DESIGN AND CONSTRUCTION PROGRESS OF *CYCIAE-100*, a 100 MEV H- CYCLOTRON AT CIAE

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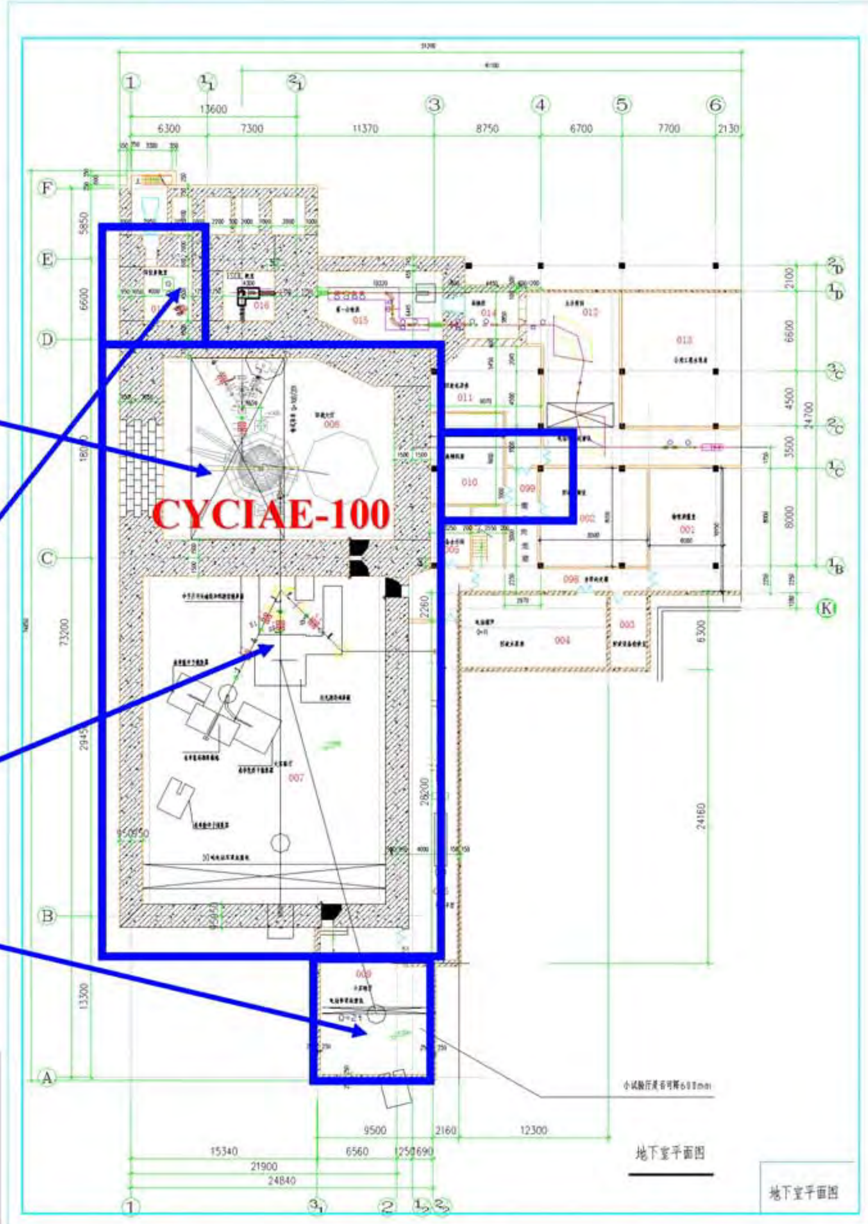
China Institute of Atomic Energy

2007-10-01

Introduction about BRIF

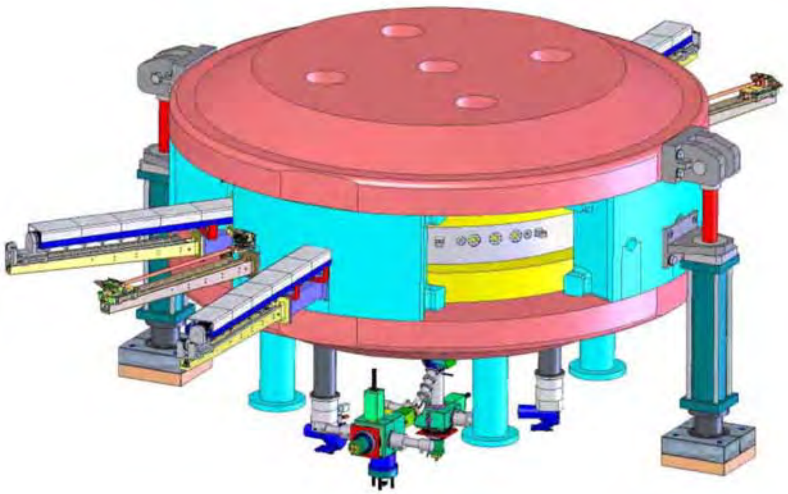
- **H- Cyclotron:** 100MeV/200uA
- ISOL:Resolution, 20000
- SC Linac: 2MeV/u
- Beam Lines



BRIF - The Beijing Radioactive Ion-beam Facility

100MeV强流回旋加速器

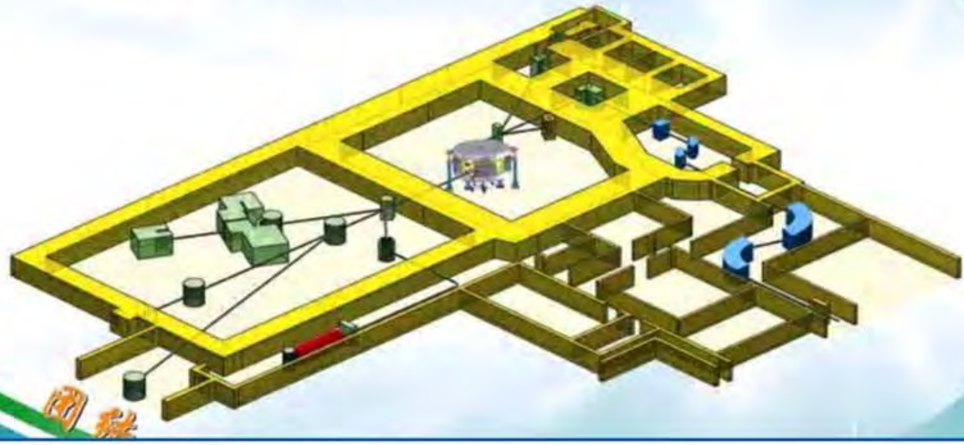
100MeV强流回旋加速器是BRIF工程的主要组成部分。它能够提供能量75-100MeV连续可调，流强200μA的质子束。其特点是：紧凑型、高调变度的磁铁结构；加速电压随半径增加的双D盒谐振腔；强流外部负氢离子源与轴向注入；负氢剥离双向引出。建



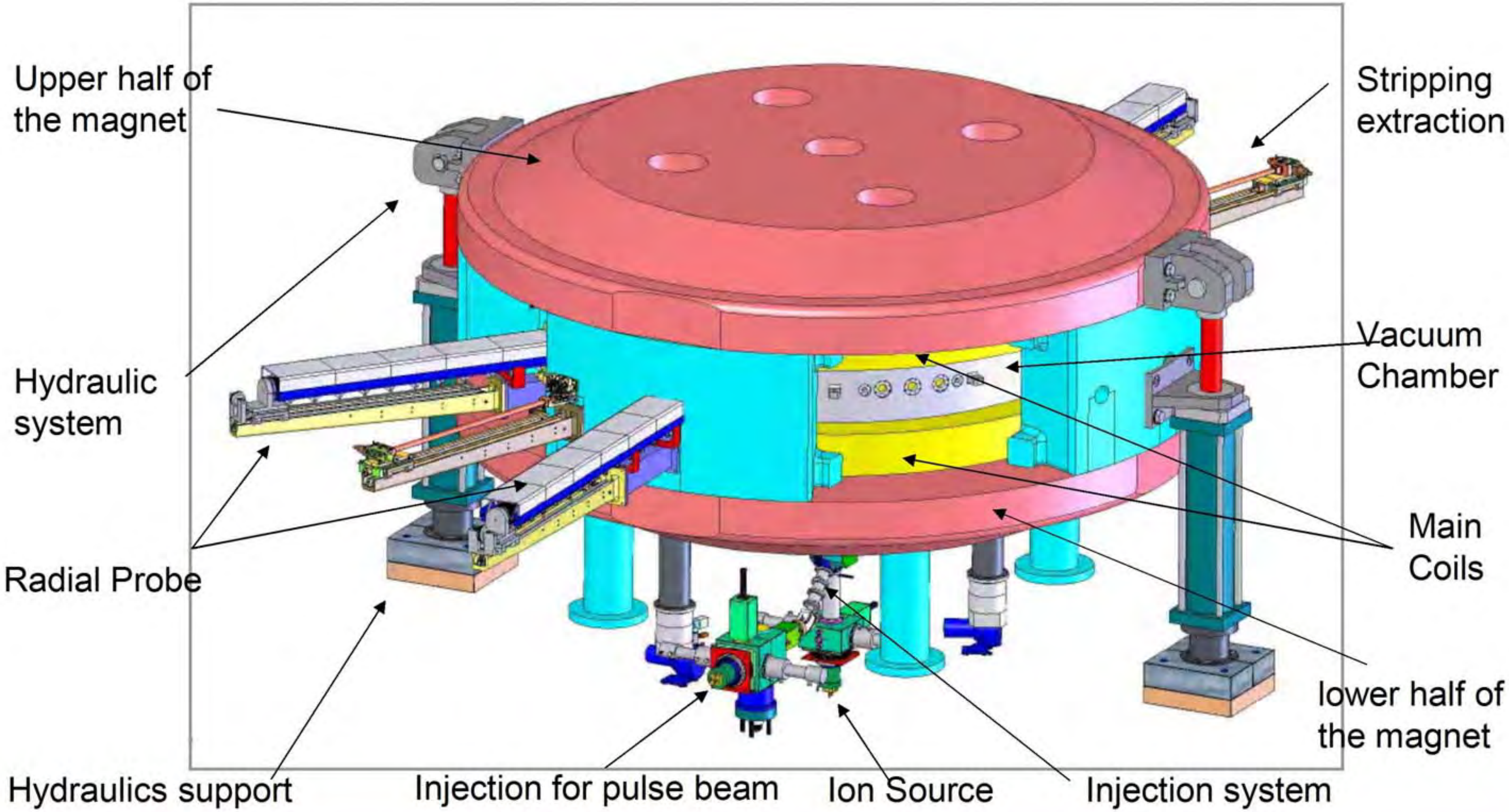
团结 敬业 求实 创新

HI-13串列加速器

串列加速器升级工程



General View of CYCIAE-100



Plan of Talk

A: DESIGN HIGHLIGHT

- Magnet
- RF
- Source, Injection and Central Region
- Extraction
- Beam Lines / Beam Dump
- Vacuum system and other

B: CONSTRUCTION PROGRESS

- Magnet
- RF System
- Other

C: R&D

- H- Source
- Central Region Model
- RF Cavity & LLRF

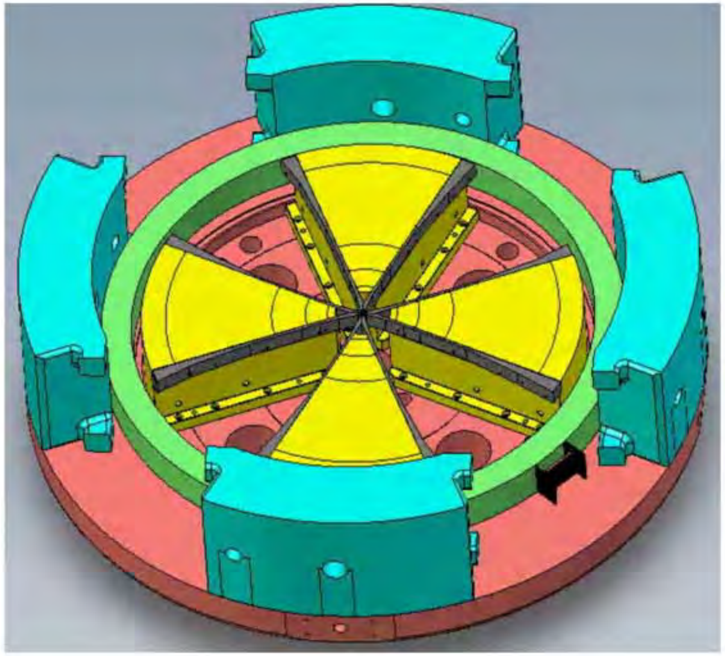
1. DESIGN HIGHLIGHT

– General Description

- Based on the basic design requirement of the energy and current for this machine, we decided to use a compact magnet and acceleration with stripping extraction for CYCIAE-100.
- It is a fixed field, four sectors cyclotron.
- Tow cavities installed into the valleys of the magnet will accelerate beam 4 times per turn.
- The beam will be injected axially into the central region from two injection lines, for high average current and for pulse beam respectively.

