



Superconducting Passive Harmonic RF Cavity for Diamond II

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For DLS RF Group

Diamond-II | Advancing Science

Agenda

- Introduction
- High Harmonic RF Cavity for Diamond II
- HHC Design
- HHC Progress

Parameter	Units	Diamond (no IDs)	Diamond (with IDs)	Diamond-II (no IDs)	Diamond-II (with IDs)
Energy	GeV	3.0	3.0	3.5	3.5
Beam current	mA	300	300	300	300
Beam lifetime	h	~ 10	~ 10	7.0	7.5
Circumference	m	561.571	561.571	560.561	560.561
Harmonic number		936	936	934	934
RF frequency	MHz	499.654	499.654	499.511	499.511
Total bending angle	deg.	360	360	388.8	388.8
Emittance (horizontal, natural)	pm rad	2729	3100	163	120
Emittance (vertical)	pm rad	8	8	8	8
Energy spread (rms)	%	0.096	0.107	0.095	0.109
Energy loss per turn	MeV	1.01	1.52	0.72	1.68
Momentum compaction factor	10 ⁻⁴	1.57	1.56	1.042	1.041
Damping partition number J_x	-	1.00	1.01	1.87	1.37
Optimum RF voltage	MV	2.2	2.5	1.4	2.5
Natural bunch length (rms)	ps	11.4	11.0	12.5	11.7
Average bunch length (rms)	ps	17	17	49	48

■ Parameters of significance to RF

- Small change in RF frequency
- Very little change to total voltage
- Increase in energy loss per turn
- Harmonic cavity needed for bunch lengthening



■ Conceptual Design Report (May 2019)

- <https://www.diamond.ac.uk/dam/jcr:e67b7e1-fb91-4a65-b1ce-f646490b564d/Diamond-II%20Conceptual%20Design%20Report.pdf>

■ Technical Design Report (August 2022)

[Diamond Communications - Diamond II Technical Design Report.pdf \(sharepoint.com\)](#)

Harmonic Cavity for Daimond II

Higher harmonic cavity
is needed for Bunch
Lengthening

*Alleviate collective
instabilities*

*Maximise beam
lifetime*

*Minimise storage
ring component
heating*

- Lifetime including errors, harmonic cavity and gas lifetime:

	Average Touschek lifetime	Total lifetime activated NEG	Total lifetime saturated NEG
No HC	0.95 ± 0.12 h	0.95 ± 0.12 h	0.93 ± 0.11 h
With HC, uniform fill	4.37 ± 0.56 h	4.32 ± 0.55 h	3.96 ± 0.46 h
With HC, standard mode	1.91 ± 0.24 h	1.90 ± 0.24 h	1.83 ± 0.22 h

- For lifetime reasons, preferable to aim for an increase above 4 times
→ highly dependent on the fill pattern
- For the current standard mode (900 bunches) and 8 NC MCs + 1 SC
HC according to SLS parameters only roughly 2 times lifetime
increase can be achieved.

Basic Parameters for HHC

For a double RF system the voltage seen by the beam is given by

$$V = V_{rf} \left[\sin \left(\frac{\omega_{rf}}{c} z + \phi_1 \right) + k \sin n \left(\frac{\omega_{rf}}{c} z + \phi_n \right) \right]$$

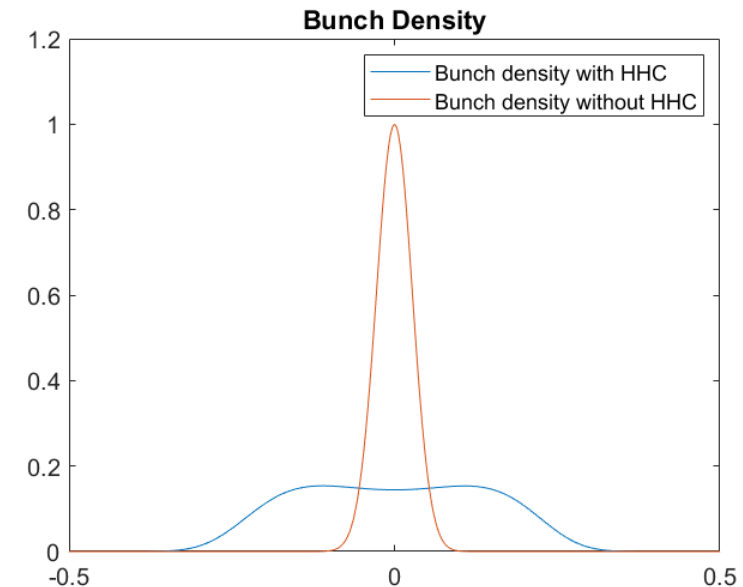
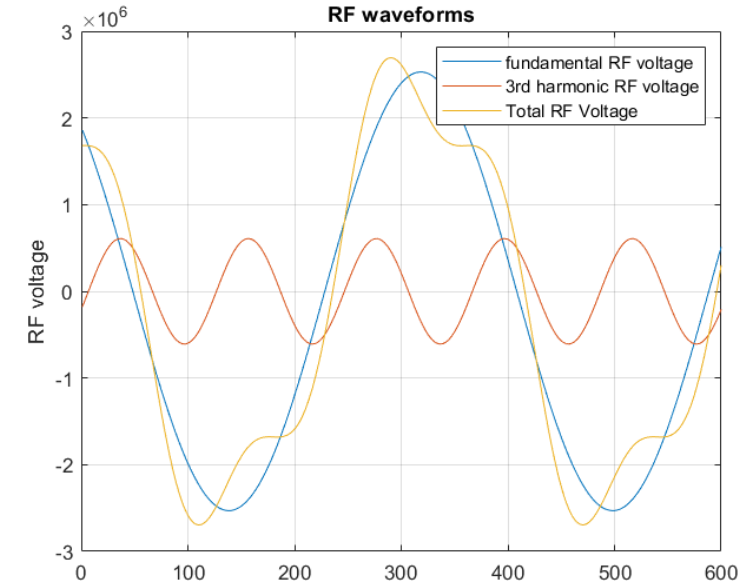
Optimal k under flat potential condition

$$k^2 = \frac{1}{n^2} - \left(\frac{1}{n^2} - 1 \right) \left(\frac{U_0}{eV_{rf}} \right)^2$$

Using 2.53 MV main cavity voltage and 1.68 MeV radiation loss, we have

K	0.2366
Main cavity Synchronous phase with HHC [°]	138.39
Main cavity Synchronous phase without HHC ϕ_1 [°]	131.67
Harmonic cavity phase [°]	-6.8449

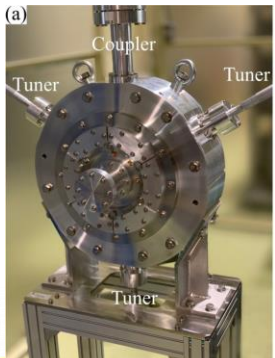
About 600 kV from HHC is required.



