

# Commissioning of the RF System for HEPS

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# Outline

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## **HEPS: High Energy Photon Source**

- Introduction to HEPS & its RF system
- Hardware development highlight
- Installation, commissioning & operation
- Summary



# HEPS in general

- **Project outline**

- A diffraction-limited SR light source (4<sup>th</sup>-gen)
- **1<sup>st</sup> high-energy SR light source in China**
- **Location:** Huairou Science City, Beijing
- **Construction time:** 06.2019 – 12.2025
- Commissioned in 10.2025, in pilot user op.



[1] Y. Dong *et al.*, *IPAC2026*, TUI2M02.

[2] Y. Jiao *et al.*, *IPAC2026*, TUP2601, TUP2602.

TUI2M02

- **HEPS accelerator complex**

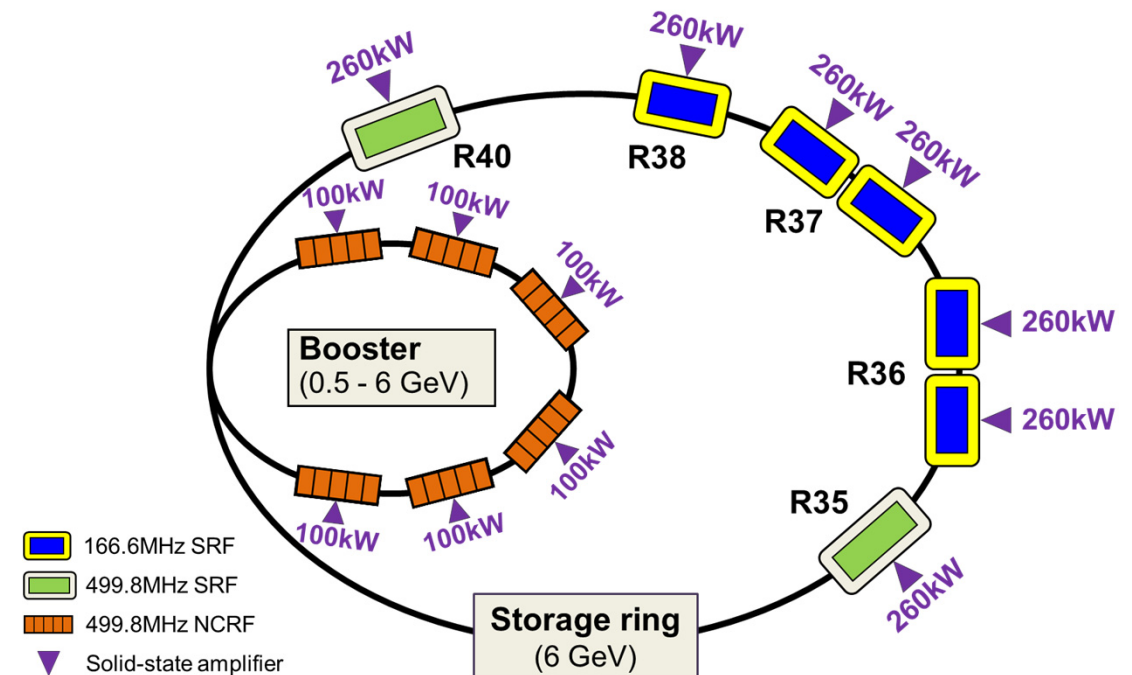
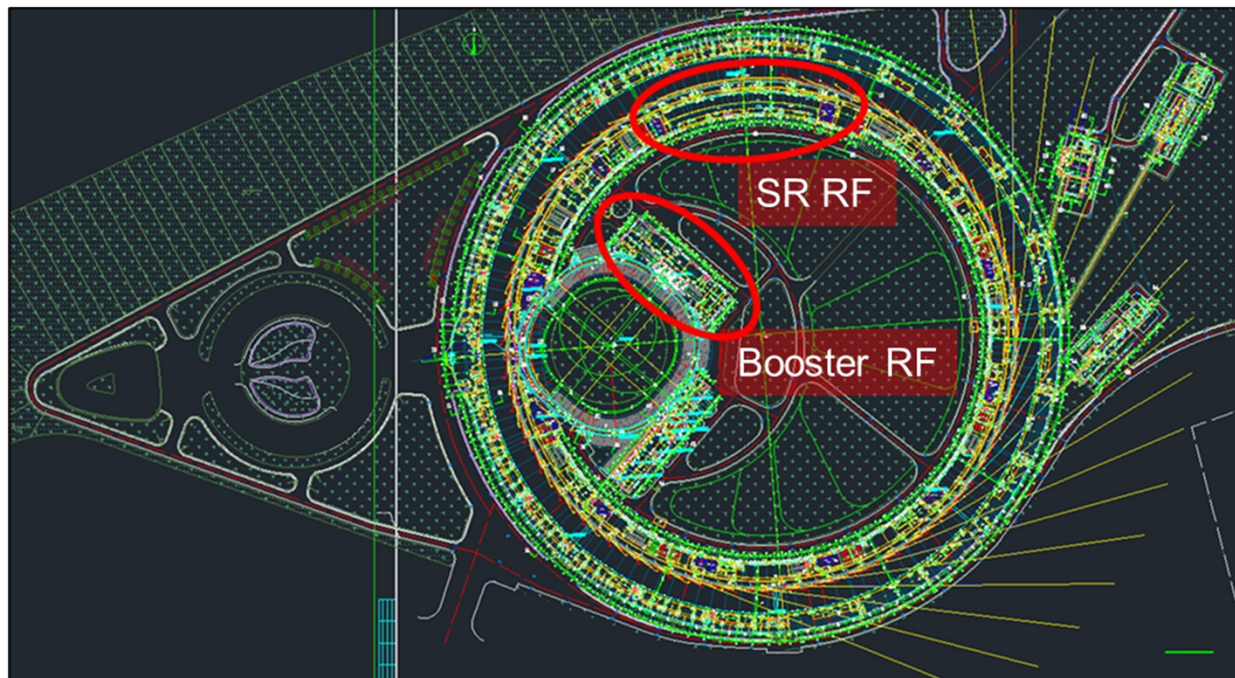
- Linac: 500 MeV, 49 m
- Booster: 500 MeV to 6 GeV, 1 Hz, 454 m
- Storage ring: 6 GeV, top-up, 1360 m

Parameter	Value	Unit
Beam energy	6	GeV
Circumference	1360.4	m
Lattice type	Hybrid 7BA	
Hori. Natural emittance	34.2	pm·rad
Brightness	$> 1 \times 10^{22}$	*
Beam current	200	mA
Injection mode	Top-up	-

\*: phs/s/mm<sup>2</sup>/mrad<sup>2</sup>/0.1%BW

# Main features of HEPS RF system

- Double-frequency RF system: 166.6 MHz + 499.8 MHz
- Active harmonic RF for bunch lengthening, compatible w/ on-axis swap-out (baseline) & on-axis accumulation injections (in the future)
- Superconducting RF for storage ring, normal-conducting RF for booster ring
- Heavy damping of higher order modes for storage-ring SRF cavities
- Solid-state amplifiers (SSAs) for all RF transmitters, digital low-level RF control

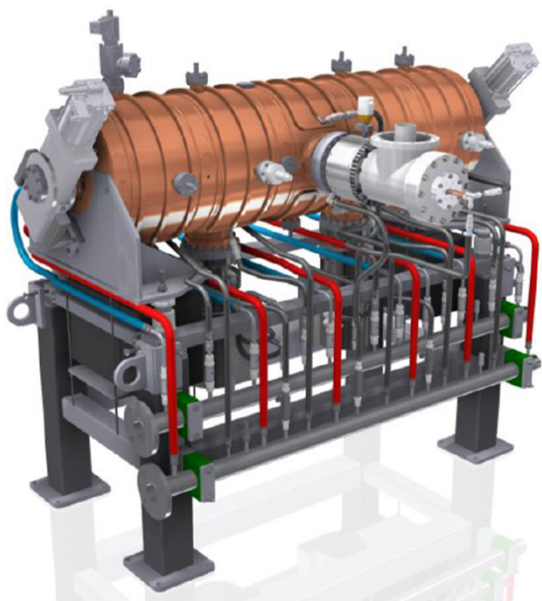


P. Zhang *et al.*, "Radio-frequency system of HEPS", *Radiation Detection Technology and Methods* 7, 159-170 (2023).

# Main RF parameters

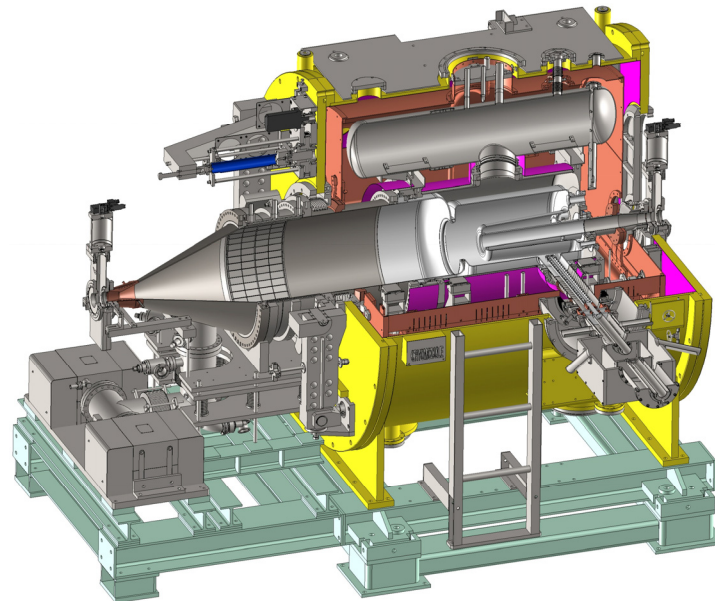
Parameter	Booster	SR (main)	SR (HC)	Unit
RF frequency	499.8	166.6	499.8	MHz
Total RF voltage	2 – 8	5.4	0.91	MV
Cavity technology	Normal-conducting	Superconducting	Superconducting	-
Cavity type	5-cell	$\beta=1$ quarter-wave	1-cell elliptical	-
Technology readiness	Mature product	In-house new dev.	In-house dev.	-
No. of cavities	6	5	2	-
RF voltage per cavity	1.35 (op.) 1.9 (design)	1.2 (op.) 1.5 (design)	0.91 (op.) 1.75 (design)	MV
RF power per cavity (max)	70 (61 cav. + 9 beam)	191	105	kW
No. of transmitters	6	5	2	-
RF power per transmitter	100 (c.w.)	260 (c.w.)	260 (c.w.)	kW
Transmitter technology	SSA	SSA	SSA	-
LLRF control stability (p-p)	$\pm 1\%$ , $\pm 1^\circ$	$\pm 0.1\%$ , $\pm 0.1^\circ$	$\pm 0.1\%$ , $\pm 0.1^\circ$	-
LLRF technology	Digital LLRF (in-house dev.)			-

# RF cavities



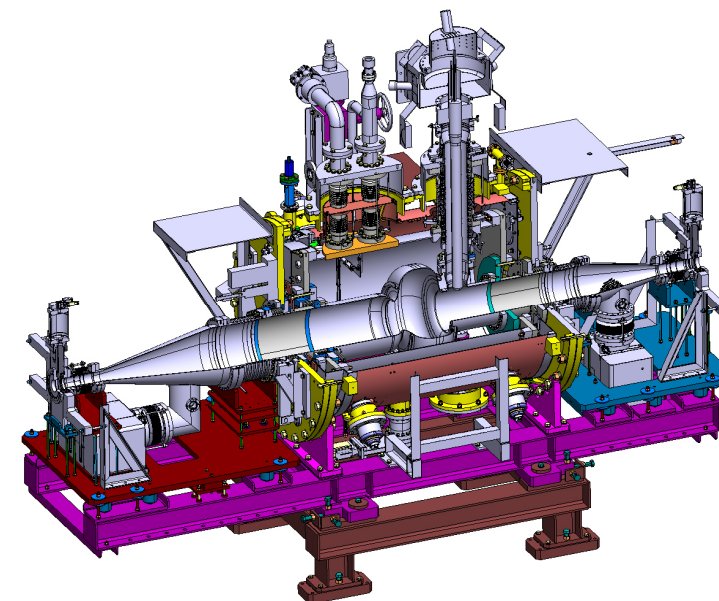
500MHz PETRA-type  
5-cell copper cavity  
(Booster)

Procured from RI  
(Minor modifications)



166MHz quarter-wave  
 $\beta=1$  SRF cavity  
(Storage ring)

In-house development  
(**New design**)



500MHz KEKB-type  
1-cell elliptical SRF cavity  
(Storage ring)

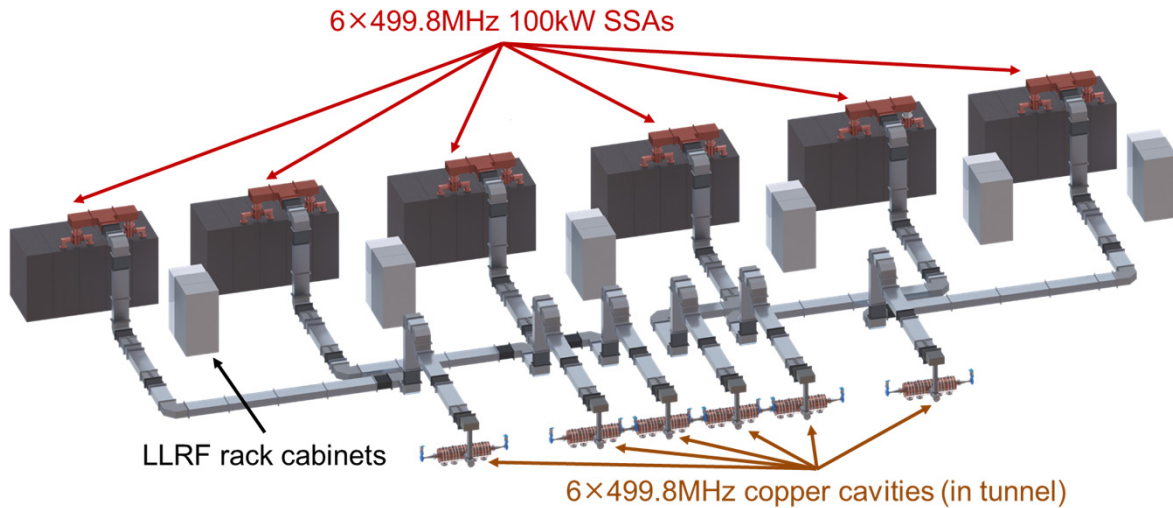
In-house development  
(Mechanically-improved)

- [1] T. Huang *et al.*, “Design modification and high-power tests of the 500 MHz normal-conducting 5-cell cavities for HEPS”, *JINST* 19, P06031 (2024).
- [2] P. Zhang *et al.*, “Development and high-current cw operation of 166.6 MHz high-power, HOM-damped  $\beta = 1$  quarter-wave SRF modules at HEPS”, *Phys. Rev. Accel. Beams* 29, 032002 (2026).
- [3] H. Zheng *et al.*, “Development and tests of the 499.8 MHz srf cryomodules for HEPS”, *JINST* 19, P10031 (2024).

