Design and Beam Commissioning of the LEAF-RFQ

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Acknowledgements

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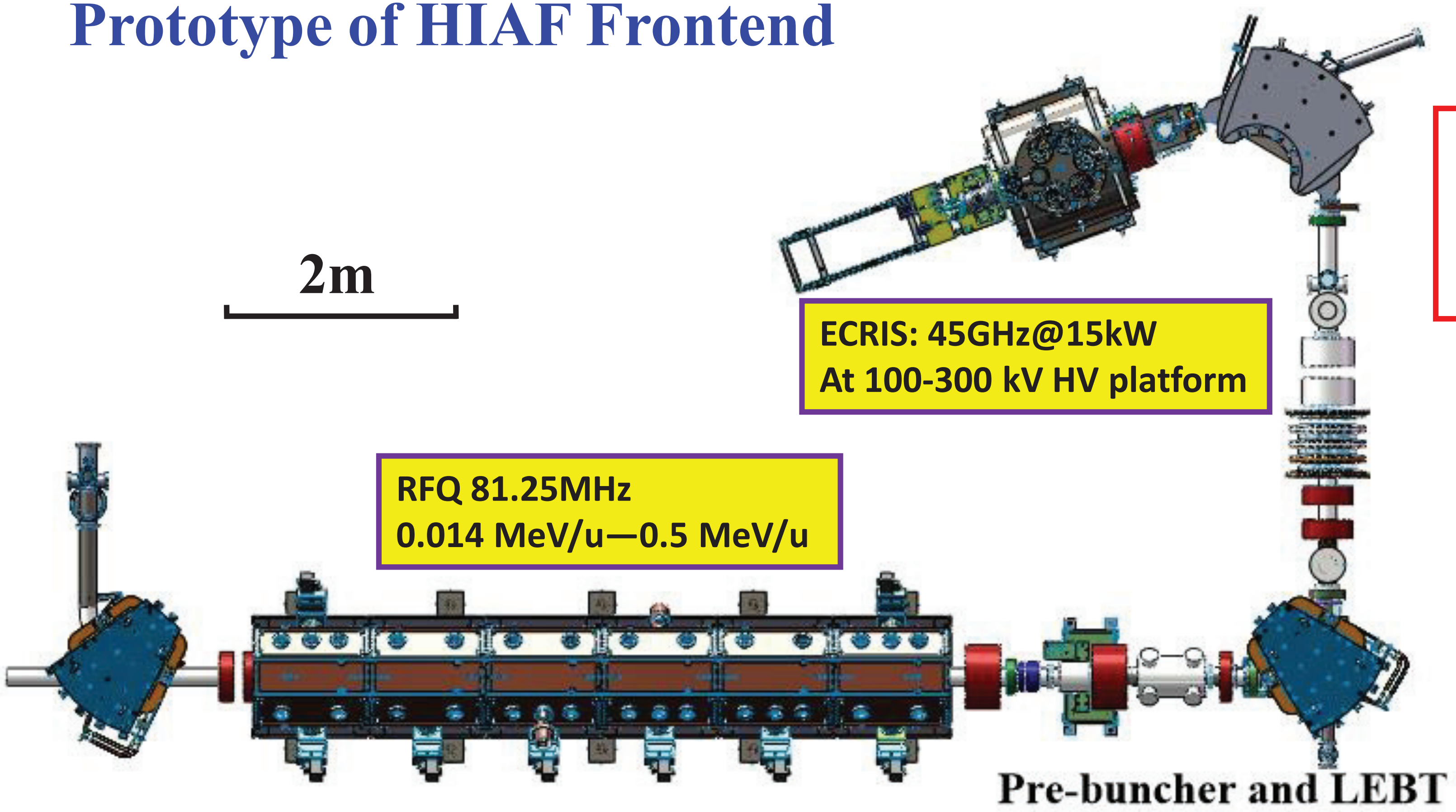
Outline

- RFQ design
- Fabrication and low power test
- RF conditioning
- Beam commissioning and measurement

IMP Facilities: HIAF front-end R&D

Prototype of HIAF Frontend

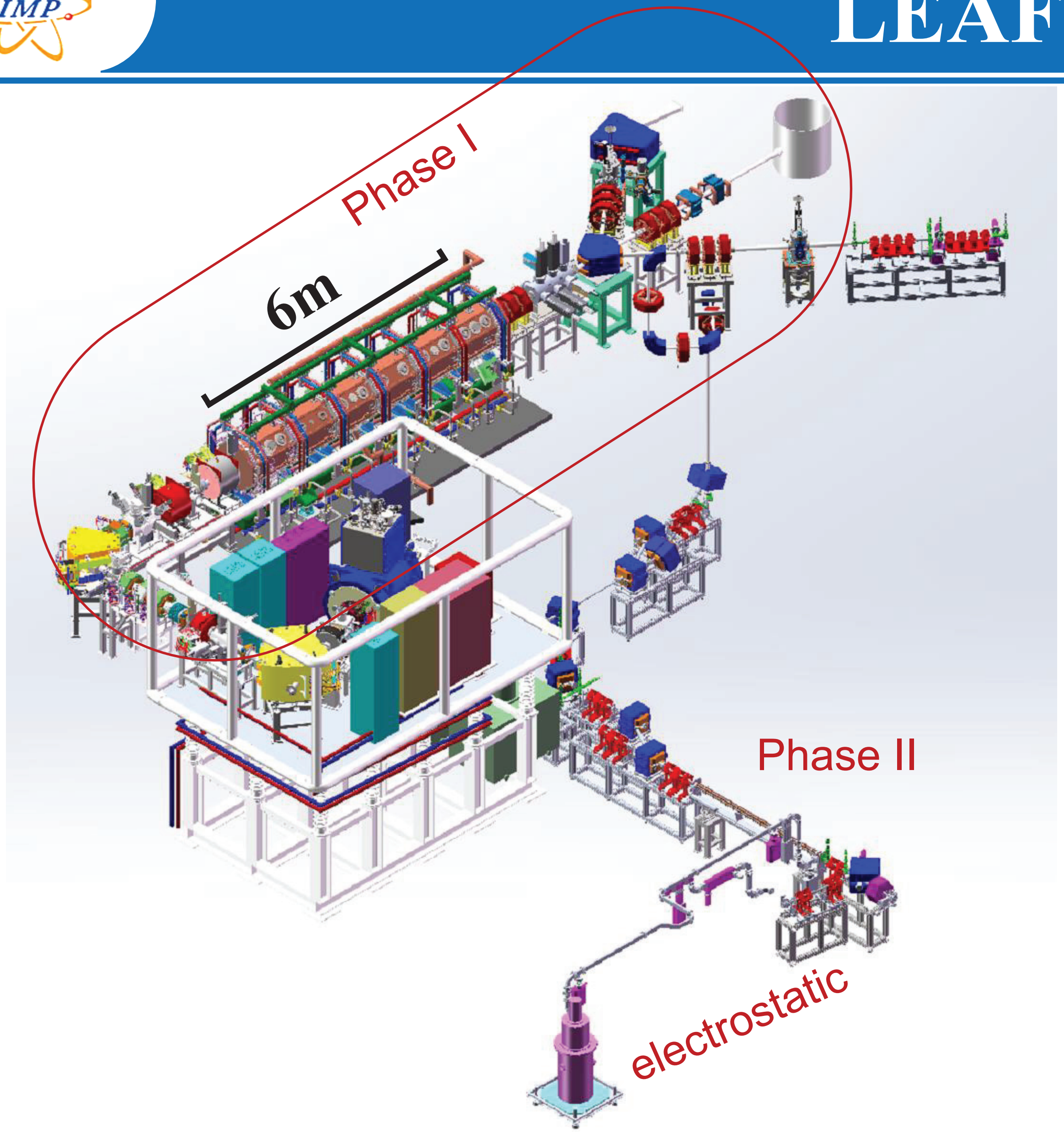


- Irradiation material
- Highly charged atomic physics
- Low energy Nuclear astrophysics

Xe^{30+},Bi^{31+},U^{34+}	1.5 emA
$^{129}Xe^{45+}$	30-100 μA
$^{209}Bi^{55+}$	30-100 μA
$^{238}U^{56+}$	30-100 μA

Low Energy Accelerator Facility (LEAF)

LEAF Project



Low Energy Accelerator Facility (LEAF)

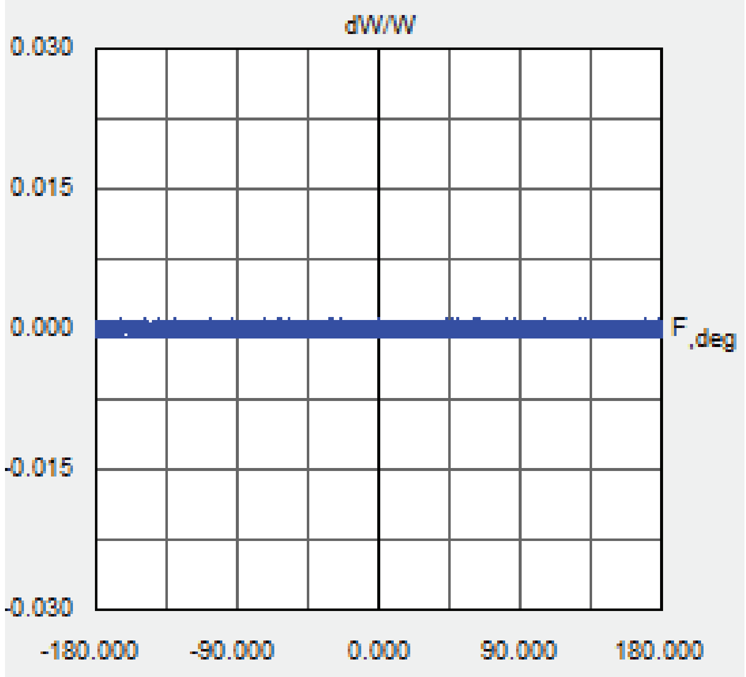
- A pre-research facility for HIAF project;
- Accelerating H_2^+ to U^{34+} in both CW & pulse mode;
- Material irradiation; electron cooling; imagination; et al.;
- Low energy, high intensity; high charged ions; cocktail beam (H_2^++He^{2+}+$^{58}Ni^{28+}$);

ions	current
$^{4}He^{1+}$	10-15 mA
$^{13}C^{4+}$	1-2 mA
$^{129}Xe^{45+}$	30-100 μA
$^{209}Bi^{55+}$	30-100 μA
$^{238}U^{56+}$	30-100 μA
H_2^++He^{2+}+$^{58}Ni^{28+}$	30-50 μA

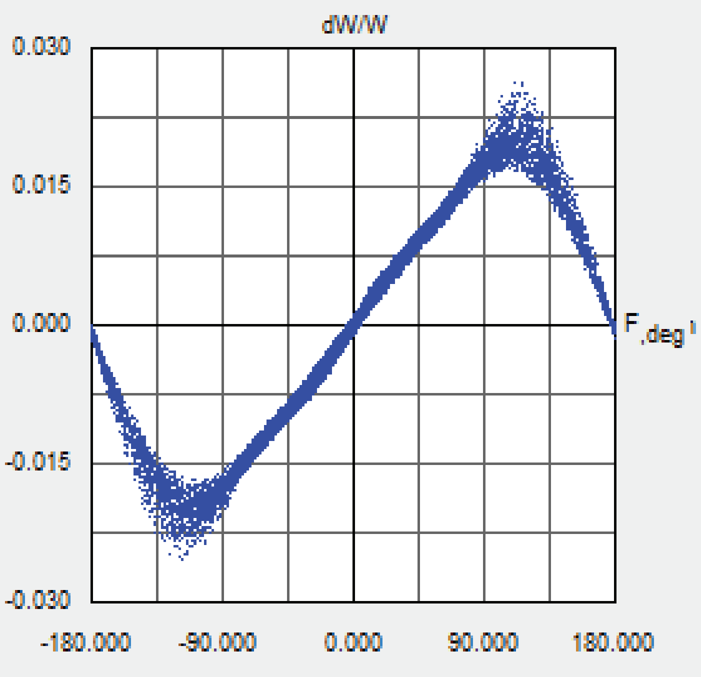
Beam dynamics： multi-harmonic buncher (MHB)

Purpose of using MHB：
- Decreasing longitudinal emittance
- Shorten RFQ length

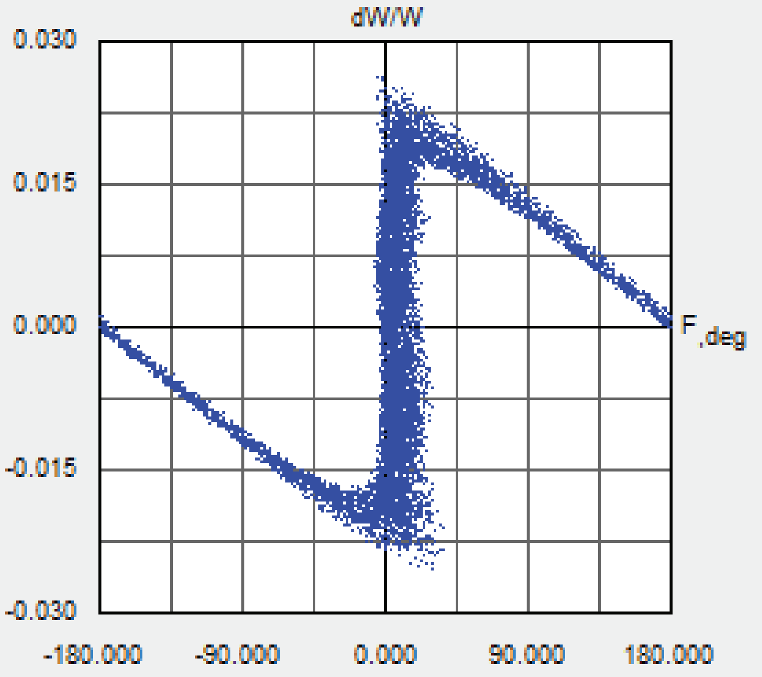
- **frequency：** 40.625 MHz、81.25 MHz、121.875 MHz
- **Amplitude：** 1：-0.23：0.044



Separatrix @ MHB entrance



Separatrix @ MHB exit



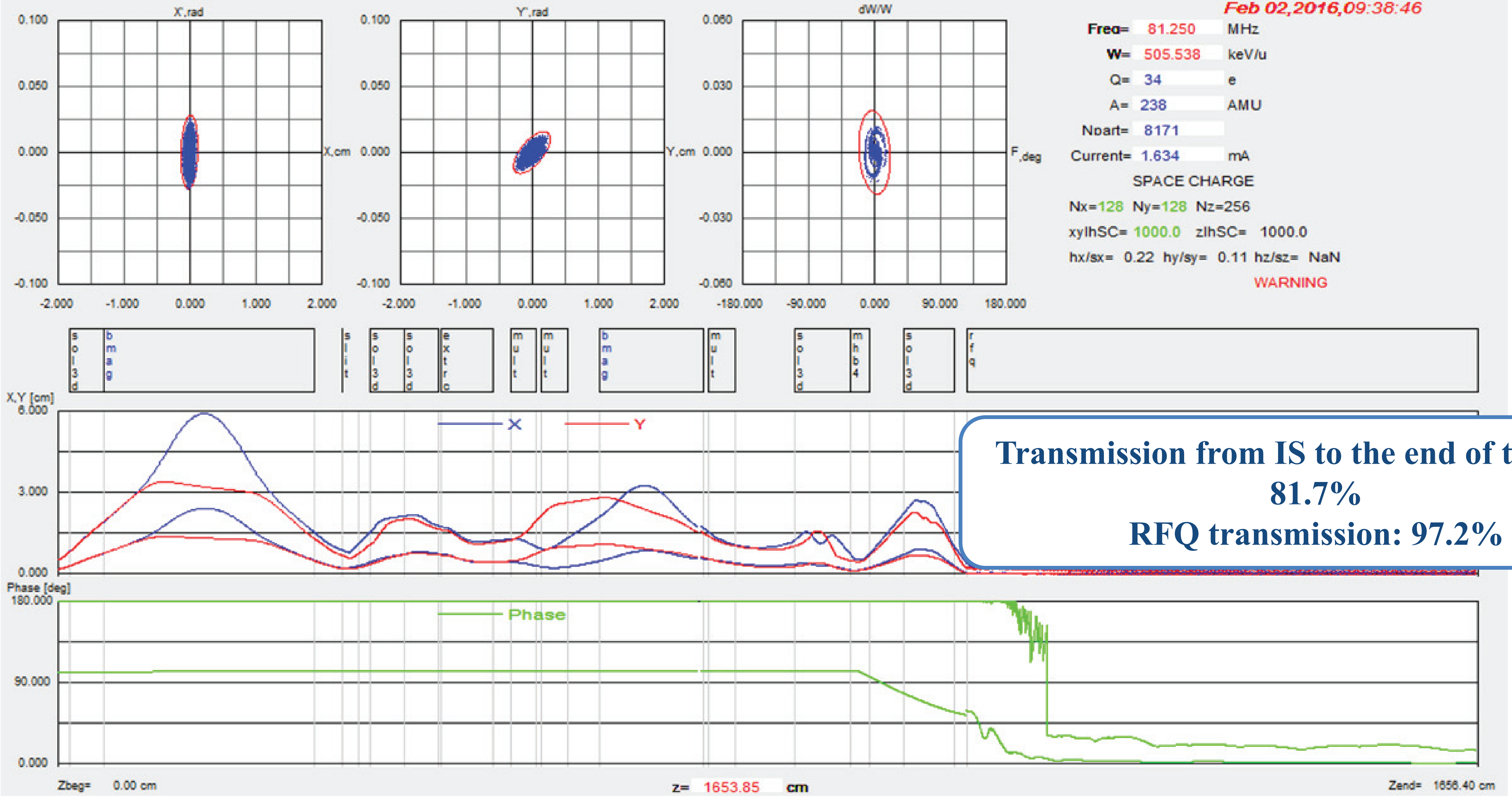
Separatrix @ RFQ entrance

- **The RFQ length was shortened from 7m to 5.96m.**

Beam dynamics： cavity parameters

Parameters	Value
Centeral particle	$^{238}U^{34+}$
Current （emA）	2
Inter-vane voltage （kV）	70
Kilpatrick	1.56
Input / output energy (MeV/u)	0.014/0.5
R0 (mm)	5.805
Synchronous （deg.）	-45~ -25
Modulation	1.05~2.04
Transverse RMS of input beam （pi·mm·mrad）	0.3
Transverse RMS of output beam （pi·mm·mrad）	0.293
longitudinal RMS of input beam （pi·mm·mrad）	0.098
Cavity length (cm)	596.4

