9th Asian Forum for
Accelerator and Detectors

# Construction and Preliminary Beam Test of RISP 81.25MHz CW RFQ for Heavy Ions

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Rare Isotope Science Project

# Contents

# Ⅰ. Introduction

# Comparisons of Heavy Ion RFQ Projects

RISP

| Parameter | Unit | HLI GSI[1)] | SPIRAL II GANIL[1)] | ISAC TRIUMF[1)] | ATLAS ANL[1)] | FRIB MSU[1)] | 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** | | Operated | Test | Operated | Operated | Test | Test |

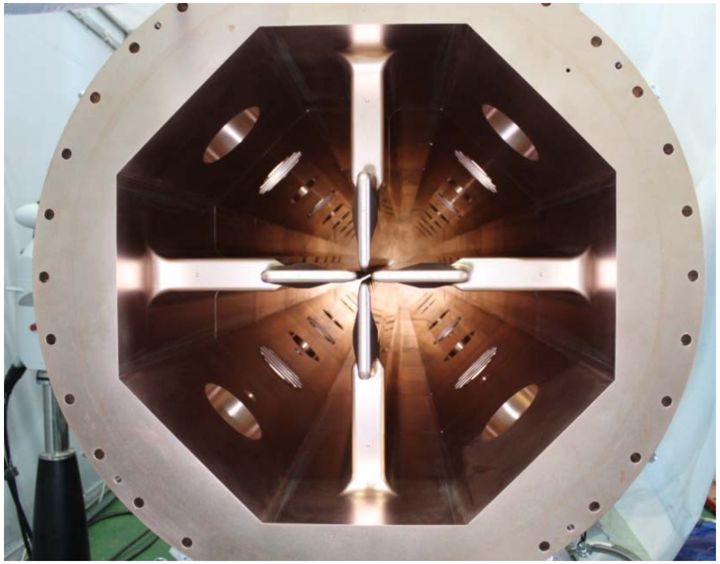
# Comparisons of RFQ types

## Pros and cons of RFQ types

| RFQ type | Pros | Cons |
|---|---|---|
| Four rod | -Inexpensive<br>-Compact size at low RF frequency | -Cooling has been a problem<br>-RF joints have melted<br>-Structural & RF field stability have been poor |
| Split coaxial (Window type) | -Compact size<br>-Low dipole sensitivity due to windows | -Complicate structure and cooling paths<br>-Low RF power operation |
| Four vane | -High RF power operation<br>-High structural rigidity<br>-Easy to cooling<br>-Good for CW operation | -Large transverse dimensions<br>-High dipole sensitivity<br>-*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)

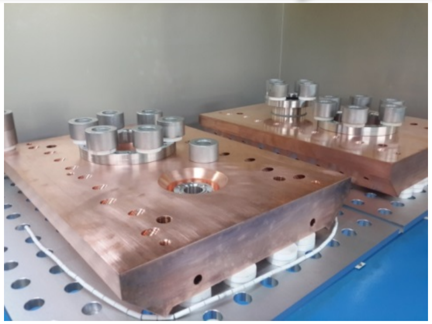
  => Four-vane type RFQ (Lower specific thermal load and easier cooling)
- Fabrication of a low frequency RFQ with large transverse dimensions by using the brazing technology

  => No ever existed(<200MHz).
- Reduce the RFQ length while increase the output energy for the cost effectiveness

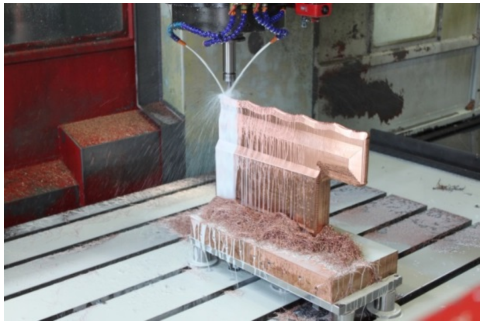
# II. Fabrication & Installation

# RFQ Fabrication Procedure

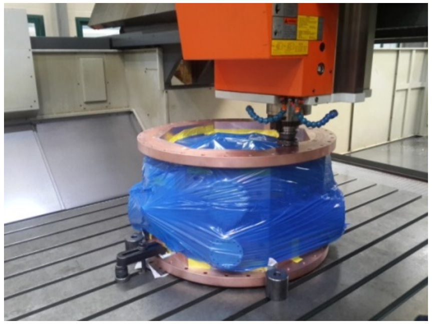
- Physical & mechanical design
- Rough machine for vanes and quadrants
- 1st and 2nd Braze for cooling channels and vacuum flanges
- Flow and leak test
- Fine machining including the vane modulations
- Dimension inspection with CMM(Coordinate Measurement Machine)
- 1st assembly
- Inspect the alignment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

