IPAC'16

Korea Heavy-ion Medical Accelerator Project

13 May 2016

Heejoong Yim

On behalf of the KHIMA project collaboration

KIRAMS

(Korea Institute of Radiological And Medical Science)

KIRAMS

KOREA INSTITUTE OF RADIOLOGICAL & MEDICAL SCIENCES

KOREA HEAVY ION MEDICAL ACCERATOR PROJECT

Introduction to KHIMA Project

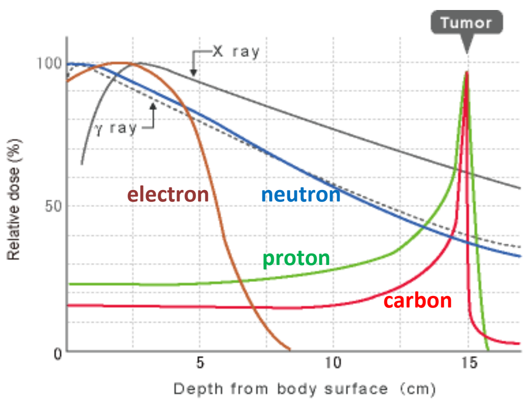
KOREA INSTITUTE OF
RADIOLOGICAL & MEDICAL SCIENCES

KOREA HEAVY ION
MEDICAL ACCERATOR PROJECT

Heavy Ion Therapy

- Less normal tissue complication compared to X-ray, neutron and gamma ray
- Enhanced cell killing in the tumor region (High RBE) compared with proton
- Enhanced 5-year survival rate up to 22.3% compared to conventional radiation therapy (proton, X-ray) *clinical trials from Japan and German*

▣ Bragg Peak



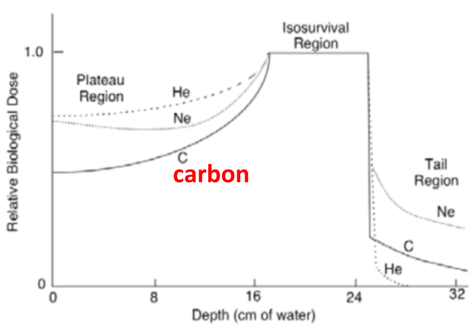


TABLE 1. RBE Values for Heavy Charged Particles vs. ^{60}Co Gamma Rays

Particle	Peak RBE	Plateau RBE	Peak to Plateau RBE Ratio
Proton	1.2	1.2	1.00
Helium	1.5	1.3	1.15
Carbon	1.8	1.2	1.50
Neon	3.0	2.3	1.30

RBE values for jejunal crypt cell survival [65]

▣ 5-year survival rate

Treatment outcome for 8 intractable cancers → 5y survival rate up to ~22.3%

Tumors	Conventional Radiation Therapy	Heavy Ion Therapy (Japan)
Head & Neck	38%	88.5%
Lung	15%	44%
Liver	19.3%	35%
Prostate	62%	91%
Sarcoma	<10%	46%
Cervix	19.9%	38%

Heavy Ion Therapy

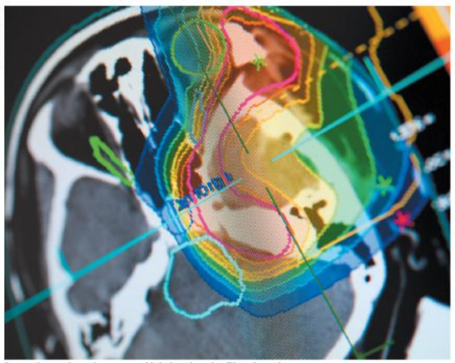
TECHNOLOGY FEATURE

SHARP SHOOTERS

Beams of charged particles can treat cancer more safely and effectively than X-rays. Physicists and biomedical researchers are working to refine the technology for wider use.

NATURE

Vol. 508, 133
3 April 2014



A computed-tomography scan shows a tumour and the ion-beam dosage that will be used to treat it.

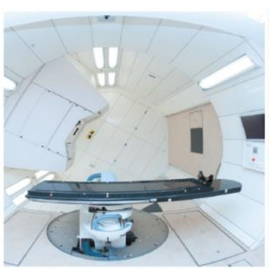
BY VIVIEN MARX

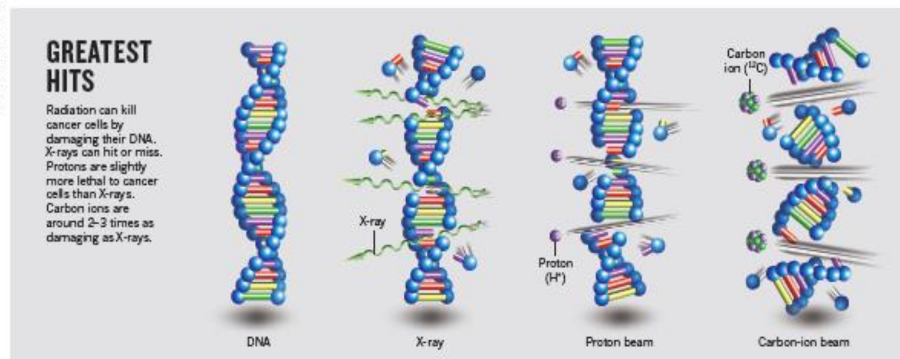
Clinicians attack cancer with many types of weapon, ranging from scalpels to physically remove all or most of a tumour to drugs that kill the tumour cells where they are. In about half of people with cancer, doctors go after the malignant cells with ionizing radiation.

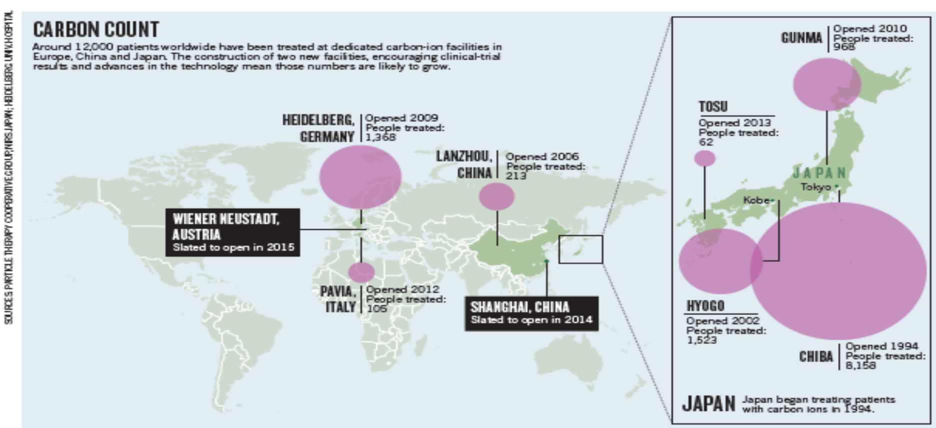
Classic radiation treatment involves mainly X-rays. But because these lose energy all along their path through the body — damaging healthy cells as they go — clinicians and researchers are increasingly paying attention to beams that use charged particles such as protons and carbon ions[1]. Charged particles can deposit most of their lethal energy mainly at the tumour site, largely sparing the healthy tissue. Protons are slightly more lethal to cancer cells than X-rays, and carbon ions seem to be around 2–3 times as deadly.

Worldwide, around 100,000 people have received proton treatments for cancer. Japan, China, Germany and Italy have built ion-beam facilities that have treated some 12,000 patients with carbon ions, the majority in Japan and Germany (see 'Carbon count').

Carbon ions are heavier than protons, so the facilities to deliver them are pricier. The charged-particle facilities in Germany and Japan cost between US$130 million and $200 million each to build. Nonetheless, there has been a spike in research and







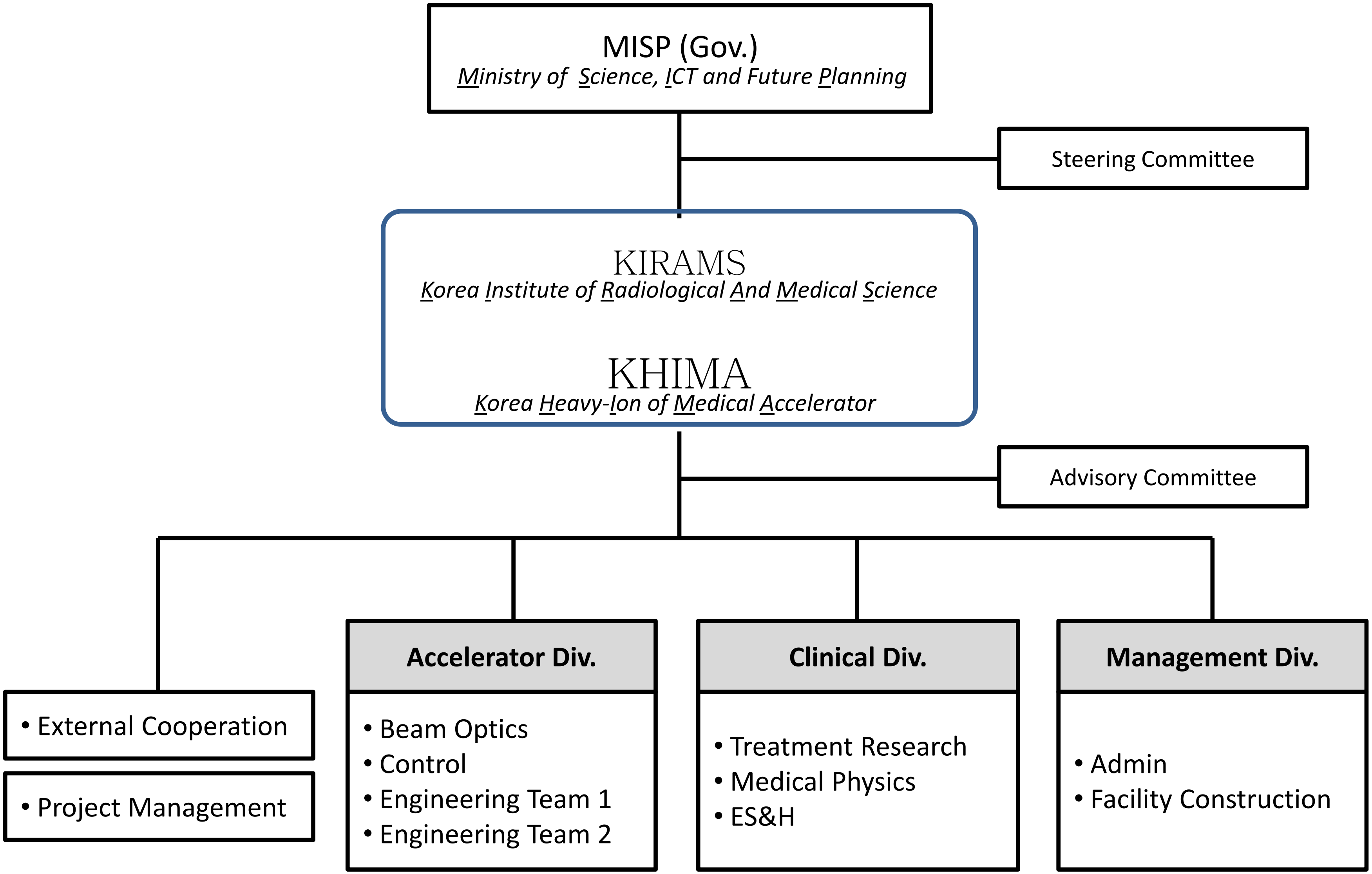
KHIMA Project

Leading Organization : KIRAMS (Korea Institute of Radiological & Medical Sciences)
Location : Gijang County, Busan City
Project Start : April 2010
Project Budget : about 195 million USD(195 billion KWR)
(Funding from Korean government, Local governments and KIRAMS)

KHIMA Project History

2009	11.	• [KDI] Feasibility Study (B/C 1.02, AHP 0.516)
2010	04.	• Organization of KHIMA Project Group, Project Start
	10.	• Research of a Accelerator Type (Synchrotron *or* Cyclotron)
2011	01.	• Workshop (Evaluation Index Development for Selection of a Accelerator type)
	06.	• [Steering Committee] Approval of a Superconducting Cyclotron
2012		• Design of a Superconducting Cyclotron (Draft)
		• Designs and Prototype Fabrications of Main Equipments
2013	03.	• [Steering Committee] Approval of Making Engineering Drawings
	08.	• Designation of new Director General of KHIMA Project (Dr. Nam)
	11.	• International Evaluation(IEC), National Evaluation(NEC)
2014	01.	• Groundbreaking Ceremony
	05.	• [Steering Committee] Approval of Switching to a Synchrotron
		• KHIMA Synchrotron Handbook
	10.	• Conceptual Design Report (CDR)
2015	02.	• Technical Design Report (TDR)

Organization



Human Resource

<table>
<tr><th colspan="2">Division</th><th>~'16</th><th>'16(recruit)</th><th>'17(recruit)</th><th>SUM</th></tr>
<tr><td colspan="2">Director General</td><td>1</td><td></td><td></td><td>1</td></tr>
<tr><td colspan="2">Project Management</td><td>4</td><td></td><td></td><td>4</td></tr>
<tr><td colspan="2">External Cooperation</td><td>3</td><td></td><td></td><td>3</td></tr>
<tr><td colspan="2">Part Sum</td><td>8</td><td></td><td></td><td>8</td></tr>
<tr><td rowspan="4">Accelerator Div.</td><td>Beam Optics</td><td>3</td><td rowspan="4">4</td><td rowspan="4">4</td><td>5</td></tr>
<tr><td>Magnet, Vacuum, Utility
Mechanical System</td><td>5</td><td>8</td></tr>
<tr><td>ECRIS, RF, High Voltage
Beam Irradiation, Diagnostic</td><td>7</td><td>8</td></tr>
<tr><td>Control</td><td>4</td><td>6</td></tr>
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<tr><td>Treatment Research</td><td>1</td><td>4</td></tr>
<tr><td>Medical Physics</td><td>7</td><td>11</td></tr>
<tr><td>ES&H</td><td>4</td><td>4</td></tr>
<tr><td colspan="2">Part Sum</td><td>13</td><td>5</td><td>5</td><td>23</td></tr>
<tr><td rowspan="2">Management Div.</td><td>Facility Construction</td><td>5</td><td></td><td></td><td>5</td></tr>
<tr><td>Admin.</td><td>5</td><td>2</td><td>2</td><td>9</td></tr>
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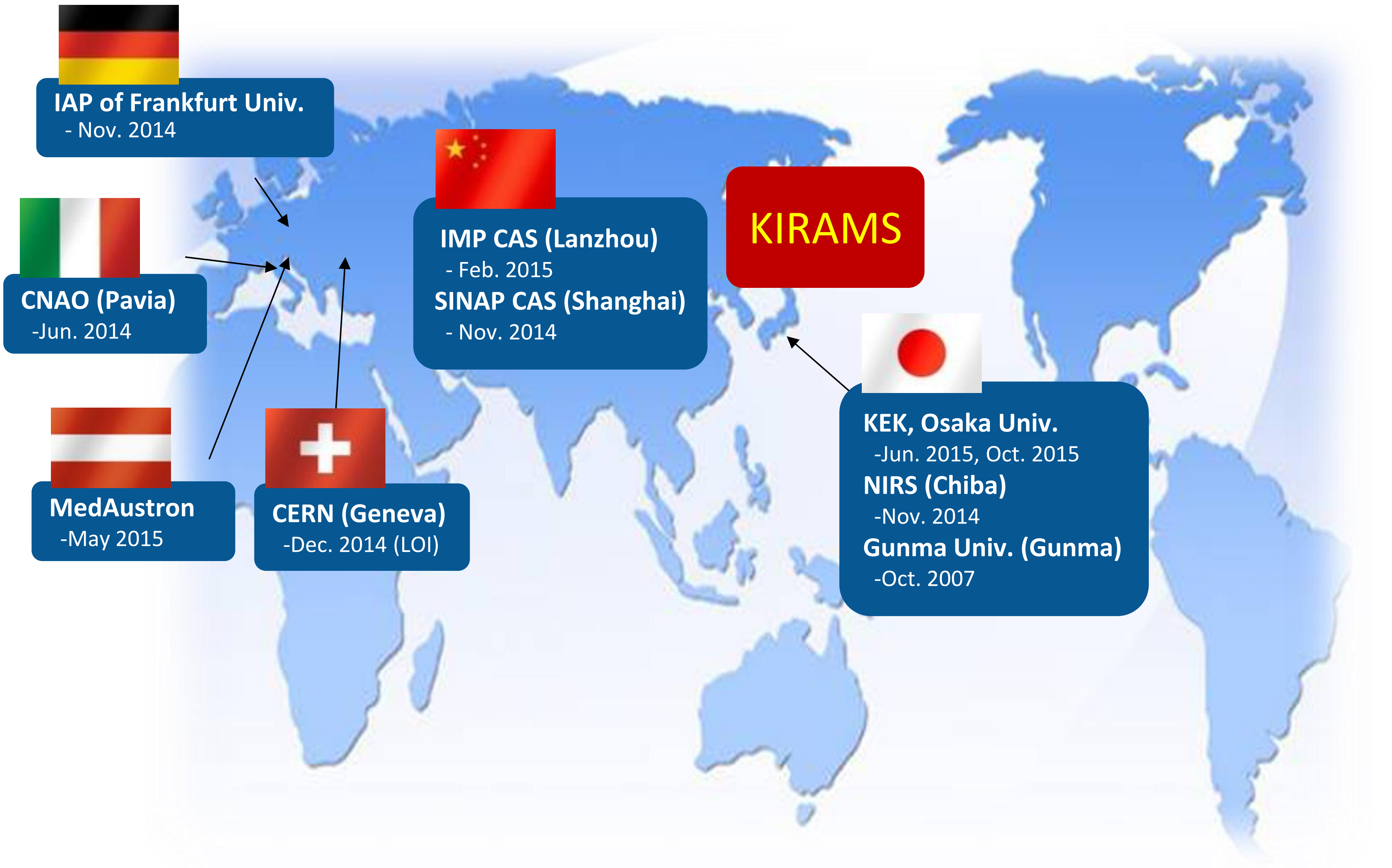

IAP of Frankfurt Univ.
- Nov. 2014
CNAO (Pavia)
-Jun. 2014
MedAustron
-May 2015
CERN (Geneva)
-Dec. 2014 (LOI)
IMP CAS (Lanzhou)
- Feb. 2015
SINAP CAS (Shanghai)
- Nov. 2014
KIRAMS
KEK, Osaka Univ.
-Jun. 2015, Oct. 2015
NIRS (Chiba)
-Nov. 2014
Gunma Univ. (Gunma)
-Oct. 2007

Domestic Collaborations

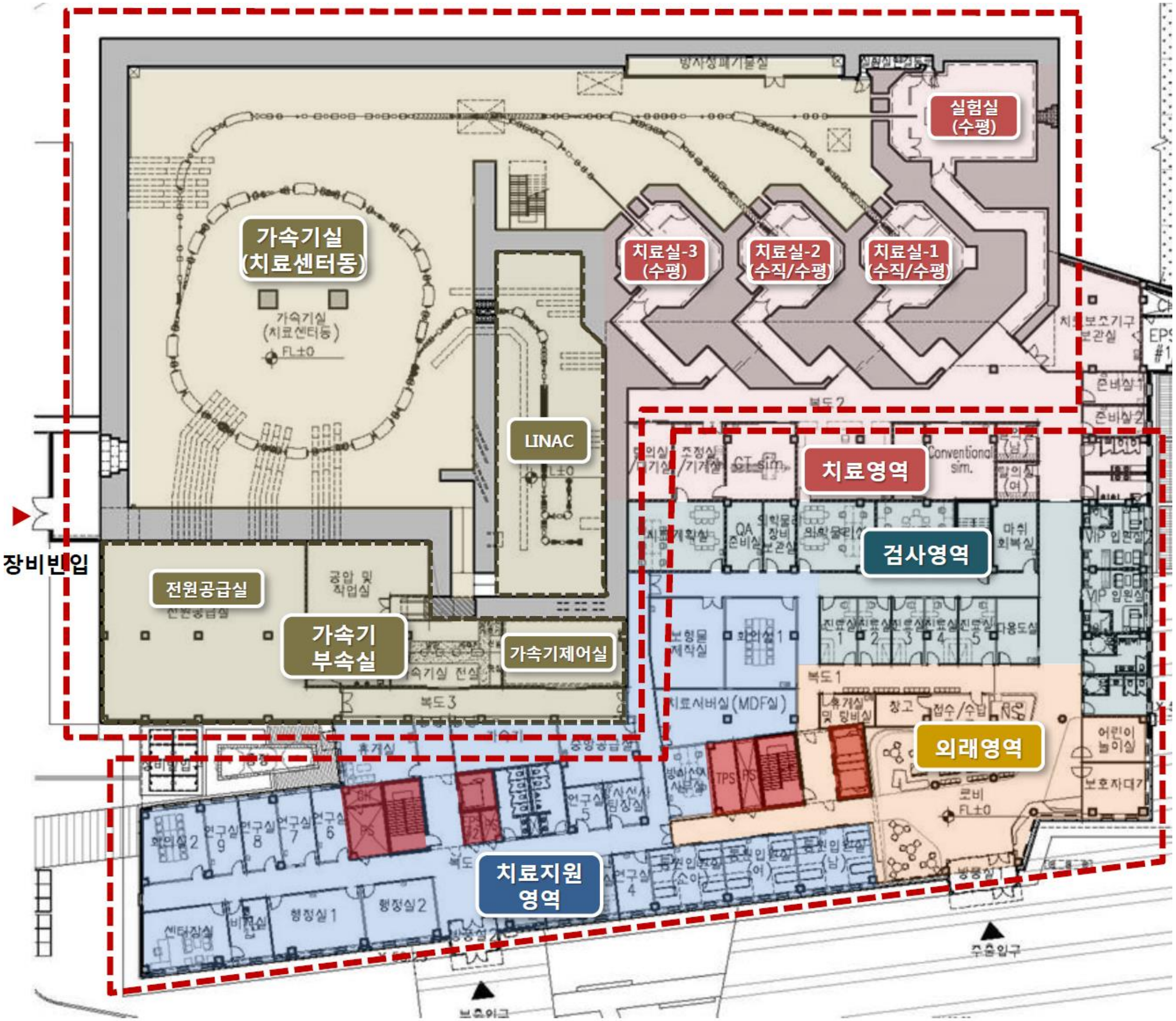
Institute	Subject
Catholic Univ.	2012 2013 2014 2015 2016 • Verification system for treatment planning
Chonnam Univ.	2012 2013 2014 2015 2016 • Robotic bed system
KAIST (Korea Advanced Institute of Science and Technology)	2012 2013 2014 2015 2016 • Real time monitoring system for patient positioning
Hanyang Univ.	2012 2013 2014 2015 2016 • Dose tracking system
Korea Univ.	2014 2015 2016 • Injector design and diagnostics
POSTECH (Pohang Institute of Science and Technology)	2014 2015 2016 • Beam dynamics for synchrotron and HEBT
PAL (Pohang Accelerator Laboratory)	2014 2015 2016 • Vacuum system