Beam dynamics： LEBT+MHB+RFQ



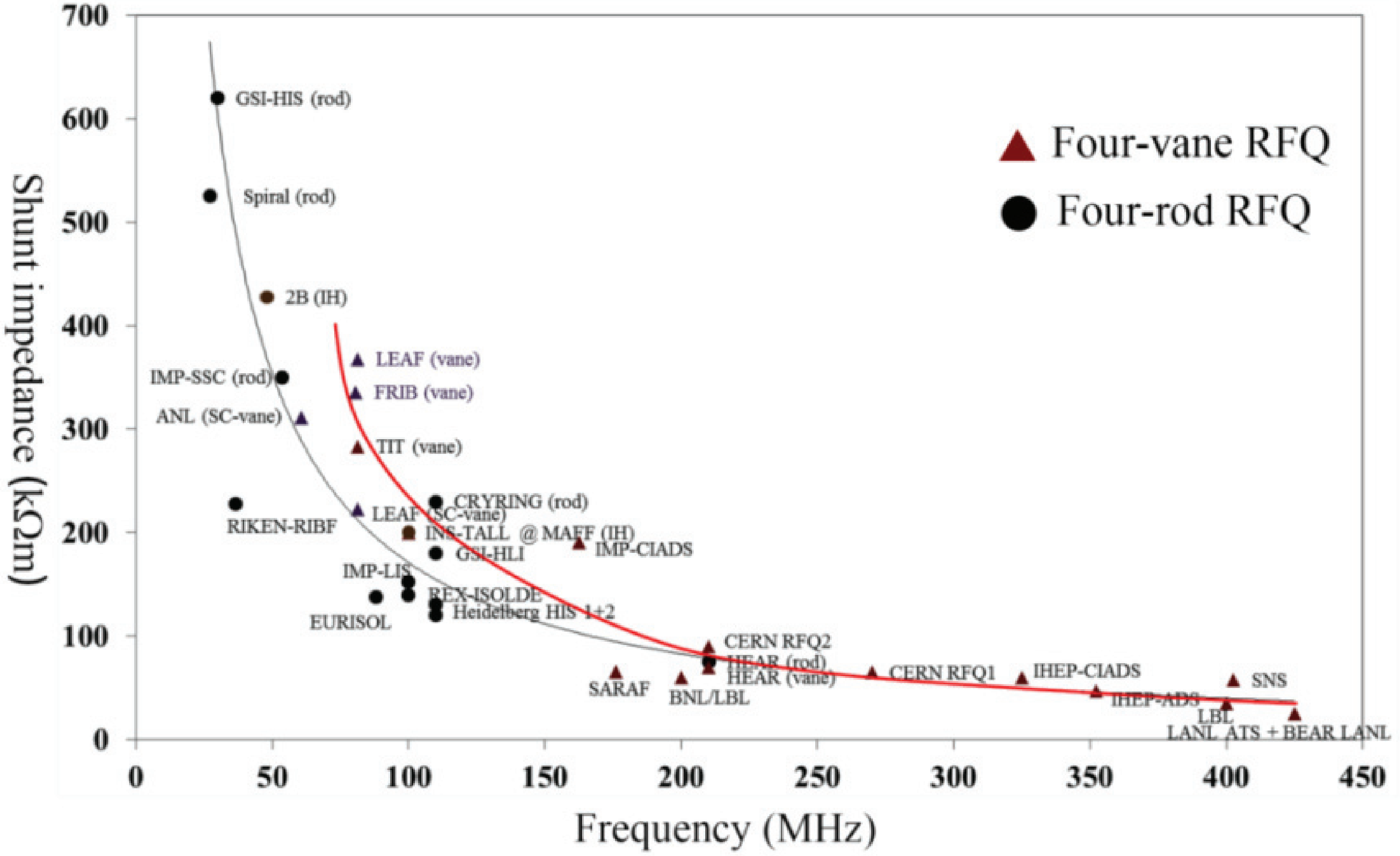
Transmission from IS to the end of the RFQ: 81.7%

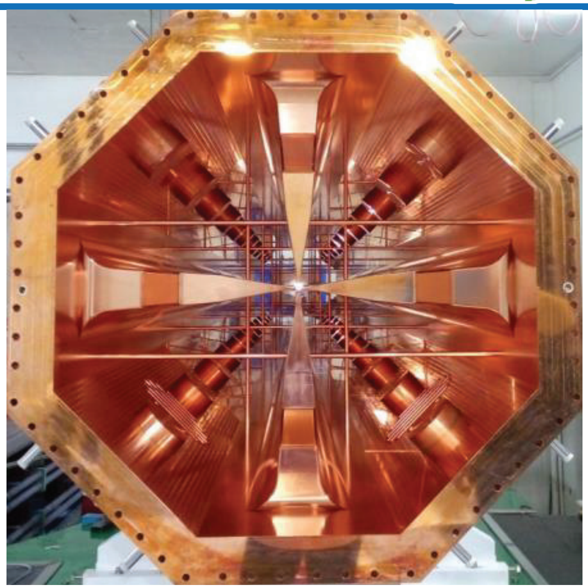
RFQ transmission: 97.2%

Structure design： vane or rod

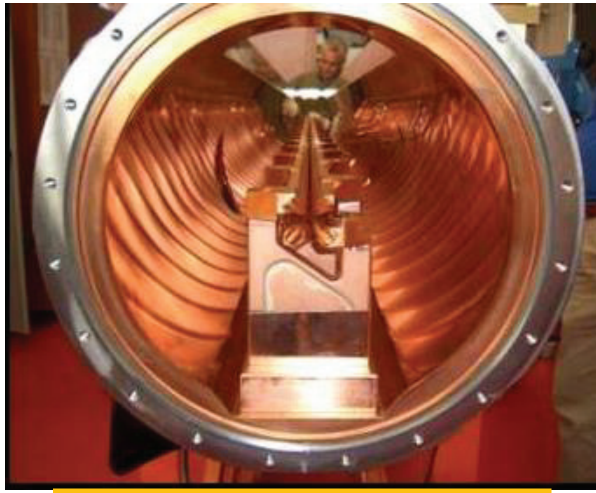
Merits of 4-vane type：
- Easy to cooling, stable, CW OK
- High shunt-impedance @ low frequency

Demerits of 4-vane type：
- Bigger structure
- Need mode separation structure





four-vane type RFQ

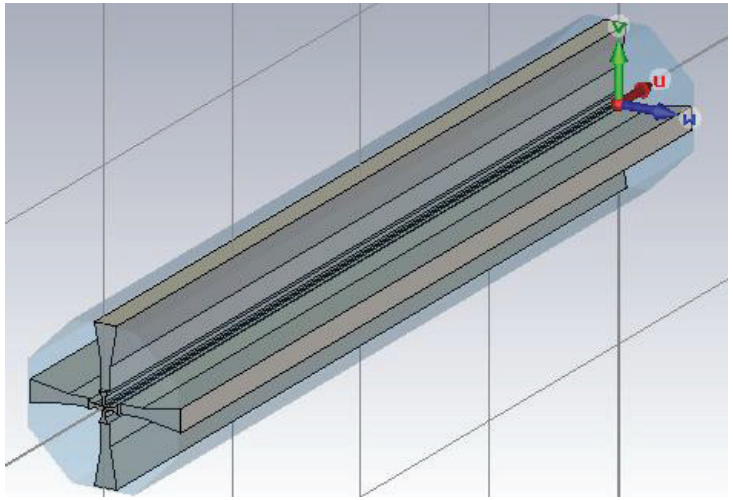


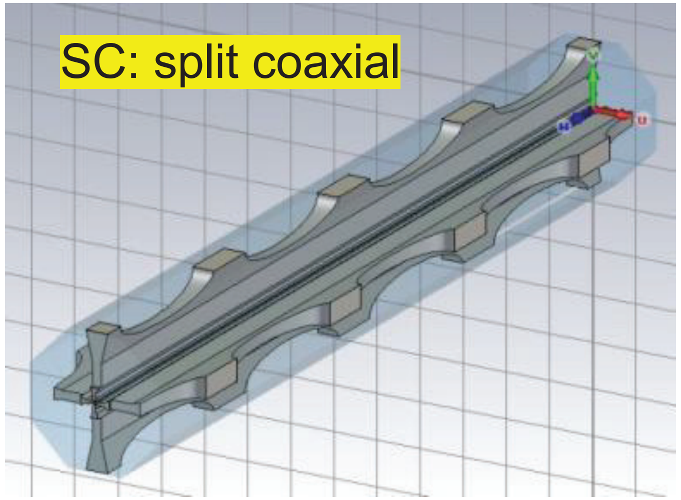
four-rod type RFQ

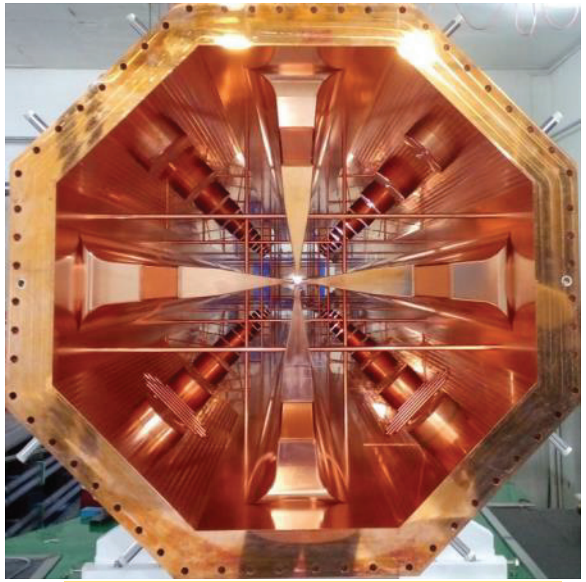
Structure design： normal vane or SC vane

Merits of normal 4-vane type：
- Easy to shape and cooling
- Low power density, few deformation
- High Q

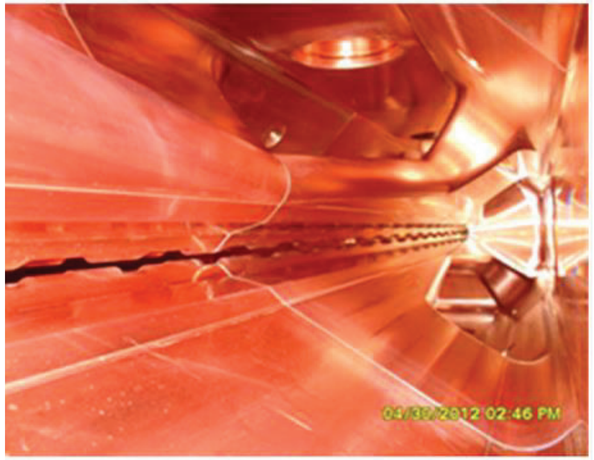
Merits of SC-vane type：
- Compact size even in low frequency







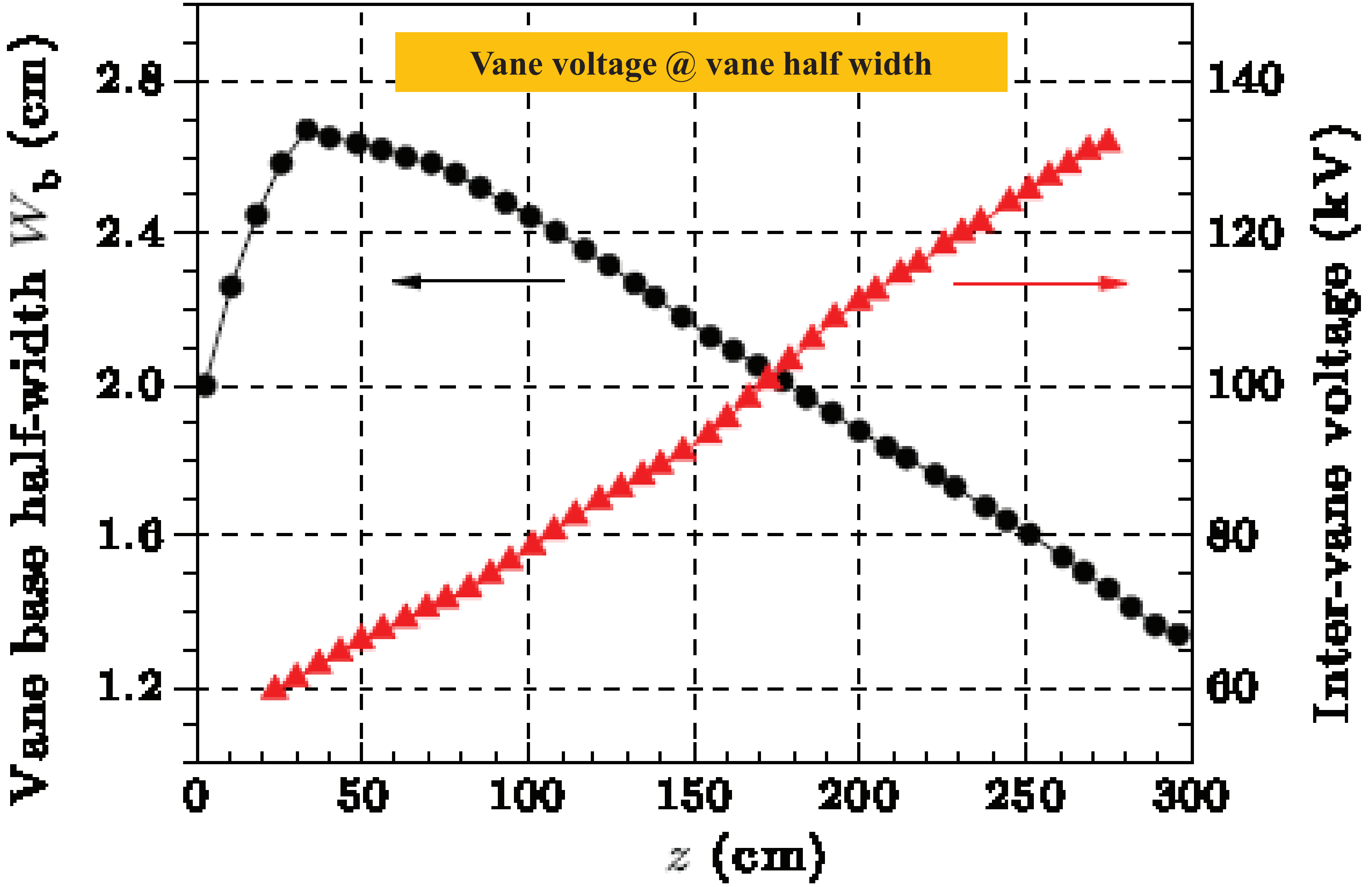
Normal vane RFQ



SC RFQ

Structure	Frequency (MHz)	Q	Loss (kw/m)	Vane H (mm)
Four vane	82.4	1.32e4	9.0	360.5
SC	82.6	9.76e3	12.8	225