Higher Harmonic Cavity Selection

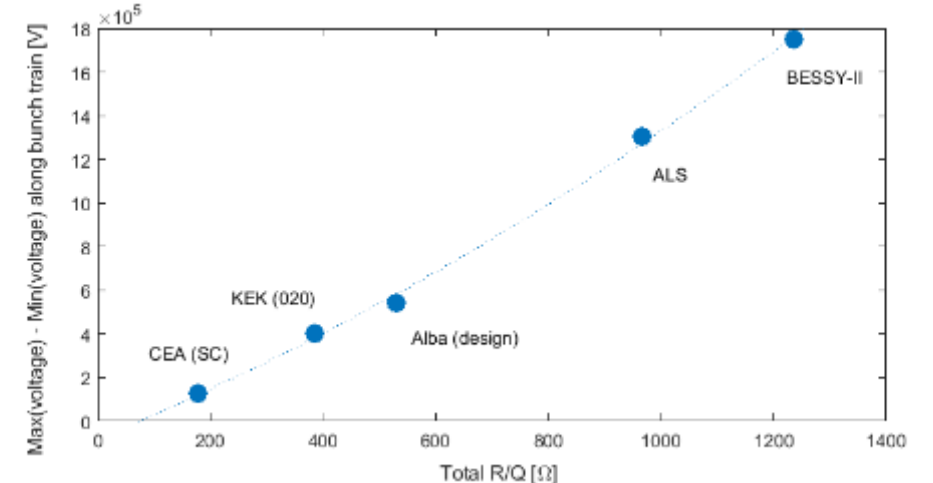
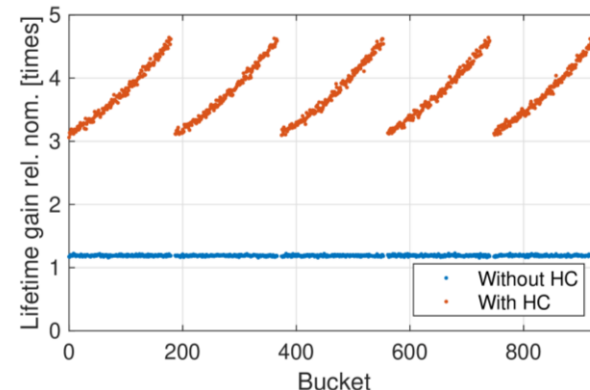
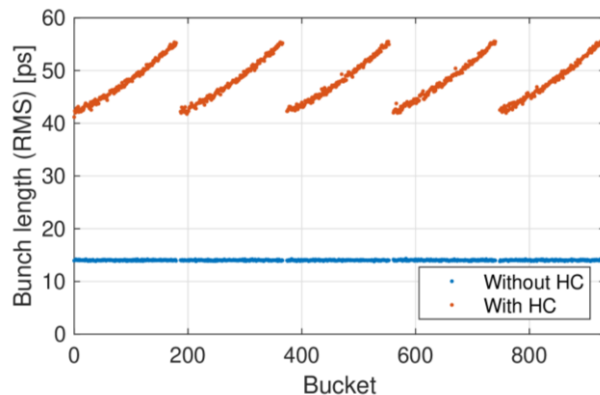
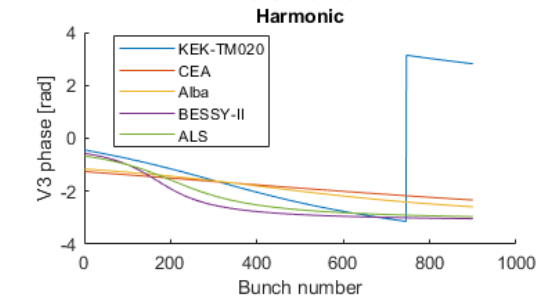
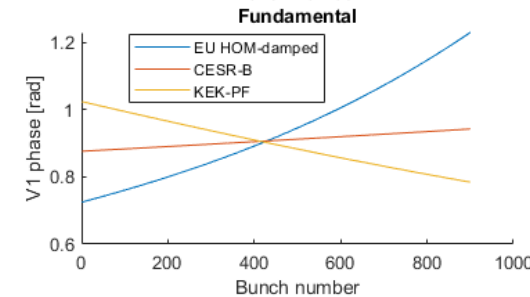
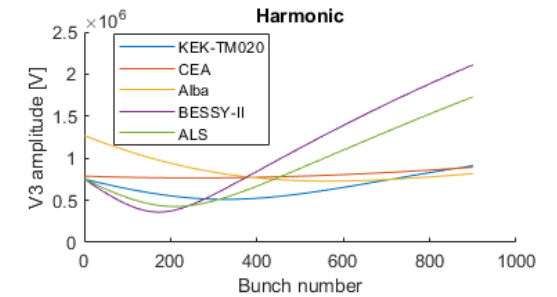
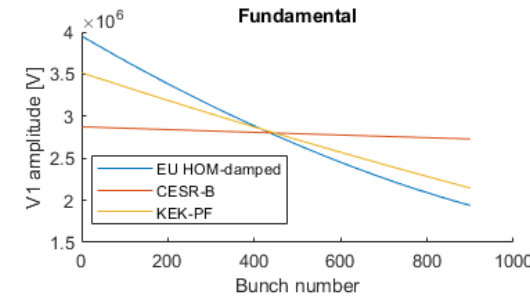
	Passive NC	Active NC	Passive SC
Advantages	Simple	Allows operation at optimal voltage and phase for any beam current	Operates to low current Less sensitive to filling pattern Less sensitive to Robinson instability as bandwidth is small and detune is near 90°
Disadvantages	Optimal operation only at one beam current Gap in fill pattern induces strong modulation which reduces effectiveness Operation well into the Robinson unstable slope	RF amplifier required Gap in fill pattern induces strong modulation which reduces effectiveness Operation well into the Robinson unstable slope	Cryogenic system required Narrow bandwidth means cavity is harder to control

- Select passive superconducting third harmonic cavity
 - Using cryogenic plant for Diamond
 - Detune is almost constant for all conditions allowing wide range of operating currents
 - Robinson destabilisation is small and can be damped by fundamental cavity detune