# High-power RF

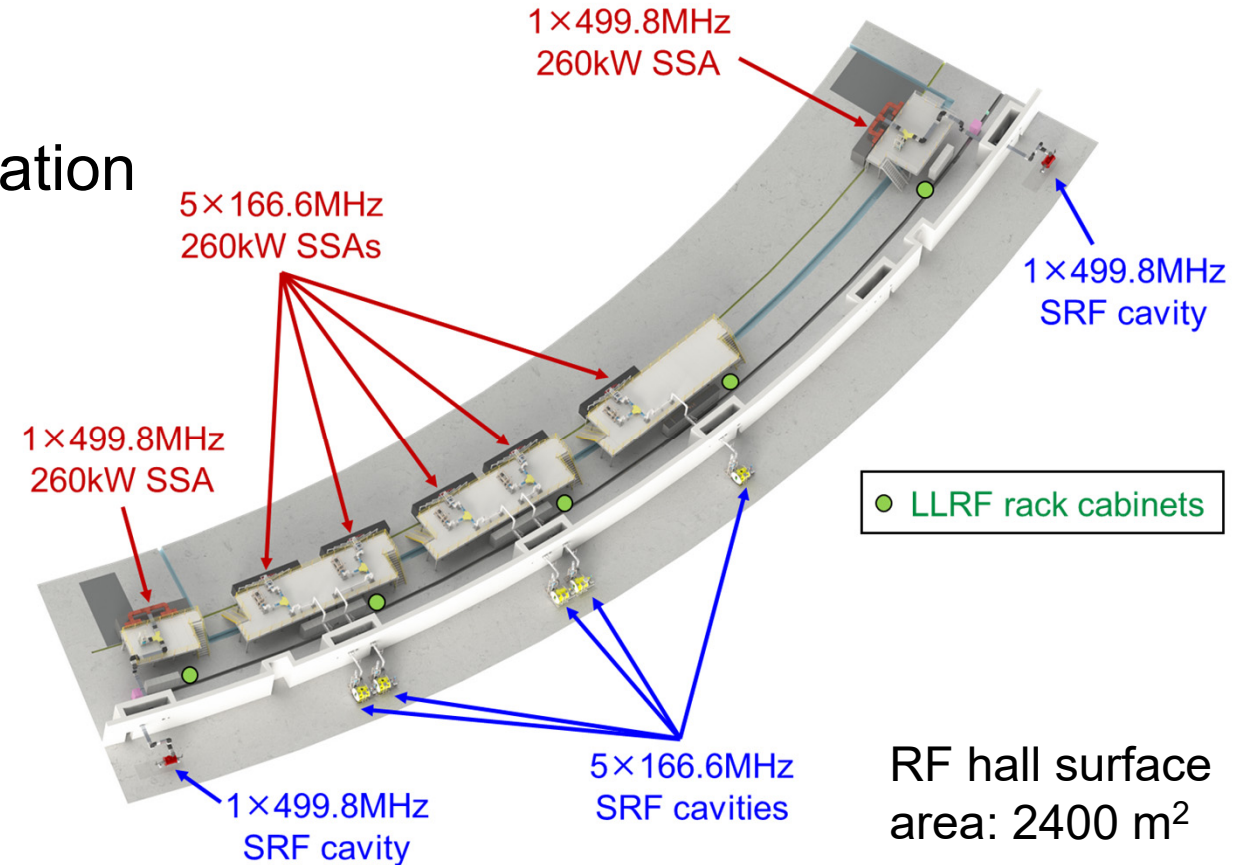
- Transmitter type: SSA
- Power transmission
  - 9-3/16" coaxial rigid lines for 166MHz
  - WR1800 rectangular waveguide for 500MHz
- High-power circulator for each SR RF station

## Booster RF



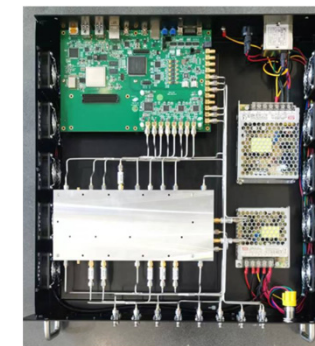
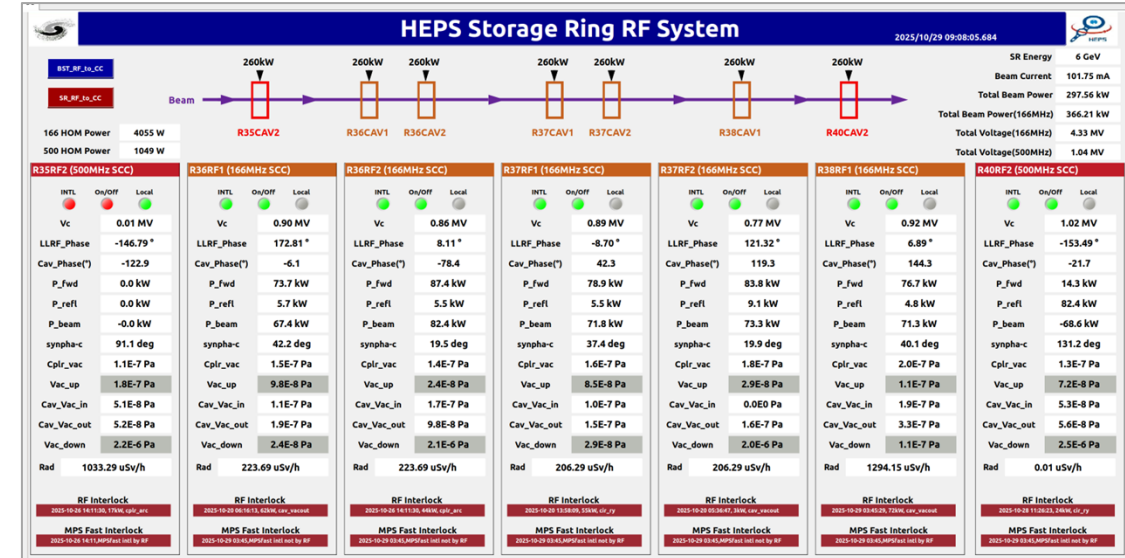
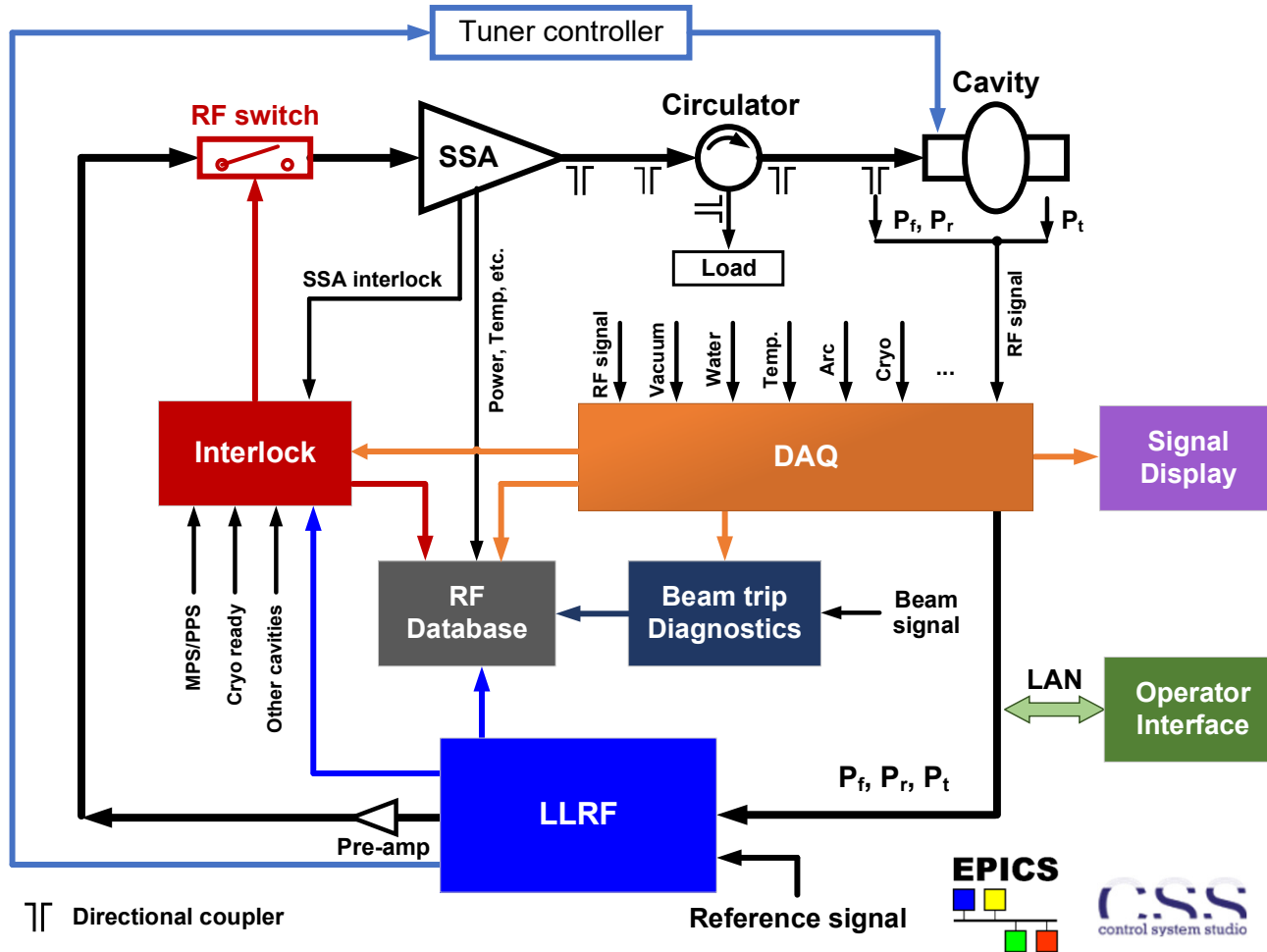
RF hall surface area: 1600 m<sup>2</sup>

## Storage-ring RF



# RF control

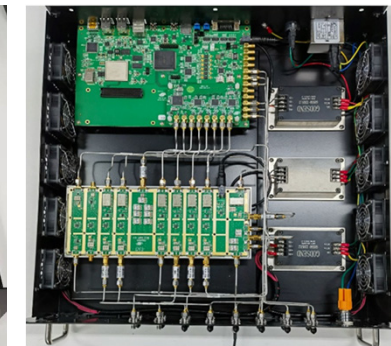
- In-house development: LLRF, RF interlock, Beam trip diagnostics, Operator interface, RF local EPICS database



LLRF



RF interlock

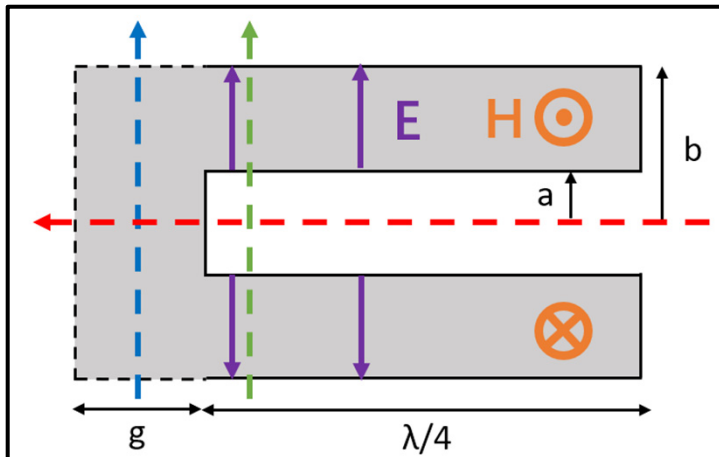


Beam trip diag.

# **Hardware development highlight**

# 166MHz cavities: demanding requirements

- **Low frequency SRF: 166.6MHz,  $\beta=1$ , superconducting cavities**
- High current: 200mA  $\rightarrow$  **heavy HOM damping:  $Q_L < 1000$**
- **High RF power: 190kW per cavity**
- **Compact:** limited straight section space (6 meters for 2 cavities)
- **Reasonable cryogenic heat load and acceptable loss factor**
- Stable operation (user facility): **large margin** in RF parameters



- QWR, unconventional acceleration path
- New application of SC QWRs as main acc. cavities

→ **Low- $\beta$  QWR**

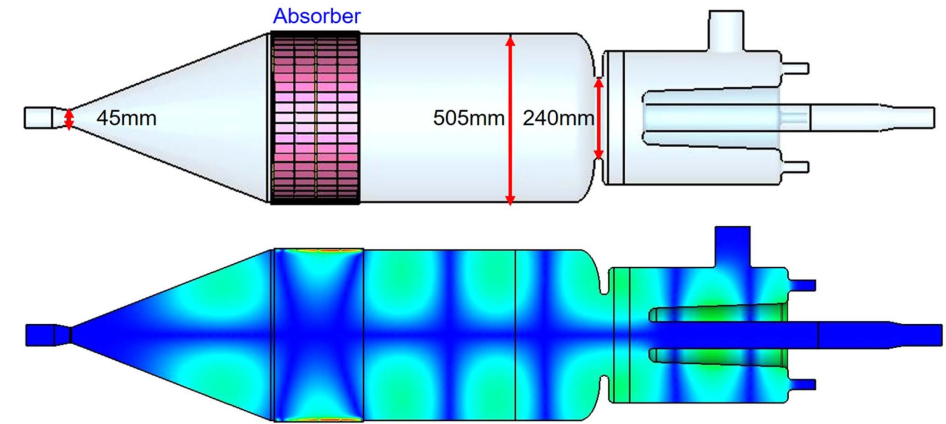
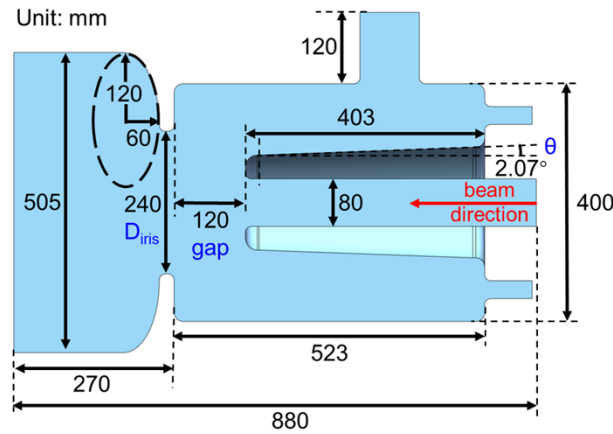
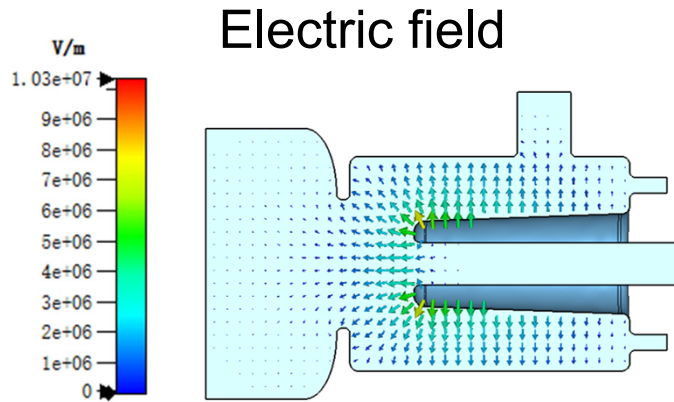
→ **Crab cavity**