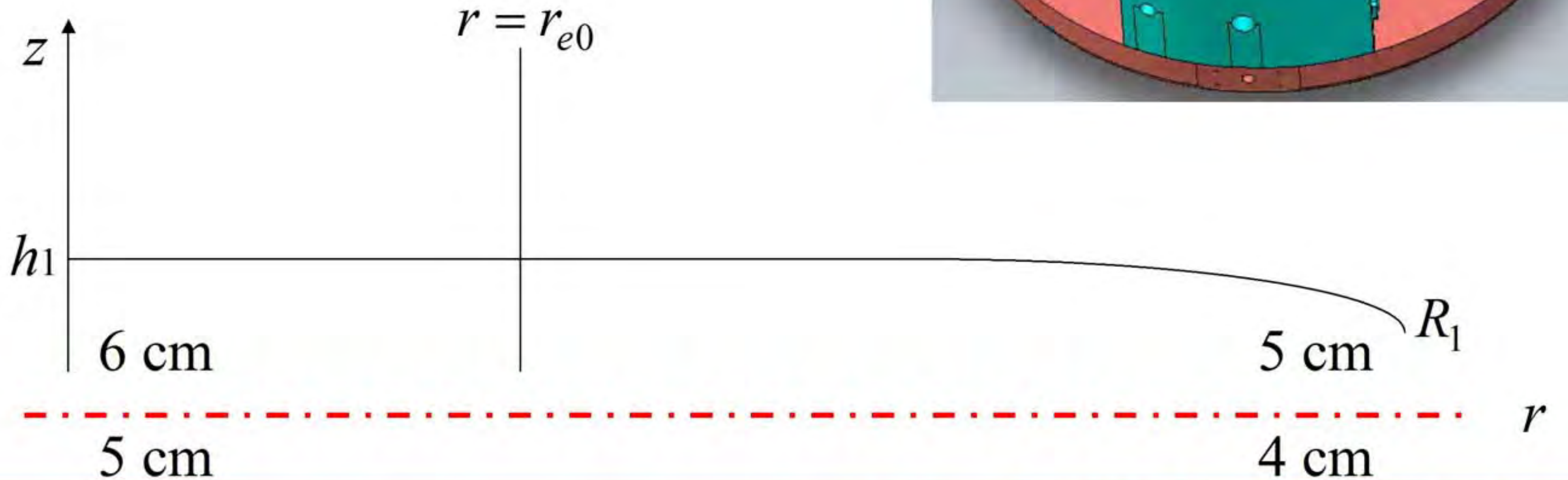
1. DESIGN HIGHLIGHT

– Magnet



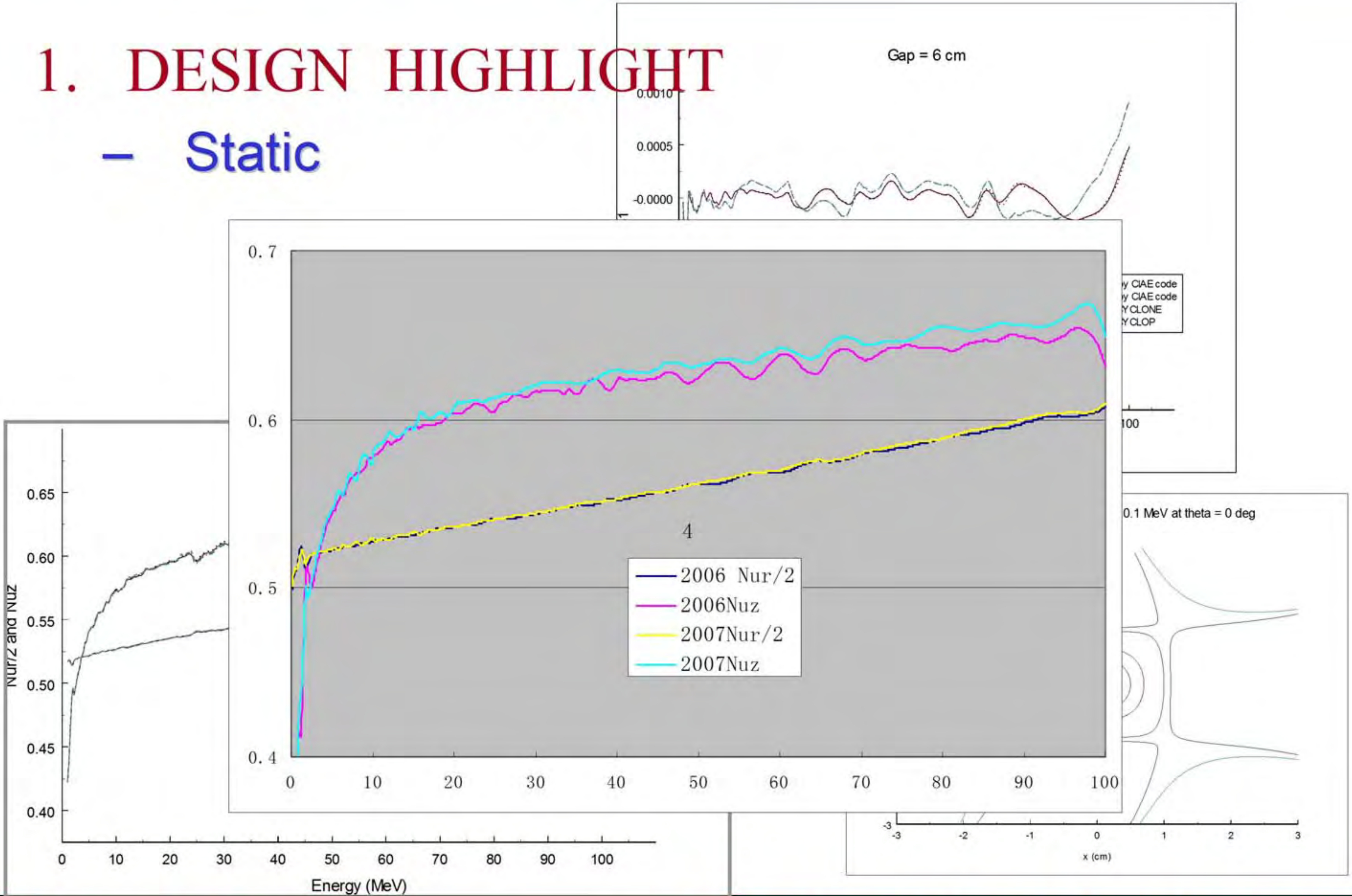
$0 < r < r_{e0}$ **h_1, uniform gap**

$r_{e0} < r < R_1$ $\quad \dfrac{r^2}{a^2} + \dfrac{z^2}{b^2} = 1$



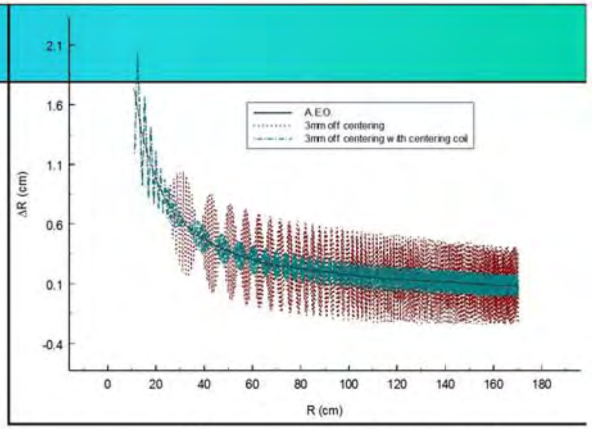
1. DESIGN HIGHLIGHT

– Static



1. DESIGN HIGHLIGHT

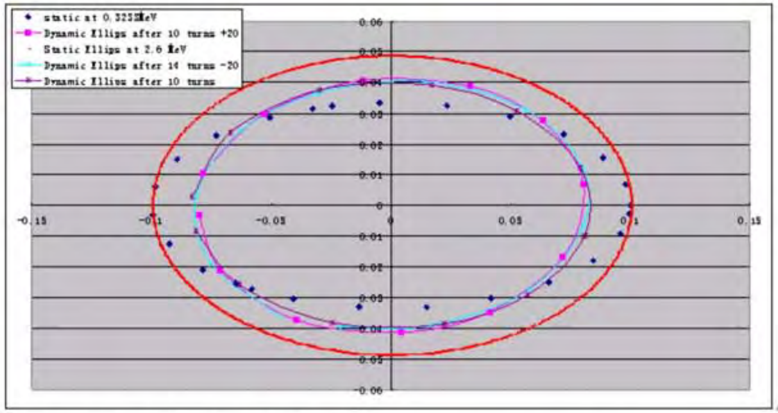
– Accelerated

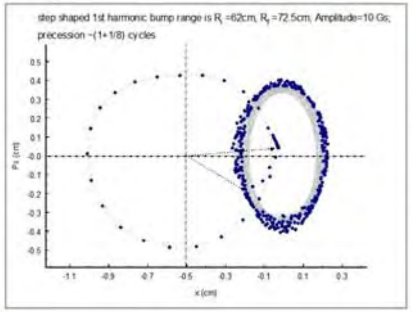


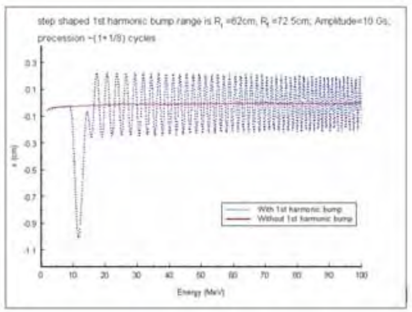
Beam Certering

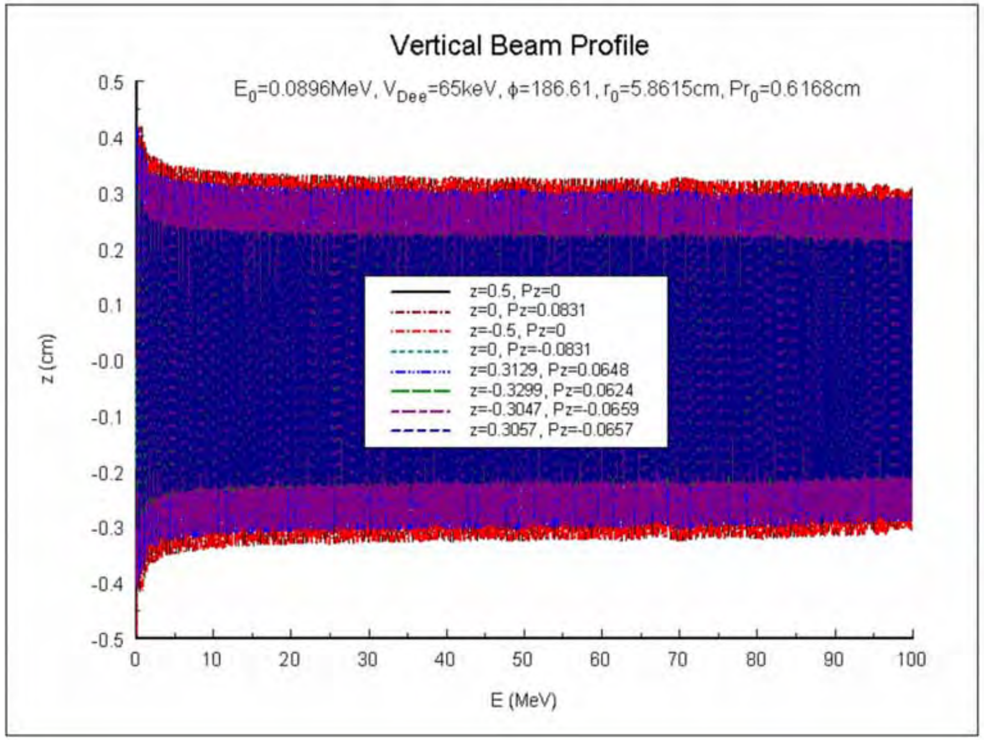
Change initial RF phase by ±20°, i.e.

z_{max}=0.1cm, E_0=0.3MeV, R_0=Raeo =10.8425cm, Pr_0=Praeo =0.306cm, $\Phi RF_0 = \Phi RFaeo \pm 20°$



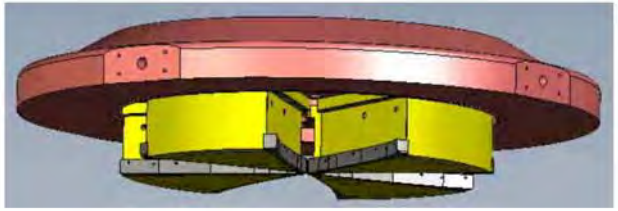




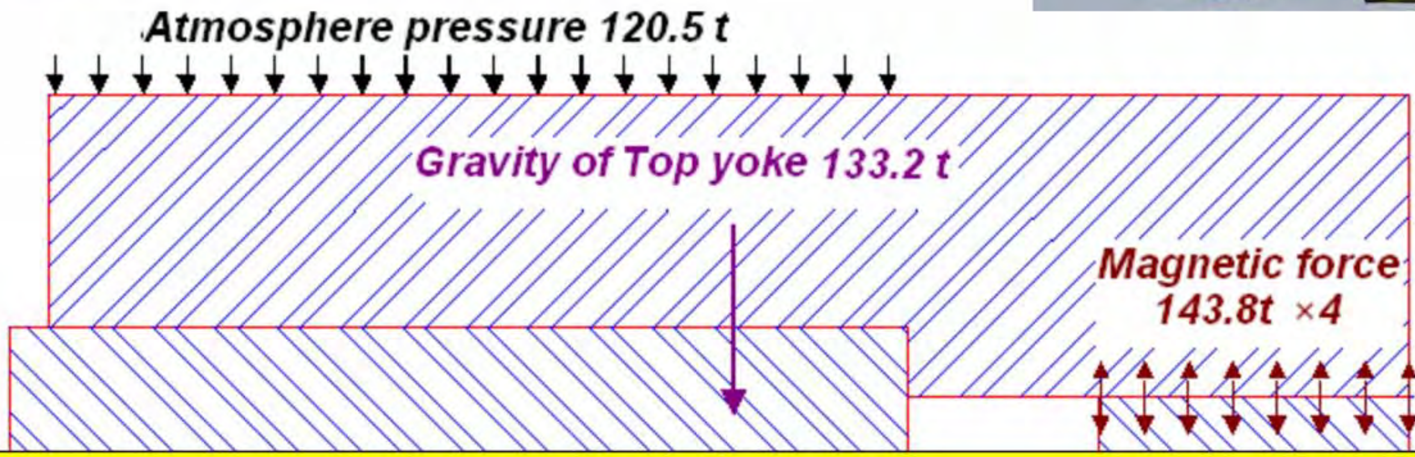


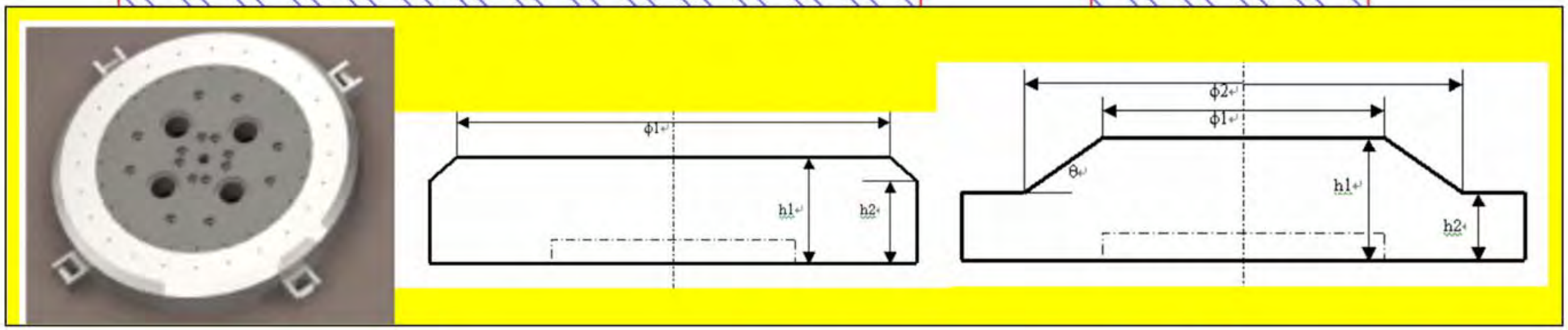
1. DESIGN HIGHLIGHT

– Magnet



Force & Deformation

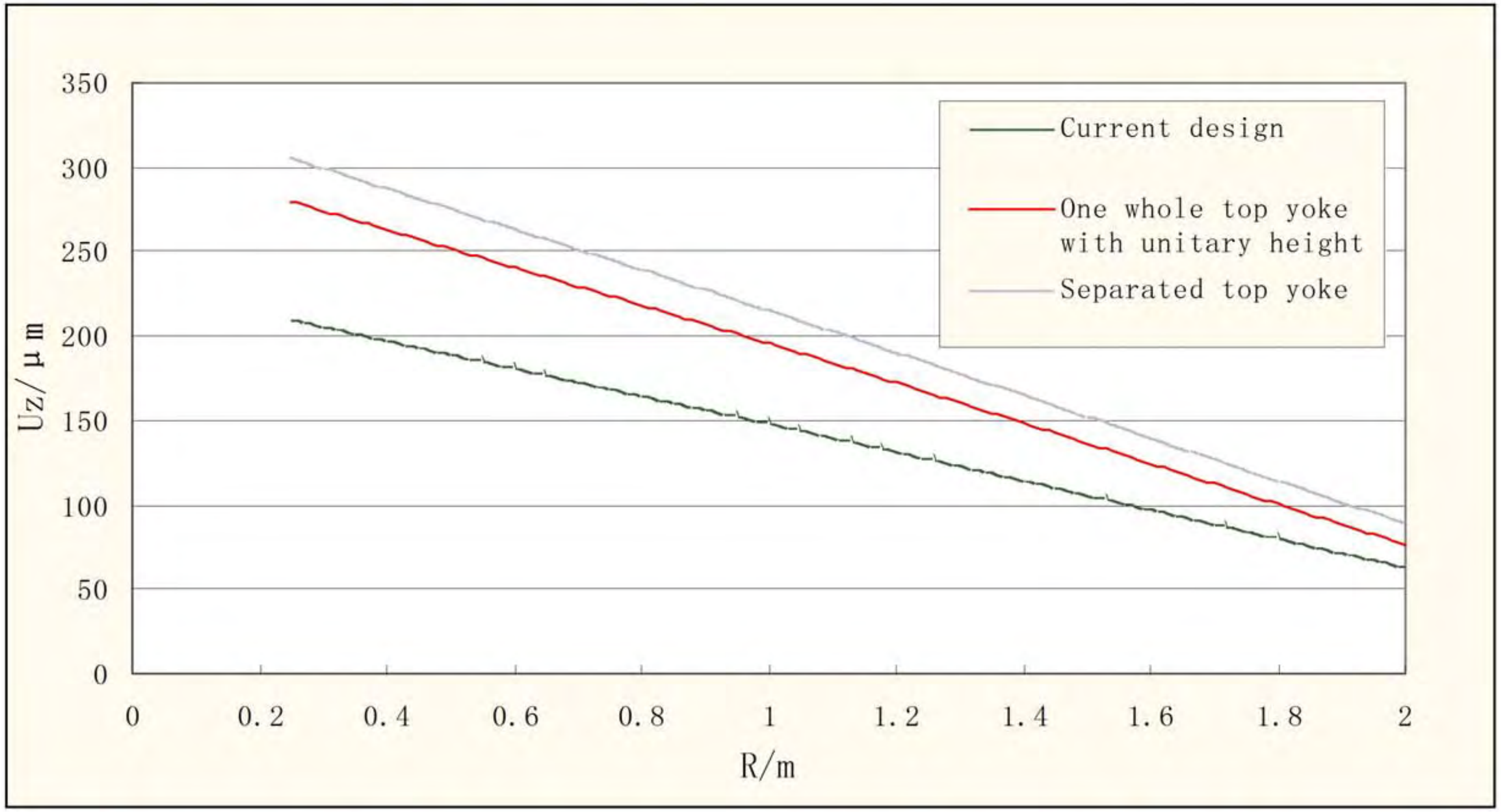




1. DESIGN HIGHLIGHT

– Magnet

Force & Deformation

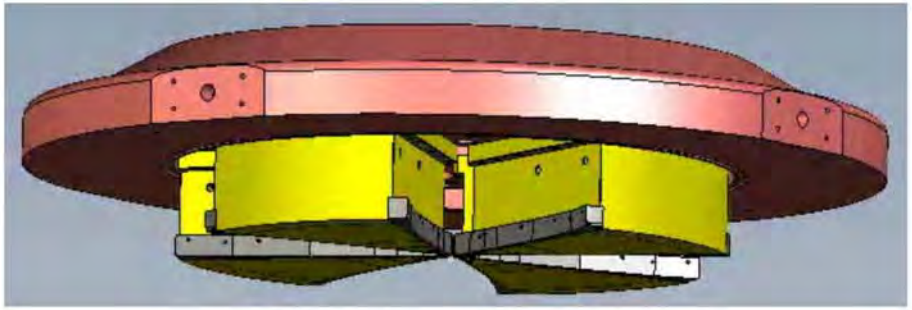


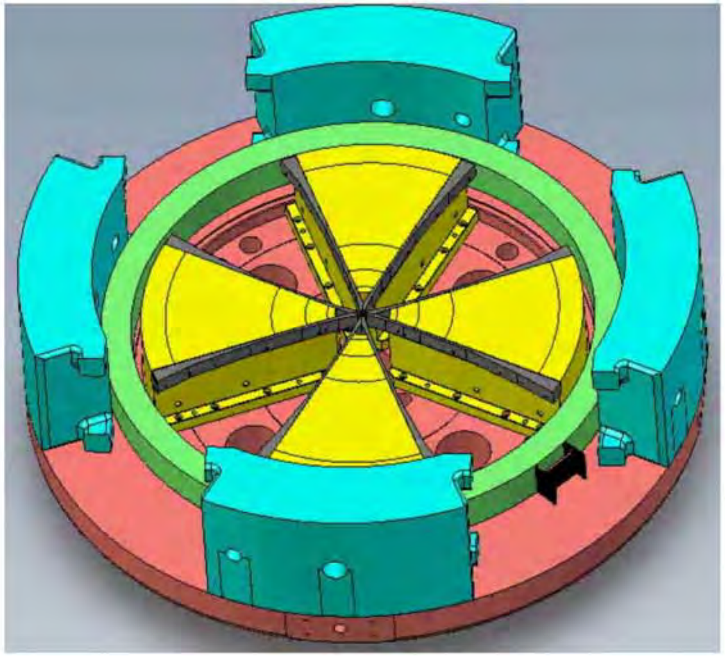
1. DESIGN HIGHLIGHT

– Magnet

The final dimension:

Several other parameters of the magnet are also optimised.



