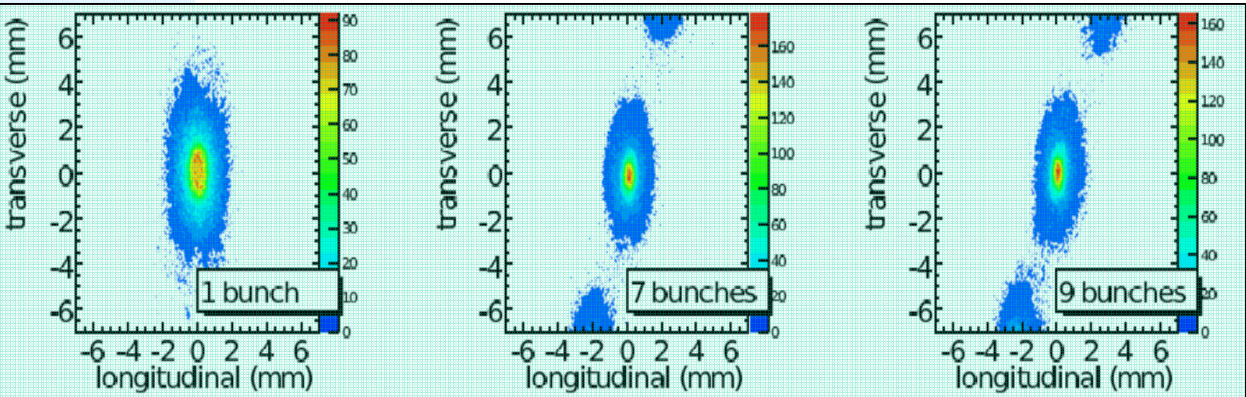
Dia.: 6160 mm
Height: 2820 mm
Weight: 435 t



Whole field map is measured within vacuum for the first time, the final phase slop less than ±10°

Various technologies for high current compact H- cyclotron have been developed

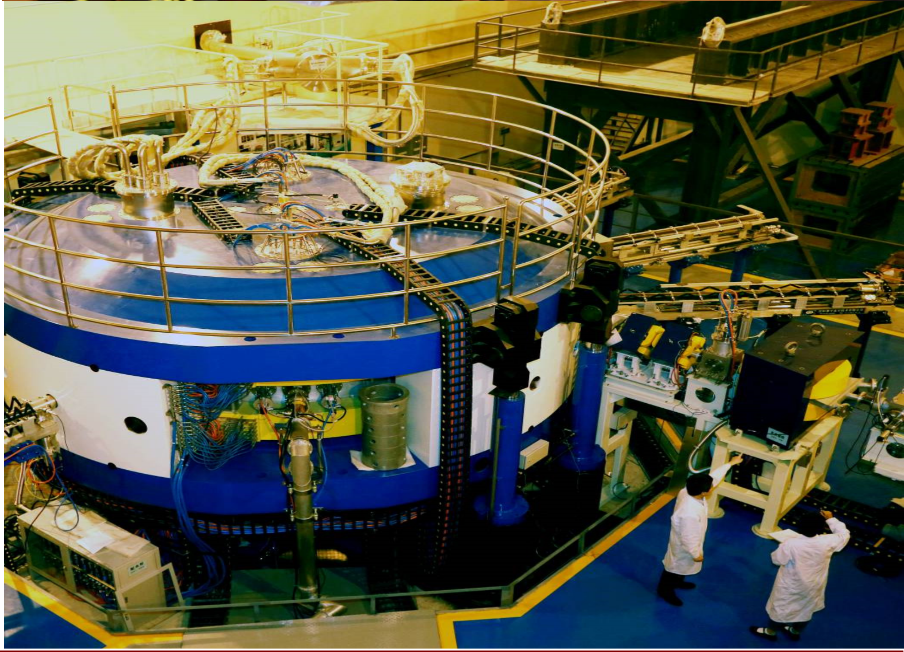




It is first time to Develop a parallel computation code for multi-bunch simulation, which is implemented in 6 international institutes to study space charge effects and multi-pacting effects.

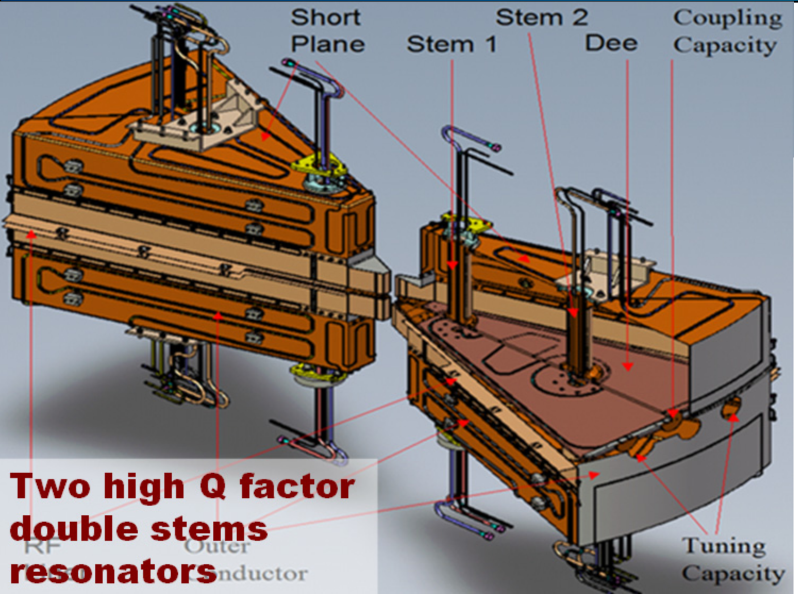
Tolerance Control:

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

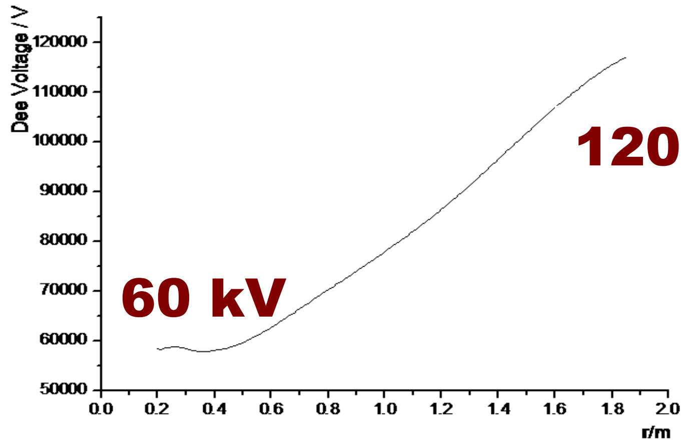


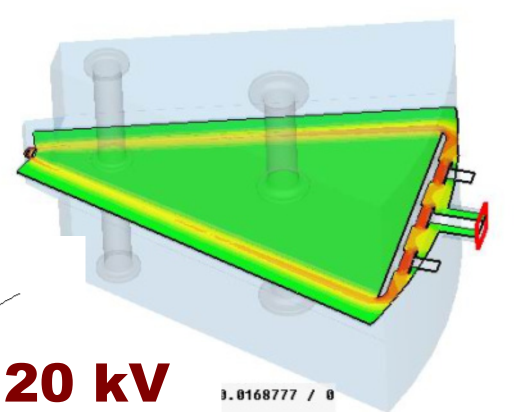
The installation, mapping and shimming of the main magnet system are finished by July, 2013

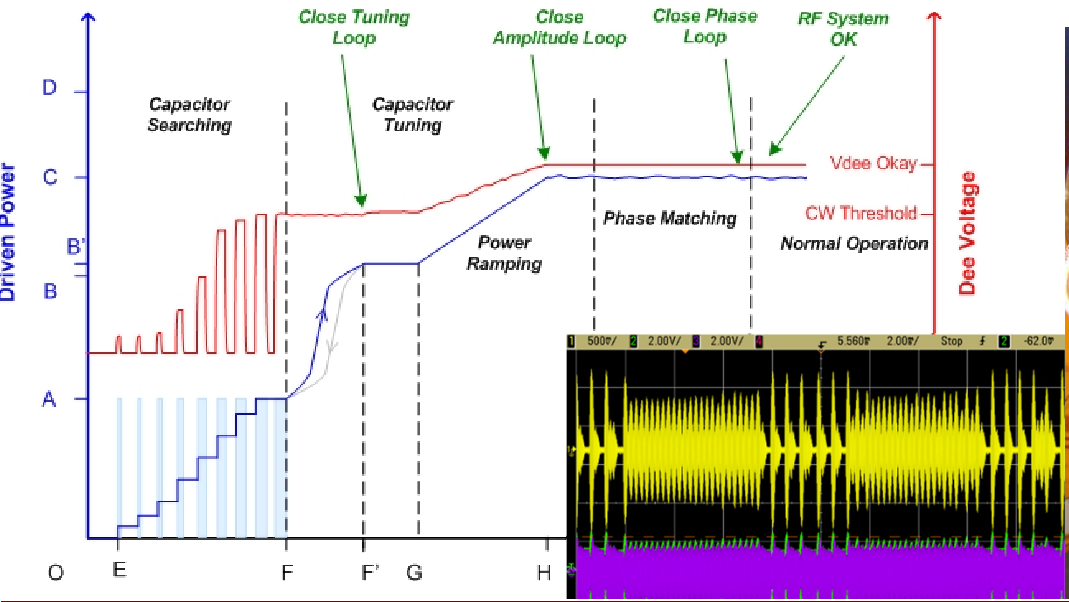
100 MeV H- Cyclotron Development and 800MeV Proton Cy



Dee Voltage



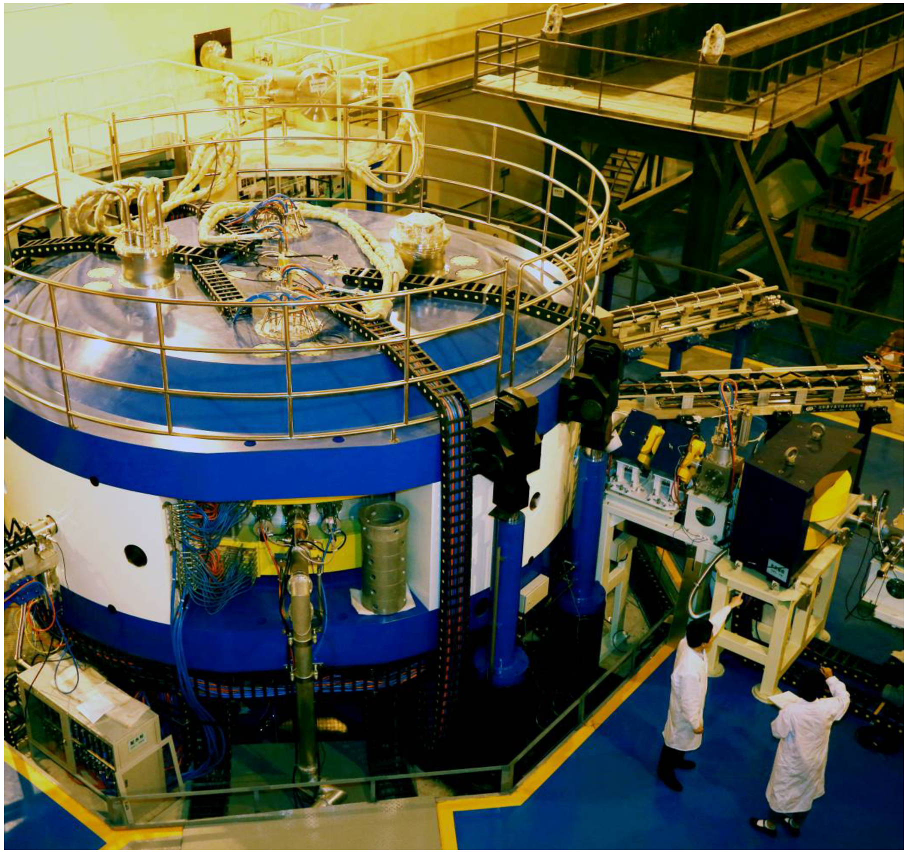




Installation of RF, Vacuum, R-probes, extractors, central region, RF conditioning were finished by the end of 2013

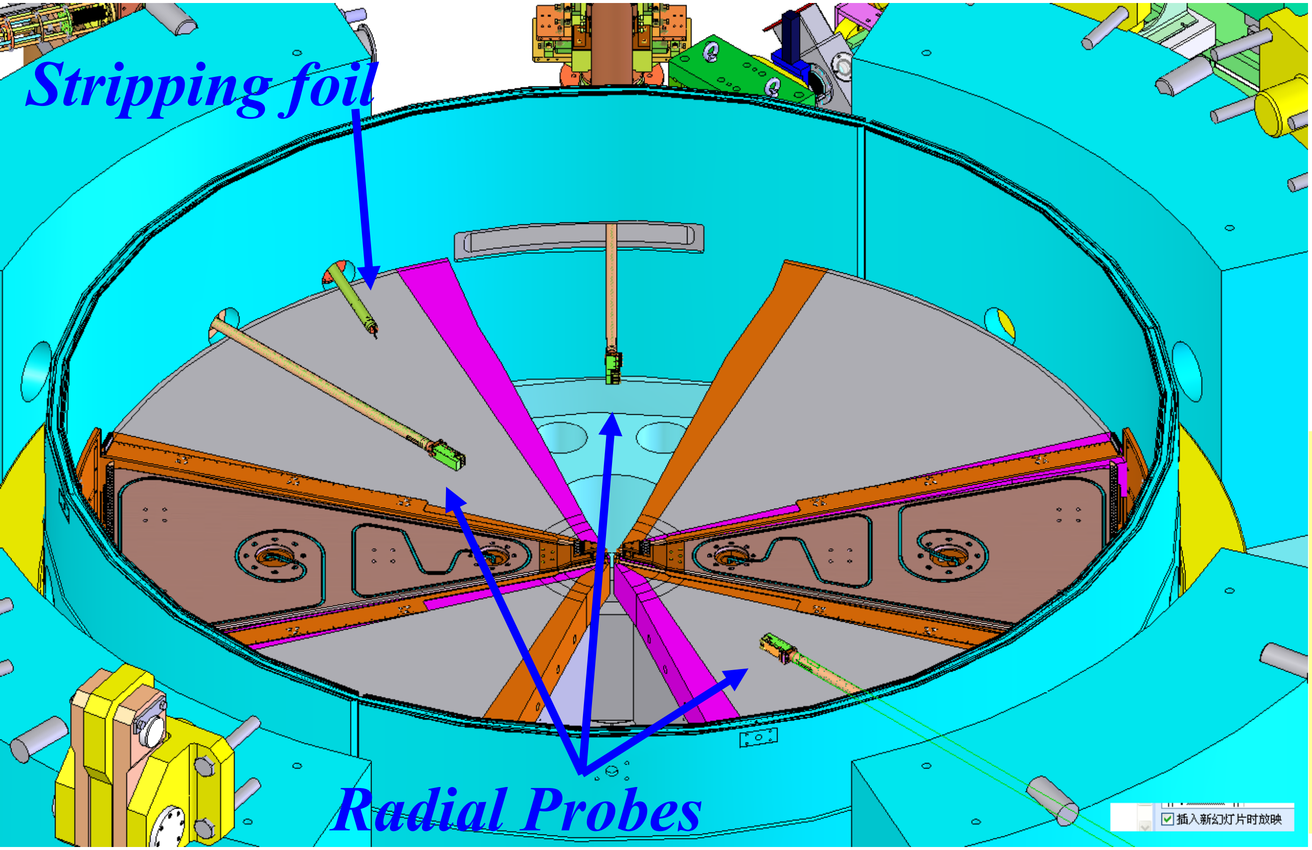
Beam Commissioning

- 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 June 16, 2014, the internal target is moved to 1 MeV region and successfully got **109 μA** beam with 20% RF duty cycle.



we gradually increased the duty cycle and reached CW mode operation.

Beam Commissionin

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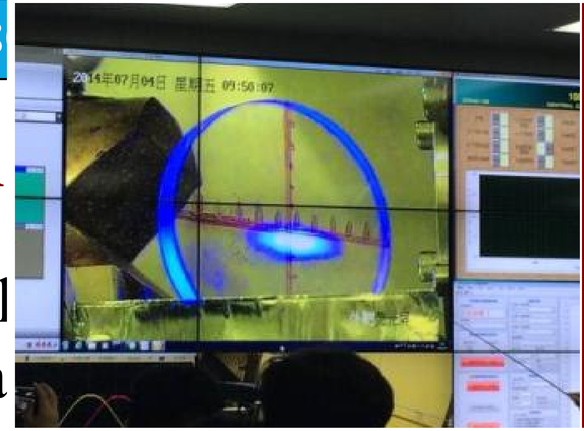
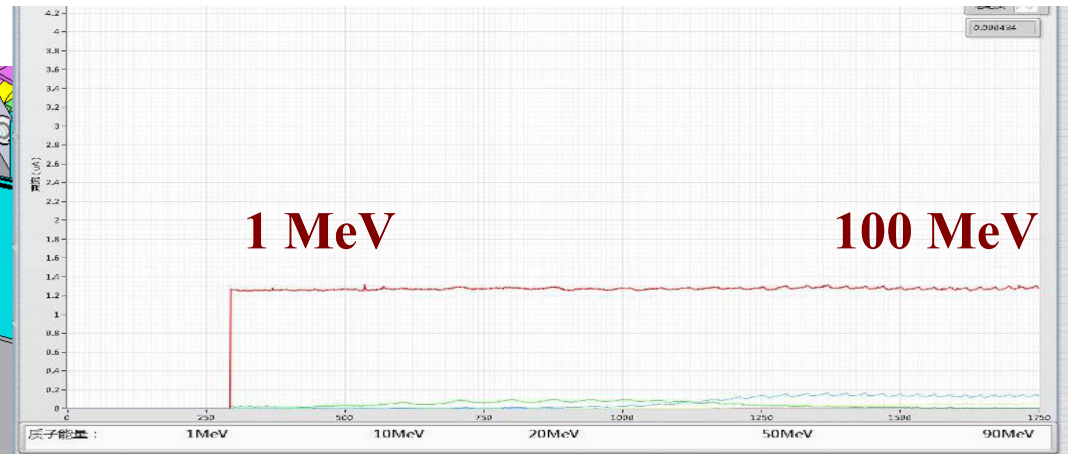
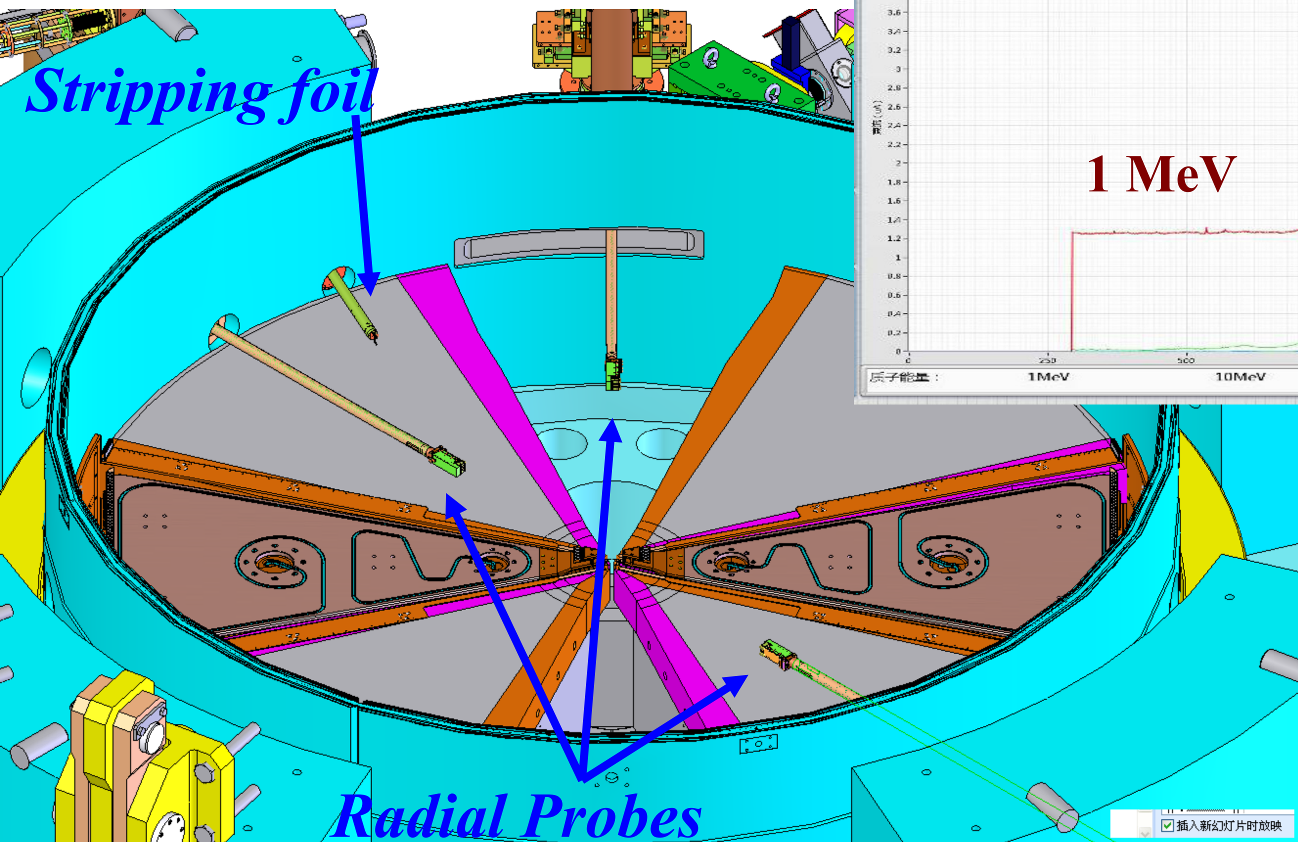


