IRIS
(Institute for Rare Isotope Science)

SRF Cavities

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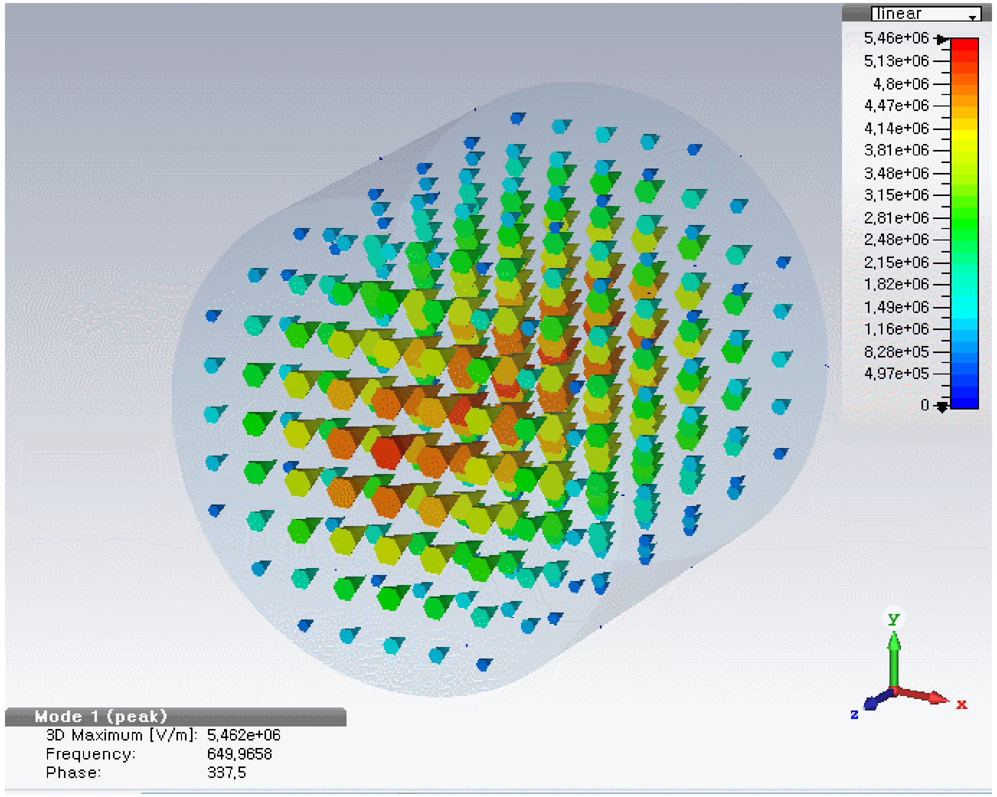
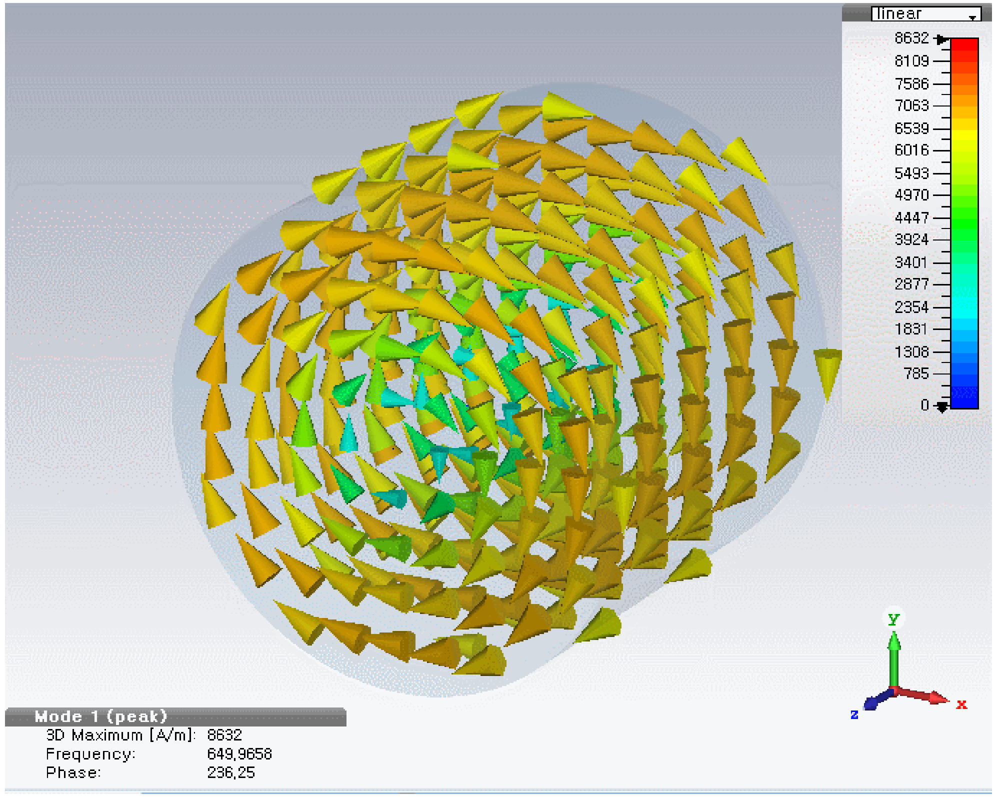
Institute for Rare Isotope Science

IRIS: SRF Cavities

▪ 강의 목표

- 고주파 시스템에 대한 이해 → Eiji Kako, "Fundamental of SRF Cavity System"
- 중이온가속기연구소에서 연구중인 초전도 가속관에 대한 이해





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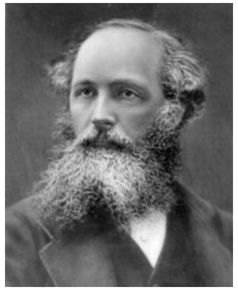
▪ 고주파(RF)란 무엇인가?

- 무선주파수(Radio Frequency)는 30 Hz ~ 300 GHz 범위의 전자기파

▪ 전자기파

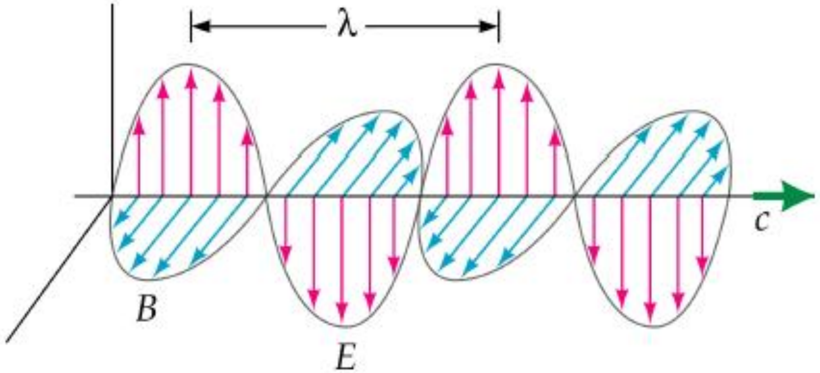


- 전자기파는 전기장과 자기장으로 이루어진 파동이다.
- 스코틀랜드의 물리학자 제임스 클럭 맥스웰(James Clerk Maxwell, 1831~1879)이 처음으로 전기와 자기현상을 통합
- 특정 조건에서 전기장이 자기장을 유도하고 자기장이 전기장을 유도하는 것을 맥스웰 방정식으로 정리함.

$\vec{E}$ = 전기장
$\vec{H}$ = 자기장
$\vec{D}$ = 전속밀도
$\vec{J}$ = 전류

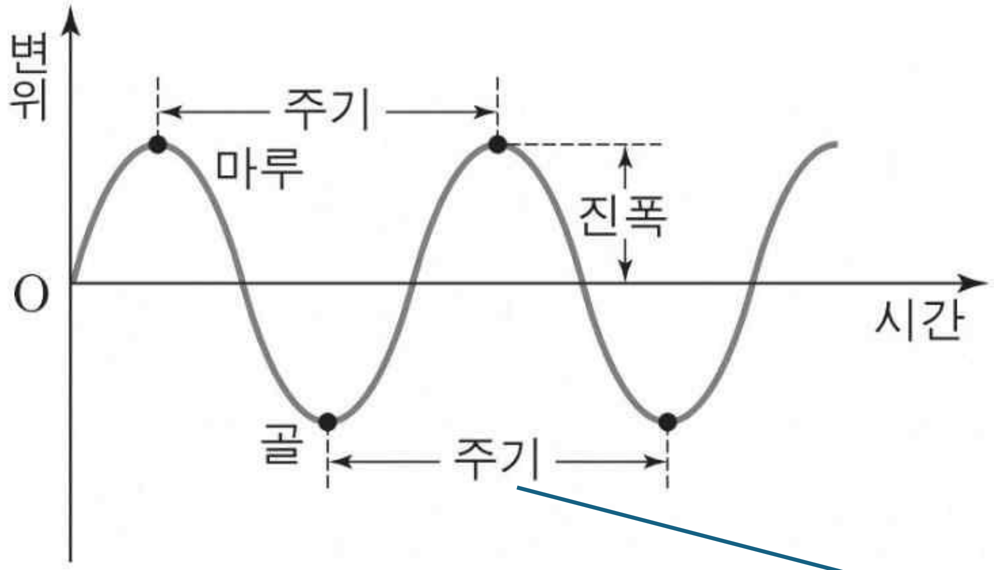
$$\nabla \cdot \vec{D} = \rho_V$$
$$\nabla \cdot \vec{B} = 0$$
$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$
$$\nabla \times \vec{H} = \frac{\partial \vec{D}}{\partial t} + \vec{J}$$

시간에 따라 변화하는 자기장은 전기장을 생성한다.
시간에 따라 변화하는 전기장은 자기장을 생성한다.

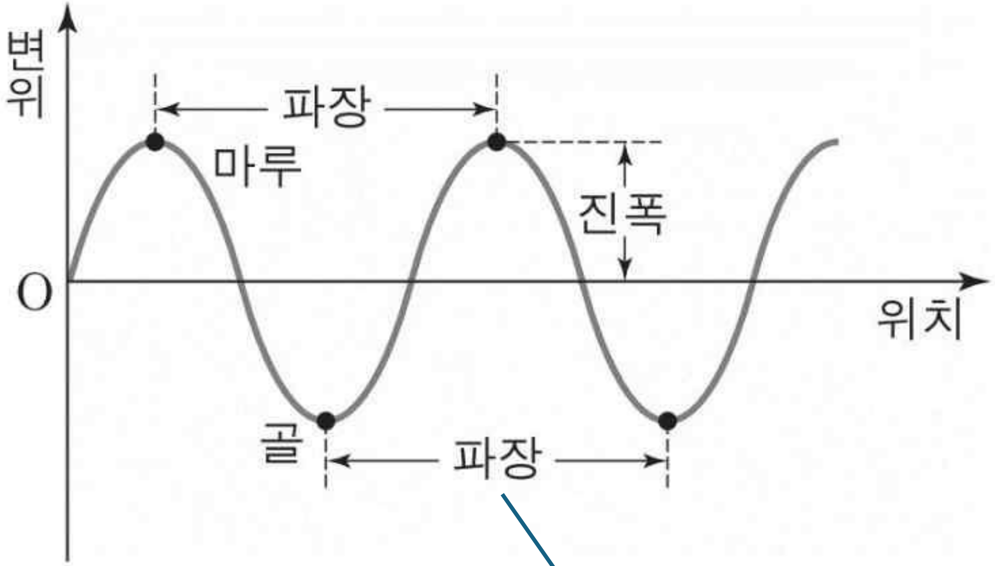


- 파동

파동의 주기



파동의 파장



$$T = \frac{1}{f}$$

$$\text{주기} = \frac{1}{\text{진동수}}$$

$$v = \frac{\lambda}{T} = f\lambda$$

$$\text{파동의 속력} = \frac{\text{파장}}{\text{주기}} = \text{진동수} \times \text{파장}$$

01 개요

▪ 주파수 분류

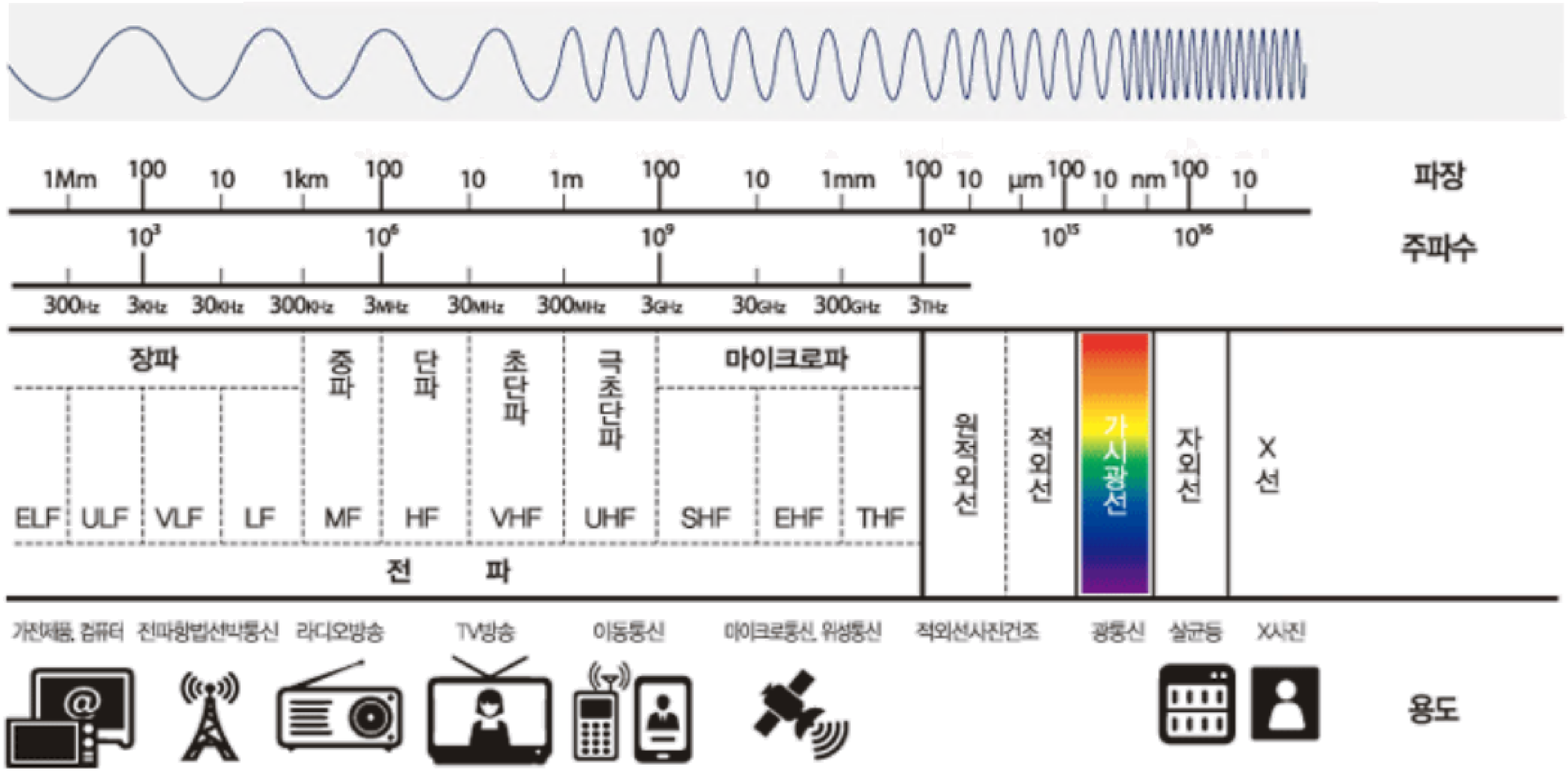
명칭	주파수 대역	비고
HF (High Frequency)	3 ~ 30 MHz	-
VHF(Very High Frequency)	30 ~ 300 MHz	RAON[1] QWR(81.25 MHz) RAON HWR(162.5 MHz)
UHF(Ultra High Frequency)	0.3 ~ 1 GHz	RAON SSR1 & 2(325 MHz) PLS[2] main RF cavity(500 MHz)
L band	1 ~ 2 GHz	TESLA[3] 9-cell cavity(1.3 GHz) 4GSR[4] 3rd harmonic cavity(1.5 GHz)
S band	2 ~ 4 GHz	PLS Linac(2856 MHz)
C band	4 ~ 8 GHz	-
X band	8 ~ 12 GHz	CLIC[5](12 GHz)

출처: IEEE 521-2002, IEEE Standard Letter Designations for Radar-Frequency Bands

1) RAON: Rare isotope Accelerator complex for ON-line experiments
2) PLS: Pohang Light Source
3) TESLA: linear electron-positron collider, DESY, Germany
4) 4GSR: 4th Generation Storage Ring
5) CLIC: Compact LInear Collider

01 개요

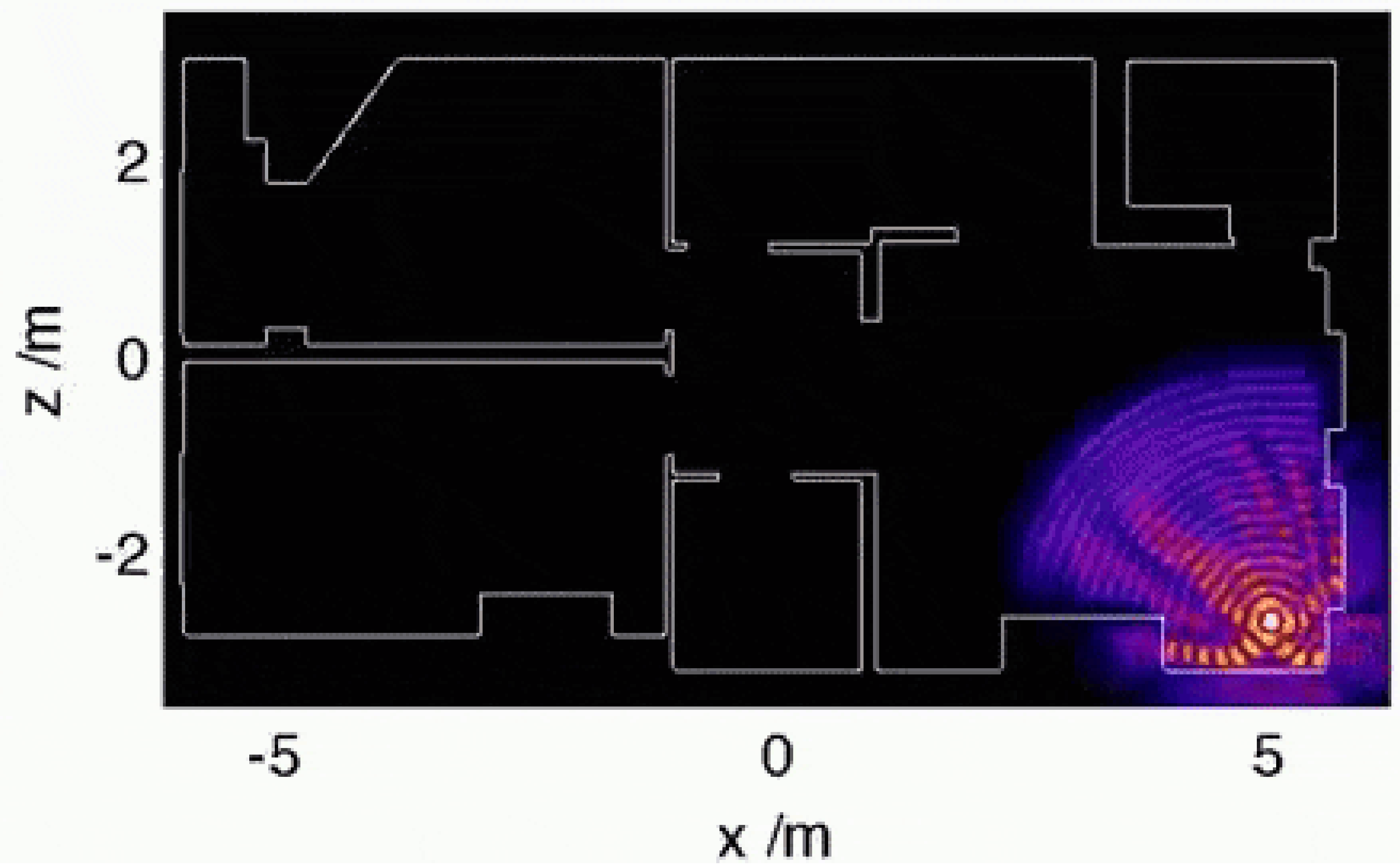
■ 주파수 분류



출처: 한국방송통신전파진흥원

01 개요

- WiFi



출처: YouTube, Jason Cole

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01 개요

- RF(Radio Frequency)란?

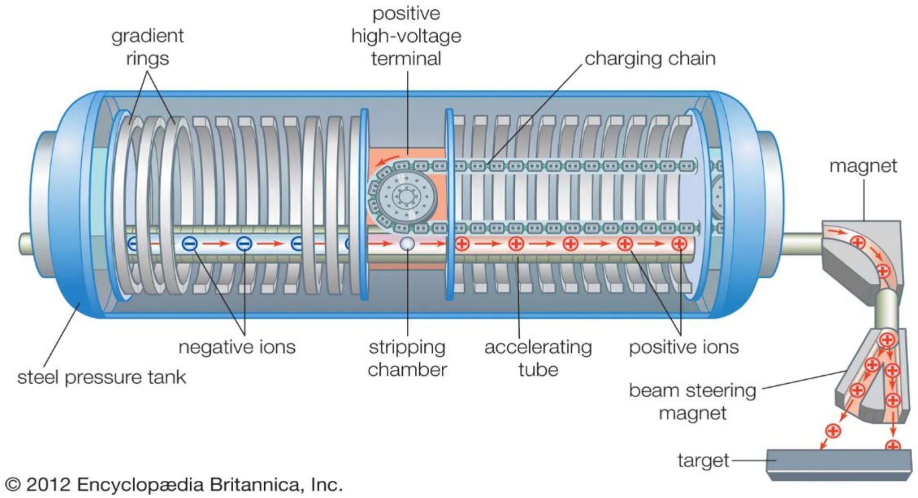
02 고주파 가속관

- 기초
- RAON 가속기 시스템 개요
- QWR, HWR 가속관 제작 및 활용 사례
- SSR1, SSR2 가속관 연구 현황

▪ 기초: RF를 쓰는 이유

- 더 작은 cavity로 더 강한 가속 전압을 만들어 낼 수 있음.

정전형 가속기(Constant-voltage accelerator)

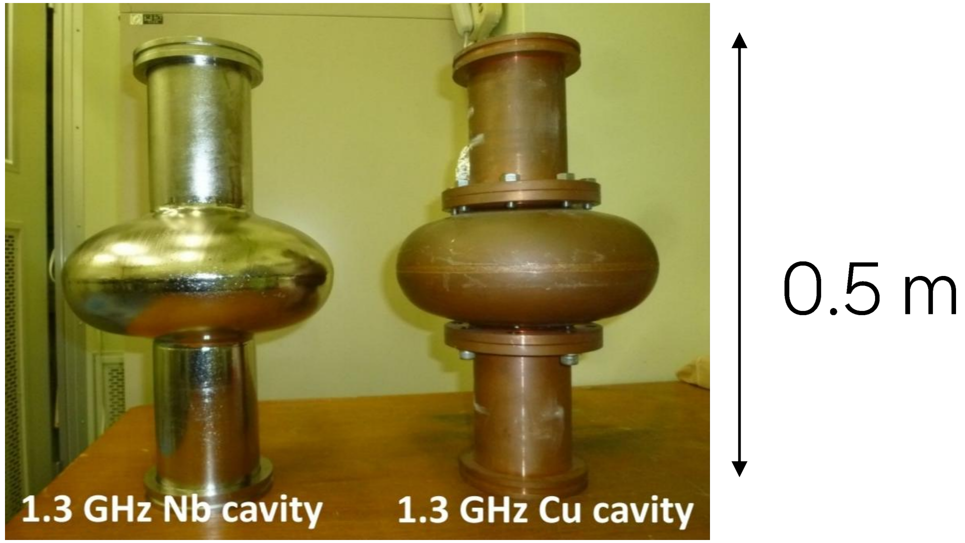


~10 m

< Two-stage tandem particle accelerator>

V_{acc} = 6 MV KIST Tandetron

RF cavity



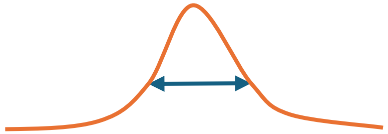
< 1.3 GHz cavity (KEK) >

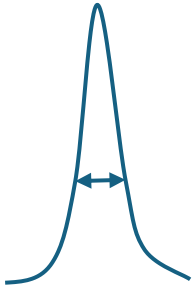
Course materials, ASSCA2022 ,February 11-20, 2022, Korea University, Sejong, Korea.

