China ADS Linac R&D Progress

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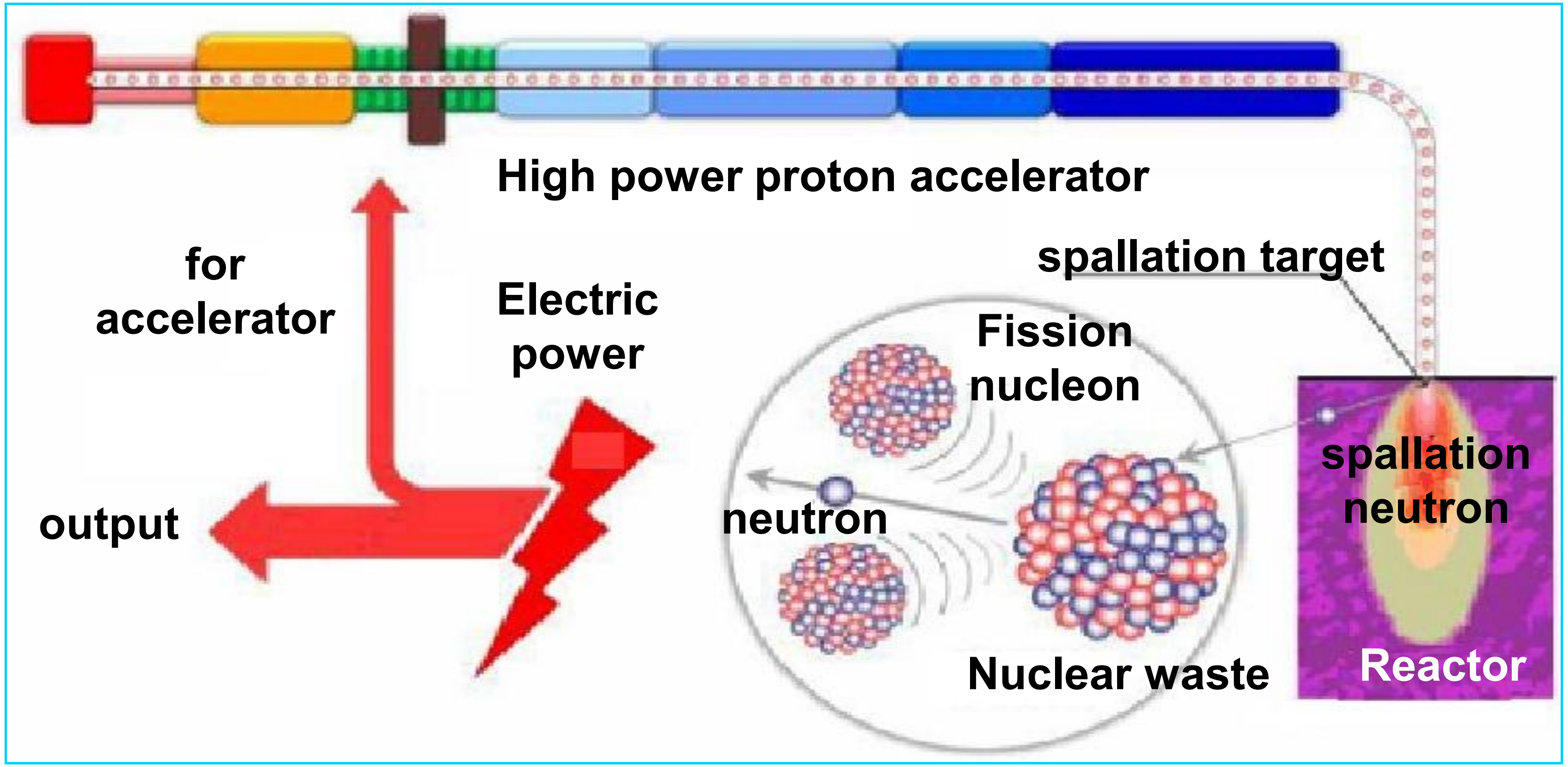
Outline

- Brief introduction of China ADS Linac and R&D program
- R&D progress of China ADS Linac
  - 10 MeV Injector I and Injector II
  - Proton source and LEBT
  - Injector I RFQ and Injector II RFQ
  - Injector I Spoke012 and Injector II HWR010
  - Main Linac Cavity prototypes
  - Cryomodules for Injector I and Injector II
  - SRF Infrastructure
- Summary

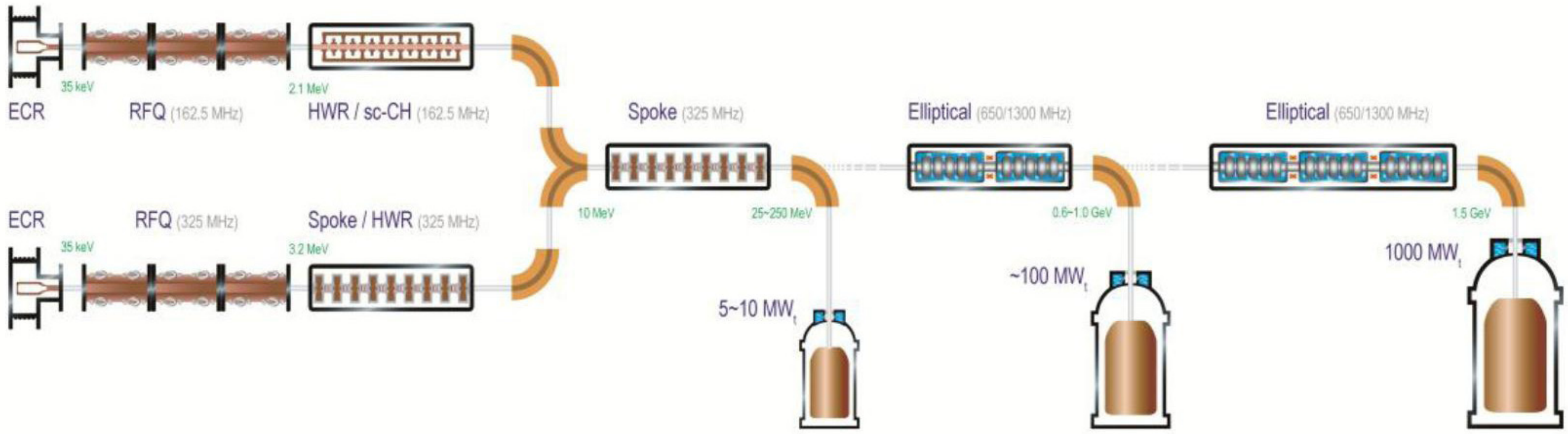
China ADS Motivation

- Accelerator Driven System was proposed for
  - Nuclear Waste Transmutation – rapid development of NPP in China. 10% in 2030
  - Accelerator Driven Thorium Reactor (ADTR)
  - Isotopes Production … (ex. ISOL RIA)



China ADS Roadmap

2011 2016 2023 203x



1st Phase
R&D

2st Phase
CIADS

3rd Phase
RESEARCH FACILITY

4th Phase
DEMO FACILITY

CIADS: INITIAL FACILITY

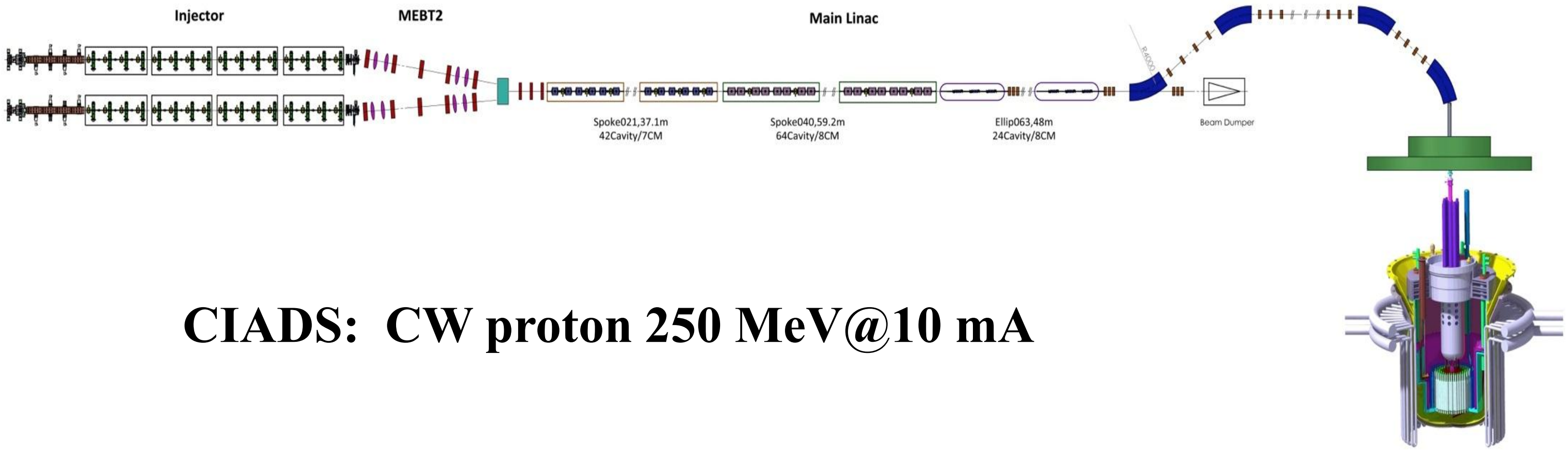
25MeV@3-10 mA

250MeV@10mA

1.5 GeV@10 mA

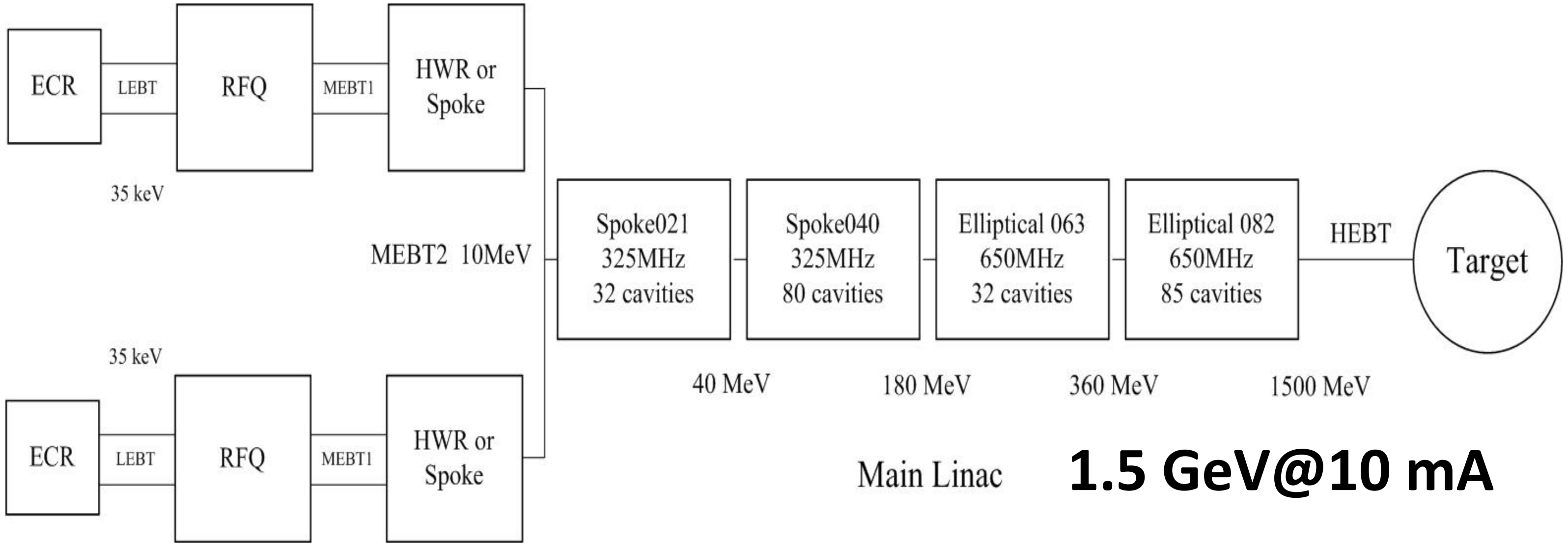
Configuration of China-ADS Linac

2nd Phase



CIADS: CW proton 250 MeV@10 mA

3rd Phase



1.5 GeV@10 mA

Challenges of ADS Linac

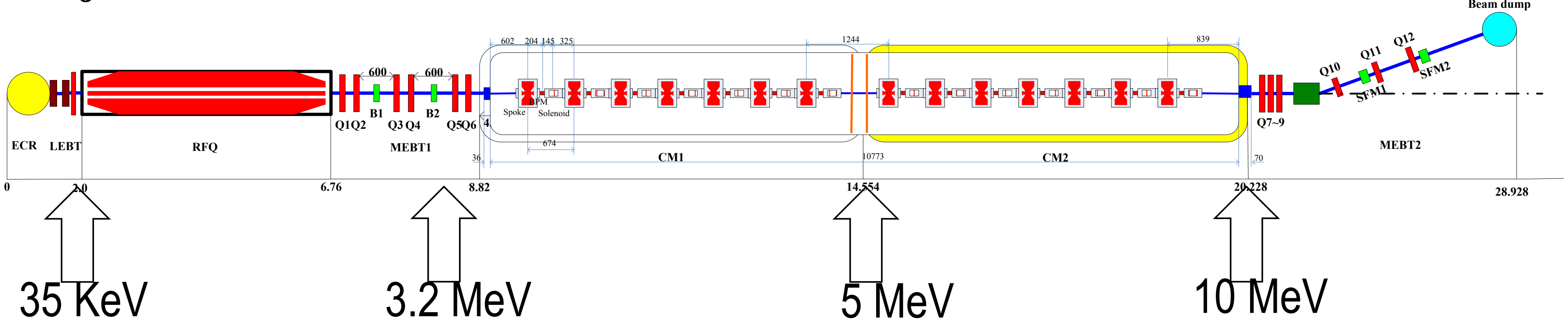
- Beam loss : Causes of beam loss, beam loss detection and control
- Beam trip and failure
- Rapid recovery after beam trip or failure
- High power beam commissioning and machine protection
- Fault-tolerance design and reliability-orientated design
- Operation with high reliability and high availability
- …..

10MeV injector – Different technology R&D

Injector I

Based on 325 MHz Spoke012

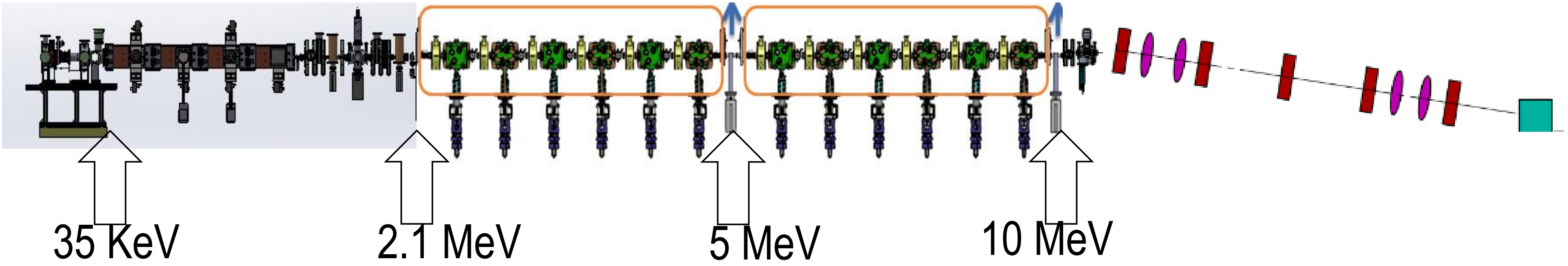
IHEP/Beijing



IMP/Lanzhou

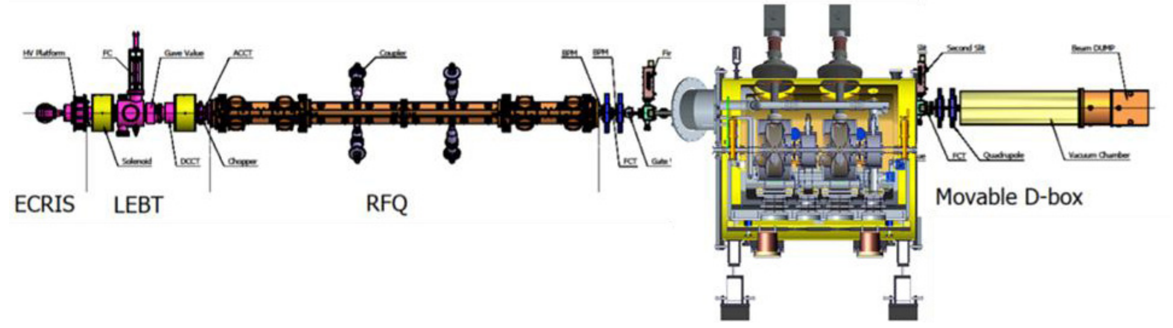
Injector II

Based on 162.5MHz HWR010



10 MeV injector I strategy — (IHEP)

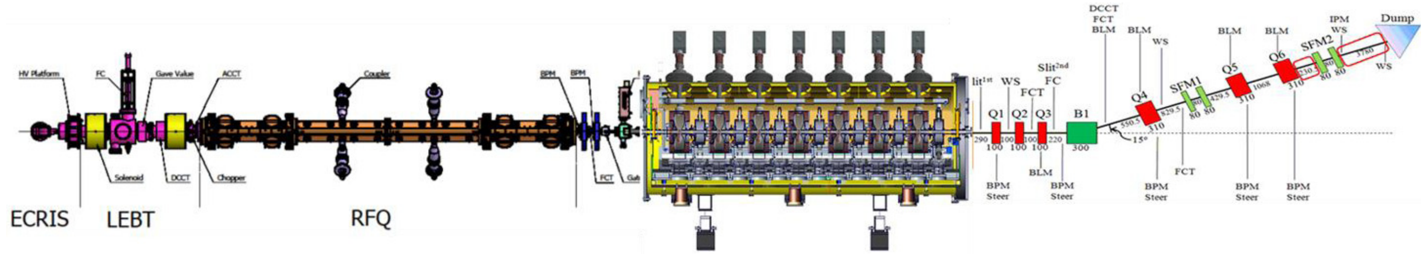
1



325 MHz Spoke012

- ECRIS + LEBT + RFQ + MEBT + TCM2, 3.6 MeV
- RFQ commissioning, validate CM design.
- Ongoing, beam commissioning in 2014

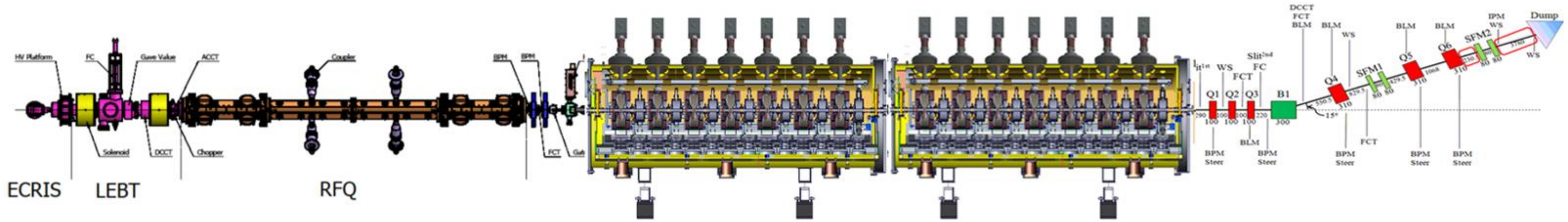
2



325 MHz Spoke012

- ECRIS+LEBT+RFQ+MEBT+CM7
- 5 MeV
- Beam commissioning in March 2015

3

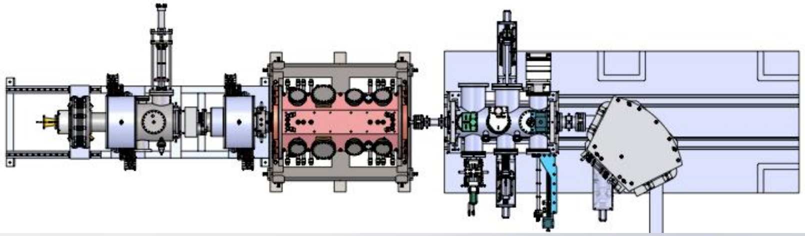


325 MHz Spoke012

- ECRIS + LEBT + RFQ + MEBT + 2xCM7 +HEBT
- 10 MeV
- Dec. 2015--Feb.2016

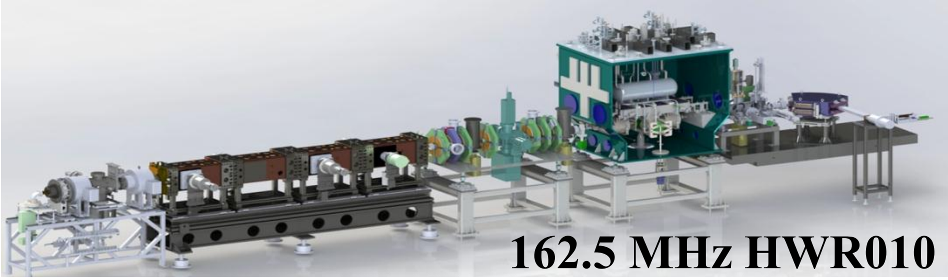
10 MeV injector II strategy — step by step (IMP)

