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High RF Power Conditioning of the RISP RFQ

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Rare Isotope Science Project

Contents

Ⅰ. Introduction

Comparisons of Heavy Ion RFQ Projects

RISP

Parameter	Unit	HLI GSI	SPIRAL II GANIL	ISAC TRIUMF	ATLAS ANL	FRIB MSU	RISP
Particle		A/q<8	**A/q= 2,3**	A/q <30	A/q <7	3<A/q<7	1<A/q<7
Frequency	MHz	108.5	88	35.3	61	80.5	81.25
Type		4-rod	4-vane	4-rod	**Window**	4-vane	**4-vane**
Injection Energy	keV/u	2.5	20	2	30	12	10
Final Energy	keV/u	300	750	150	297	500	500
Current	uA				**5**	450	400
Length	m	3	5.077	8	3.75	5.04	**4.94**
Inter-vane Voltage	kV	80	100 – 113 Voltage Ramp	75	70	60-112 Voltage Ramp	**50-140 Voltage Ramp**
RF Power	kW			75-100	**60**	15-100	**94**
Beam Power	kW				<1	1	1.4
Kilpatrick factor			1.65			1.6	**1.70**
Duty	%	50	100	100	100	100	100
Transmission efficiency	%		97			**80**	**98**
Status		Operation	Test	Operation	Operation	Test	Test

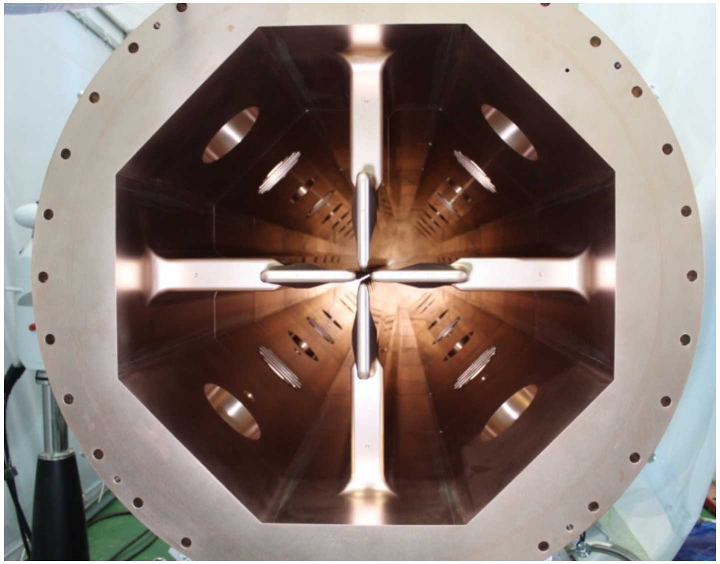
Comparisons of RFQ types

Pros and cons of RFQ types

RFQ type	Pros	Cons
Four rod	**-Inexpensive** **-Compact size at low RF frequency**	**-Cooling has been a problem** **-RF joints have melted** **-Structural & RF field stability have been poor**
Split coaxial (Window type)	**-Compact size** **-Low dipole sensitivity due to windows**	**-Complicate structure and cooling paths** **-Low RF power operation**
Four vane	**-High structural rigidity** **-Easy to cooling** **-Good for CW operation** **-High RF power operation**	**-Large transverse dimensions** **-High dipole sensitivity** **-*No ever existing for the low frequency (<200MHz for A/q >3)***

RISP RFQ

Parameter	Value
Frequency	81.25 MHz
Particle	H^{+1} to $^{238}U^{33+}$ and $^{238}U^{34+}$
Input Energy	10 keV/u
Output Energy	0.507 MeV/u
Current	0.4 mA
Transmission	~ 98 %
Peak surface field	1.70 Kilpatrick
Total RF Power	94 kW
Duty Factor	100 %(CW)



Challenges for the development of RISP RFQ

- Continuous wave operation
- High RF power operation (~100kW)

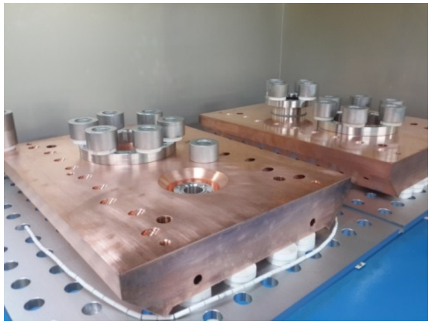
  => Four-vane type RFQ (Lower specific thermal load and easier cooling)
- Fabrication of a low frequency RFQ with large transverse dimensions by using the brazing technology

  => No ever existed(<200MHz).
- Reduce the RFQ length by using the ramped inter-vane voltage profile.

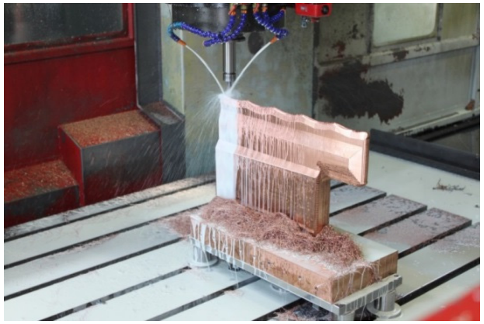
Ⅱ. Fabrication and Installation

RFQ Fabrication Procedure

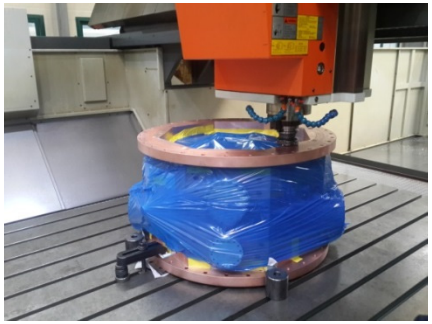
- Physical & mechanical design
- Rough machine for vanes and quadrants
- 1st and 2nd Braze for cooling channels and vacuum flanges
- Flow and leak test
- Fine machining including the vane modulations
- Dimension inspection with CMM(Coordinate Measurement Machine)
- 1st assembly
- Inspect the alignment
- Installation of the dowel pins for re-assembly
- Disassemble and clean
- 2nd assembly
- Inspect the alignment
- Final braze
- Frequency and vacuum leak test
- Final machine