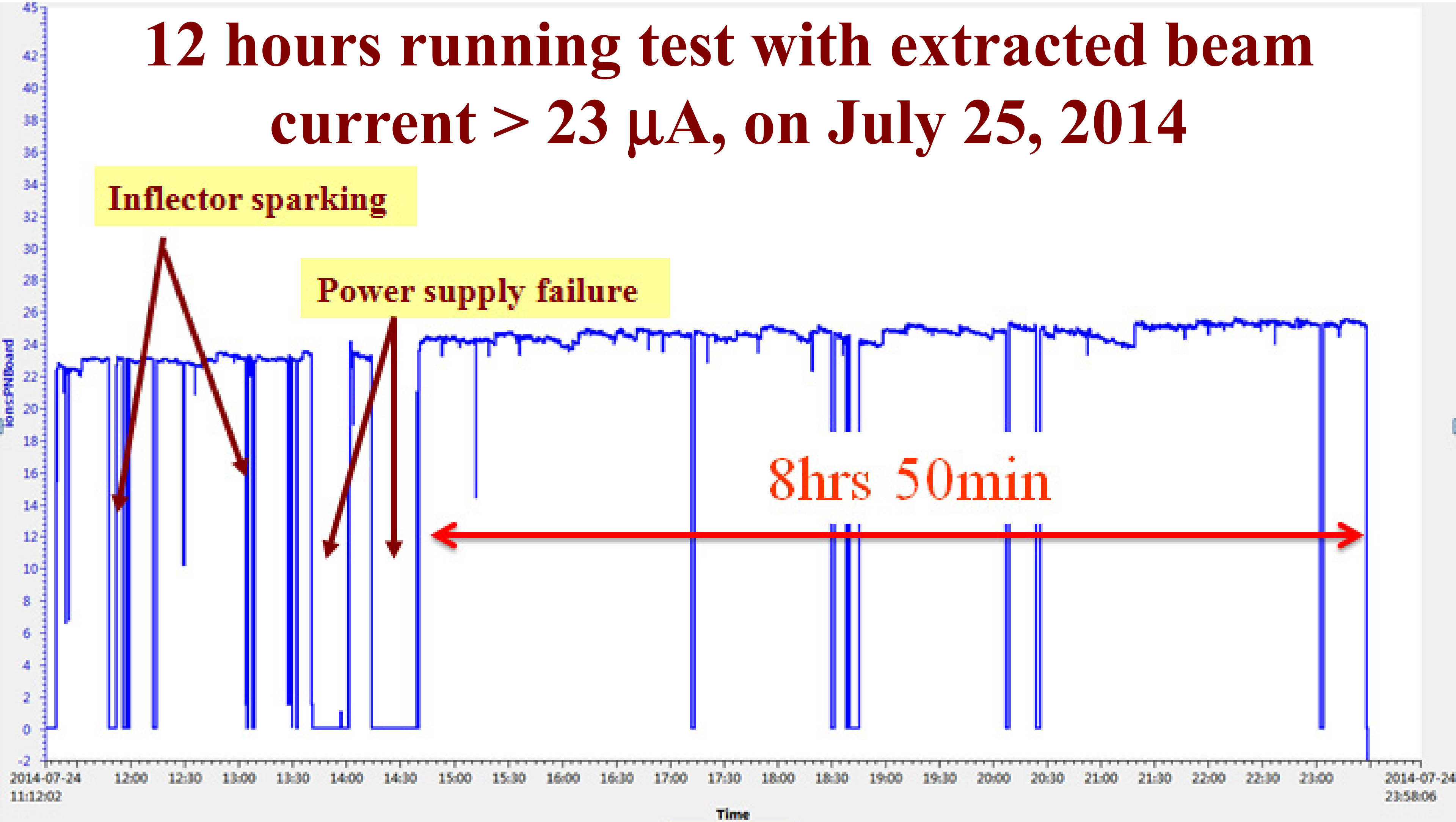
July 4, 2014, we got first 100 MeV proton beam Extracted





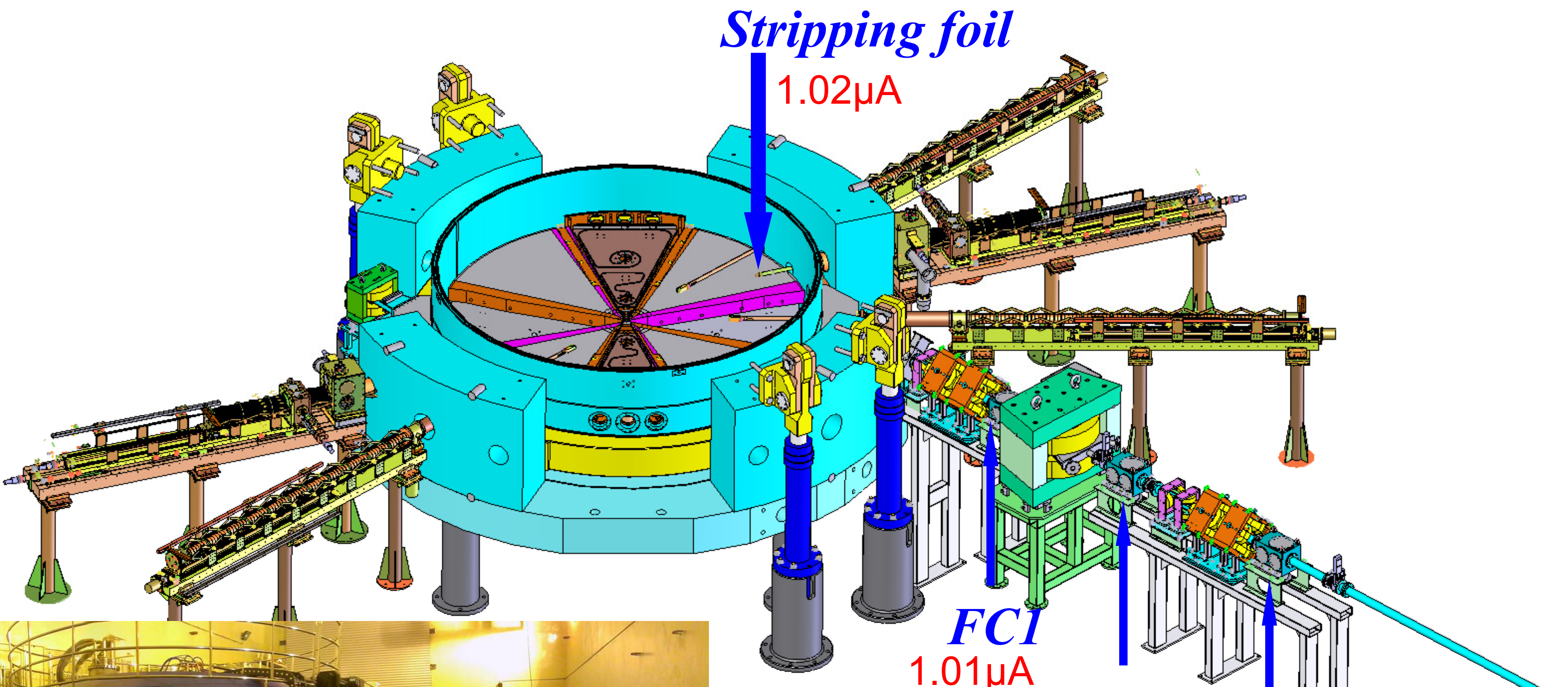
we gradually increased the duty cycle and reached CW mode operation.

Beam Commissioning



Beam Commissioning

ISOL system is driven by CYCIAE-100

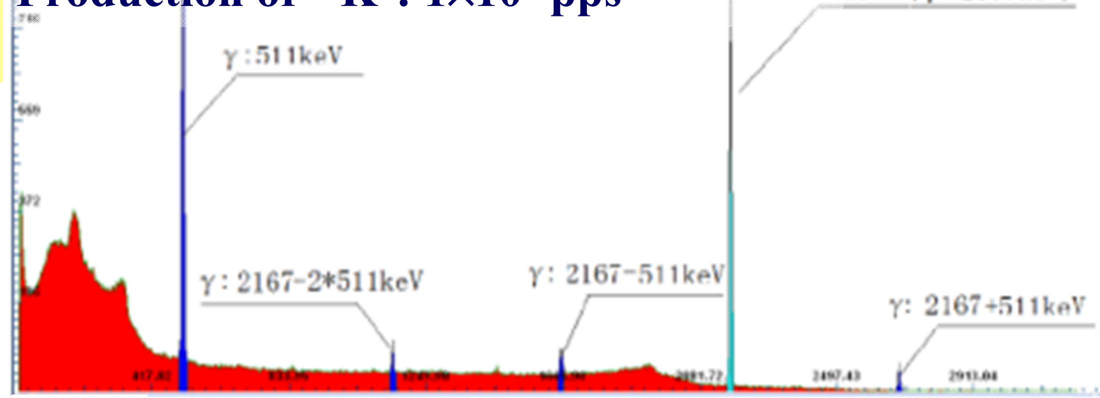


Transmission of ISOL beam line

ISOL system is driven by CYCIAE-100

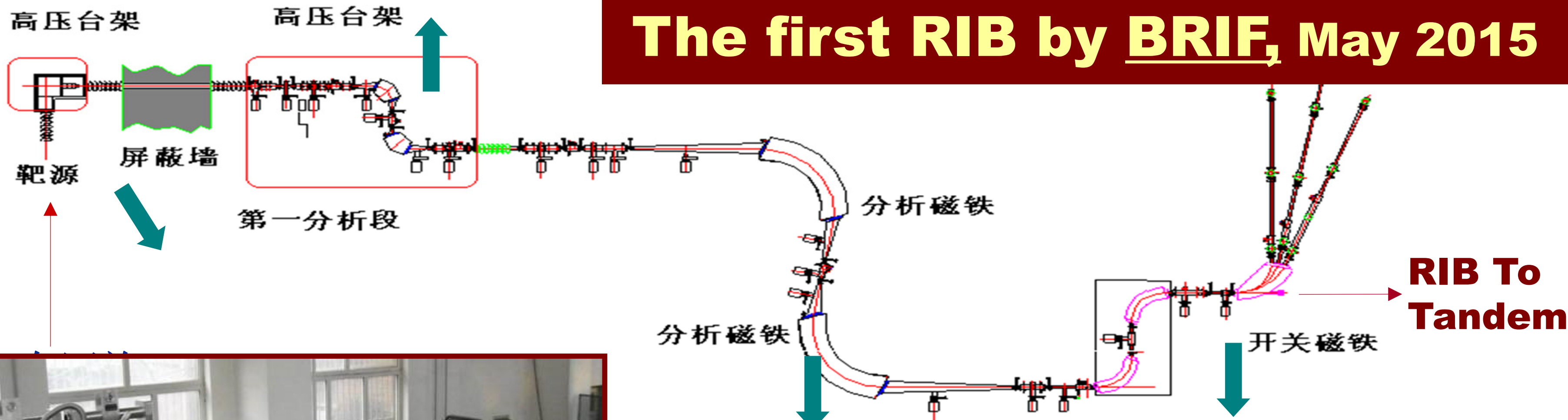
100 MeV proton beam on CaO target

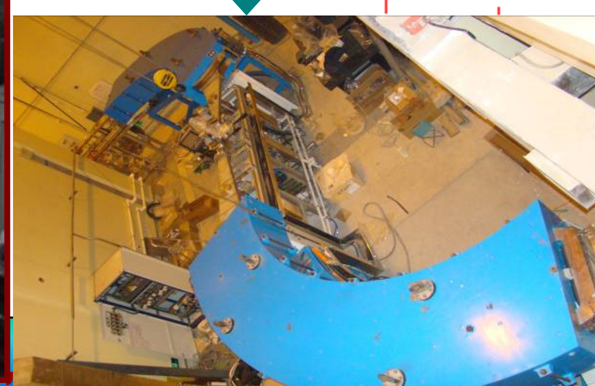
Production of $^{38}K^{+}$: 1×10^{6} pps



The gamma spectra of ^{38}K after separator

The first RIB by BRIF, May 2015





From the first beam to mA 2016

- Beam Development, 1000 hrs beam time
  - ✓ Re-Matching for the injection line
  - ✓ Improvement of the ion source
  - ✓ Addition of a buncher for beam injection
  - ✓ Optimization for LLRF control and power coupling
  - ✓ Water cool central region (in progress)
  - ✓ High power beam dump (in progress)
- Operation for Applications, 700 hrs beam time
  - ✓ RIB Production, 230 hrs
  - ✓ Radiation effects in electronics and biology, 150 hrs
  - ✓ Neutron physics, 120 hrs
  - ✓ Proton Radiography Experiment and others, 200 hrs