1



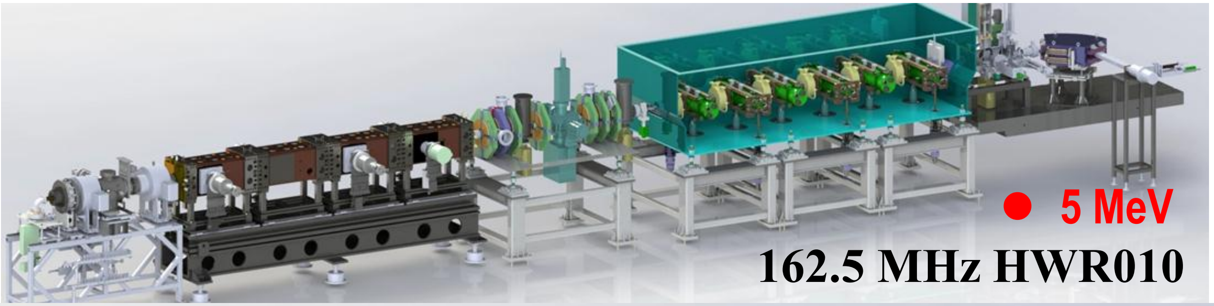
- ECRIS + LEBT + 560keV RFQ prototype
- Validate LIS+LEBT+RFQ design. Learn experiences.
- Completed, 2013

2



- ECRIS + LEBT + RFQ + MEBT + TCM1, 2.5 MeV
- RFQ commissioning, validate CM design.
- Ongoing, beam commissioning in Sept. 2014

3



- ECRIS+LEBT+RFQ+MEBT+CM6,
- 5 MeV
- Beam commissioning in March 2015

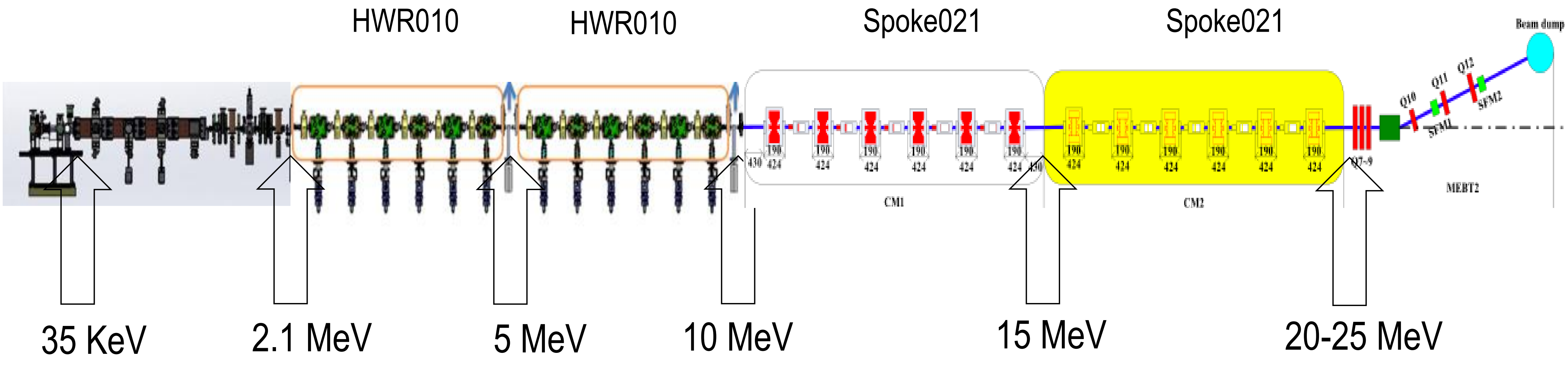
4

- ECRIS + LEBT + RFQ + MEBT + 2xCM6 +HEBT
- 10 MeV
- Dec. 2015—Feb. 2016

The 1st phase: R&D goal (2016-2017)

IHEP+IMP

- **Build 20-25 MeV@3 mA CW proton SC linac to learn technology of intense beam SC linac**
- **R&D for 250 MeV@10 mA CIADS linac**
- **Study the challenging issues based on construction and operation of the 25 MeV@3 mA linac**

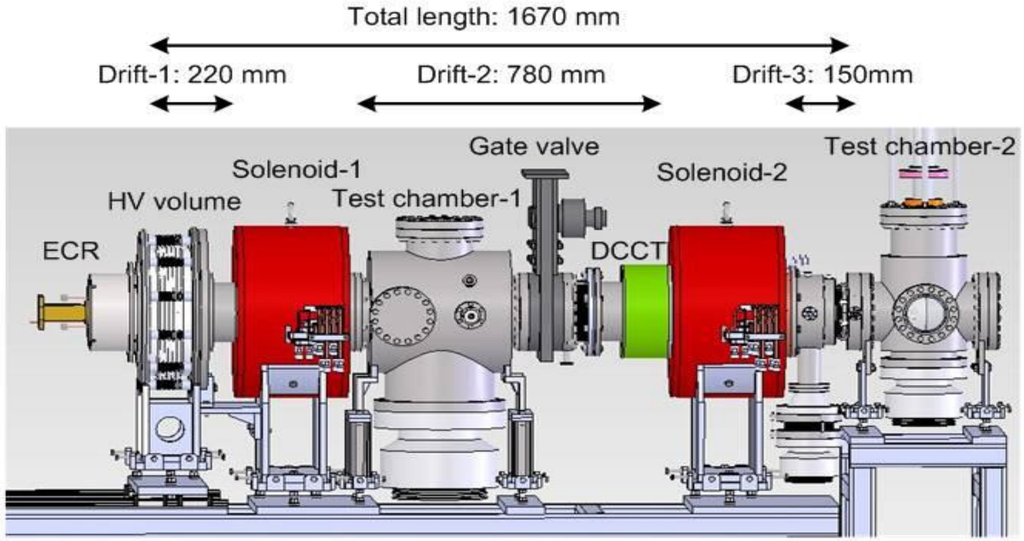


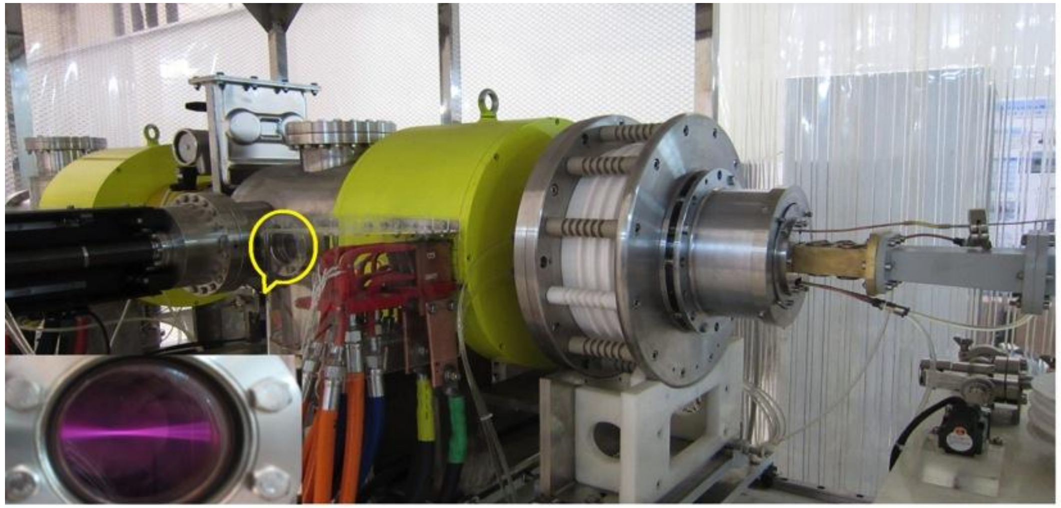
162.5 MHz

325 MHz

20-25 MeV@3 mA

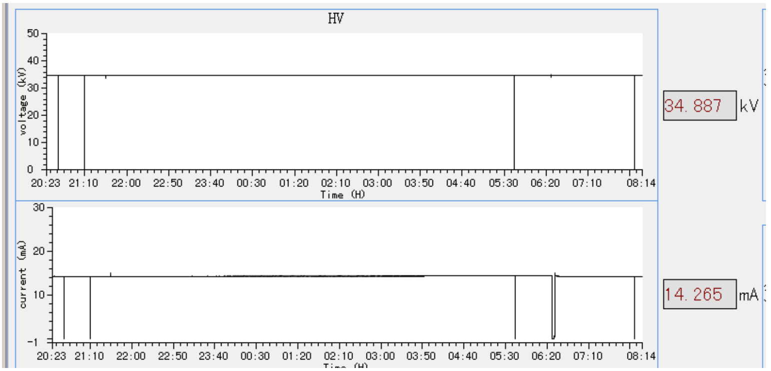
Proton source and LEBT

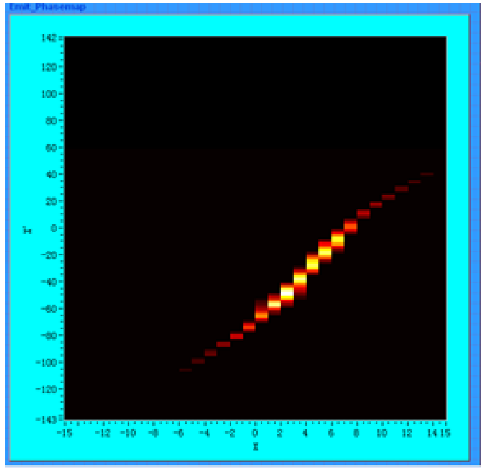




Two proton sources for Injector I and Injector II by IMP

35keV@14 mA, 12 hours

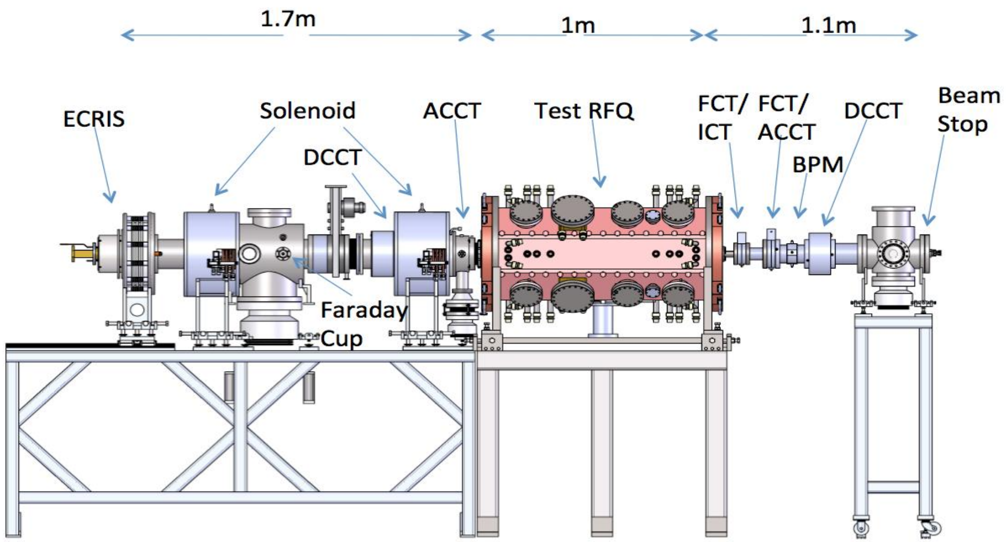


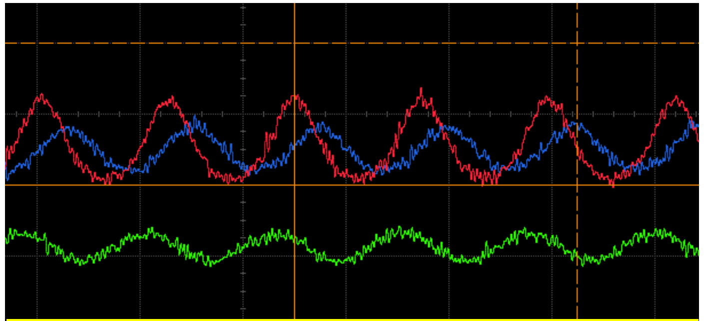


35keV@11.4 mA

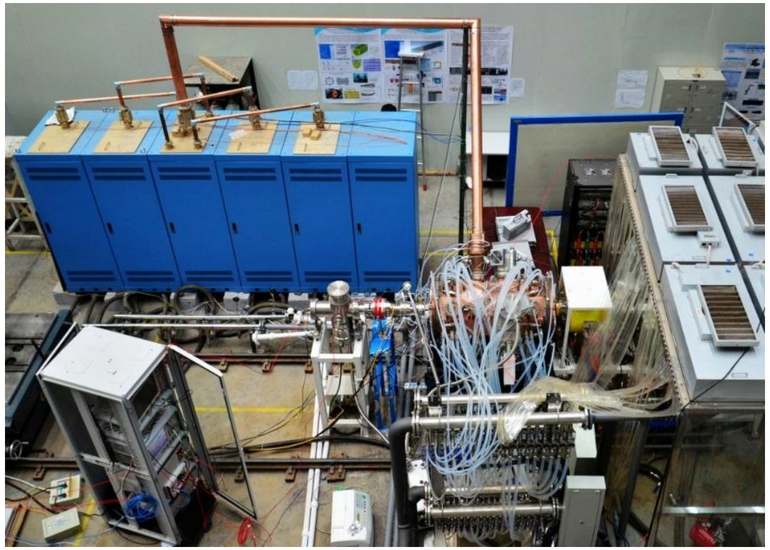
$\varepsilon_{n\text{-}rms}$=0.15 π mm.mrad

560keV 162.5MHz RFQ prototype at IMP

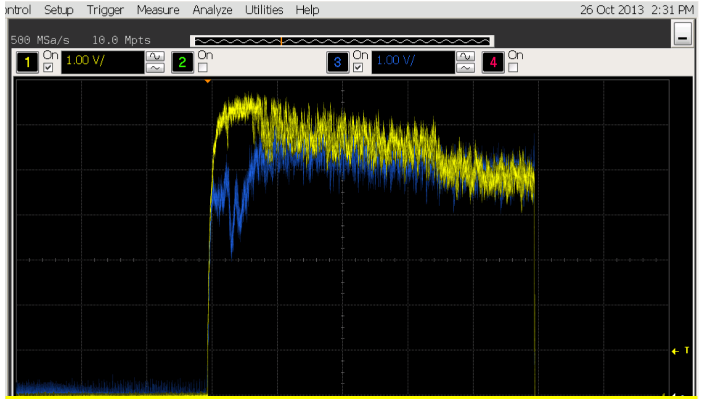




Signals on 2 FCTs, E=558keV



- August-Nov. 2013
- ECR-LEBT-560keV RFQ
- Beam commissioning
- CW 10.5 mA, 558 keV
- Transmission >90%。

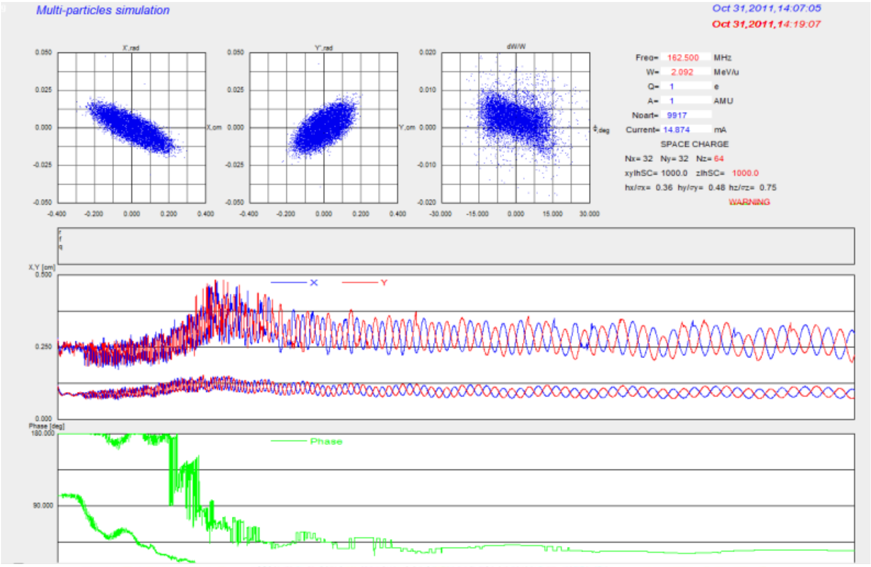


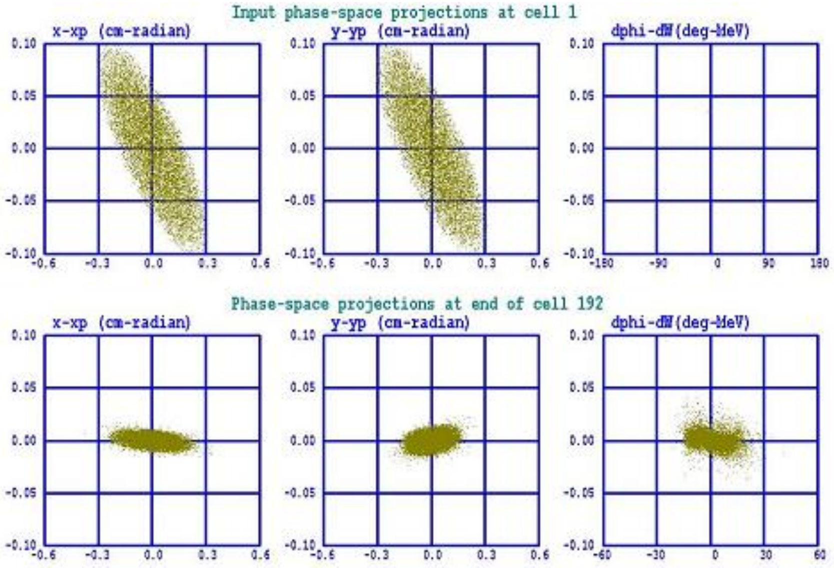
Signals on 2 DCCTs, η=91.7%

Injector II RFQ 162.5MHz

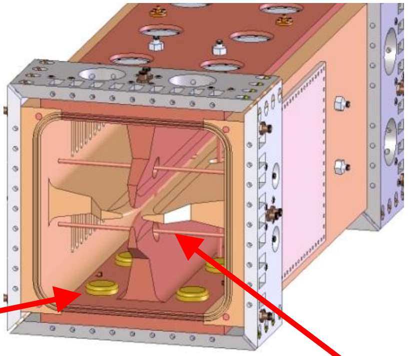
Collaboration IMP-LBNL

Parameter	Value
Ion species	Proton
frequency [MHz]	162.5
Inter-vane voltage V (kV)	65
Average bore radius r_0 (cm)	0.5731
Vane tip curvature (cm)	0.4298
ρ / r_0	0.75
Vane length / Total length (cm)	419.2 / 420.8
$m_{\max}$	2.38
Number of cells	192 (including 2 T cell)
Maximum surface field (MV/m)	15.7791
Synchronous phase (^{0})	from -90 to -22.7
$a_{\min}$ (cm)	0.3158
Transverse acceptance (RMS, x/y, πmm.mrad)	0.3/0.3
Input norm. RMS emittance (x/y, πmm.mrad)	0.3/0.3
Output norm. RMS emittance (x/y/z, πmm.mrad, keV.ns)	0.31/0.31/0.92
Overall beam transmission @ 0 /15 mA	99.7% / 99.6%