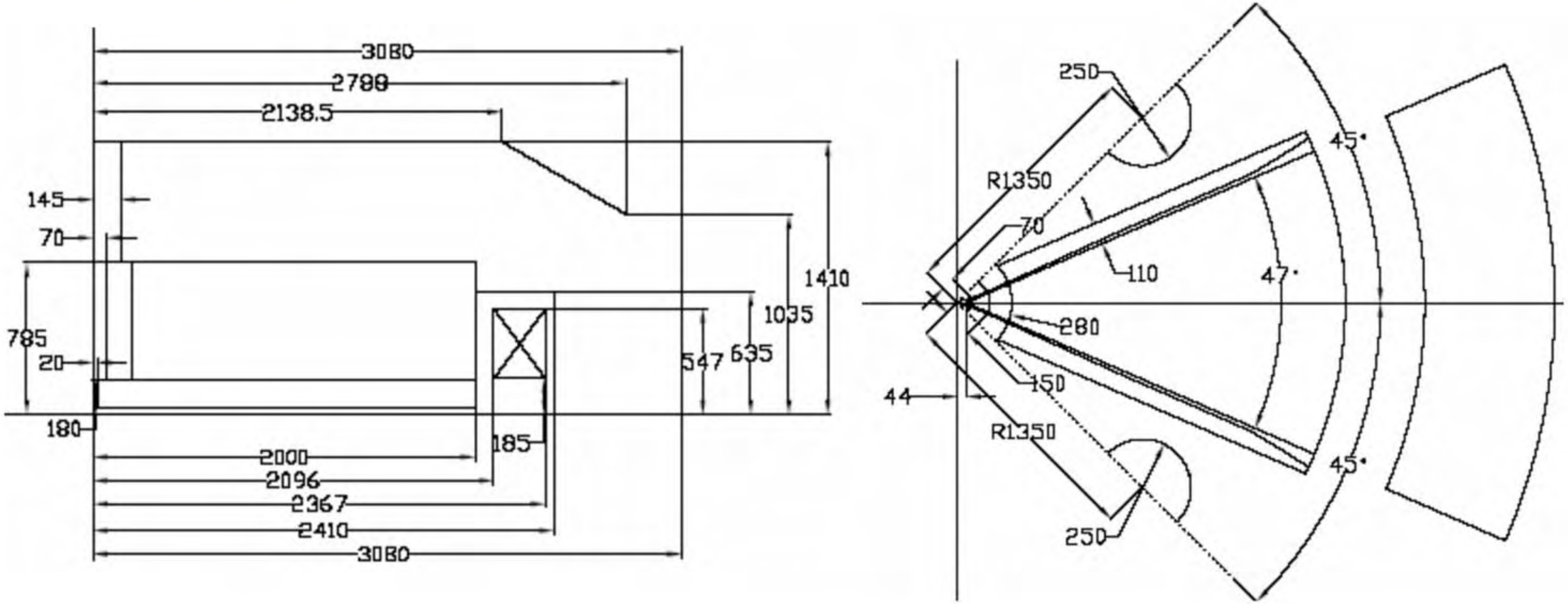


Dia.: 6160 mm
Height: 2820 mm
Weight: 435 t

1. DESIGN HIGHLIGHT

– Magnet

The final dimension:



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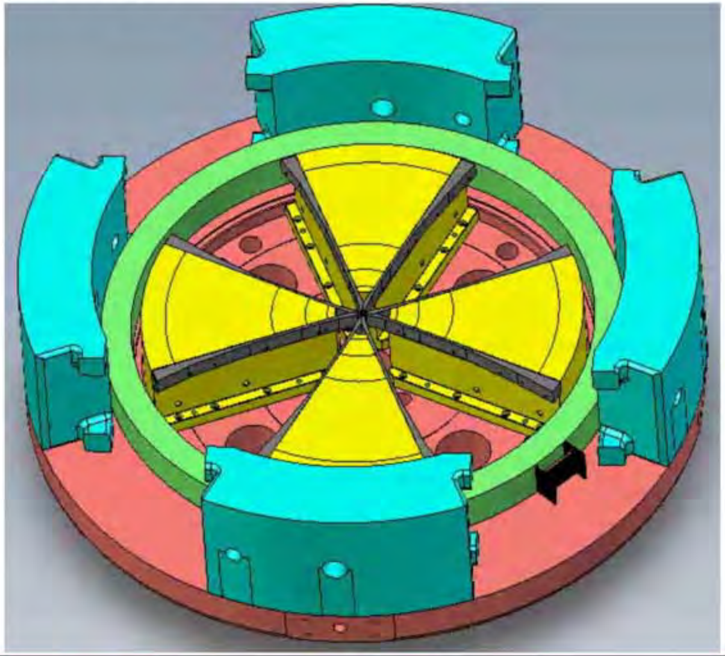
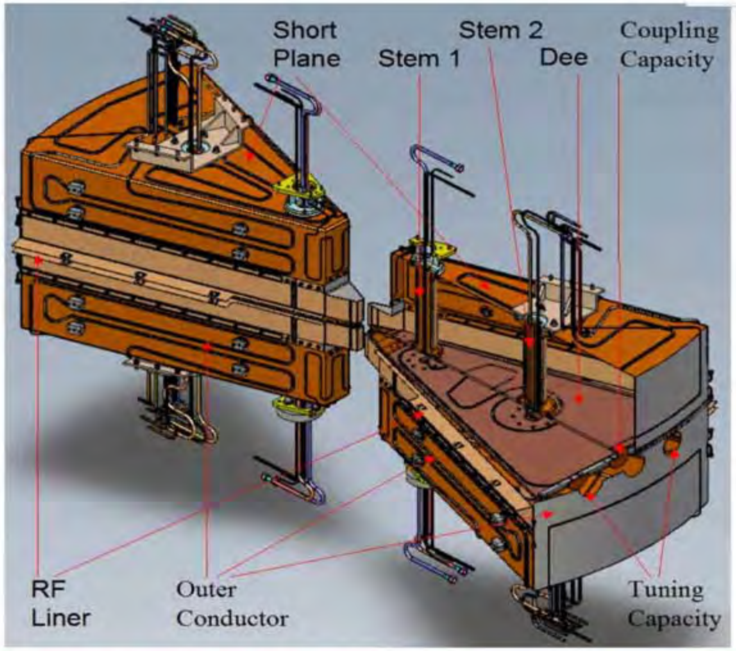
1. DESIGN HIGHLIGHT

– RF System

- There are tow half wave length cavities installed into the valleys of the sector.





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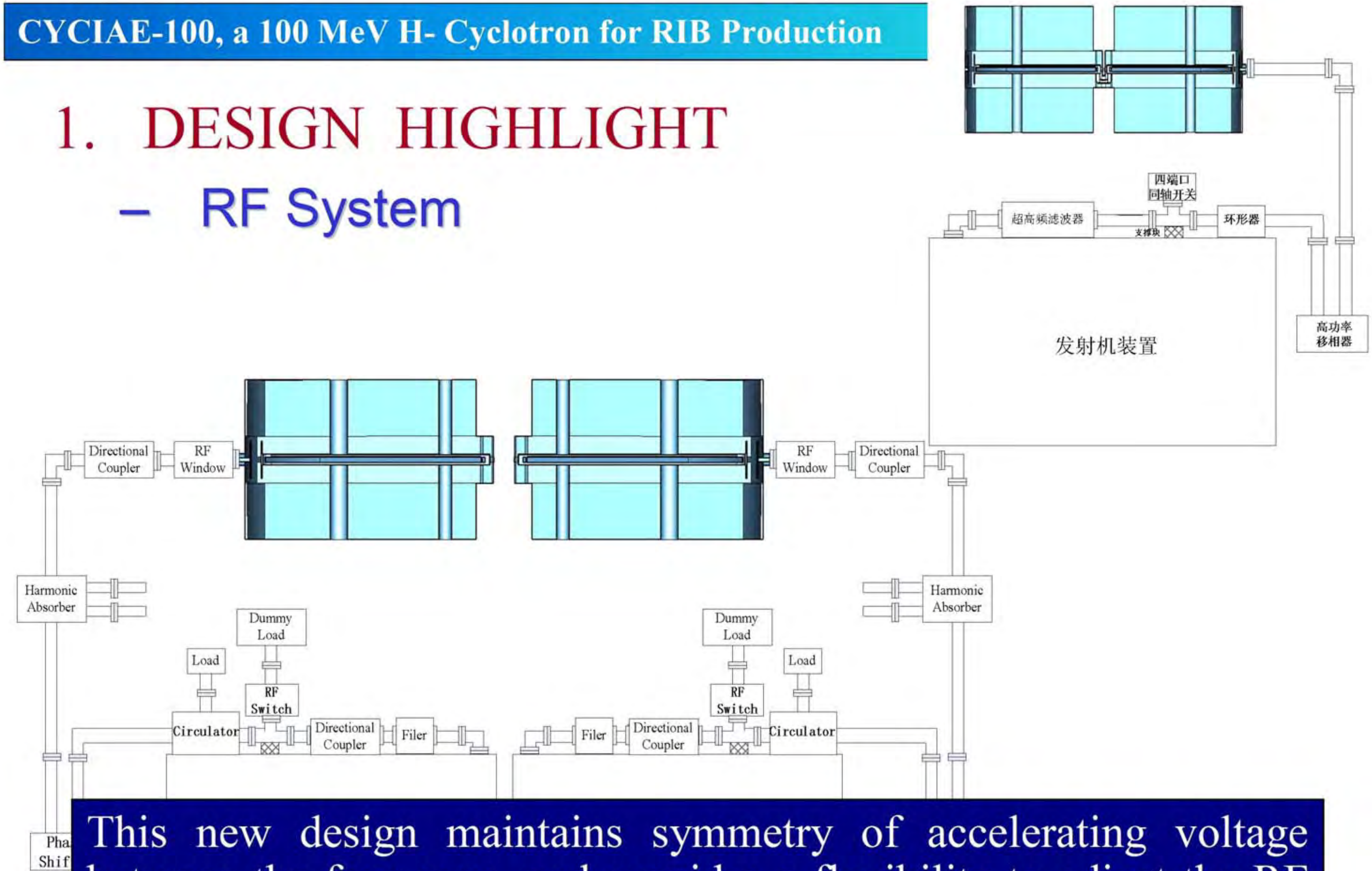
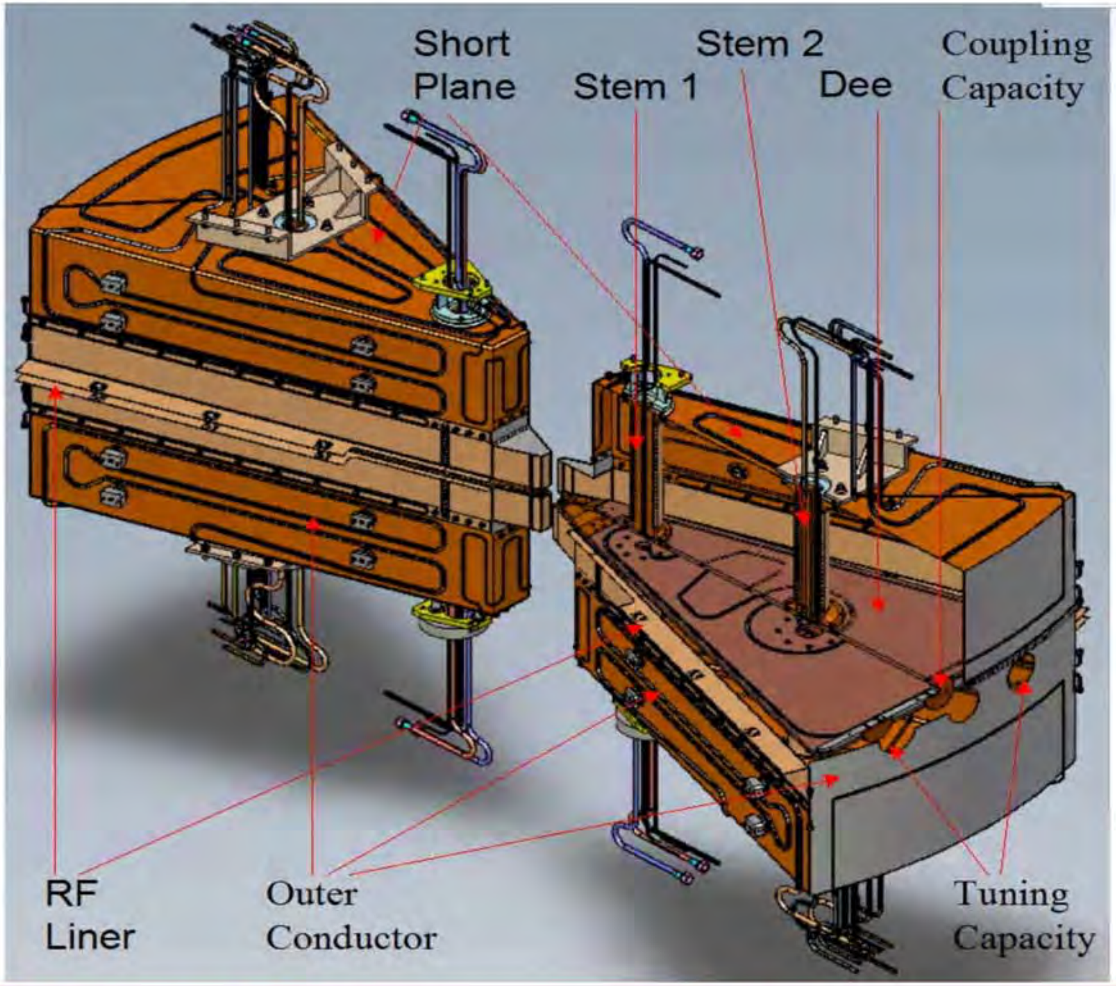
– RF System



This new design maintains symmetry of accelerating voltage between the four gaps, and provides a flexibility to adjust the RF power coupling for the machine commissioning.

1. DESIGN HIGHLIGHT

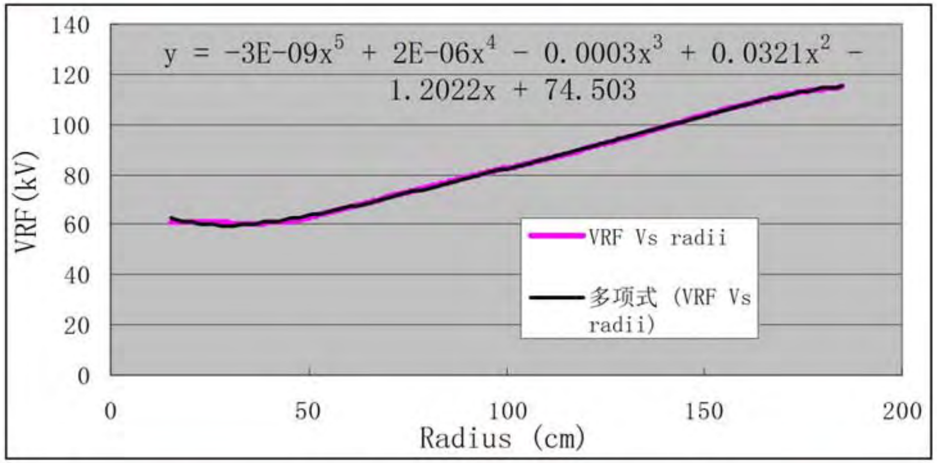
– RF System



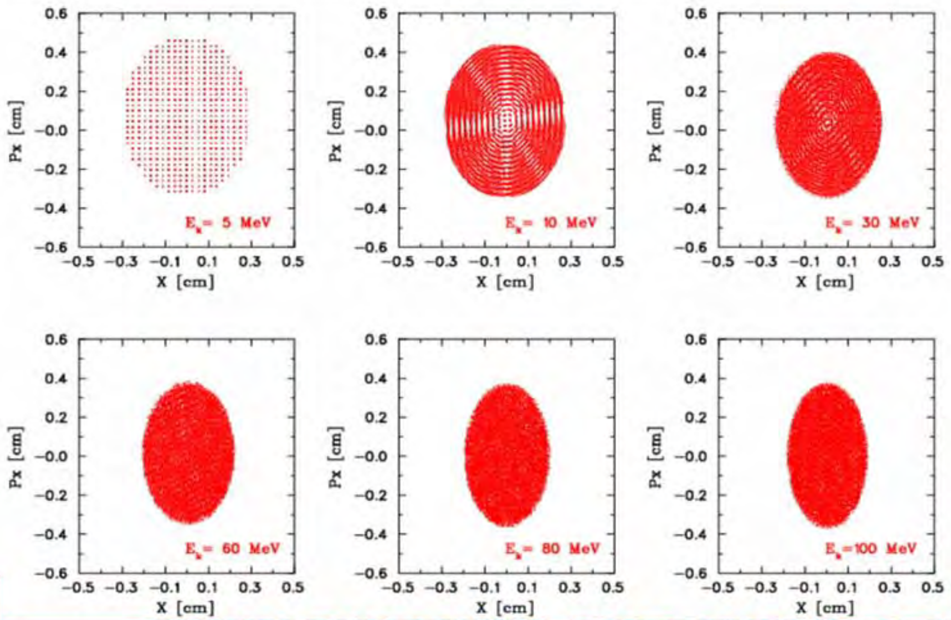
The option of stems, at low and higher radii, for each cavity was studied and the result proved to be desirable.

