22nd International Conference on Cyclotrons and their Applications (CYC2019)

Design of Accelerator Mass Spectrometry Based on Cyclotron

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Contents

CYC 2019 22-27 SEPTEMBER CAPE TOWN

Recent activity

■ 9 MeV Cyclotron SKKUCY-9 [2010 ~ 2013]

SKKUCY-9	D x H (mm) 1250 x 1257	
Weight	8 tons	
Beams	Ions	Protons
	Energy / current	9 MeV / 50 μA
Magnet	Type	Comapact cylindrical
	Number of sectors	4
	Pole diameter	700 mm
	Hill / Valley gap	20~30 mm / 350 mm
	Extraction radius	310 mm
	B_{max} / B_{min}	1.89 T / 0.24 T
	Center B	1.366 T
RF	RF	83.2 MHz
	Harmonics	4
	Number of dees	2
	Q_0	4500
	Dee voltage	40 kV
Extraction	Charge Exchange Carbon Foil	
Ion Source	Internal Cold Cathode PIG	

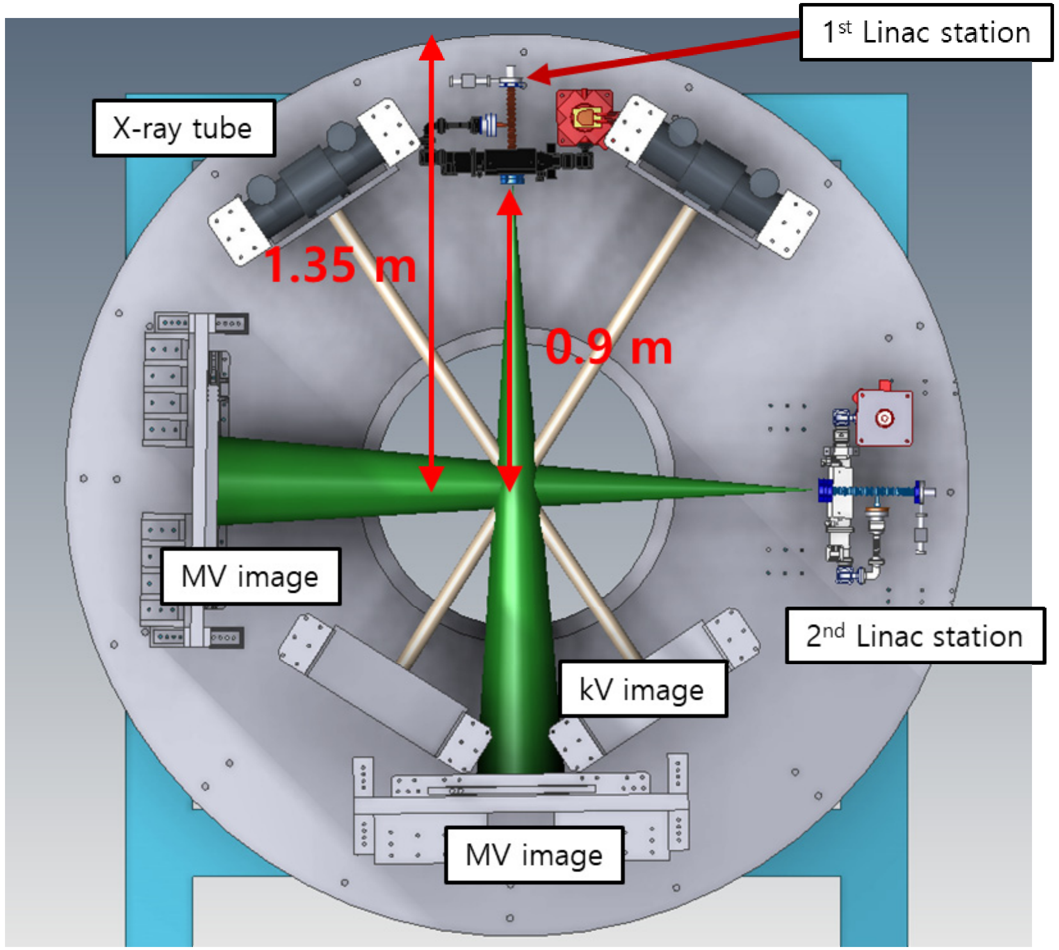
Recent activity

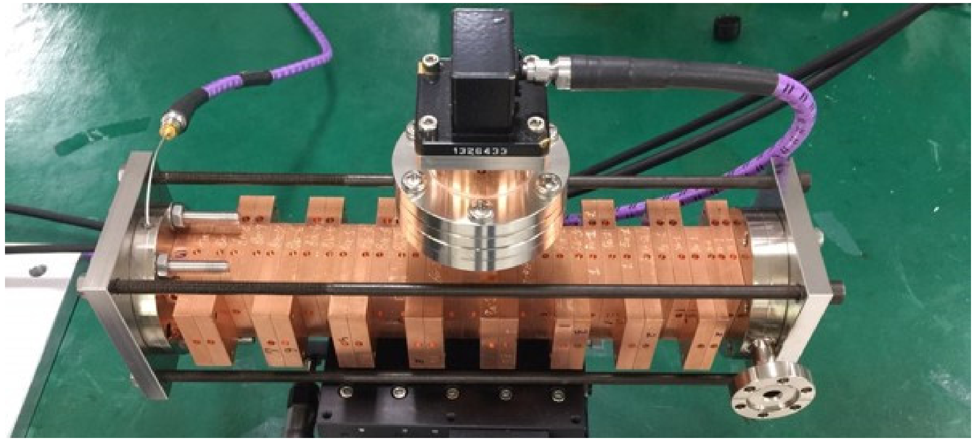
■ 10 MeV Cyclotron SKKUCY-10 [2013 ~ 2015]

SKKUCY-10	D x H (mm) 1500 x 1542	
Weight	12 tons	
Beams	Ions	Protons
	Energy / current	9.6 MeV / 90 μA
Magnet	Type	Compact cylindrical
	Number of sectors	4
	Pole diameter	730 mm
	Hill / Valley gap	32~30 mm / 560 mm
	Extraction radius	330 mm
	B_{max} / B_{min}	2.05 T / 0.45 T
	Center B	1.365 T
RF	RF	83.2 MHz
	Harmonics	4
	Number of dees	2
	Q_0	5960
	Dee voltage	40 kV
Extraction	Charge Exchange Carbon Foil	
Ion Source	Internal Cold Cathode PIG	

Recent activity

■ Dual-head gantry (Cancer therapy machine) [2012 ~ 2018]