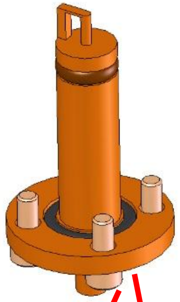




Injector II RFQ 162.5MHz Structure design

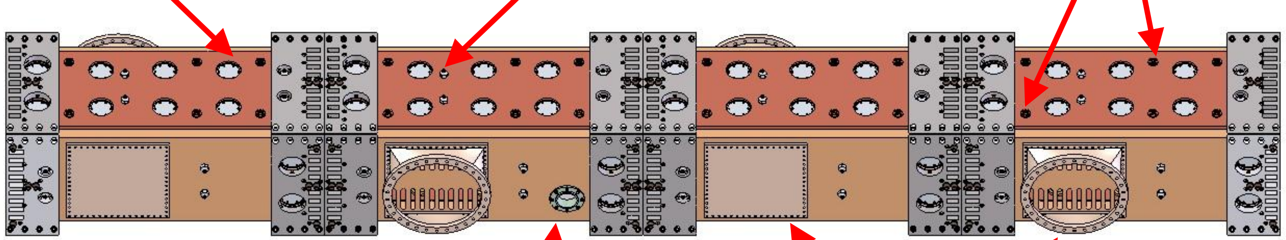


80 Tuners
Equal spaced
20 per module

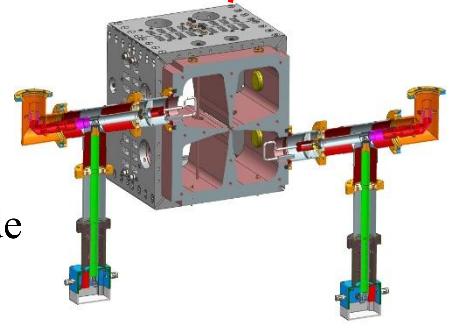


48 sensing
loop ports,
Regularly spaced

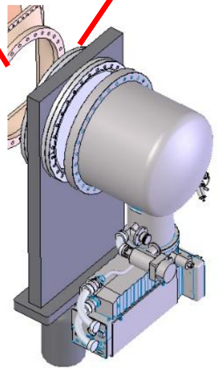
32 Pi-mode Rods
Equal space, 8 per module



Consists of four modules, each module is 1050mm long

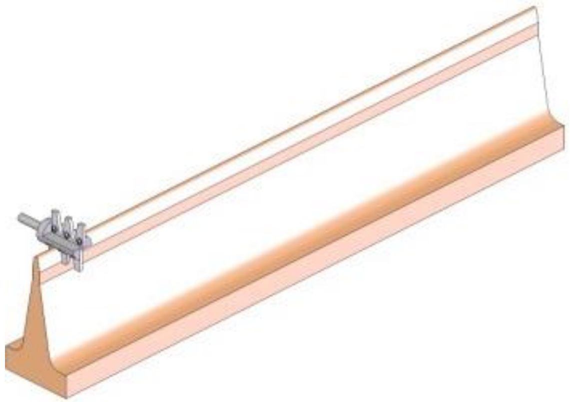


2 RF input ports
Both in Module 2
One near side, one far side

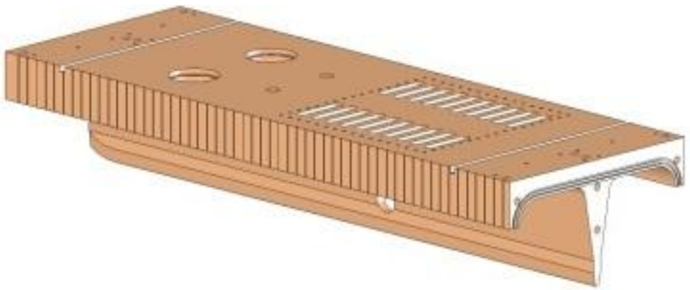


8 vacuum ports
Not all are used

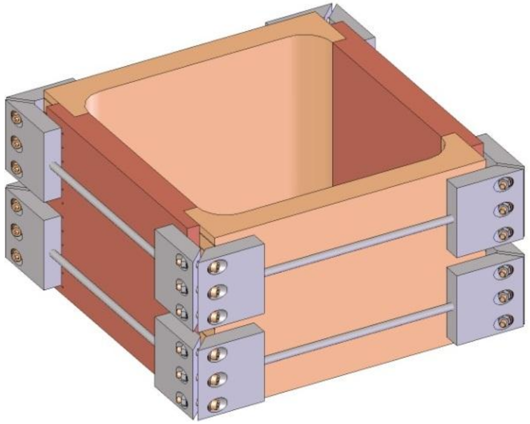
Injector II RFQ 162.5MHz 4 fabrication tests



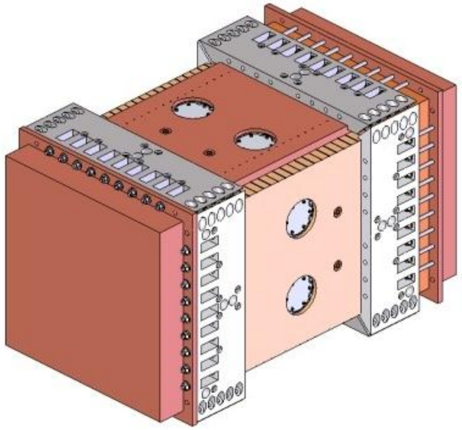
Vane cutting tool test



Full length vane fabrication test



Braze clamp test

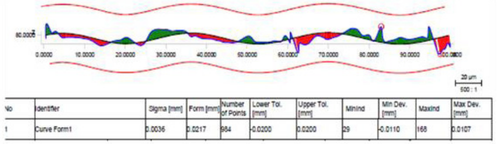


Test module

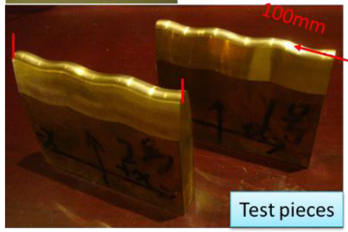
Injector II RFQ 162.5MHz

Test fabrication at IMP/Lanzhou

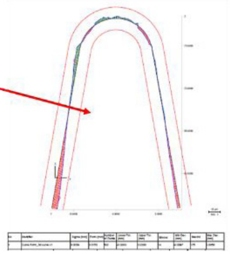
Flying cutter



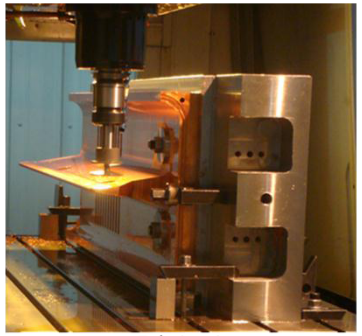
Modulation measurement (by CMM): Max. error. 0.0107mm



Test pieces



Profile measurement (by CMM): Max. error. 0.0056mm



Fabrication

CMM measurement

Upper deviation: 0.0200

Lower deviation: -0.0200

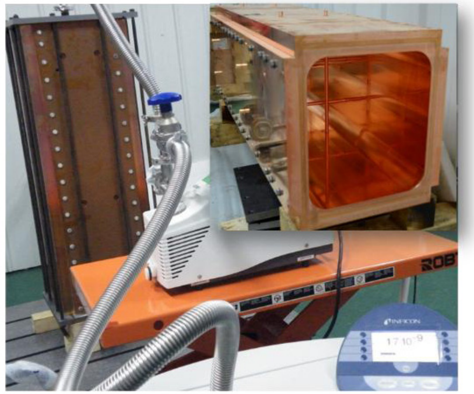
Max. deviation: 0.0272 (2)

Min. deviation: -0.0202 (562)

Max. fabrication error:0.0272mm

Brazing test was done in a hydrogen oven

hydrogen oven

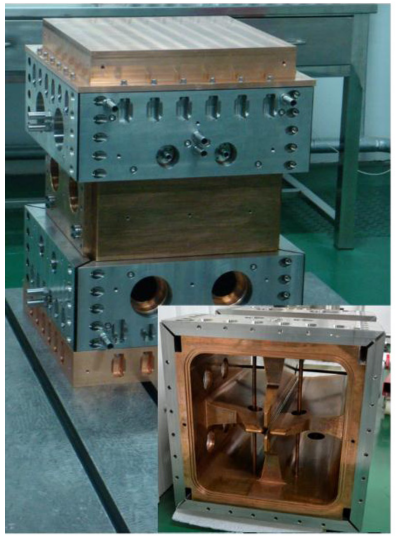


Vacuum test

Size (inner surface) of test piece: 250×290×1050

Leakage rate: < 1×10^{-9} Pa.L/S.

Maximum deformation before and after brazing is 0.037mm



A half length module was fabricated, comparison between test and simulation results was made

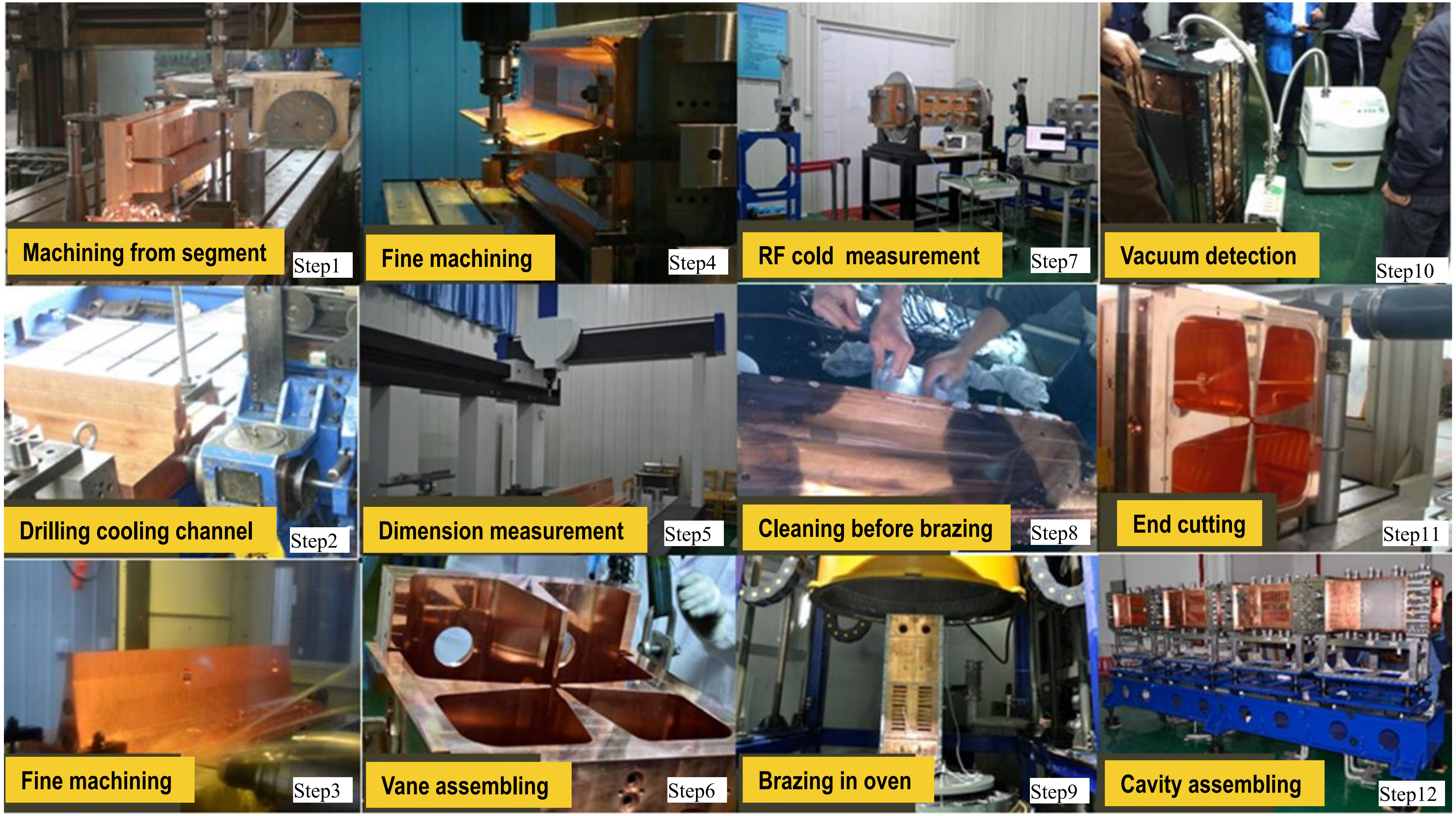
Frequencies with tuners inserting 0mm

	Simulation results	Measured results
Fq / MHz	164.339	163.951
Fd / MHz	189.040	188.223

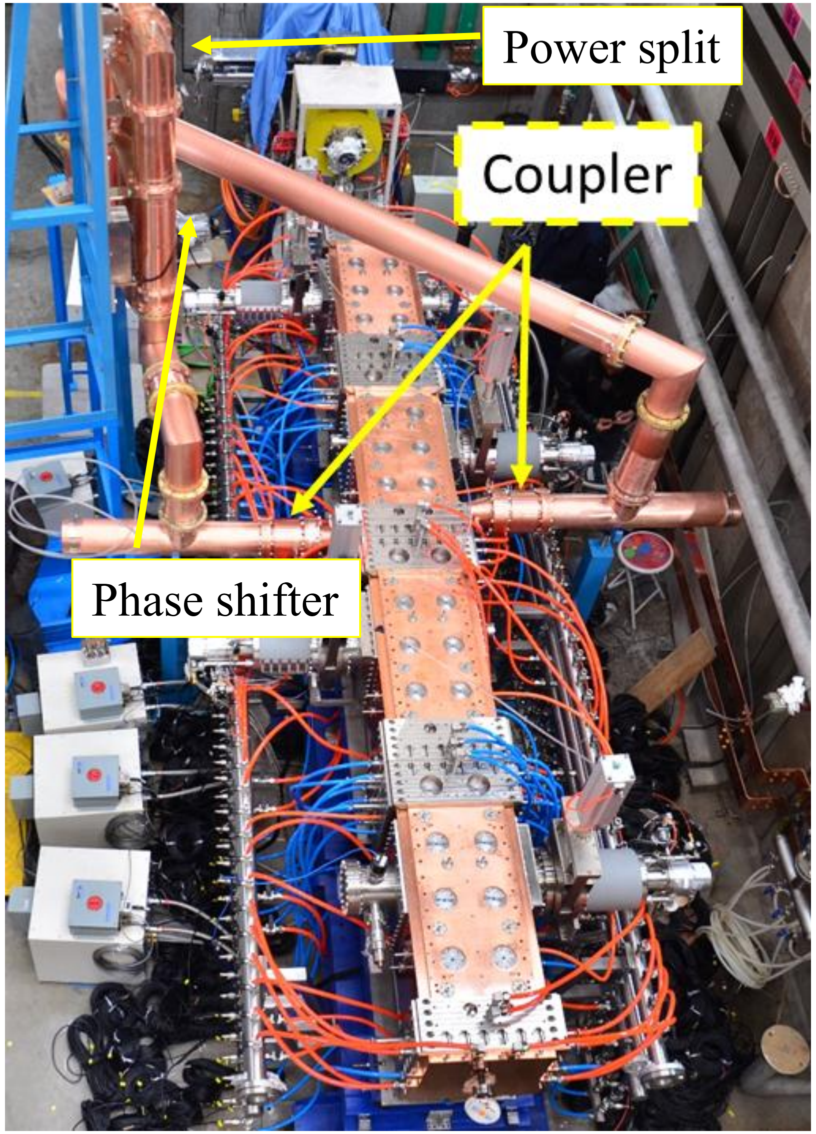
Frequencies with tuners inserting 20mm

	Simulation results	Measured results
Fq / MHz	165.769	165.349
Fd / MHz	190.252	189.386

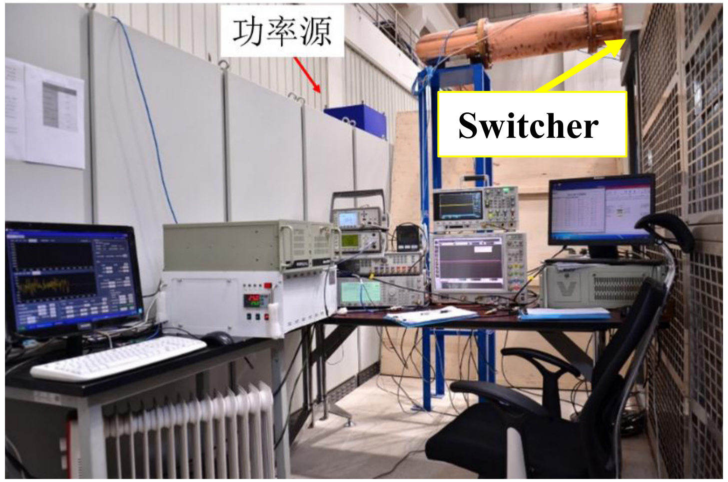
Injector II RFQ 162.5MHz Fabrication、brazing at IMP