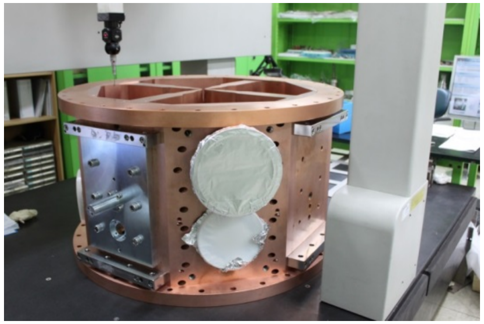


Machine the vane modulations

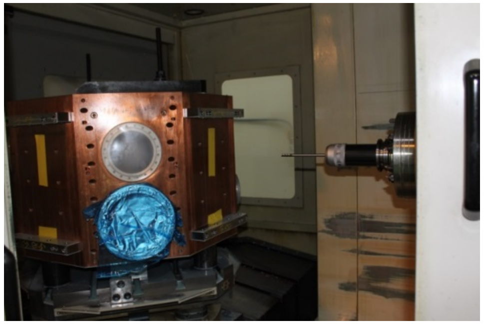


Final machine

Final braze



Inspect the assembly



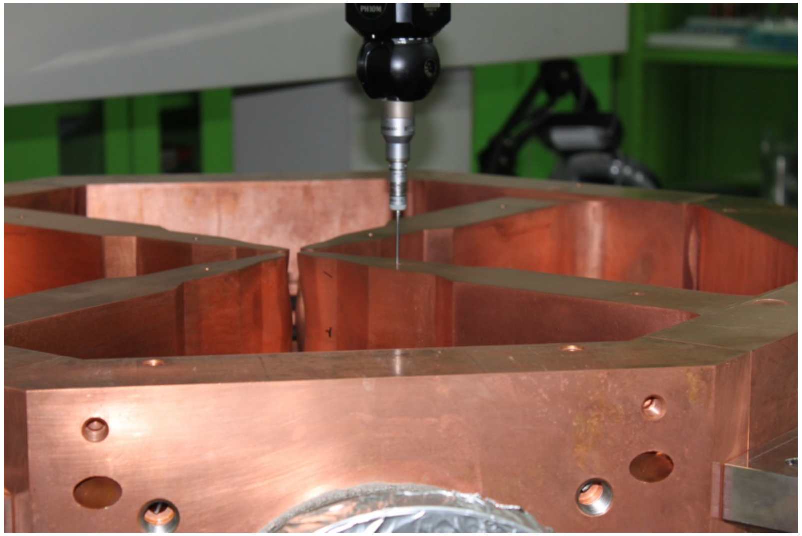
Installation of the dowel pins

# Inspect the Alignment

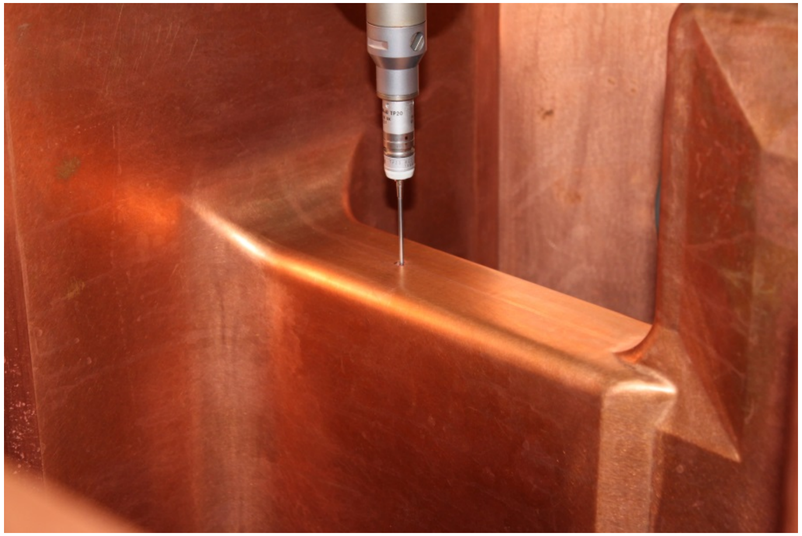
- Pin gauge (±50um)
 : The gap was checked in every step

- Machine the dowel pin holes at section ends
: to measure the vane position indirectly
: measured the hole position after the every assembly process