KHIMA Layout

Construction Area : 7,035 m^2

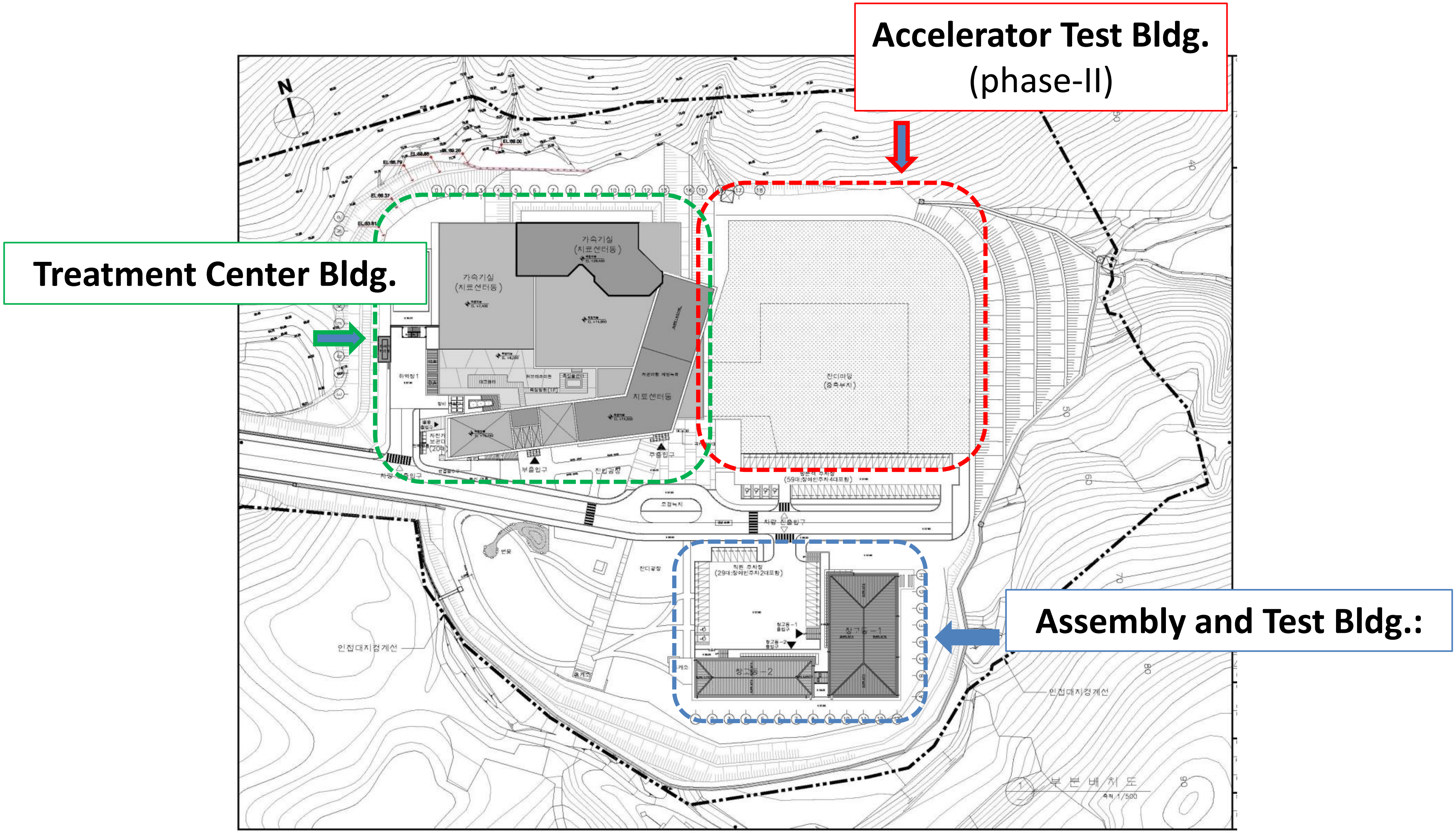
Gross Area : 12,898 m^2

2016.12. Construction Status



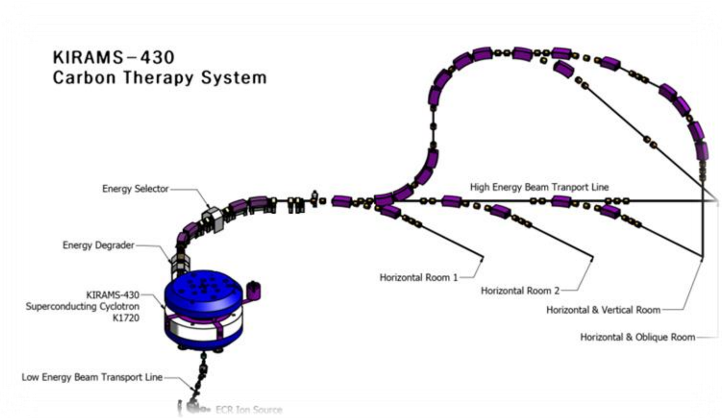
Site View(Mar. 2016)

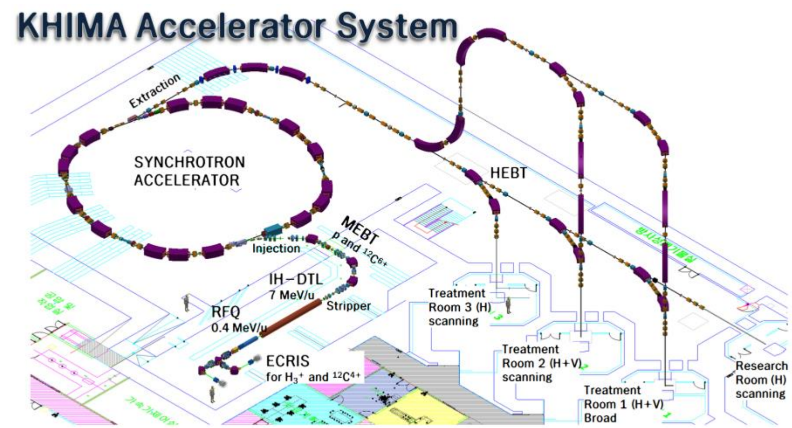
Site Plan



Accelerator Test Bldg.
(phase-II)
Treatment Center Bldg.
Assembly and Test Bldg.:
N
인접대지경계선

Switching Accelerator Type to a Synchrotron (2013)





Sep. 2013

Internal Review

7 Nov. 2013

IEC

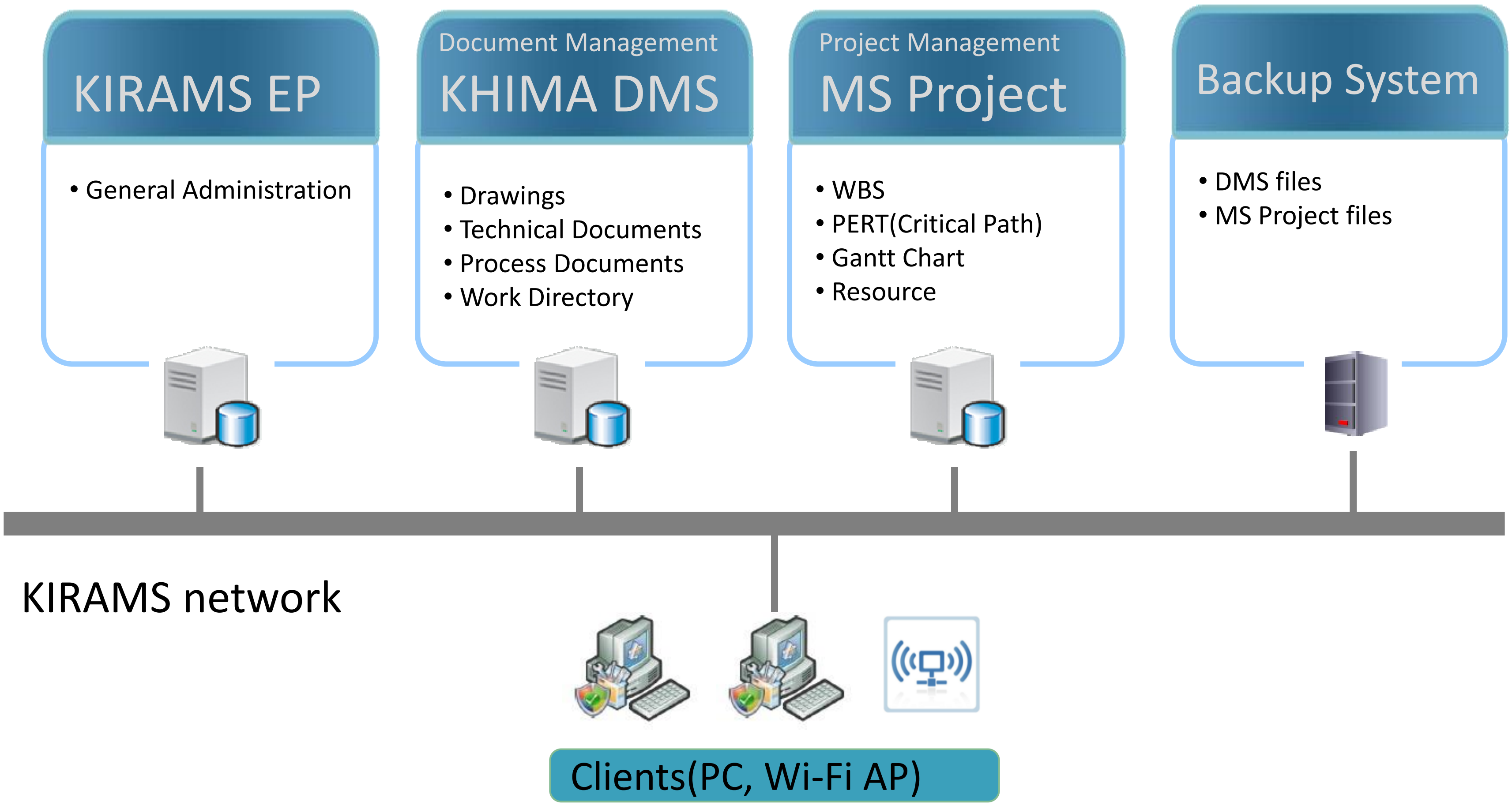
(International Evaluation Committee)

21 Nov. 2013

NEC

(National Evaluation Committee)

Project Management System



KHIMA WBS

KHIMA PROJECT

Accelerator System	Therapy System	Control System	Conventional Facility	Management
• Beam Optics • ECRIS System • RF System • HV System • Magnet • MPS • Vacuum System • Diagnostic System • Irradiation System • Alignment System • Commissioning	• Clinic • Medical Physics • Treatment System • Radiobiology	• Accelerator Control System • Treatment Control System • Oncology Control System • Safety System	• Management • Construction • Electrical System • Mechanical System • Communication System • Utility System	• Project Management • Administration • ES&H • Technical Commercialization

Current Status of KHIMA Project

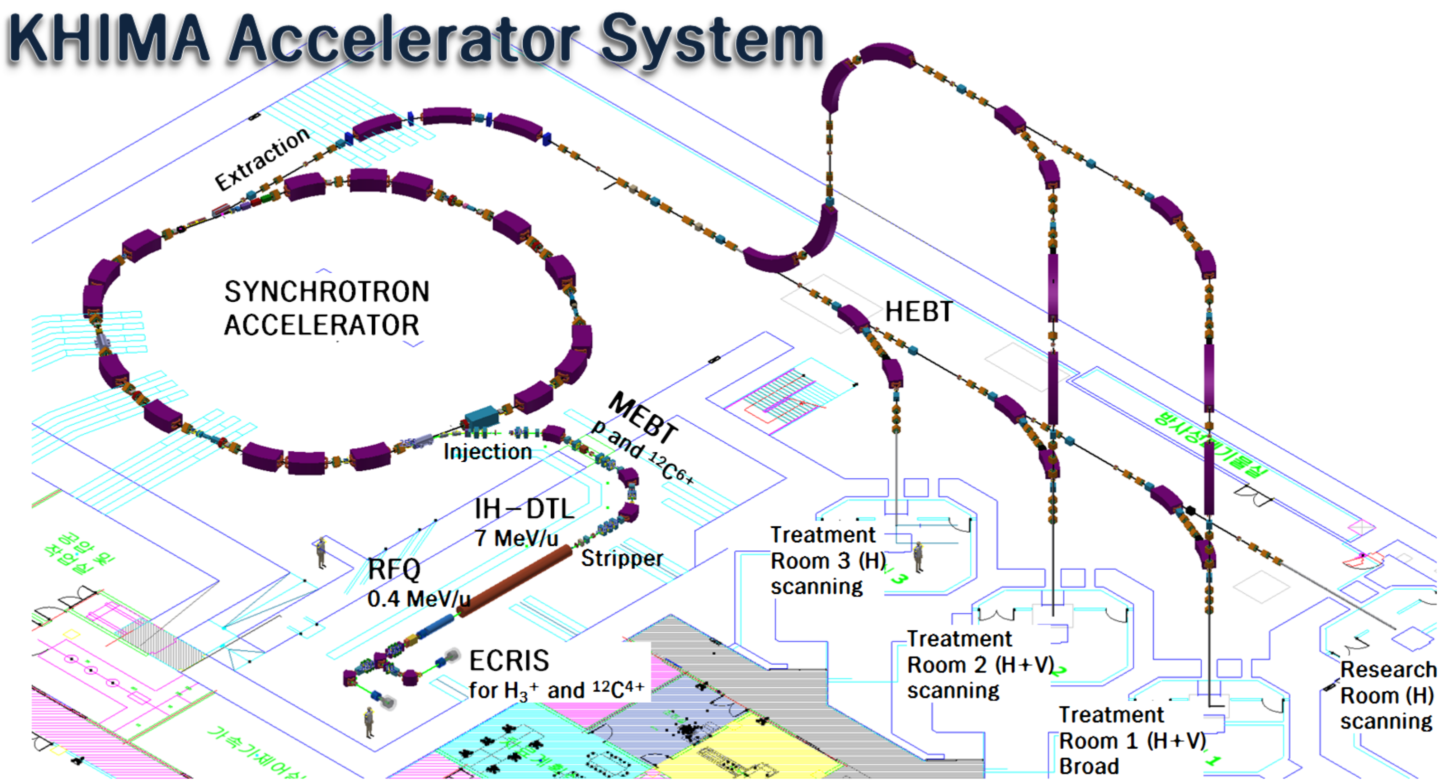
KOREA INSTITUTE OF
RADIOLOGICAL & MEDICAL SCIENCES

KOREA HEAVY ION
MEDICAL ACCERATOR PROJECT

Contents

- Beam Specifications
- ECR Ion Source and Diagnostics
- Linac System
- Synchrotron
- High Energy Beam Transport (HEBT)
- Magnets
- RF Cavity
- Vacuum System
- Installation (Girder, SA)
- Irradiation System

Layout of KHIMA Accelerator System



Beam particle species	p, ^{12}C	**Type of ion**	$^{1}H_3^+$ for proton and $^{12}C^{4+}$ for carbon at ECRIS
Beam Range	3.0 g/㎠ to 27.0 g/㎠	**Energy range**	60-230 MeV for proton 110-430 MeV/u for carbon
Dose rate	2 Gy/min for 1 liter	**Beam intensity**	$1x10^8 \sim 1x10^{10}$ protons/spill at Isocenter $4x10^6 \sim 4x10^8$ carbons/spill at Isocenter Nominal number of spills : 60 spills in 2~3 min
Beam size	4 to 10 ㎜ FWHM	**Injection**	Multi-turn injection
Field Size	20x20 ㎠	**Extraction**	RF-KO slow-extraction
Irradiation Room	Gating / 1 H (Scanning), 1 H+V (Scanning), 1 H+V (Broad), 1 H (Scanning, Research)		

Beam specifications for KHIMA

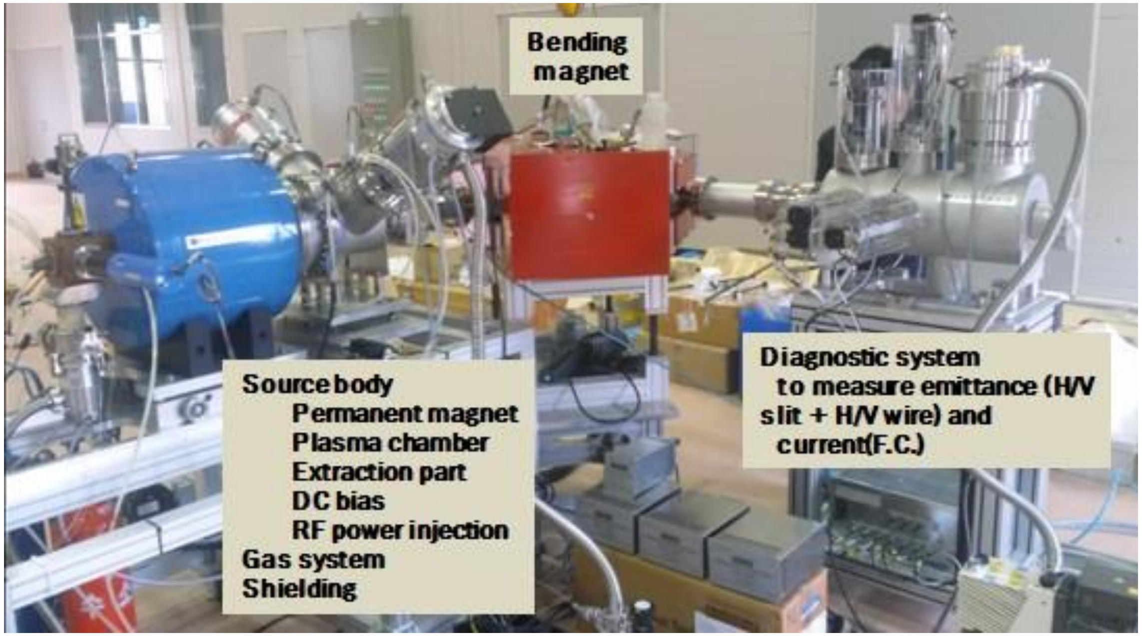
	Clinical Requirements			items	Beam Specifications for KIRAMS
1	Beam particle species	proton, carbon-12		Type of ion	$^{1}H_3^{+}$ for proton and $^{12}C^{4+}$ for carbon at ECRIS
2	Beam Range	3.0 to 27.0 in body	g/㎠	Energy range	60~230 MeV for proton 110-430 MeV/u for carbon (with the consideration of 3-5 ㎝ scatterer)
3	Bragg peak modulation steps	0.1~0.2	g/㎠	Energy steps	>250 steps
4	Range adjustment	0.1	g/㎠	Energy adjustment	1.101~0.416 MeV for proton 2.030~0.878 MeV/u for carbon
5	Adjustment/modulation accuracy	≤± 0.025	g/㎠	Energy adjustment accuracy	≤± 0.274~0.104 MeV for proton ≤± 0.505~0.219 MeV/u for carbon
6	Distal dose fall-off (80%-20%) (in addition to the intrinsic DFO)	< 2	㎜	Energy spread [1σ in Gaussian dist.]	< 0.12 % at 230 MeV for proton < 0.12 % at 430 MeV/u for carbon
7	Average dose rate (for treatment volume of 1000 ㎤)	2	Gy/min	Beam intensity at Isocenter	Min./Max. No. of particles per spill $1x10^{8}$ / $1x10^{10}$ for proton $4x10^{6}$ / $4x10^{8}$ for carbon Nominal number of spills : 60 spills in 2~3 min
8	Beam size (FWHM)	4 to 10	㎜	Beam size (FWHM)	4 to 10 ㎜
9	Beam size step	1	㎜	Beam size step	1 ㎜
10	Beam size accuracy	≤± 0.2	㎜	Beam size accuracy	≤± 0.2 ㎜
11	Beam axis height (above floor)	120	㎝	Beam axis height	120 ㎝
12	Irradiation Room	1 H (scanning) 1 H+V (scanning) 1 H+V (broad) 1 H (scanning, Research)		Irradiation Room	1 H (scanning) 1 H+V (scanning) 1 H+V (broad) 1 H (scanning, Research)

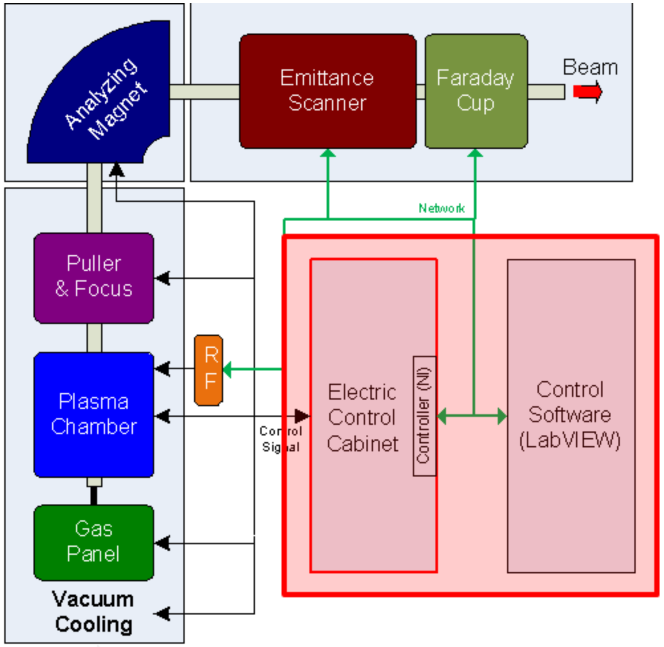
Beam energy
Beam Intensity
Beam Size and Position

ECRIS: Requirements

Extraction Ion	Specification		Test Result	
	Min. Current	Emittance [π.mm.mrad]	Current	Emittance [π.mm.mrad]
$^{12}C^{4+}$	122 μA	< 0.75	200 μA	< 0.75
H_3^+	328 μA		754 μA	1.23

