SRF in Heavy Ion Projects

Dong-O Jeon
Representing RAON
Institute for Basic Science

기초과학연구원
Institute for Basic Science

Acknowledgement

- Thanks go to Y. Chi (IEHP) and P. Ostroumov for providing slides about C-ADS and ATLAS Upgrade.

Design considerations

- SC linacs are built to accelerate high intensity beams.
- Solenoids and cavities in cryomodule move more than 1 mm during cool down.

- Pros & Cons of SC solenoid option (C-ADS, ATLAS Upgrade, FRIB, SARAF etc)
  - Less warm-to-cold transitions
  - Alignment control of SC solenoids is challenging
  - SC solenoid needs current leads that increase cryogenic load and cost

- Pros & Cons of NC quadrupole option (SPIRAL2, RAON)
  - Alignment of NC quadrupoles is straightforward
  - NC quadrupole and PS are cheaper
  - More warm-to-cold transition

Design considerations

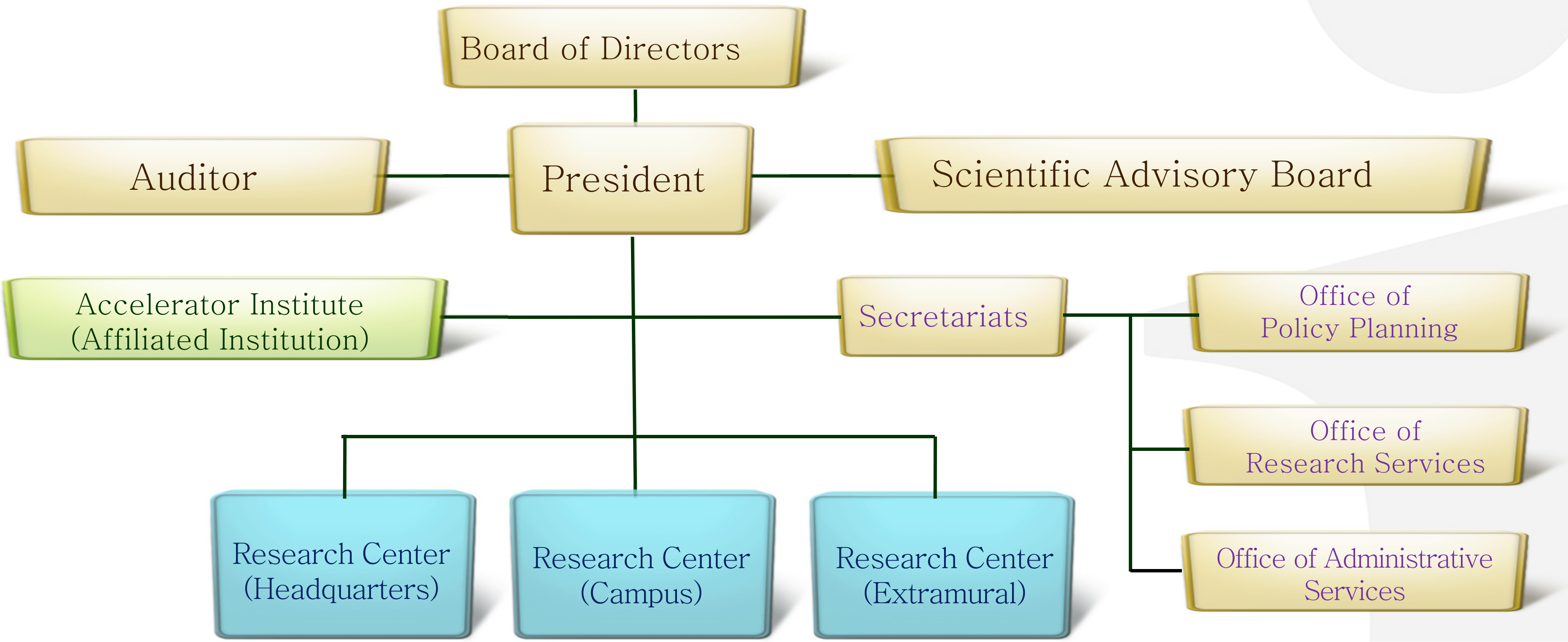
- High cavity field
  - Both EP and BCP can produce high fields
  - EP is considered slightly more effective (more expensive)
  - ANL implemented EP for low beta cavities
  - Upstream part of SCL can not use cavity field fully due to space charge resonances ($\mu < 90^o$)

RAON

RAON

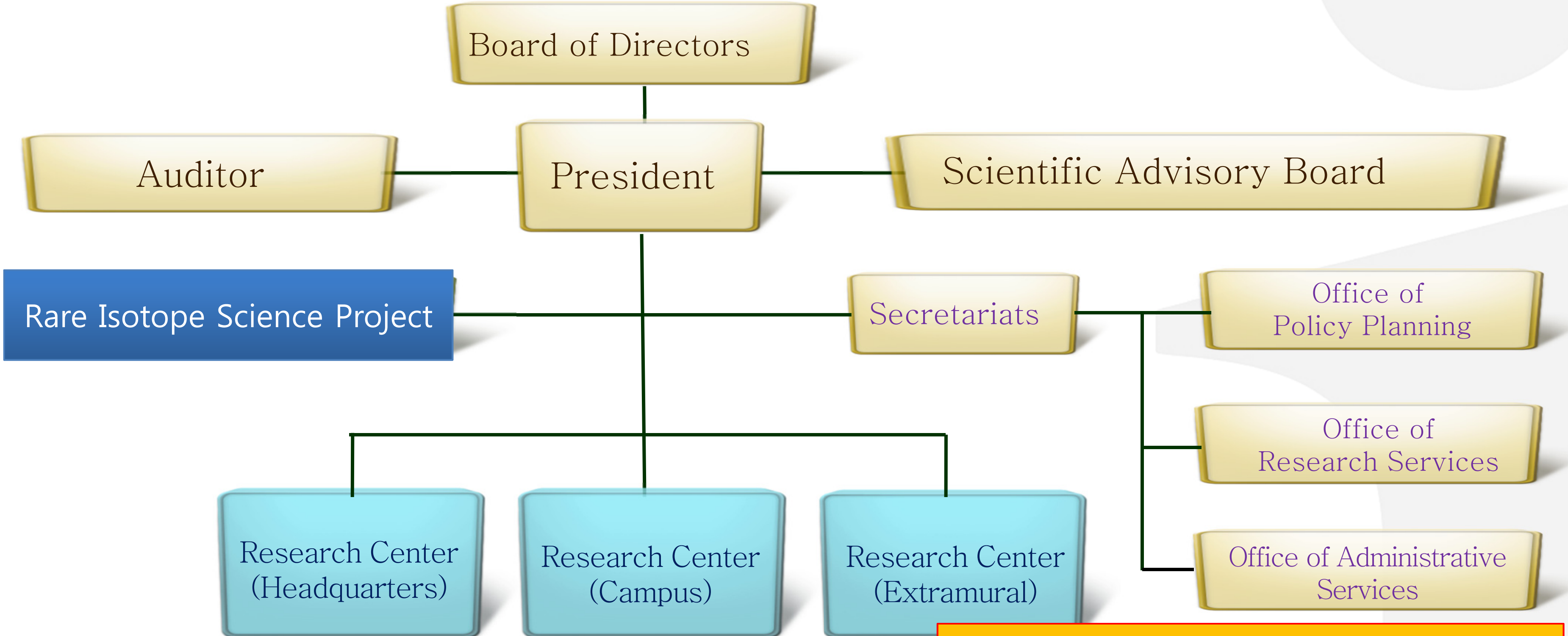
- Name of the Heavy Ion Accelerator in Korea.
- Pure Korean word meaning delightful or happy.
- Reflecting the wish that this Heavy Ion Accelerator would be a delightful gift for scientists all over the world.
- RAON is a core facility of Institute for Basic Science.

Institute for Basic Science (Korea)



- IBS consists of 50 research centers, supporting organizations, and affiliated research institutes
- Each Research Center : ~50 staff, average annual budget ~ 9 M USD
- The number of staff: 3,000 (2017, including visiting scientists and students)
- Annual Budget: USD 610 million (2017, including operational cost for the Accelerator Institute)

Institute for Basic Science (Korea)



16 centers were selected so far !

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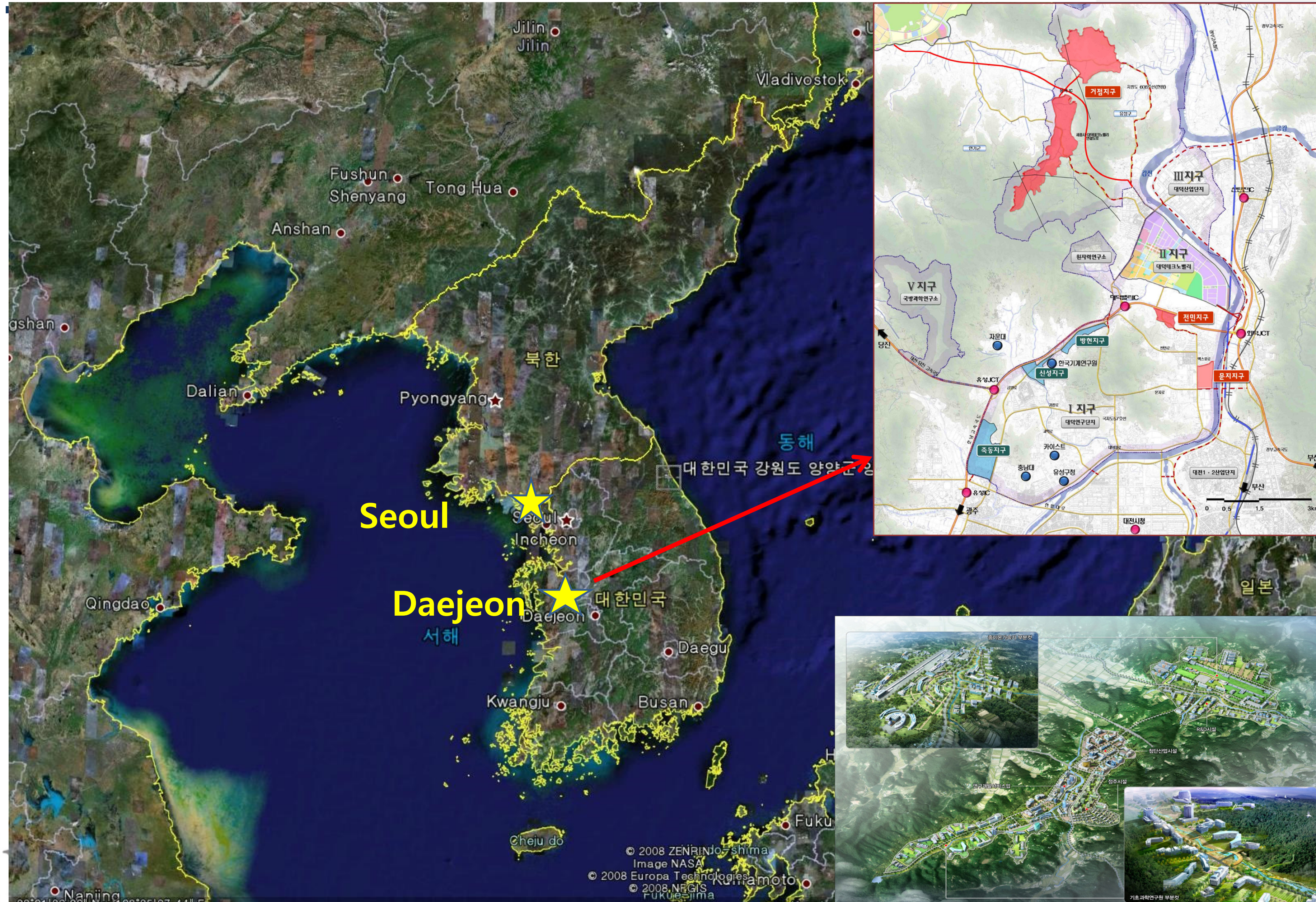
RAON Site


Jilin
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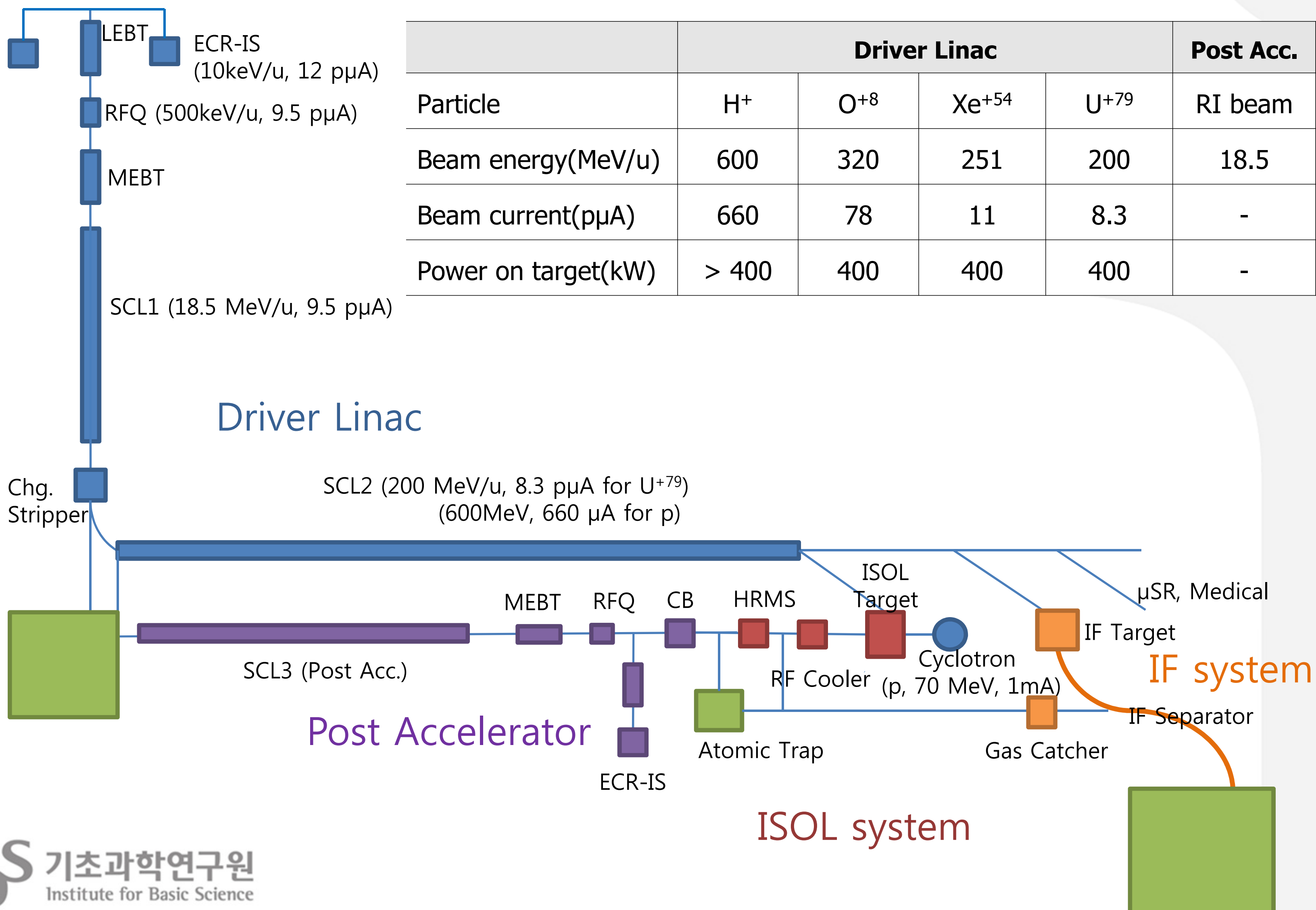
신탄진IC
I 지구
대덕연구단지
죽동지구
카이스트
충남대
유성구청
대전1 · 2산업단지
유성IC
대전시청
당진
광주
부산
0 0.5 1.5 3km