Gap gauge



Dowel hole



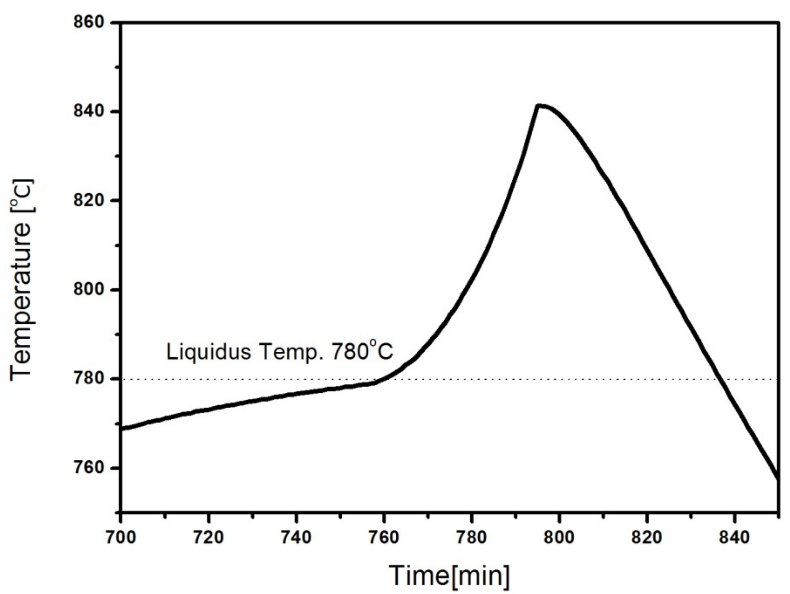
Dowel hole

# 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, BAg-8 copper alloy (Liquidus Temp. 780 ℃)




Temp. profile during final brazing

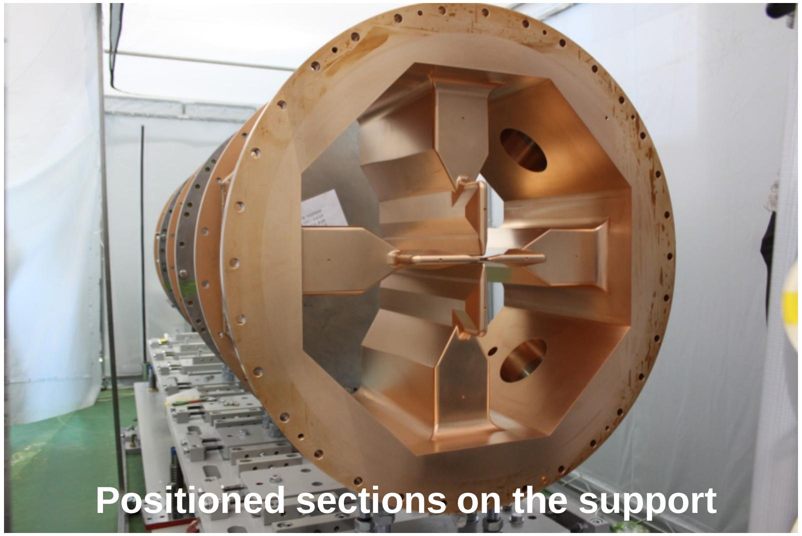
Final brazing process

# RFQ Installation

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

Girder type support installation

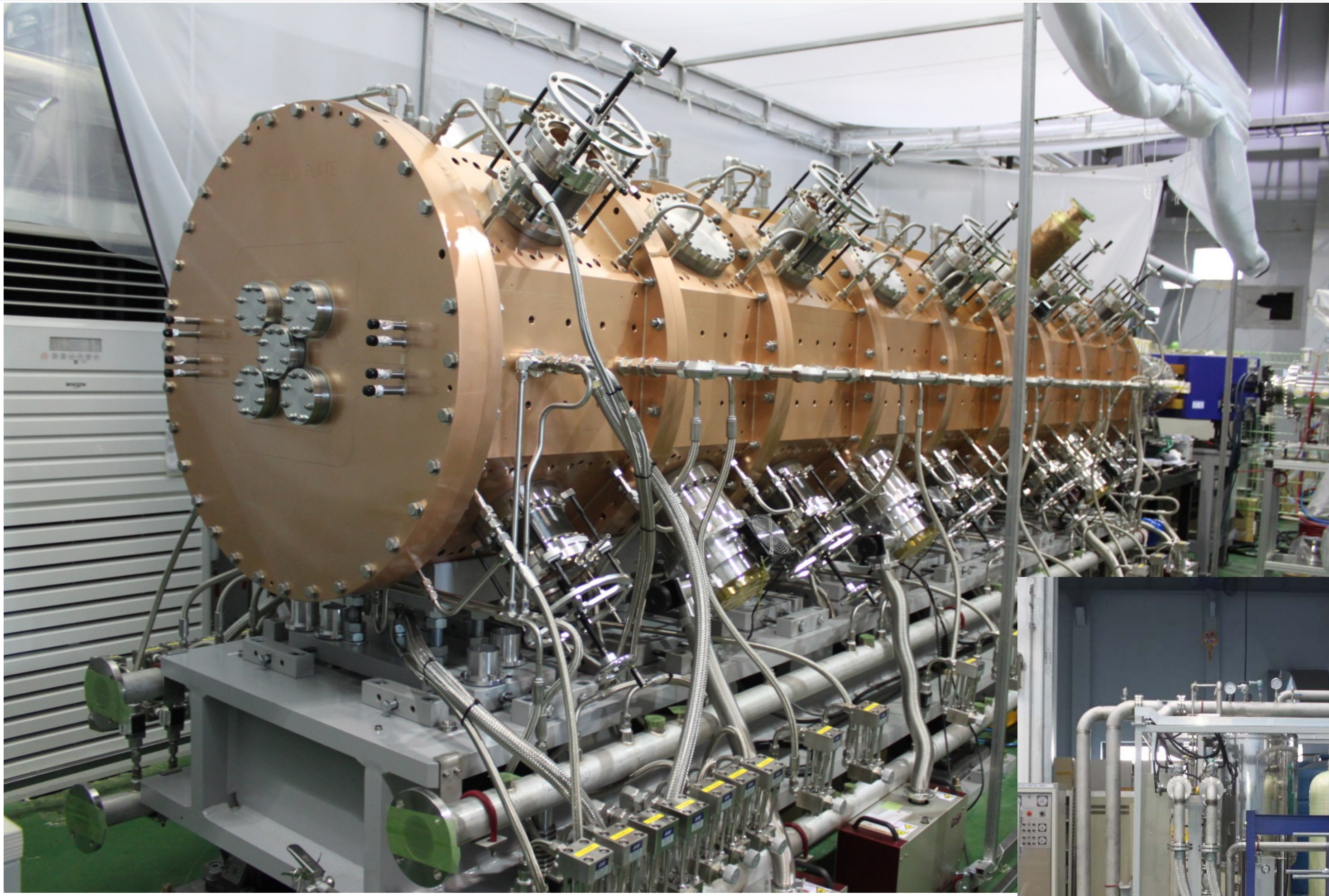
Transport nine sections



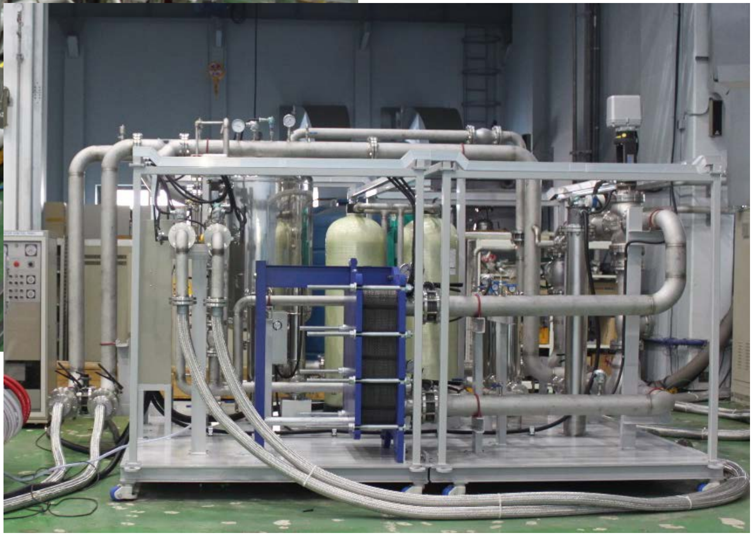
Positioned sections on the support

Alignment with a laser tracker

# Installed RFQ



Fabricated RFQ with cooling system



Resonance Control Cooling System (±0.1℃)

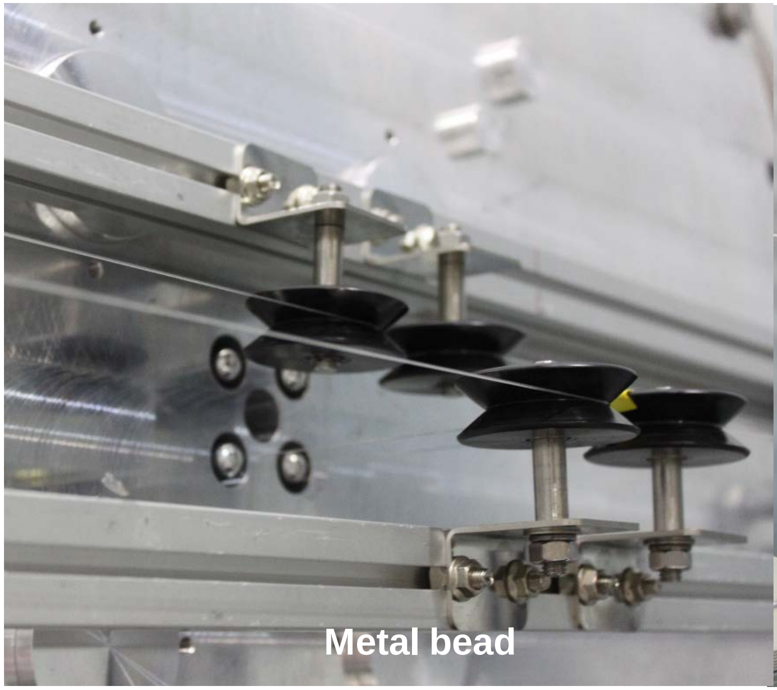
# Bead-pull Measurement

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

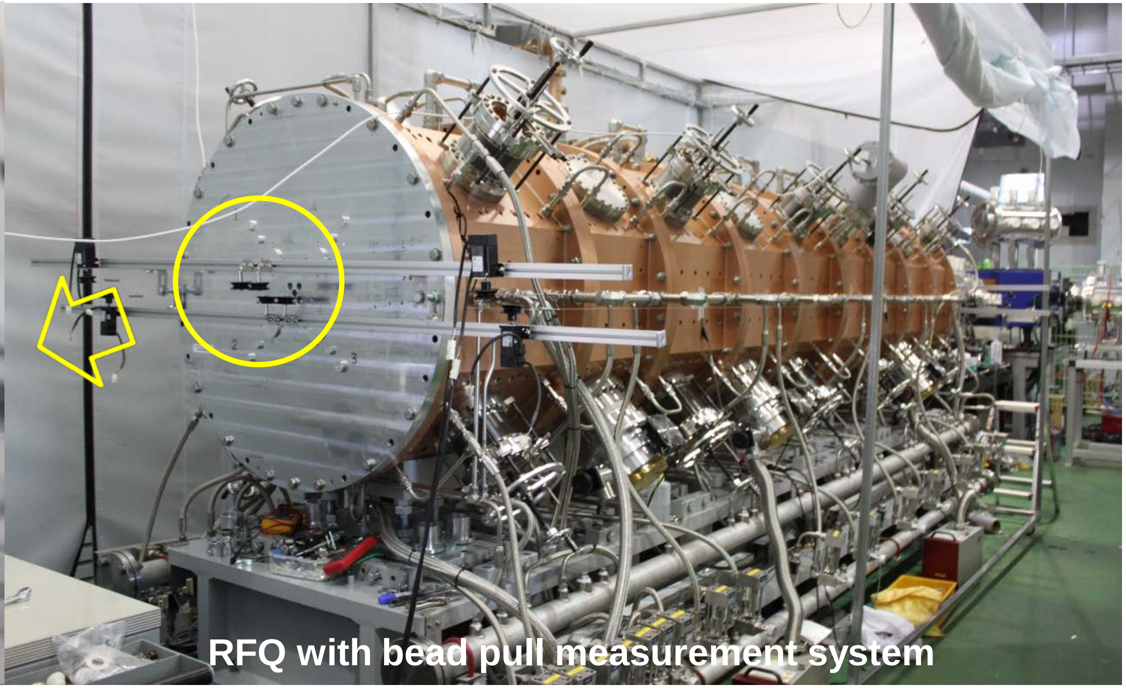
**For spherical metal bead,**

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

$\Delta V$ : *bead volume*,
$U$ : *stored energy in the cavity*
$E_0$ : *unperturbed electric field*,
$H_0$ : *unperturbed magnetic field*