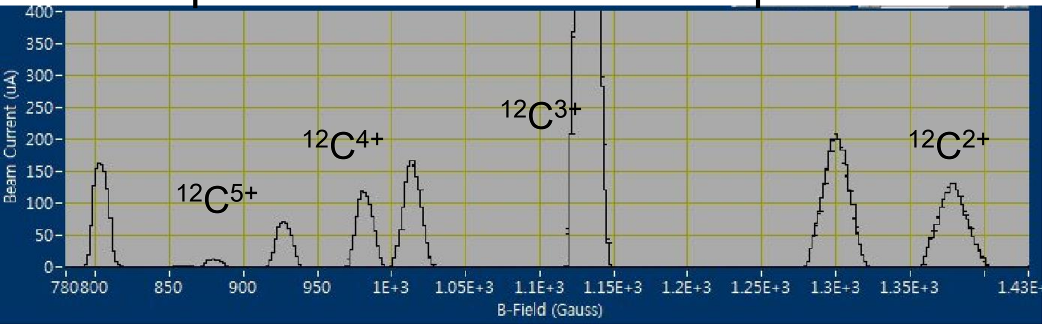
ECR ion source setup at the test site



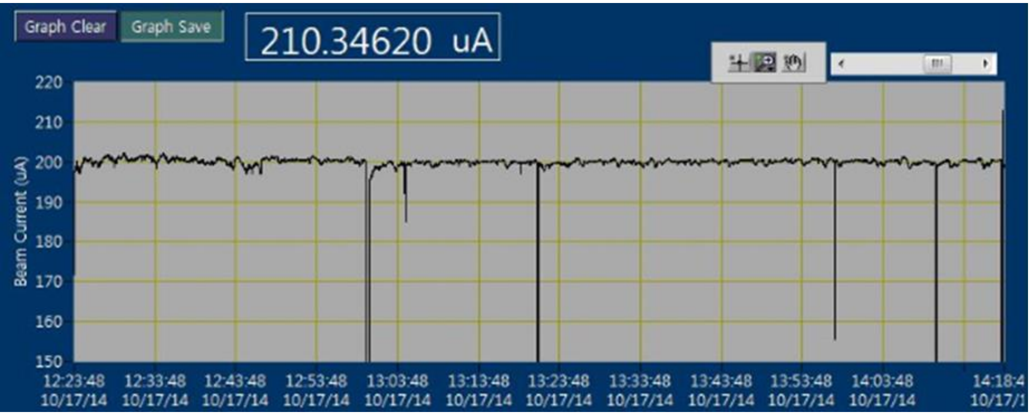


ECRIS Beam Test

Spectrum next to a mass separator



Beam intensity variation



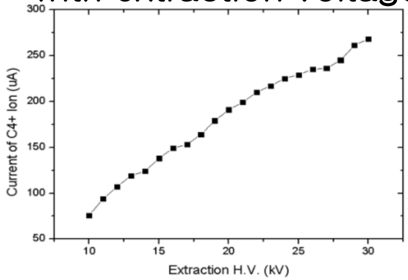
Chamber status

After 500 hours operation with CO_2+He gas

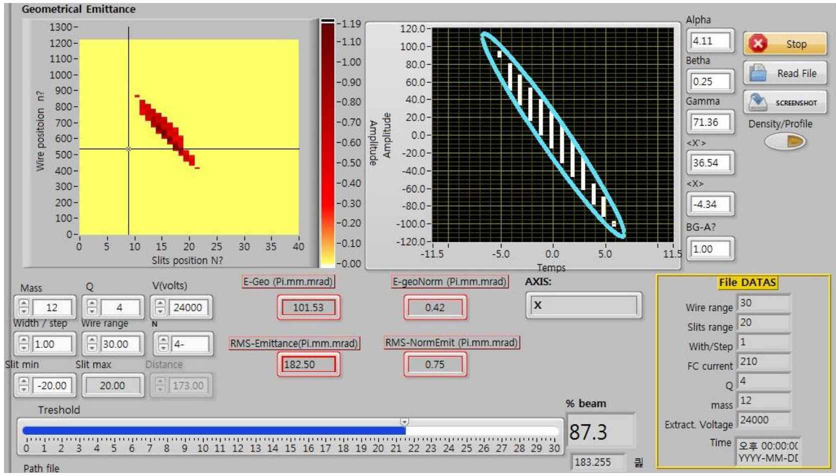
Plasma lens

Inside plasma chamber

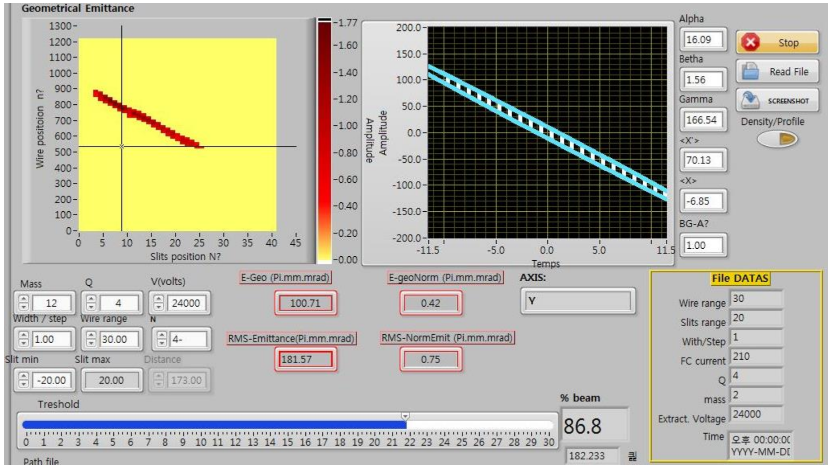
Beam intensity with extraction voltage



Horizontal emittance

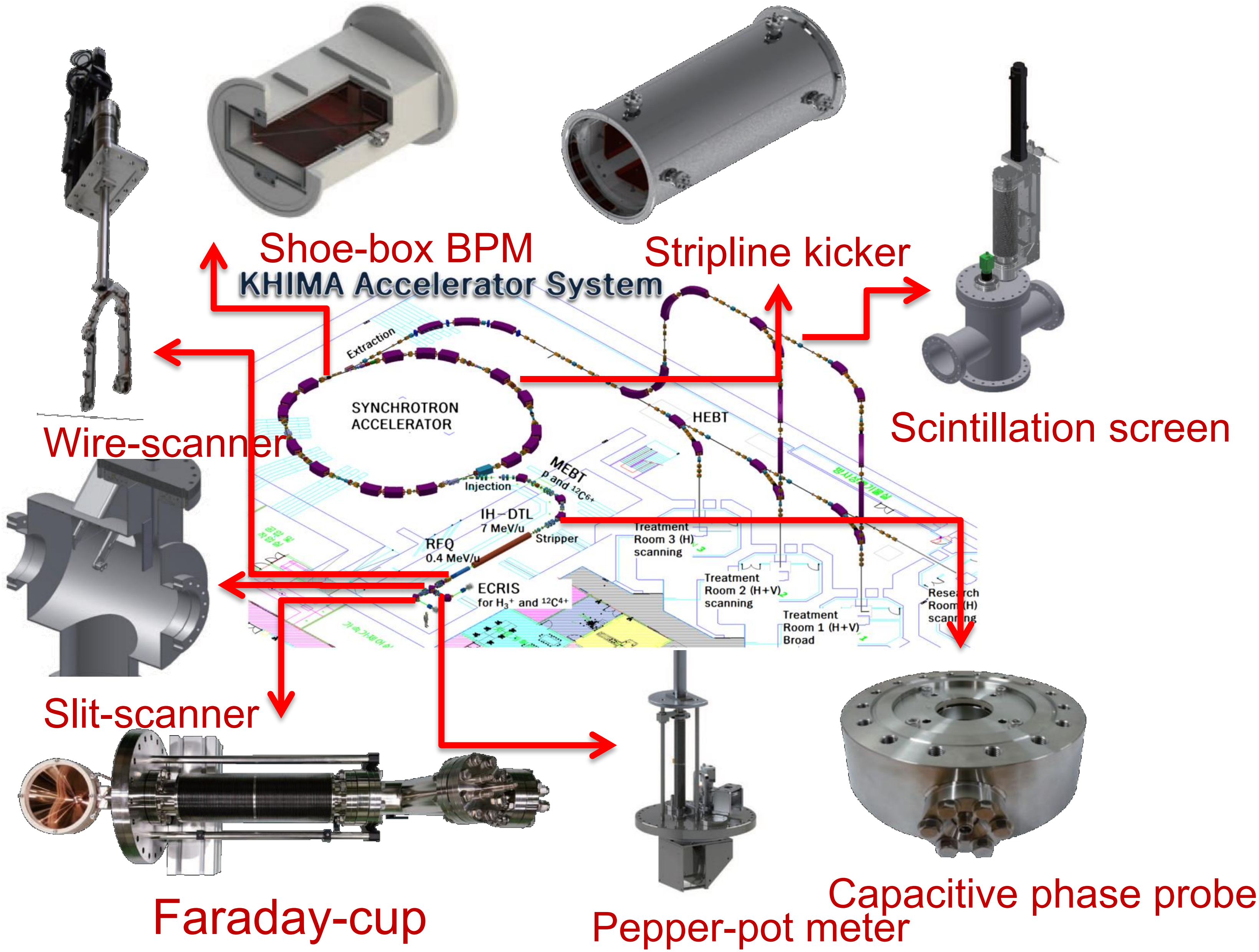


Vertical emittance



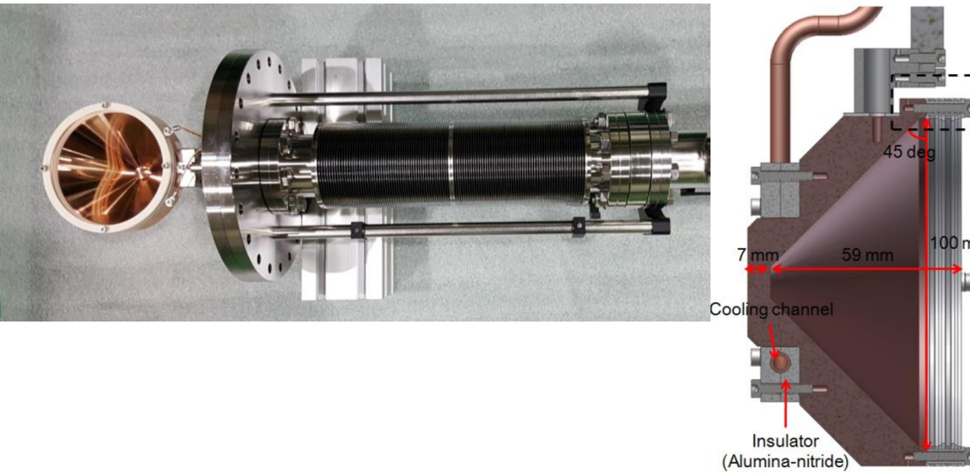
KOREA INSTITUTE OF RADIOLOGICAL & MEDICAL SCIENCES
KOREA HEAVY ION MEDICAL ACCELERATOR PROJECT

Beam Diagnostic Instruments

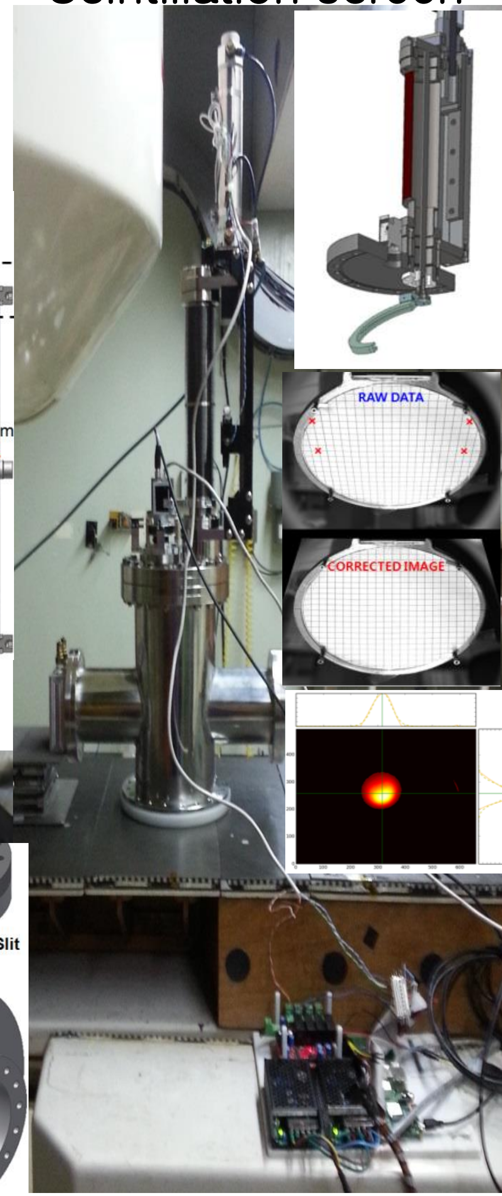


Diagnostics Test (1)

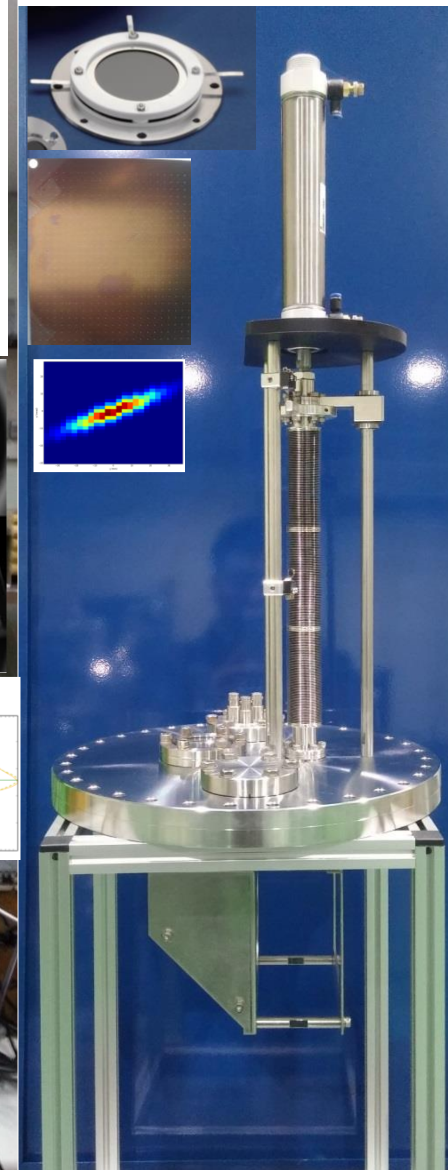
Faraday Cup (with cooling)



Scintillation screen



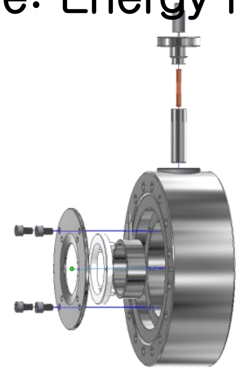
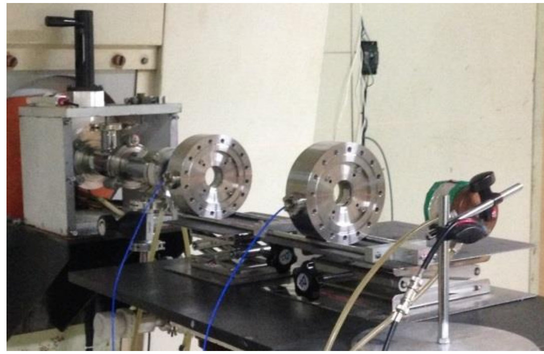
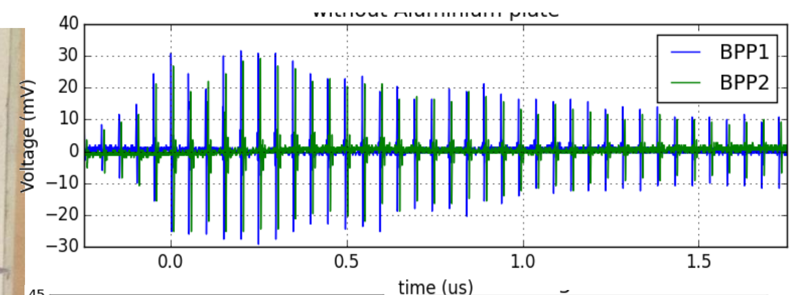
Pepper pot

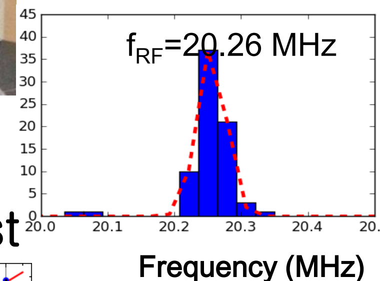


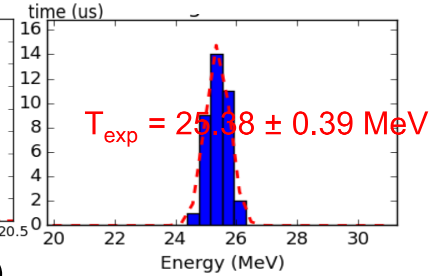
Wire scanner

Diagnostics Test (2)

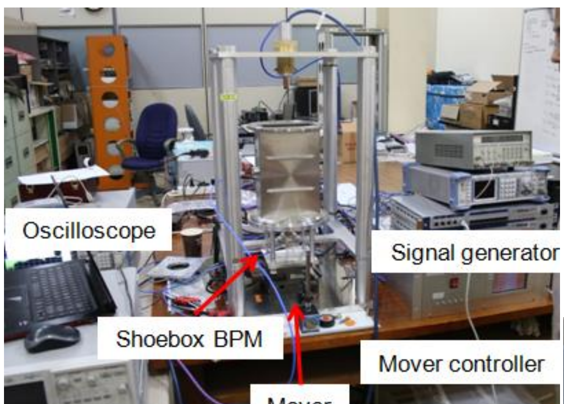
Phase Probe: Energy resolution test with proton beam

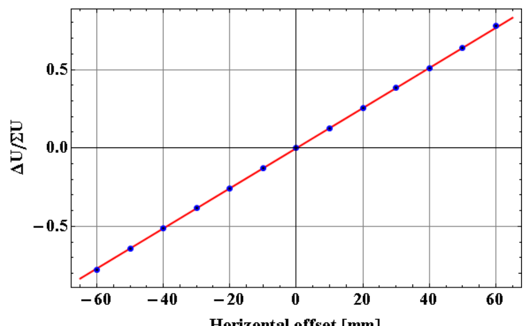





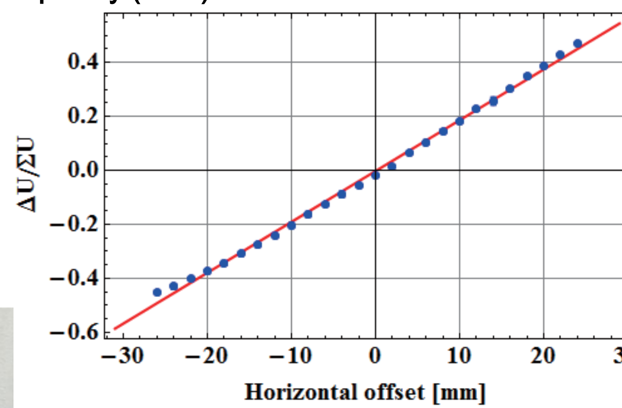




Shoe box for BPM at a ring: Position linearity test

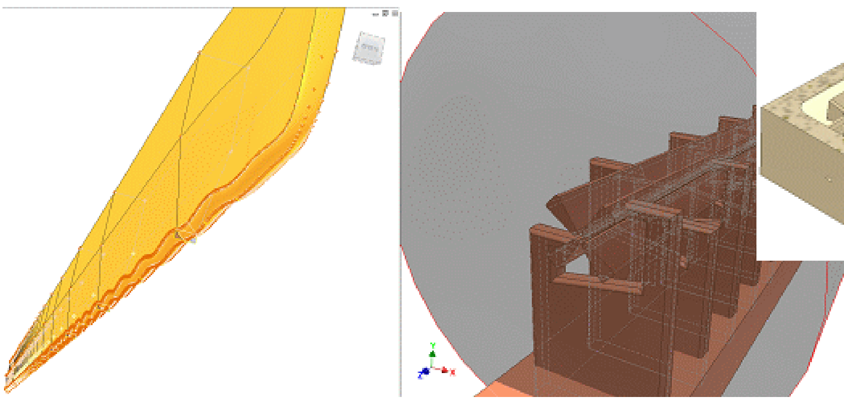




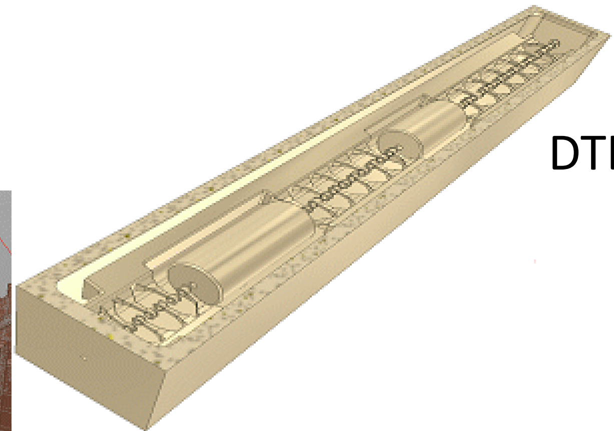



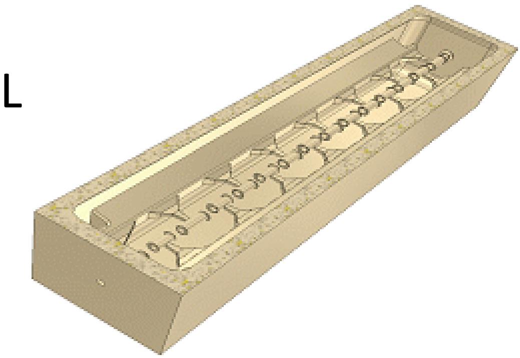
LINAC System

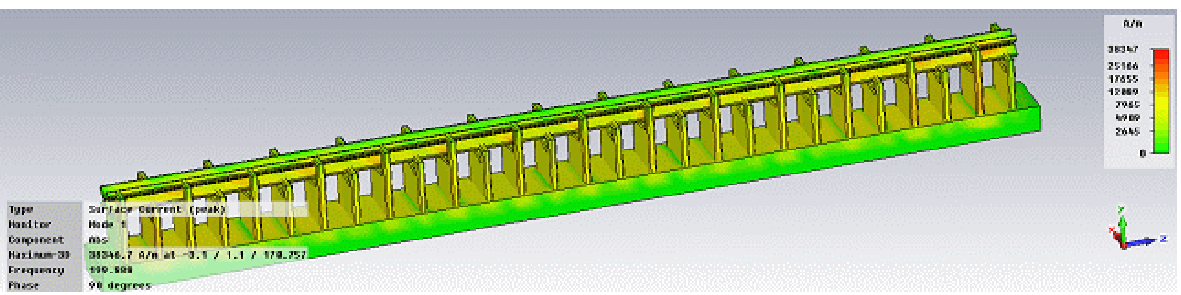
RFQ



DTL

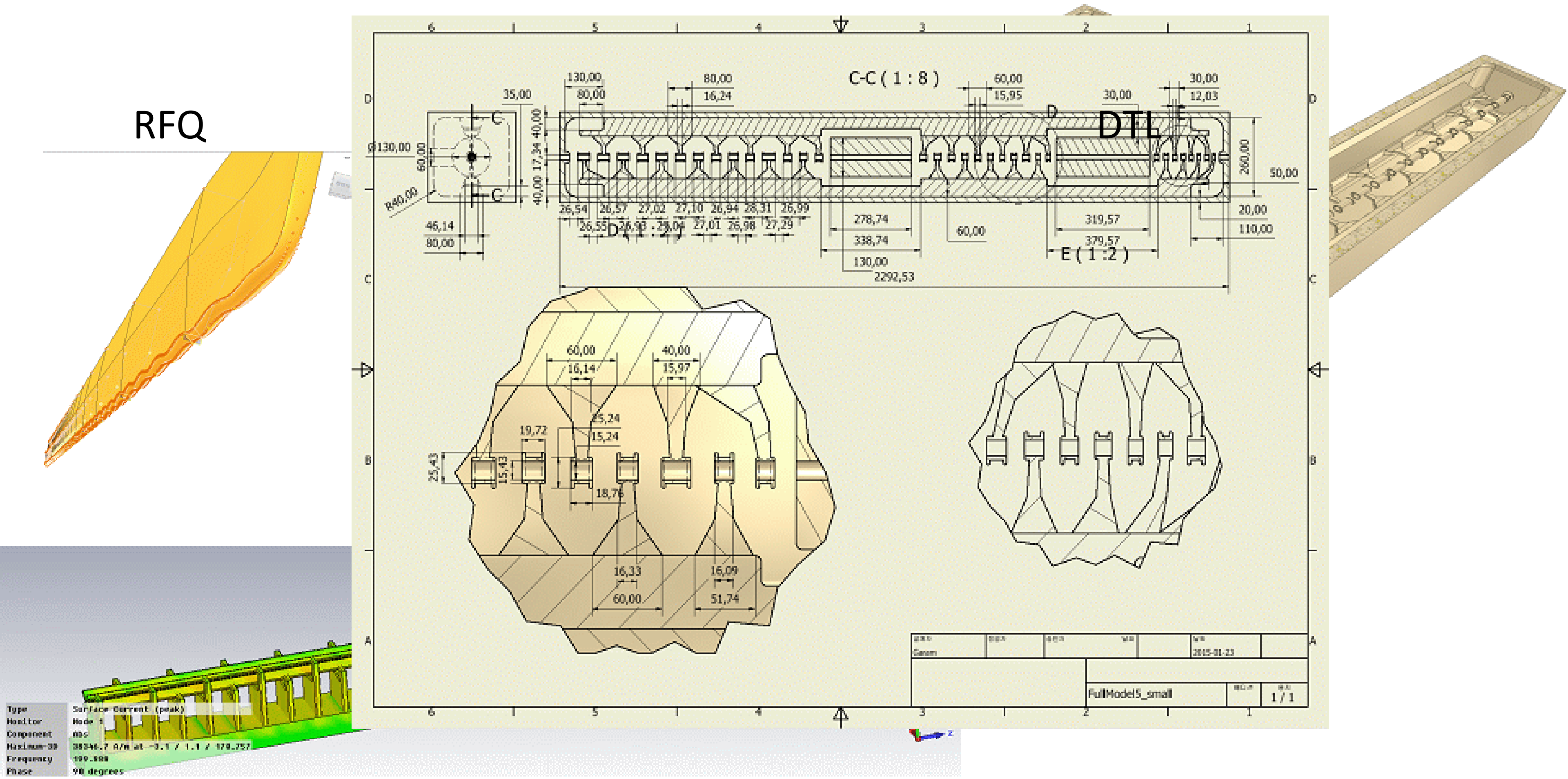






- In April of 2016, bid process of injector Linac was finalized through Public Procurement Service (PPS).
- It is expected that manufacturing and beam test of whole injector system will take about two years.