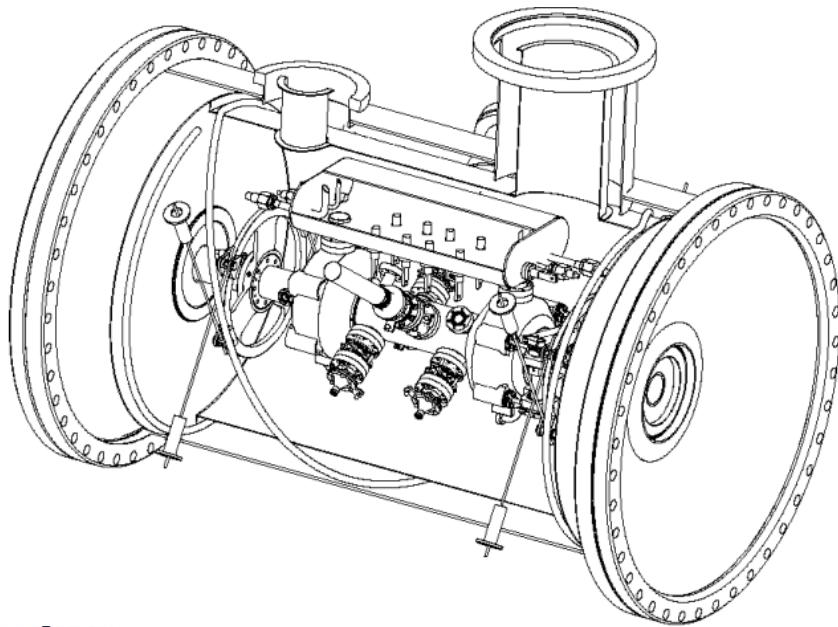
Transient beam loading effects

- Gap in fill pattern is needed for ion clearance
 - Introduces transient beam loading effects
 - Degrades effective bunch lengthening
 - Bigger effects from longer trains and gaps
- Can calculate field variation from loss parameter*
 - $\tilde{V}_b^{(i,j)} = \left(\tilde{V}_b^{(i-1,j)} - 2 \frac{\omega_{res}}{4} \frac{R}{Q} q_m \right) e^{\alpha \Delta t^{(i)}}$
 - Magnitude of effect is dependent on R/Q
 - Phase drift arises from complex α
- Can partially compensate fundamental with LLRF feed forward/feedback



Higher Harmonic Cavity Selection

- Diamond-II will use a proven design of passive superconducting third harmonic cavity
 - Two designs identified: CEA/SLS/ELETTRA “Super3HC” and SSRF third harmonic cavity
 - Super3HC module can be manufactured under licence
 - Two European manufacturers identified
 - SSRF module has been more recently constructed
 - Lower start-up cost and preparation effort
- Both can fit in Diamond II



diamond

CEA/SLS/ELETTRA “Super3HC” cryomodule



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SSRF cavity

HHC Specification

Super-3HC Specification

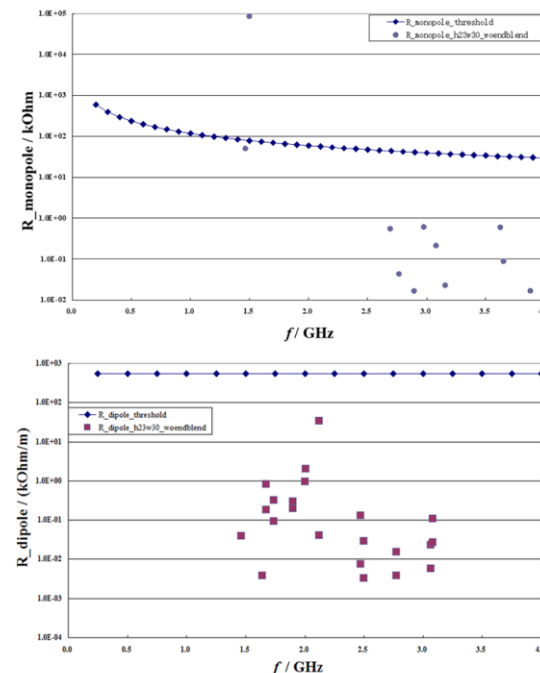
Frequency at 4K	1498.95 MHz
Working temperature	4.5 K
Maximum total voltage	1.0 MV
R/Q ($P=V^2/2R$)	88 Ω
Q0 vertical tests at 5MV/m and 4.5K	$2 \cdot 10^8$
QL loaded at 4MV/m and 4.4K	$1 \cdot 10^8$
Tuning range	$\pm 500\text{kHz}$
Tuning resolution	$\sim 10\text{Hz}$
Longitudinal HOMs damping fR.R//	7.0 k Ω .GHz
Transverse HOMs damping R $\perp$	130 k Ω /m

SSRF 3HC Specification

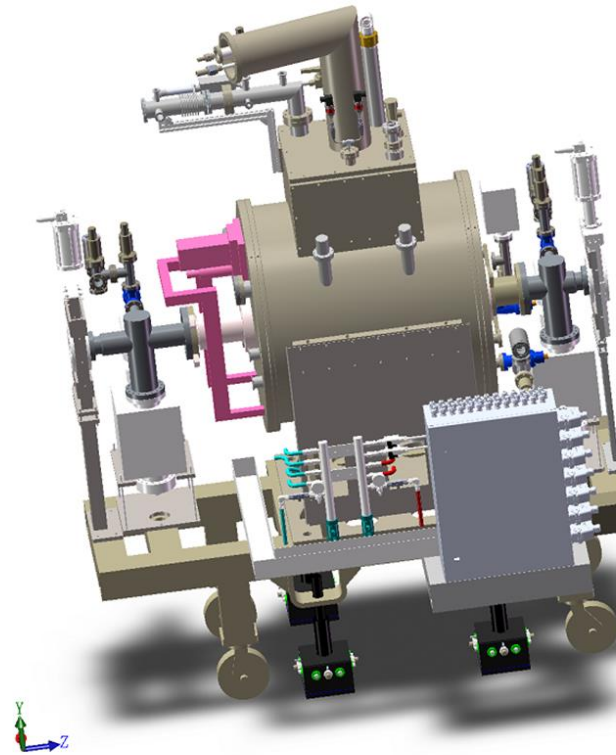
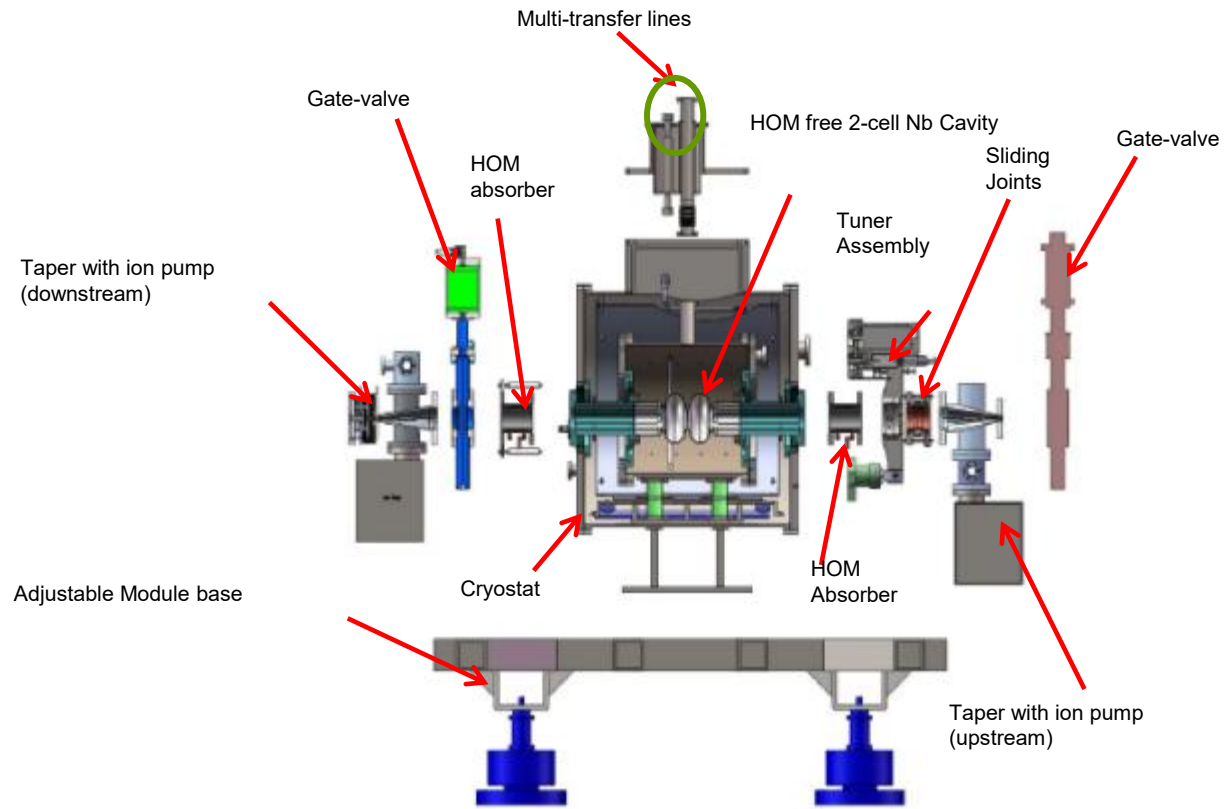
Frequency at 4K	1498.96 MHz
Working temperature	4.2 K
Maximum total voltage	>1.8 MV
R/Q ($P=V^2/2R$)	85 Ω
Q0 horizontal tests at 7.5MV/m and 4.2K	4×10^8
Tuning range	$> \pm 500\text{kHz}$
Tuning resolution	$\sim 10\text{Hz}$
Longitudinal HOMs damping fR.R//	<10 k Ω .GHz
Transverse HOMs damping R $\perp$	<150 k Ω /m