→ **166MHz  $\beta=1$**

**First of its kind**

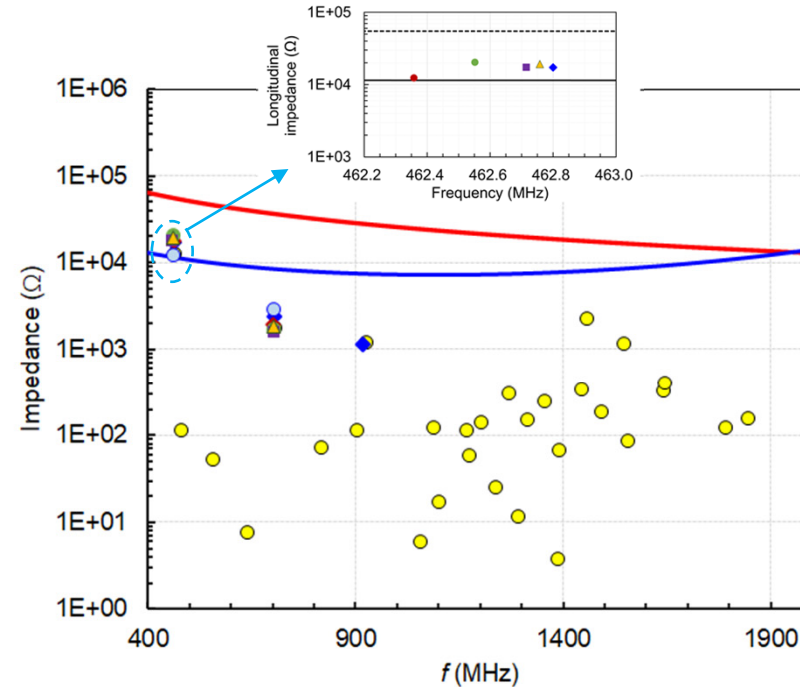
**New development**

# HOM-damped 166MHz $\beta=1$ SRF QWR



M2, 464 MHz, R/Q = 45  $\Omega$ , Q = 576

Parameter	Value	Unit
RF frequency	166.6	MHz
Operating temperature	4.4	K
Design voltage (Vc_d)	1.5	MV
Operating voltage (Vc_op)	1.2	MV
E <sub>peak</sub> at Vc_op	32	MV/m
B <sub>peak</sub> at Vc_op	50	mT
R/Q (=V <sup>2</sup> /ωU)	139	$\Omega$
Q0 at Vc_d (VT)	>1e9	-
Q0 at Vc_op (HT)	>5e8	-
External Q	5e4	-
Nominal input power	170	kW
Lowest mechanical mode	108	Hz



- Zth\_1C(no\_HC)
- Zth\_1C(w\_HC)
- ZL\_SingleCavity (Simu)
- ◆ ZL\_SingleCavity (CM1\_meas at RT)
- ◆ ZL\_SingleCavity (CM1\_meas at 4K)
- ZL\_SingleCavity (CM2\_meas at RT)
- ZL\_SingleCavity (CM3\_meas at RT)
- ▲ ZL\_SingleCavity (CM5\_meas at RT)
- ZL\_SingleCavity (CM4\_meas at RT)

Average HOM power  
7.3 kW / cavity  
(high-charge mode)

2.6 V/pC ( $\sigma_z=5$  mm)  
0.8 V/pC ( $\sigma_z=30$  mm)

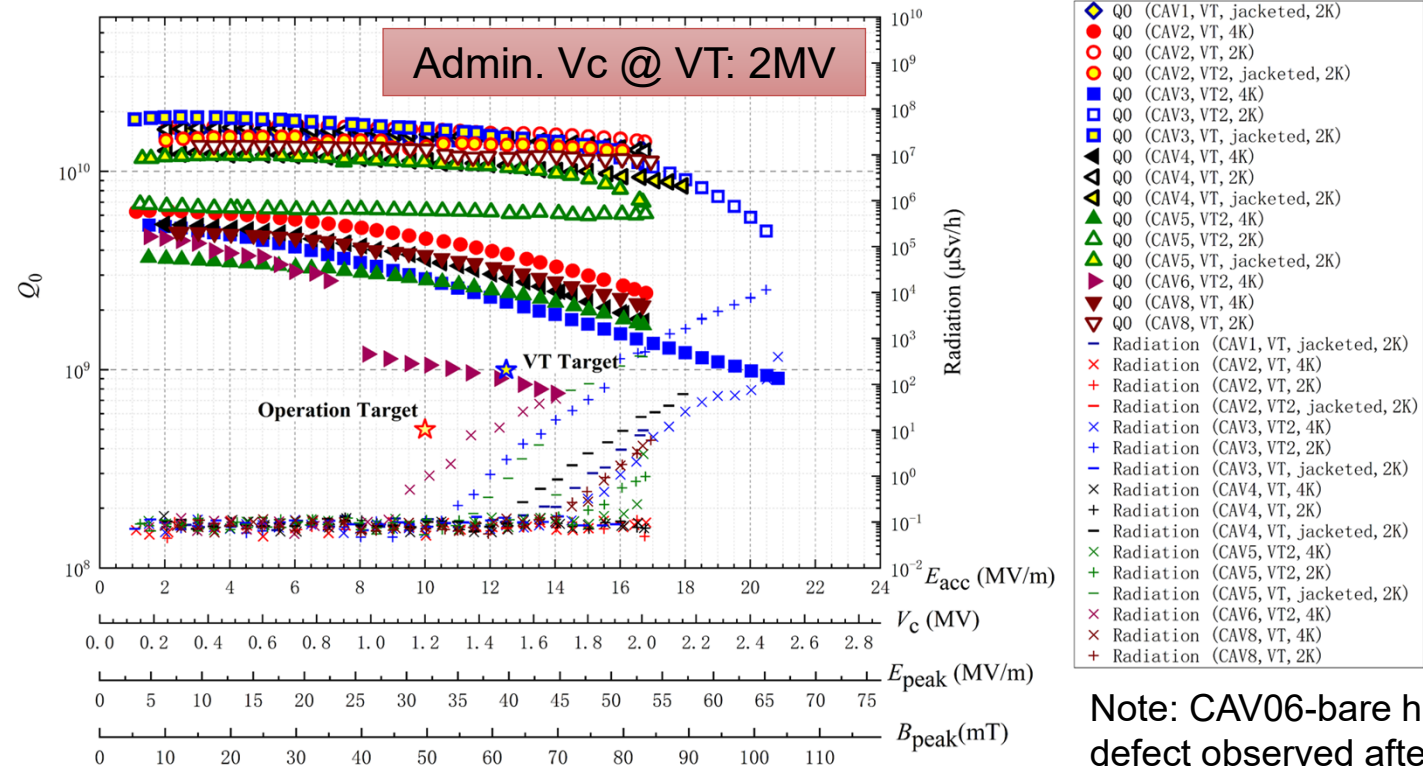
[1] L. Guo *et al.*, *Rev. Sci. Instrum.* 95, 074702 (2024).  
[2] H. Zheng *et al.*, *IEEE-TAS* 34, 3500309 (2024).

# 166MHz SRF cavities: VT performance

- Established BCP recipes for bare cavities, no chemistry required for jacketed cavities, excellent cryogenic performance demonstrated, optimized procedure ensuring no field-emission on onset & considerably reduced multipacting
- Series cavities outperformed qualification criteria**



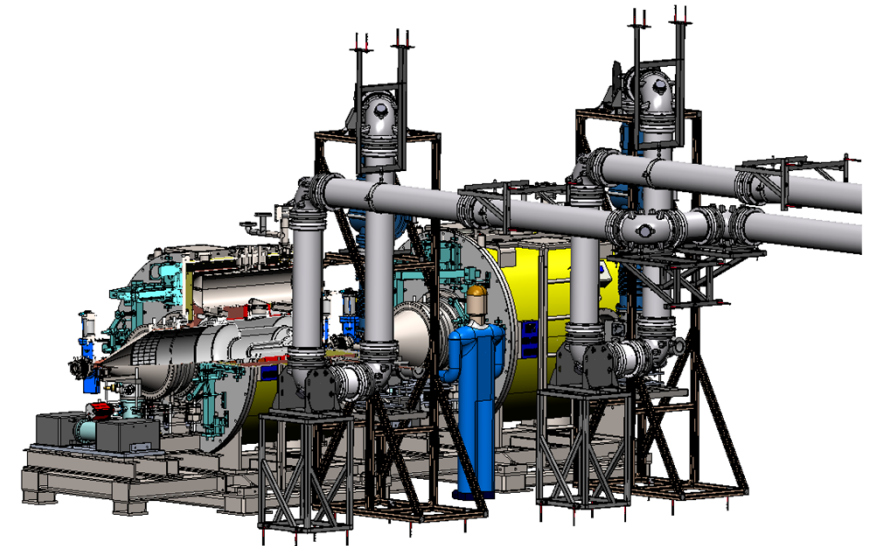
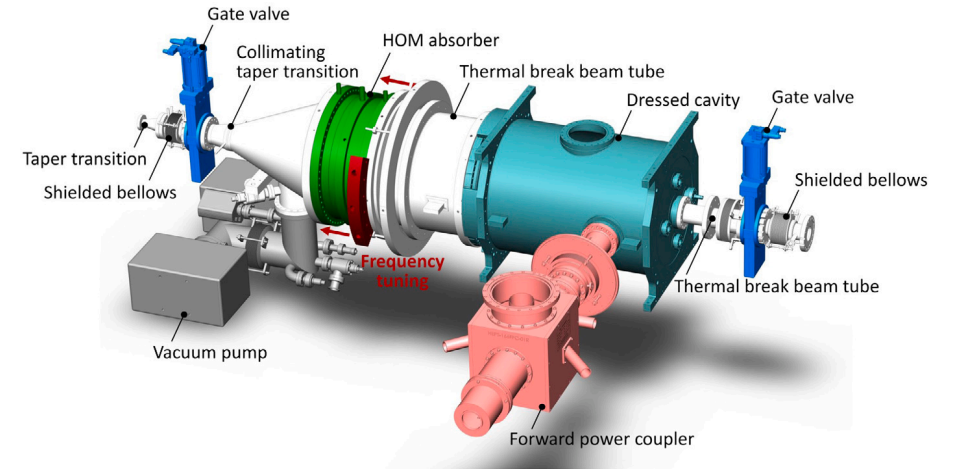
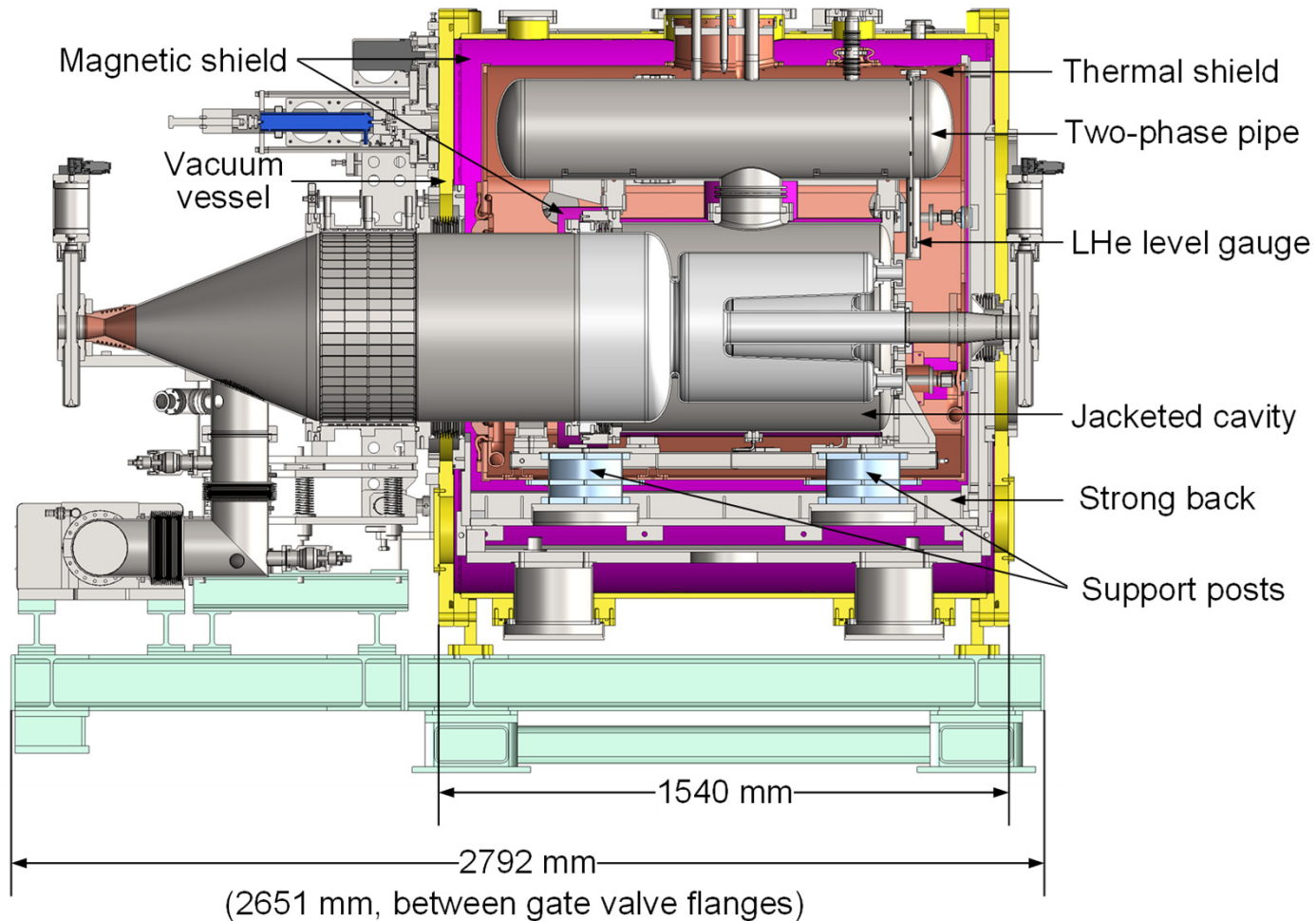
Vertical test results of 166MHz SRF cavities



[1] P. Zhang, et al., *Rev. Sci. Instrum.* 90, 084705 (2019). [2] L. Guo, et al., *Rev. Sci. Instrum.* 95, 074702 (2024).

# 166MHz SRF module

**Compact:** limited straight section space (6 meters for 2 cavities), accessibility for maintenance



[1] P. Zhang, *et al.*, *Phys. Rev. Accel. Beams* 29, 032002 (2026).