V_{acc} > 7 MV Nb V_{acc} > 2.4 MV Cu

02 고주파 가속관

▪ 기초: 상전도 vs 초전도





	상전도 가속관 (NC, Normal conducting)	초전도 가속관 (SC, Superconducting)
재질	OFHC, Cu, 무산소동	Nb, Niobium 또는 Nb-coated Cu
운전 온도	상온 (293 K)	2 ~ 4.5 K
운전 조건	Pulse 운전에 적합	CW, Continuous wave 가능
표면 저항	수 mΩ, RF 손실이 큼, 같은 조건에서 수십 kW	수 nΩ, RF 손실이 작음, 같은 조건에서 수 W
Q값 $\left(= \frac{\omega U}{P_{loss}}\right)$	$10^3 \sim 10^5$, 낮은 가속 효율	$10^9 \sim 10^{11}$, 높은 가속 효율
초기 구축 비용	낮음 (비교적 단순한 장비와 구조)	높음 (액체 헬륨 냉각 시설, 전송 시설 등) (복잡한 구조로 제작 비용과 난이도가 높음.)
운전	• RF 전력 손실로 인해 운전 비용이 비교적 높음. • 제작 비용이 저렴함. • 넓은 bandwidth로 외부 영향이 적음.	• RF 전력 손실이 적어 장기적으로 운전 비용이 낮음. • 운전 중 quench 관리 등 복잡함. • 좁은 bandwidth로 외부 진동에 취약

02 고주파 가속관

- 기초: 정전형 가속관 vs 고주파 가속관

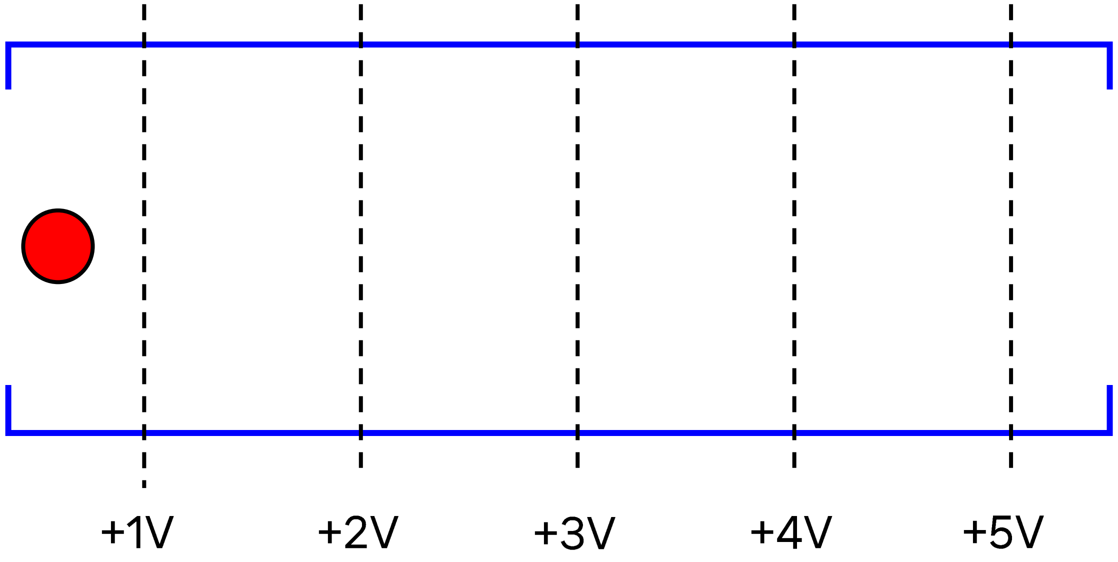
폭포와 같음.

파도와 같음.

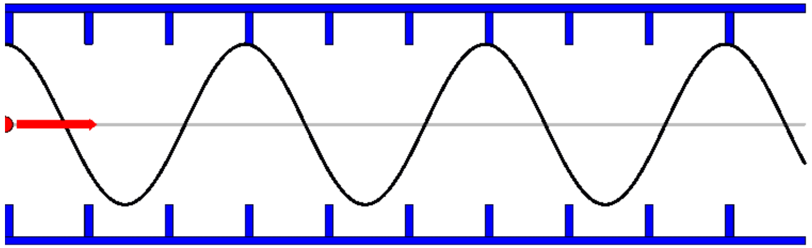
02 고주파 가속관

▪ 기초: 정전형 가속관 vs 고주파 가속관

정전형 가속기(Constant-voltage accelerator)

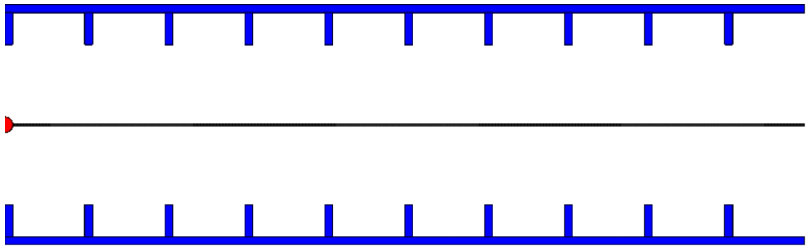


고주파 가속관(RF cavity)



< Traveling wave (TW) >

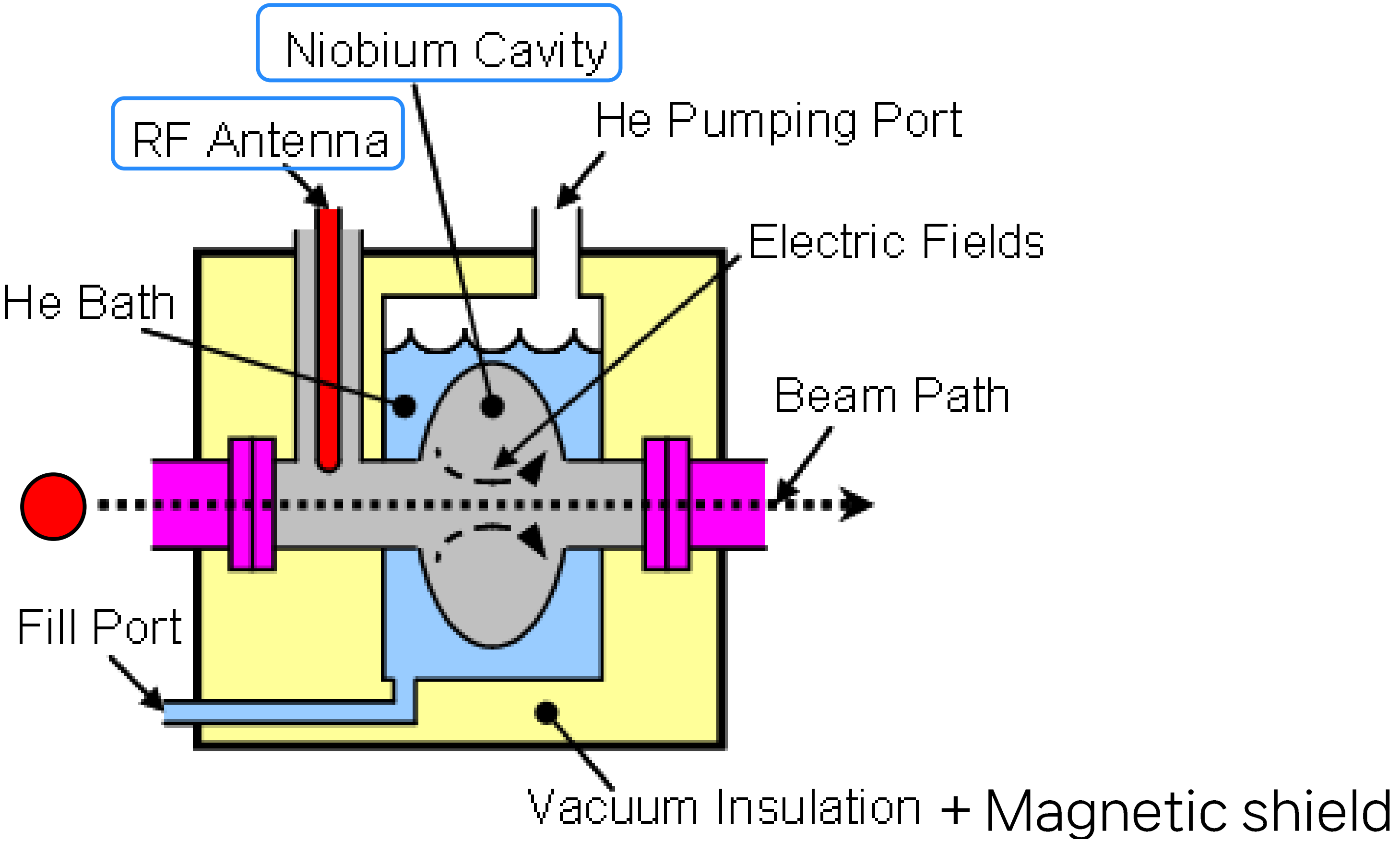
- 도파관의 길이가 길어짐.
- RF 전력 손실이 상대적으로 적음.



< Standing wave (SW) >

- 도파관의 길이가 짧아도 가능함.
- RF 전력 손실이 상대적으로 많음.

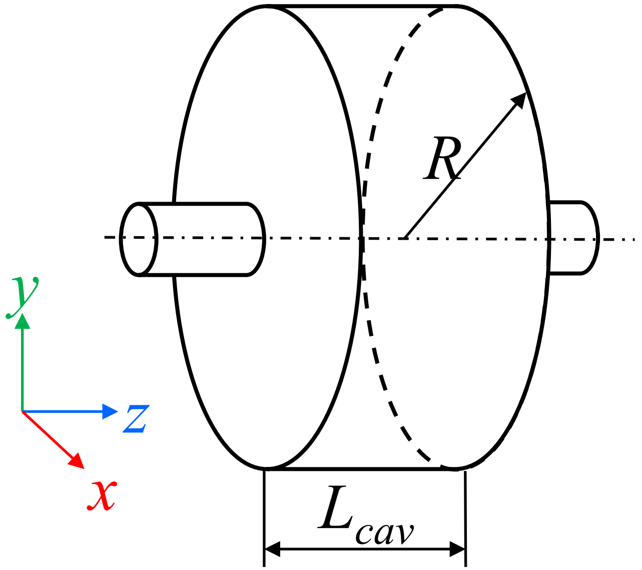
- 기초: 초전도 가속관



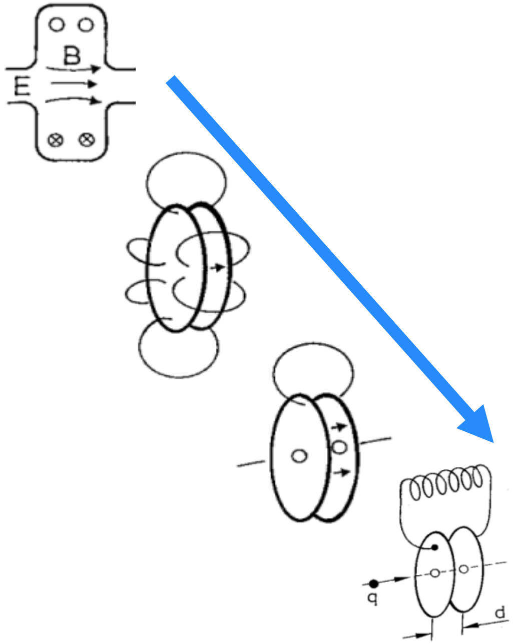
- 극저온(2 K or 4.5 K)에서 빔의 가속을 위해 운용하는 장치
- 고주파, 극저온, 초전도체, 진공 기술 등을 필요로 함.

Wikipedia: Superconducting Radio Frequency

▪ 기초: 초전도 가속관의 크기 결정



< Pill-box cavity >



빛의 속도

$$f_{TM010} = \frac{2.405c}{2\pi R} = \frac{1}{2\pi\sqrt{LC}}$$

< TM010 모드 공진 주파수 >

Cavity 공진 주파수의 파장 길이

$$L_{cav} = \frac{\beta\lambda}{2}$$

< 입자의 속도(β)에 따른 cavity 길이 >

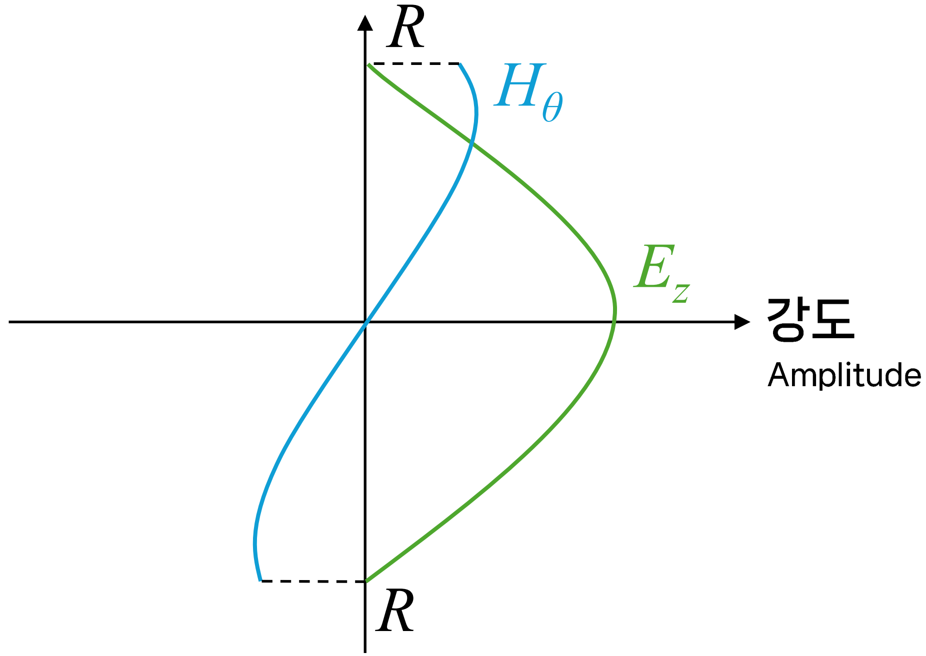
$$\vec{F} = q\vec{E} + q\vec{v} \times \vec{B}$$

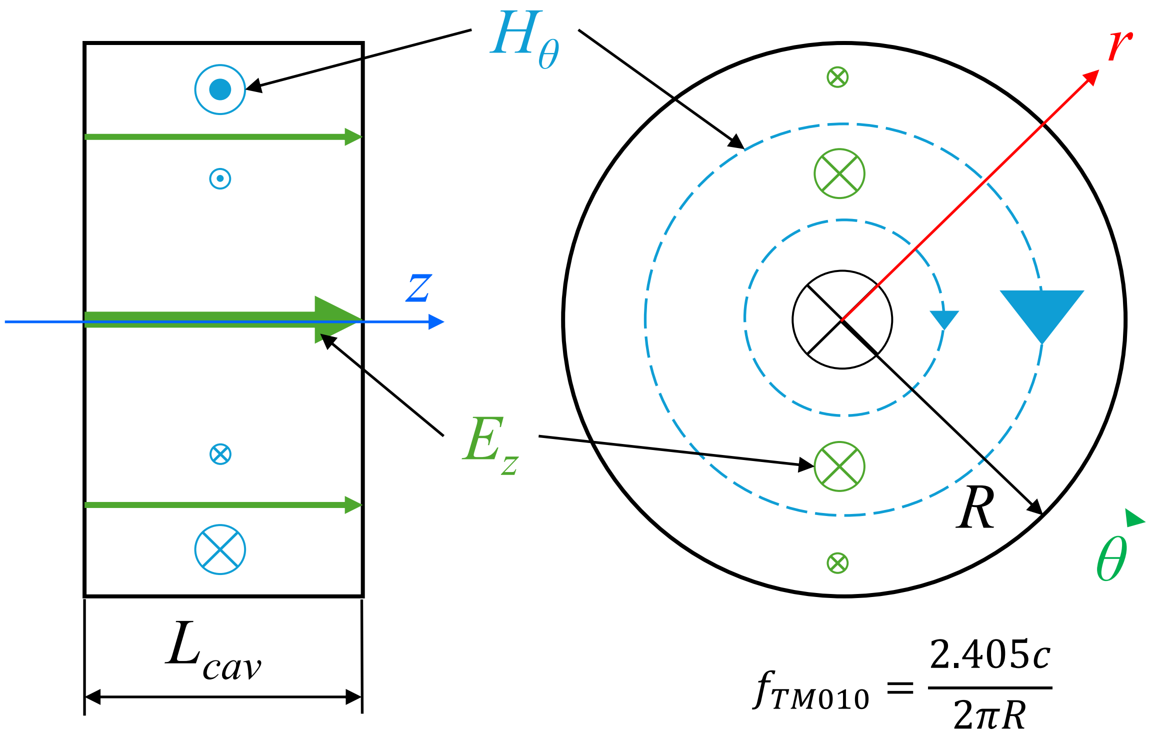
< Lorentz force >

- Cavity의 공진주파수는 반지름(R)에 의해 결정됨.
- Cavity의 길이는 cavity를 지나는 하전 입자의 속도에 의해 결정됨.

▪ 기초: 일반적인 초전도 가속관의 가속 모드 (TM_{010})

$$E_z = E_0 J_0\left(\frac{2.405r}{R}\right)e^{j\omega t} \qquad H_\theta = -j\frac{E_0}{\sqrt{\mu/\epsilon}}J_1\left(\frac{2.405r}{R}\right)e^{j\omega t}$$



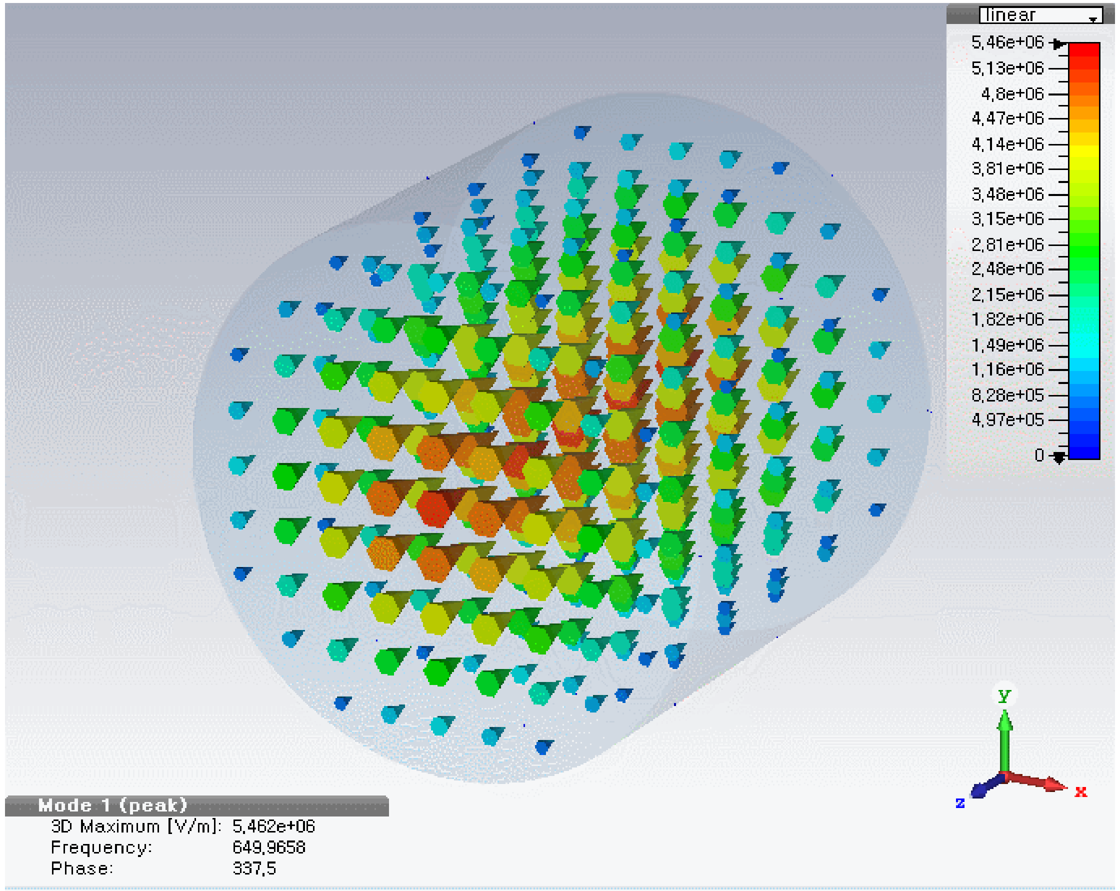


$$f_{TM010} = \frac{2.405c}{2\pi R}$$

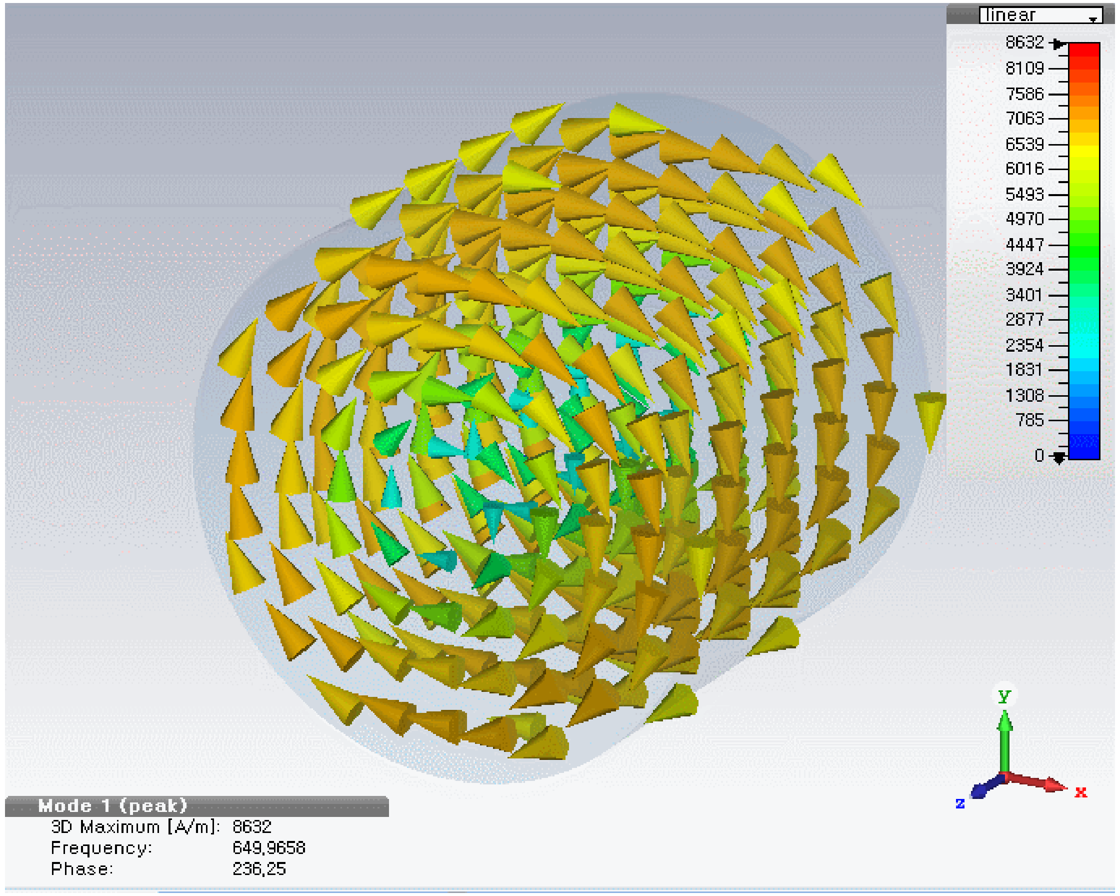
- 전기장은 R = 0 인 지점에서 제일 강하여 하전 입자를 가속시킴.
- 자기장은 R = max인 지점에서 제일 강하며 RF 손실(RF losses)를 일으킴.