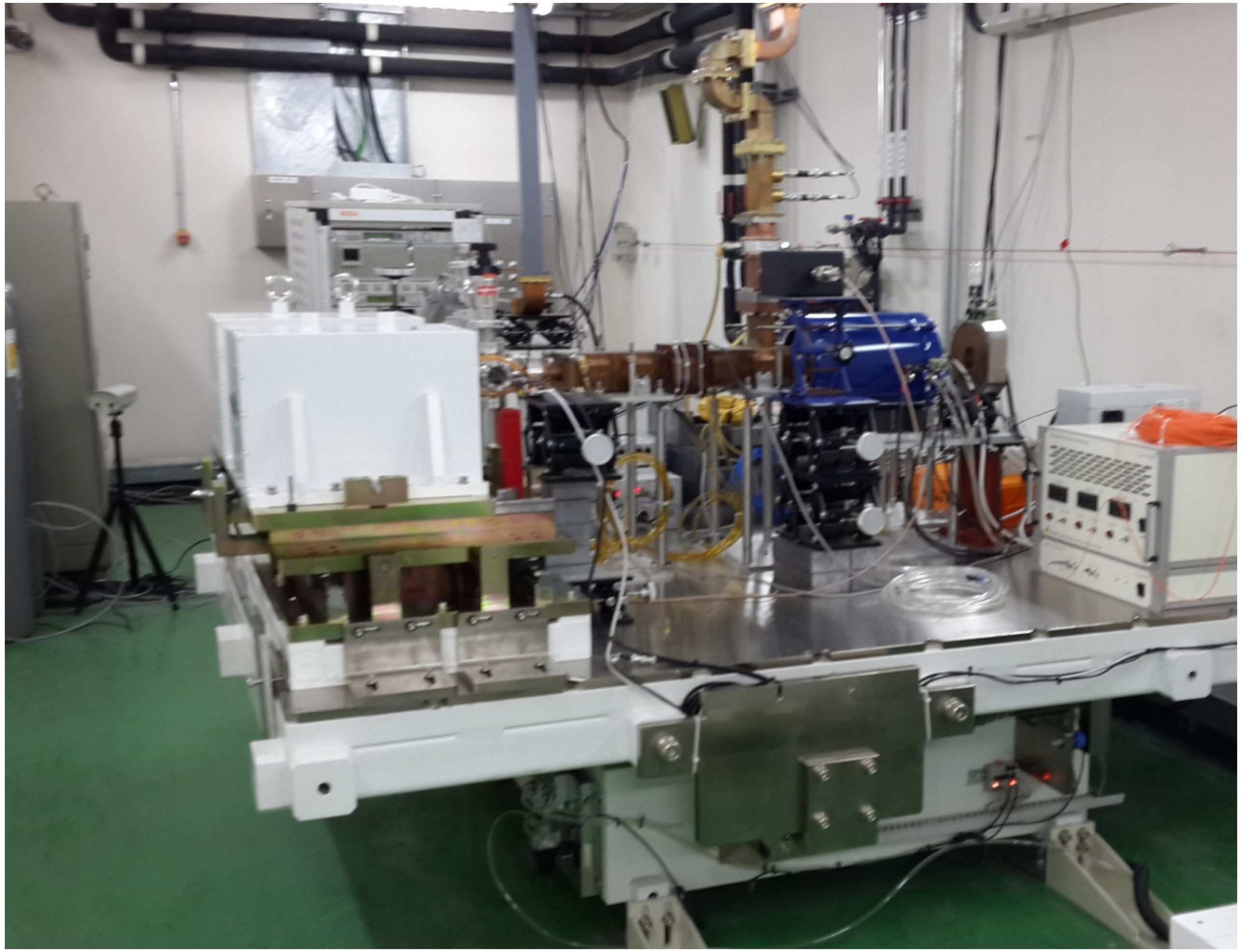


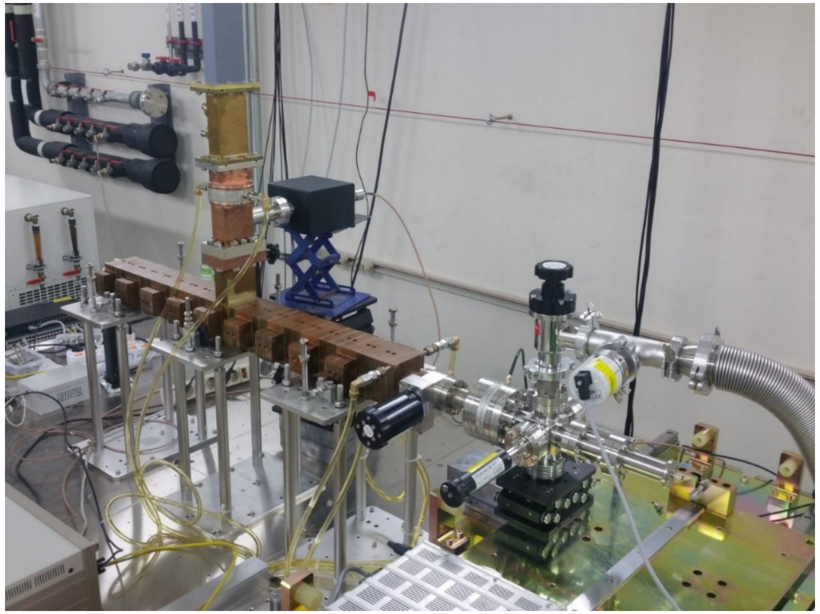


Parameters	Value
Operating Frequency	9.3 GHz
Input RF power (pulsed)	< 2 MW
Pulse Length	4 us
Duty Factor	0.0018
E-gun Volage	15 kV
Output Beam Current(Pulsed Maximum)	30 mA
Average Beam Current	55 uA
Beam Spot Size (FWHM)	2 mm
Output Beam Energy	6 MeV
Effective Shunt Impedance per Unit Length	90 MΩ/m
Operating Mode	Standing Wave, Pi/2 mode
Structure Type	Side-coupled Cavity
Structure Aperture Radius	4 mm
Length of the Accelerating Structure	< 30 cm

Recent activity

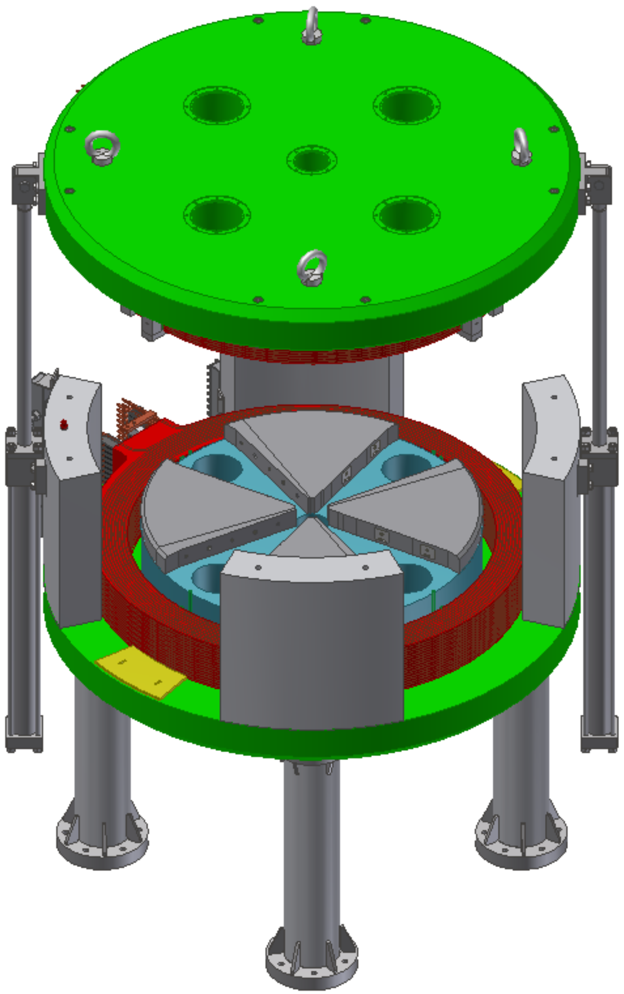
■ Cargo inspection [2013 ~ 2018]

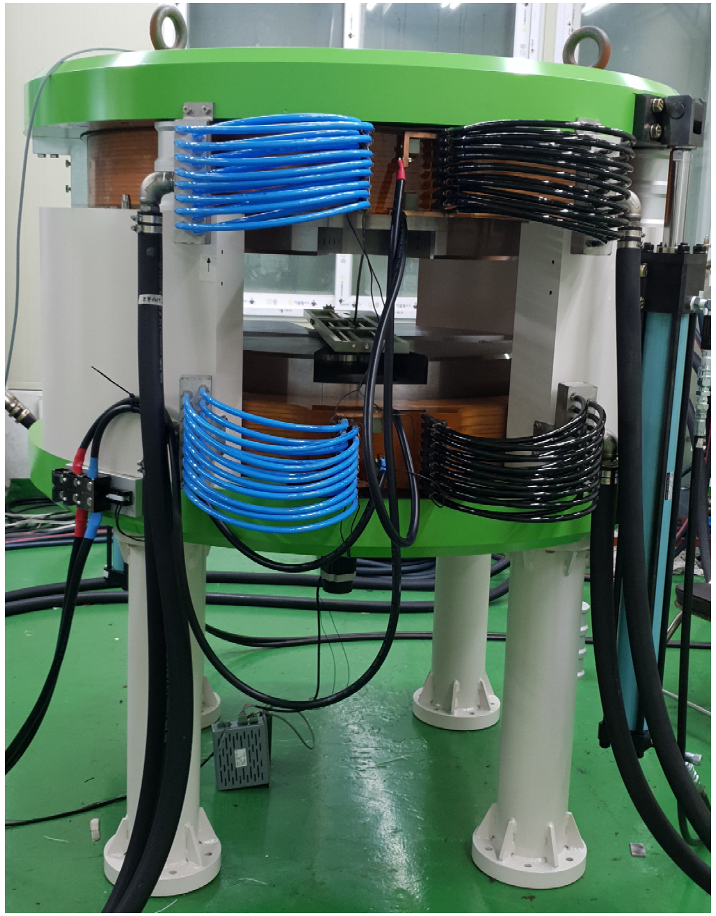




Parameters	Value
Energy	> 16 MeV
Klystron	2.5 MW(@16 MeV)
Dose Rate	141 Gy/min-m
Spot Size	~ 1 mm
Radiographic Quality	1-2T
Penetration	< 600 mm

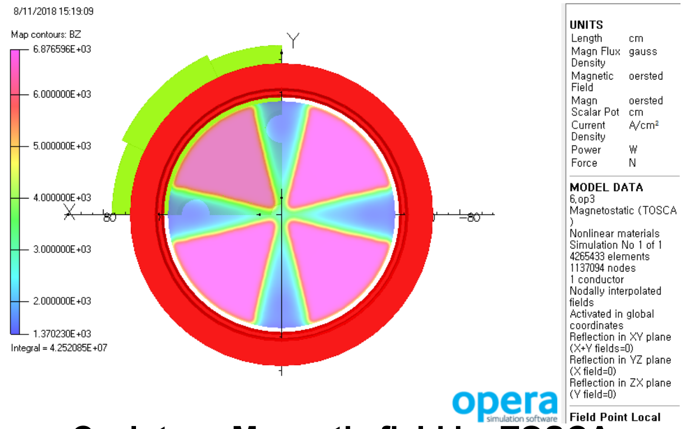
Development of AMS Cyclotron





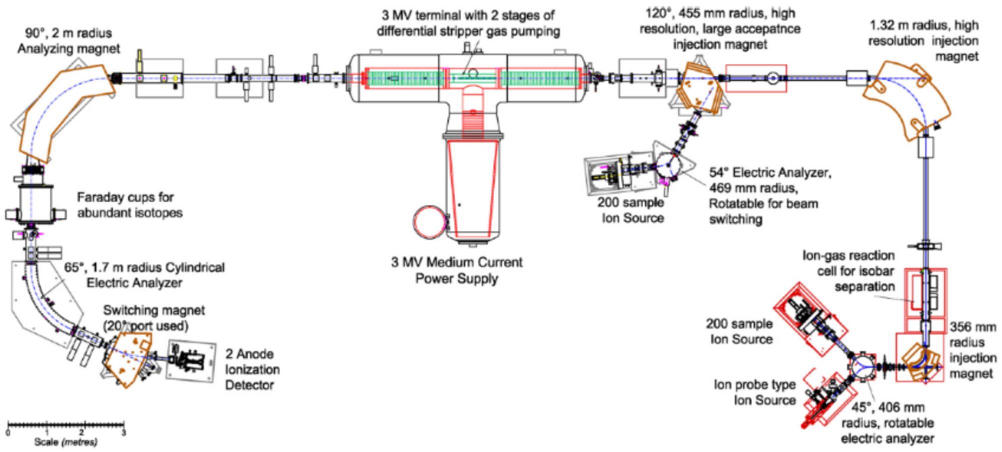
< Development of Cyclotron >

Specification	Value
E [KeV]	200
R_{in} / R_{ext} [mm]	138 / 457.2
Mass Resolution	5000
Turn number	159
Harmonic	10
B_0 [T]	0.5332
B_{max} / B_{min} [T]	0.688 / 0.137
Magnet Size [mm]	D 1580 x H 800
Minimum Turn separation [mm]	1.2
E_{in} [KeV]	25
Dee angle [º]	20
Number of Dee	2



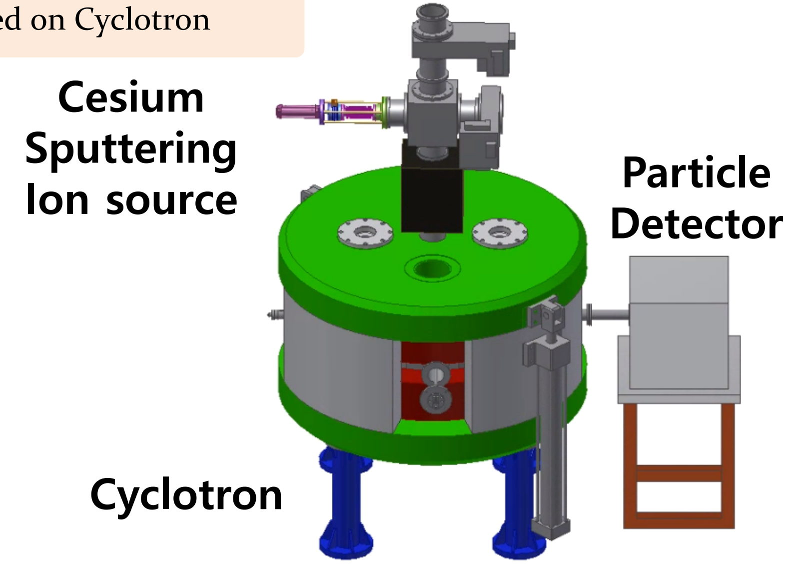
< Cyclotron Magnetic field by TOSCA >

AMS based on Tandem



(reference: Ottawa university, NIMB, 361, pp.110-114)

AMS based on Cyclotron



Advantage

- **Compact system**
  - ✓ Based on Cyclone for C-14 particle analysis composed of 5 components
  - ✓ Self mass analysis
- **Low cost**
  - ✓ Low-cost, compact system due to AMS minimization

Disadvantage

- **Relatively fewer samples than static AMS**
  - ✓ The tandem type accelerator is an electrostatic type, and the finally discharged particles are DC type.
  - ✓ In the case of cyclotron, the electric field of RF emits the emissive particles in AC form.