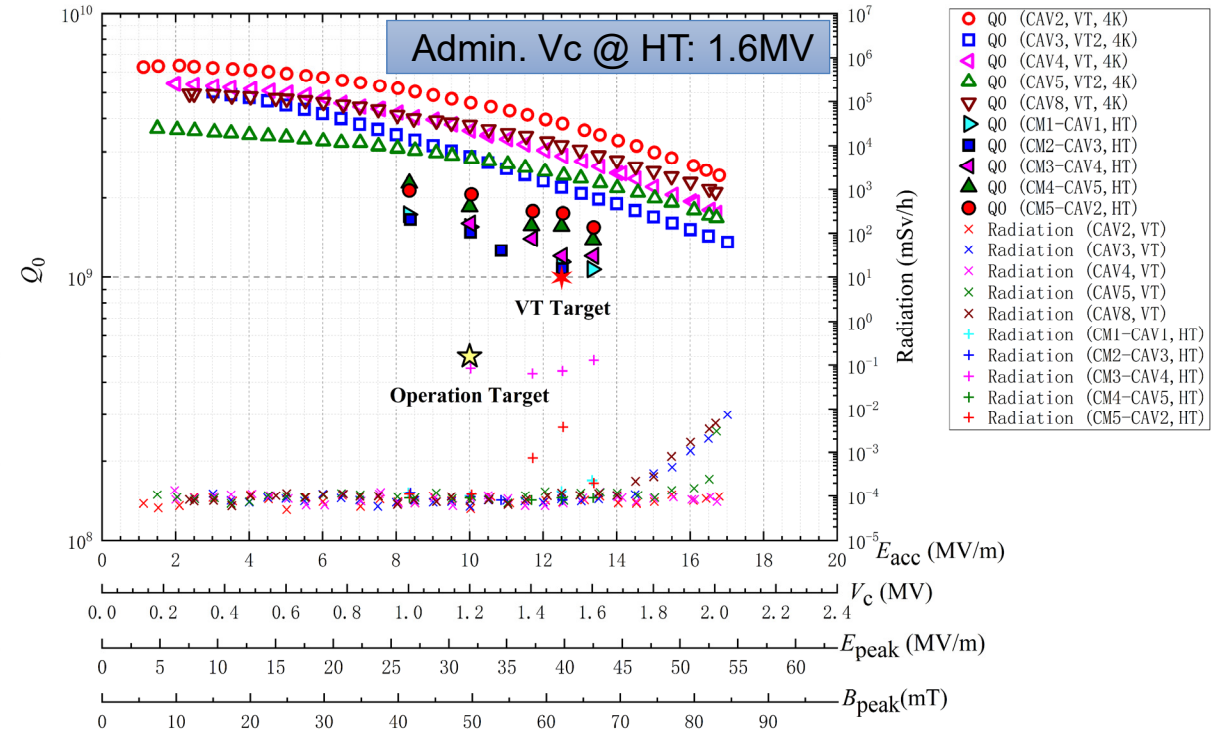
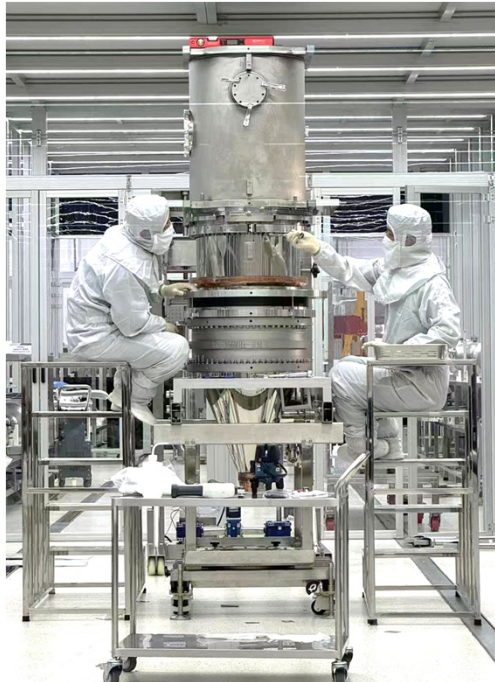
[2] X. Zhang, *et al.*, *NIM-A* 1059, 168972 (2024). [3] R. Han, *et al.*, *NIM-A* 1070, 170000 (2025).

# 166MHz SRF modules: HT performance

Parameter	Spec.	Test	Unit
Vc_op	≥ 1.2	1.5~1.6	MV
Q <sub>0</sub> @ Vc_op	≥ 5e8	1.5~2.1e9	-
Radiation @ Vc_op	< 500	0.08~84	μSv/h
Static HL @ 4K	< 40	33~36	W
Dynamic HL @ 4K	< 21	5~7	W

- **Comfortable margin for all CMs**
  - RF voltage: > 25%
  - Quality factor: a factor of 3~4
  - FE radiation: no FE ~ 1/6 of spec. thresh.

166MHz cavities & CMs: HT and VT results at 4K



# **Installation & RF commissioning**

# Milestones

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## Booster ring

- **Oct. 2023, Booster RF system commissioned**
- **Nov. 2023, Booster ring commissioned**

## Storage ring

### □ Stage 1 commissioning

- Jul. 2024, Storage-ring RF system (stage 1) commissioned
- **Aug. 2024, HEPS achieved 25mA current in storage ring**

### □ Stage 2 commissioning

- **Aug. 2025, Storage-ring SRF system commissioned**
- **Sep. 2025, 166MHz+500MHz SRF cavities accelerated 100mA beam**
- **Oct. 2025, HEPS commissioned and passed acceptance tests**
- Since Nov. 2025, HEPS in pilot operation & machine study

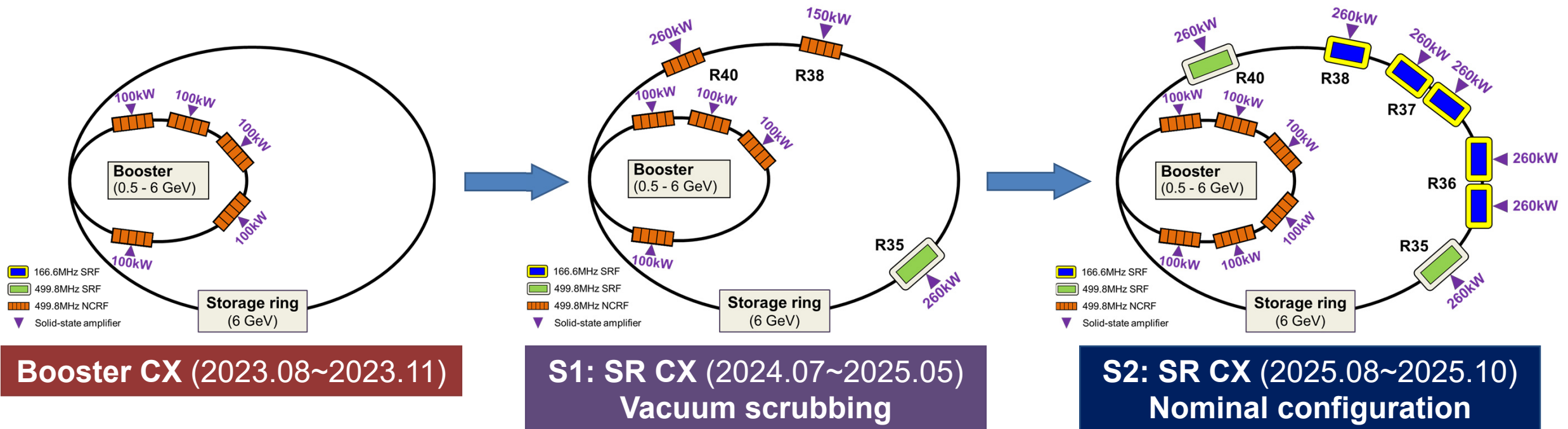
# Staged RF installation & commissioning

- **Commissioning strategy (modified, pragmatic approach)**

- S1: Initial beam commissioning using 500MHz “NCCs + SCC” RF configuration (vacuum scrubbing)
- S2: Install remaining SRF cavities as soon as they are ready w/ lower accum. beam dose (~41 A·h)

- **Purpose**

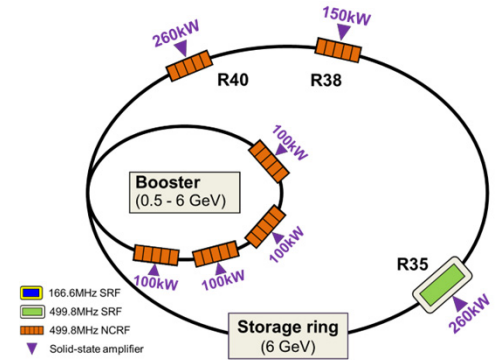
- **Vacuum scrubbing of the SR:** Large outgassing from sync. light irradiation on vacuum chambers
- **Minimize contamination risk:** Avoid exposing SRF cavities to vacuum incidents and gas absorption
- **Allow more development time:** Reserve additional time for the new 166MHz SRF cavities



# SR commissioning: stage 1 (07.2024~05.2025)

- Total RF voltage: 3.85MV
- Total beam power: 159kW, **max. beam current: 60mA**
- Stable op. for NCC (<90kW), limit for SCC (<180kW, <1.75MV)

2×500MHz NCCs + 1×500MHz SCC

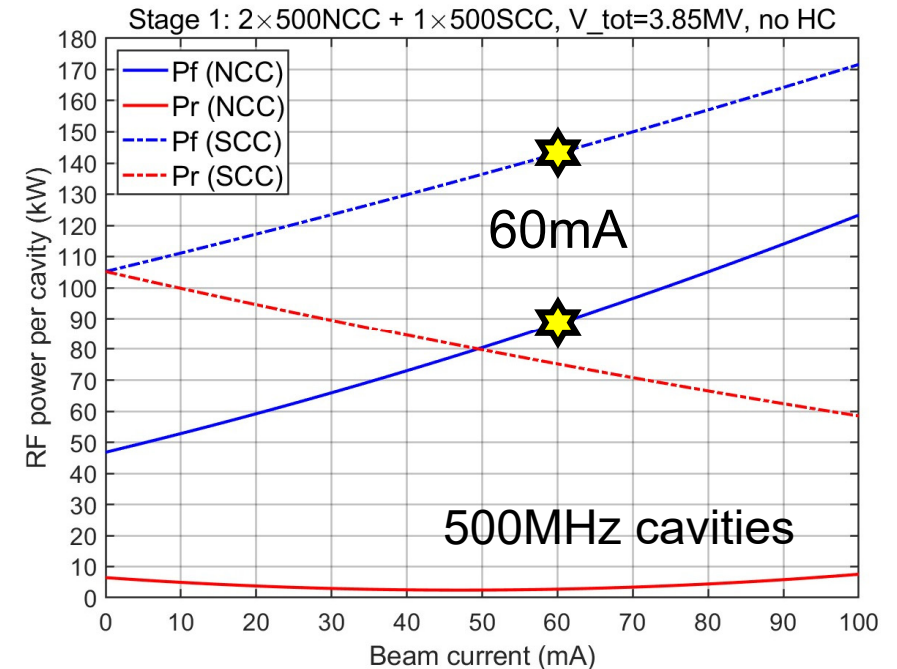


High reflection

## Vacuum threshold (Stage 1)

- 500SCC\_cav < 1e-6 Pa, 500SCC\_FPC < 1e-6 Pa
- 500NCC\_cav < 3e-5 Pa

SR cavity parameter	500NCC	500SCC
No. of cavities	2	1
Rf frequency (MHz)	499.8	499.8
Vc per cavity (MV)	1.1	1.65
Cavity wall loss	41 kW	~0 kW
Coupling	$\beta=2$	$Q_e=8e4$
Beam current	<b>60 mA</b>	
U0 (w/o IDs)	<b>2.64 MeV</b>	
Forward power per cavity	<b>88 kW</b>	143 kW
Reflected power per cavity	3 kW	<b>75 kW</b>
Beam power per cavity	44 kW	68 kW

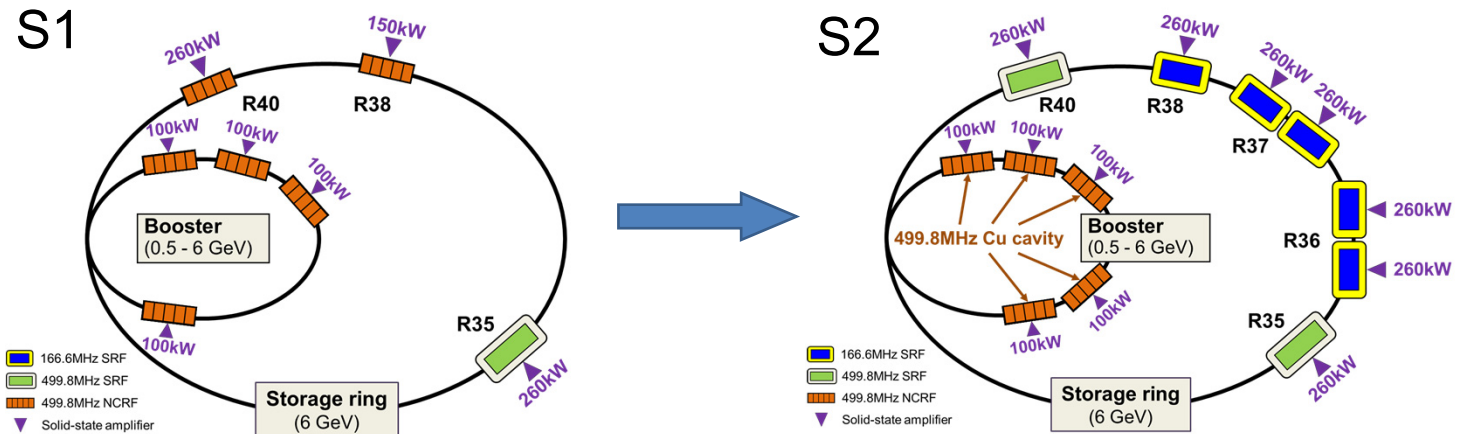
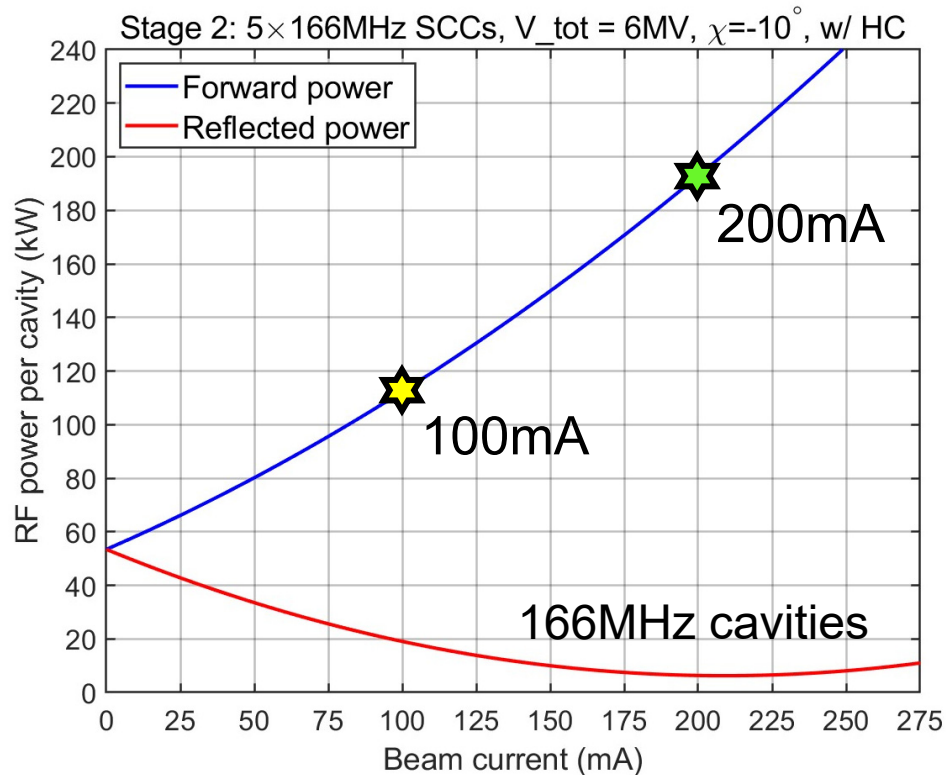


