2026 ASCCA

SRF for Heavy Ion Accelerator in RAON/RISP

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Introduction

Overview

- **Goal:** To build **a heavy ion accelerator complex RAON,**
  for **rare isotope science** research in Korea.
  * RAON - Rare isotope Accelerator complex for ON-line experiments

- **Budget: KRW 1,432 billion (US$ 1.26 billion, 1$=1,135krw, as of the project start)**
  - accelerators and experimental apparatus : 460.2 billion won
  - civil engineering & conventional facilities : 972 billion won (incl. site 357 billion won)

- **Period: 2011.12 ~ 2021.12**

System Installation Project

Development, installation, and commissioning of the accelerator systems that provides high-energy (200MeV/u) and high-power (400kW) heavy-ion beam

Facility Construction Project

Construction of research and support facility to ensure the stable operation of the heavy-ion accelerator, experiment systems, and to establish a comfortable research environment

※ Accelerator and experiment buildings, support facility, administrative buildings, and guest house, etc.

❖ **Providing high intensity RI beams by ISOL and IF**
ISOL: direct fission of ^{238}U by 70 MeV proton
IF: 200 MeV/u ^{238}U (intensity: 8.3 pμA)

❖ **Providing high quality neutron-rich beams**
e.g., ^{132}Sn with up to 250 MeV/u,
up to 10^9 particles per second

❖ **Providing More exotic RI beam production by combination of ISOL and IF**

RAON layout

▌ SCL1 has been decided to be postponed

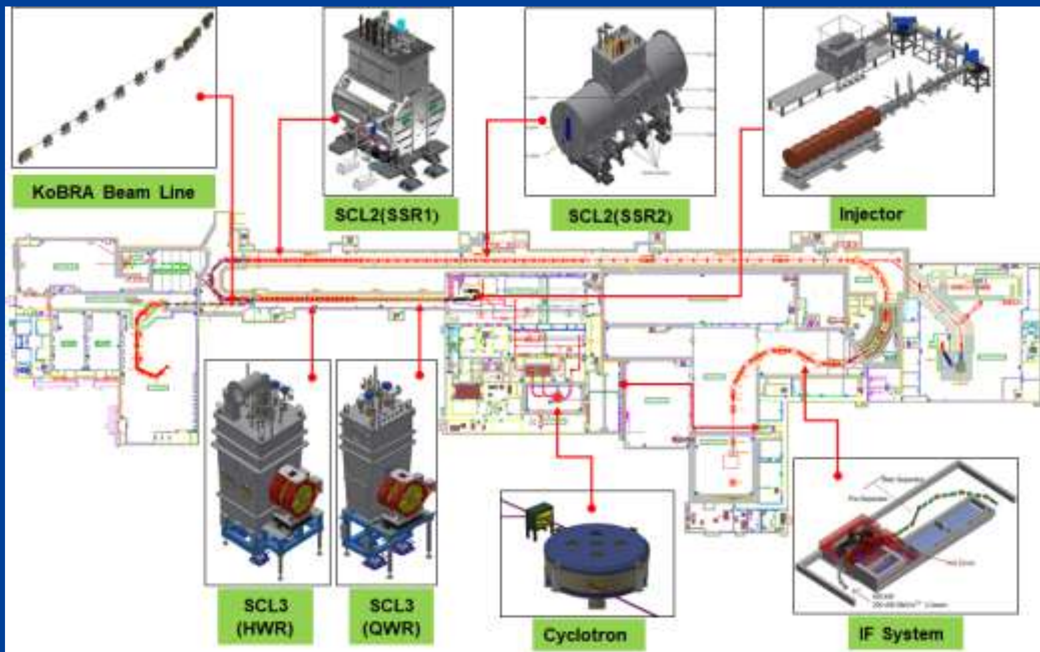
: SCL3 is going to be taking a role of SCL1 in the early operation

Project milestone

- Project milestone of RAON were modified 3 times as in 2015, 2018, and 2021 due to;
  - Too optimistic and aggressive plan at planning phase of RAON
  - At the project outset, dedicated manpower, facilities, and enabling technologies were limited, so we built the required capabilities in phases.
  - A lot of trial & errors from lacks of technology and experience during implementation

- Current status
  - Installation of low energy linac(SCL3) and high energy linac(SCL2) is separated as phase 1 and phase 2, respectively.
  - Beam commissioning of SCL3 is finished and user service is ongoing from 2024.
  - The 1st step of phase 2, R&D of SCL2 linac is ongoing from 2022~2027

Introduction on SCL3



RF Parameter of QWR and HWR

	QWR	HWR
β_{opt}	0.051	0.13
f [MHz]	81.25	162.5
L_{eff}	186.5	236.3
R/Q [Ω]	474	298
E_p/E_{acc}	6.0	5.5
B_p/E_{acc} [mT/(MV/m)^2]	10.8	9.6
E_{acc} [MV/m]	5.7	6.2
V_{acc} [MV]	1.07	1.47
QR_s	18.1	37.1




	Cavity	# of cav.	# of CM	Cav. Op. T (K)
SCL1,3	QWR	1	22	4.5
	HWR	2	13+2	2.05
		4	19	2.05
SCL2	SSR1	3	23	2.05
	SSR2	6	23+2	2.05

Introduction on SRF Cavity

Why use SRF cavities?

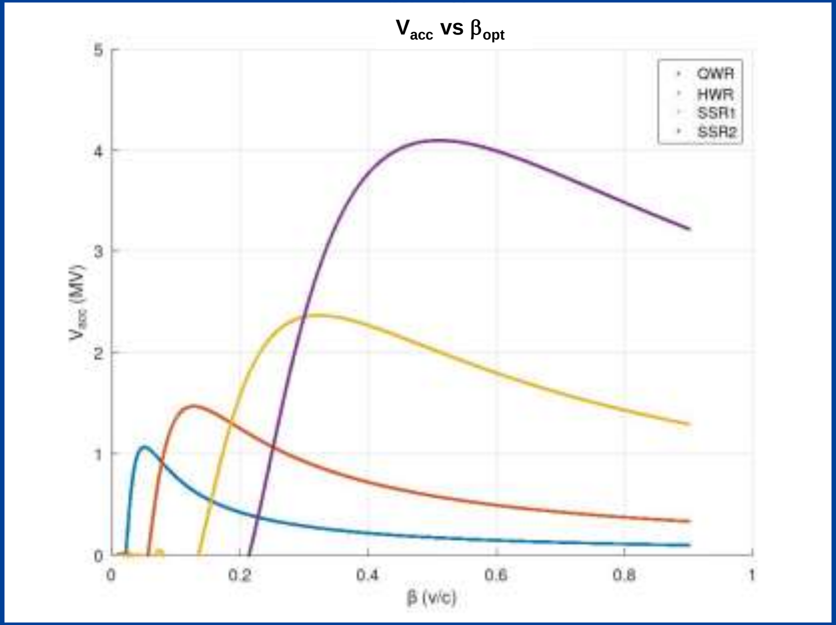
- Superconducting niobium reduces RF surface resistance R_s to the nΩ range → very high Q_0
- For the same accelerating voltage, wall loss (P_d) is much lower than normal-conducting cavities
- Enables high-duty-factor / CW operation and high average beam power (depending on machine design)
- Q_0 and E_{acc} together serve as the "standard stamp" of cavity performance
- Requires 2–4 K (or ~1.8–2 K) cryogenics → system-level optimization matters

- Lower R_s → lower P_d
- Higher Q_0 → less dynamic cryogenic load

Acceleration: V_{acc}, E_{acc}, and L_{eff}

$$E_{acc} = V_{acc} / L_{eff}$$

- V_{acc}: accelerating voltage (on-crest energy gain for a reference particle).
- β_{opt}: optimal beta is the reference particle velocity. When $\beta \neq \beta_{opt}$, the accelerating voltage is reduced.
- L_{eff}: effective accelerating length (definition depends on cavity type and β_{opt}).
- E_{acc}: gradient used to compare cavities independent of length.
- In practice, V_{acc} is derived from RF measurements (stored energy & (R/Q)) and calibration.



Loss & heat load: U, P_d, Q_0, R_s, and G

- Stored energy: U [J]
  - energy stored in the RF fields inside the cavity (electric + magnetic).
- Dissipation power: P_d [W]
  - RF power dissipated on the cavity wall (surface resistance).
- Intrinsic Q: $Q_0 = \omega U / P_d$
  - quantifies how "lossless" the cavity is (intrinsic, excluding external couplers).
- Surface resistance: $R_s = R_{BCS} + R_{res}$
- Geometry factor: $G = Q_0 \cdot R_s$

Key relations

- $R/Q = V^2/(\omega U)$ (geometry)
- $R_{sh} = (R/Q)\cdot Q_0$ (includes losses)
- $P_d \propto E_{acc}^2 / Q_0$ (higher $Q_0 \rightarrow$ lower cryo load)

VT/HT focus

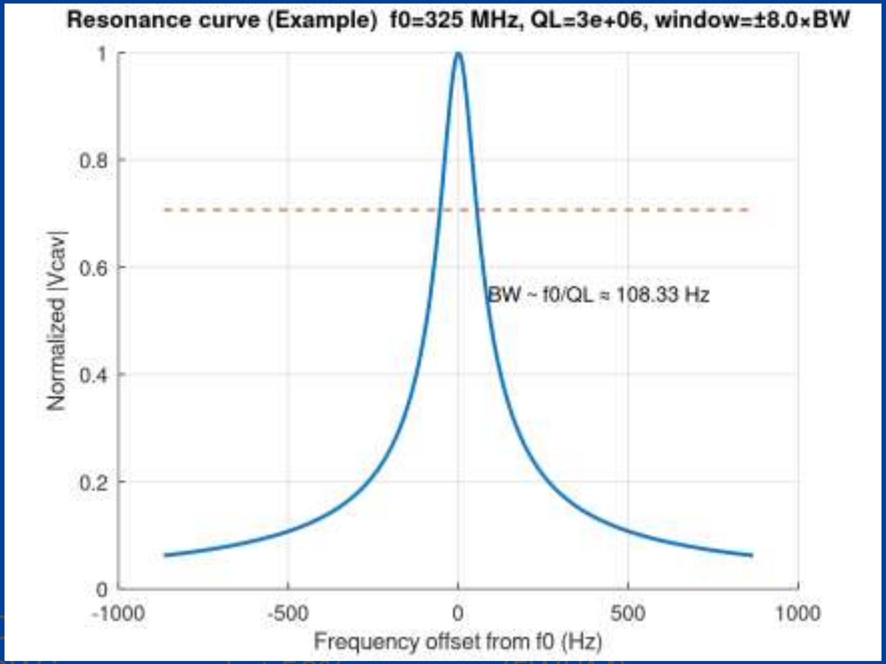
- $Q_0(E_{acc})$ = dynamic loss vs gradient
- Field emission / vacuum / radiation trends
- Quench & defect signatures

Example
f_0 = 325 MHz (325 MHz)
Q_0 = 3.2e+09
If U = 1 J → $P_{loss} = \omega U/Q_0 \approx 0.64$ W
P_{loss} scales linearly with U.

Basics: Q_L and Bandwidth (BW)

$$\frac{1}{Q_L} = \frac{1}{Q_0} + \frac{1}{Q_{\text{ext}}}, \qquad BW = \frac{f_0}{Q_L}$$

- Q_L: loaded quality factor (includes both cavity wall losses and external coupling).
- BW: full-width at half-maximum (FWHM) of the resonance response.
- Higher QL → narrower bandwidth → more sensitive to detuning (microphonics/LFD).
- In pulsed operation: Q_L relates to cavity fill time ($\tau \approx Q_L/\omega$).
- LLRF and tuner requirements scale with BW and expected detuning.



BW is measured at 50% response (FWHM).

Example

f_0 = 325 MHz (325 MHz)

Q_0 = 3.2e+09, Q_{ext} = 3e+06

$Q_L \approx$ 3e+06 ($\approx Q_{ext}$ when $Q_0 \gg Q_{ext}$)

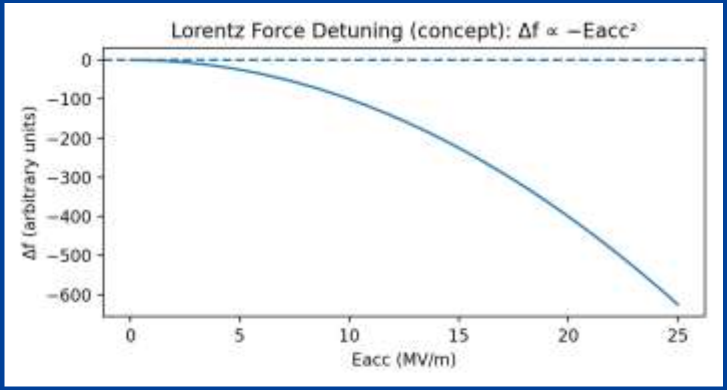
BW = $f_0/Q_L \approx$ 108.33 Hz

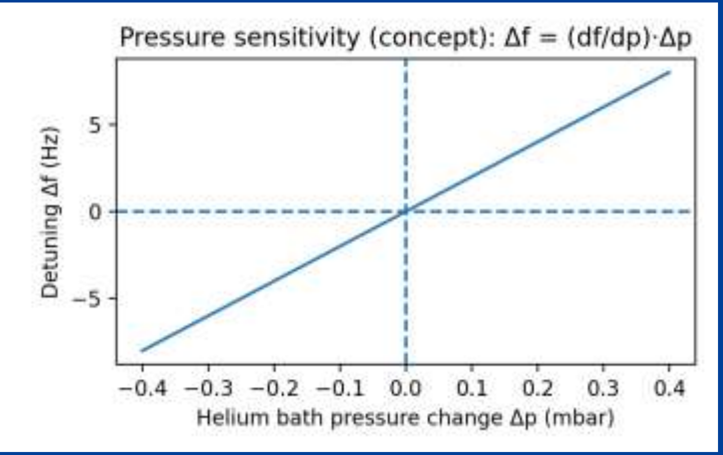
$\tau \approx Q_L/(\pi f_0) \approx$ 2.94 ms

Basics: β (RF coupling), Δf, LFD, and df/dp

$\beta = Q_0 / Q_{ext}$ | $\Delta f = f - f_0$

- β (coupling factor): how strongly the cavity is coupled to the RF source (via coupler).
- $\beta < 1$ under-coupled, $\beta = 1$ critically coupled, $\beta > 1$ over-coupled
- Δf: detuning from the nominal resonance (microphonics + LFD + pressure effects).
- LFD (Lorentz Force Detuning): EM pressure deforms the cavity → typically $\Delta f \propto -E_{acc}^2$.
- df/dp: pressure sensitivity (Hz/mbar or Hz/Pa) from helium bath pressure fluctuations.





Example

f_0 = 325 MHz (325 MHz)

Q_0 = 3.2e+09, Q_{ext} = 3e+06

$\beta = Q_0/Qext \approx$ 1,067 (strongly over-coupled)

Coupling β → Reflected Power P_{rfl}

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$$\beta \equiv \frac{Q_0}{Q_{\text{ext}}} \qquad Q_L = \frac{Q_0}{1+\beta} \qquad \Gamma \equiv \frac{V_{\text{rfl}}}{V_{\text{fwd}}} \equiv \frac{\beta-1}{\beta+1}$$

$$\frac{P_{\text{rfl}}}{P_{\text{fwd}}} = |\Gamma|^2 = \frac{(\beta-1)^2}{(\beta+1)^2} \qquad \frac{P_{\text{cav}}}{P_{\text{fwd}}} = 1 - |\Gamma|^2 = \frac{4\beta}{(\beta+1)^2}$$

- On resonance ($\Delta f = 0$), critically coupled ($\beta = 1$): $\Gamma = 0$ (no reflection).
- Undercoupled ($\beta < 1$): most power is reflected at resonance (Γ negative; magnitude close to 1 when $\beta \ll 1$).
- Overcoupled ($\beta > 1$): reflection at resonance also nonzero; for very large β, $|\Gamma| \approx 1$ near resonance.
- Use $|\Gamma|$ (voltage) or $|\Gamma|^2$ (power) depending on what your directional couplers measure.

Undercoupled (β = 0.1)

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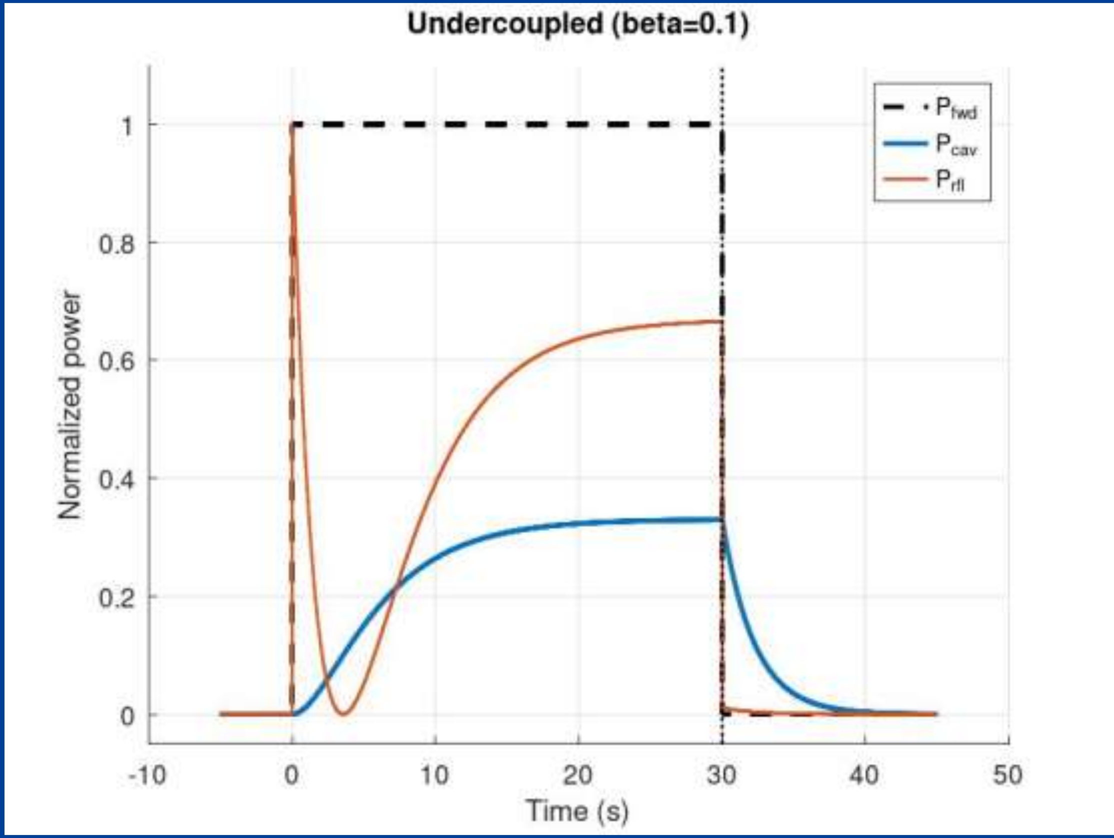
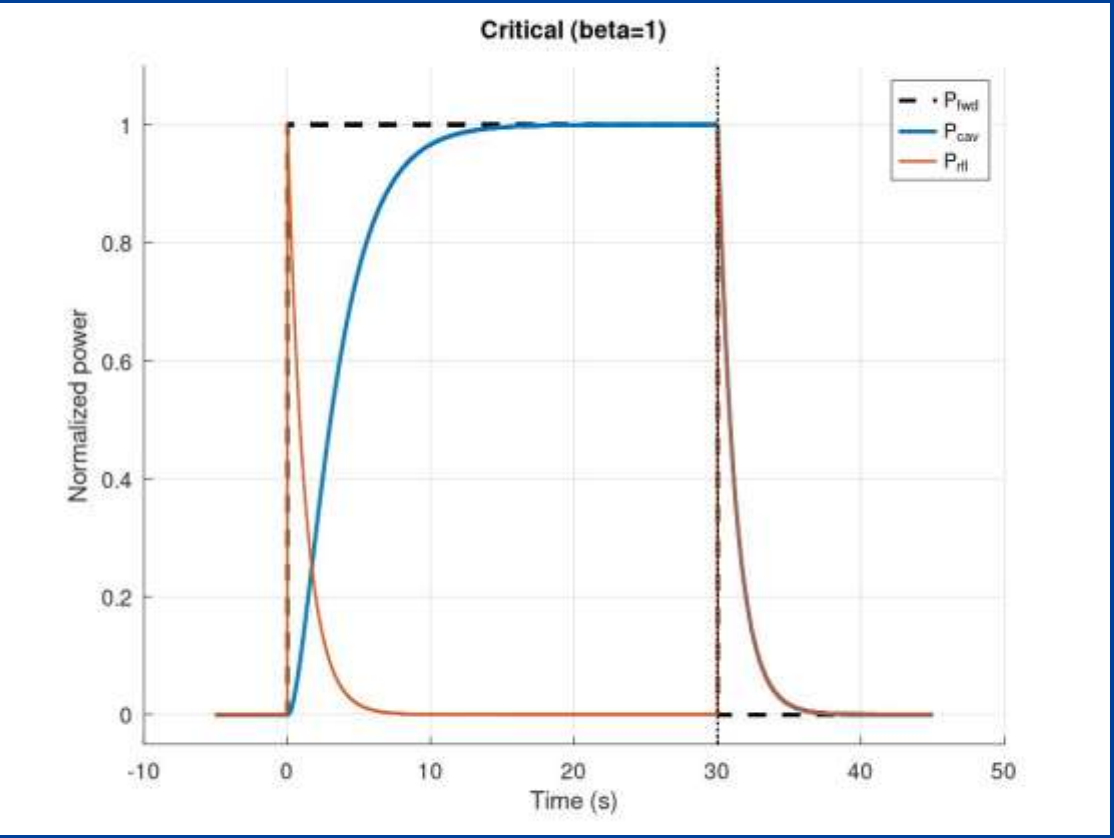


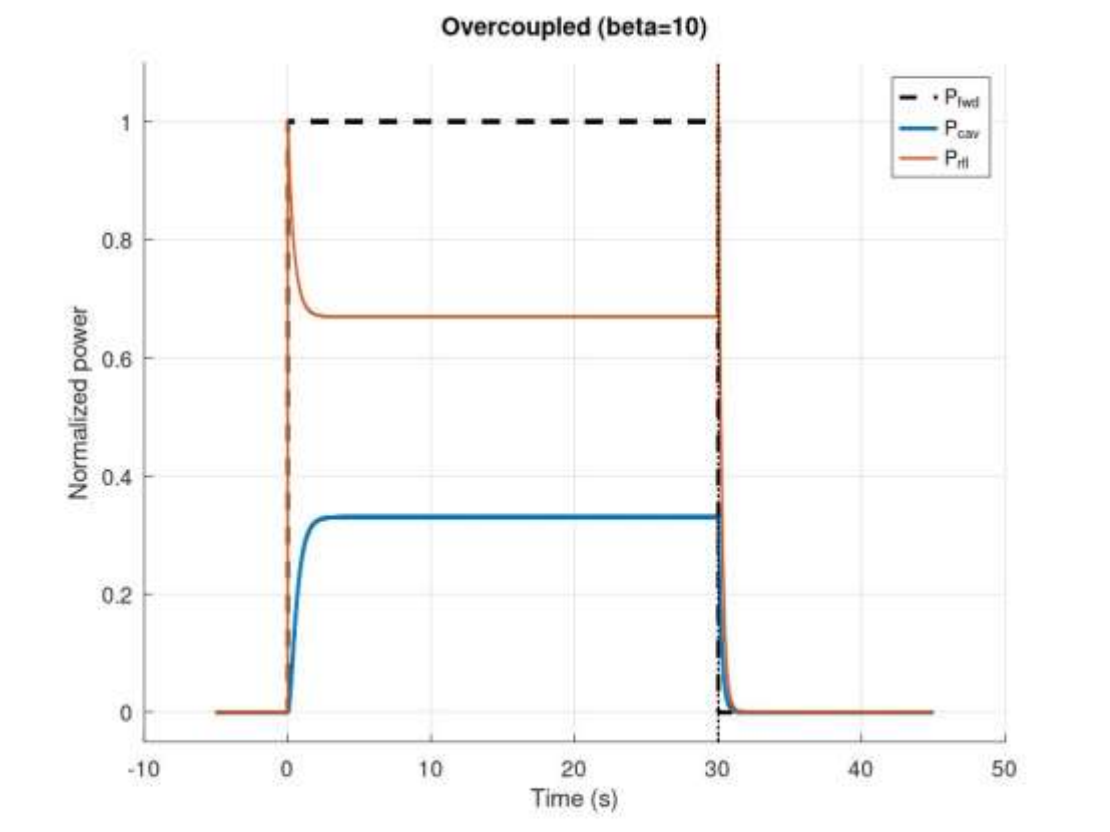
- Weak coupling → larger QL → slow fill and slow decay after RF-off.
- Steady state: large reflected power (same magnitude as overcoupled in power, different phase in voltage).
- P_{cav} builds up slowly and stays relatively small for fixed P_{fwd} (empty cavity).
- After RF-off, energy remains longer and dissipates mainly on the walls (long tail).