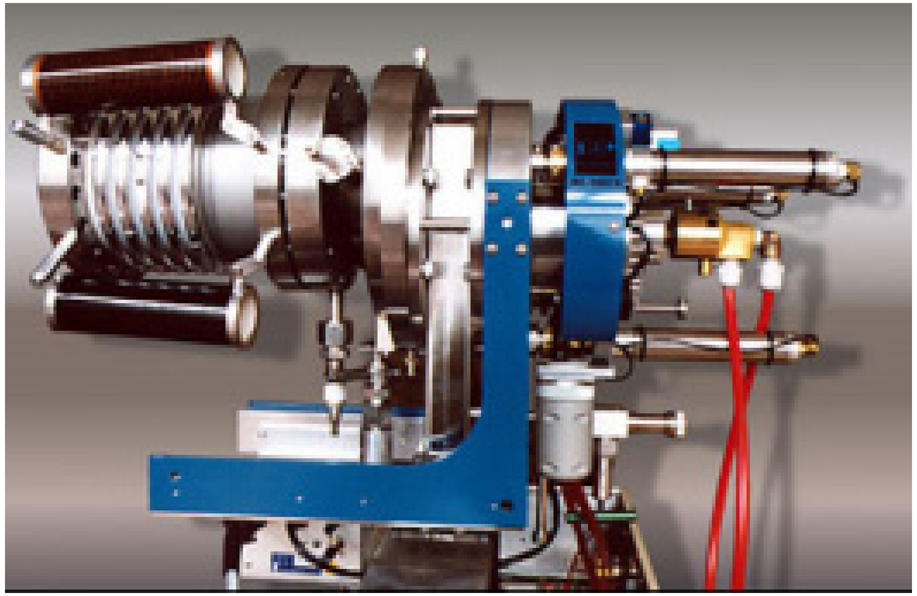
Innovation point

- **AI-based system control and machine-learning particle discrimination for multi-mass spectral analysis**
  - ✓ It is possible to adjust isochronous and magnetic field RF frequency and output simultaneously by AI system control according to particle type.
  - ✓ Machine running Improving accuracy by particle sorting and applying to mass spectrometry for new industries such as dating and bio-nano.

Design Process of the AMS cyclotron

AMS cyclotron Design

2017	2018	2019	2020
Gathering Information	**Design & Fabrication**	**Measurement and Modification**	**AMS System Test**
System Requirement ▪ Mass resolution ▪ Frequency ▪ RF Power ▪ Size ▪ Beam line	Magnet Mechanical design & fabrication	Magnetic field measurement & Shimming	Combine all components
Conceptual design ▪ Cyclotron Magnet ▪ RF Amp ▪ RF Dee ▪ Ion source ▪ Inflector & Extraction ▪ Detection system ▪ AI-based control system	Magnetic field measurement instrument design & Fabrication	RF cavity fabrication & Test	AMS system test
	Design of AI based control algorithm	Ion source Test	AI-based control algorithm implementation
		AI based control algorithm test & modification	Total system optimization



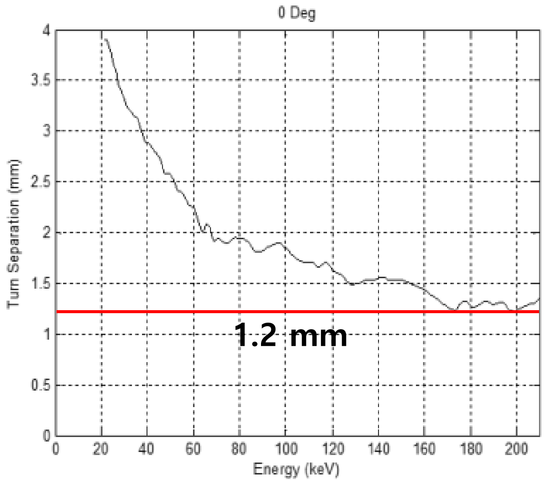
Cesium Sputtering Negative Ion source - SNICS

National Electrostatics Corp.

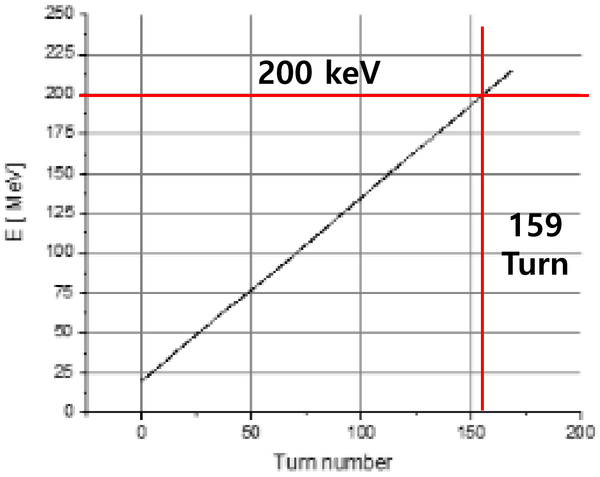
Recommended Power Supplies		
Cs Ionizer	20VDC, 30A	Current regulated
Cathode Bias	-10kV, 15mA	Voltage regulated
Extractor	15kV, 8mA	Voltage regulated
Focus	5kV - 3mA	Voltage regulated
Cs Oven	0-120VAC, 2.2A	

Negative Ion	Current after Analysis (μA)	Negative Ion	Current after Analysis (μA)
H^-	130	As^-	60
D^-	150	Se^-	10
Li^-	4	Br^-	40
BeO^-	10	Sr^-	1.5
B^-	60	Y^-	0.66
B_2^-	73	Zr^-	9.4
C^-	260	Nb^-	7
C_2^-	40	Mo^-	5
CN^-	12	Rh^-	5
$CN^-(^{15}N)$	20	Ag^-	13
O^-	300	CdO^-	7
F^-	100	InO^-	20
Na^-	4.0	Sn^-	20
MgH_2^-	1.5	Sb^-	16
Al^-	7	Te^-	20
Al_2^-	50	I^-	220
Si^-	430	Cs^-	1.5
P^-	125	CeO^-	0.2
S^-	100	NdO^-	0.3
Cl^-	100	EuO^-	1.0
CaH_3^-	0.8	ErO^-	10
TiH^-	10	TmO^-	1.0
VH^-	25	YbO^-	1.0
Cr-	5	Ta^-	9.5
MnO^-	4	TaO^-	6
Fe^-	20	W^-	2.5
Co^-	120	Os^-	15
Ni^-	80	Ir^-	100
Cu^-	160	Pt^-	250
ZnO^-	12	Au^-	150
GaO^-	7	PbO^-	1
Ge^-	60	Bi^-	3.5