02 고주파 가속관

- 고주파 가속관의 가속 모드 (Fundamental mode, TM_{010})



< 전기장 공진 >



< 자기장 공진 >

RF Superconductivity for Accelerators, by H. Padamsee, Wiley-VCH (1998)의 제 2장 내용

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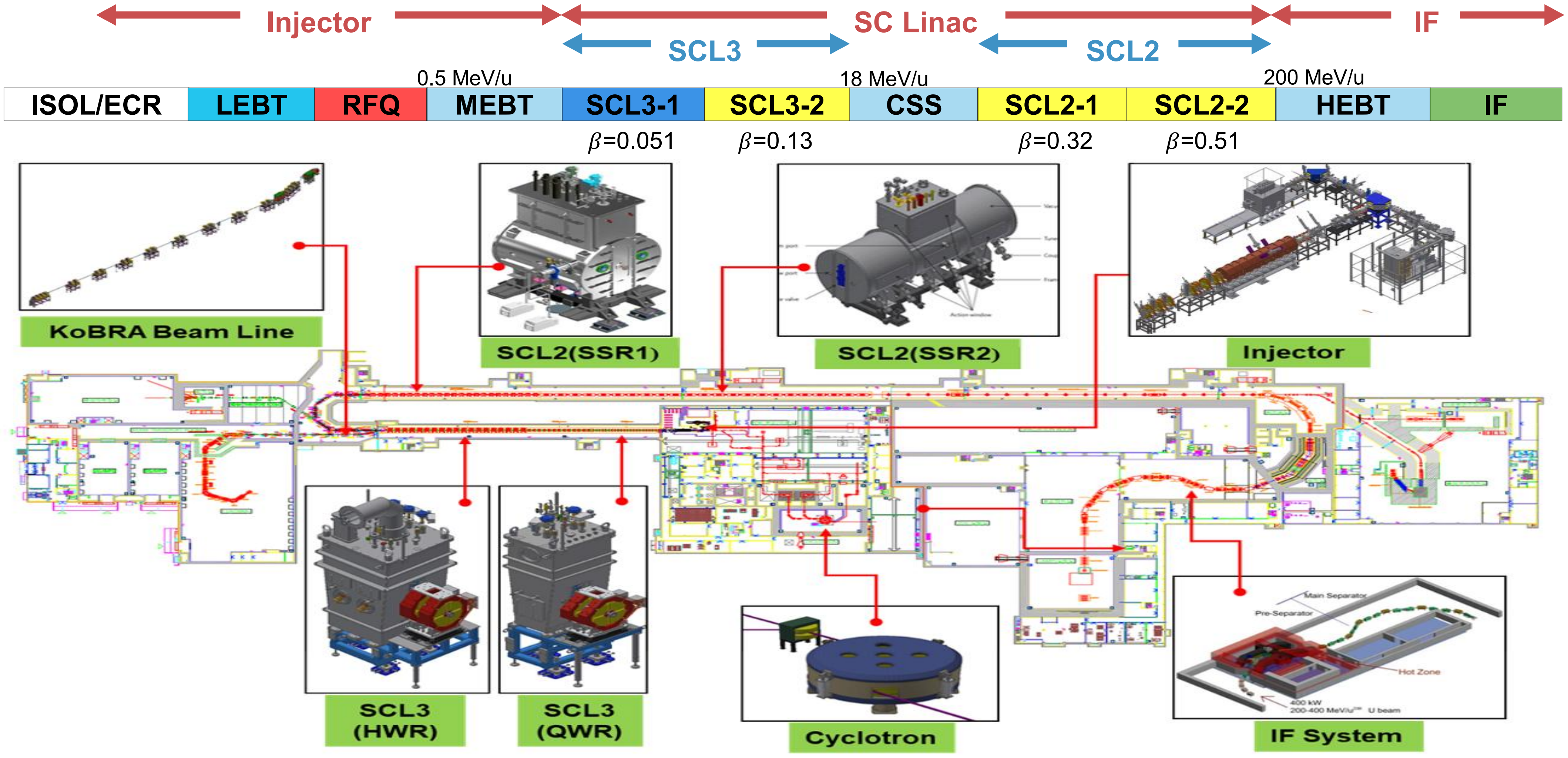
02 고주파 가속관

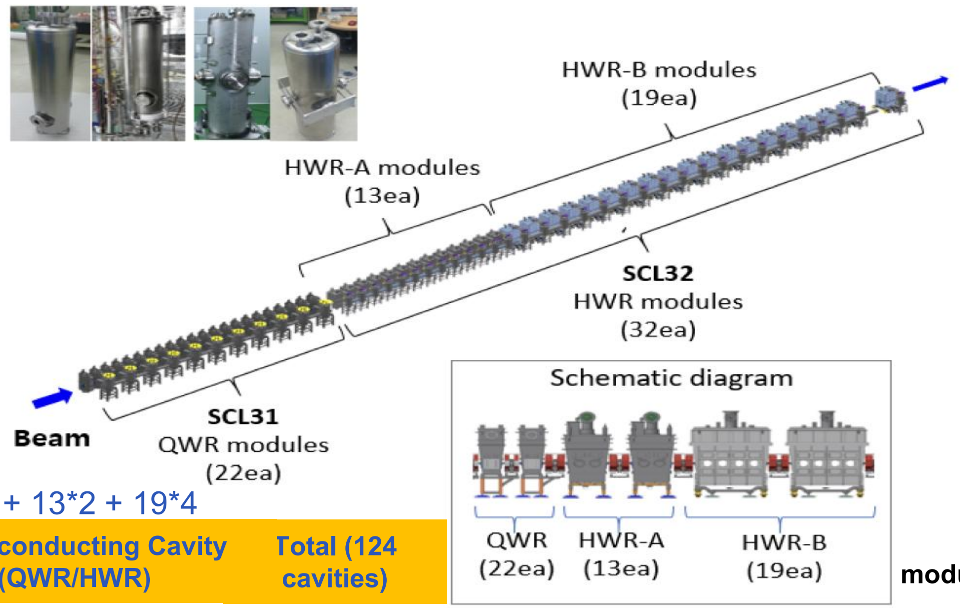
- RAON Accelerator Systems → 정연세 연구위원, IRIS Overall



02 고주파 가속관

▪ Superconducting Linear Accelerator

Superconducting Linac 3 (SCL3, Low-energy section)



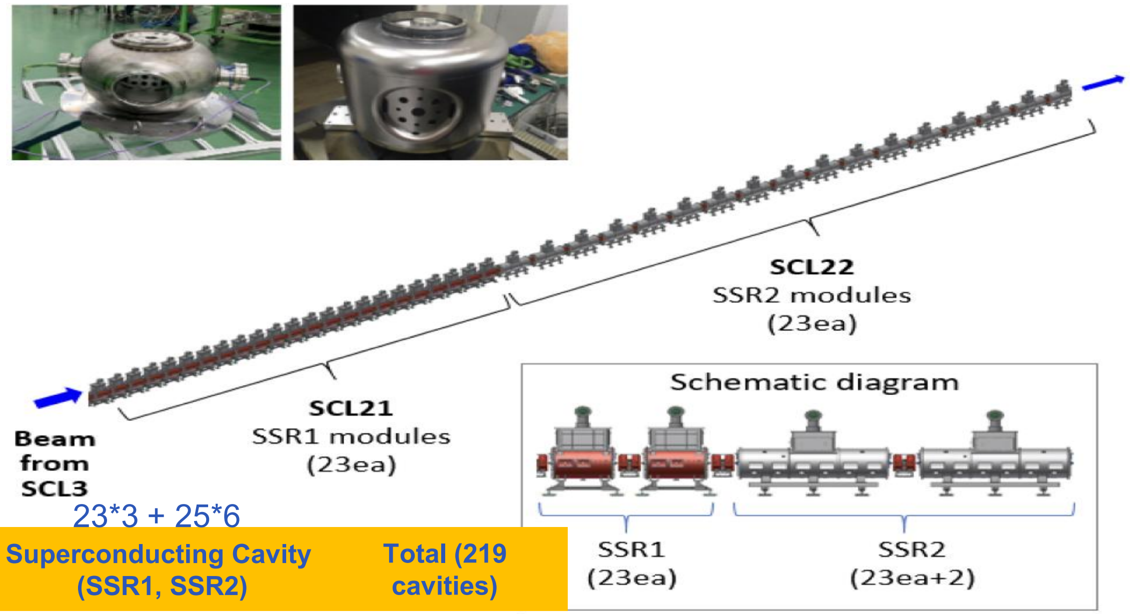
22*1 + 13*2 + 19*4

Superconducting Cavity (QWR/HWR) | Total (124 cavities)

modules

선행 R&D

Superconducting Linac 2 (SCL2, High-energy section)



23*3 + 25*6

Superconducting Cavity (SSR1, SSR2) | Total (219 cavities)

RF parameter

Type of cavity		Optimum β	f [MHz]	E_{pk}/E_{acc}	B_{pk}/E_{acc} [mT/MV/m]	E_{acc} [MV/m]	V_{acc} [MV]	QRs [Ω]
SCL3	QWR	0.051	81.25	6.0	10.8	5.7	1.07	18.1
	HWR	0.13	162.5	5.5	9.6	6.2	1.47	37.1
SCL2	**SSR1**	0.32	325	4.1	6.9	7.9	2.36	92.2
	SSR2	0.51	325	3.7	9.0	8.7	4.10	123.0

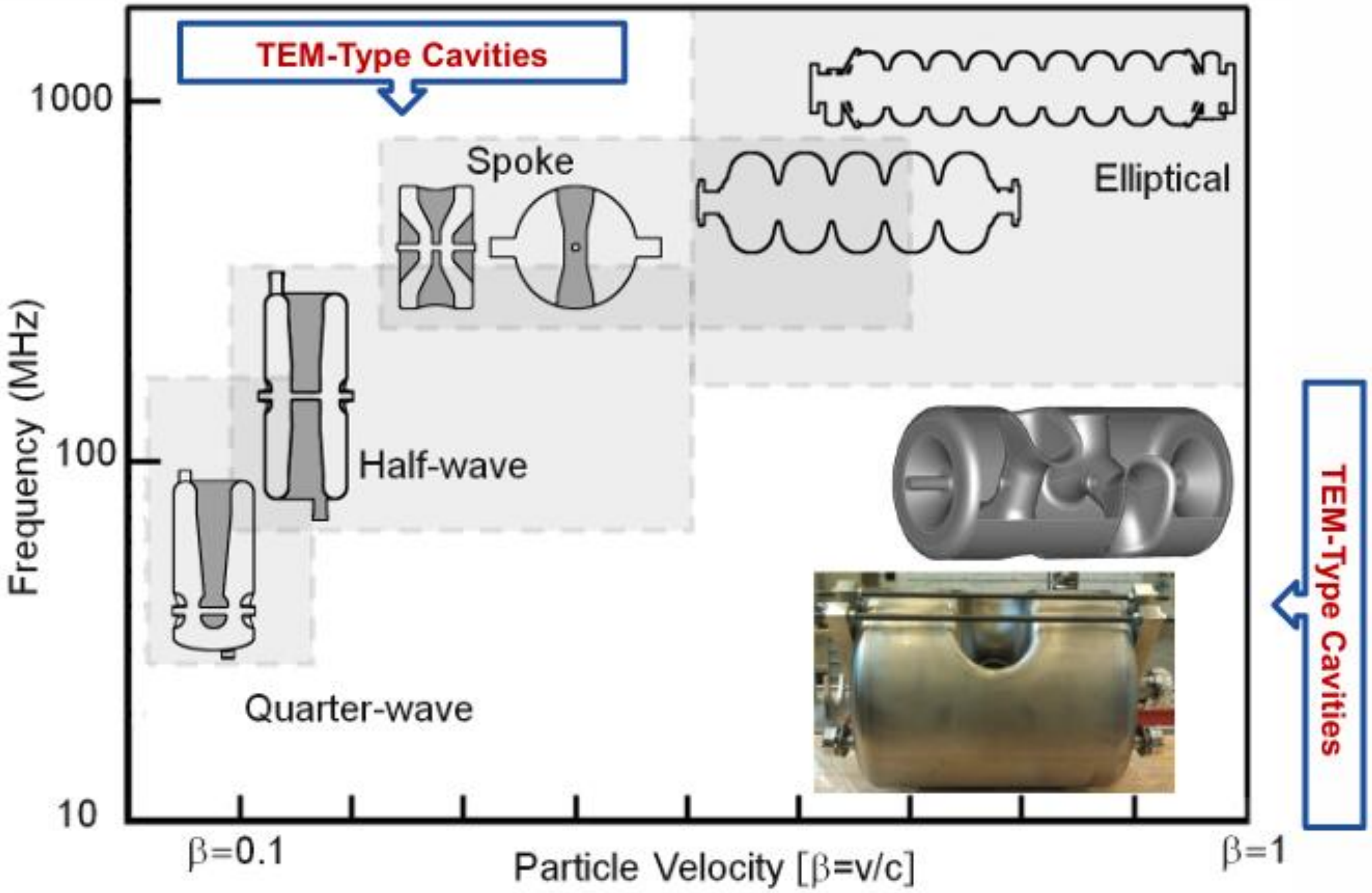
SCL2 beam parameter

Particle / parameter	Uranium	Proton
Energy [MeV/u]	200	600
Beam current [pμA]	8.3	660
Power (@ target) [kW]	400	400

02 고주파 가속관

▪ TEM class Cavity

- 중이온가속기는 전자가속기와 달리 입자의 속도가 비교적 느려 TEM class 가속관을 활용하여 빔을 가속함.



Subashini De Silva, "Superconducting Non-Elliptical Cavities (TEM Cavity Design)", Tutorial Session, June 22-24, SRF2023, Grand Rapids, MI, USA.

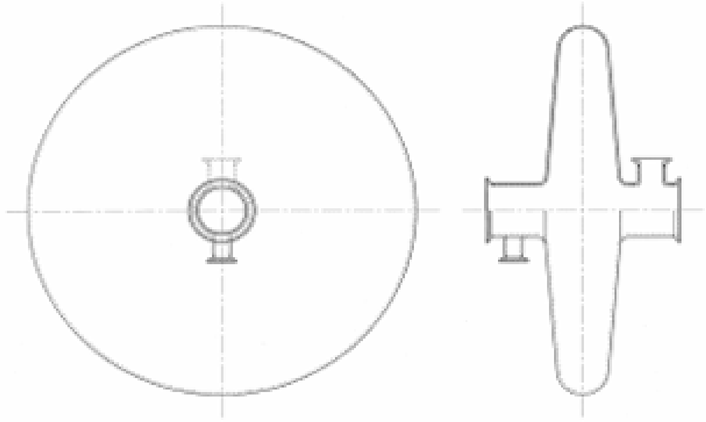
▪ TEM class Cavity

- TEM-class cavity는 4.5 K 운용 가능성과 같은 주파수의 TM 가속관에 비해 크기가 작은 이점이 있음.

TM_{010} Structures

Dia ~ 0.88 – 0.92 λ

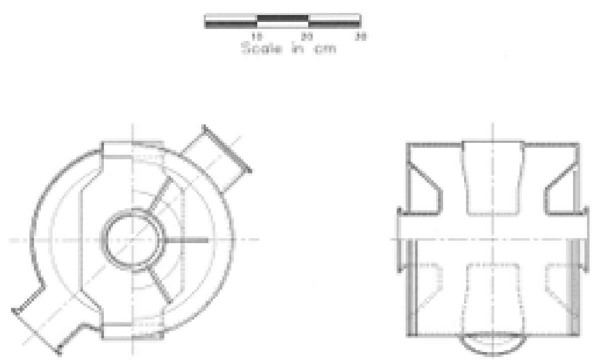
Coupling ~ 2%



λ /2 Structures

Dia~ 0.46 – 0.51 λ

Coupling ~ 20 - 30%



Example : 350 MHz, β= 0.45

Jean Delayen, "TEM-Class Cavity Design", Course Materials, June, USPAS2015

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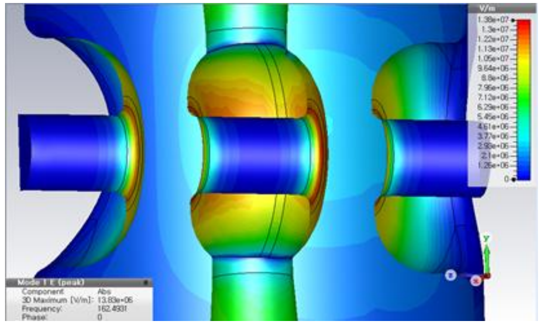
02 고주파 가속관: HWR, 설계

Electromagnetic field analysis

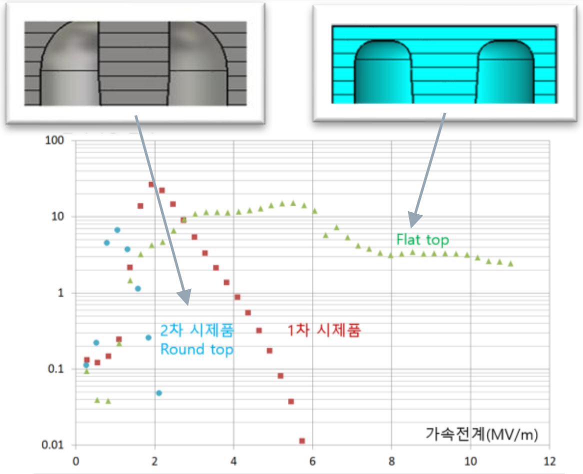
Beam port and beam sphere design



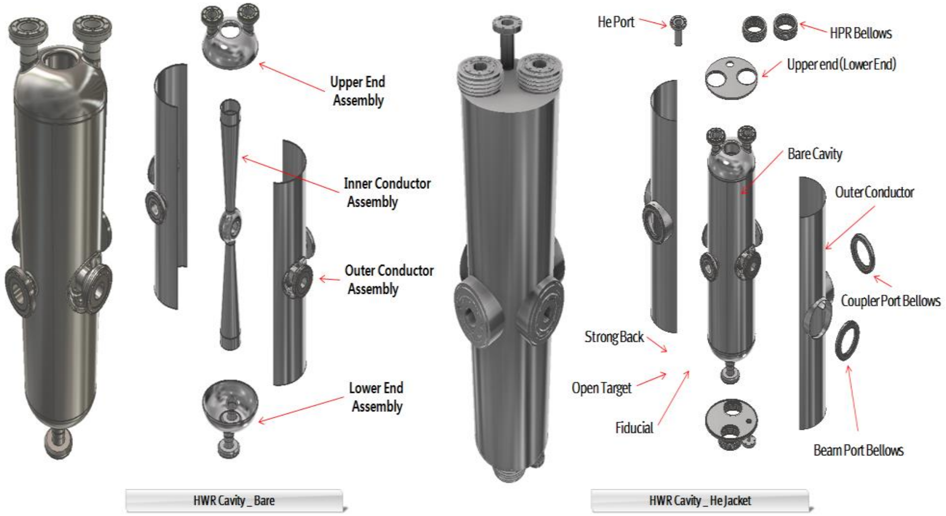
Minimize E_{pk}/E_{acc} → Suppress field emission

Minimize B_{pk}/E_{acc} → Enable higher operational gradient

Multipacting analysis

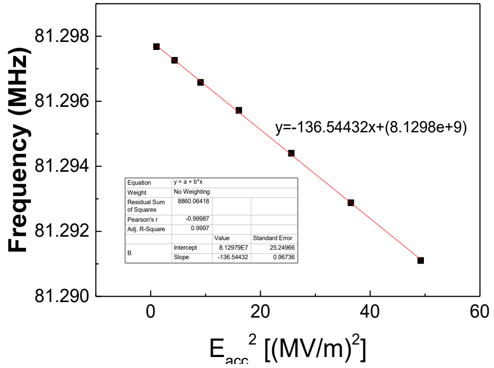


MP band below 2 MV/m



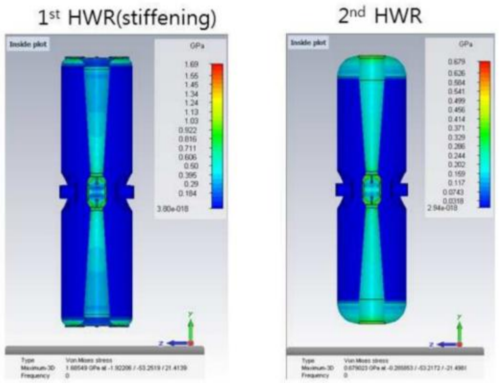
- Nb로만 구성된 Bare cavity
- 외부에 액체 헬륨을 담기 위한 He jacket

Lorentz force detuning (LFD)



- For beam port free, LFD_{cal} = -16.4 Hz / (MV/m)^2
- For beam port free, LFD_{Meas} = -14.7 ~ -44.6 Hz / (MV/m)^2