Braze in cooling parts, vacuum ports

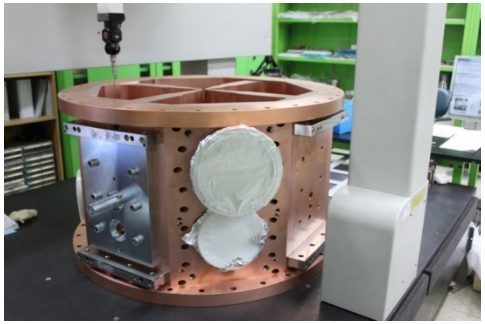


Machine the vane modulations

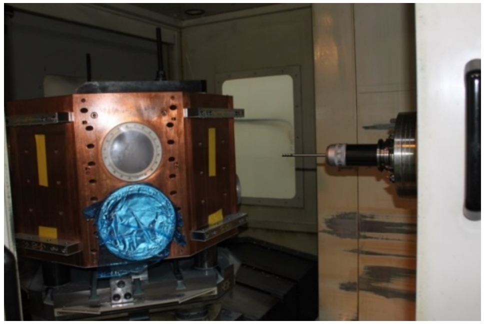


Final machine

Final braze



Inspect the assembly

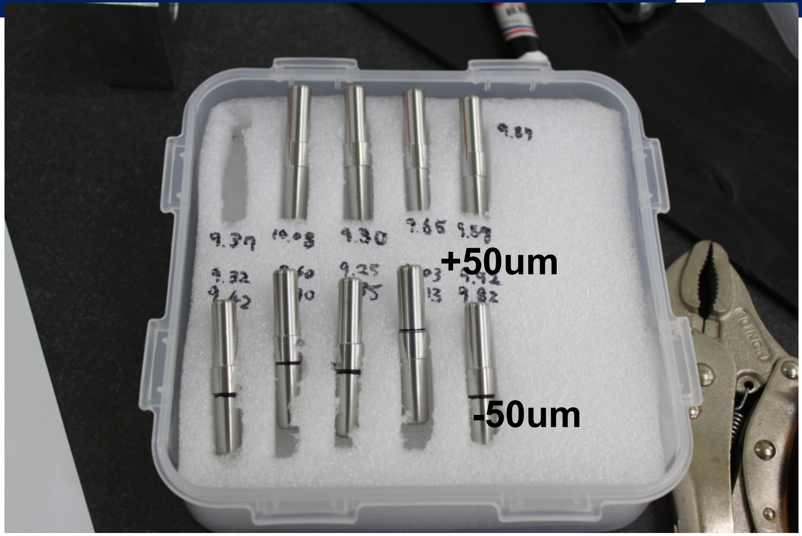


Installation of the dowel pins

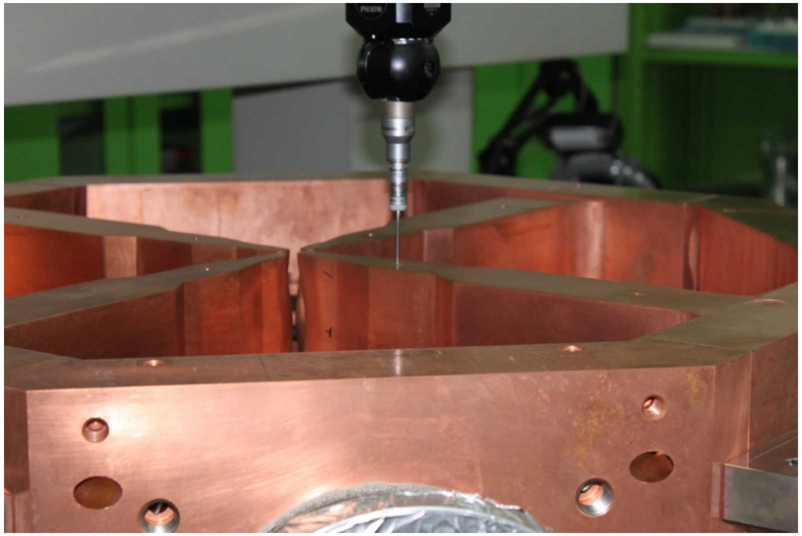
Inspect the Alignment

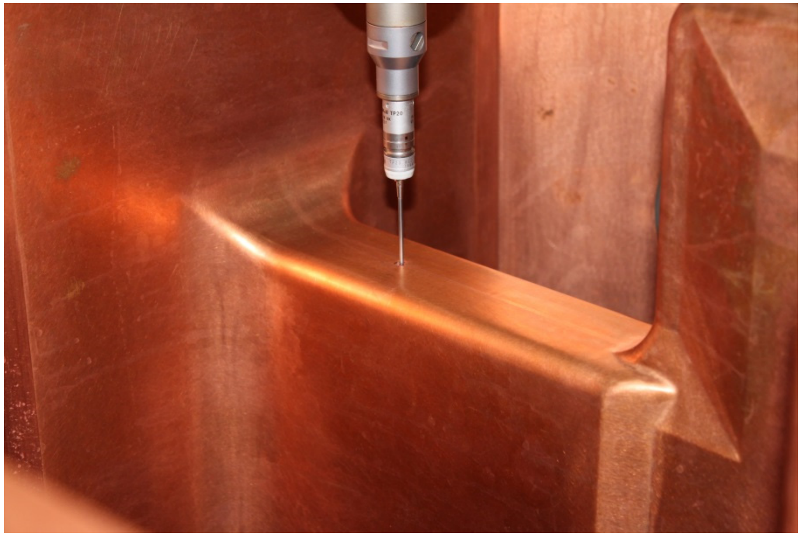
1. Pin gauge (±50um)
: The gap was checked in every step

2. Machine the dowel pin holes at section ends
: to measure the vane position indirectly with a CMM
: measured the hole position after the every assembly process



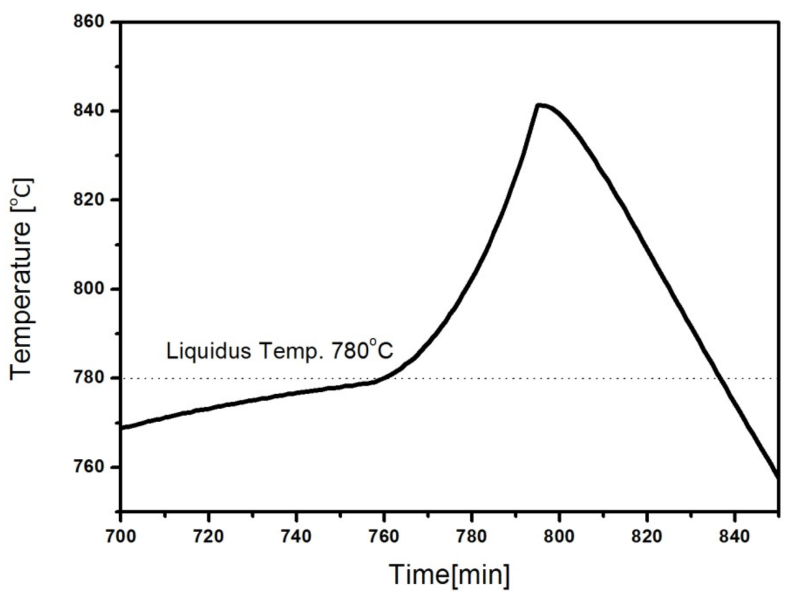
Gap gauge


Dowel hole


Dowel hole

Braze

1. **Three steps of brazing processes**
2. **For various flanges, BNi-2 brazing alloy (Liquidus Temp. 1010 ℃)**
   For cooling channel, 50% Gold / 50% copper alloy (Liquidus Temp. 970 ℃)
   For assembly, Cusil(BAg-8) alloy (Liquidus Temp. 780 ℃)