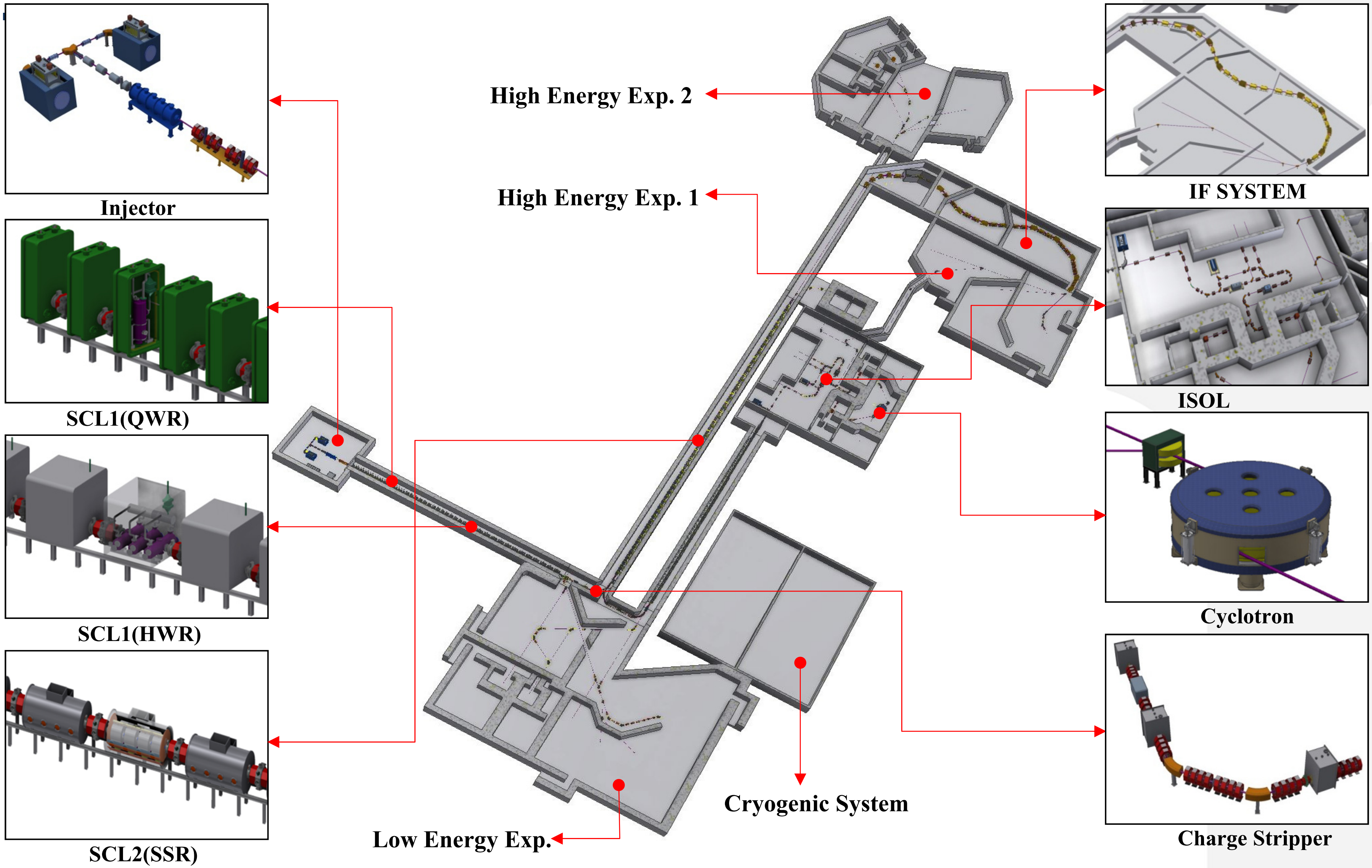
RAON Facility

Beam Parameters of RAON

	Driver Linac				Post Acc.	Cyclotron
Particle	H^+	O^{+8}	Xe^{+54}	U^{+79}	RI beam	proton
Beam energy(MeV/u)	600	320	251	200	18.5	70
Beam current(pμA)	660	78	11	8.3	-	1000
Power on target(kW)	> 400	400	400	400	-	70



RAON Layout

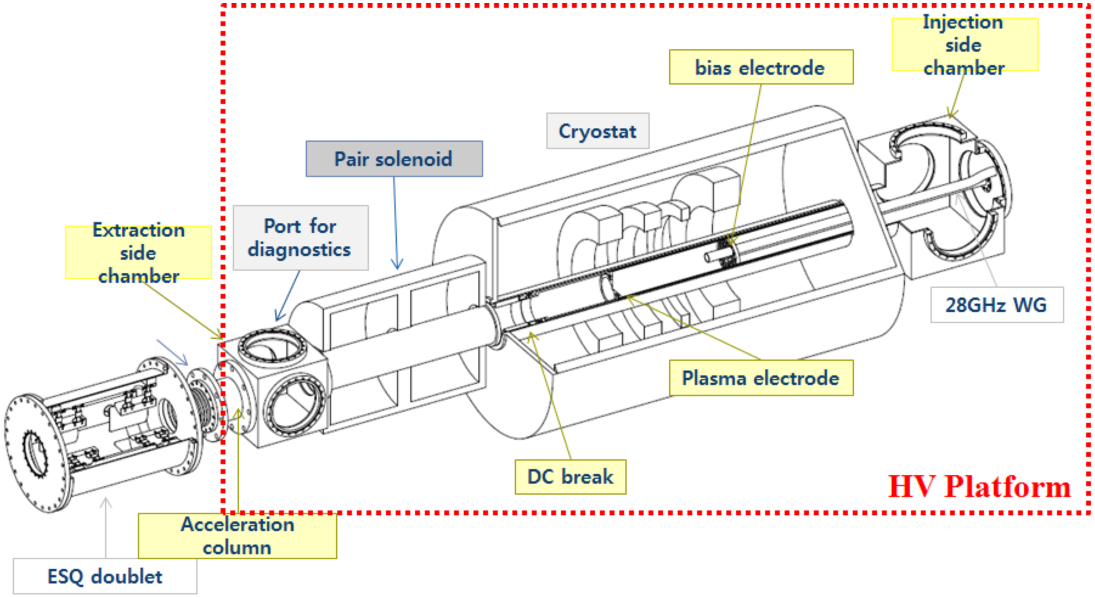


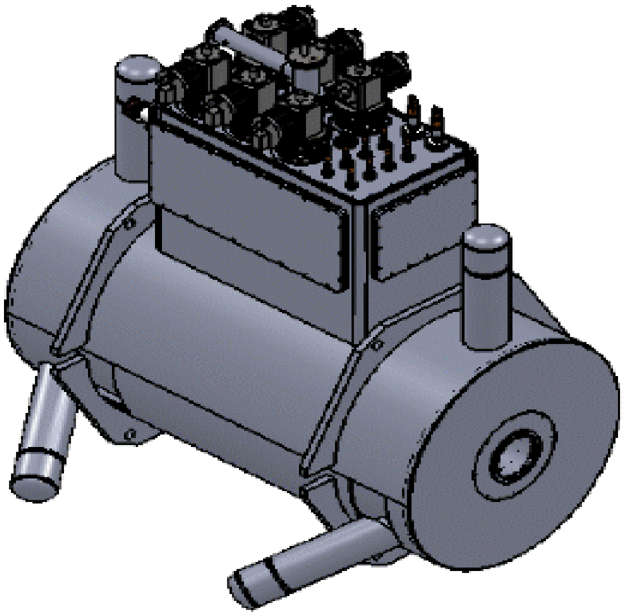
ibs 기초과학연구원 Institute for Basic Science

RISP

Superconducting ECR Ion Source

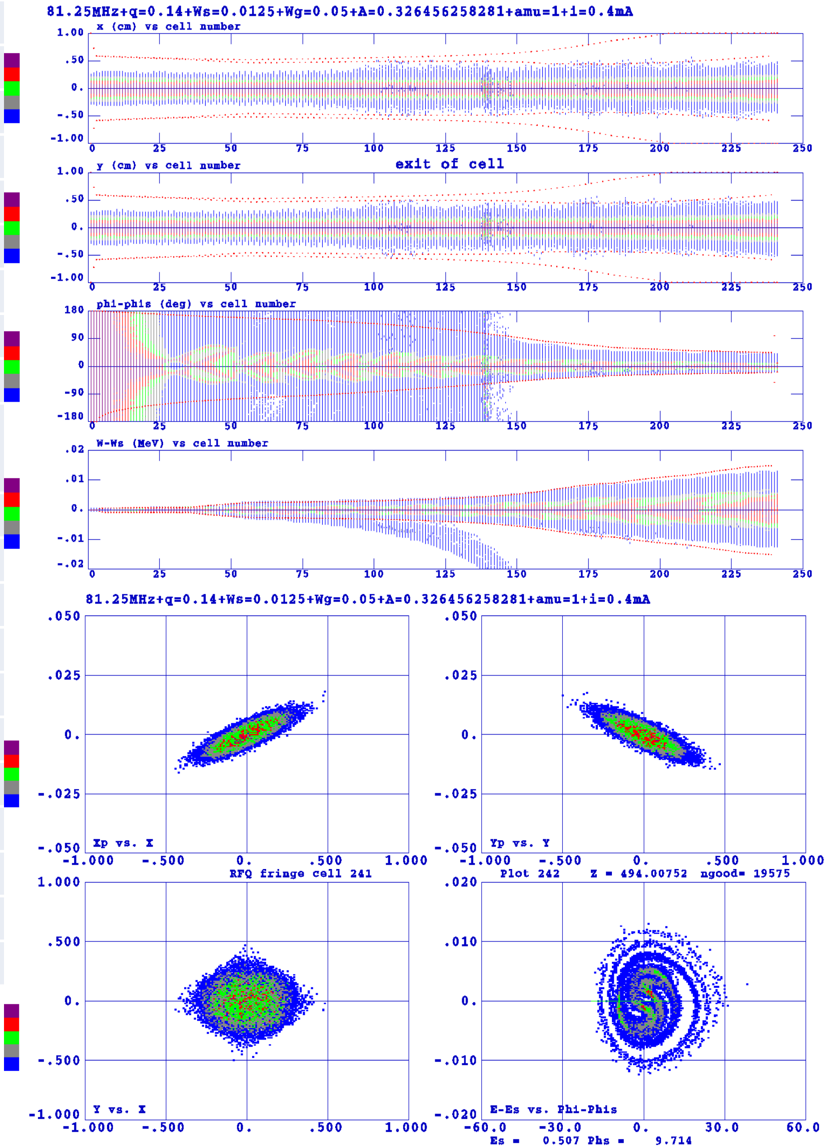
- **Prototype sextupole tested achieving 120% of design (2013.03)**
- **With reinforcing structure, achieved 150% of design (2013.08)**



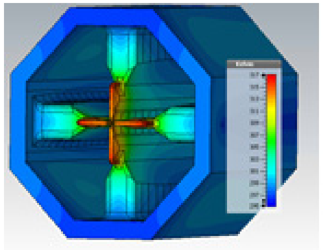


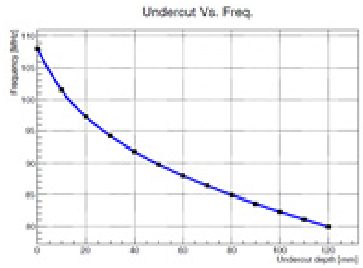
500 keV/u RFQ design parameters

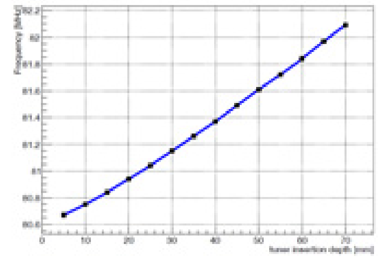
PARAMETER	VALUE
Beam Properties:	
Frequency	81.250 MHz
Particle	H^{+1} to $U_{238}{}^{+33}$
Input Energy	10 keV/u
Input Current	0.4 mA
Input Emittance: transverse (rms, norm)	0.012 .cm. mrad
Output Energy	0.507 MeV/u
Output Current for 0.4mA in.	~0.39 mA
Output Emittance: transverse (rms, norm) longitudinal (rms)	0.0125 .cm. mrad ~26 keV/u-Degree
Transmission	~98 %
Structures and RF:	
Peak surface Field	1.70 Kilpatrick
Structure Power (for $U_{238}{}^{+33}$)	92.4 kW
Beam Power (for 0.2mA each $U_{238}{}^{+33\&+34}$)	1.44 kW
Total Power	94 kW
Duty Factor	100%
RF Feed	1 Drive loops
Mechanical:	
Length	4.94 meter
Operating Temperature	TBD Degree C