LINAC System



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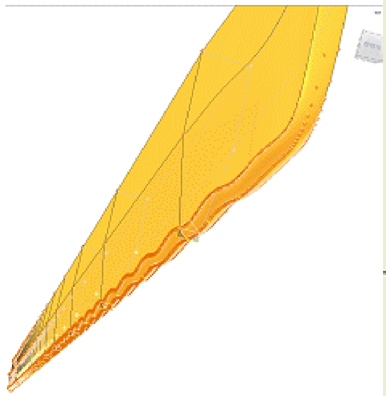
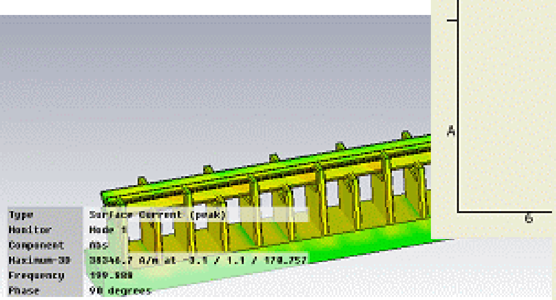
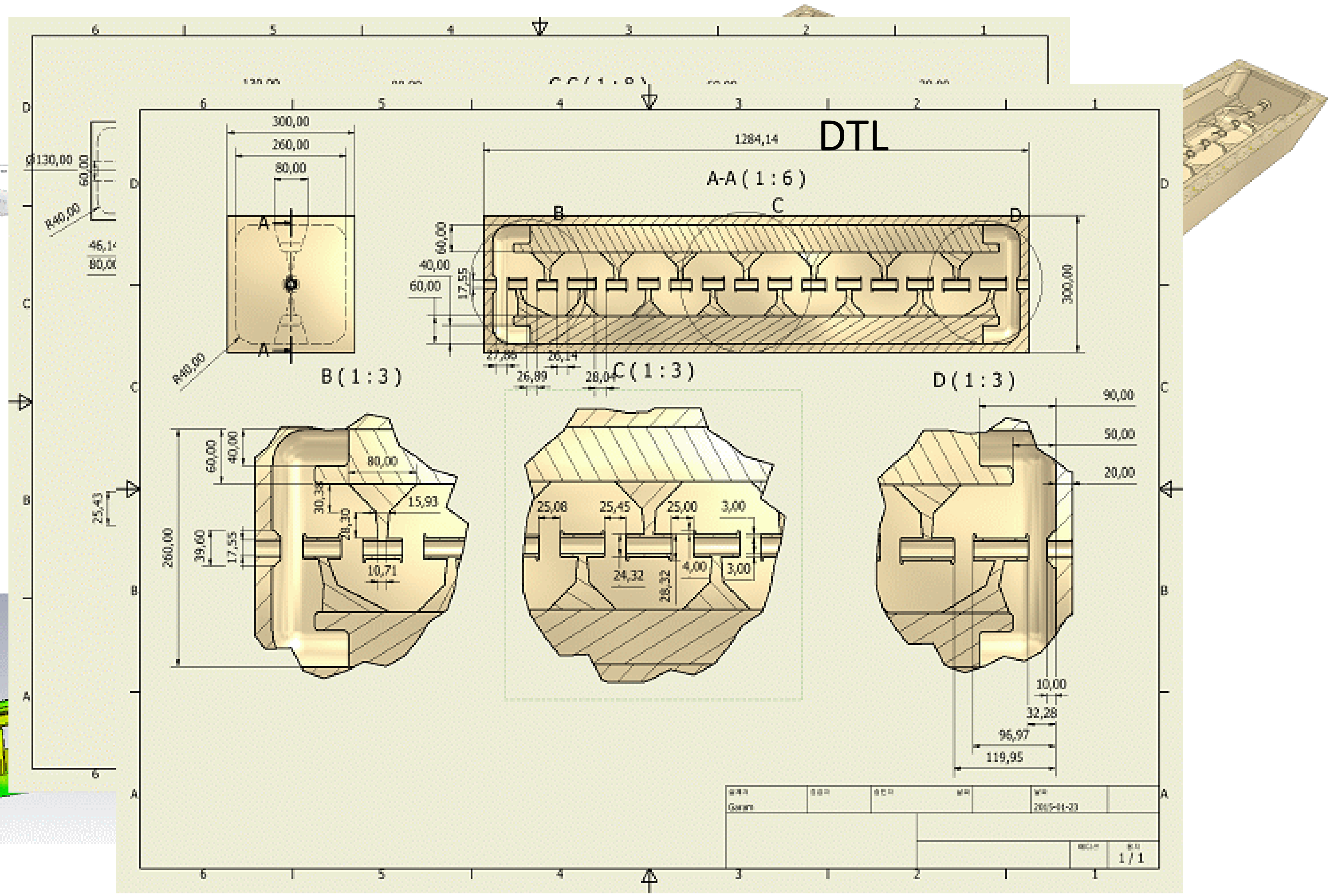
LINAC System

RFQ

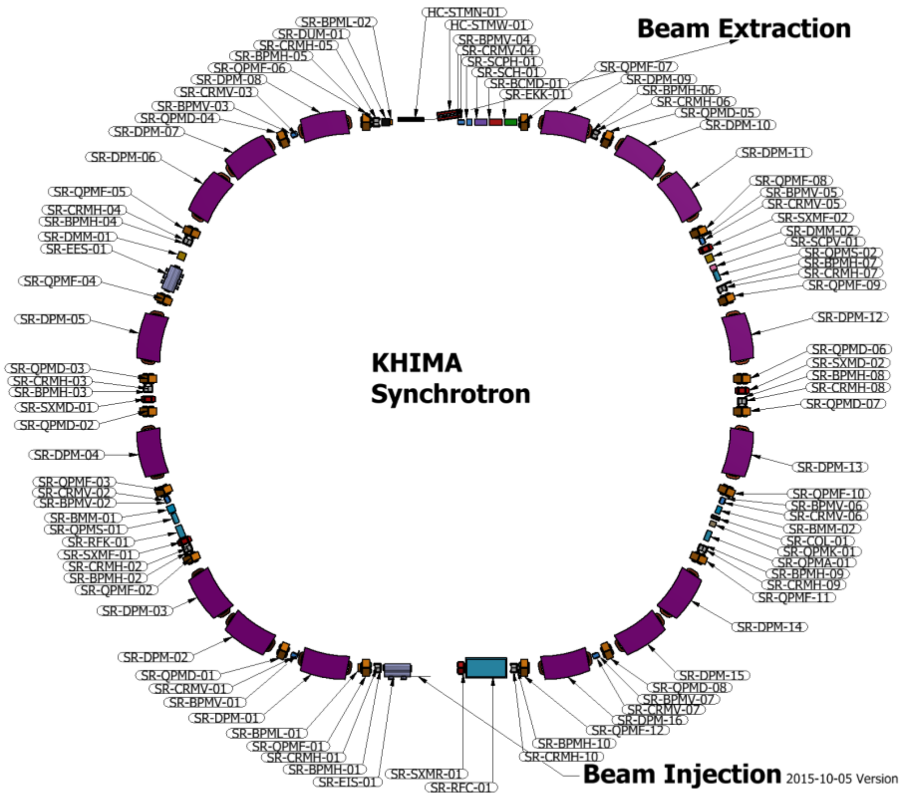


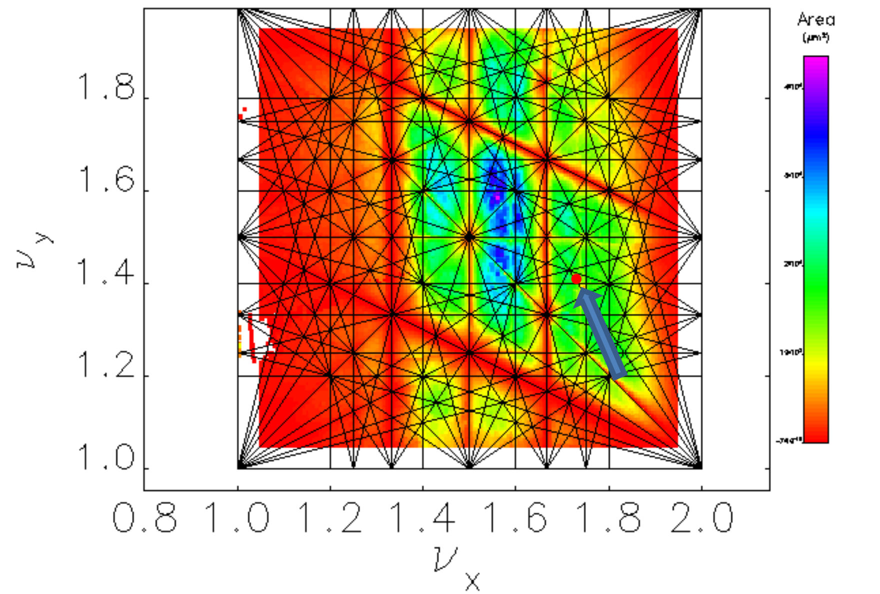


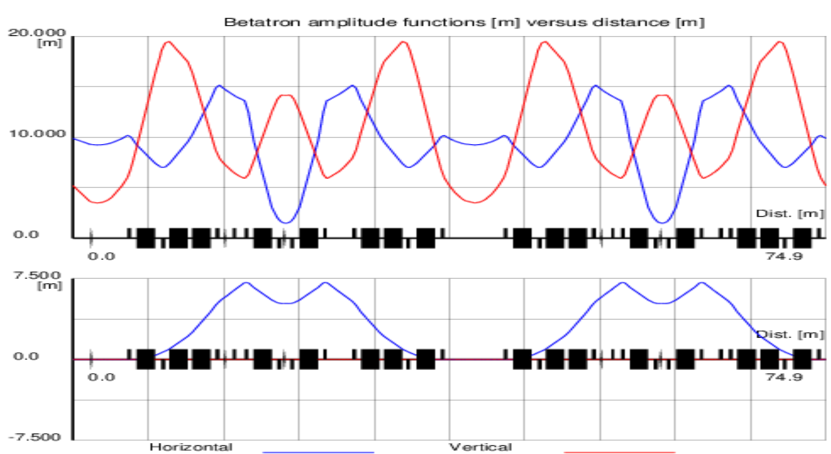


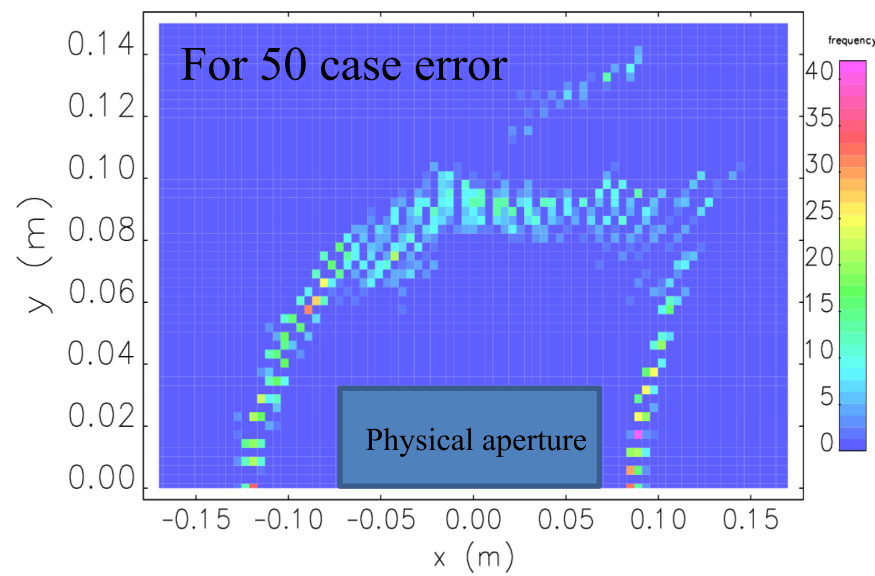
- In April of 2016, bid process of injector Linac was finalized through Public Procurement Service (PPS).
- It is expected that manufacturing and beam test of whole injector system will take about two years.

Synchrotron Design Results



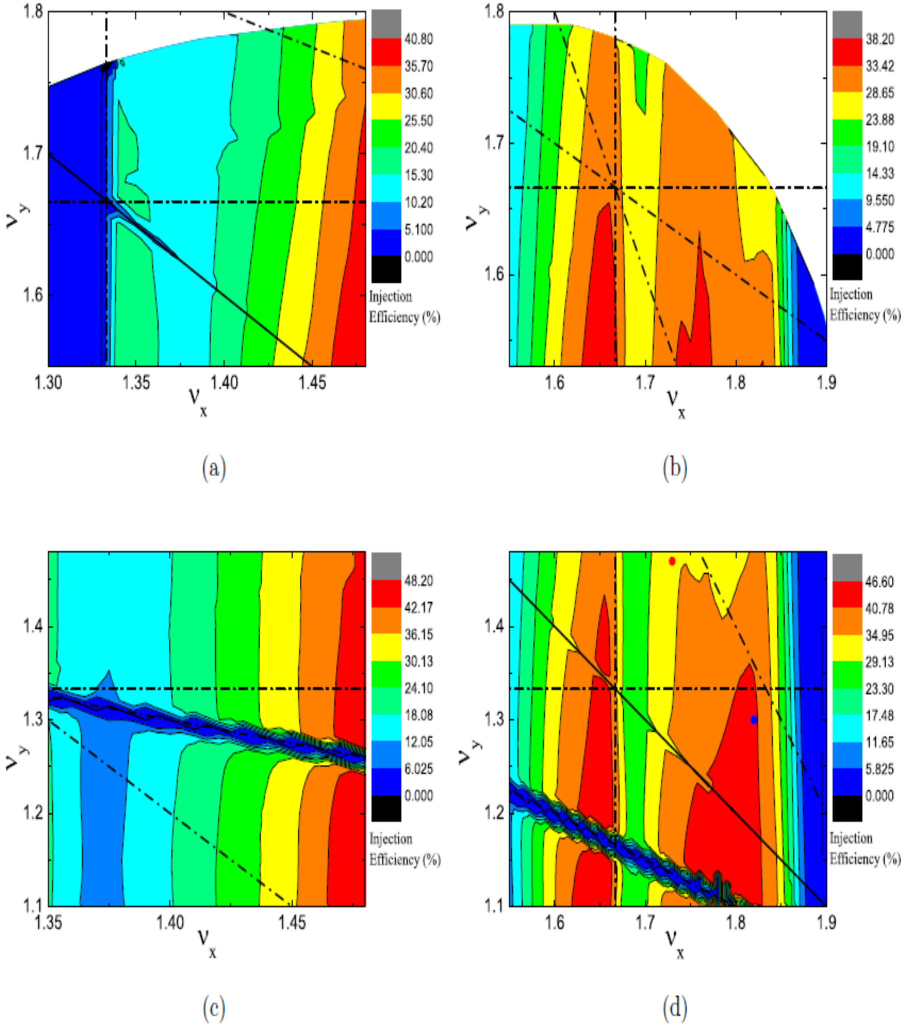


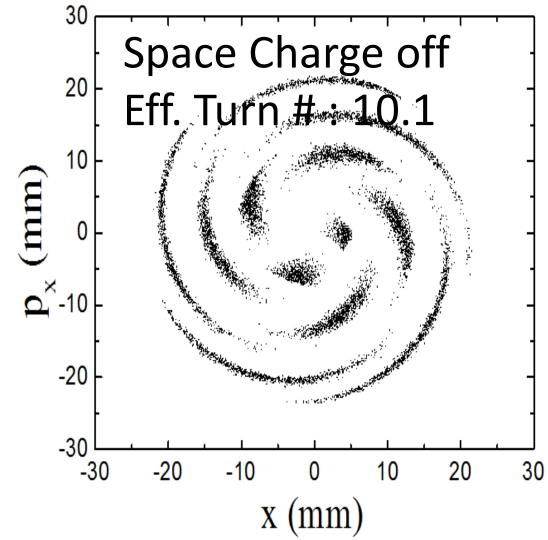


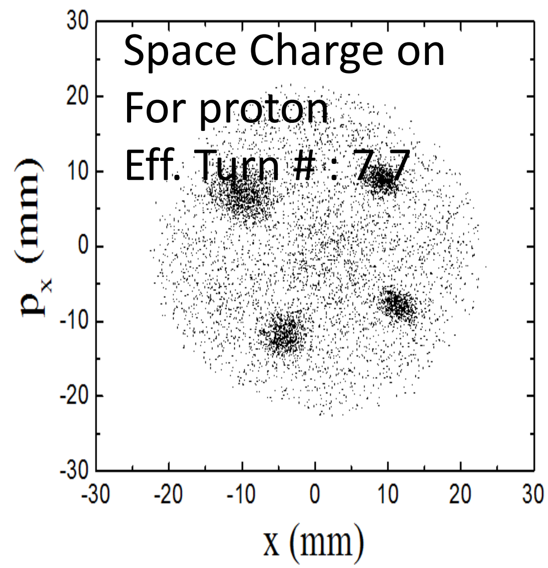


Multi-turn Injection

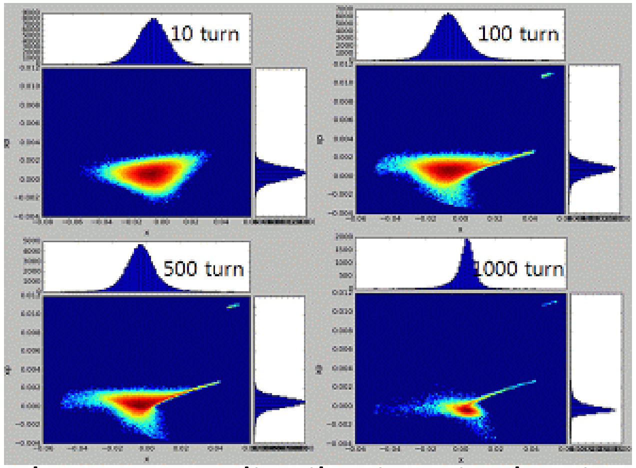
Multi-turn Injection Efficiency vs. Tune