Structure design： constant V or inconstant V



Feature of inconstant V type：
Increasing V due to decreasing width of vanes
Bigger surface e field

Merits of normal 4-vane type：
- High Q, lower power loss
- Lower surface e field, lower SEC

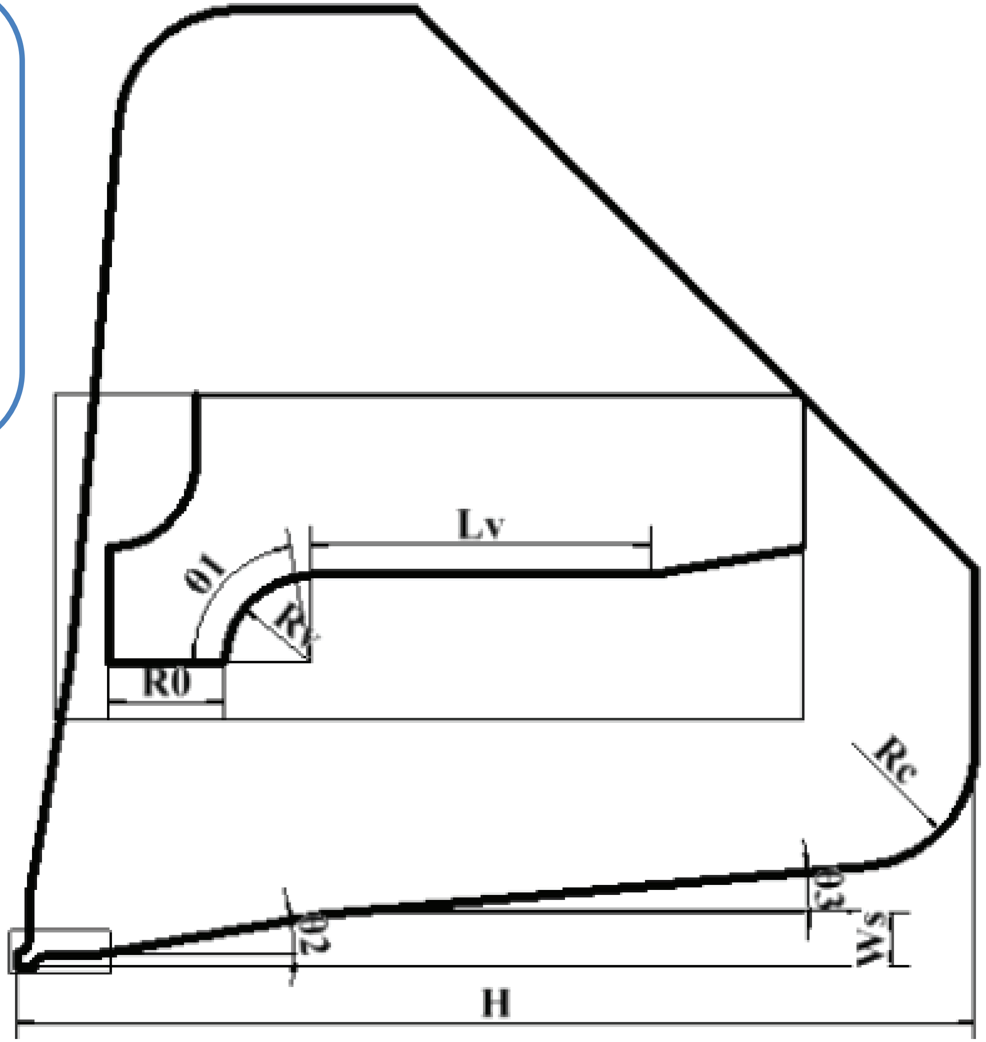
Demerits of normal 4-vane type：
- Longer length

LEAF-RFQ requirements： CW operation → low RF power, low surface E field
Finally normal 4-vane type was chosen.

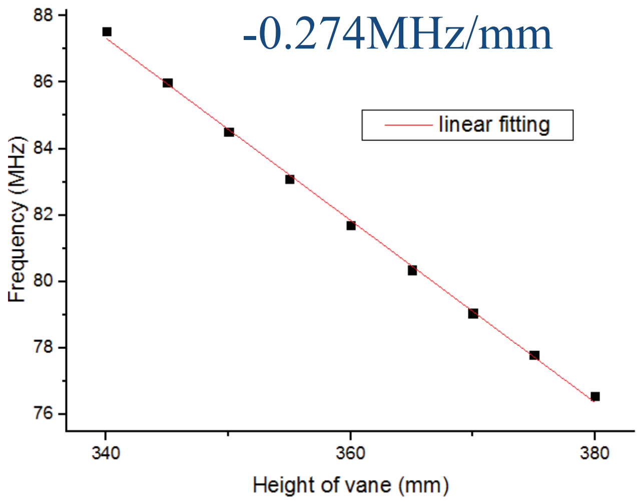
Design principle：

- Resistance to deform. → octagonal shape
- Parametric modeling
- f separation: PISL (π-mode stabilizing loops) structure

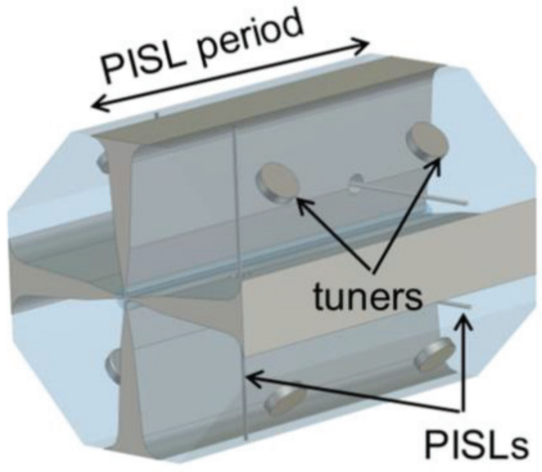
Parameters	value
Shape	octagonal
R0	5.805mm
Rv	0.75*R0
θ1	800
Lv	17mm
θ2	10°
θ3	5°
Ws	20mm
Rc	50mm
H	360.5mm



Cross section design

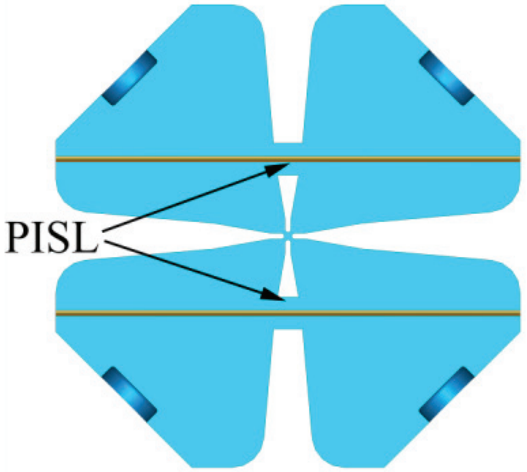


Vane Height & frequency

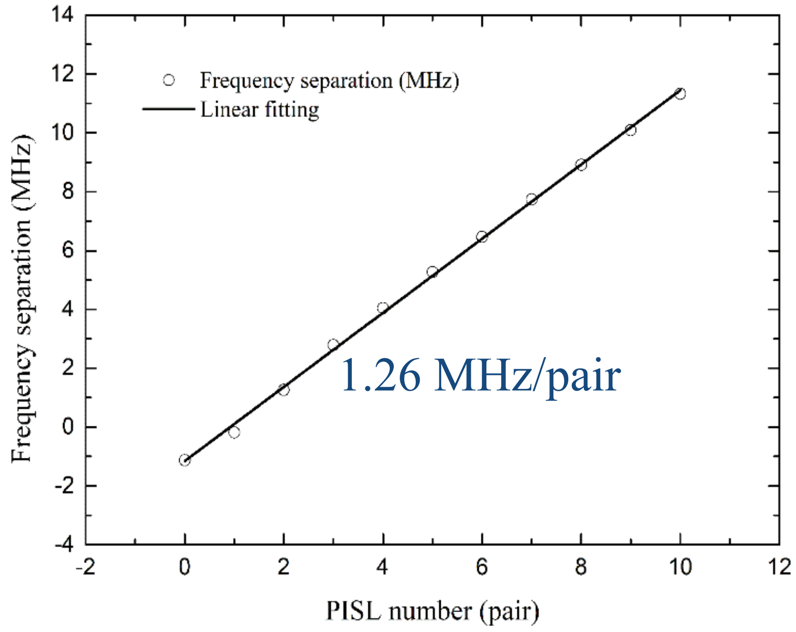


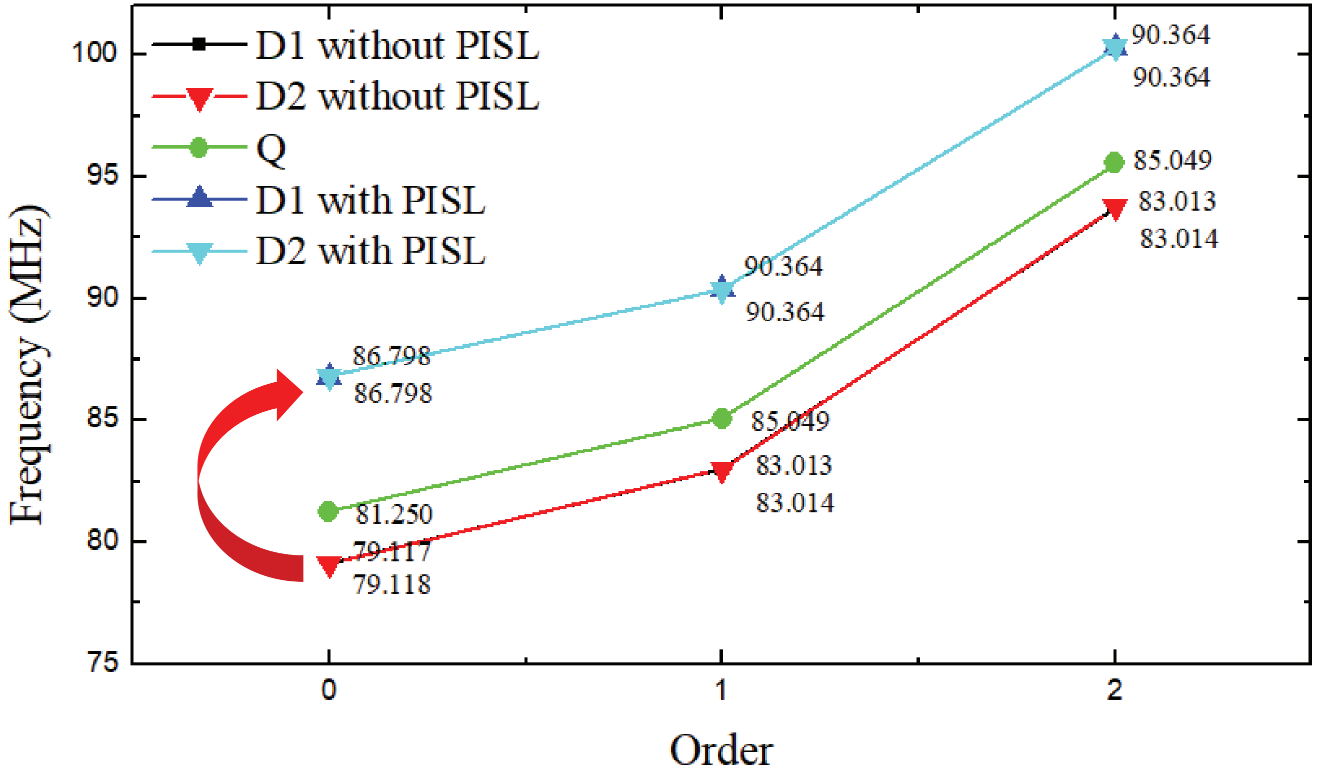
PISL periodic model

Structure design： frequency separation



Cross section of cavity with PISL





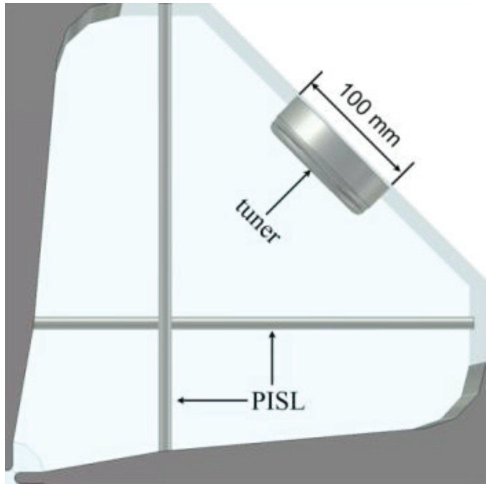
f separation with 6 pair PISLs

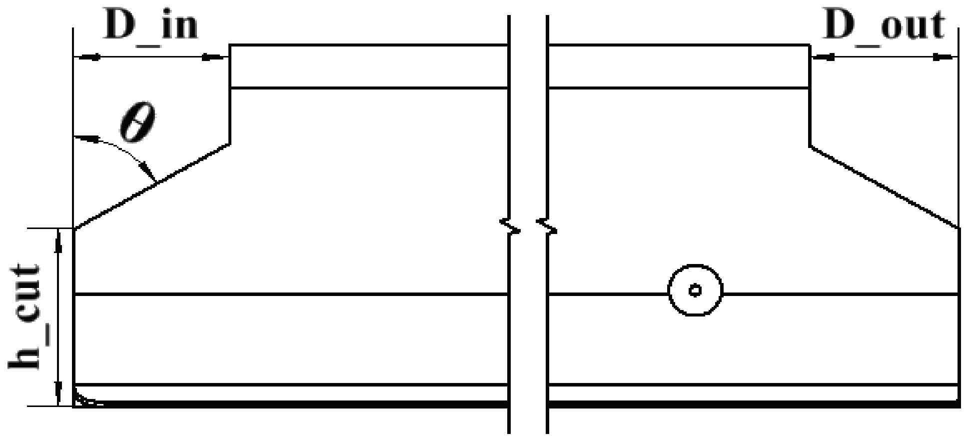
Final separated frequency ：

-2.133 MHz → 5.548 MHz

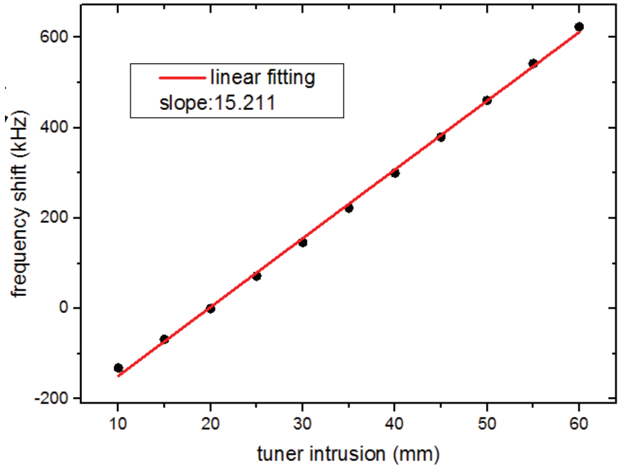
Structure design: field tuning

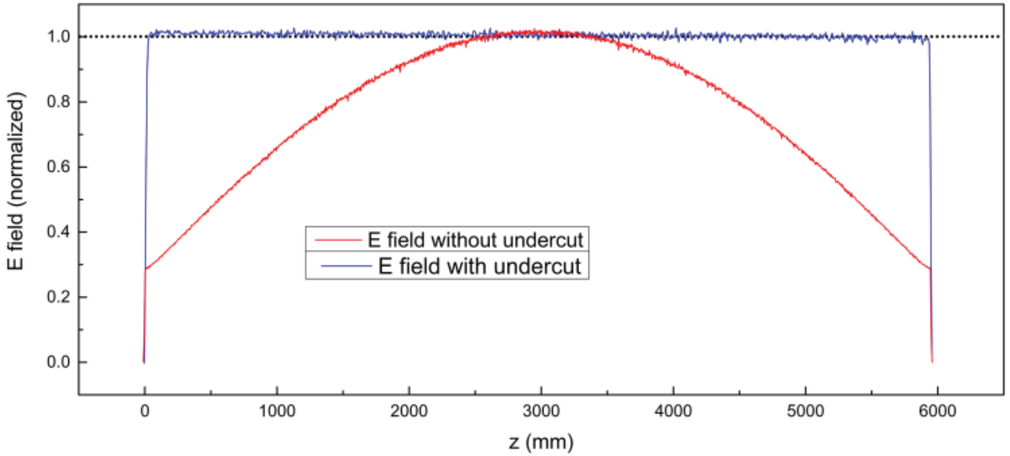
LEAF RFQ tuner





LEAF RFQ under cut





Adopted 48 tuners:

- tuning sensitivity (kHz/mm): 15.21
- tuning ability: -380 kHz~532 kHz

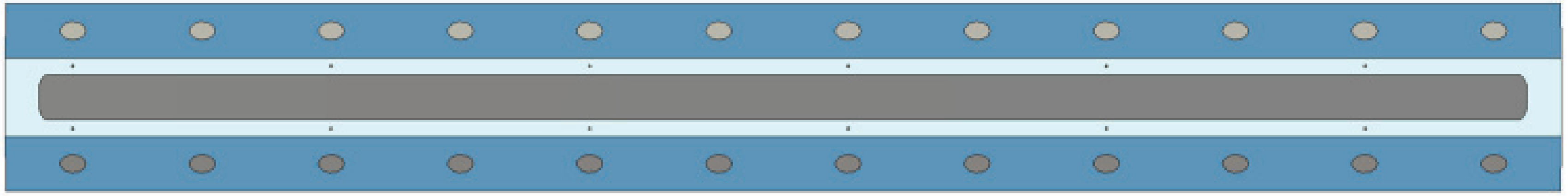
Under cut design:

- D @ entrance: 143mm
- D @ exit: 139mm

Structure design： whole length model simulation

LEAF RFQ model

5946.92 mm



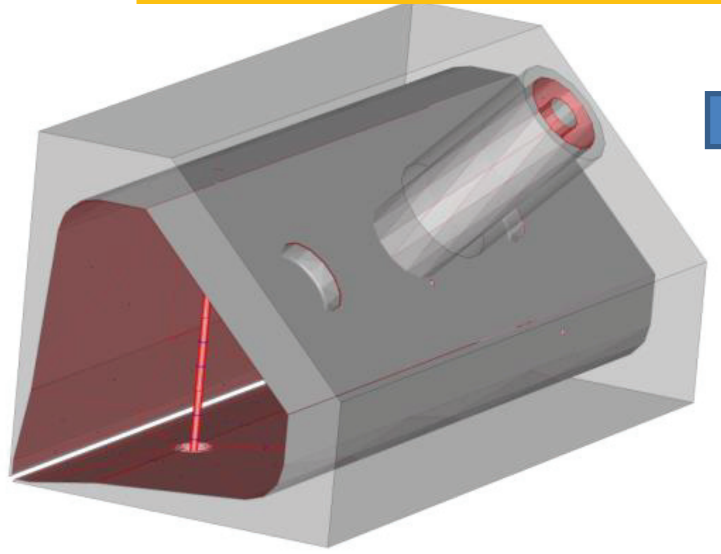
length： 5.969m； tuner： 12*4； PISLs： 2*12 pair； with modulation

Parameters of the final model	LEAF RFQ	FRIB RFQ
frequency (MHz)	81.246	80.5
Q	**17963**	**16500**
neighbor dipole mode (MHz)	86.812	78.3/83.2
dissipated RF power (kW)	**53.196**	**100**
power loss (kW/m)	8.945	19.8

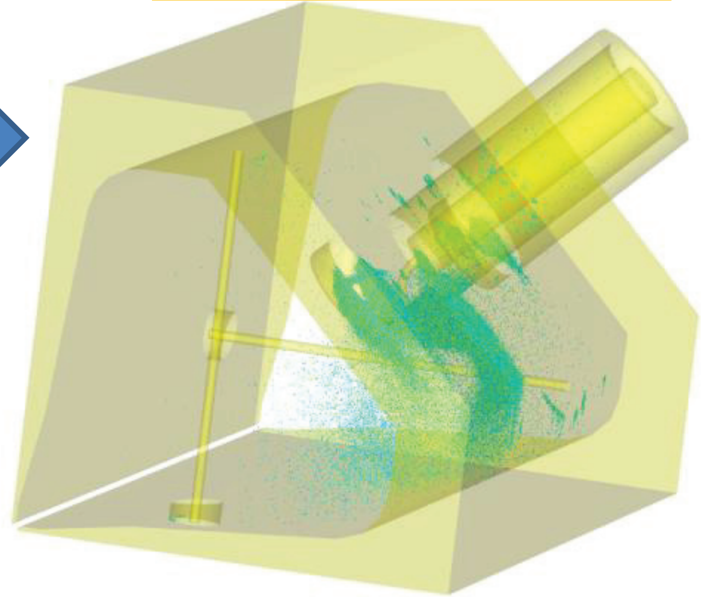
parts	Power loss
Vanes	4.81 kW/m
Wall	3.18 kW/m
Tuners	42.7 W / tuner
PISLs	144 W / pair

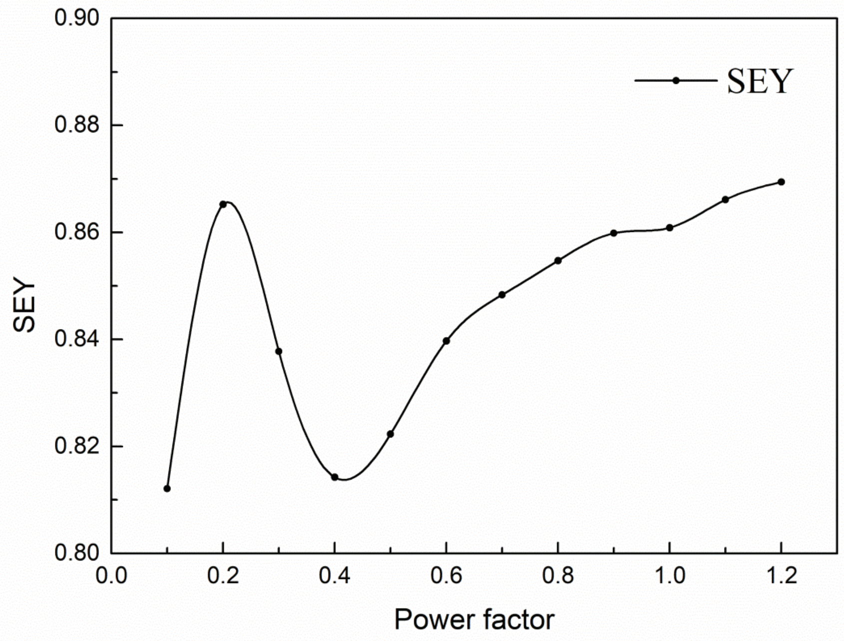
Structure design: secondary electron simulation

Model for SE simulation



SE: secondary electron





LEAF RFQ二次电子倍增模拟结果

$$< SEY >= I_{emission} / I_{collission}$$

SE multipacting:

- Surface damage
- RF instable, total reflection
- Bad vacuum

Emission electron

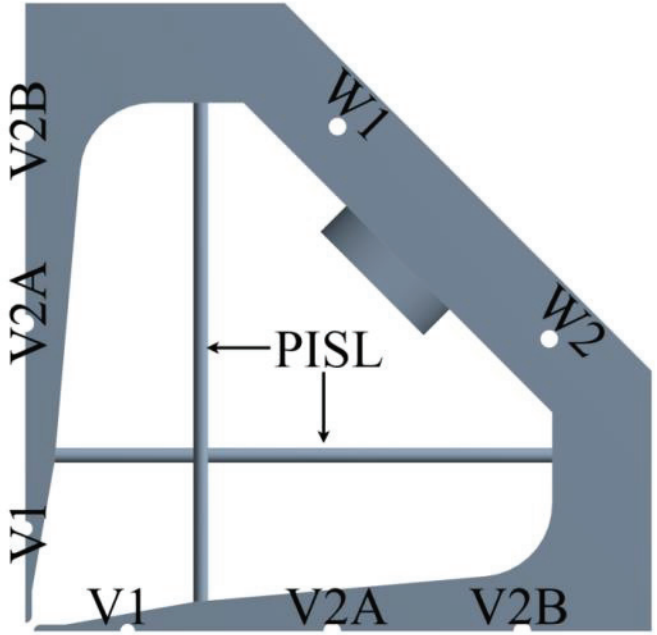
Collision electron

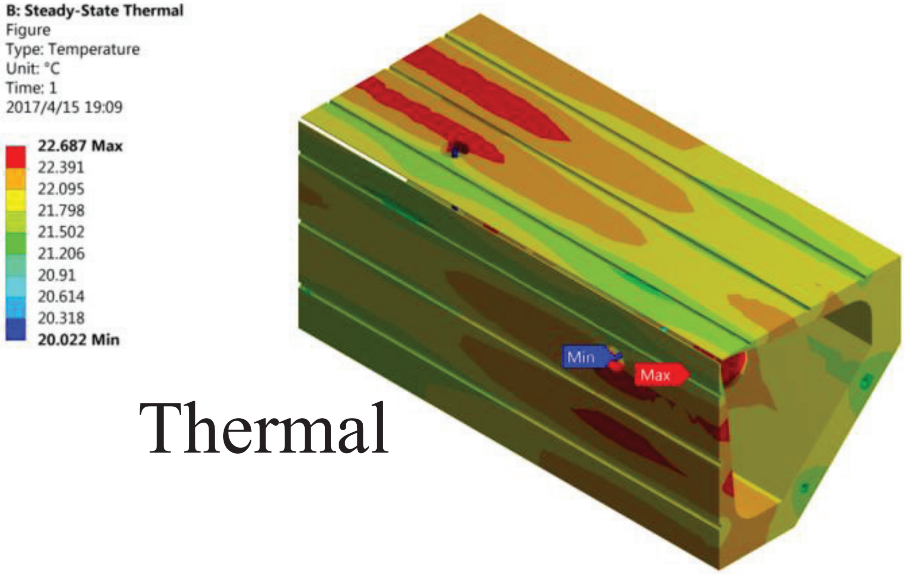
Multipacting judgement:
<SEY> >1 or <1

<SEY> was less than 1 in full RF operation

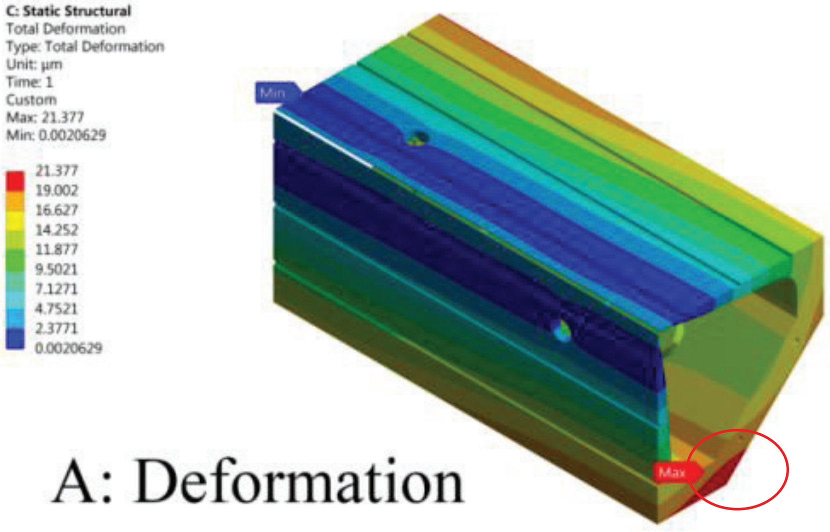
ARC were not observed in RF conditioning

Structure design： whole length model simulation

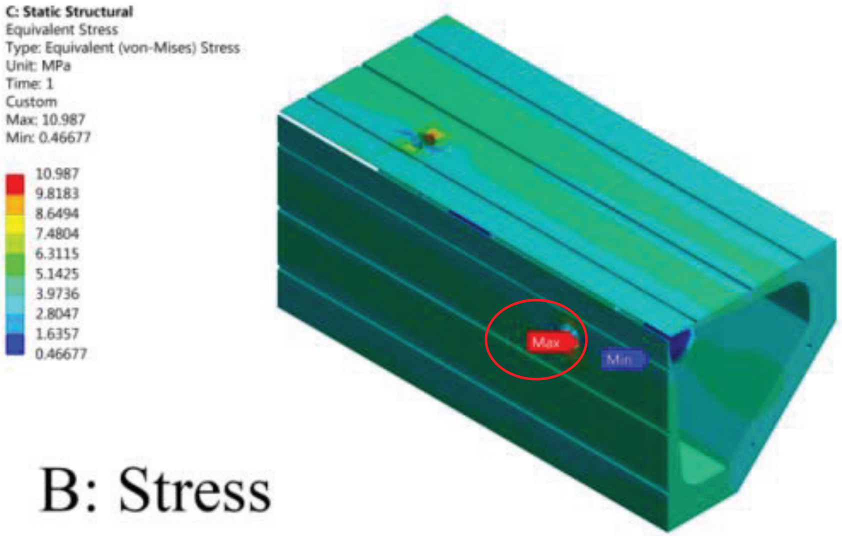




Thermal



A: Deformation

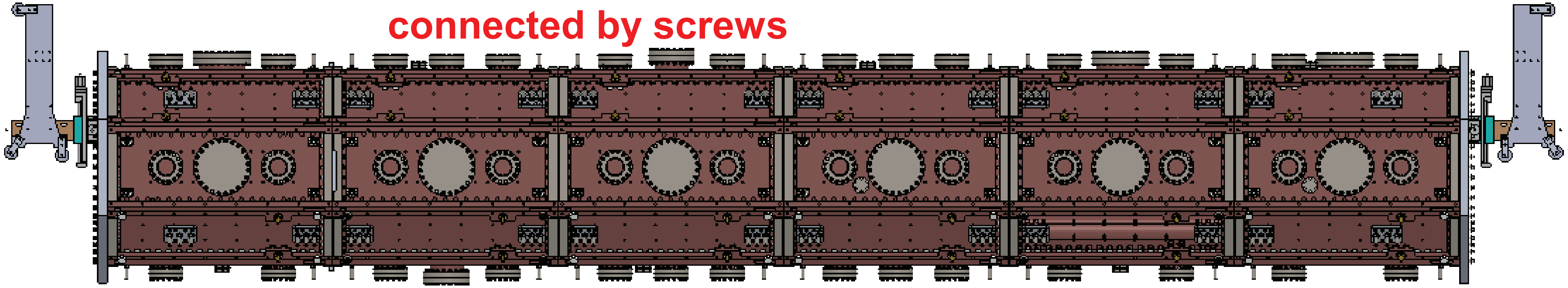


B: Stress

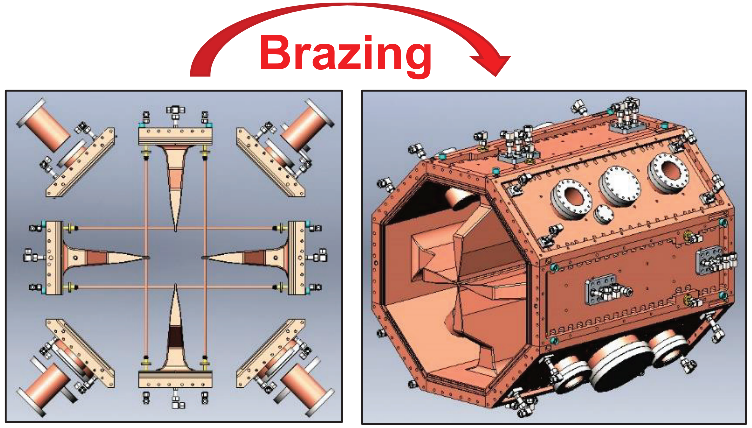
- Max. T: 22.7°C
  rised 2.7 °C （water 20 °C ）
- max deform.: 21.4 μm
- max. stress: 10.99 MPa
- Δ f: -17.9 kHz

thermal, deformation, stress and frequency shifting were acceptable

RFQ Designs



Parameters	Value
Particle	U34+ (center q, q/A=1/7)
Operation	CW
Vane type	Four vane
Frequency (MHz)	81.25
Input energy (keV/u)	14
Output energy (MeV/u)	0.5
Inter-vane voltage (kV)	70
Peak current (emA)	2
Kp. factor	1.55



- 5.96m; octagon shape; 6 segments; 48 tuners; two couplers; 9 pump ports;
- PISLs were designed to separate the dipole mode; under-cuts were used to adjust field distribution.