Temp. profile during final brazing

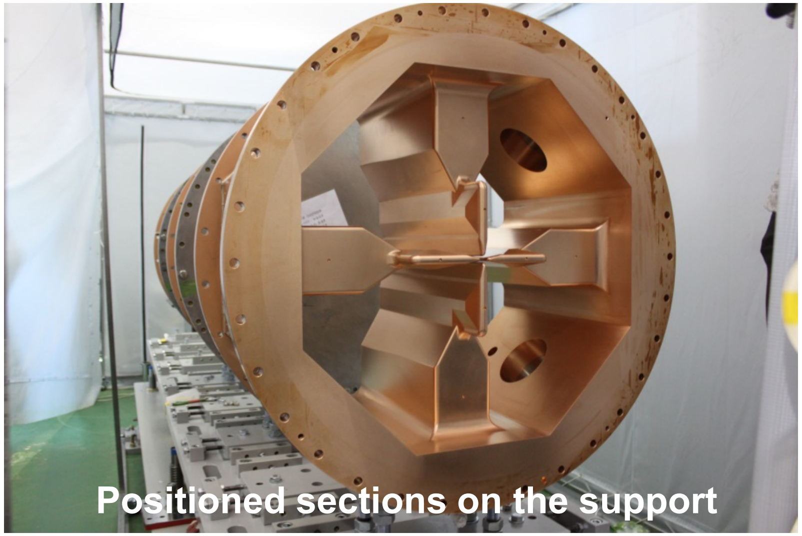
Final brazing process

RFQ Installation

Vane gaps in the joints of each modules : tolerance ≤ ± 100㎛

Girder type support installation

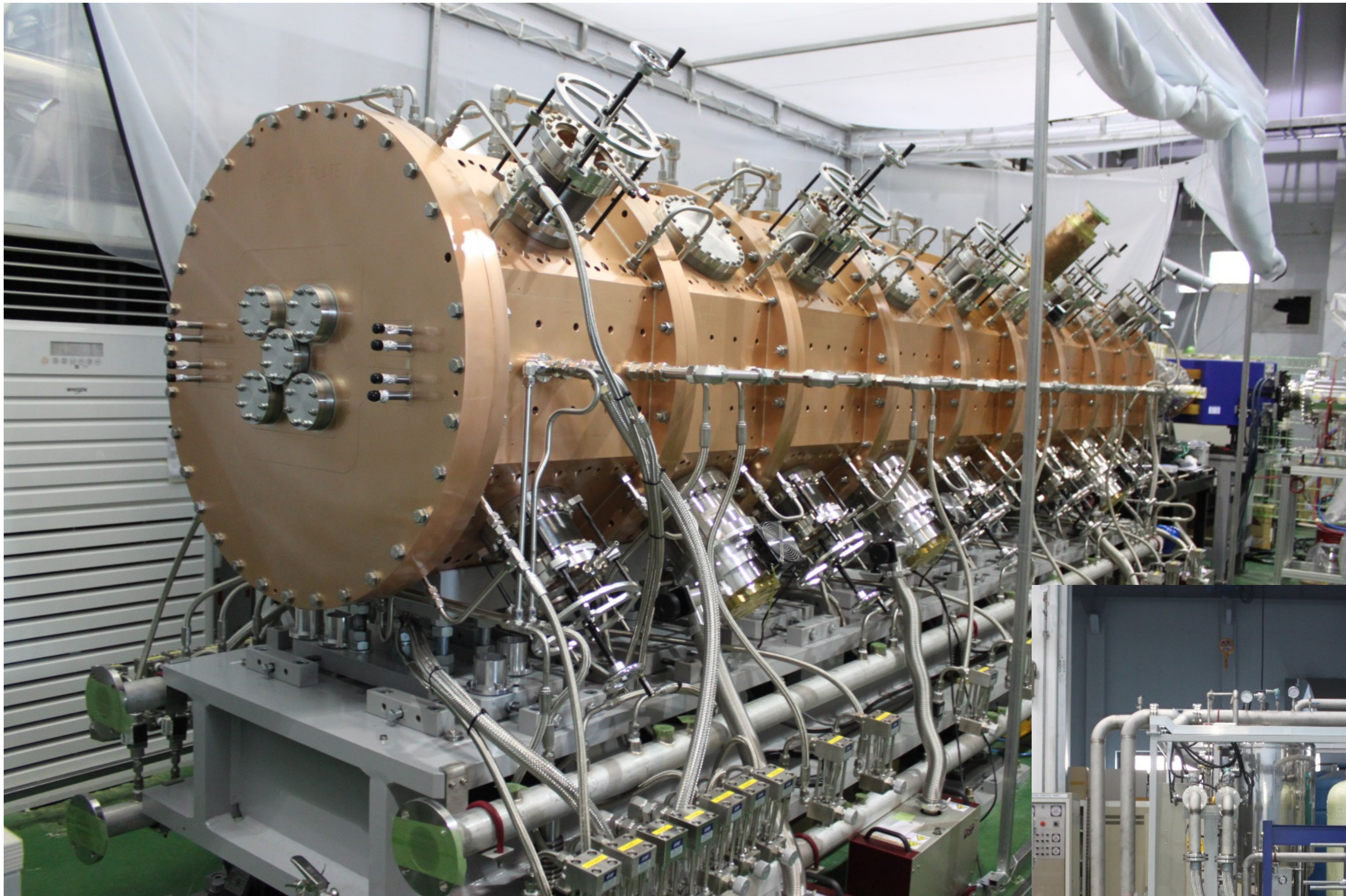
Transport nine sections



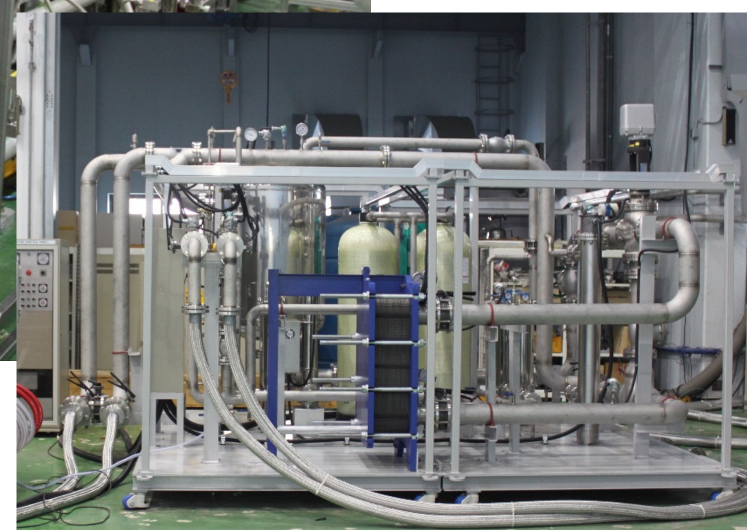
Positioned sections on the support

Alignment with a laser tracker

Installed RFQ



Installed RFQ with cooling system



Resonance Control Cooling System (±0.1℃)

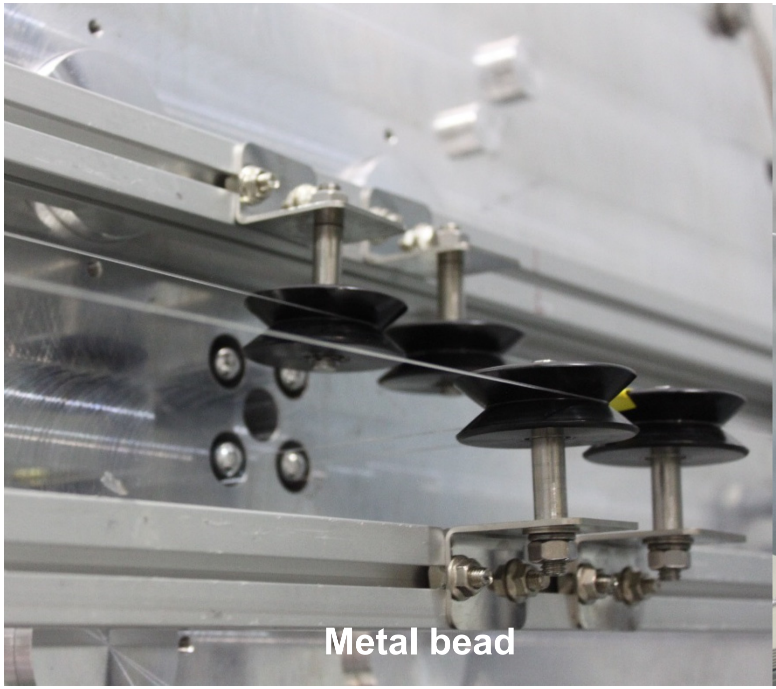
Bead-pull Measurement

Frequency shift due to the bead perturbation (Slater perturbation theorem)

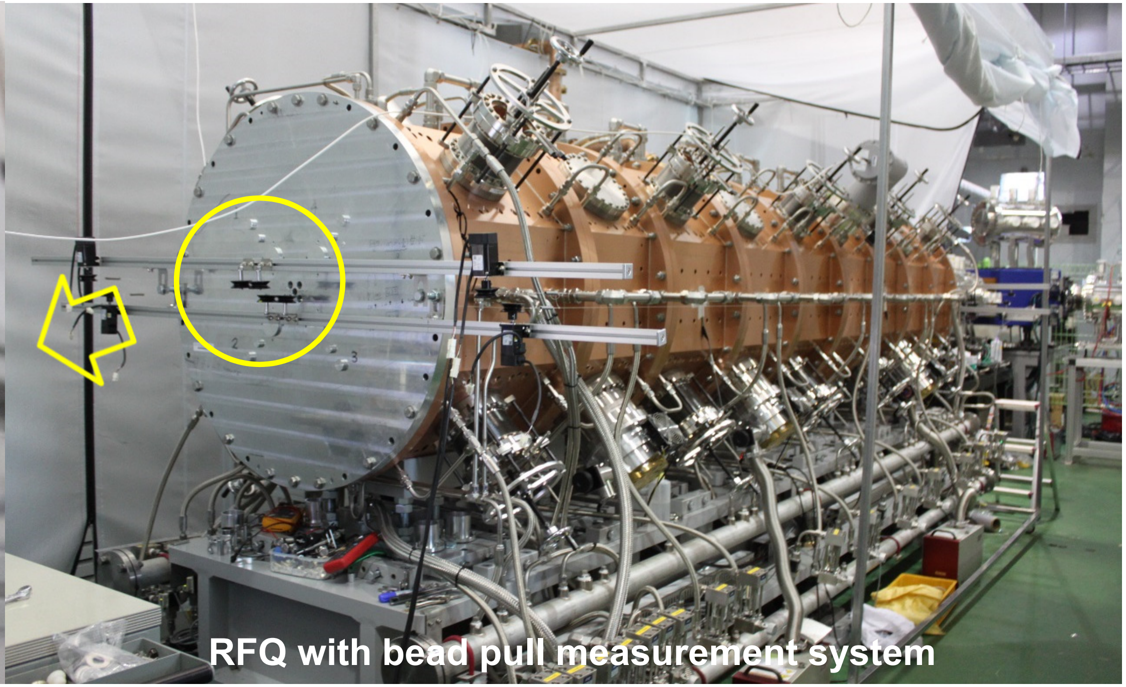
For spherical metal bead,

$$\frac{\Delta\omega}{\omega_0} = -\frac{3\Delta V}{4U}\left[\varepsilon_0|E_0|^2 - \frac{\mu_0|H_0|^2}{2}\right]$$

ΔV : *bead volume,*
U : *stored energy in the cavity*
E_0 : *unperturbed electric field,*
H_0 : *unperturbed magnetic field*



Metal bead



RFQ with bead pull measurement system

RF Tuning Tool

By adjusting the radial perturbation with slug tuners, the magnetic field distribution and the frequency can be controlled.