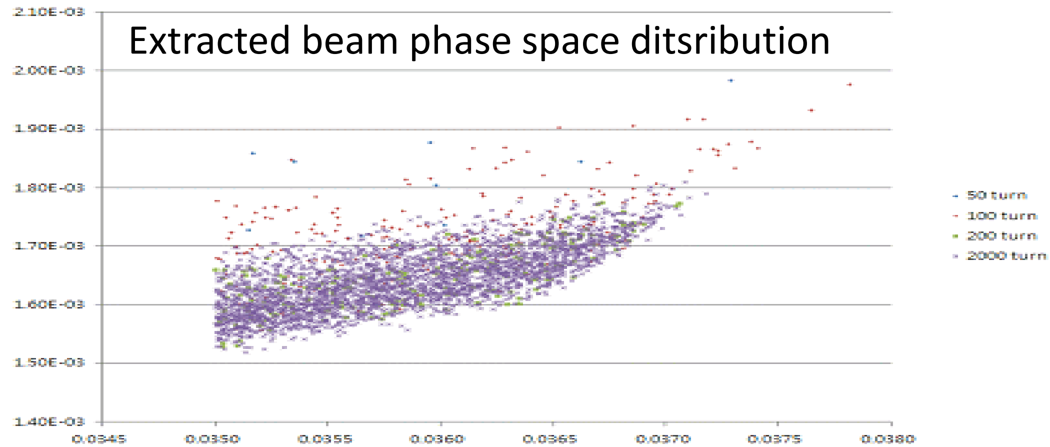




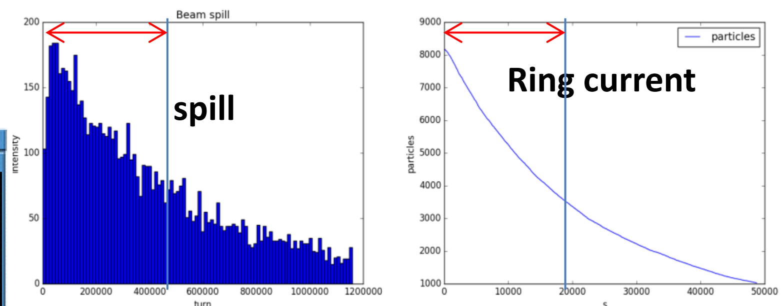
Extraction Studies

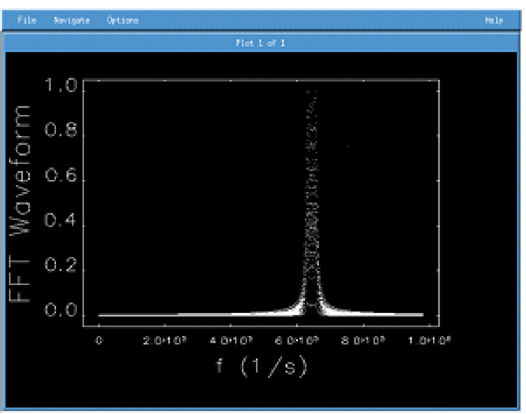


Phase space distributions in the ring

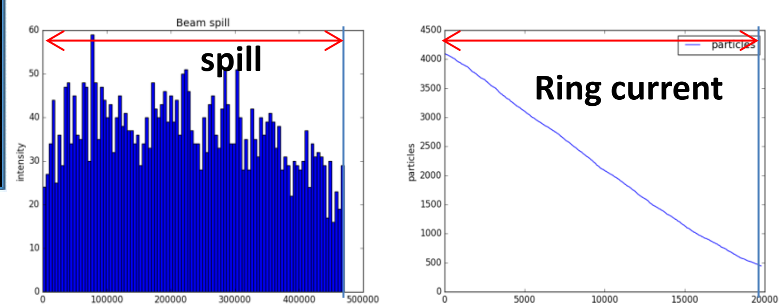


1.7 urad const. RFKO

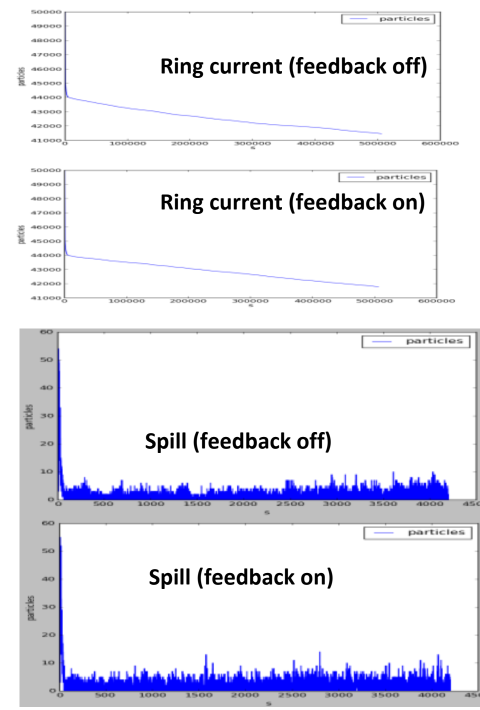




Frequency Distribution

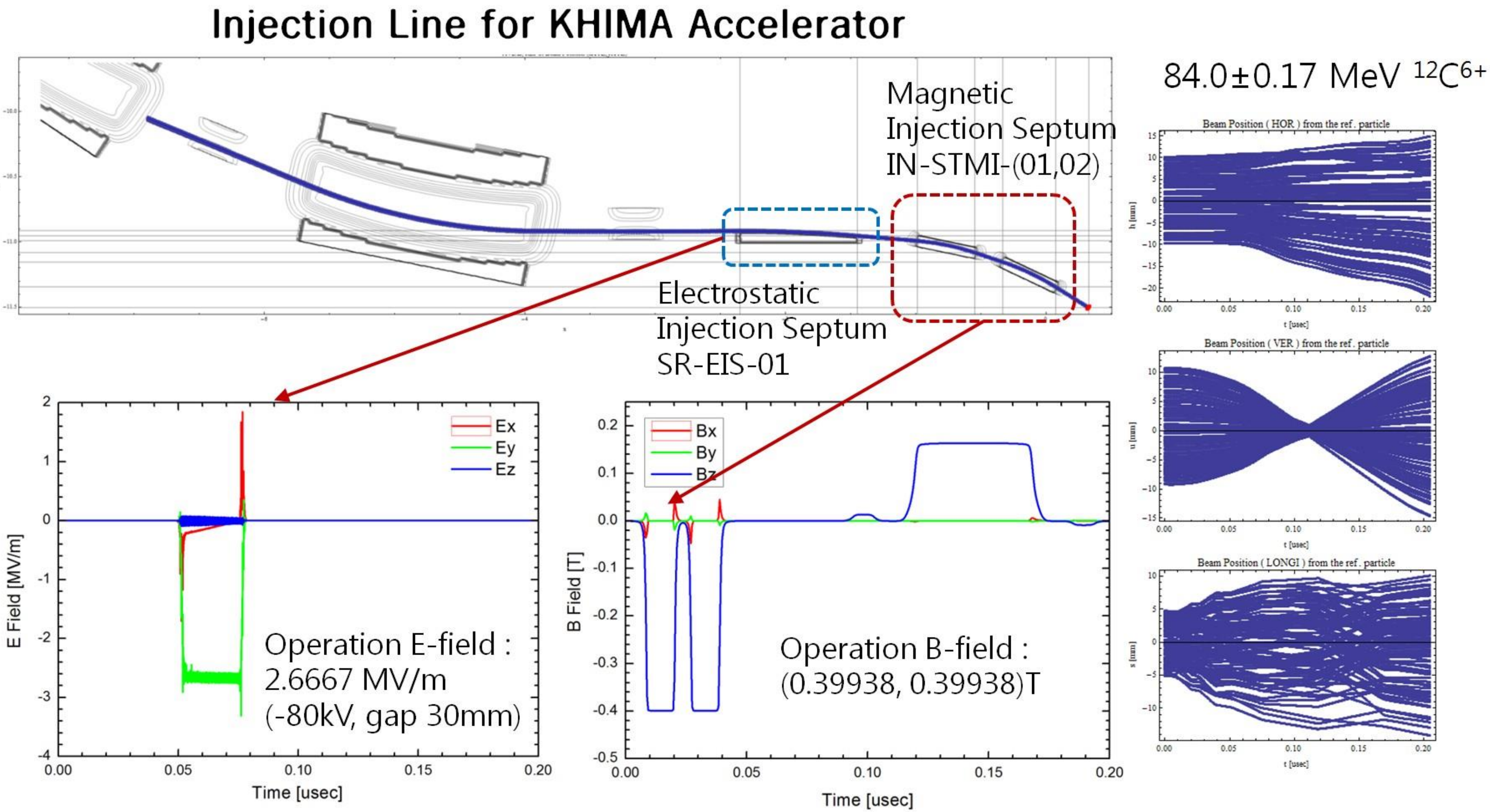


Amplitude Modulated RFKO



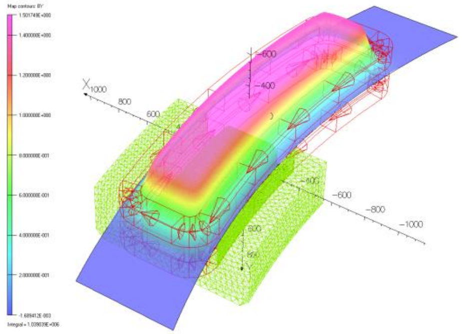
RFKO with Feedback

3D Fieldmap Tracking for the Injection Part

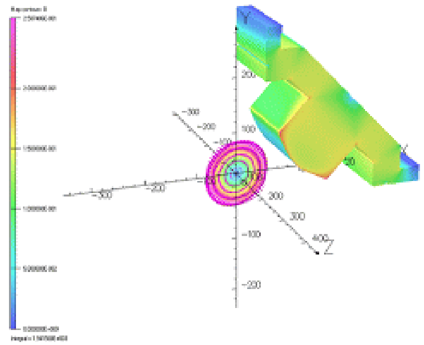


3D Fieldmap Tracking for the Ring

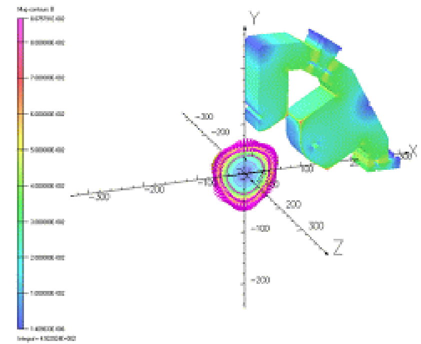
-Particle tracking was performed with 3D field map of Bending/Quadrupole/Sextupole magnet
-Beam envelope and Twiss functions are checked



22.5 Bending

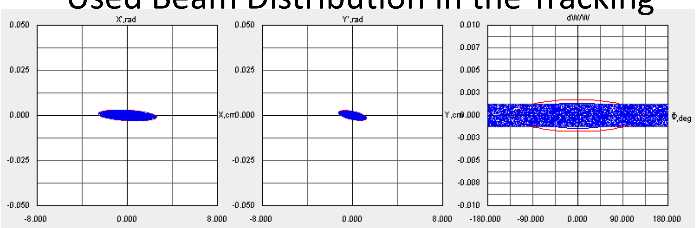


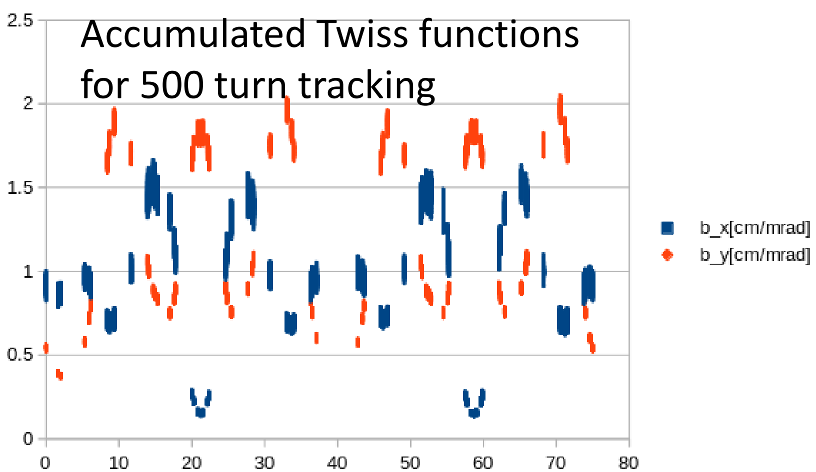
Quadrupole



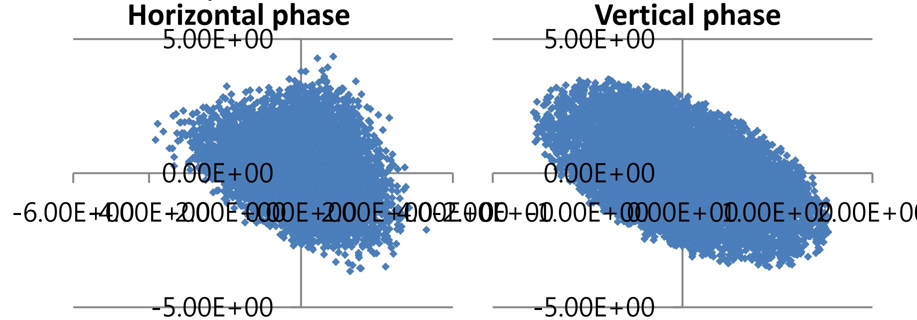
Sextupole

Used Beam Distribution in the Tracking

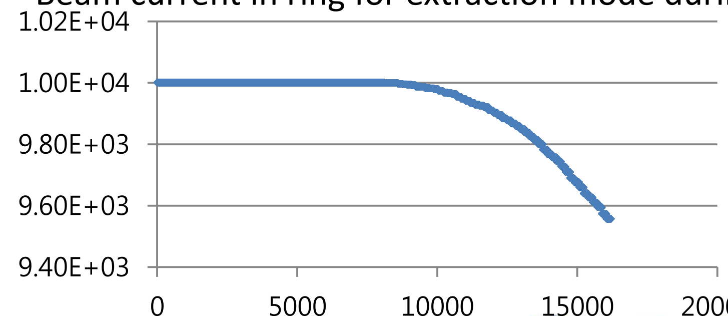




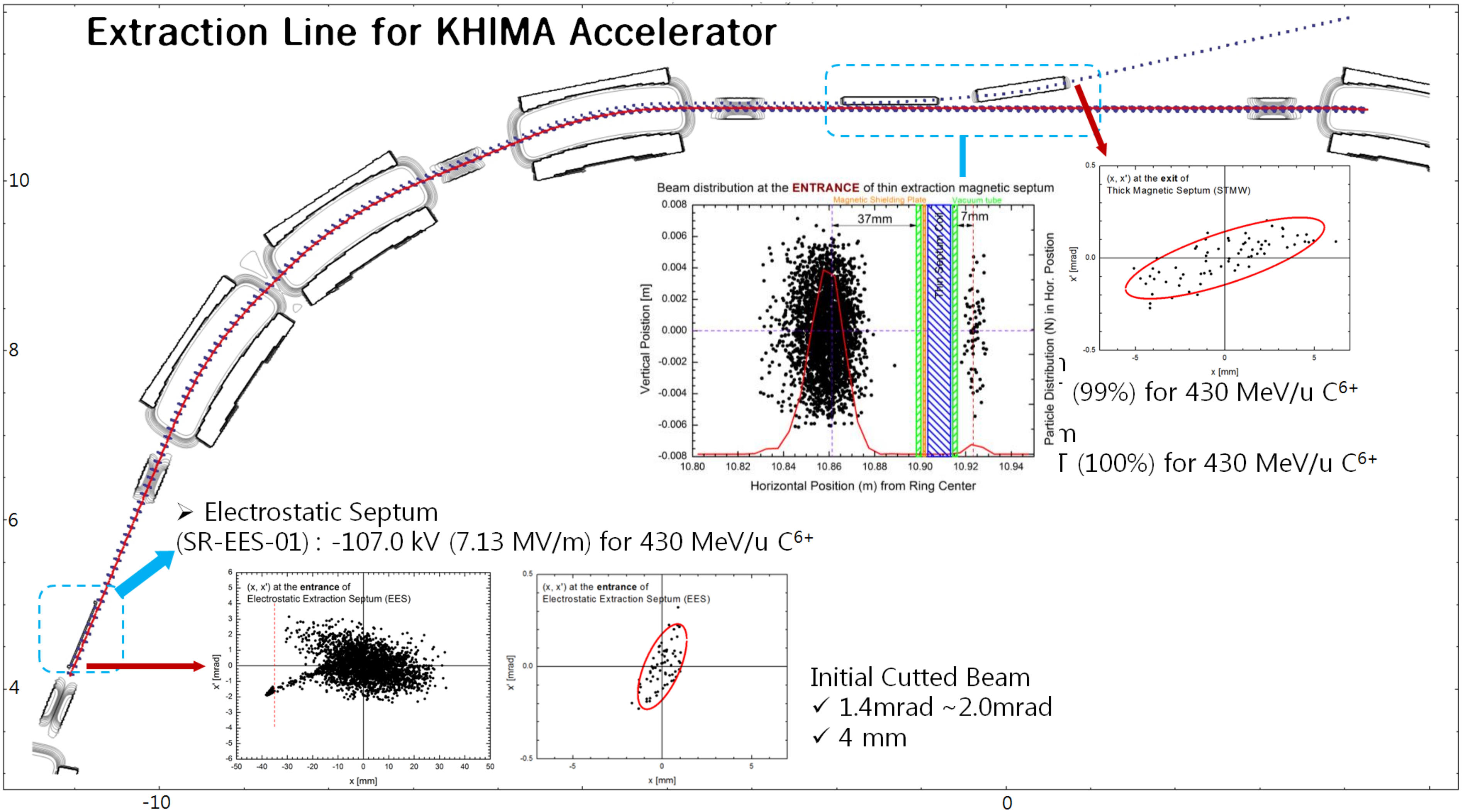
Phase space dist. for extraction mode after 1000 turn



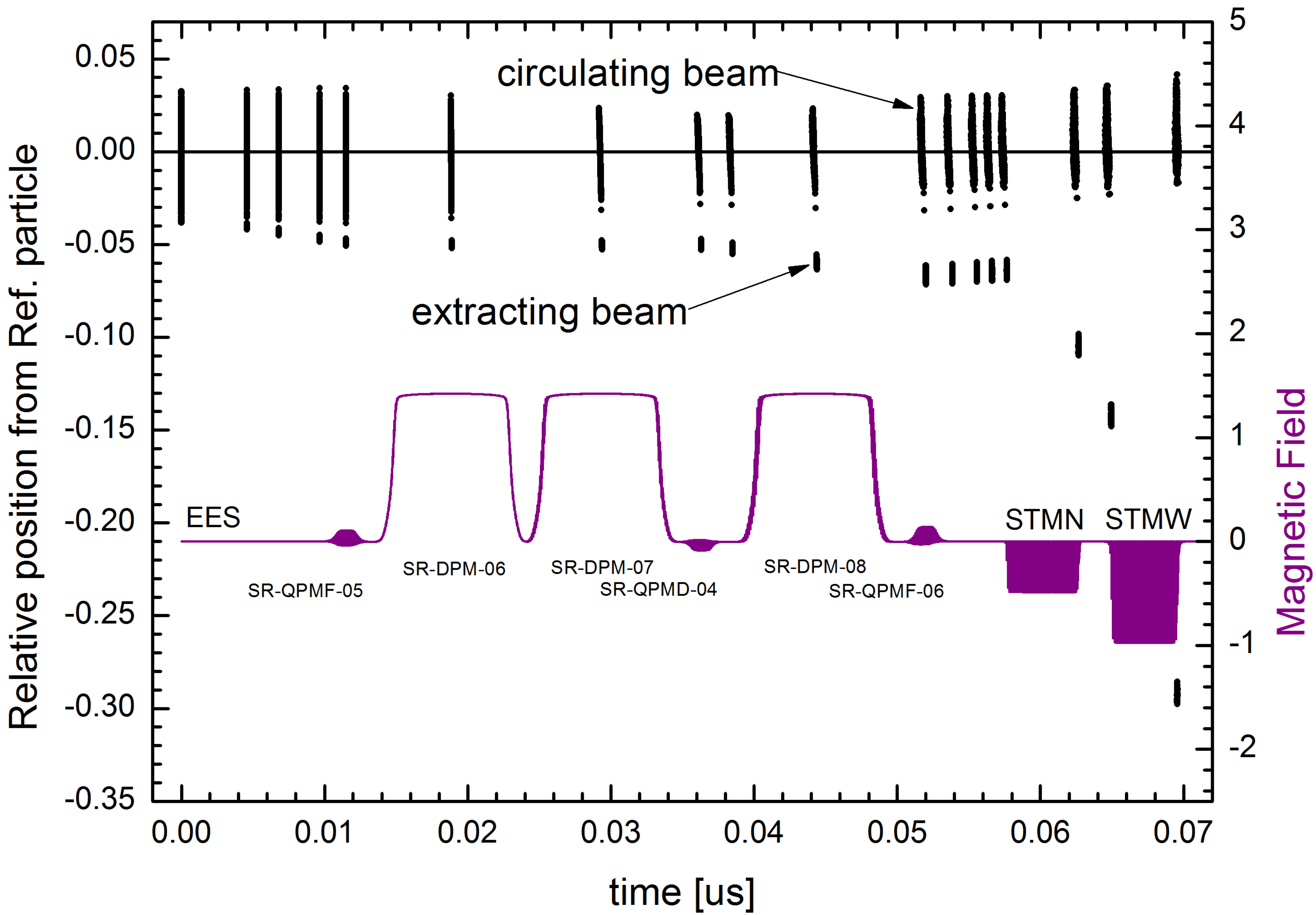
Beam current in ring for extraction mode during 1000 turn



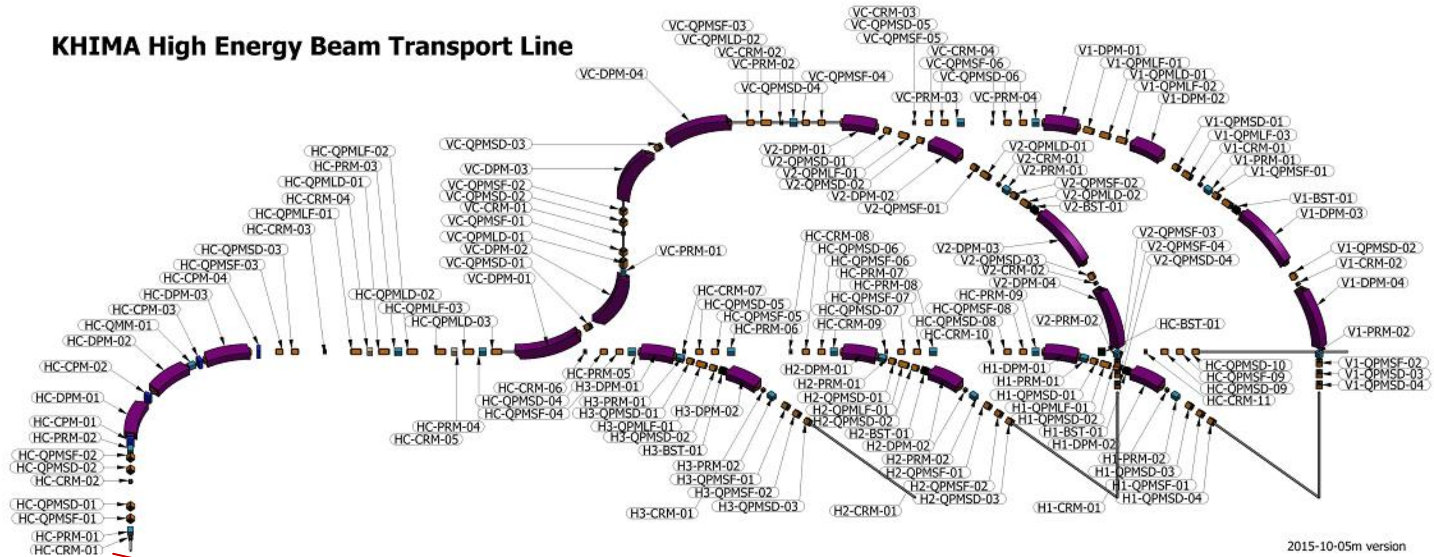
3D Fieldmap Tracking for the Extraction Part