Structure analysis

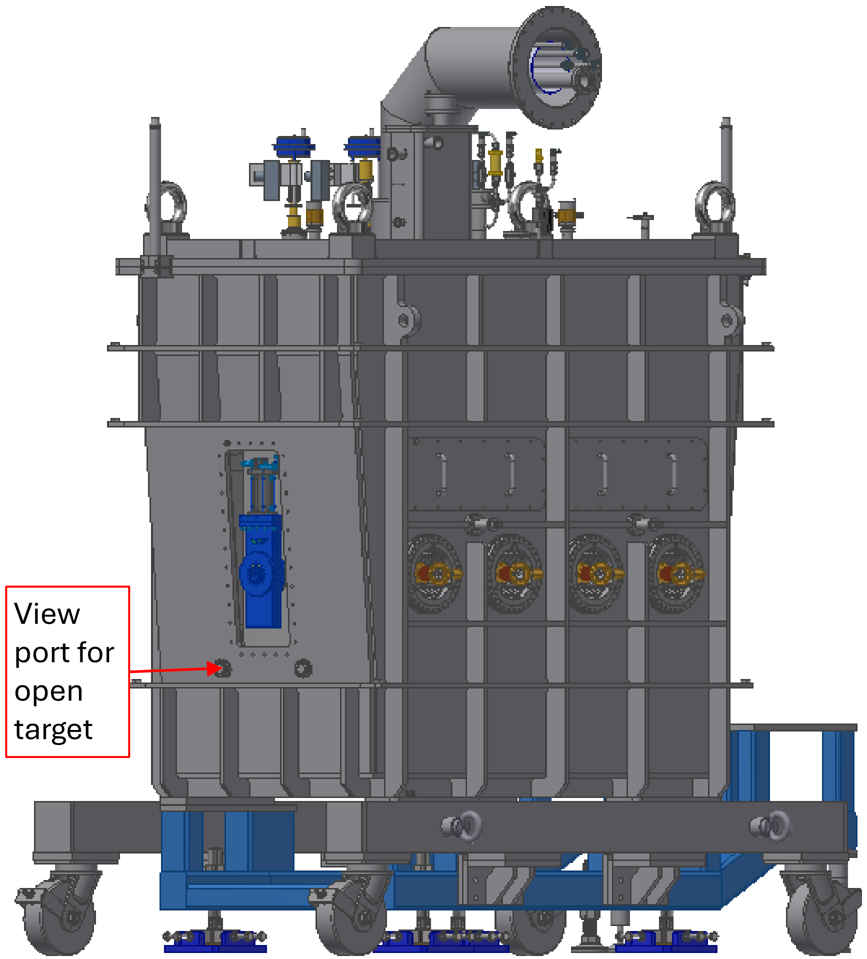


1.69GPa/100Bar　　679MPa/100Bar

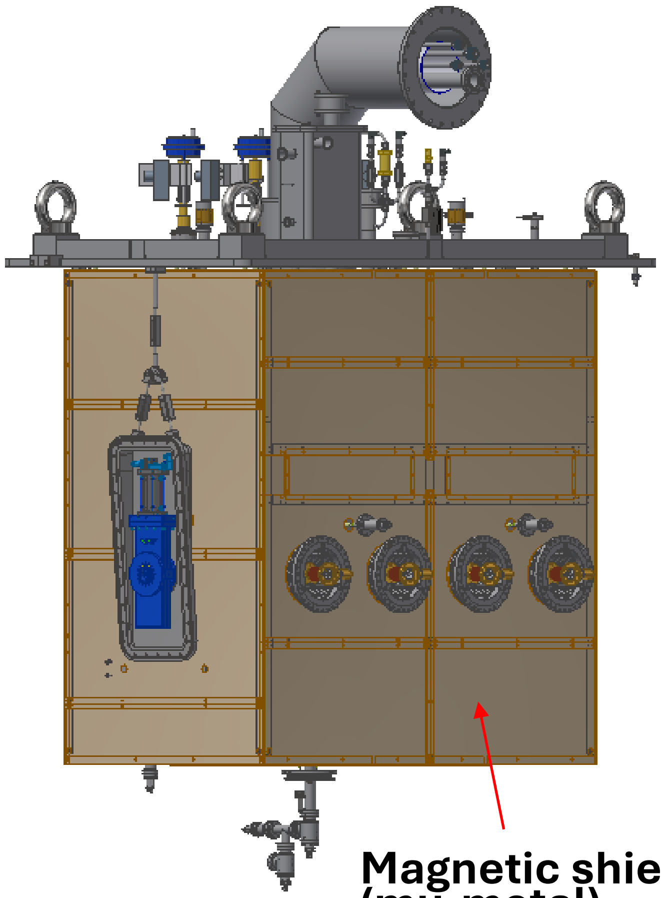
- Max. deformation: 1.9 mm → 0.86 mm
- Max. stress: 1.69 Gpa → 679 MPa

Youngkwon Kim, "QWR and HWR Cryomodules for Heavy Ion Accelerator in RAON/RISP", ASSCA2023

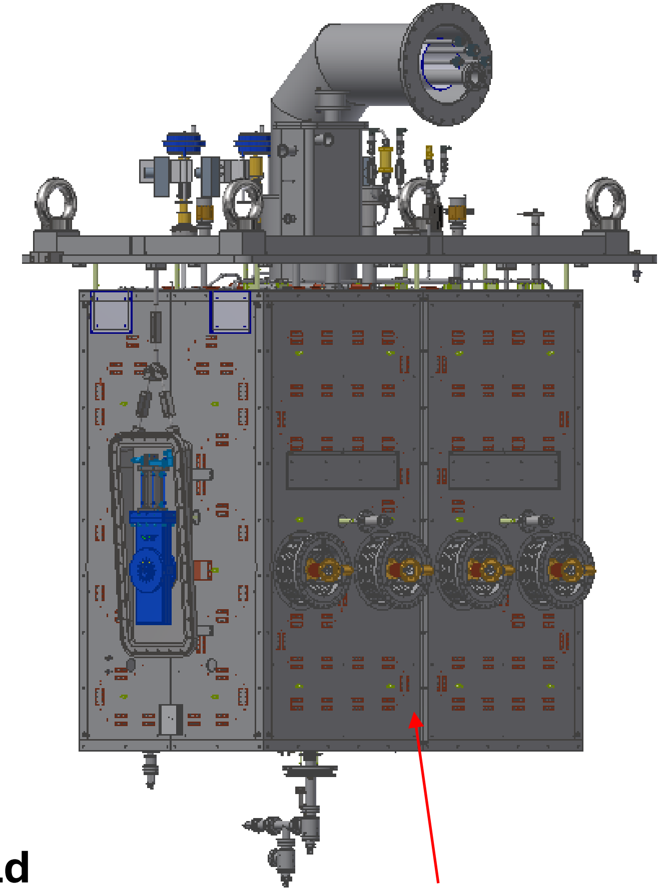
02 고주파 가속관: HWR 가속모듈



Cryomodule assembly



Magnetic shield (mu-metal)



Thermal shield (Al plate + Cu pipe)

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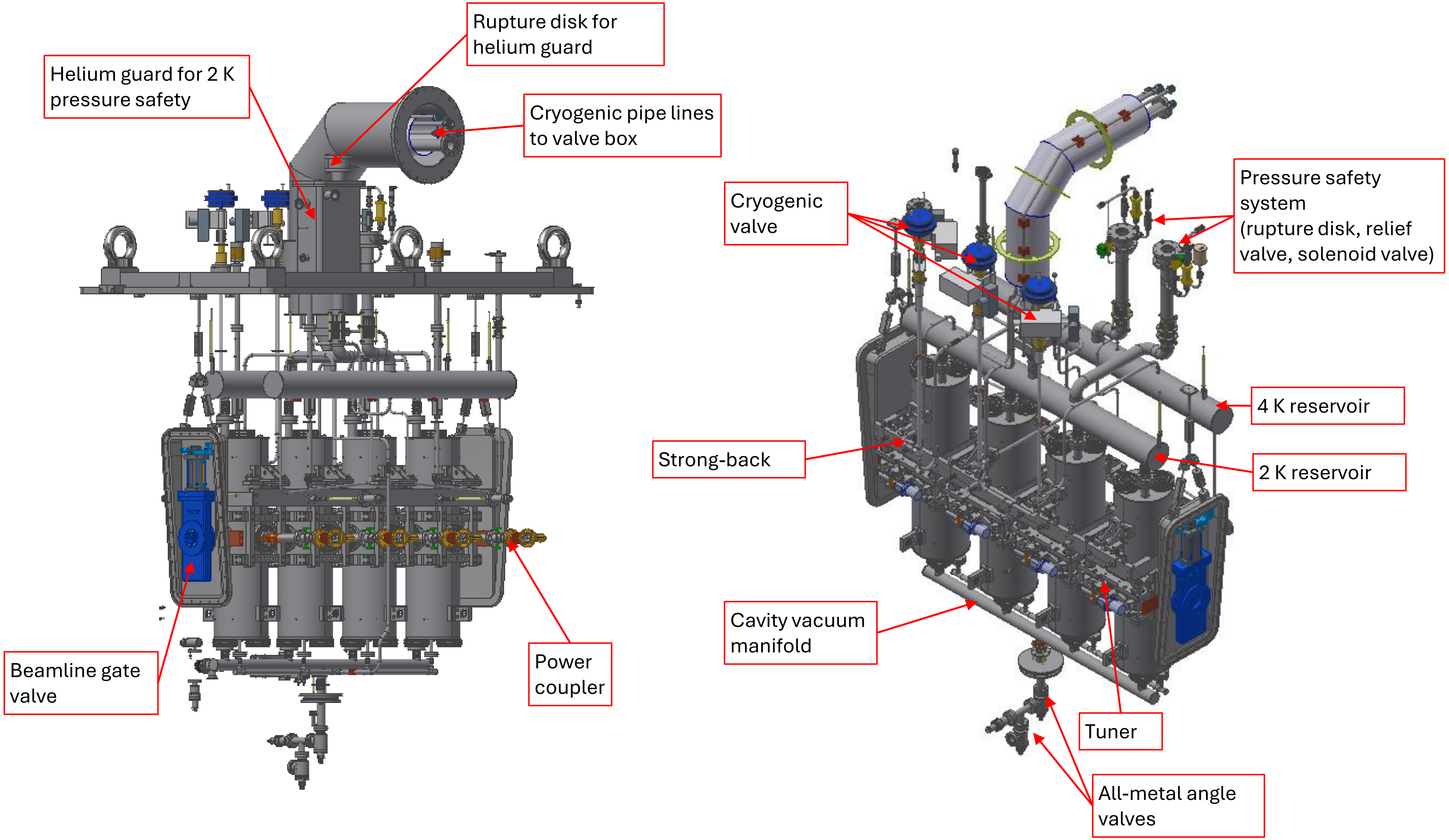
02 고주파 가속관: HWR 가속모듈



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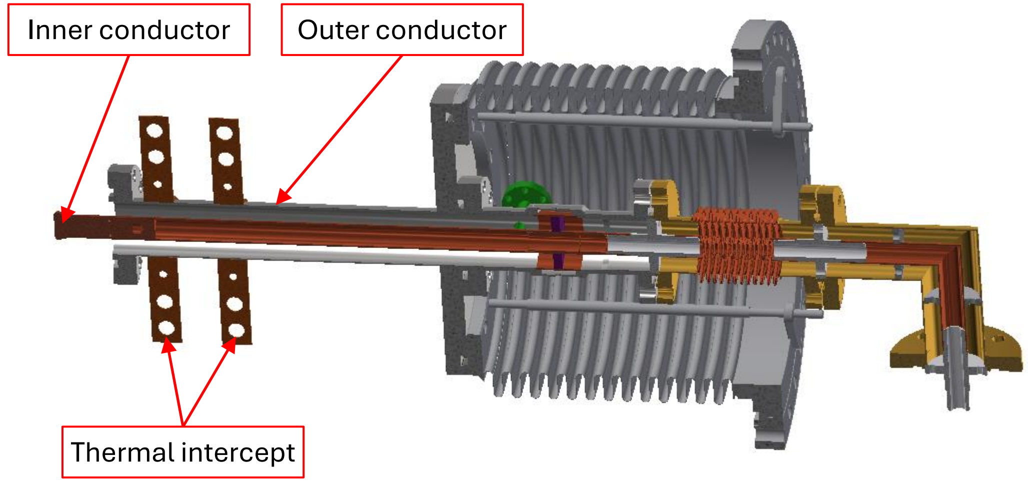
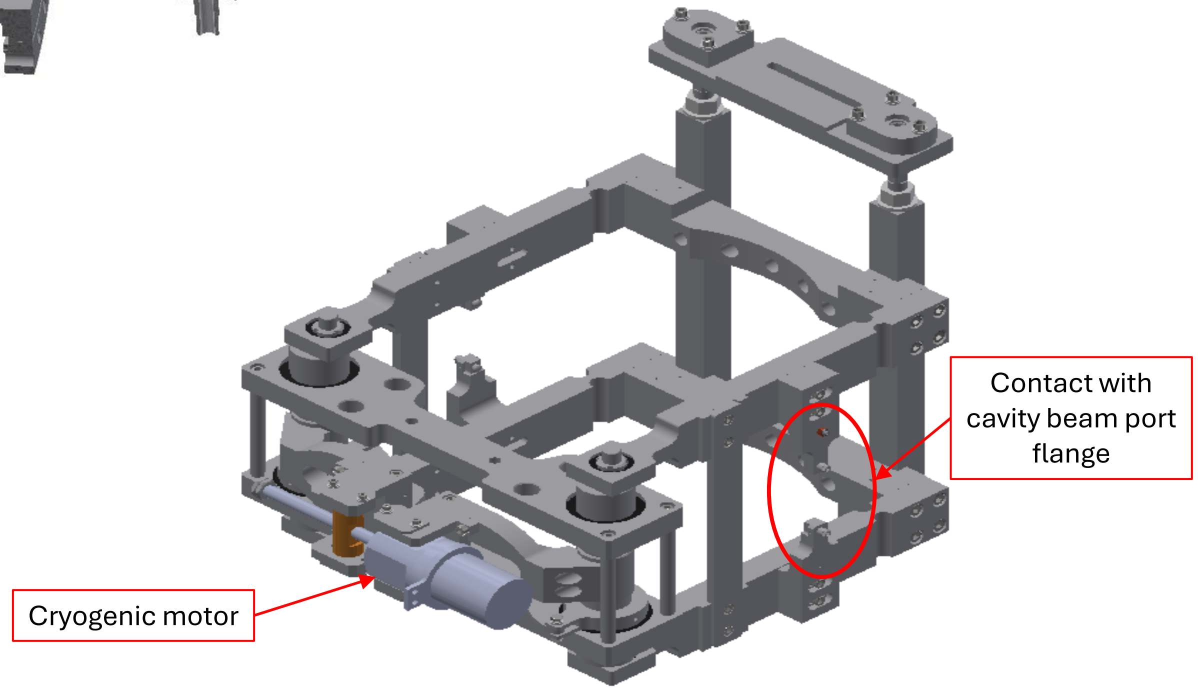
02 고주파 가속관: HWR 가속관 외 장치



Power coupler



Tuner

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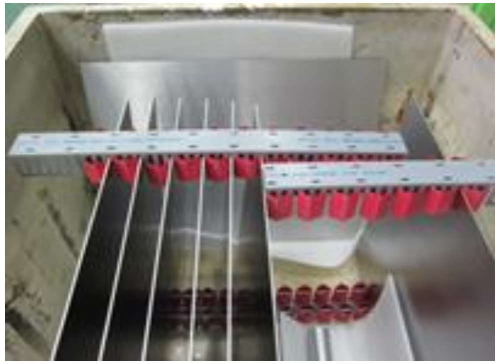
02 고주파 가속관: HWR 제작

- HWR: 원자재 검수

Material



Material inspection
- Visual inspection, Soaking test
- Structural characteristics

Cutting of materials

브라질이 전 세계 생산량의 95% 공급

EDM (Electrical Discharge Machining): (좌) 실패 사례, (우) 정상 공정

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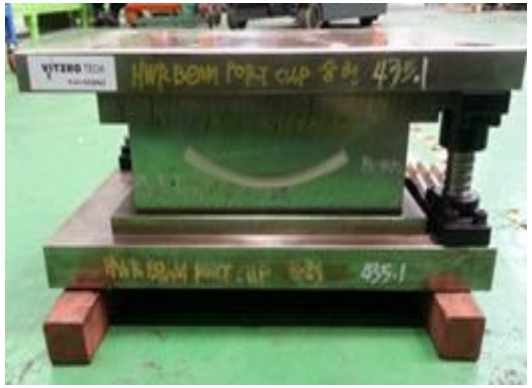
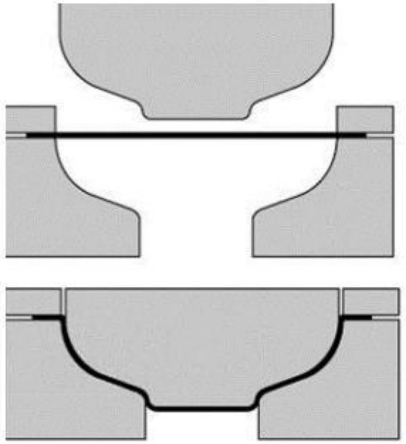
02 고주파 가속관: HWR 제작

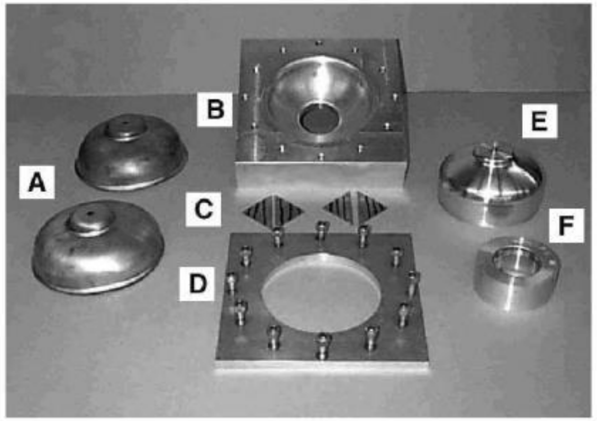
- HWR: Deep drawing



Pressing & machining for parts

Deep Drawing





T. Saeki, "Superconductive RF", LC school 2016, Fuji, Japan / Youngkwon Kim, "QWR and HWR Cryomodules for Heavy Ion Accelerator in RAON/RISP", ASSCA2023

02 고주파 가속관: HWR 제작

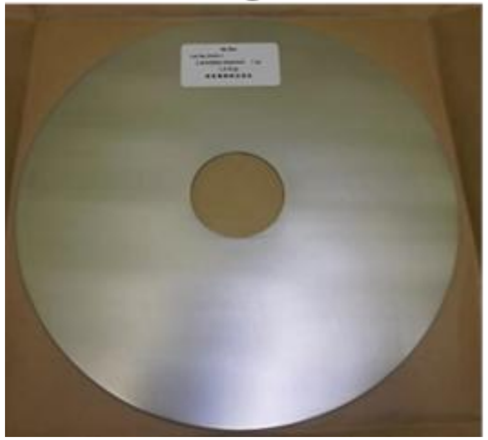
▪ HWR: Deep drawing

Large grain

- Difficulty due to deformation caused by asymmetric grains
- Relatively cheep
- Grain size : from several to more than 10 cm

Half-cell made by large-grain disk

Fine grain



- Easy and stable fabrication
- **Grain size : a few to several 10 μm**

	H	C	O	N	Fe	Si	Ta	RRR
Large grain	< 5	< 10	< 10	< 10	< 10	< 10	80	**416**
Fine grain	< 10	40	<10	40	20	20	100	**258**

T. Saeki, "Superconductive RF", LC school 2016, Fuji, Japan

02 고주파 가속관: HWR 제작

- HWR: Mechanical grinding

Mechanical Grinding

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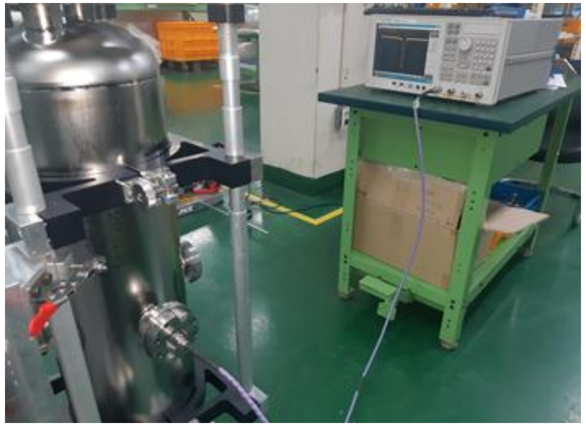
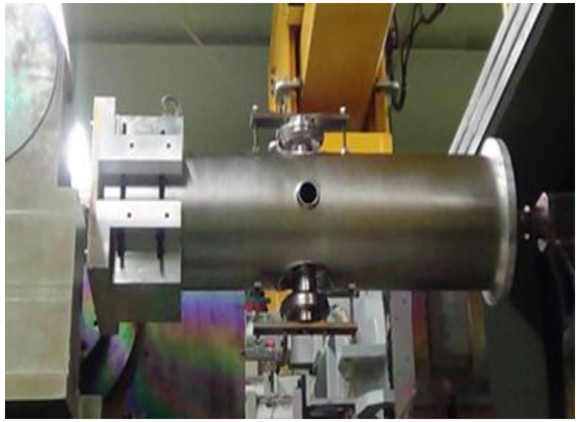
02 고주파 가속관: HWR 제작

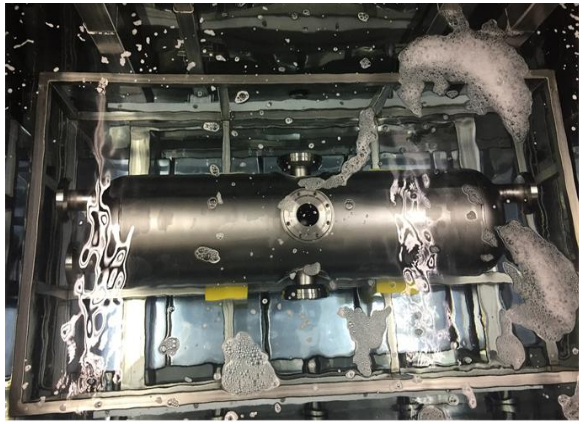
- HWR: Electron beam welding



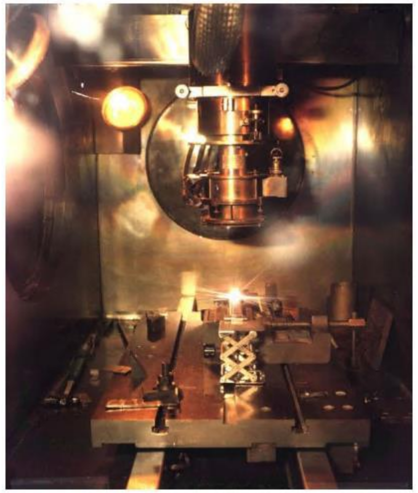
Clamp-up test
- Frequency adjustment before final welding

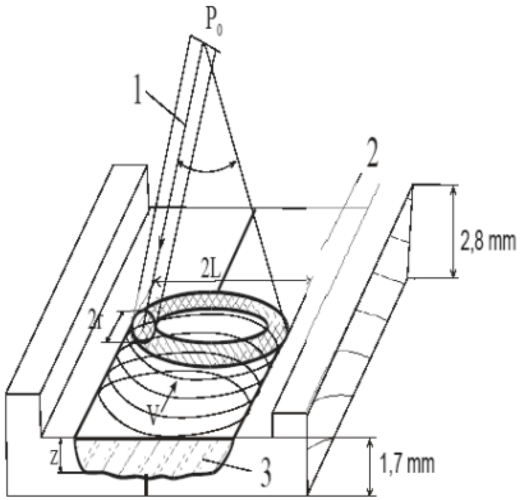


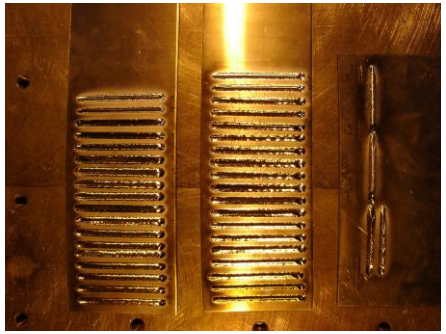
E-beam welding



Ultrasonic cleaning (USC)







T. Saeki, "Superconductive RF", LC school 2016, Fuji, Japan / Youngkwon Kim, "QWR and HWR Cryomodules for Heavy Ion Accelerator in RAON/RISP", ASSCA2023

02 고주파 가속관: HWR 제작

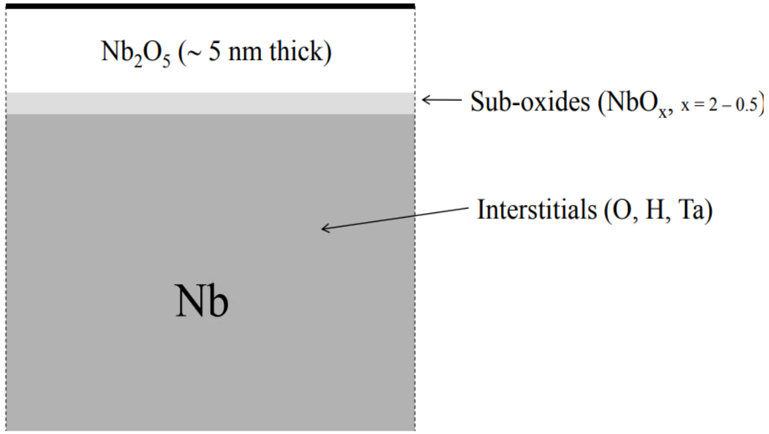
- HWR: 표면 처리

BCP

HPR

High temperature heat treatment

Nb Surface



Buffered Chemical Polish (BCP)