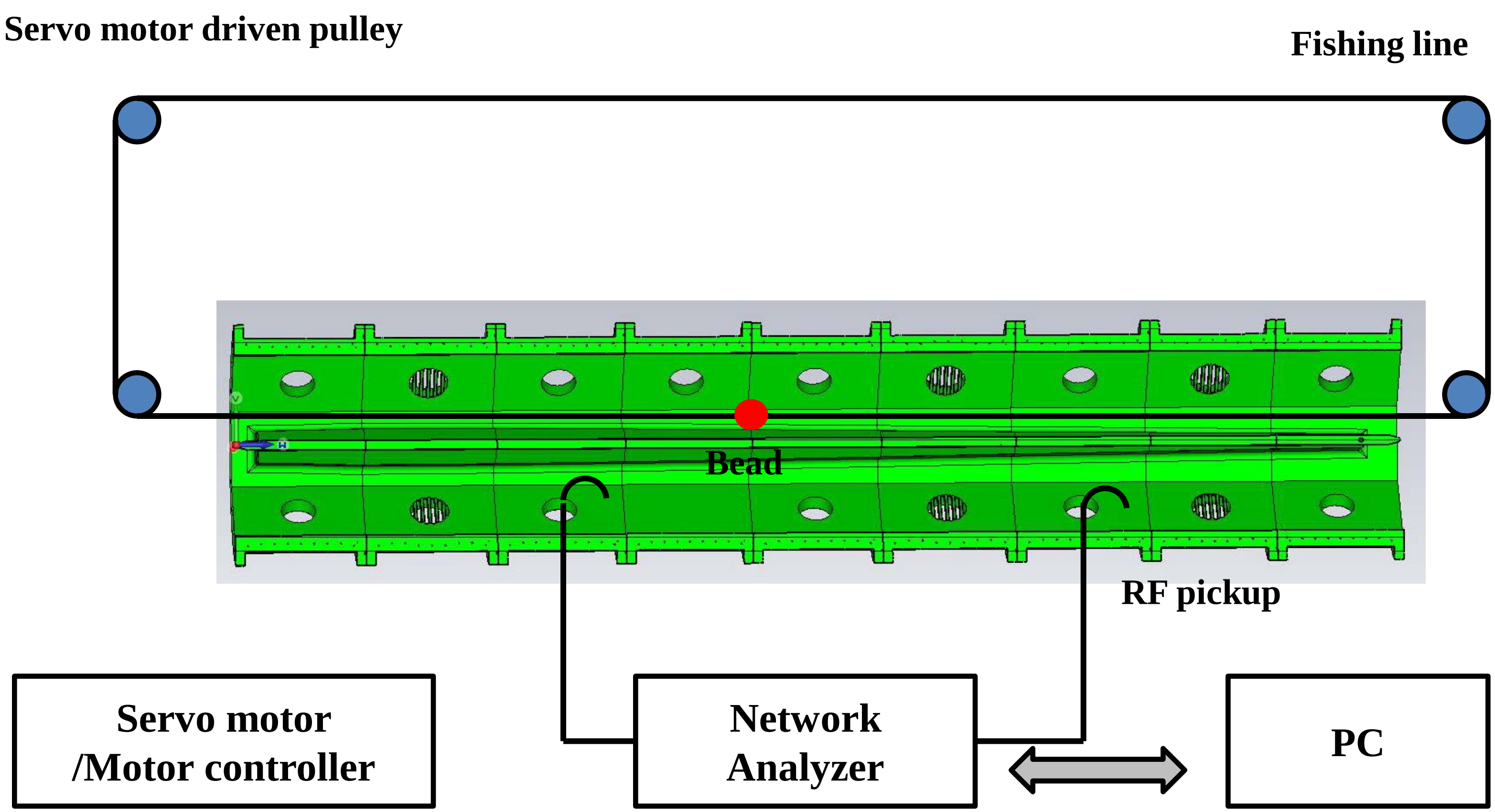


Metal bead



RFQ with bead pull measurement system

# RF Tuning setup




**Bead pull measurement system**

# RF Tuning Tool

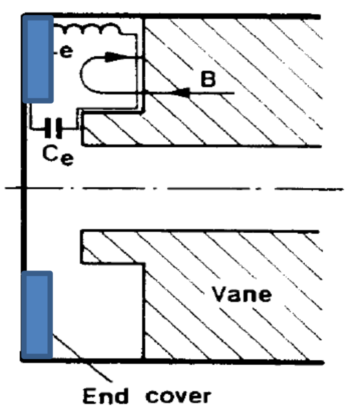
**By adjusting the radial perturbation with slug tuners, the magnetic field distribution and the frequency can be controlled.**

***The machining and alignment error can be compensated with slug tuners.***

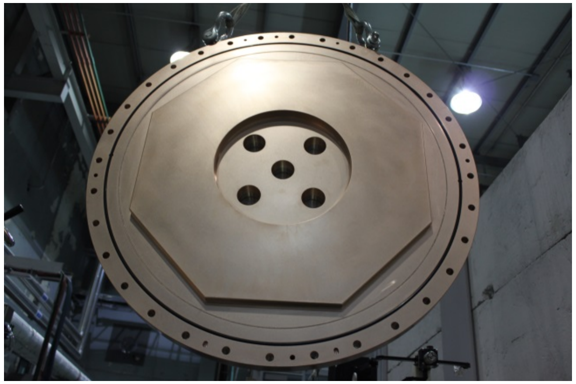
***- Number of movable slug tuners : 20 ea ( five for each quadrant)***

***Due to the insensitivity for the perturbation, the geometry of endplates was adopted as the tuning tool to control the capacitive and inductive components***

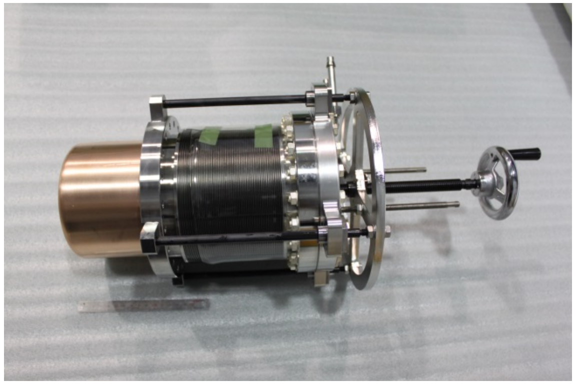
$$\frac{\delta V_0(z)}{V_0(z)} \propto -\left(\frac{\ell_v}{\lambda}\right)^2$$