# SR commissioning: stage 2 (since 08.2025)

## Equipment relocation & install.

- Relocate: 2×NC cavities (SR→BS)
- Relocate: 1×150kW SSA (SR→BS)
- Installed: 5×166MHz SRF cavities in SR to support 200mA current

Parameter	CX stage 1	CX stage 2	Nominal op.
Time period	2024.07~2025.05	2025.08~present	2026 onward
Booster	4×500NCCs	6×500NCCs	6×500NCCs
SR	2×500NCCs 1×500SCC	5×166SCCs 1×500SCC	5×166SCCs 1×500SCC
Max. Ib (U0)	<b>60mA</b> (2.64MeV)	<b>100mA</b> (4.14MeV)	<b>200mA</b> (4.14MeV)
RF voltage	500SCC: 1.65MV 500NCC: 1.10MV Total: 3.85MV	166SCC: 1.2MV 166SCC_ttl: 6MV 500SCC_ttl: 0.9MV	166SCC: 1.2MV 166SCC_ttl: 6MV 500SCC_ttl: 0.9MV
RF power	500SCC: 143kW 500NCC: 88kW Total: 319kW	166SCC: 112kW 166SCC_ttl: 562kW HC_Pb: -52kW	166SCC: 193kW 166SCC_ttl: 964kW HC_Pb: -104kW



# RF installation

## Booster RF



## Storage-ring RF



# Transportation of SRF modules

- Maximum recorded shock: **< 0.5g** in all directions for all 166MHz modules during the entire transportation & installation process
- All cavities transported **under cavity vacuum** via active pumping, **vacuum integrity well preserved**

Loading on truck



Freight transport (air-suspension)



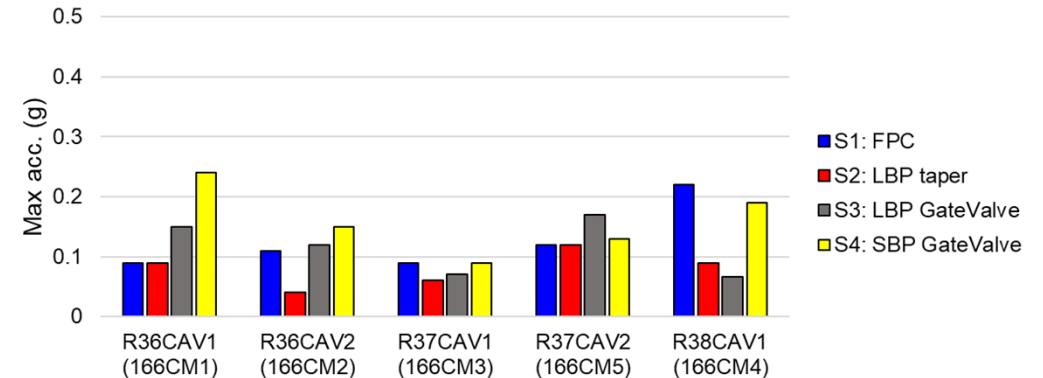
Unloading at tunnel entrance



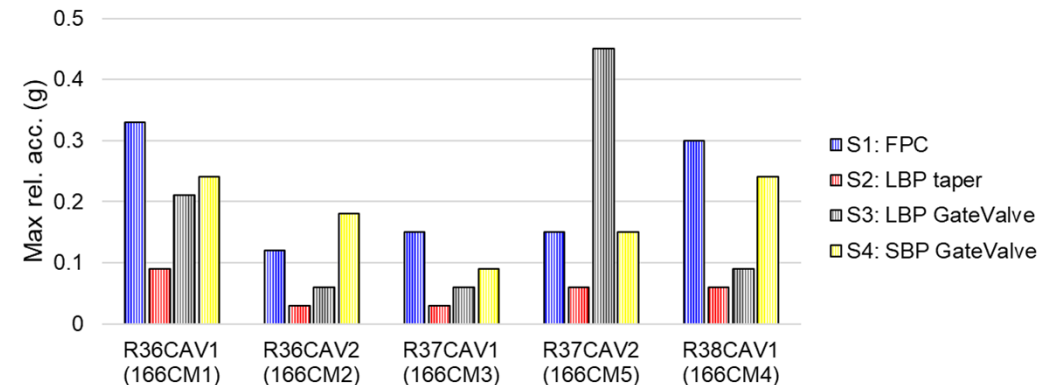
Move to final position



Transportation of 166MHz modules from PAPS to HEPS:  
maximum recorded shock (horizontal)



Transportation of 166MHz modules from PAPS to HEPS:  
maximum recorded shock (vertical)



# Vacuum connections in the tunnel

- **Cleanroom practices implemented** during beamline connections with adjacent sectors to minimize contamination to SRF cavities, RF WP responsible with Vacuum WP participated in
- **First cavity valve opening (300K)** on Jul 15, 2025: All cavities at 300K, closed after a few mins
  - Before:  $10^{-7}$  Pa (cavity),  $10^{-7}$  Pa (vac. chamber); Upon opening: worst vacuum  $1.6 \times 10^{-5}$  Pa; Recovery: ~2hrs
- **Second cavity valve opening (4K)** before beam CX on Aug 11, 2025
  - Before:  $10^{-8}$  Pa (cavity),  $10^{-9}$  Pa (vac. chamber); Upon opening: worst vacuum  $5 \times 10^{-7}$  Pa; Recovery: a few mins



Purge w/ dust-free nitrogen

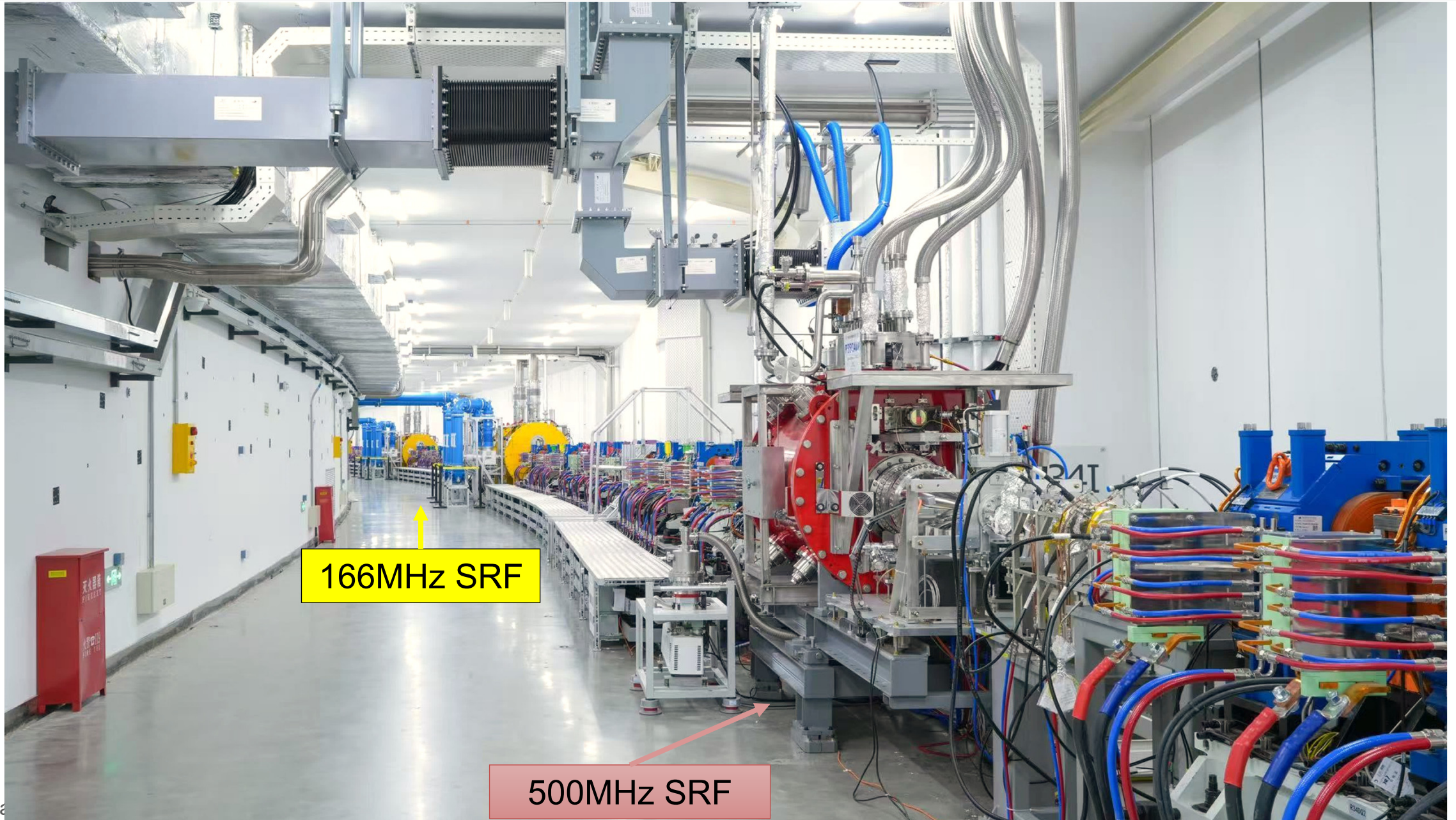


Vacuum connection

# 166MHz SRF modules in the tunnel

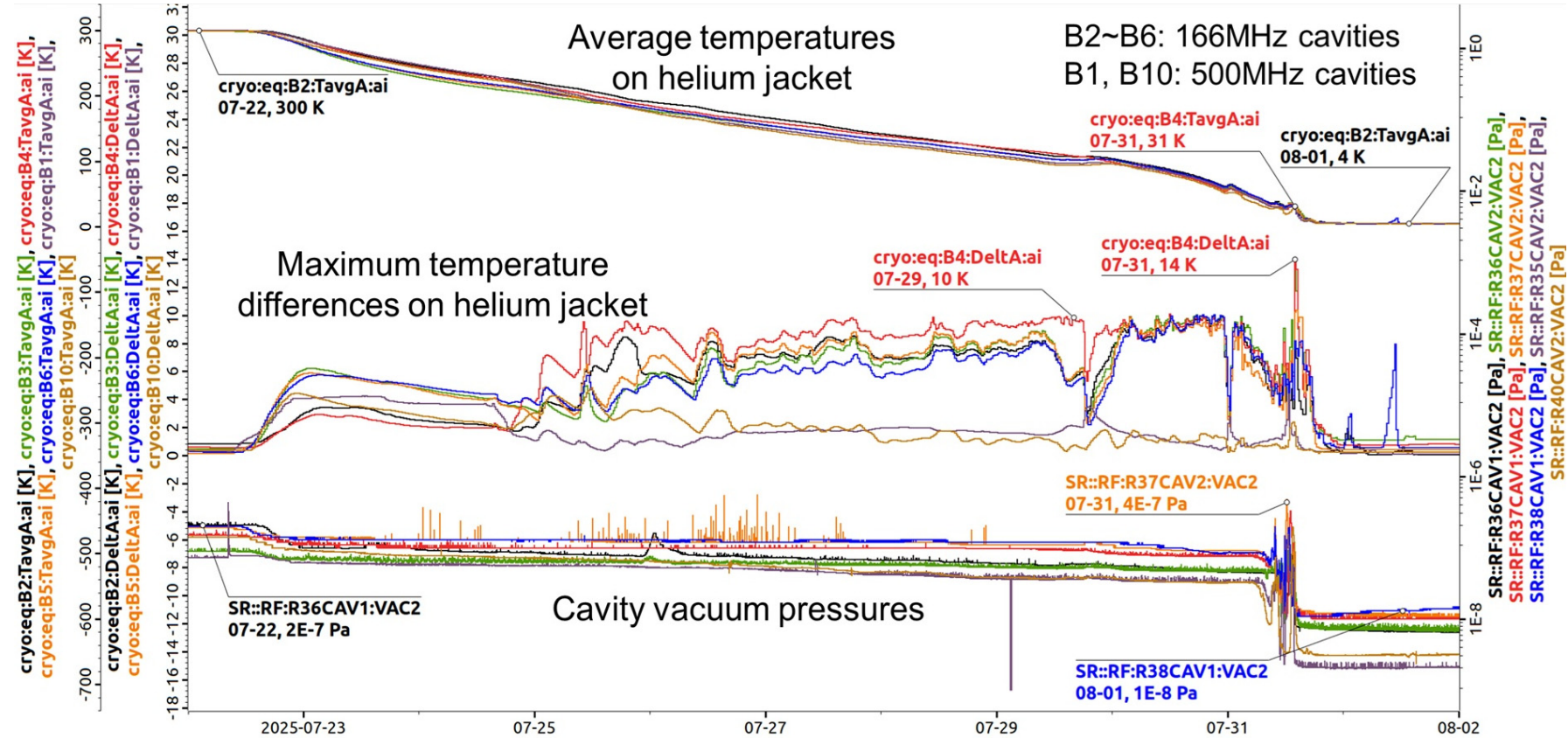
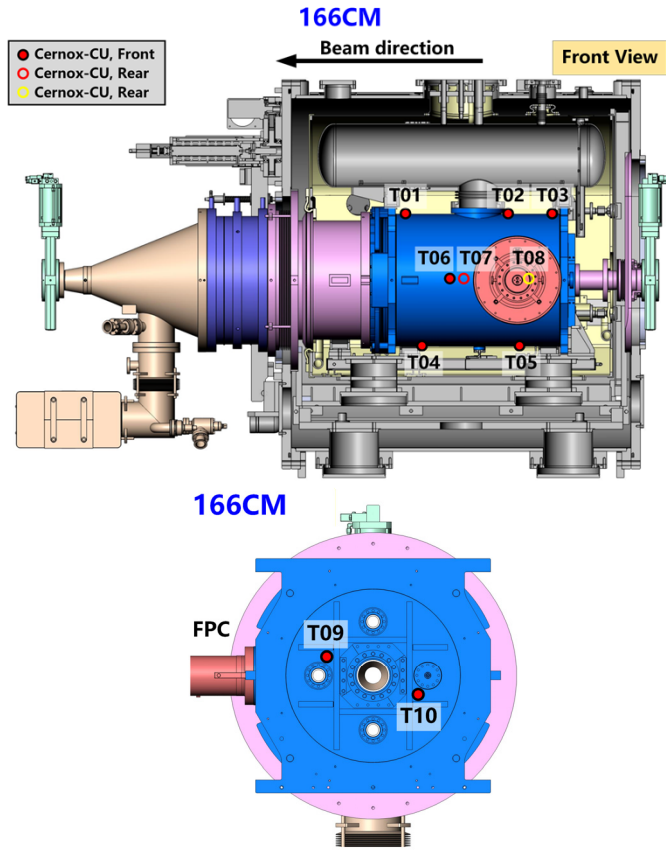