Injector II RFQ 162.5MHz Assembling

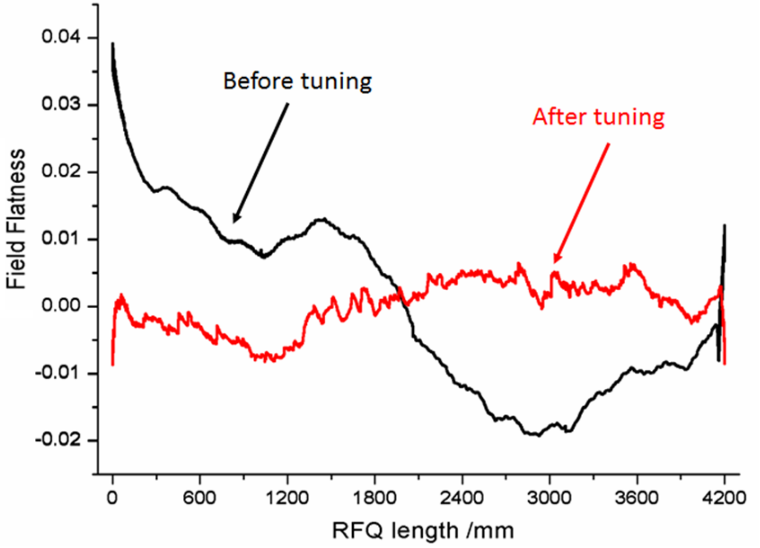


High power coupler

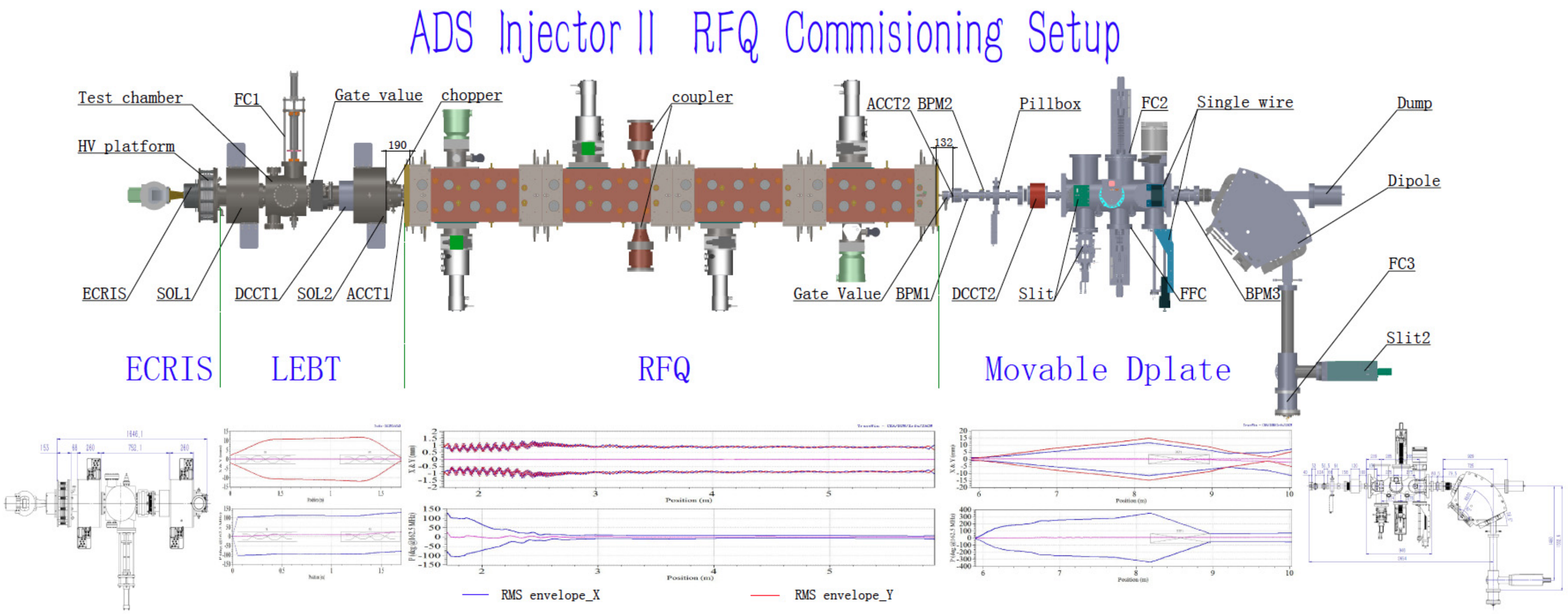


RF power source and control system

3.9% → 1%



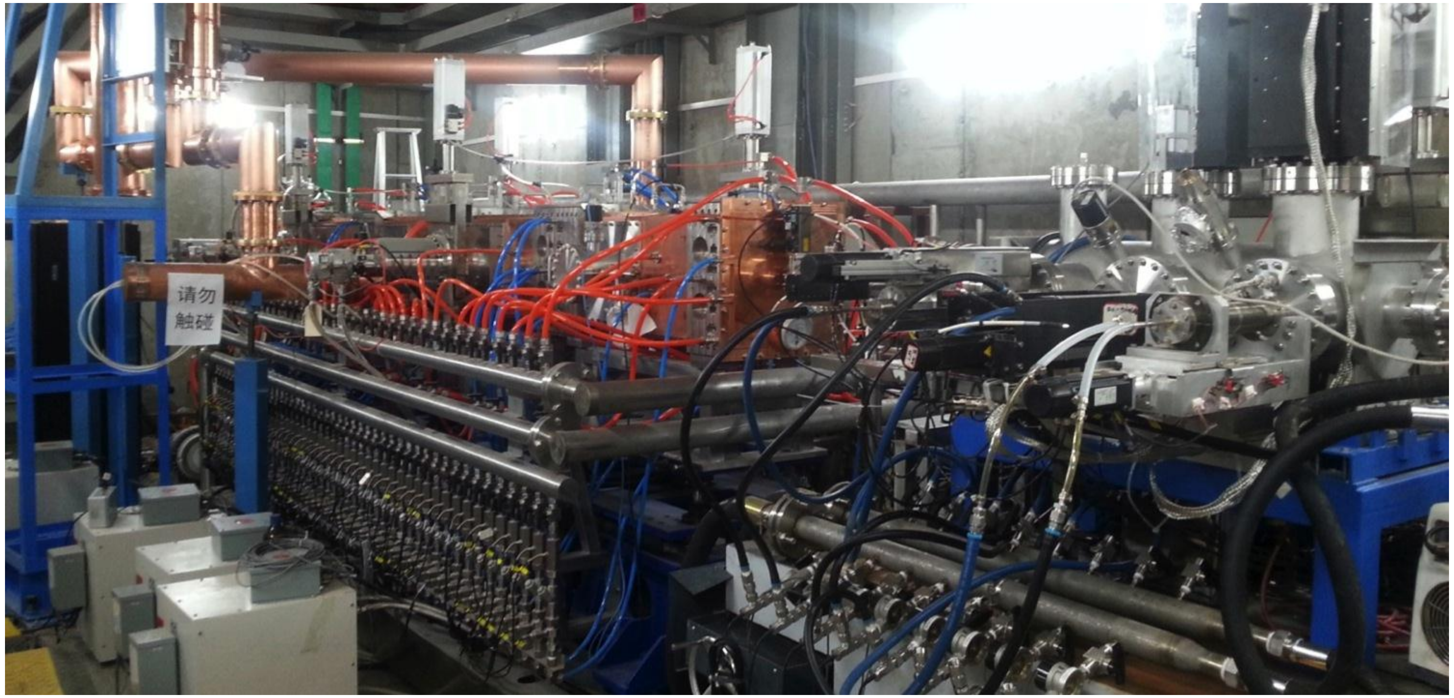
Injector II RFQ 162.5MHz Diagnostics



Diagnostics

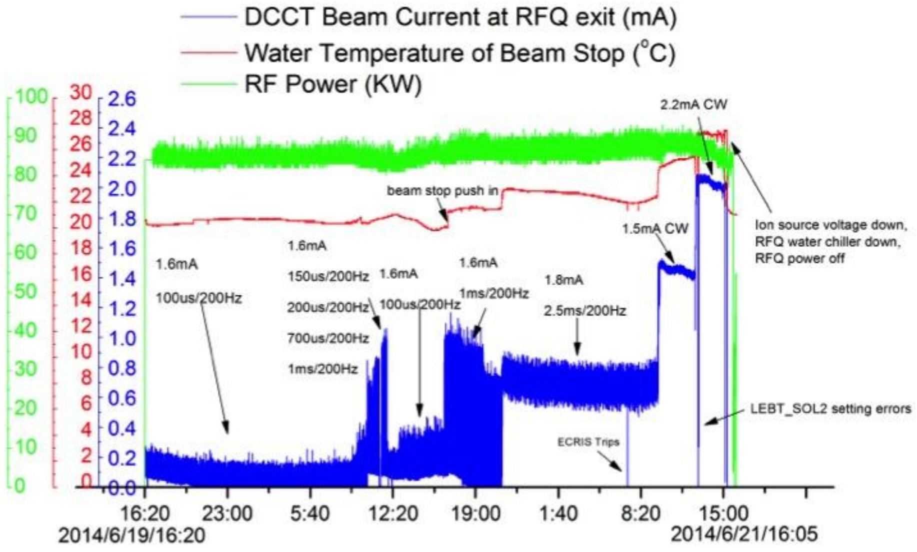
Energy: BPM1, BPM3, TOF
Energy spread: slit2, dipole, FC3
Emittance: slit1+wire scanner
Beam current: DCCT2, ACCT2
Transmission: ACCT1, ACCT2

Injector II RFQ 162.5MHz Commissioning



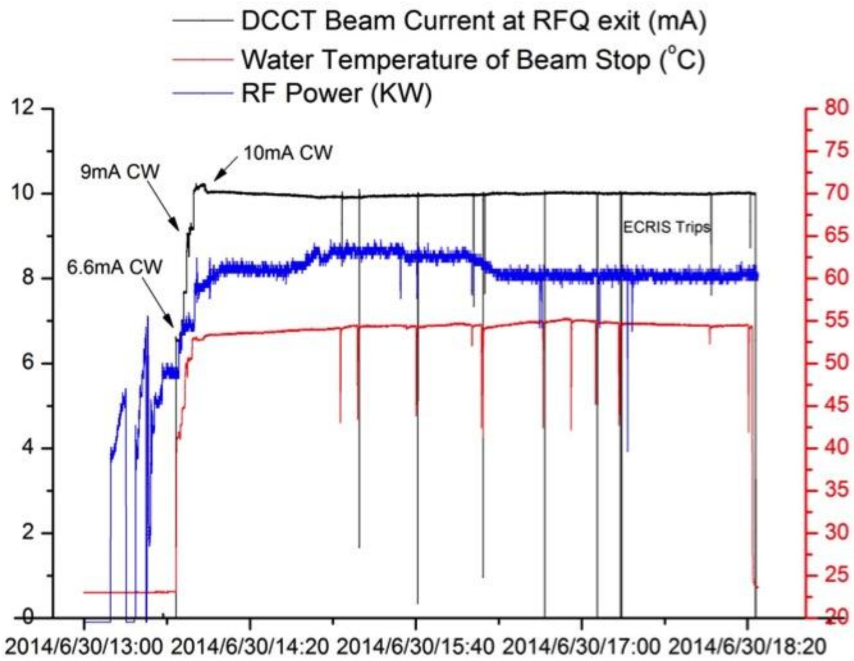
- April 2014: assembling completed
- May-June 2014: RF training
- June 12, 400ms/1Hz **pulsed beam 8mA**
- June 21 **CW** **2.2mA@2.5hours**
- June 30 **CW** **10mA@4.5 hours**

Injector II RFQ 162.5MHz CW 2-10 mA beam commissioning

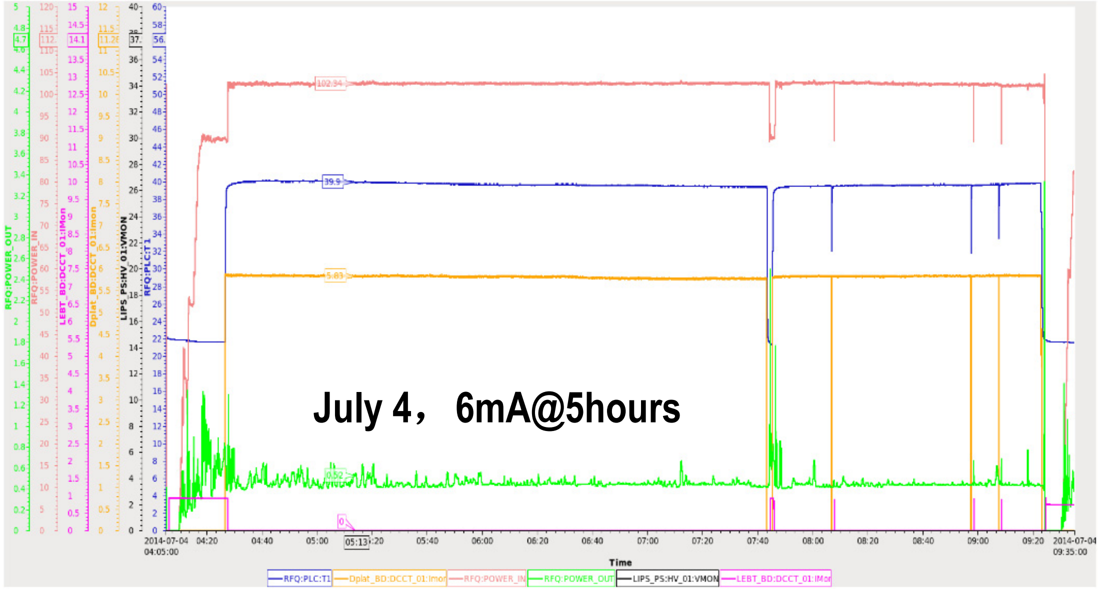


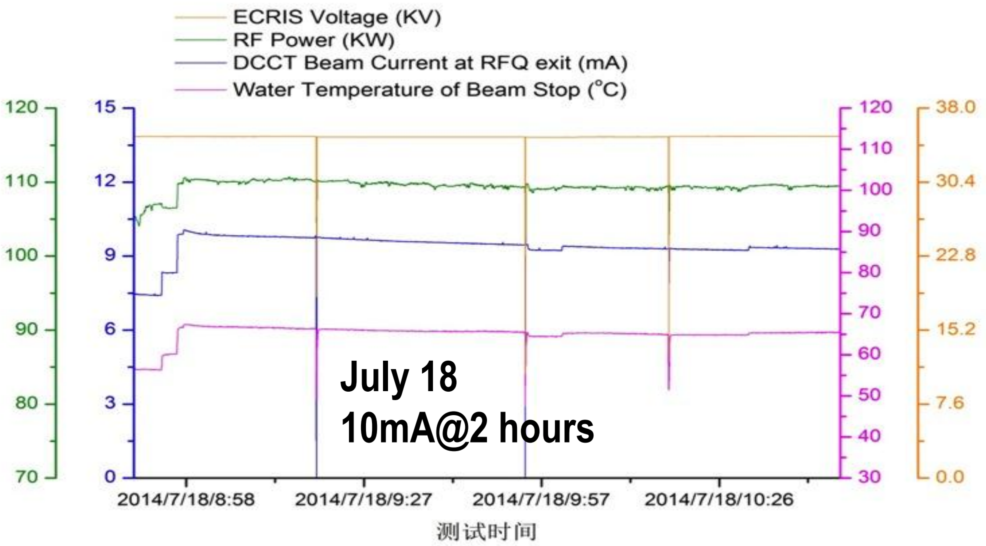
*The DCCT waveform signal is acquired by PLC with sampling rate 2Hz.
*The DCCT beam current number is measured by Oscilloscope.

June 21, toal 47 hours，2mA@5.5hours



June 30 10mA@4.5 hours





Injector II RFQ 162.5MHz Energy and transmission measurement

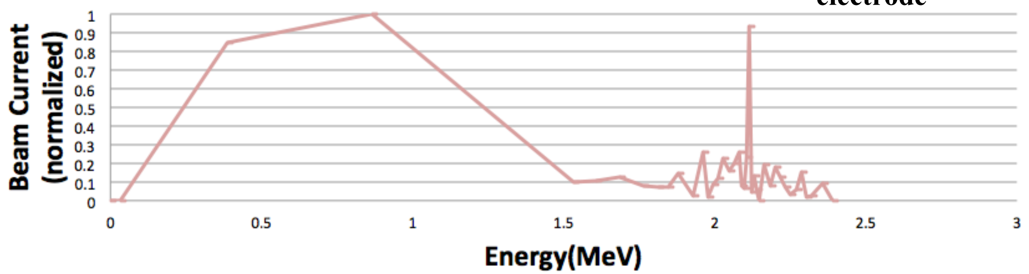
Yellow: LEBT ACCT;Voltage: 5.419V
Beam Current: 10.84mA
Blue: RFQ exit ACCT; Voltage: 2.625V
Beam Current: 10.50mA

June 29, 5ms/1Hz, 10.5 mA
97% transmission efficiency

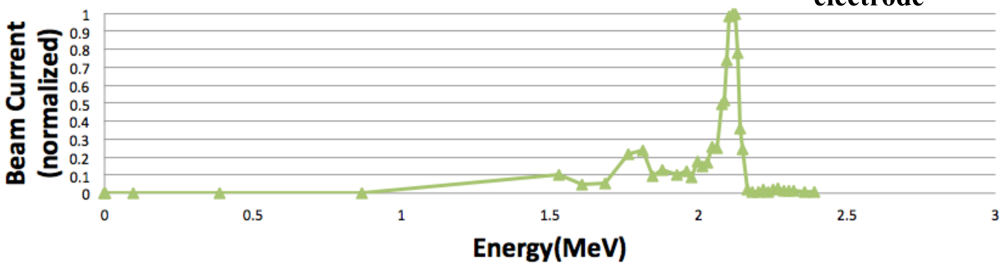
Flight time between BPM1 and BPM3: 77.989 ns
Beam energy: 2.165MeV

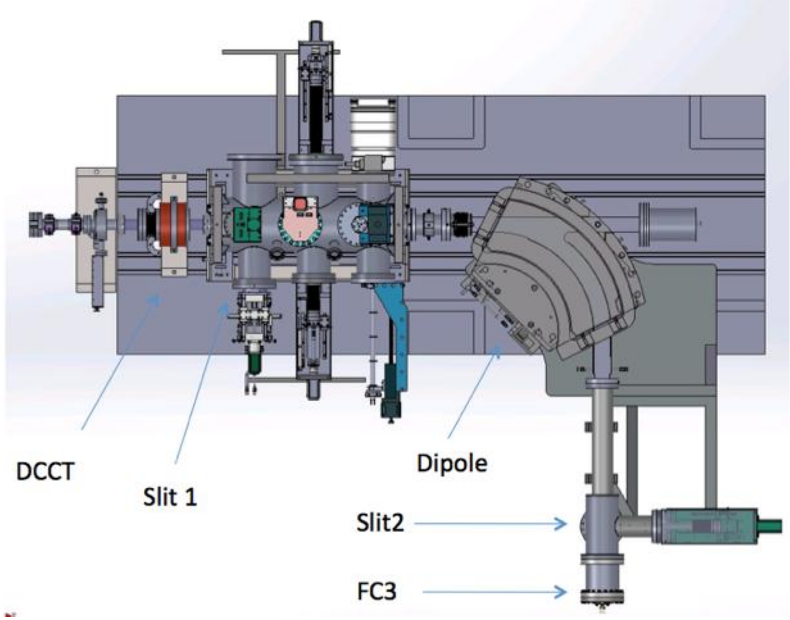
Injector II RFQ 162.5MHz Electrode voltage VS energy spread

Energy spread measurment@ Vp=1.387V $V_{electrode}$ 65 kV

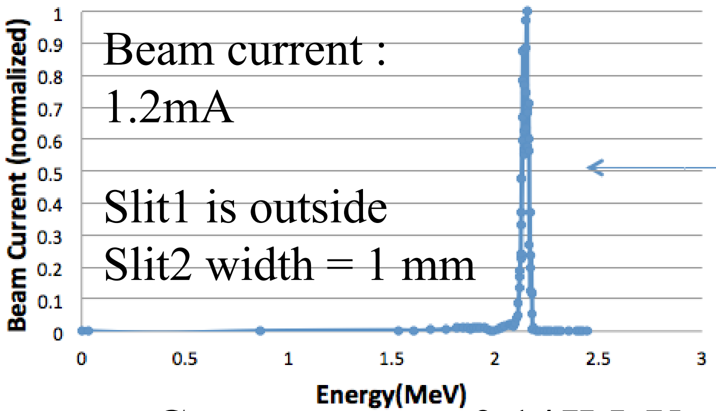


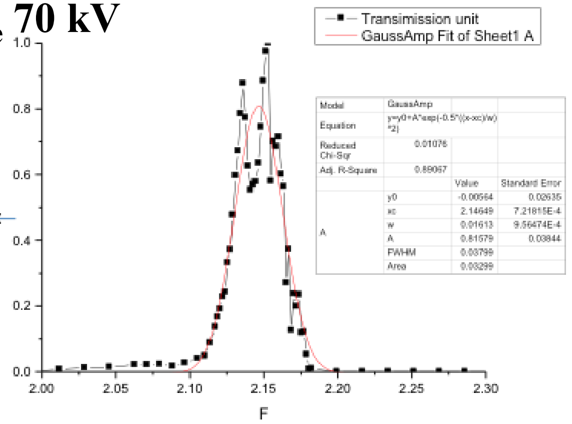
Energy spread measurment@Vp=1.445V $V_{electrode}$ 68 kV