**Schematic of endplate modification**



**Modified endplate**

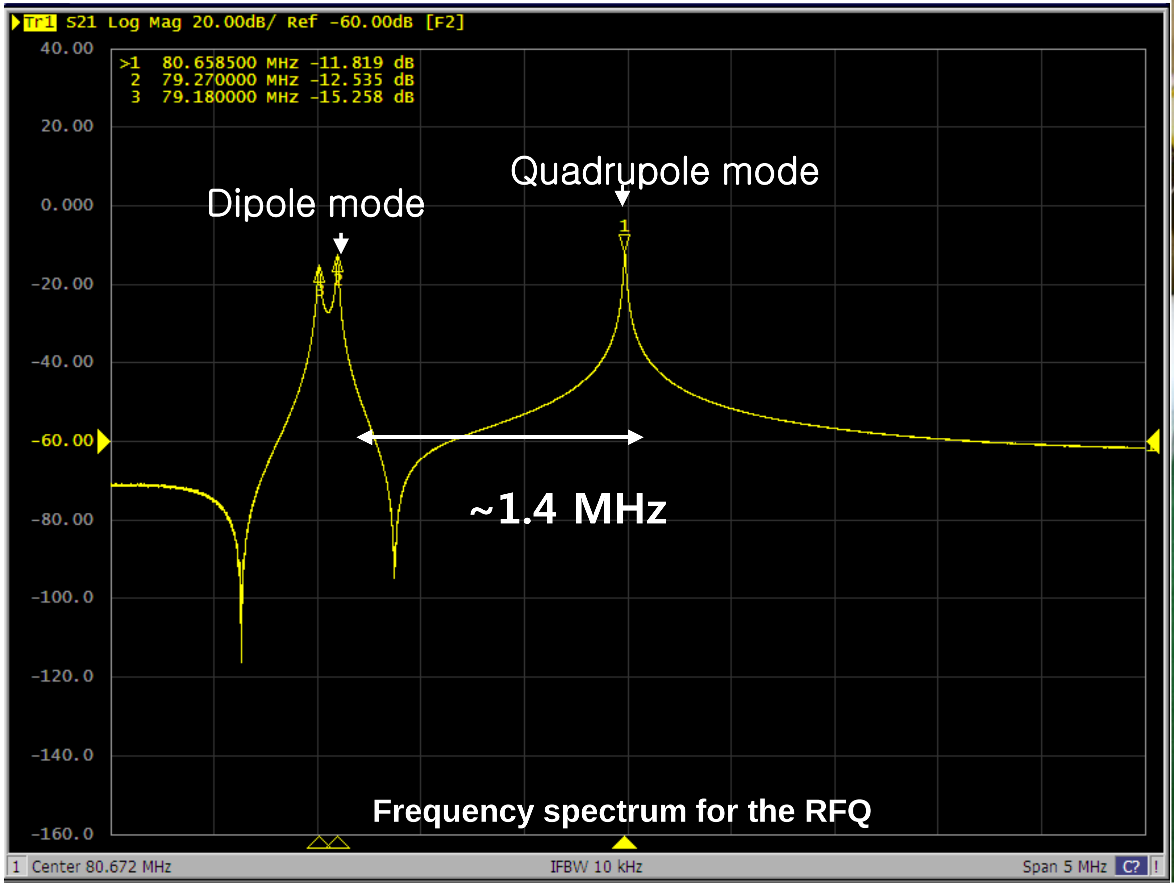


**Movable slug tuner(stroke 90mm)**

# 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

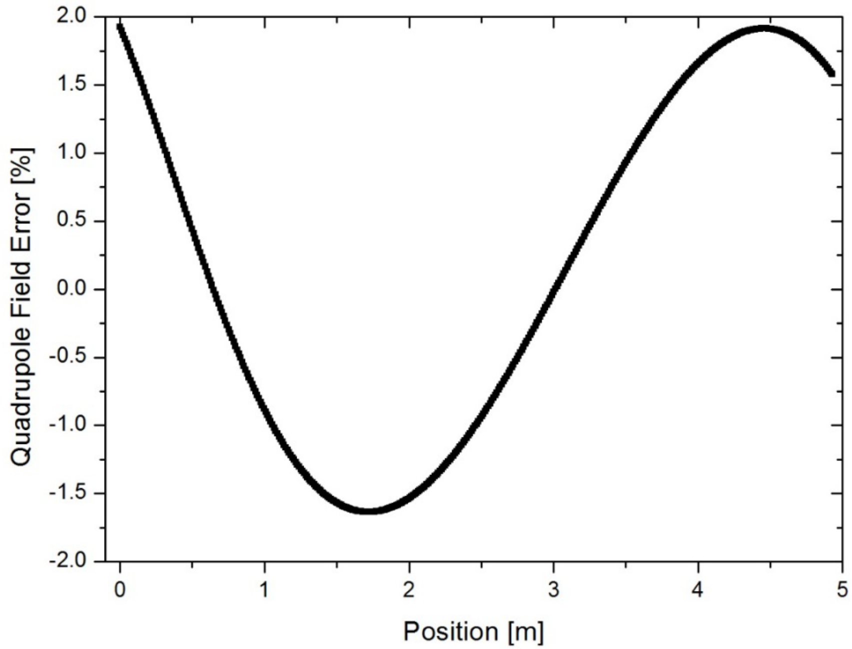
# Final Tuning Result

Quadrupole mode amplitude $A_Q = |B_1 - B_2 + B_3 - B_4| / 4$

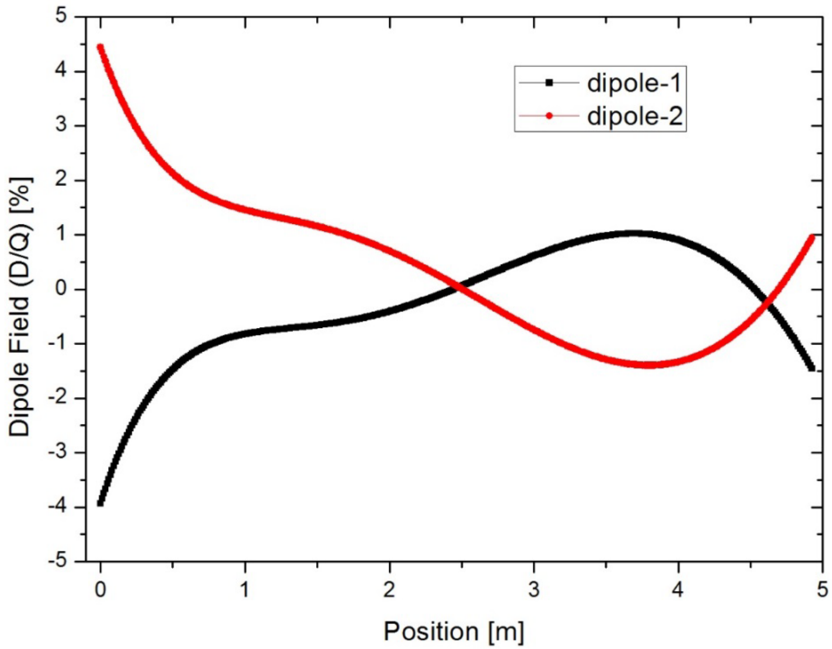
Dipole mode amplitude for each position $A_{D1} = |B_1 - B_3| / 2$ $A_{D2} = |B_2 - B_4| / 2$