Measurements of segments

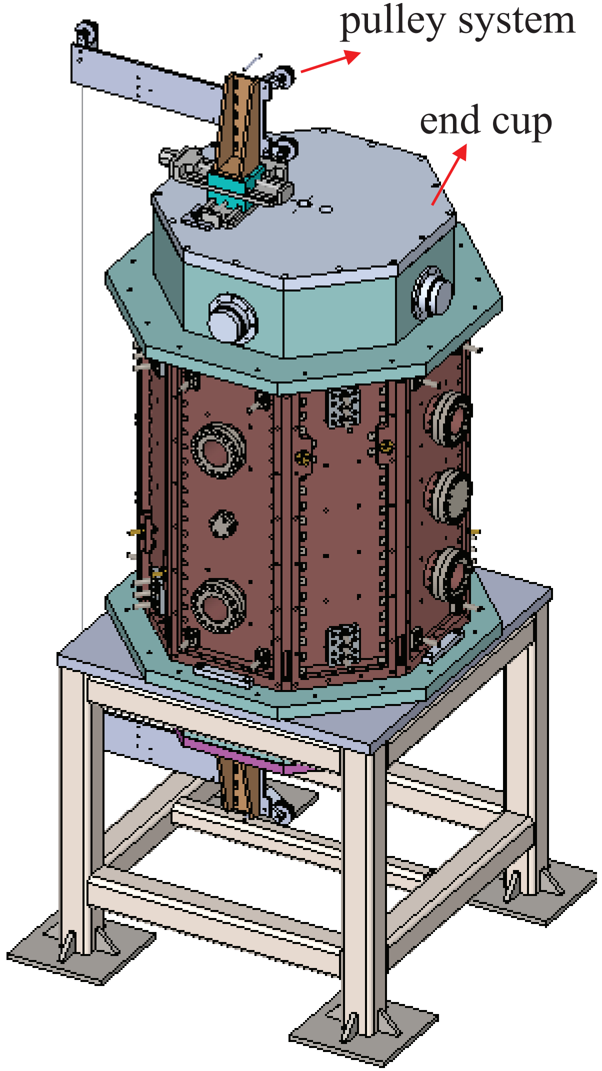


Image of measuring

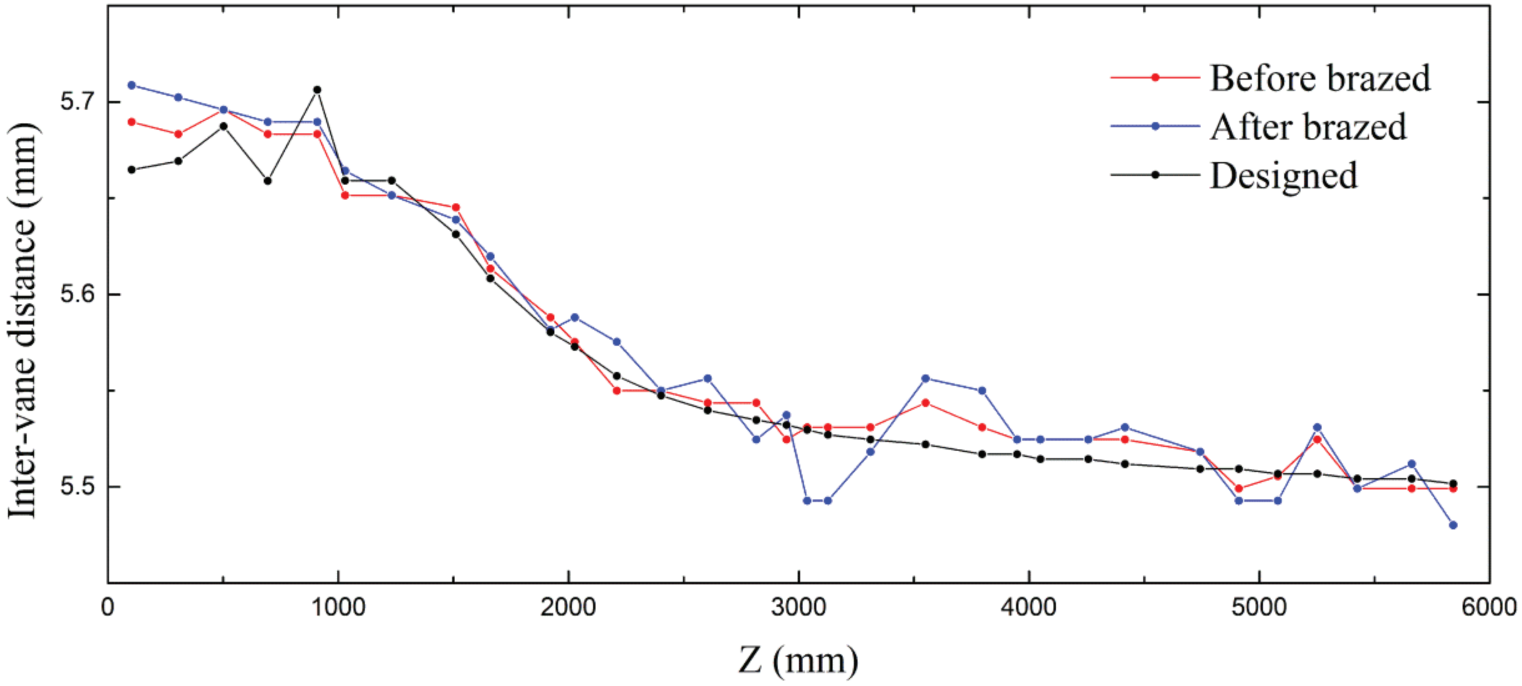
Items		Seg.1	Seg.2	Seg.3	Seg.4	Seg.5	Seg.6
frequency	*f*-designed	81.2596	81.2103	81.2062	81.2192	81.2192	81.2199
	f-before brazing	81.3035	81.2250	81.1678	81.2310	81.2209	81.2654
	f-after brazing	81.2437	81.2048	81.1680	81.1967	81.2005	81.2598
	Δ*f*	-15.9	-5.5	-38.2	-22.5	-18.7	+39.9
Q	*Q*-designed	14457	15517	15525	15532	15526	14414
	Q-before brazing	8344(Cu)	7040(Al)	8100(Cu)	7839(Al)	7918 (Al)	7930 (Al)
	Q-after brazing	9020(Cu)	8200(Al)	7900(Al)	7930 (Al)	7370 (Al)	8594 (Al)
	Q%	62.4	52.8	50.9	51.1	47.5	59.6

f unit: MHz | 1 Al end-cup | 2 Al end-cups | Al Cu: tuner material

- Perturbation method was used in the low power test;
- Both the frequency and field distribution were very good;
- Q values were very low because of adopting Al end cups and Al tuners;

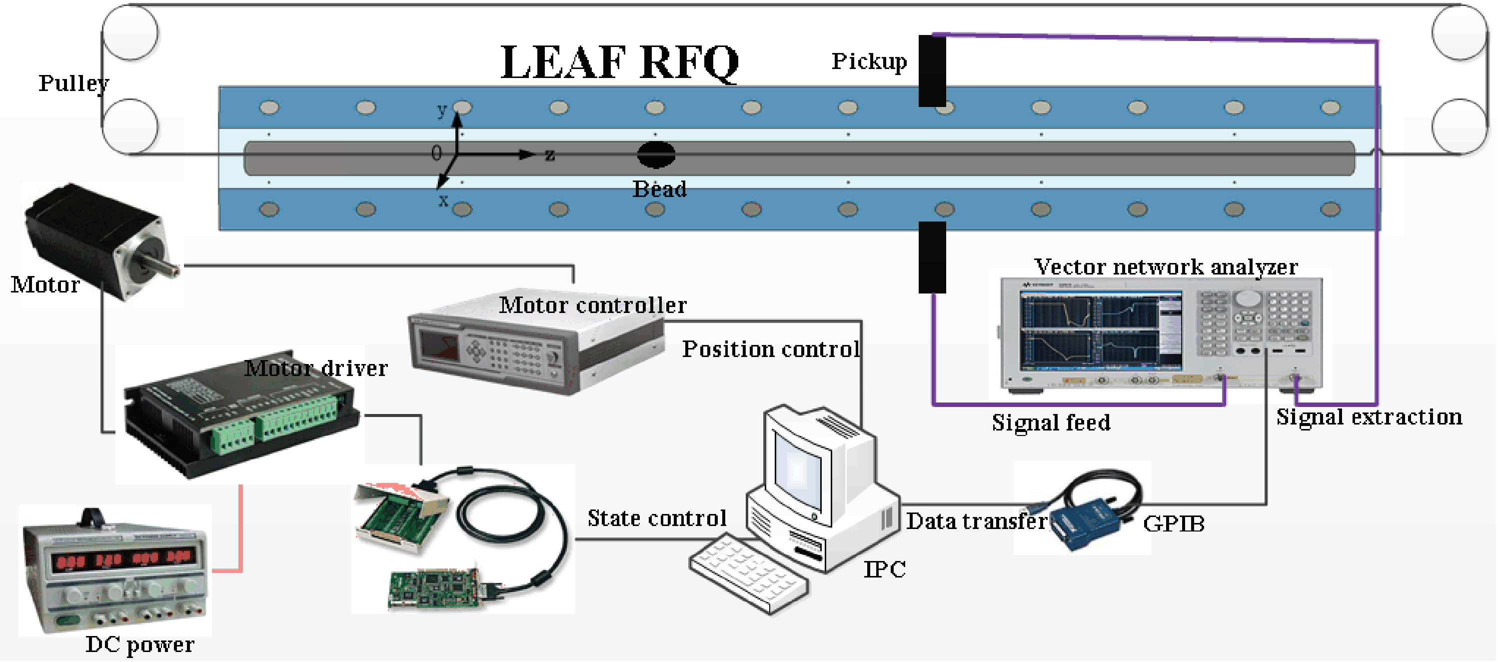
alignment and low power test

Items	Measured @ KL	Measured @ IMP	Δ
frequency	81.24526 MHz	81.25346 MHz	3.46 kHz to design
Q_0	75.3% (Al end-cups + Al tuners)	90.37%	15.1%
Flat of Q field	<0.5%	<0.8%	-0.3%
Flat of D field	<1.5%	<1%	0.5%