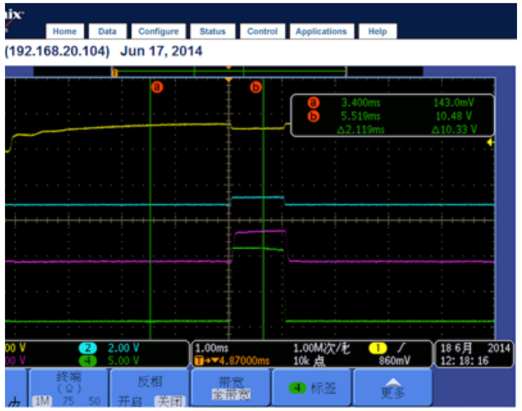




Energy spread measurment@Vp=1.473 $V_{electrode}$ 70 kV

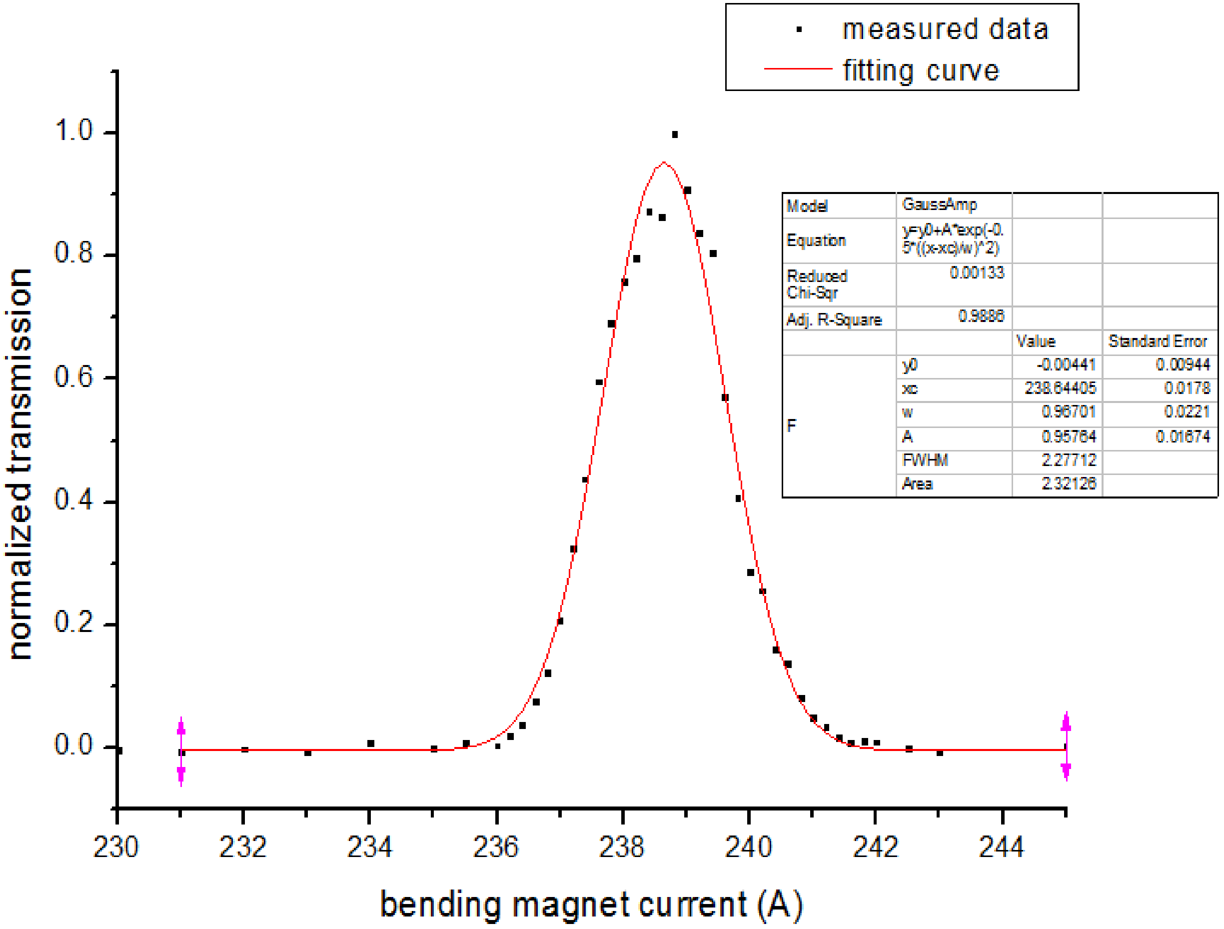






Center energy: 2.145MeV; Energy spread : 0.038MeV(FWHM)

Injector II RFQ 162.5MHz Energy spread measurement

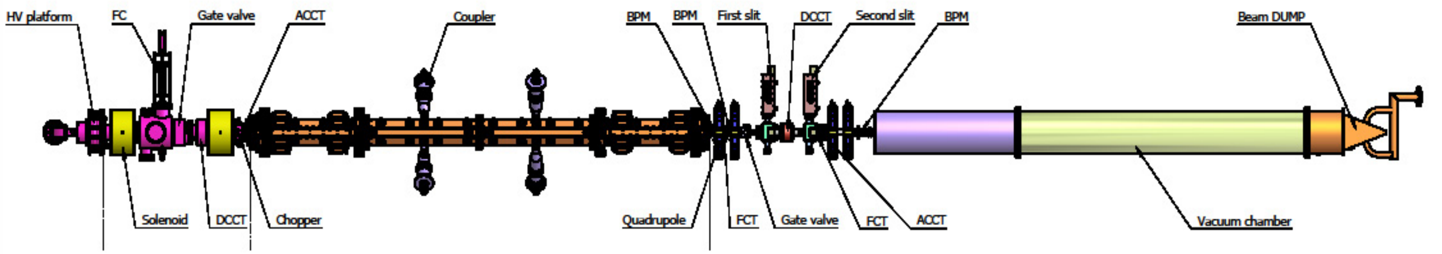


Beam：10mA，1Hz，500us　　Energy spread：1.9%

Injector I RFQ 325MHz

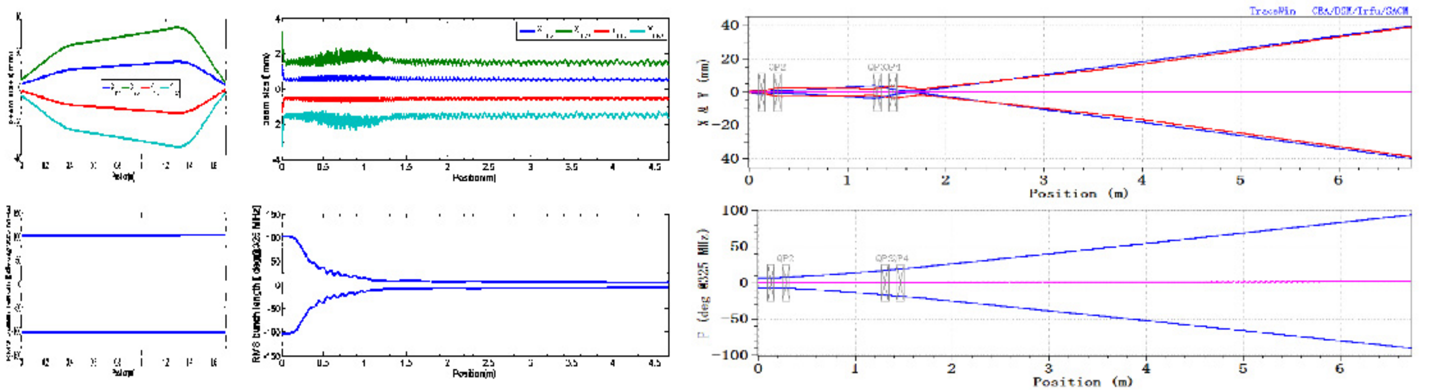
Developed by IHEP independently

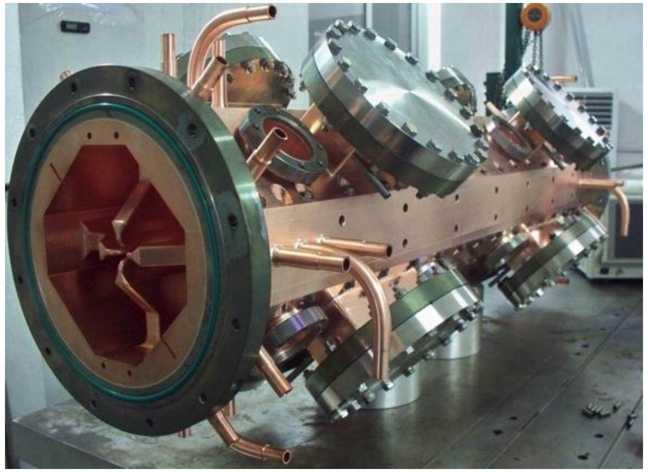
ADS injector I RFQ commissioning setup



ECRIS LEBT RFQ Movable beam DUMP line

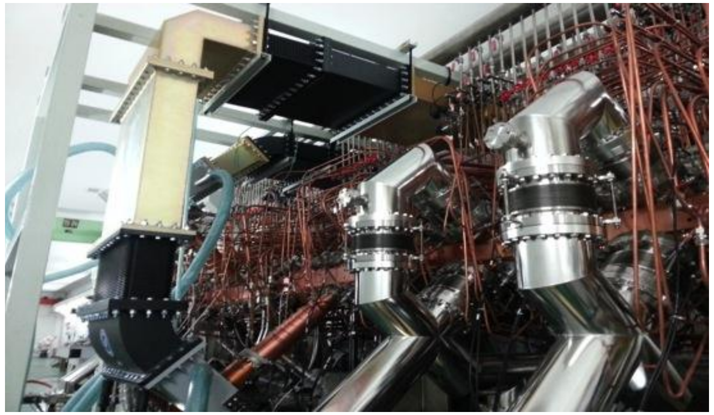
Beam envelope evolutions along the LEBT, the RFQ, the movable beam DUMP line



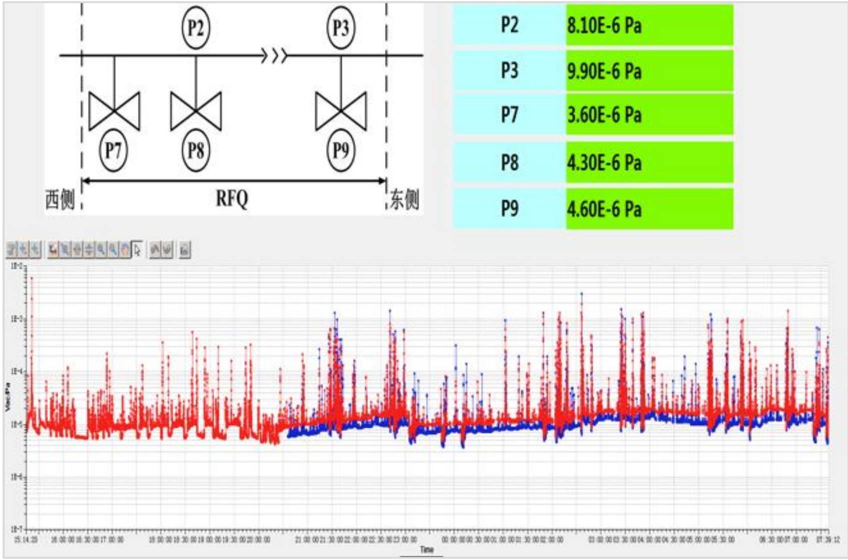


Injector I RFQ 325MHz Assembling and RF training

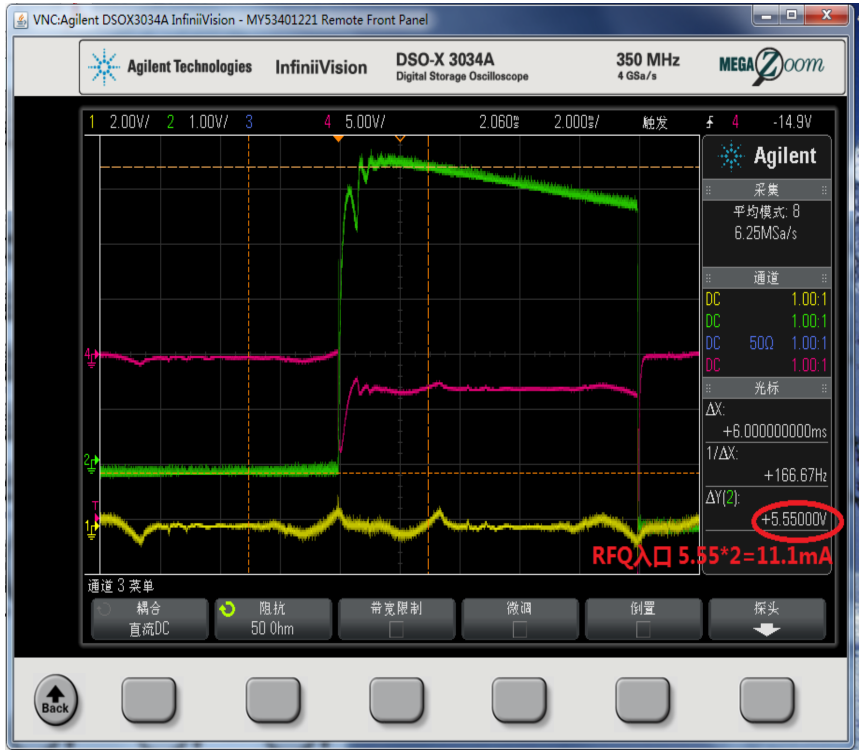
RF source: E37705 600 kW 325 MHz klystron and 80 kV PSM power supply



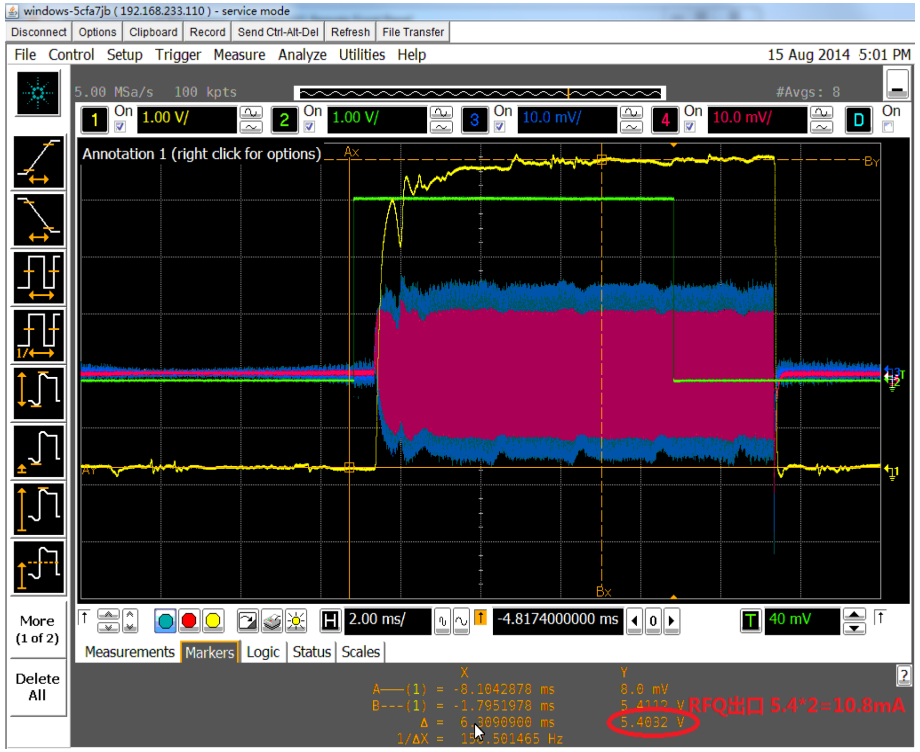
- **May 2014, assembling completed;**
- **July 21, 99.6% duty factor,250kW;**
- **July 22, CW， 200kW**



Injector I RFQ 325MHz Pulsed beam commissioning



LEBT ACCT: 11.1mA

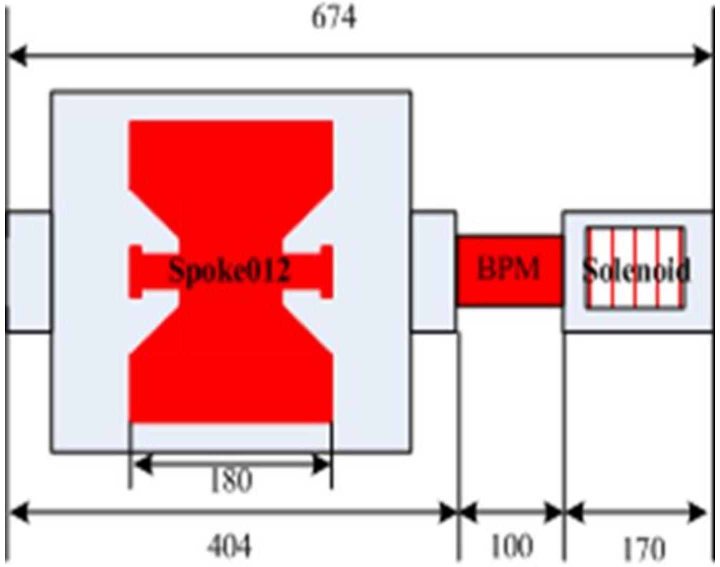


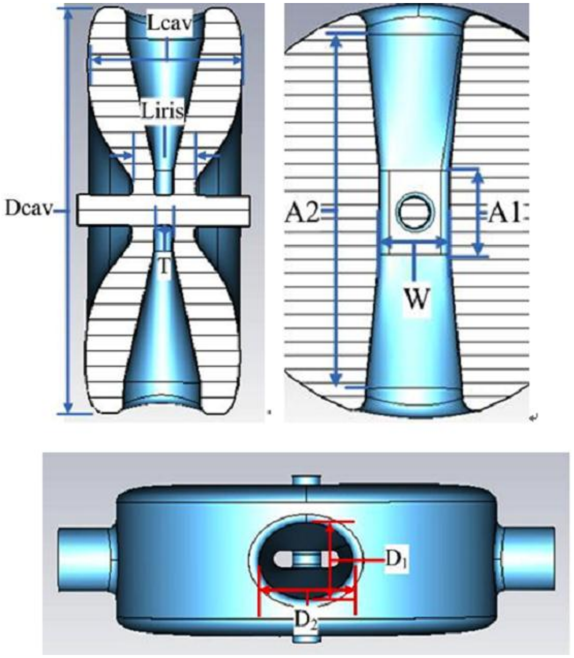
RFQ exit DCCT:10.8mA

Transmission: 97% （Duty factor 20%）

Injector I Spoke012 Optimized design and key parameters

Parameter	Value
Frequency	325 MHz
G	61 Ω
R/Q_0	142 Ω
E_{peak}/E_{acc}	4.5
B_{peak}/E_{acc}	6.4 mT/(MV/m)



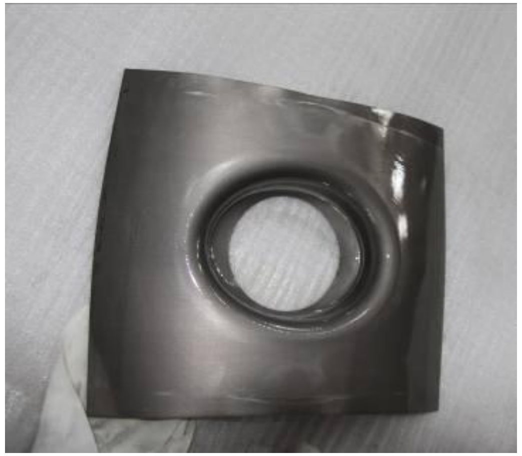
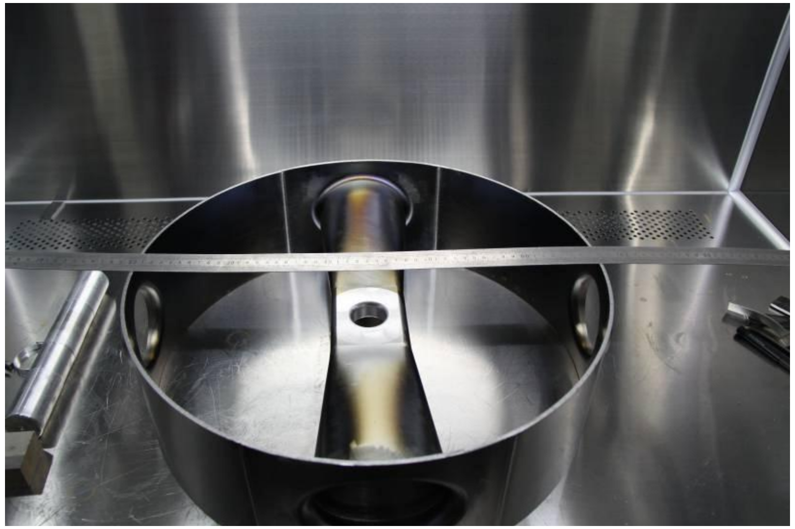


Geometry Parameters

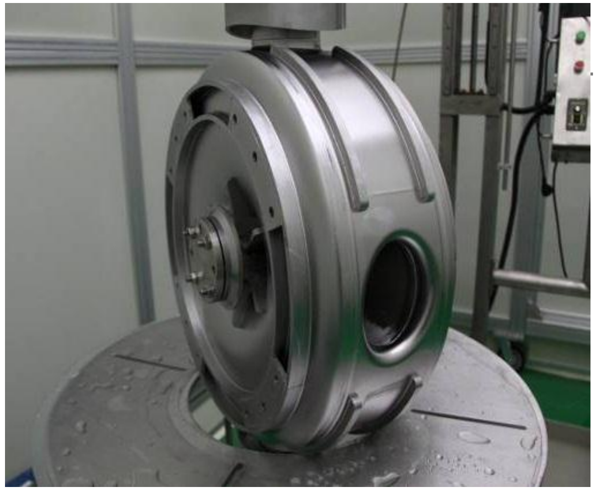
Parameter	Value
T	22
W	82
D	90
Factor	1.25
R1in	47
R2in	199
R1out	35
R2out	164
Lcav	180
Liris	73
R	234