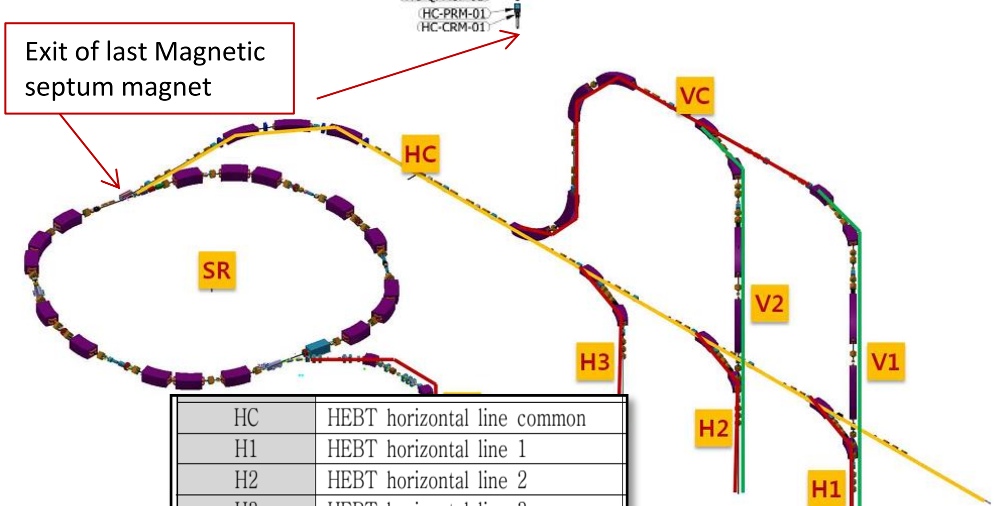


3D Fieldmap Tracking for the Extraction Part



HEBT Layout and Configurations





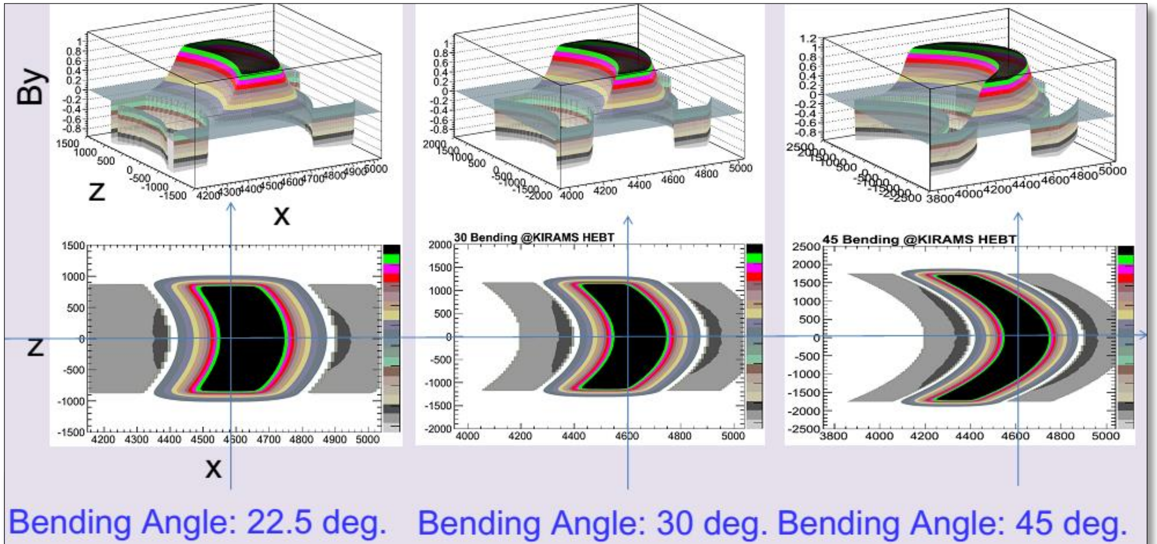
HC	HEBT horizontal line common
H1	HEBT horizontal line 1
H2	HEBT horizontal line 2
H3	HEBT horizontal line 3
VC	HEBT vertical line common
V1	HEBT vertical line 1
V2	HEBT vertical line 2

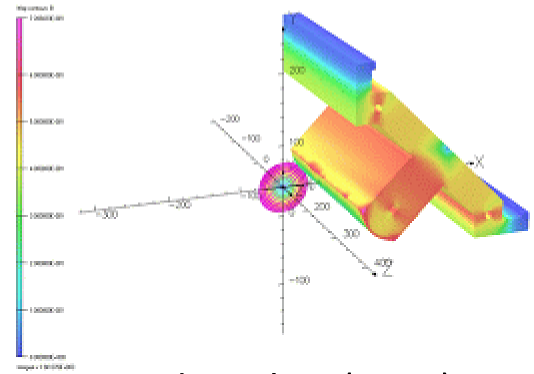
표 80 Classifications of HEBT elements

Position of reference	Components	Types	family ID/Total	Number	Comments
6.4.1	Magnets	Dipole magnet	BM1/3	10	22.5
			BM2/3	3	30.0
			BM3/3	8	45.0
6.4.2		Quadrupole	QM1/2	60	L_{eff} = 0.35m
			QM2/2	19	L_{eff} = 0.55m
6.4.3		H & V Corrector	CRM/1	22	H/V dual
6.4.4		Chopper magnet	CPM	4	
10.3	Monitors	profile monitor	PRM/1	23	
		Qualification Monitor	QMM (QPM/QIM/DUMP)	1	set with profile, intensity monitor, and dump
		Beam Stopper	BST	6	For safety of patient

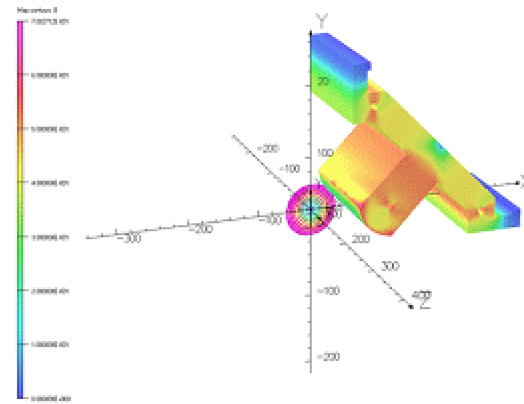
3D Fieldmap Tracking for HEBT(1)

- Using field map data from OPERA3D model





Quadrupole 1 (QM1)



Quadrupole 2 (QM2)

- EMStudio_To_TRACK.dat: The input file
- QM1.dat, QM2.dat: Example of input Magnetic field files from Opera3D
- EMStudio_To_TRACK.log: A log file with useful listings and eventual error messages
- eh_EMS.#12: The output file = TRACK field file
- EMStudio_To_TRACK.exe: The executable

```
! Input file to the code emstudio_to_track: E or B file names, ...
!-------------------------------------------------------------------------
QM2.dat
1                               ! Field type: 0:E, 1:B
0,  0,  0                       ! Input Symetry keys in XYZ: 0:No, 1:Yes
12                              ! Track Field file number: 1,2,...
2                               ! Track Field file format: 0,1,2,...
0,  0,  0                       ! Output Symetry keys: 0:No, 1:Yes
75.0d0                          ! Element/Field length in cm
3.6d0                           ! Element/Field aperture in cm
-1.3793d-04                     ! Field scaling factor (0.28/2030)
1d0                             ! Unit distance scaling factor to cm
25, 25, 201                     ! Output Grid
```

K430_HEBT_QM1_0p600T.table
K430_HEBT_QM2_1p720T.table

Head of QM1.dat (or QM2.dat)

					-86.6634			
					-99.1211	0	0	0
					-113.108	0	0	0
					-129.219	0	0	0
					-147.234	0	0	0
-3.6	-3.6	-25.6	102.282	102.077	-167.919	0	0	0
-3.6	-3.6	-25.2	117.468	117.313	-191.191	0	0	0
-3.6	-3.6	-24.8	134.315	134.484	-217.498	0	0	0
-3.6	-3.6	-24.4	153.577	153.962	-247.92	0	0	0
-3.6	-3.6	-24	176.11	175.762	-281.766	0	0	0
-3.6	-3.6	-23.6	201.244	200.85	-320.978	0	0	0
-3.6			228.547	228.597	-365.021	0	0	0
-3.6			260.248	260.106	-416.01	0	0	0

https://www.phy.anl.gov/atlas/TRACK/Trackv39/Manuals/Quadrupoles.txt

Head of eh_EMS.#22

```
1
        0              0              0
 -3.60000000000000      3.60000000000000      25
 -3.60000000000000      3.60000000000000      25
 -37.5000000000000      37.5000000000000      201
-8.454158576093754E-003 -8.426394991218760E-003  1.427548603650001E-002
-9.668148528212900E-003 -9.638219011306653E-003  1.617164072687111E-002
-1.099679187689064E-002 -1.099228630723439E-002  1.826279707971878E-002
-1.249138918025781E-002 -1.258658057299804E-002  2.062242318626952E-002
-1.426114131650000E-002 -1.426123786750000E-002  2.340123828249999E-002
-1.634593370845704E-002 -1.636124948798438E-002  2.637553305486329E-002
```

Part of sclinac.dat

22 qua3d 1238.3 55 3.6 50

field strength [G]

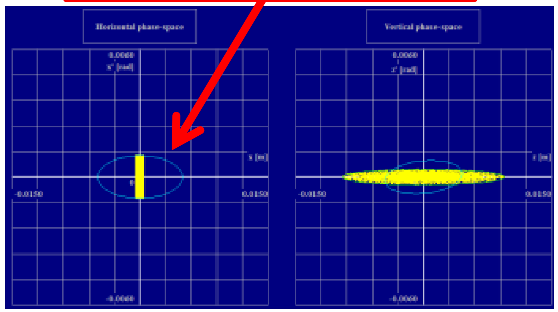
aperture radius

quad. Length including fringe field

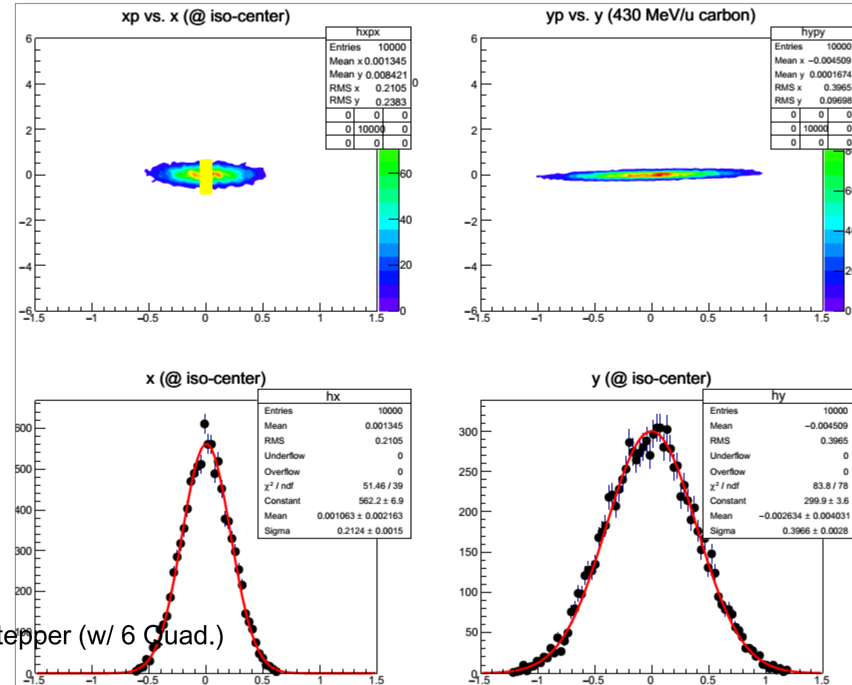
KOREA INSTITUTE OF RADIOLOGICAL & MEDICAL SCIENCES
KOREA HEAVY ION MEDICAL ACCELERATOR PROJECT

3D Fieldmap Tracking for HEBT(2)

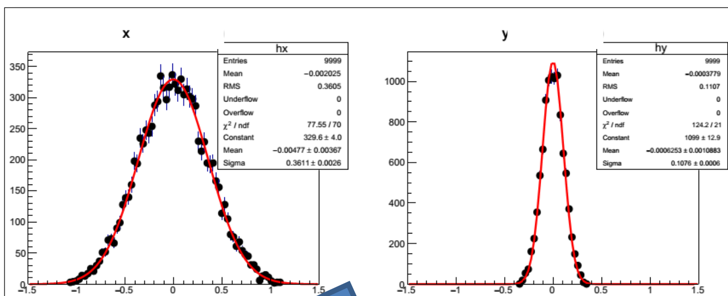
430 MeV/u carbon, TR3, Odd-Phase Advance (Γ_y = 10 mm)



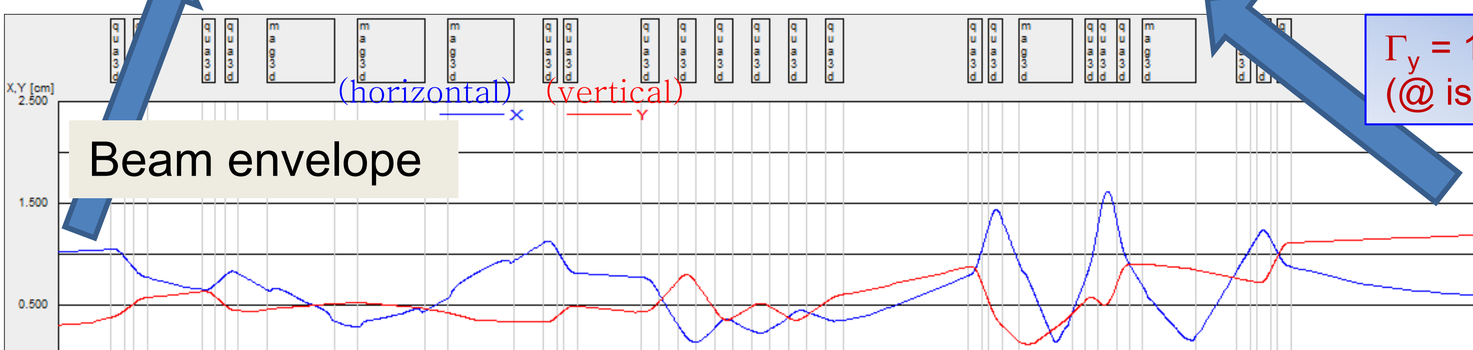
@ Iso-center



Exit of last Magnetic septum magnet



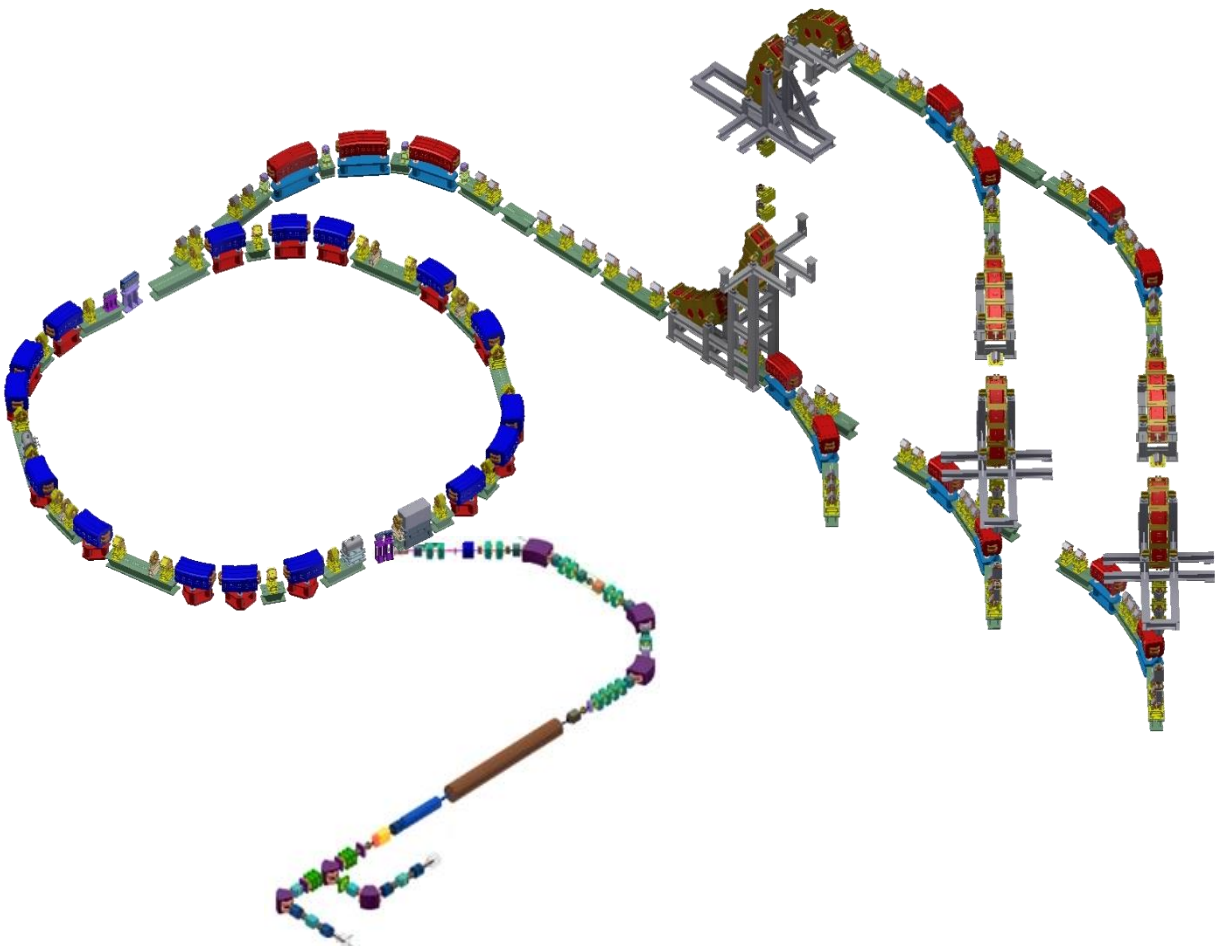
Phase shifter & stepper (w/ 6 Quad.)



Γ_y = 10 mm
(@ iso center)

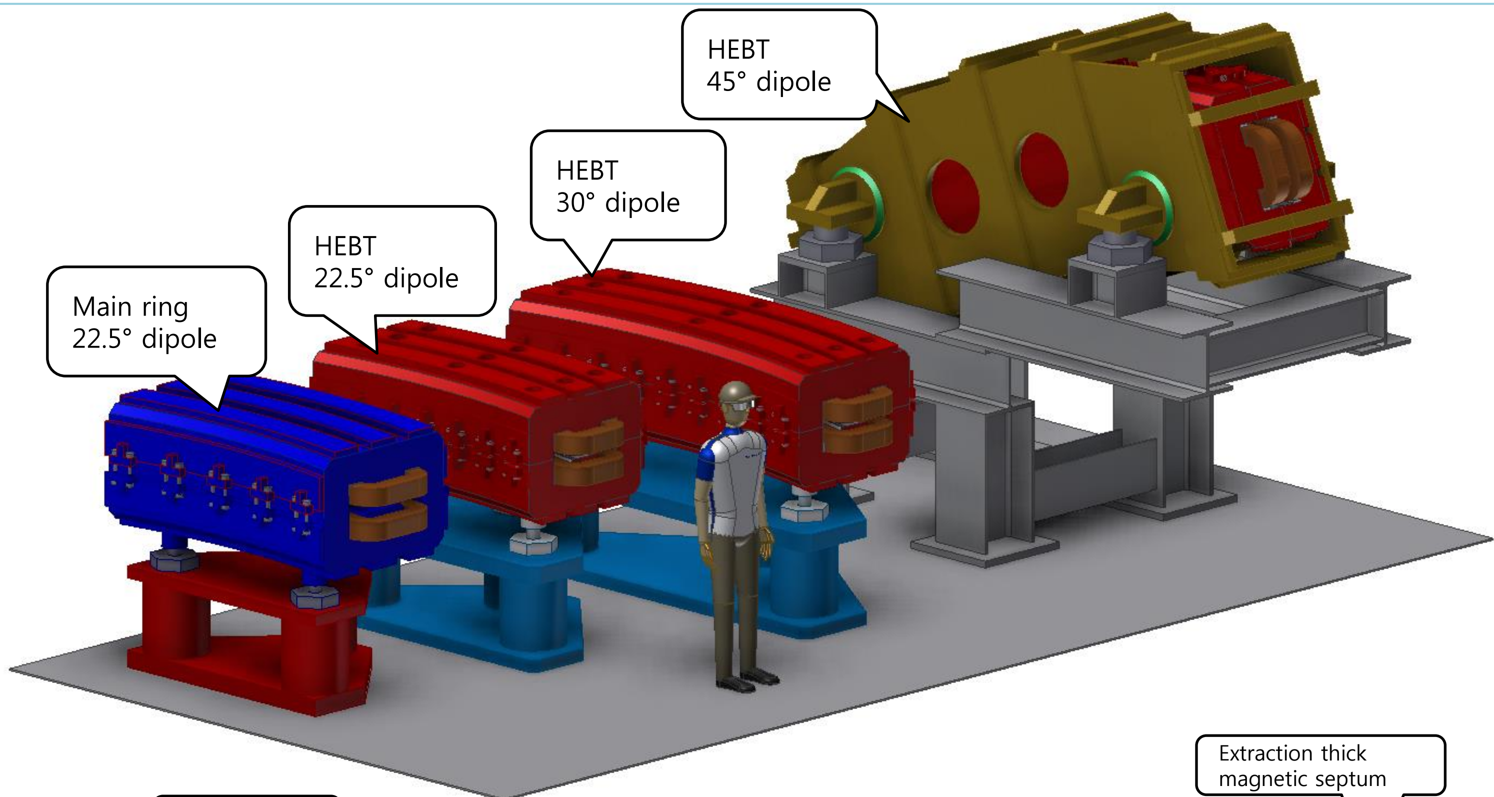
Magnet Configurations

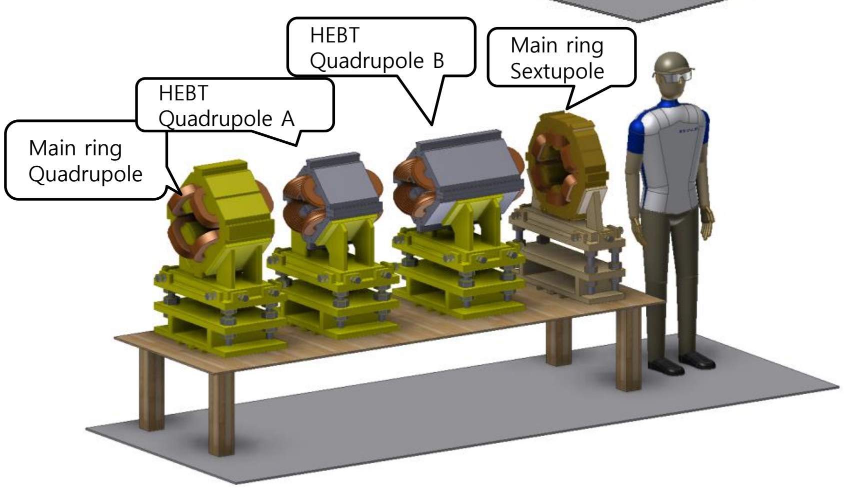
28 Types, Quantity : 236

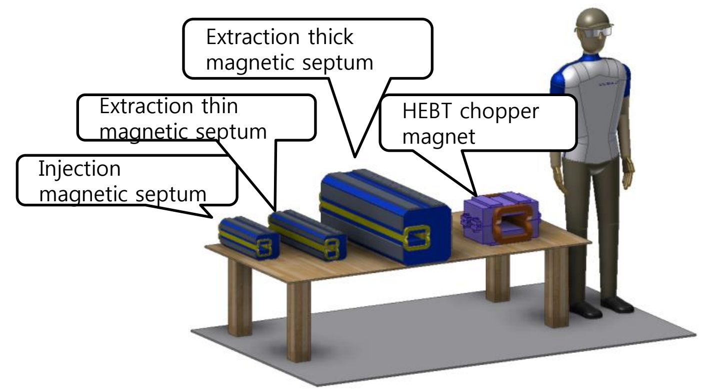


FM #		Parameters	Qty.
1	LEBT	LE Solenoid	3
2		LE dipole A	2
3		LE dipole S	1
4		LE quadrupoles	7
5		LE correctors H/V	5
6	MEBT	ME dipole	3
7		ME quadrupoles	12
8		ME correctors H/V	6
9	Synchrotron Ring	SR dipole	17
10		SR quadrupole (F, D)	20
11		SR air-core quadrupole	1
12		SR fast quadrupole	2
13		SR skew quadrupole	1
14		SR sextupole (F, D, R)	5
15		SR horizontal corrector	10
16		SR vertical corrector	7
17	HEBT	HE dipole (22.5 deg)	10
18		HE dipole (30 deg)	3
19		HE dipole (45 deg)	8
20		HE short quadrupole	60
21		HE long quadrupole	19
22		HE correctors H/V	22
23	Special Magnets	Injection septum	2
24		Injection bumper	2
25		Dump bumper	2
26		Extraction septum N	1
27		Extraction septum W	1
28		Chopper bumpers	4
		Total	**236**