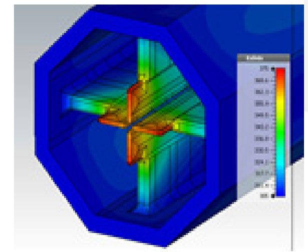


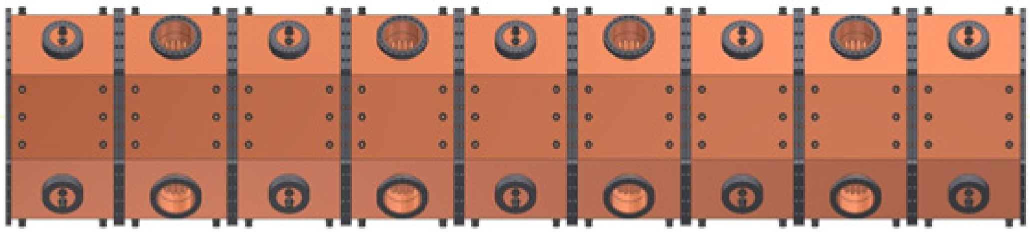
RFQ Engineering Design

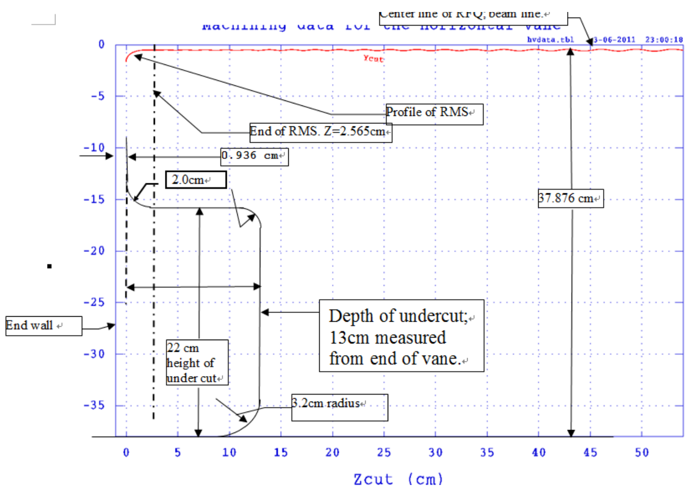




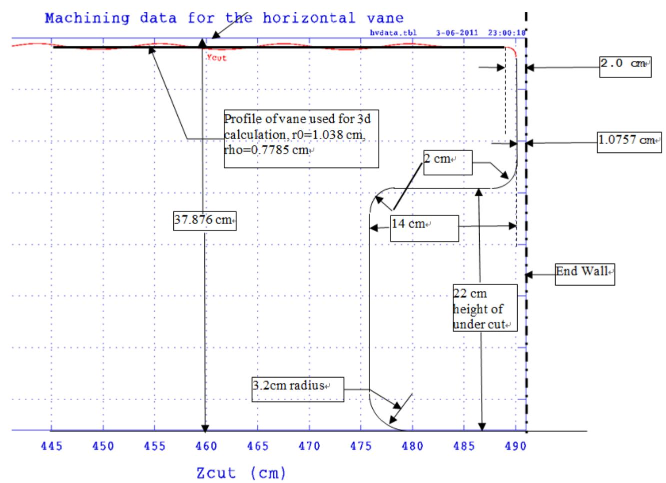








Low energy end



High energy end

RAON Superconducting Linac

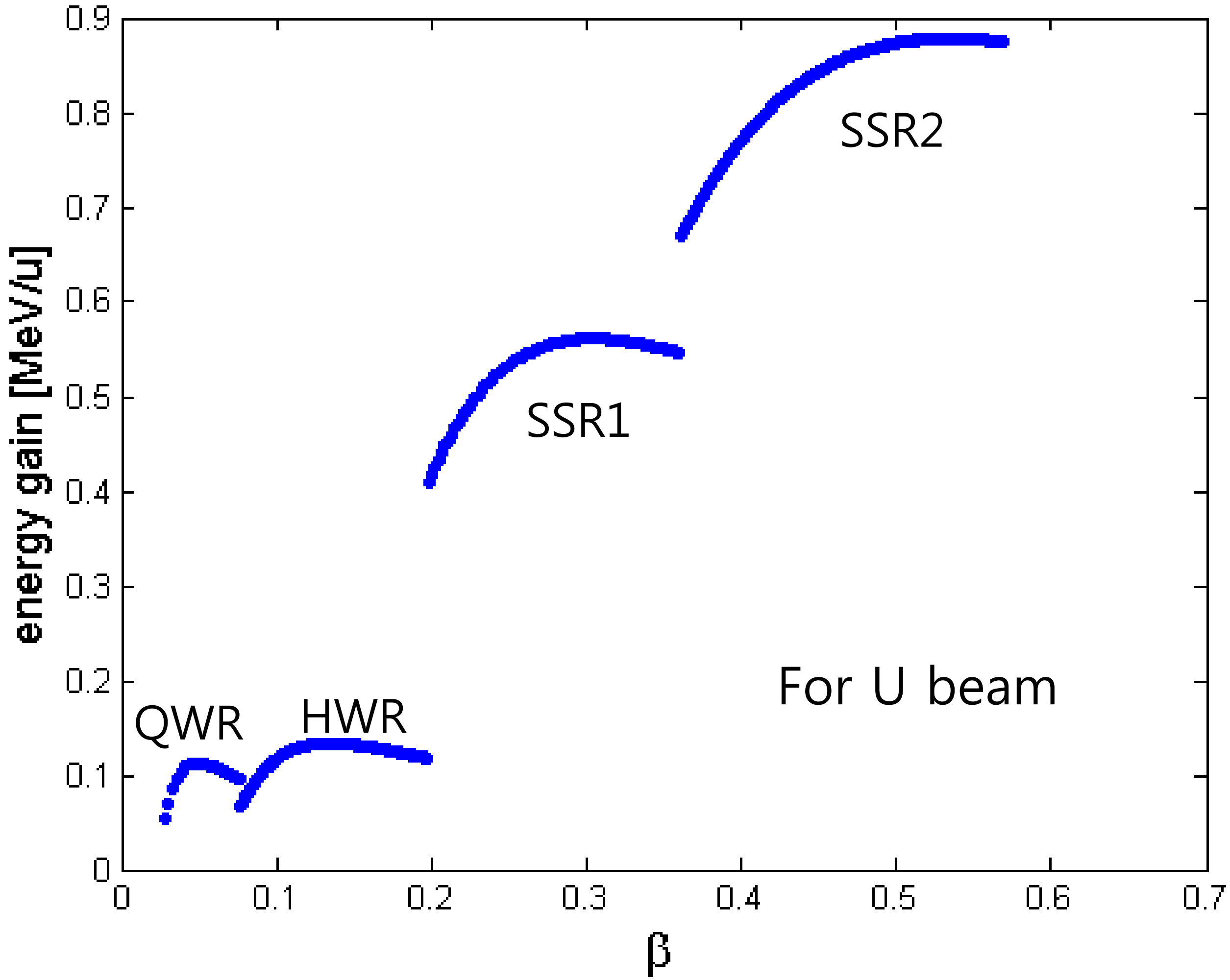
- RAON SCL is designed to accelerate high intensity beams.
- Focusing by NC quad doublets rather than SC solenoids.
- Optimized geometric beta of SC cavities (0.047, 0.12, 0.30, 0.51).
- Employs larger aperture to reduce beam loss (40 mm and 50 mm aperture).
- Cavity geometry optimized for E_{peak}/E_{acc} , B_{peak}/E_{acc} , R/Q, $QR_{s.}$
- Prototyping of SC cavities and cryomodules is under way presently.

SCL Layout

NC quadrupole lattice option has the following merits:

1. Accurate alignment < ±150 um of NC quadrupoles is straightforward.
2. Beam quality control is straightforward and adequate for high power beam operation.
3. Advantages in beam diagnostics and collimation through beam boxes.
4. The linac cost estimation is comparable to the SC solenoid option. (← costly SC solenoids and current leads)
5. Detailed cryo-load comparison suggests that overall cryo-load is comparable to SC solenoid option.

Cavity Geometric Beta Optimization



RISP: 0.047, 0.120, 0.30, 0.51

Superconducting cavity

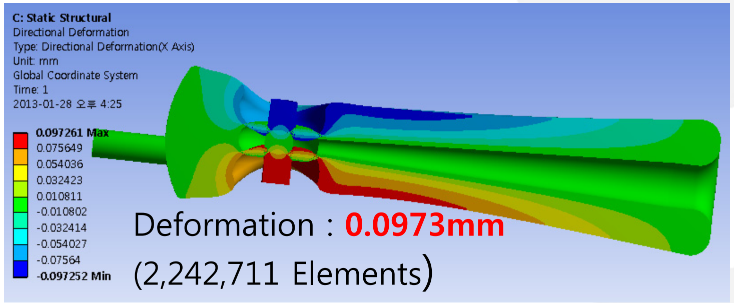
Parameters	Unit	QWR	HWR	SSR1	SSR2
β_g	-	0.047	0.12	0.30	0.51
F	MHz	81.25	162.5	325	325
Aperture	mm	40	40	50	50
QR_s	Ohm	21	42	94	112
R/Q	Ohm	468	310	246	296
V_{acc}	MV	1.05	1.52	2.22	4.20
E_{peak}/E_{acc}		5.6	5.0	4.4	3.9
B_{peak}/E_{acc}		9.3	8.2	6.3	7.2
$Q_{calc}/10^9$	-	2.1	4.1	9.2	10.5
Temp.	K	2	2	2	2

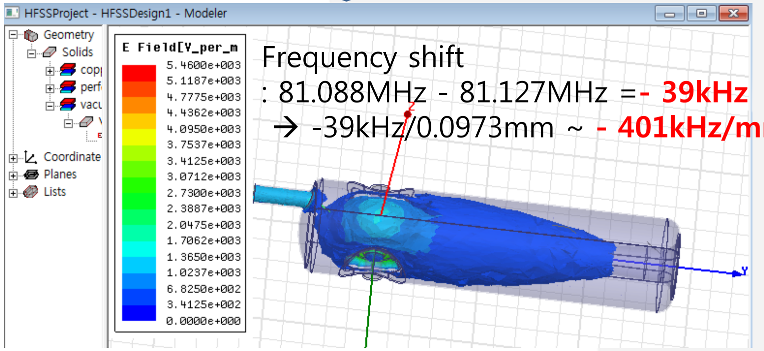
(Ep = 35MV/m)

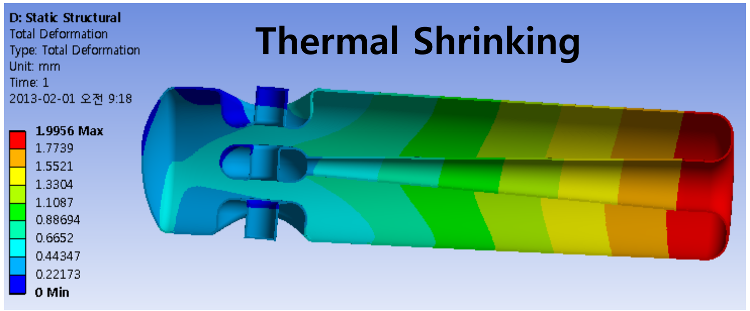
Frequency shift in QWR

Frequency shift	Naked QWR
Resonant Frequency	81.25MHz
Cavity length(upper)	-67.1kHz/mm
Cavity length(lower)	+1.3kHz/mm
Welding (0.58mm shrink)	+38.2kHz
EP/BCP (125um base, 187um @ DT & Nose)	+267kHz
External pressure (Vacuum, L-He)	-4.6Hz/mbar
Cool down(293K→2K)	+203kHz
Lorentz Detuning	-1.7Hz/(MV/m)^2

Pressure

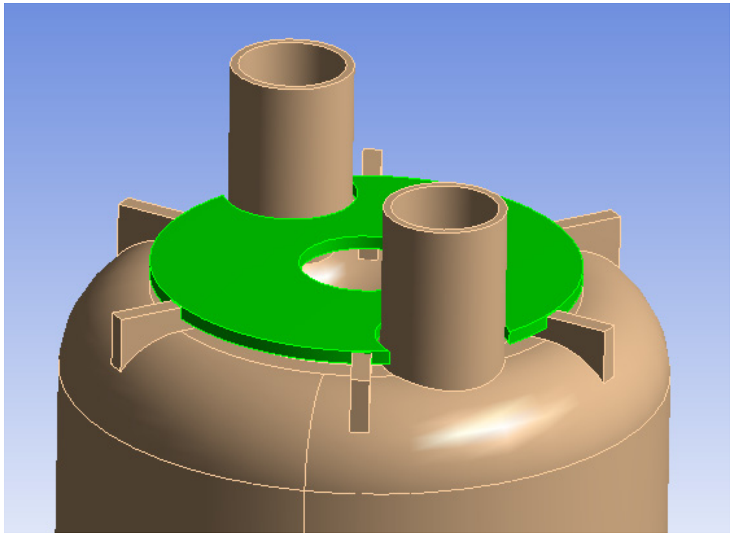






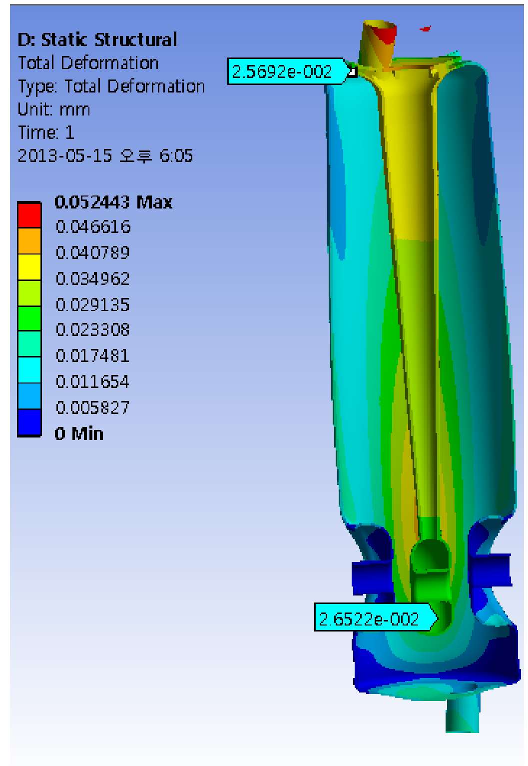
Max. Deformation : **1.996mm**
(840,437 Elements)
→ Frequency shift
: 81.330MHz - 81.127MHz = **+ 203kHz**

Stiffening Analysis

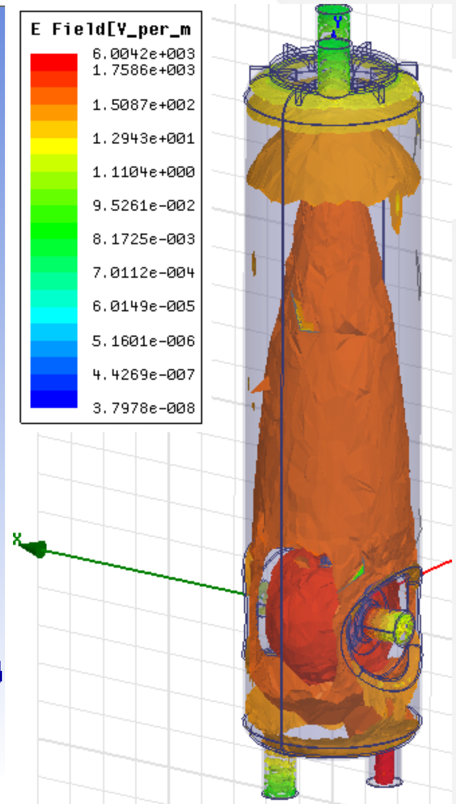


Parameters	Value
Outer diameter of disk	160 mm
Inner diameter of disk	50 mm
Thickness of disk	5 mm
Number of gussets	6
Outer diameter of gussets	210 mm
Inner diameter of gussets	94 mm
Thickness of gussets	7 mm