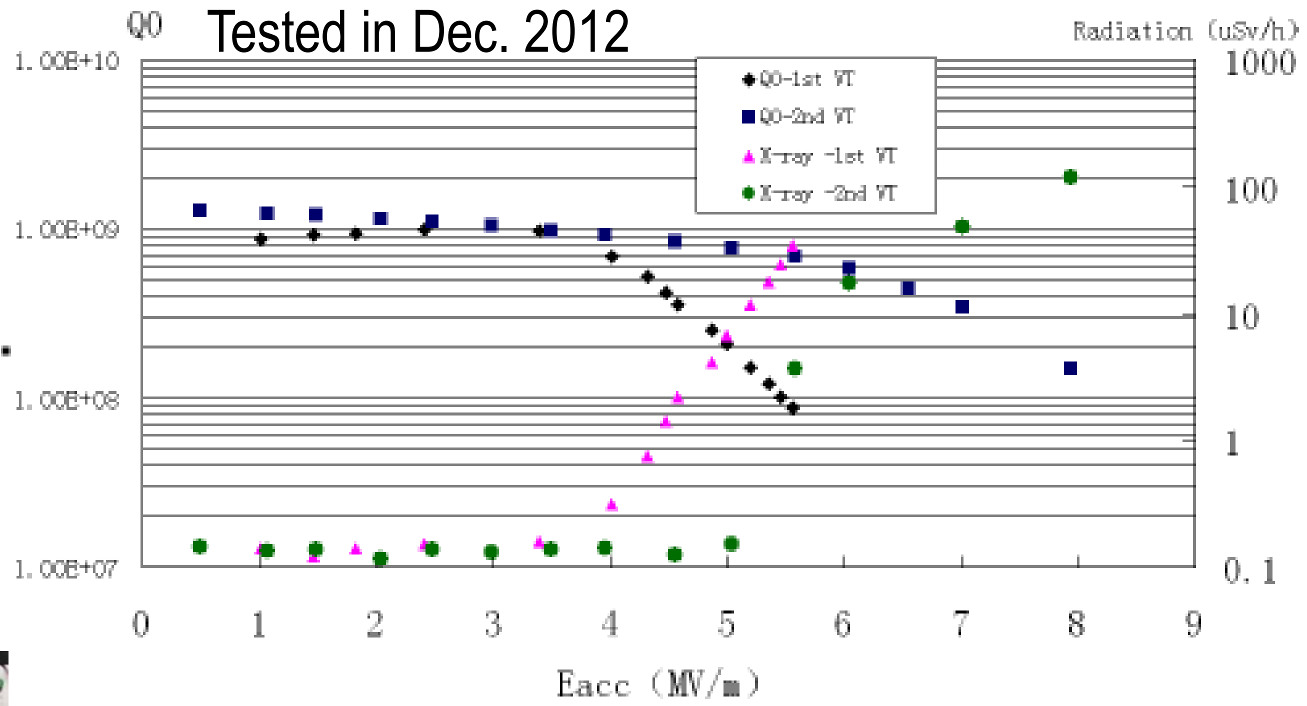
Injector I Spoke012　　　Fabrication by HIT



Injector I Spoke012 Vertical test





✓$Q_0=5.8\times10^8$ @6MV/m, 4K;

✓$Q_0=3.4\times10^8$ @7MV/m, 4K

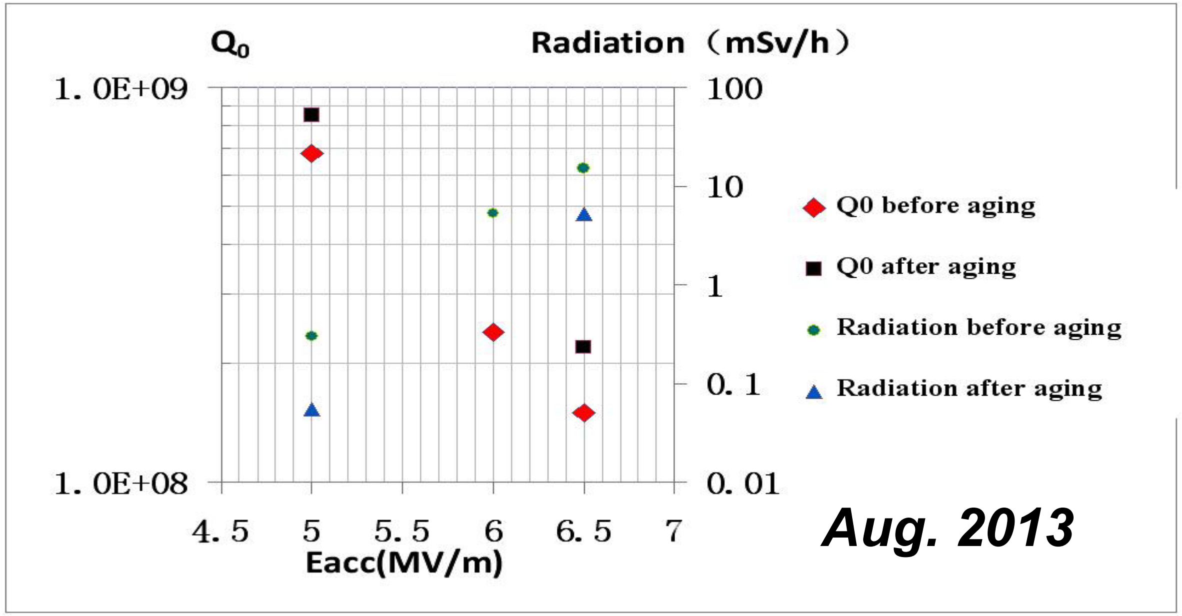
✓Max. Eacc. >14.6MV/m

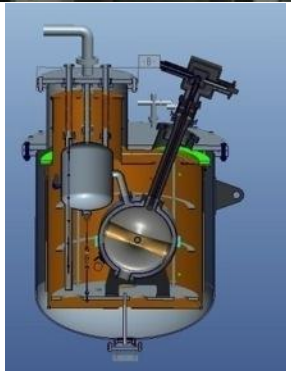
No quench but heavy MP and FE.

Bulk BCP 150 um
Annealing 750 C, 3 hours
Light BCP 30um
Baking 100 C, 48 hours

Injector I Spoke012 Horizontal test

Integration of Spoke012-2#

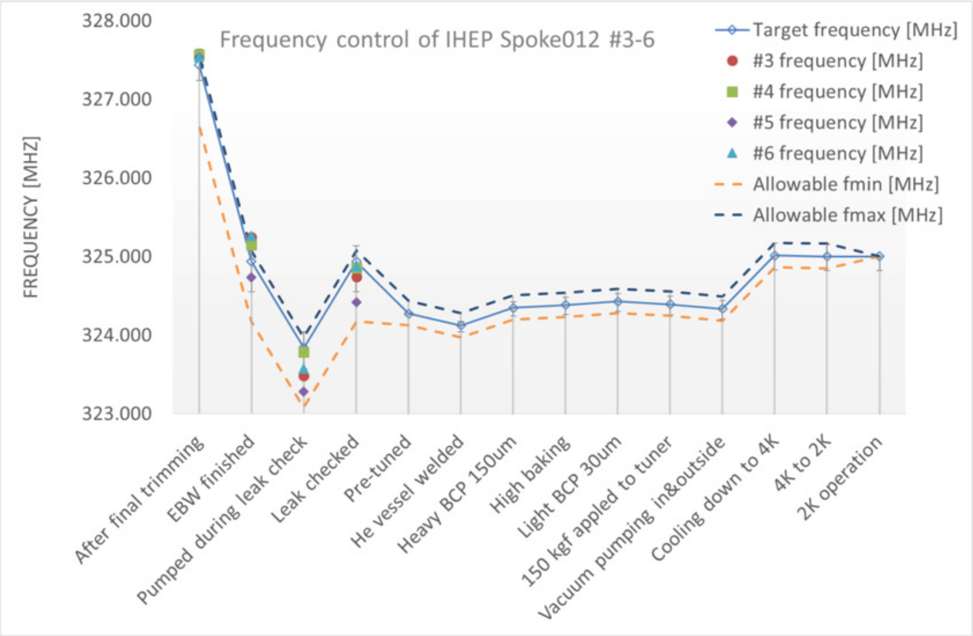


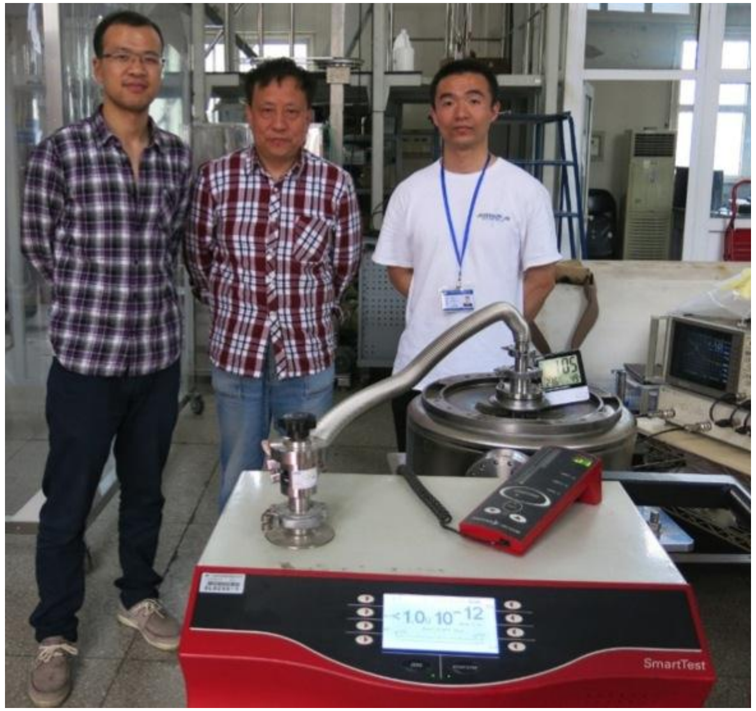


- ✓ Q_0=8.5x10^8 @ 5MV/m, 4.2K;
- ✓ Q_0=2.2x10^8 @ 6.5MV/m, 4.2K

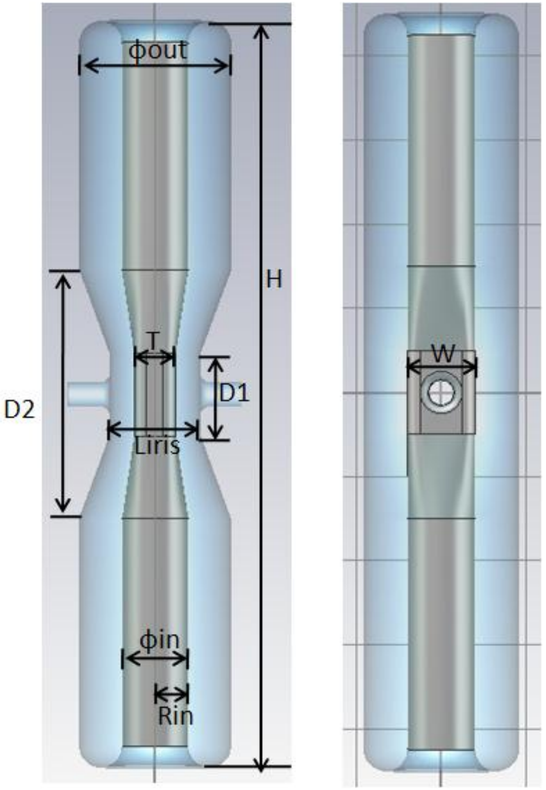
Injector I Spoke012 Mass-production

- 5.23, 2014, 4 sets of Spoke012 (#3-6) fabrication、frequency and vacuum tests completed.
- Other 7 sets of of Spoke012 (#7-13) being fabricated.





Injector II HWR010 Optimized design and Parameters



B_{pk}/E_{acc} ; E_{pk}/E_{acc}

R/Q_0 ; G

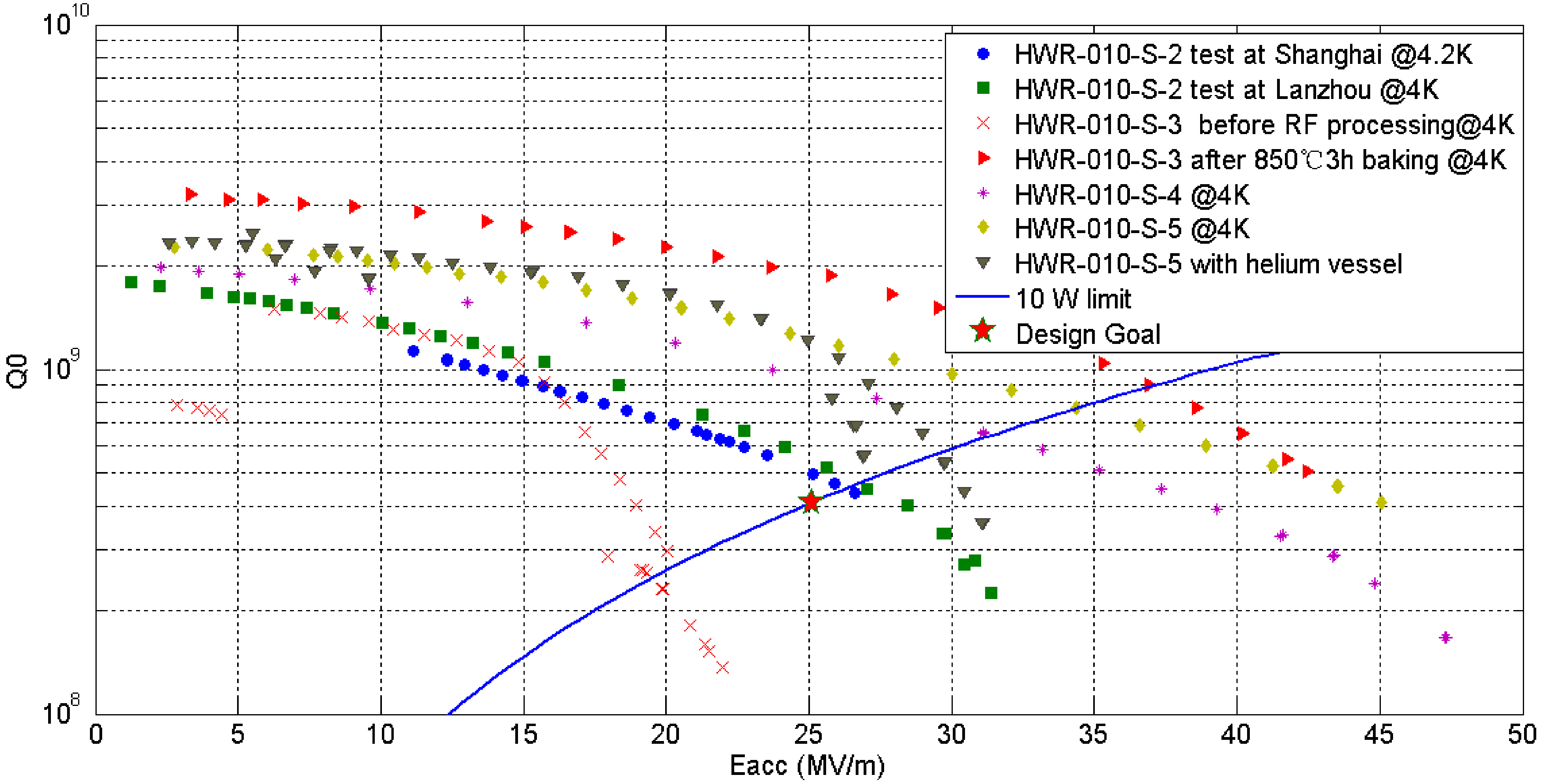
Rin (mm)	40
Rout (mm)	92
Liris (mm)	110
T (mm)	45
W (mm)	90
D1	100
D2	300
Rblend2	15

	HWR010 Squeezed
Freq(MHz)	162.5
βopt	0.101
Uacc(MV)	0.78
Eacc(MV/m)	4.5
Epeak(MV/m)	25
Bpeak(mT)	50
$G=Rs*Q_0(\Omega)$	28.5

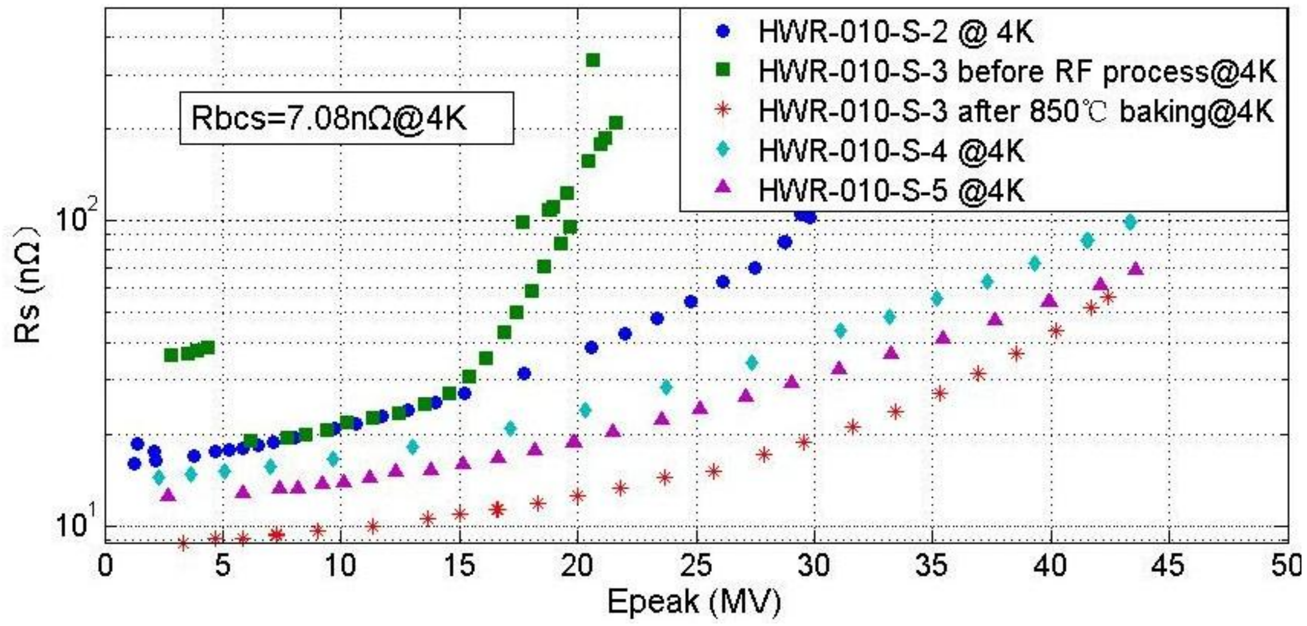
Injector II HWR010 Fabrication

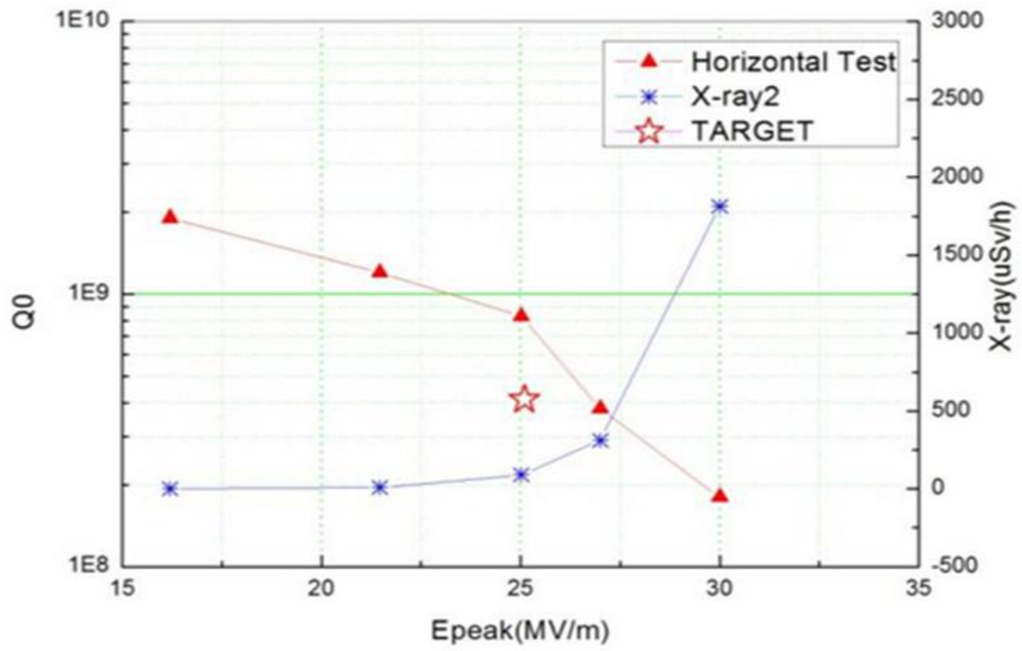
- **Material**
  - OTIC, RRR>300, partly RRR>380
- **Drawing, machining and BCP**
  - Punching die, Al 7075
  - Surface survey before every step of fabrication
  - BCP (65%HNO_3:40%HF:85%H_3PO_4=1:1:2) 10um, resin by UPW, drying in cleanroom of class 100
  - Polishing every seam and BCP 10um before EBW
- **E-beam welding**
  - EBW by two different parameters:
    - #01, #02;
    - #03, #04, #05.