Table 2: HOM damping specifications

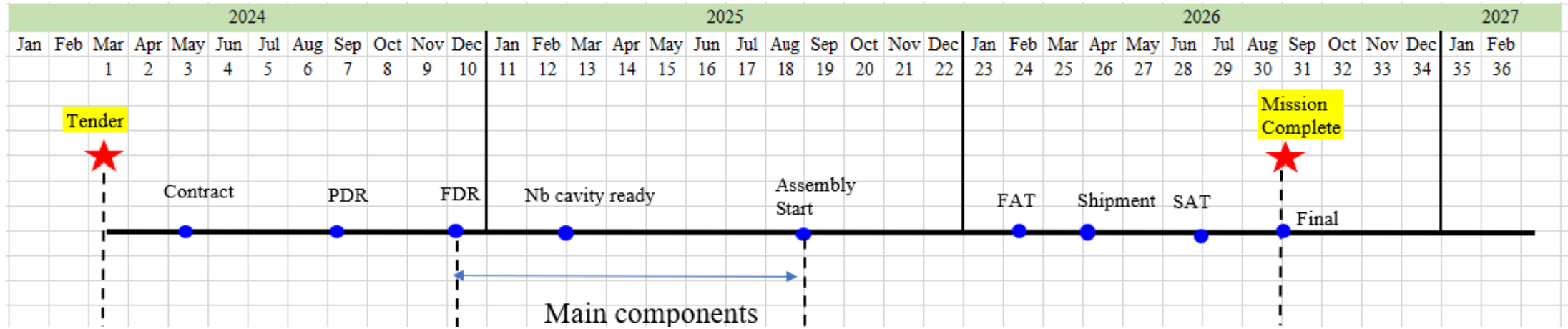
F (MHz) Long.	R/Q (Ω)	Q _{max}	F (MHz) Trans	R/Q (Ω /m)	Q _{max}
2466	0.17	16000	1721	20.0	6500
2532	2.60	1100	1723	21.8	600
2606	11.0	240	1935	0.01	$1 \cdot 10^7$
2695	0.12	22000	2056	255	510
2826	6.57	380	2103	27.6	4710
2979	8.61	270	2148	437	300
3084	1.93	1200	2303	10.1	12900
3180	0.30	7500	2503	11.1	11700
3358	0.86	2400	2712	63.8	2040
3594	0.43	4500	2865	10.3	12600



SSRF HHC



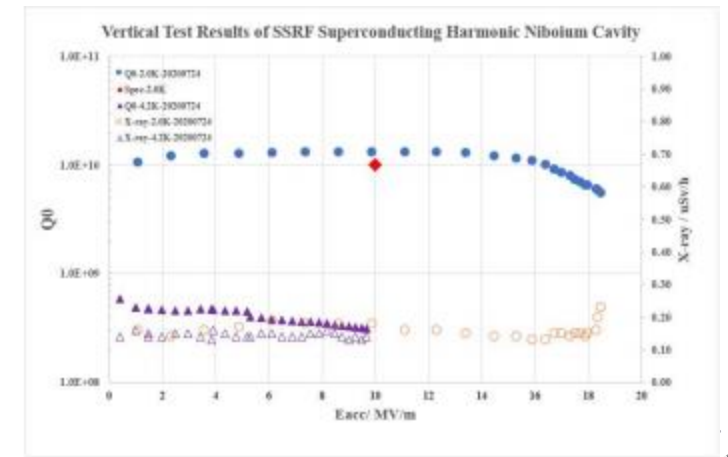
Project Plan



Nb Cavity



- **Two cell: advantage**—— lower gradient, stable operation performance
- **HOM free: fluted-beam-pipes for Monopole and dipole HOMs propagation**
- **TM010-0 mode is designed to have low r/Q and avoid resonant with beam frequency**
- **Fabrication procedure: standard niobium production and BCP surface treatment method.**
 - RRR>300 pure niobium material
 - Deep drawing with electron beam welding
 - Heavy BCP + HPR + 800°C annealing + light BCP + HPR + clean assembly + 120°C baking + vertical test

