Performance of the First Mid-T 1.3 GHz Module

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Outline

1. Introduction
2. Cryomodule assembly
3. Horizontal test result
4. Summary

Mid-T Bake Cavity and Cryomodule Development

- **Fermilab:** in-situ mid-T bake of assembled cavity (*S. Posen, et al, SRF19 MOP043, Jul. 2019; PHYSICAL REVIEW APPLIED 13, 014024, 2020*). Discovery of high Q by 250~400 C mid-T bake.

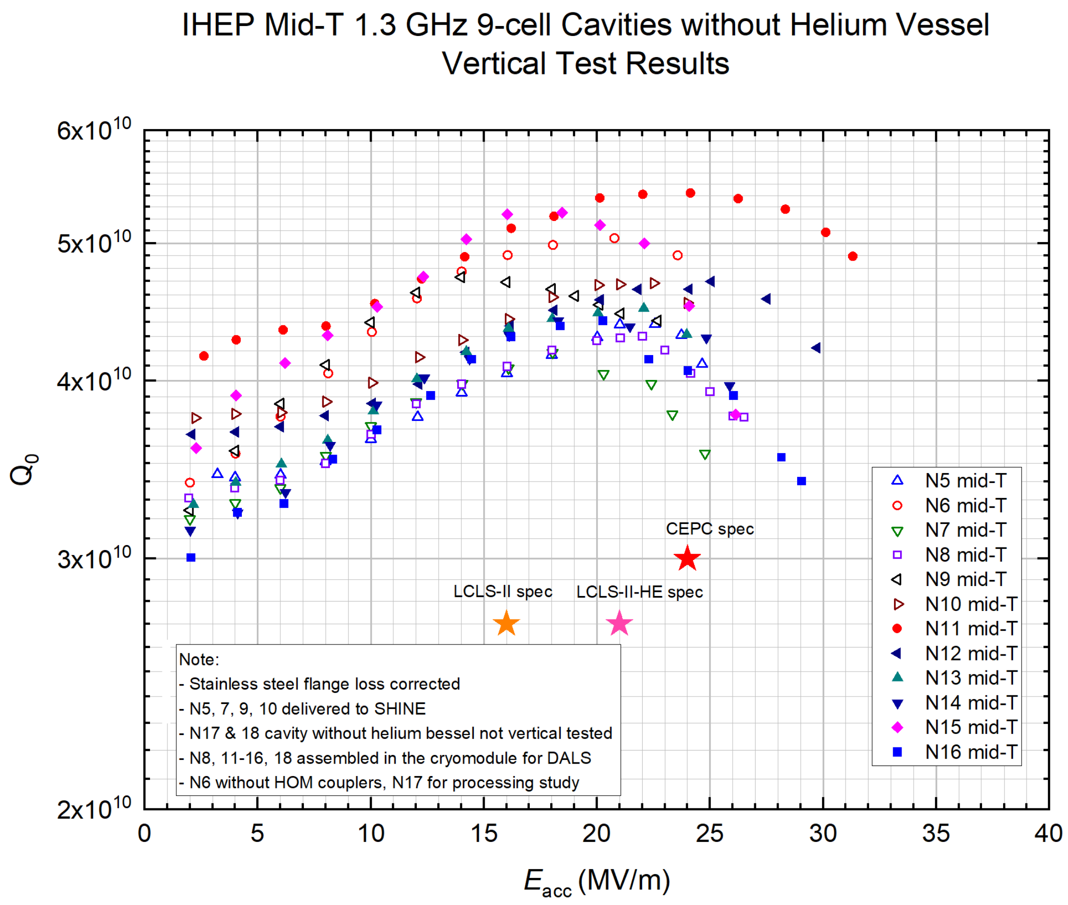
- **KEK:** regular furnace mid-T bake of unassembled cavity (*K. Umemori, TTC meeting at CERN, Feb. 2020; H. Ito, et al, Prog. Theor. Exp. Phys. 2021, 071G01*). Simplified the implementation of mid-T bake.

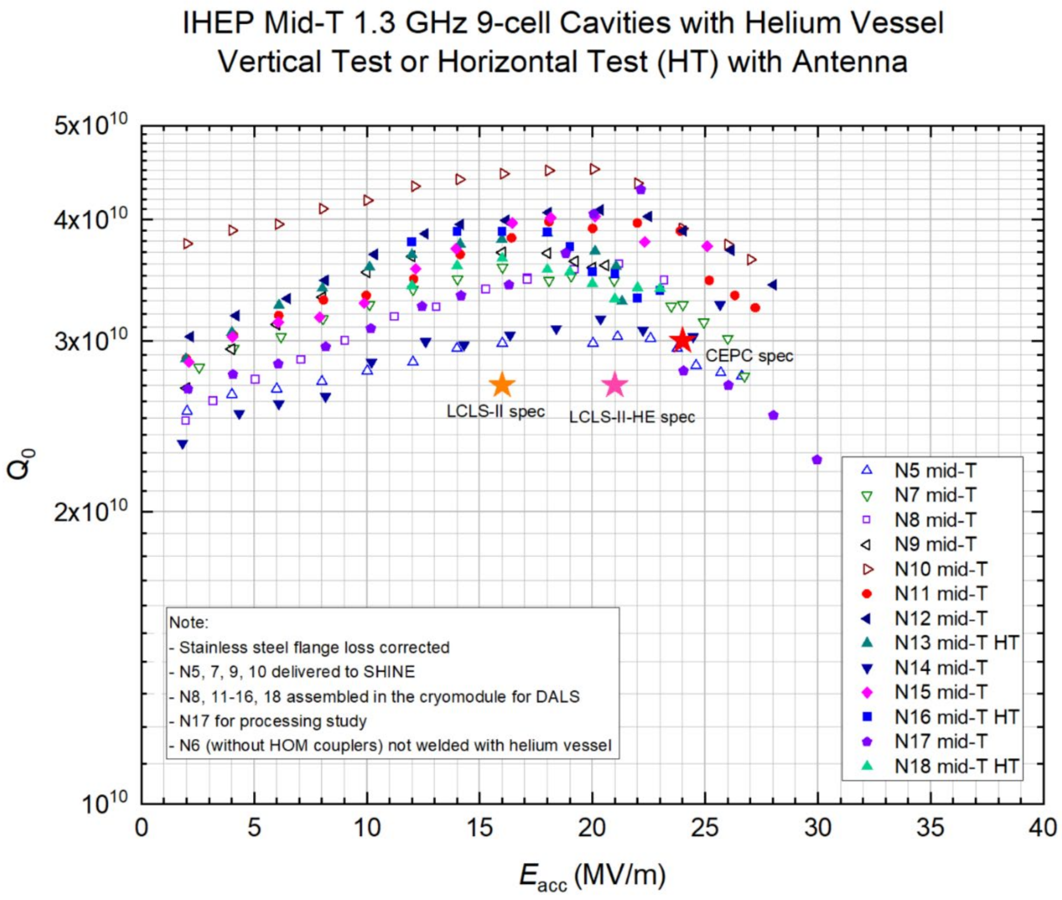
- **IHEP:**
  - Further simplified furnace mid-T bake procedure (only one bulk EP, no light EP).
  - Successfully applied mid-T bake to 1.3 GHz 9-cell cavities in Oct. 2020 (*F. He, et al, Superconductor Science and Technology, 34, 2021, 095005*). 14 mid-T 9- cell cavities tested in 2020-2022.
  - Cryomodule with eight mid-T 9-cell cavities achieved world leading high Q and high gradient in June 2023 (https://arxiv.org/abs/2312.01175) for Dalian Advanced Light Source (DALS) R&D, based on the important experience gained in Euro-XFEL and LCLS-II (&HE) cryomodules.

- **Advantages:** mid-T 1 EP vs N-doping 3 EPs, no NbN precipitates, no careful EP after doping, stable and reliable performance … (*H. Padamsee. Superconducting Radiofrequency Technology for Accelerators: State of the Art and Emerging Trends. Wiley-VCH, Feb. 2023*)

- **Application:** PIP-II 650 MHz β=0.61 5-cell cavities will use mid-T bake. SHINE, S^3FEL, DALS, CEPC, CW upgrade of Euro-XFEL and other projects are considering to use mid-T bake for large number of cavities.