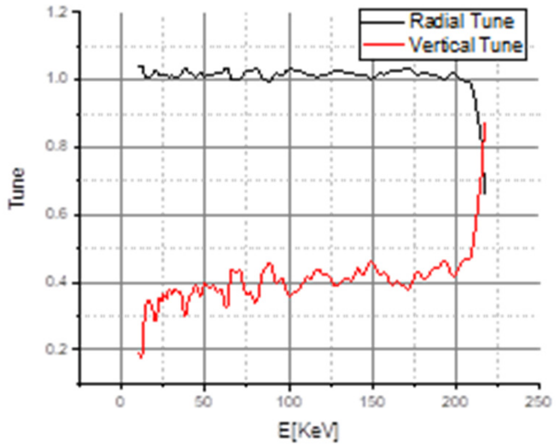
Cyclotron Beam dynamics



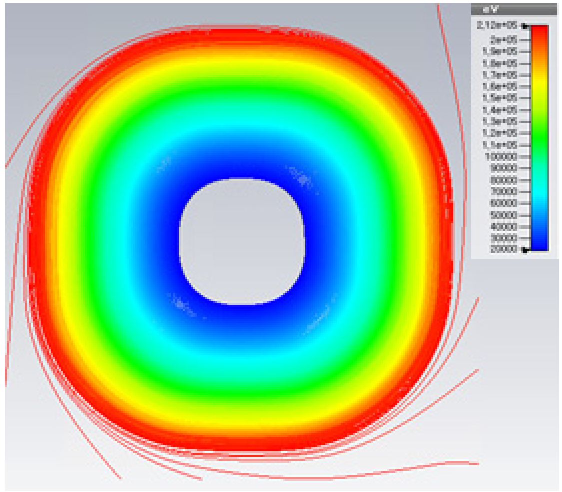
< Turn separation >



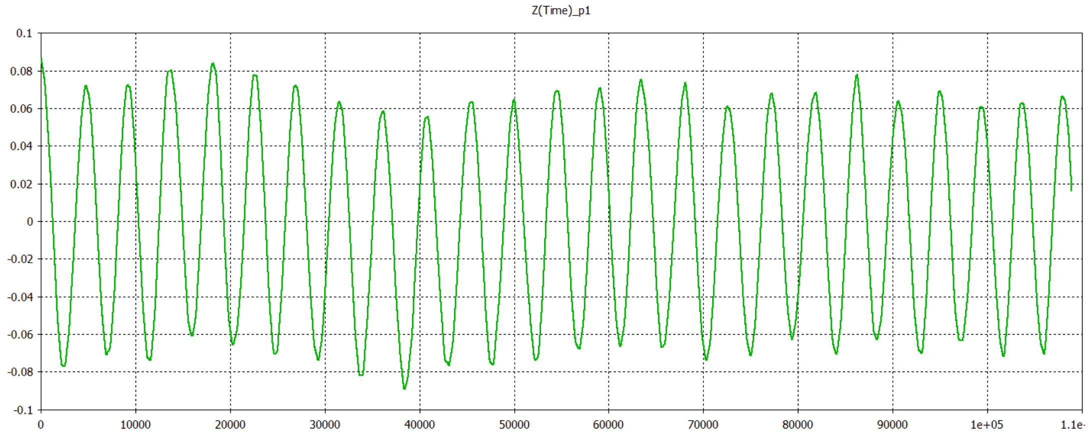
< Energy gain >



< Tune>

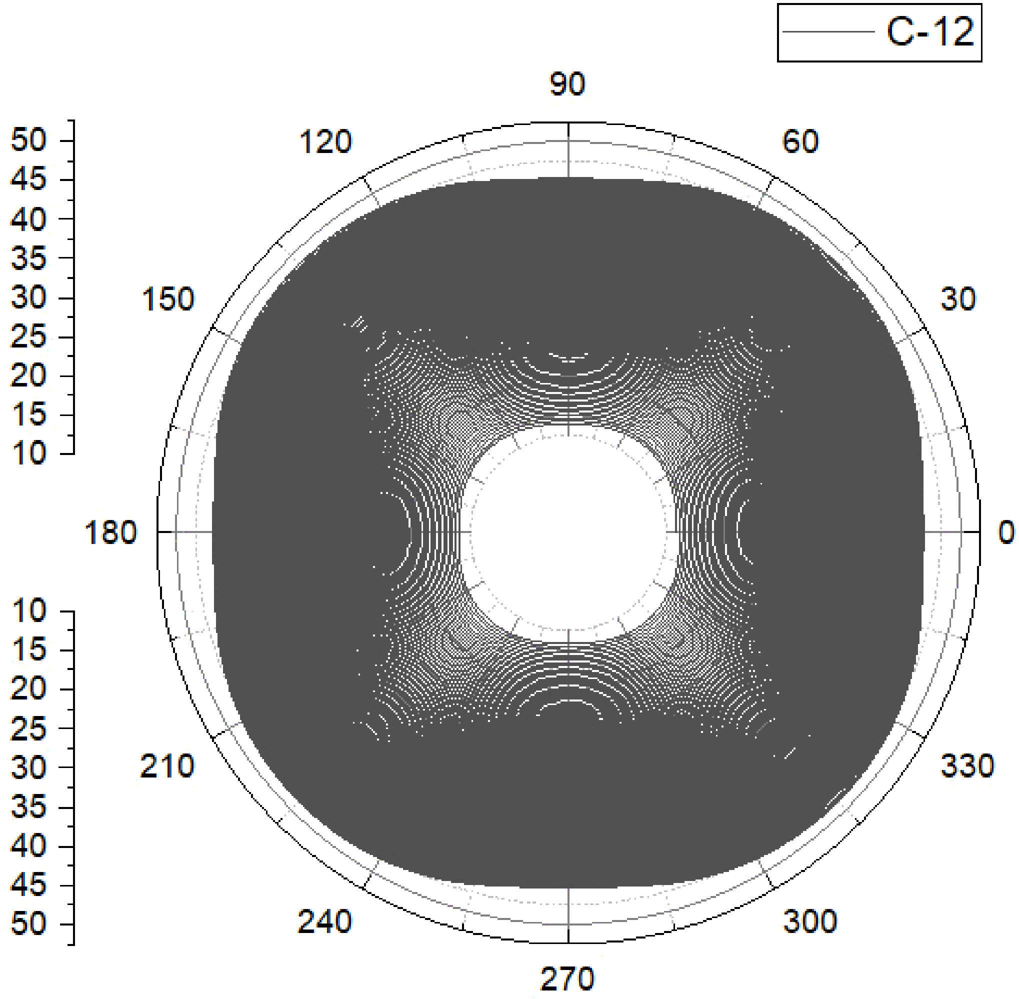


< multi beam analysis >

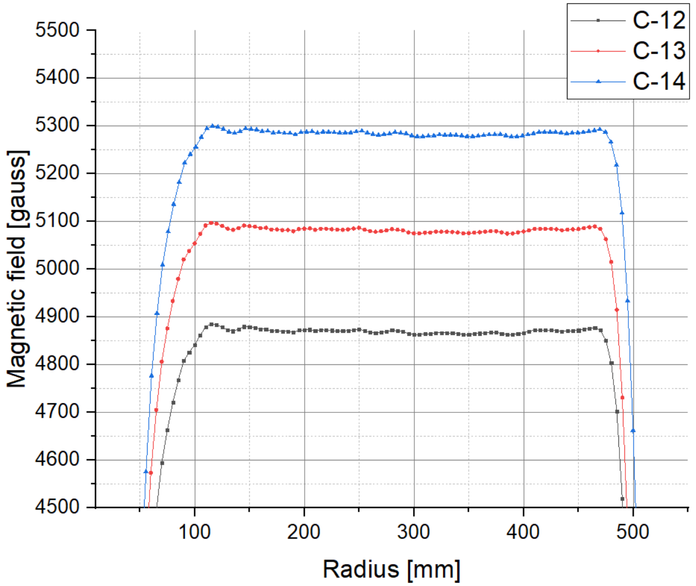


< Z-Direction distribution >

Cyclotron Beam dynamics



< Single beam trajectory of negative carbon particles >

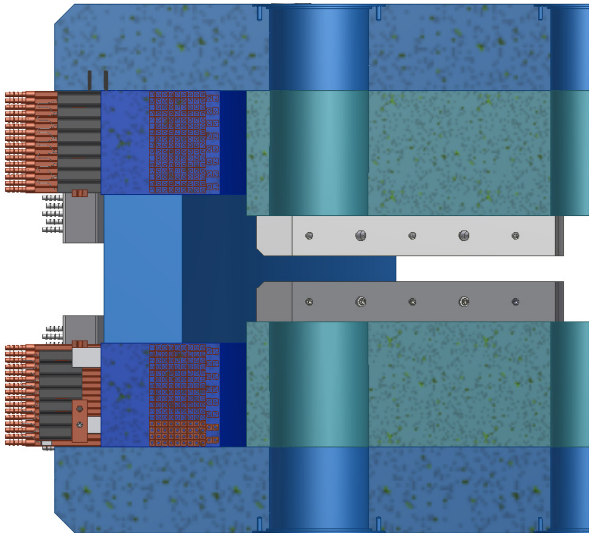


< Average magnetic field of Carbon particles >

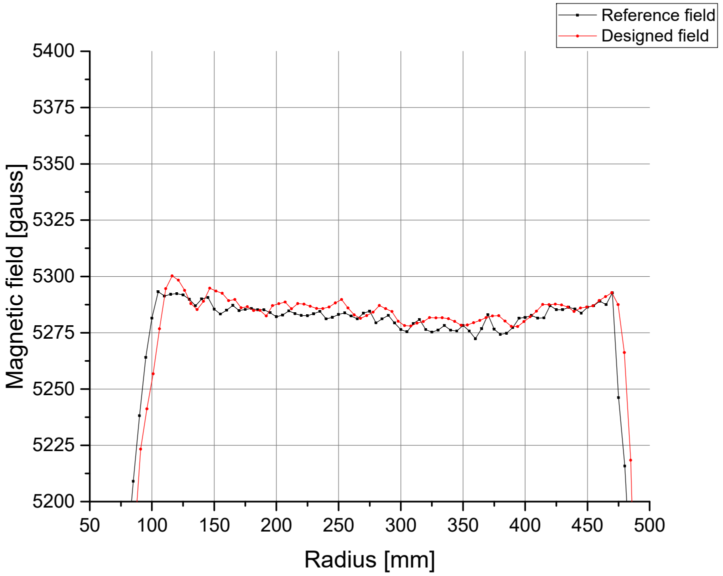
Particle	C-12		
R_{in} [mm]	138.1	R_{out} [mm]	460.3
f [Mhz]	6.25	B_0 [T]	0.49215
Particle	**C-13**		
R_{in} [mm]	138.1	R_{out} [mm]	458.5
f [Mhz]	6.01	B_0 [T]	0.51314
Particle	**C-14**		
R_{in} [mm]	138.1	R_{out} [mm]	457.2
f [Mhz]	5.8	B_0 [T]	0.53325

< Initial condition of Carbon particles >

AMS Cyclotron Magnet



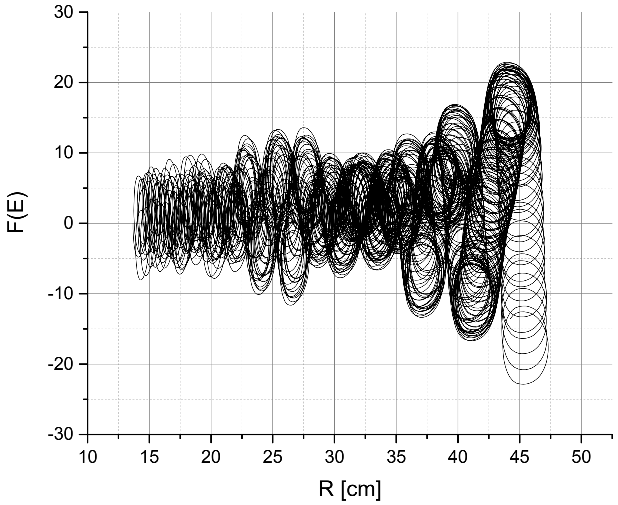
< AMS Magnet Side view >



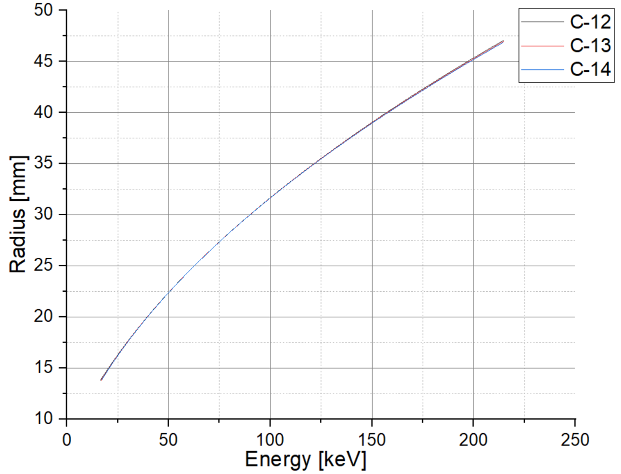
< Average magnetic field >

Specification	Value
Square [mm]	9
Hole [phi]	4.5
Coil Turn	160
A-T	13700
Current [A]	85
Voltage [V]	32
P [kW]	2.75