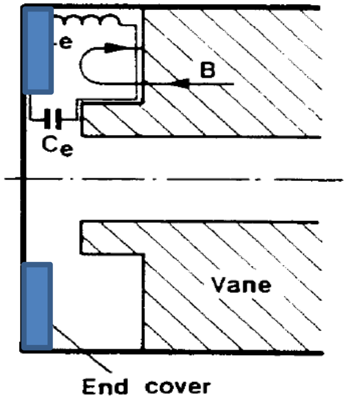
<u>The machining and alignment error can be compensated with slug tuners.</u>

<u>- Number of movable slug tuners : 20 ea (five for each quadrant)</u>

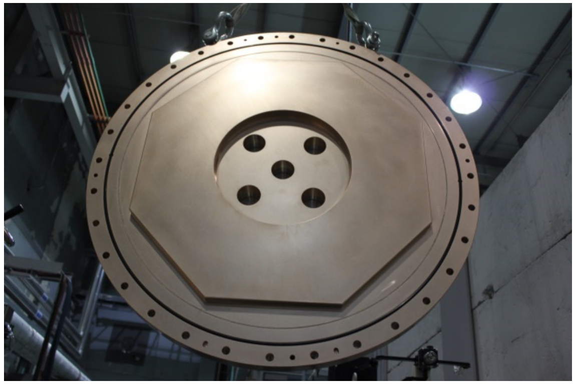
<u>Low frequency RFQ with a short length is insensitive for the perturbation.</u>

$$\frac{\delta V_0(z)}{V_0(z)} \propto -\left(\frac{\ell_v}{\lambda}\right)^2$$

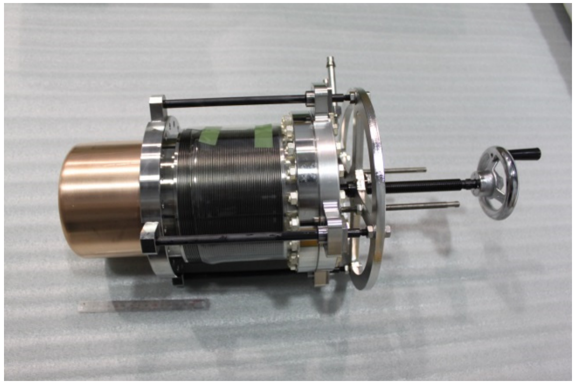
<u>The geometry of endplates was adopted as the tuning tool to control the capacitive and inductive components to overcome the slug tuner limitation.</u>



Schematic of endplate modification



Modified endplate

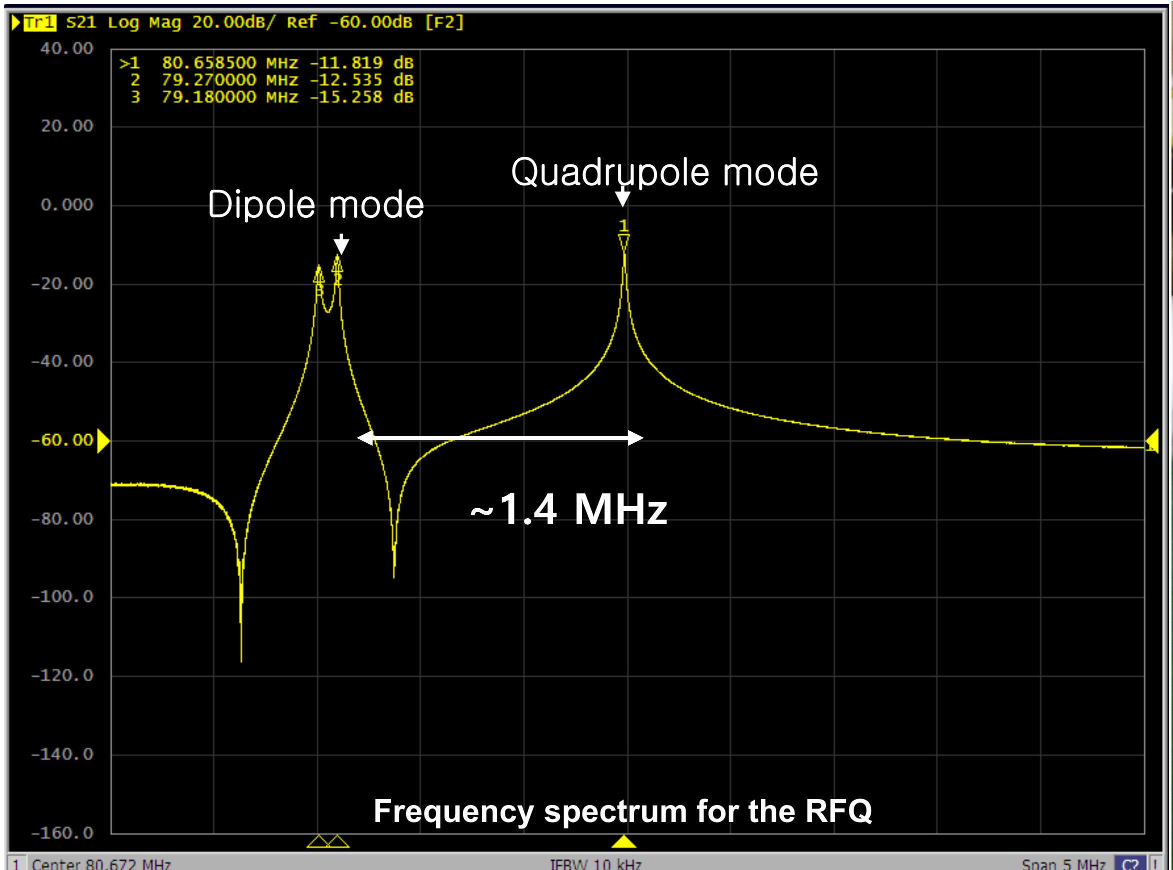


Movable slug tuner(stroke 90mm)

Mode Stability

Frequency gap between the lowest dipole mode and the quadrupole mode : ~ 1.4 MHz

=> *Need not dipole rod stabilizers for this study*



Frequency spectrum for the RFQ


Dipole stabilizer rods for tuning

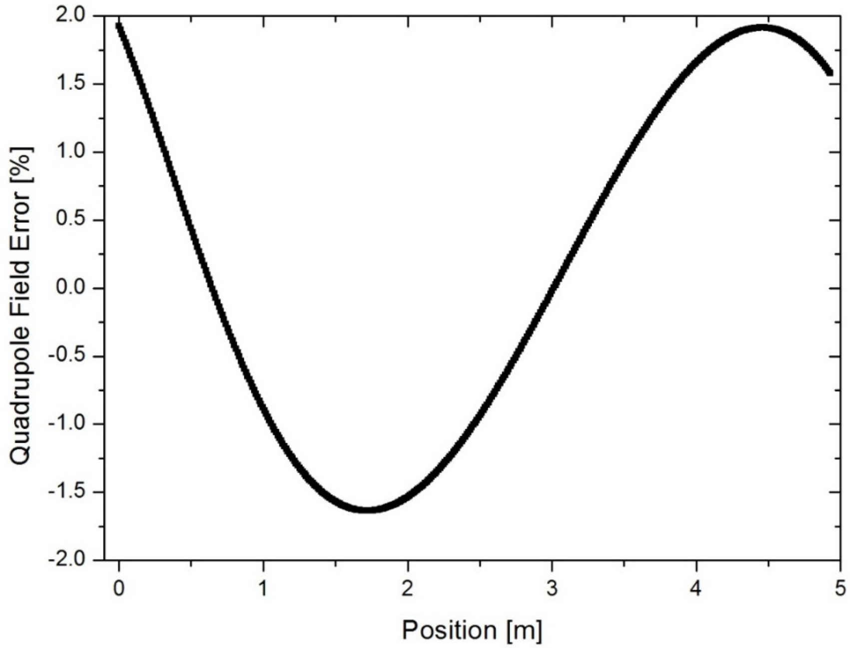
Final Tuning Result

Quadrupole mode amplitude $\mathbf{A_Q} = |\mathbf{B}_1 - \mathbf{B}_2 + \mathbf{B}_3 - \mathbf{B}_4| / 4$