Vertical Test Results of Mid-T Bake 9-cell Cavities at IHEP



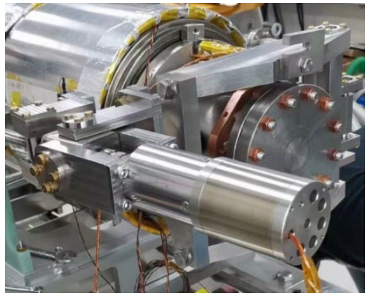
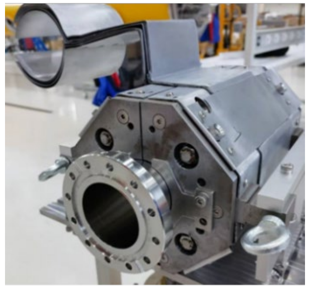


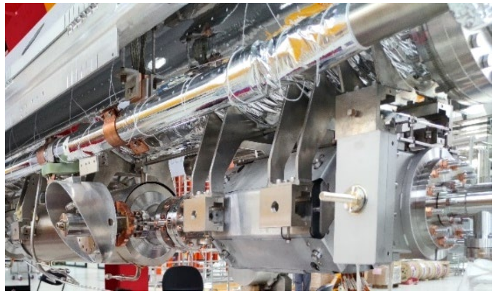
Average Q_0 4.5E10 at 16~21 MV/m of 12 mid-T 9-cell cavities. Q_0 corrected for stainless steel flange loss (0.8 nΩ) in order to compare with module test results directly.

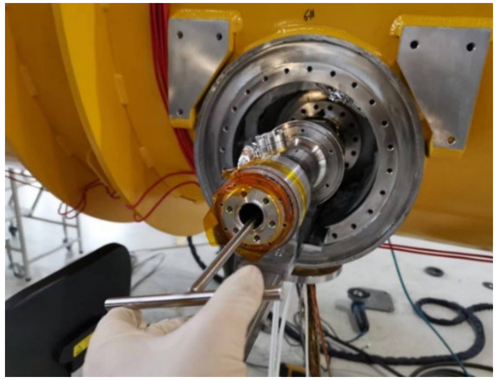
Due to tight schedule, no time to warm-up and cool down some of the dressed cavities to recover the degraded Q_0 after quench, or with not-optimized fast cool down, or by thermal current.

Module Assembly



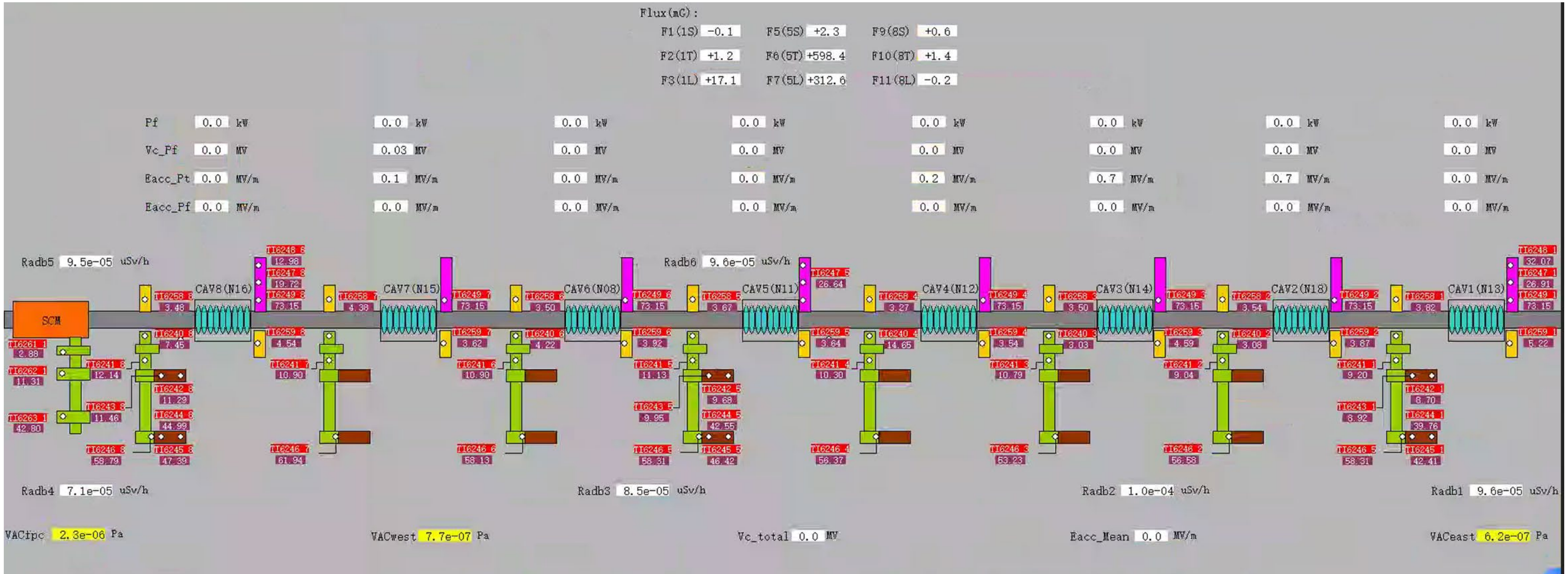






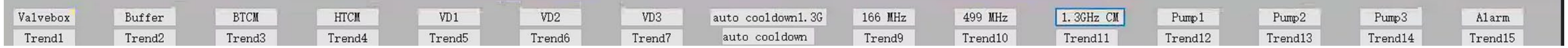

- cavity string kept in vacuum during the cold mass assembly all through to the horizontal test.
- cavity string pumped by TMP whenever possible during the cold mass assembly outside the clean room.

Module Instrumentation

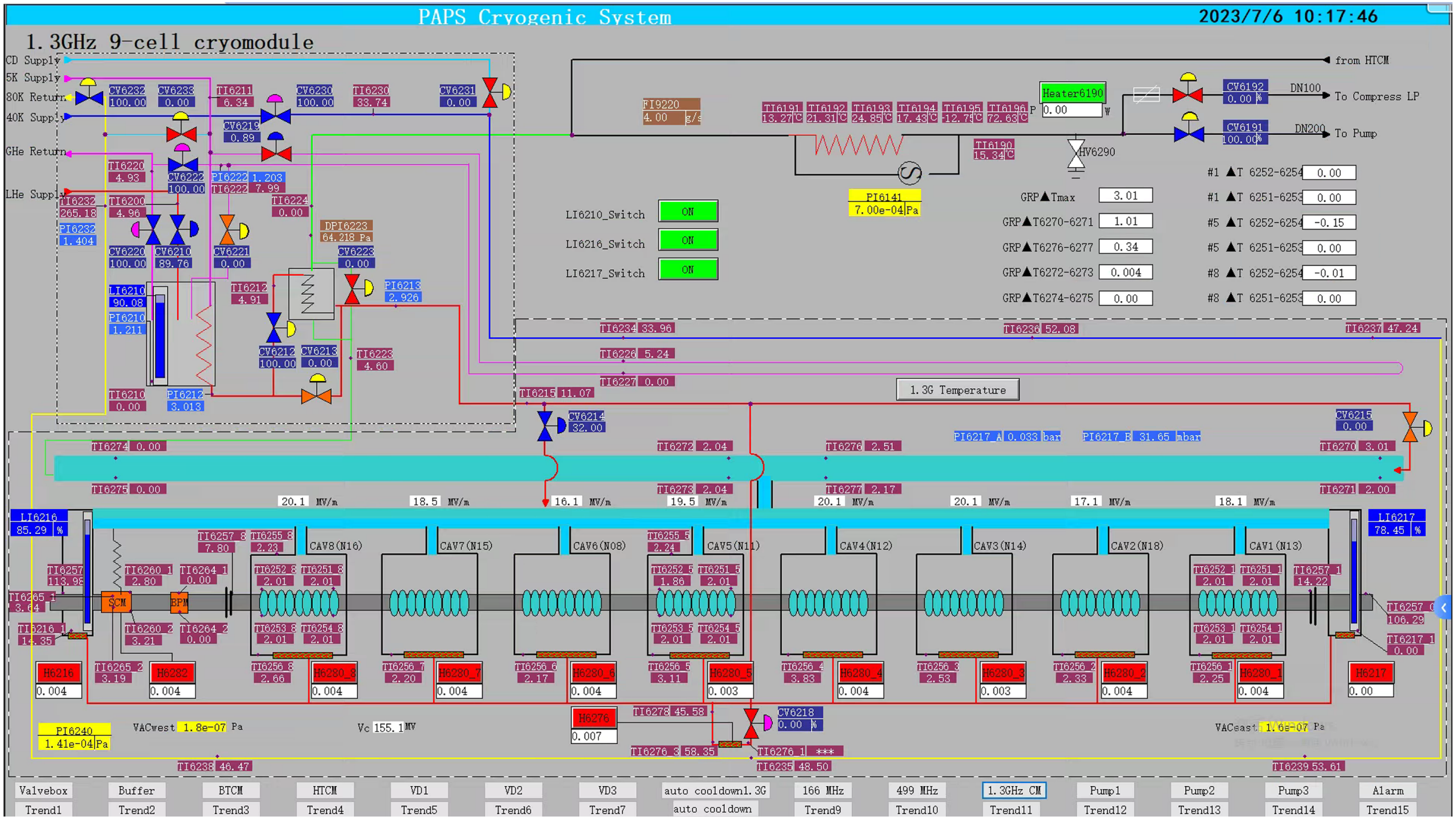


143 temperature sensors, 12 flux gates, 6 radiation detectors…e.g. important to find:

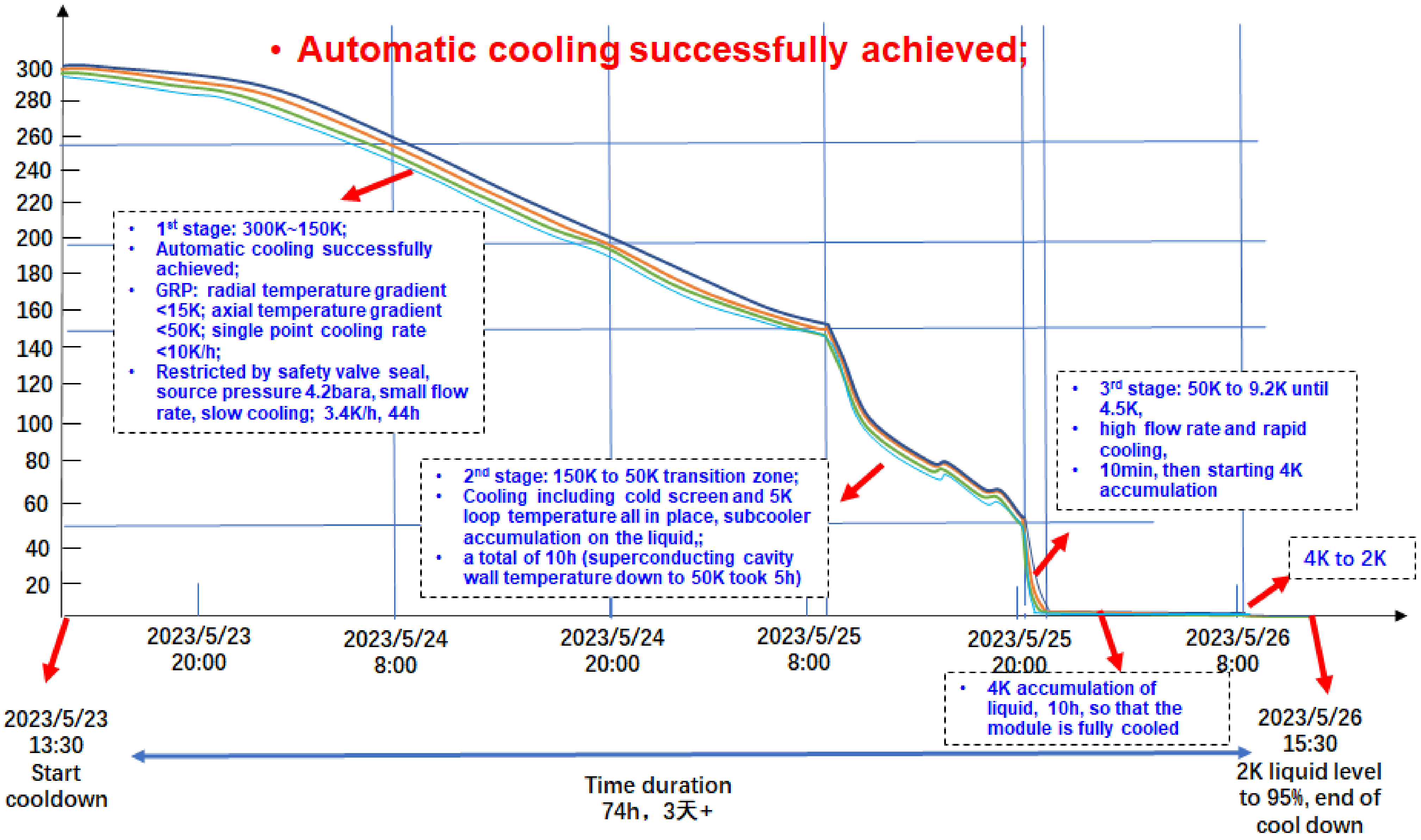
- overheating of the HOM coupler caused by poor thermal conduction (limit to < 10 MV/m)
- overheating of input coupler caused by poor mechanical connection of the warm part and cold part of the inner conductor …



Module Cooldown



Module Cooldown



Cavity Processing

- High Q TESLA cavities (MP band at 17-24 MV/m) sometimes need more multipacting processing than baseline (EP+120C) cavities, especially in the module.
- Two of the eight (25 %) cavities show repetitive quenching.
- Cavity processing takes two days (May 28-29, 2023).

1#: 5.28 10:16-10:40, 2 quenches at 20-21 MV/m.

2#: 5.28 9:29-13:26, 14 quenches at < 14 MV/m, 12 quenches at 17-19 MV/m. HOM2 heating and quench at > 20 MV/m with X-ray

3#: 5.28 9:17-10:40, no MP quench.

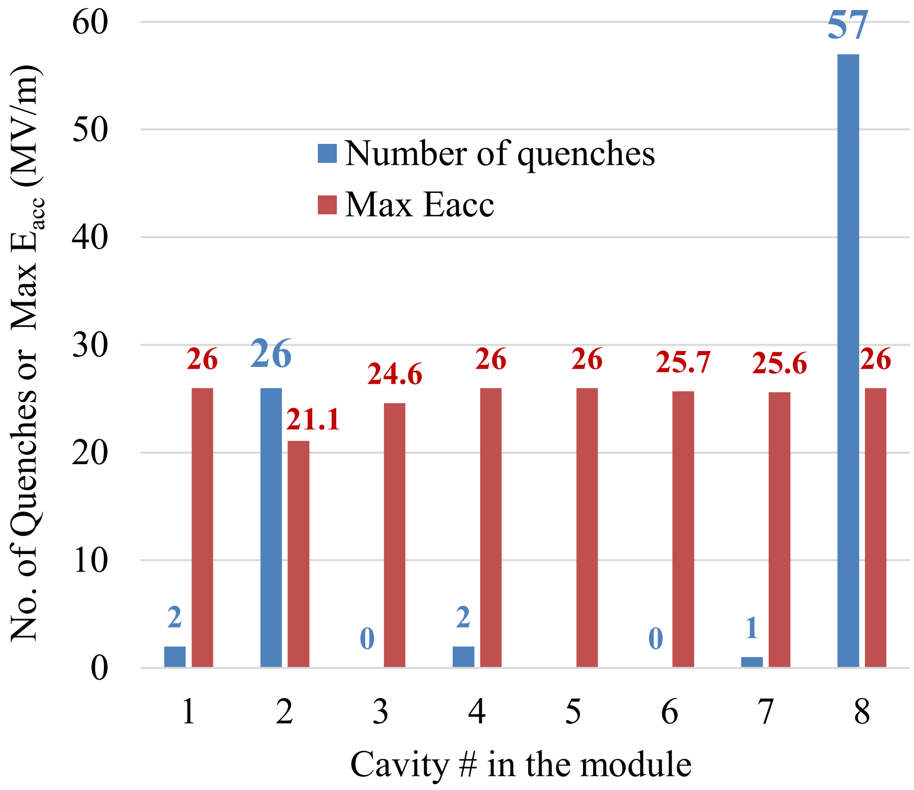
4#: 5.28 13:02-13:30, 1 quench at 19 and 23 MV/m.

5#: 5.29 outgassing by pulsed processing, reach 26 MV/m after 80 min. Quench number NA.

6#: 5.28 12:42-12:49, no MP quench.