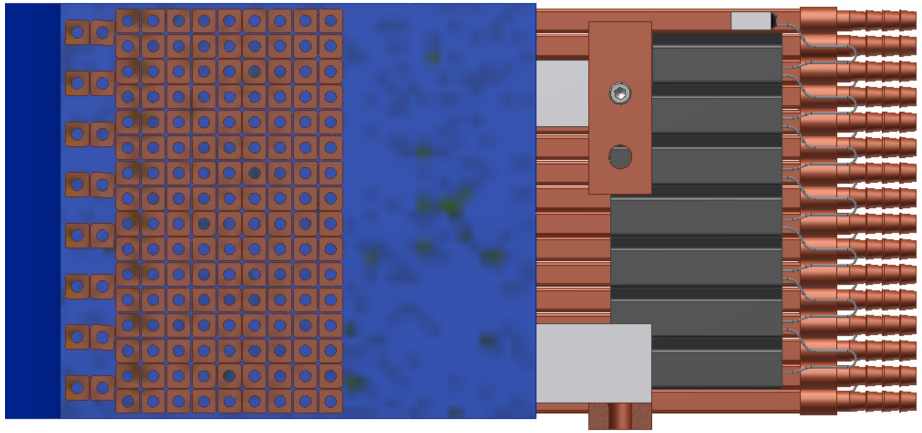
< AMS Coil Specification >



< Phase error of carbon beam >

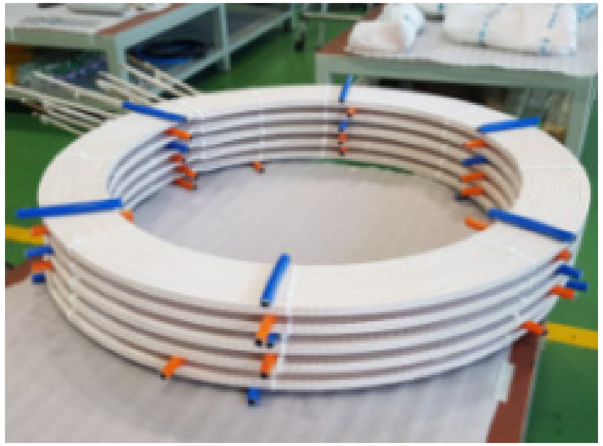


< Energy-Radius graph (C-12,13,14) >

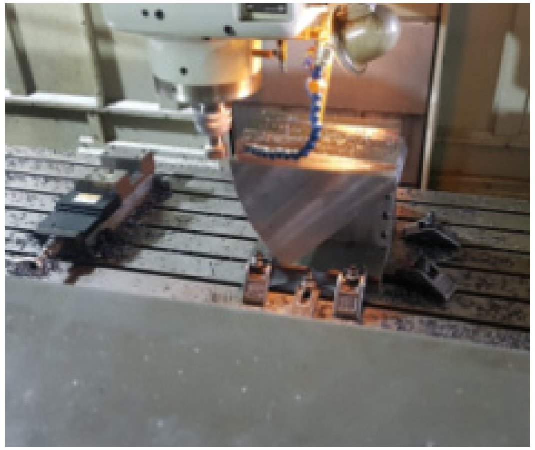


< AMS Coil side view >

Manufacturing of AMS Cyclotron (Magnet)