scheduled

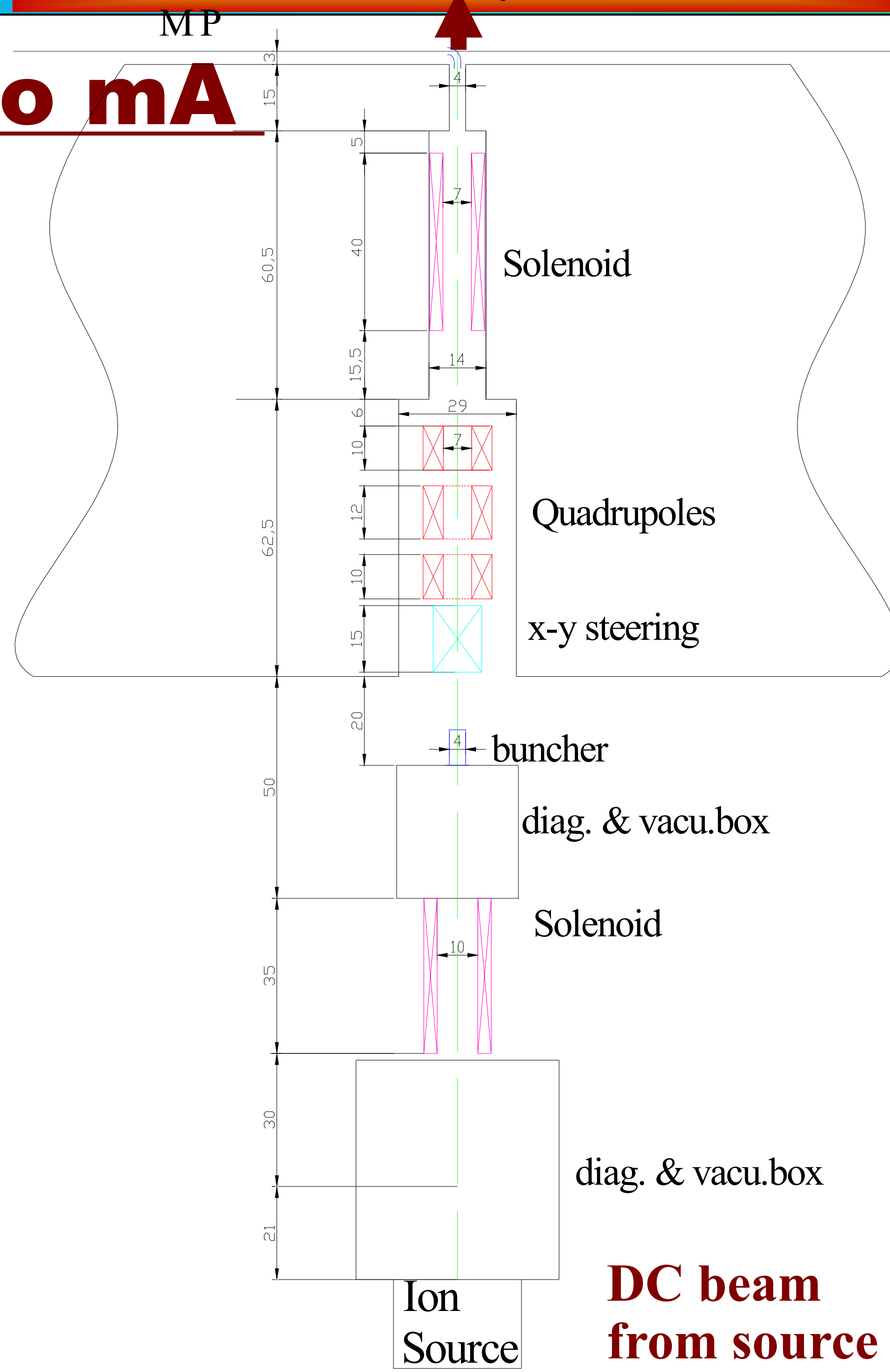
Center of Cyclotron

From the first beam to mA

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

2016

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

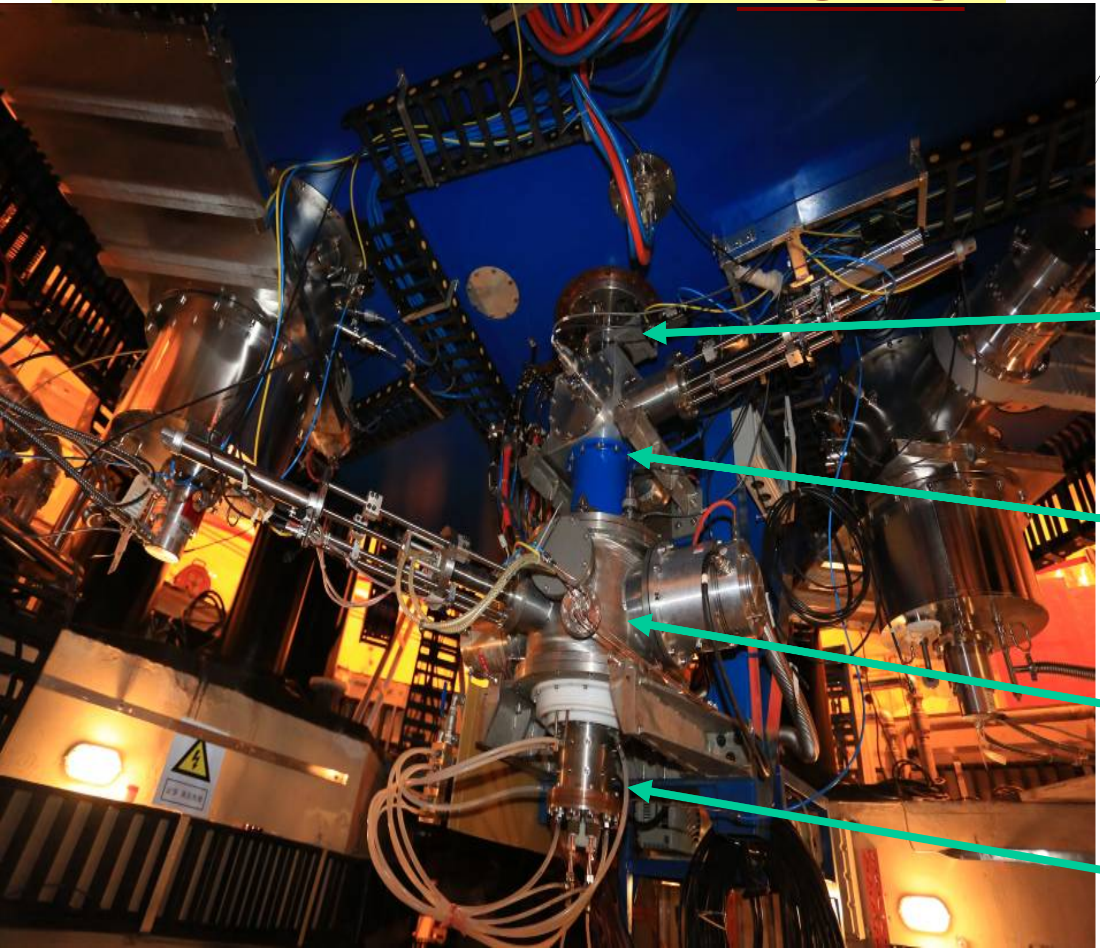


DC beam from source

From the first beam to mA

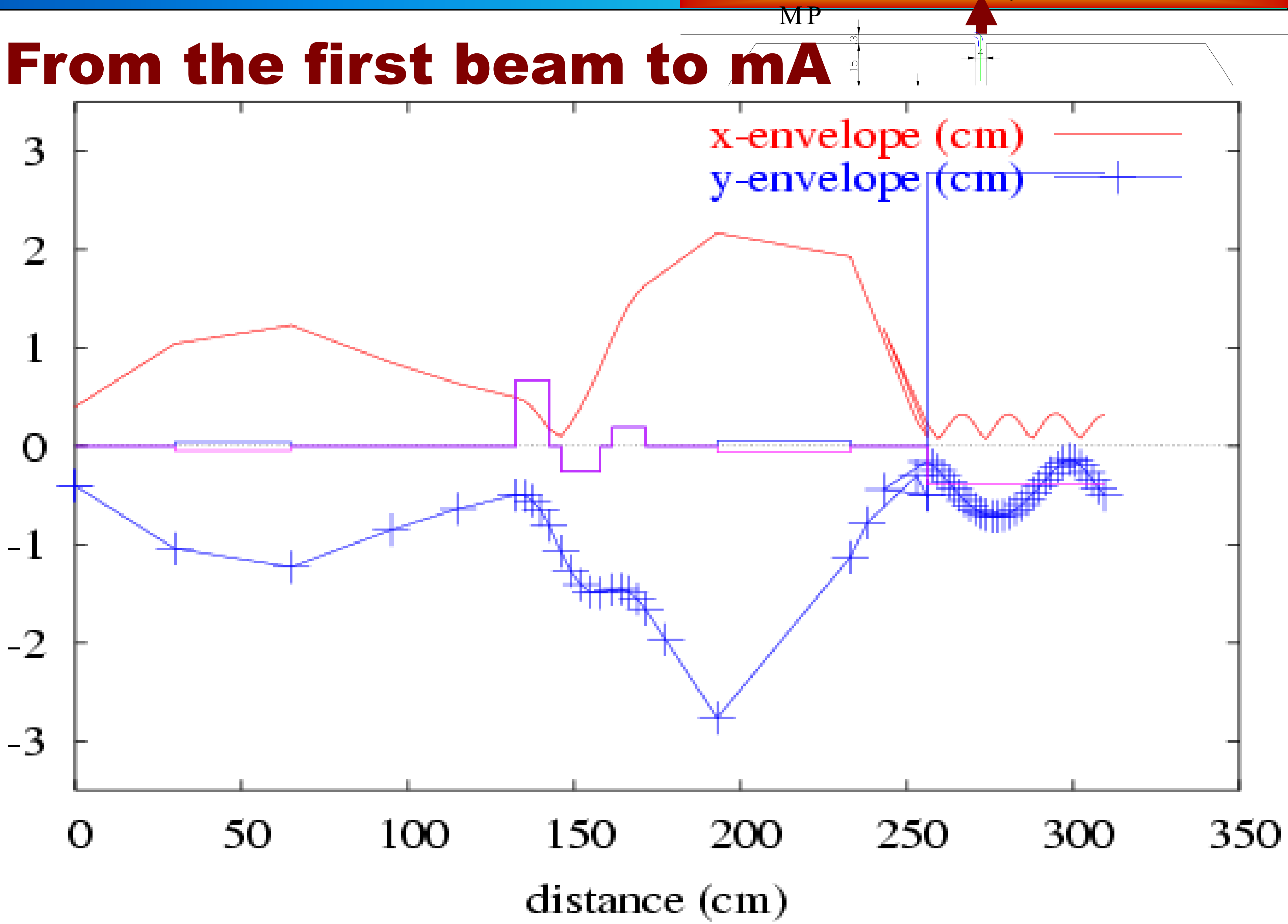
- Matching for injection line:
- S-B-QQQ-S, 2.5m
- 8-10 mA, 40keV

2016



Center of Cyclotron

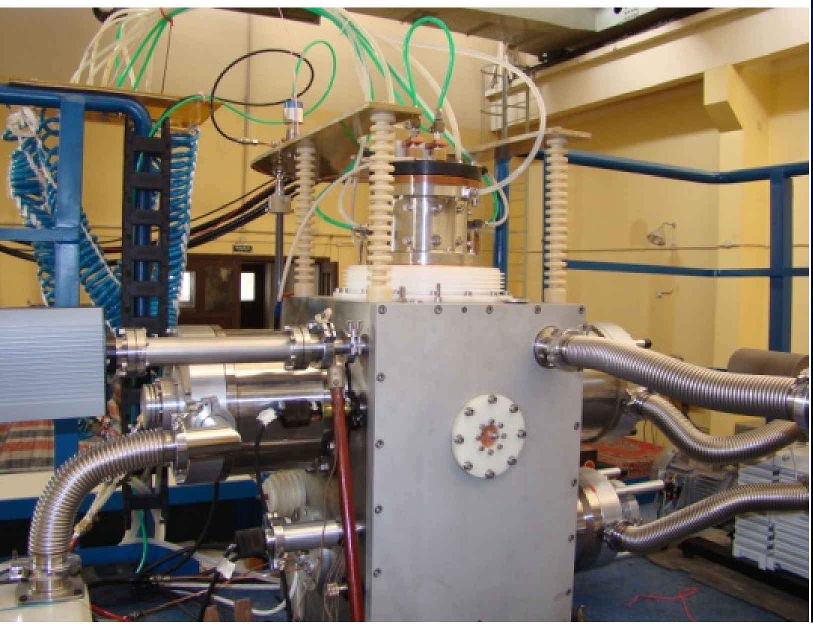
From the first beam to mA

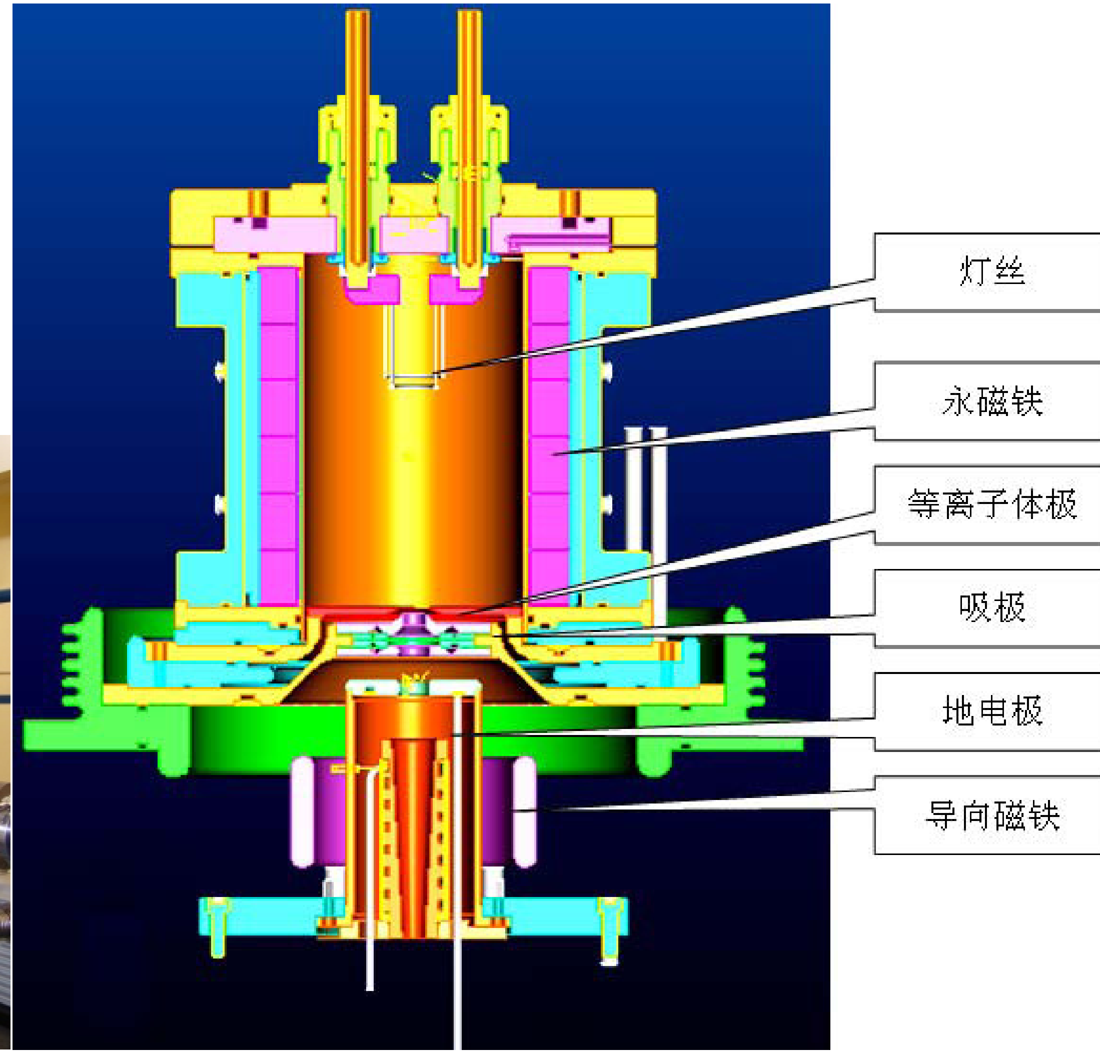


From the first beam to mA

Ion source

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



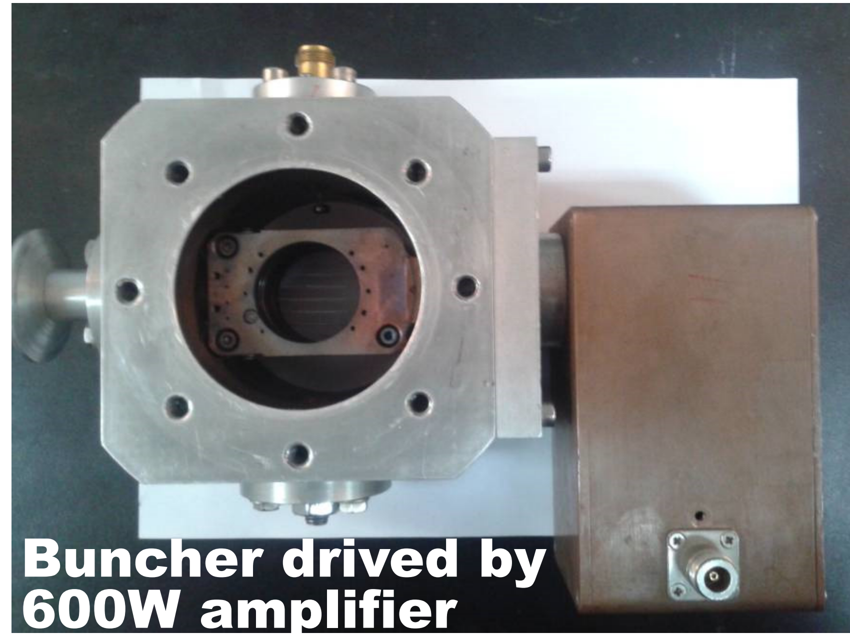


The new extractor, ground electrode, new XY steeling

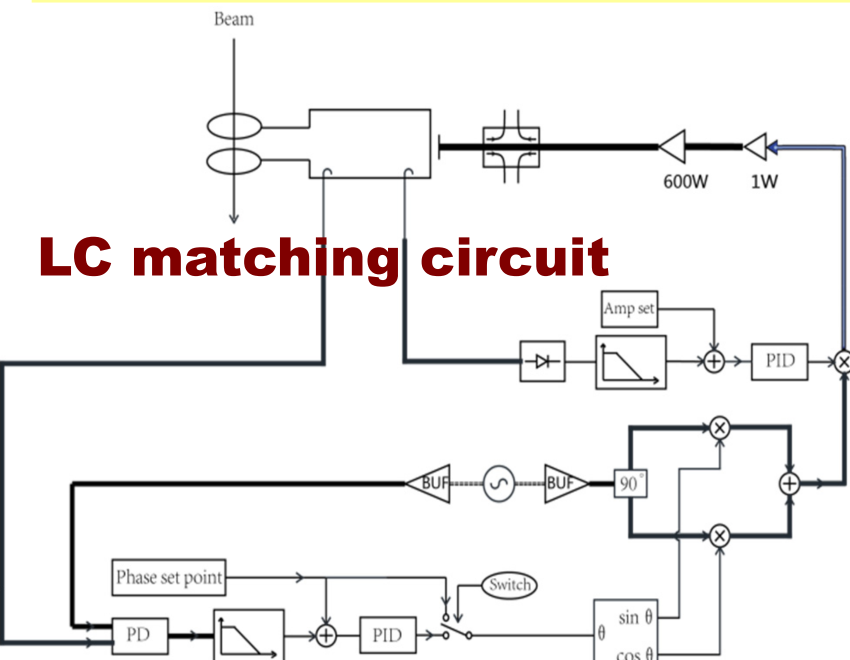
From the first beam to mA

Buncher

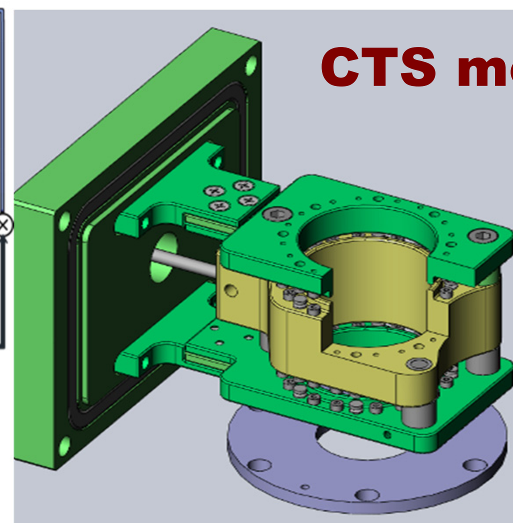
- Non-intercepting 2-gap buncher
- Between the first solenoid and the triplet, ~1.1m away from the inflector.
- Gap=5 mm and D=0.5βγ instead of 1.5βγ at TRIUMF

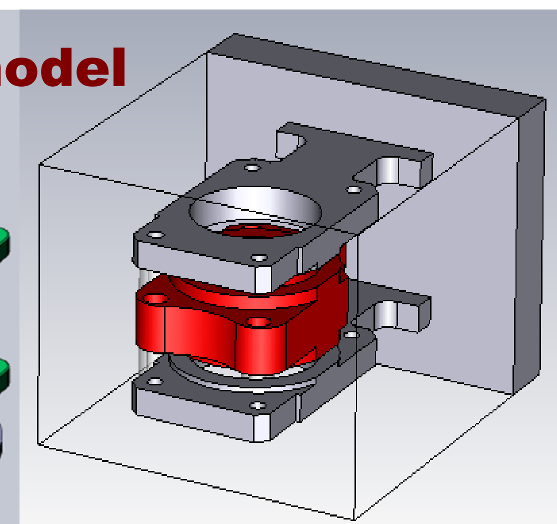


Buncher drived by 600W amplifier



LC matching circuit



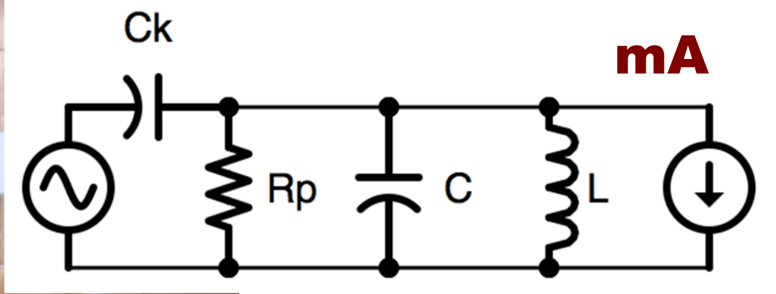


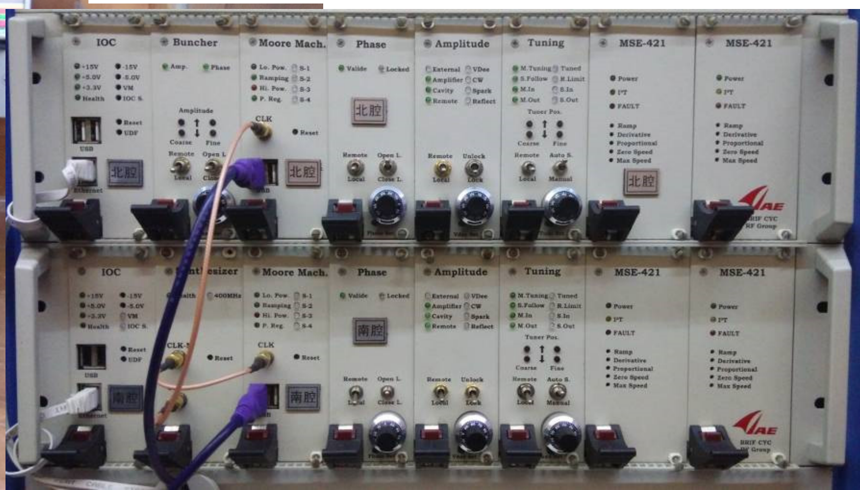
CTS model

From the first beam to mA

LLRF Control

- 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.