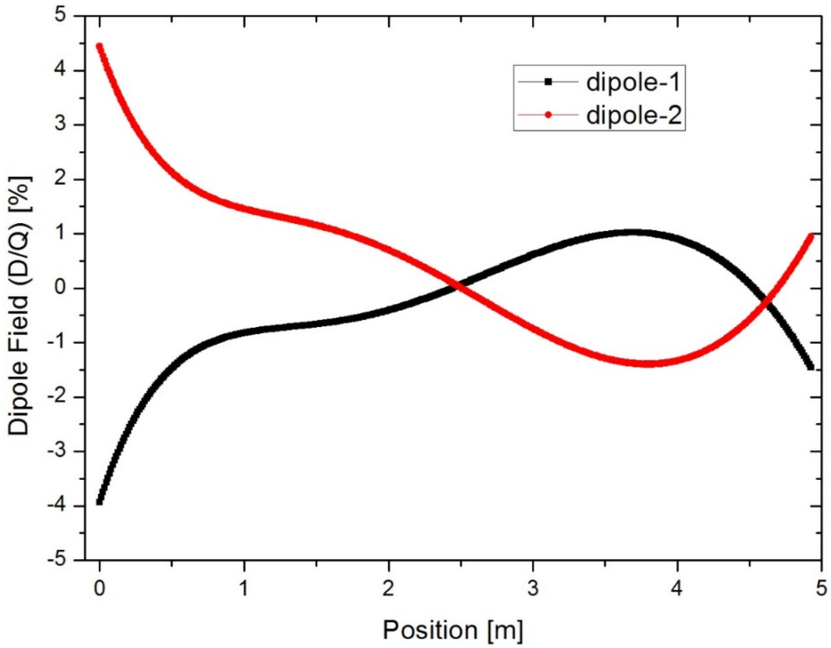
Dipole mode amplitude for each position $\mathbf{A_{D1}} = |\mathbf{B}_1 - \mathbf{B}_3| / 2$ $\mathbf{A_{D2}} = |\mathbf{B}_2 - \mathbf{B}_4| / 2$

Quadrupole field error compared to the designed value < $\pm$ 2%

Dipole field compared to the quadrupole field < $\pm$ 5%



Quadrupole field error



Dipole field compared to the quadrupole field

III. Preliminary Beam Experiment & RF Conditioning

Preliminary Beam Experiment

Particle : O^{+7}

RF power : 80 kW SSPA

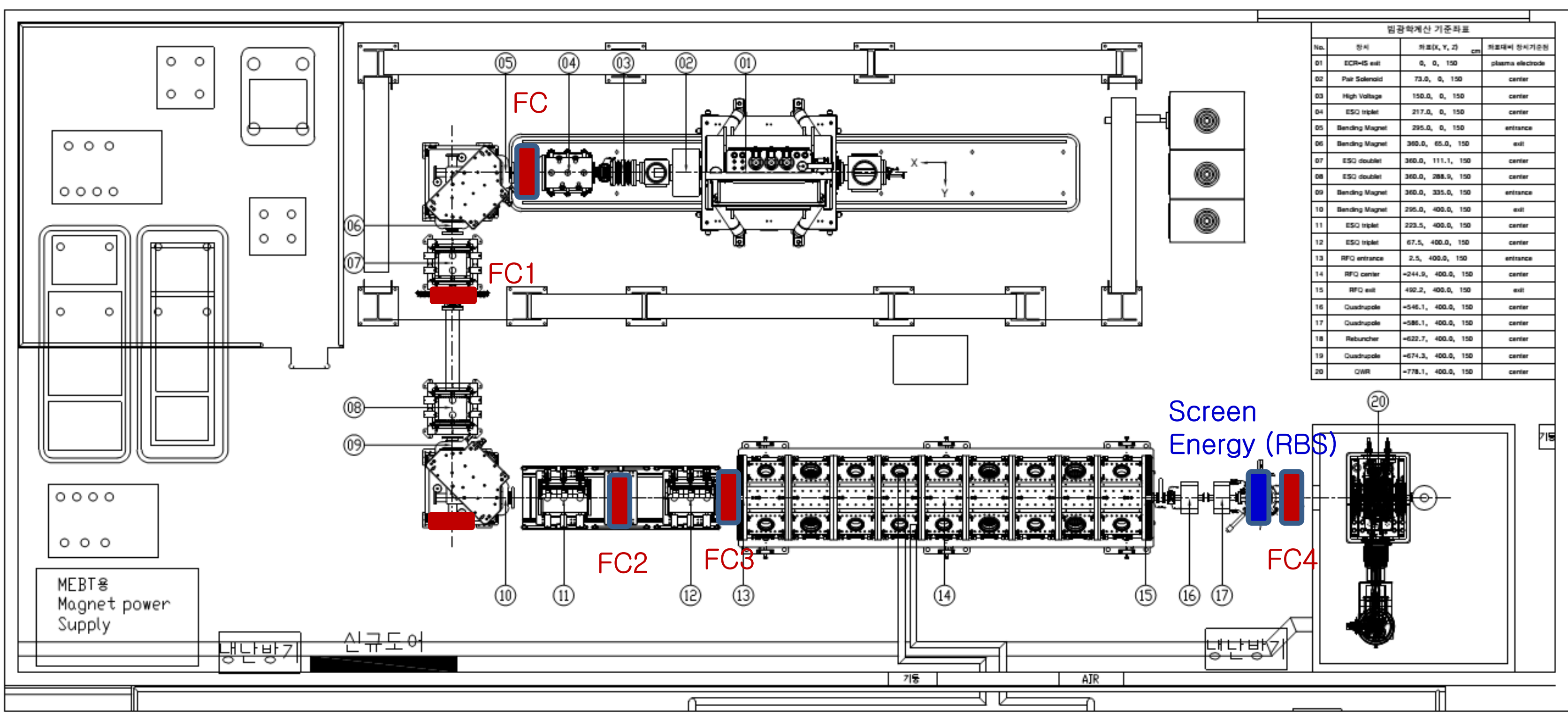
Input energy : 10 keV/u (22.8kV)