# 500MHz SRF module in the tunnel



# Frist cooldown in the tunnel (11 days, 7CMs)

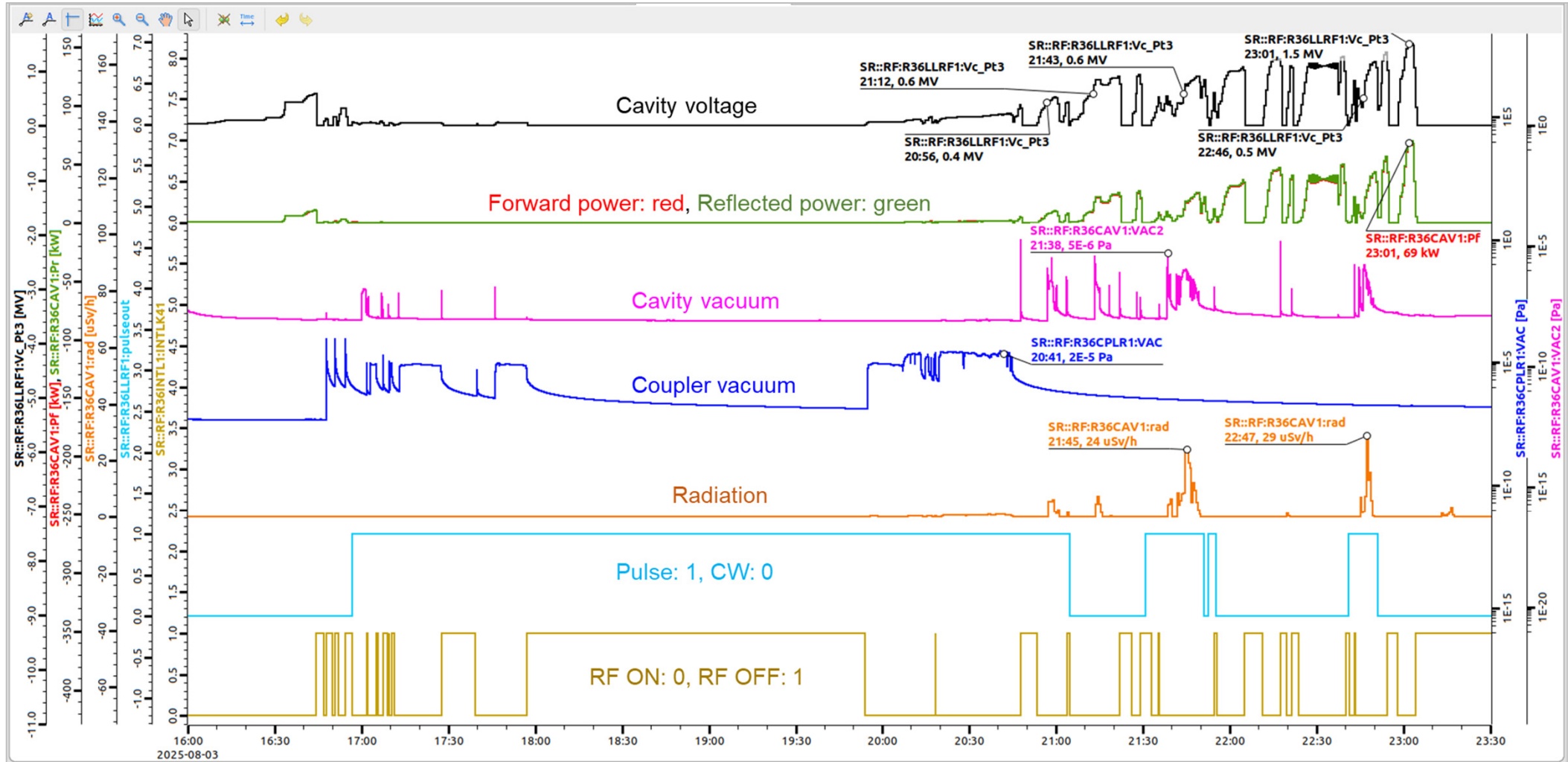
- All 7 CMs cooled down simultaneously (166MHz & 500MHz)
- Cooldown requirements: max.  $\Delta T < 10K$ , cooling rate  $< 5K/h$** 
  - Uniform cooling to minimize thermal stress on large flanges (505mm for 166MHz, 300mm for 500MHz)



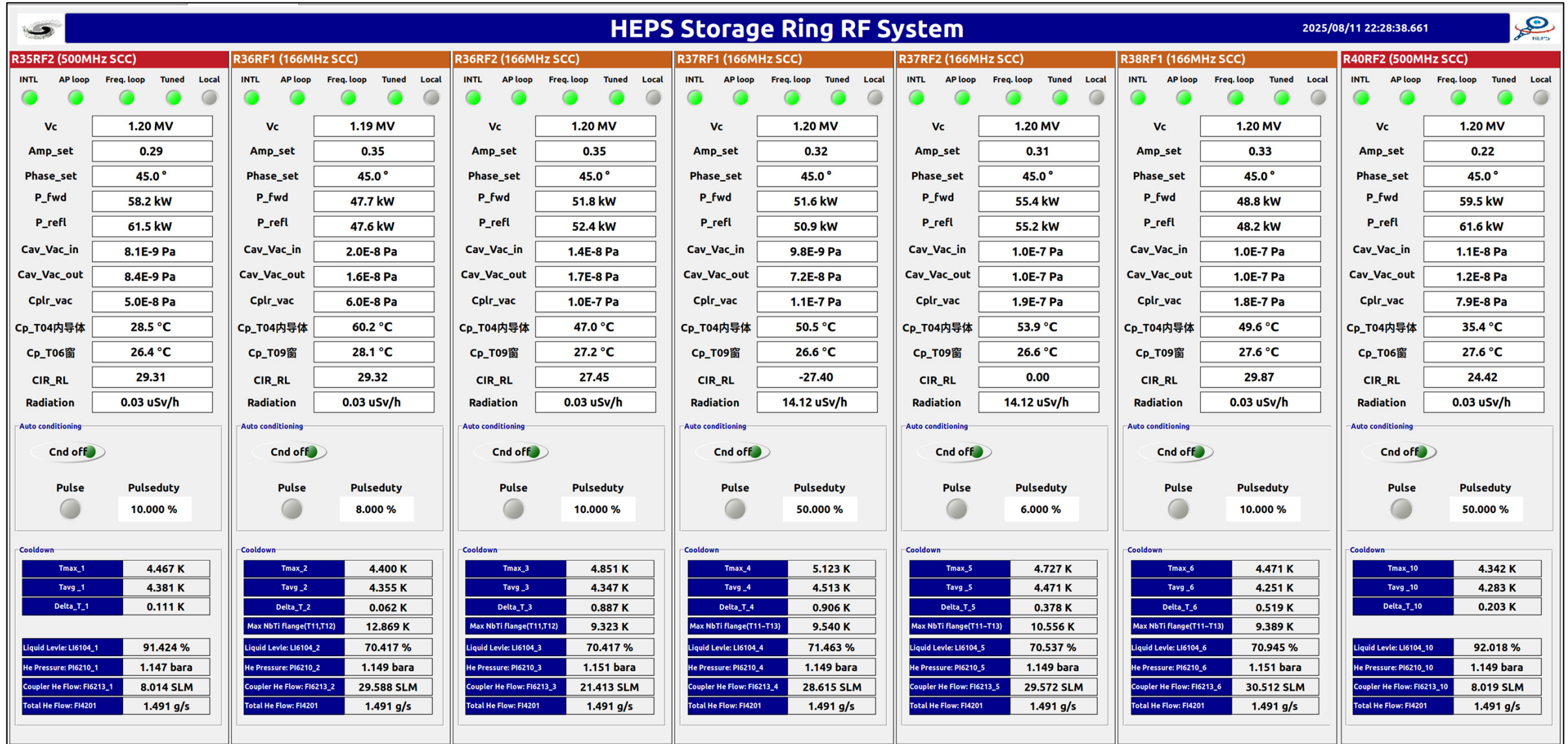
Use T01-T10 to calculate  $\Delta T$

# Conditioning at 4K

Vacuum threshold during 4K conditioning:  $3 \times 10^{-5}$  Pa

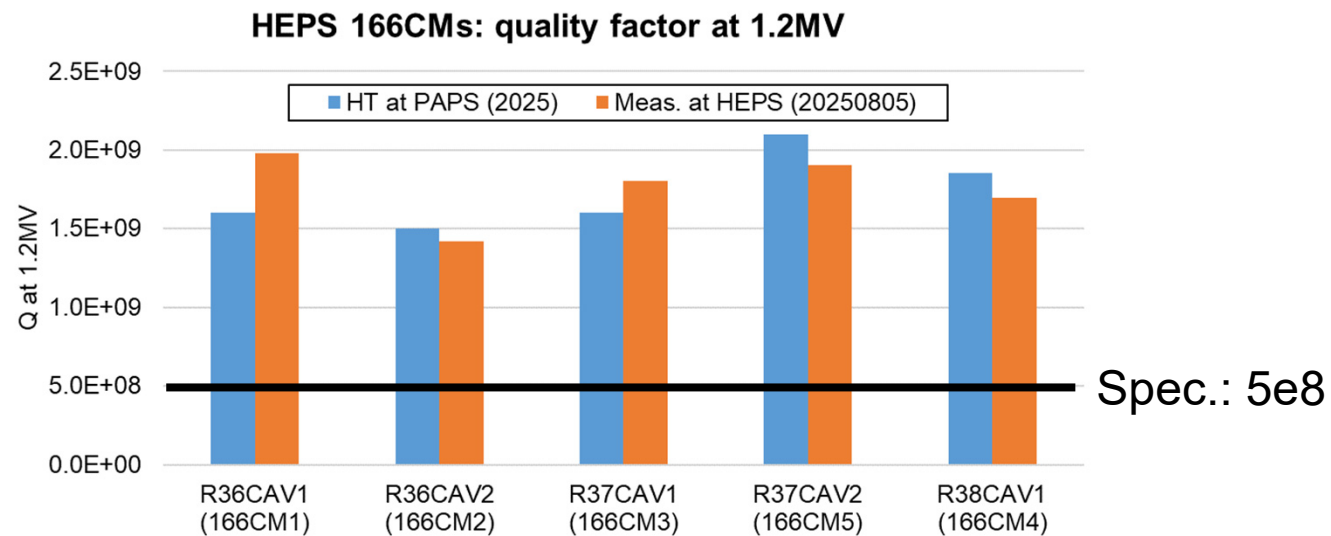
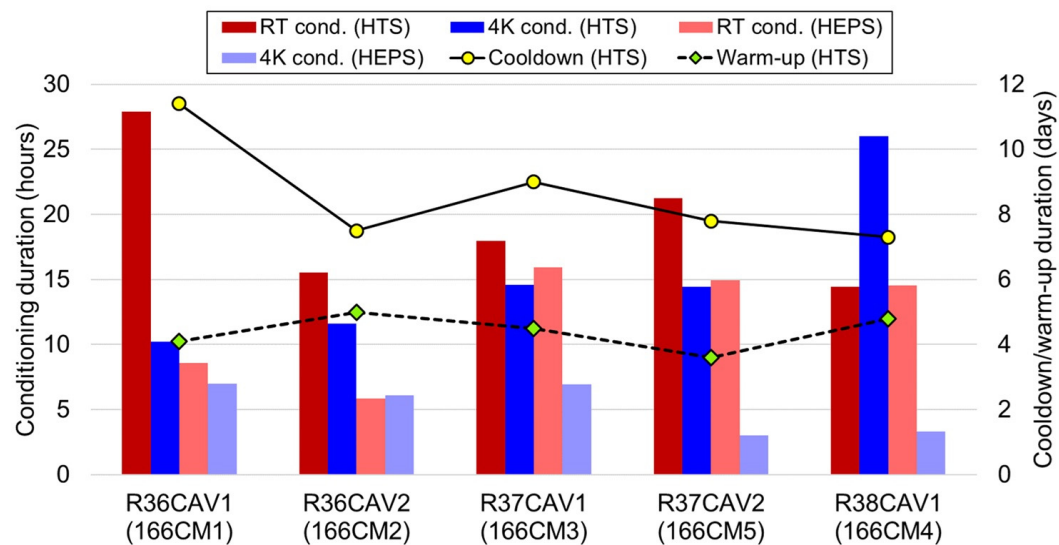


# SRF cavities after RF conditioning



# Cavity performance check: no degradation

166MHz	HEPS spec.		Measurement at HEPS tunnel (20250805)					
Cav #	Vc (MV)	Q0	Vc (MV)	Q0	Dyn. (W)	Stat. (W)	HL_tot (W)	Rad ( $\mu\text{S/h}$ )
R36CAV1	$\geq 1.1$	$\geq 5e8$	1.2	2.0E+09	5.3	39.8	45.1	0.03
R36CAV2			1.2	1.4E+09	7.3	39.9	47.2	
R37CAV1			1.2	1.8E+09	5.8	38.7	44.5	14.12
R37CAV2			1.2	1.9E+09	5.5	32.8	38.3	
R38CAV1			1.2	1.7E+09	6.2	32.7	38.9	0.03