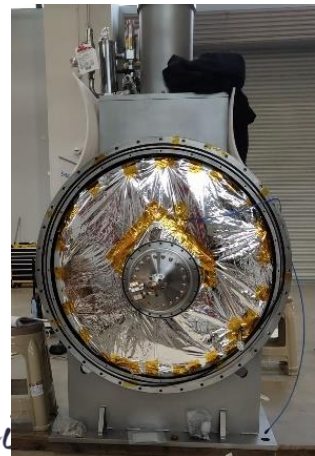
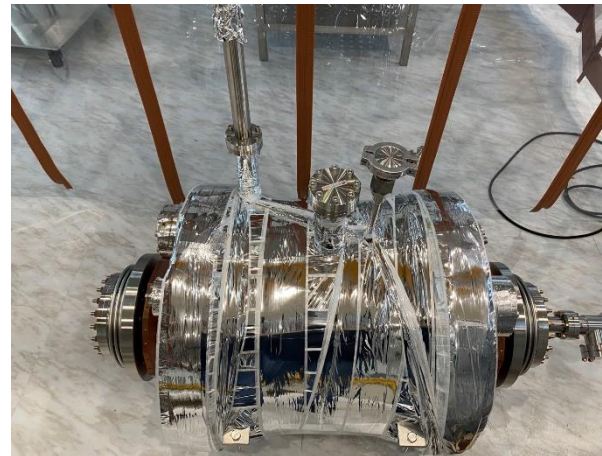
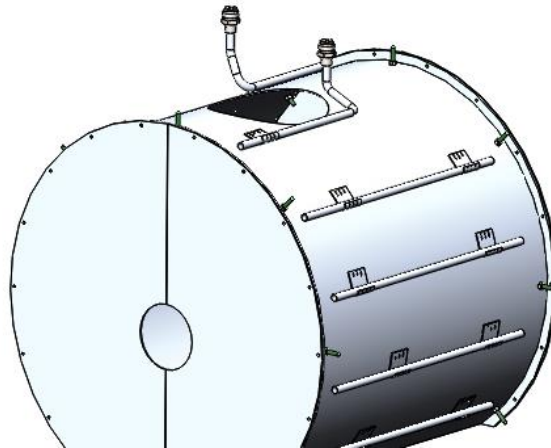
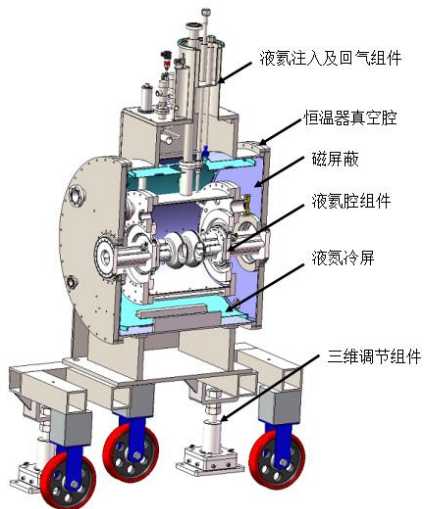
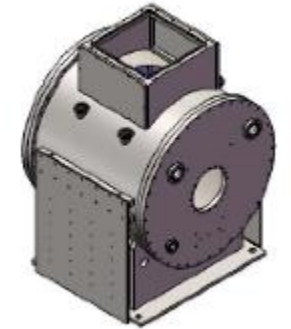


SSRF Superconducting Harmonic Niobium Cavity

Cryostat

- Compact design, composed of helium vessel, thermal shielding vessel (LN2 cooling) , vacuum vessel and magnetic shielding layers locates at inside of helium vessel and outside of thermal shielding vessel
- **Safety:** spring relief valve (1.3 bar) and burst disc (1.5 bar)
- **Residual magnetic** shielding layer: lower than 10 mGauss

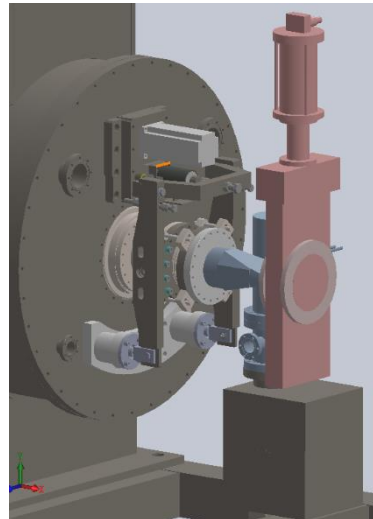
Temperature	2K ~ 300K	LR of Helium vessel	$\leq 2.0 \times 10^{-10} \text{mbar.l/s}$
Pressure of vacuum vessel	$\leq 5.0 \times 10^{-6} \text{mbar}$	Pressure of helium vessel	-0.1MPa ~ 0.2MPa
Thermal shielding	LN2	LR of vacuum vessel	$\leq 1.0 \times 10^{-8} \text{mbar.l/s}$
weight	~1.5 t	L*W*H	1420×900×2651mm



Displacement

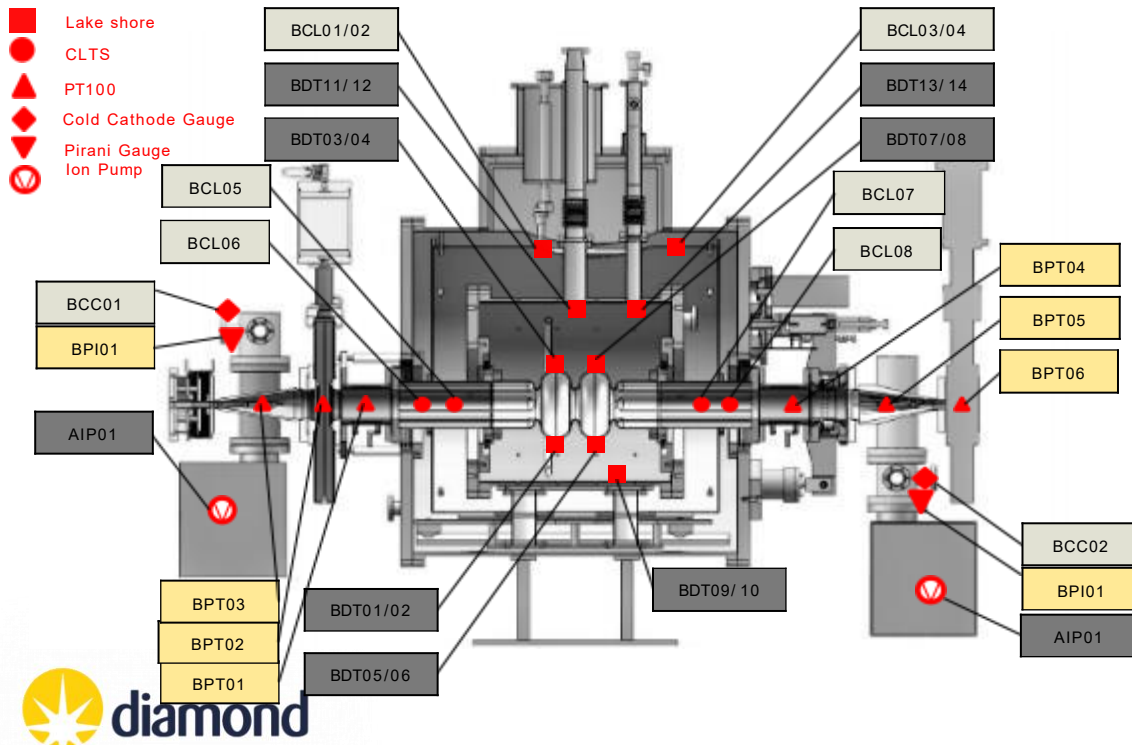
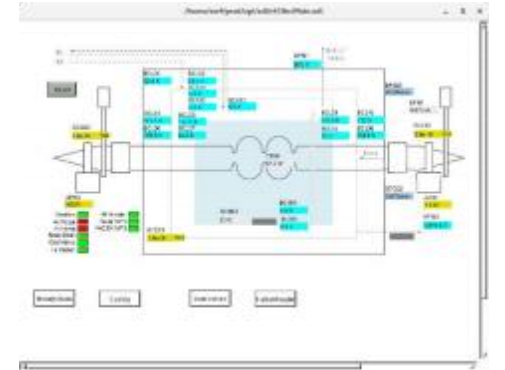
Tuner