Critically Coupled (β = 1)



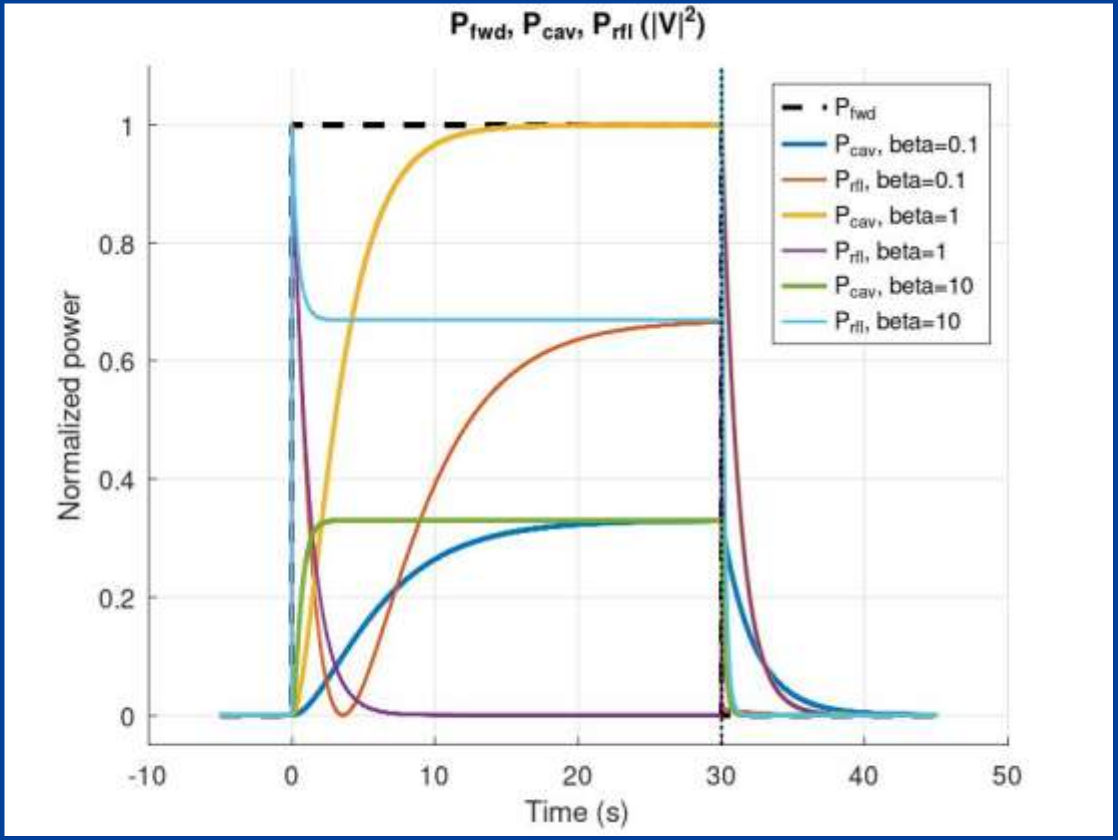
- Matched for an cavity with no beam, no detuning : Γss = 0 → P_{rfl} → 0 at steady state.
- Maximum power transfer → P_{cav} reaches the highest steady level for fixed Pfwd.
- Time constant: $\tau \approx Q_L/(\pi f_0)$ with $Q_L = Q_0/(1+\beta)$.
- After RF-off, P_{cav} decays with the same τ; P_{rfl} shows a brief transient as energy leaves.

Overcoupled (β = 10)



- Strong coupling → smaller Q_L → fast fill and fast decay after RF-off.
- Steady state: large reflected power remains ($P_{rfl}/P_{fwd} \approx ((\beta-1)/(\beta+1))^2$).
- For a cavity with no beam, no detuning, only small P_{fwd} transferred to P_{cav}; the rest is reflected.
- After RF-off, stored energy dumps quickly through the coupler (short transient).

Overlay: P_{fwd}, P_{cav}, P_{rfl} for β = 0.1, 1, 10



- Overlay view emphasizes the trade-off between power partition and dynamics as β changes.
- Critical coupling (β=1): minimizes steady reflected power (matched), maximizes delivered power to the cavity.
- Under/over coupling (β≪1 or β≫1): similar reflected-power magnitude on resonance, but differe nt time constants (Q_L).

How Q_0 is obtained in RF tests

- From decay time / bandwidth
  - $Q_L = f_0 / BW$
  - $\tau = Q_L / (\pi f_0)$
- Measure cavity field decay after RF-off $\rightarrow \tau \rightarrow Q_L$

- From coupling
  - $\beta = Q_0 / Q_{ext}$
  - $Q_0 = Q_L (1+\beta)$
- Power balance (common)
  - Use calibrated P_{fwd} / P_{rfl} / P_{tr}
  - Solve for P_d and Q_0

Example

What is the QL of this system?

Testing of SRF Cavity

- Cavity: Nb (bare or jacketed); equipped with pickup coupler
- Helium vessel: provides 2 K bath / pressure boundary; affects mechanical modes
- Input power coupler (FPC): transfers RF power; can multipact and outgas
- Tuner: compensates detuning (microphonics / Lorentz force)

- VT (vertical): cavity alone in vertical cryostat
  - minimal external hardware
  - focus on cavity surface/process qu ality
- HT (horizontal): cavity integrated in cryomodule, with coupler, tuner
  - high-power RF and conditioning
  - similar to real operating conditions

Surface preparation & clean

- Surface processing: EP/BCP, ultrasonic cleaning, high-pressure rinsing (HPR)
- Heat treatments / baking: reduce hydrides, modify mean free path, mitigate Q-slope (recipe dependent)
- Cleanroom assembly: particle control is critical
- Vacuum integrity and leak checking: outgassing impacts conditioning and stability
- Magnetic field shielding: residual fields can trap flux → degrade Q_0

Many performance issues ultimately arise from contamination or particulates (field emission), trapped magnetic flux (increased residual resistance), or localized defects that trigger premature quench.
Treat VT as process feedback.

Vertical Test (VT): purpose and typical outputs

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- Goal: qualify the cavity performance before integration
- Measures: $Q_0(E_{acc})$, resonant frequency, radiation (X-ray), field emission onset
- Use results to provide feedback to processing steps (EP/HPR/bake/clean assembly)
- Acceptance criteria are project-specific (e.g., Q_0 at target E_{acc}, max radiation, max field emission)

- Strengths:
  - clean separation of cavity vs subsystem effects
  - faster iteration for surface/process improvement

- Limitations:
  - does not include coupler/tuner behavior
  - does not represent full operational RF power chain

VT setup (concept)

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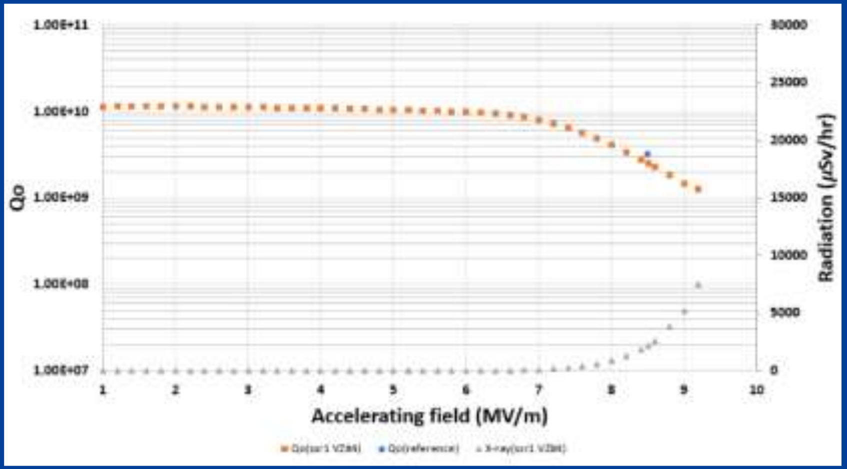
- Vertical cryostat: cavity suspended in a helium bath; magnetic shielding often applied
- RF measurement chain: forward/reflected/pickup signals → calibrate Q_{ext} and stored energy
- Instrumentation: vacuum gauges, X-ray detectors
- Key calibrations: cable loss, couplings, power meter calibration, decay-time measurement
- Data products: $Q_0(E)$, radiation(E), vacuum(t), frequency(t)

- Typical sequence:
  1) Pump-down & leak check
  2) Cooldown (monitor trapped flux conditions)
  3) Power ramp / Q measurements
  4) If needed: conditioning and repeat

How to read Q_0–E_{acc} curves

- Low-field region: baseline Q_0 (sensitive to trapped flux and residual resistance)
- Medium field: Q-slope behavior (depends on surface treatment recipe)
- High field: limitations often appear (field emission, quench, or coupling limits)
- Field emission signature: rising X-ray + Q_0 drop; sometimes accompanied by vacuum bursts
- Quench signature: abrupt, repeatable E_{acc} limit (often with thermal hotspot)



- Common patterns:
- • Multipacting: discrete barriers; improves after conditioning
- • Coupling issue: measurement artifacts / insufficient drive
- • Microphonics: frequency jitter; affects measurement stability

VT procedure checklist

- Pre-test: vacuum bake / pump-down; verify interlocks and instrumentation
- Cooldown: record temperature gradient, magnetic field, pressure; avoid flux trapping if required
- RF calibration: measure Q_{ext}, cable losses
- Measurement: change E_{acc}, record Q_0, radiation, vacuum, frequency; repeat for reproducibility
- Post-test: warm-up, venting/backfill procedure, data archiving and summary report

Horizontal Test (HT): what it adds beyond VT

- Goal: verify integrated performance under conditions close to real operation
- Includes: input coupler, tuner, cryomodule
- High-power RF: coupler conditioning, arc detection, vacuum protection, reflected power handling
- Mechanical dynamics: microphonics, Lorentz force detuning, tuner performance

- Typical outputs:
  - Achievable E_{acc} with high-power system
  - Coupler conditioning history (vacuum, arcs)
  - Detuning and control performance (Tuner+LLRF)
  - Heat loads (static + dynamic)
  - Stability under pulsed/CW modes

HT Test Setup

- Cryomodule or horizontal cryostat: alignment, thermal anchoring, vibration environment
- Input coupler: warm/cold transitions; feed high power RF to cavity
- Tuner: slow motor + piezo; characterize tuning range, bandwidth, response
- LLRF: amplitude/phase regulation; resonance control loop
- Interlocks: arc, vacuum, temperature, RF power and etc.

- Typical sequence:

  1) Vacuum & leak check (coupler lines included)

  2) Cooldown / thermal cycles as required

  3) Low-power checkout → then cavity or coupler conditioning

  4) High-power operation at target gradient

  5) Detuning characterization and control stability check

High-power RF chain & interlocks

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- RF source: SSA/klystron → LLRF → amplifier chain
- Protection: circulator/isolator, RF loads, fast interlock logic
- Sensors: forward/reflected power, arc detectors, vacuum gauges, temperature sensors
- Arc events: can damage coupler ceramics; require fast shutdown and controlled recovery
- Vacuum bursts: indicate multipacting/outgassing; correlate with power level and time

- Interlock examples (site-specific):

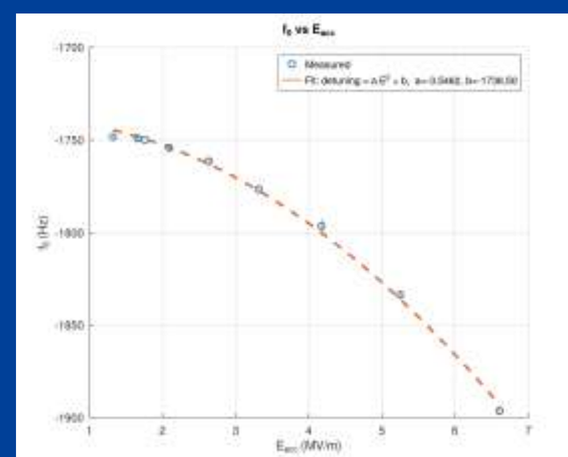
  - Arc detector trips
  - Coupler vacuum thresholds
  - Cavity quench detection
  - Excess reflected power
  - Bias-T voltage

- Careful! protect hardware first; performance comes second.

Microphonics & detuning

- Microphonics: vibration/pressure fluctuations → frequency jitter → reduces RF control margin
- Lorentz force detuning: gradient-dependent detuning, especially in pulsed operation
- Bandwidth : narrow bandwidth cavities are more sensitive to microphonics
- Controls: slow tuner for static offsets; piezo for fast compensation

- Practical checks:
  - Measure LFD (detuning vs E_{acc})
  - Mechanical resonance identification
  - Helium pressure sensitivity (df/dP)



Example : LFD Measurement

Common limitations & diagnostics

Phenomenon	Typical signature	Likely cause(s)	What to try / check
Multipacting	Vacuum rise, absorbed power, discrete barriers; improves with time	Coupler or RF line geometry; surface conditioning	Pulse conditioning, dwell at barrier, verify interlocks and diagnostics
Field emission	X-ray increases; Q_0 drops; sometimes vacuum bursts	Particles/contamination, roughness, local high field	Improve cleanliness (HPR/assembly), re-process surface, inspect
Quench (thermal/magnetic)	Abrupt repeatable Eacc limit; thermal hotspot	Local defect, poor thermal contact, trapped flux	Inspect/repair, improve magnetic hygiene
Microphonics / detuning	Frequency jitter; regulation margin reduced; trips at lower gradients	Vibration, helium pressure fluctuations, tuner issues	Vibration hunting, tuner/piezo tuning, df/dP characterization

VT vs HT: what each test tells you

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Item	VT (Vertical Test)	HT (Horizontal Test)
Primary objective	Qualify cavity performance; process feedback	Verify integrated performance under operational conditions
Configuration	Cavity only in vertical cryostat	Cavity + vessel + coupler + tuner (in cryomodule)
RF power level	Low to moderate (measurement-focused)	High power
Dominant issues	Surface/cleanliness, trapped flux, intrinsic quench limits	Coupler/cavity multipacting, arcs, detuning control
Typical outputs	$Q_0(E)$, FE onset, quench limit	Dynamic/static heat load of cryomodule, tuner/coupler status (Q_{ext}, BW, etc.), microphonics
Time/cost	Faster iteration, lower integration overhead	More complex and resource-intensive

Mass production of SCL3 cryomodules

Mass production of SCL3 cryomdoules

Contracts

	SCL31		SCL32	
	Products	Quantity	Products	Quantity
Final deliverables	QWR cryomodule	22	HWR cryomodule A	15
			HWR cryomodule B	19
Subcomponents to be fabricated	Superconducting cavities	18	Superconducting cavities	104
	Power couplers	20	Power couplers	104
	Tuners	22	Tuners	104
	Cryostat	21	Cryostat A	14
			Cryostat B	18
Contract amount	$ 9,065,128		$ 25,457,148	
Period	2017. 12 ~ 2020. 07		2018. 05 ~ 2022. 01	

- **Domestic vendor: VitzroTech (cavity: RI as subcontractor)**

Mass production of SCL3 cryomdoules

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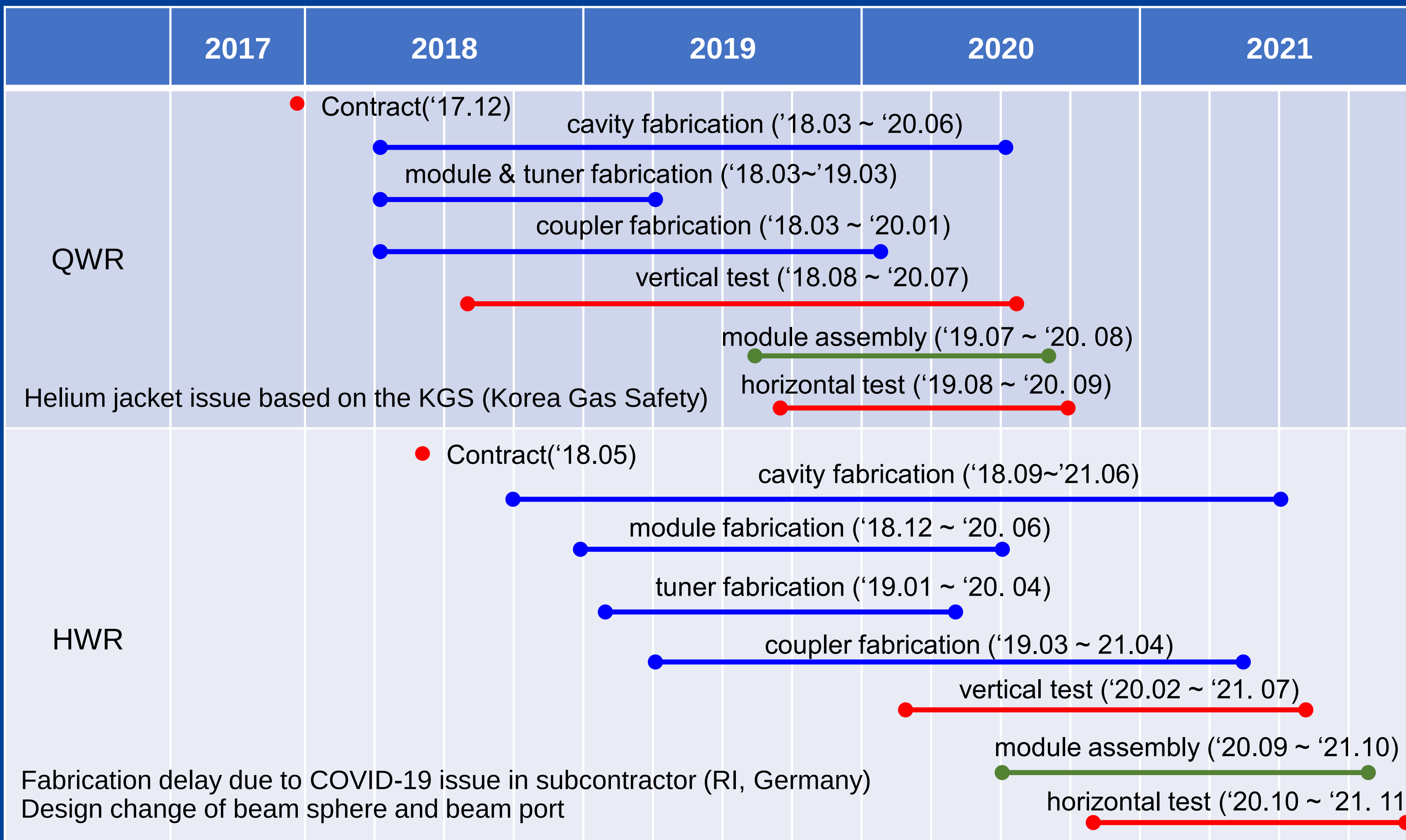
Acceptance test for final deliverable

	QWR cryomodule	HWR cryomodule
Performance requirements	Total thermal load at 4.2 K below 20 W	Total thermal load at 2.05 K below 14.1 W (module A) below 26 W (module B)
Test conditions	E_{acc}: 6.1 MV/m Frequency: 82.15 MHz Cavity vacuum<5e-8 mbar Insulation vacuum<1e-5 mbar Resolution of frequency tuning< 5 Hz	E_{acc}: 6.6 MV/m Frequency: 162.5 MHz Cavity vacuum<5e-8 mbar Insulation vacuum<1e-5 mbar Resolution of frequency tuning< 5 Hz
Function test	Coupler: RF power supply more than 8 hours at room temperature Tuner: tuning range over 50 kHz Cavity alignment Operation of sensors, valves, and so on.	

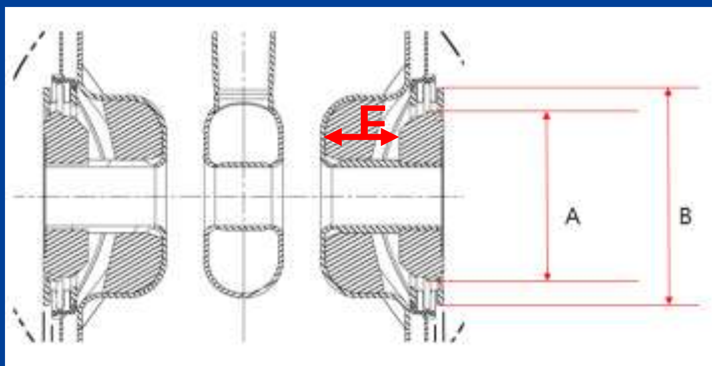
※ Vertical test must be done for all cavities before cryomodule assembly

Schedule for mass production



Changes in mass production

Reduction of df/dp of QWR cavity



	A	B
Prototype	115.7	148
Pre-production	96.7	120

	Estimated (Hz/mbar)	Measured (Hz/mbar)
Prototype (bare) Beam port free	-37.9	-33.4[#2-1], -37[#3-1], -31[#3-2]
Prototype (jacketed) Beam port free	**36.7**	33.6[#1-1], 36.5[#2-1]
Pre-production (jacketed) Beam port free	**12.7**	13.97
Pre-production (jacketed) Beam port fixed	-4.6	5.2

- Force balance b/w cavity and helium jacket of cavity beam port
  - Beam port-to-beam port length of the dressed cavity increases due to the helium pressure
  - Reduction of outward force by reducing beam port flange size

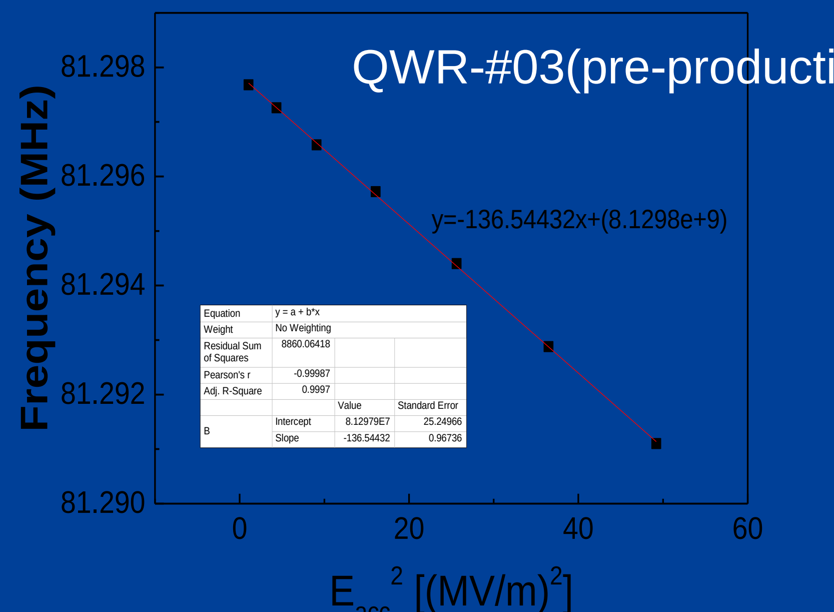
Changes in mass production

Uniform LFD of QWR cavity

	Calculated [Hz/(MV/m)^2]	Measured [Hz/(MV/m)^2]
Prototype (bare) Beam port free	**-16.4**	$-20^{\#1\text{-}1}$, $-32.7^{\#2\text{-}1}$, $-17.4^{\#2\text{-}2}$, $-44.6^{\#3\text{-}1}$, $-14.7^{\#3\text{-}2}$

Before modification
(Cracks in welding point)

After modification
(Cracks in welding point)



- LFD variation due to the welding of disk and rib on the top of the cavity
  - Change the welding method from tack welding to line welding

Changes in mass production

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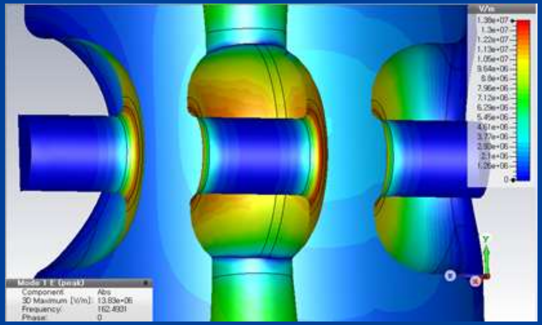
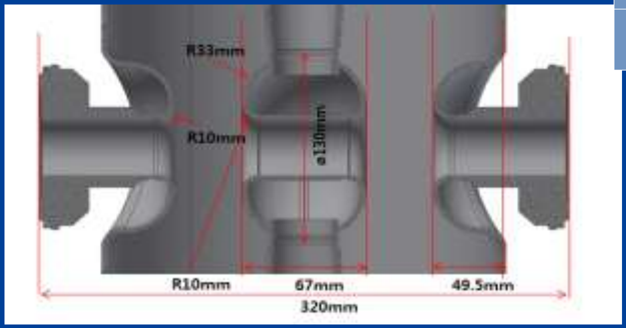
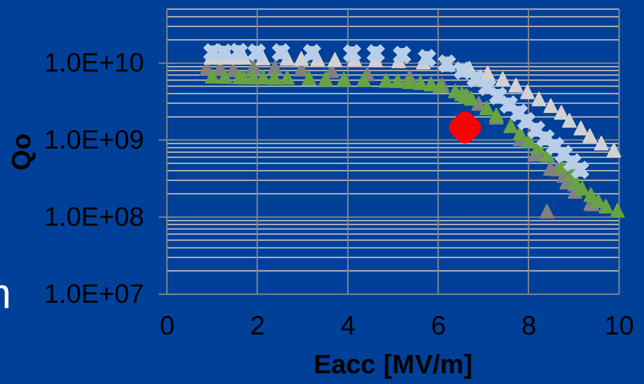
Beam port and beam sphere design change of HWR cavity





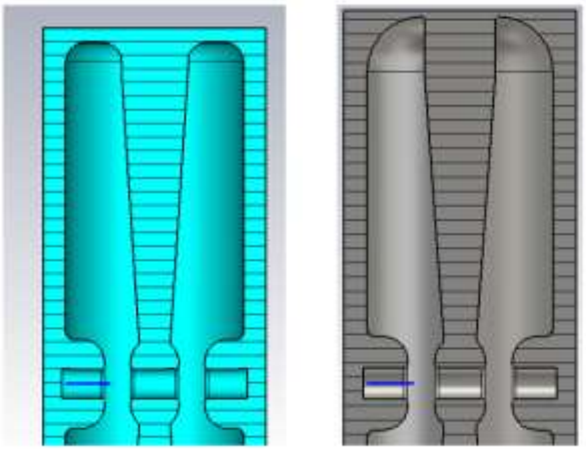
Parameter	Original	Modified
Rounding of Beam tube	5mm	10mm
H of Beamport cup	52.5mm	49.5mm
Diameter of Ring	120mm	130mm
Width of Ring	65mm	67mm
Rounding of Ring	30mm	33mm
E_{peak}/E_{acc}	5.54	5.05



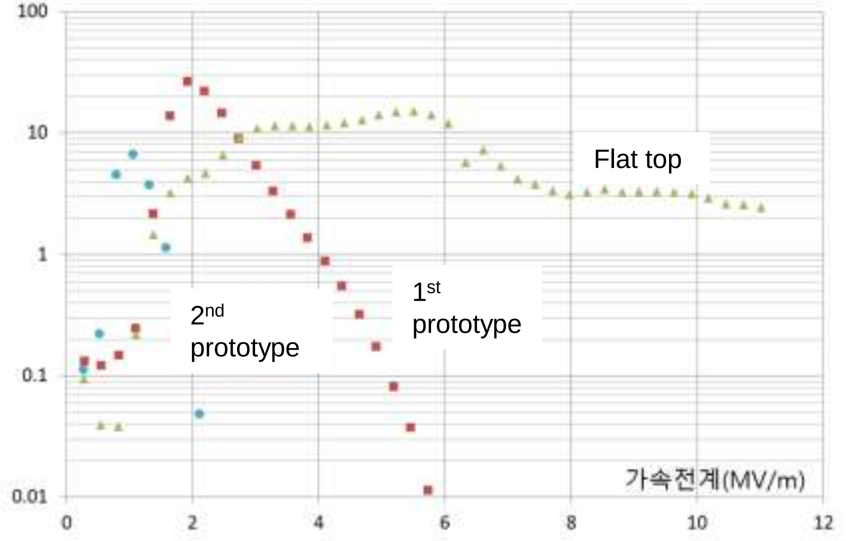
- Improvement EM performance of cavity
  - FE starts around 6 MV/m while operating E_{acc} is 6.6 MV/m
  - Decreasing E_{peak}/E_{acc} by 9.8 %
  - Location of welding lines are moved away from the high E_{acc} region