Quadrupole field error compared to the designed value < ± 2%

Dipole field compared to the quadrupole field < ± 5%




Quadrupole field error




Dipole field compared to the quadrupole field

# III. Preliminary Beam Experiment

# Beam Acceleration Experiment

**Particle : $O^{+7}$**

**RF power : 80 kW SSPA**

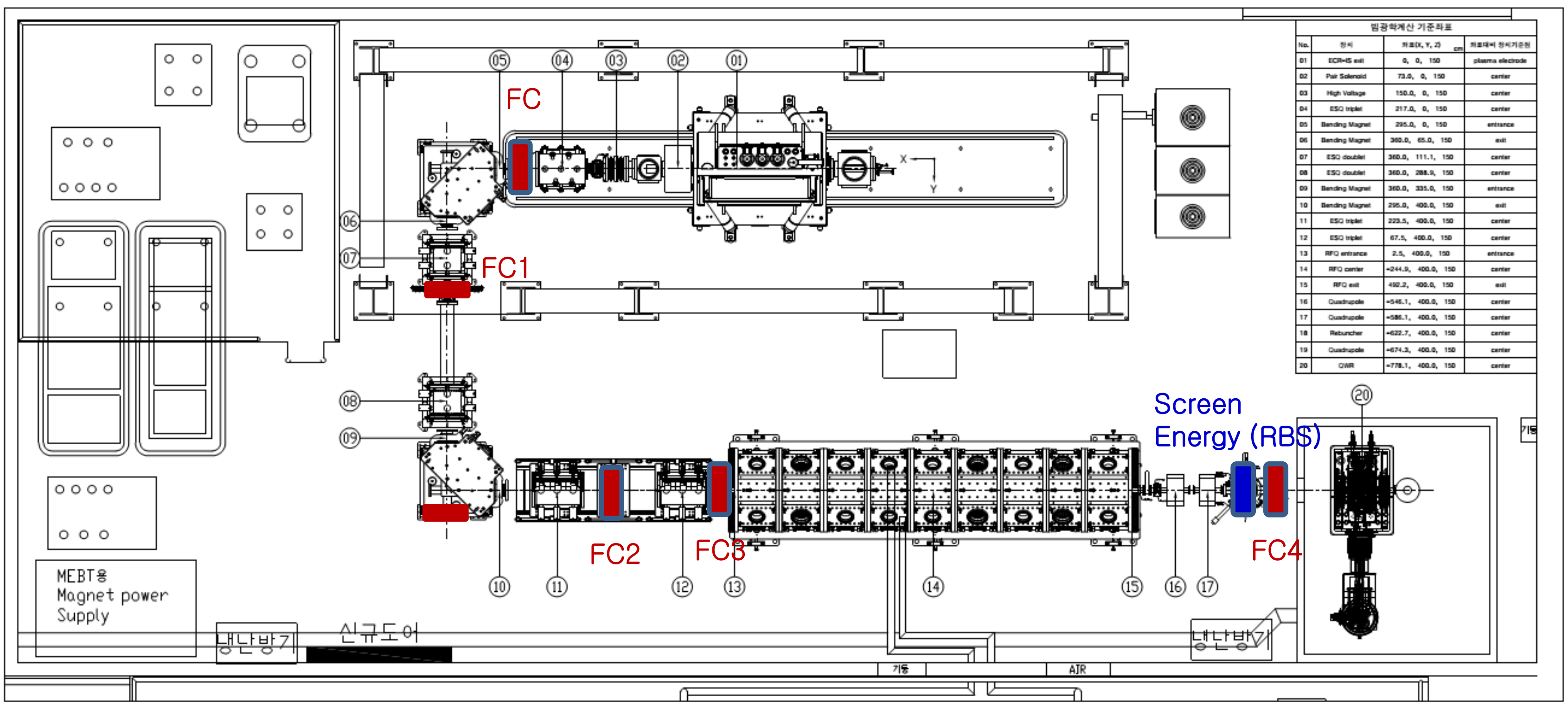
**Input energy : 10 keV/u (22.8kV)**

**Output energy : ~500 keV/u**

**Accelerated beam current : ~3 μA**

**RF set value vs. oxygen charge**

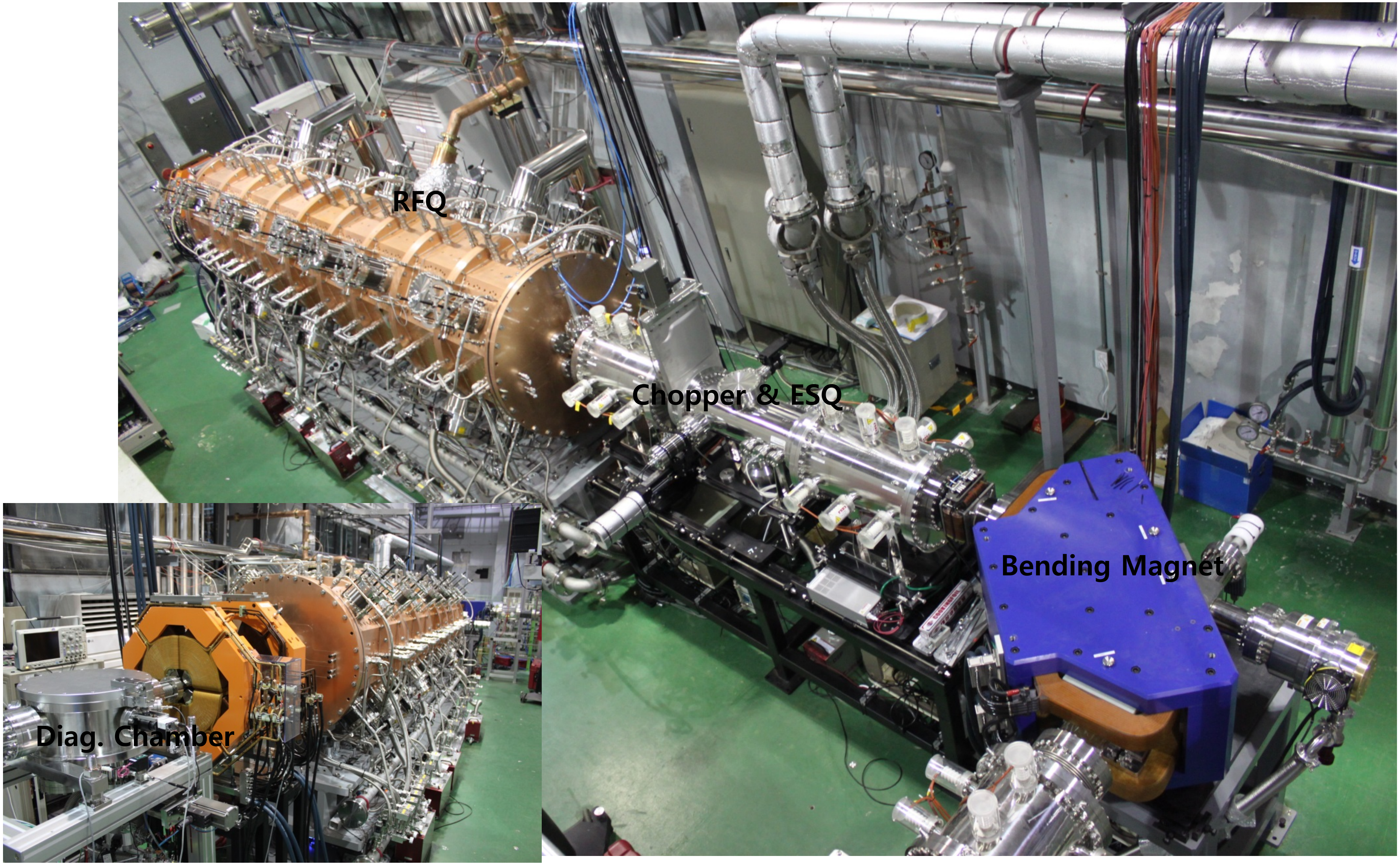
| q | A/q | Power(kW) | Power(kW) 20% margin |
|---|---|---|---|
| 4 | 4.0 | 25 | 32 |
| 5 | 3.2 | 16 | 20 |
| 6 | 2.7 | 11 | 14 |
| 7 | 2.3 | 8 | 10 |
| 8 | 2.0 | 6 | 8 |