1. DESIGN HIGHLIGHT

– RF System

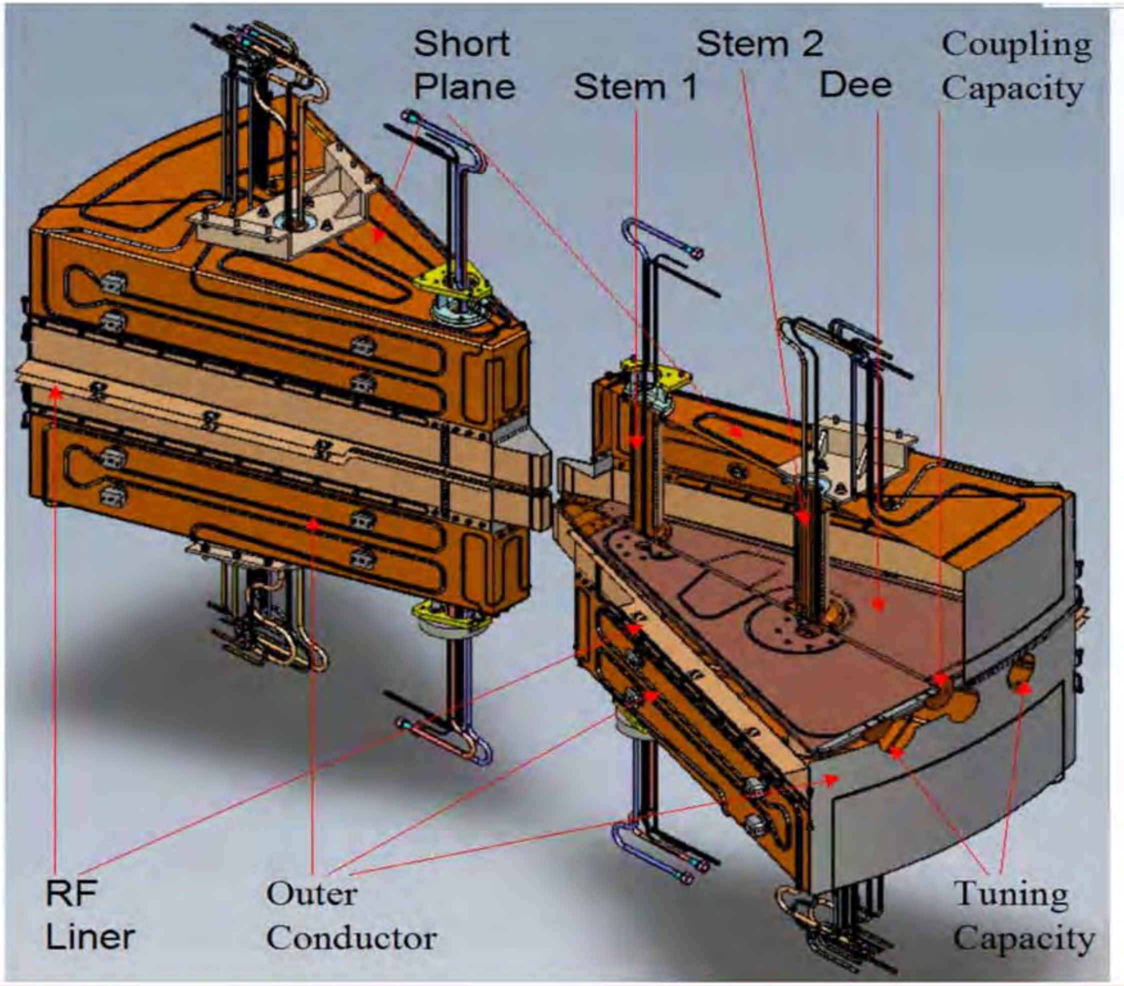


Tracking of about **20 thousand particles** by COMA is started from a static ellipsoid with 0.3 cm displacement, center at the AEO at the energy of 5 MeV, and with RF phase band of 40°.



1. DESIGN HIGHLIGHT

– RF System



Calculated frequency: **44.32 MHz**, Q value: **10300**, dissipated power on the two cavities: **57kW**.

1. DESIGN HIGHLIGHT

– RF System

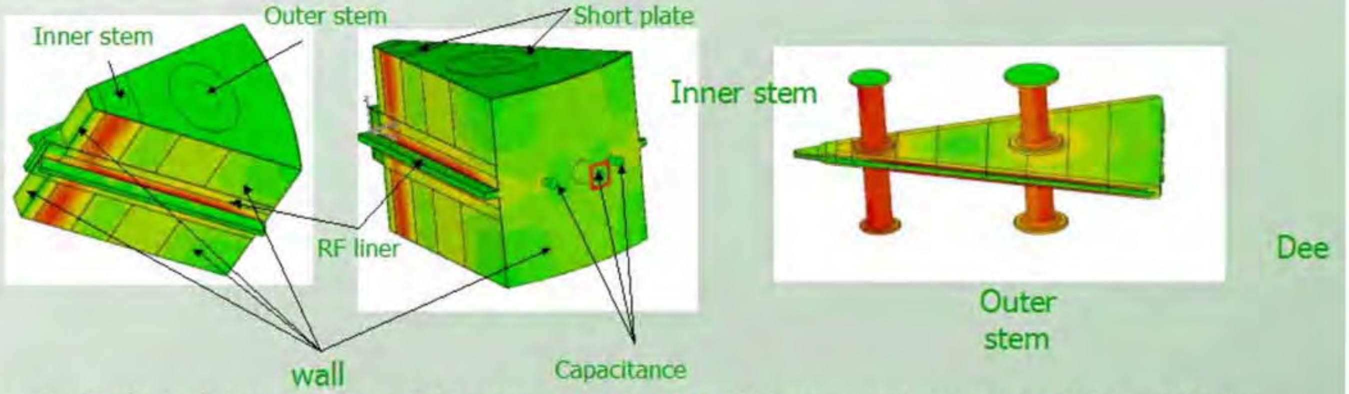
- **Cavity, RF Leakage and Dissipated Power**

Table 3: RF Dissipated Power by one Cavity

Parts	Outer Conductor	Short Plane	Dee	RF Liner	Stem 1	Stem 2	Coupling Capacity	Tuning Capacity
Dissipated Power (w)	5235.0	3327.7	7198.0	668.0	6534. 0	5380. 0	20. 5	61.8
Total Dissipated Power / cavity, w	28336.5							
Percentage	18.47%	11.74%	25.40%	2.36%	23. 06%	18. 99%	0. 07%	0.22%

1. DESIGN HIGHLIGHT

– RF System



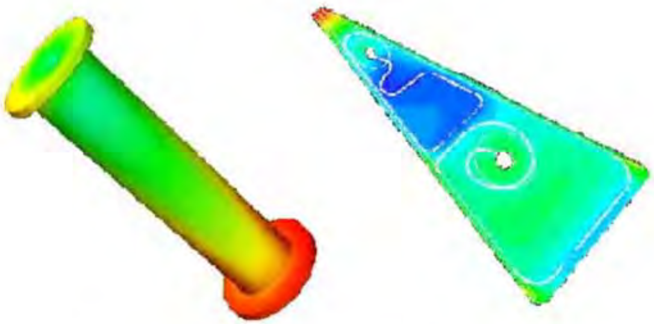
Calculated by a finite difference code,the RF power loss on each cavity is about 28.1 kW at the Q value is 10300. However, due to some non-ideal factors during the fabrication process, one may estimate the actual Q value at ~6000. As a result, the loss on each cavity will be approximately 48.2 kW.

Power distributions on the each RF cavity

Q value	Total power lost /kW	Power distribution / W						
		Dee	Inner stem	Outer stem	Wall	Short plate	Capacitance	RF liner
Q=10300	28.1	6280	7920	5840	3246.8	1408	76	3324
Q=6000	48.2	10800	13600	10020	5575	2417	130	5706

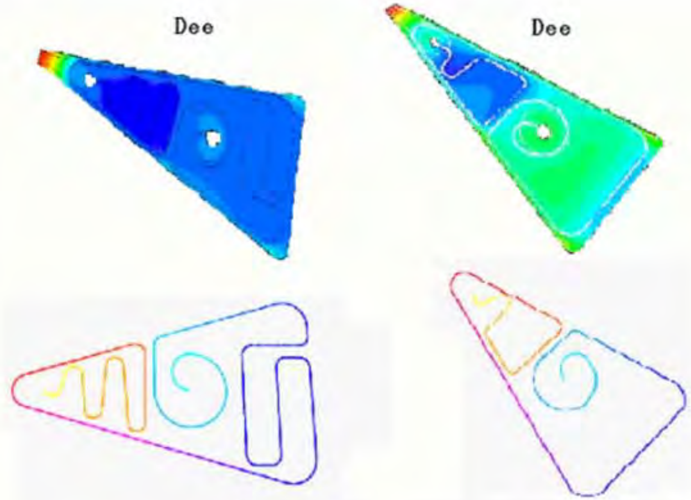
1. DESIGN HIGHLIGHT

– RF System



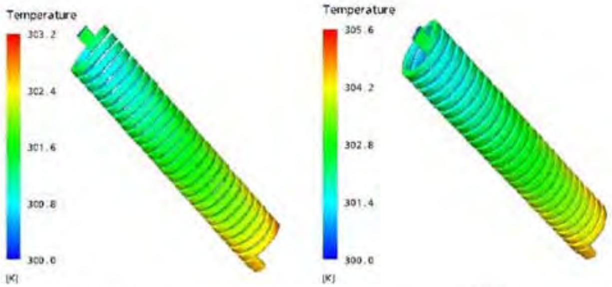
Thermal distribution on inner stem

Thermal distribution on Dee



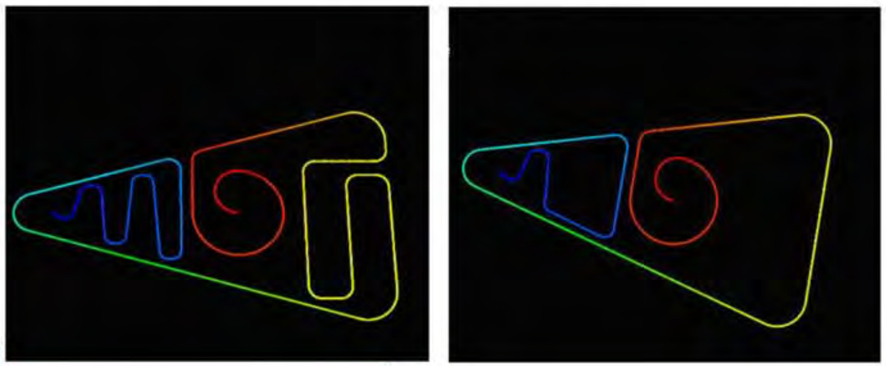
initial water cooling tube

optimized water cooling tube



Q=10300

Q=6000



Thermal distribution, **TUPPRA14**.
Fabrication and assemble tolerance, **TUPPRA13**

1. DESIGN HIGHLIGHT

– RF System

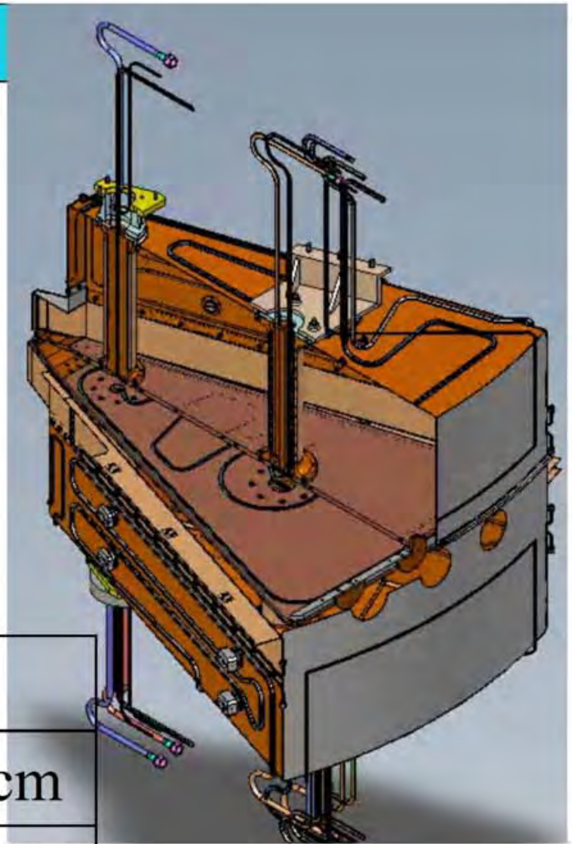
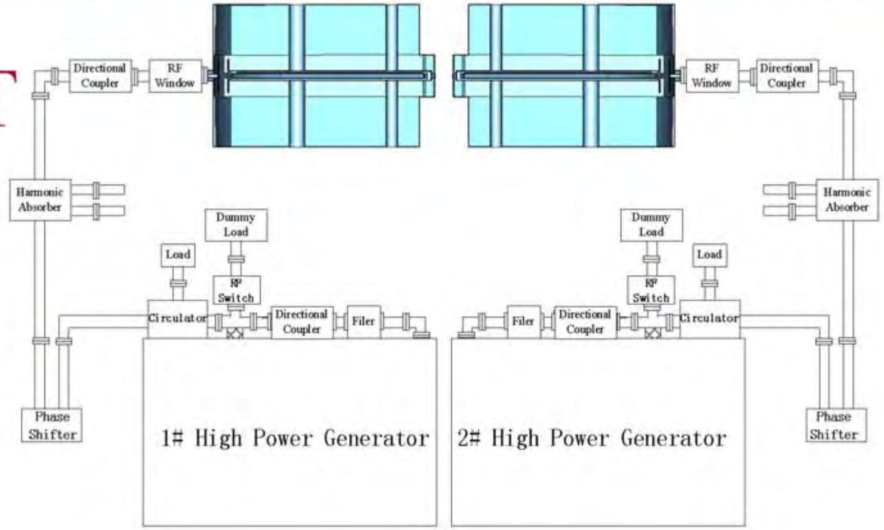


Table 2: RF Cavity Dimensions

Outer conductor		Inner conductor	
Height of the Cavity	1.26m	Radius of Stem 1	6.4cm
		Radius of Stem 2	7cm
Outer Radius	1.98m	Length of Dee along its symmetric axis	1.86 m
Angle	36.6°	Dee Angle	34.4°

1. DESIGN HIGHLIGHT

– RF System



The 100kW final power amplifier
FPA
4CW150000E tetrode
produced by Eimac

- **High Power Transmission and LLRF Control**
- The RF power transmission system use 6 inch coaxial line and a number of transmission components such as RF filter, directional couplers, harmonic absorber, phase shifter (trombone), RF switch, dummy load, and so on.
- The low level RF control loops will be described in the fowling section of R & D.