HF (49%), HNO_3 (65%), H_3PO_4 (85%)
Mixture 1:1:1 , or 1:1:2 by volume typical

불산, 질산, 인산

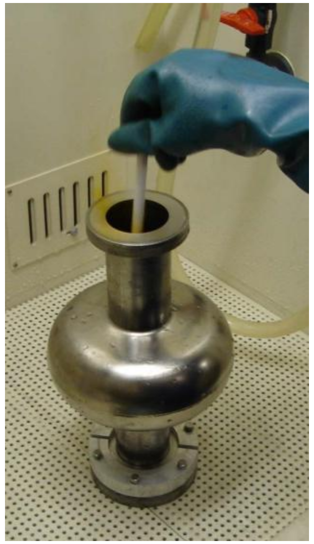
Oxidation

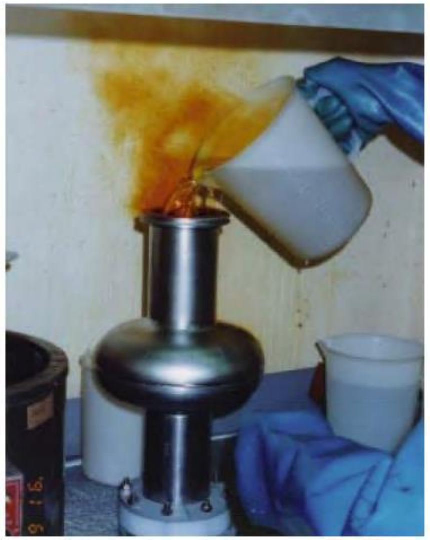
$2Nb + 5HNO_3 \rightarrow Nb_2O_5 + 5NO_2$ Brown gas

Reduction

$Nb_2O_5 + 6HF \rightarrow H_2NbOF_5 + NbO_2F\ 0.5H_2O + 1.5H_2O$

$NbO_2F\ 0.5H_2O + 4HF \rightarrow H_2NbOF_5 + 1.5H_2O$





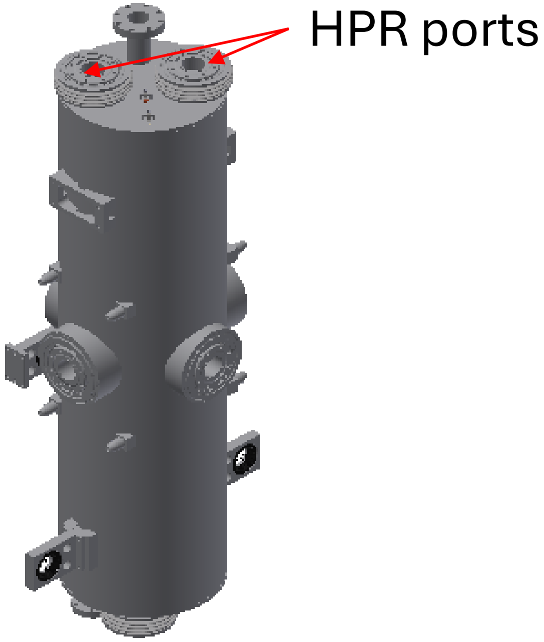
T. Saeki, "Superconductive RF", LC school 2016, Fuji, Japan / Youngkwon Kim, "QWR and HWR Cryomodules for Heavy Ion Accelerator in RAON/RISP", ASSCA2023

02 고주파 가속관: HWR 제작

- HWR: 표면 처리, HPR 상세

Visual inspection → **USC** → **HPR** → **Drying** → **Clean assembly**

- **Visual inspection** ↓ Scratch, dent, oil
- **USC** ↓ DI water, 50°C, 20 min.
- **HPR** ↓ Fixture installation ↓ DI water quality check (18MΩ) ↓ Beam port (5cm/min, 20rpm) ↓ 2 x HPR port (5cm/min, 20rpm) ↓ 2 x HPR port (5cm/min, 20rpm)
  - 10 ~ 12 hours
- **Drying** ↓ 10 class cleanroom



Youngkwon Kim, "QWR and HWR Cryomodules for Heavy Ion Accelerator in RAON/RISP", ASSCA2023

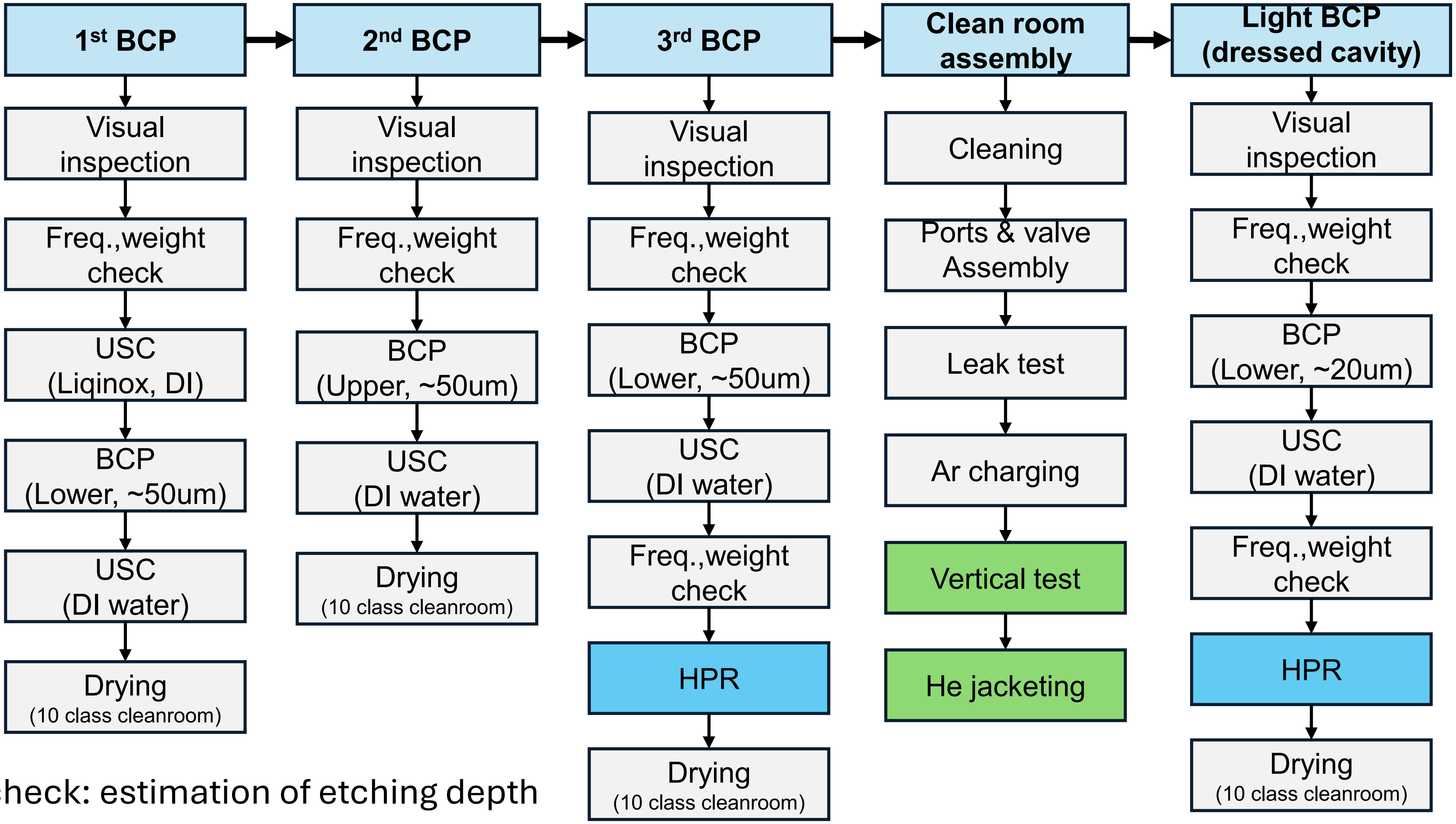
02 고주파 가속관: HWR 제작

- HWR: 표면 처리, USC

- Class1000 (ISO6) cleanroom
- Double bath type
  - 1^{st} bath(degreasing) : 1% liquinox
  - 2^{nd} bath(rinsing) : DI water
- Ultrasonic Power : 1.5kW
- Ultrasonic Frequency : 40kHz
- Heating up to 60℃

Youngkwon Kim, "QWR and HWR Cryomodules for Heavy Ion Accelerator in RAON/RISP", ASSCA2023

▪ HWR: BCP procedure in detail



* Weight check: estimation of etching depth

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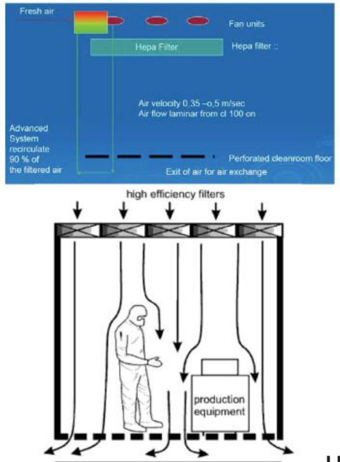
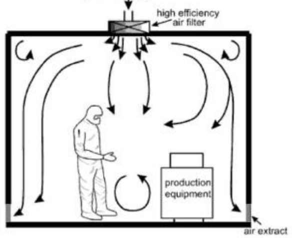
- HWR: Clean Assembly



Non-Unidirectional airflow type (JLab)



Unidirectional airflow type (DESY)

Cleanroom Classification

ISO Classification number	Maximum concentration limits (particles/m³ of air) for particles equal to and larger than the considered sizes shown below					
	>=0.1µm	>=0.2µm	>=0.3µm	>=0.5µm	>=1µm	>=5.0µm
ISO Class 1	10	2				
ISO Class 2	100	24	10	4		
ISO Class 3	1 000	237	102	35	8	
ISO Class 4	10 000	2 370	1 020	352	83	
ISO Class 5	100 000	23 700	10 200	3 520	832	29
ISO Class 6	1 000 000	237 000	102 000	35 200	8 320	293
ISO Class 7				352 000	83 200	2 930
ISO Class 8				3 520 000	832 000	29 300
ISO Class 9				35 200 000	8 320 000	293 000

ISO 14644-1 Classes	Class 3	Class 4	Class 5	Class 6	Class 7	Class 8
FS 209 Classes	Class1	Class 10	Class 100	Class 1000	Class 10, 000	Class 100, 000

Cavity assembly

Cleanroom for SRF

반도체

T. Saeki, "Superconductive RF", LC school 2016, Fuji, Japan

▪ HWR: Clean Assembly

USC & HPR

Parts using USC	Parts not using USC
Less than 1 particle (≤ 0.3μm) /5s	Less than 1 particle (≥ 1.0 μm) /1s

Particle counting

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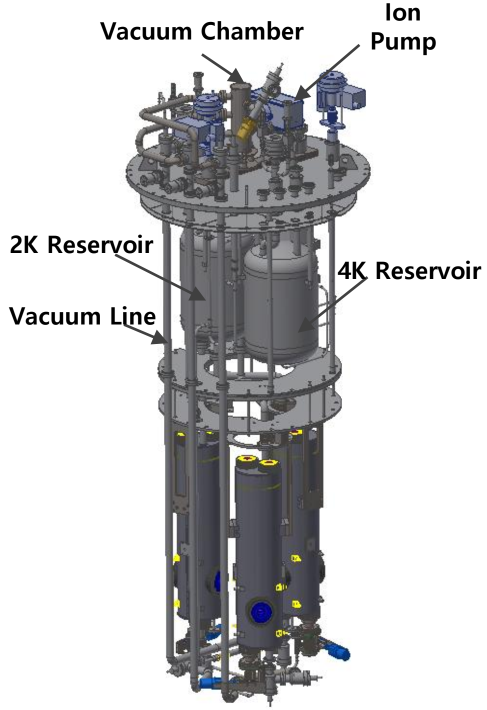
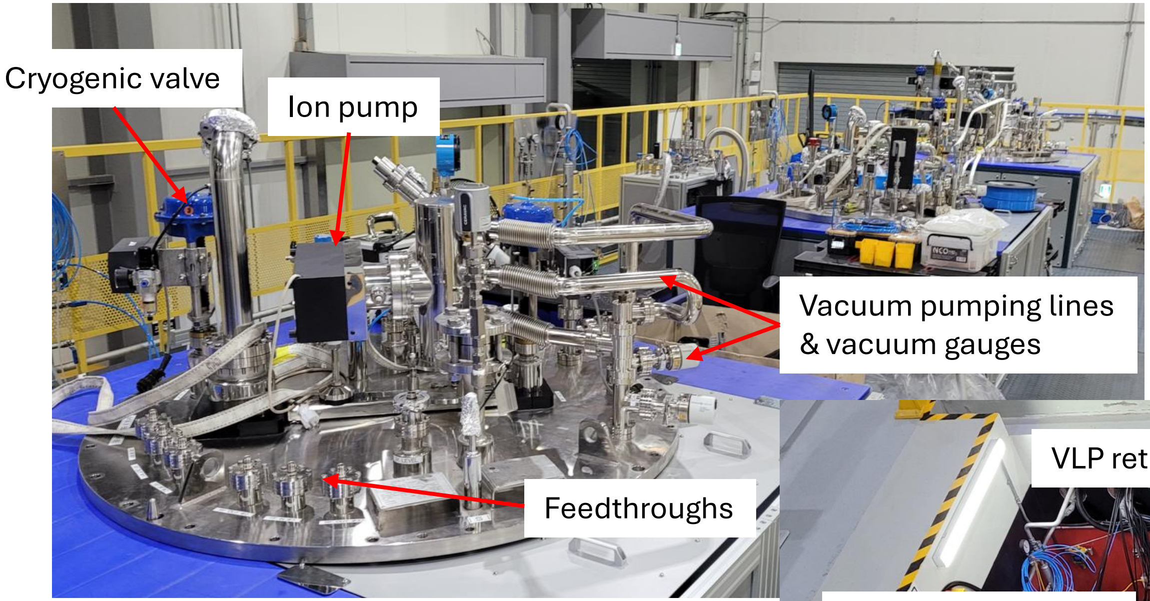
- HWR: Vertical test facility

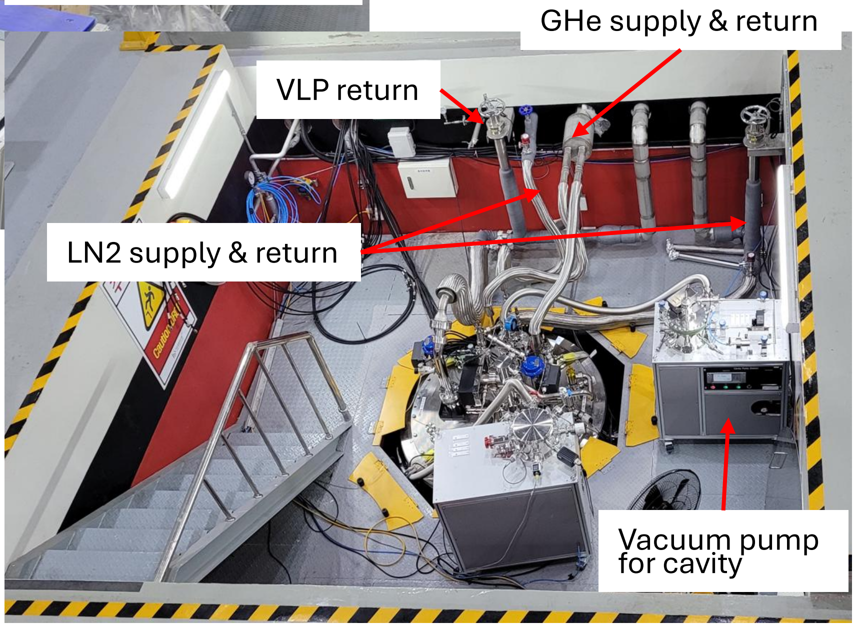

Cryostat
+ Magnetic shield



Top flange
한번에 4개의 HWR 가속관 동시 냉각 가능



Assembly area(clean room) for vertical test



Top flange in the vertical test pit

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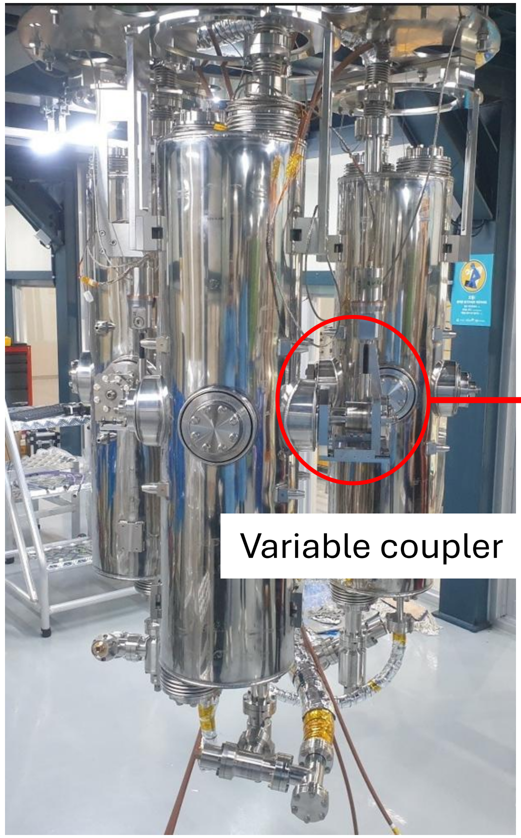
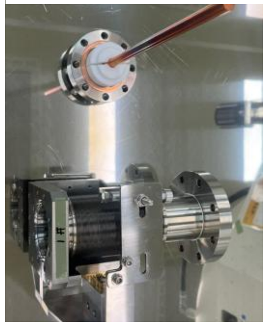
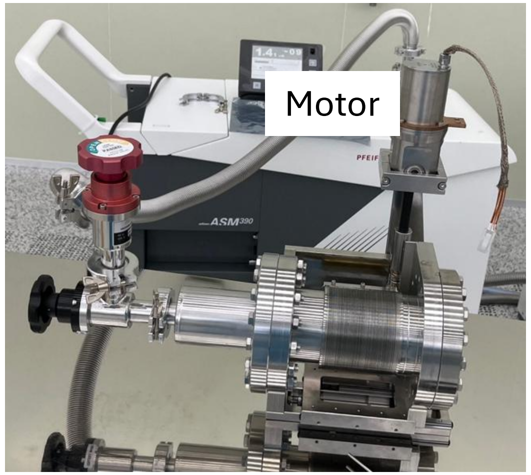
▪ HWR: Vertical test facility



Inner conductor



Outer conductor and bellows



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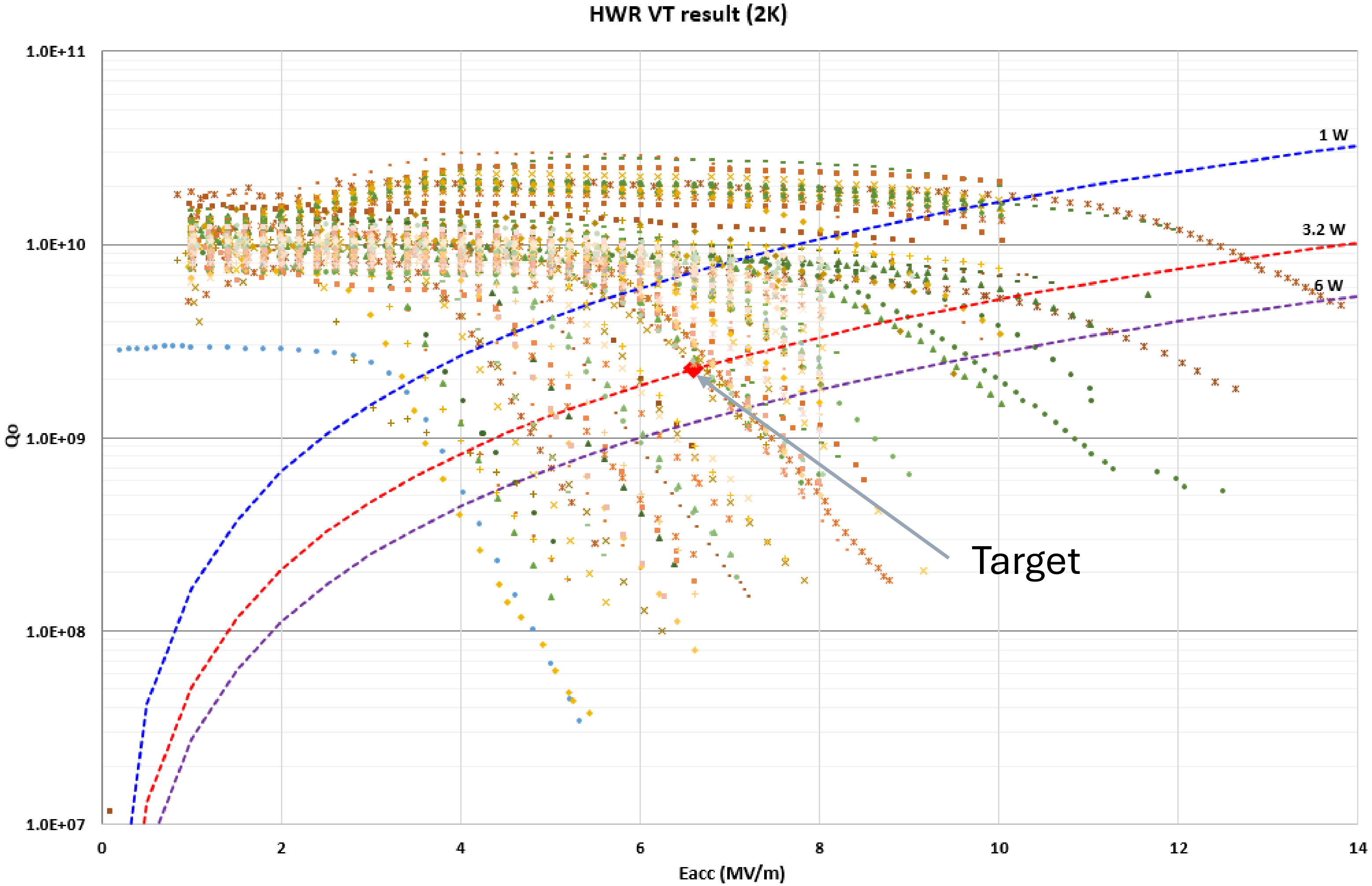
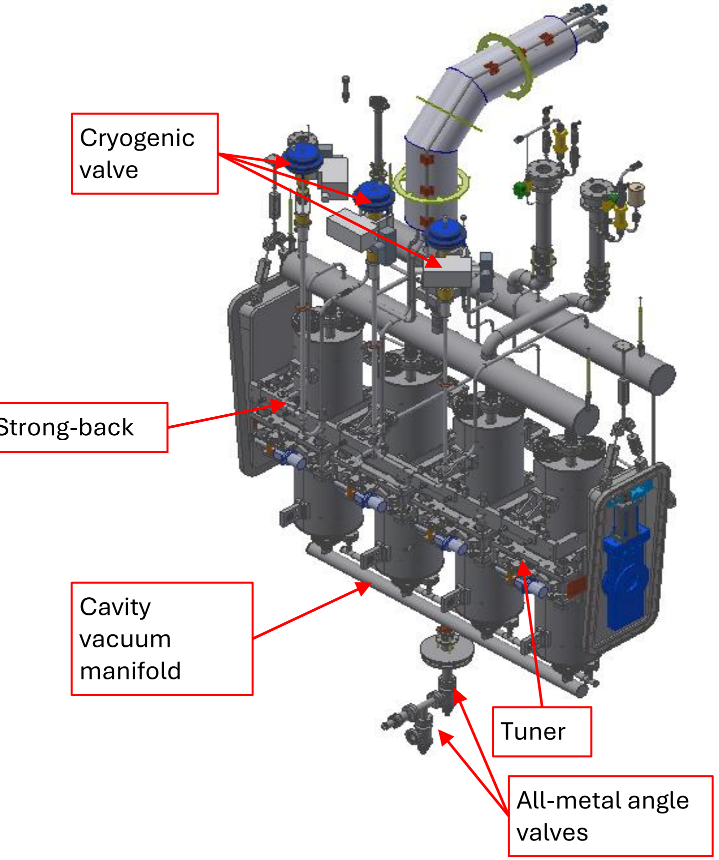
- HWR: VT Results