Deformed shape

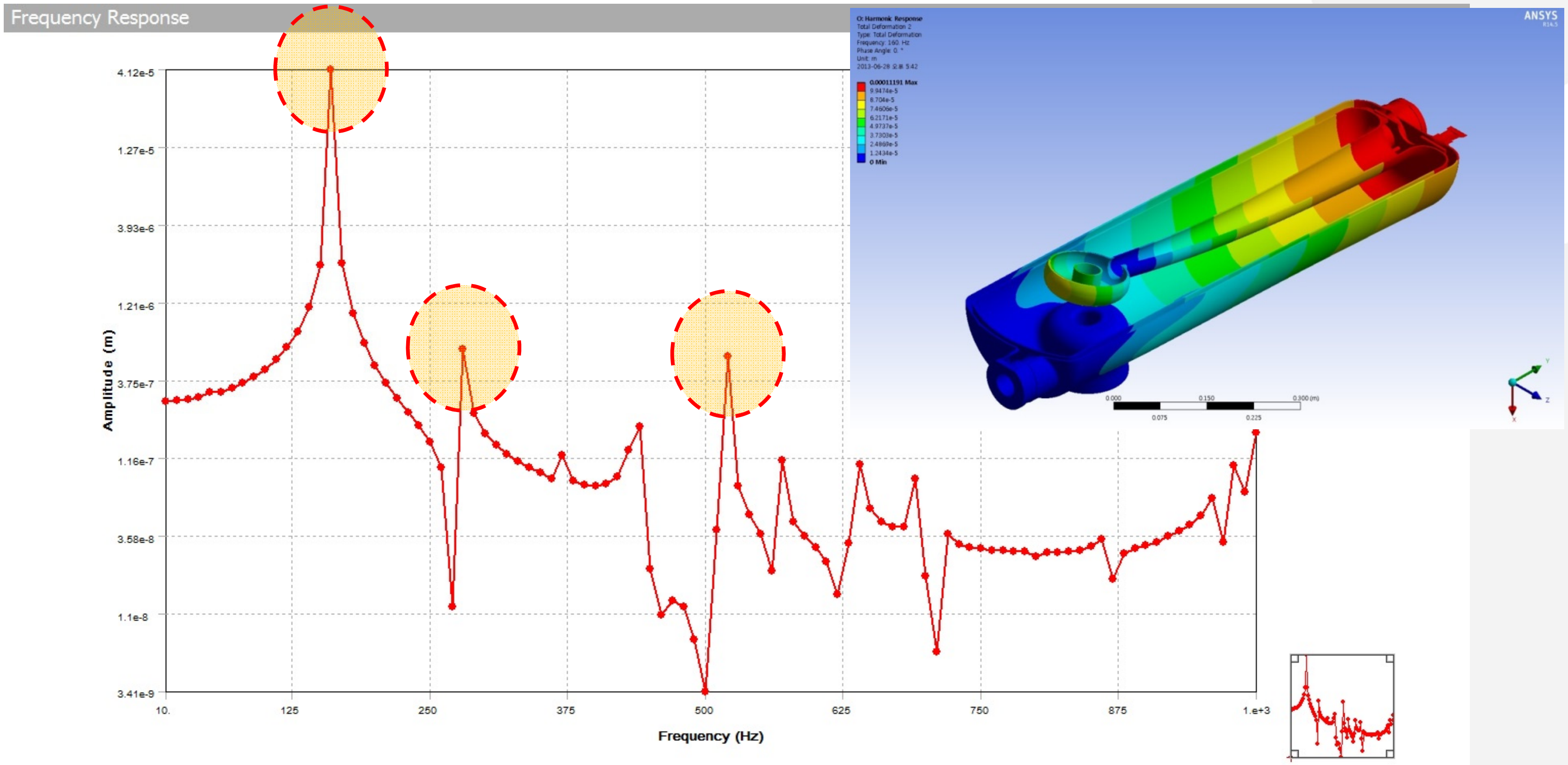


Deformed shape



-0.6Hz/mbar (with stiffener)

Modal Analysis – Cavity Assembly

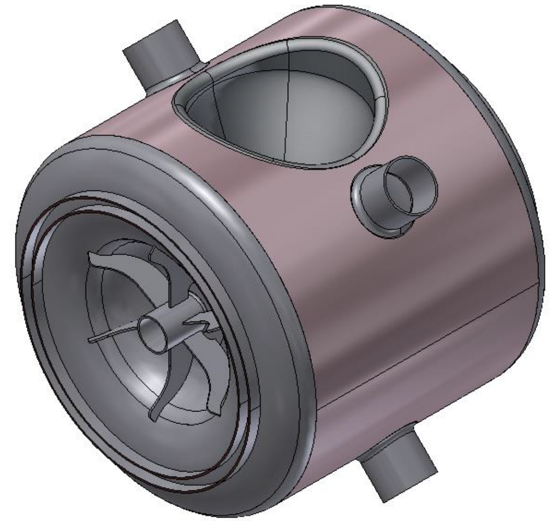


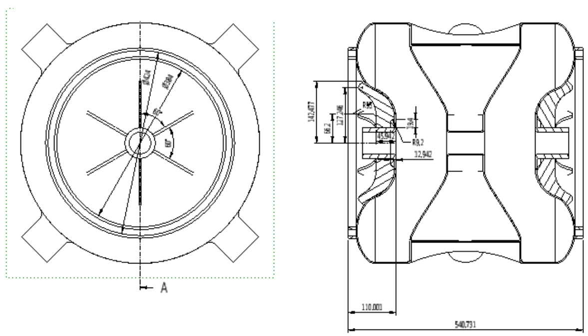
Bode Plot

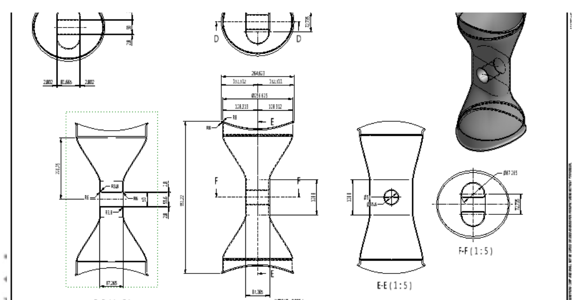
– Boundary Conditions: beam port flange fix

– Main peak : 160Hz(side & core 1st bending), 280Hz(core 2nd bending)

Cavity Prototyping is under way







	항목	진공부피 연관유무	IBS REF. DIM	IBS 소숫점첫째자리	화학세정	SFA SFA 제작(금형) 도면 DIM
	Beam pass in dia(Ø)	O	50	5	0.15	49.7
	Beam pass out dia(Ø)	X	55.6		0.15	55.7
	Beam pass 두께	X	2.8		0.15	3
	Beam pass 내경쪽 R	O	6		0.15	6.15
	Beam pass 외경쪽 R	X	3.8		0.15	3.15
	Beam pass welding dia(Ø)	X	67.368		0.15	63
	Spoke slot width(beam length)	O	87.265	87.	0.15	87.5
	Spoke slot length	O	160	16	0.15	160.3
	Spoke slot center	O	72.735	72.		72.8
	Spoke slot height	O	128.8	128.		128.8
	Spoke pot height	O	220.75	220.		220.8
	Spoke pot out dia(Ø)	O	256.625	256.	0.15	256.9
	Spoke pot R	O	8		0.15	8.3
	Spoke pot R(외경)	O	8			11.3
	Spoke pot welding dia(Ø)	X	264.623	273.	0.15	286
	Spoke beam pass welding dia(Ø)	X			0.15	63
	챔버내경(Ø)	O	545.62	545.	0.15	545.3
	챔버외경(Ø)	X	551.22		0.15	551.3
	챔버두께	X	272.81		0.15	3
	챔버폭	O	414.946	414.	0.15	414.9
	챔버 Spoke pot welding dia(Ø)	X	264.623		0.15	286
	챔버 진공포트 welding dia(Ø)	X			0.15	102
	진공포트 내경(Ø)	O	76.9	76.	0.15	76.6
	진공포트 외경(Ø)	X	(82.5)	82.	0.15	82.6
	진공포트 두께	X	(2.8)	2.	0.15	3
	진공포트 내경쪽 R	O	12.2	12.	0.15	12.35
	진공포트 외경쪽 R	O	(15)	14.		9.35
	진공포트 welding dia(Ø)	X	(106.693)	101.	0.15	102
	진공포트 Length	O	345	34		345
	빔포트 내경(Ø)	O	50	5	0.15	49.7
	빔포트 외경(Ø)	X	(70)		0.15	55.7
	빔포트 두께	X	10			3
	빔포트 내경쪽 R	O	6		0.15	6.15
	빔포트 외경쪽 R	X	3.8		0.15	3.15
	빔포트 welding dia(Ø)	X			0.15	63
	빔포트 Length	O	78.001	7		78
	STIFFNESS RING 1 내경(Ø)	X	384	38	0.15	383.7
	STIFFNESS RING 1 외경(Ø)	X	(396)		0.15	389.7
	STIFFNESS RING 1 두께	X	6		0.15	3
	STIFFNESS RING 1 폭	X	110	11	0.15	110.15
	STIFFNESS RING 2 내경(Ø)	X	424	42	0.15	423.7
	STIFFNESS RING 2 외경(Ø)	X	(436)		0.15	429.7
	STIFFNESS RING 2 두께	X	6		0.15	3
	STIFFNESS RING 2 폭	X	110	11	0.15	110.15
	TOTAL LENGTH	X	540.731		0.15	541

Flow chart of pressing

Fabrication of Press jig
(SKD11)

↓

Cleaning of Pressing machine

↓

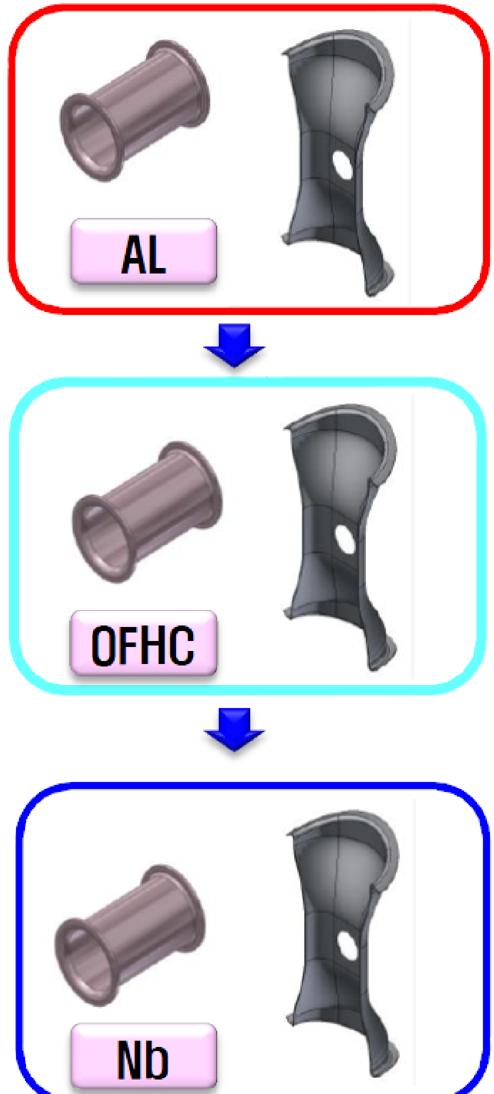
Pressing test
(A6061 3T plate)

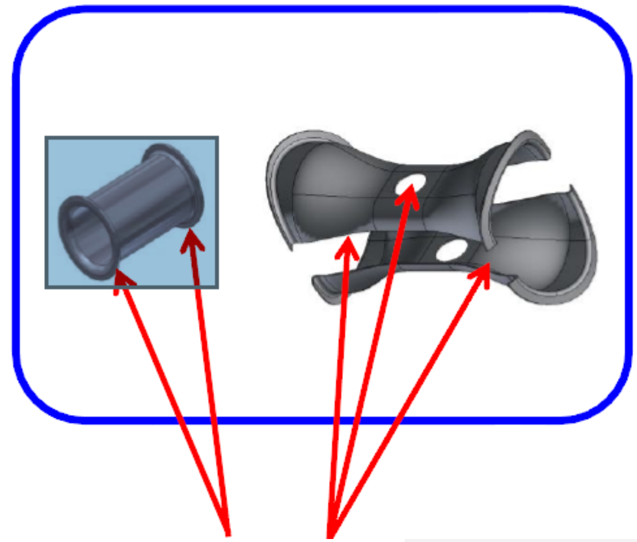
↓

Pressing
(OFHC 3T plate)

↓

Pressing
(Nb 3T plate)





1.Pass Tube :
-Ø62 g6 / (87.5±0.05)
2.Spoke welding edge:
Flatness 0.05μm / 550mm
3.Pass Tube welding Hole:
-Ø62 H7

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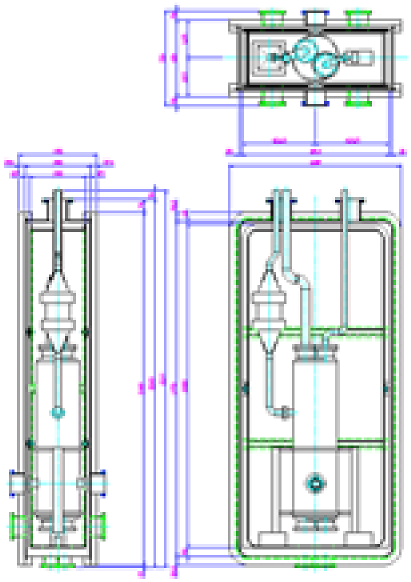
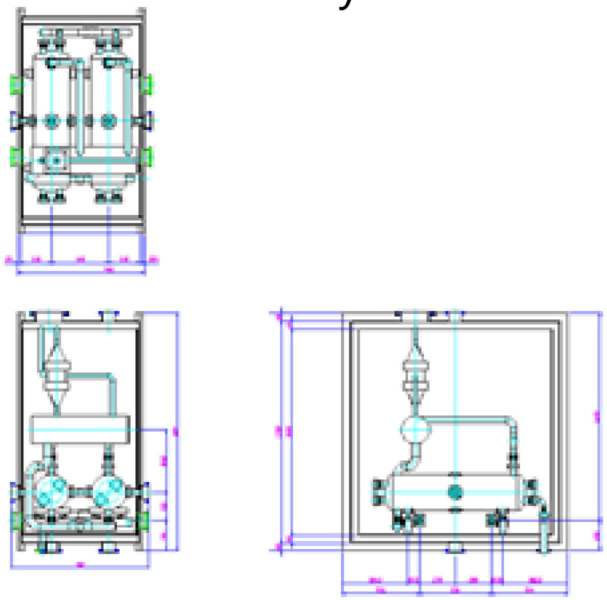
Cryomodule Design and Prototyping