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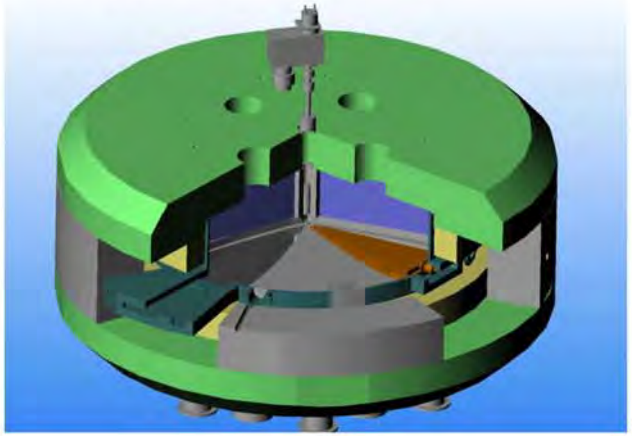
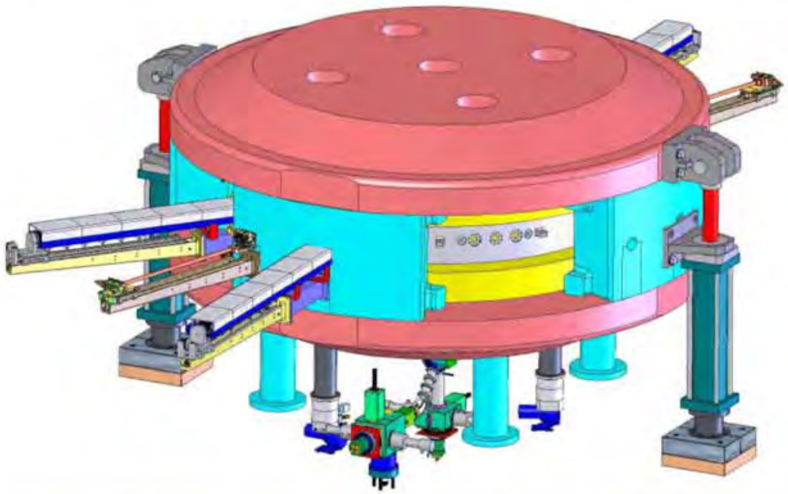
1. DESIGN HIGHLIGHT

– Injection and Extraction

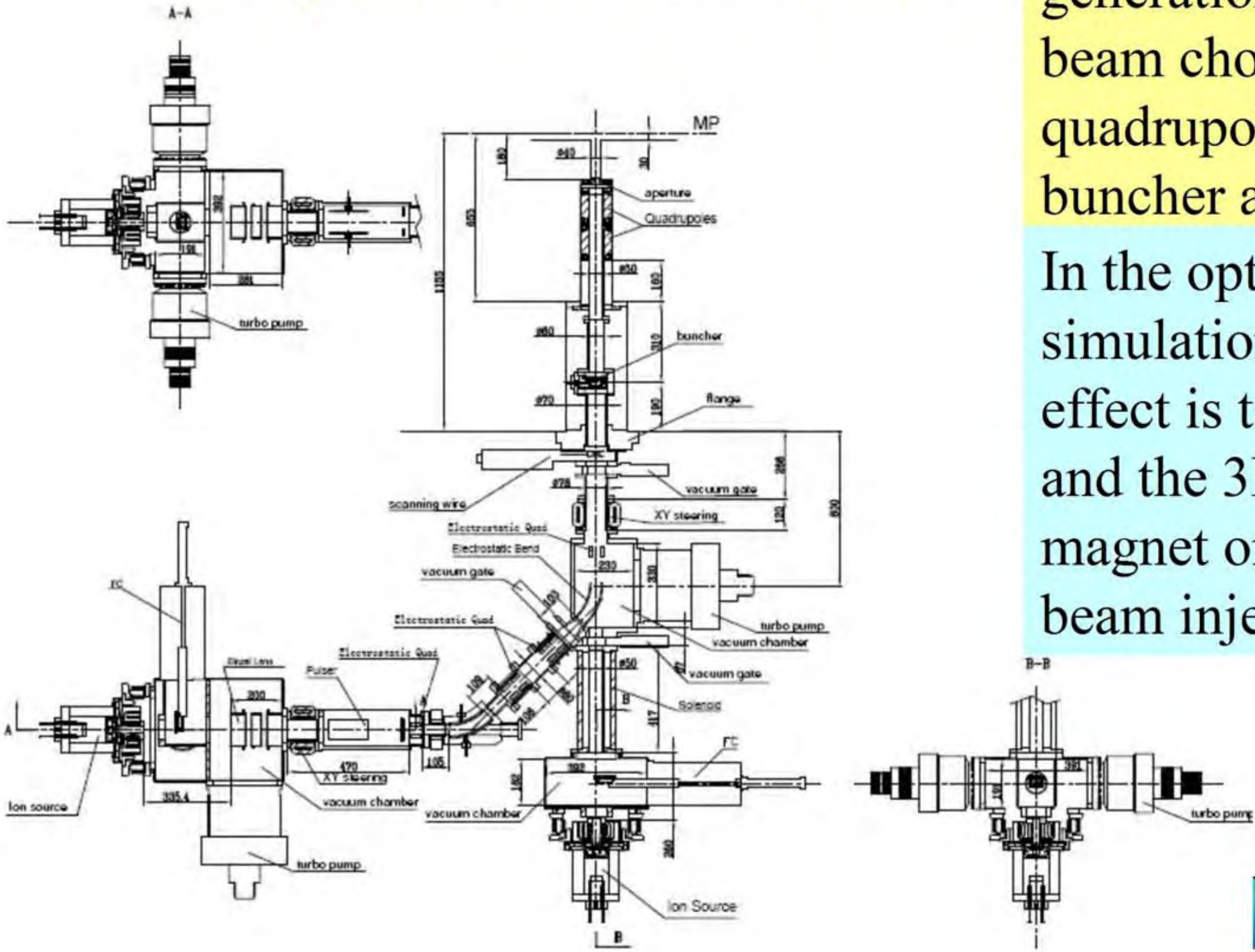
- **Ion source, injection line and central region**
- The multicusp source is selected for H- beam generation. The beam will be injected along the vertical axis into the central region. The arrangement of injection line above the machine is changed to below.





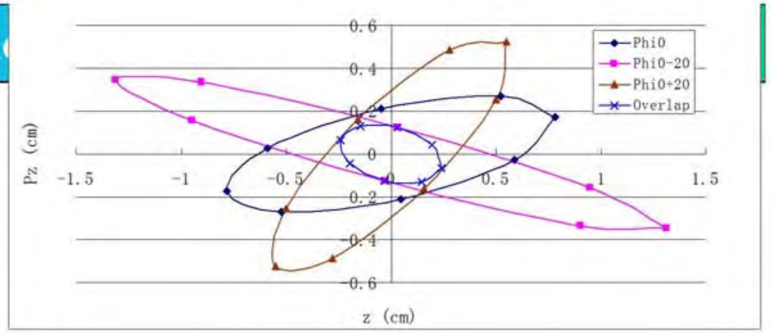
1. DESIGN HIGHLIGHT

– Injection and Extraction



One line is optimized for high current injection and the other for pulse beam generation, in which the beam chopper, electrostatic quadrupole, deflector and buncher are used.

In the optics matching simulation, the space charge effect is taken into account and the 3D field of the main magnet on the path during beam injection is employed

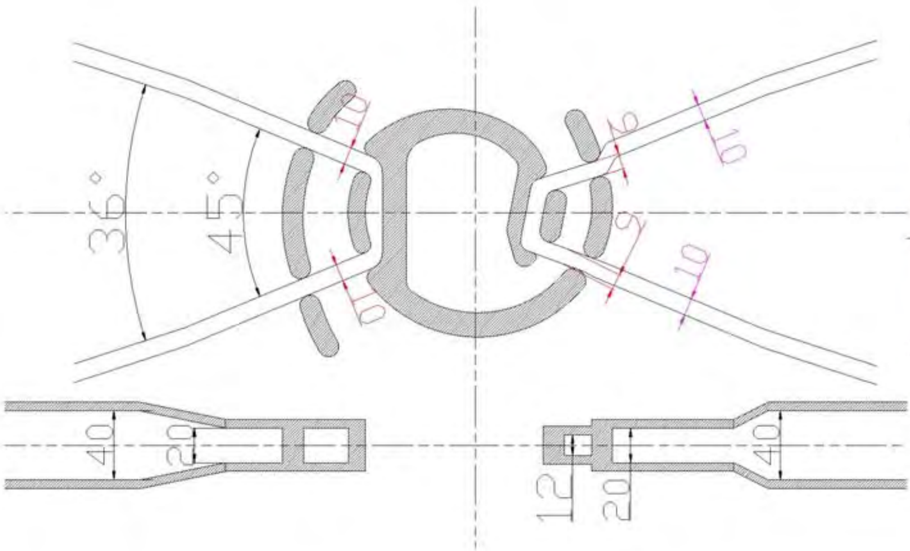


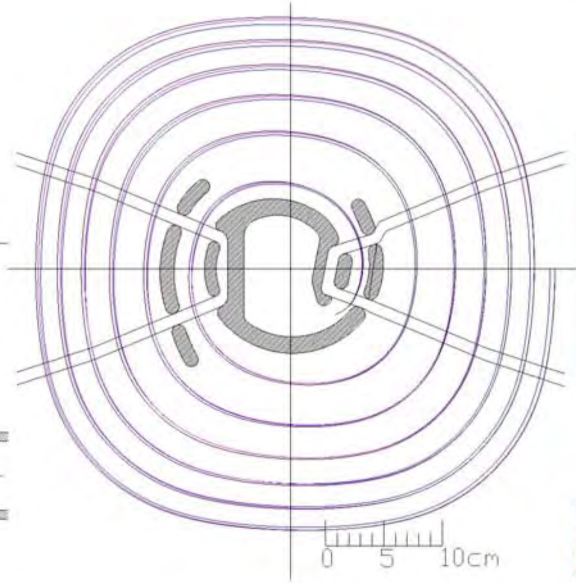
1. DESIGN HIGHLIGHT

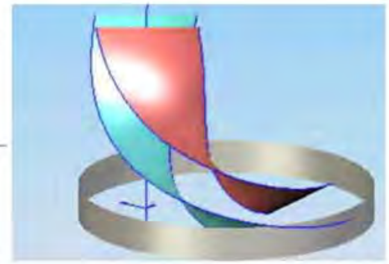
– Injection and Extraction

Ion source, injection line and central region

- The simulation results show that 5 mA beam with energy of 40 keV and emittance of 32 π mm mrad can be injected. And the RF acceptance at the central region is about 40°. This will bring the machine an ability to provide 200–500 μA proton beam. **MOPPRA13**.



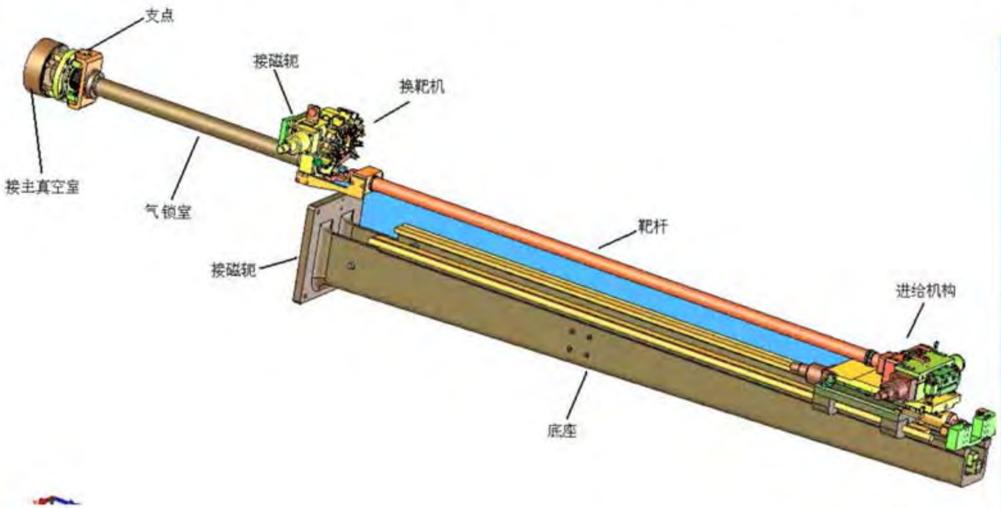


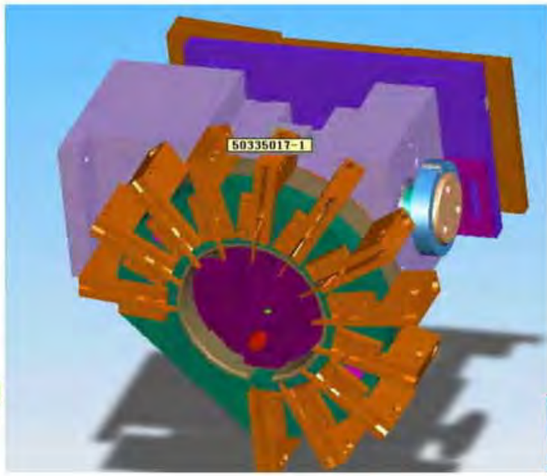


1. DESIGN HIGHLIGHT

– Injection and Extraction

- **Extraction**
- Two proton beams will be extracted in dual opposite directions by stripping.
- The extraction system includes the following parts: Stripper Probes, Positioning and driving system, Foil changing system.



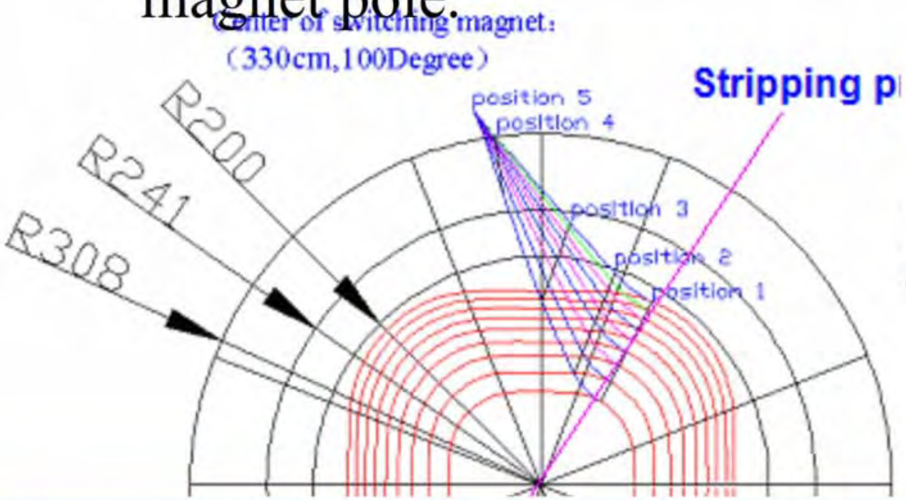


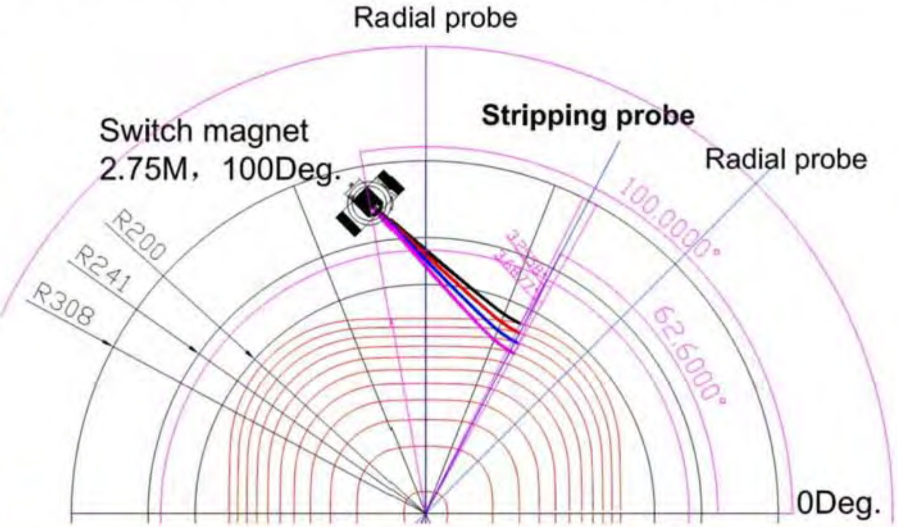
1. DESIGN HIGHLIGHT

– Injection and Extraction

Extraction

- The proton beams with energy from 70 MeV to 100 MeV will be extracted. We also try to extract beam with lower energy. The position of switch magnet is inside the magnetism yoke and the stripping probe is inserted radially from the main magnet pole.



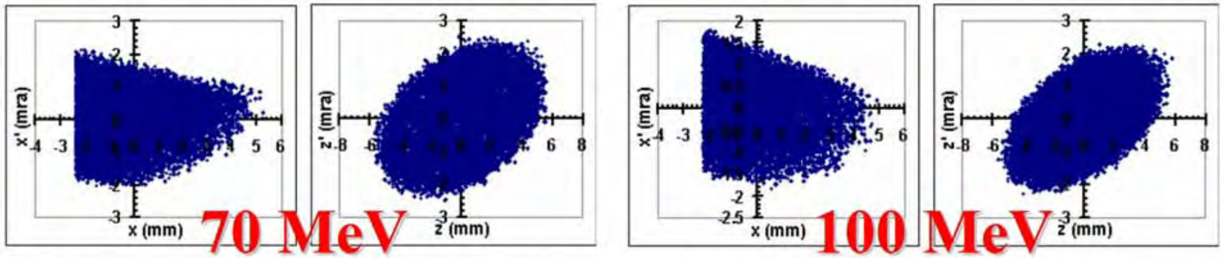


1. DESIGN HIGHLIGHT

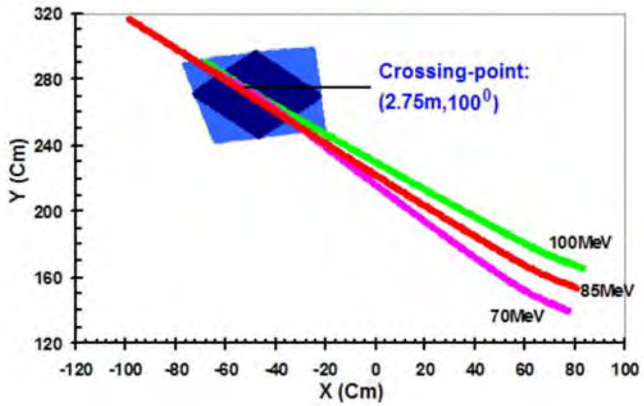
– Injection and Extraction

Extraction

- The extraction optics is investigated by numerical tracking started from the stripping foil for the various energies. All the beams will be delivered from the stripping points to the center of switching magnet inside the return yoke. **MOPPRA16**.



The distribution on the foil, normalized emittance of 4 π -mm-mrad.