빔광학계산 기준좌표

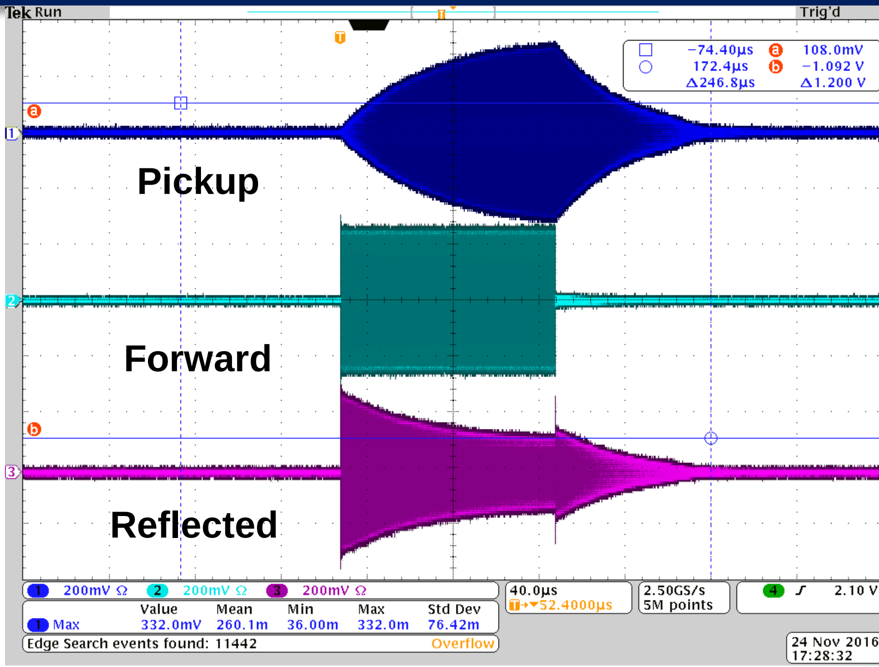
| No. | 장치 | 좌표(X, Y, Z) cm | 좌표대비 장치기준점 |
|---|---|---|---|
| 01 | ECR-IS exit | 0, 0, 150 | plasma electrode |
| 02 | Pair Solenoid | 73.0, 0, 150 | center |
| 03 | High Voltage | 150.0, 0, 150 | center |
| 04 | ESQ triplet | 217.0, 0, 150 | center |
| 05 | Bending Magnet | 295.0, 0, 150 | entrance |
| 06 | Bending Magnet | 360.0, 65.0, 150 | exit |
| 07 | ESQ doublet | 360.0, 111.1, 150 | center |
| 08 | ESQ doublet | 360.0, 288.9, 150 | center |
| 09 | Bending Magnet | 360.0, 335.0, 150 | entrance |
| 10 | Bending Magnet | 295.0, 400.0, 150 | exit |
| 11 | ESQ triplet | 223.5, 400.0, 150 | center |
| 12 | ESQ triplet | 67.5, 400.0, 150 | center |
| 13 | RFQ entrance | 2.5, 400.0, 150 | entrance |
| 14 | RFQ center | -244.9, 400.0, 150 | center |
| 15 | RFQ exit | 492.2, 400.0, 150 | exit |
| 16 | Quadrupole | -546.1, 400.0, 150 | center |
| 17 | Quadrupole | -586.1, 400.0, 150 | center |
| 18 | Rebuncher | -622.7, 400.0, 150 | center |
| 19 | Quadrupole | -674.3, 400.0, 150 | center |
| 20 | QWR | -778.1, 400.0, 150 | center |

# Experiment Setup

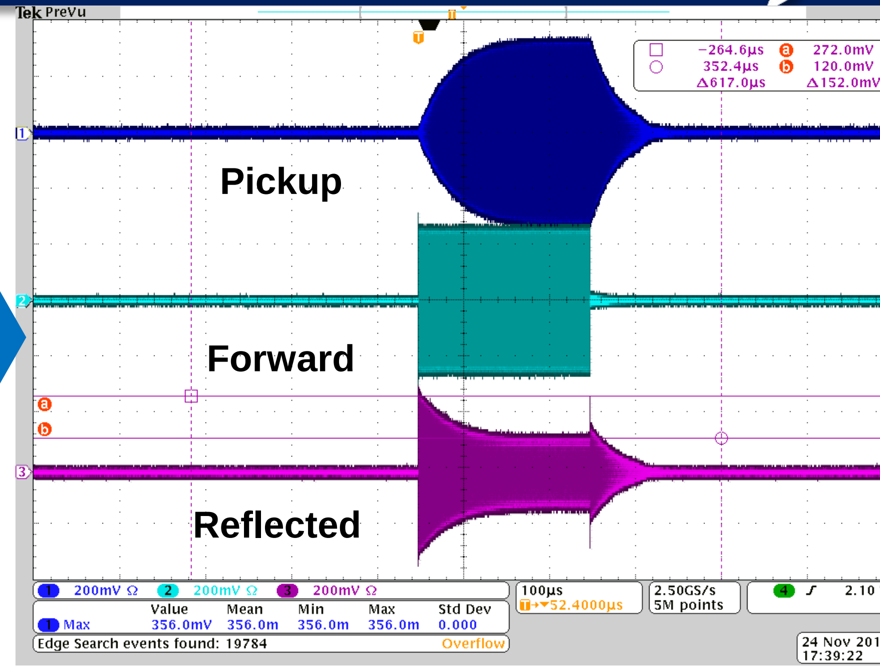



**Off-site Test Facility for RFQ Beam Experiment**

# RF Conditioning (one coupler)




Initial RF signal




Under conditioning RF signal

RF coupler under the baking

- Under 8kW(forward power), more RF condition is needed.
- Maximum conditioned power : 70 kW
- Pulse repetition : 1 Hz
- Pulse width : 100 us