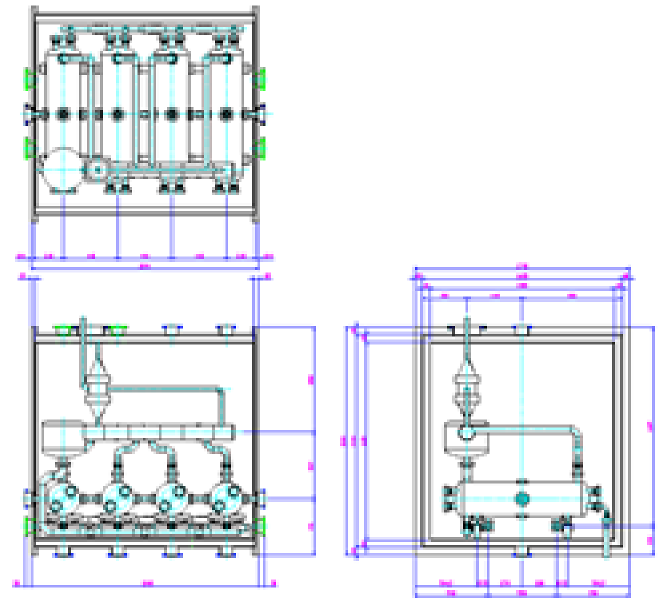
QWR Cryomodule



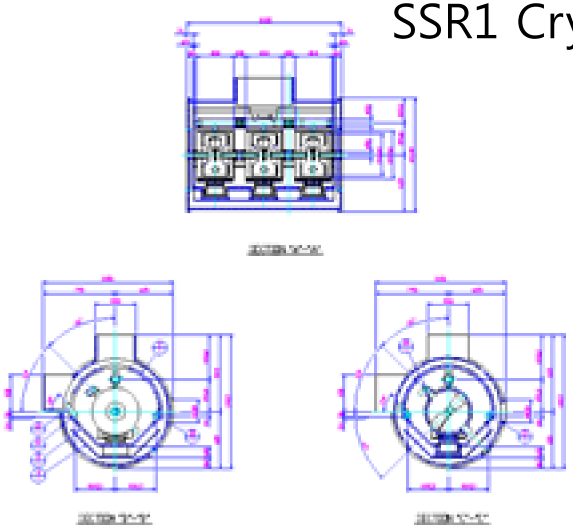
HWR Cryomodule



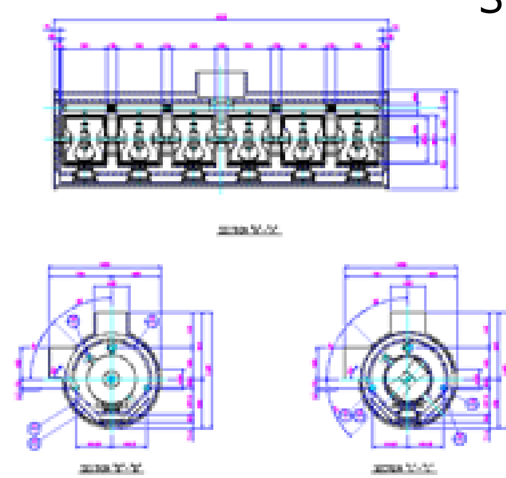
HWR Cryomodule



SSR1 Cryomodule

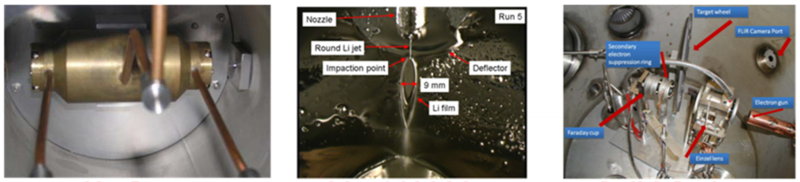


SSR2 Cryomodule

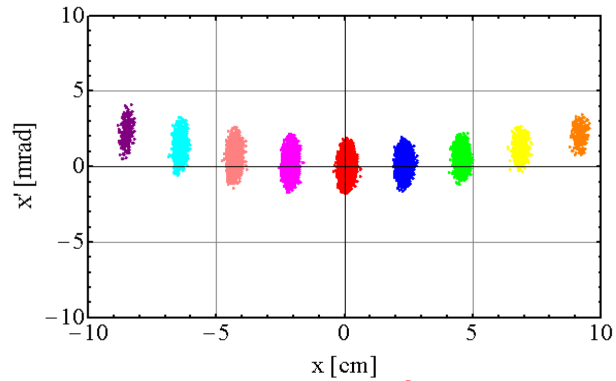


Charge Stripper Section

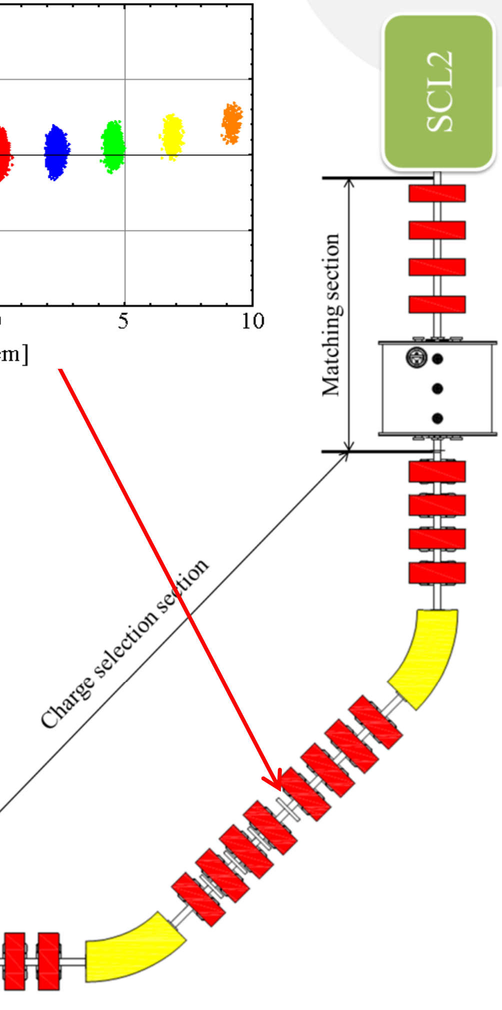
Candidate for charge stripper



He Gas (BNL) | Liquid Lithium (ANL) | Solid Carbon (MSU)

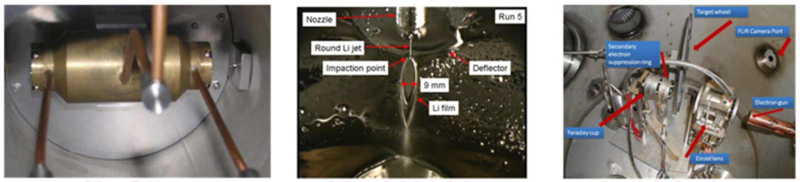


E_0 : 18.5 MeV/u
Magnetic rigidity : 1.90 Tm
Momentum dispersion : 1.77 m
Path length : 27.87 m
Str. Of QM < 21.1 T/m (0.526 T) - Matching section
< 7.75 T/m (0.466 T) - Charge selection section
Radius of dipole : 1.6 m (1.2 T)

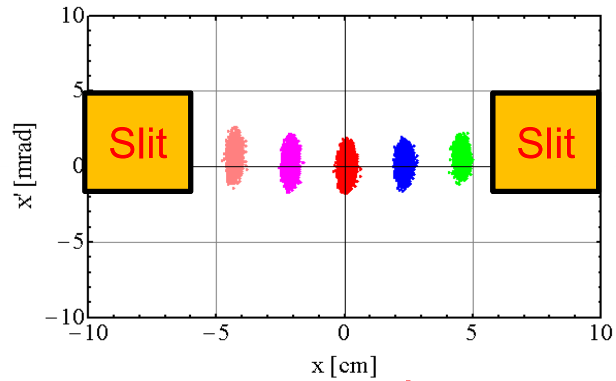


Charge Stripper Section

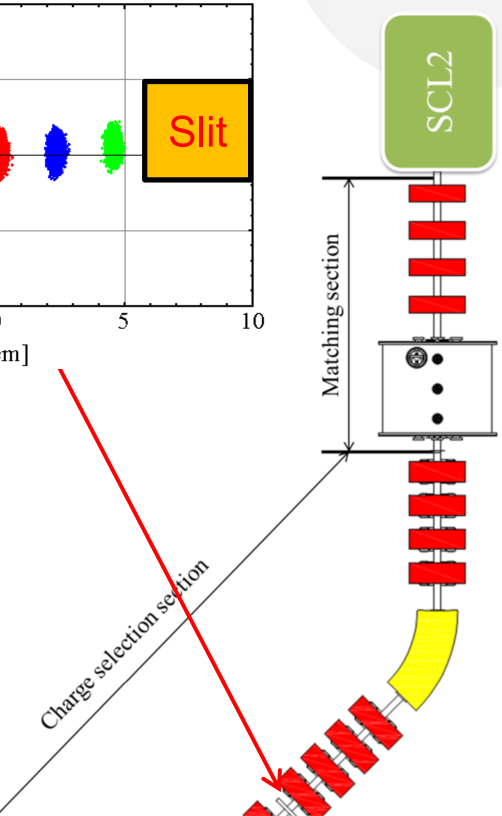
Candidate for charge stripper

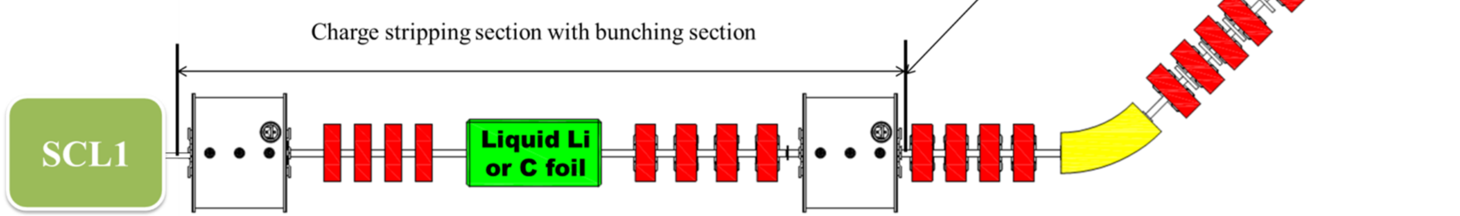


He Gas (BNL) | Liquid Lithium (ANL) | Solid Carbon (MSU)



E_0 : 18.5 MeV/u
Magnetic rigidity : 1.90 Tm
Momentum dispersion : 1.77 m
Path length : 27.87 m
Str. Of QM < 21.1 T/m (0.526 T) - Matching section
< 7.75 T/m (0.466 T) - Charge selection section
Radius of dipole : 1.6 m (1.2 T)





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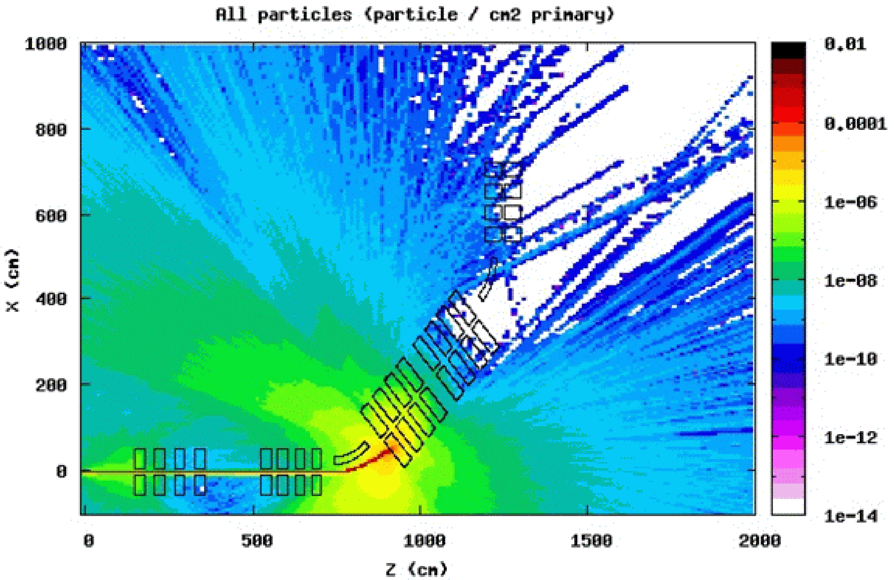
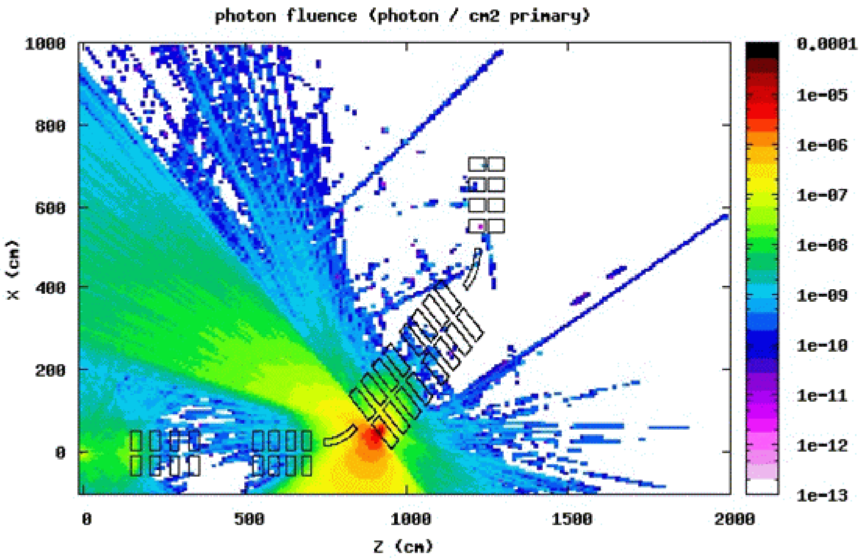
RISP