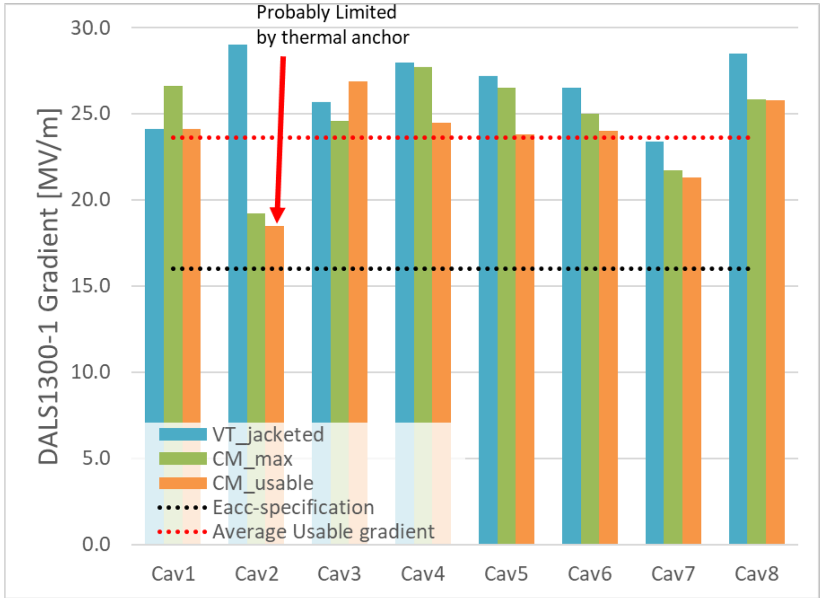
7#: 5.28 10:30-13:05, no MP quench.

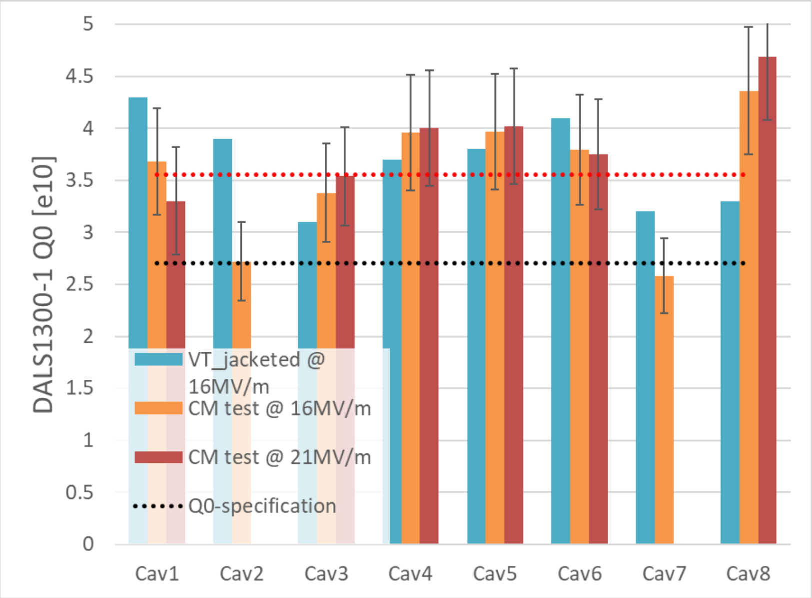
8#: 5.28 10:37-15:50, 57 quenches at 17-24 MV/m.



Cryomodule Performance

Parameters	IHEP Mid-T CM1 test results	DALS, SHINE, S^3FEL spec.	CEPC Spec.
CM usable RF voltage (MV)	**> 191.2**	128	180
Average usable E_{acc} (MV/m)	**> 23.1**	16	21.8
2 K heat load @ 128 MV (W)	83.5	93	/
Average Q_0 @ 16 MV/m	**3.8×10^{10}**	2.7×10^{10}	/
2 K heat load @ 173 MV (W)	133	/	140
Average Q_0 @ 21 MV/m	**3.6×10^{10}**	/	3.0×10^{10}





Radiation Dose and Dark Current

Each of the eight superconducting cavities powered to 16 MV/m, and the radiation dose parameters of each cavity were monitored separately.

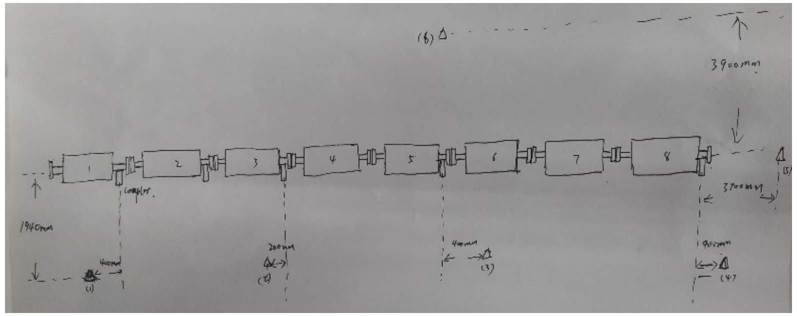
CAV1: onset@10 MV/m, ~ 5 uSv/h

CAV6: onset@10.8 MV/m, ~ 13 uSv/h

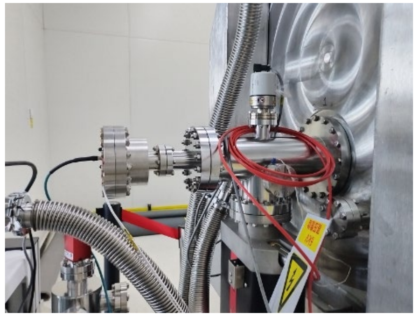
Other cavities: NO FE

8 cavities radiation dose < 0.08 mSv/h (spec 0.5 mSv/h)

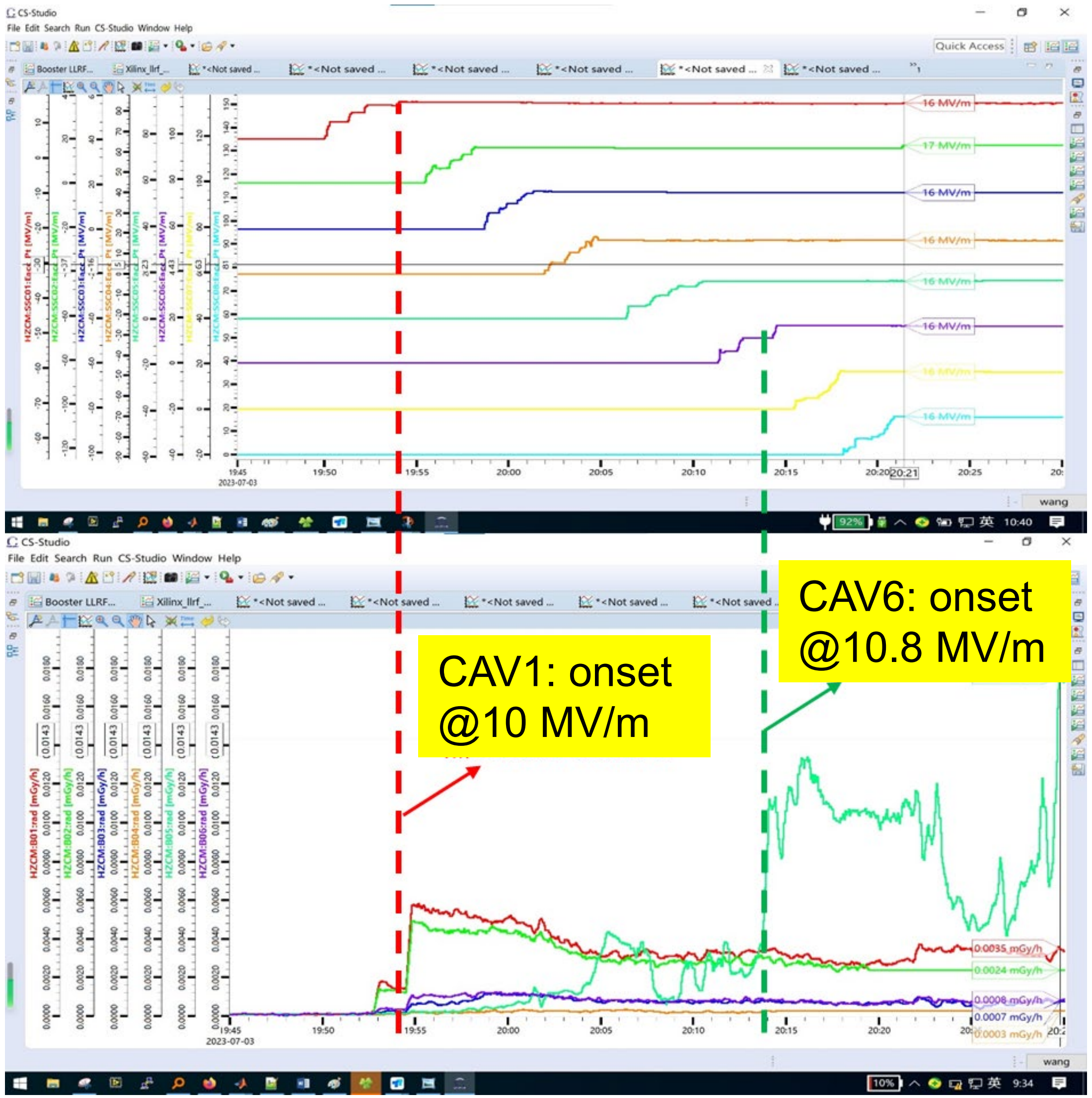
The dark current is smaller than the spec (1 nA)