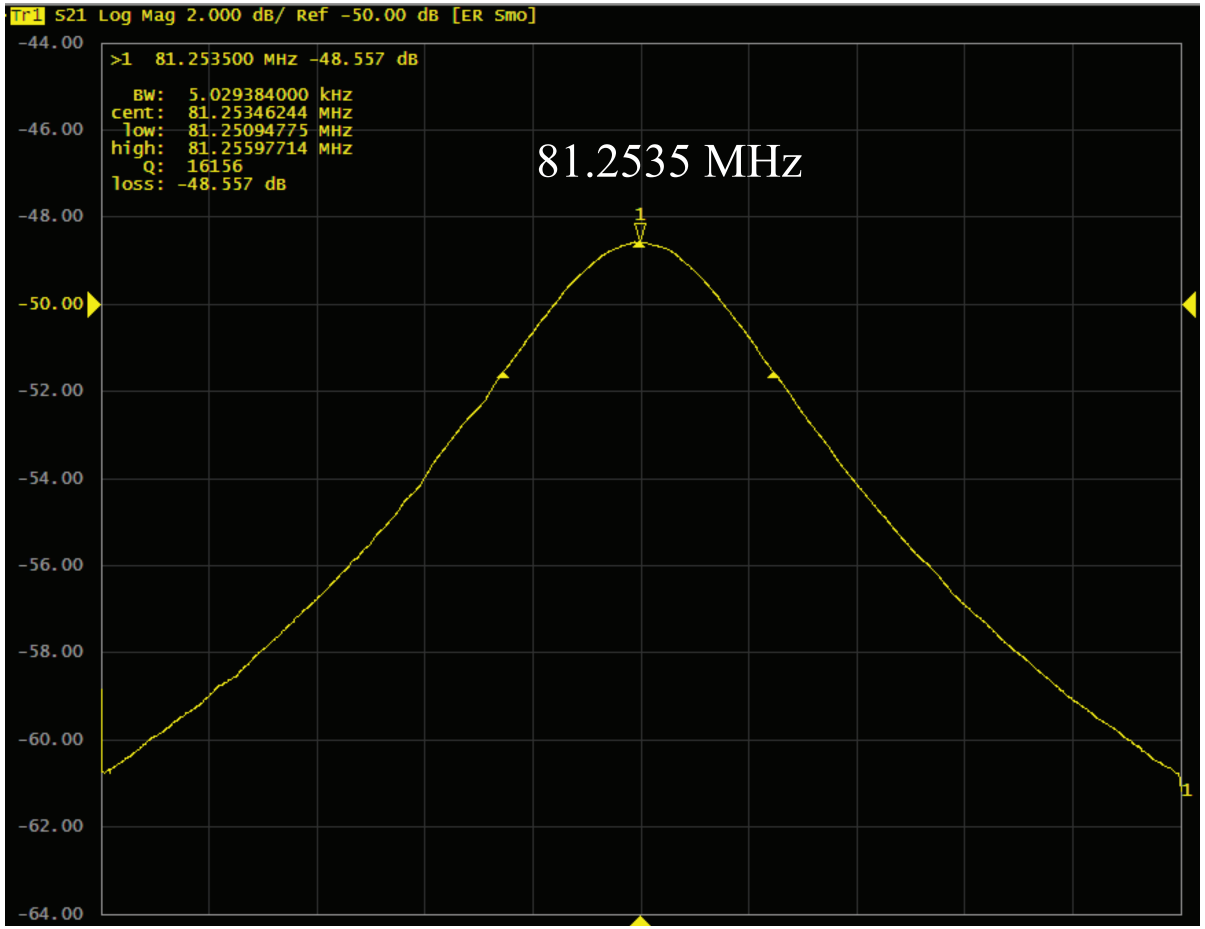


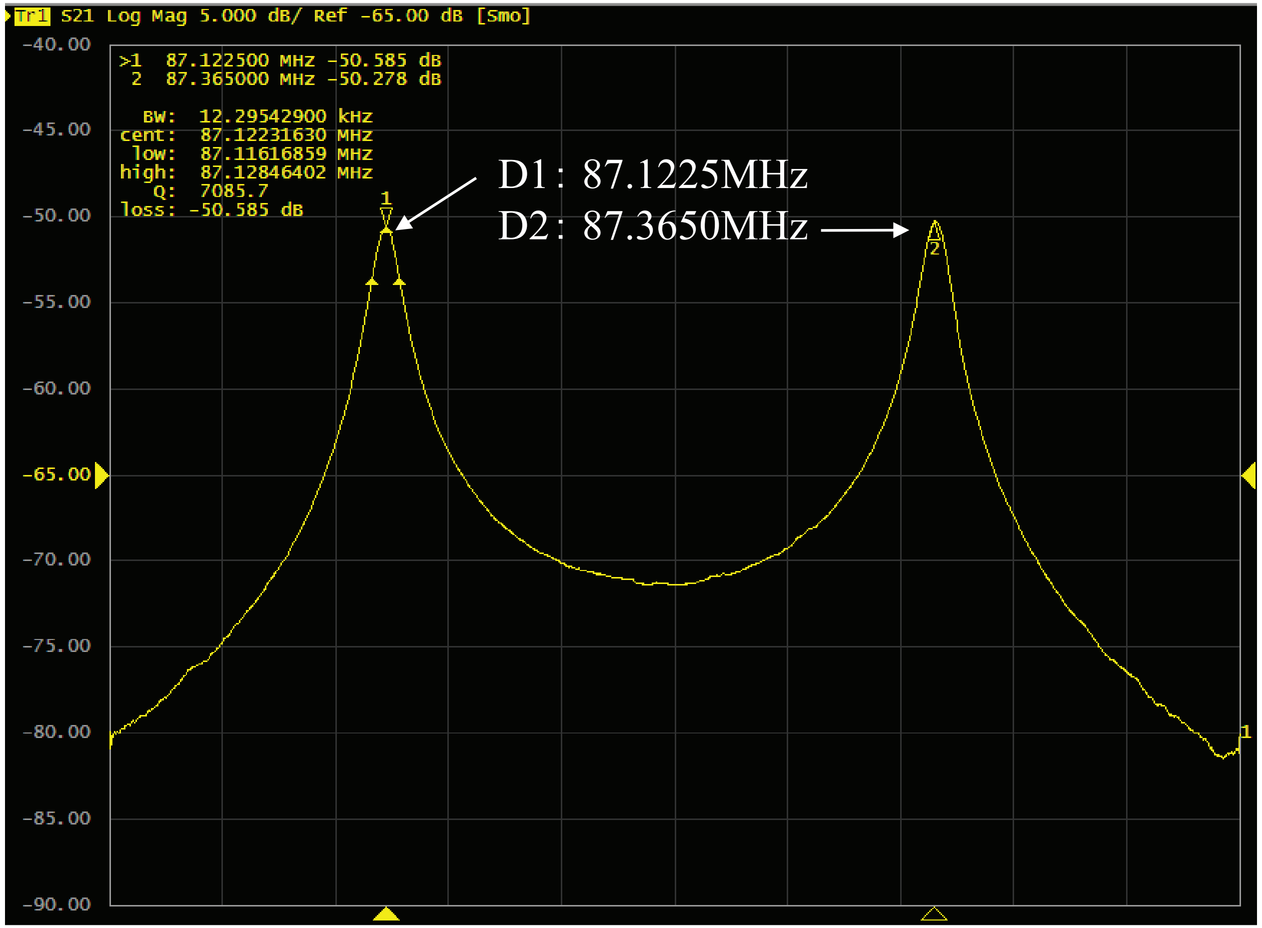
Max error： 43.89 μm

Measurements of full length RFQ



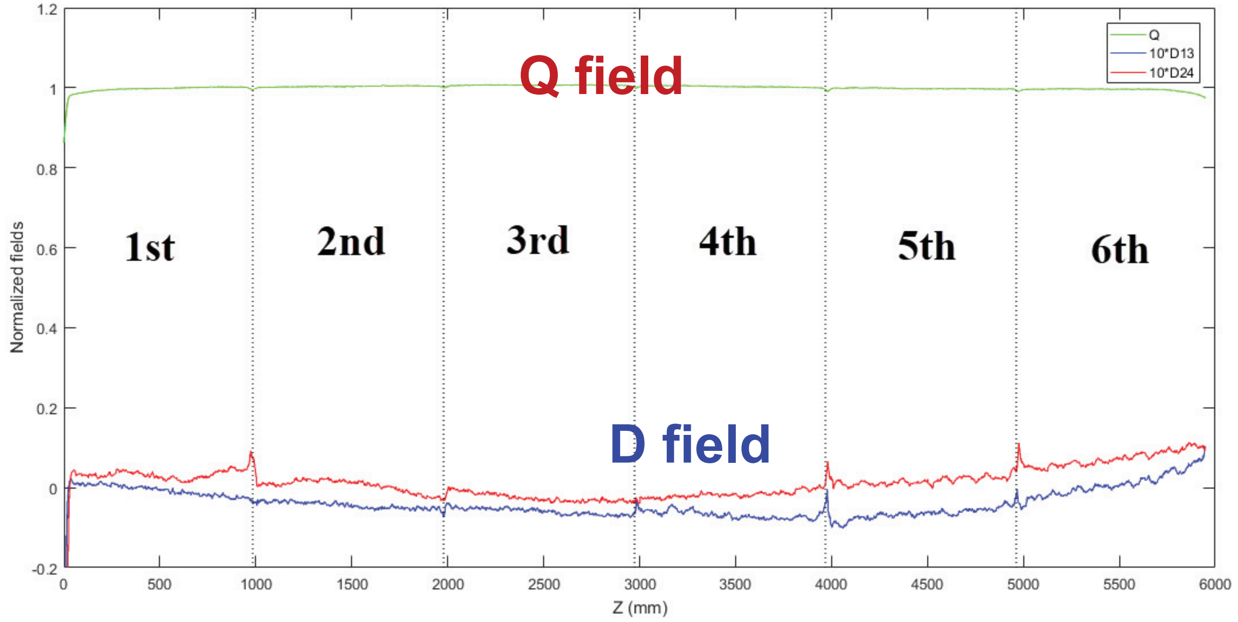
Measured Results



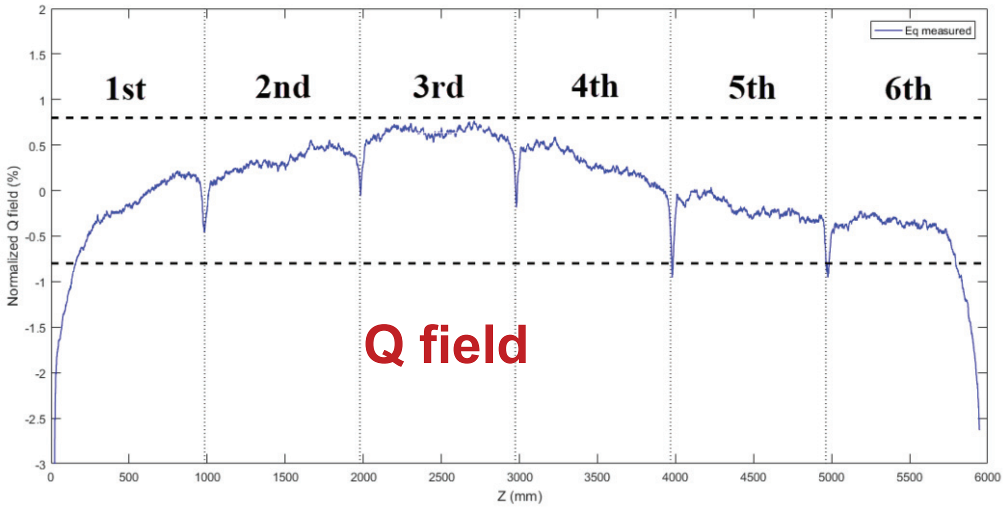


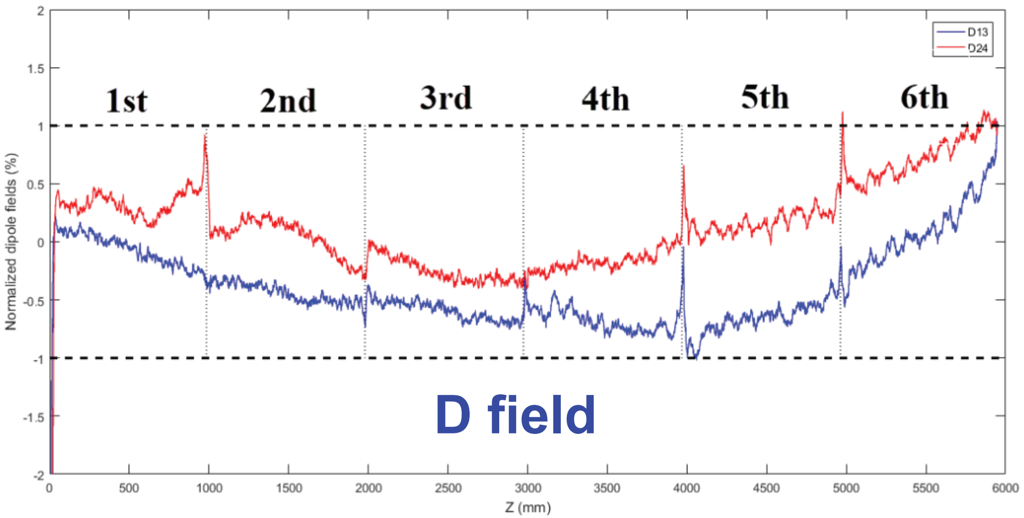
- ➢ Target frequency was measured 81.25346MHz, only 3kHz different
- ➢ 5.87 MHz separated

Measured Results

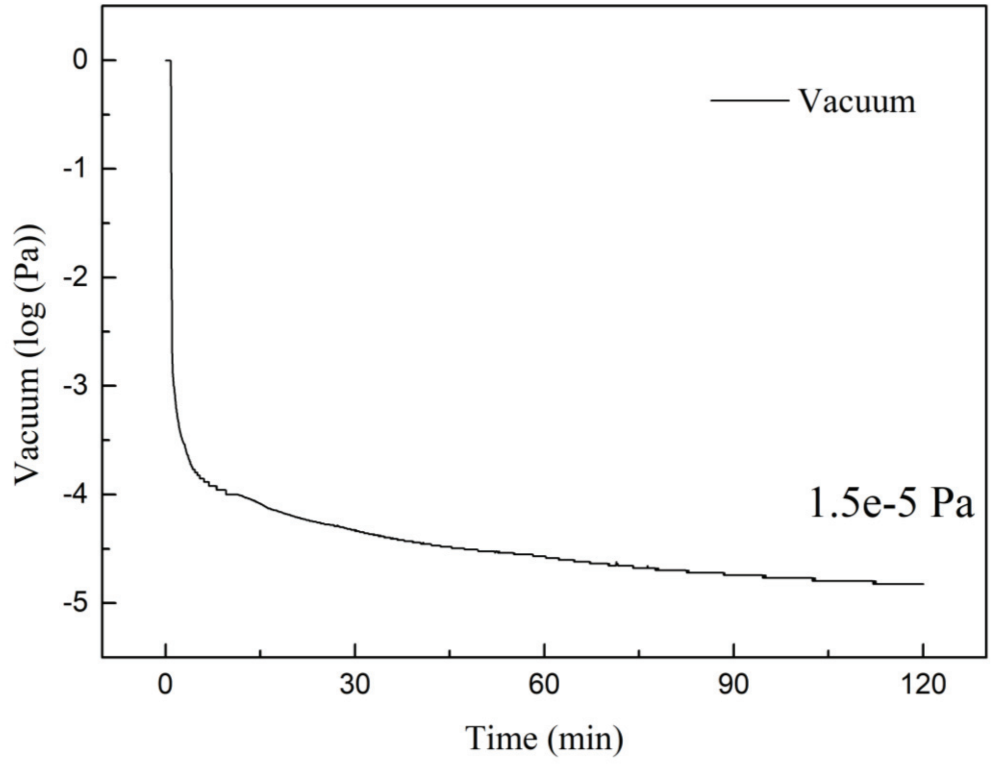


- The flat of Q field is lower than 0.8%, the flat of D field is lower than 1%;
- Measurements @ KL is better than IMP, but it is good enough for RF power load and beam acceleration;

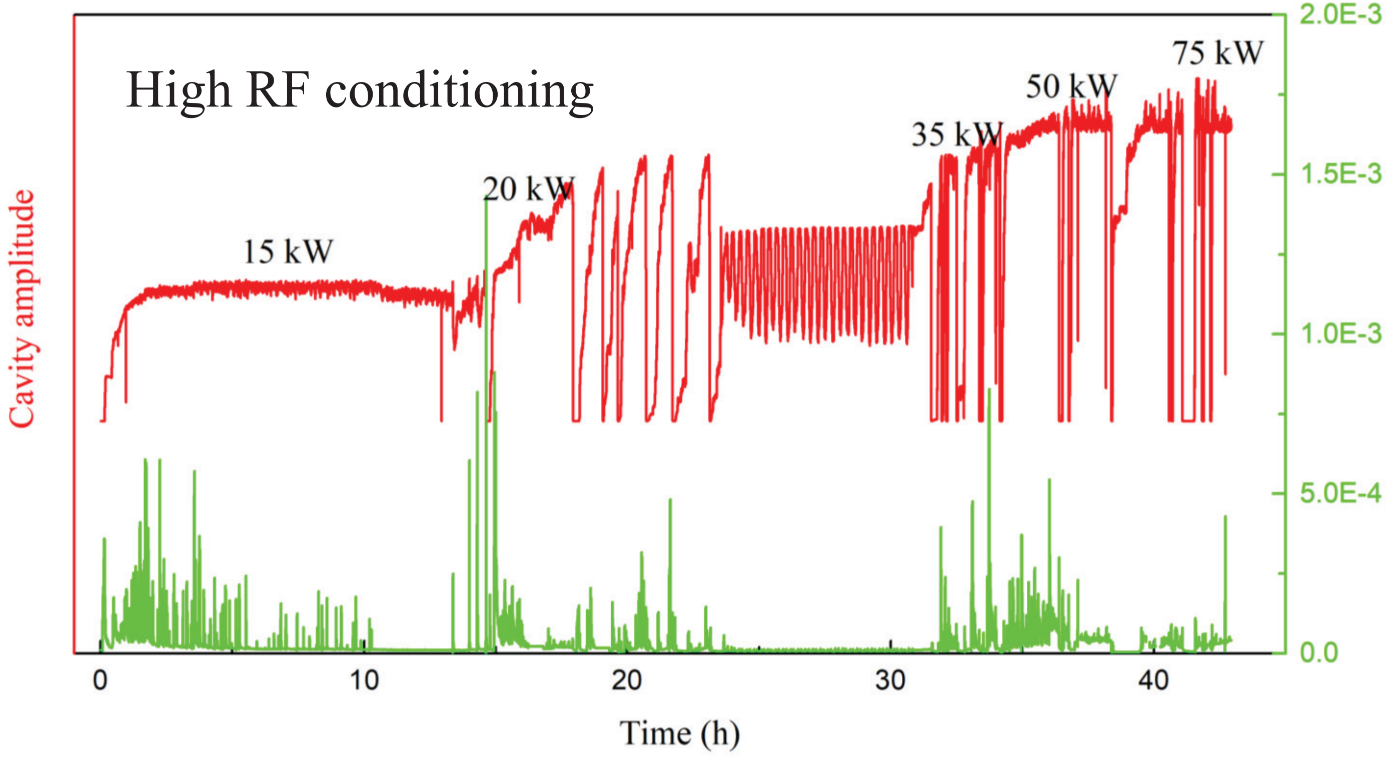




RF Conditioning

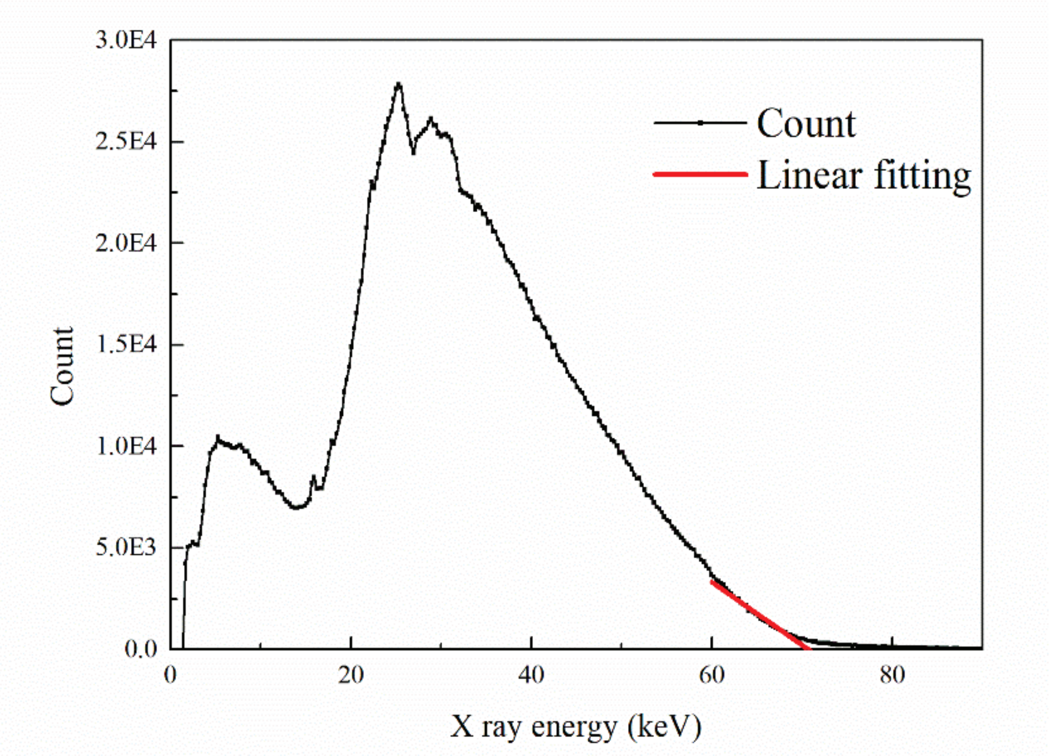


LEAF RFQ vacuum

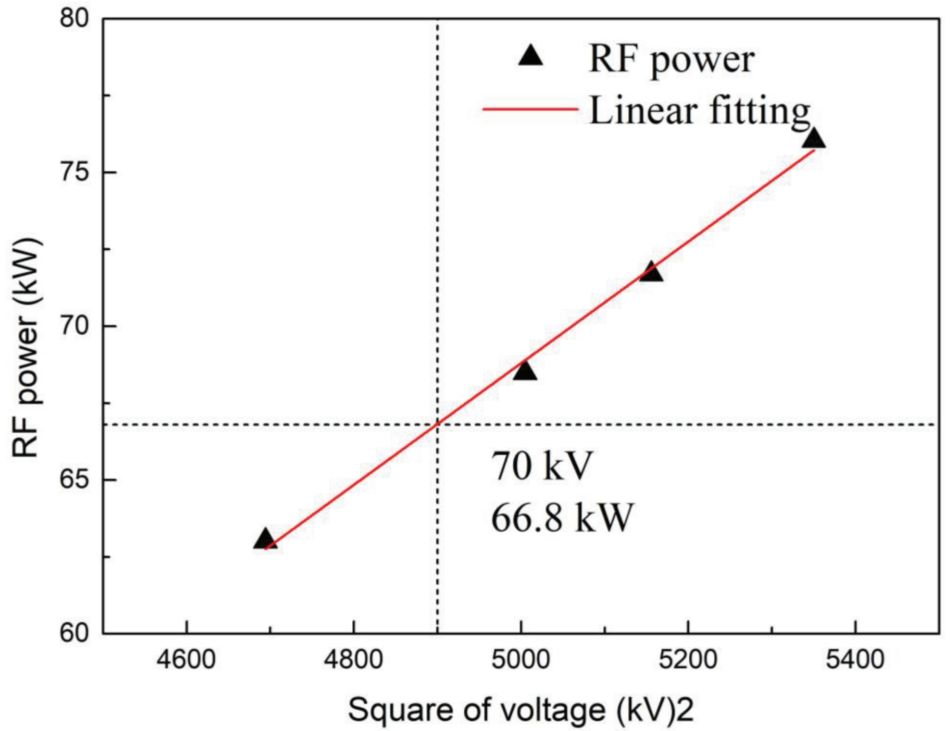


High RF Conditioning process of LEAF RFQ

- **Achieved CW** 75 kW in 44h；
- Heavy/continuous Arc and multi-parckting are not observed；
- Final vacuum achieved 3e-6 Pa；



X ray measurement



Fitting of voltage and RF power

➢ 测量方法:
- ✓ CdTe detector for X ray;
- ✓ high energy region.