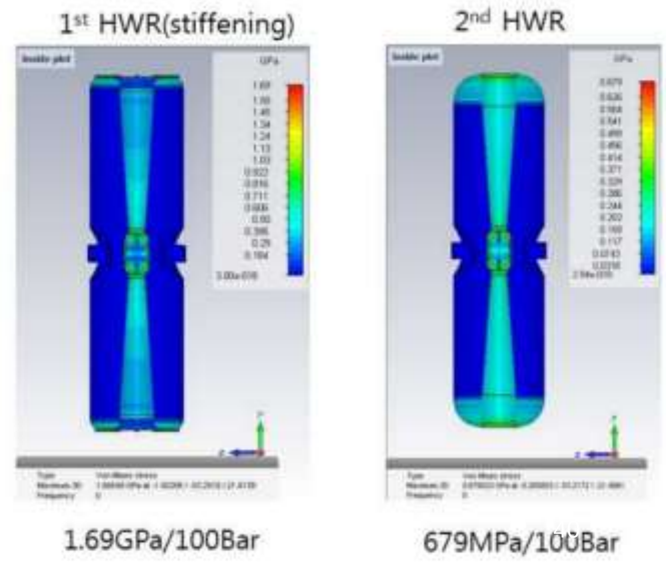
Changes in mass production

Round top for HWR cavity (during prototyping)



1st prototype   2nd prototype





- Multipacting suppression: MP band below 2 MV/m
- Structural stability of cavity w/o stiffener
  - Deformation and stress reduced by half
    - Max. deformation: 1.9 mm → 0.86 mm
    - Max. stress: 1.69 GPa → 679 MPa

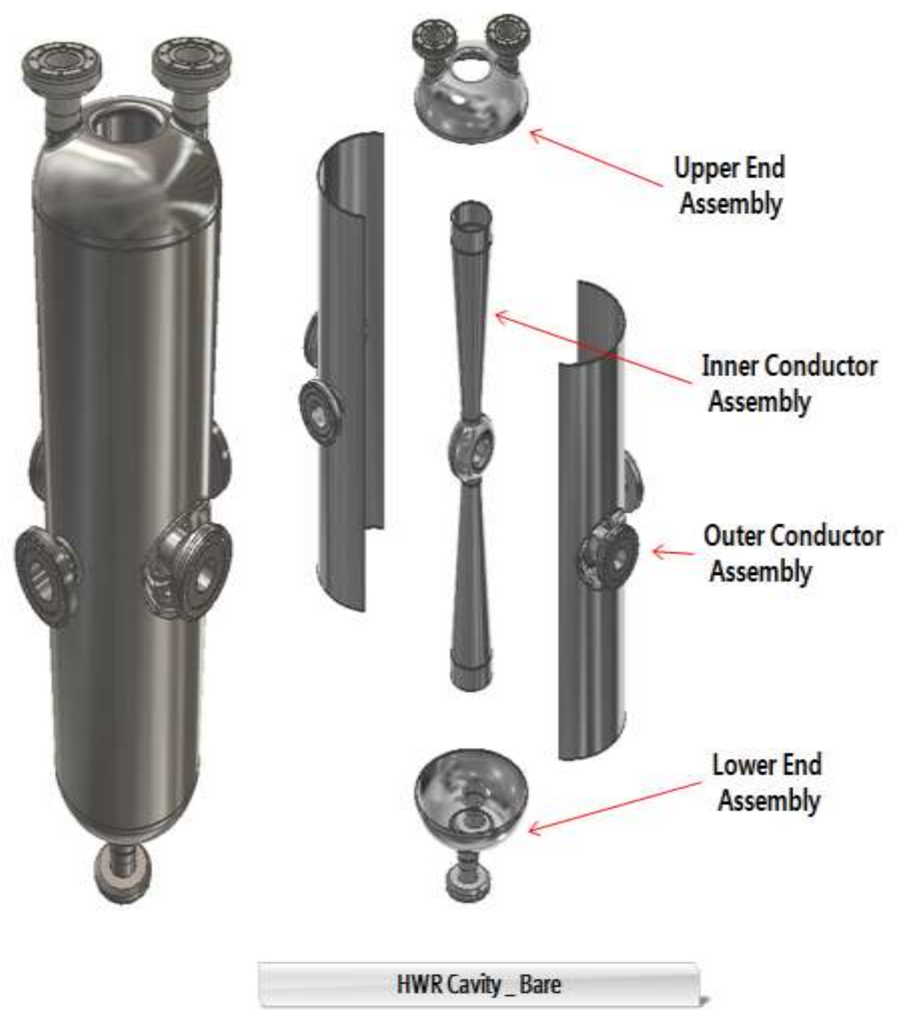
Changes in mass production

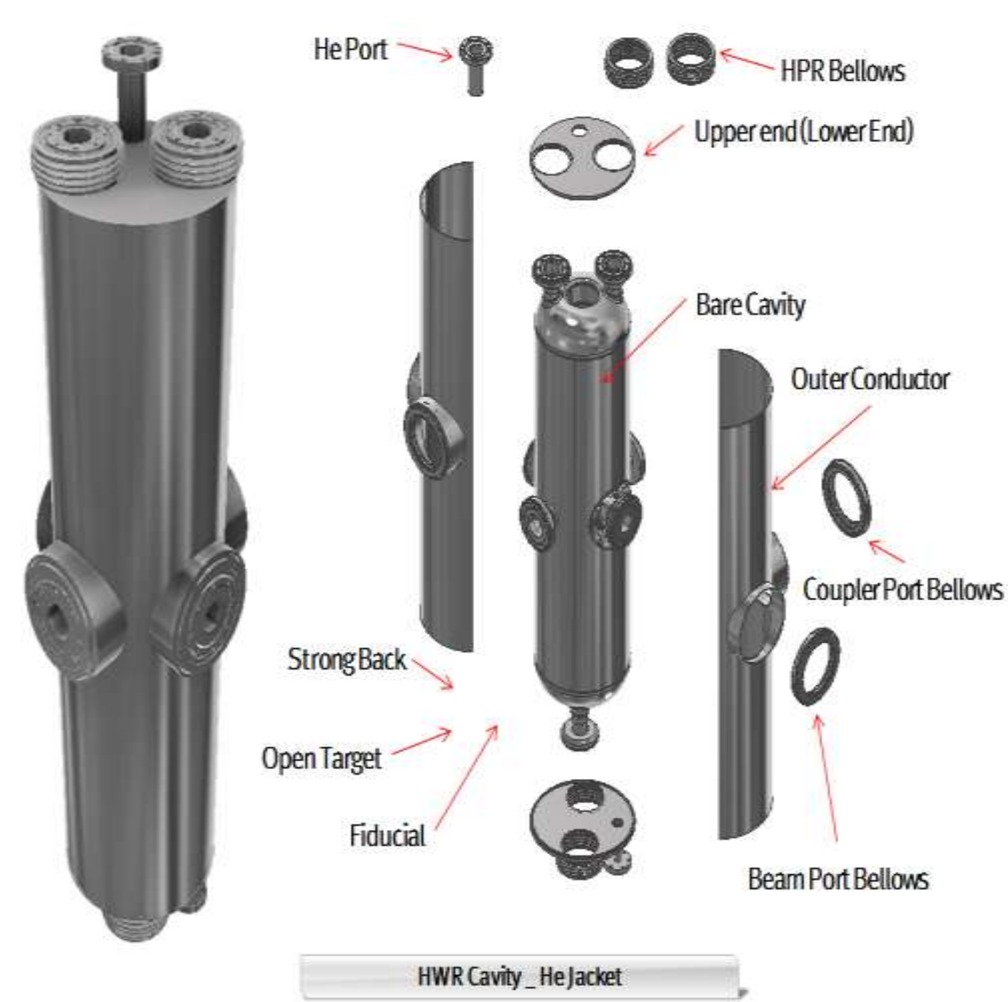
Changes in fabrication methods

- Rib of beam port
  - Welding crack in beam port rib: tack welding → line welding

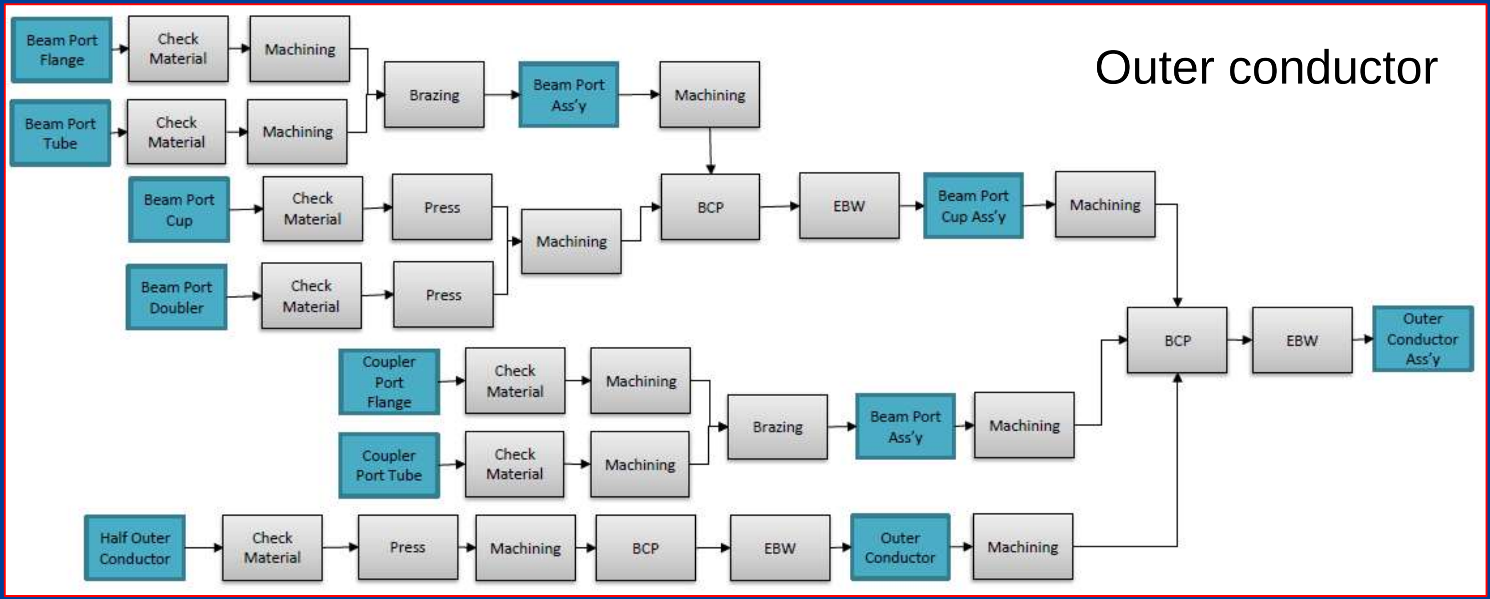
- **Knife edge of CF flanges**
  - Brazing between Nb tube and STS CF flange
  - Heat treatment during brazing affecting the STS material → decrease of hardness of knife edge
  - Machining of knife edge of CF flange after the brazing procedure

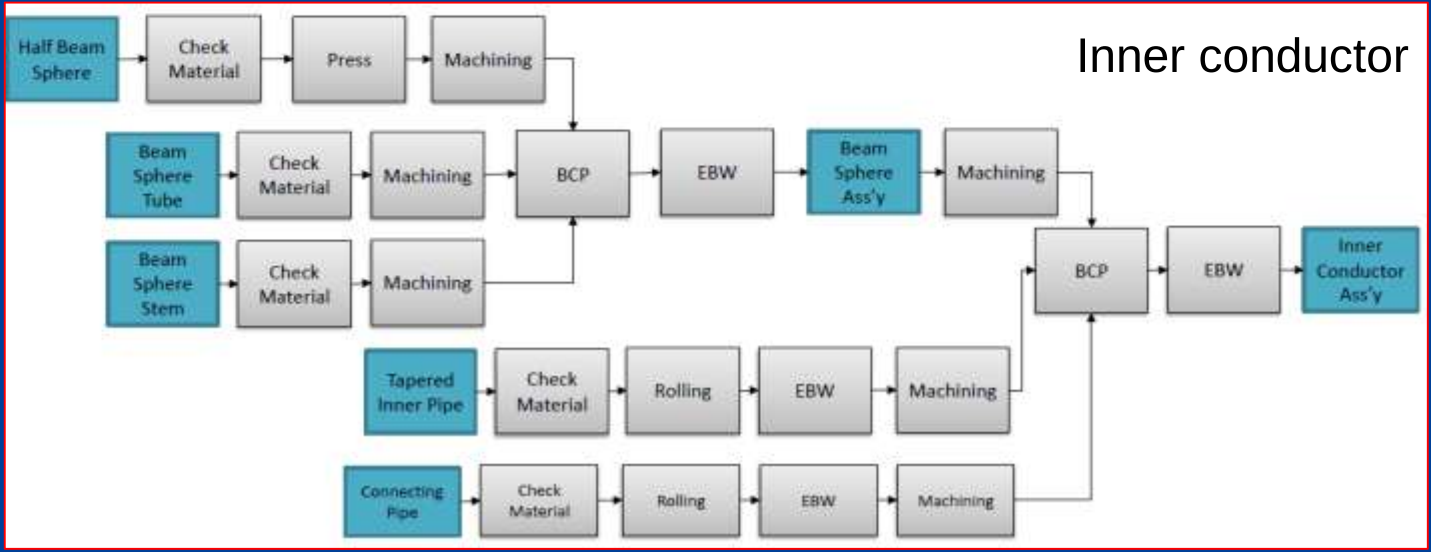
Cavity fabrication





Cavity fabrication





Cavity fabrication

Material

Material inspection
- Visual inspection, Soaking test
- Structural characteristics

Cutting of materials

Pressing & machining for parts

Cavity fabrication

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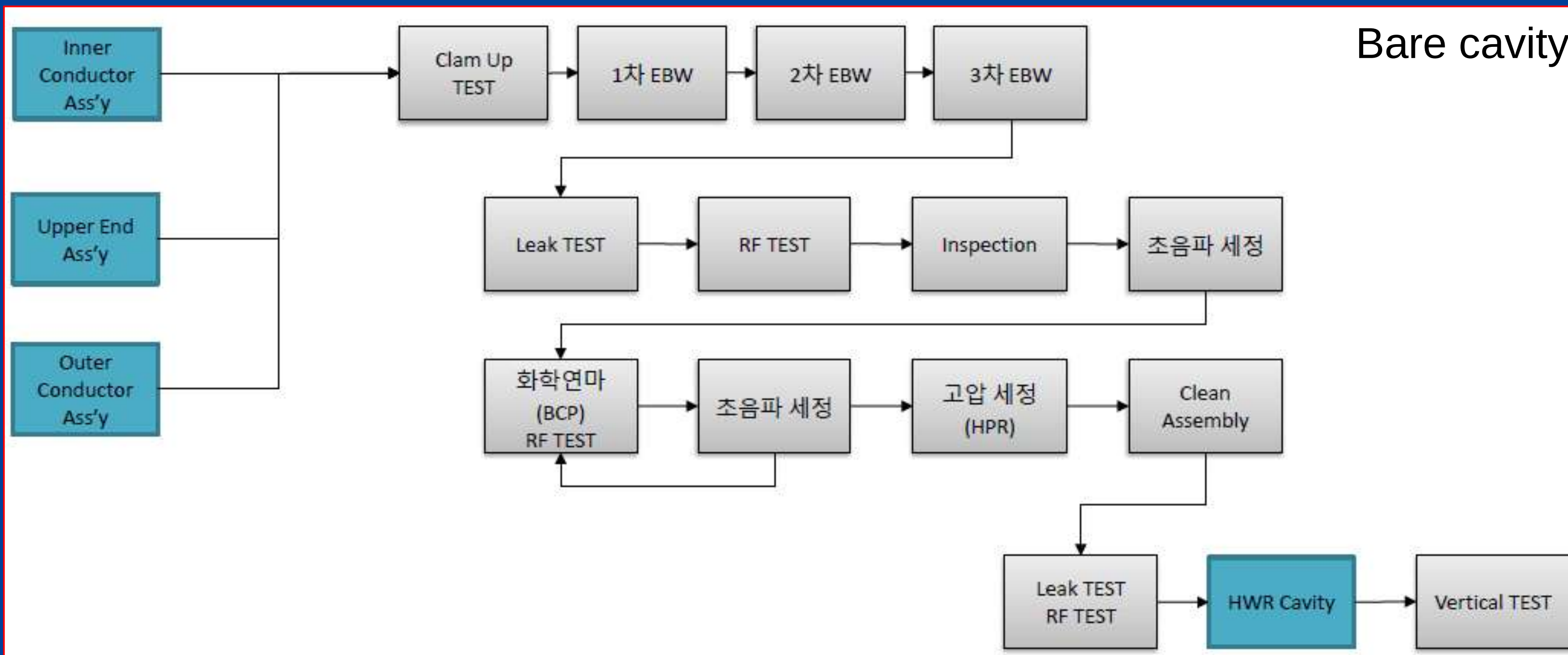


Cavity fabrication

Clamp-up test
- Frequency adjustment before final welding

E-beam welding

Ultrasonic cleaning (USC)

BCP

HPR

High temperature heat treatment

Cavity fabrication

Full and light BCP procedure in detail

1st BCP → **2nd BCP** → **3rd BCP** → **Clean room assembly** → **Light BCP (dressed cavity)**

1st BCP
- Visual inspection
- Freq.,weight check
- USC (Liqinox, DI)
- BCP (Lower, ~50um)
- USC (DI water)
- Drying (10 class cleanroom)

2nd BCP
- Visual inspection
- Freq.,weight check
- BCP (Upper, ~50um)
- USC (DI water)
- Drying (10 class cleanroom)

3rd BCP
- Visual inspection
- Freq.,weight check
- BCP (Lower, ~50um)
- USC (DI water)
- Freq.,weight check
- HPR
- Drying (10 class cleanroom)

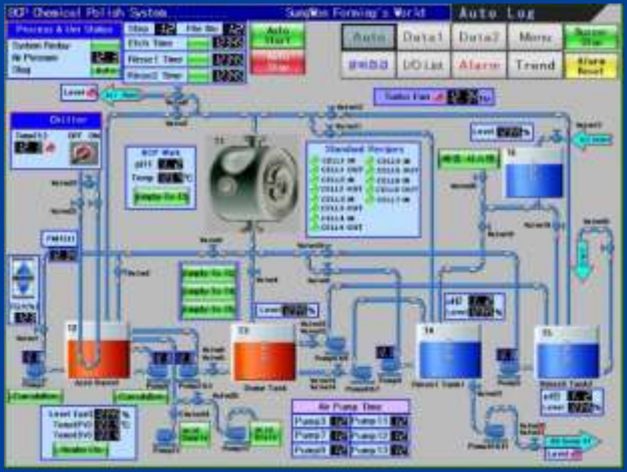
Clean room assembly
- Cleaning
- Ports & valve assembly
- Leak test
- Ar charging
- Vertical test
- He jacketing

Light BCP (dressed cavity)
- Visual inspection
- Freq.,weight check
- BCP (Lower, ~20um)
- USC (DI water)
- Freq.,weight check
- HPR
- Drying (10 class cleanroom)

* Weight check: estimation of etching depth

Cavity fabrication

BCP system



- Closed-loop chemical circulation type
- 49%HF+69%HNO_3+85%H_3PO_4 (1:1:2)
- Keeping Nb concentration in acid below 15g/L
- Acid flow rate : 2~10LPM
- Etch rate : 0.7~1㎛/min
- Target removal : 120~150㎛(Bulk BCP) + 15~20㎛(light BCP, bare) + 15~20㎛(light BCP, jacketed)
- Temperature control (23kW chiller) : below 15℃ during the process
  - The acid is pre-cooled down to 5~9℃ in the acid storage tank. (cooling water temp. is just above freezing level of chiller)

HPR procedure in detail

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 (for the three port steps)
- **Drying**: 10 class cleanroom

HPR ports

Cavity fabrication

HPR system

- Water pressure: 100 bar
- Nozzle rotating speed : 20rpm
- Nozzle/Cavity moving speed : 5cm/min
- High pressure filter : 0.5㎛

USC (Ultrasonic cleaning) system

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

Cavity fabrication

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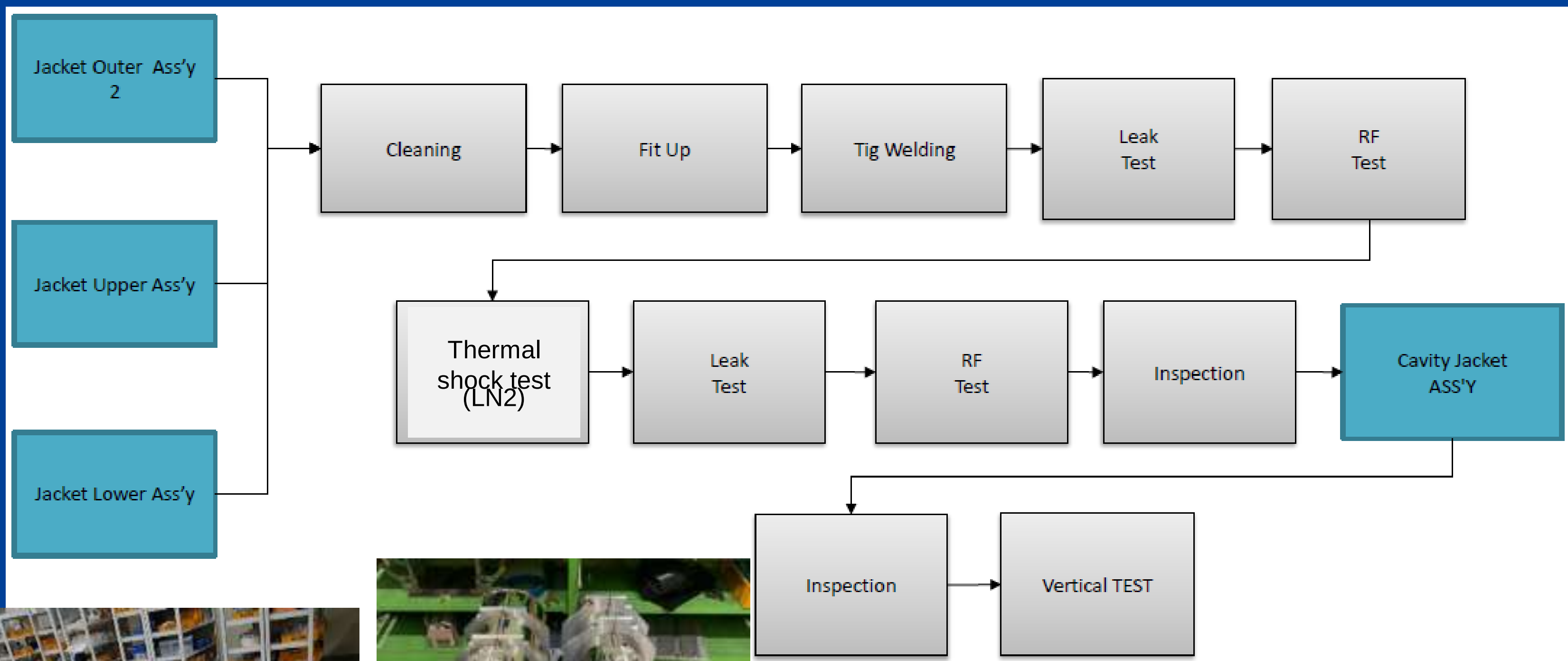
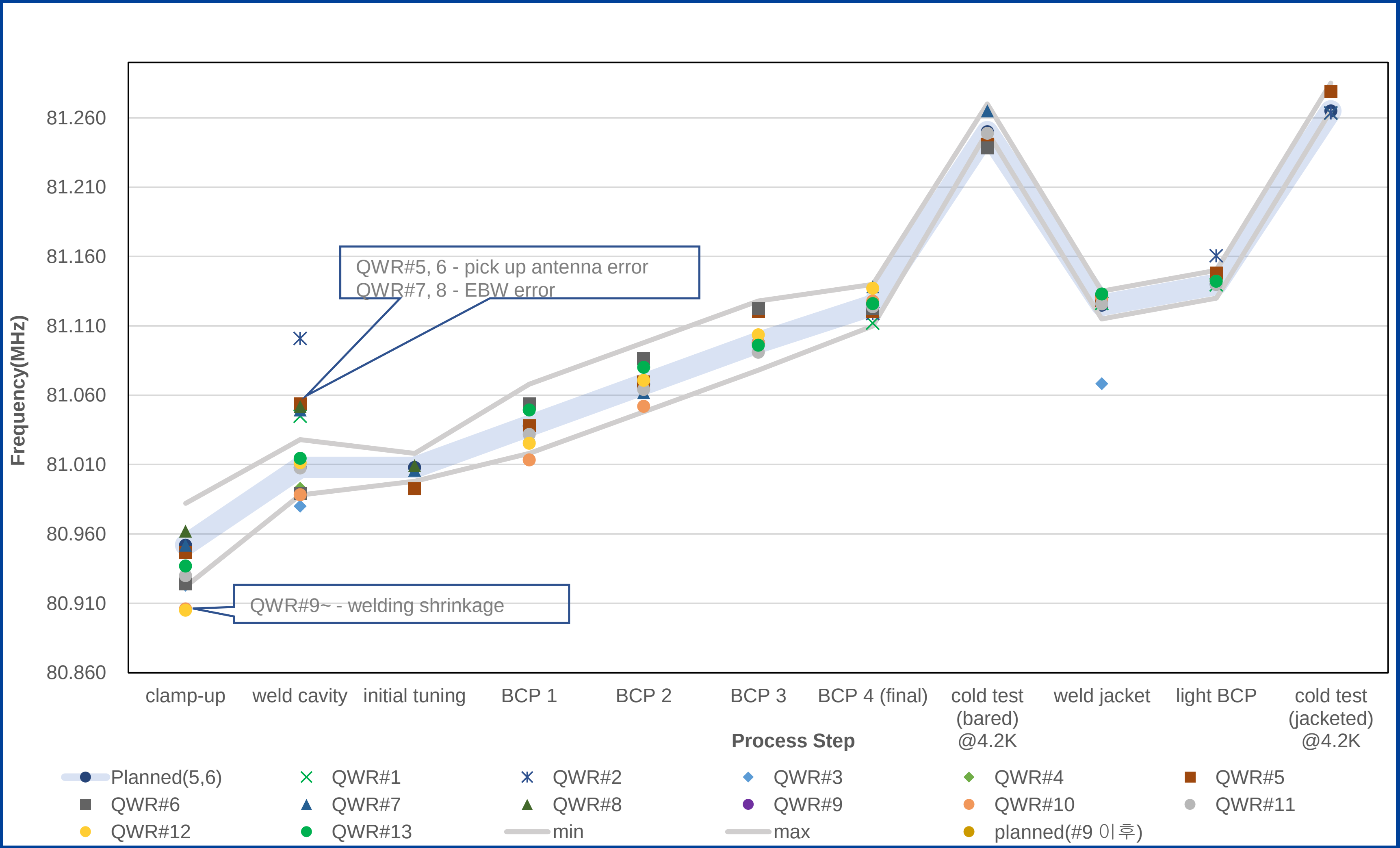
He jacketing procedure