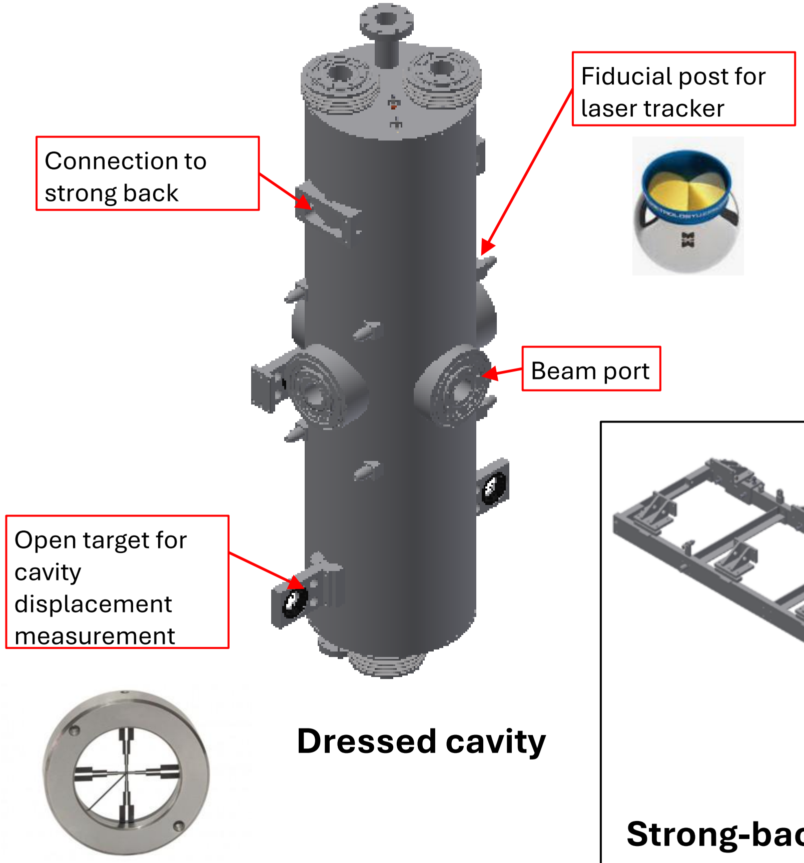


E_{acc}: 6.6 MV/m, Q_0=2.3e+9@2.05K, Number of cavity: 106 ea

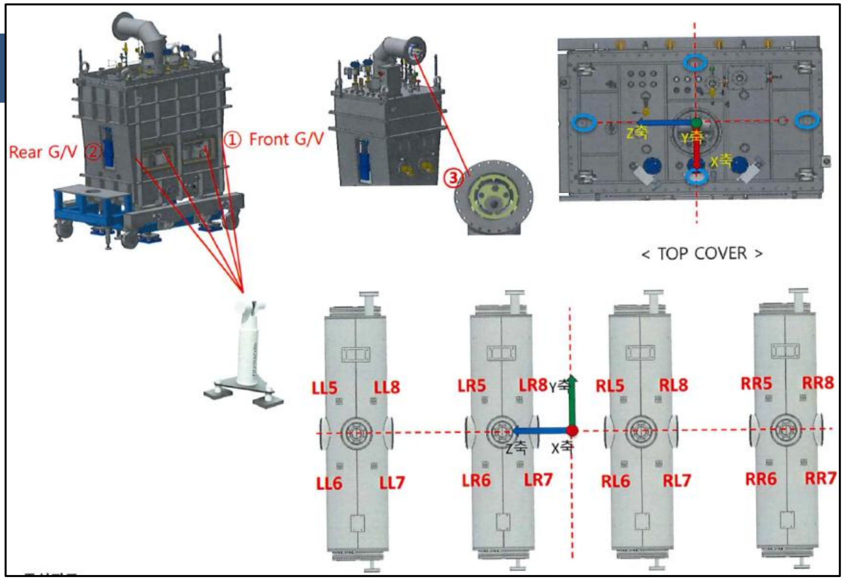
▪ HWR: 가속모듈 조립



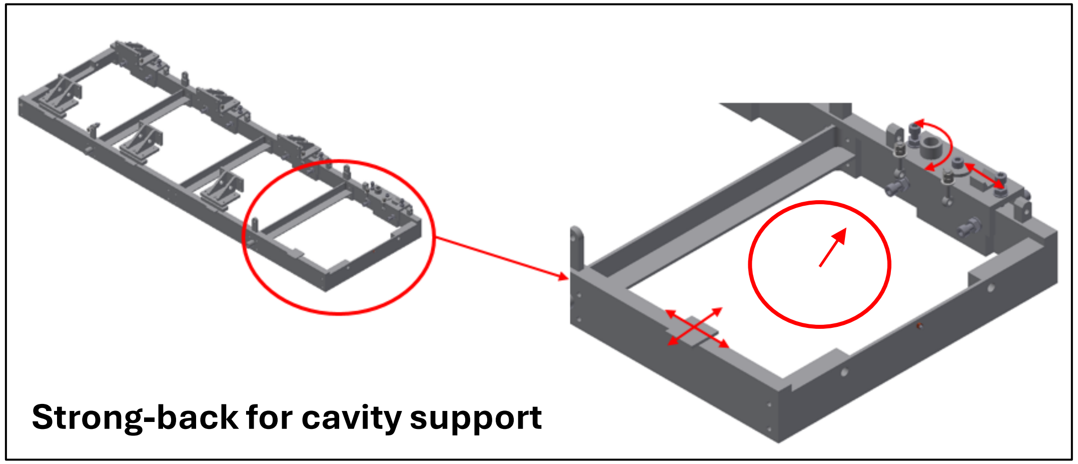
Precision assembly in cyromodule



Dressed cavity



Cavity position measurement during assembly



Strong-back for cavity support

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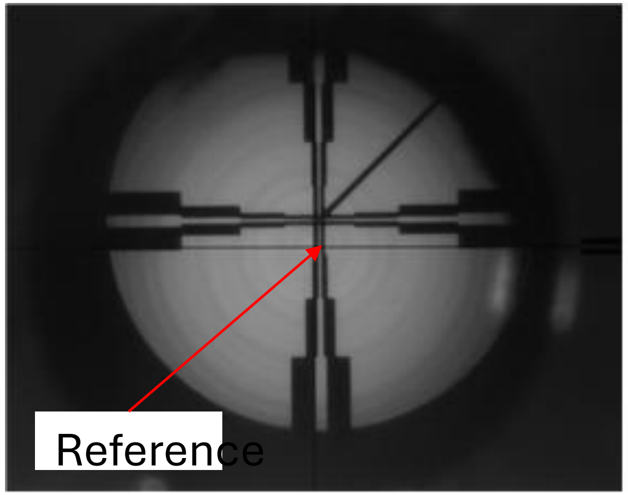
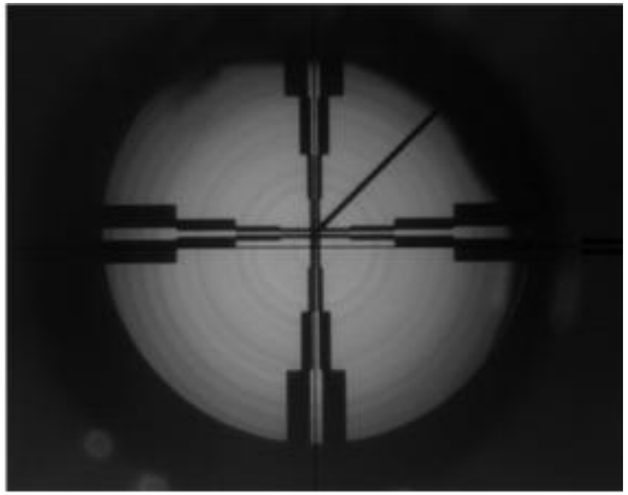
02 고주파 가속관

▪ HWR: 가속모듈 조립

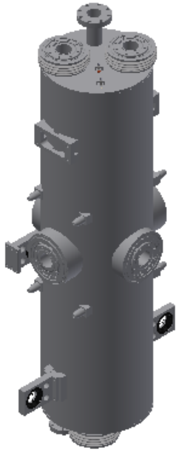
Micro Alignment Telescope (MAT)





Measurement of open target position before and after cool-down

- Measurement of cavity's displacement before and after vacuum pumping and cool-down
- Location of the beam port can be estimated by the displacement of the open targets



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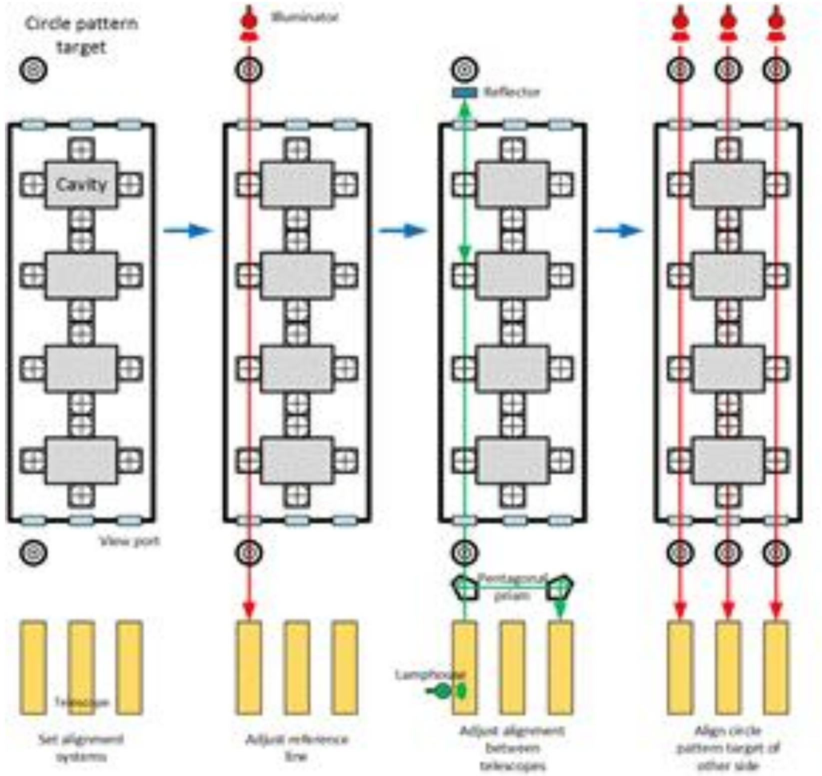
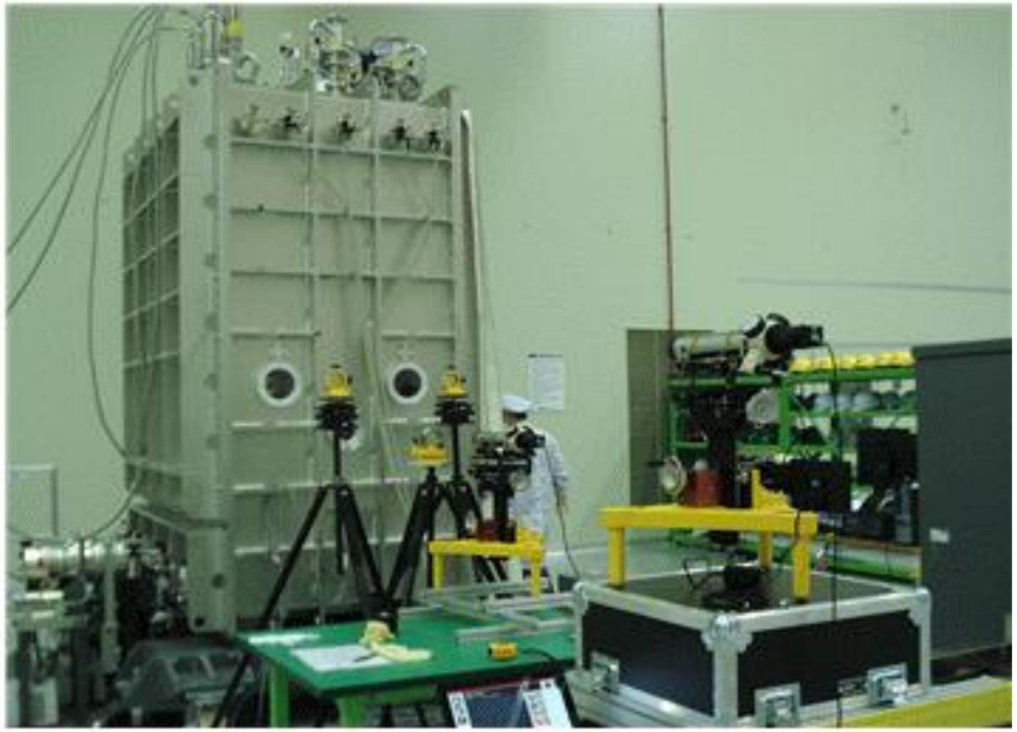
▪ HWR: 가속모듈 조립





- Open targets on the beam ports to know the actual position of beam ports
- To check the repeatability and to know the amount of vertical calibration

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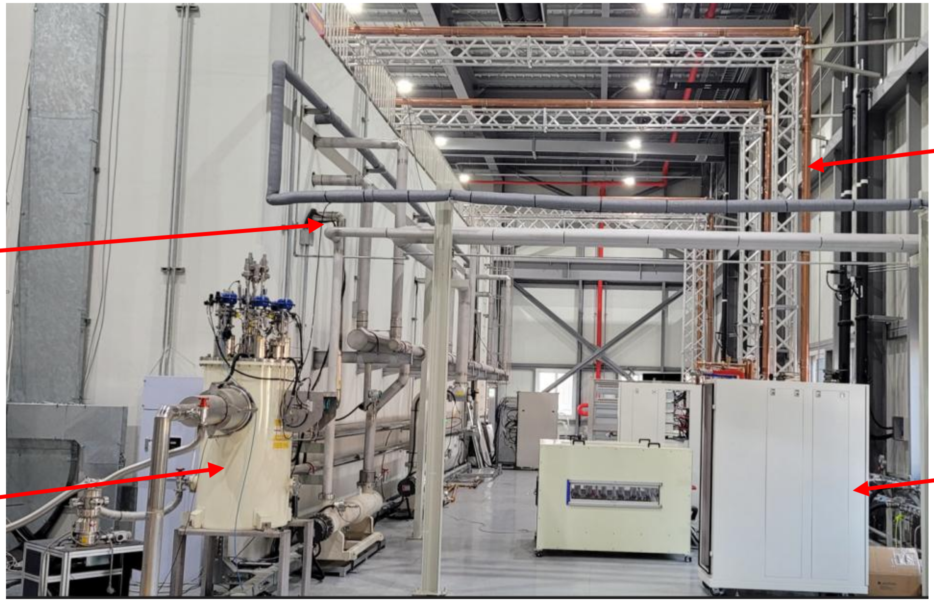
- HWR: Horizontal test facility

Horizontal test bunkers



Helium distribution lines

신재희 연구위원, “IRIS Cryogenics”

Valve box for HT

RF transmission line

설경태 연구위원, “IRIS RF other than SRF Cavities”

SSPA

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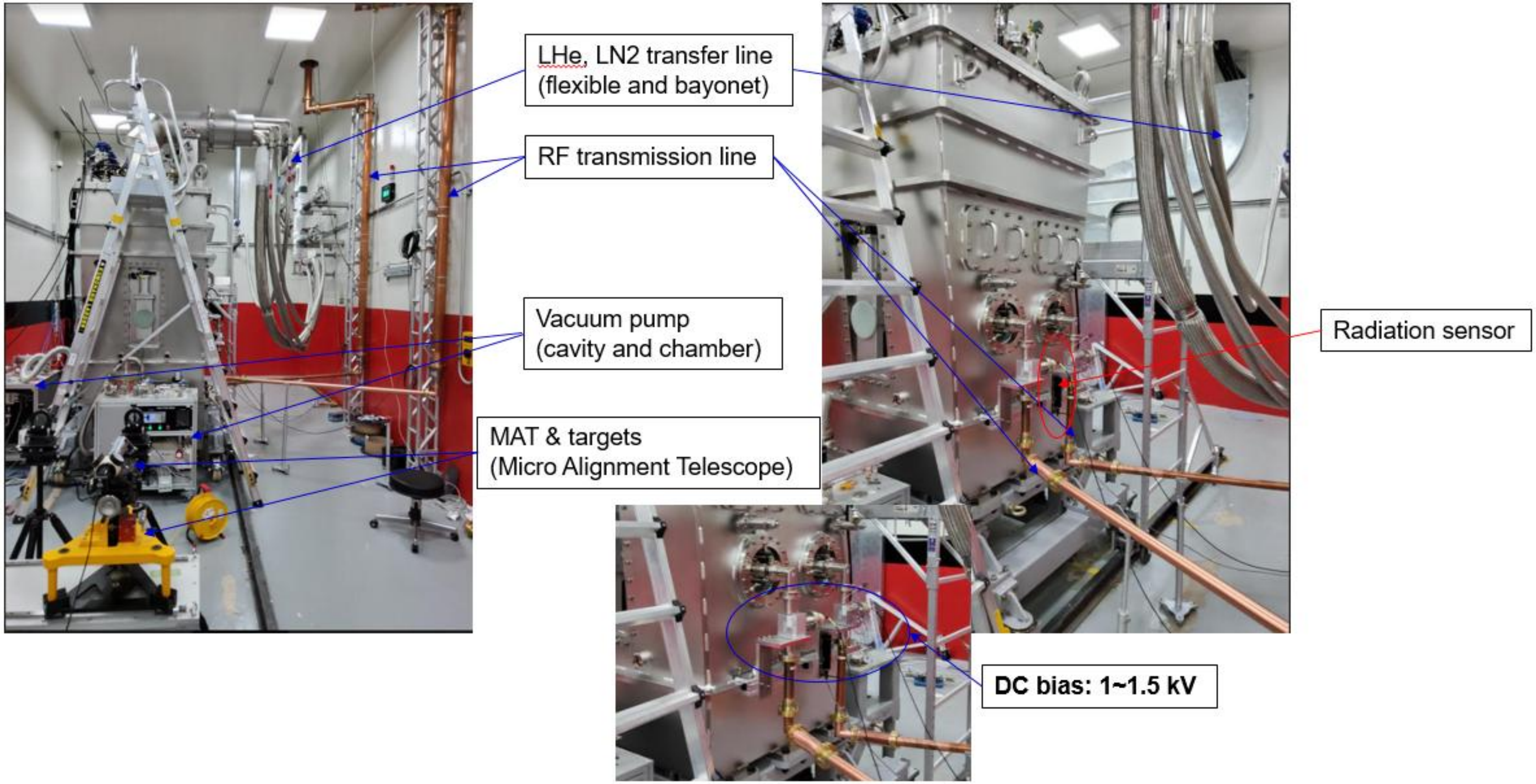
- HWR: Horizontal test facility



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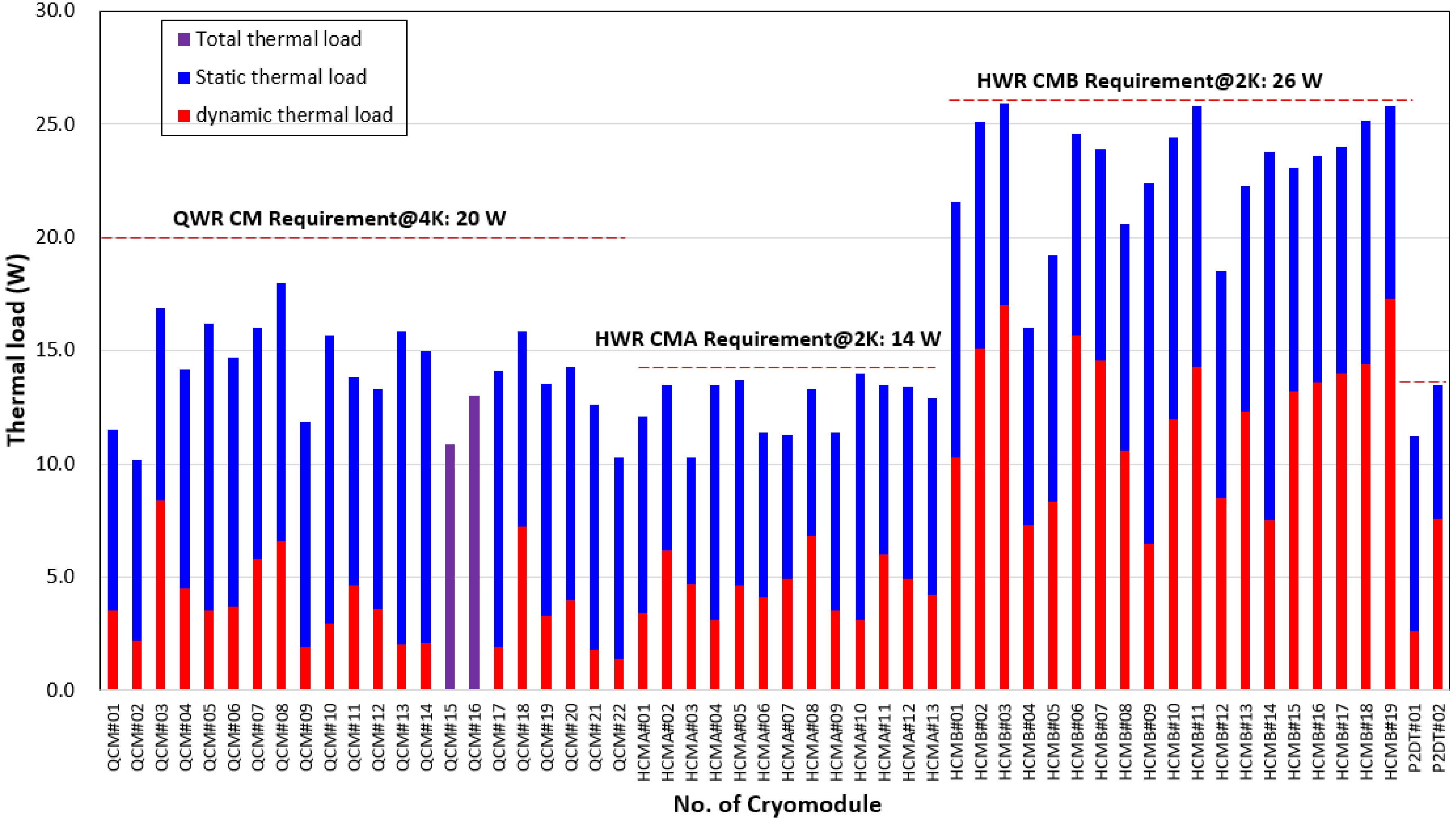
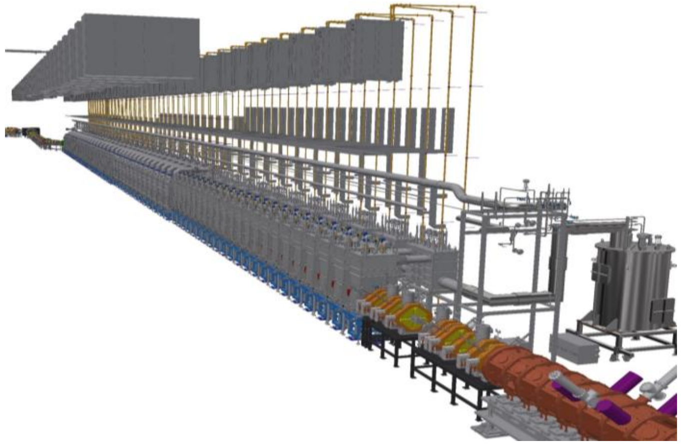
▪ HWR: Thermal load measurement results