Radiation Detectors



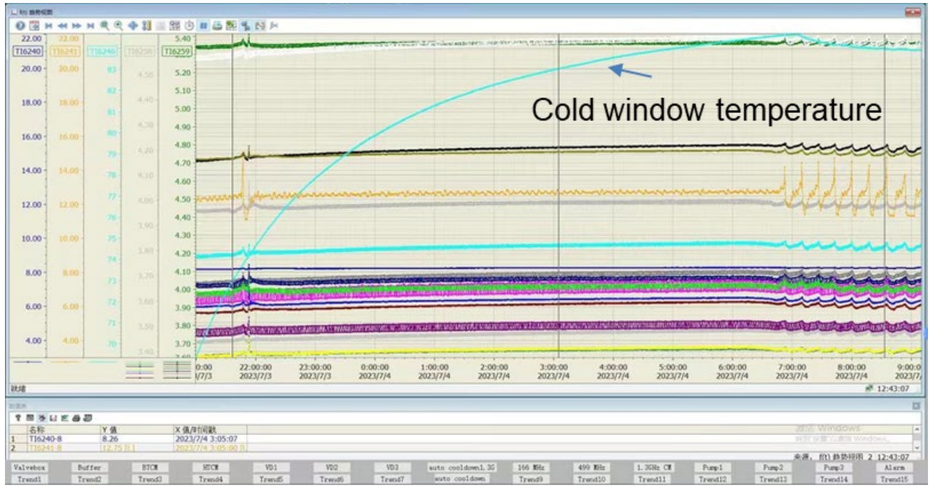
Faraday Cup

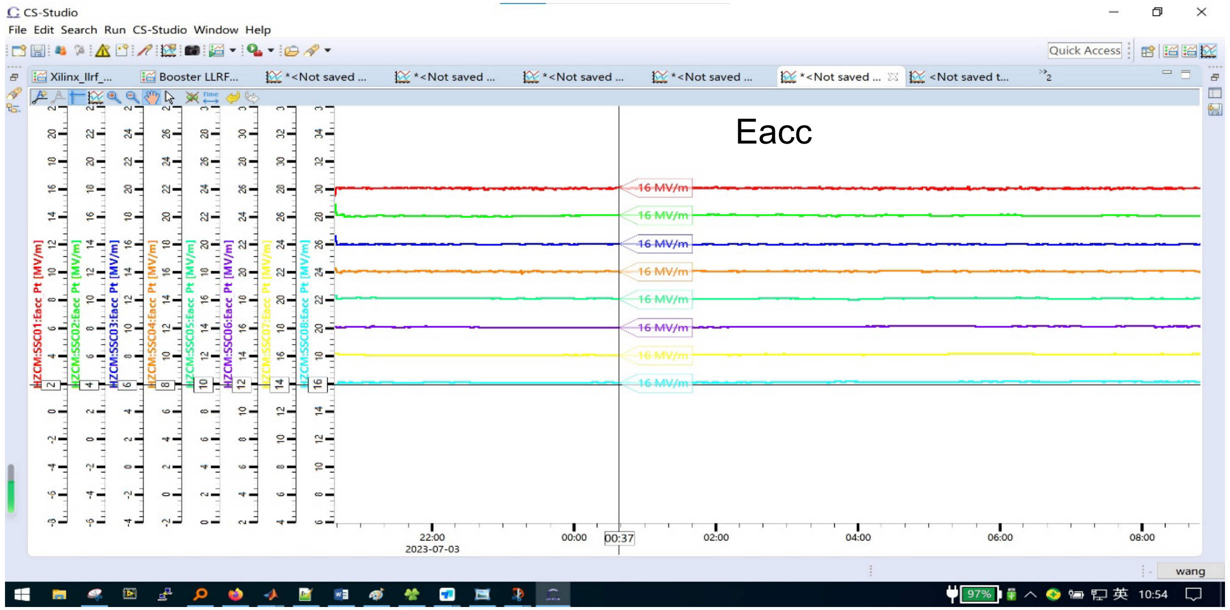


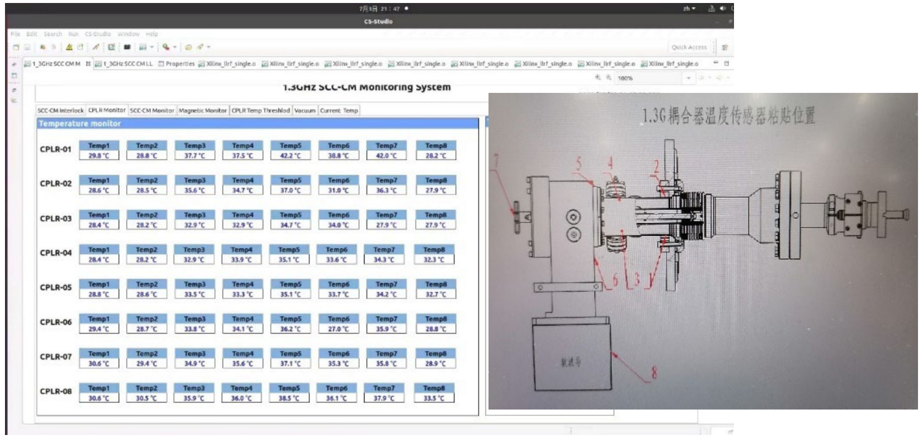
Stable Operation

Continuous stable operation for 12 hours at 133 MV (each cavity working at 16.0 MV/m)

Coupler cold window maximum temperature < 100 K; Radiation dose ＜0.08 mSv/h







Coupler warm part temperature

Cool Down Rate and Average Q_0

Single cavity Q_0:

$$Q_0 = \frac{(E_{acc\_P_t} \cdot L_{\text{eff}})^2}{R/Q * Q_{\text{dynamic}}} = \frac{Q_t \cdot P_t}{Q_{\text{dymamic}}}$$

Average Q_0 of 8 cavities:

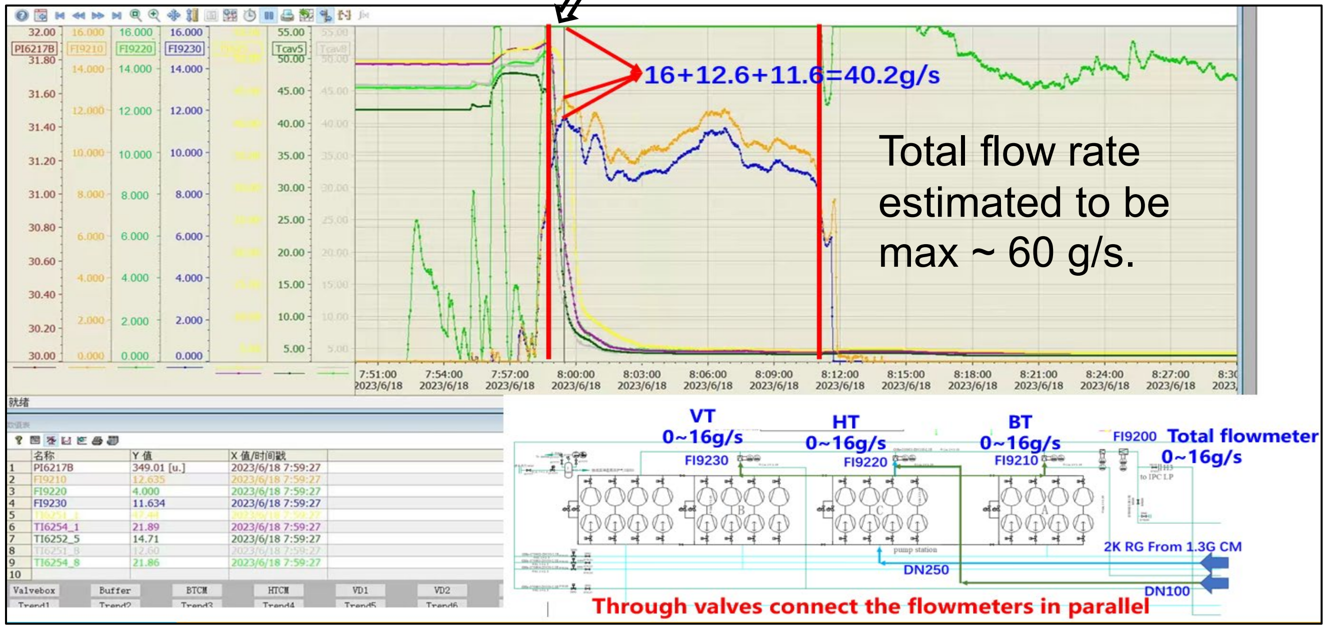
$$\overline{Q_0} = \frac{\left(\frac{1}{8}\Sigma E_{acc\_P_t} \cdot L_{\text{eff}}\right)^2}{R/Q * Q_{\text{dynamic}}/8}, \text{ or } \overline{Q_0} = \frac{\Sigma(E_{acc\_P_t} \cdot L_{\text{eff}})^2}{R/Q * Q'_{\text{dymamic}}}$$