The extracted trajectories, with the field of switching magnet fields

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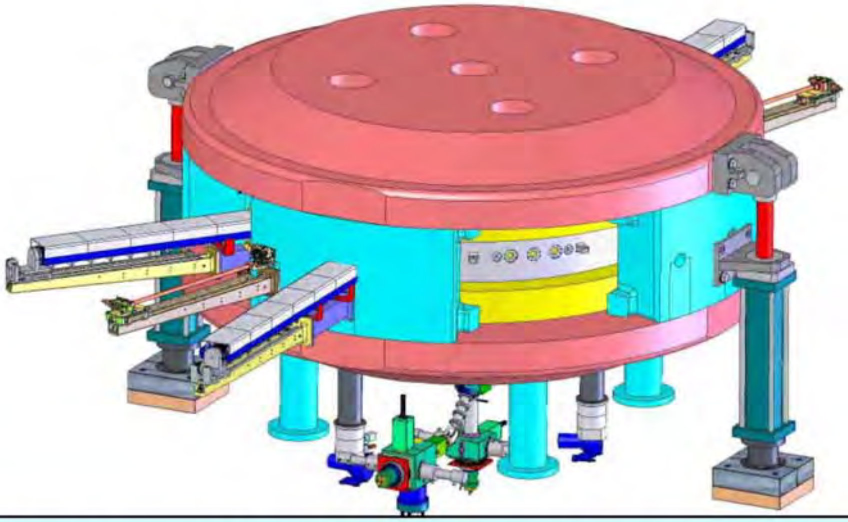
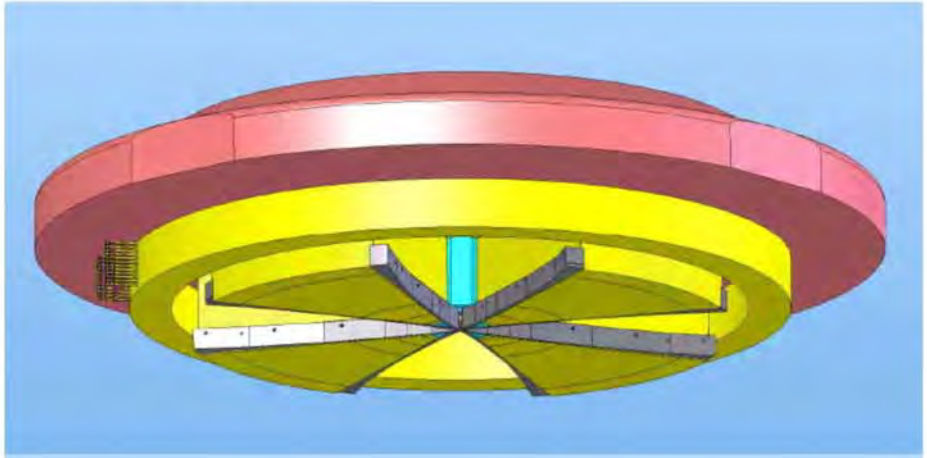
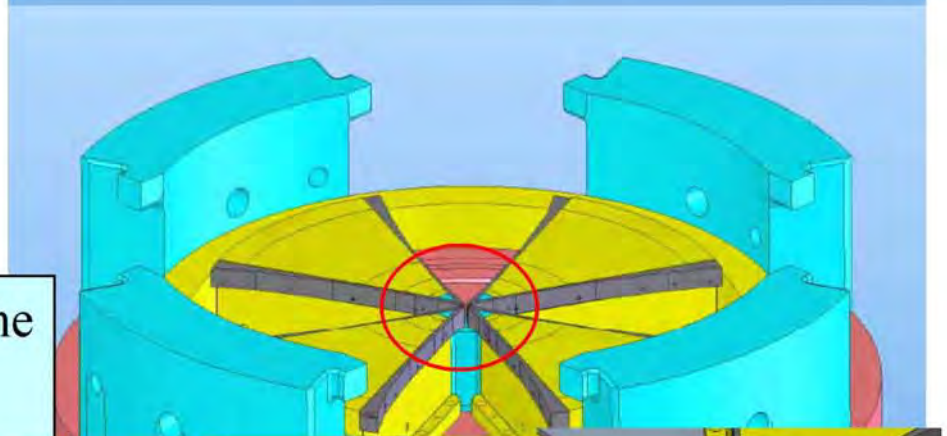
2. CONSTRUCTION PROGRESS

– Magnet

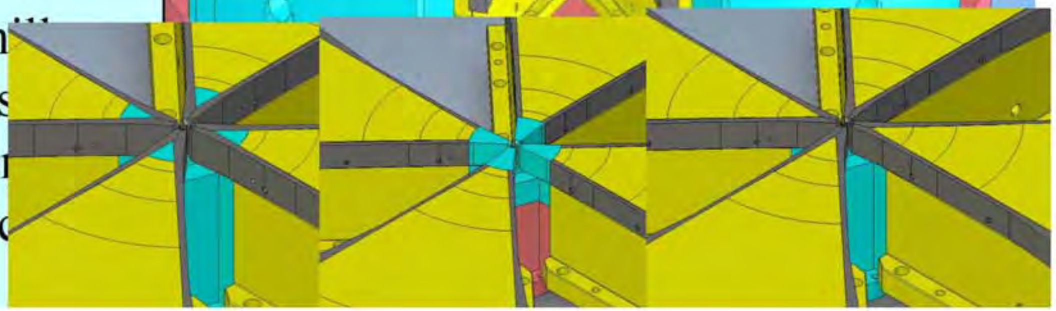






The concept and engineering design for the 435 tons main magnet had been finished.

The requirement for the tolerance of h[...] is about 0.1 mm, one of the most s[...] challenges in the magnet constructio[...] other challenge is the QA of oversize [...] piece.



2. CONSTRUCTION PROGRESS

– Magnet

Imperfaction

- Internal defect
  - chemical compositions
  - Shrinkage, Carbon segregation
- magnetic heat treatment
- fabrication and assembling tolerance

Resonance	Driving term	Field Error
$\nu_r=1$	B_{z1}	2 Gauss
$2\nu_r=2$	B_{z2}	40 Gauss
$2\nu_r=2$	$\partial B_{z2}/\partial r$	8 Gauss/cm
$2\nu_z=1$	$\partial B_{z1}/\partial r$	5 Gauss/cm
$\nu_r = 2\nu_z$		

2. CONSTRUCTION PROGRESS

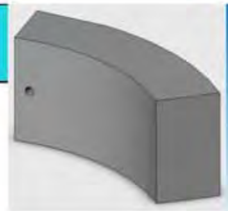
– Magnet

The chemical compositions for the pole (Forgings or hot-rolled plates)

	C maxi	Mn Maxi	S maxi	P Maxi	Si maxi	Cr maxi	Mo maxi	Ni Maxi	Al
Heat Analysis	0.060	0.350	0.020	0.025	0.200	0.080	0.040	0.080	0.020-0.060
Product Analysis	0.070	0.390	0.023	0.030	0.230	0.110	0.060	0.100	0.015-0.070

XC06 => C05RR

- The segregation should be controlled within 0.01%-0.02%;
- Or measure the BH curve which should keep the deviation less than 1.5%.



2. CONSTRUCTION PROGRESS

– Magnet

The chemical compositions for the Yokes (Castings)

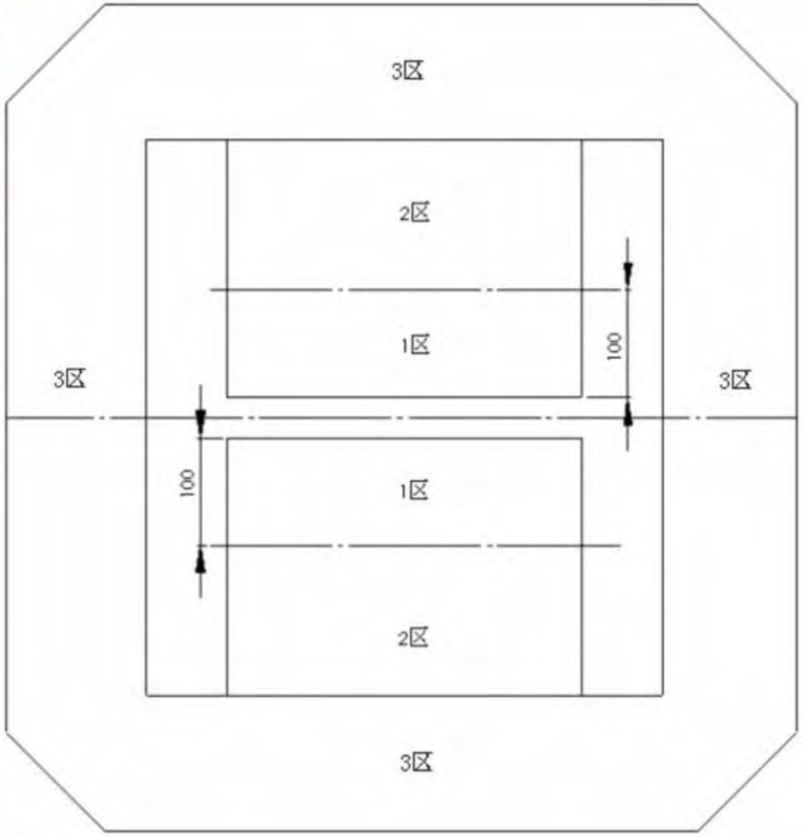
C	Si	*Mn	P	S	Ni	Cr	Cu	Al
≤0.11	≤0.37	0.35-0.65	≤0.035	≤0.035	≤0.25	≤0. 10	≤0. 25	≤0. 1

ANSI 1008 => 08# Steel in China

- The carbon segregation at the same circle and same height should be within 0.02%-0.04%.

2. CONSTRUCTION PROC

– Magnet



Ultrasonic Flaw Detection

Table 3 requirement for ultrasonic flaw detection

	Zone 1 (the poles, central plugs and shimming bars)	Zone 2	Zone 3
Should not have any one "Φ"	Φ3mm	Φ6mm	Φ8mm
In 200mm x 200mm, less than 5 "Φ"	Φ2mm	Φ4mm	Φ6mm

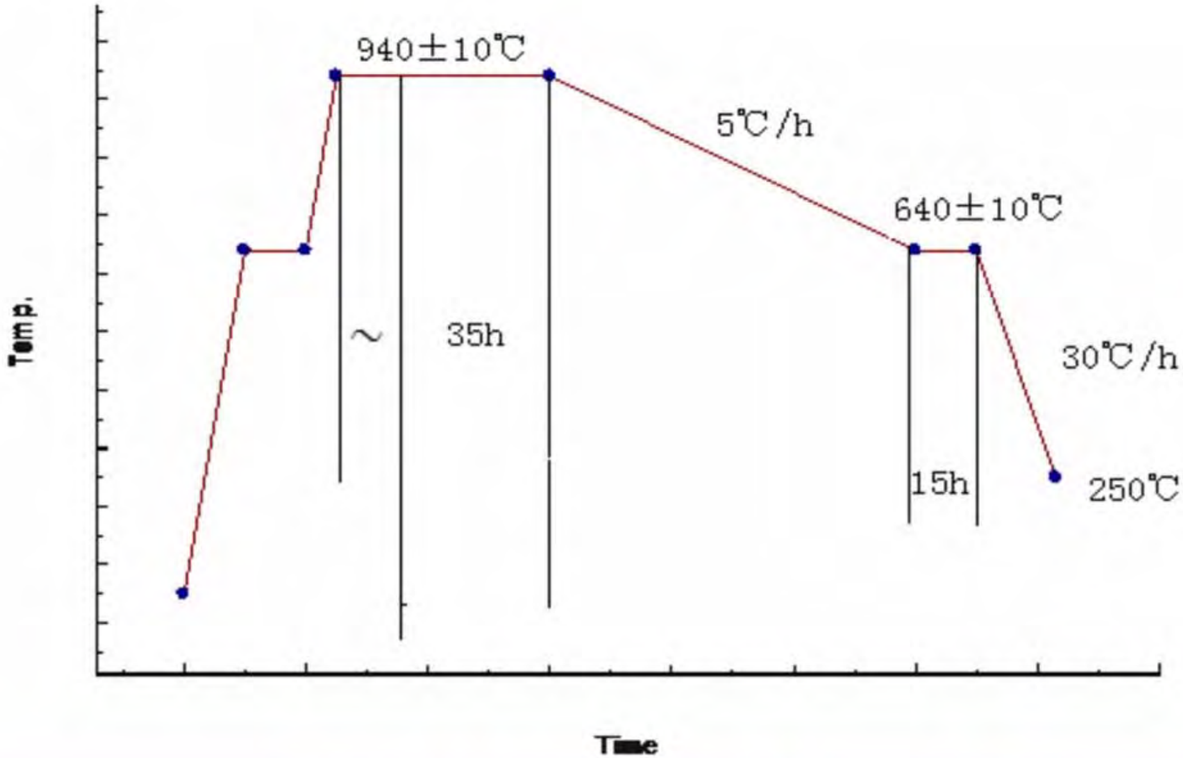
2. CONSTRUCTION PROGRESS

– Magnet

Magnetic annealing
for casting piece

Tmax=940℃

ΔT=5℃



2. Magnet, Imperfection and tolerance

1. The four sectors are uniformly distributed on the same circle. The magnetic pole face is left-right symmetric. The symmetric planes are through the vertical axis of the machine and are mutually perpendicular. The range for angular errors is 90 ° ±0.002 ° (The arc length is ±0.1mm at 2000mm of the outer radius).
2. After the sectors are installed, the magnetic pole face is on the theoretically designed surface. The requirement for the profile tolerance is 0.1mm.
3. Th error of slips shou ple).
4. Af aces could be chan eneral profile toler nteed that the profile tolerance of each magnetic pole surface is within 0.1mm, we could merely check the parallelism of the uniformed gap in the central region and the outer radius).
5. The upper and lower parts of the main magnet can be opened by hydraumatic for maintenance It is required that when it returns to its normal position, the position accuracy should be ± 0.02mm.
6. The roughness should be less then 3.2 μm for both the surfaces of the eight sectors and some specified portions of the yoke surfaces.

Tolerance: Hill gap, 0.1 mm.
Pole radius: 2 m, Weight: 435 t.

2. CONSTRUCTION PROGRESS

– Magnet

Comparison of the tolerance requirement of hill gaps for different cyclotrons

2. CONSTRUCTION PROGRESS

– Magnet

- The steel for the poles is contracted with Industeel in Lyon, France. And will be shipped to Tianjin Port, China in Nov. 2007.
- The casting piece and rough machining are contracted with CITIC Heavy Machinery Co. Ltd. in Luoyang, China. And will be finished by Apr. 2008.

2. CONSTRUCTION PROGRESS

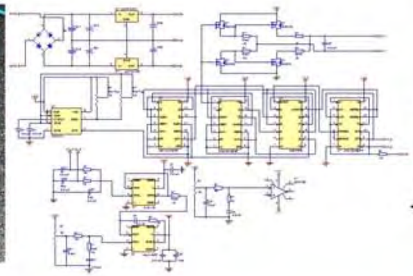
– RF System and Others

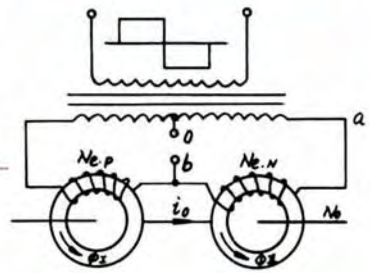
- Finished the construction design of two 100kW RF amplifiers and the power transportation system,
- the tendering and bidding work,
- and signed the contract with China Aerospace Science and Industry Corporation for the collaborative fabrication of relevant devices.
- The construction of the RF power system will be finished by Dec. 2008.

2. CONSTRUCTION PROGRESS

– RF System and Others

- The construction of various other items, e.g. the ion source, the double-wire scanner and DCCT for beam diagnostics are conducted.





Plan of Talk

A: DESIGN HIGHLIGHT

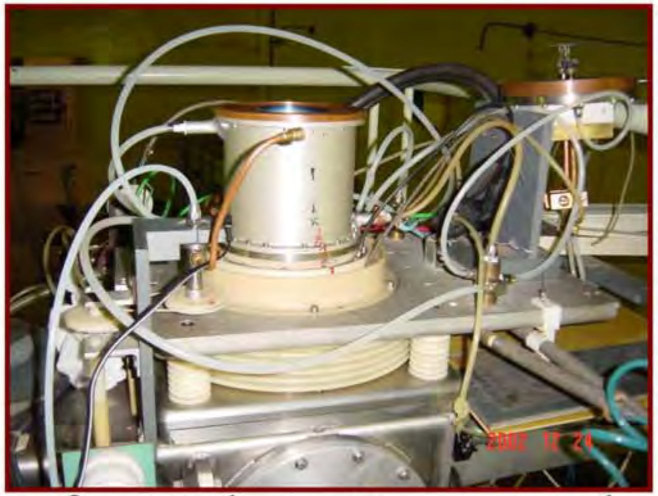
- Magnet
- RF
- Source, Injection and Central Region
- Extraction
- Beam Lines / Beam Dump
- Vacuum system and other

B: CONSTRUCTION PROGRESS

- Magnet
- RF System
- Other

C: R&D

- H- Source
- Central Region Model
- RF Cavity & LLRF



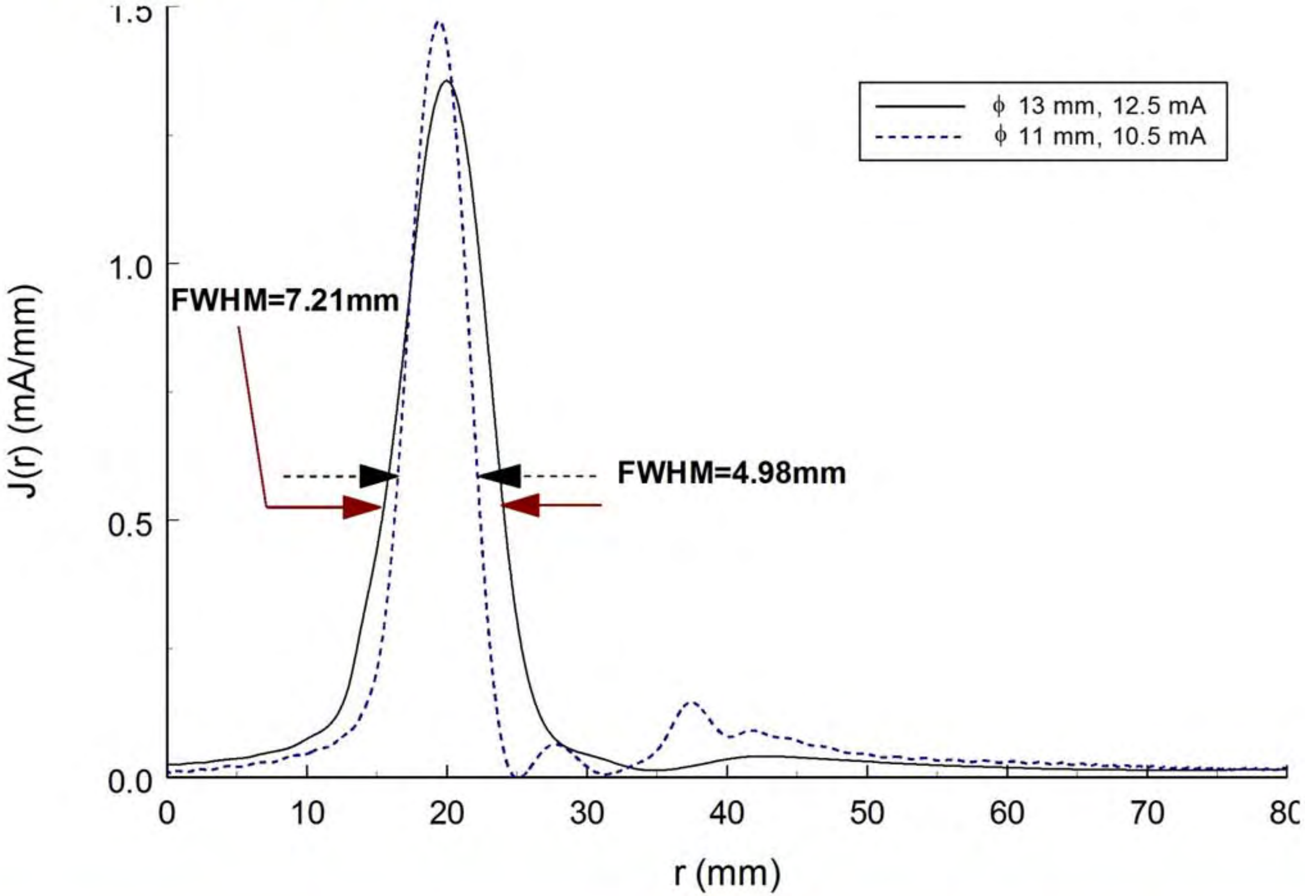
3. R & D

– H- Ion Source

- To optimize the injection efficiency from the source to the cyclotron central region, a cusp source was developed at CIAE since 2002.
- **The design of this new source is based on TRIUMF's experience.**
- More than 10 mA of beam with a measured emittance of 0.65 π mm mrad is obtained at a voltage of 28 kV from an extraction hole of 11 mm in diameter.