SCL3 Installation

- Dynamic thermal load of each cryomodule is the sum of the dynamic thermal load of cavities in the cryomdoules

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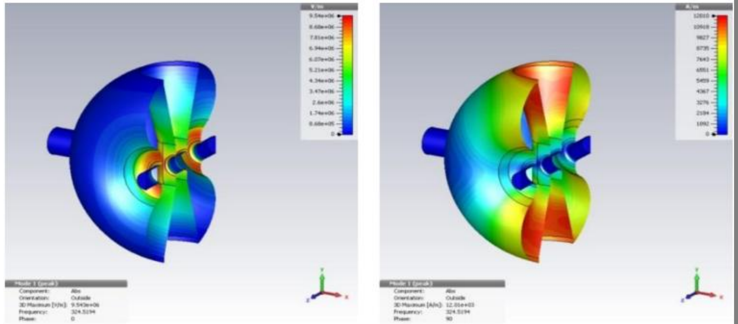
- 목 차 -

02 고주파 가속관: SSR1, 설계

Electromagnetic field analysis

E-field & B-field distributions

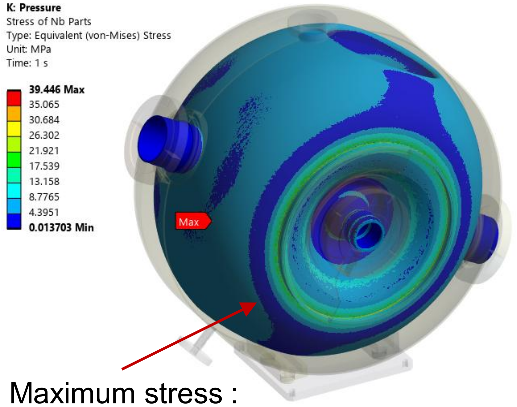


Minimize E_{pk}/E_{acc} → Suppress field emission

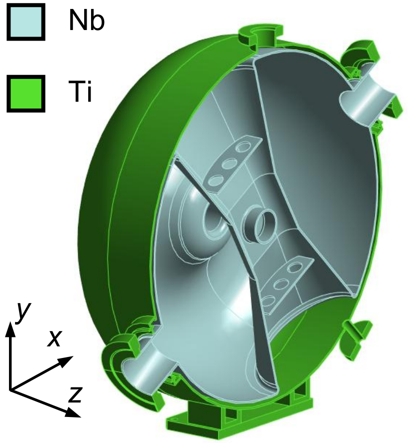
Minimize B_{pk}/E_{acc} → Enable higher operational gradient

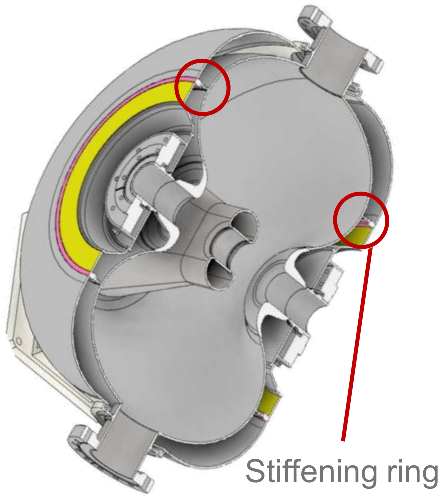
Structure analysis

Under vacuum after jacket-stiffening ring welding



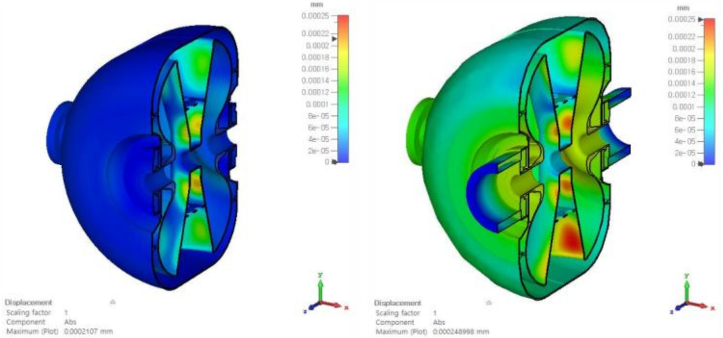
Maximum stress :
39.5 MPa < (47.0 MPa)





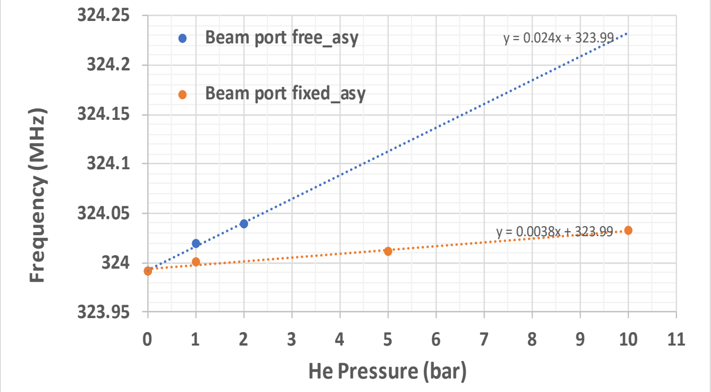
Lorentz force detuning (LFD)

Beam port fixed **Tuner assembled condition**



- For beam port fixed, LFD = -2.45 Hz / $(MV/m)^2$
- For tuner assembled, LFD = -3.67 Hz / $(MV/m)^2$

df/dp analysis



Beam port free condition : 24 kHz/mbar

Beam port fixed condition : 3.8 kHz/mbar

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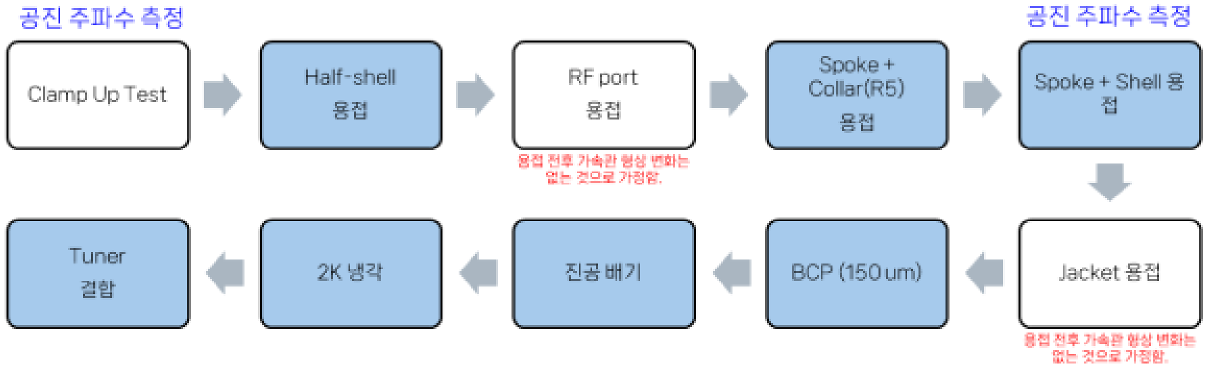
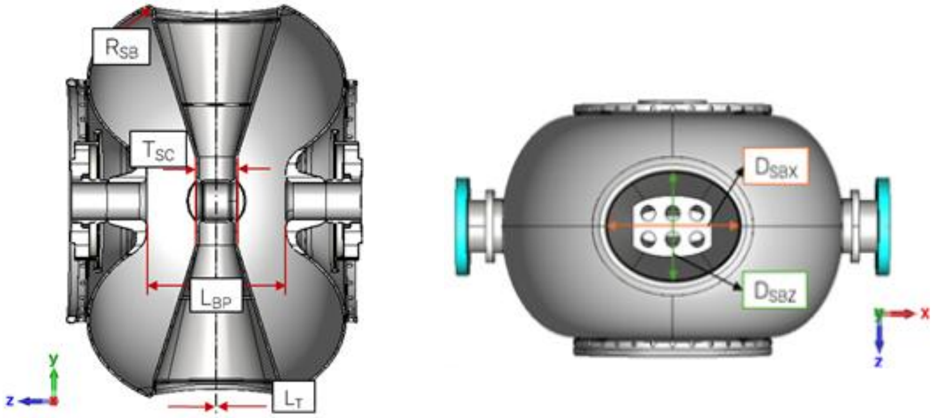
SSR1 가속관 가공 중 예상되는 주파수 변화 민감도 해석

연구내용	▪ 해석을 통하여 가속관 형상 변수에 따른 주파수 변화 민감도 확인

✓ 클램프업 시험 후 가속관 주파수에 영향을 미치는 공정 식별

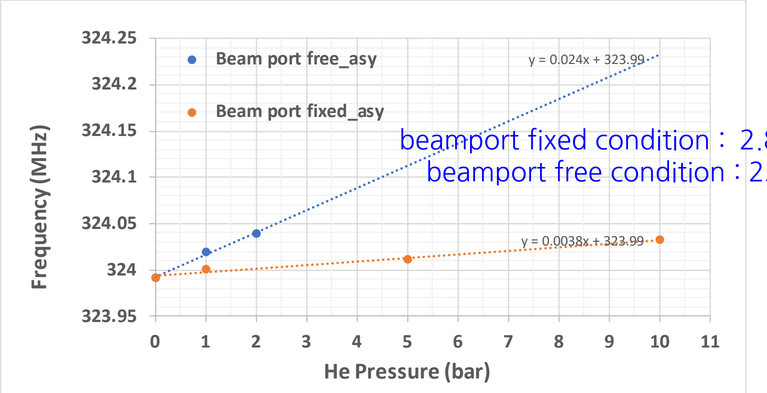


✓ 해석을 통한 주파수 변화 및 민감도



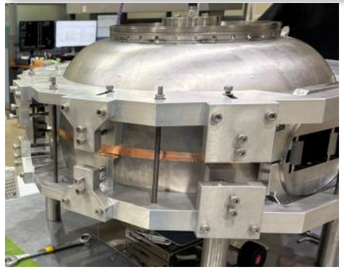
변수	주파수 변화 및 민감도	비고
R_{SB}	+196 kHz	Spoke base의 Collar 부품 곡률
L_{BP}	+235 kHz/mm	Beam port 간 간격
L_T	+129 kHz/mm	Half-shell의 trimming 길이
T_{SC}	-462 kHz/mm	Spoke Center 두께
D_{SBX}	+235 kHz/mm	Spoke base의 직경 (x축)
D_{SBZ}	+287 kHz/mm	Spoke base의 직경 (z축)

✓ (df/dp 해석) 헬륨 압력과 주파수 해석 : 선형성 확인



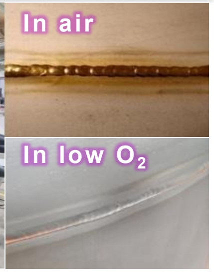
02 고주파 가속관: SSR1, 제작

Clamp up test

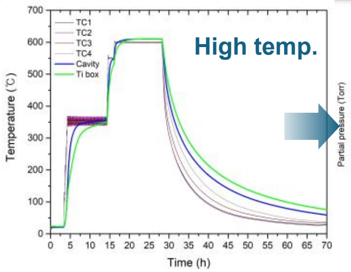


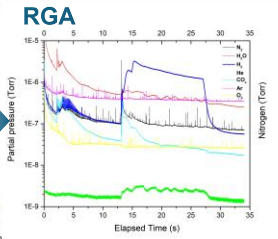
- **Sub-part alignment for frequency tuning and optimal positioning**
- Frequency adjustment using shell trimming (conventional) and beam cup trimming (recently) methods

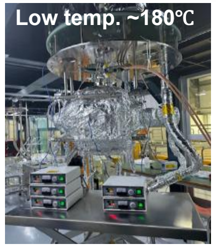
E-beam & Tungsten inert gas welding



High/low temperature baking



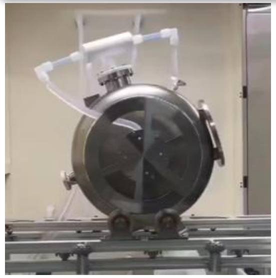




- **For hydrogen degassing from Nb**
- **For reduction of SEY**

Single spoke resonator1 (SSR1)

Buffered chemical polishing (BCP)



- **Wet chemical etching process for Nb to remove surface damages, contaminations, and native oxides**
- $HF : HNO_3 : H_3PO_4 = 1 : 1 : 2$
  (HF: 40%, HNO_3: 65%, H_3PO_4: 85%)
- ~150um

High pressure rinsing (HPR)

- **Cleaning process to remove residual particles, acids, and contaminants from Nb surfaces.**
- The critical step in SRF cavity preparation; it strongly influences field emission (FE), resulting in quality factor (Q_0)

Clean assembly

- **Assembly of SRF cavity components in a cleanroom to prevent particle contamination and ensure ultra-high vacuum (UHV) conditions**
- Critical process similar to the HPR for minimizing FE and achieving Q_0

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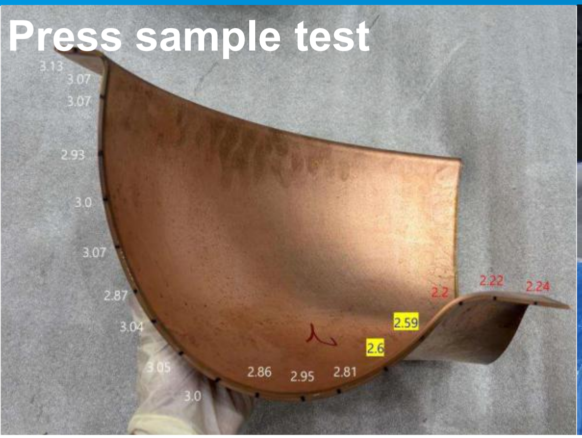
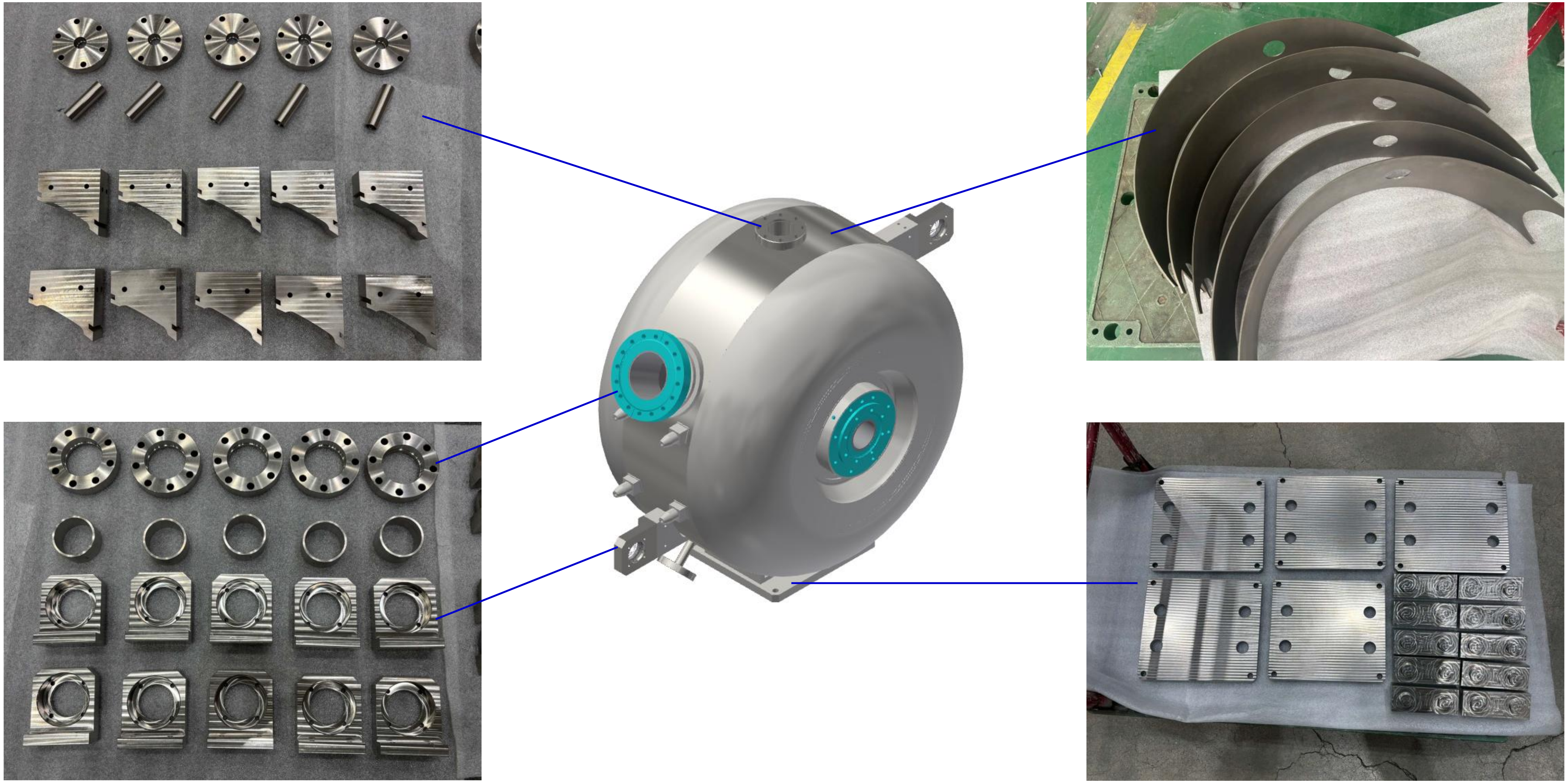
02 고주파 가속관: SSR1, 제작



- Half shell is fabricated by deep drawing process from raw material
- Flaws on cavity inner surface due to deep drawing process were eliminated
- Beam port cup and stiffener ring are welded to half shell by E-beam welding
- Stitch welding to minimize the cavity deformation (stiffening ring)

  → 30 % of each outer / inner diameter of stiffening ring is welded
- Spoke and collar is welded to cavity after clamp up test

02 고주파 가속관: SSR1, 제작



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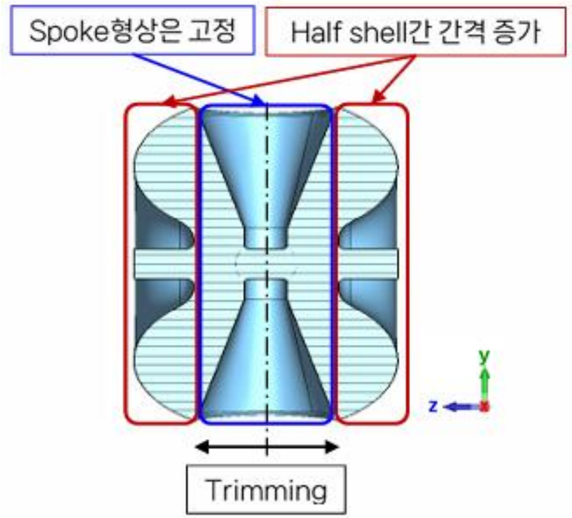
02 고주파 가속관: SSR1, 제작

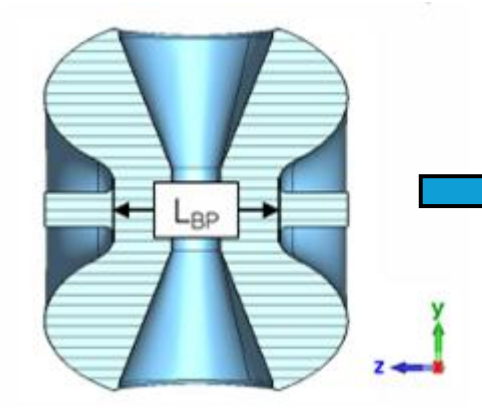
가속관 주파수 튜닝공정 개선

개선결과	▪ 주파수 튜닝공정을 위한 트리밍 가공이 최종 용접 품질에 영향을 최소화 하도록 공정 수정 ➔ **최종용접 품질 향상**

- ✓ (기존 시작품) 클램프 업 공정을 shell to shell 거리를 조절하여 주파수 조절
  이 과정에서 spoke와 shell에 단차 발생하여 최종용접 품질 저하
- ✓ (시제품 개선) spoke와 shell간 단차 없도록 용접품질 향상을 위해 빔포트 컵을 연마하여 주파수 튜닝 공정 진행

[기존] **[개선]**

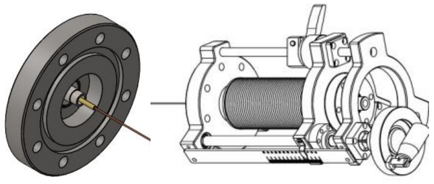




[빔포트컵 연마 후]

번호	공정	공진 주파수 [MHz]	주파수 변화 [MHz]
8	Tuner 결합	**325.000**	-0.050
7	2K 냉각 및 운용	325.050	+0.835
6	진공 배기	324.215	+0.095
5	BCP (150 um)	324.120	-0.002
4	Spoke + Shell 용접	324.122	+0.157
3	Spoke + Collar(R5) 용접	323.965	+0.196
2	Half-shell 용접	323.769	-0.039
1	Clamp up Test	**323.808**	-

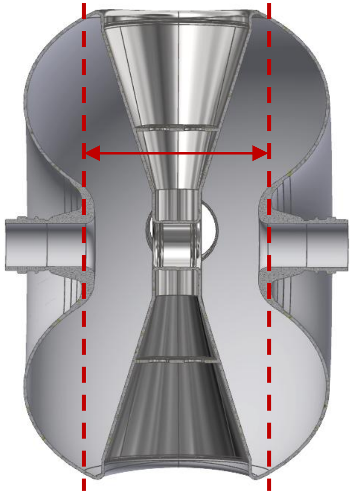
- ✓ 클램프업 시험용
  Variable 픽업커플러 제작



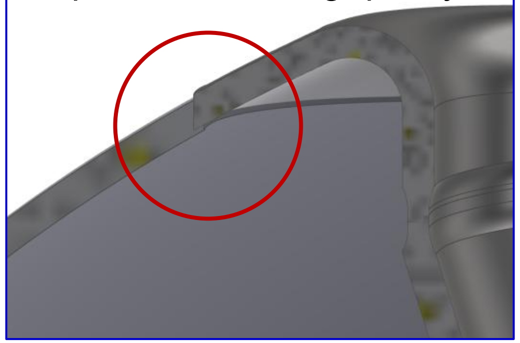
[기존] [개선]

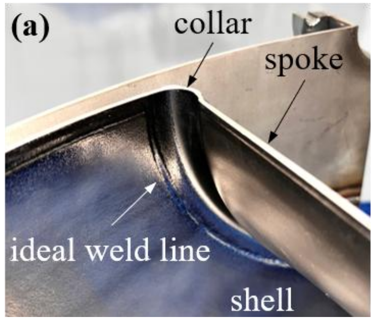
02 고주파 가속관: SSR1, 제작

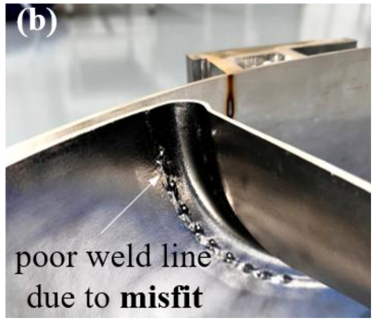
Shell trimming



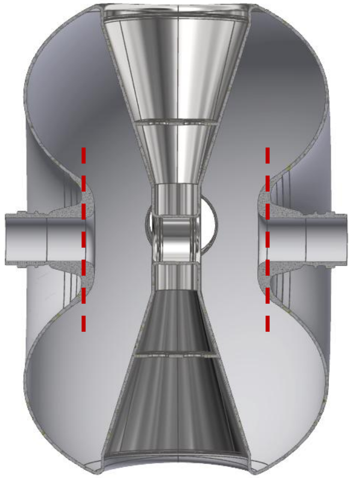
misfit due to shell trimming
→ poor EB welding quality