- Mechanical slow tuner + piezo fast tuner
- Limit switch and hard stops
- Adjustable range: > 1.0 MHz.
 - For example: revolution frequency of SSRF is 694 kHz, thus parking and operation frequency adjustable shall be larger than 694 kHz, 1.0 MHz is preferred.
- Resolution: ~ 10Hz, high enough to promise amplitude stability +/- 1.0% tuning
- Backlash of slow tuner: < 20 kHz (while with low tuning speed, backlash is small)
- Piezo : high voltage type, 1000V → PI, P235.40



Control and interlock

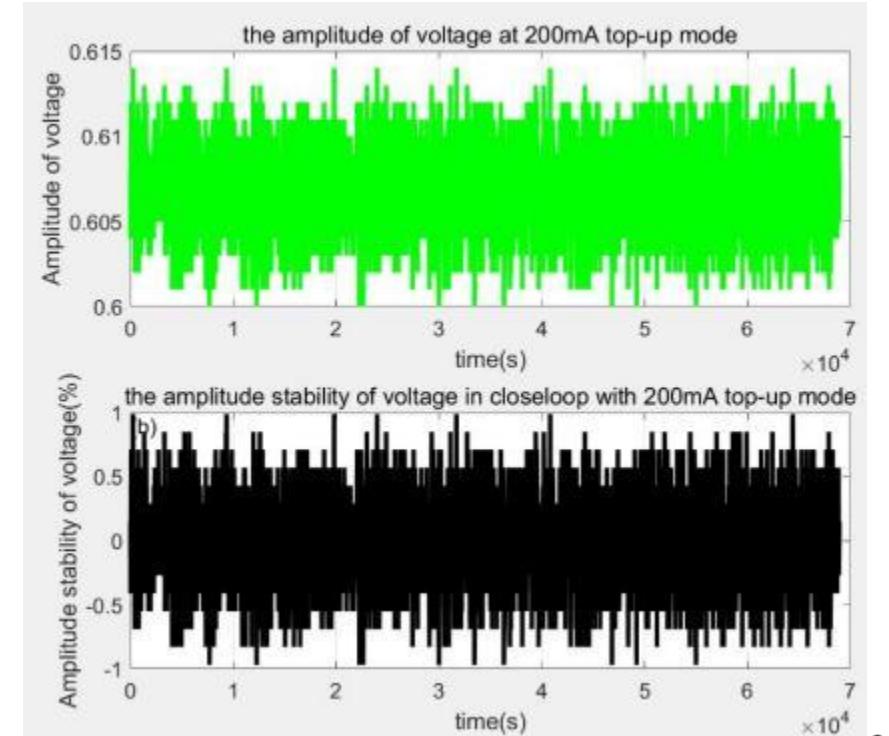
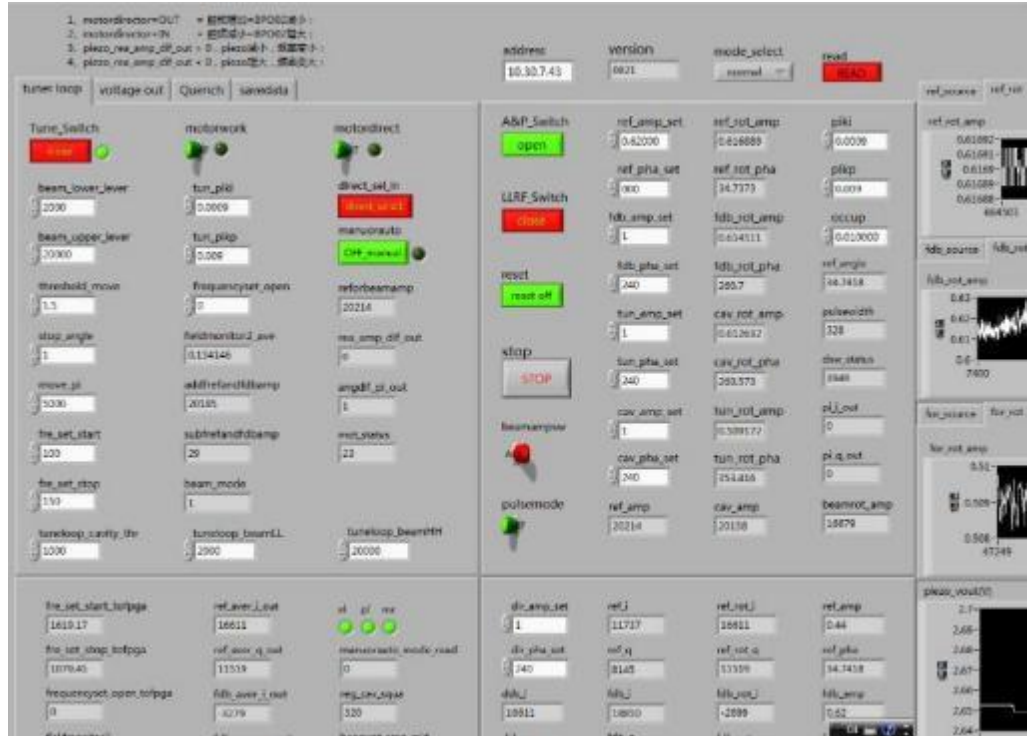
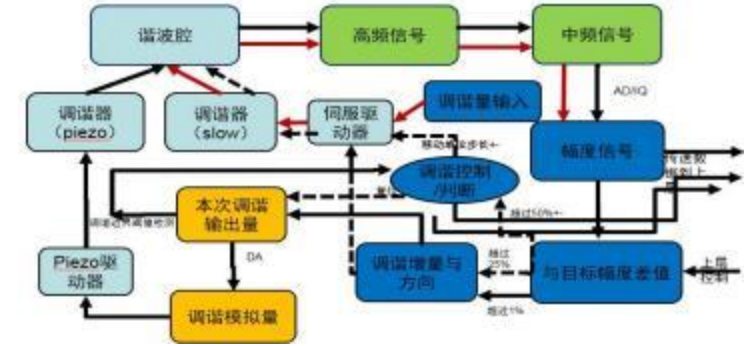
- PLC based control and interlock
- Readychain interlock and first fault signal locked (red LED)
- Temperature, pressure, helium level, cooling water flowrate are monitored



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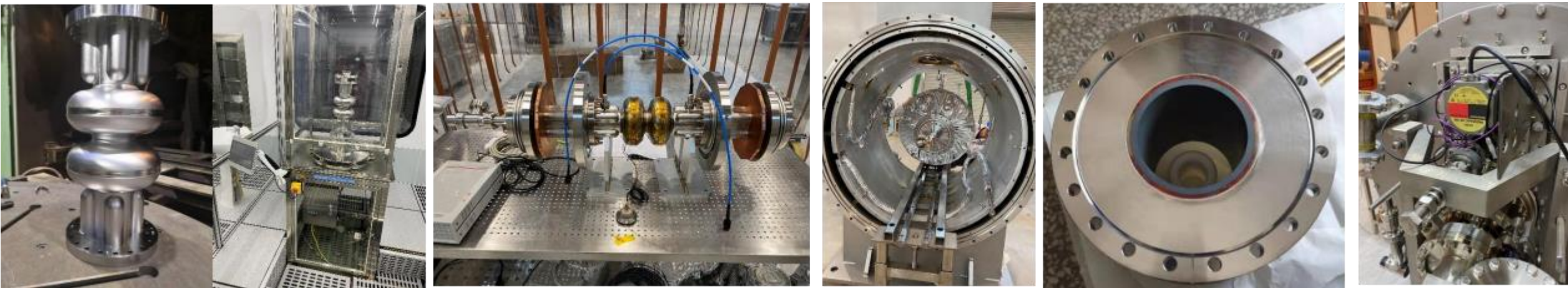
LLRF Controller

- Digital IQ based
- Quench protection integrated
- Amplitude stability: $\pm 1.0\%$



Document II | ...