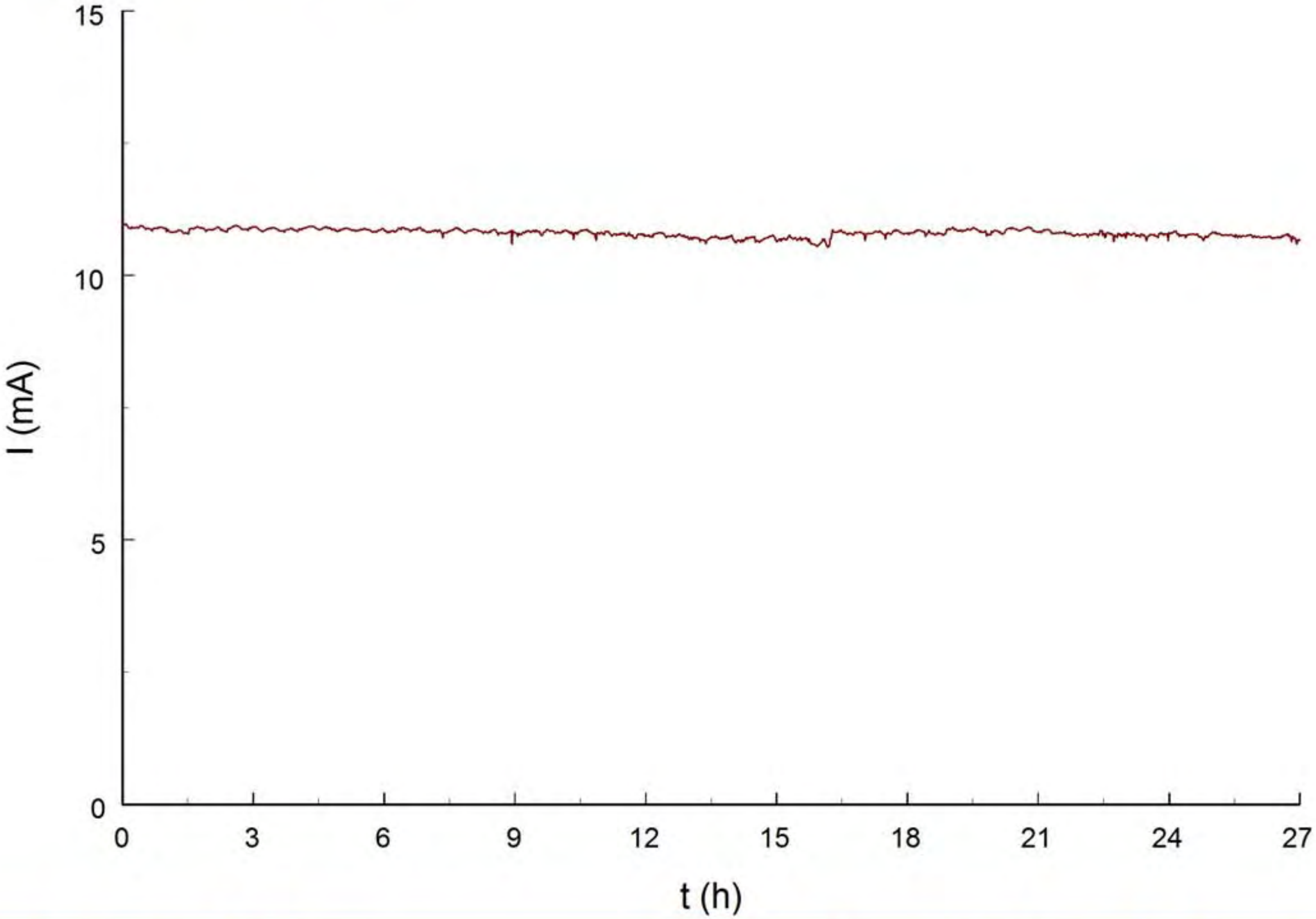
3. R & D

– H- Ion Source



3. R & D

– H- Ion Source



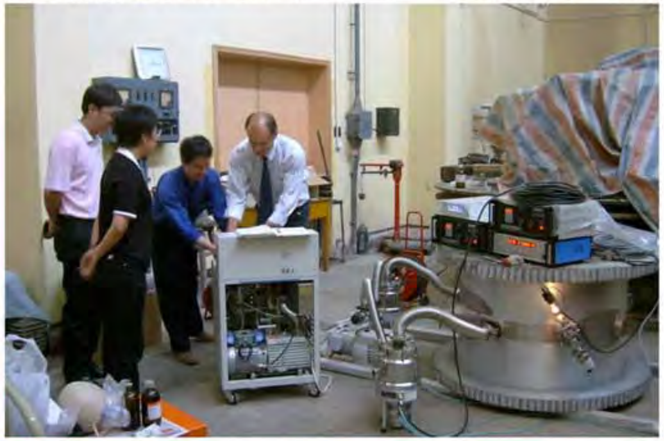
3. R & D

– H- Ion Source

- Recently, a new source is being development in CIAE.
- The body of the source is fabricated. But some of the detail has to be modified further.
- And a new test stand for the new source is under construction since the old one was used for the CRM cyclotron.

3. R & D

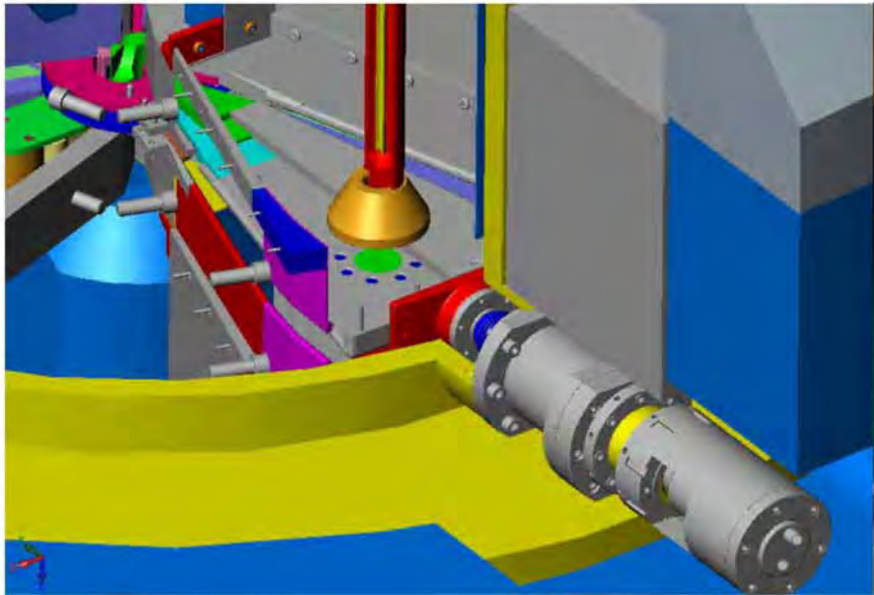
– CRM (Central region model) Cyclotron

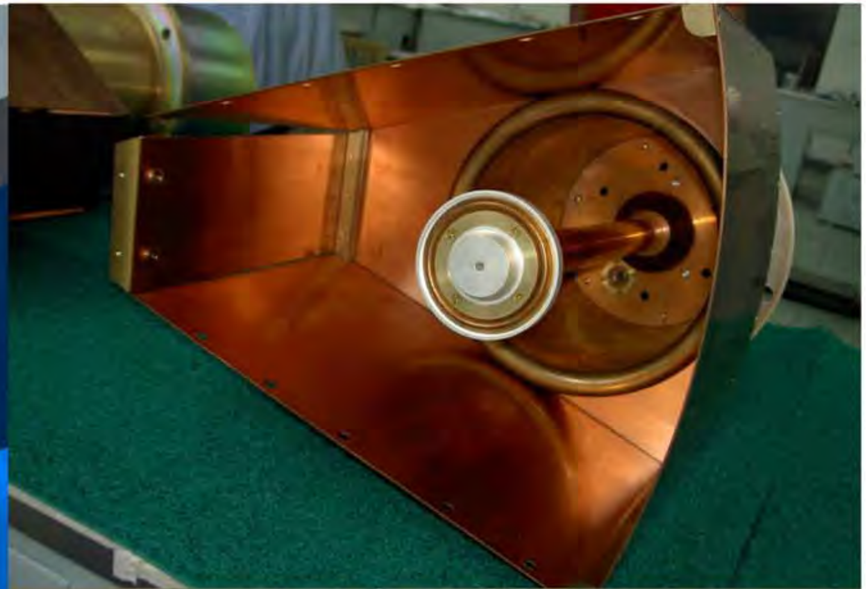


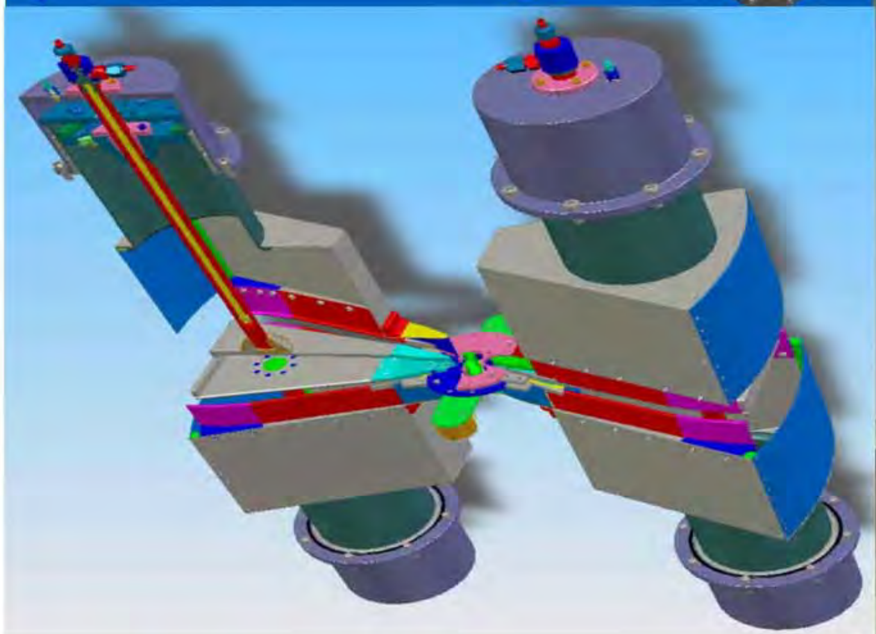
A central region model (CRM) is specially designed to confirm the design results and test various aspects of techniques, which will be used for CYCIAE-100.