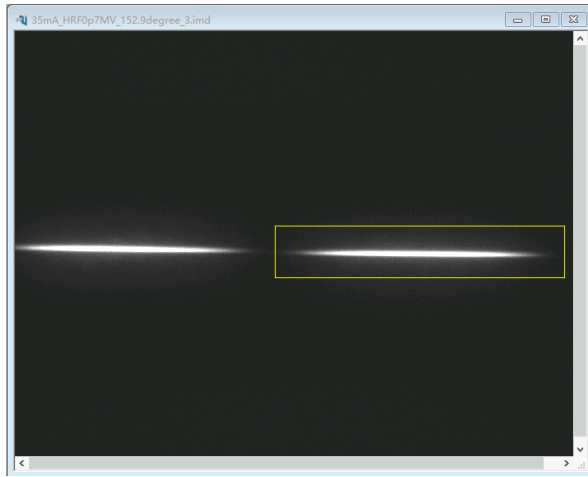


# **Beam commissioning**

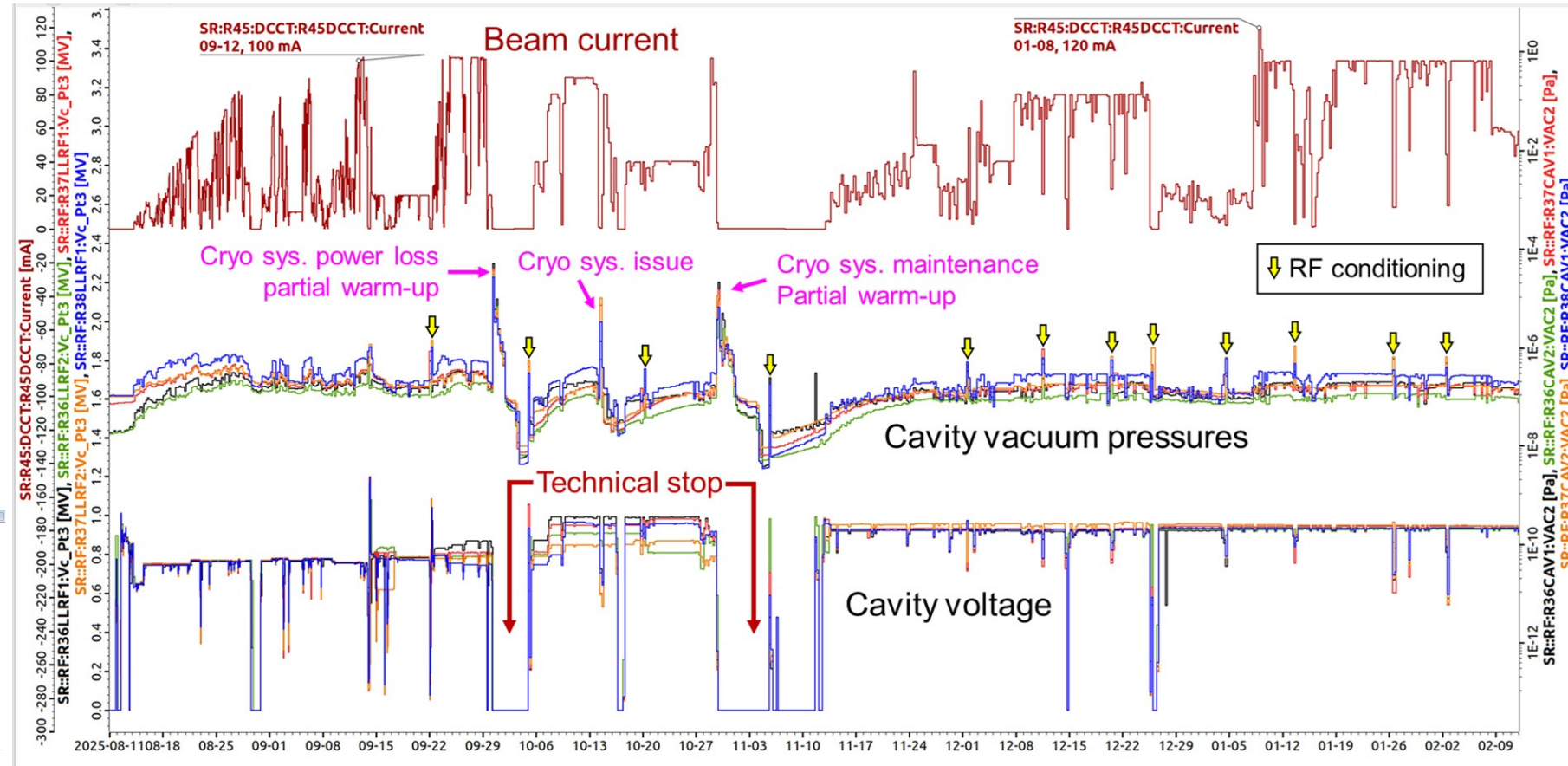
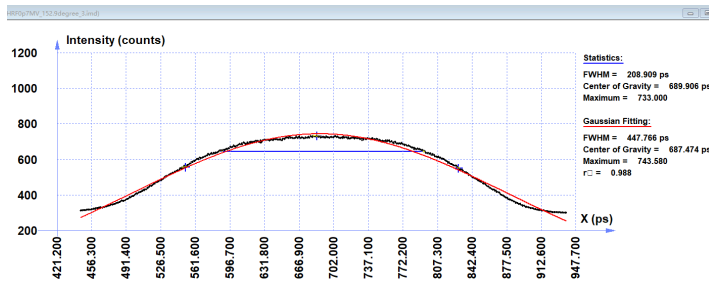
# Beam commissioning

Admin. vacuum threshold  
 $1 \times 10^{-6}$  Pa for SRF cavities

- Aug. 12, 2025, SR beam commissioning began
- Aug. 18, 2025, first bunch lengthening achieved (166MHz + 500MHz)
- Sep. 12, 2025, beam current reached 100mA, beam power 310kW (HHC ON)
- Jan. 8, 2026, beam current reached 120mA, beam power 380kW (HHC ON)
- Mar. 7, 2026, beam current reached 150mA, beam power 468kW (HHC ON)



Bunch lengthening



# Bunch lengthening

- Nearly ideal flat bunch distribution at arbitrary beam current
  - e.g.  $\sim 1.2$  nC / bunch, 28 mA @ 108 bunches,  $\sim 3.2$  times bunch lengthening

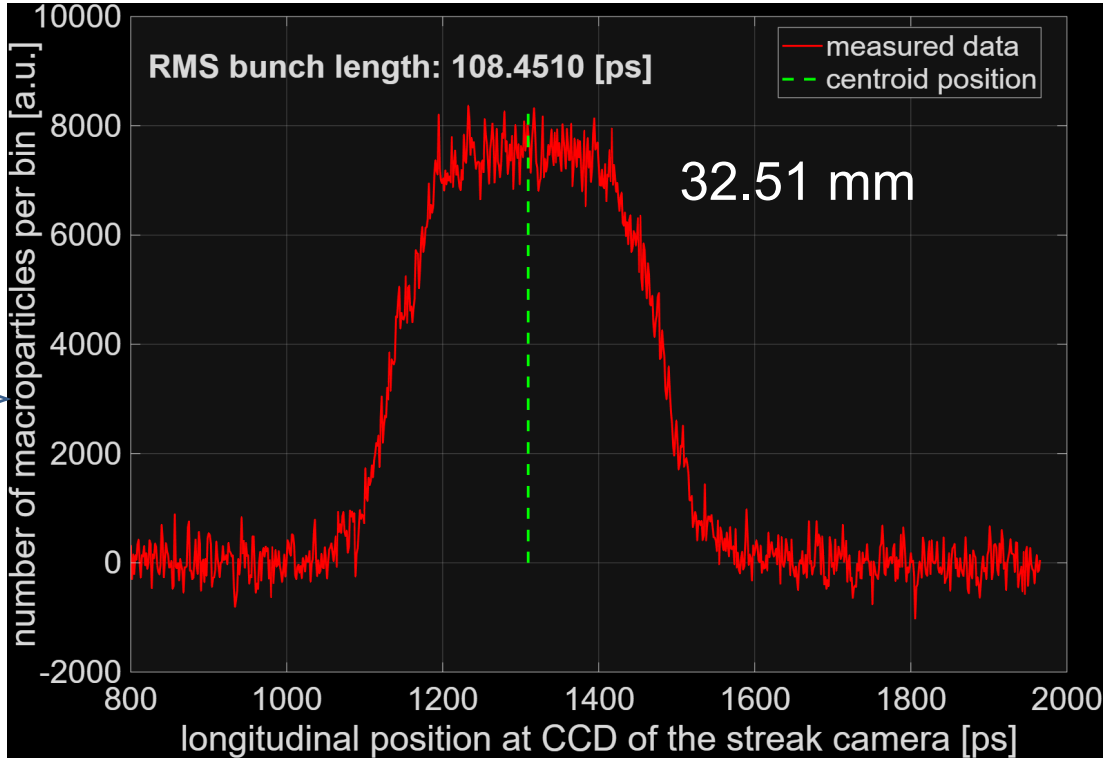
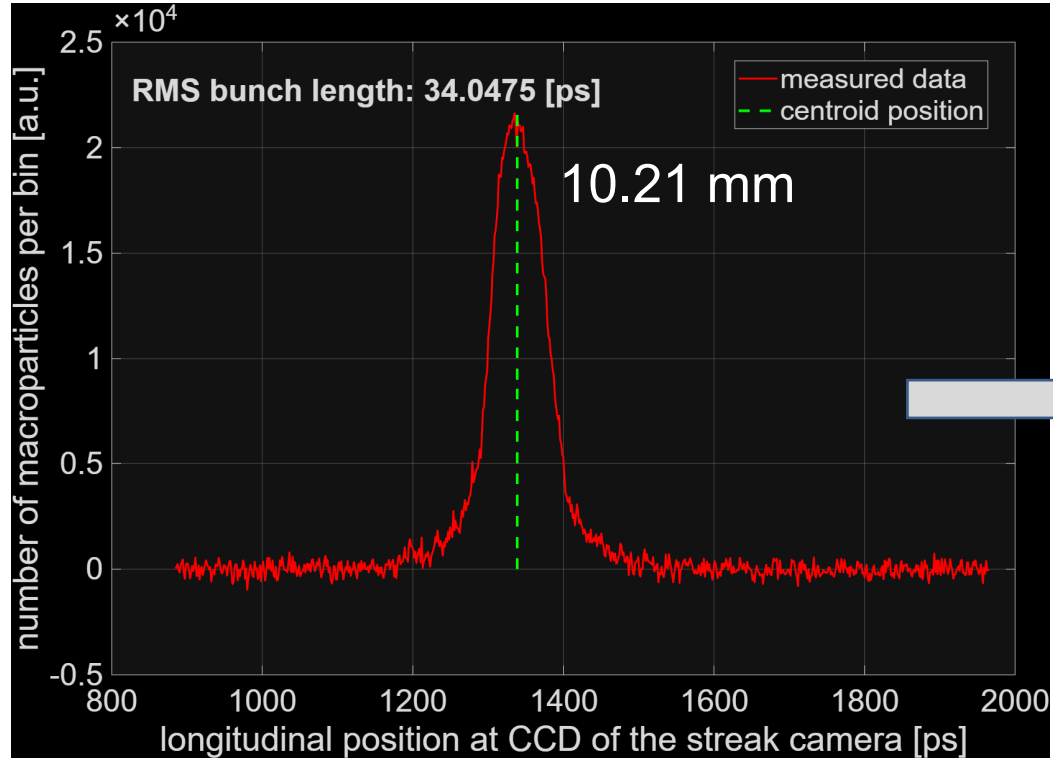
TUP2673

HC phase control

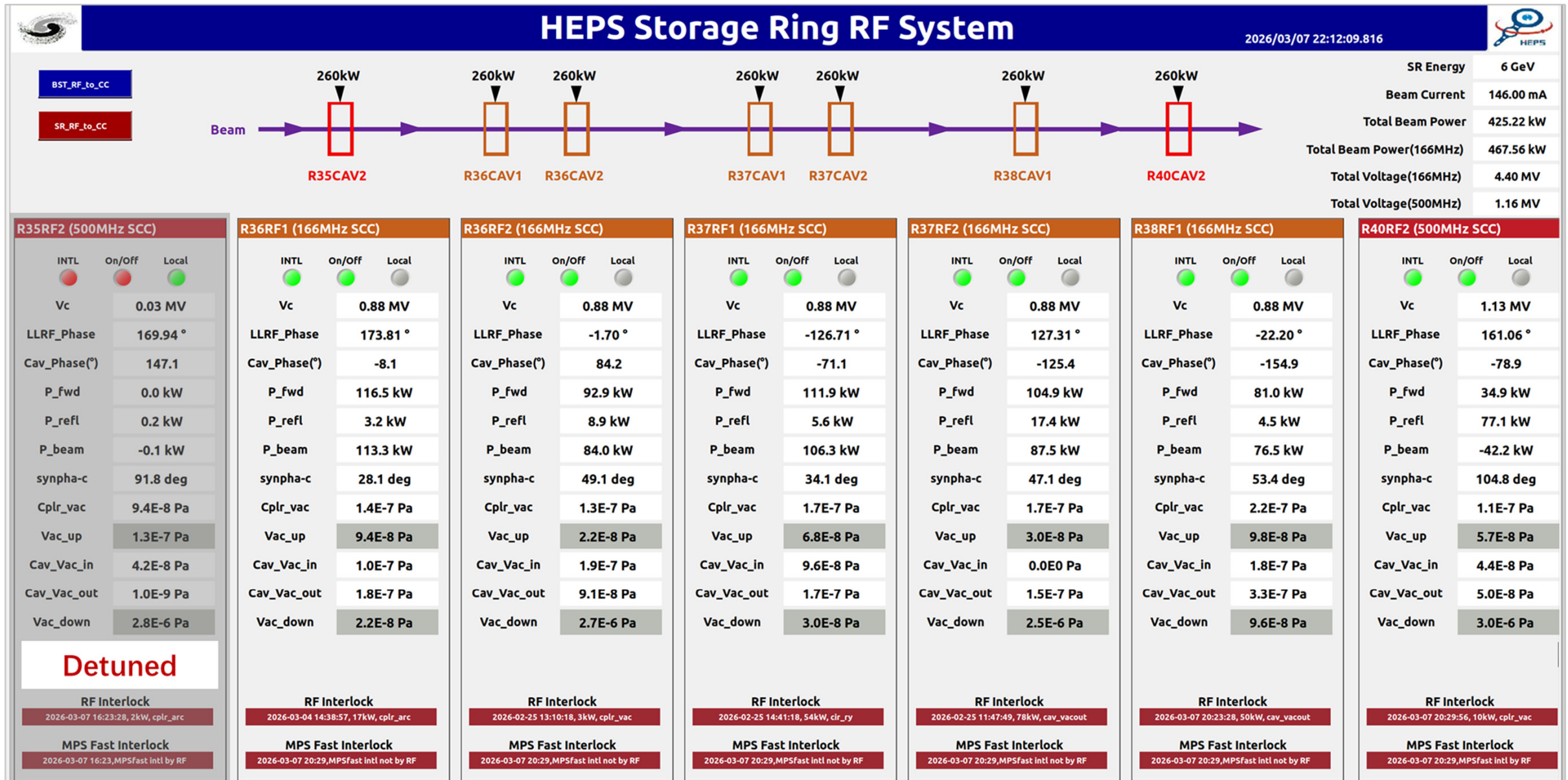
Enable SW	Loop SW
1. <input checked="" type="checkbox"/>	2. <input checked="" type="checkbox"/> Closed
R35 target $\Phi_s$	R40 target $\Phi_s$
<input type="text" value="110.00 deg"/>	<input type="text" value="104.47 deg"/>
R35 $\Phi_s$ readback	R40 $\Phi_s$ readback
<input type="text" value="91.82 deg"/>	<input type="text" value="104.15 deg"/>

## HC control loop

$\cos(\Phi_s) = P_b / (I_b \cdot V_c)$   
 Control target:  $\Delta\Phi_s < 1^\circ$   
 RF phase tuning step:  $0.03^\circ \sim 0.2^\circ$  (3 gears)  
 Enable when  $I_b > 30$  mA