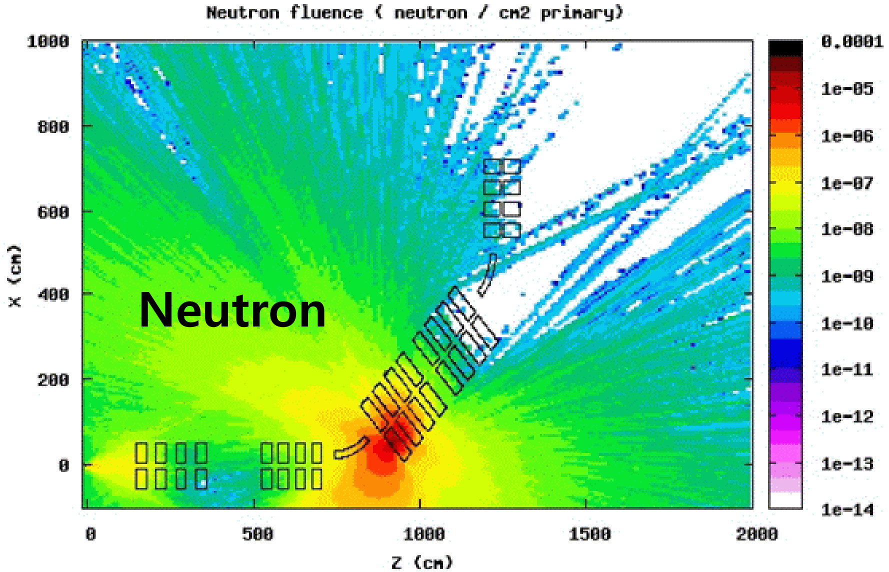
Radiation Effects of Stripper Section



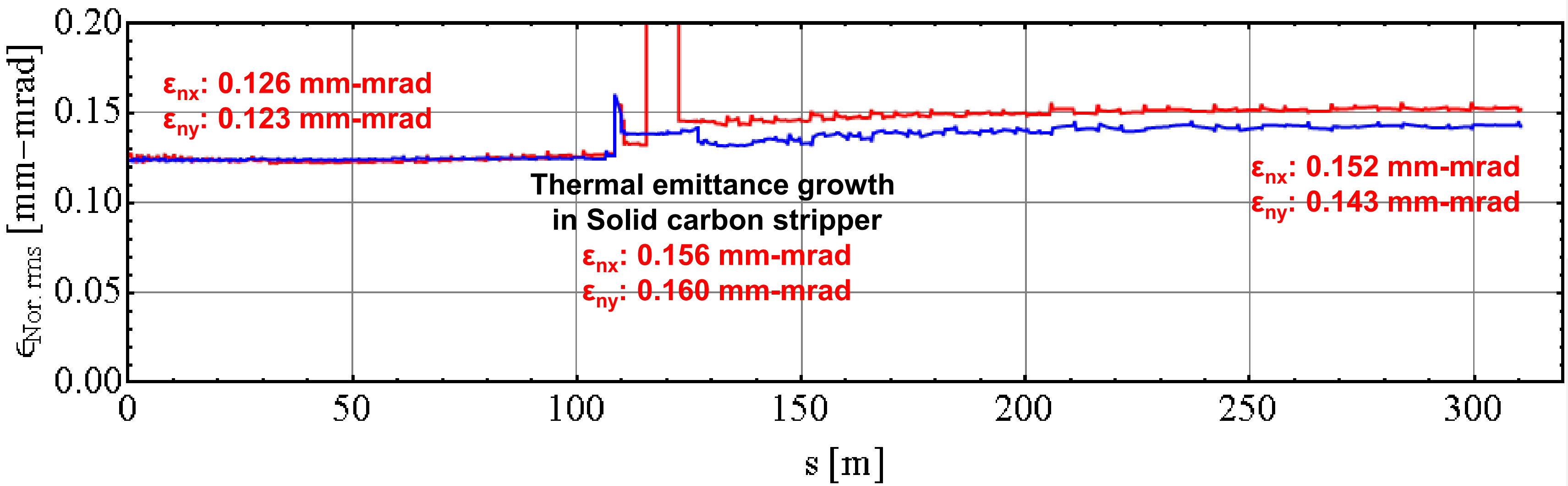
All Particles

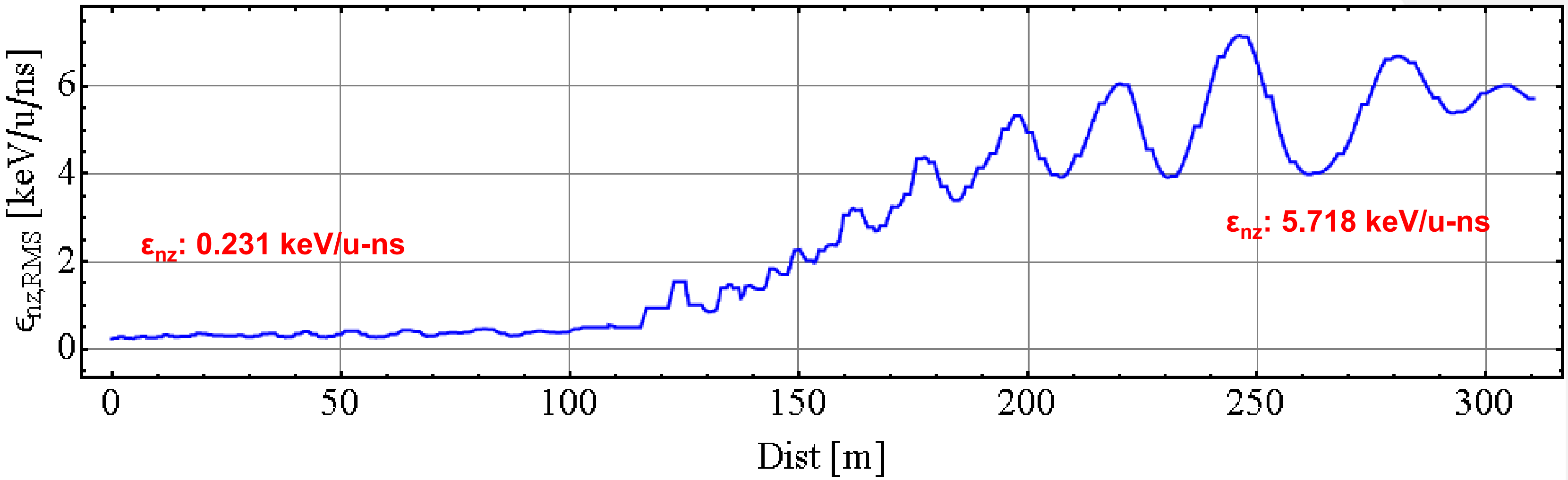


Photon

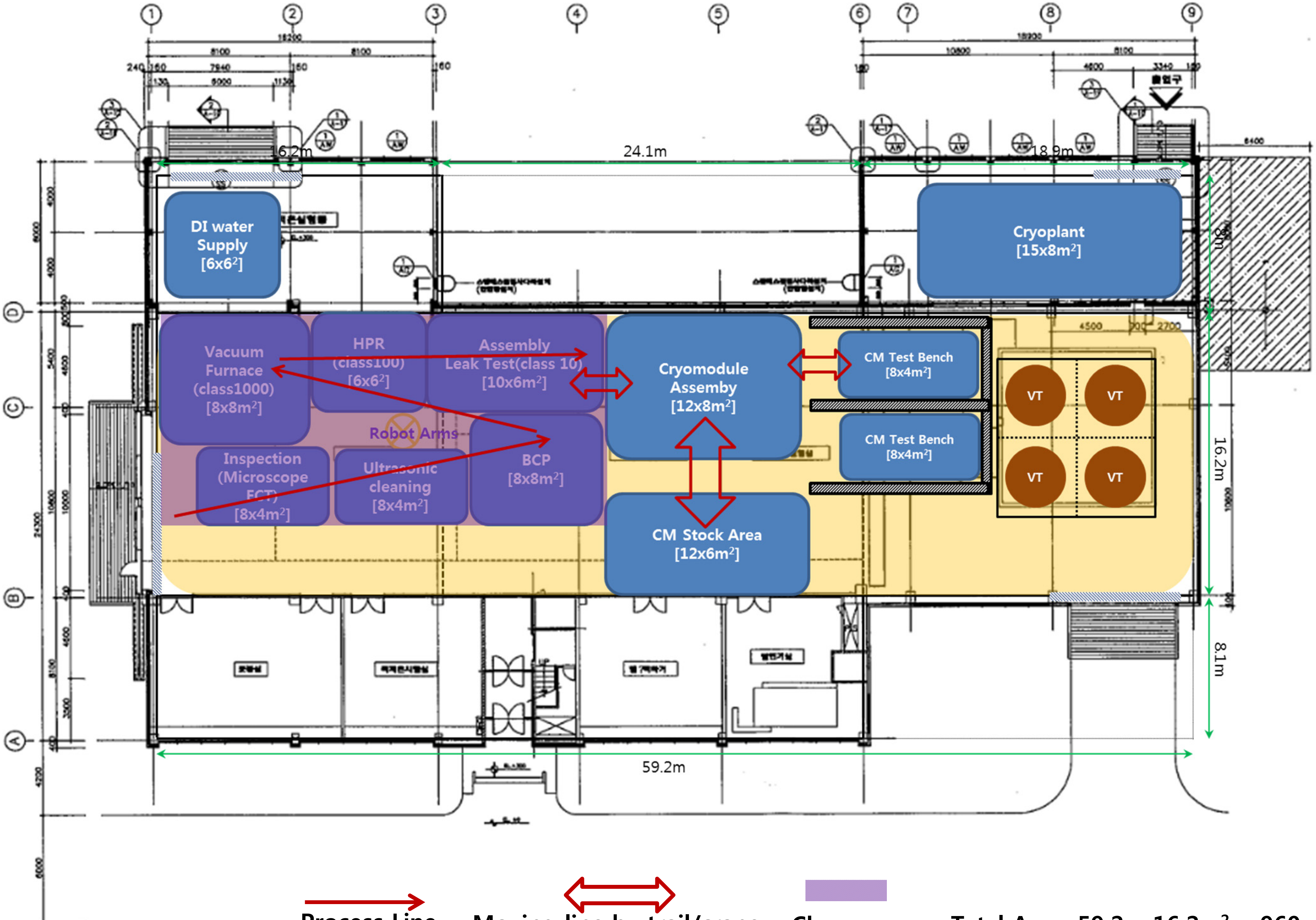


Start-to-End Simulation





SRF Test Facility Layout



Process Line Moving line by trail/crane Cleanroom Total Area: 59.2 x 16.2m² ~ 960m²

Chinese ADS

Chinese ADS Proton Accelerator

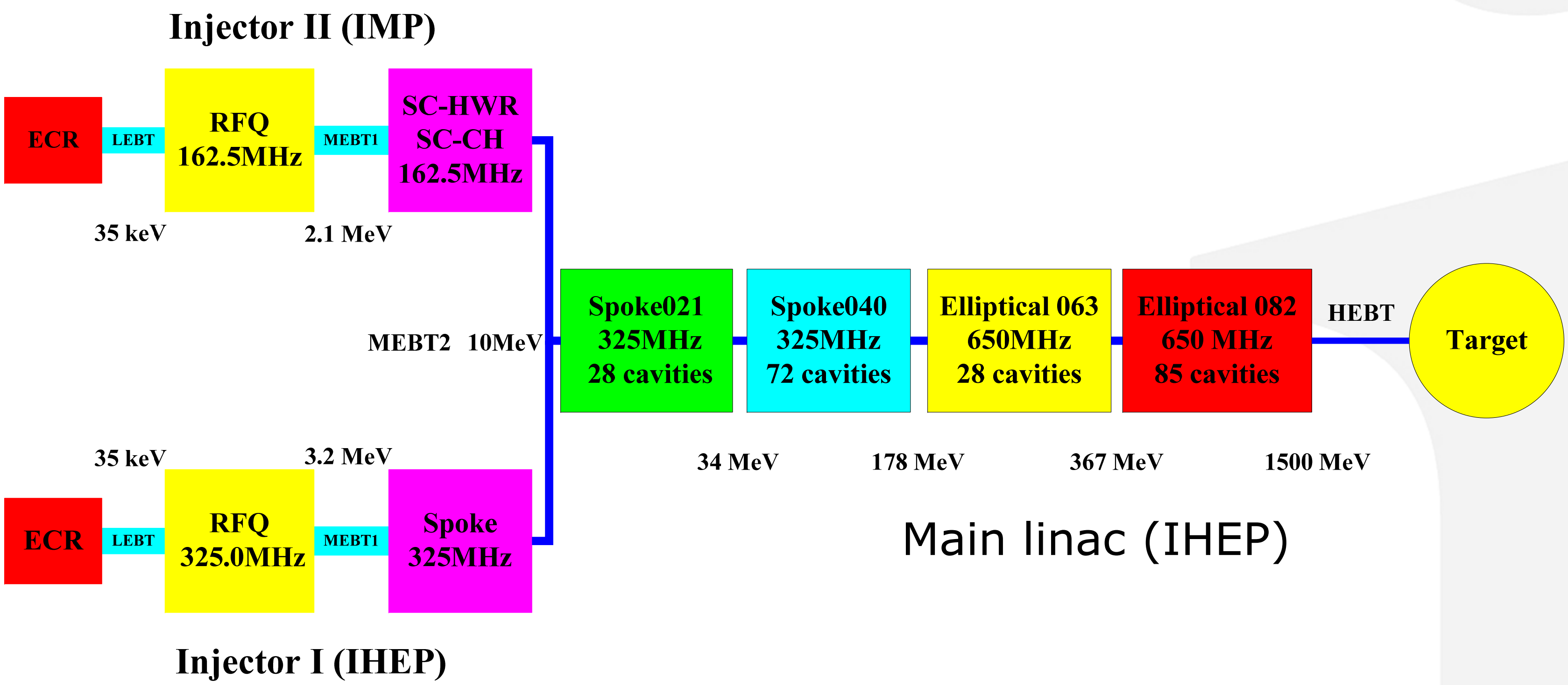
Courtesy of IHEP

Beam Requirements

Particle	Proton	
Energy	1.5	GeV
Current	10	mA
Beam power	15	MW
Frequency	162.5/325/650	MHz
Duty factor	100	%
Beam Loss	<1 (0.3)	W/m
Beam trips/year	<25000 <2500 <25	1s<t<10s 10s<t<5m t>5m

Chinese ADS Layout

Courtesy of IHEP



- This project has begun from early 2011.