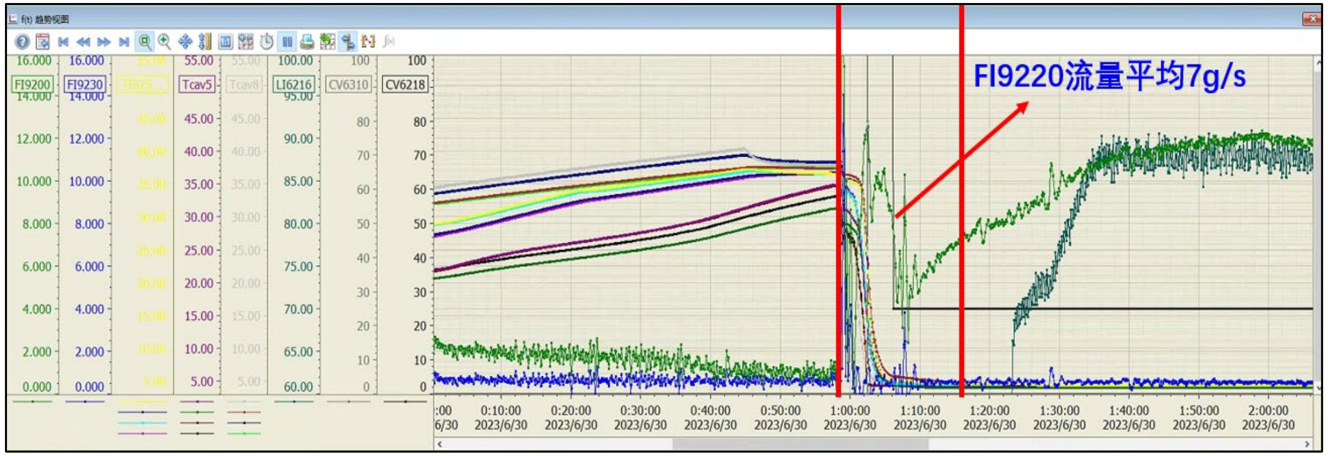
RF Voltage, cool down (date)	Measurement Date	Average E_{acc} [MV/m]	Q_{dyn} [W]	Average Q_0
133 MV, fast cool down (6.1)	6.12	15.9±0.9	60.5±1.9	**(3.6±0.4)E10**
133 MV, fast cool down (6.1)	6.12	15.9±0.9	62.3±1.9	(3.5±0.4)E10
133 MV, slow cool down (6.19)	7.3	16.1±0.9	57.2±1.9	**(3.8±0.4)E10**
133 MV, slow cool down (6.19)	7.4	16.1±0.9	58.4±1.9	(3.7±0.4)E10
174 MV, fast cool down (6.1)	6.12	20.9±1.2	104.4±1.7	(3.6±0.4)E10

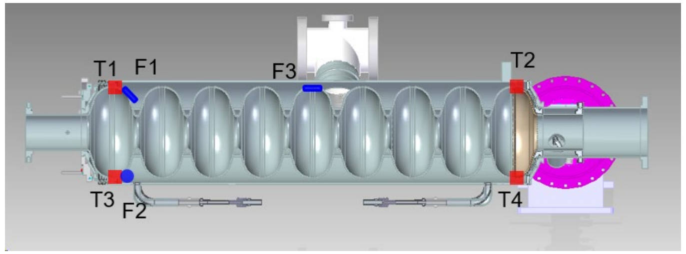
Heat load measurement details in Feisi He's talk on Wed, WG4.

Temperature Difference of Fast / Slow Cooldown

Out of measurement range of flow meter FI9220.







ΔT: top (T1, T2) to bottom (T3, T4) temperature difference of a cell

CAV #	Cool down rate* [g/s]	1#cell ΔT [K]	9#cell ΔT [K]	45° [mG]	Trans-verse [mG]	Axial [mG]
1	> 39	6.4	3.6			
5	> 41	5.23	3.94			
8	> 39	5.76	5.57			
1	8	3.89	3.96	-1.84	-0.49	
5	12	7.45	7.49	- 3.91		1.93
8	8~11	12.16	4.64		0.36	2.54

* when cell bottom reaches critical temperature of 9.2 K

Future Work

1. **Optimize VT procedure of jacketed cavity** to have similar Q_0 with bare cavity (for mass production without VT of bare cavities).

2. **Reduce module static heat load** (25 W, details in Feisi He's talk on Wed, WG4).

3. **Investigate the relation of Q_0 with different cooldown speed**, top to bottom cavity temperature difference at critical temperature, flux expulsion, remnant magnetic field and thermal current etc.

4. **Investigate gradient drop of individual cavities** and avoid systematic risk.

5. **Investigate cavity processing and input coupler outgassing issues** and reduce processing time.

6. Increase cavity gradient, reduce Q spread. Statistics with more mid-T cavities and cryomodules.

Summary

- IHEP successfully developed world's first medium temperature baking (mid-T) high Q_0 1.3 GHz cryomodule. Main performance meets the requirement of DALS / S^3FEL / SHINE, and is beyond LCLS-II-HE and CEPC spec.

- Module total CW RF voltage greater than 191 MV (> 23 MV/m). Multipacting processing time quite different for the eight cavities.

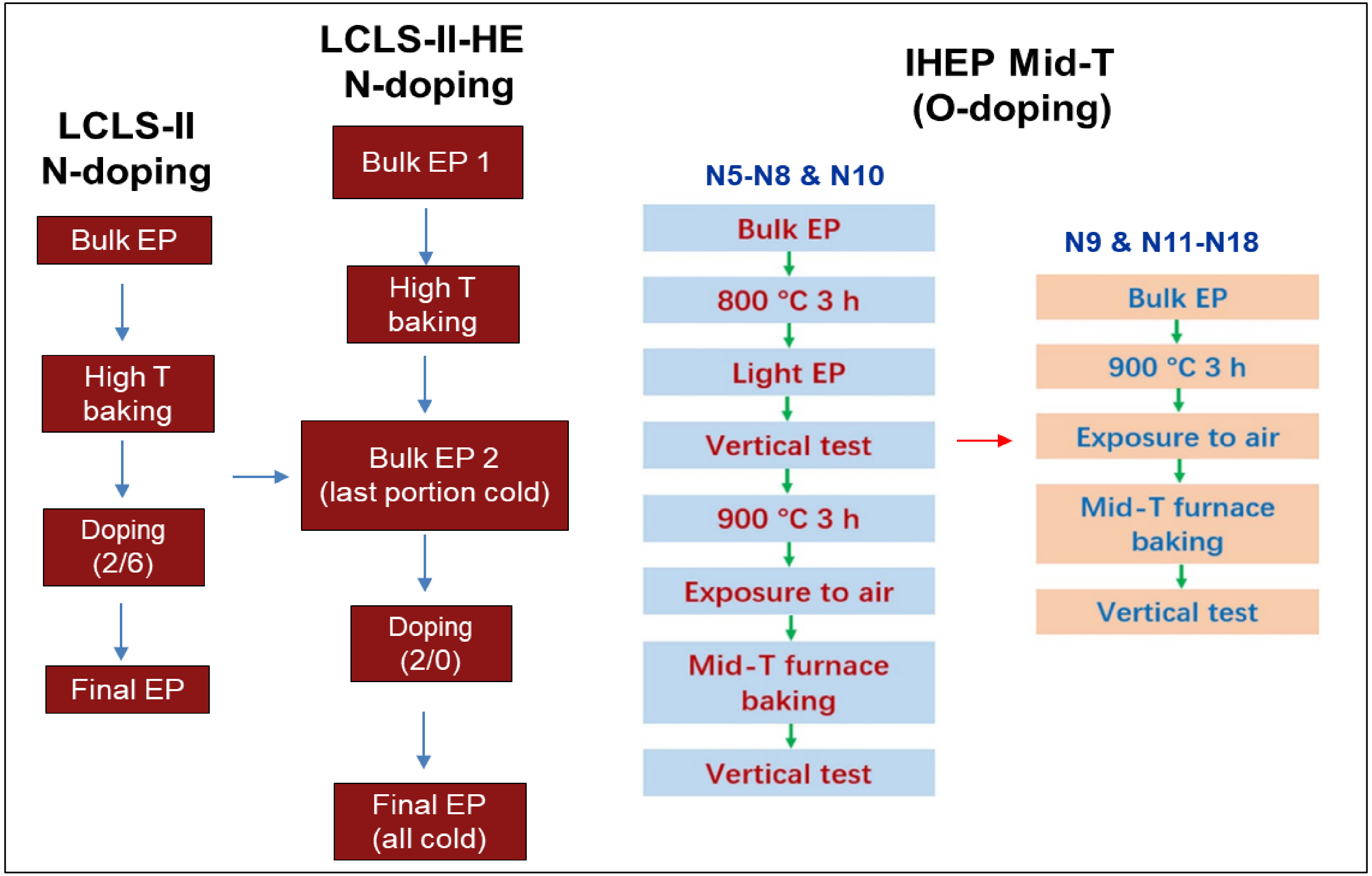
- Unprecedented high average Q_0 of 3.8E10 at 16 MV/m and 3.6E10 at 21 MV/m of eight mid-T bake 9-cell cavities in the module. Preliminary results show the slow and fast cooldown have similar Q_0.