From the first beam to mA

LLRF Control

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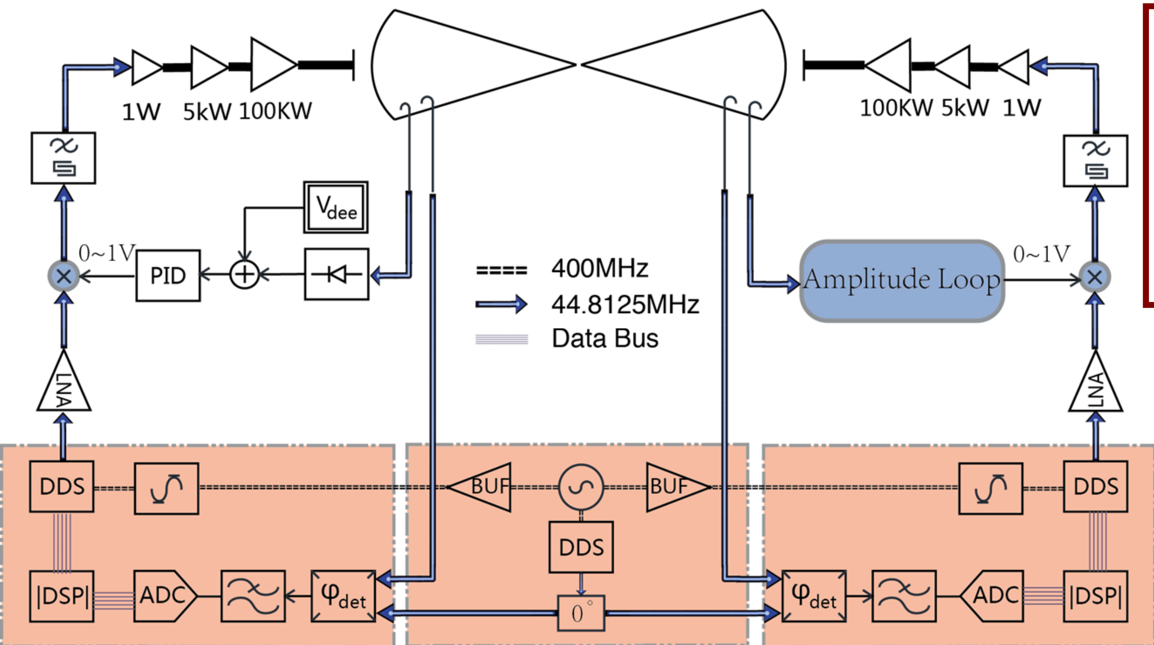
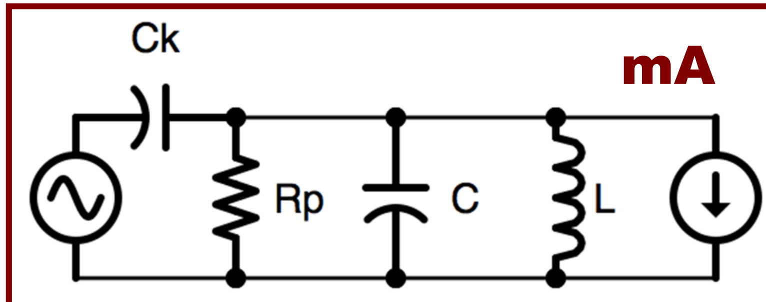
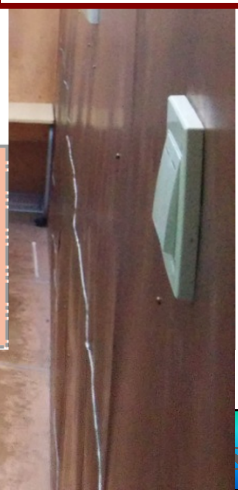
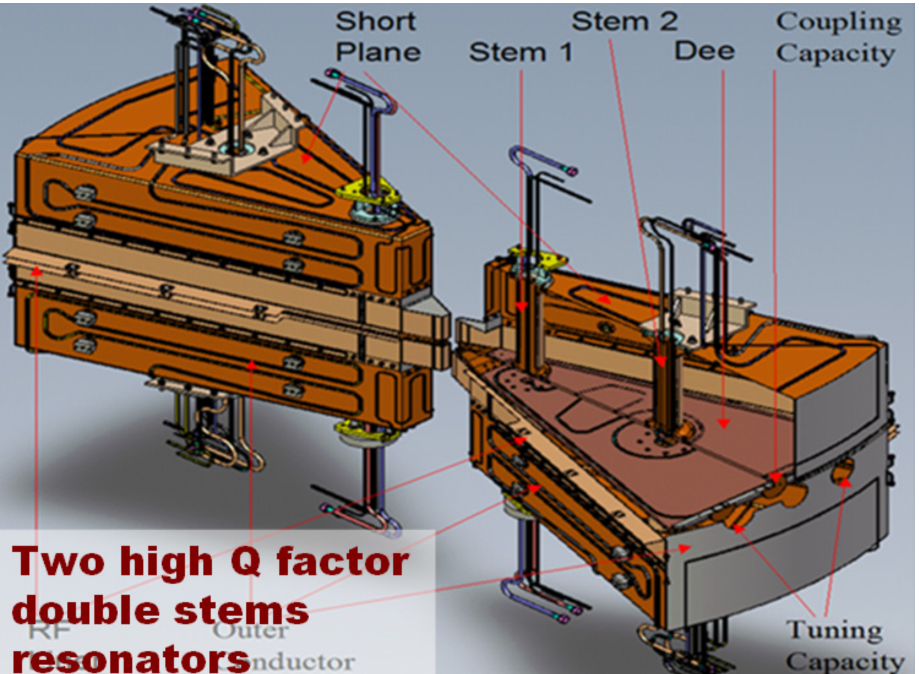






From the first beam to mA

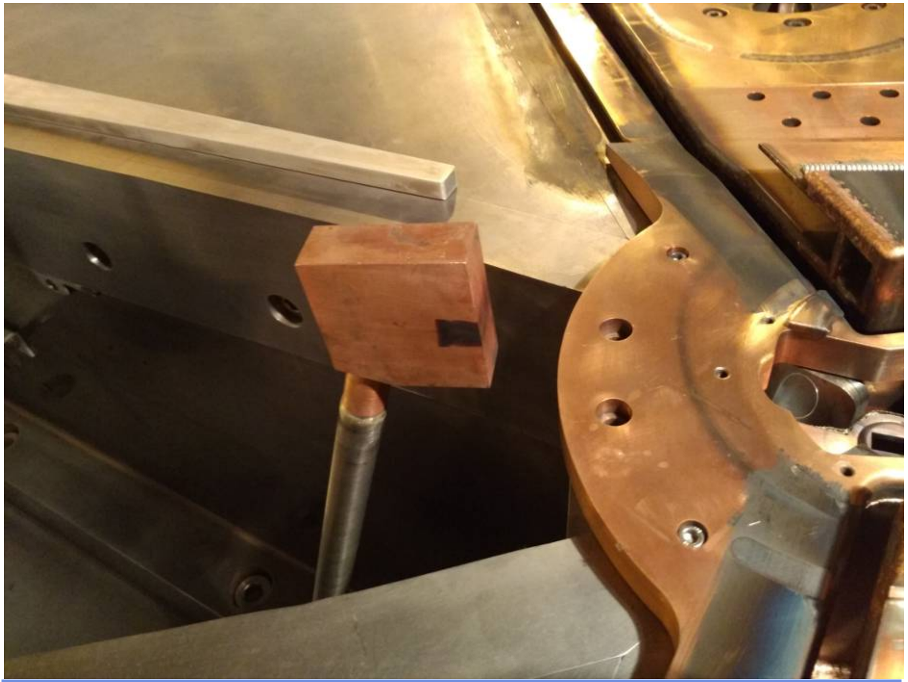
RF Cavity

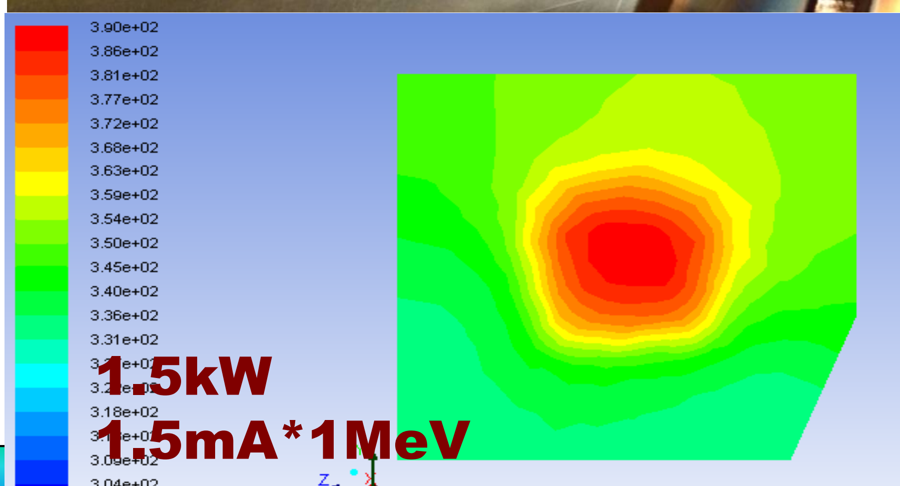


- The tuner of the cavity consists of a fine capacitor and a coarse capacitor drived by two DC motors.
- Based on the thermal situation after some operation of the cavities,
- the fine tuner was changed to a smaller one to achieve more precise tuning of the RF cavity. **The residual tuning errors are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

From the first beam to mA

Removable internal Target





- The removable target is put at the valley of main magnet, can be control to move in and out of the mid-plan.
- It is well water cool with secondary electron collection, which is not shown in the photo.
- The removable target was designed for 1.5kW beam power. It is installed in the central region of the machine (@ about 1 MeV) to stop the beam for low energy beam commissioning.

From the first beam to mA

mA Beam Acceleration

In June, 2016, we got accelerated beam > mA

1073μA

From the first beam to mA

mA Beam Acceleration

In June, 2016, we got accelerated beam > mA

1073μA

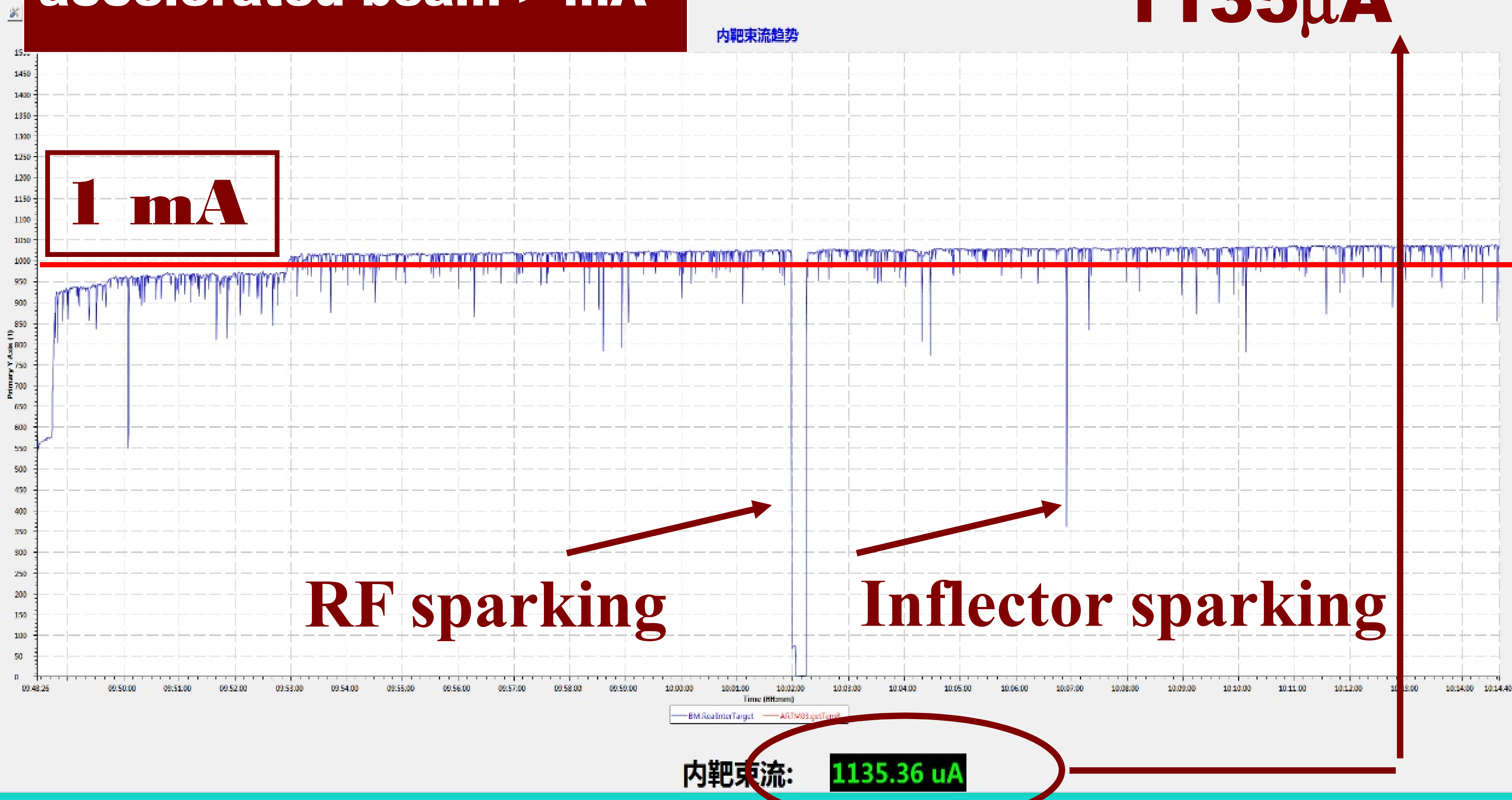
Ion source (mA)	No Buncher (μA)	With Buncher (μA)	Bunching efficiency	Acceleration efficiency (%)
1.33	100	201	2.01	15.1
1.91	145	310	2.14	16.2
3.25	201	399	1.99	12.3
4.27	258	490	1.90	11.5
4.71	410	633	1.54	13.4
6.43	542	740	1.37	11.5
8.69	610	950	1.56	10.9
9.52	**636**	**1073**	**1.68**	**11.2**

From the first beam to mA

mA Beam Acceleration

In June, 2016, we got accelerated beam > mA

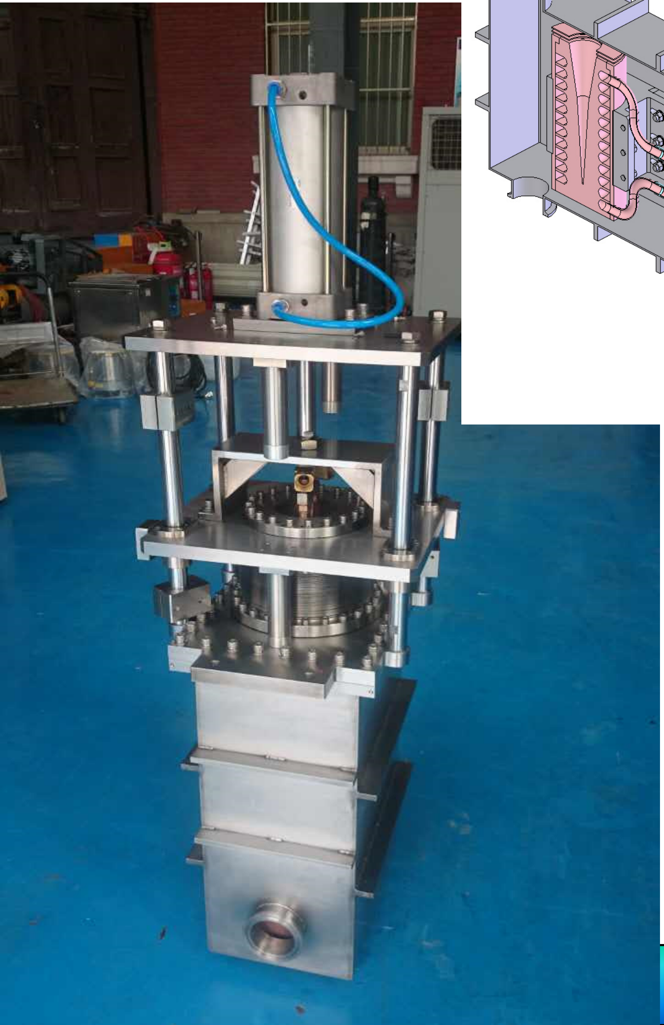
1135μA

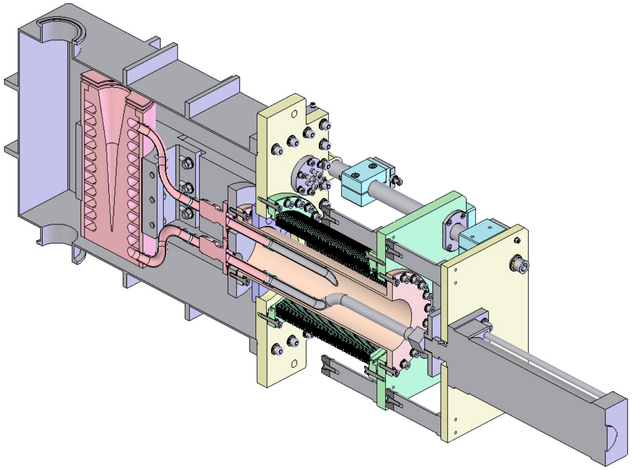


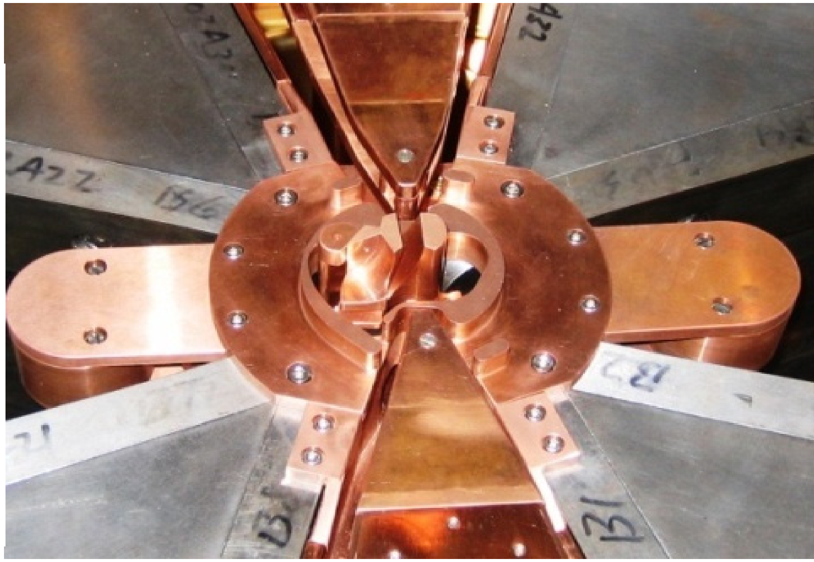
From the first beam to mA

Water cool Central region

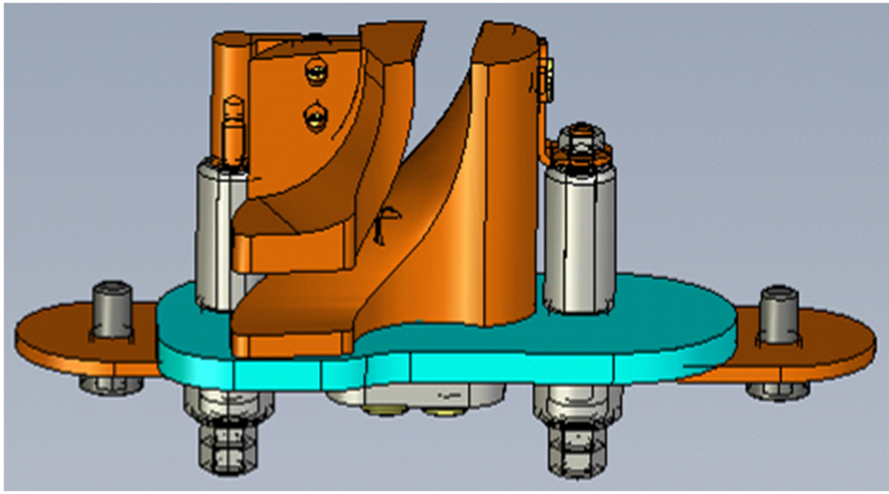
High Power Beam Dump







- For 100 MeV extracted beam
- 1 mA



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  - ✓ RIB Production, 230 hrs
  - ✓ Radiation effects in electronics and biology, 150 hrs
  - ✓ Neutron physics, 120 hrs
  - ✓ Proton Radiography Experiment and others, 200 hrs