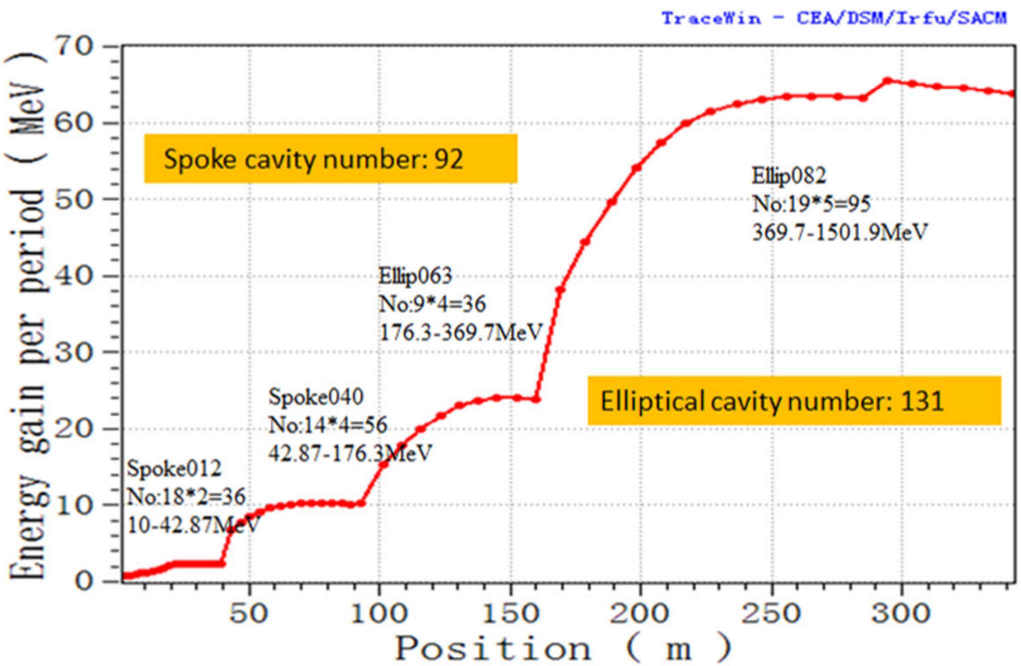
Key parameters of design

Courtesy of IHEP

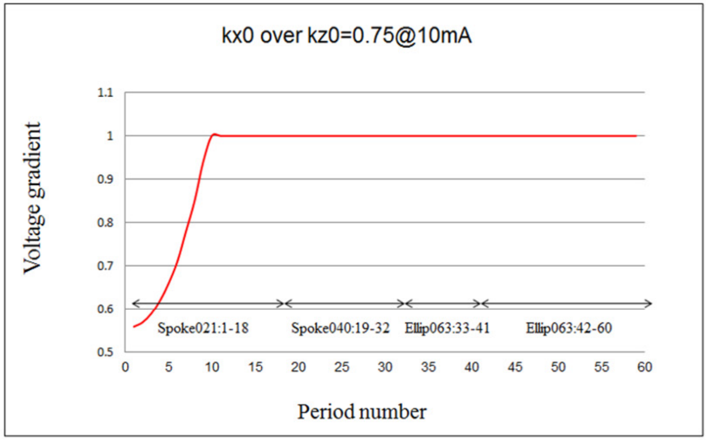
- SC spoke cavities: Epeak<32.5 MV/m, Bpeak<65 mT
- SC elliptical cavities: Epeak<39 MV/m, Bpeak<65 mT
- Operation temperature for all SC cavities: 1.8 K
- Apertures for SC cavities: 35 mm for E<10 MeV; 40 mm for Spoke021; 50 mm for Spoke040; 100mm for Ellip063 and Ellip082. HWR cavities for Injector II: 40 mm
- Phase advance per cell (zero current, both transverse and longitudinal): <90 degree
- RF frequency
  - Injector-I: 325 MHz
  - Injector-II：162.5 MHz
  - Main linac: 325 MHz (Spoke) and 650 MHz (Elliptical)
- Maximum magnetic field for solenoids: 5 T

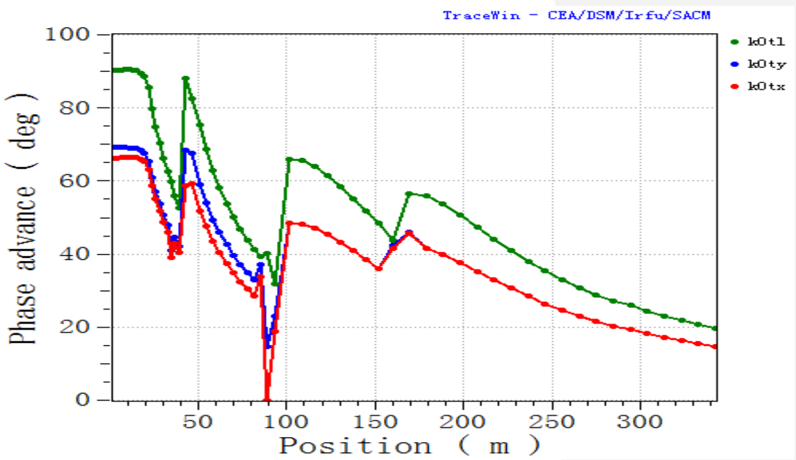
C-ADS linac design

Total: 223cavities, 342.5m



* Note: The nominal gradient of 6 last period of Ellip082 section is 1.04.



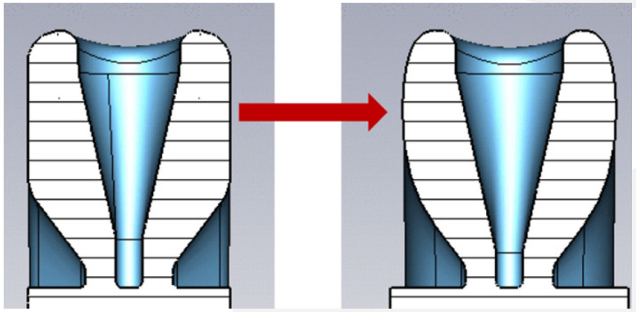


Spoke012 Cavity (β=0.12) of Injector I

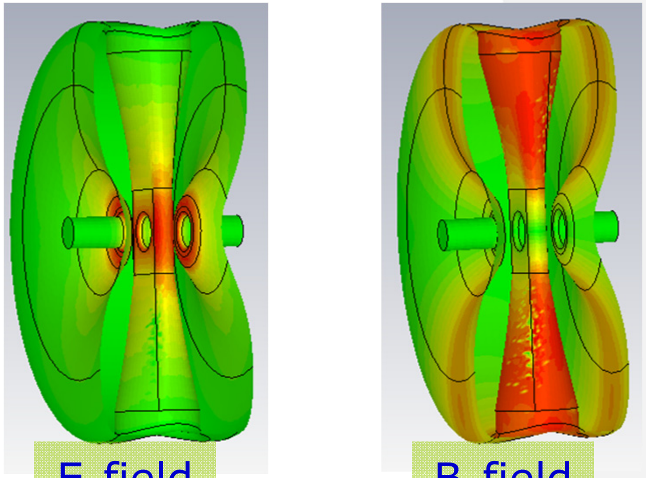
Courtesy of IHEP

Main Geometrical parameters	Units	Value
Diameter of cavity	mm	468
Length of cavity	mm	180
Diameter of beam tube	mm	35
RF parameters	Units	Value
E_{peak}/E_{acc}		4.54
B_{peak}/E_{acc}	mT/(MV/m)	6.37
G	Ω	61
Transition Time Factor		0.76
R/Q@β=0.12	Ω	142

Note: Effective length for Eacc is defined as βλ



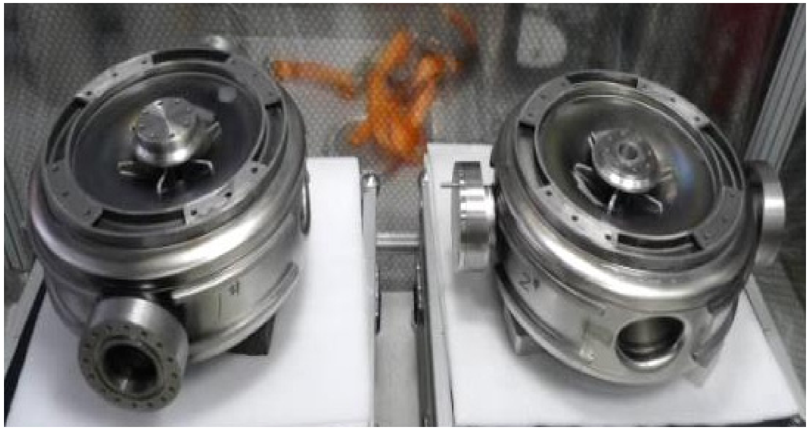
The Convex end wall (right) is adopted,which has better mechanical performance than the flat one (left).

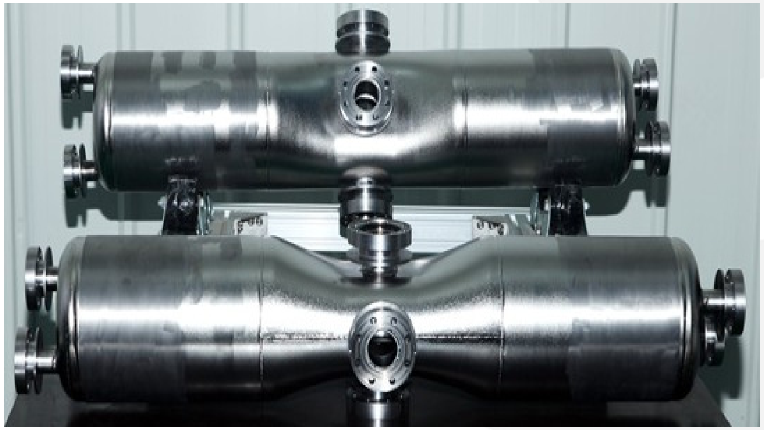


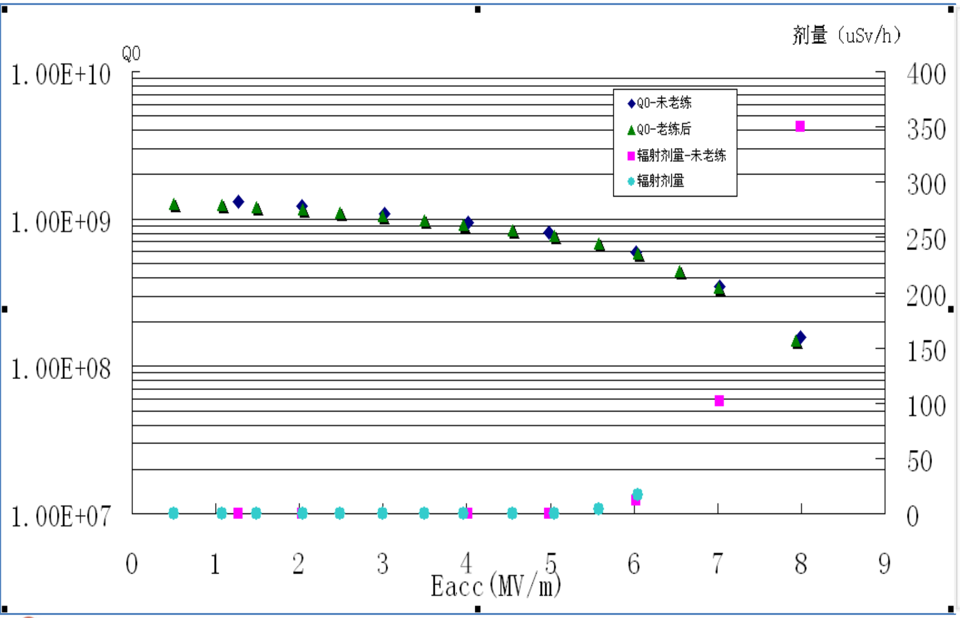
E-field B-field

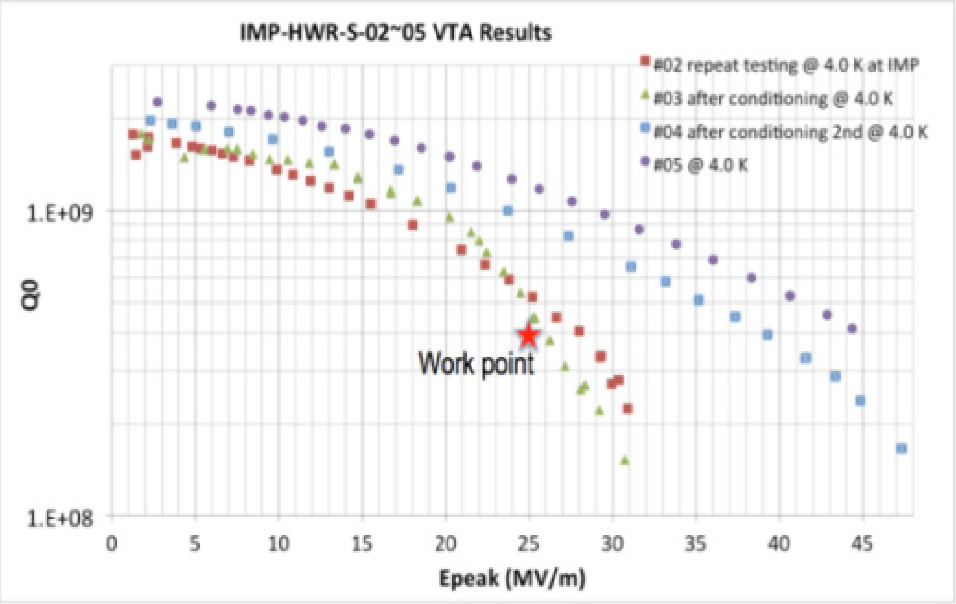
Prototyping on-going

Courtesy of IHEP









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RISP

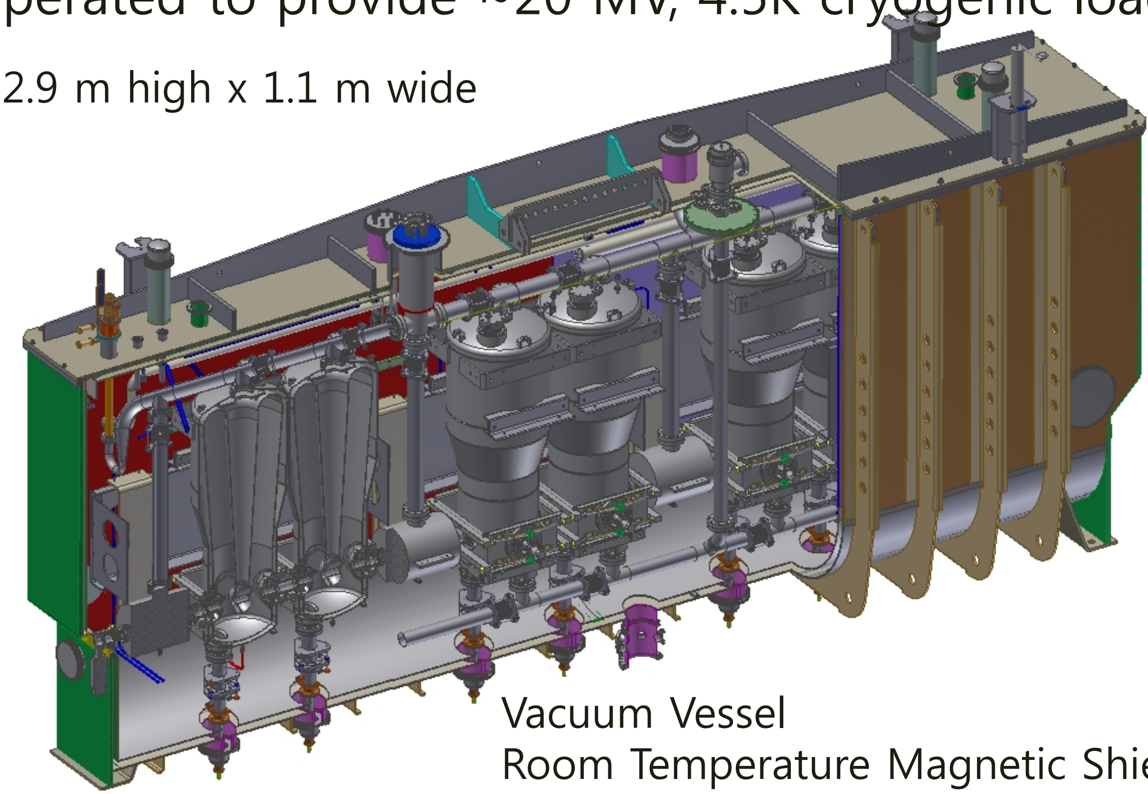
ATLAS Upgrade

ANL ATLAS Intensity Upgrade Cryomodule

Courtesy of ANL

- Seven β = 0.077, 72.75 MHz quarter-wave cavities
- Four 9-Tesla superconducting solenoids
- Replaces 3 old cryomodules with split-ring cavities
- Total design voltage is 17.5 MV, expected 4.5K cryogenic load is 70 W
- Will be operated to provide ~20 MV, 4.5K cryogenic load is 85 W