SSRF Superconducting 3HC cryomodule development



Commissioning with Beam at SSRF

■ Bunch size (Half Band Width) lengthening factor is larger than twice

Stretching factor is 2.2 with uniform filling pattern four bunch trains each contains 130 buckets separated by 50 empty buckets, total current 200mA

Stretching factor ~ 3 , a long bunch train(~ 520 buckets) with a single bunch, 200 empty buckets, total current 220mA

Single bunch beam current reached **24.5 mA** in hybrid filling pattern, **Year 2021**;

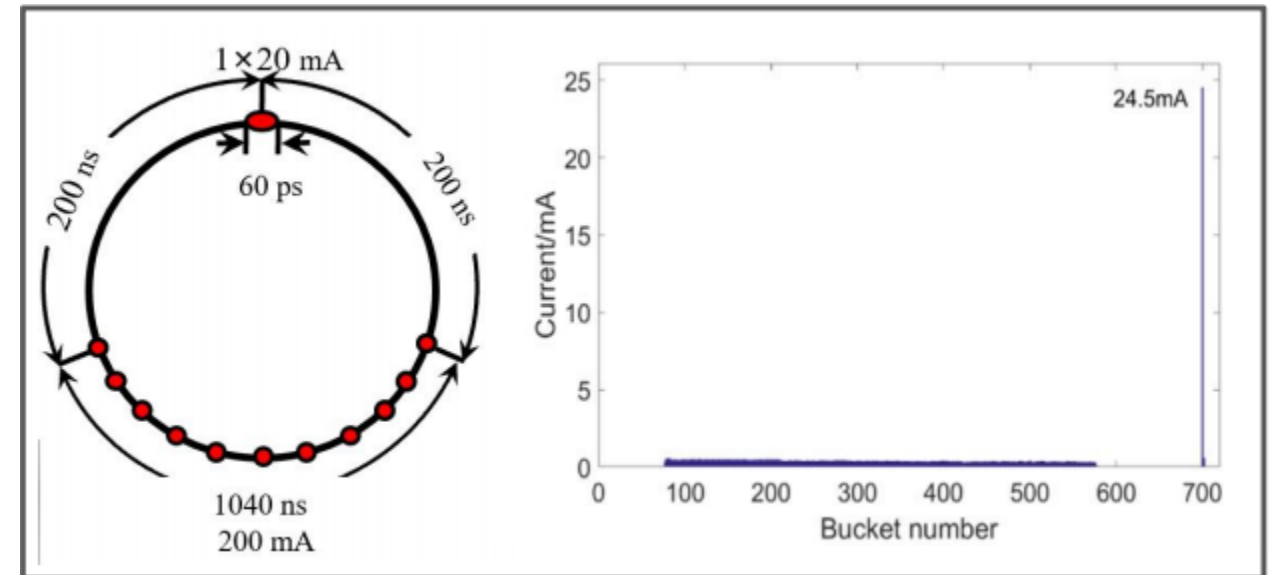
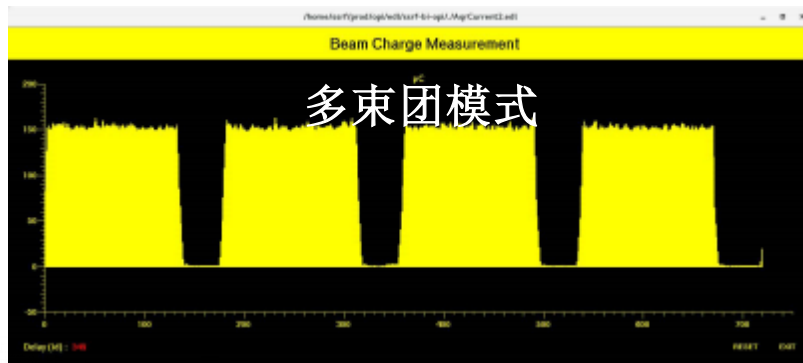
Steam camera is used to measure bunch length

■ 3 HC operation state

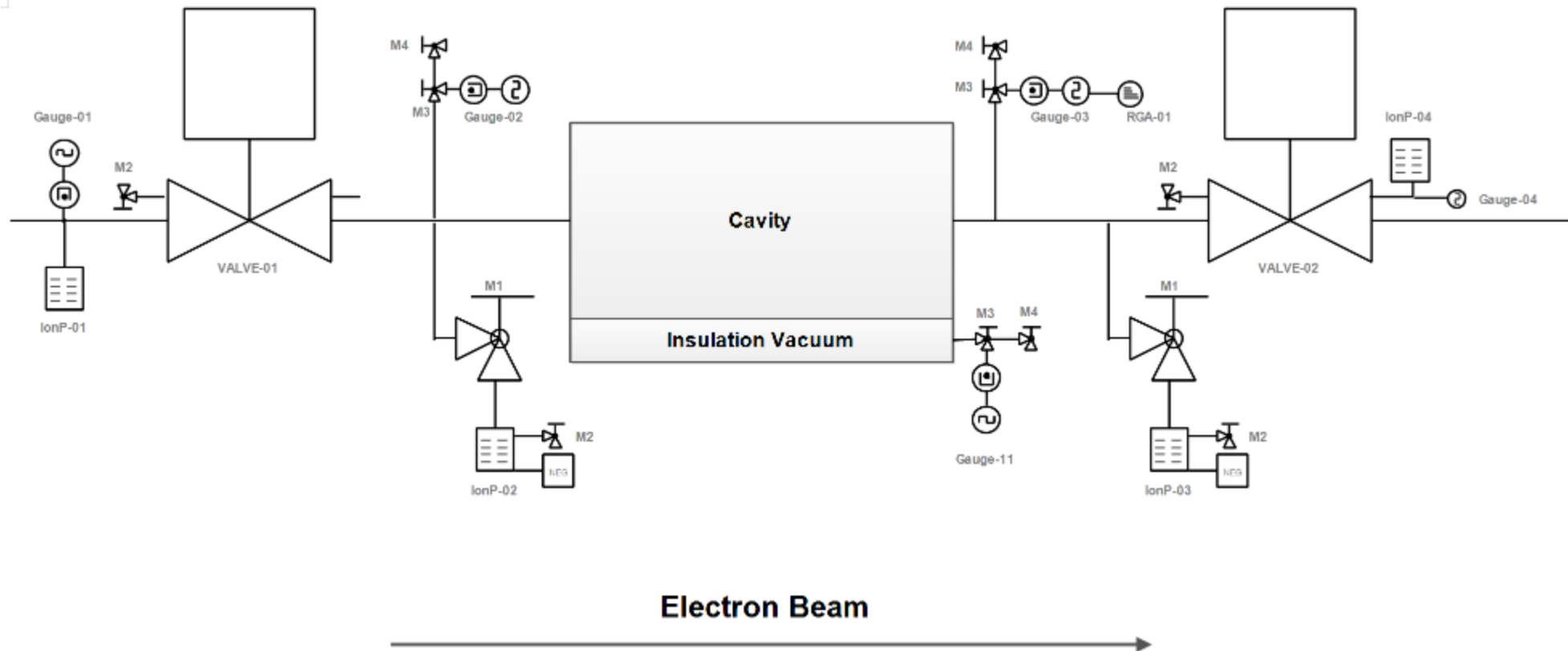
Stable cavity voltage, adjusted smoothly by tuner