Beam Line for
ISOL System
Beam Line for
Isotope
Production
Beam Line for
Radiation effects in
electronics and biology
Beam Line for
Proton Radiography
Principle Experiment
Beam Line for
Neutron physics
15/30 m Neutron
Beam Line

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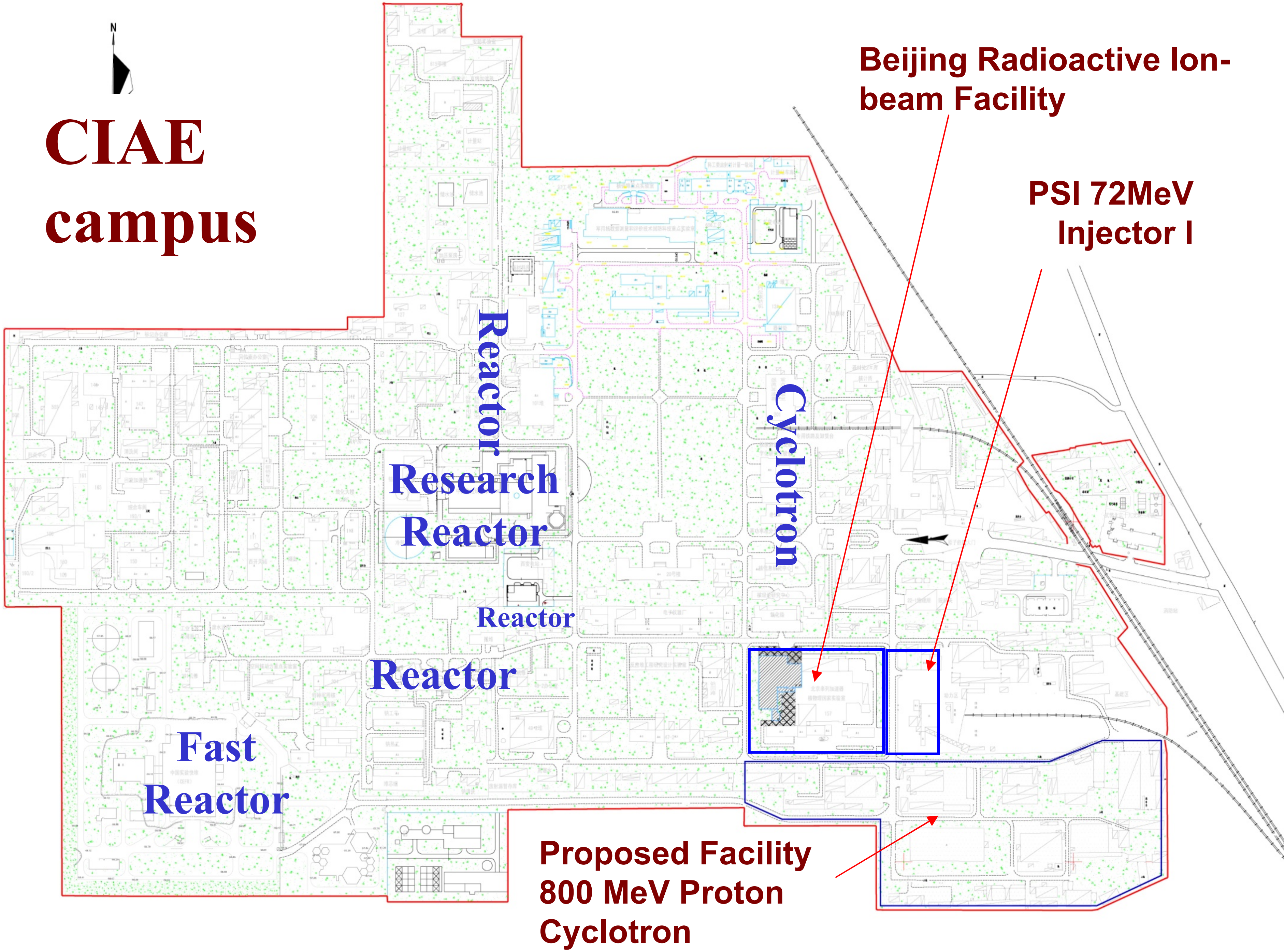
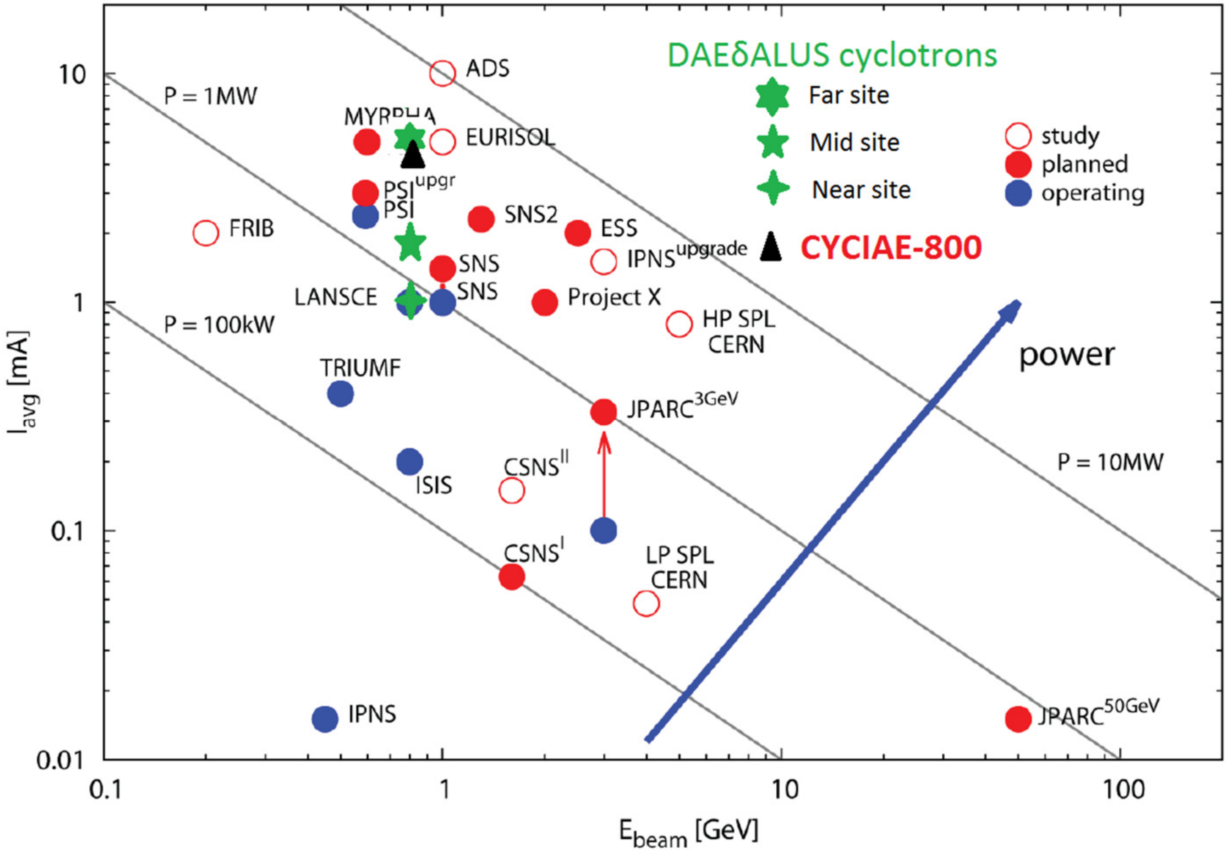
CIAE campus


N
Reactor
Research Reactor
Cyclotron
Reactor
Reactor
Fast Reactor
Beijing Radioactive Ion-beam Facility
PSI 72MeV Injector I
Proposed Facility 800 MeV Proton Cyclotron

Top proton beam power accelerators



Courtesy M. Seidel

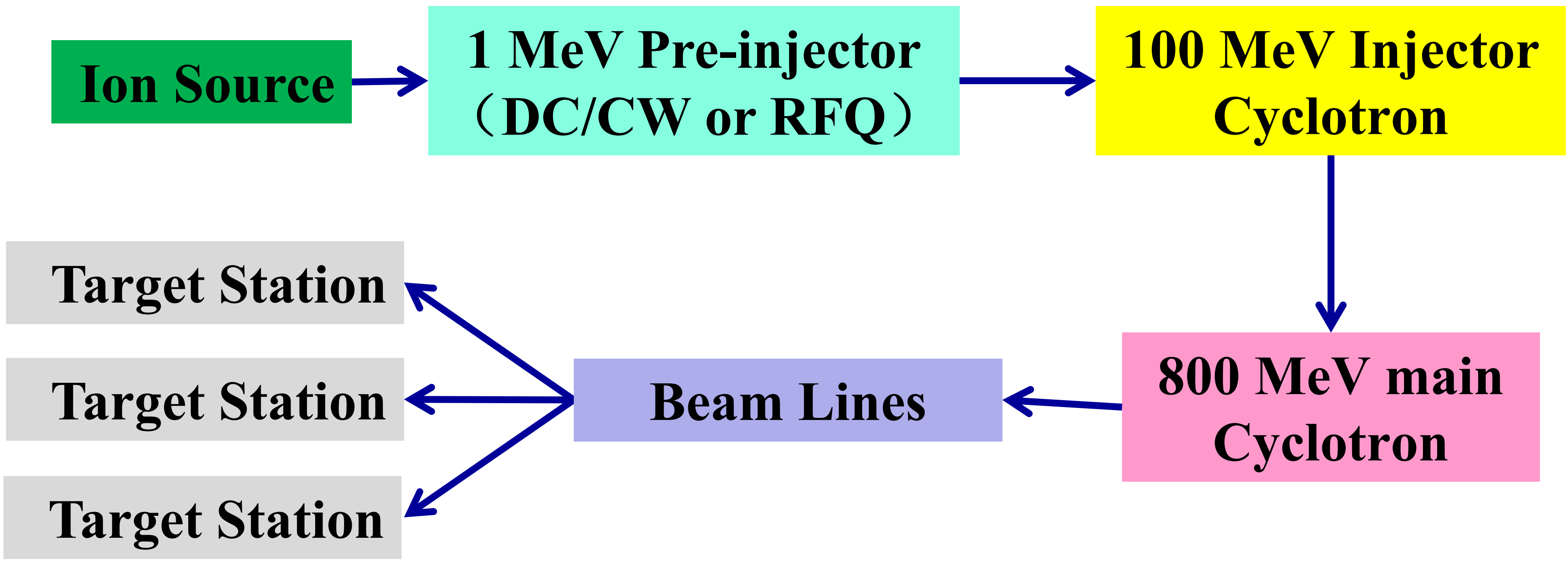
Energy （MeV）	800
Beam current (mA)	4
Bunch length（ns）	1.25
Particle per bunch	$7x10^8$
Bunch interval（ns）	22.5
Beam power（MW）	3-4

CYCIAE-800
Beam parameters

Staged Plan of the proposal

Construction contents	Beam parameter	Applications
Stage one: ■ Construction of CYCIAE-800 ■ CYCIAE-100 of the BRIF project as the injector	0.5 mA， 0.4 MW	1. nuclear data measurement, 2. single event effects 3. radiation physics 4. Isotope production
Stage two: ■ A dedicated new injector, 100 MeV separated-sector cyclotron ■ CW spallation neutron source	2 mA, 1.6 MW	1. neutron science 2. proton radiography 3. spent fuel post-process 4. Neutrino physics
Stage three: ■ Increase the beam power	5 mA, 4 MW	

CIAE High Power Cyclotron Proposal



Since the year of 2009, we carried out conceptual study on this proposal:

- *T.J. Zhang et al., NIM- B, 2011*
- *M. Li et al., ICC2013, 2013*
- *J. J. Yang et al., IPAC2013, 2013*
- *J.J. Yang et al., Mod. Appl. Phys., 2015*
- *T. J. Zhang et al., EMIS2015, 2015*
- *J. J. Yang et al., IEEE Tran. Appl. Superconductivity. 2016*

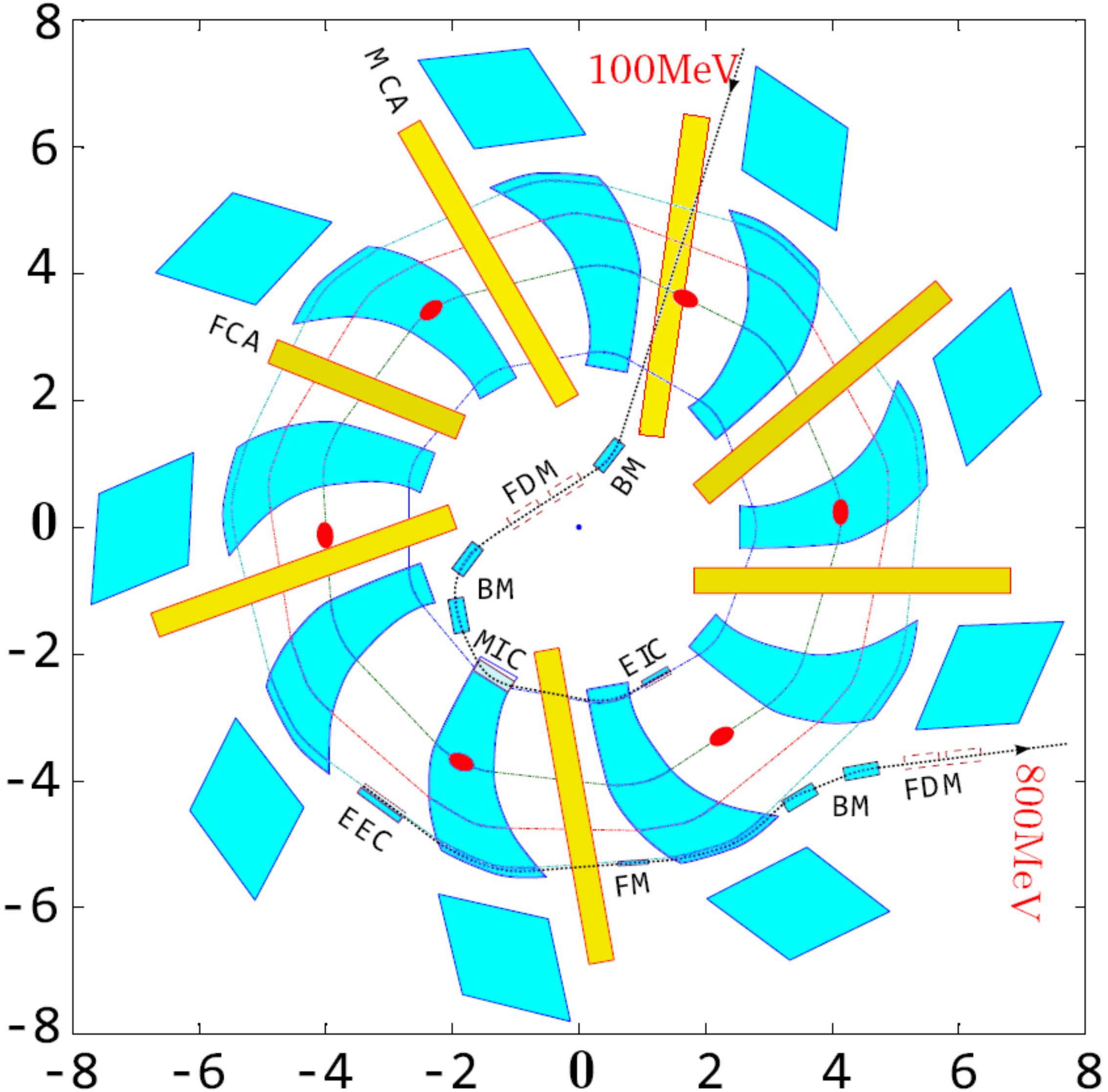
Proton Vs. H_2^+ (bachelor Vs. family of three)

	H2+ Superconducting	Proton Room Temperature
pro	a) Multi-turn stripping extraction; b) low RF voltage is OK; c) Smaller space charge effects	a) Mature technology at MW level (PSI, TRIUMF); b) Require low B field, warm magnet is OK; c) Good extraction beam quality; d) Low Vacuum is OK
con	a) Long-lived vibrational states →dissociate b) Require SC magnet c) Need high vacuum d) No construction experience at MW level	a) Require single-turn extraction; b) Require high RF voltage; c) Larger space charge effects; d) Need flat-top cavities and/or buncher

Our selection: proton →

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

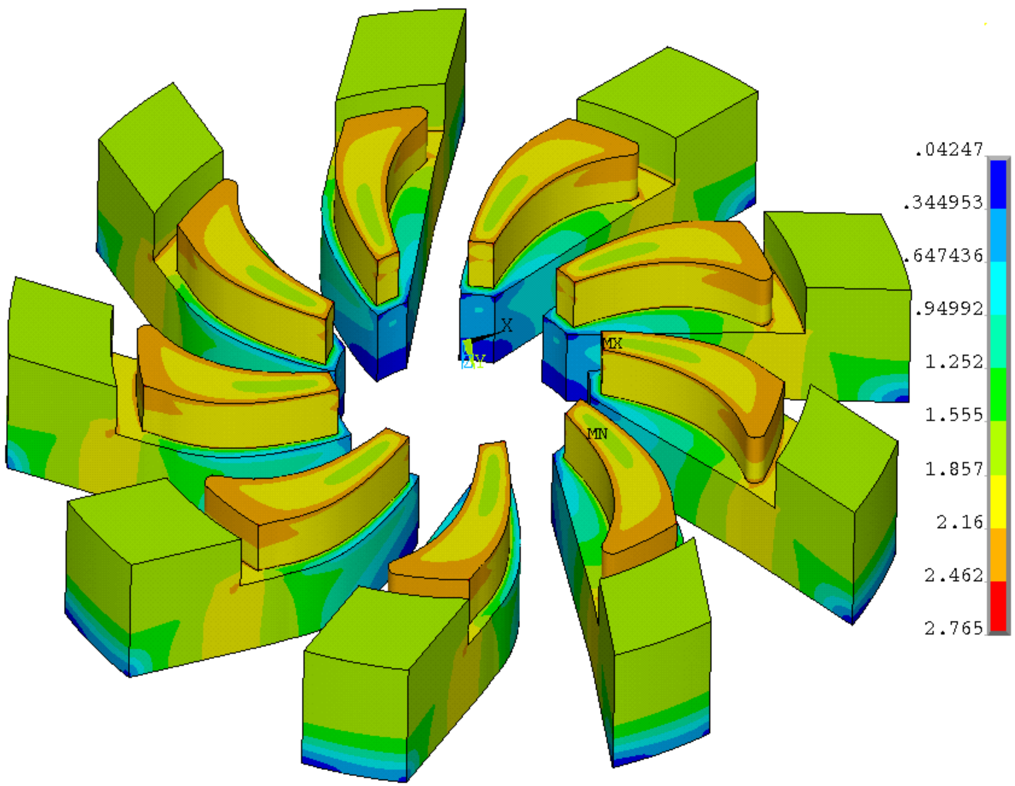
Layout of the 800MeV cyclotron CYCIAE-800