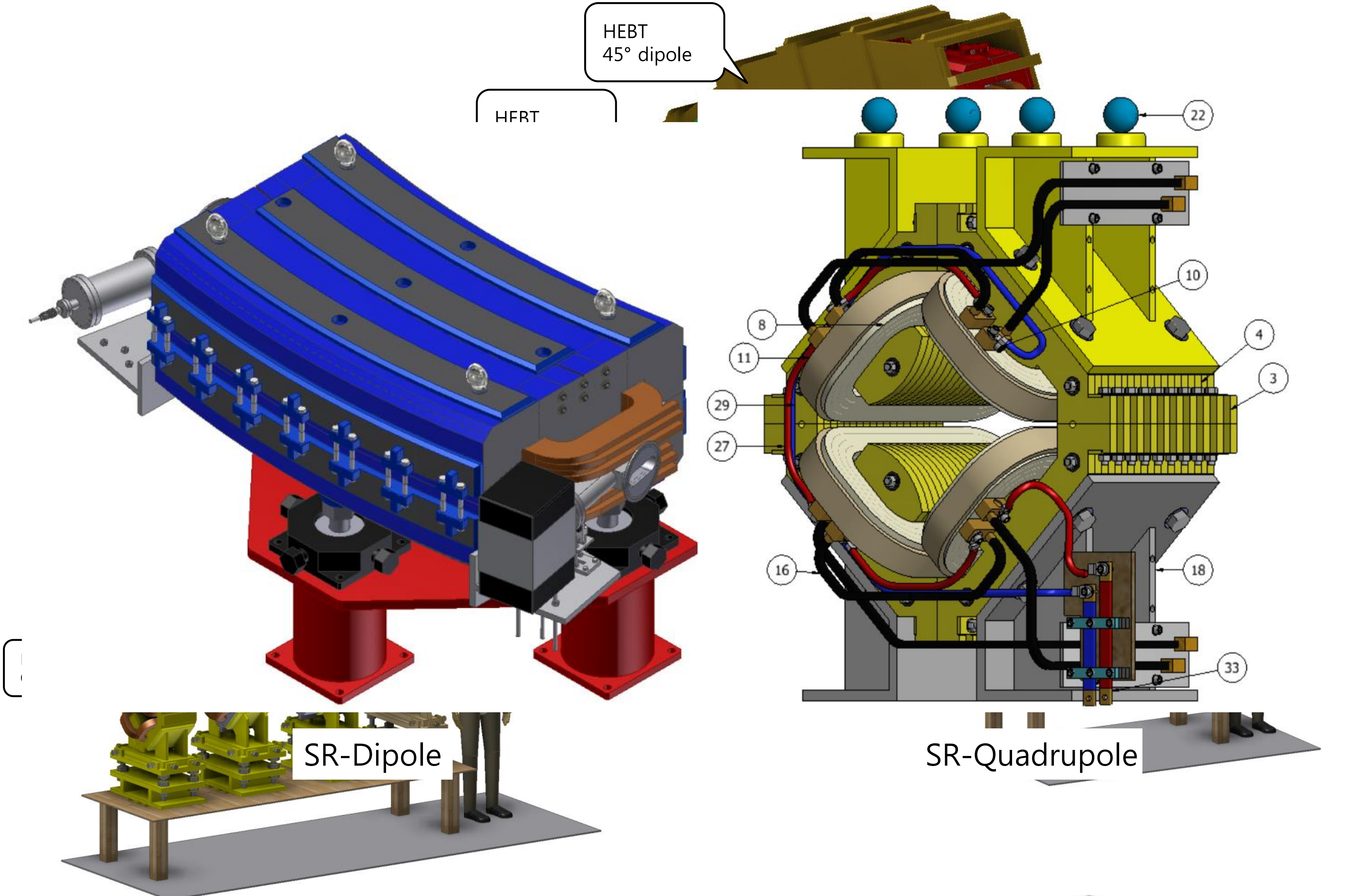
Magnet CAD Images







Magnet CAD Images



Specifications for the Magnets

Field specifications

	1	2	3	4	5	6	7	8	9	10		11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
Location	LEBT					MEBT			Synchrotron Ring									HEBT						Special Magnets					
Parameters	LE solenoid	LE dipole A	LE dipole S	LE quadrupoles	LE correctors H/V	ME dipole	ME quadrupoles	ME correctors H/V	SR dipole	SR quadrupole (F, D)	SR quadrupole - aux coil	SR air-core quadrupole	SR fast quadrupole	SR skew quadrupole	SR sextupole (F, D, R)	SR horizontal corrector	SR vertical corrector	HE dipole_1	HE dipole_2	HE dipole_3	HE quadrupole_1	HE quadrupole_2	HE correctors H/V	Magnetic injection septum	Injection bumper	Dump bumper	Thin M extraction septum	Thick M extraction septum	Chopper bumpers
Quantity of magnets [EA]	3	2	1	7	5	3	12	6	17	20	20	1	2	1	5	10	7	7	3	6	45	13	17	2	2	2	1	1	4
Required spec. [Oct.19, 2015]																													
Magnetic rigidity [T-m]	0.0386	0.0386	0.0386			0.7632			0.38~6.62	0.38~6.62					0.38~6.62			6.62	6.62	6.62									
Bending an…																													
Entry/Exit edge…																													
Max. magnetic f…nt [T, T/m…																													
Bending rad…																													
Deflection an…																													
Magnetic len…																													
Good field re…																													
Good field…																													
Integral fie…																													
Required free a…																													
Max. repetitio…																													
Duty c…																													
Rise tim…																													

Mechanical specifications

	1	2	3	4	5	6	7	8	9	10		11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
Location	LEBT					MEBT			Synchrotron Ring									HEBT						Special Magnets					
Mechanical spec.																													
Aperture of vacuum chamber [mm]	D100	w124, h64	D104	D104	D104	w124, h64	D84	D84	w190, h72	w186, h78		w186, h78		w186, h78	w186, h78	w186, h108	w186, h108	w84, h64	w84, h64	w84, h64	D70	D70	D70		w196, h88	w196, h88			D80
Yoke length [mm]	180	645.2		126	40	830	209		1738	302		370		140	140	160	160	1814.3	2407	3559	324	532	200	424	150	150	1060	954	140
Width of cross-section [mm]	D100	-		460	154	714	478.4		1140	620.56		240		241	617	380	300	724	724	724	504	504	370	155	241	290	187.5	320	364
Height of cross-section [mm]	D100	-		460	154	564	478.4		680	620.56		240		241	556.68	200	300	486	486	486	504	504	370	150	150	160	150	330	230
Overall length [mm]	180	710		200	76	1084	277		2072	482		416		320	220	250	202	2118.3	2711	3863	496	720	238	465.6	202	202	1118.6	1012.6	240
Overall width [mm]	100	696.2		500	189	714	478.4		1208.4	620.56		240		241	617	540	300	813.35	882.44	1078									
Overall height [mm]	100	416		500	189	564	478.4		740	620.56		240		241	556.68	200	338	486	486	486									
Air-gap, Aperture [mm]	D108	70		R54	R40	70	R44		72	R85		R80		R85	R100	R68.5	R100	66	66	66									
Yoke mate…																													
Lamination […																													
Packing fac…																													
Total weight…																													
Wt. of yoke…																													
Wt. of coil…																													
Wt. of magnet * N…et																													
Magnetic s…																													
Max. magnetic field…nt [T or T/m or…																													
Magnetic lengt…																													
Good field region,…																													
Integral field c…																													

Electric, cooling specifications

	1	2	3	4	5	6	7	8	9	10		11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
Location	LEBT					MEBT			Synchrotron Ring									HEBT						Special Magnets					
Conductor & coil spec.																													
Conductor dimension [mm]	w9 x t9, d7.9, r1	w6 x t9, d1.5, r1		w6 x t2, d0, r0	w3 x t3.8	w12 x t12, d5.5, r1	w7 x t7, d3, r1		w25 x t25, d8, r0.5	w11 x t10, d5, r0.5	w4 x t2	w4 x t4		w11 x t10, d5, r0.5	w8, t8, d4, r0.1	w3 x t3.8	w7 x t3	w13.5 x t13.5, d10, r1	w13.5 x t13.5, d10, r1	w13.5 x t13.5, d10, r1	w8 x t8, d4, r	w8 x t8, d45, r		w8, t8, d4, r0.1	w3 x t10	w3 x t10	w12.375, t9.9, d3 (w38, t9.9, d3)	w9.5, t9.5, d3 (w9.5, t19.5, d3)	w8, t15, d4.5, r
Conductor area [mm2]	44.21	52.73		12	11.4	120.24	41.931		574.4	90.17	4	16		90.17	48.3	11.4	63	102.85	102.85	102.85	51.43	51.43		48.93	30	30	115.44 (369.13)	61.98 (156.98)	104.1
Coil dimension (a1,a2,b1,b2)* [mm]									174, 281, 48, 155	174, 281, 48, 155				174, 281, 48, 155	56, 77, 135.33, 200.33			130, 232, 61, 113	130, 232, 61, 113	130, 232, 61, 113								w9.5, t9.5, d3	
No. of coils / magnet	1	2		4	4	2	4		2	4	4	4		4	6	2	2	2	2	2	4	4		2	8	12	2	2	2
Average turn length [mm]	810.53	1825		505.05	173.26	2657.5	685.95		4747.8	1132.7	1510	907.12		728.69	616.4	529.08	453.68	4534.8	5749.4	8192.8	1200	1616		1129.2	384.56	454.56	2525.7	2344.1	919.3
No. of turns / (coil/pole)	H15 x V18	H4 x V6		H6 x V16	H3 x V17 2x(H1 x V3)	H8 x V8	H4 x V8 +3		H4 x V4	H4 x V5	H3 x V14	H1 x V1		H4 x V5	H2, V7	H10 x V25	H28 x V4	H8 x V8	H8 x V8	H8 x V8	50 (2,3,4,5,6,7,8,8,7)	50 (2,3,4,5,6,7,8,8,7)		2 (V2 x H1)	2 (H1 x V4)	H12 x V1	H1 x V2	H2 x V2	8 (V4 x H2)
Current density [A/mm2]	5.65	2.84		1.3542	0.51	2.4	3.1957		5.04	6.97	1.5	5.44		0.03	11.18	1.5	2.74	6.27	6.27	6.31	4.63	4.9		38.62	54.13	54.13	33.71 (10.54)	62.875 (24.86)	7.7
Max. current [A]	250	150		16.25	5.76	288.6	134		2898	628.43	6	87		1.7	540	28.8	57.6	644.9	644.9	648.8	252	252		2515	1623.9	1623.9	3892	3897	1309
Total ampere-turns [A-turn]	67500	7200		6240	1313.28	36940	18760		92736	50274	1008	348		182.52	45360	14400	12902	82544	82544	83040	50400	50400		10060	12991	19487	15570	15588	20944
Max. current ramp [A/s]									5796																				
Resistance / magnet @ 20℃ [mΩ]	83.155	27.912		67.879	58.215	47.52	38.476		4.441	16.88	1065.5	53.34		10.86	18.01	389.85	81.3	94.8	120.2	171.3	78.392	105.57		1.242	1.72	3.05		3.83	2.3738
Inductance / magnet [mH]	3.857	8.74		81.052	0.39	93.723	13.417		11.14	6.42	-	0.0032		10.67	2.395	89.21	13.47	159.02	211.44	313.37	27.452	45.099		0.0255	0.0049	0.0146		2.395	0.0837
Max. voltage [V]	20.789	4.19		4.4121	0.33532	13.72	5.1558		12.87	10.608	6.3927	4.6406		0.0185	9.7254	11.228	4.6829	61.137	77.517	111.14	19.755	26.603		3.1236	2.7931	4.9529		14.926	3.1072
Power dissipation / magnet [kW]	5.1972	0.628		0.0717	0.002	3.9584	0.6909		37.297	6.6663	0.0384	0.4037		3E-05	5.2517	0.323	0.27	39.427	49.991	72.107	4.9782	6.704		7.8559	-	-		58.165	4.0674
Power of magnet * No. of magnet	15.592	1.256		0.5019	0.01	11.875	8.2905		634.05	133.33	0.7671	0.4037		3E-05	26.259	3.23	1.89	275.99	149.97	432.64	224.02	87.152		15.712	-	-		58.165	#REF!
Cooling spec.																													
# of cooling circuit / coil	1	0.5		-	n/a	1	0.5		2	0.5	n/a	n/a		0.5	0.5	1 fin	n/a	2	2	4	1	1		2			2	4	1
Pressure drop [bar]	7	7		-	n/a	7	7		7	7	n/a	n/a		7	7	n/a	n/a	7	7	7	7	7		7			7	7	7
Water flow / cooling circuit [l/min]	3.76	0.79		-	n/a	1.62	0.64		10.6	2.68	n/a	n/a		7.03	2.54	n/a	n/a	6.79	7.89	7.2	0.86	1.0395							
Total water flow rate / magnet [l/min]	3.76	0.79		-	n/a	3.23	1.28		42.4	5.36	n/a	n/a		14.06	7.62	n/a	n/a	27.17	31.58	57.6	3.43	4.158							
Temperature rise [℃]	19.79	2.99		-	n/a	17.55	7.76		12.62	17.85	n/a	n/a		0	9.88	n/a	n/a	20.8	22.68	17.94	19.69	23.105							
Water flow of magnet * No. of magnet	11.28	1.58		-	n/a	9.69	15.36	0	720.8	107.2	n/a	n/a		14.06	38.1	n/a	n/a	190.19	94.74	345.6	154.35	54.054	0						

Magnet Power Supplies

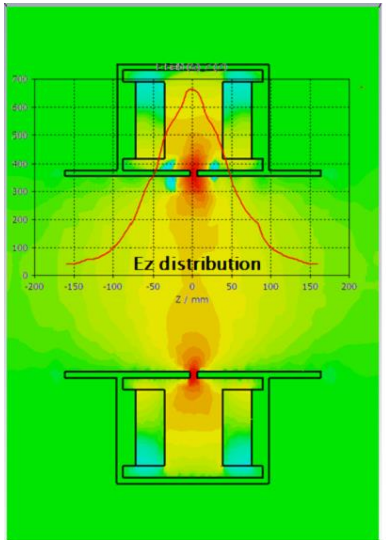
Specifications of Power Supplies (1)

Group	Index	Type	Quantity	Current I_nom [A]	Voltage V_nom [V]	Voltage V_ ramp [V]	Accuracy ± stability [ppm]	Accuracy accuracy (linearity) ± [ppm]	Accuracy ripple ± [ppm]	Accuracy reproducibility ±[ppm]	Accuracy Tracking /overshoot ±[ppm]	Accuracy resolution ±[ppm]	Power [kW]	Effi. Air (85%), Water (95%)	Power Factor	Input [kVA]
A	1	LEBT - Solenoid	3	275	± 30	na	100	100	100	50	100	100	8.3	0.85	0.95	10.2

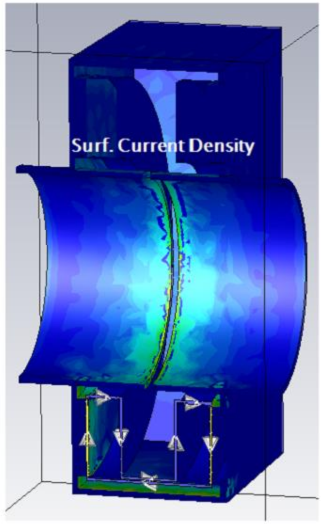
Specifications of Power Supplies (2)

Group	Index	Type	Quantity	Current I_nom [A]	Voltage V_nom [V]	Voltage V_ ramp [V]	Accuracy ± stability [ppm]	Accuracy accuracy (linearity) ± [ppm]	Accuracy ripple ± [ppm]	Accuracy reproducibility ±[ppm]	Accuracy Tracking /overshoot ±[ppm]	Accuracy resolution ±[ppm]	Power [kW]	Effi. Air (85%), Water (95%)	Power Factor	Input [kVA]
C	13	SR - Sextupole_F/D	2	± 595	± 40	na	100	100	100	50	100	100	23.8	0.95	0.95	26.4
C	14	SR- Sextupole_R	1	± 595	± 30	120	100	100	100	50	100	100	71.4	0.95	0.95	79.1
C	15	SR-Hor. Corrector (10) SR-Ver. Corrector (7)	17	± 65	± 50	na	1000	250	250	500	250	1000	3.3	0.85	0.95	4.0
D	16	HEBT - Dipole_22.5 A	4	715	± 150	650	25	25	25	12.5	25	25	148.1	0.95	0.95	164.1
D	17	HEBT-Dipole_30B (1) HEBT-Dipole_45D (1)	2	715	± 270	1250	25	25	25	12.5	25	25	295.3	0.95	0.95	327.2
D	18	HEBT-Dipole_45C	1	715	± 500	2400	25	25	25	12.5	25	25	583.6	0.95	0.95	646.6
D	19	HEBT-Quadrupole_S (45) HEBT-Quadrupole_L (13)	58	280	± 70	na	50	25	50	25	50	50	19.6	0.85	0.95	24.3
D	20	HEBT-Corrector	34	± 150	± 30	na	500	250	250	500	250	1000	4.5	0.85	0.95	5.6
E	21	SR-InjectionSeptum	1	2770	± 40	na	100	50	100	50	100	100	110.8	0.95	0.95	122.8
E	22	SR - Injection Bumper	1	1790	± 150	2000	100	50	100	50	100	100	268.5	0.95	0.95	297.5
E	23	SR-DumpBumper	1	1790	± 40	2000	100	50	100	50	100	100	71.6	0.95	0.95	79.3
E	24	SR - Ext. Septum_thin	1	4290	± TBD	TBD	100	50	100	50	100	100	TBD	TBD	TBD	TBD
E	25	SR - Ext. Septum_thick	1	4290	± 50	na	100	50	100	50	100	100	214.5	0.95	0.95	237.7
E	26	HEBT - Chopper bumper	1	1450	± 30	2500	100	50	100	50	100	100	357.1	0.95	0.95	395.7