Cavity fabrication

Frequency Control during the whole fabrication



Target: 81.14 MHz ±10kHz before assembly in cryomodule

Cavity fabrication

Clean assembly

USC & HPR

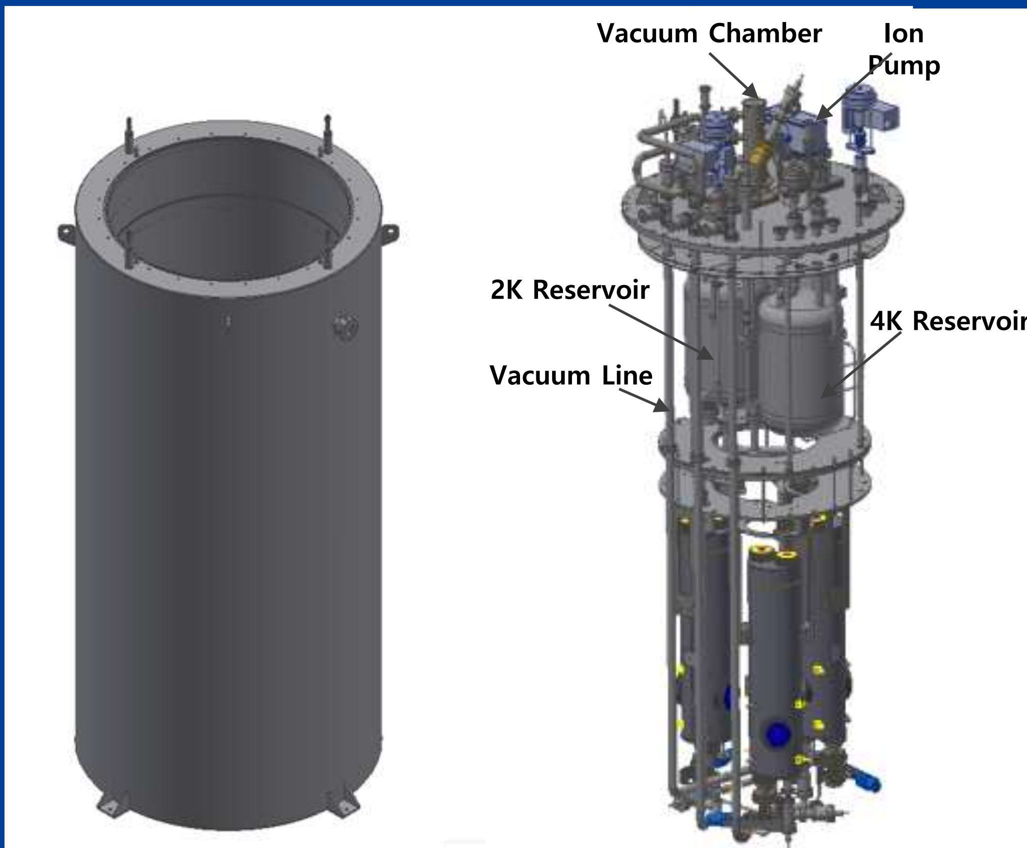
Parts using USC	Parts not using USC
Less than 1 particle (≤ 0.3μm) /5s	Less than 1 particle (≥ 1.0 μm) /1s

Particle counting

Reference: TTC topical workshop on clean room assembly, 2014

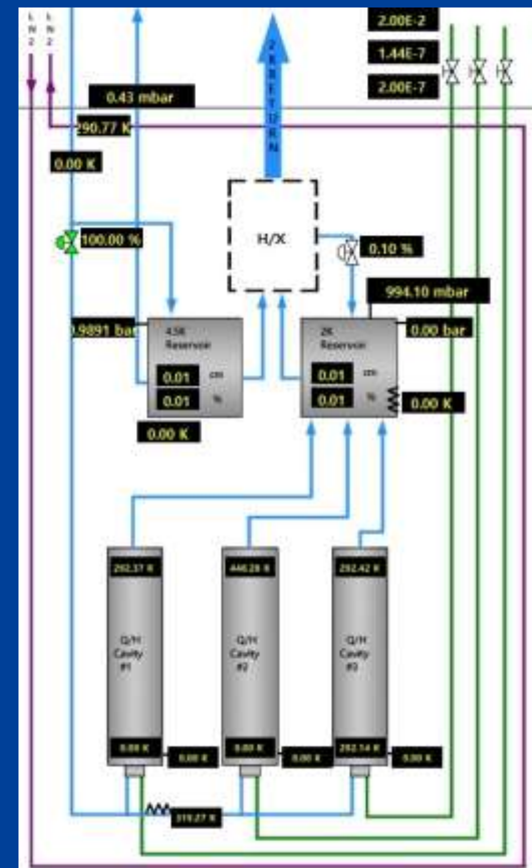
Performance Test

Vertical Test



Cryostat

Top flange



Performance Test

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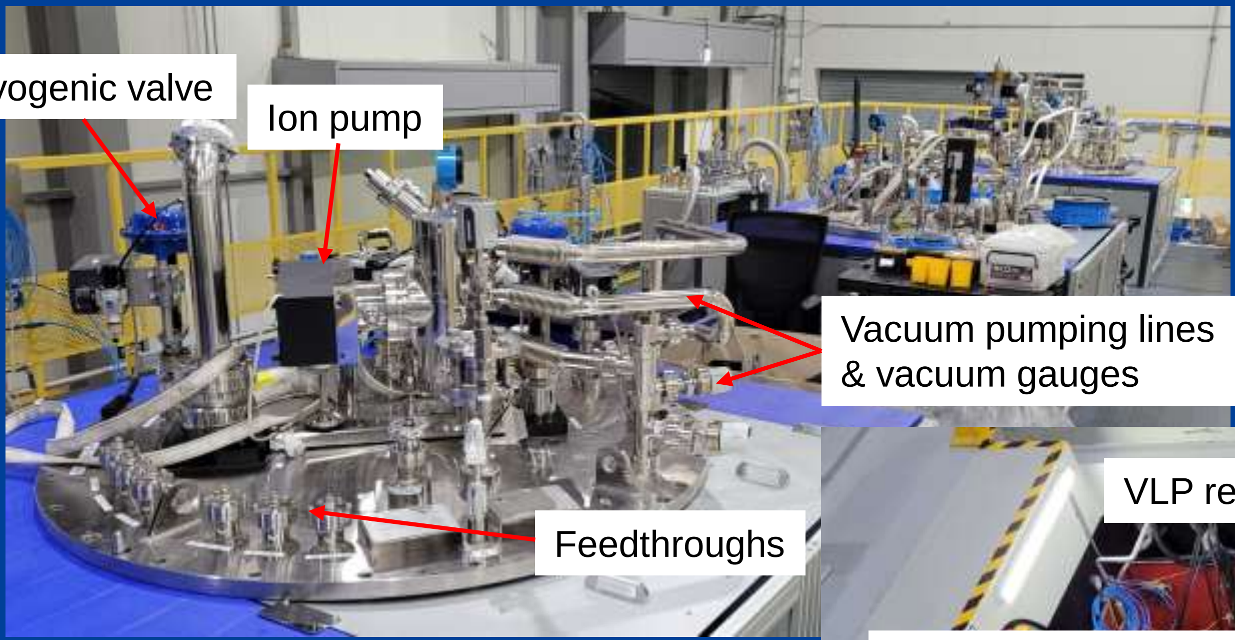
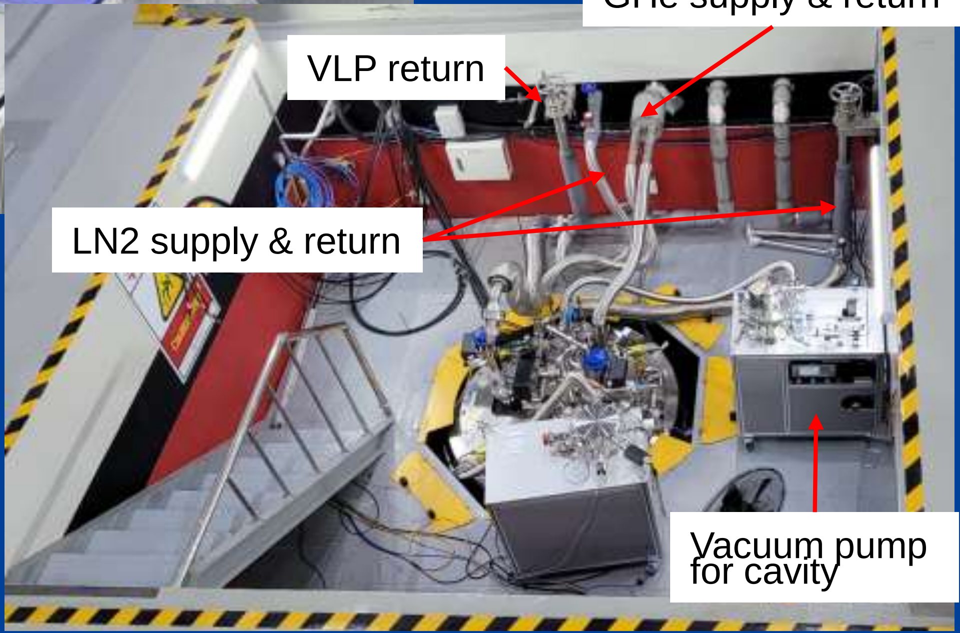
Vertical Test



Assembly area(clean room) for vertical test

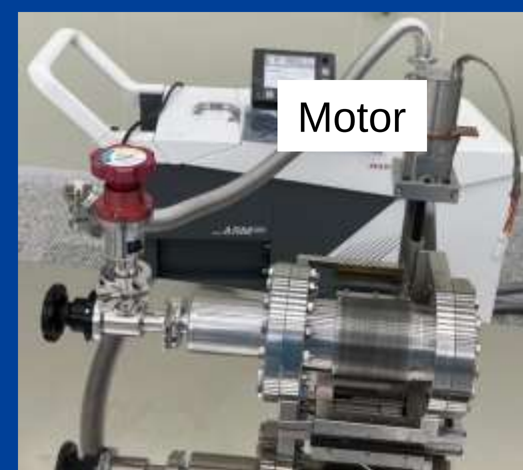


Top flange in the vertical test pit

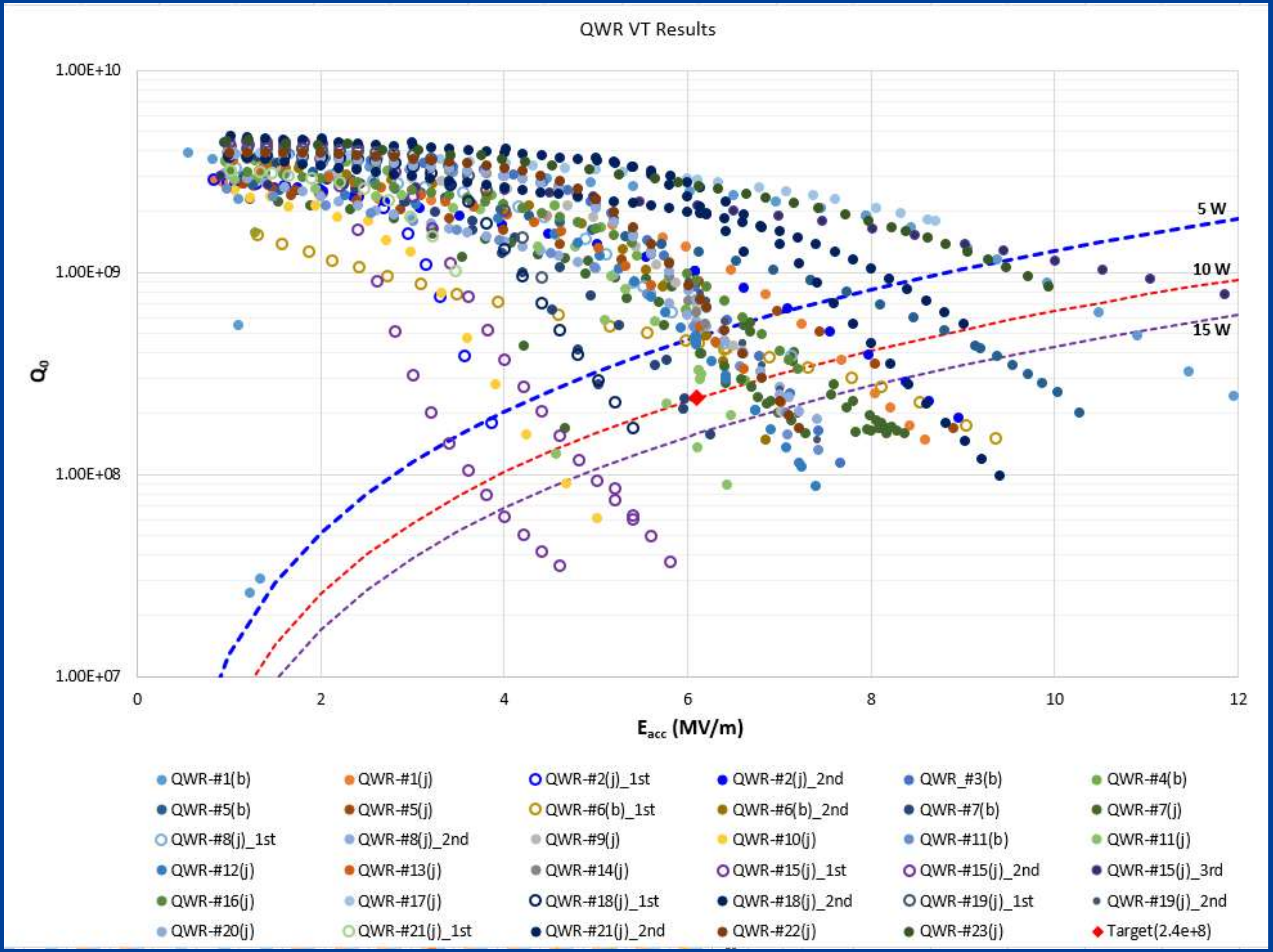
Vertical Test

Inner conductor

Outer conductor and bellows



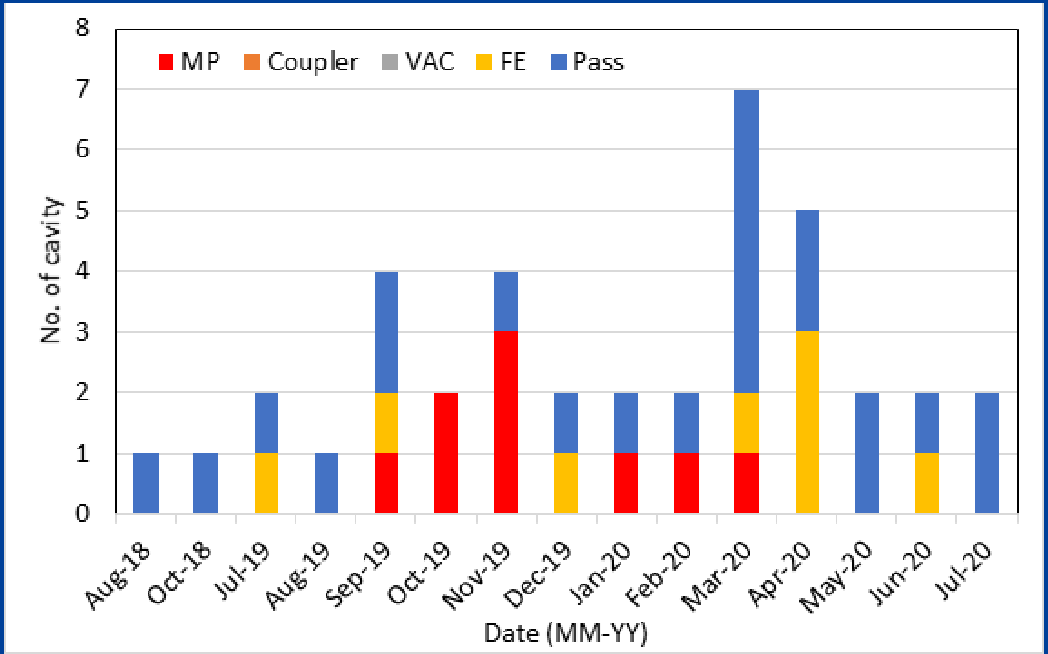
QWR VT results



$$Q_0 = \frac{\omega U}{P_d}$$

E_{acc}: 6.1 MV/m, Q_0=2.4e+8@4.2K, Number of cavity: 22 ea

QWR VT results



Baking of cavity and variable coupler

- Acceptance rate: 56 % (18 pass / 32 test, 4 prototype cavity)
  - Failure for multipacting conditioning due to insufficient baking of variable coupler
  - Field emission due to contamination

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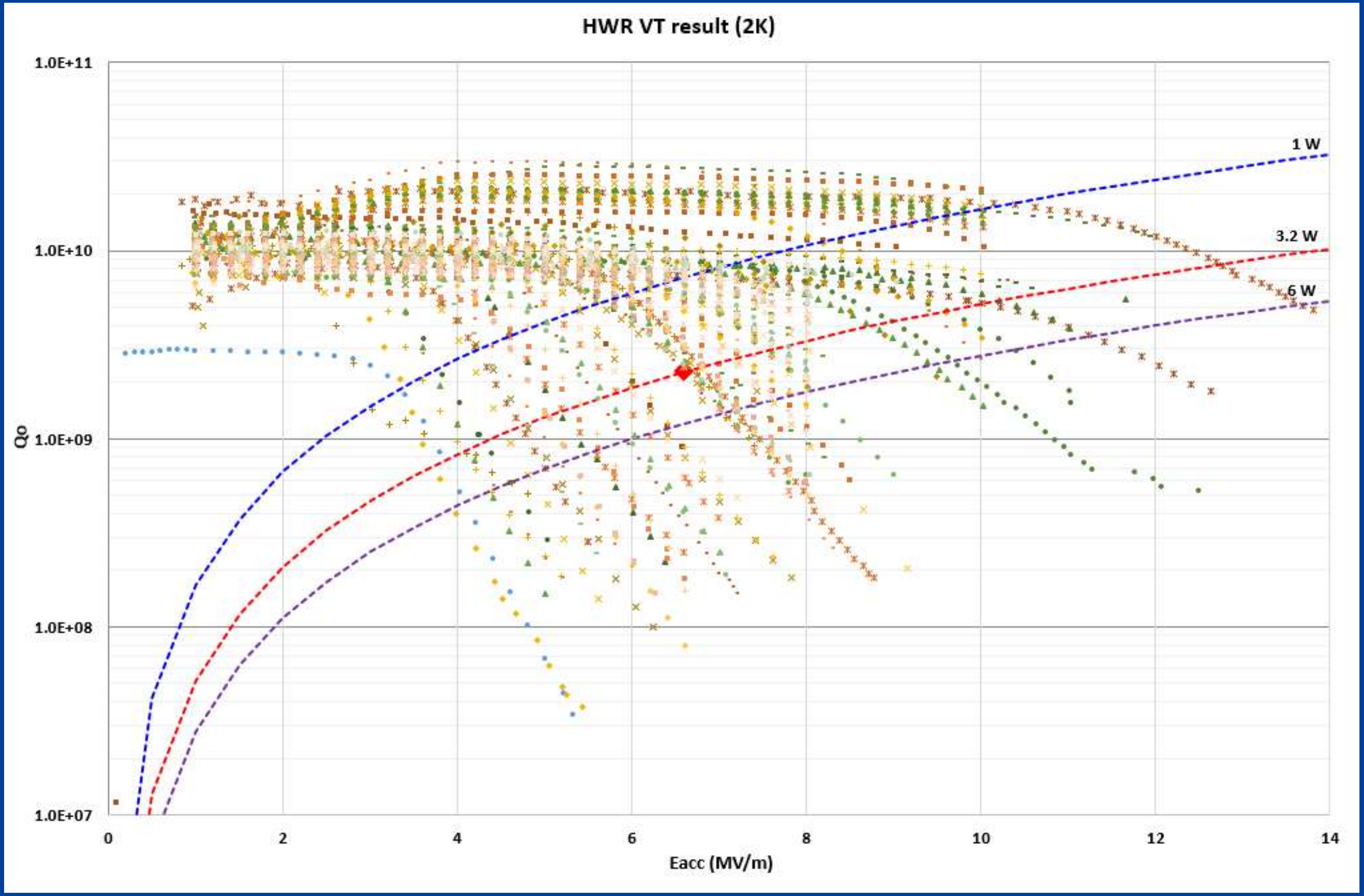
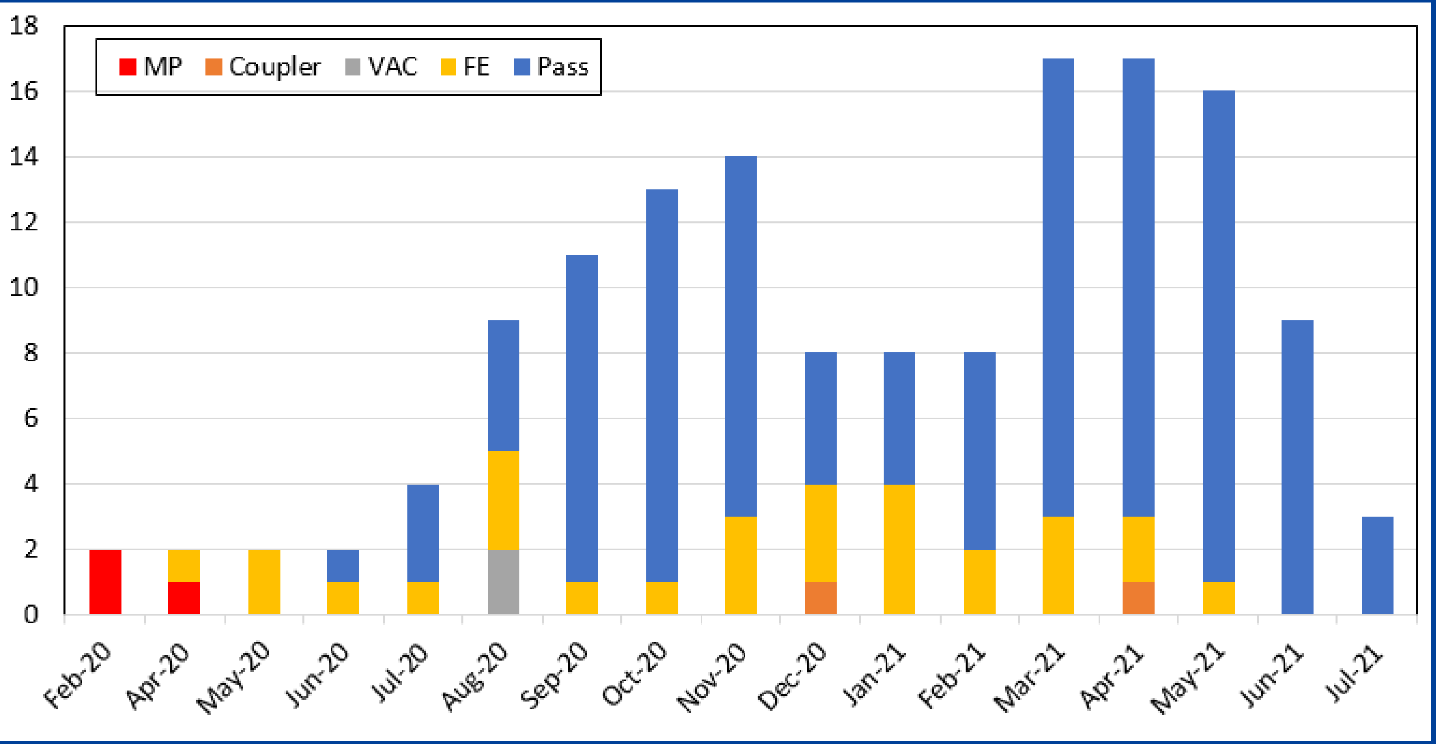
HWR VT results



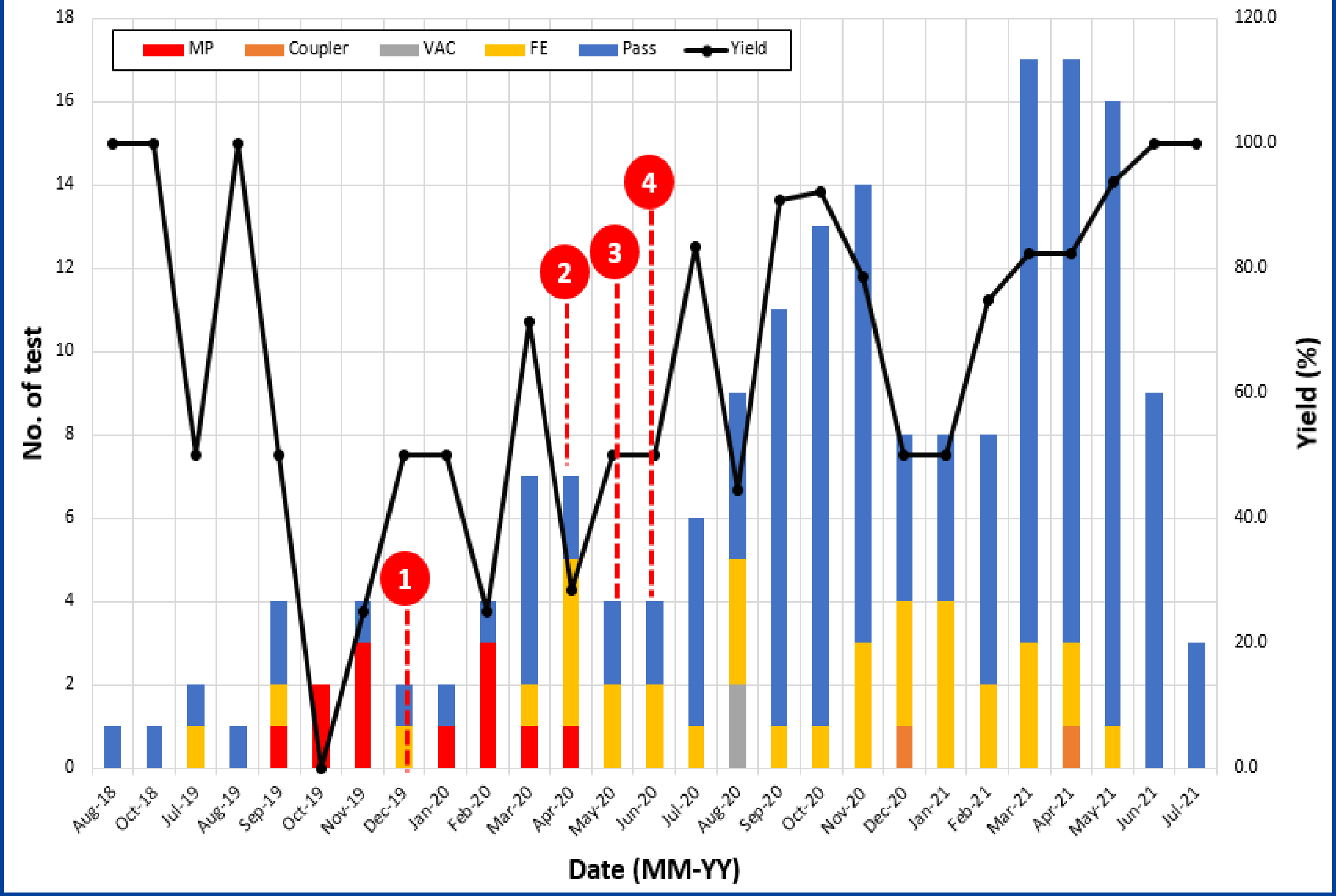
E_{acc}: 6.6 MV/m, Q_0=2.3e+9@2.05K, Number of cavity: 106 ea