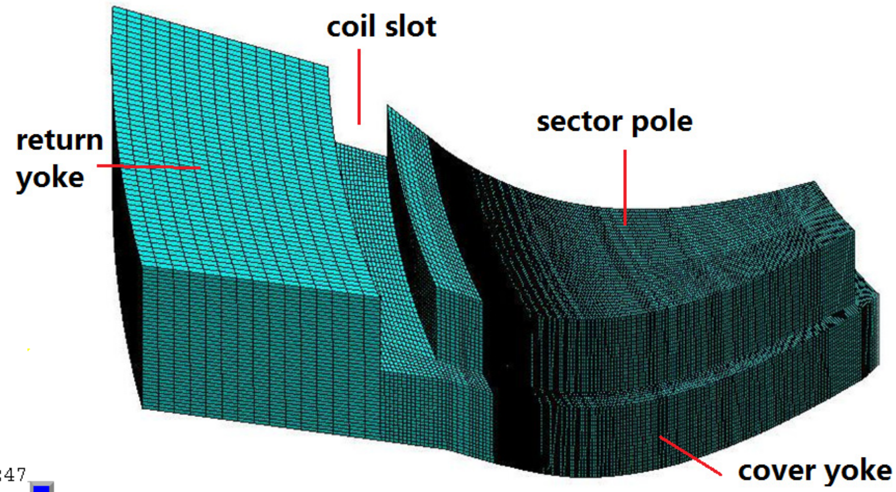


pole number	9
kinetic energy (MeV)	**100-800**
magnetic rigidity (T·m)	**1.48-4.88**
average orbit radius (m)	**2.76-5.42**
cyclotron radius (m)	**8.0**
RF frequency(MHz)	**44.37**
harmonic number	**6**
main cavity number	**5**
flat-top cavity number	**1 or 2**
Q_r/Q_z at extraction	**1.55/1.40**
Q_r 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

Magnet Design



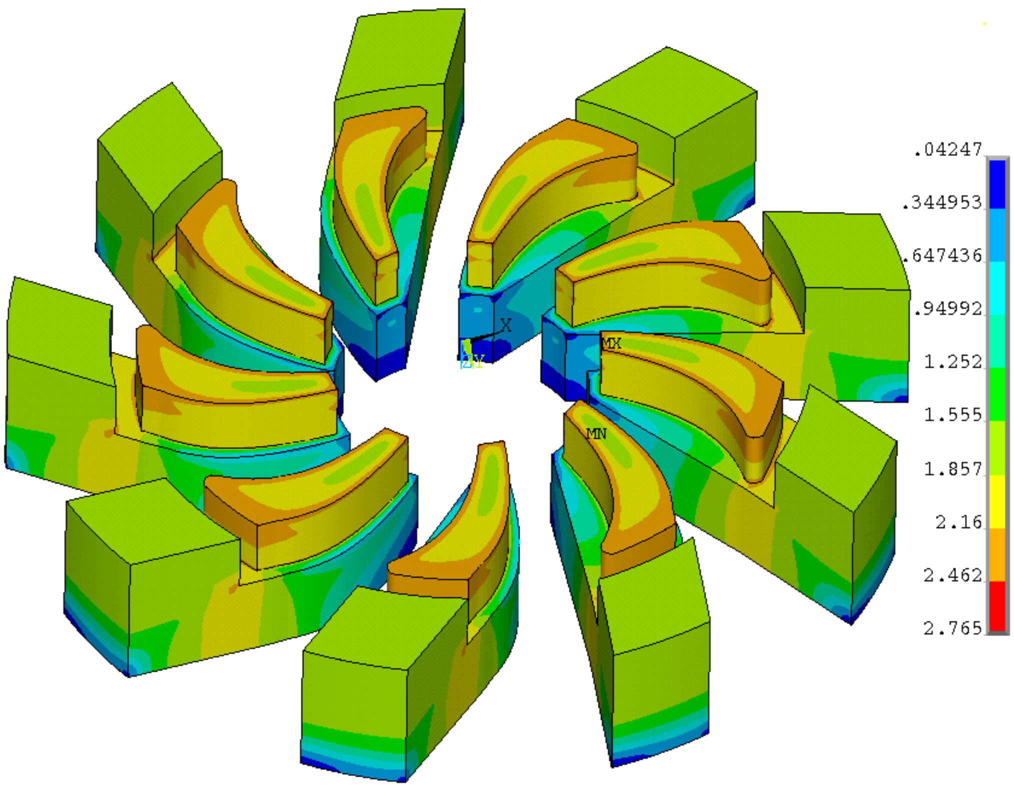


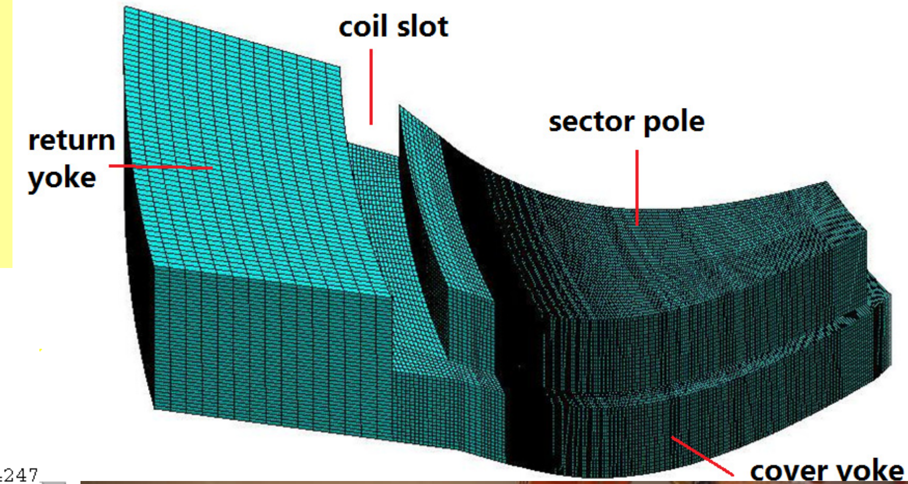
Item	Value
sector number	9
spiral angle	0~50 º
sector width	13~17 º
sector radius	2.46~5.73 m
hill gap	90~54 mm
magnet diameter	16 m
magnet height	5.8 m
total stored energy	3.96 MJ
exciting current per pole	187 kA.turns

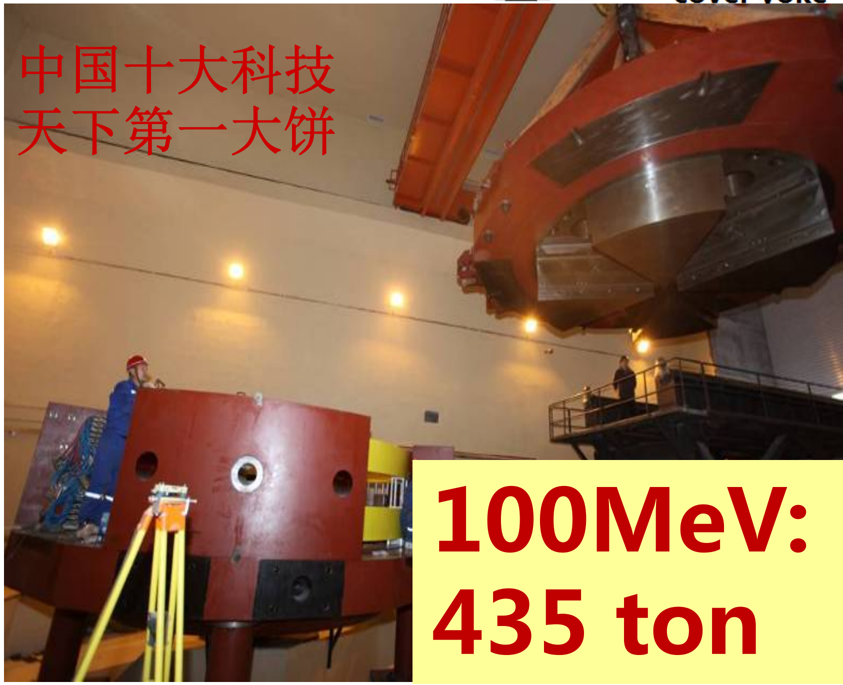
J. J. Yang et al., IEEE Tran. Appl. Superconductivity. 2016

Proton Cyclotron Proposal

9 sectors , 380 ton per sector
Total: 3420 ton





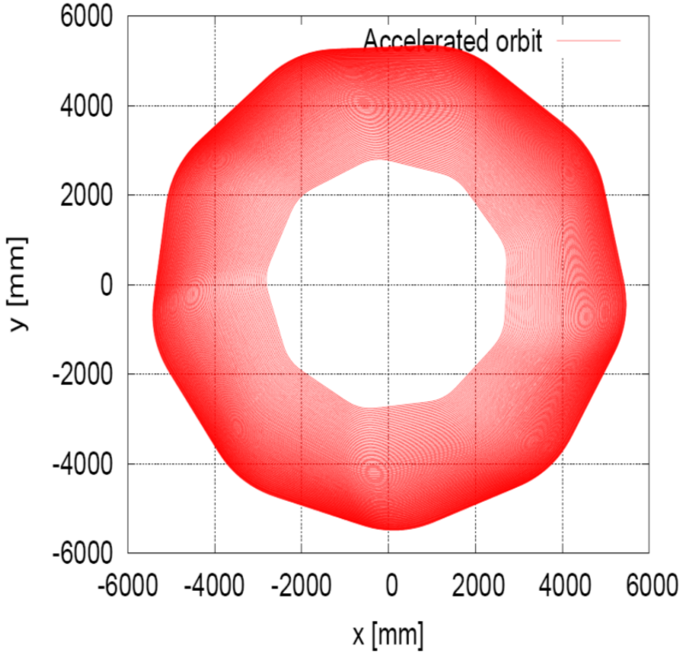


100MeV: 435 ton

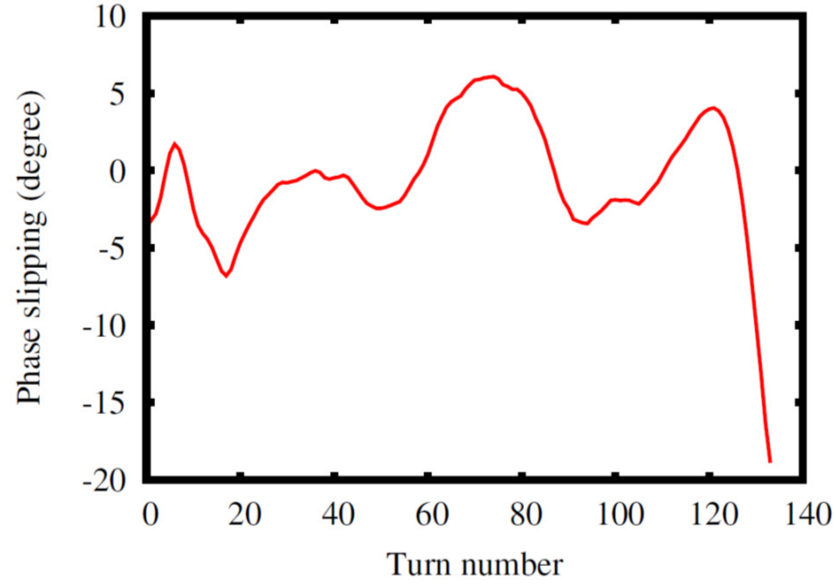
J. J. Yang et al., IEEE Tran. Appl. Superconductivity. 2016

Beam Dynamic Design

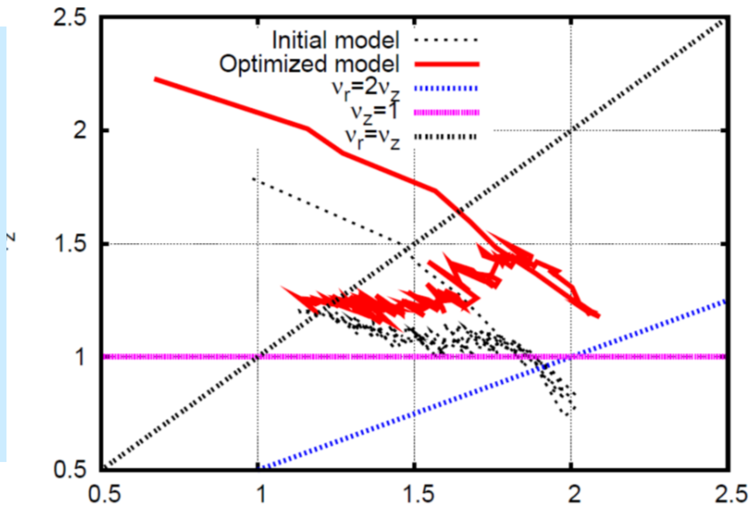
Orbit design



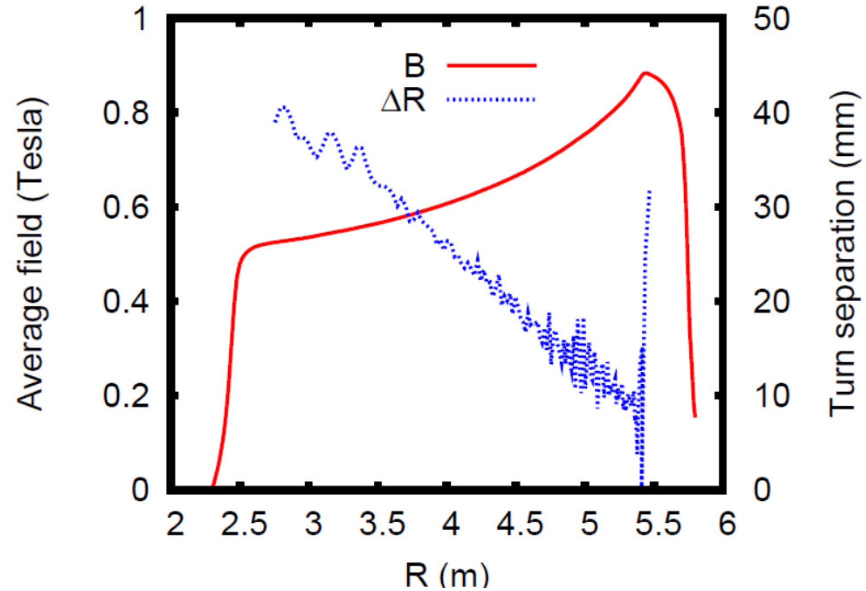
Phase slip



Tune diagram



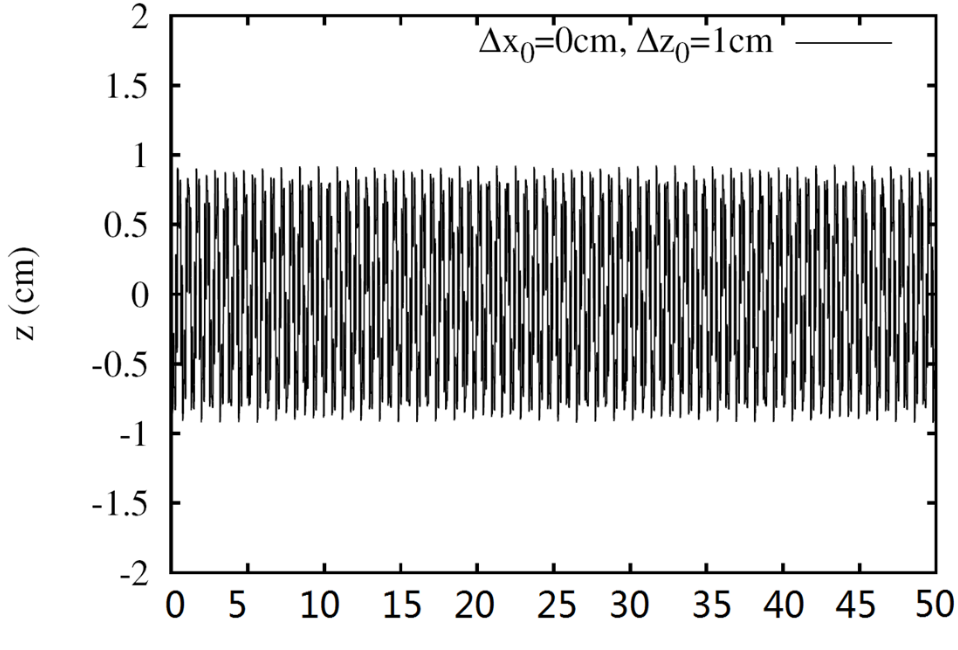
Average field

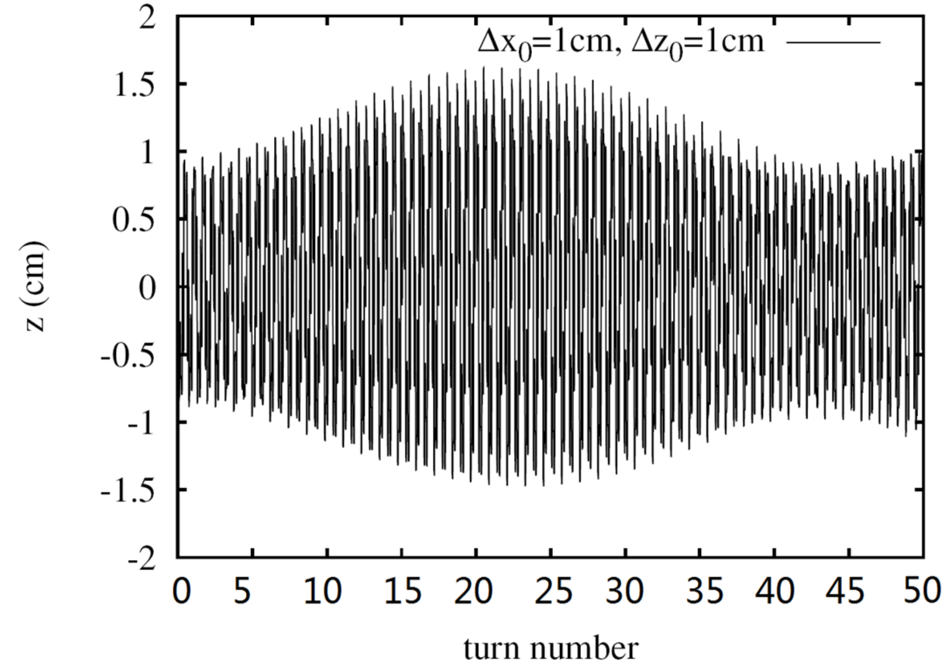


J. J. Yang et al., IEEE Tran. Appl. Superconductivity. 2016

$\nu_r=2\nu_z$ resonance in original structure

■ The vertical beam trajectory in 50 turns for two particles with different initial offset: radially centered (left) and off-centered (right).