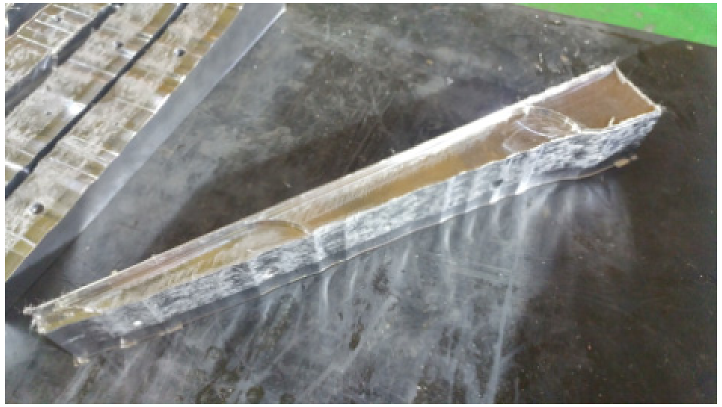


< Cyclotron Coil >



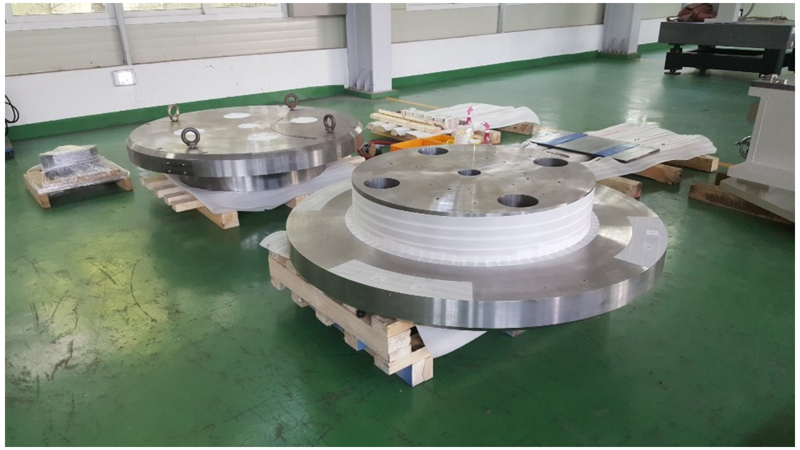
< Magnet core >

< Side yoke >



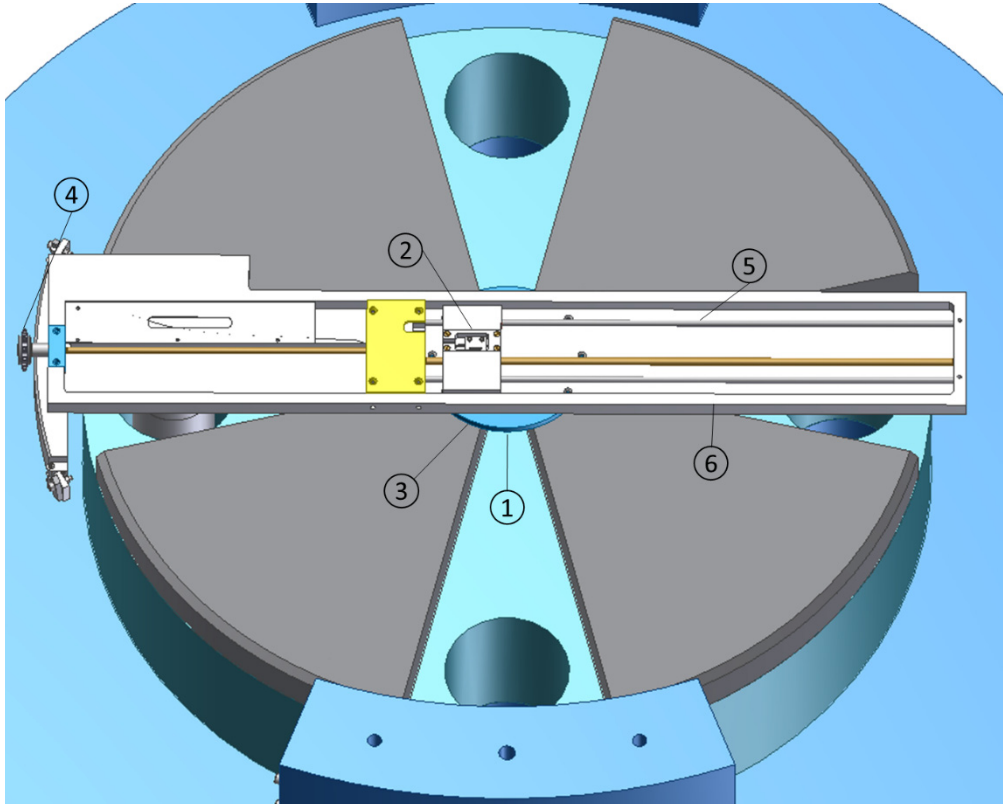
< Magnet shimming bar >

< Magnetic field measurement >



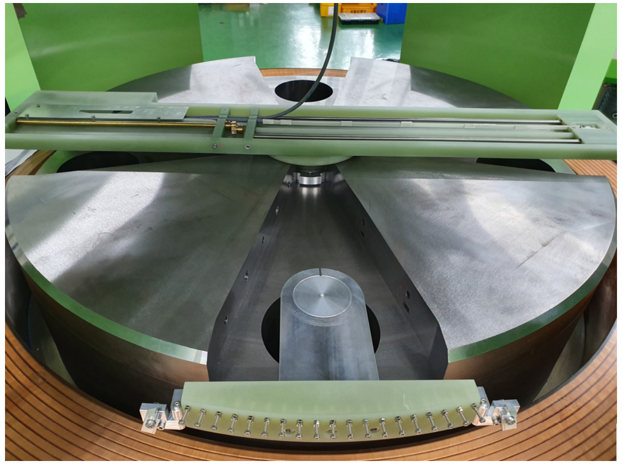
< Top, bottom yoke and valley >

Magnet measurement system

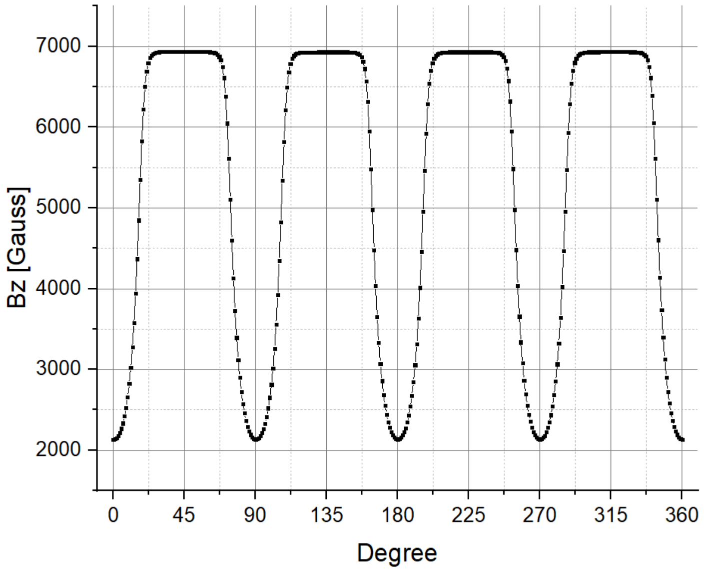


< 3-D drawing of measurement system >

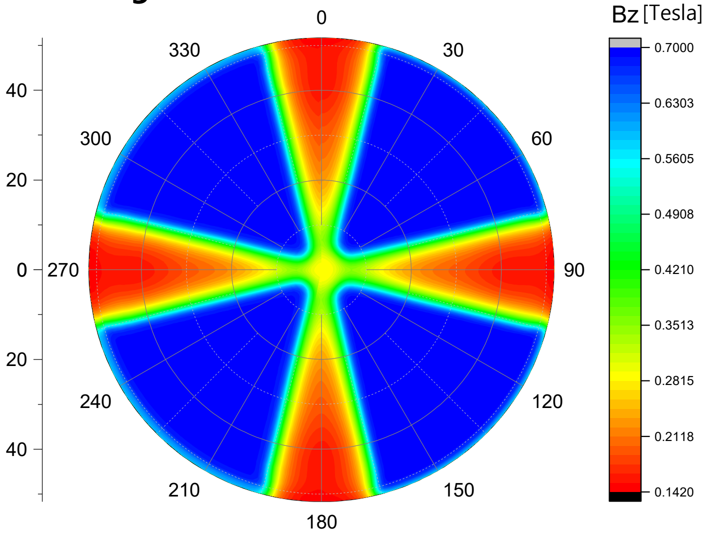
< Measurement tools>



< Magnetic field instrument >

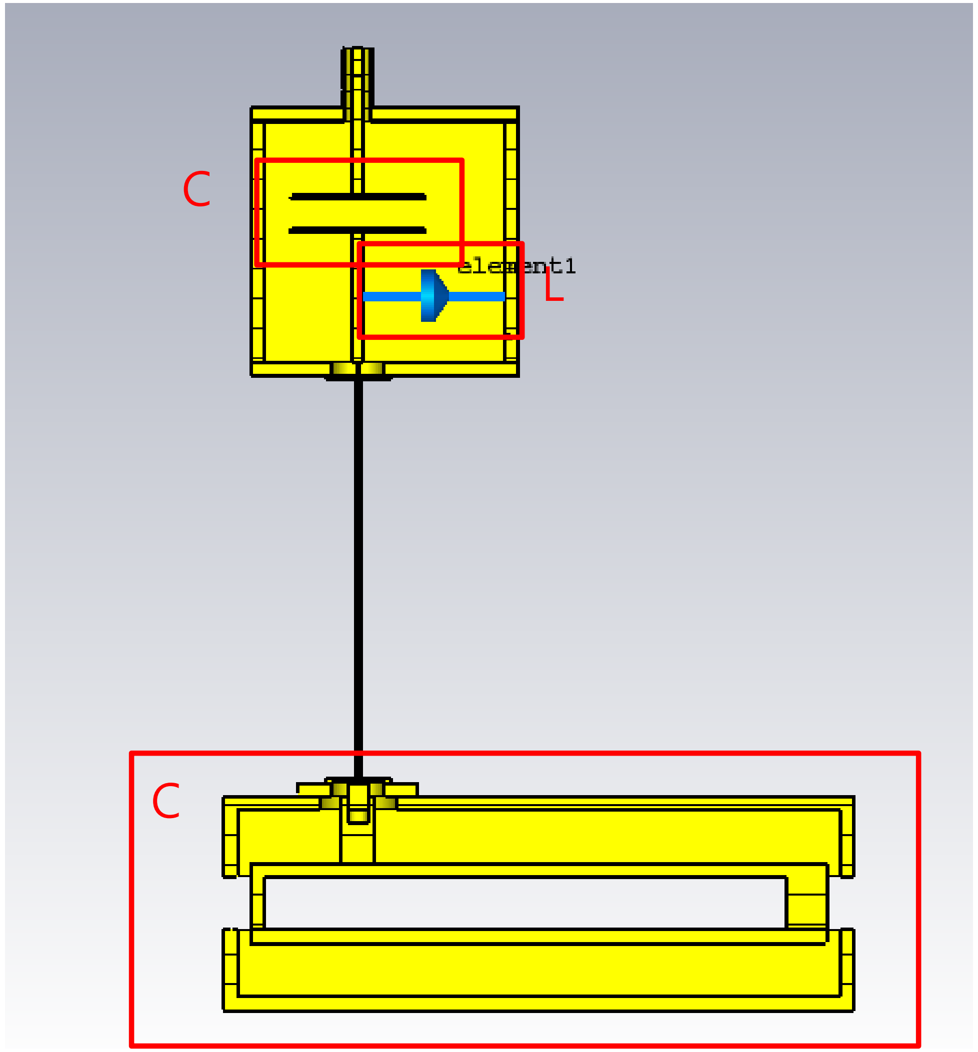


< magnetic field measurement test >

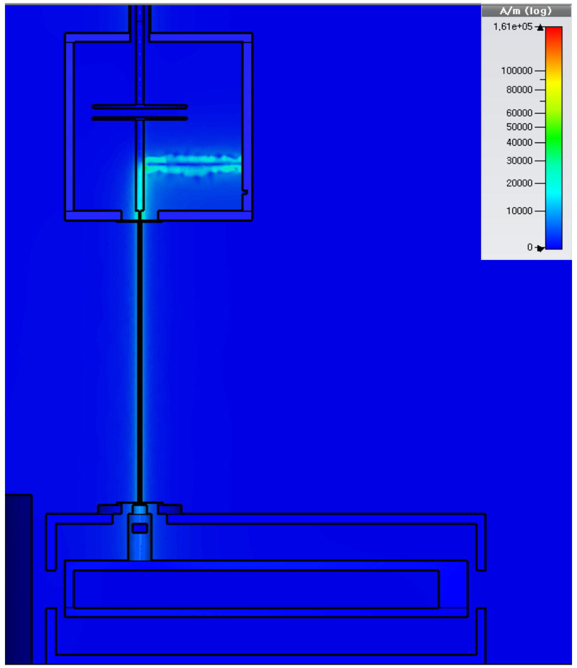


< Magnetic field mapping >

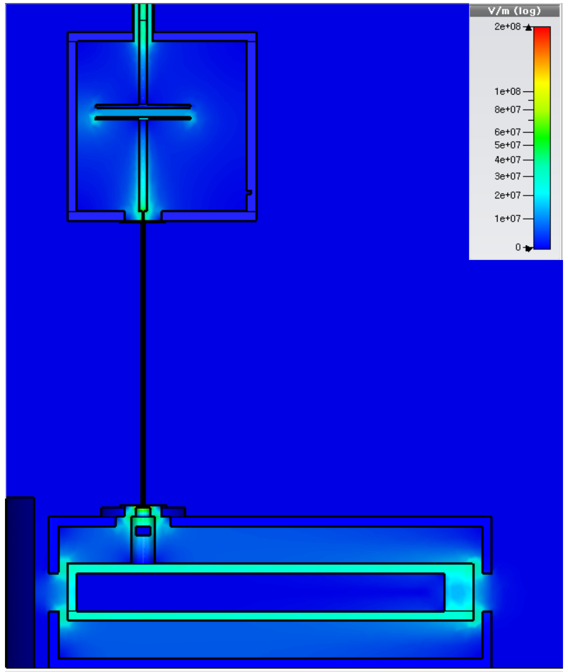
Dee electrode



< Electrode >



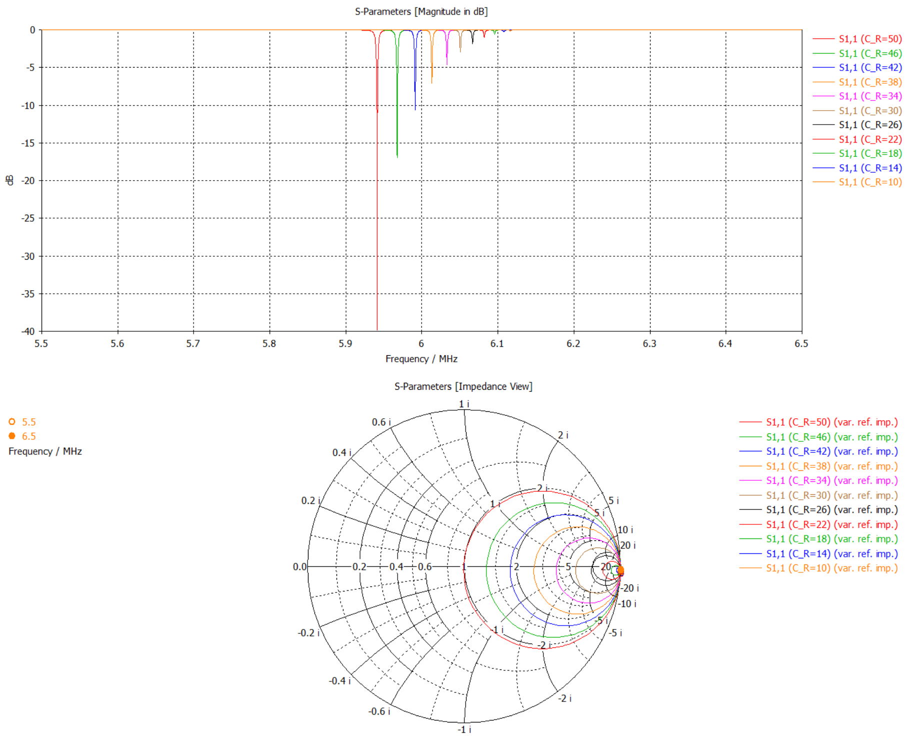
< H-field>



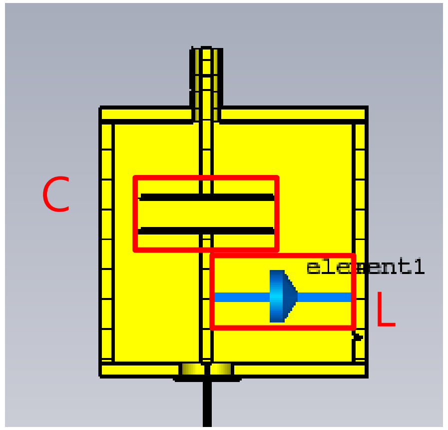
< E-field>

Specification	Value
Vacc	300 V
Frequency	5.8 MHz
Accelerating distance	138 mm ~ 453 mm
Dee angle [º]	20
Number of Dee	2