HWR VT results



- Acceptance rate: 76 %
  - FE: 28 cases, MP failure: 3 cases, Vacuum failure: 3 cases, Malfunction of test coupler: 2 cases

Performance vs. processing



① Hand HPR and baking for variable coupler ('19.12) ➔ overcoming MP failure
② N2 purging before the vacuum line connection ('20.04)
③ 100 bar HPR for variable coupler bellows to prevent contamination of cavity('20.05)
④ Cleanroom management: cleaning tools, clothes, etc. ('20.06)

Horizontal Test

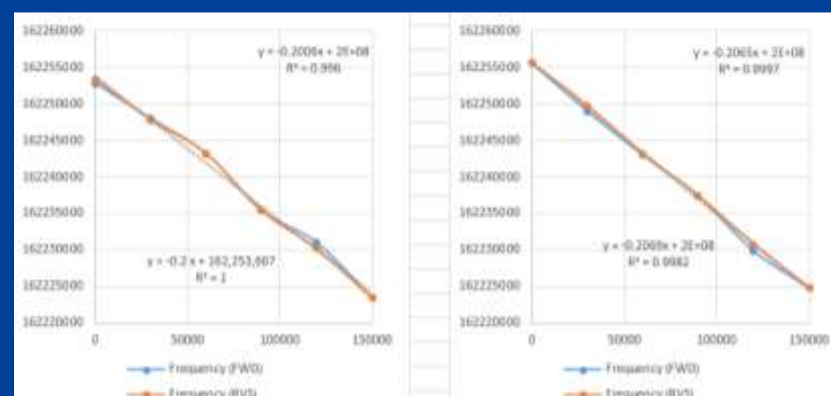
Test Procedure

Installation in the bunker
- Cavity frequency check & tuner operation test
- Leak test and vacuum pumping for cavity
- Leak test and Purging cryogenic pipes
- Connecting cryogenic lines, signal cables, DC bias,
  RF transmission lines, etc

Cool-down
- Thermal shield cool-down by LN2
- Cavity cool-down through cool-down line

4K Test
- MP conditioning
- Cable calibration
- Static and total thermal load measurement
- Field emission conditioning with pulsed RF power, if necessary

2K Test
- 2 K pump-down: df/dp measurement (~3MV/m)
- Q_{ext} measurement with VNA
- Static and total thermal load measurement
- LFD & tuner operation test
- Alignment measurement



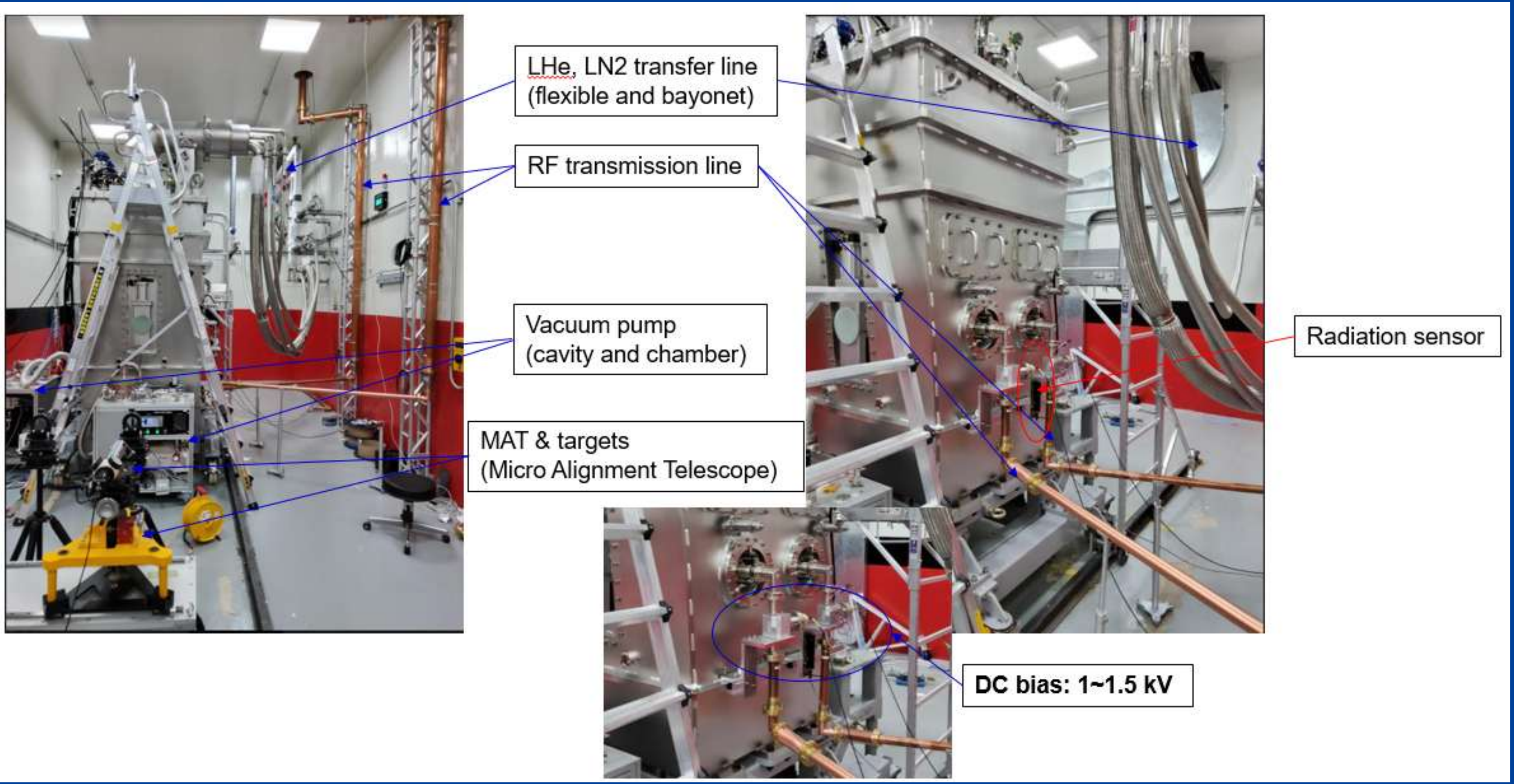
Tuner test at room temp. (~0.2 Hz/pulse, ~30 kHz span)

Horizontal test facility

Horizontal test bunkers

Performance Test

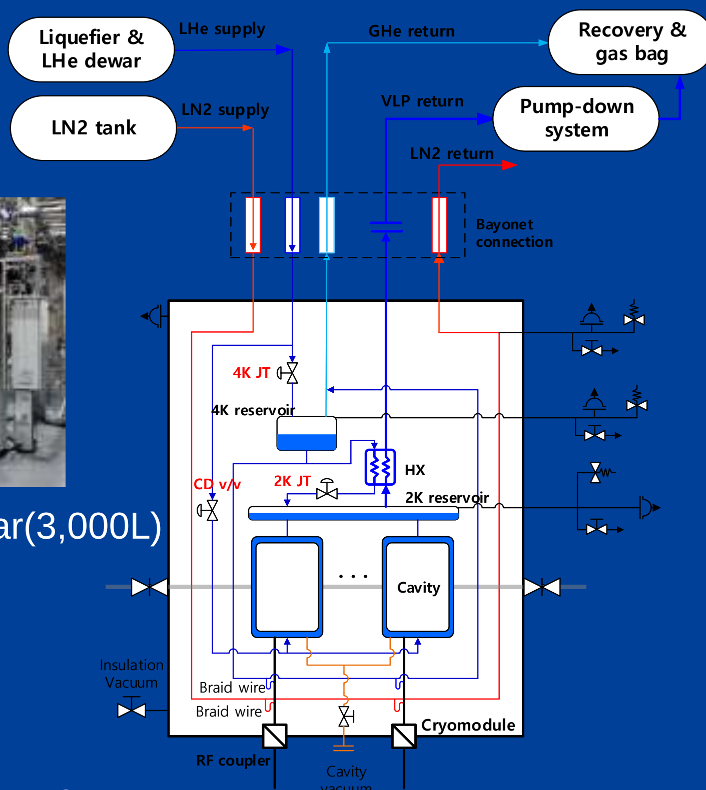
Test setup



Performance Test

P&ID for cryomodule and cryogenic system

Liquefier (280L/h) and dewar(3,000L)

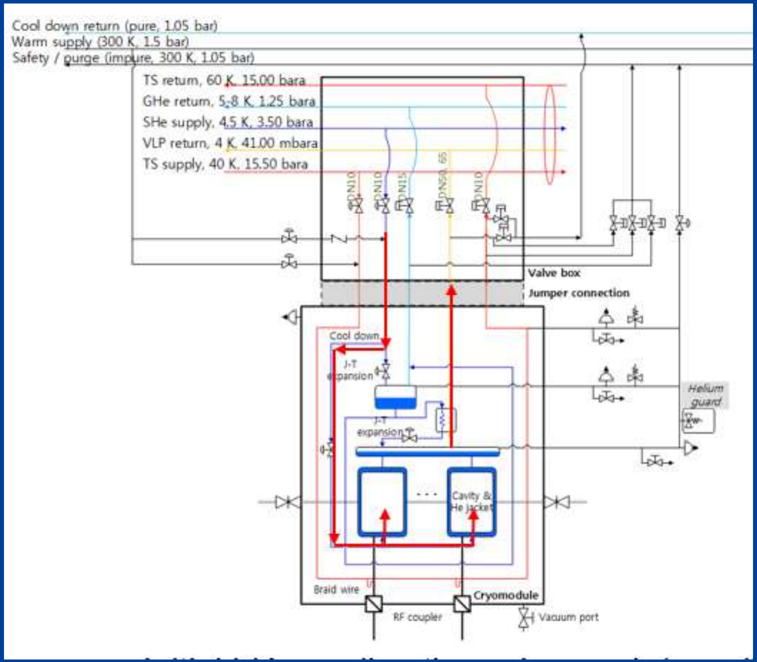


- Thermal shield cooled by LN2
- Thermal intercepts
  - 4 K intercepts: loop thermosiphon connected with 4 K reservoir
  - 40 K intercepts: copper braid wire connected with thermal shield
- 3 cryogenic valves: 1 for cool-down and 2 for JT expansion
- Heat exchanger to precool the LHe before 2 K expansion
- Vacuum pumping system to maintain 35 mbar

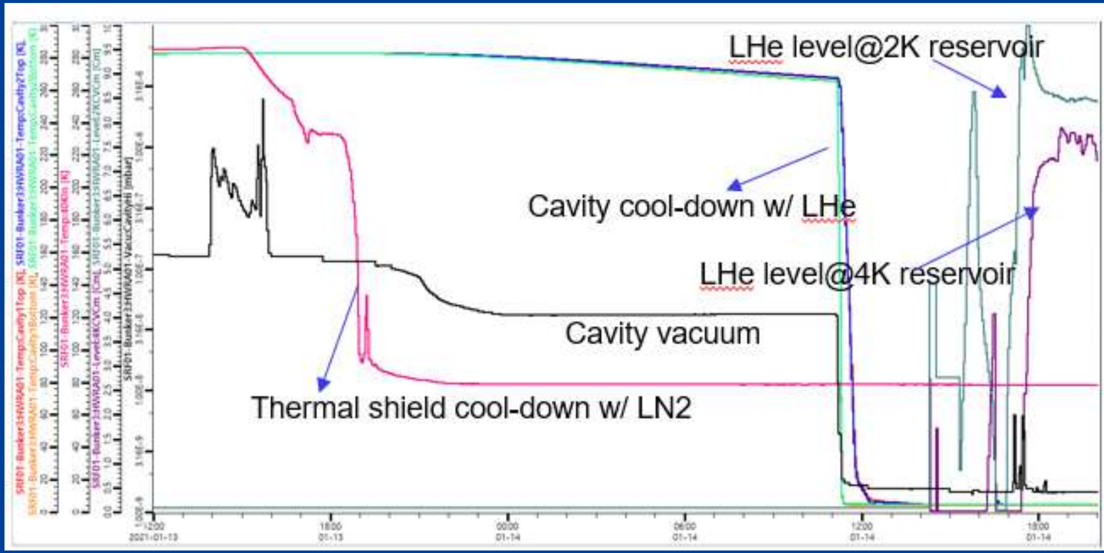
Recovery compressor
and gas bag

Pump-down system(vacuum pumps): 1.5g/s each

Cool-down of cryomodule

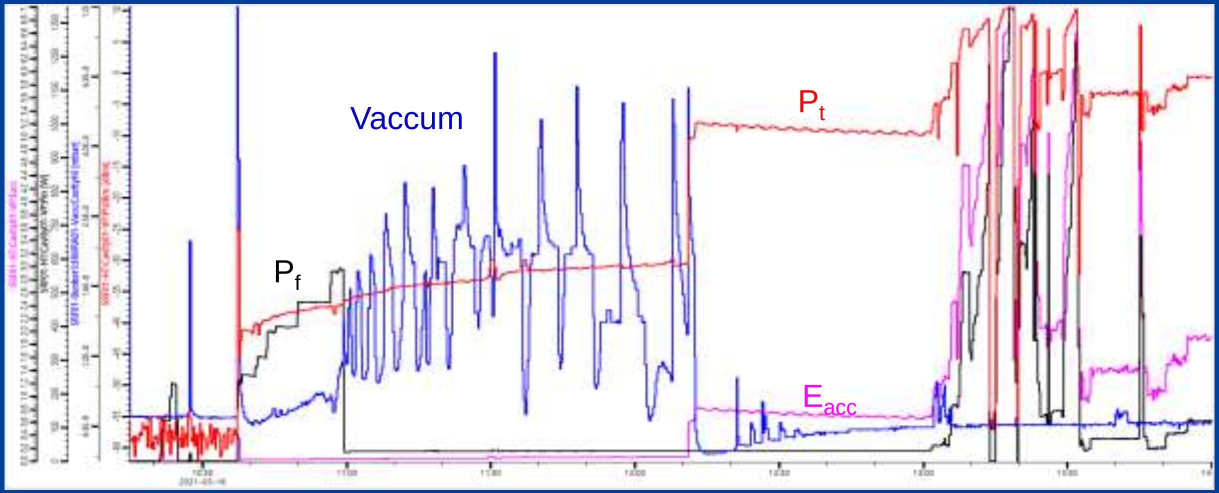


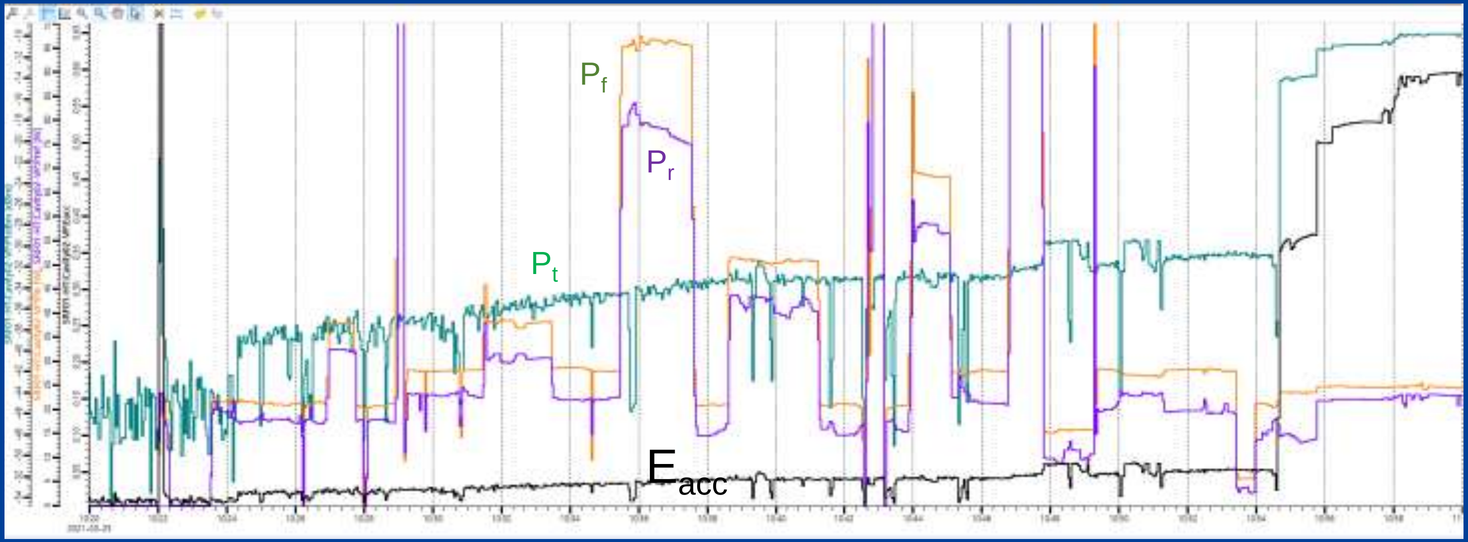
Initial LHe cooling through a cool-down line



Cool-down history of HWR cryomodule

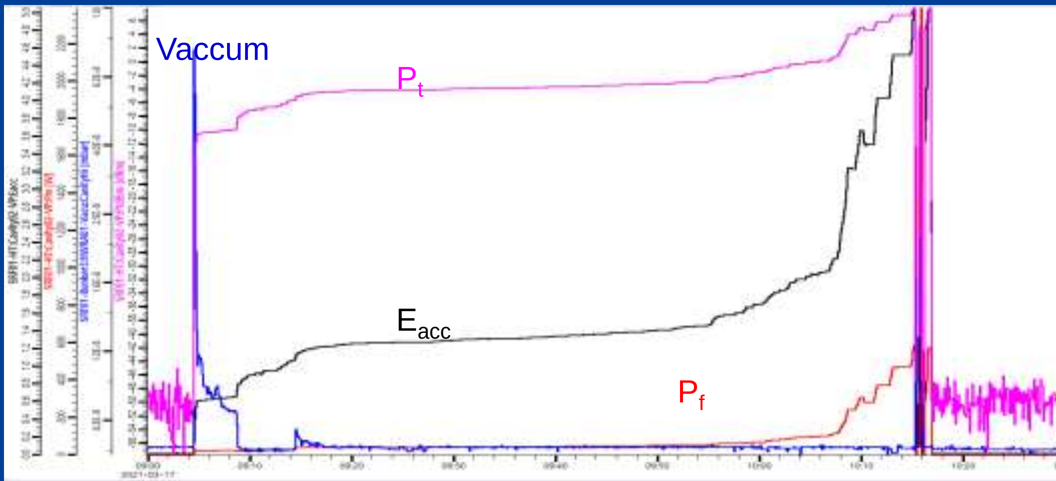
Multipacting conditioning (HWR cavity)



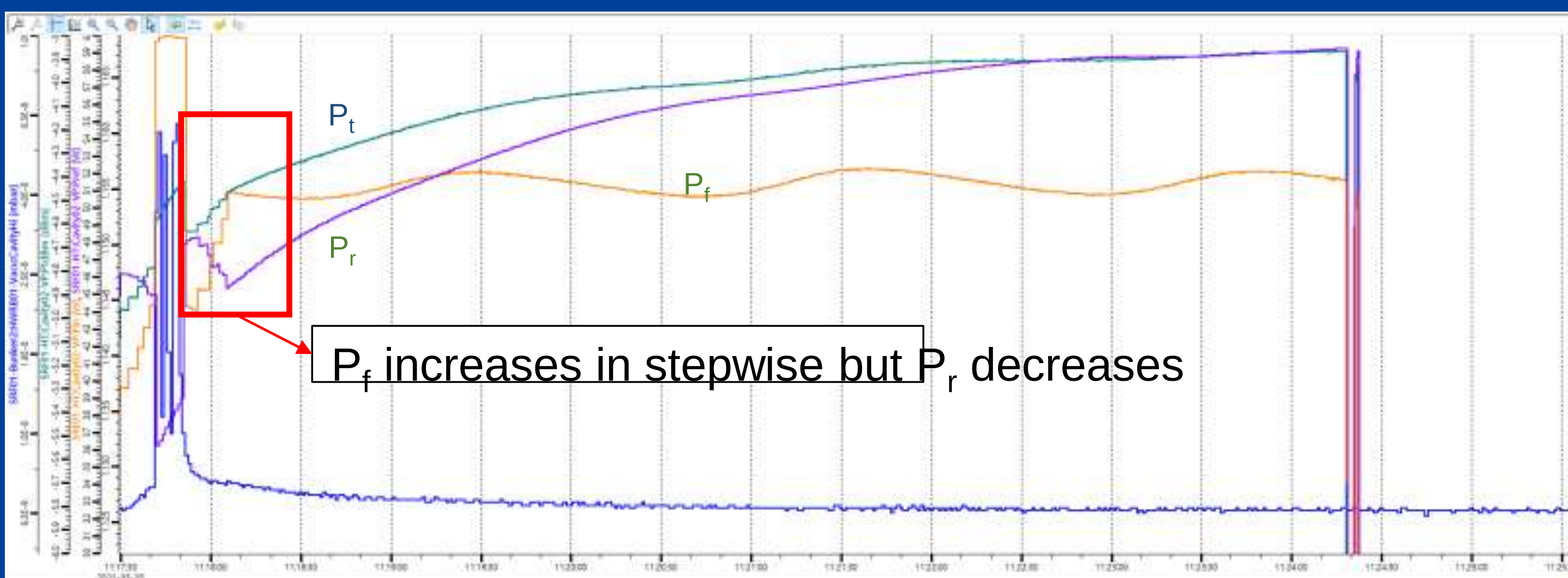


- MP in low field (<1MV/m)
  - P_f below 40 W
  - Vacuum level fluctuation

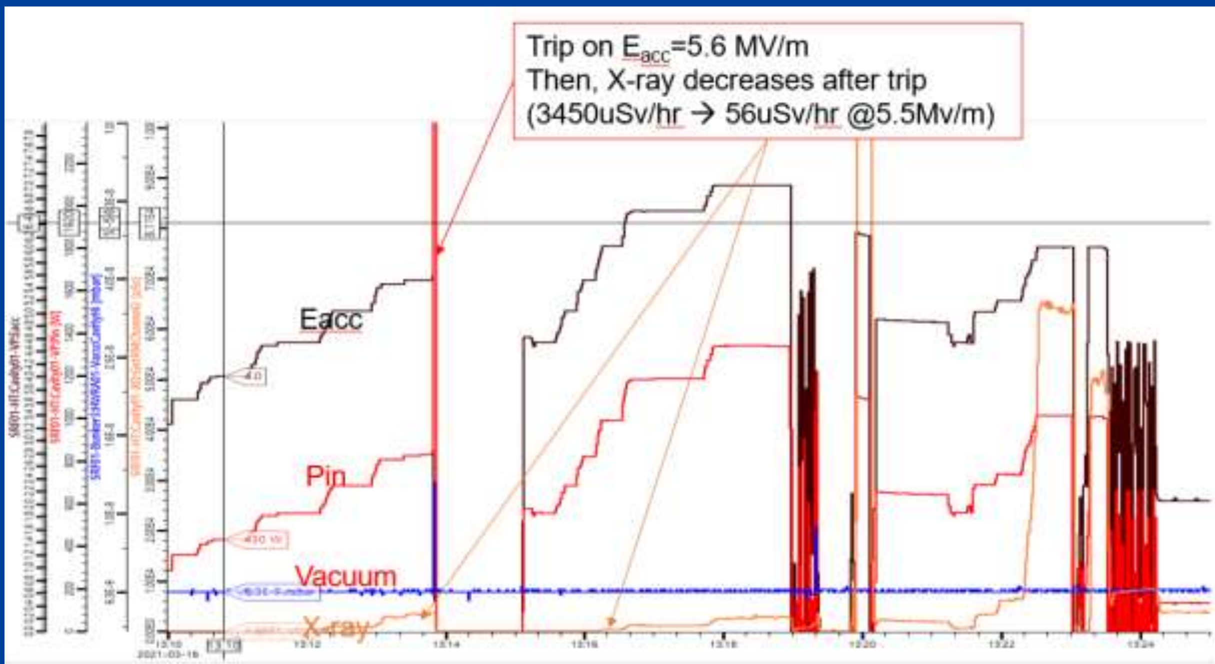
Multipacting conditioning (HWR cavity)



- MP in high field (<2MV/m)



Conditioning effect during E_{acc} increase

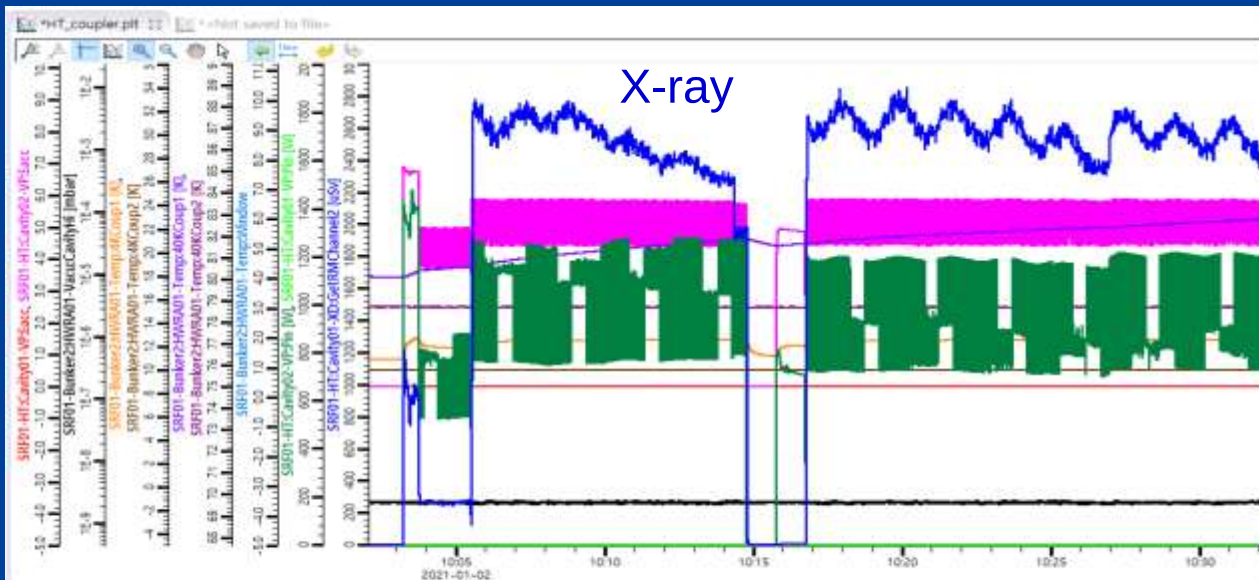


X-ray: amount of field emission
➔ quick view of cavity's performance

Conditioning of cavity (Burning of field emitter)