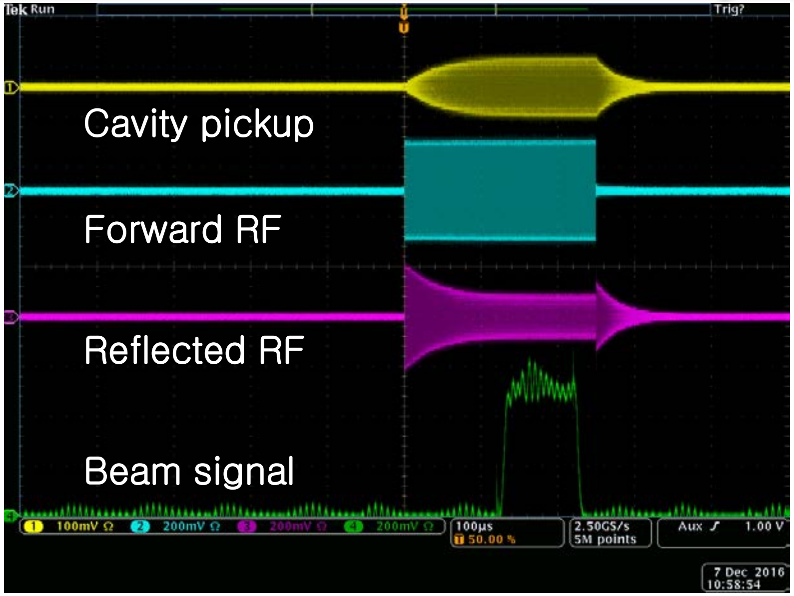
# First Beam Experiment – Current


**Timing structure**

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

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

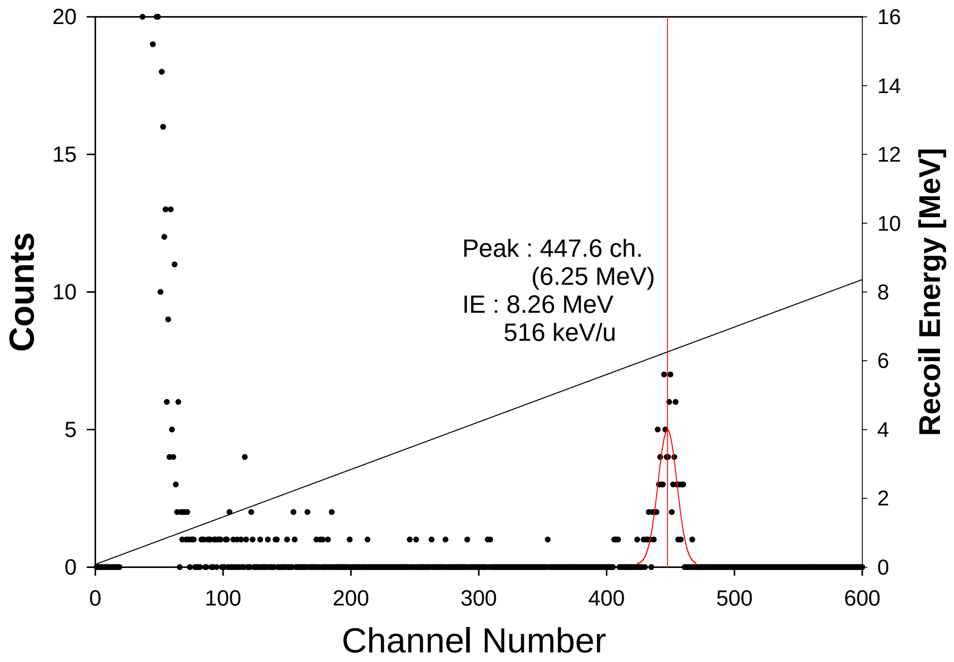
  rising and falling delay 5us+5us,




**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

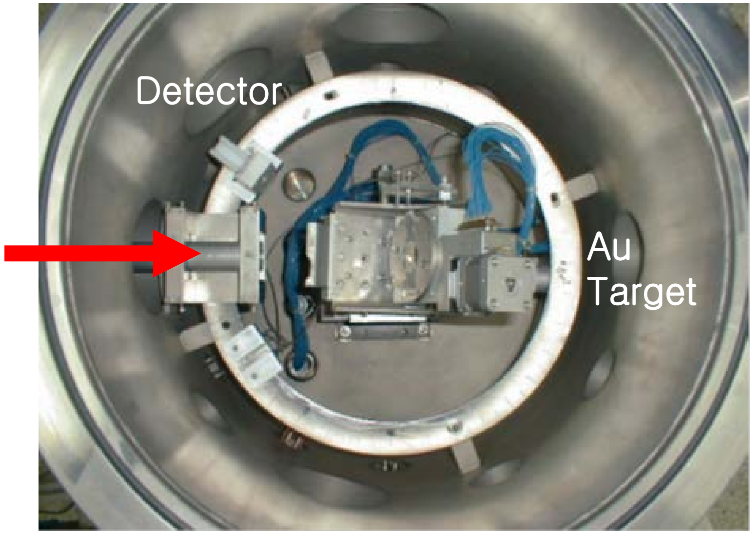
# First Beam Experiment – Energy




Energy measurement by the RBS(Rutherford Back Scattering) method

**Accelerated beam energy was measured**

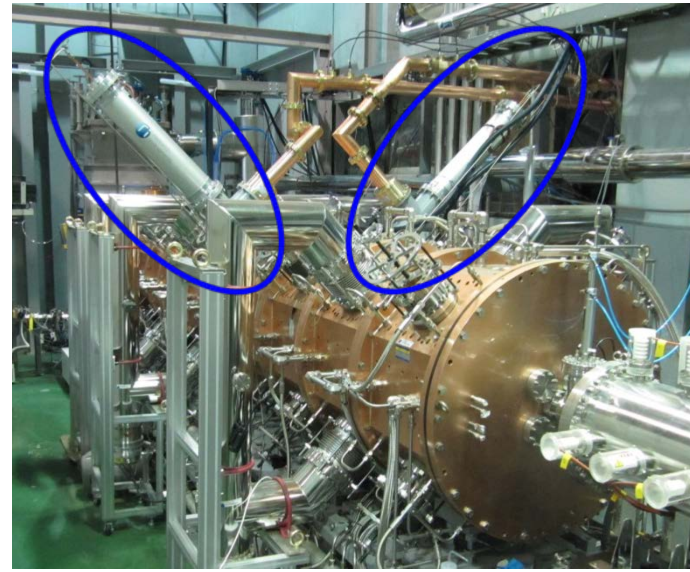
- **Field profile tuning was confirmed.**
- **Input & output beam characteristic will be measured.**

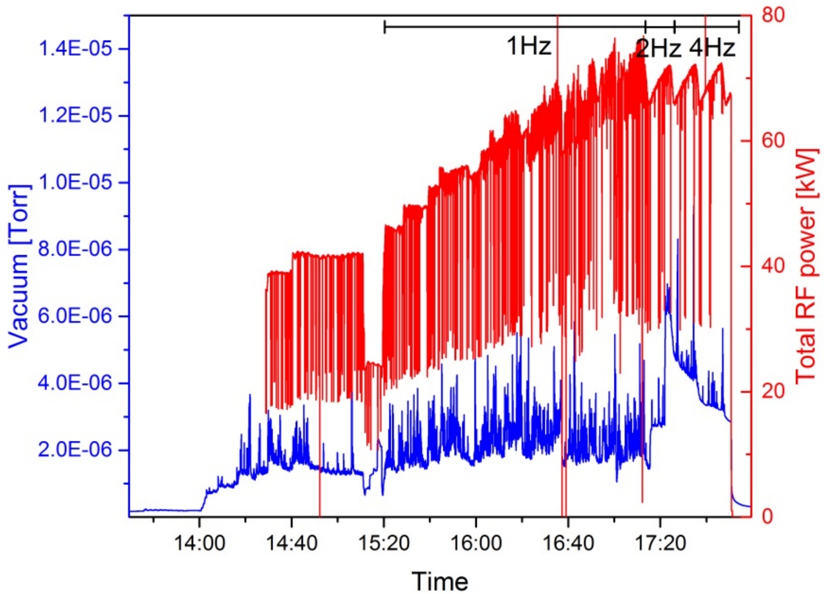


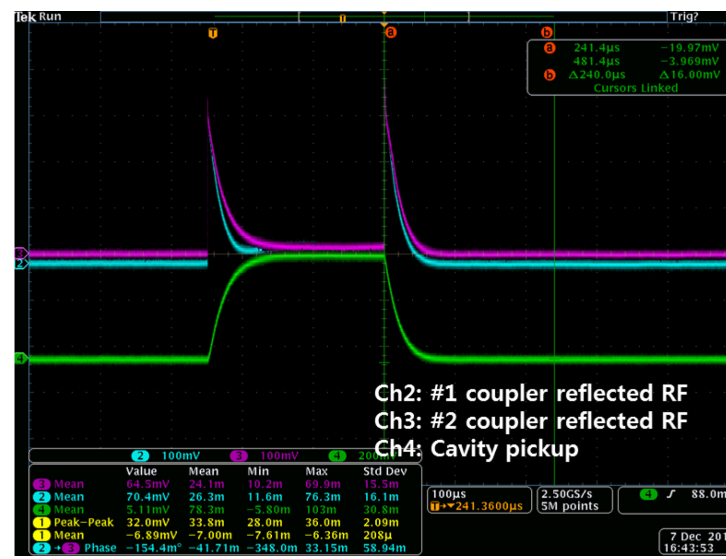

**Energy measurement system(RBS)**

# RF Conditioning (two coupler)

- RF conditioning with two power couplers
- Phase difference was compensated between coupler 1 and 2.
- Conditioning to 70kW, 4Hz in pulse mode operation (pulse width 250 us)
- Continuing to increase the repetitions





# 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.

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.