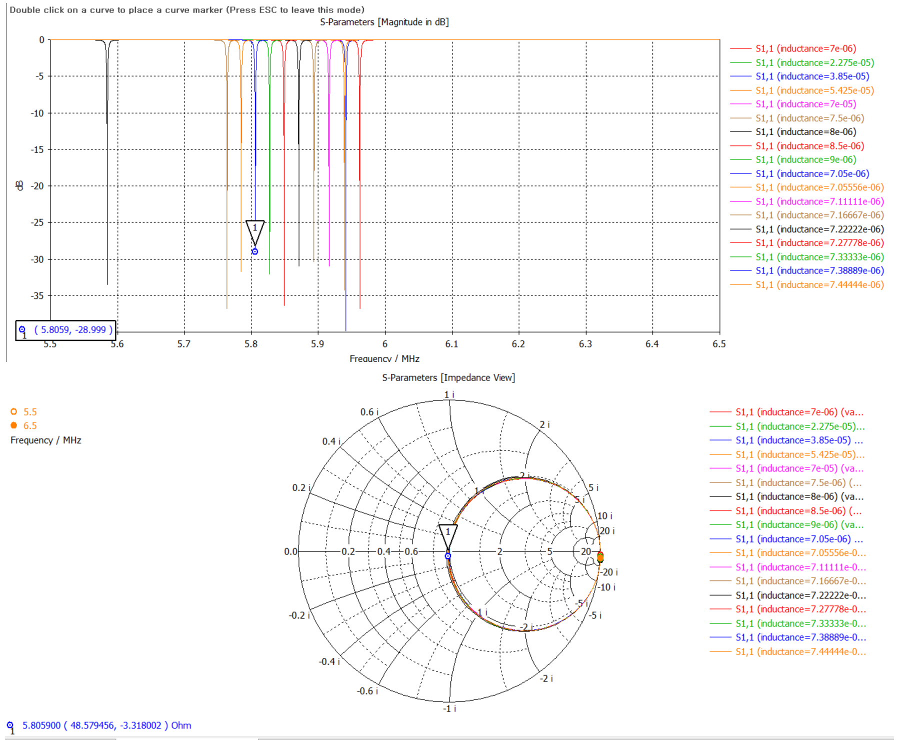
Impedance & Frequency matching



< Variable Capacitance>



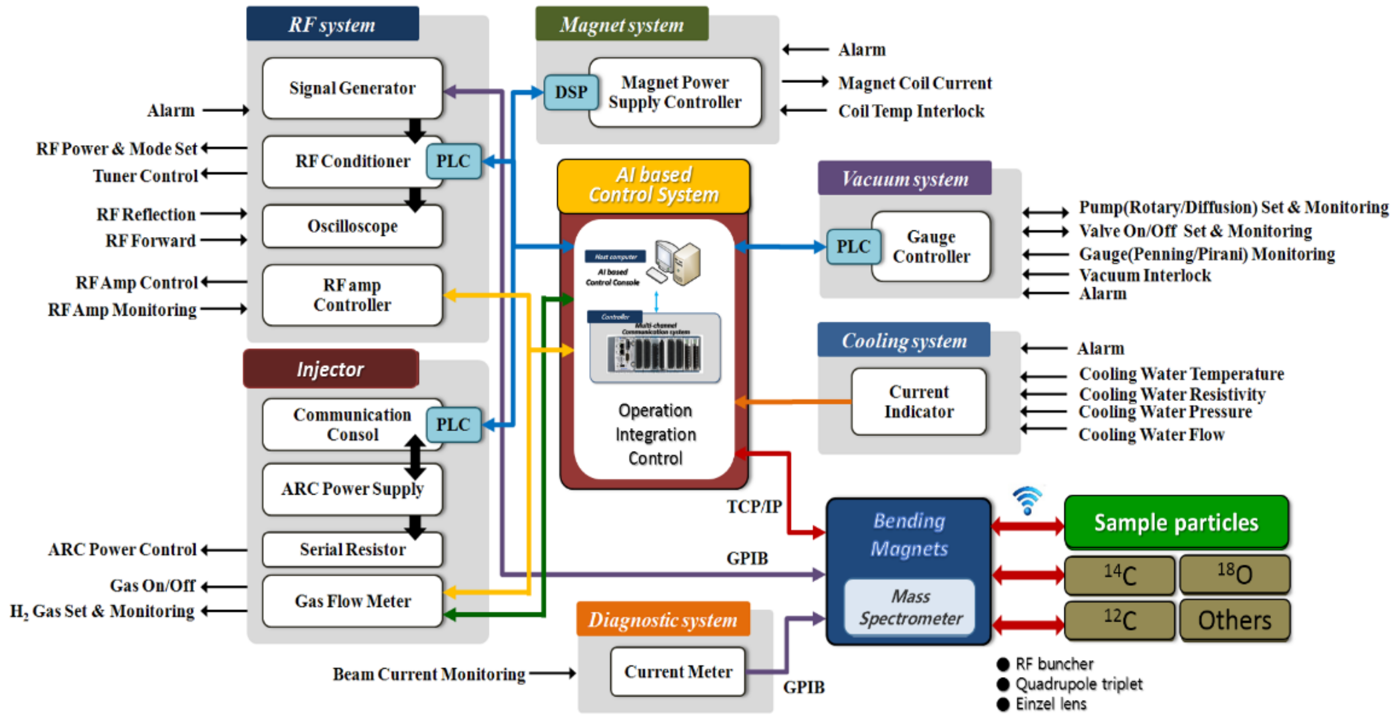
< RF Circuit Box >



< Variable Inductance>

- The circuit box is designed for impedance and frequency matching
- Approximate frequencies are set through inductance, impedance and detail frequency is set through capacitance

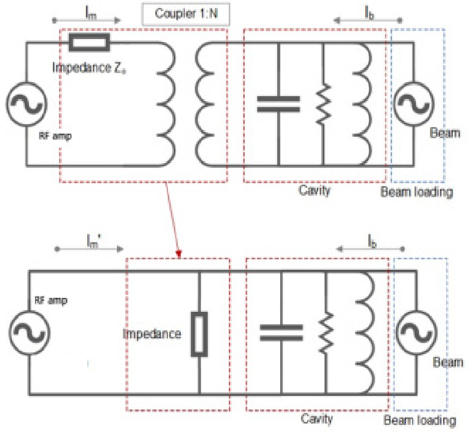
Machine-learning based control system and particle discrimination for mass spectral analysis



<AI-based accelerator control system configuration diagram>

- Compared to tandem accelerators, acceleration particles are relatively small.
- Improved accuracy by particle sorting based on machine learning and applied to new industrial mass analysis such as dating and bio-nano
- Simultaneously adjust isochronous and magnetic field RF frequency and output through AI system control for optimal particle extraction according to particle type

High-level system model study and artificial intelligence control system implementation

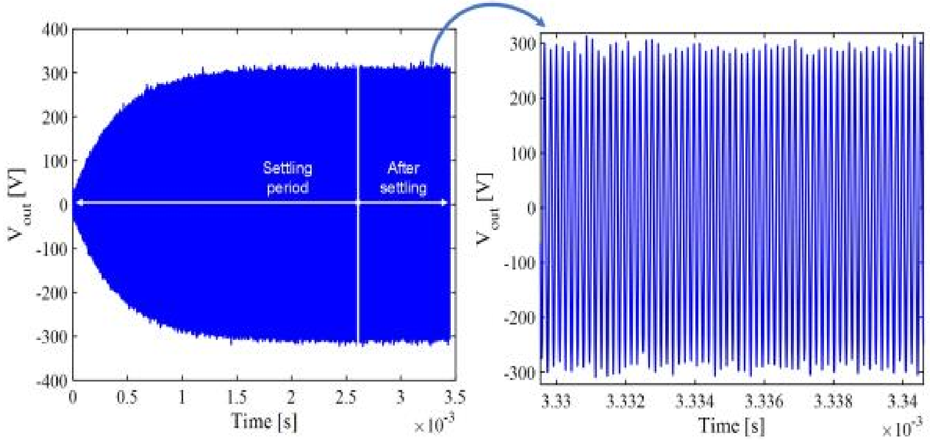


임피던스 산출

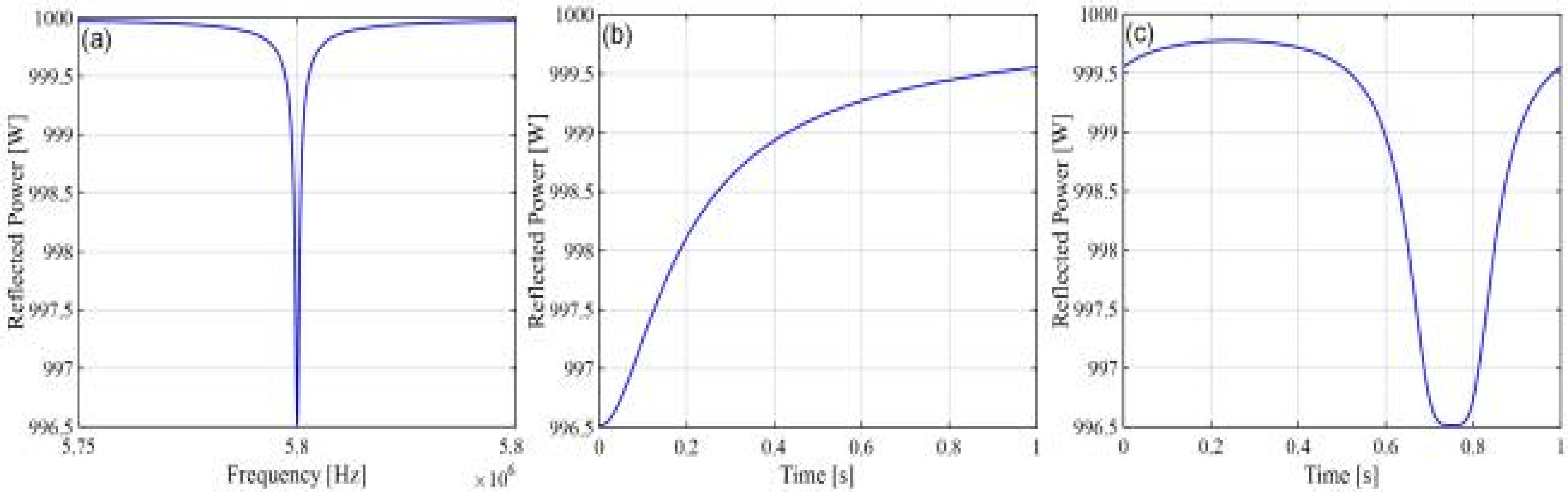
$$Z_L = \frac{R_L L s}{Ls + R_L L C s^2 + R_L} = \frac{\frac{1}{C}s}{\frac{1}{R_L C}s + s^2 + \frac{1}{LC}}$$

$$= \frac{R_L \frac{w_0}{Q_L} s}{s^2 + \frac{w_0}{Q_L} s + w_0^2} = \frac{R_L w_{\frac{1}{2}}}{\frac{(s^2 + w_0^2)}{2s} + w_{\frac{1}{2}}}$$