Output energy : ~500 keV/u

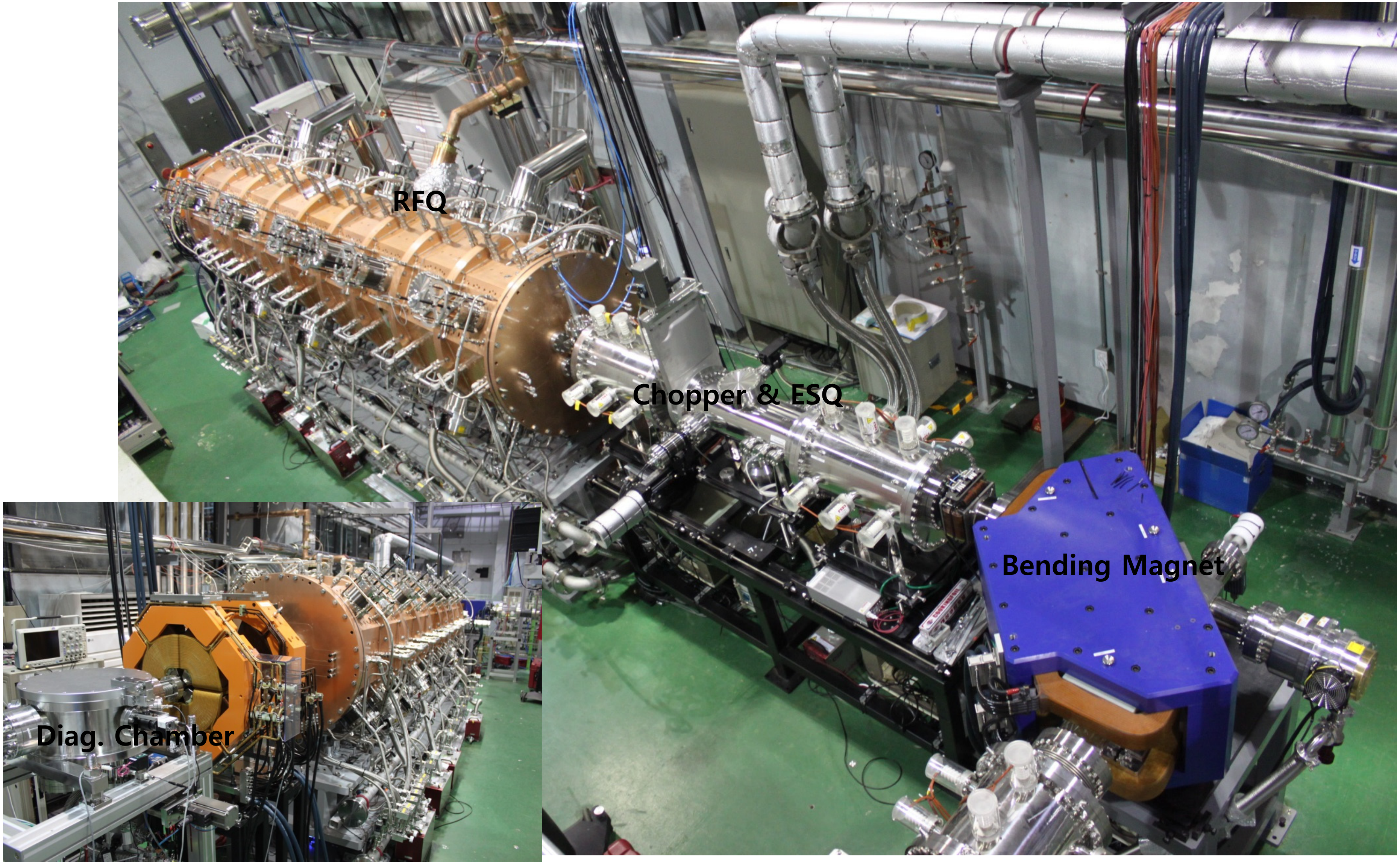
Accelerated beam current : ~3 μA

RF set value vs. oxygen charge

q	A/q	Power(kW)	Power(kW) 20% margin
4	4.0	25	32
5	3.2	16	20
6	2.7	11	14
7	2.3	8	10
8	2.0	6	8

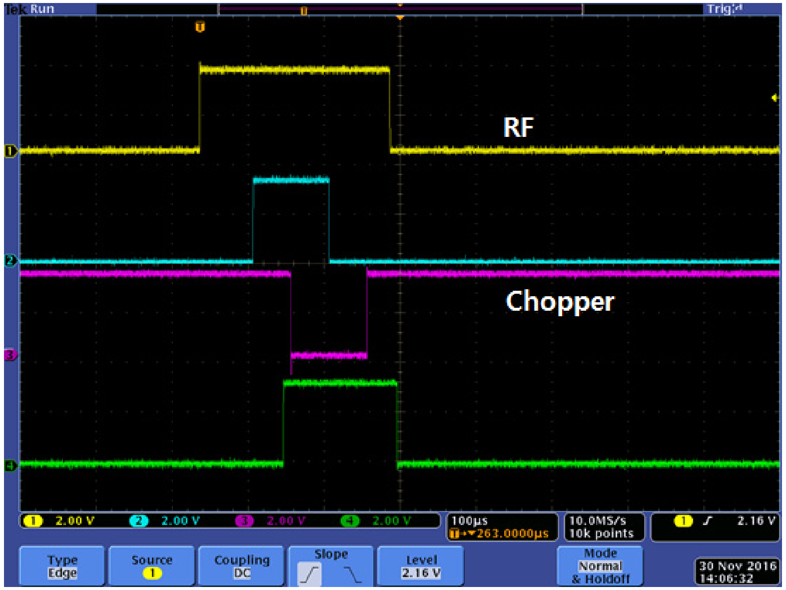


Experiment Setup



Off-site Test Facility for RFQ Beam Experiment

Preliminary Beam Experiment – Current

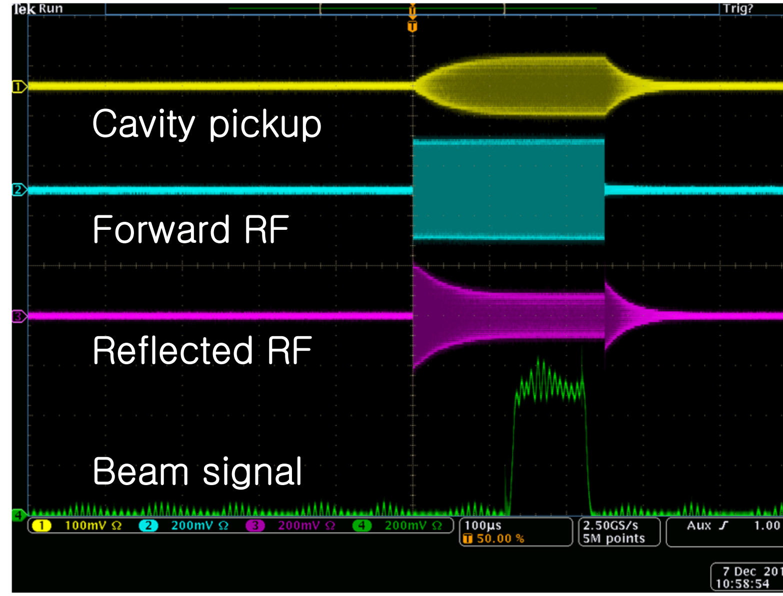


Timing structure

- Repetition rate : 1Hz
- RF pulse width : 250 us
- Chopper pulse width : 110 us

  : flat top 100us, RF filling delay 120 us,

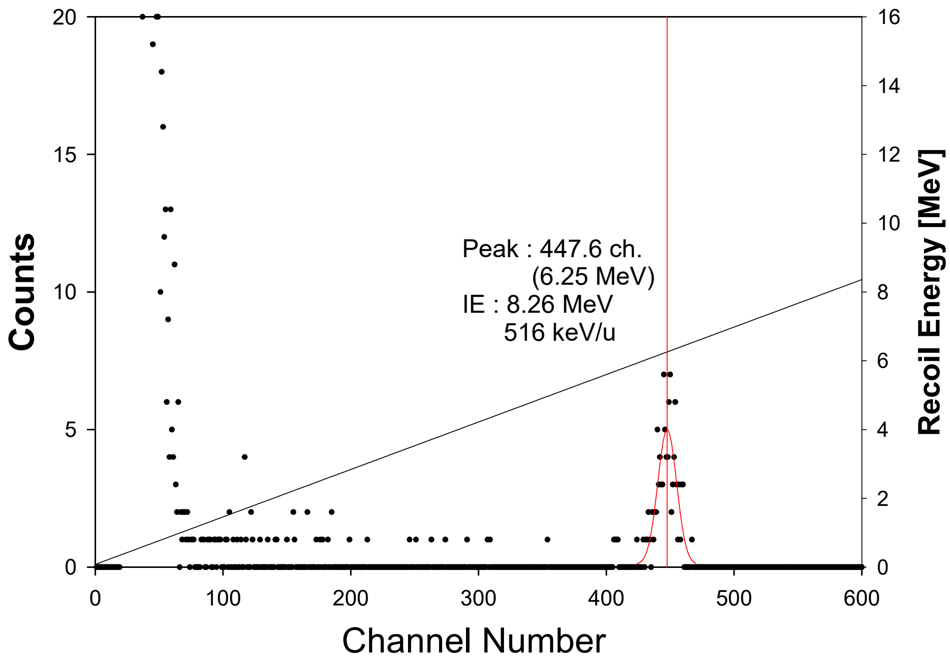
  rising and falling delay 5us+5us,



RF power and beam signals during the beam acceleration

- Coupling beta : 0.48
- Forward RF power : 13.2 kW
- Delivered RF power : 10.4 kW
- Measured beam current @Faraday cup : ~3μA