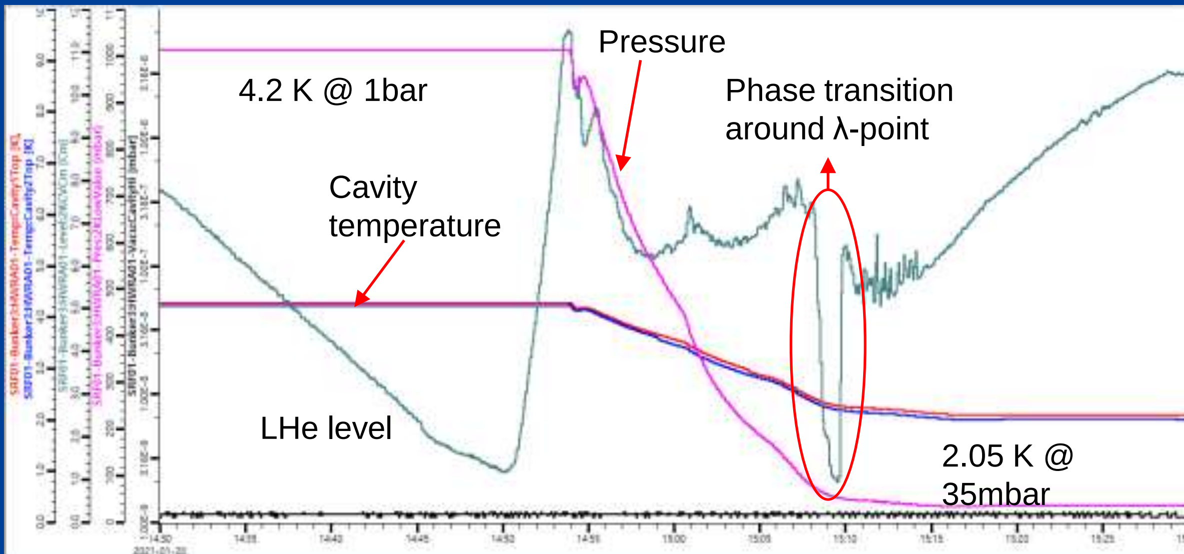
E_{acc} (Mv/m)	3.5	4.0	4.5	5.0	5.5	6.0	6.6	Remarks
HWR#13 (uSv/hr)	8.5	48	352	800	3450			Trip on 5.6
	After trip →		0.7	8	56	300	1250	
HWR#32 (uSv/hr)	4	89	223	400				Trip on 5
	After trip →			65	300	430	1800	

Pulse conditioning

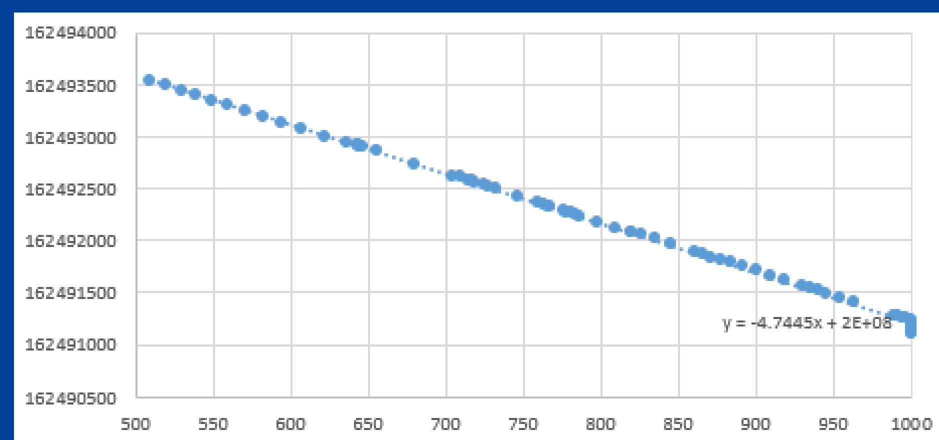


- High E_{acc} without quench (Max. P_{out} of SSPA = 4 kW)
- Monitoring X-ray value
- P_t signal in oscilloscope

2K pump-down

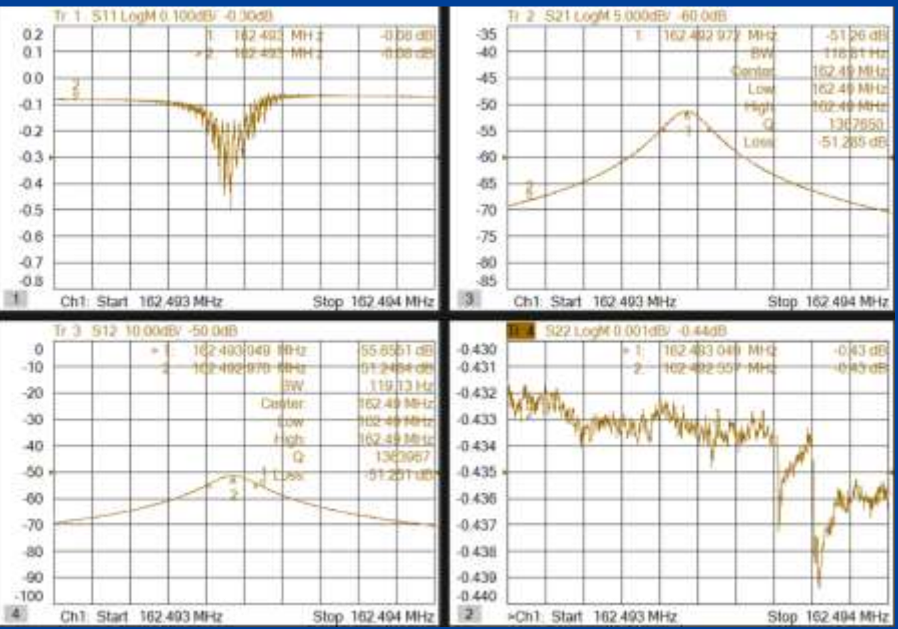


2K pump-down



df/dp measurement during 2K pump-down (E_{acc} < 3MV/m)

Q_{ext} measurement with VNA



CM number	HWR #B07			
CAV	HWR #51	HWR #77	HWR #80	HWR #81
Freq [MHz]	162.5	162.5	162.5	162.5
S_{21} (dB)	-52.22	-52.05	-51.19	-50.91
S_{21}	2.45E-03	2.50E-03	2.76E-03	2.85E-03
Q_L	1.07E+06	8.01E+05	9.98E+05	1.13E+06
S_{11} (dB)	-6.00E-02	-8.00E-02	-7.00E-02	-6.00E-02
S_{11}	9.93E-01	9.91E-01	9.92E-01	9.93E-01
S_{22} (dB)	-4.70E-01	-3.80E-01	-3.90E-01	-4.40E-01
S_{22}	9.47E-01	9.57E-01	9.56E-01	9.51E-01
Q_t	7.13E+11	5.14E+11	5.25E+11	5.58E+11
S_{21}' (dB)	-51.96	-51.82	-50.96	-50.66
S_{21}'	2.52E-03	2.56E-03	2.83E-03	2.93E-03
Q_t'	6.71E+11	4.87E+11	4.98E+11	5.27E+11

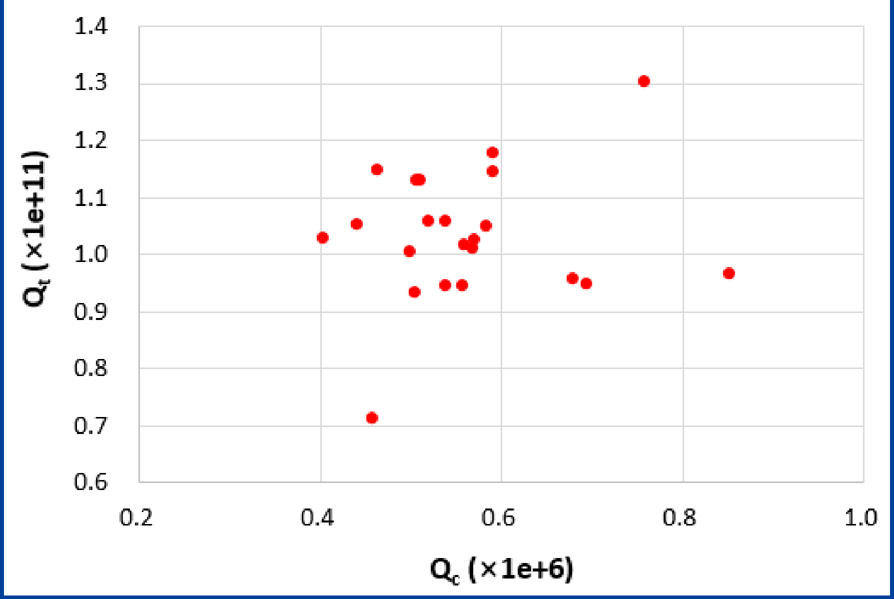
$$S'_{21} = S_{21} - \frac{(S_{11} + S_{22})}{2}$$

$$Q_t = \frac{1}{Q_c}\left(\frac{2Q_L}{S_{21}}\right)^2$$

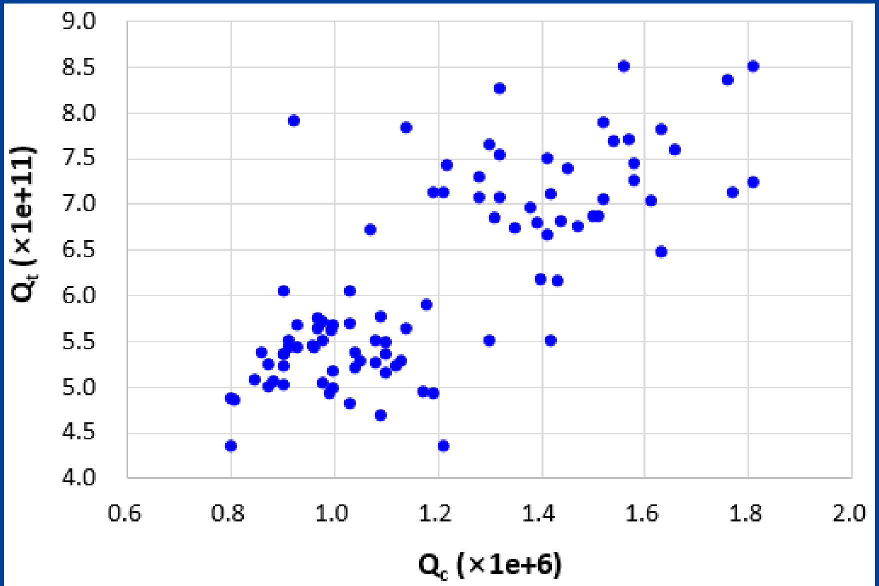
$Q_c \approx Q_L$, since $Q_0 \sim O(10^9), Q_c \sim O(10^6)$

H. Hahn et al., Calibration of the ERL cavity FPC and PU couplers, 2010

Q_{ext} measurement of QWR and HWR cavities



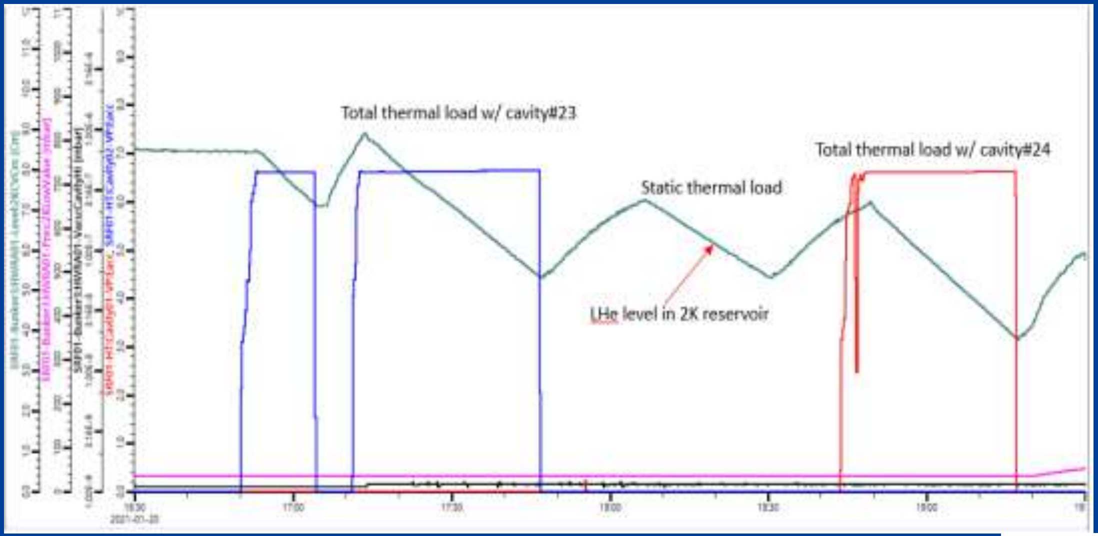
QWR



HWR

- Requirement for Pickup Q_{ext}(Q_t) from LLRF system: two orders higher than Q_0
- Power coupler Q_{ext} (Q_c): control bandwidth and required RF power
  - Average control bandwidth: QWR (149 Hz), HWR (143 Hz)

Thermal load measurement



Measurement of thermal loads

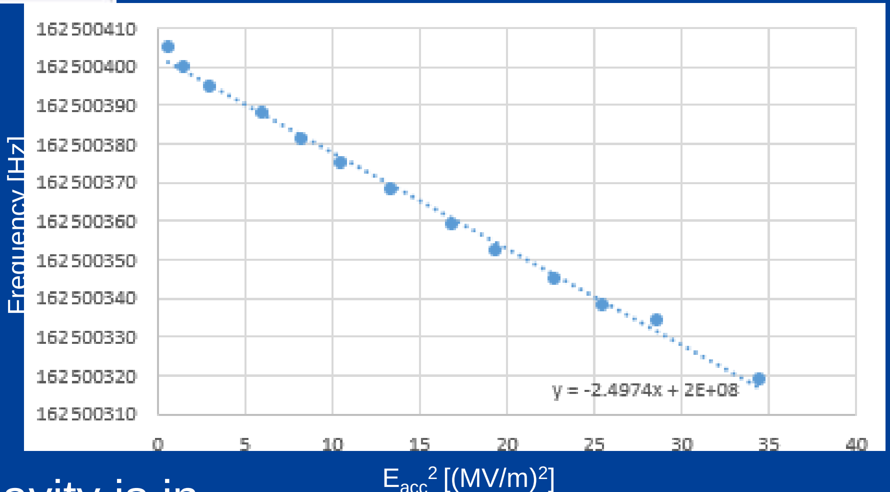
- Thermal load measured by boil-off calorimetry

$$Q = \dot{m}h_{fg} = \rho_l \frac{dV}{dt} h_{fg}$$

- Dynamic thermal load of each cavity

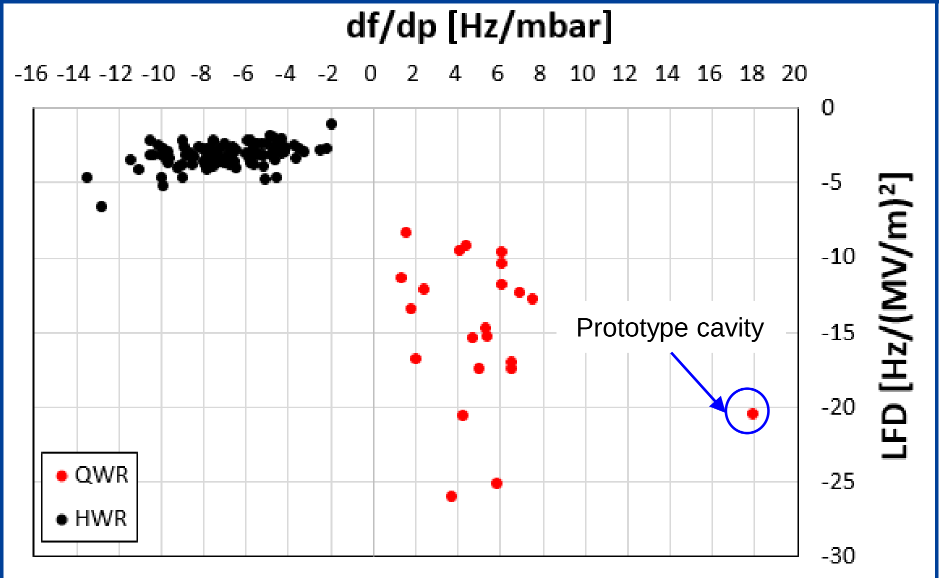
$$Q_{dynamic} = Q_{t1} - Q_{static}$$

, where Q_{t1} is thermal load when only one cavity is in its operating E_{acc}

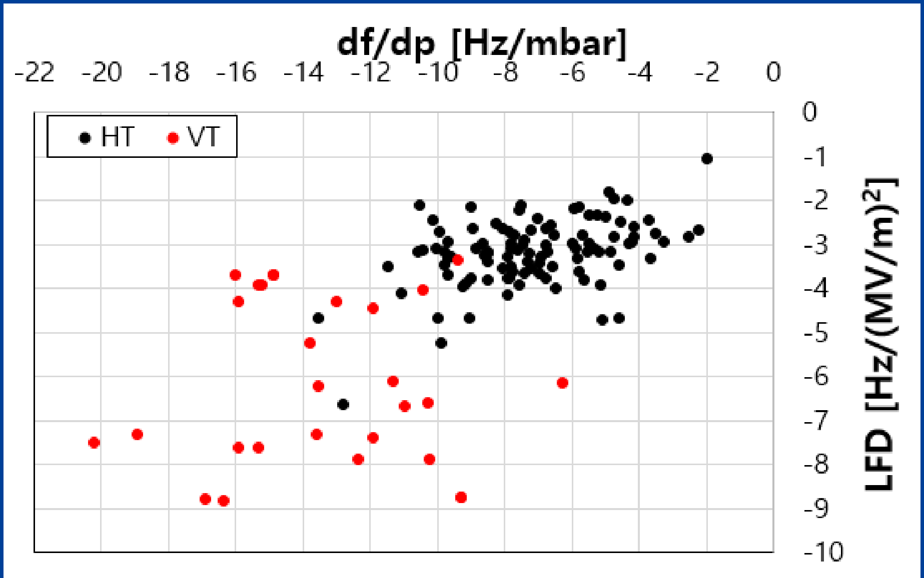


LFD measurement

df/dp and LFD measurement



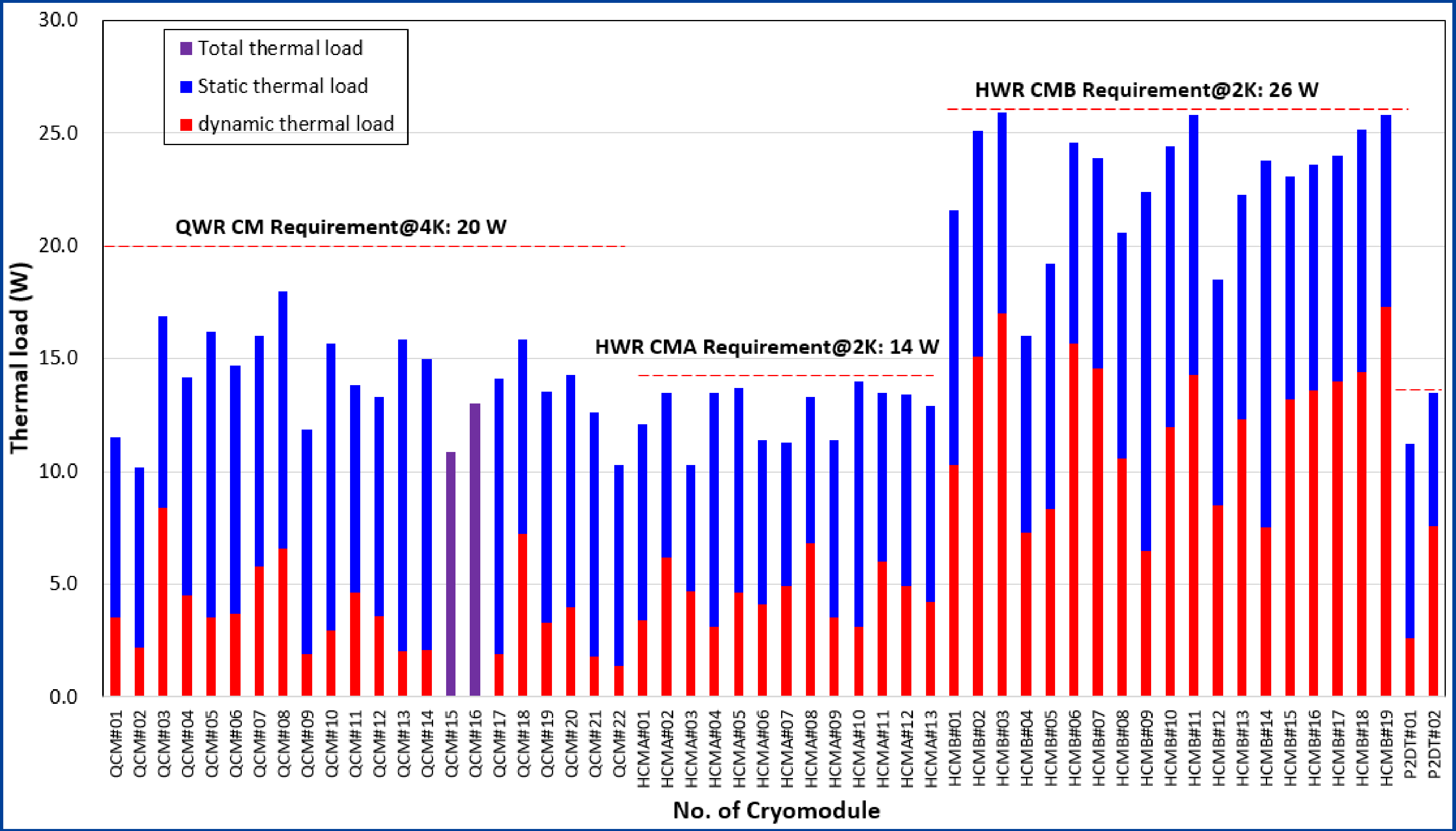
df/dp and LFD measurement results



Comparison of VT and HT

- Relatively larger df/dp of HWR cavities but lower pressure fluctuation at 2.05 K
  - Pressure fluctuation: ~ ±1 mbar at 4.5 K, ~ ±0.3mbar at 2.05 K
- Enhancement of cavity's stiffness by tuner in cryomodule: 45 % lower df/dp and LFD

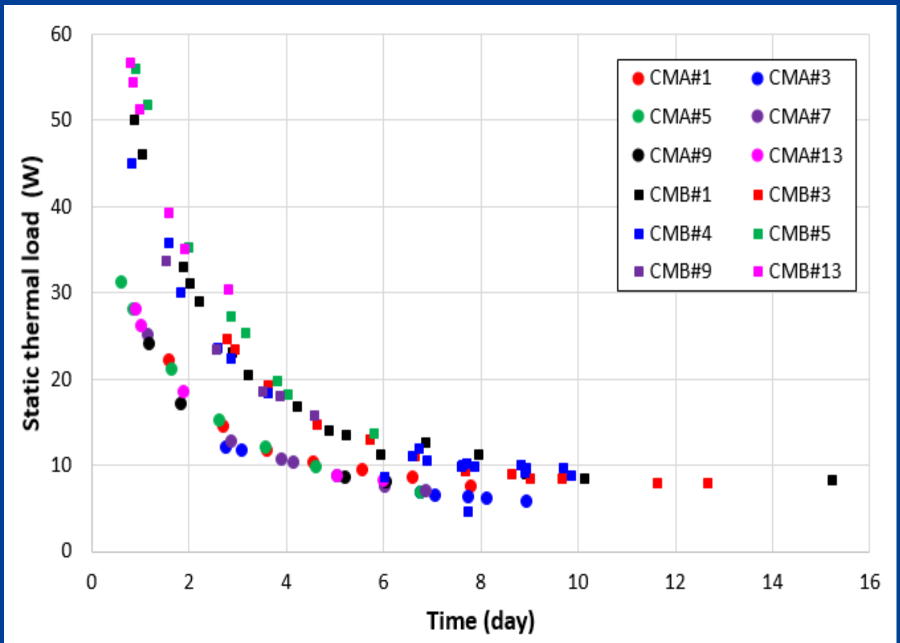
Thermal load measurement results



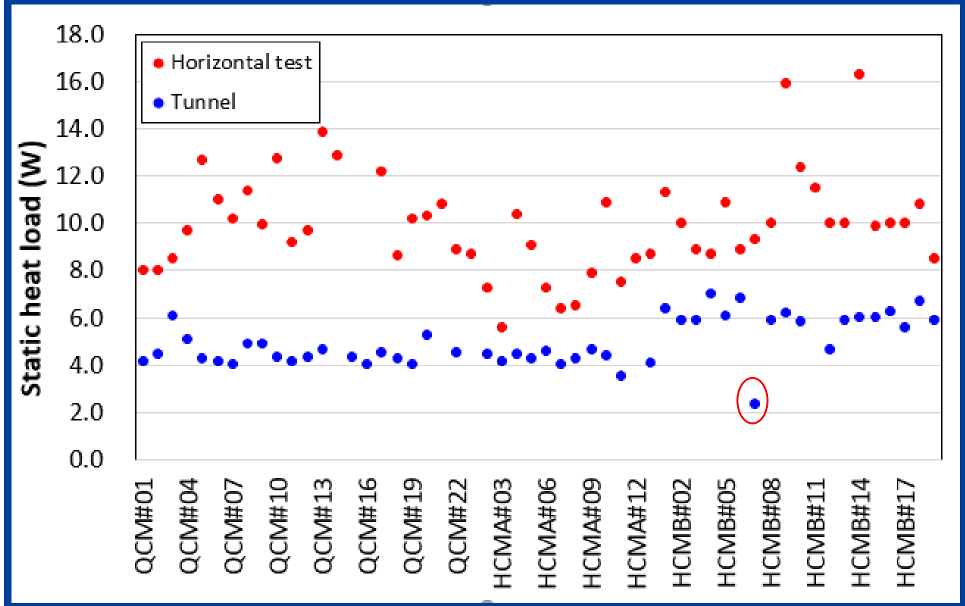
- Dynamic thermal load of each cryomodule is the sum of the dynamic thermal load of cavities in the cryomdoule

Static thermal load

Static thermal load change w.r.t. time during HT



Static thermal load of HT vs. tunnel



- Main reason: Large mass (~40 Kg) of tuner
- Static thermal load that we had measured were 5.6 W and 8.3 W for HWR CMA and HWR CMB, respectively while the average static thermal load measured during the experiments were 8.0 W and 10.7 W, respectively.