<High-level modeling of mass spectrometer accelerator RF system>

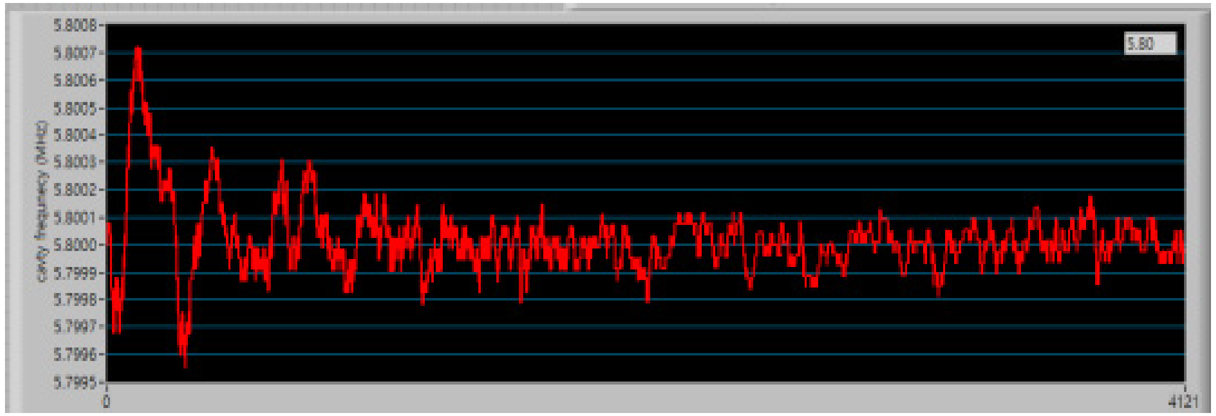


<Example of Time Domain Simulation of RF System Model (30dB SNR) >

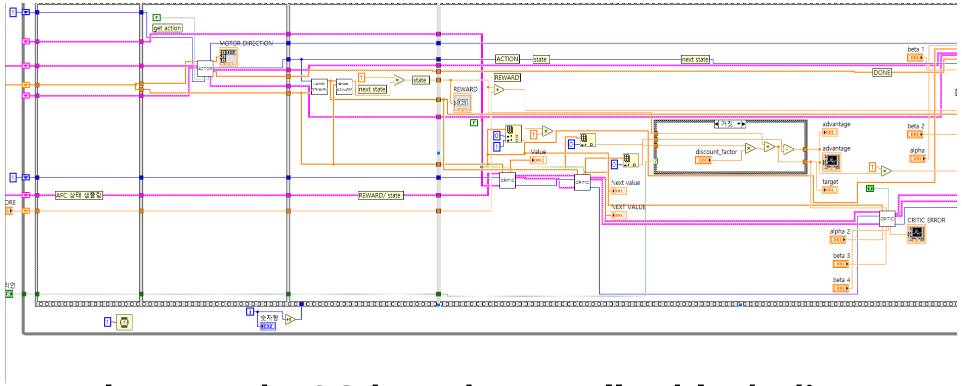


(a) normal resonance point, (b) variation of reflected power due to temperature rise, (c) variation of reflected power with respect to period temperature change

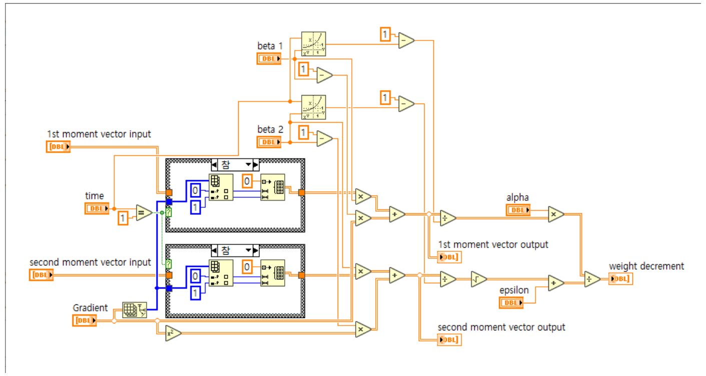
Reinforcement learning based accelerator beam control algorithm design



A2C resonance control learning process at 5.8 Mhz constant resonance point



Implemented A2C-based controller block diagram

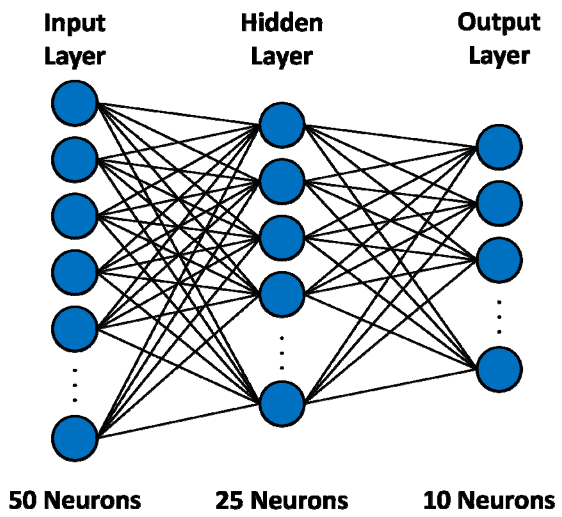


ADAM optimizer implementation block diagram

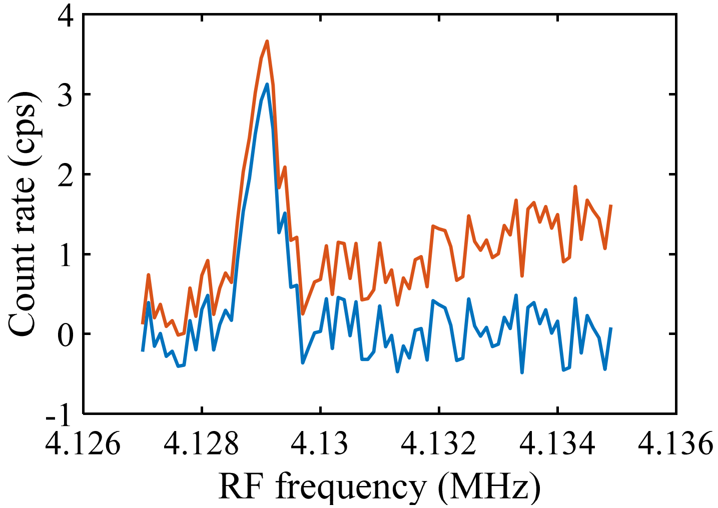
The Advantage Actor-Critic (A2C) method, a kind of reinforcement learning, is selected as a control method for beam current and energy optimization.

^{14}C particle detection with artificial neural network

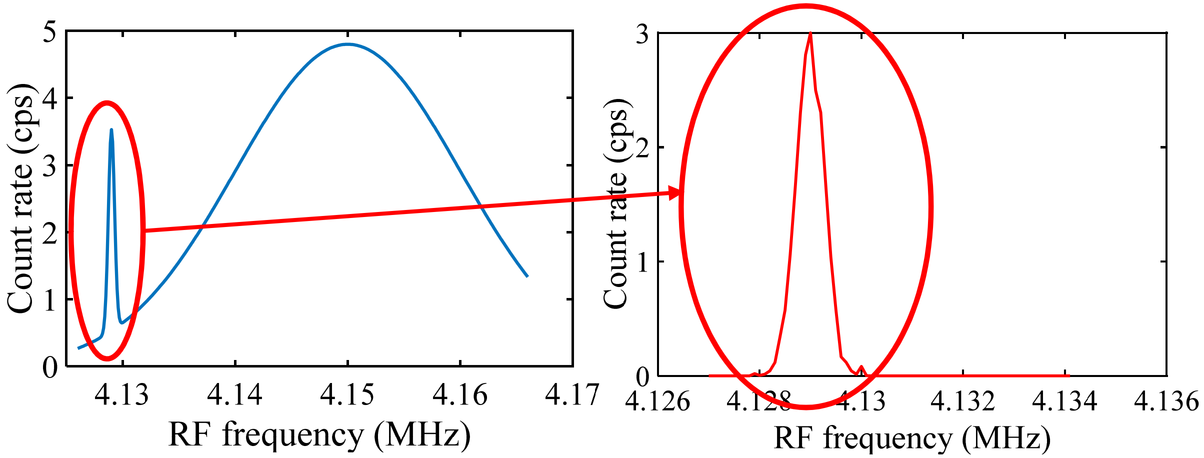
- Detection raw data
- **fully-connected neural network**
- Noise filtered data
- Analysis



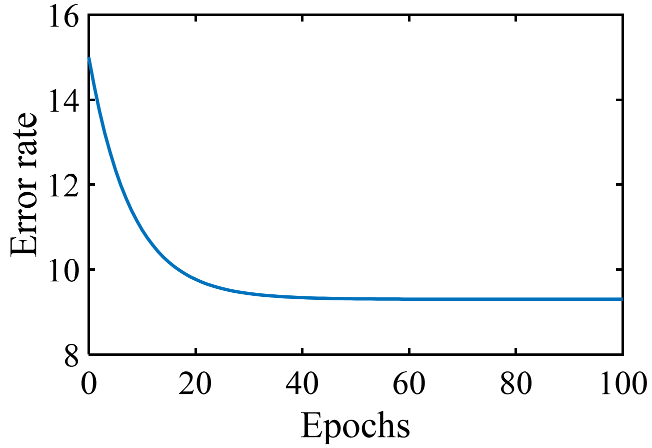
fully-connected neural network



<Training dataset with noise model>



<Signal reconstructed through artificial neural network>



<Reduction of error rate due to repeated learning>

Summary and Future plan

AMS cyclotron Design

2017 — Gathering Information

System Requirement ✓
- Mass resolution
- Frequency
- RF Power
- Size
- Beam line

Conceptual design ✓
- Cyclotron Magnet
- RF Amp
- RF Dee
- Ion source
- Inflector & Extraction
- Detection system
- AI-based control system

2018 — Design & Fabrication

- ✓ Mechanical design & fabrication
- ✓ Magnetic field measurement instrument design & Fabrication
- ✓ Design of AI based control algorithm

2019 — Test and modification

- ● Magnetic field measurement & Shimming
- ● RF cavity fabrication & Test
- ● Ion source Test
- ● AI based control algorithm test & modification

2020 — AMS System Test

- Combine all components
- AMS system test
- AI-based control algorithm implementation
- Total system optimization

Thank you

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