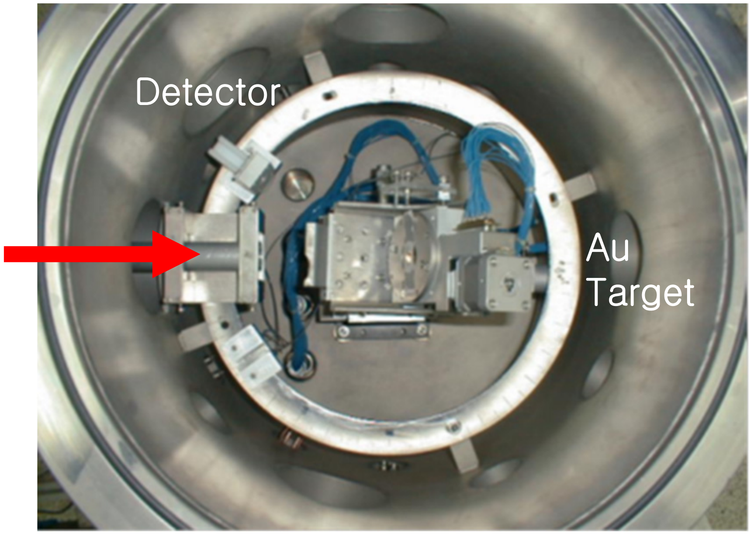
Preliminary Beam Experiment – Energy



Energy measurement by the RBS(Rutherford Back Scattering) method

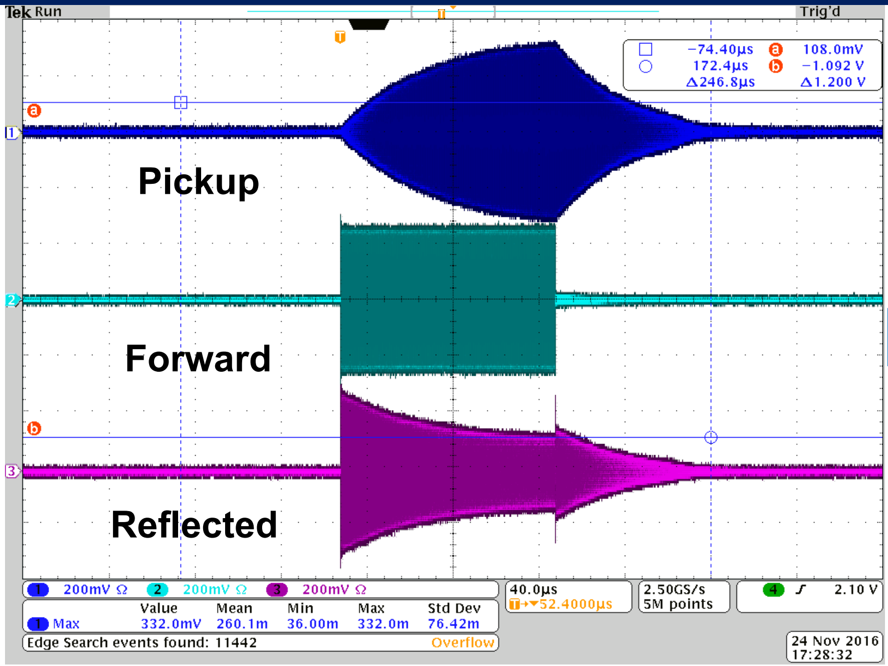
Accelerated beam energy was measured

- **Field profile tuning was confirmed.**
- **Input & output beam characteristic will be measured.**

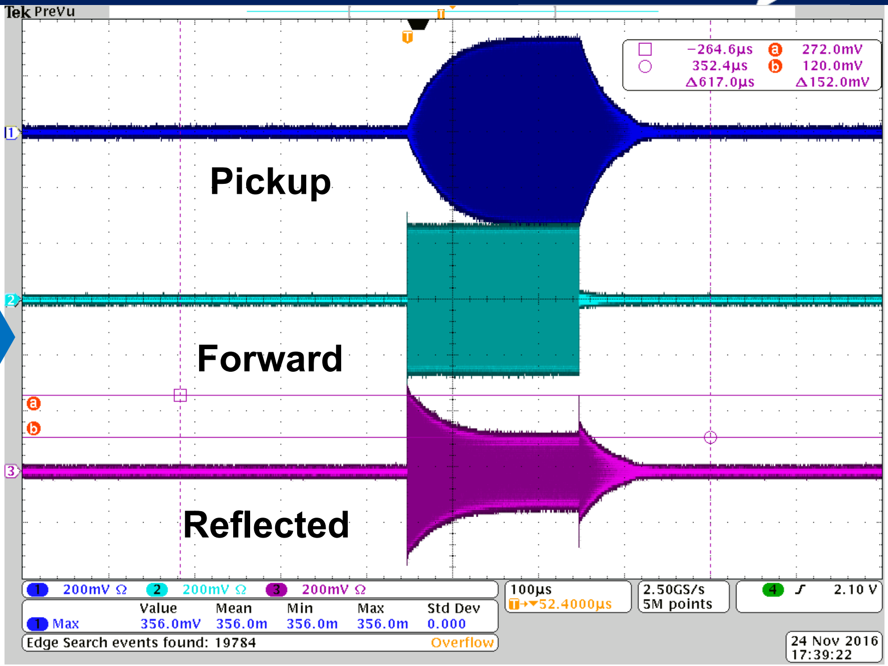


Energy measurement system(RBS)

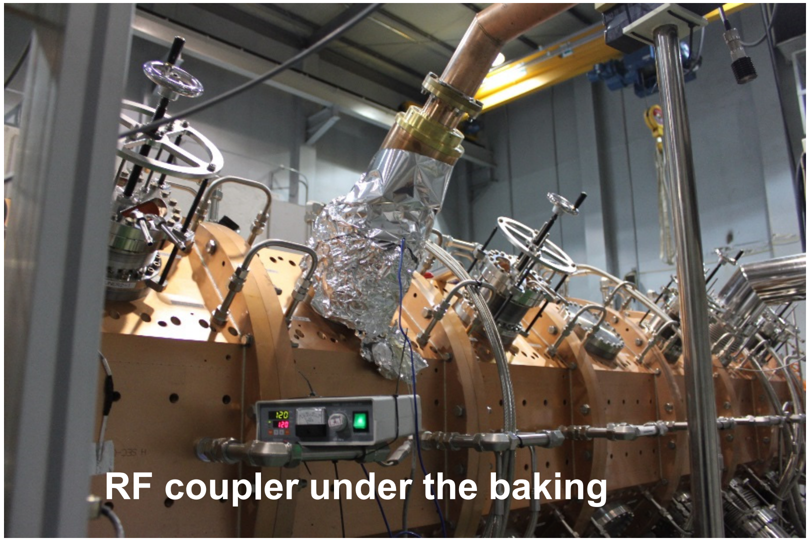
RF Conditioning (one coupler)