Injector II HWR010 Vertical test



Injector II HWR010 Horizontal test





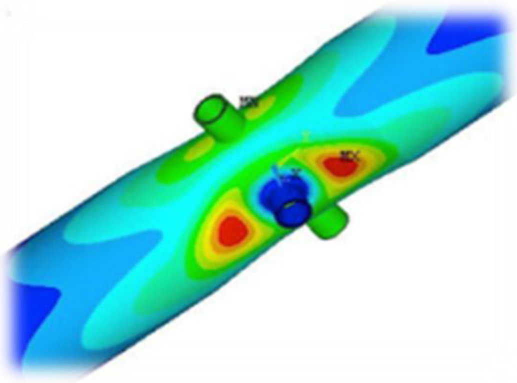
Cryoperm shielding, < 20 mGs, at room temp.
<7mT at 4 K, Rmag=0.8 nΩ

$Q_0 = 8.1\times10^8$ @E_{peak} 25MV/m

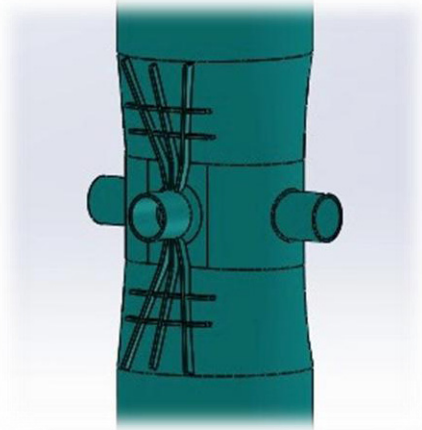
Rs of the #5 cavity is around10 nΩ.
Rs of the #3 after 850 C baking is around 2 nΩ.

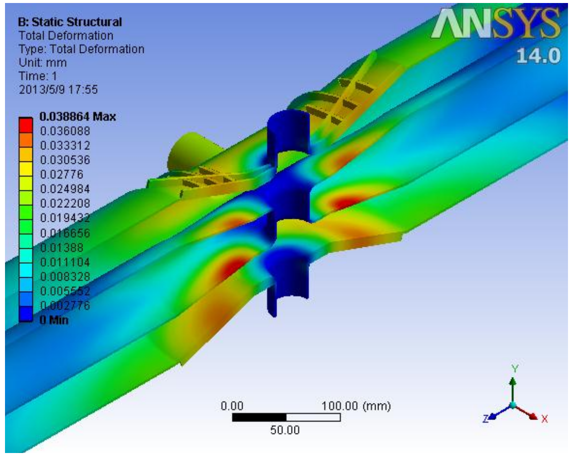
Ribs to df/dp

df/dp 70Hz/mbar → Goal → <5 Hz/mbar

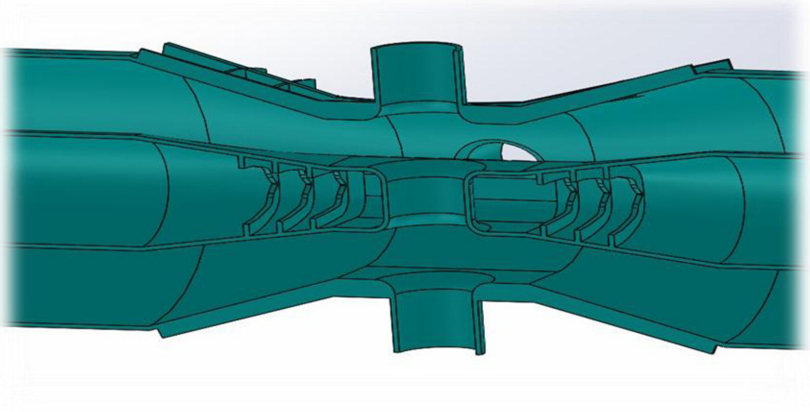


<5Hz → Ribs on one

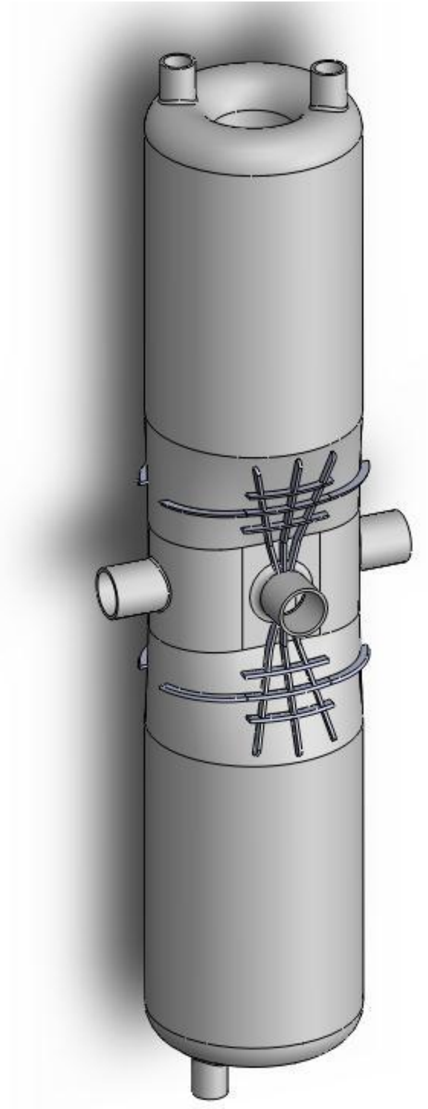


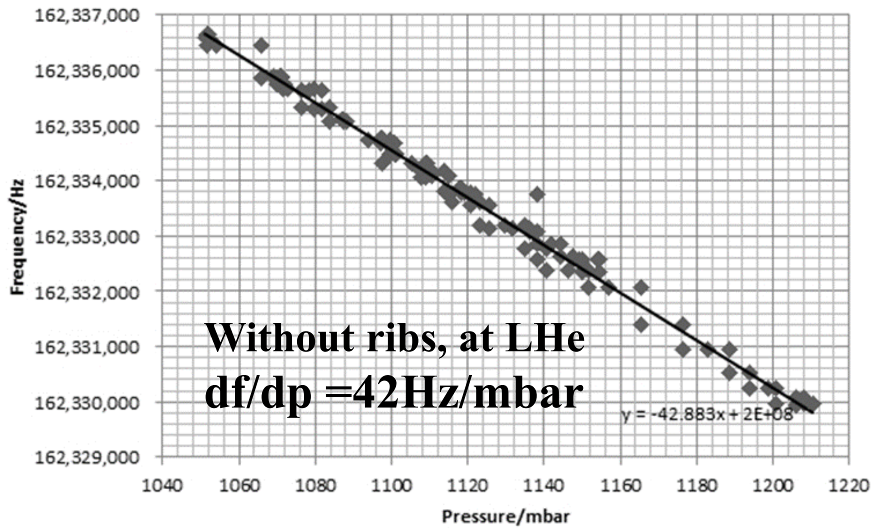


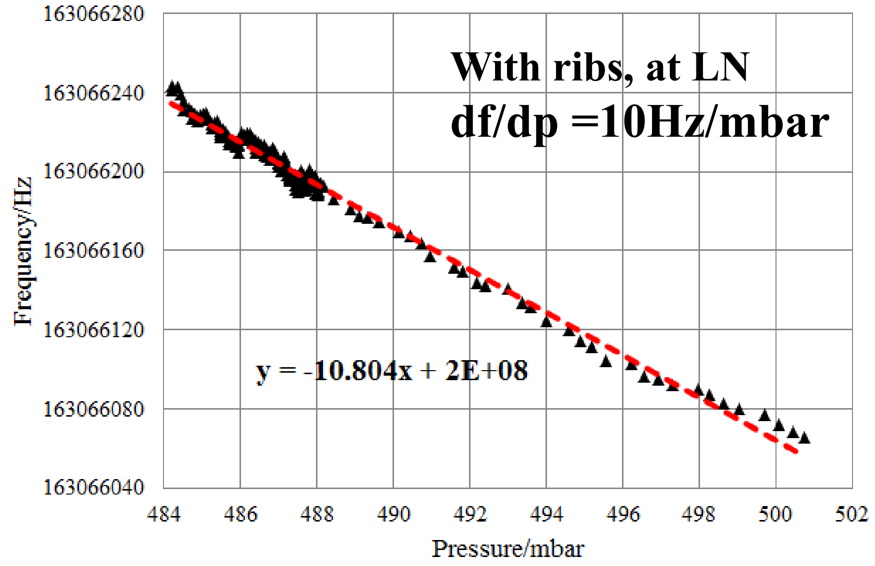
<1Hz → Ribs on both



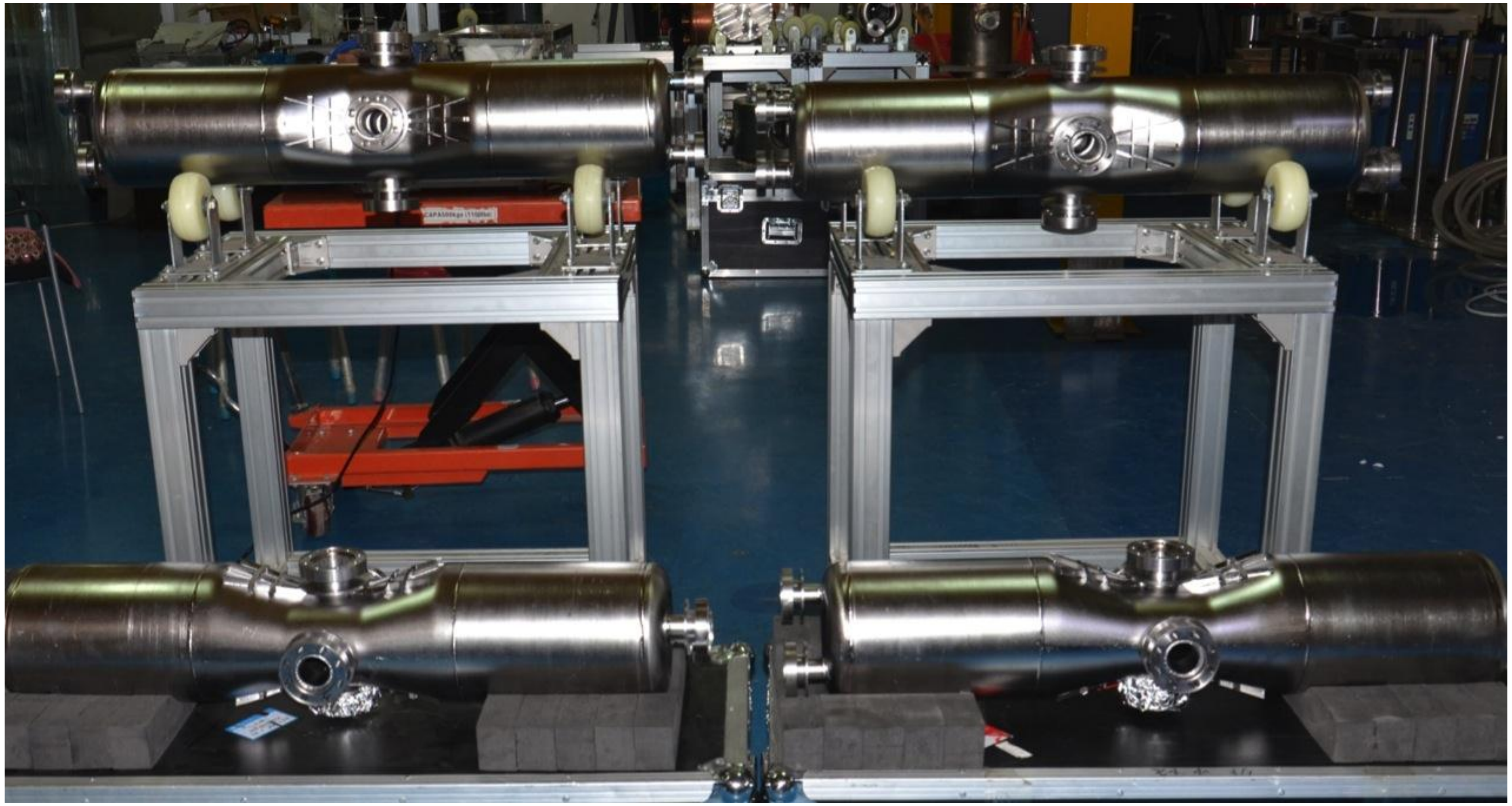
Injector II HWR010 df/dp measurement with ribs





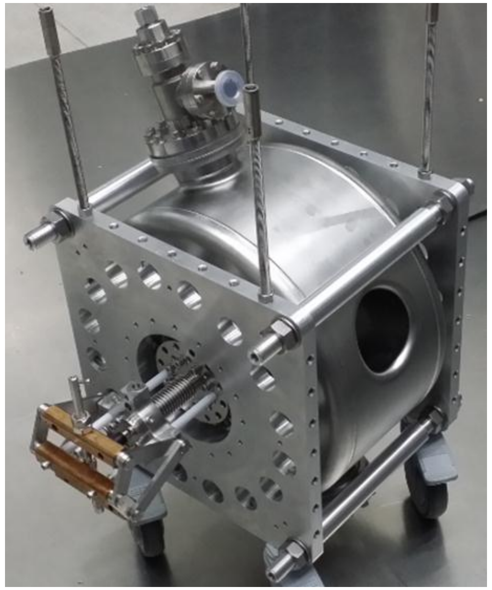


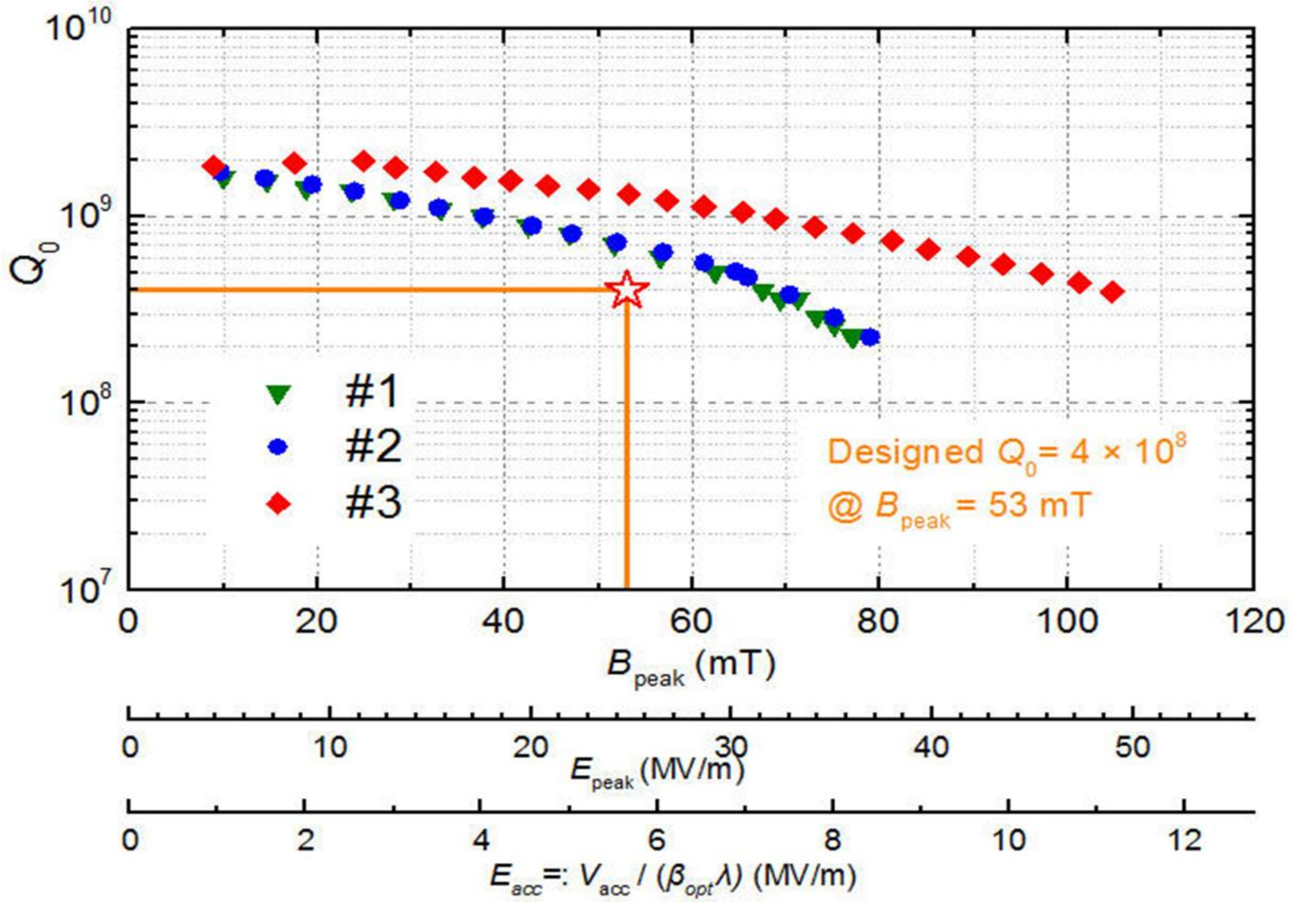
Injector II HWR010 Mass-production



8 HWR010 cavities completed

Main Linac Spoke021-325MHz Vertical test

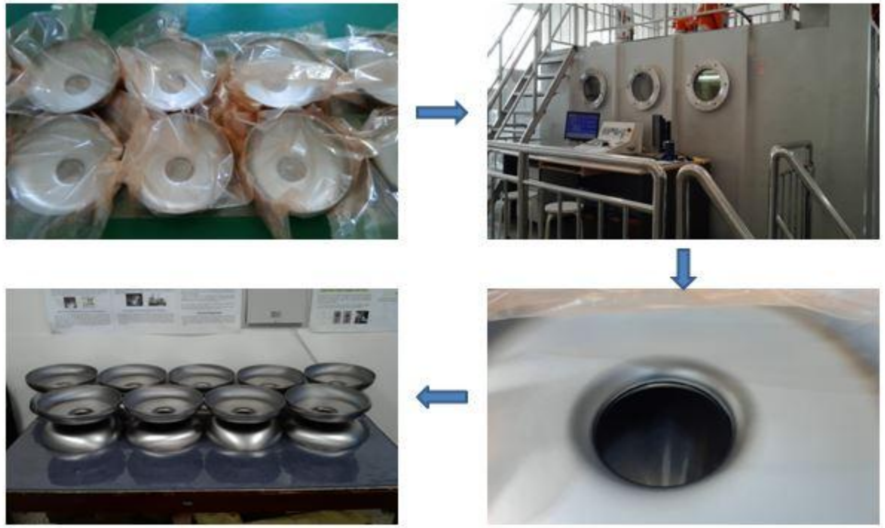




✓Max. B_{peak}=107 mT @ Q_0=4.0x10^8

Main Linac Spoke040-325MHz Fabrication

Main Linac Ellip082-650MHz Fabrication



High Power Input Couplers for Injector I &II

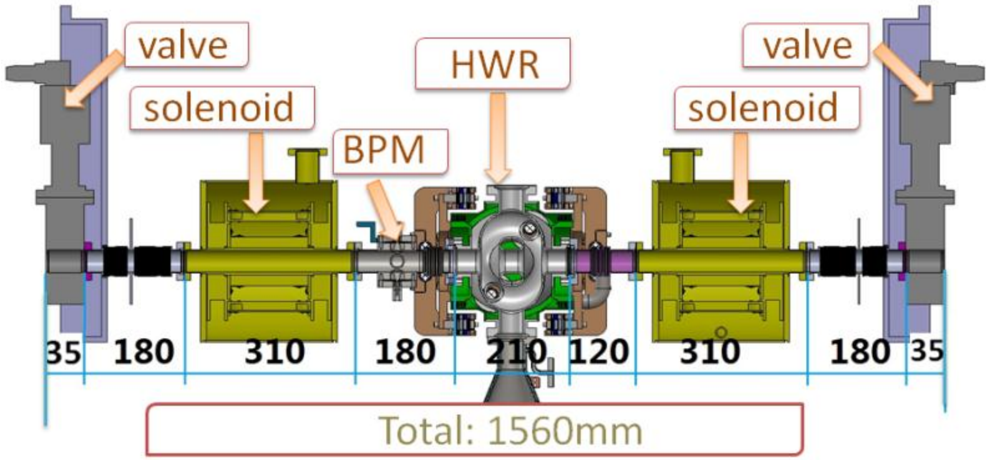
Spoke012 cavity couplers were tested over 10 kW CW power and operated in horizontal test.