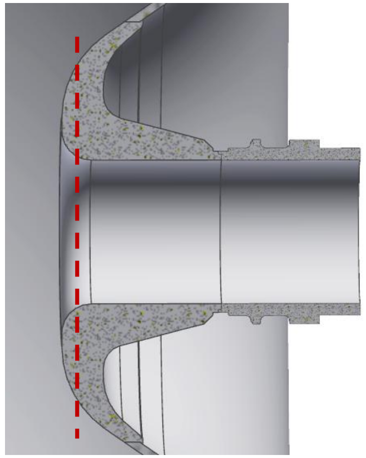




Beam port cup trimming



trimming



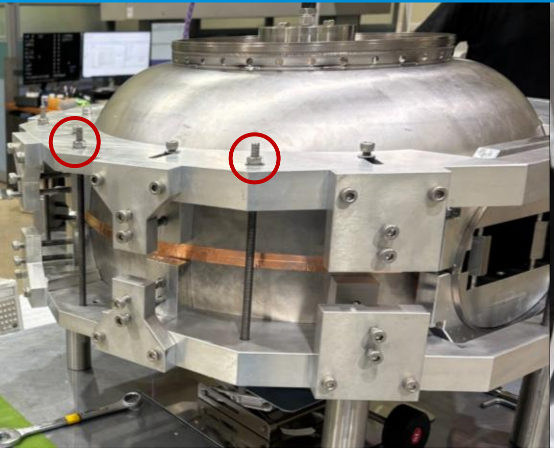
Frequency sensitivity

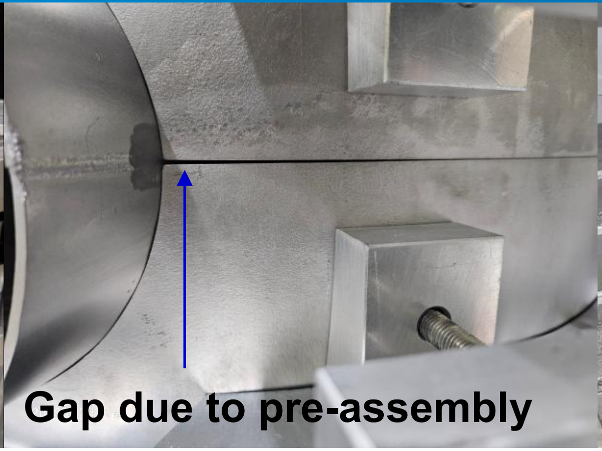
Shell trimming : **- 129 kHz/mm**

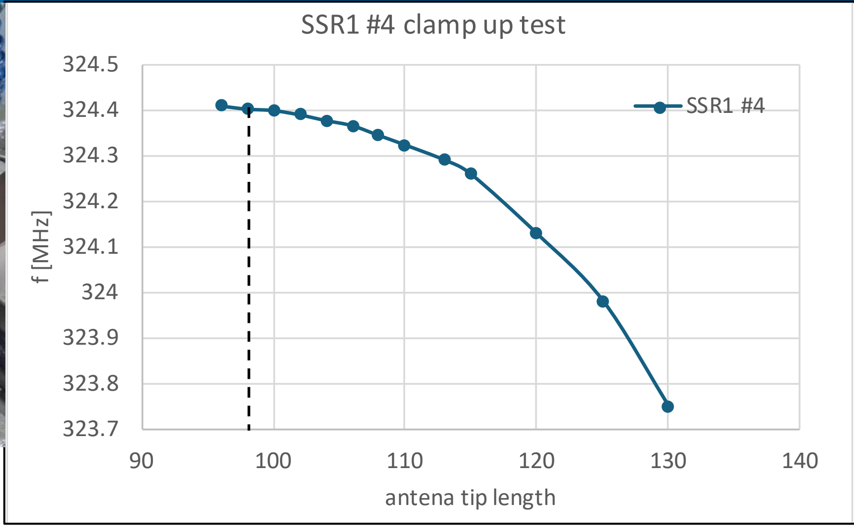
Beamport cup : **+ 235 kHz/mm (simulation)**

+ 233 kHz/mm (#3 cavity)
+ 295 kHz/mm (#2 cavity)

02 고주파 가속관: SSR1, 제작







- Gap occurrence due to pre-assembly of each part

 → Apply copper tape to the gaps (results in frequency increase)

- Determine the optimal tip length by adjusting the pick-up antenna tip length and measuring the frequency
- Frequency variation occurs at each clamp-up due to assembly tolerances

 → With fixed bolt tightening torque, the frequency differs by about 200 kHz

- Trim the beamport cup after frequency measurement

Table. Frequency change during process

process	Δf [MHz]	f [MHz]
Tuner	– 0.07	325.00
2K cooldown	+ 0.84	325.07
vacuum evacuation	+ 0.09	324.23
BCP (150um)	– 0.002	324.14
Spoke – shell welding	+ 0.16	324.14
Spoke – collar welding	+ 0.2	323.98
Half shell welding	– 0.04	323.78
Clamp-up test		323.82

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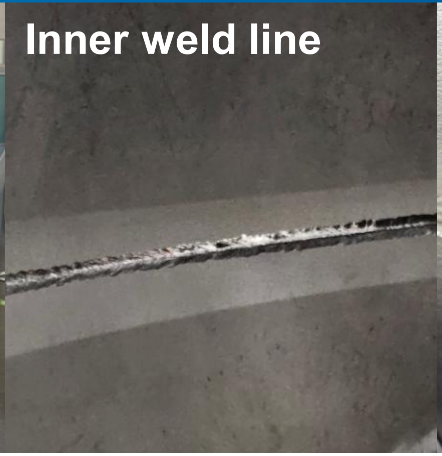
02 고주파 가속관: SSR1, 제작

- Clamp-up target frequency 323.8 MHz 달성 후 half shell – shell 용접 진행
- Beamport cup trimming에 따른 용접 전 전체 면 사상 진행

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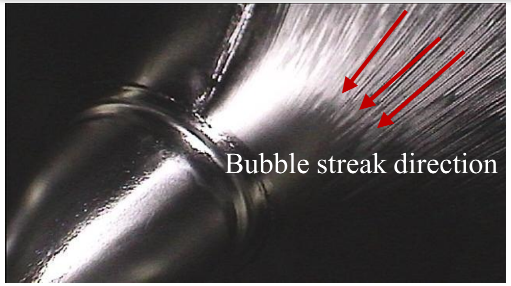
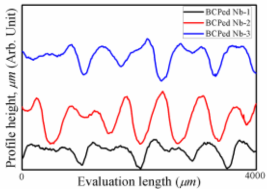
02 고주파 가속관: SSR1, 표면 처리

Rotational buffered chemical polishing (BCP)





Chemical reaction mechanism

$6Nb + 10HNO_3 \rightarrow 3Nb_2O_5 + 10NO(g) + 5H_2O$

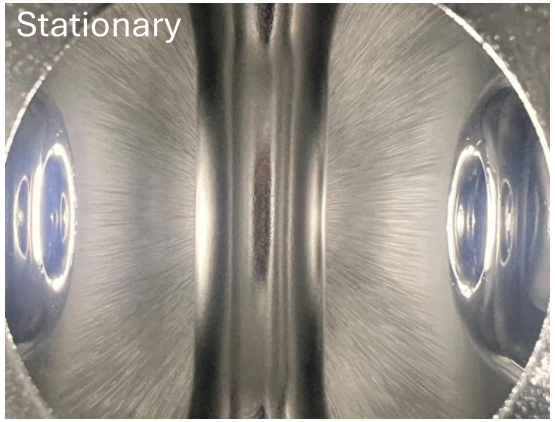
$Nb_2O_5 + 6HF \leftrightarrow H_2NbOF_5 + NbO_2F + 2H_2O$

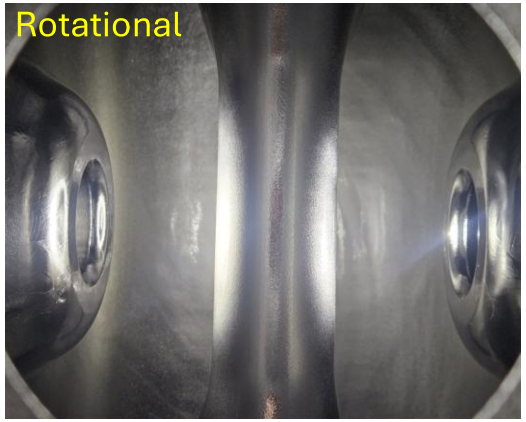
$Nb_2O_5 + 4HF \leftrightarrow H_2NbOF_5 + H_2O$

Concept of the improved process

- ✓ NOx gas bubble adhere to the RF surface, causing bubble streak defects.
- ✓ An approach using **rotational BCP with external cooling circulation** was adopted to mitigate bubble adhesion.
- ✓ This leads to suppressed FE and enhanced quench field.

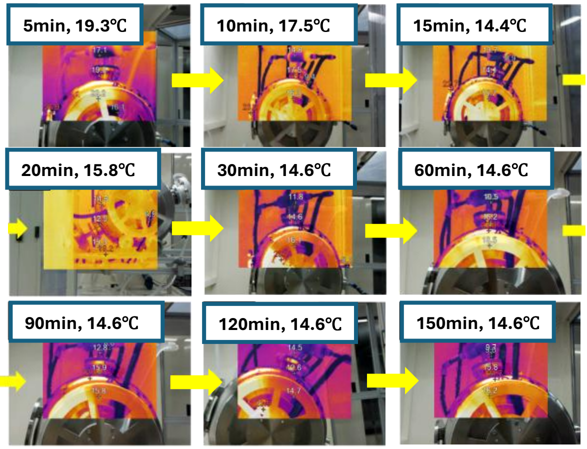
Visual inspection of RF surface





- No bubble streak observed by visual inspection

Temperature monitoring during BCP process



Further consideration

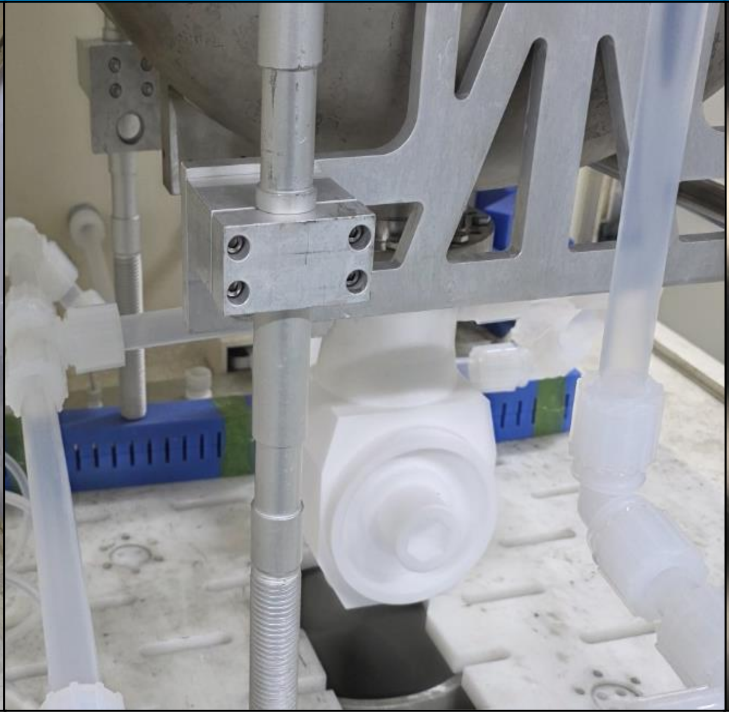
✓ Process optimization for uniform etching rate

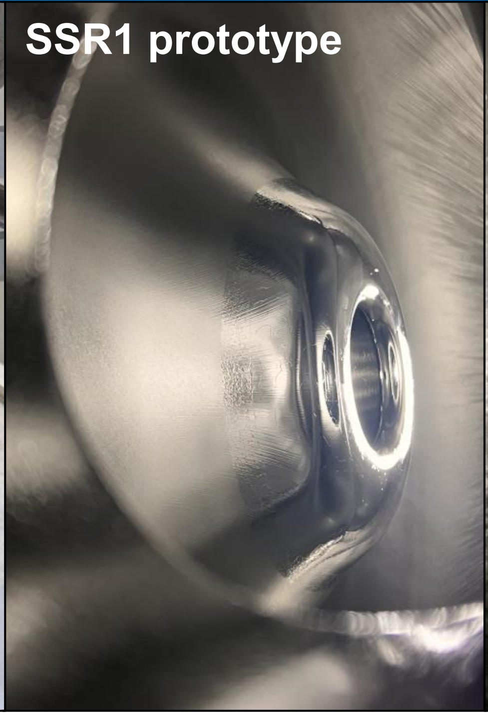
R-BCP run	1st	2nd	3rd	4th	5th
Etch rate (μm/min)	1.09	0.78	0.78	0.67	1.78

✓ Surface analysis via coupon tests
- Surface roughness measurement
- SEM analysis for surface morphology
- SIMS analysis to examine residual defect along the depth direction

✓ **Correlation between surface condition and RF performance (Q_0, Quench, FE)**

02 고주파 가속관: SSR1, 표면 처리





- Bubble streaks are observed in both SSR1 and SSR2 cavities
- A new BCP acid drain system has been introduced to minimize the acid drain time after the BCP process
- HF, HNO3, H3PO4 = 1:1:2, drain time < 15s (decreased from 90s for previous BCP facility)

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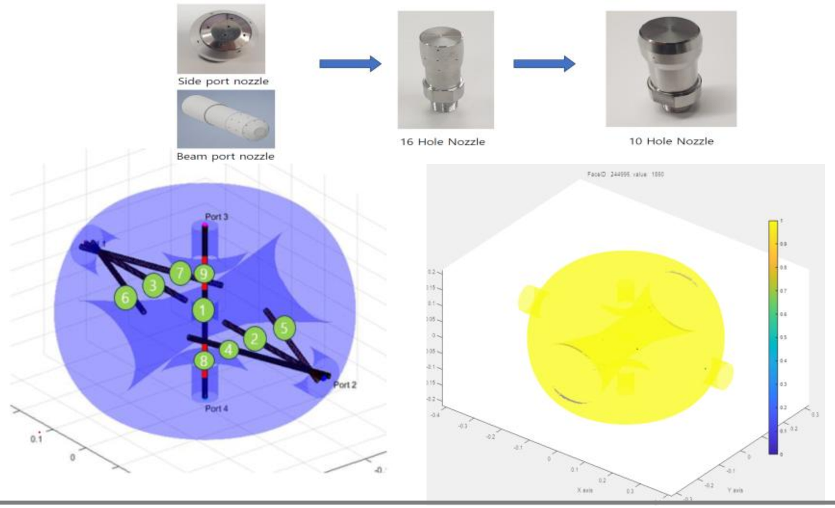
02 고주파 가속관: SSR1, 고압 수세

High pressure rinsing (HPR)

Nozzle & HPR coverage simulation



Further consideration

- Introduction of an external cleaning process
- Optimization of nozzle angle, position and rotational speed for maximum HPR coverage
- Correlation with RF performance (field emission)

Qualification of ultra pure water

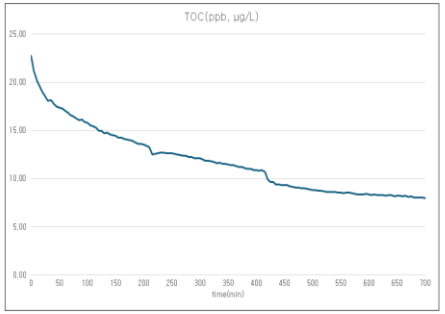
✓ **Target of ultra pure water**

Time (m)	Unit	Target
Resistivity	M/cm @25℃	> 17.5
Particles	ea/ml under 0.5 mm dia.	10~20
TOC (total organic carbon)	Ppb	< 10
D.O.	Ppb	< 50

✓ **Liquid particle measurement**

Datetime (Y-Axis)	0.1 μm	0.15 μm	0.2 μm	0.3 μm	0.5 μm
2026-01-14 10:56	47	30	24	13	10
2026-01-14 13:39	55	33	22	6	2
2026-01-14 13:40	56	31	19	4	2
2026-01-14 14:13	55	30	19	7	1
2026-01-14 14:25	54	31	19	5	0
2026-01-14 14:30	63	32	23	4	0
2026-01-14 14:34	74	42	24	7	2
2026-01-14 14:37	70	36	21	3	1
2026-01-14 14:39	62	37	29	7	1
2026-01-14 14:41	60	26	19	1	1

✓ **TOC tracking after changing UV filter**



Time (min)	TOC (ppb, mg/L)
10	22.75
12	14.96
14	12.68
16	11.54
18	9.04
20	7.99

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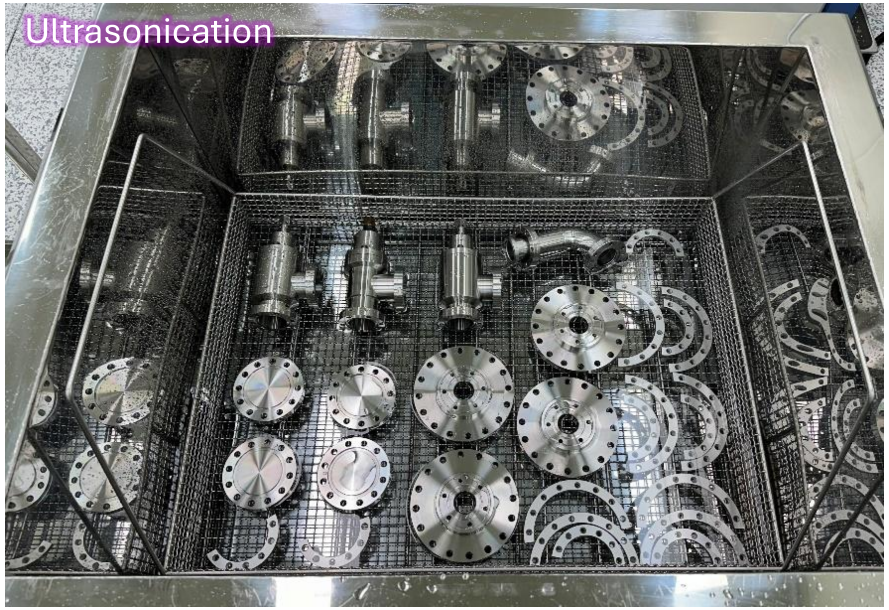
02 고주파 가속관: SSR1, 청정 조립

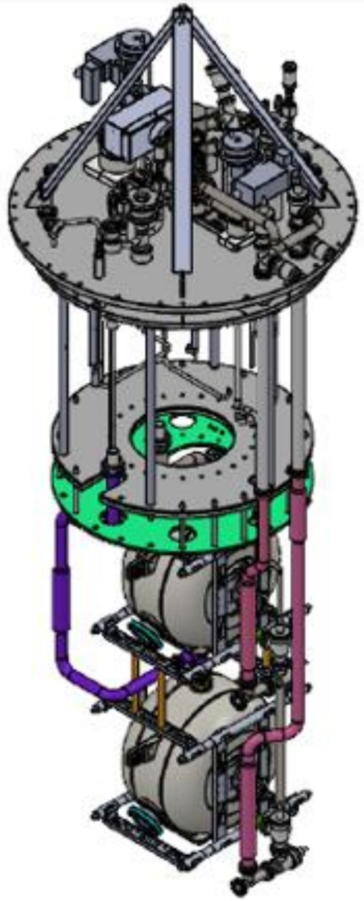
Clean assembly

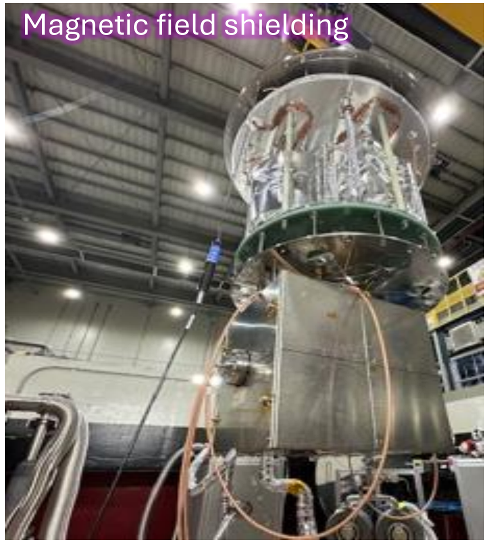


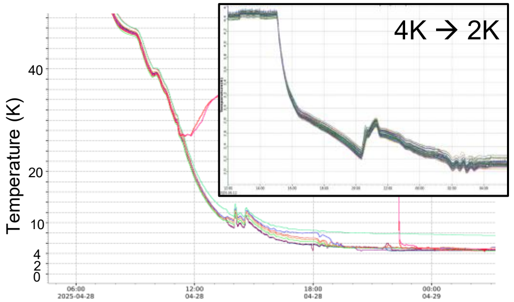
- All vacuum components used in clean assembly are cleaned by ultrasonic cleaning and ionized air blowing to remove contaminants prior to use.
- During assembly, particle levels are continuously monitored, and the process proceeds to the next step only when the particle count reaches zero.
- During evacuation, a slow pumping step is adopted to suppress particle migration and ensure stable particle conditions.

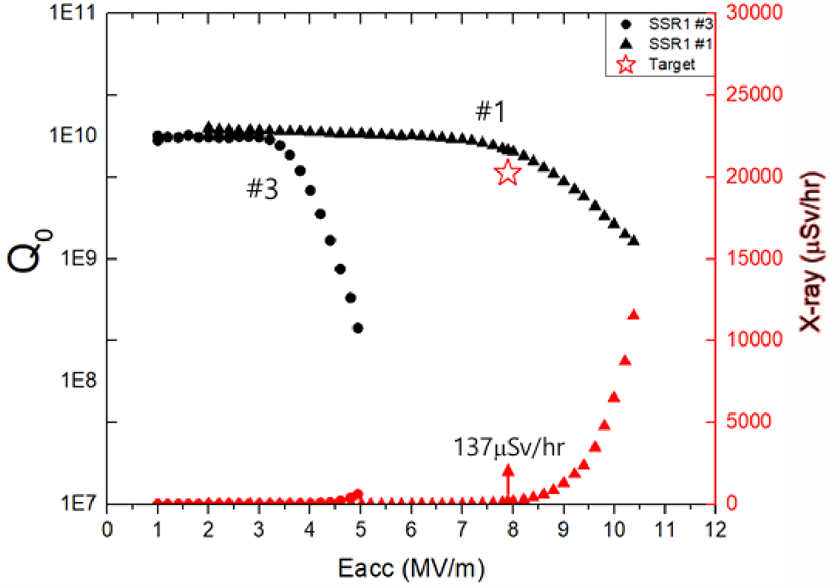
02 고주파 가속관: SSR1, VT

Vertical test









Parameters	Value
Temperature [K]	2
Q_0 at 1MV/m	1.01E+10
R_{res} (nΩ)	9.1
Q_0 at 8.5 MV/m	-
X-ray onset	3.4
LFD (Hz/(MV/m)^2)	-8.1
df/dp (Hz/mbar)	-31.1
Q_c	6.76E+10
Q_t	3.03E+11
Multipacting band (MV/m)	0.44 – 0.55

- SSR1 cavity tested in vertical cryostat
- Magnetic shielding applied to reduce ambient (earth) magnetic field and minimize trapped flux

끝