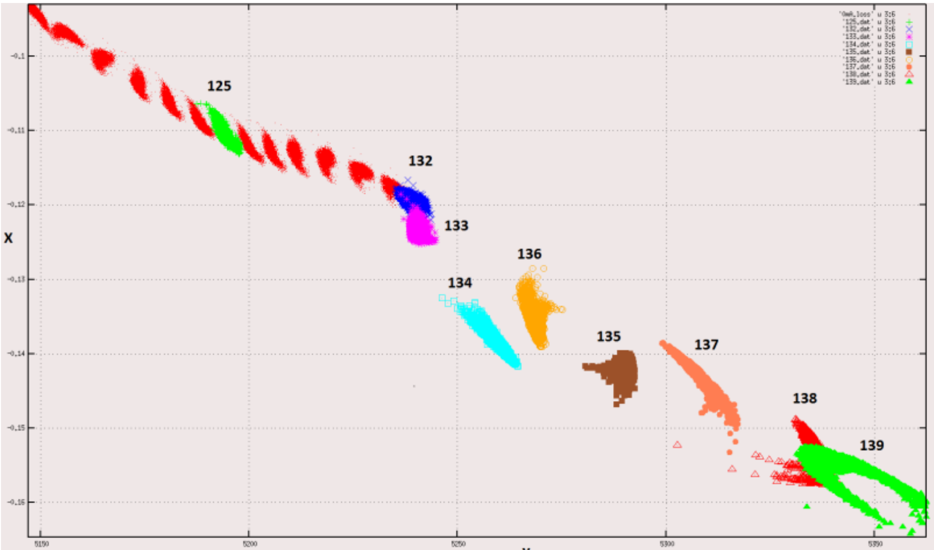


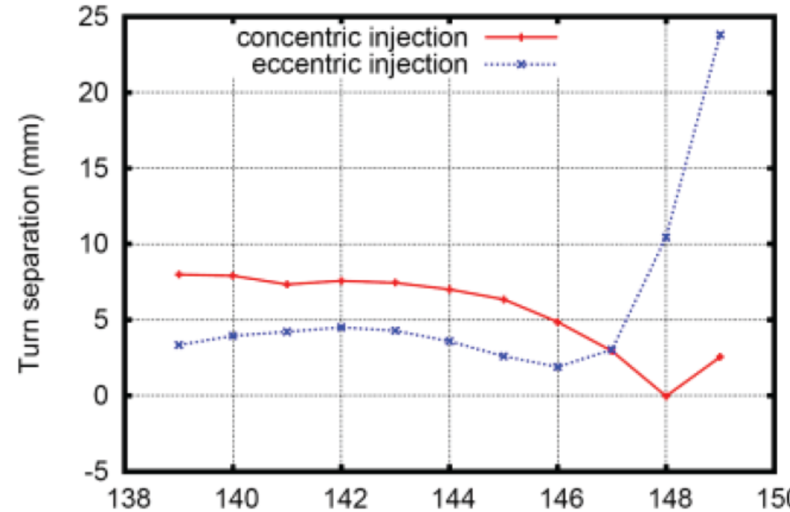


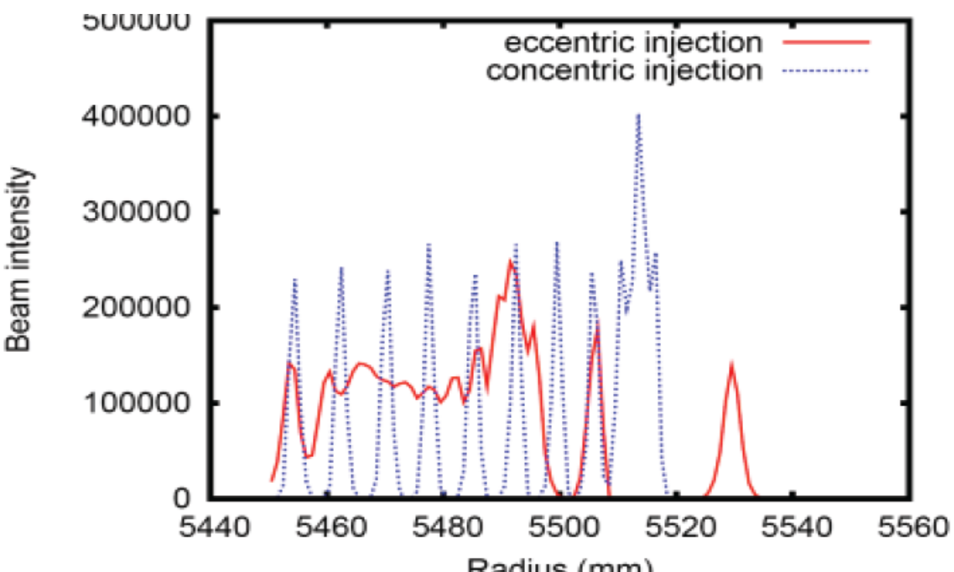
■ Structure Optimization: the magnet field flutter was enlarged by increasing the **sector height** by 12 cm and the **spiral angle** was increased by 10%.

J. J. Yang et al., IEEE Tran. Appl. Superconductivity. 2016

Single turn extraction: *eccentric injection + half integral resonance*





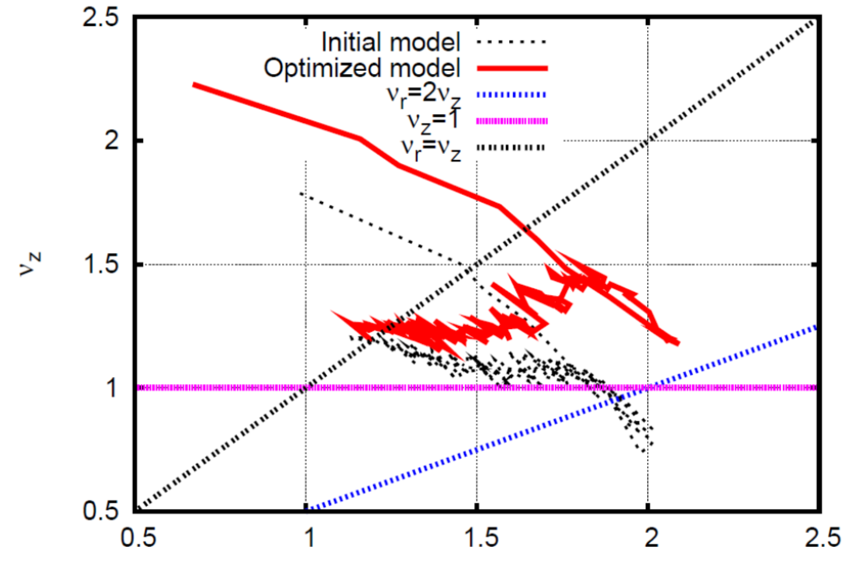


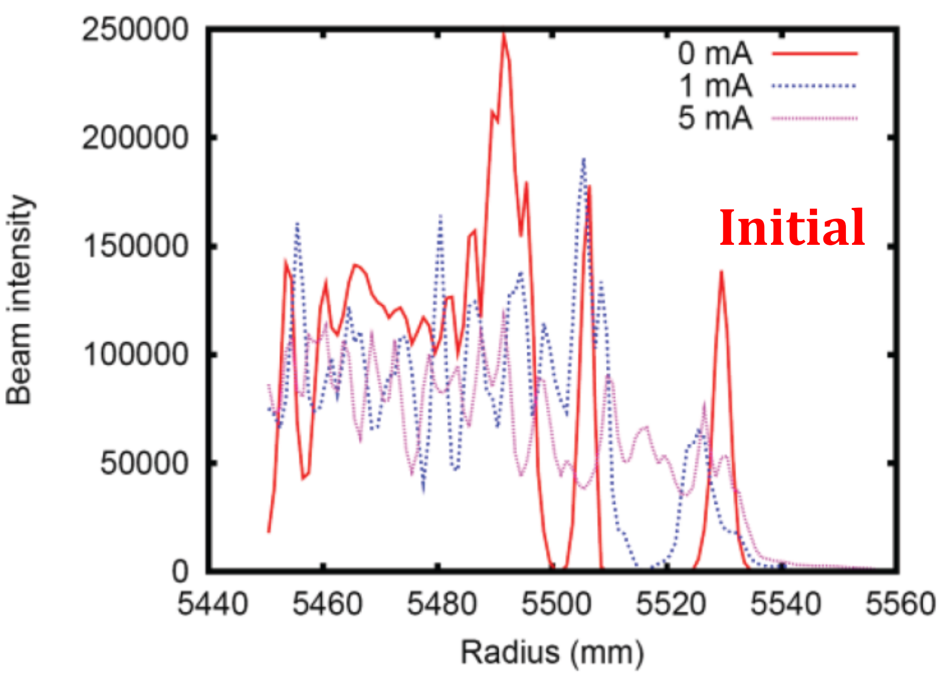
Deflector parameter	value
Electrode gap (mm)	16
Beading curvature (m)	114
Effective length (mm)	920
Voltage (kV)	144
Field strength(kV/cm)	90

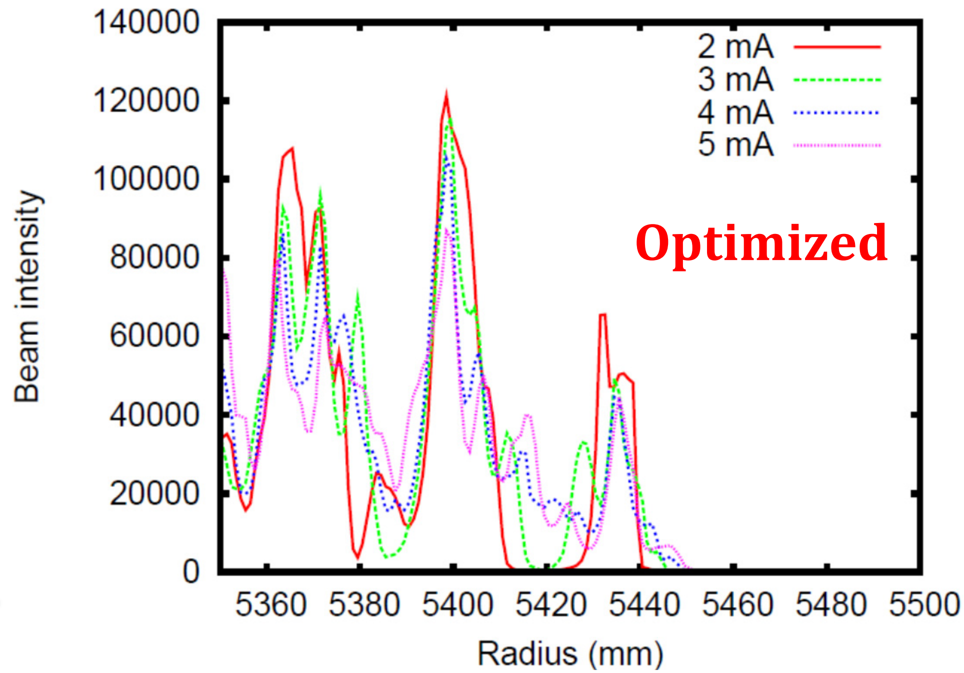
•*J. J. Yang et al., IPAC2013, 2013*

Space charge simulation by OPAL-CYCL code

The space-charge-limited beam current is increased from 1 mA to 3 mA by avoiding the crossing of $Q_r=1$ and $Q_r=2Q_z$ resonance. More work need to further increase beam current.

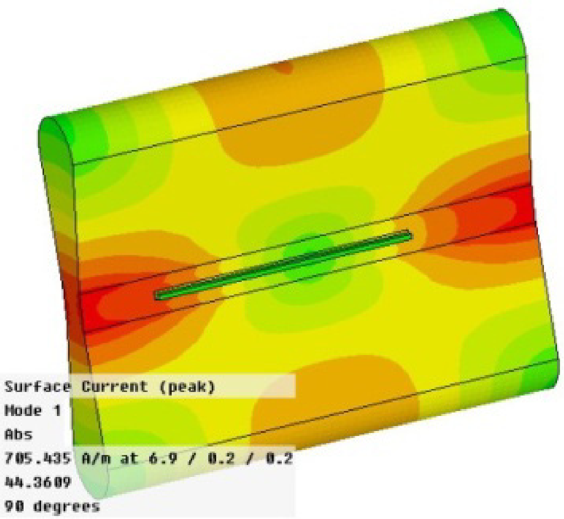


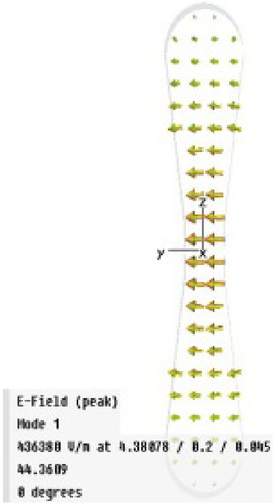




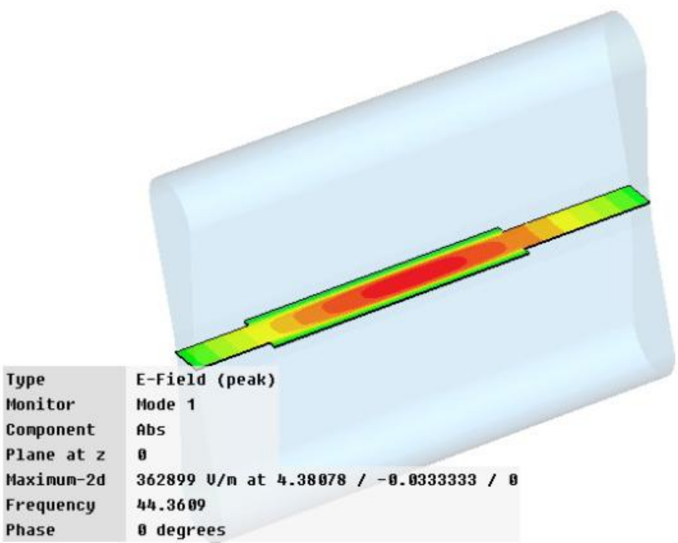
•T. J. Zhang et al., EMIS2015, 2015

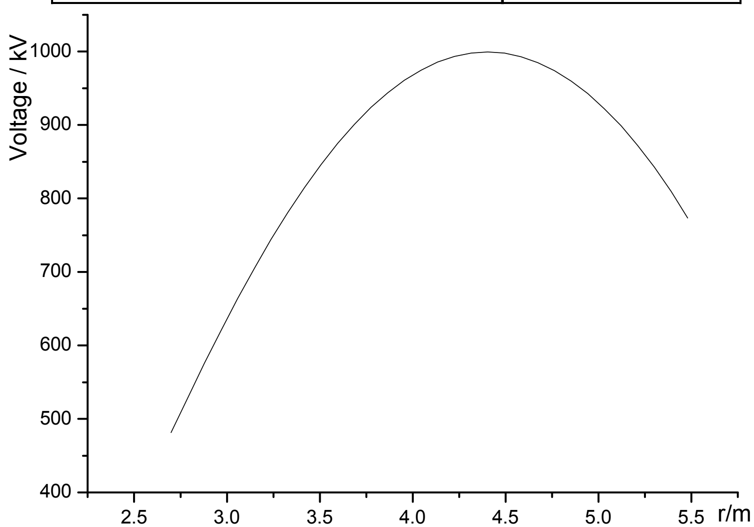
RF resonator design



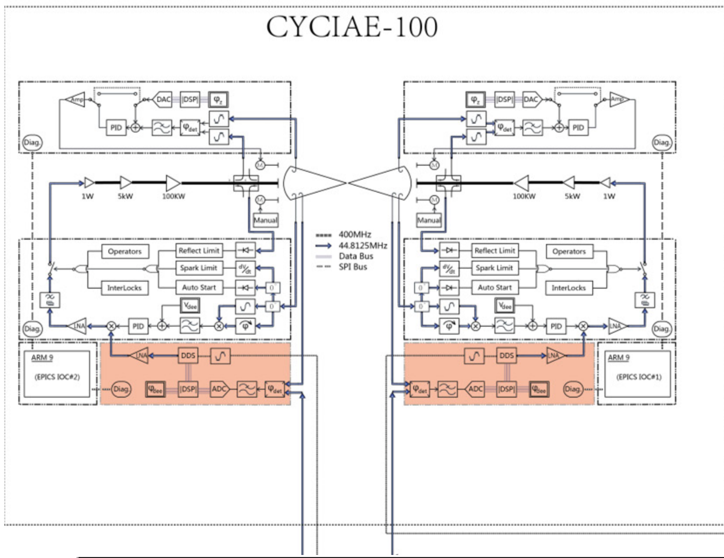


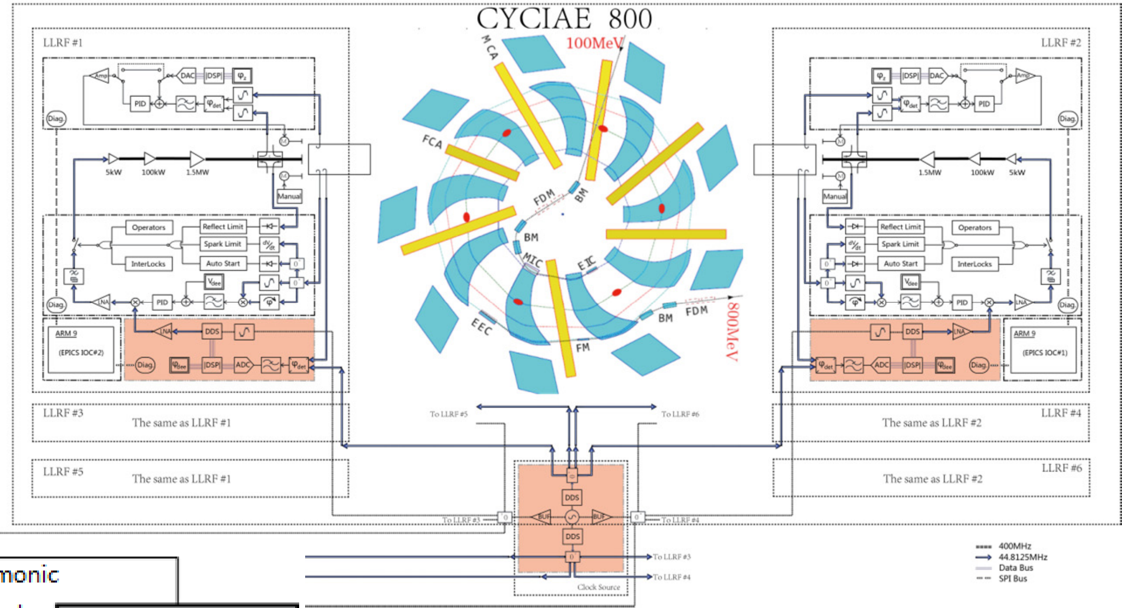
Resonator number	6
Peak voltage (MV)	1.0
Frequency (MHz)	44.37
Length (m)	5.0
Height (m)	3.63
Inner radius (m)	1.9
Outer radius (m)	6.9
Resonator width(m)	0.4
Q factor	>40000
Power dissipation(kW)	500