RF Cavity

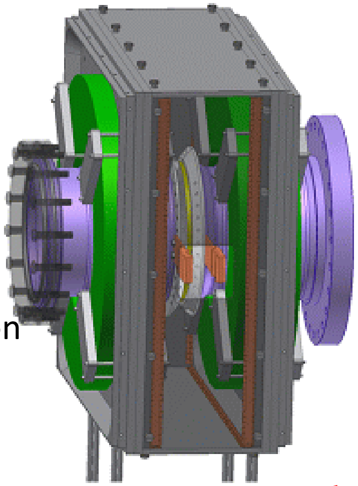


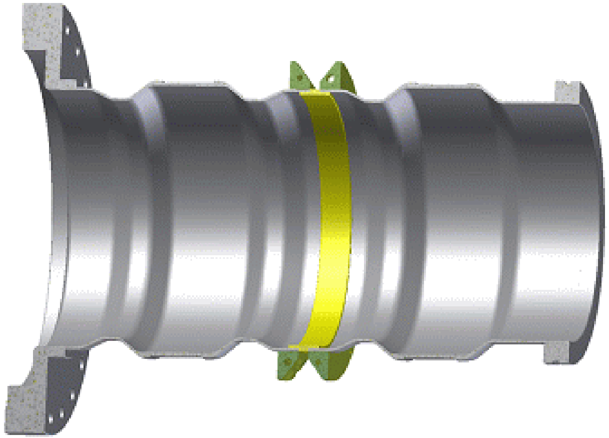
Electric Field Distribution



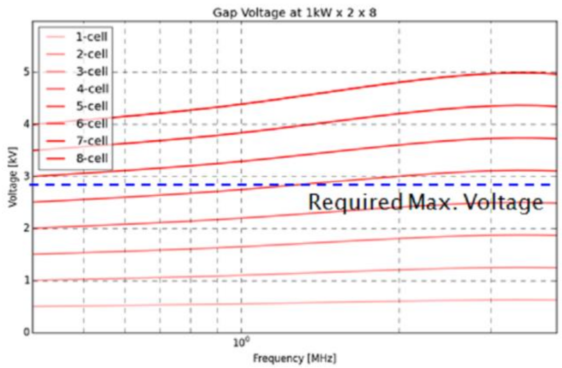
Surface Current Distribution

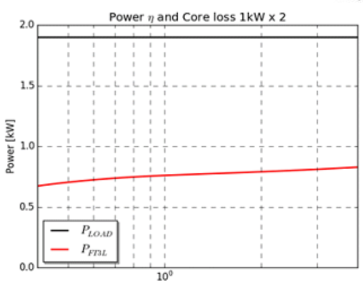
FINEMET samples from KEK

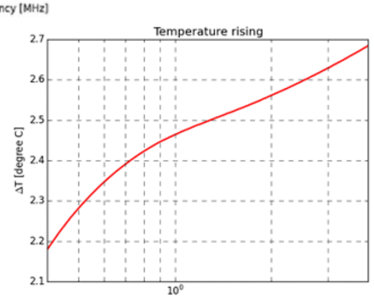




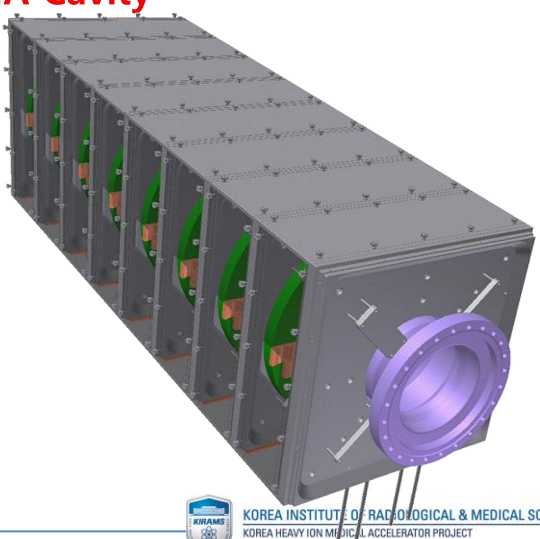
1-cell MA Cavity



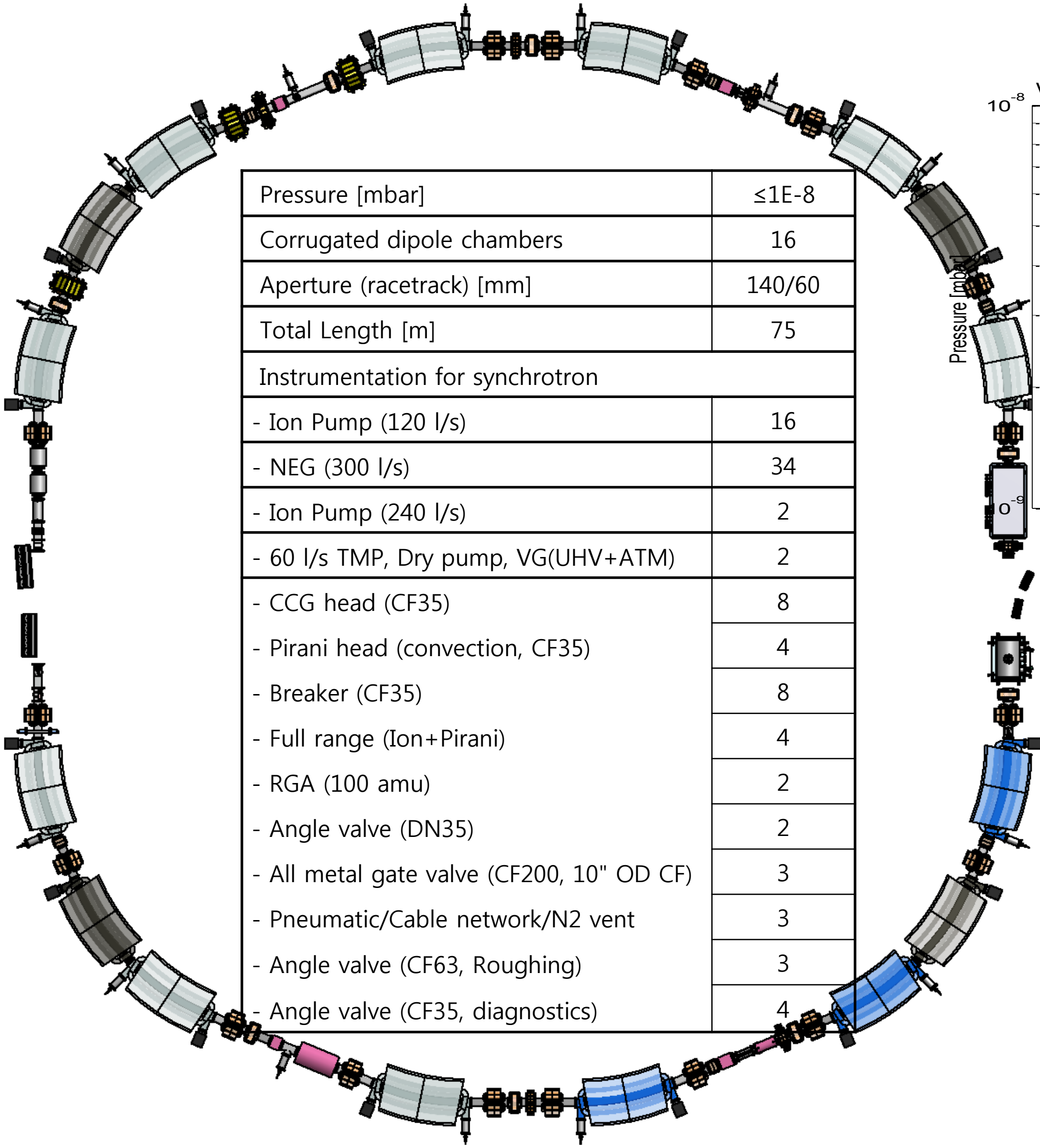




8-Cell MA Cavity

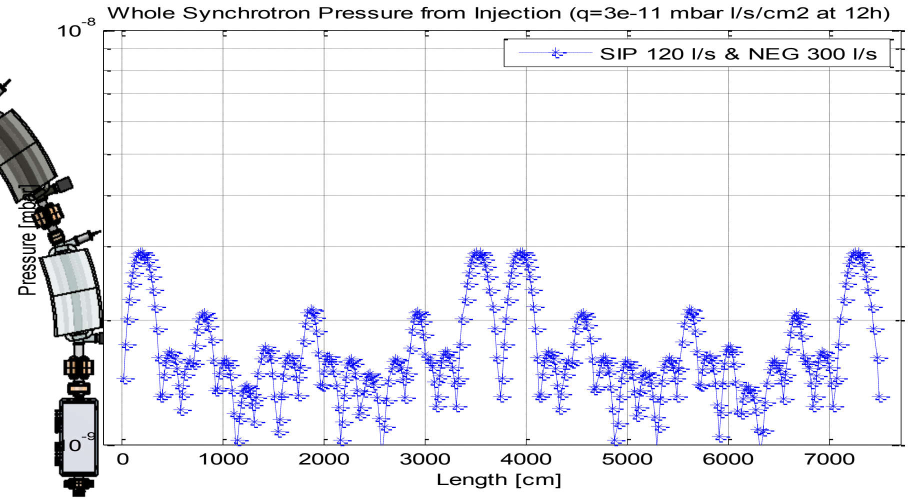


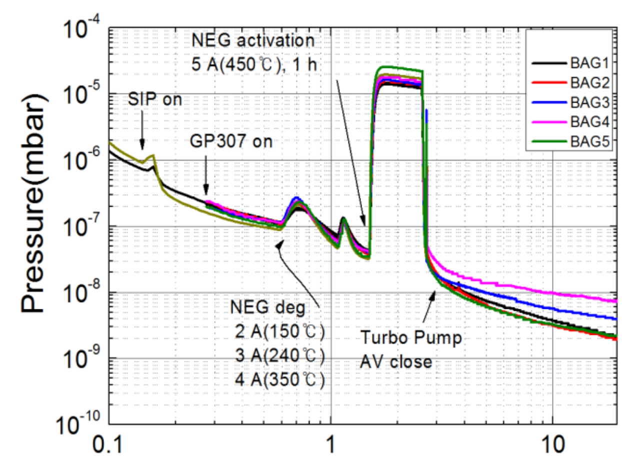
Vacuum System



Pressure [mbar]	≤1E-8
Corrugated dipole chambers	16
Aperture (racetrack) [mm]	140/60
Total Length [m]	75
Instrumentation for synchrotron	
- Ion Pump (120 l/s)	16
- NEG (300 l/s)	34
- Ion Pump (240 l/s)	2
- 60 l/s TMP, Dry pump, VG(UHV+ATM)	2
- CCG head (CF35)	8
- Pirani head (convection, CF35)	4
- Breaker (CF35)	8
- Full range (Ion+Pirani)	4
- RGA (100 amu)	2
- Angle valve (DN35)	2
- All metal gate valve (CF200, 10" OD CF)	3
- Pneumatic/Cable network/N2 vent	3
- Angle valve (CF63, Roughing)	3
- Angle valve (CF35, diagnostics)	4

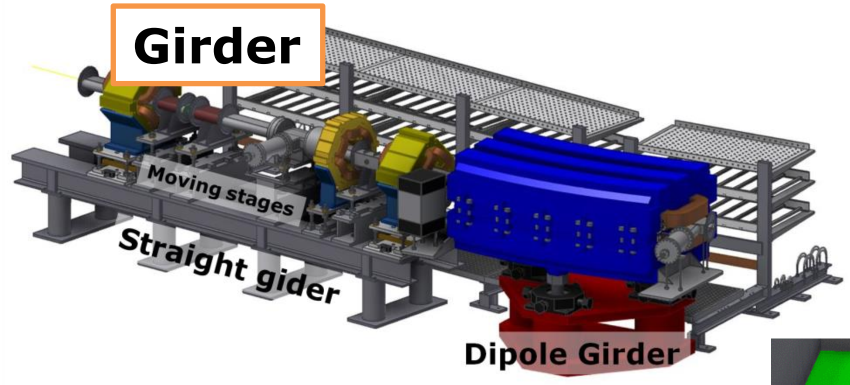
Simulated Pressure distribution





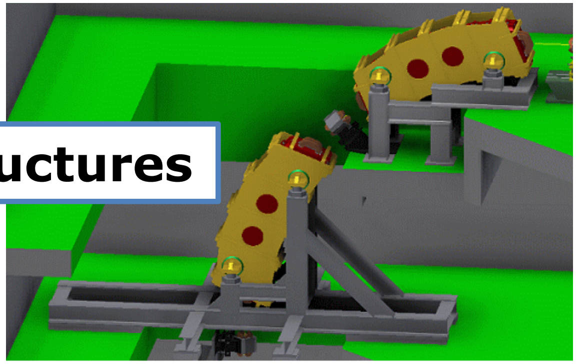
1/16 Vacuum System Model Test Results

Girders & Support Structures

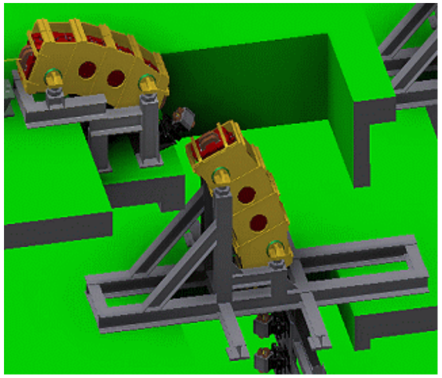


Support structures

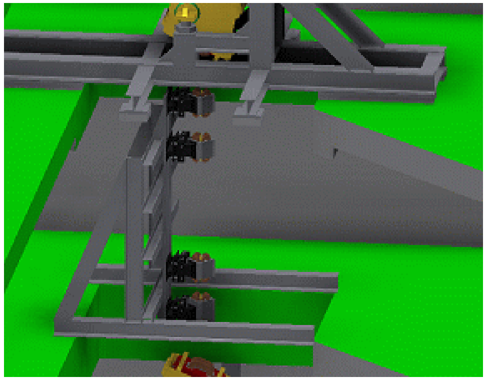
90° vertical rising



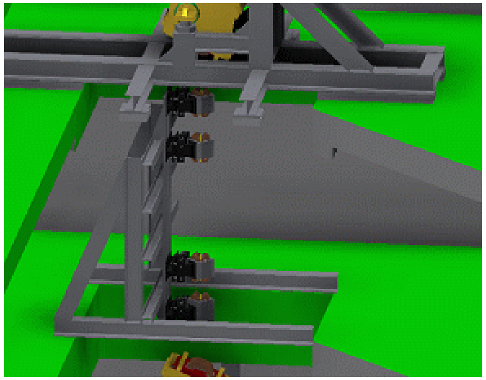
90° vertical landing



90° vertical falling

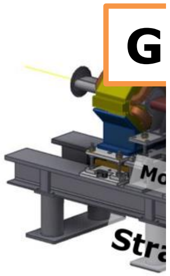


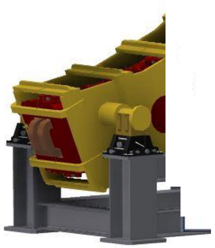
90° vertical up

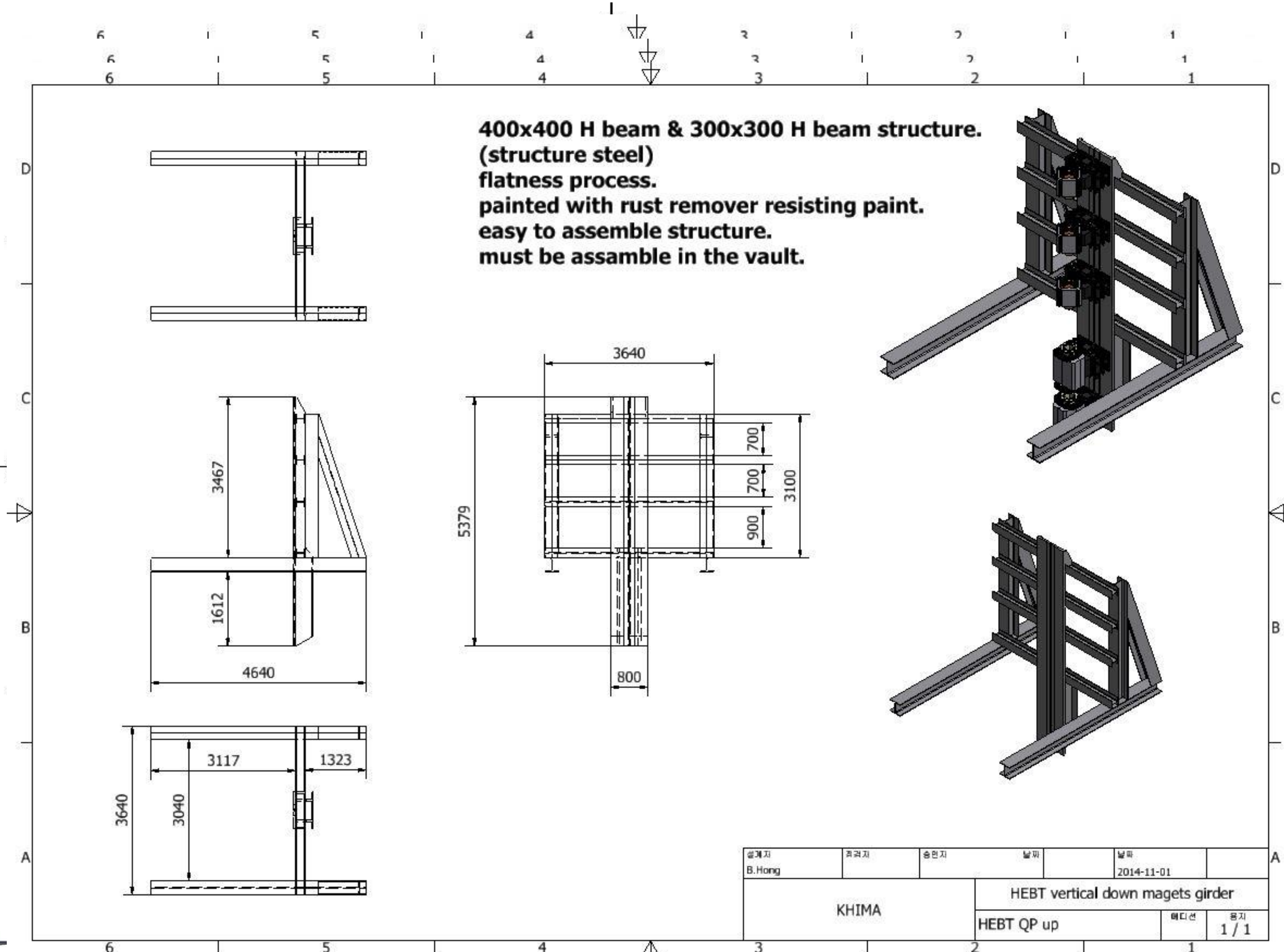


90° vertical down

Girders & Support Structures





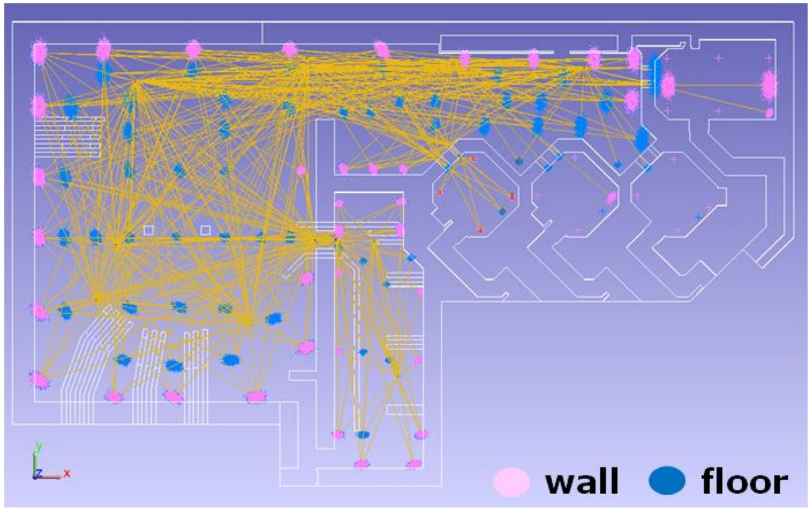


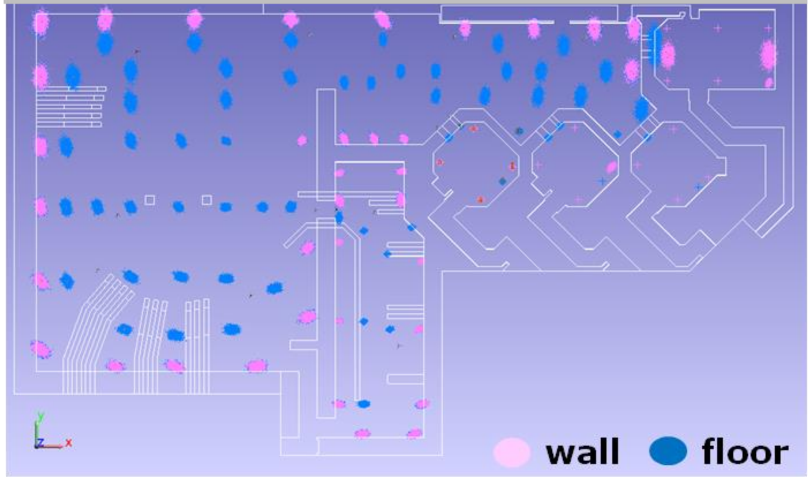
90° vertical rising　　90° vertical up　　90° vertical down

Survey & Alignment (SA)

Survey network

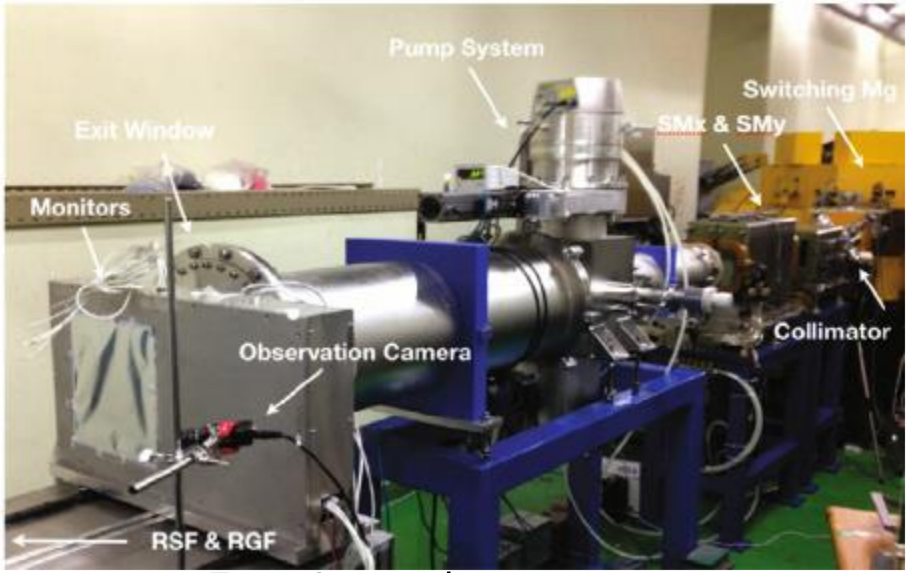
Control point error analysis



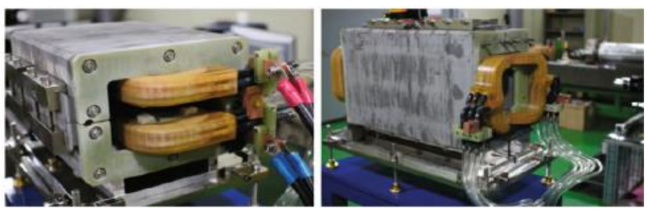


Survey Network Uncertainty (RMS)
0.059 mm, Avg. 0.040 mm

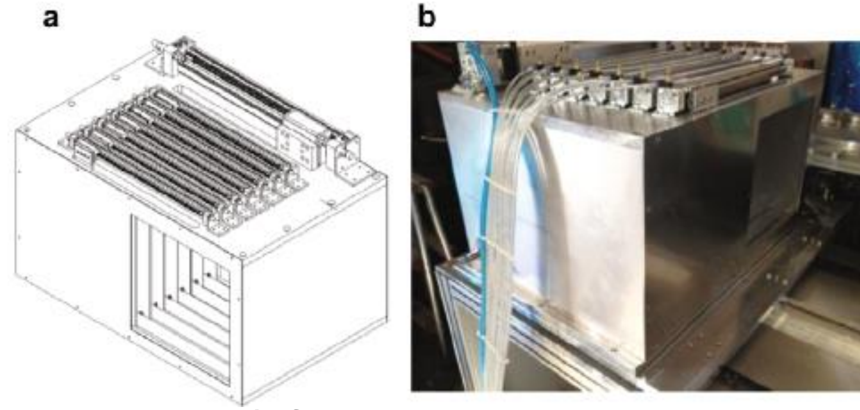
Irradiation System



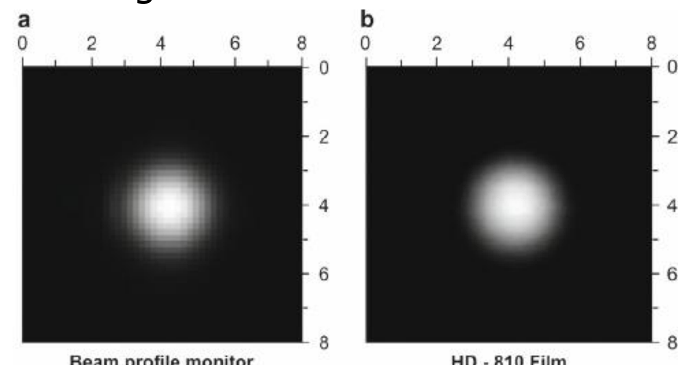
Experimental setup


Scanning magnet


Beam profile monitor



Range shifter



Beam spot image at profile monitor


Beam scanned image on a Gaf film

Summary

- The accelerator for KHIMA was changed to a synchrotron from a superconducting cyclotron since May 2014.
- Technical Design Report (TDR) was published in early 2015.
- Measured beam intensity of ECR ion source is more than targeting current.
- A bidding process for the injector was completed.
- Instruments for diagnostics are under performance test.
- A prototype of active scanning system was developed and evaluated the performance to give a reasonable result.
- Most of the accelerator components including magnets, power supply and vacuum system are currently under procurement process.

Thank you for your attention!