- Average static thermal load
  - HT: QWR (10.4 W), HCMA (9.6 W), HCMB (10.7 W)
  - Tunnel: QWR (4.5 W), HCMA (4.3 W), HCMB (6.1 W)

  ➔ Suspected insufficient thermalization (system may not have reached steady state).

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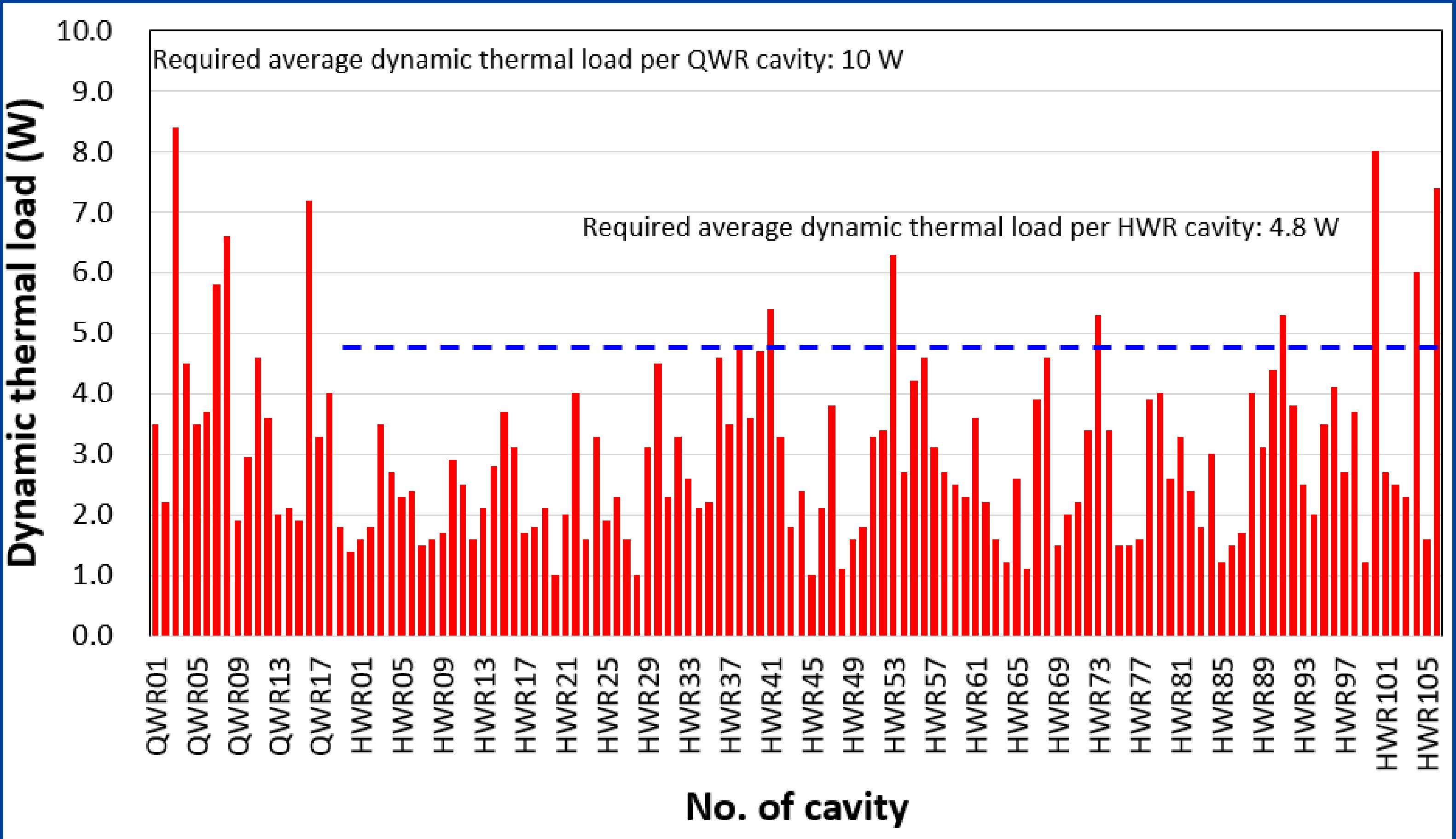
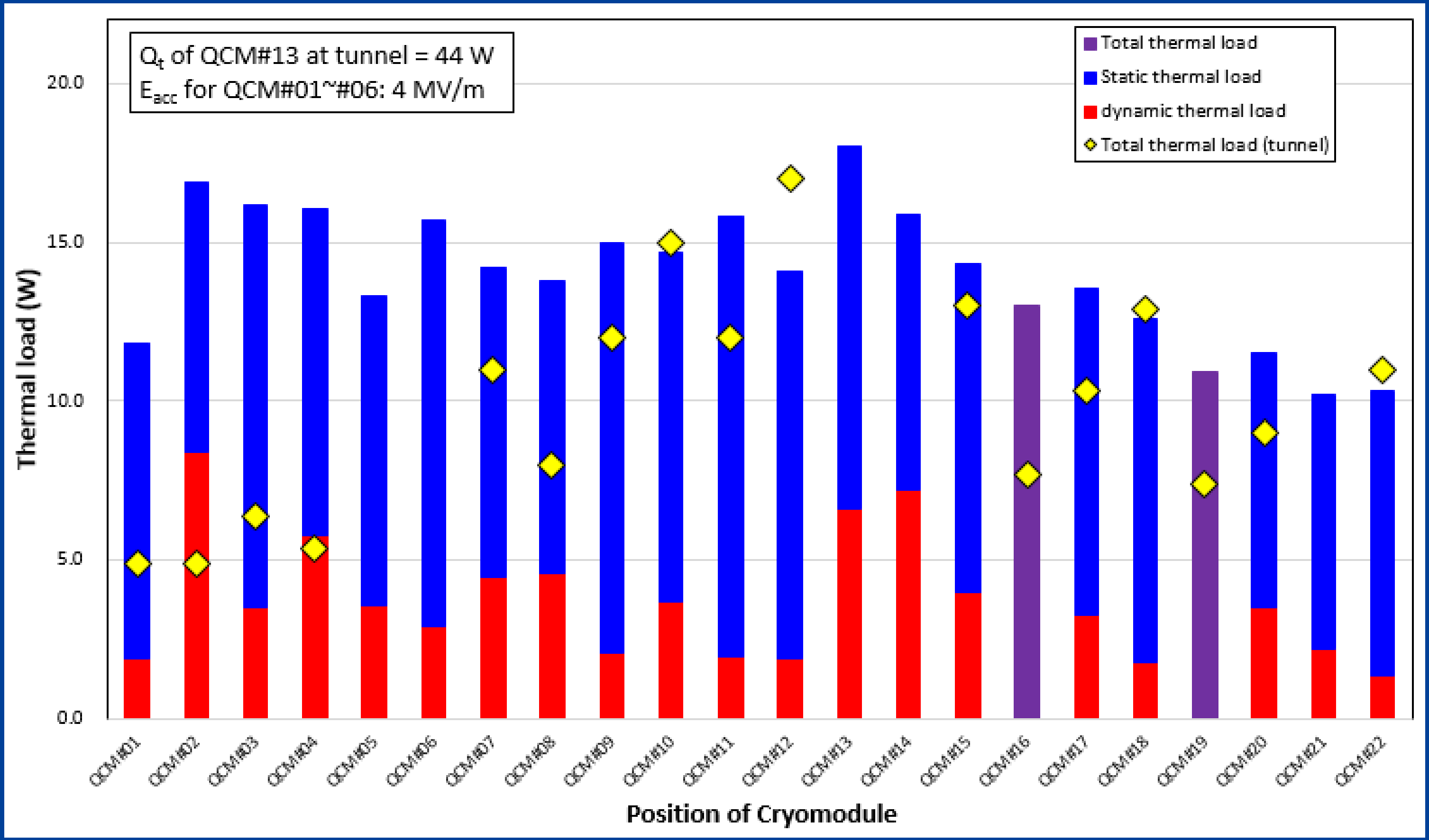
Dynamic thermal load of each cavity

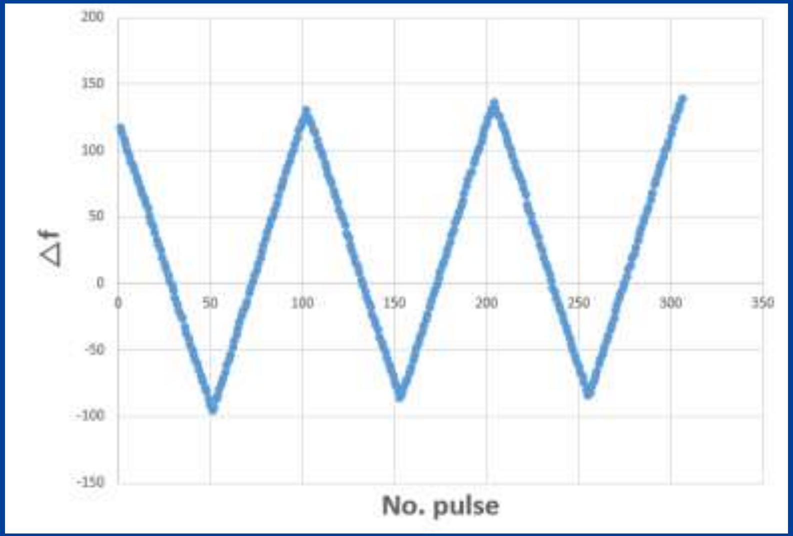


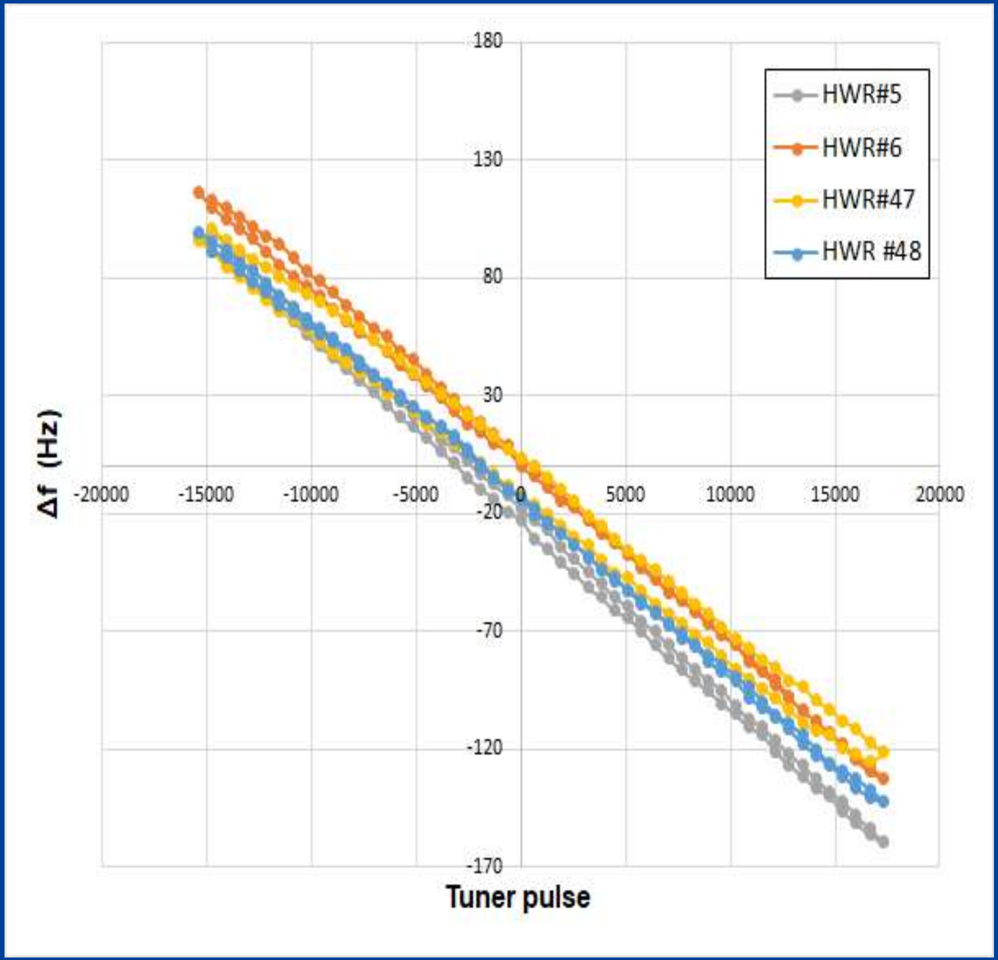
Thermal load measurement of QWR cryomdoules in tunnel



- E_{acc} of QCM #01~#06 (ramp-up section): 4 MV/m (Q_t < 1 W @ 4 MV/m)
- Malfunction of level meter of QCM#14, QCM#21
- Severe degradation of cavities in QCM #13, #14

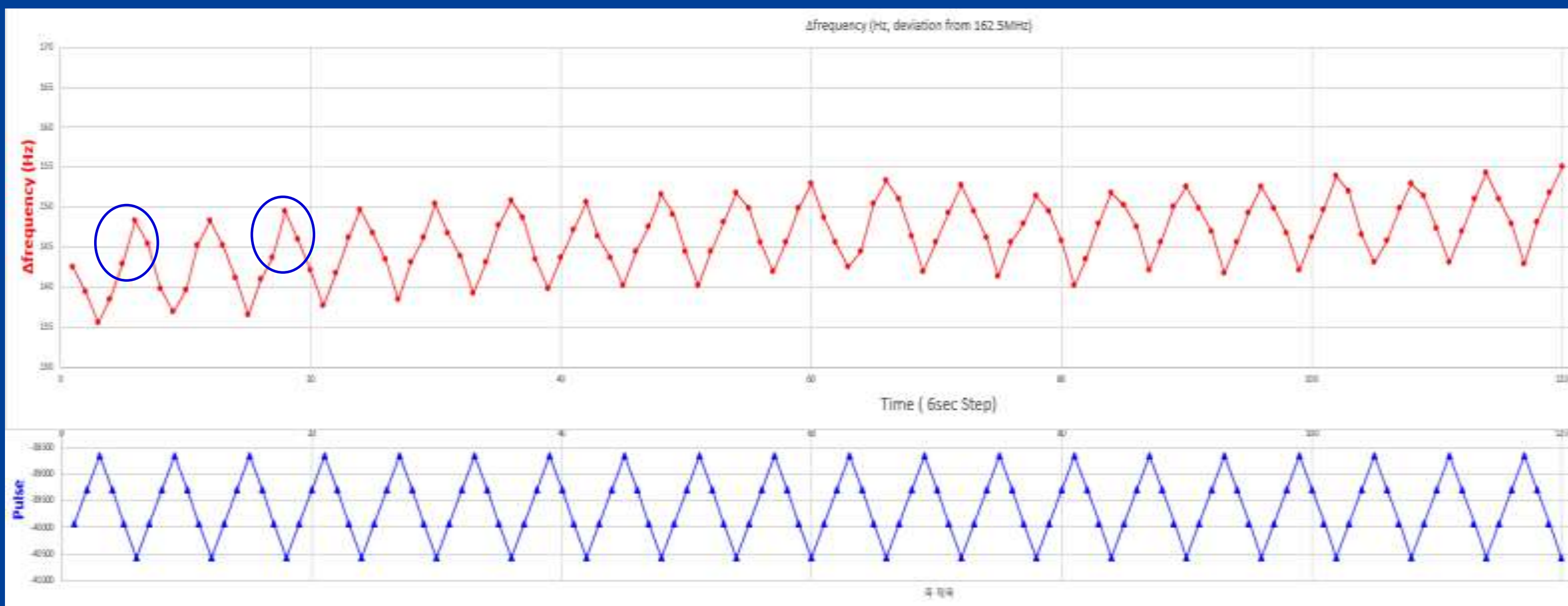
Tuner test





- Wide range test (±100 Hz span)
  - 20 pulse/step * 50 steps * 3 times up and down
  - Control bandwidth ~ 130 Hz
  - Tuning resolution: 0.2~0.25 Hz/pulse

Tuner test

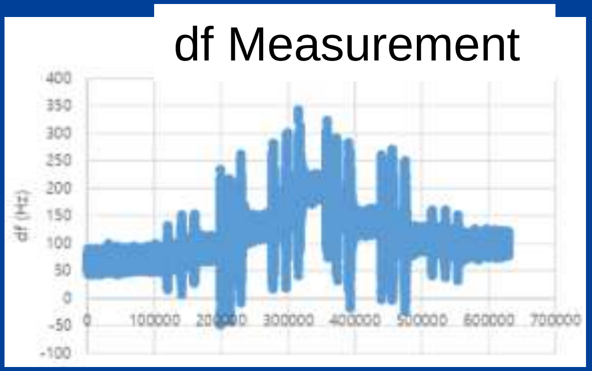


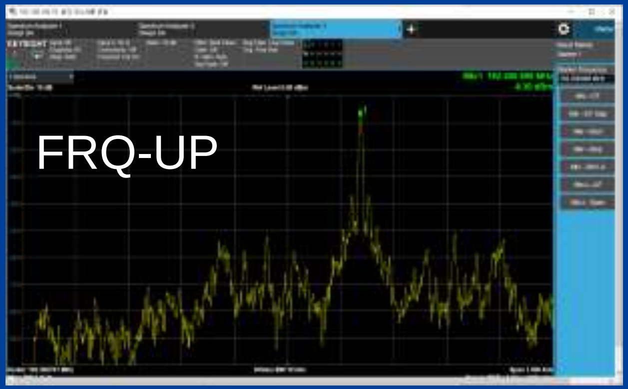
- Narrow range test

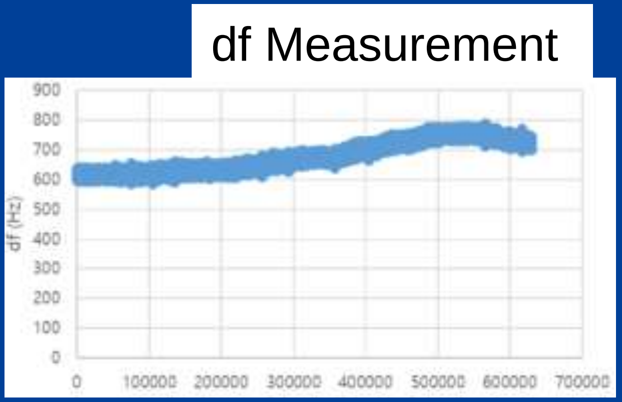
  - 20 pulse/step * 3 steps * 20 times up and down

  - Small backlash (~a few Hz)

Tuner test



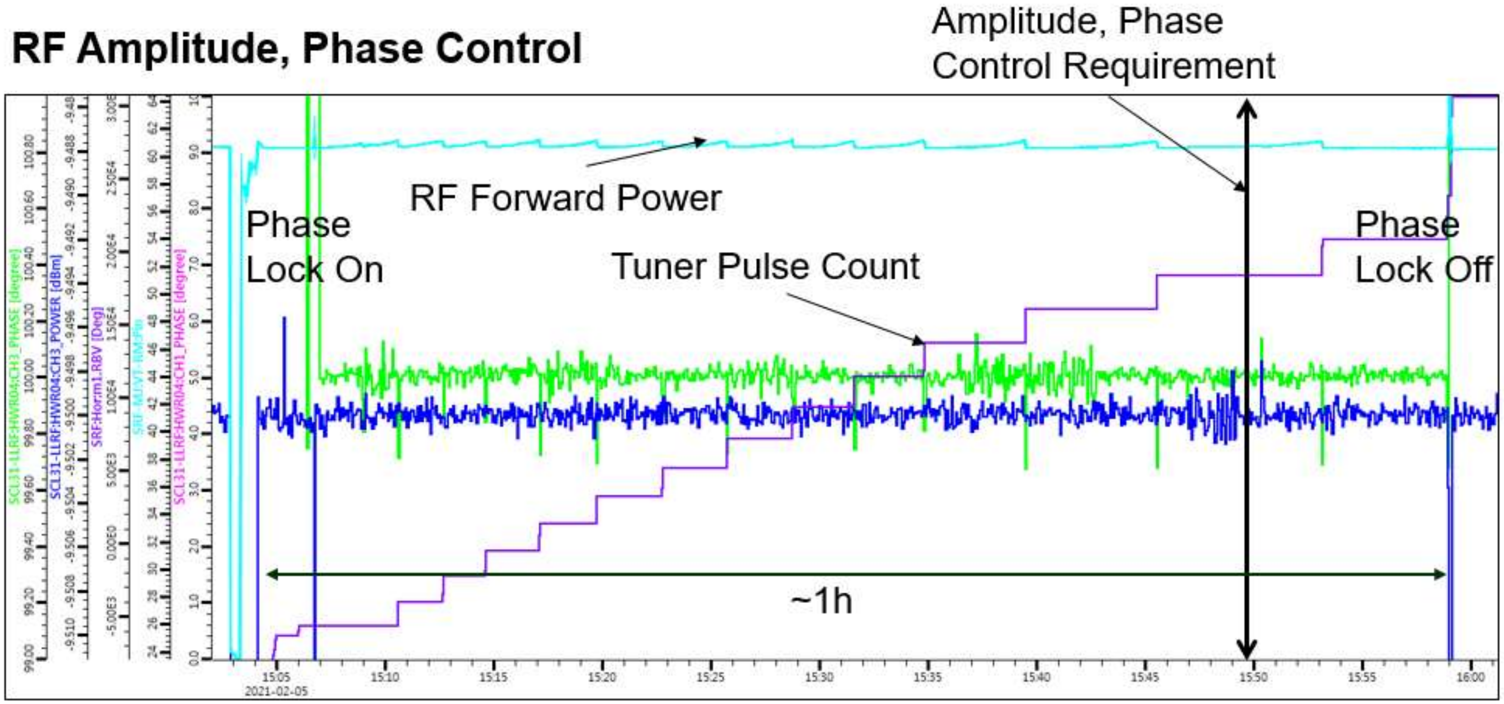




- Noise during the operation of tuner (df of cavity ~ 300 Hz)
  - Noise removed by reducing the motor speed to 1/32

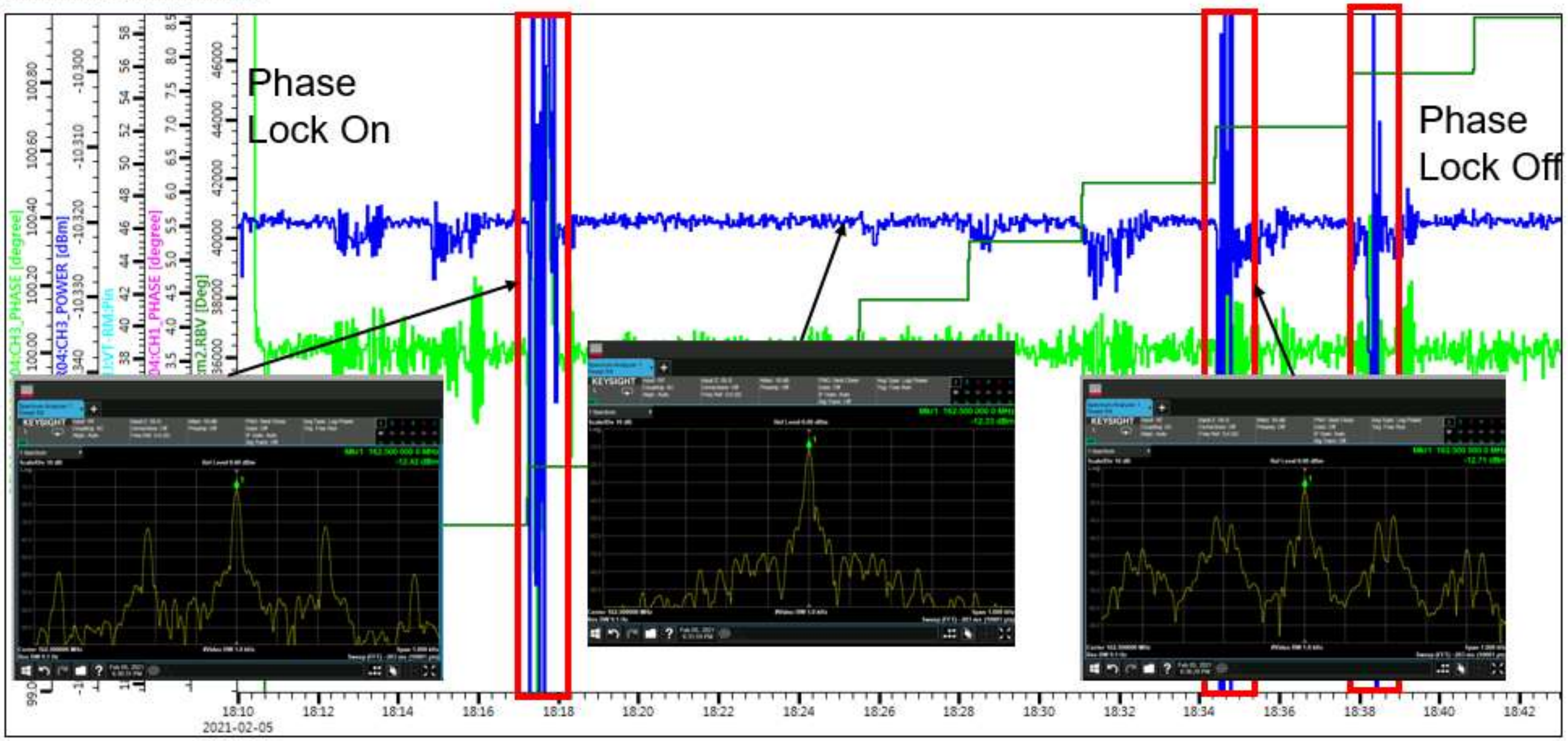
Phase and amplitude locking test of cryomdoule

RF Amplitude, Phase Control



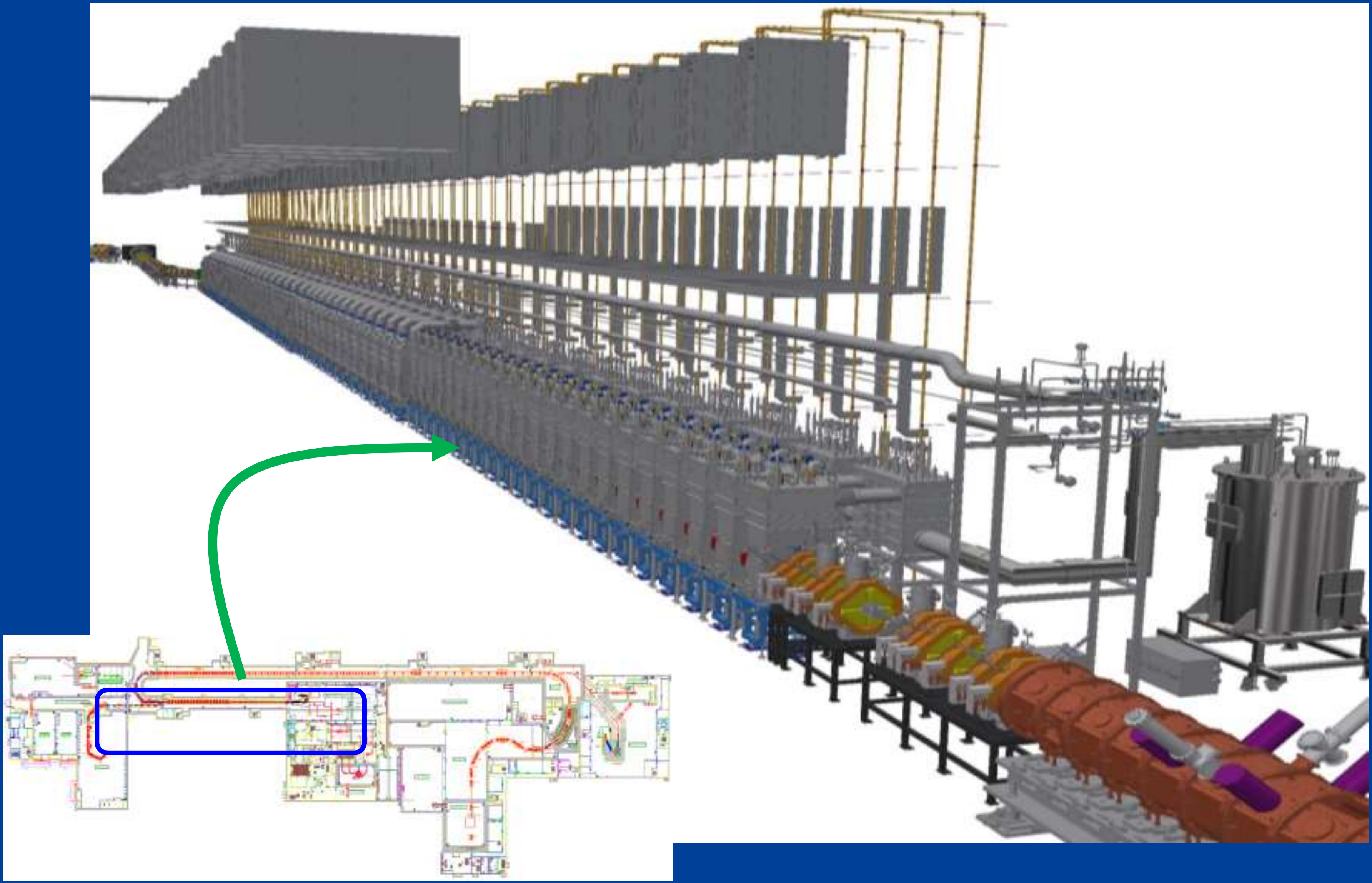
- Amplitude, Phase lock worked fine (~1h) @Eacc=6.6MV/m
- E_{acc}=6.6 MV/m (±0.13%), Phase=100° (±0.63°)
- The phase is well controlled by the integration of LLRF-Tuner control system.