5.2 m long x 2.9 m high x 1.1 m wide

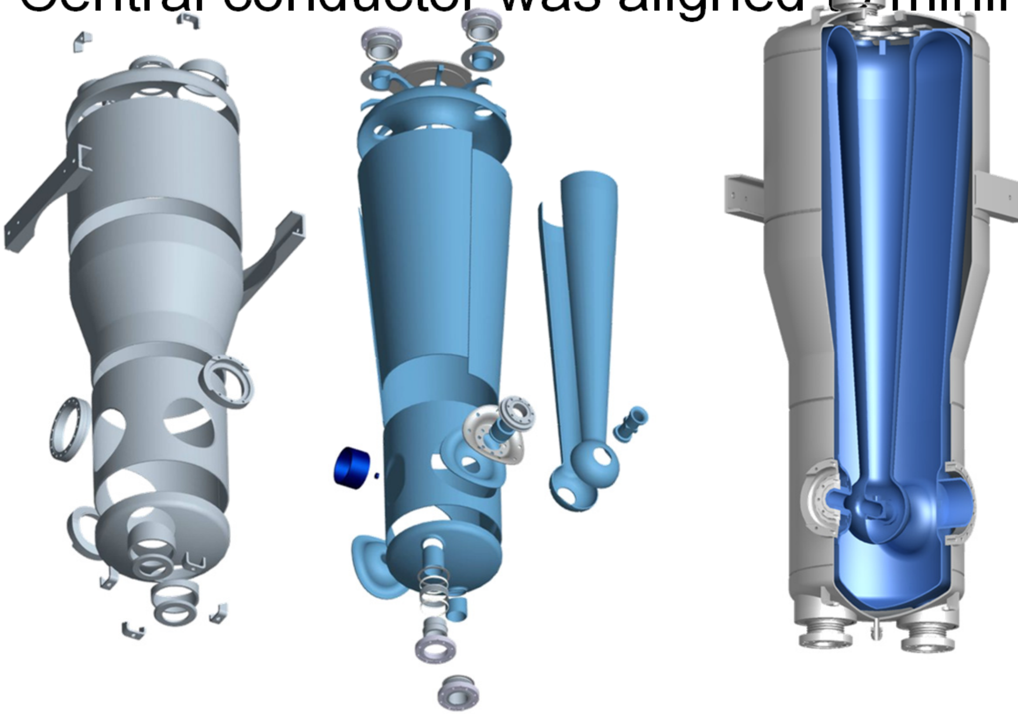


Vacuum Vessel
Room Temperature Magnetic Shield
Aluminum Heat Shield
(MLI not shown)

New 72.75 MHz QWR and Cryomodule

Courtesy of ANL

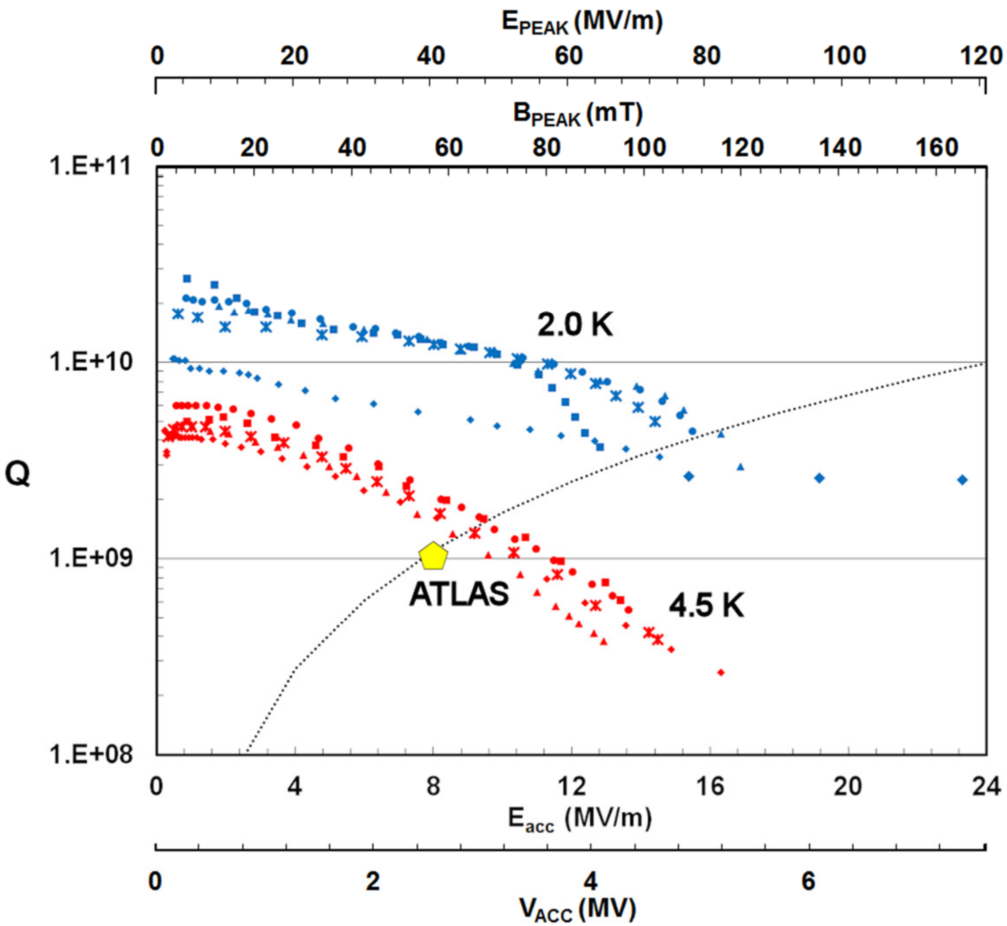
- Double conical highly-optimized design with steering correction
- Automatic compensation of beam steering by appropriate design of drift tubes
- Central conductor was aligned to minimize microphonics



	Design
V, max. voltage gain, MV	2.5
E_{PEAK}, MV/m	40
B_{PEAK}, mT	60
G, Ohm	26
R_{sh}/Q, Ohm	575
Cryogenic load at 4.5K, W	<10

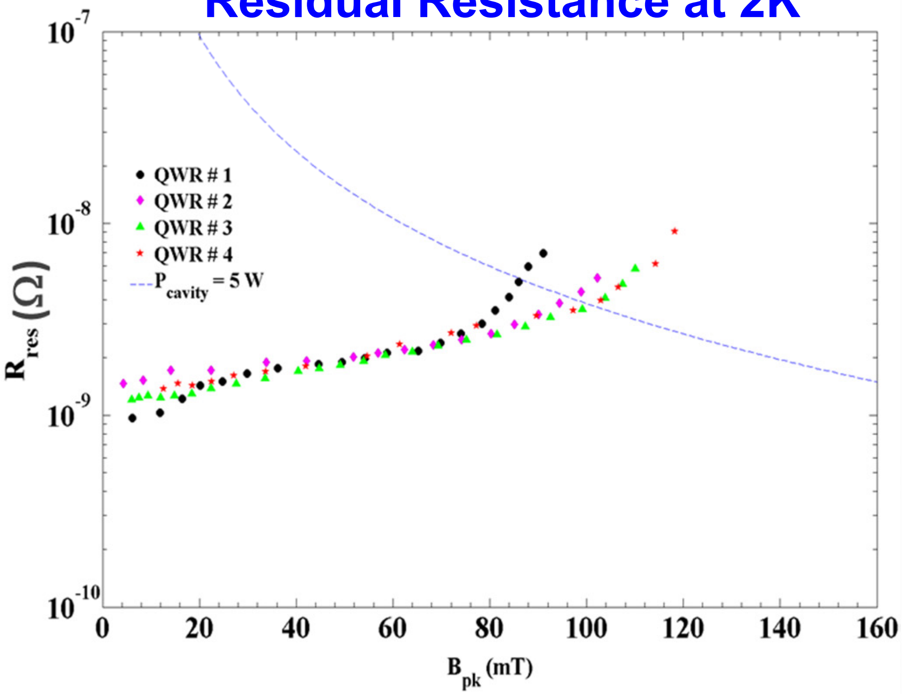
5 QWRs were tested in TC3

- Highly optimized EM design, conical shape, minimized ratio Bpeak/Eacc, Epeak/Eacc
- Only wire EDM is applied for machining of the Nb joints to be EB welded
- EP after all mechanical work including He vessel is completed



Courtesy of ANL

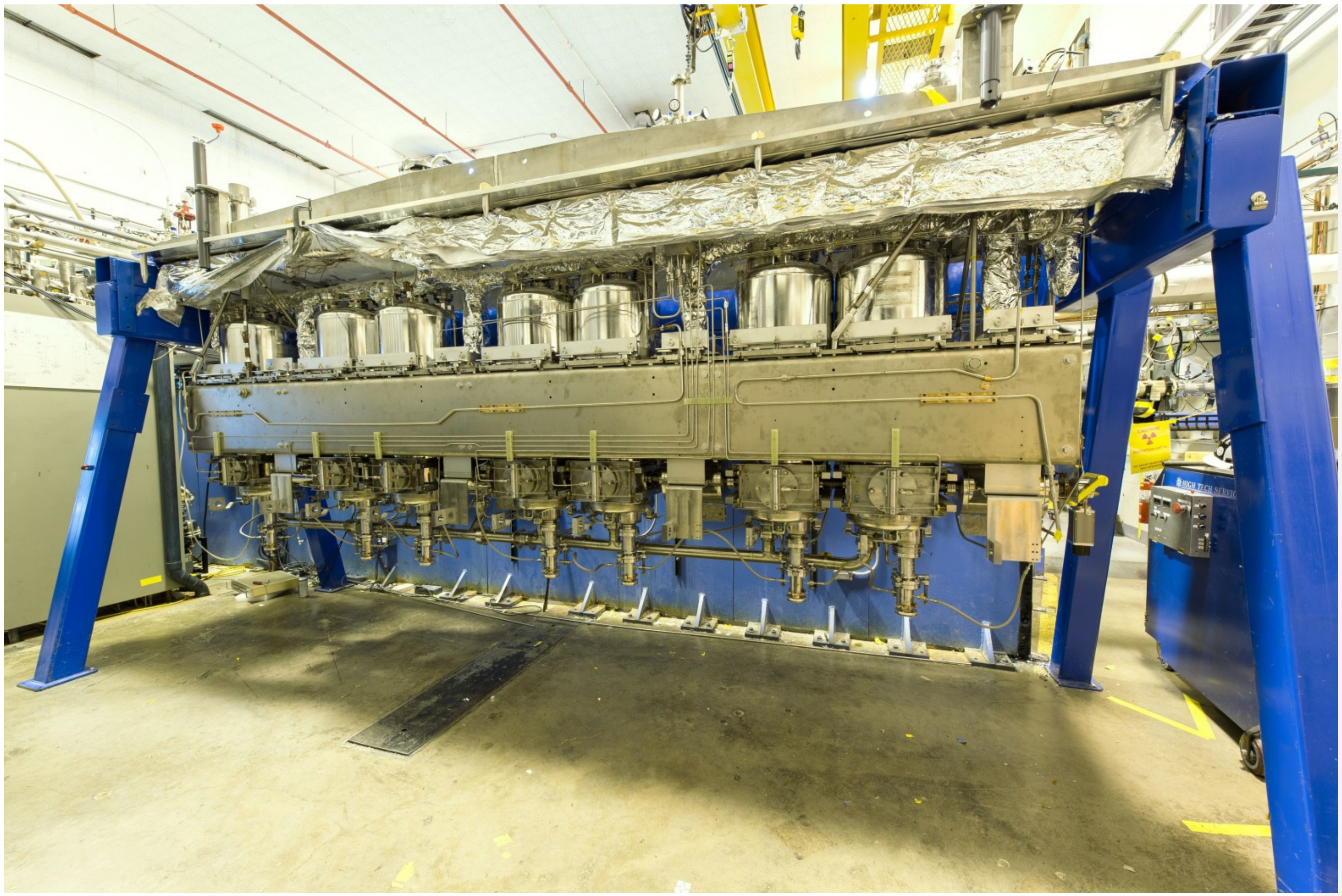
Residual Resistance at 2K



Assembly of the cold mass

Courtesy of ANL

- Off-line commissioning : summer 2013
- On-line commissioning: November-December 2013



Summary

- SRF technology is maturing and has become a technology of choice for heavy ion accelerator projects.
- Both EP and BCP produce high field cavities.
- There are several heavy ion SCL projects at present.
- Status reports of RAON, C-ADS and ATLAS upgrade are presented.
- The construction of the RAON is under way in Korea.
- Prototyping of superconducting cavities and cryomodules is under way for RAON.

- MOP008 H.J. Kim et al
- THP004 H.J. Cha et al
- THP089 Heejin Do et al
- THP027 G.T. Park et al