Cryogenic, vacuum are stable

No influence observed on main rf system

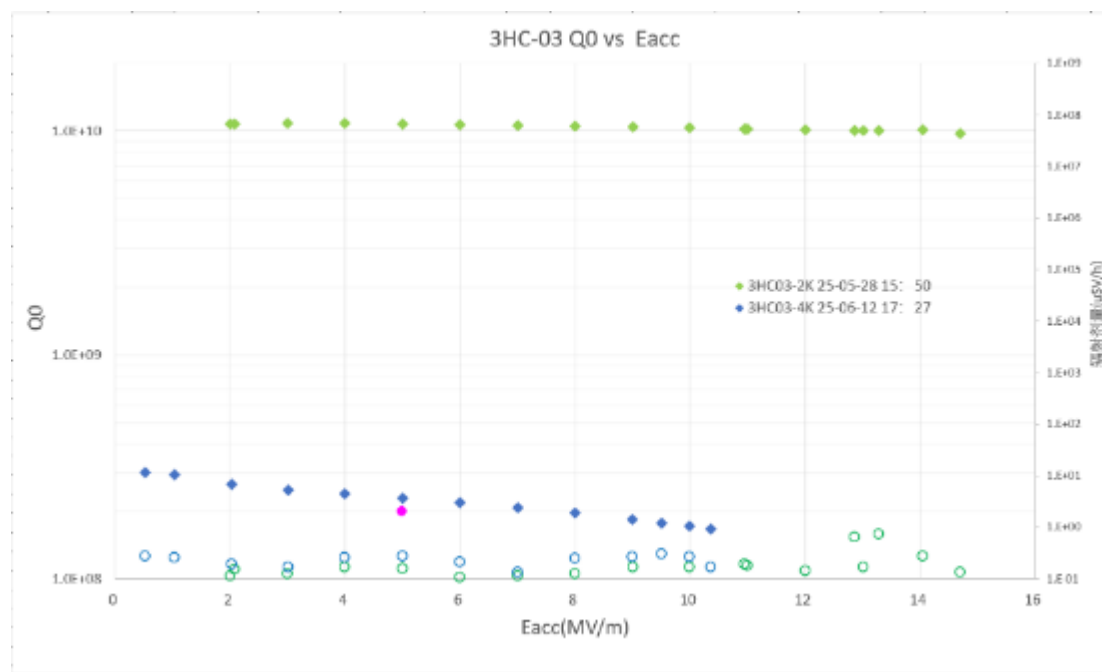


Vacuum Configuration



Vertical Test Finished

Vertical test		Date: 2025/07/03	
	Items	Results	Instruments
1	Frequency @ ~4.3 K	1498.502 MHz	Solid-state power source, digital LLRF controller, Labview program, rf cables, power meter. No pump while vertical test.
2	Q0 @ 1.0 MV (5.0 MV/m)	2.30×10^8	
	Q0 @ 1.2 MV (6.0 MV/m)	2.20×10^8	
3	Qin	2.08×10^8	
4	Qt	3.88×10^{11}	
5	Eacc_FE_onset	none	
6	Max. Gradient (Limit by forward power admin.)	10.36 MV/m	



Further Improvement of Q0

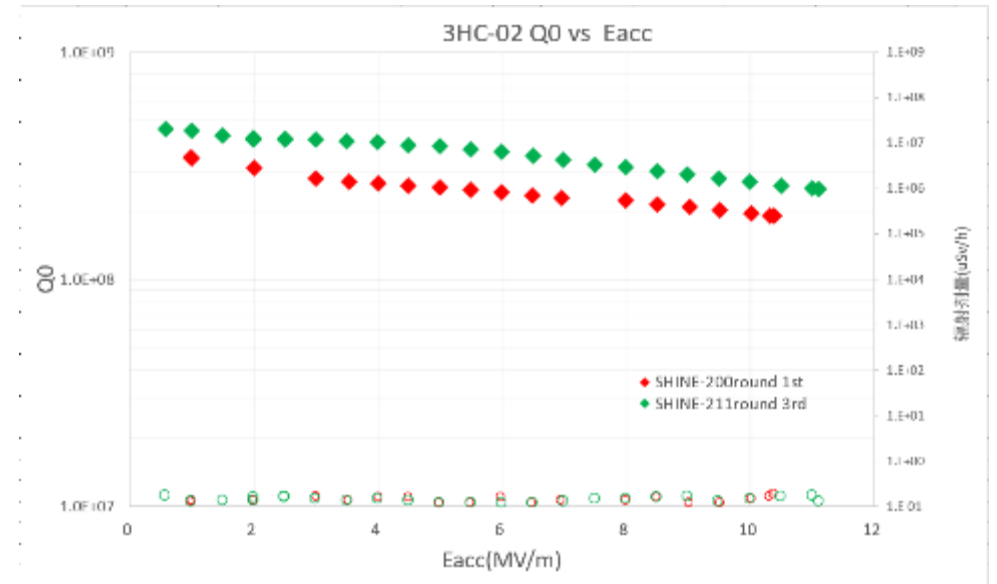
120°C baking will be carried out to 3HC-03 and vertical test again.

Reference : 3HC-02 has been 120 baked to have a higher Q0

3HC02: 08月25日, f_0 (π mode) : 1497.77 MHz,
Q0-6: $2.43\text{E}+8$, Q0-8: $2.23\text{E}+8$, Emax:
10.4MV/m

3HC02: 09月30日, f_0 (π mode) : 1497.77 MHz,
Q0-6: $3.65\text{E}+8$, Q0-8: $3.13\text{E}+8$, Emax:
11.11MV/m

Different Eacc is due to different forward power



Recent Progress

- Cryostat
 - In production
 - Stainless steel materials for LHe and vacuum vessel: ASME standard + the lower magnetic permeability, the better.
- Taper: in design / synchrotron light absorber
 - Vacuum distribution ready: RGA has been moved to upstream (tuner side)
 - Downstream $\phi 82$ mm vs Upstream $\phi 104$ mm vac pump tube : no light absorber locates at upstream which has no overlapped welding seam; while there is light absorber at downstream, if keeping same diameter as that of upstream, there will have overlapped welding seam which is not good.
 - Height of top tube at both ends will be minimized

Thank you!!