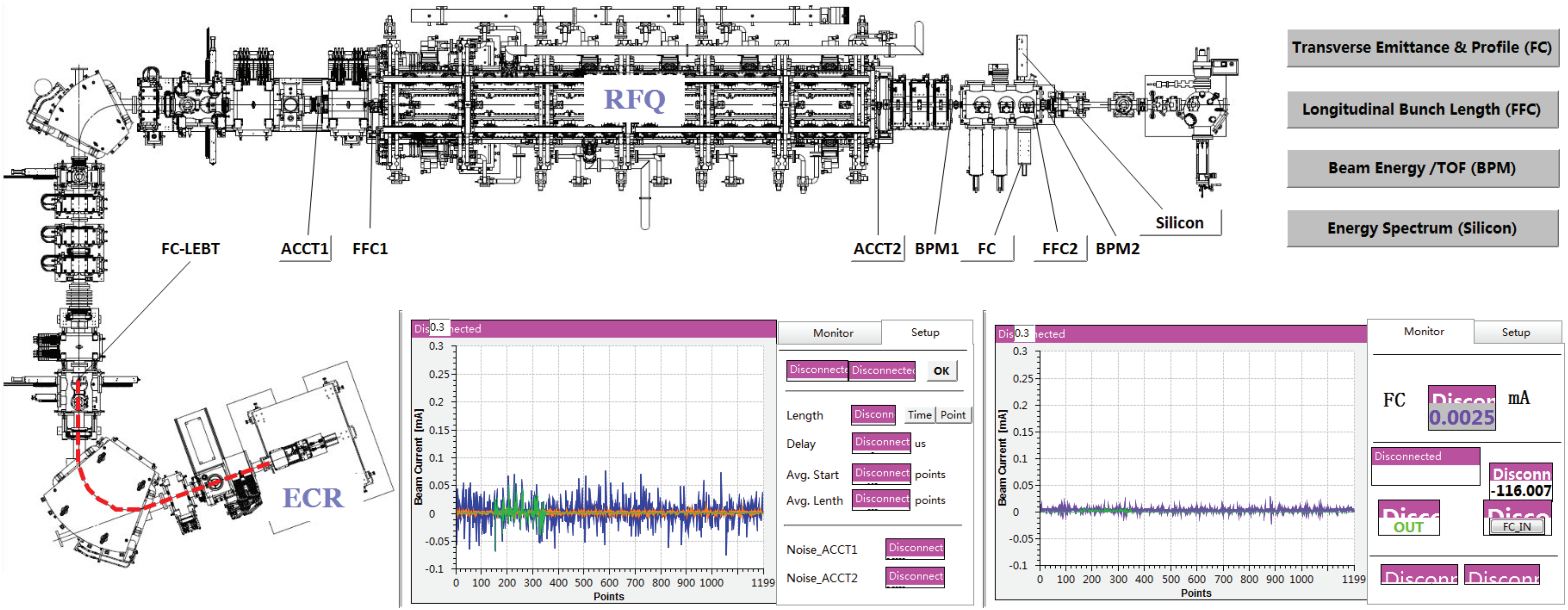
➢ 测量结果:
- ✓ Achieved 70kV when input RF is 66.8kW (designed value is 53kW@cavity + 90%@Q+7kW@beam);
- ✓ Coupling factor is 1.1

LEAF Diagnostics

LEAF - Beam Diagnostics GUI

Go back v1.0

Help



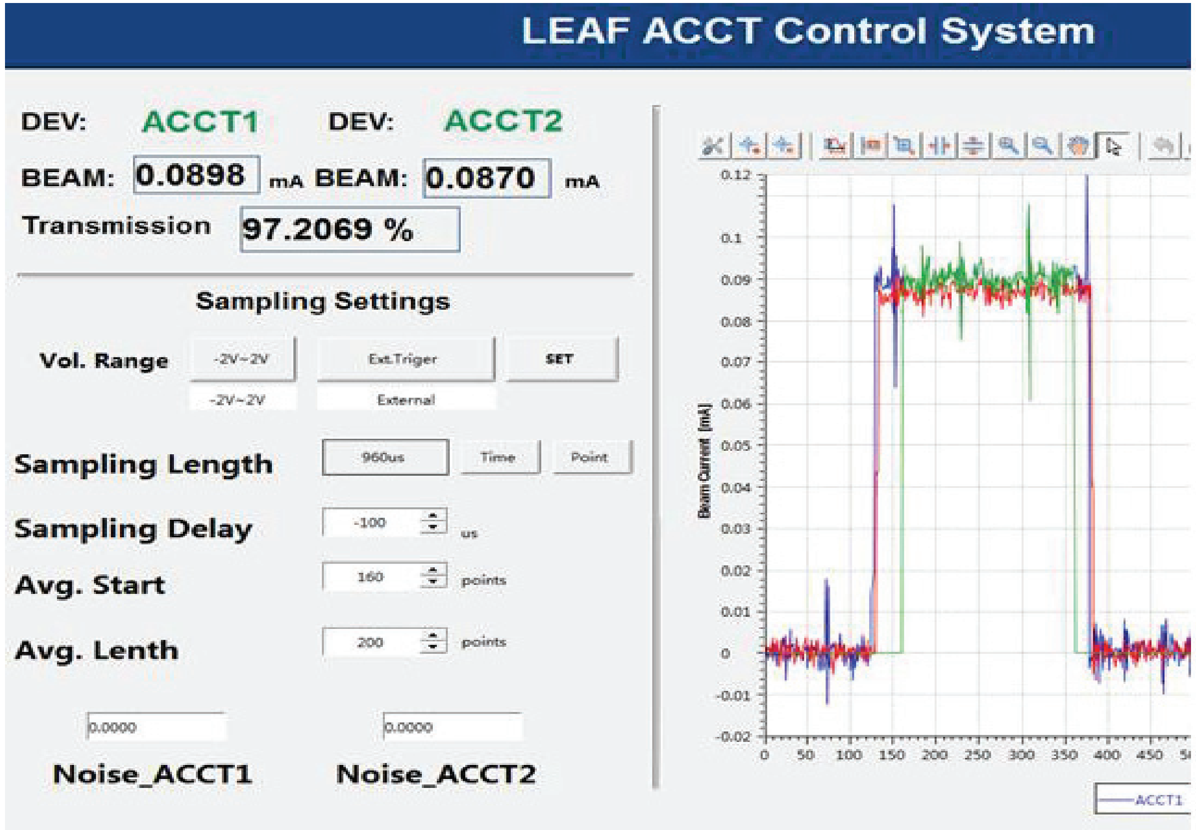
Transverse Emittance & Profile (FC)

Longitudinal Bunch Length (FFC)

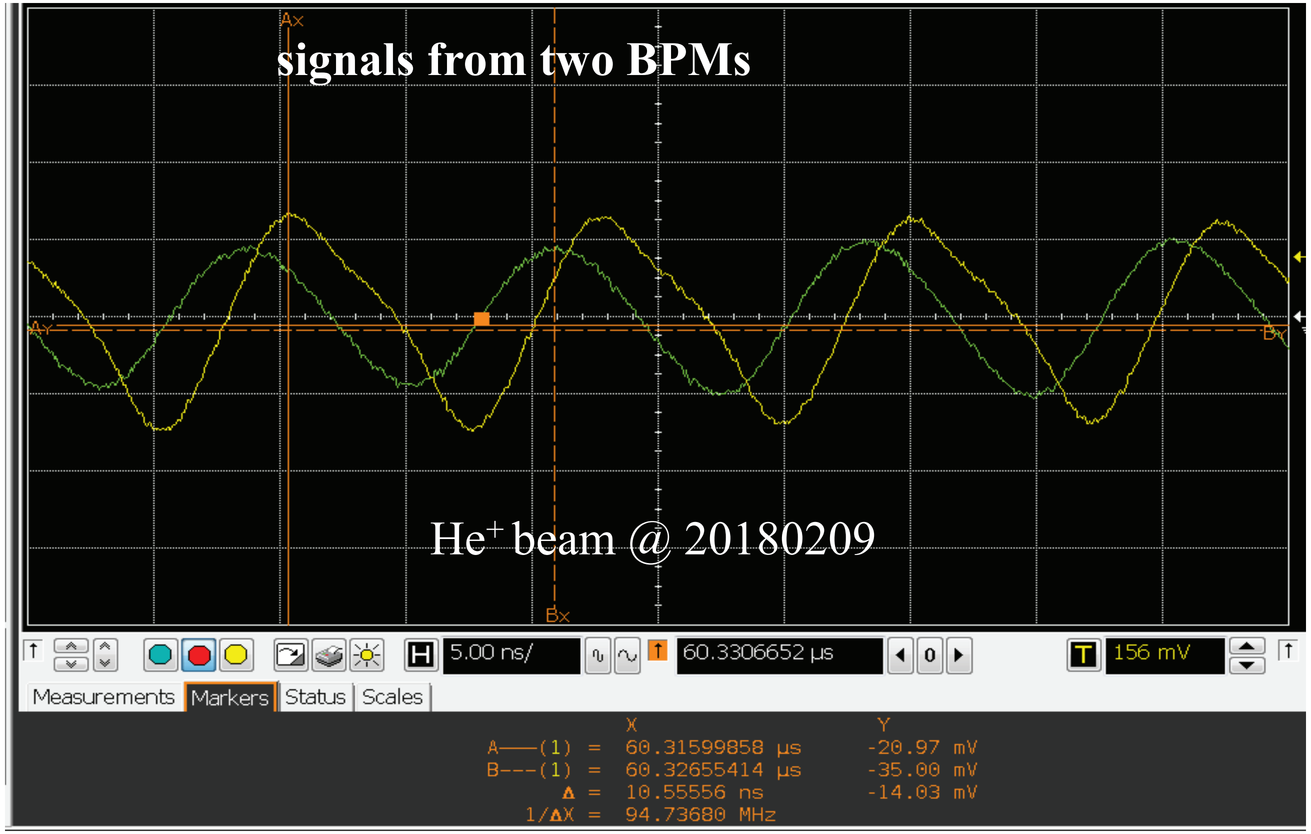
Beam Energy /TOF (BPM)

Energy Spectrum (Silicon)

Measurements: He$^+$ beam



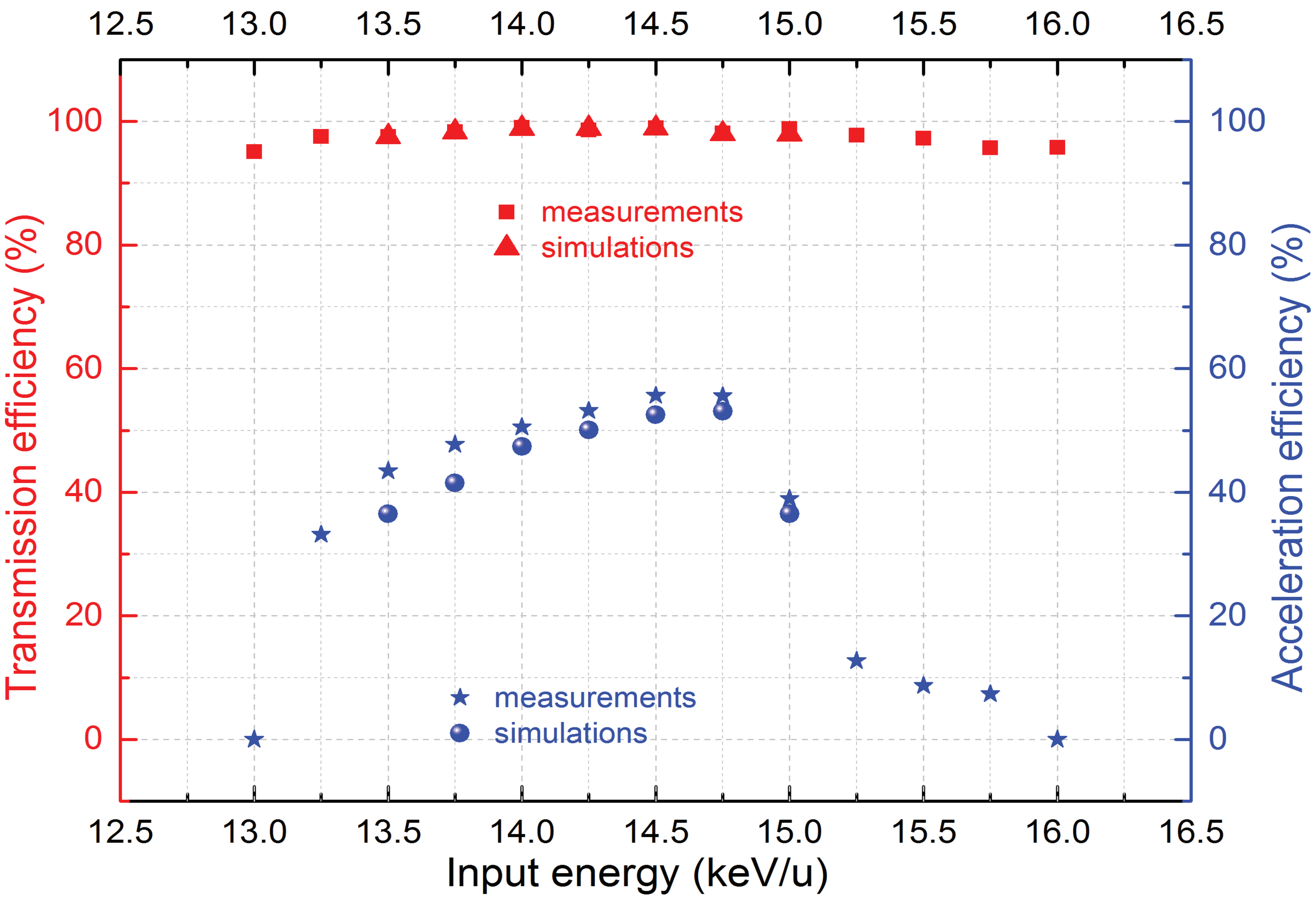
Measurements from ACCTs



Signals from BPMs

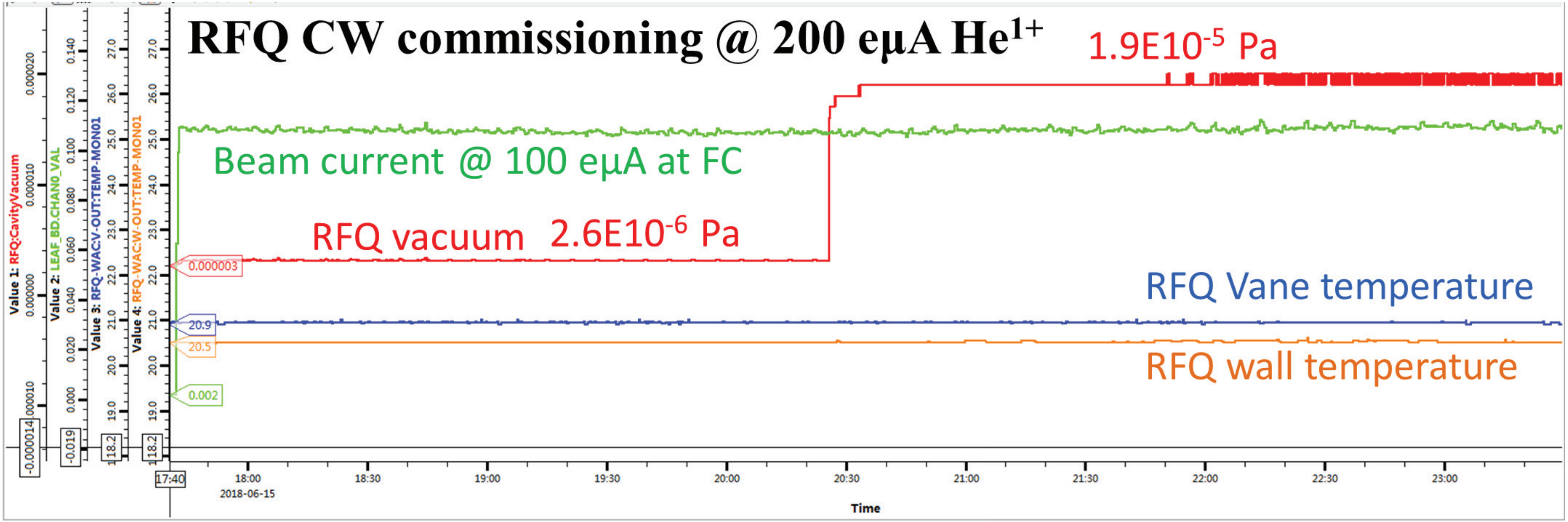
- ➢ **Measured 97.2% transmission** matched the design；
- ➢ **Measured 500keV/u beam energy** agreed well with the design；