Microphonics



- There was some strong microphonics source whose frequency is near 200Hz.
- Phase lock was recovered automatically after disappear of the external disturbance .

Installation



Installation

- Cryomodule and warm section is clean assembled in the portable clean booth in tunnel
- Particle counts (size=0.5um above/10min.) were less than 30 counts

Installation

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Cryogenic systems

- SCL3 plant: 4.2 kW at 4.5 K, SCL2 plant: 13.5 kW at 4.5 K

Cold box

Warm compressors

LHe distribution box

Welding VBx to CM

VBx connection

QWR CMs, VBx in rear side

Beam Operation (2025)

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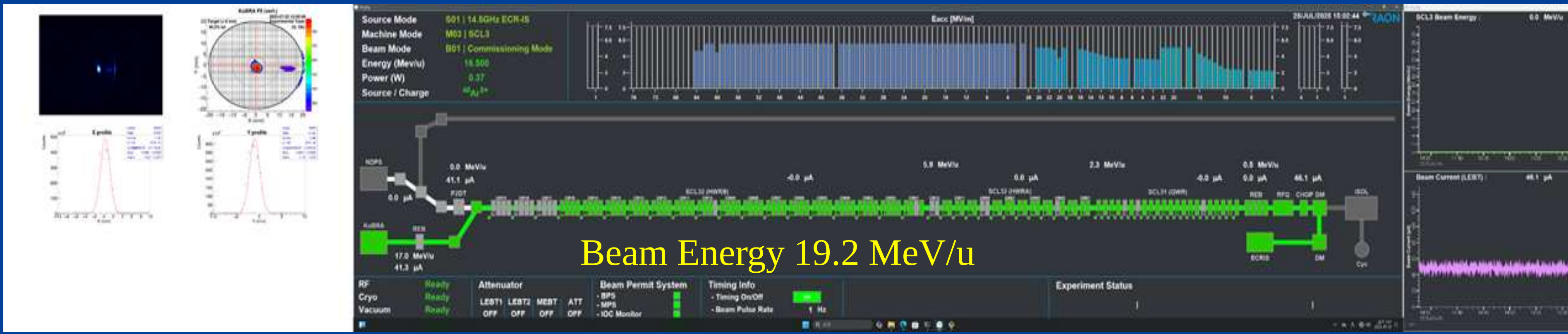
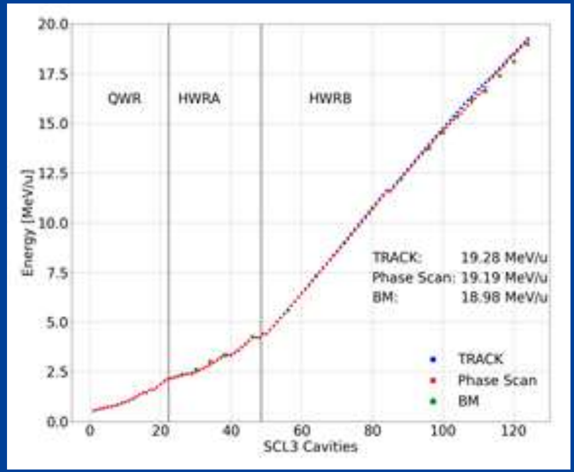
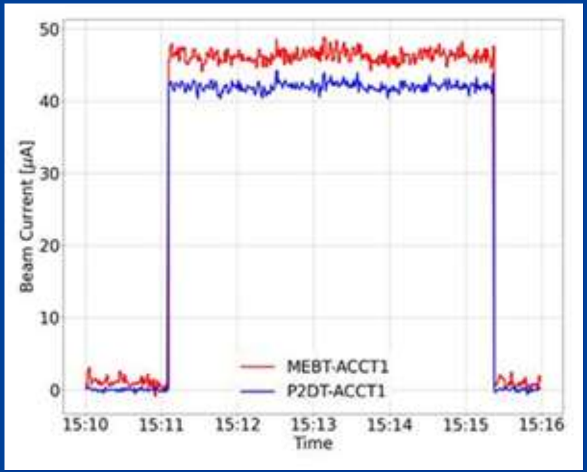
SCL3 section: $^{40}Ar^{8+}$ beam (19.2 MeV/u, 45μA)



$^{40}Ar^{8+}$ beam accelerated by the entire SCL3(QWR/HWR)

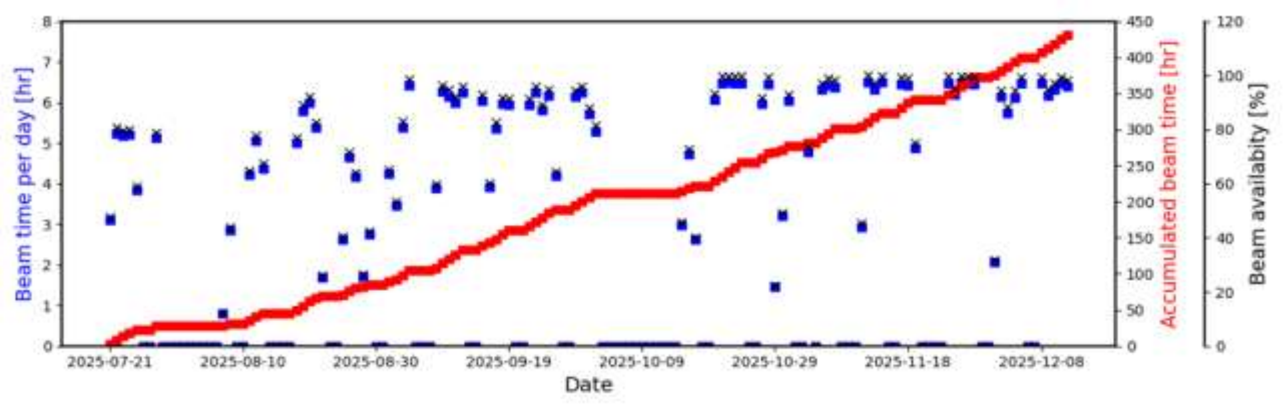


[Energy in SCL cavities]



[Beam current measured by ACCT in MEBT and P2DT]

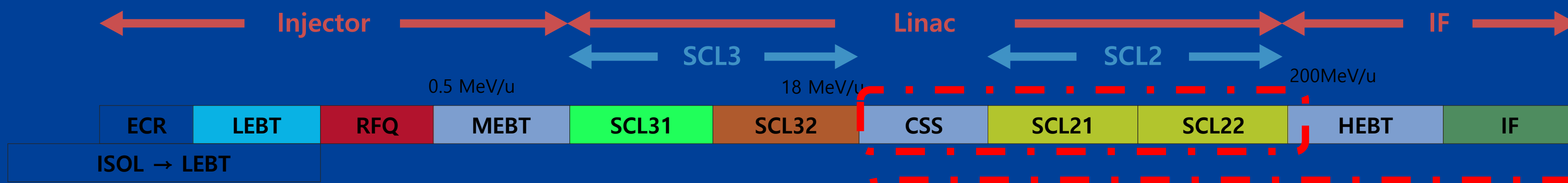
Beam Operation (2025)



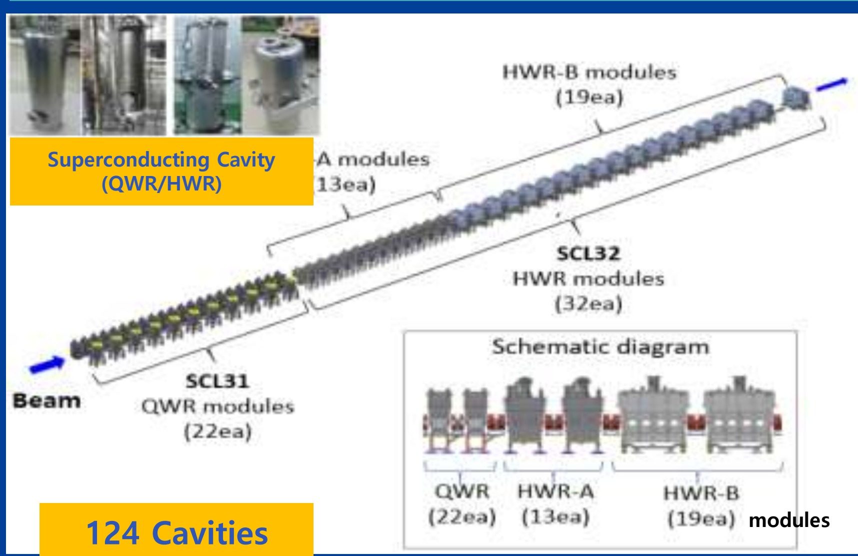
- (07.21 – 07.28) Beam parameter setting and transport test for SCL3-KoBRA beamline ($^{40}Ar^{8+}$)
- (08.08 – 08.13) Calibration of beam attenuators using KoBRA detectors and $^{85}Rb^{17+}$ beam
- (08.18 – 09.08) Calibration of KoBRA spectrometer using $^{40}Ar^{8+}$ beam
- (09.09 – 09.15) User beam test
- (09.16 – 09.26) Calibration of NDPS detectors using $^{40}Ar^{8+}$ beam
- (09.30 – 10.01) Equipment beam test
- (10.13 – 10.17) Beam parameter setting and transport test for SCL3-KoBRA beamline ($^{20}Ne^{4+}$)
- (11.11) RI (Radioactive Isotope) beam transport test for ISOL-SCL3-KoBRA beamline ($^{25}Na^{5+}$)
- (11.12 – 12.12) User beam tests

Ongoing SRF R&D

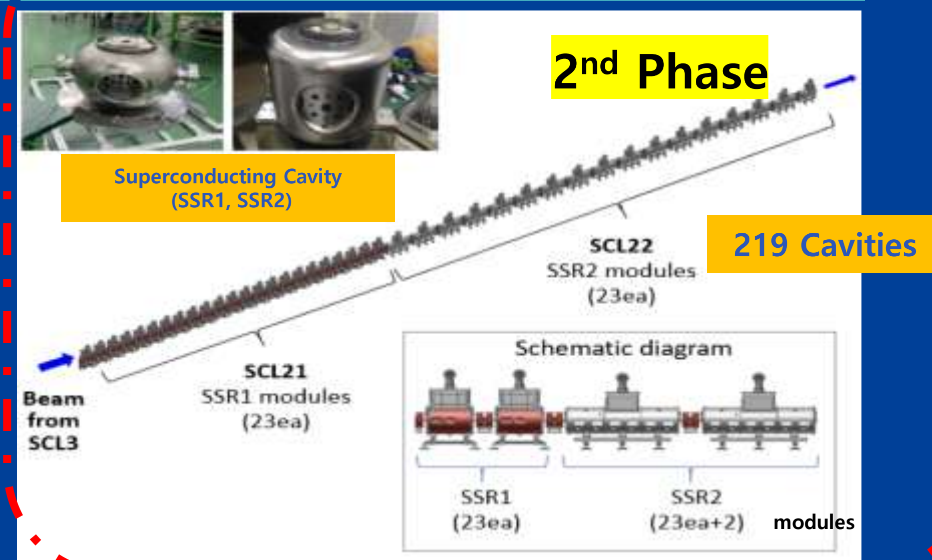
2nd Phase Construction



Low Energy Linear Accelerator SCL3



High Energy Linear Accelerator SCL2



- R&D Project for Phase 2 Construction
- Project Summary
  - Objective: Performance validation of SSR1 & SSR2 Prototype Modules
  - SSR1: Balloon Type (1 unit)
  - SSR2: Cylindrical Type (1 unit)Timeline: 2022 – 2027
  - Budget: KRW 19.0 Billion (~$14.5M)
  - Key Mission: Launch Phase 2 Construction by 2028
- Infrastructure Integration (Leveraging Phase 1 Assets)
- Maximize efficiency by utilizing existing Phase 1 facilities:
  - Cryogenic Systems: Cryoplant and LHe distribution networks
  - RF Power: Installed SSPA (Solid State Power Amplifiers) for SCL21
  - Beam Transport: Quadrupole magnets
  - Using existing tunnel (building) → The location, number, required performance of cavities are fixed

Cavities for 2nd Phase R&D

- Plan: Two SSRs (Single Spoke Resonator) with different β_{opt}

	SSR1	SSR2
Optimum β	0.32	0.51
f_0 [MHz]	325	325
L_{eff} (=$\beta_o\lambda$) [mm]	298.2	470.8
R/Q [Ω]	233	252
E_{pk}/E_{acc}	4.1	3.7
B_{pk}/E_{acc} [mT/(MV/m)]	6.9	9.0
E_{acc} [MV/m]	7.9	8.7
V_{acc} [MV]	2.36	4.10
QRs [Ω]	92.2	123.0

- Performance validation of prototype cavities (during 1st phase) by enhancing the surface treatment
- Establishing Scalable Manufacturing Processes through R&D Prototyping

1st Phase Prototype : SSR1

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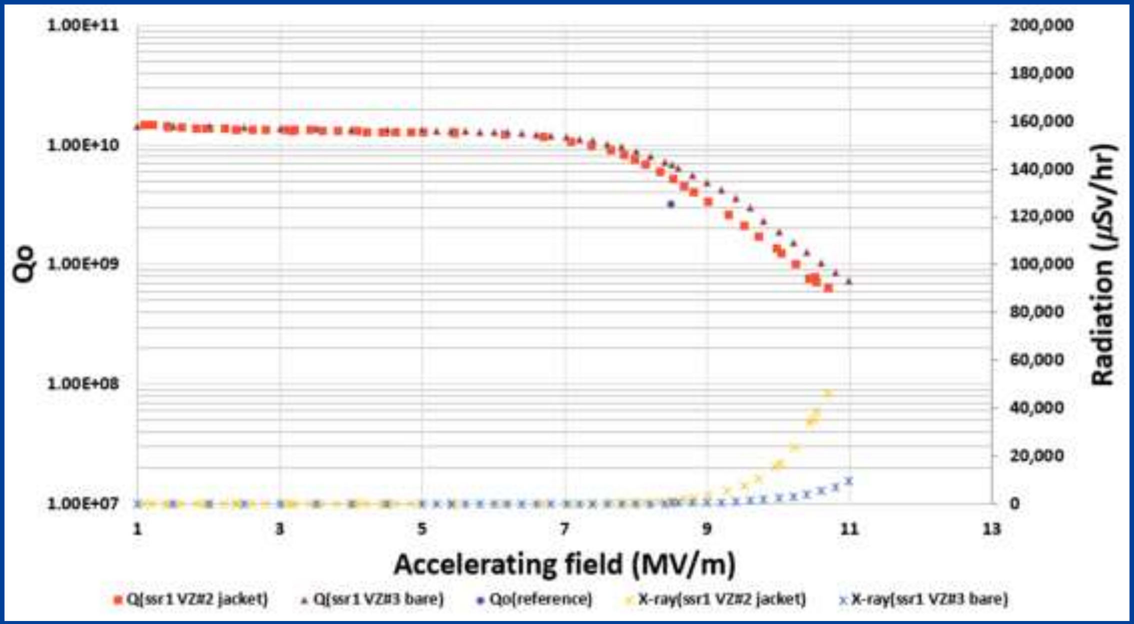
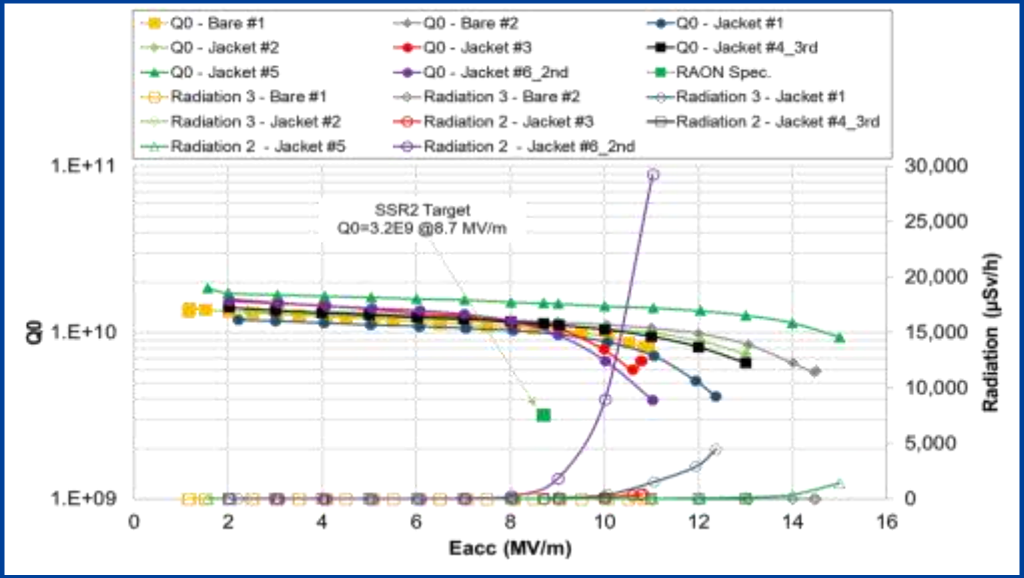
- Performance validated for 2 out of 3 prototypes
- Improving manufacturing processes for mass production (including frequency tuning methodologies, etc.)
- Developing measures to increase yield by improving surface treatment processes : Thermal quench, field emission, etc.



1st Phase Prototype : SSR2

- Performance validated for 7 prototypes cavities (VT)
- Suitable for Phase 2 Mass Production
- Performance deficiency at the module level (e.g., static heat load, cavity performance, etc.)
- Performance re-validation via Vertical Test (VT) after disassembly, followed by reassembly to validate module performance.



1st Phase Results Integration

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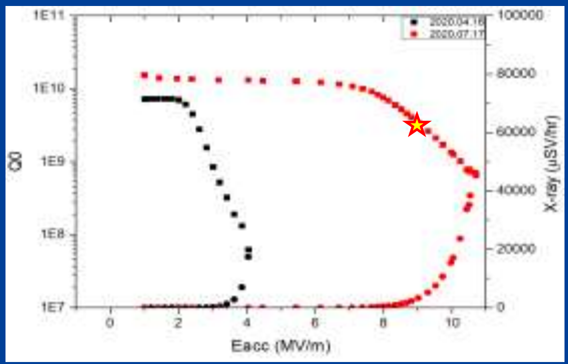
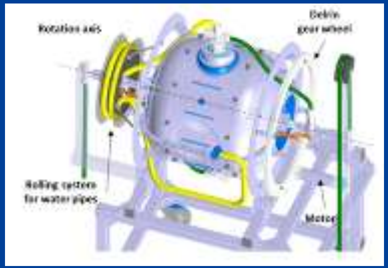
Bubble streak occurred during BCP



Degradation by field emission

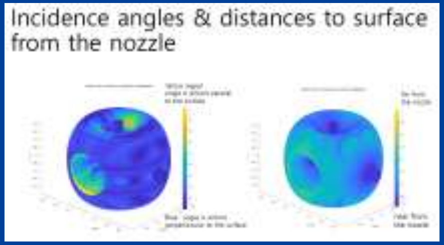
- Implementation of a Rotational BCP System and a cavity cooling system
- Removal of bubble streak and enhancement of etching uniformity

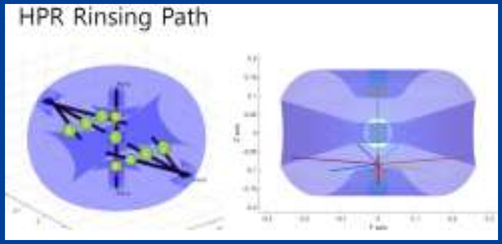
SSR1 BCP (IRIS)



Rotational BCP (IJCLab)

- Improvement of HPR process
  - HPR Simulation: nozzle shape, angle, etc.
  - Enhanced monitoring and control of ultrapure water

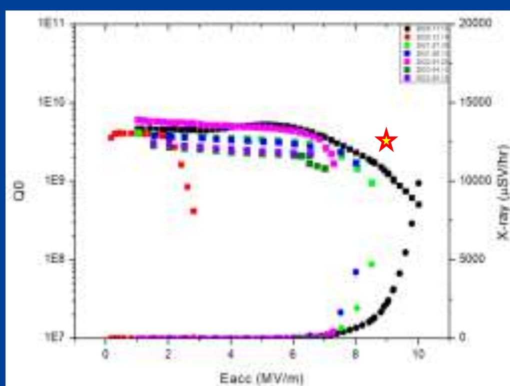




1st Phase Results Integration

SSR1-#2

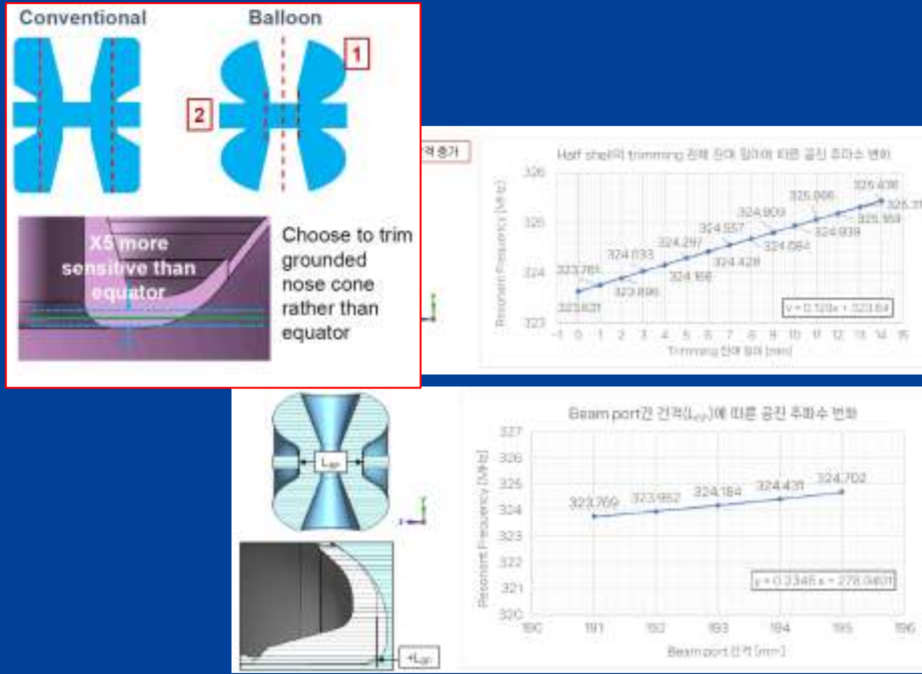
Non-uniform weld beads after final welding



VT. No	날짜	RF limit
1	2020.11.12	FE
2	2020.12.19	V/C
3	2021.07.30	FE?
4	2021.08.13	FE?
5	2022.03.25	TQ
6	2023.04.13	TQ
7	2023.05.10	TQ

Thermal quench limited E_{acc}

- Change of frequency tuning process
  - Half-shell Machining
    - Low sensitivity; however, prone to deformation during machining and difficulty in maintaining joint geometry with the spokes
  - Beam Port Machining
    - High sensitivity; crucial to maintain shell-spoke joint geometry



Thank You!

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