- Will make more mid-T module prototypes for SHINE and S^3FEL in next few years for more data and further investigation.


Thank you!

Backup

Mid-T Furnace Bake and Nitrogen Doping

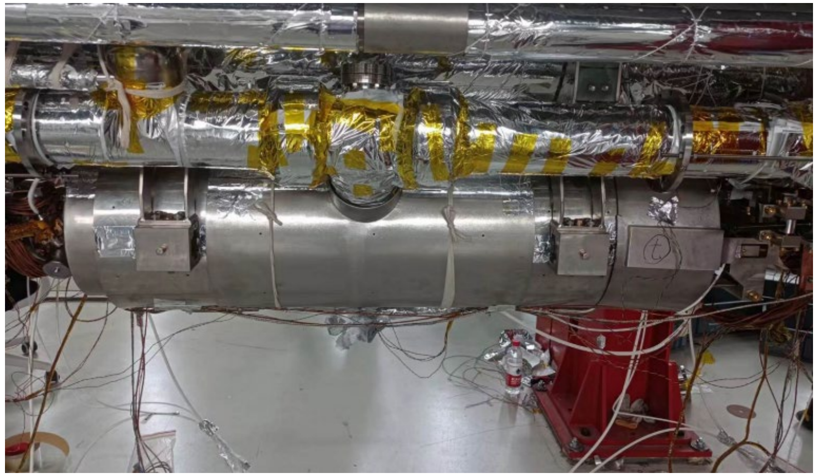


Comparison of Cavity Performance in VT and CM

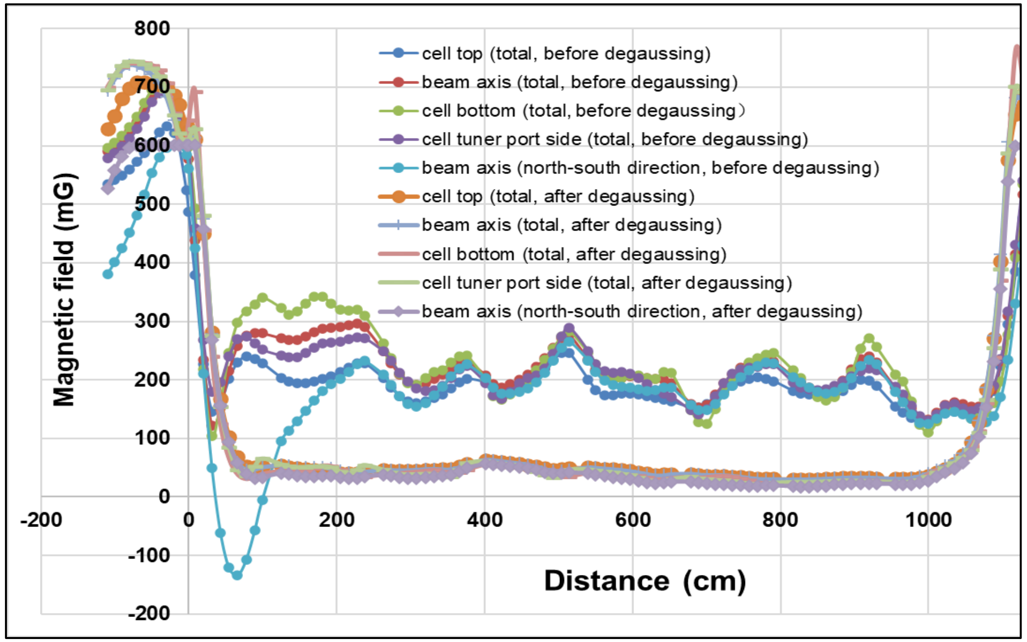
Cavity Serial #	CAV# in DALS-CM1	Bare Cavity Vertical Test				Jacketed Cavity Vertical Test				Cryomodule Test				Note
stainless steel flange loss corrected for Q_0		**Max Eacc** [MV/m]	Q0 at 16 MV/m [1E10]	Q0 at 21 MV/m [1E10]	Q0 at 23 MV/m [1E10]	**Max Eacc** [MV/m]	Q0 at 16 MV/m [1E10]	Q0 at 21 MV/m [1E10]	Q0 at 23 MV/m [1E10]	**Max Eacc** [MV/m]	**Usable Eacc** [MV/m]	Q0 at 16 MV/m [1E10]	Q0 at 21 MV/m [1E10]	
N5	/	24.6	4.0	4.4	4.3	26.6	3.0	3.0	3.0	/	/	/	/	delivered to SHINE
N6	/	23.6	4.9	5.0	4.9	/	/	/	/	/	/	/	/	bare tube without HOM
N7	/	24.8	4.1	4.0	3.8	26.7	3.6	3.5	3.3	/	/	/	/	delivered to SHINE
N8	**CAV6**	26.5	4.1	4.3	4.2	23.2	3.5	3.6	3.5	25.0	24.0	3.8	3.8	in CM1
N9	/	22.7	4.7	4.5	/	20.6	3.7	/	/	/	/	/	/	delivered to SHINE
N10	/	24.0	4.4	4.7	4.6	27.0	4.5	4.4	4.2	/	/	/	/	delivered to SHINE
N11	**CAV5**	31.3	5.1	5.4	5.4	27.2	3.8	4.0	3.9	26.5	23.8	4.0	4.0	in CM1
N12	**CAV4**	29.7	4.4	4.6	4.6	28.0	4.0	4.1	4.0	27.7	24.5	4.0	4.0	in CM1
N13	**CAV1**	24.0	4.4	4.5	4.4	23.3	4.2	4.4	4.3	26.6	24.1	3.7	3.3	in CM1
N14	**CAV3**	25.9	4.3	4.4	4.3	25.7	3.0	3.1	3.0	24.6	26.9	3.4	3.5	in CM1
N15	**CAV7**	26.1	5.2	5.0	5.0	25.1	4.0	3.9	3.8	21.7	21.3	2.6	/	in CM1
N16	**CAV8**	29.1	4.3	4.2	4.0	29.1	4.3	4.3	4.1	25.9	25.8	4.4	4.7?	in CM1
N17	/	/	/	/	/	30.0	3.4	/	/	/	/	/	/	for further study
N18	**CAV2**	/	/	/	/	32.0	2.6	2.5	2.5	19.2	18.5	2.7	/	in CM1
Average all		**26.0**	**4.5**	**4.6**	**4.5**	**25.7**	**3.8**	**3.8**	**3.7**	/	/	/	/	**Average Q0 from total dynamic heat load: 3.8E10@16 MV/m, 3.6E10@21 MV/m**
Average of CAVs in CM1		**27.5**	**4.5**	**4.6**	**4.6**	**26.7**	**3.7**	**3.7**	**3.6**	**24.7**	**23.6**	**3.6**	**3.8?**	