Measurements: He^+ beam



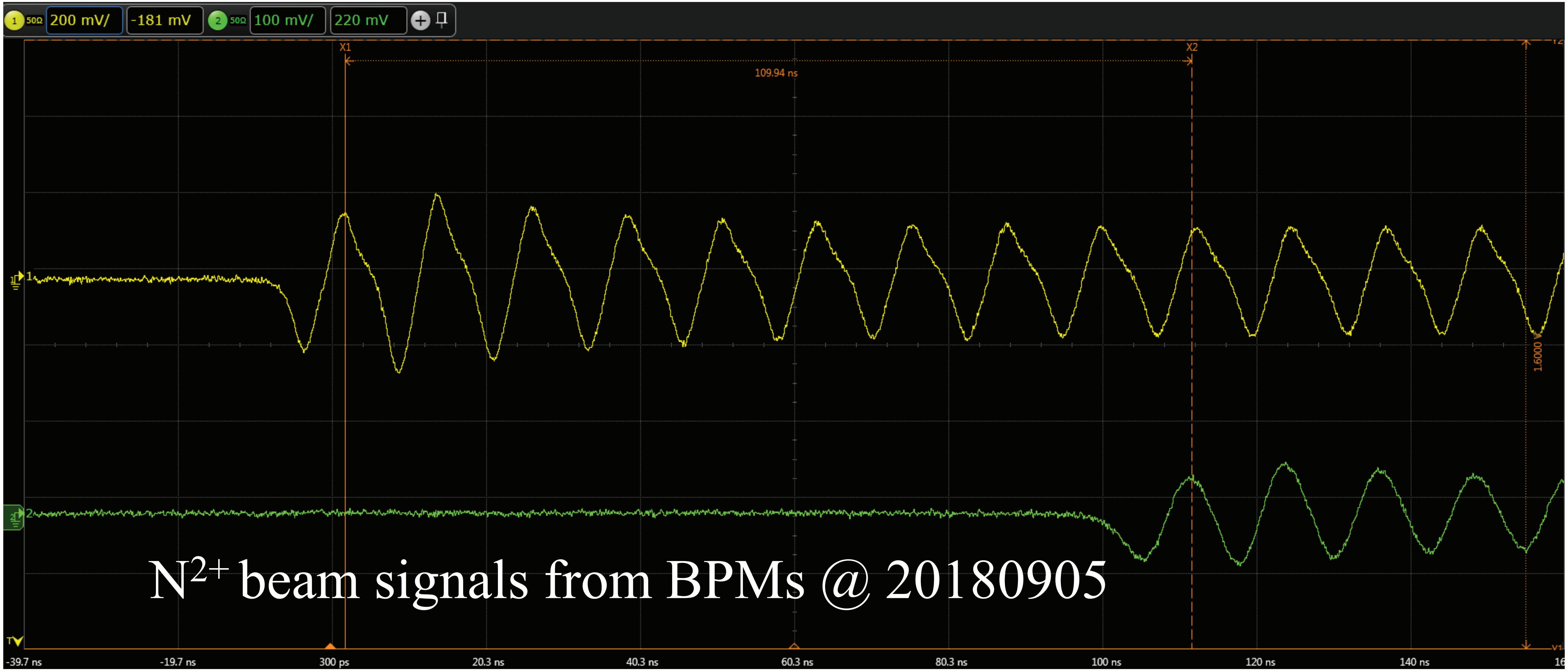
- Both the measurements and the simulations agreed well in both transmission efficiency and acceleration efficiency, under the condition of absence of the MHB.

CW beam operation



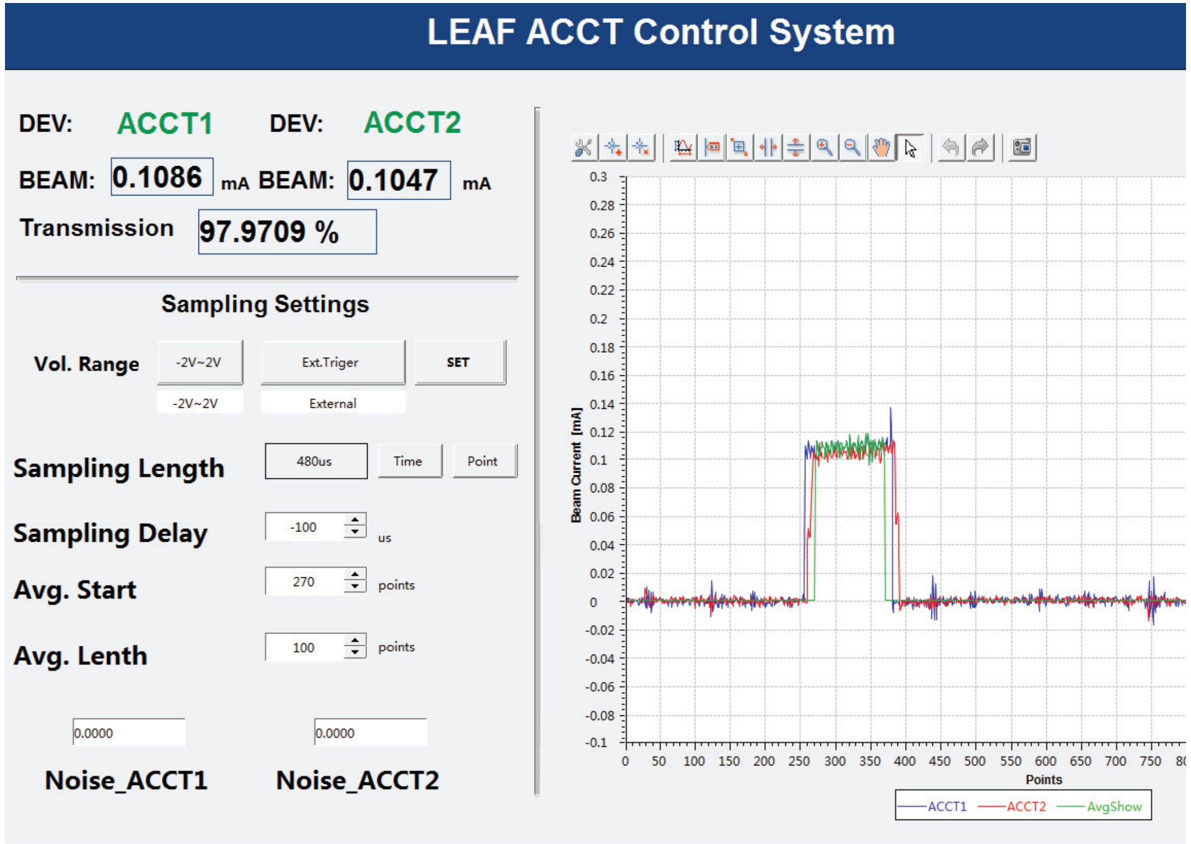
- Acceleration efficiency was about 50% because of absence of the MHB (multi-harmonic buncher)；
- **Long time CW He^{+} beam operation has being carried out for several months** ；

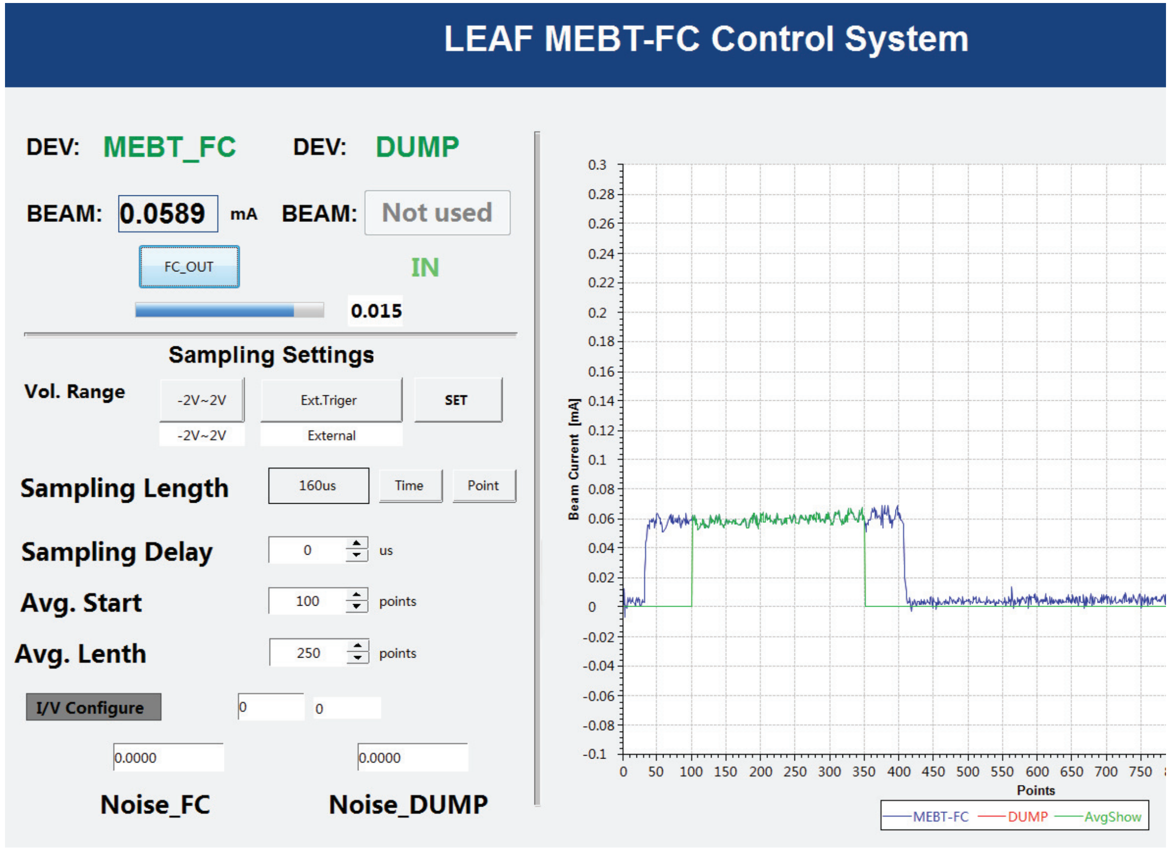
Measurements: N^{2+} beam



- **measured beam energy** was 500keV/u;

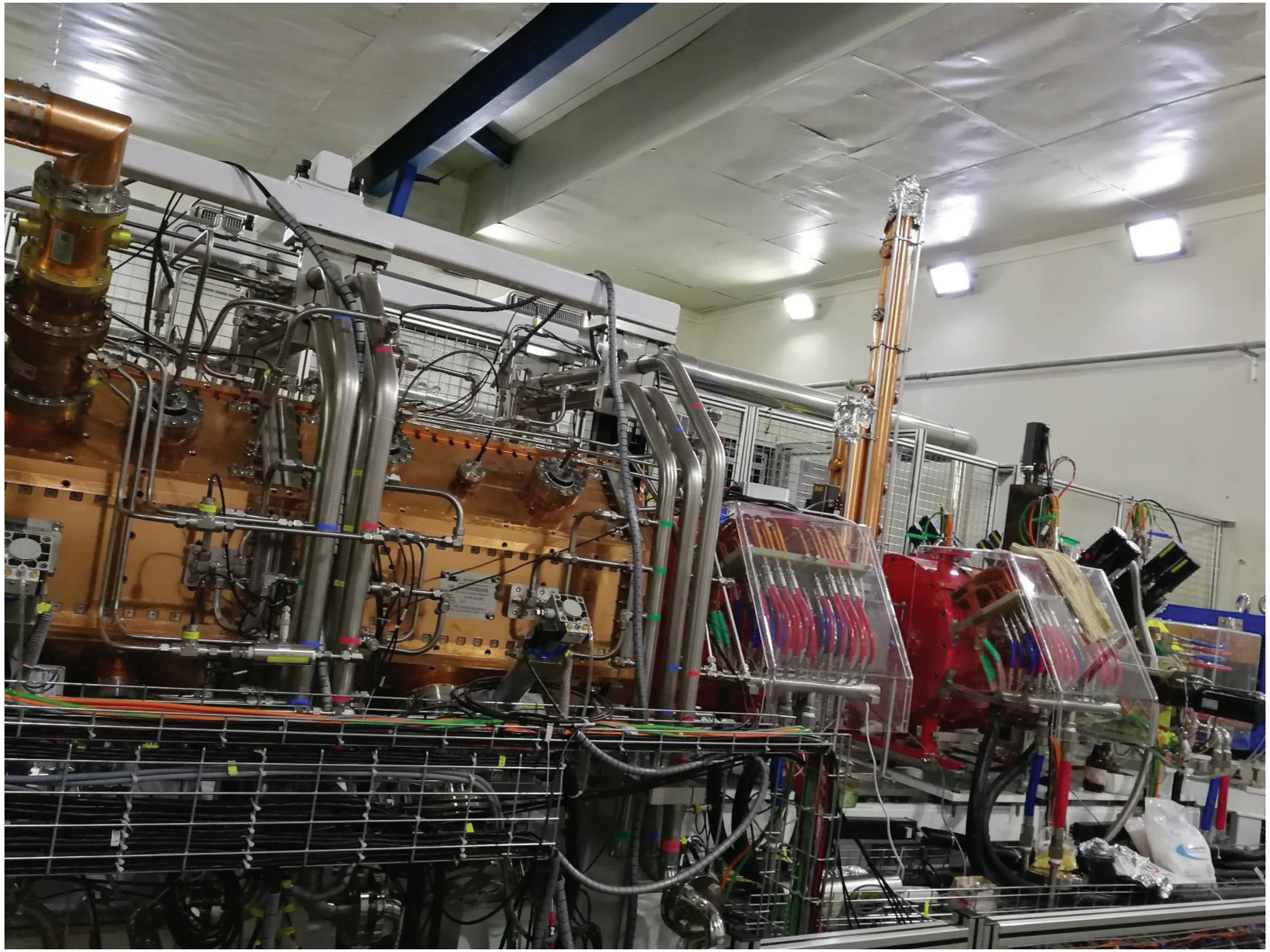
Measurements: N^{2+} beam





- **Measured 98% transmission** matched the design；
- **Measured 54.2% acceleration** efficiency (without the MHB, input current: 108.6μA, and 58.9μA was measured at FC)；

State of MHB



MHB was already offline-tested and installed between two solenoid before the RFQ

Summary

- LEAF facility has been successfully commissioned with $4He^{+}$ and $^{14}N^{2+}$
  - LEAF facility is in operation for users (He+ beam irradiation for meterial research)
- Beam energy of 500keV/u reliably demonstrated, agrees the designs
- Beam properties are consistent with calculations, satisfy requirements
- All components operate reliably and as expected
- Diagnostics and MPS verified
- MHB is already installed and ready to operate
- Heavy ion test (O, Ar, Kr) proceeds according to the established experimental chamber and schedule

Thank you very much!