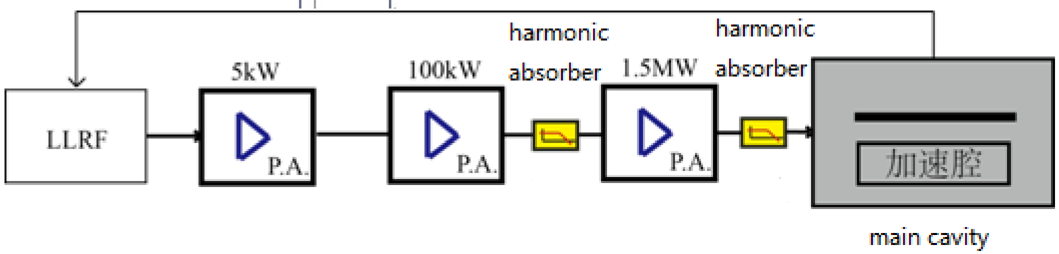


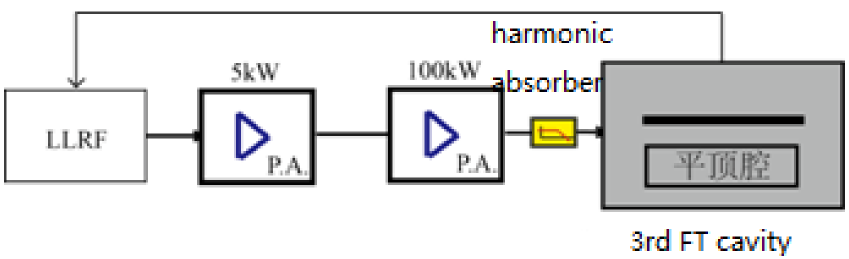


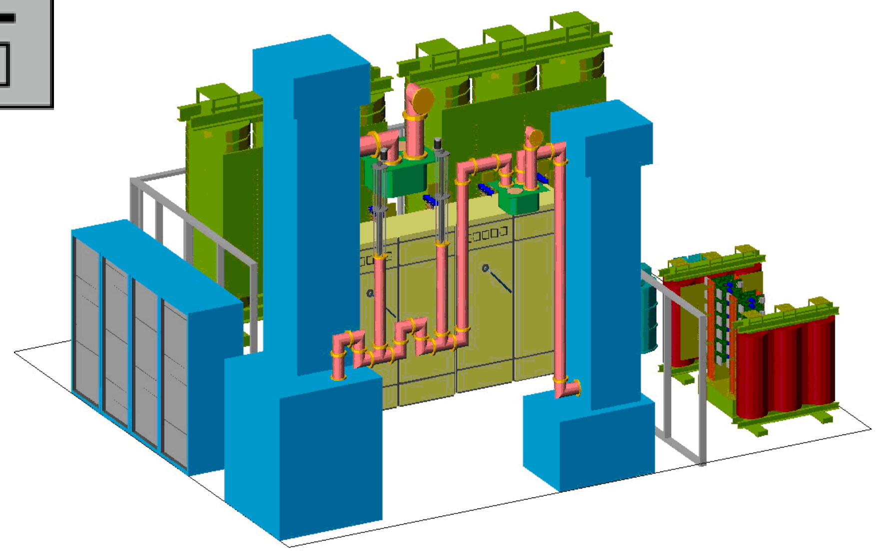
RF power supply



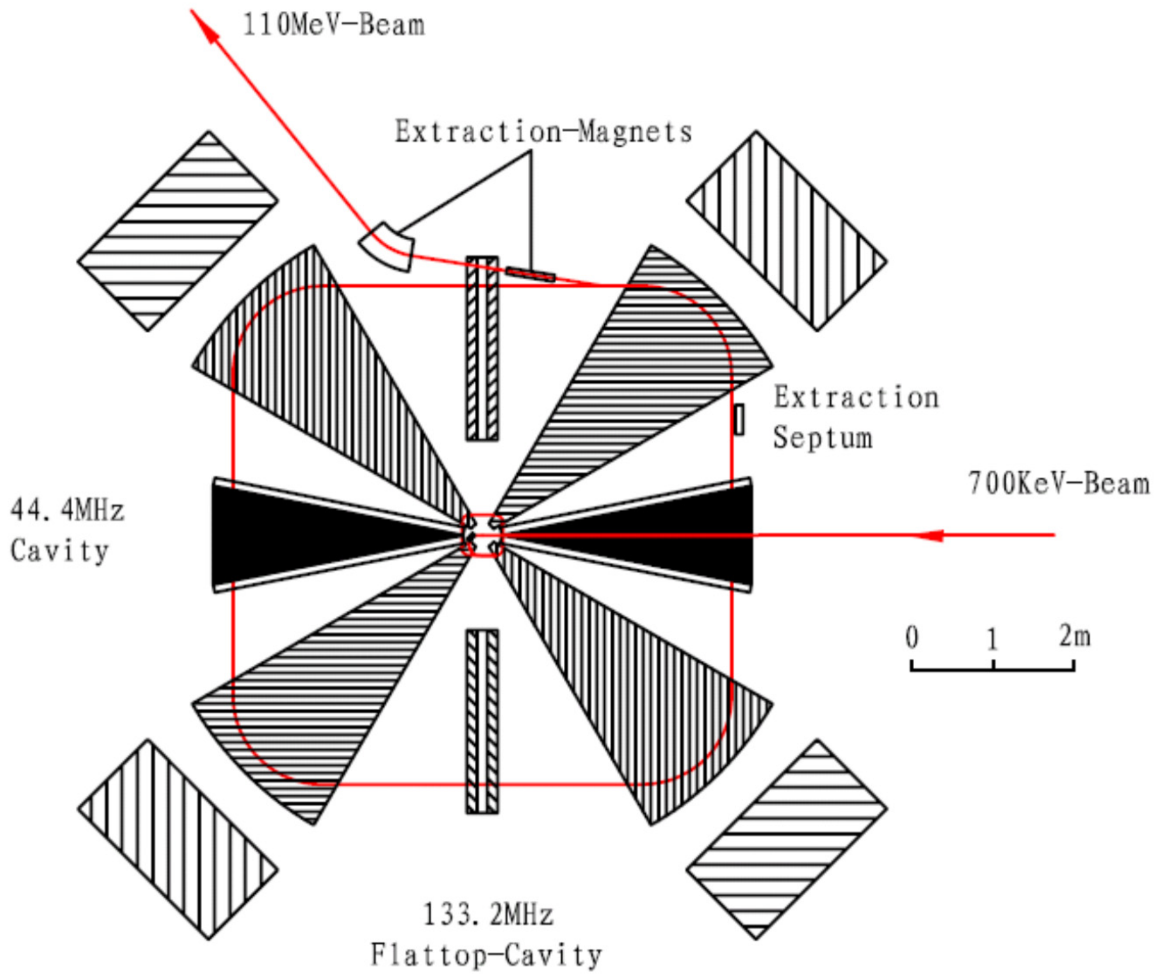








Layout of the Injector



M. Li et al., ICC2013, 2013

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**

Space charge effects study

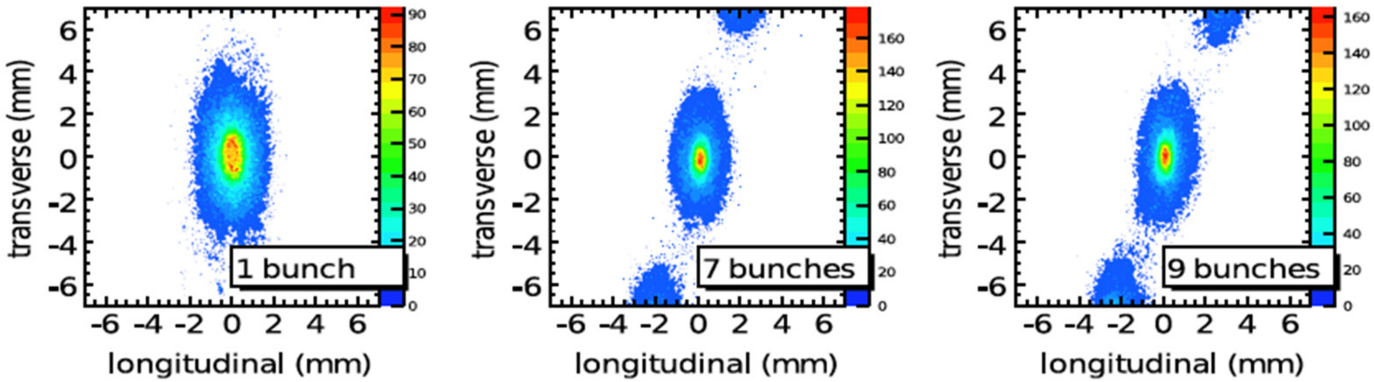
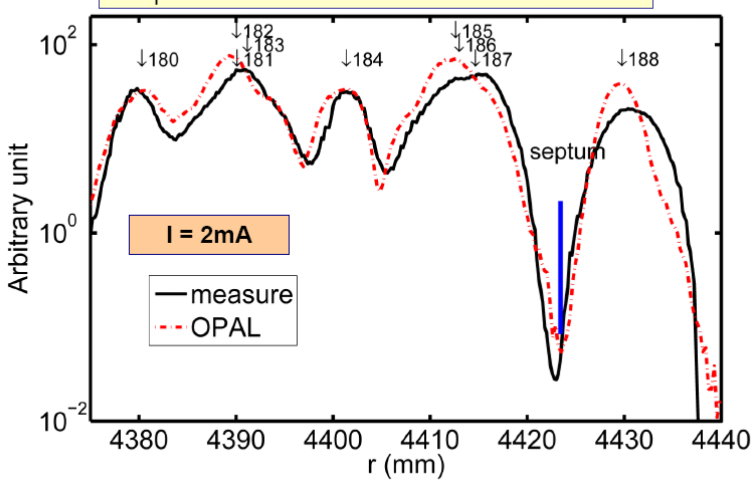
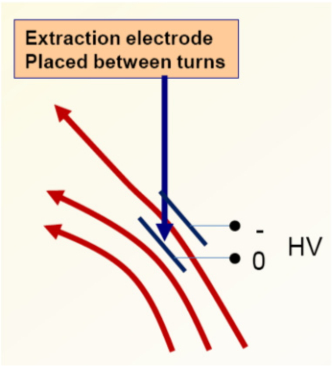


FIG. 11. (Color) Top view of 1 mA bunch distributions at the turn 130 in the local frame S_{local} at the 112° azimuthal position of turn 130 in the PSI ring cyclotron. The results are obtained from single bunch (left), seven bunches (middle), and nine bunches (right) simulations, respectively.

- *J. J. Yang, A. Adelmann PRST-AB, 2010*
- *A. Adelmann, et al., OPAL user guide, 2008*

beam profile scan of outer turns in Ring Cyclotron
comparison of simulation and data





- *Y. J. Bi, A. Adelmann PRST-AB, 2011*
- *M. Seidel, et al., IPAC2011*

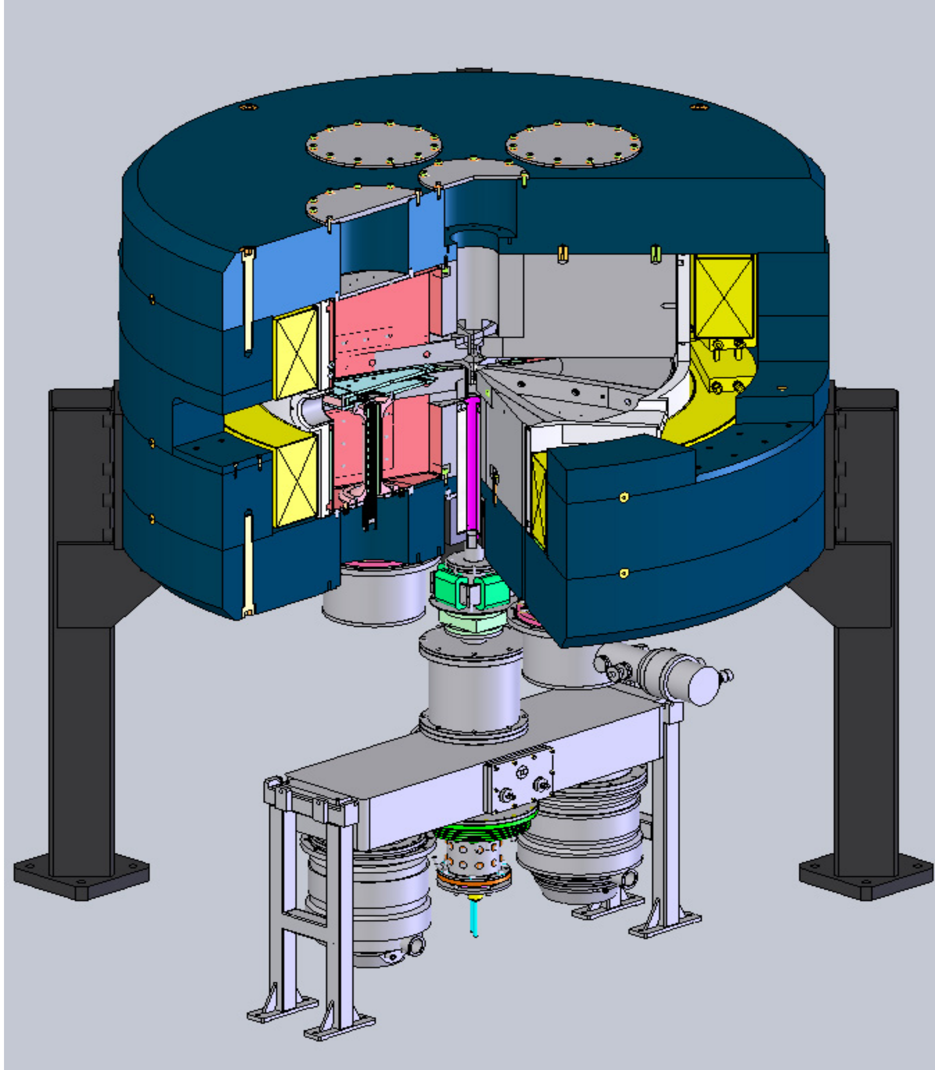
Fruitful collaboration with PSI on 590MeV, 1.4MW Ring cyclotron simulation and OPAL code development since the year of 2007

Plan of Talk

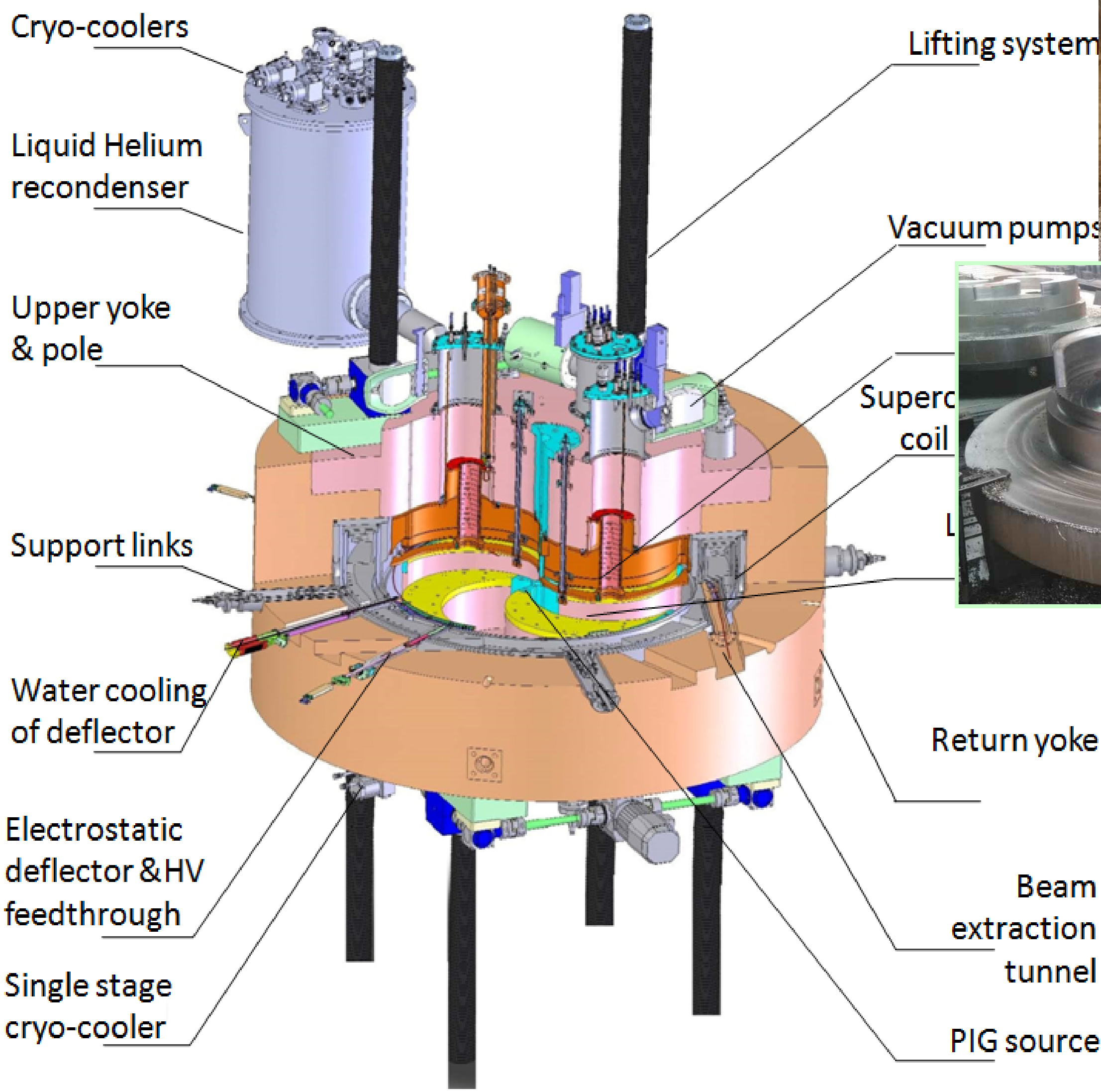
1. Introduction
2. The Beam Commissioning of CYCIAE-100
3. High Power Cyclotron Facility Proposal
4. Other Cyclotron Development

Design of a 1mA/14MeV Cyclotron CYCIAE-14B for BNCT

Extracted Beam	**H^+**
Energy/Intensity	**14 MeV / 1 mA**
Ion Source	**H^- ,10 mA**
Radius of magnet pole	**53 cm**
B-field	**2.0 kGs – 18.5 kGs**
RF frequency	**73.02 MHz**
V_{Dee}	**40-50 kV**
Harmonics #	**4**



Proton Therapy Cyclotron CYCIAE-230



Summary

- The beam commissioning on the CYCIAE-100 is in progress. We got **the first 100 MeV proton beam on July 4 2014, and the first RIB on May 4, 2015, 1mA acceleration in June, 2016**. The 100 MeV cyclotron will be able to provide 200 μA proton beam as designed, even 1mA from the recent results.
- It is confirmed that a **3-4 MW** cw proton machine, **CYCIAE-800**, should be feasible based on the existing technologies. We are eagerly expecting extensive international collaborations.
- At CIAE, a **14MeV/1mA** and a **230 MeV** cyclotrons for medical applications and proton irradiation are under construction as well.

Acknowledgement

We 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 projects.


Welcome to visit Cyclotron Lab at CIAE,
tjzhang@ciae.ac.cn