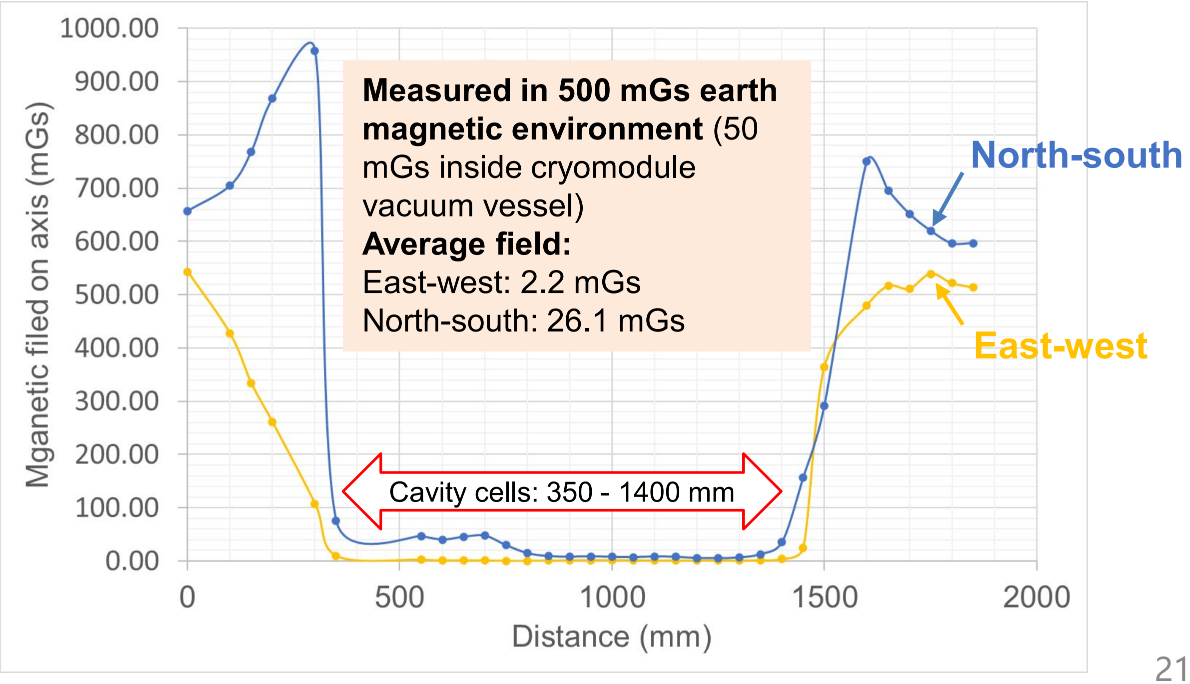
Magnetic Field Control

Vacuum vessel degaussing



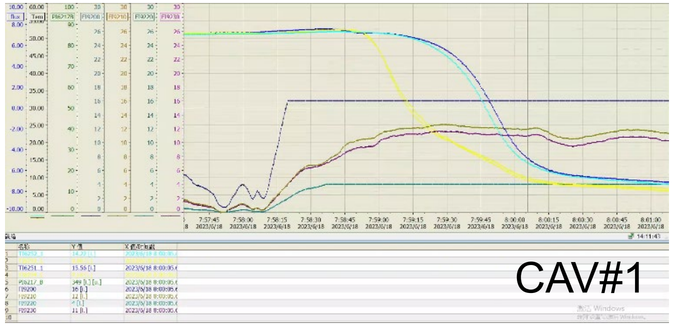
Double-layer magnetic shield

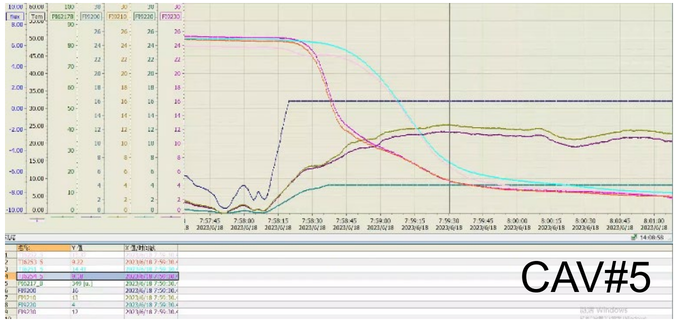




Fast / Slow Cooldown

> 40 g/s





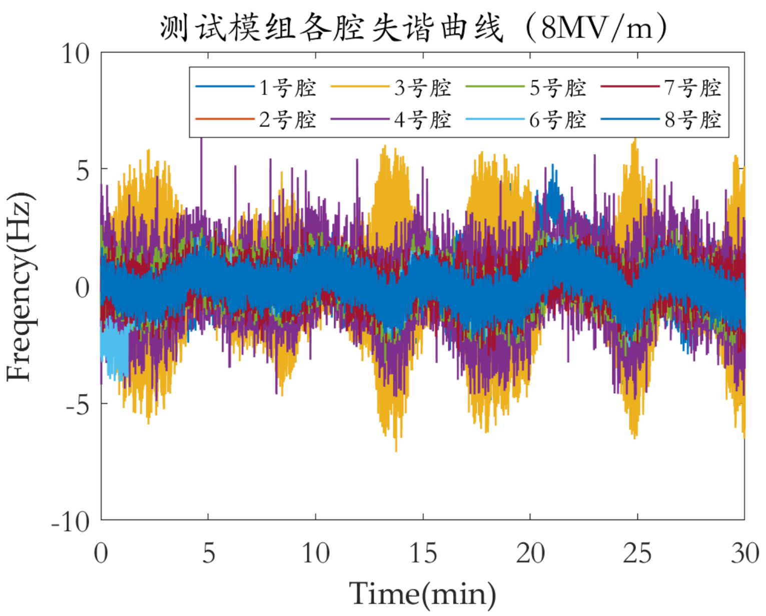
8 ~ 12 g /s

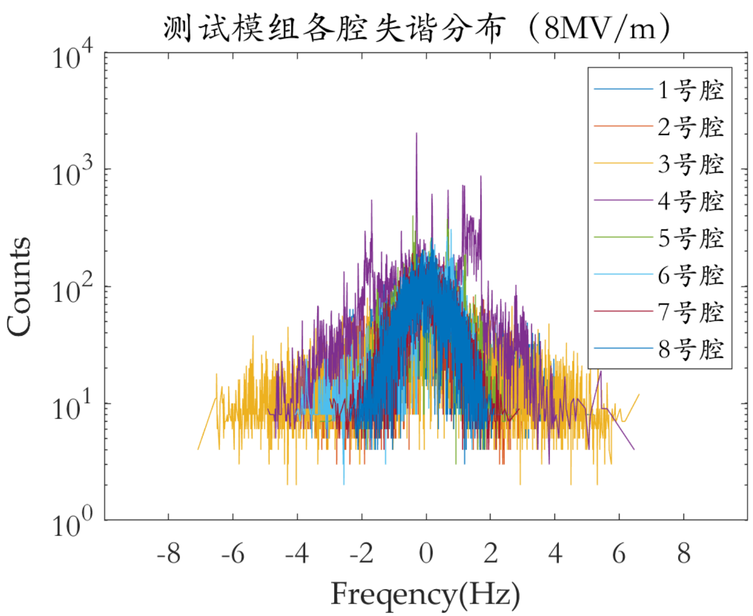
Microphonics

- **Spec: Δf (Peak to Peak) < 10 Hz**
- **Test result：**
  - ± 4 Hz （3 MV/m open loop, eight cavities）
  - ± 7 Hz （8 MV/m open loop, eight cavities）
  - ± 4 Hz （16 MV/m closed loop, two cavities）

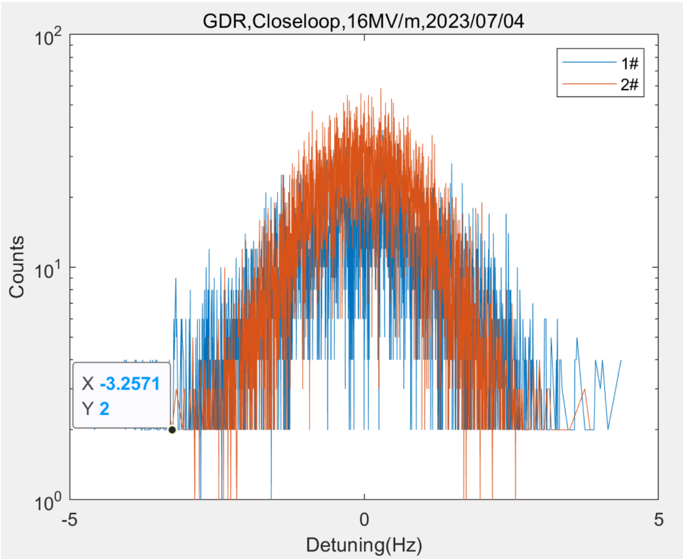
GDR open or closed, calculate detuning with the phase:

$$\Delta f = (f_0/2Q_L)\cdot\tan(\Delta\varphi)$$





Open loop @ 8 MV/m



Closed loop @ 16 MV/m