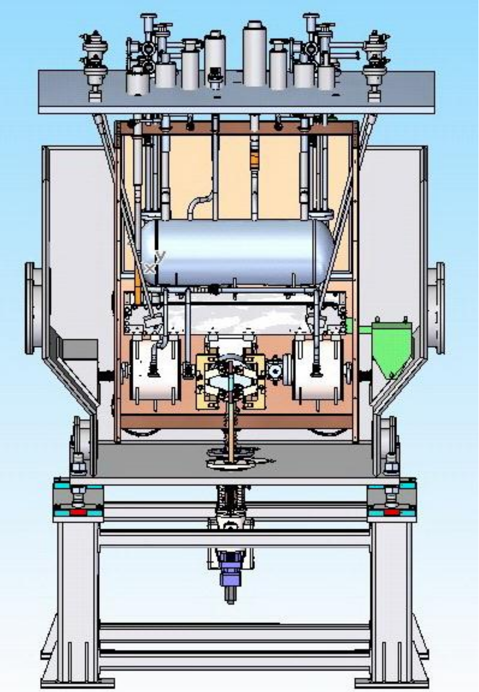
RFQ coupler's windows tested up to 100 kW CW power.

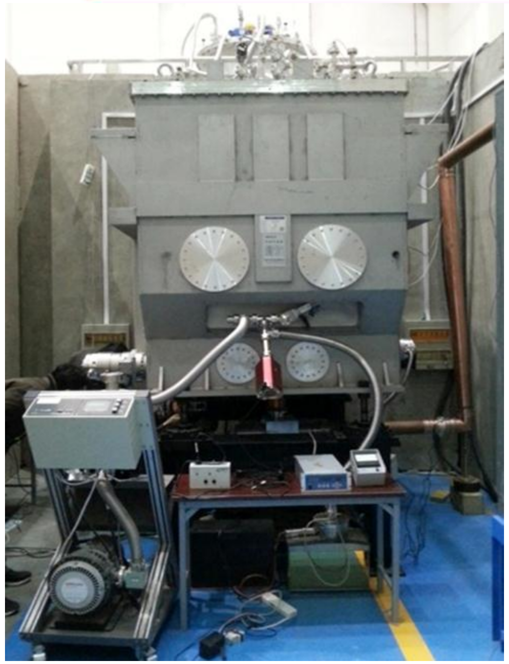
HWR010 couplers was tested over 20 kW CW, and operated in horizontal test

Cryomodule Injector II TCM1 prototype

Op. Temperature	4.4 K
Op. Pressure	1.25 bar
Cooling	bath
Pressure	±1.5 mbar
Dynamic load	10 W
Solenoid storage	27KJ



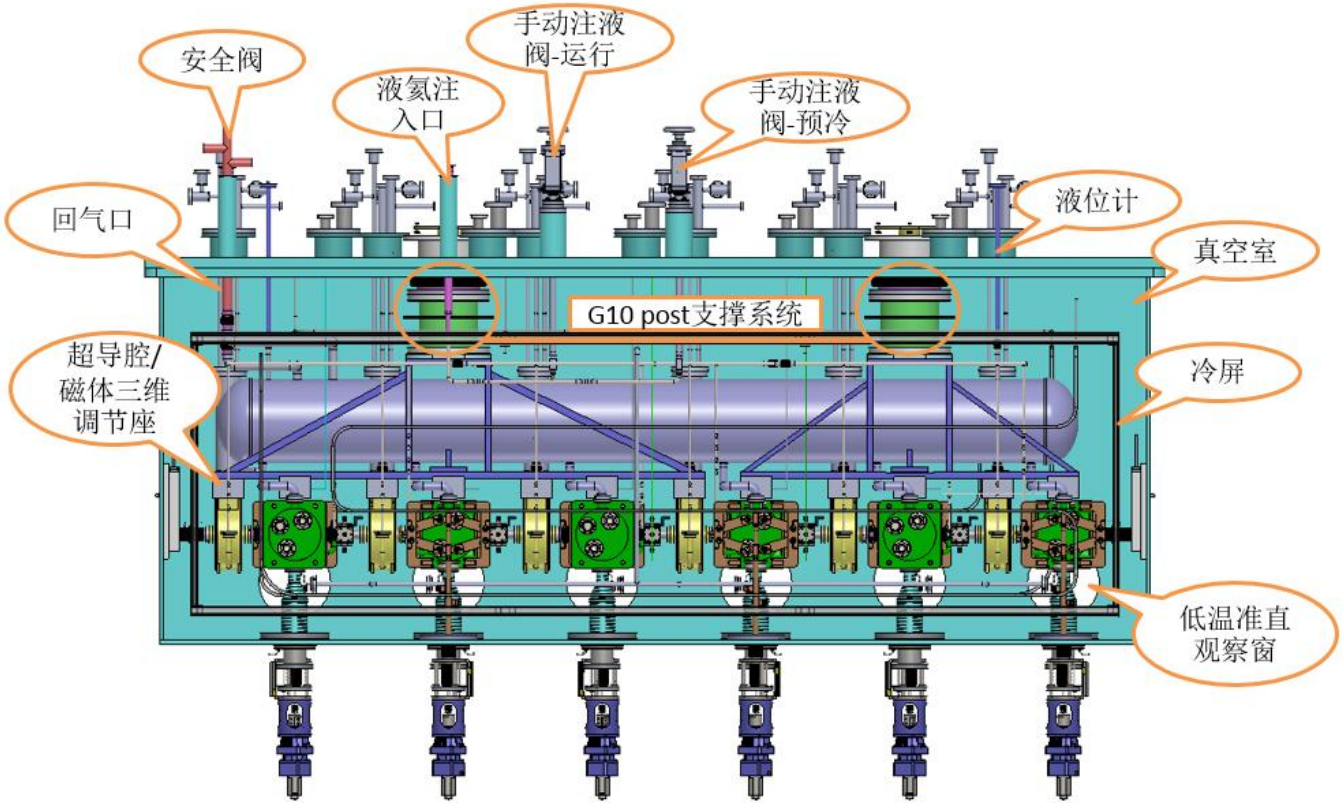




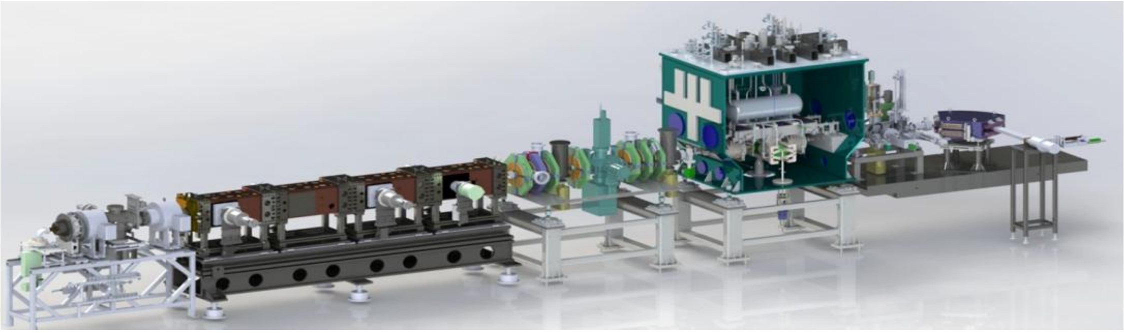
TCM1 was tested under 4.4 K condition for 3 times in 2014 so as to test cryogenic system, HWR010 performance, CM dynamic load, frequency tuner, HP coupler, df/dp, LLRF control system and so on.

Cryomodule Injector II   CM6 under fabrication

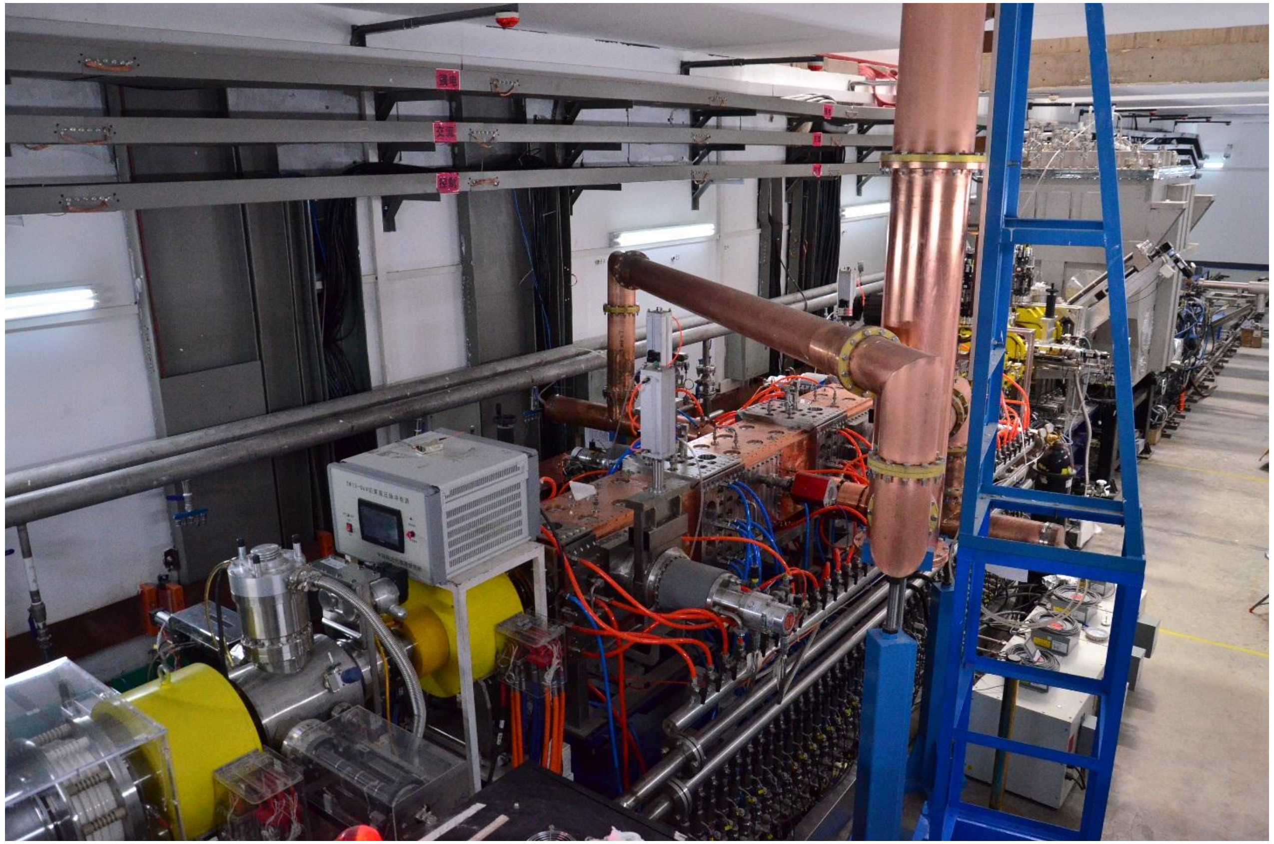
CM6-HWR010-162.5 MHz



Cryomodule prototype TCM1 ready for beam commissioning

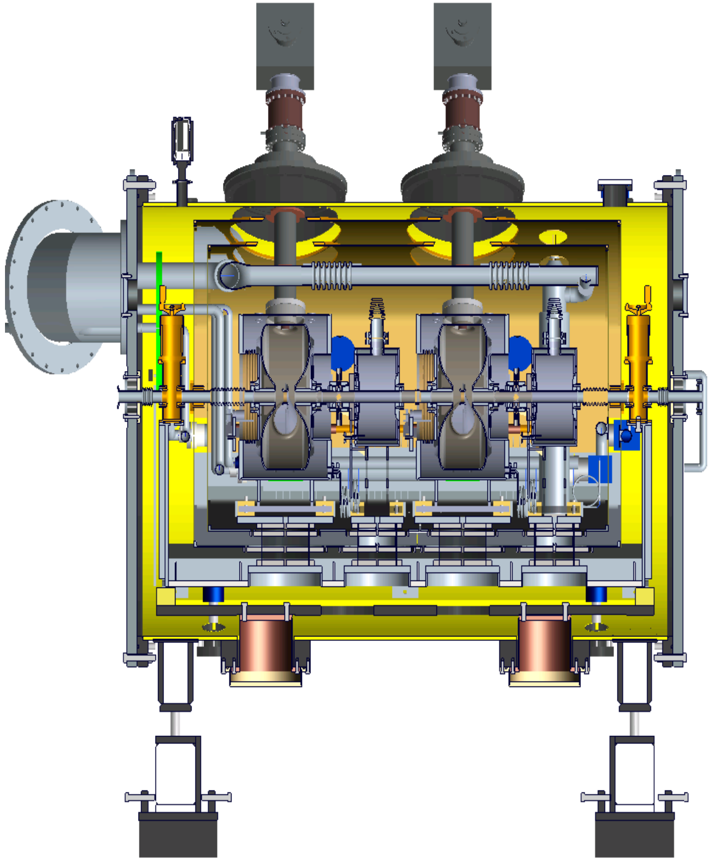


- ECRIS + LEBT + RFQ + MEBT + TCM1, 2.5 MeV
- RFQ commissioning, validate CM design.
- Ongoing, beam commissioning in Sept. 2014

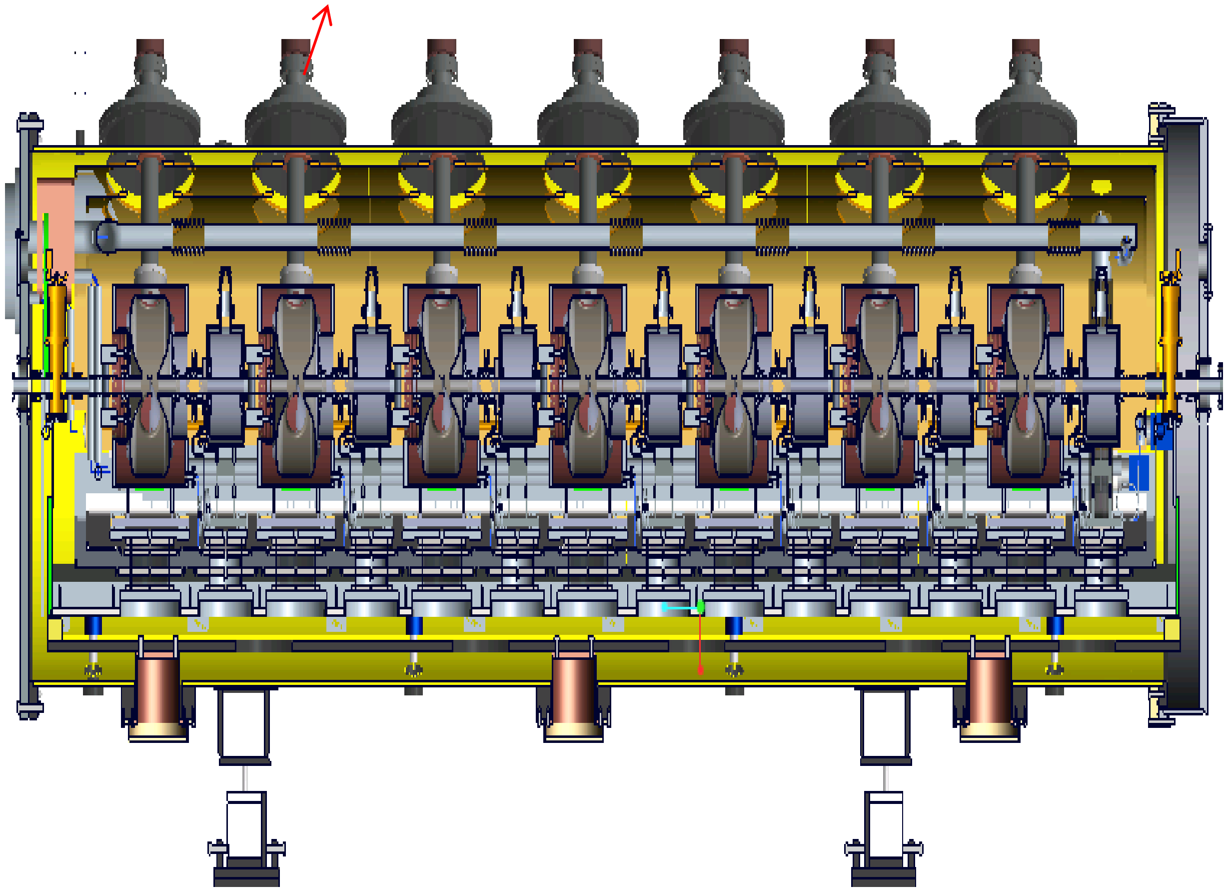


Almost ready for beam commissioning at IMP/Lanzhou

Cryomodule Injector I   CM7 under fabrication



TCM2 Spoke012 prototype



CM7-Spoke012-325MHz

SRF Infrastructure

Cryogenic Station at IMP (850 W at 4.5 K)

SRF Infrastructure

BCP system at IMP

SRF chemistry lab

BCP device for components

BCP device for whole cavity

BCP acids mixing system

SRF Infrastructure

Clean room assembling and HPR

Summary

- **R&D of China ADS linac is to build a 25MeV@3 mA CW proton SC linac which will be utilized to explore key technologies and challenges for 250 MeV@10 mA CIADS linac.**

- **It is planed : 25MeV@3 mA CW beam commissioning in the year 2016-2017.
10 MeV injector I and injector II beam commissioning by the end of 2015.**

- **Significant progress has been made for the R&D of China ADS linac.
2.1 MeV@162.5 MHz RFQ at IMP reached 10 mA CW proton beam.
3.2 MeV@325 MHz RFQ at IHEP reached 10 mA pulsed beam.**

- **It is demonstrated that HWR010 and Spoke012 have reached the designed performance and are qualified for 10 MeV injector I and injector II. Mass-productions are underway.**

- **CM6-HWR010 and CM6-Spoke012 for 5 MeV are under fabrication and will be started assembling soon.**

- **All SRF infrastructures for 25MeV@3 mA CW linac have been completed and already in operation.**

- **It remains a lot challenges for us to reach 5-10 MeV@ 3 mA SC linac stable operation!**

Acknowledgement

Team of China ADS Linac does appreciate for all those collaborations, exchanges, discussions and recommendations from the colleagues at the following labs:

LBNL, ANL, Jlab, MSU/FRIB, FNAL, ORNL, TRIUMF, CEA/Saclay, IPN/Orsay, IAP/Frankfurt Univ., KEK …..

HIT， PKU, SINAP…..

All those progress would be impossible without your help!

Thank you for your attention!

谢谢！