CYCIAE-100, a 100 MeV H- Cyclotron for RIB Production

3

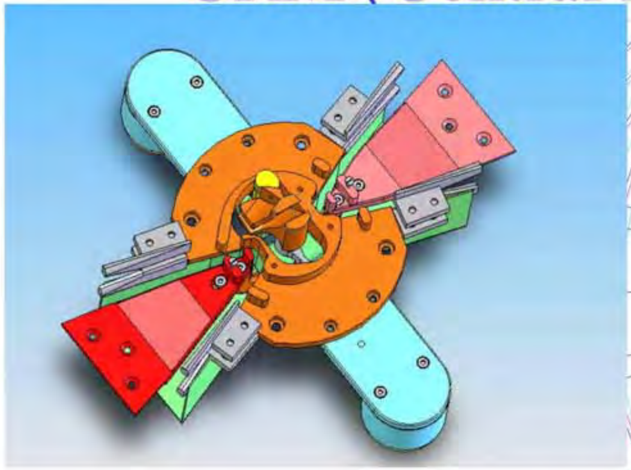


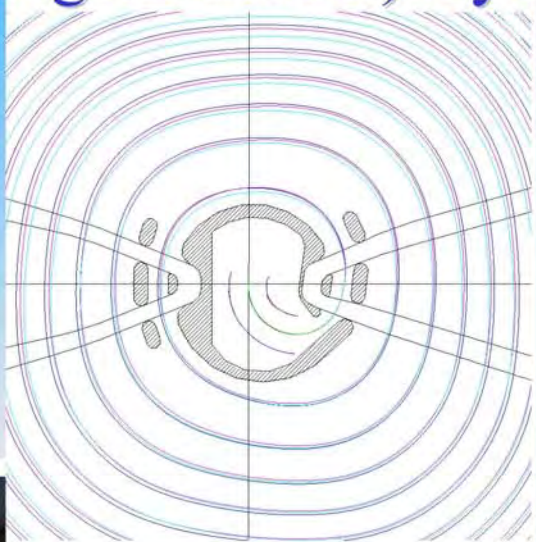


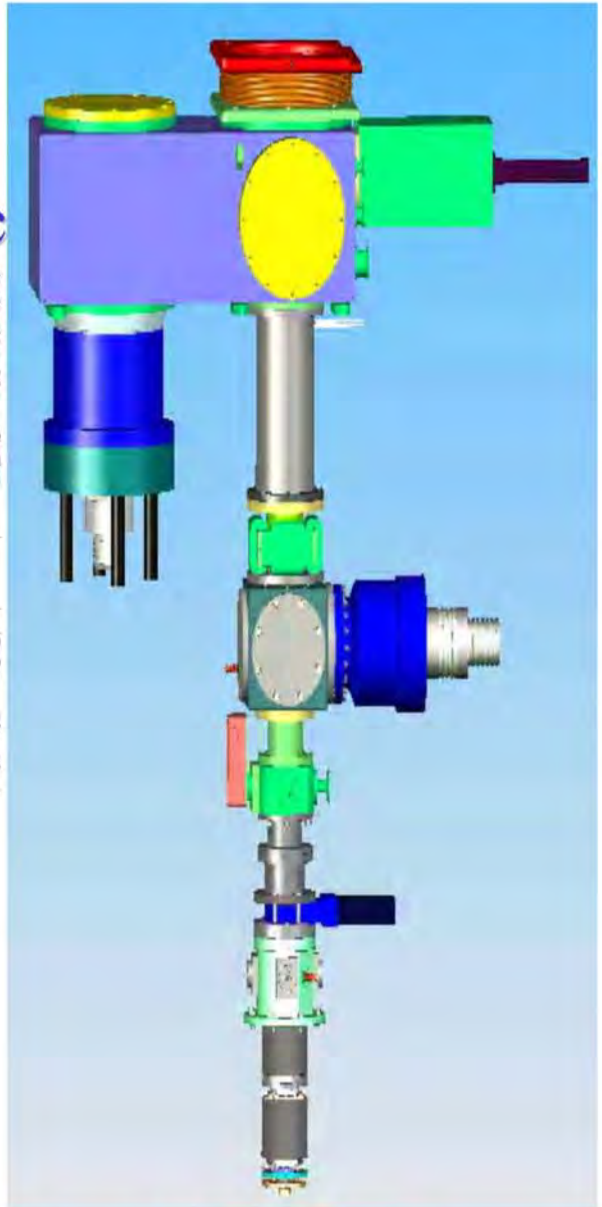


3. R & D

- CRM (Central region model) Cyc

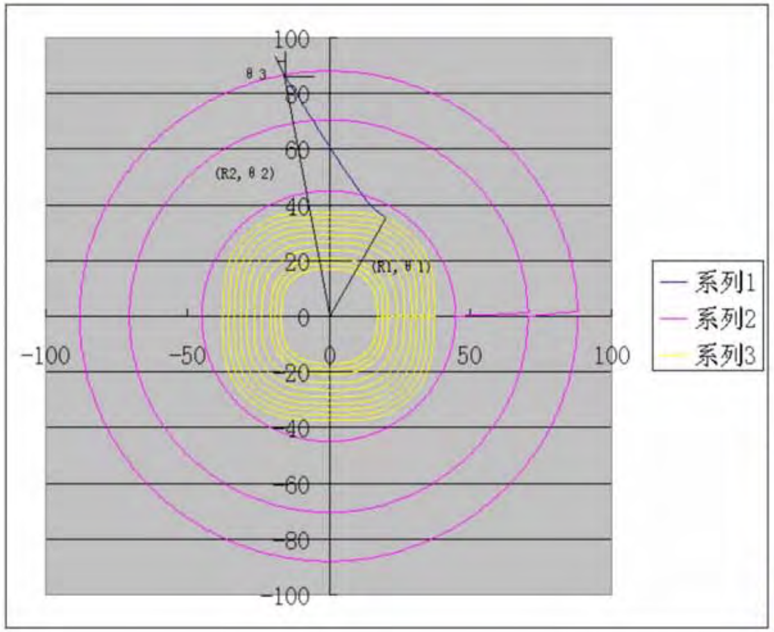






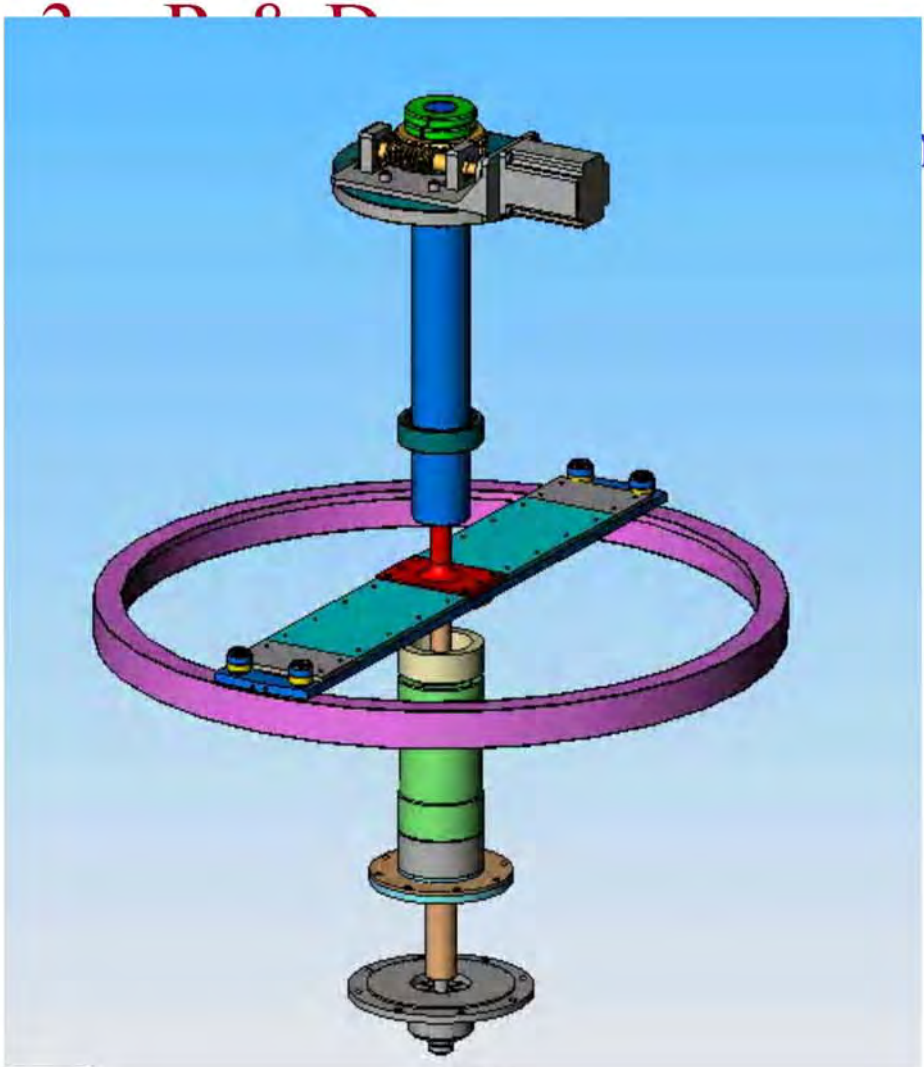
3. R & D

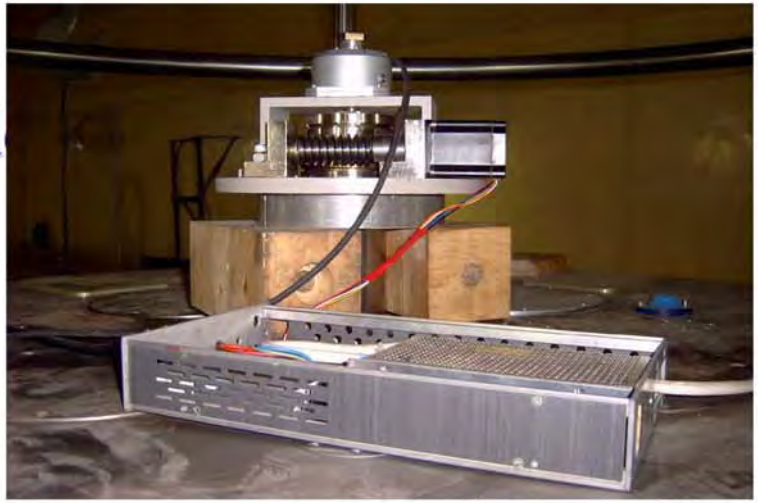
– CRM (Central region model) Cyclotron



3. R & D

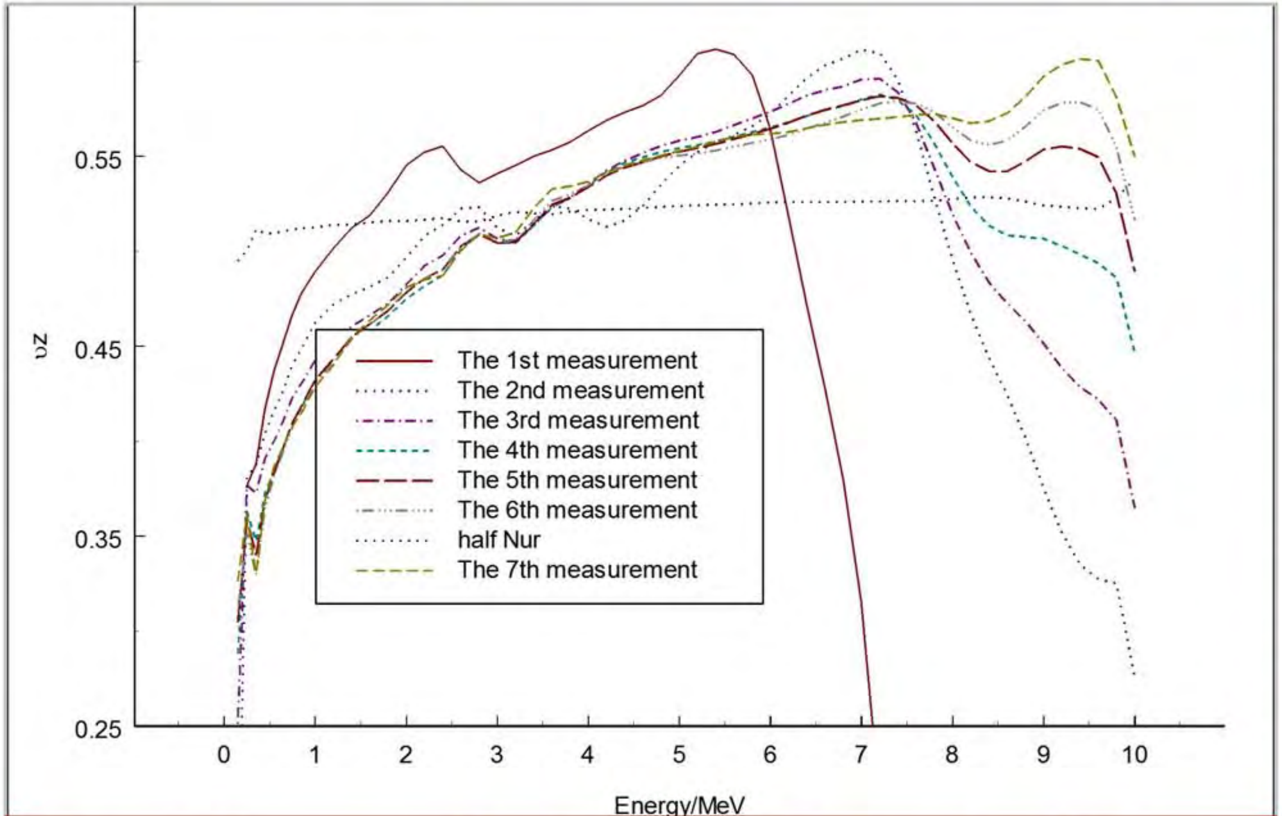
- CRM (Central region model) Cyclotron





3. R & D

– CRM (Central region model) Cyclotron



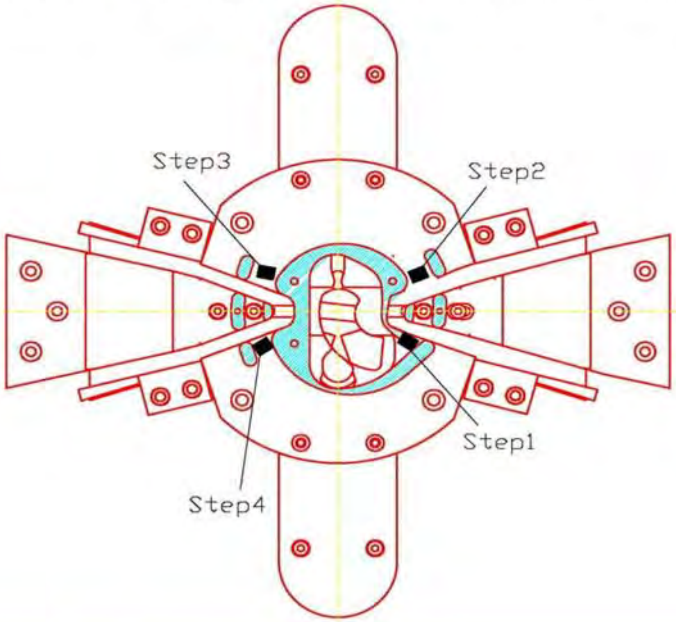
Tune Diagram, Vz increased, Varying hill gap

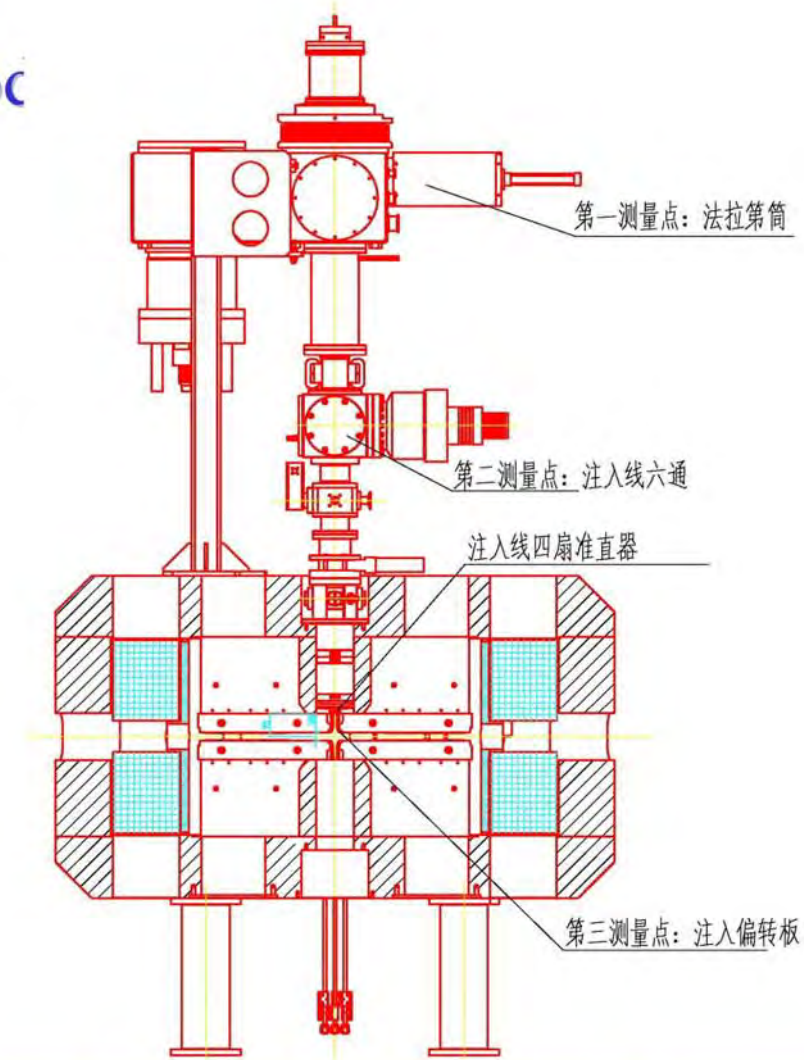
we investigated a new method for the 1st harmonic shimming. The effectiveness of this method was verified in the magnetic field shimming of CRM Cyclotron and consequently reduced the technical requirement for the top/bottom and return yokes.

3. R & D

- CRM (Central region moc

The beam was measured at the exit of the ion source, Faraday Cup on the injection line, inflector, and 4 steps in the central region.

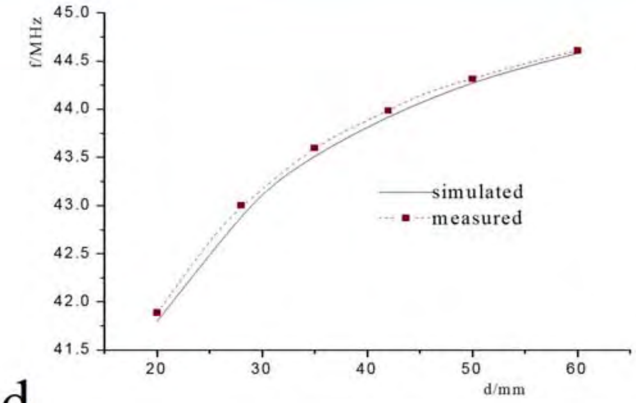




3. R & D

– CRM (Central region model) Cyclotron

- The low intensity beam was used for transmission test.
- After 700 μA beam extracted from the source, it was cut to 550 μA by a collimator.
- Right after the outlet of the spiral inflector, 500 μA (**94%**) beam was measured.
- After the RF acceleration, **60 μA** was obtained without the buncher.
- It can be estimated that the RF acceptance is about **42°**. Recently, we are working to improve the RF amplifier to couple more power into the cavity.

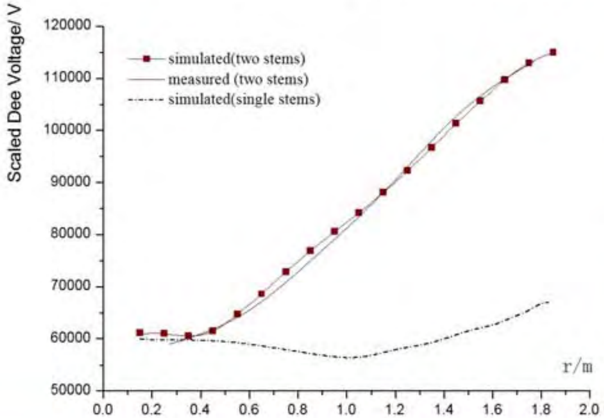


3. R & D

– RF System

Model cavity

- A 1:1 scale wooden model was fabricated.
- The resonant frequency, matching, accelerating voltage, etc. were measured and compared with the design value. The error between them is about **5% for Dee voltage** and 1% for frequency, respectively.



3. R & D

– RF System

LLRF Control

Close loop tests for 1st proto type boards have been successfully conducted in July 2006.

The phase stability is better than 0.3°, and the amplitude stability is better than 2‰.

SUMMARY

- A compact H- cyclotron is designed as the driving accelerator for the project BRIF in Beijing.
- It will provide a 75 MeV - 100 MeV, 200 μA - 500 μA proton beam for RIB generation and other application with proton directly.
- Most of the engineering designs are finished.
- The main magnet and the RF System are under construction.
- Several R & D, including a CRM Cyclotron are carried out for the experimental verification for the design of CYCIAE-100.

Acknowledgement

- The authors are very much grateful to the scientists in **TRIUMF** such as Drs. Gerardo Dutto, Michael Craddock, Paul Schmor, Philip Gardner and Roger Poirer, have rendered considerable help and given valuable advice as well as providing materials concerning the cyclotron under design.
- Moreover, the visiting scientists, Drs. Gerardo Dutto, George Mackenzie, Rick Baartman, Bruce Milton, Yuri Bylinsky, Ken Fong, Tom Kuo, Yi-Nong Rao, etc., have made outstanding contributions to this project during their stay at CIAE.
- We also would like to extend our cordial gratitude to Dr. Peter Sigg and Dr. Werner Joho from **PSI**, and Dr. Luciano Calabretta from **LNS**, for their very helpful work at CIAE and their long-term support on the project.

Welcome to visit CIAE

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