Initial RF signal



Under conditioning RF signal

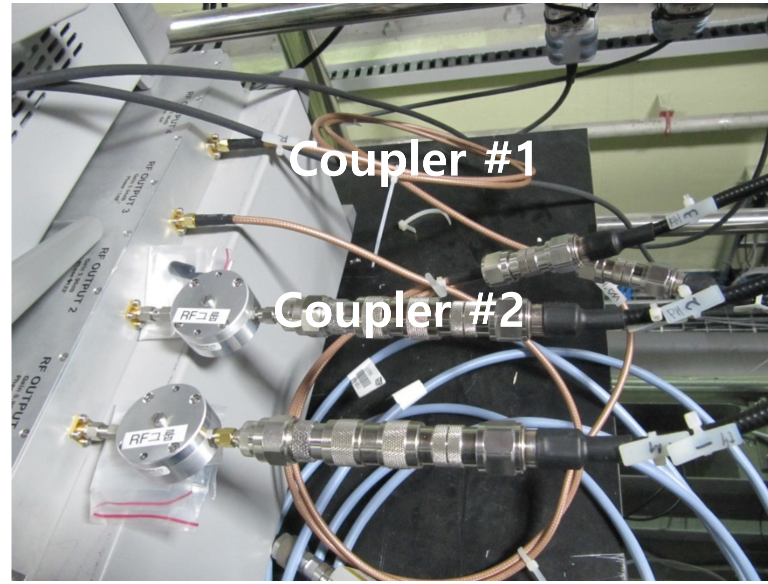


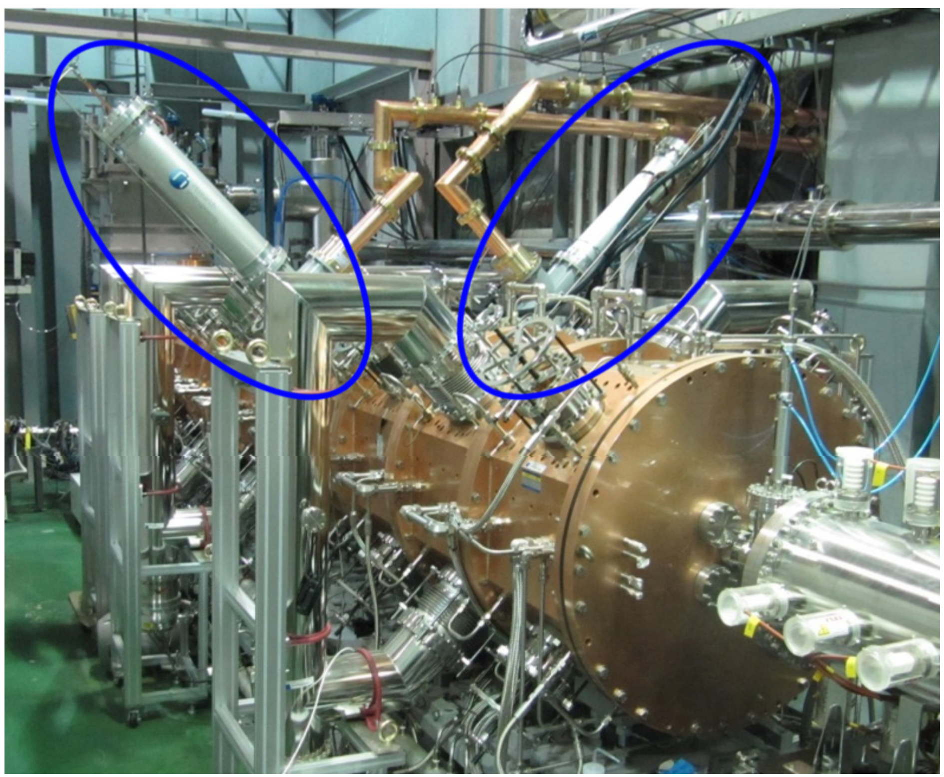
RF coupler under the baking

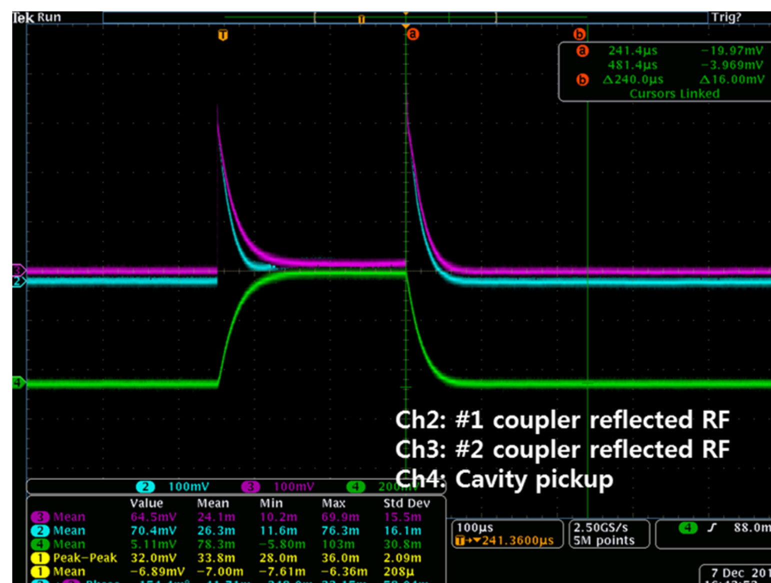
- Preliminary beam test was accomplished with one RF coupler
- Maximum conditioned power : 70 kW
- Pulse repetition : 1 Hz
- Pulse width : 100 us

RF Conditioning (Two coupler)

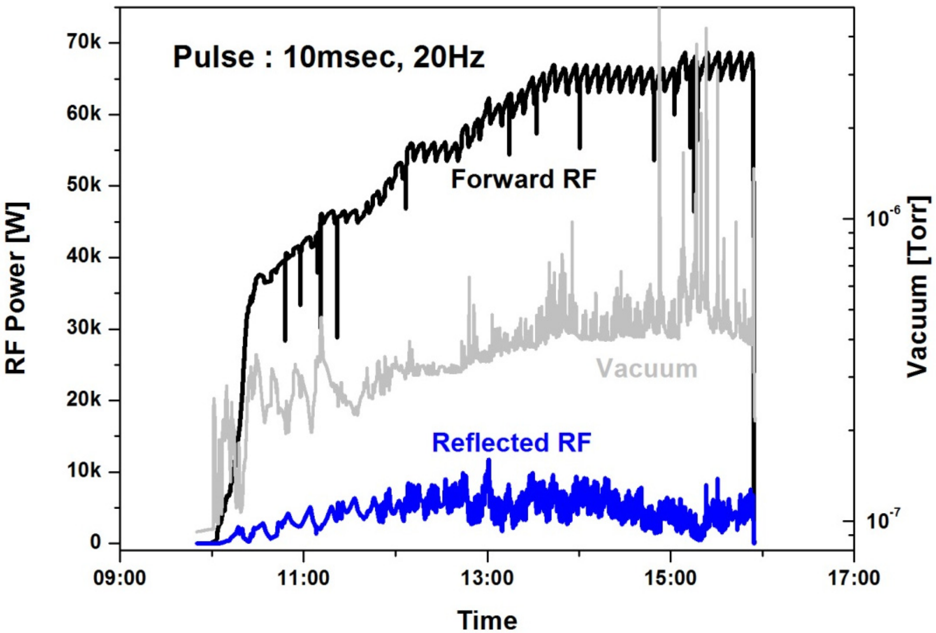
- **RF conditioning with two power couplers**
- **Phase difference was compensated between coupler 1 and 2 by the different cable length in low power level.**

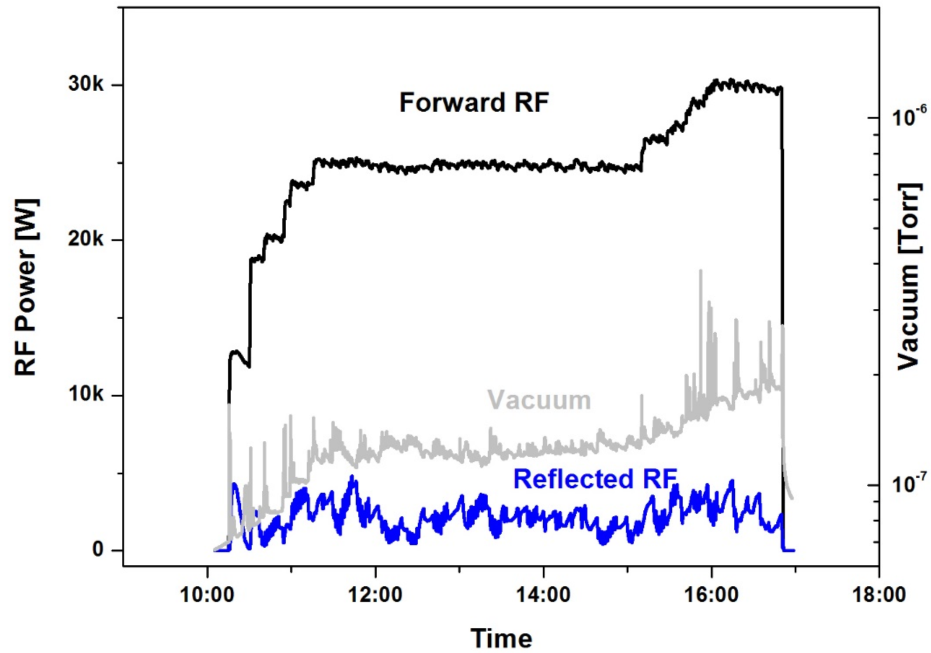






RF Conditioning – High RF Power





- **The cooling-water capacity is limited at the off-site test facility.**
- **For pulse mode, the conditioning was accomplished to 70kW. (20Hz, pulse width 10 ms)**
- **For CW mode, the conditioning was accomplished to 30kW.**
- **We will continue to experiment with increasing the RF power before the site installation.**

Summary

- Four-vane RFQ for low frequency was fabricated to accelerate heavy ion beams.
- Ramped field was tuned as the error is less than 2% for quadrupole error and 5% for dipole field by using not only the slug tuners but also the endplate geometry modification.
- RISP RFQ was installed and preliminary beam test was accomplished at the off-site test facility.
- The design, fabrication and tuning process of the RISP RFQ was confirmed by the preliminary beam test results.
- The conditioning is in progress under the limited condition. The full power test is planned to be performed after the site installation in the next year.

Many collaborators from the VitroTech Co. and RI Research Instruments GmbH contributed to the success of the RFQ fabrication. In particular, we would like to thank Dr. Y.Y. Lee (BNL retired) and Dr. D. Schrage (LANL retired) for their helpful advice and cooperation.