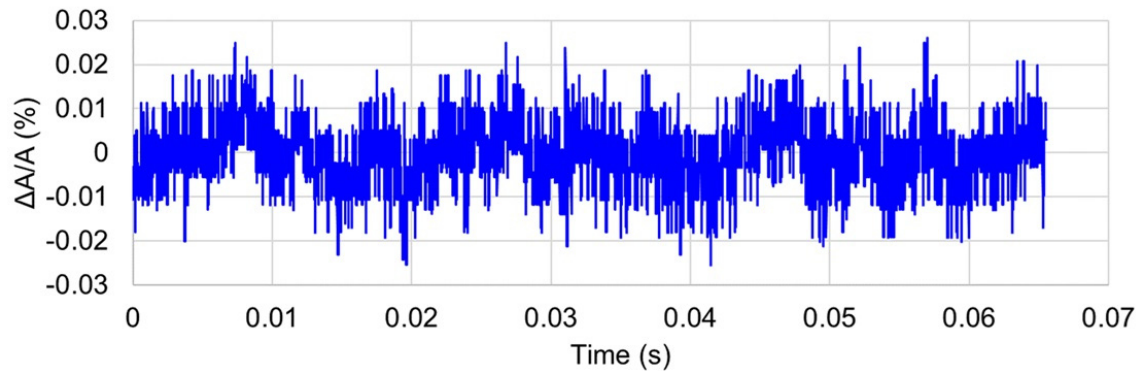
# RF operation parameters at 150mA



# RF control performance

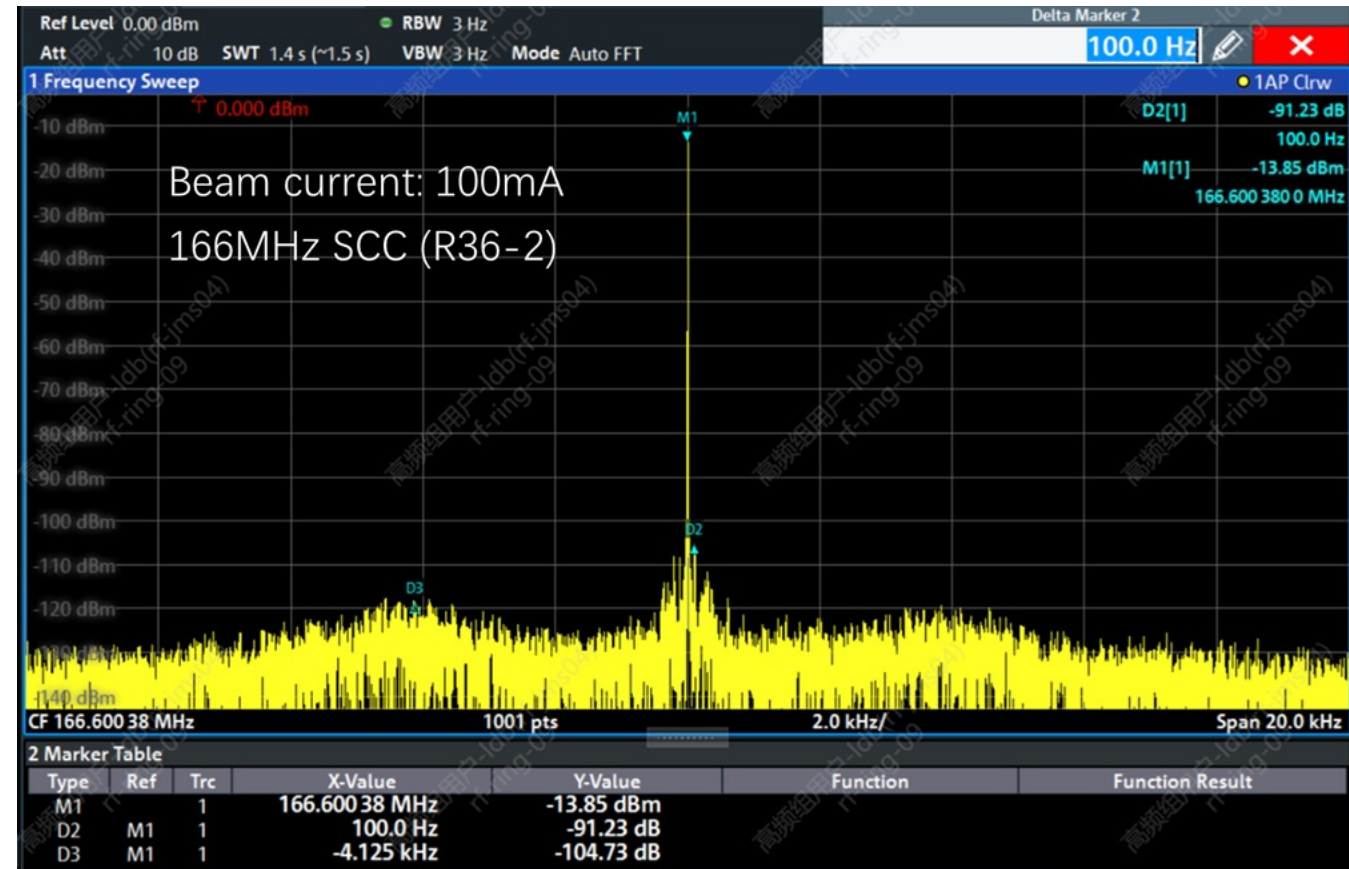
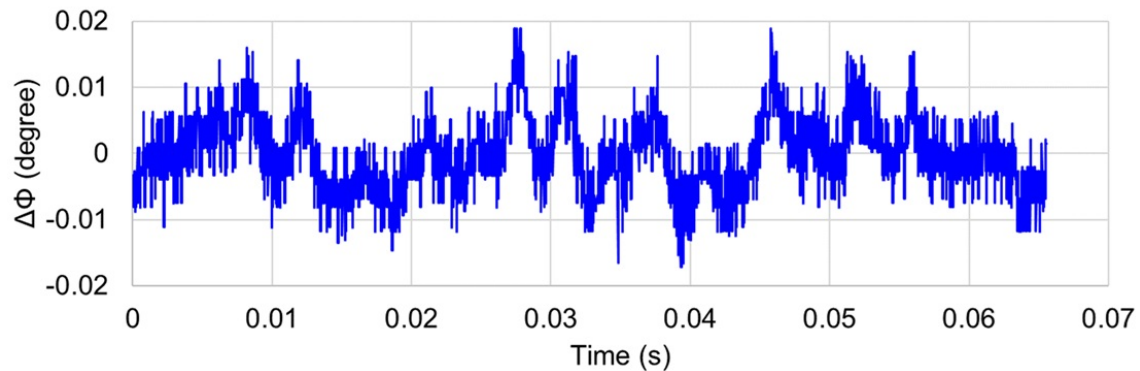
- Excellent stability performance achieved and attributed to: high-performance LLRF systems, low phase-noise SSAs, well-designed cavities, and proper grounding

(a) Amplitude stability (166MHz SCC, R36CAV2)(100mA)



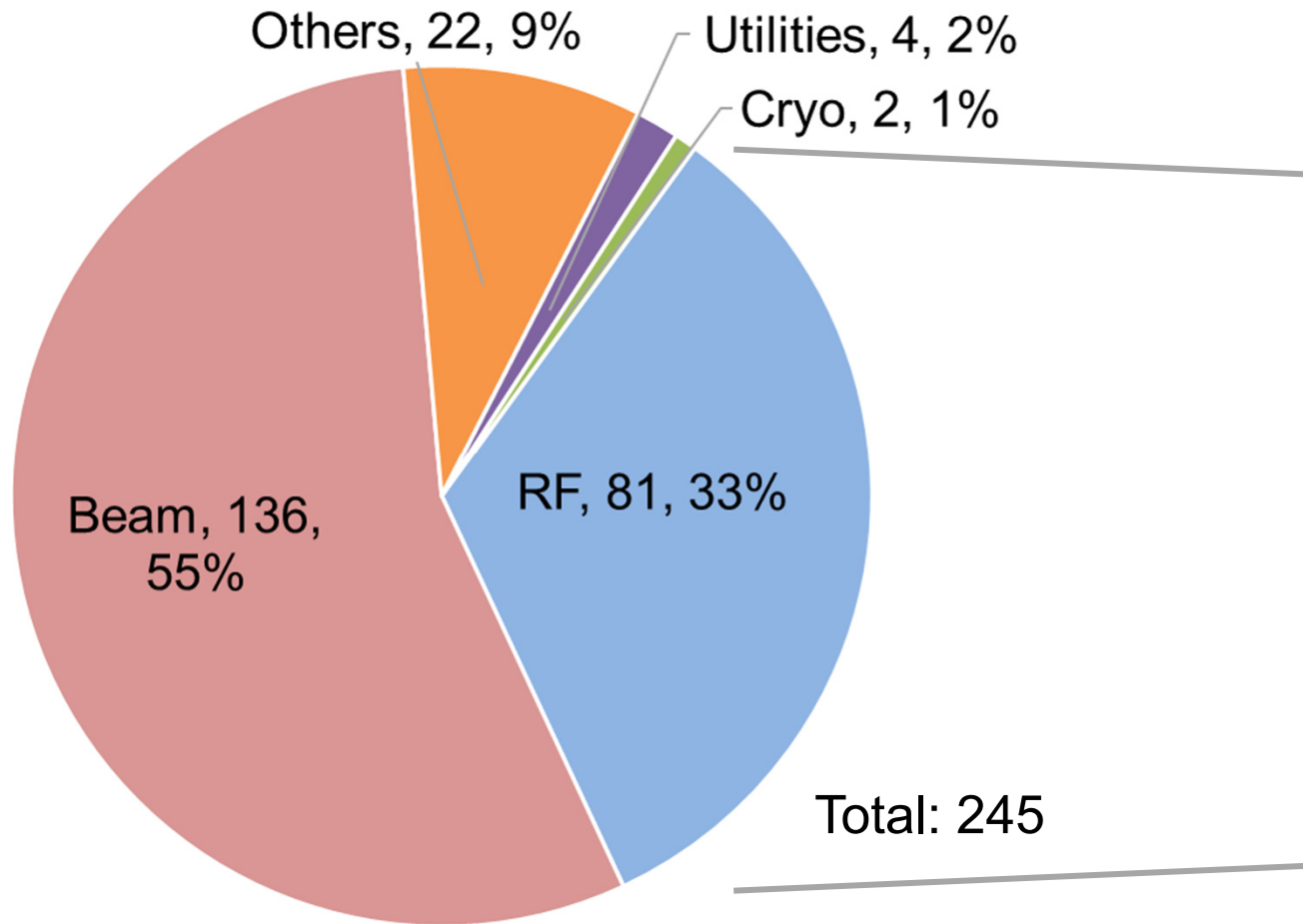
**$\pm 0.03\%$  (amp),  $\pm 0.02^\circ$  (phase)**

(b) Phase stability (166MHz SCC, R36CAV2)(100mA)

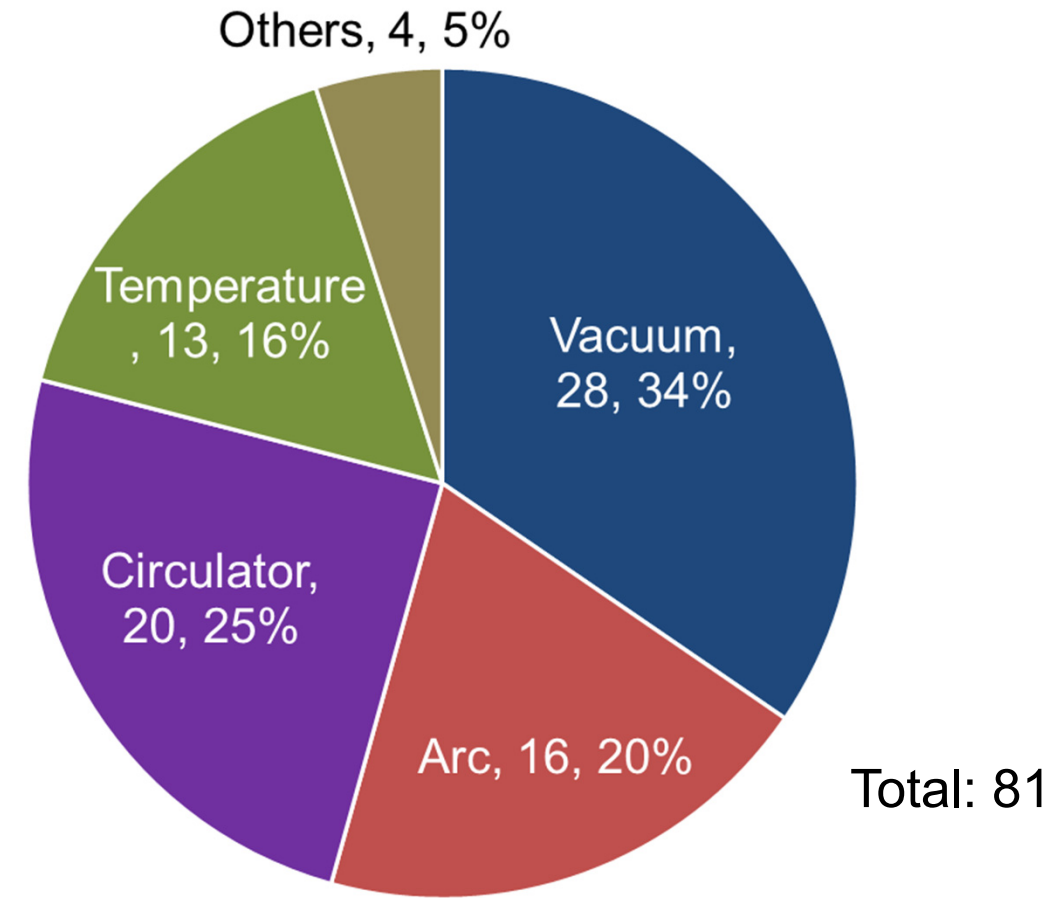


# Beam trips during S2 CX & 3 pilot user runs

2025.08.11~2026.05.01



Beam trips (RF-recorded)

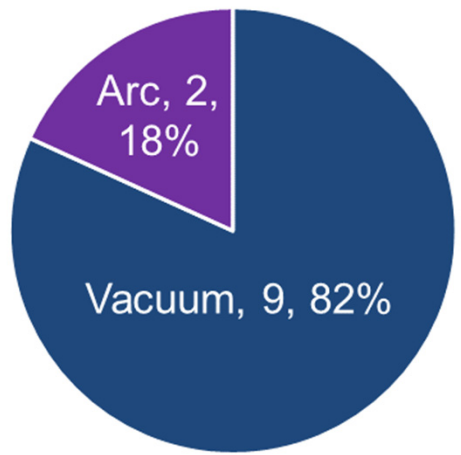


Beam trips (RF caused)

Note: Beam-related trips include all non-RF and non-RF-interfaced subsystems, such as beam orbit, fast orbit feedback (FOFB), magnet power supplies, kickers, vacuum systems, beamlines, etc.

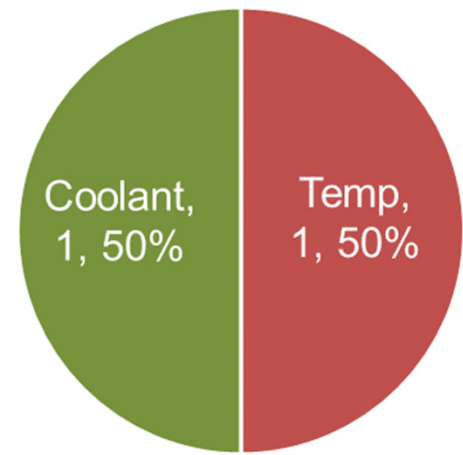
# RF-caused beam trips in pilot user runs

Pilot User Run 1  
(2025.12.03~2025.12.25)  
(22 days)



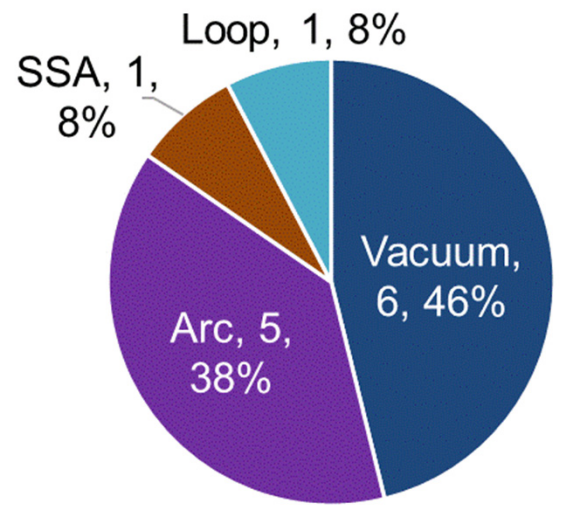
Total: 11 (6.5%)

Pilot User Run 2  
(2026.01.18~2026.02.11)  
(24 days)



Total: 2 (6.0%)

Pilot User Run 3  
(2026.04.04~2026.05.01)  
(27 days)



Total: 13 (TBA)

- **Signal interference:** occasional (2 times in Run2, 1 time in Run3)
- **Beam-loss-induced arc events:** significantly reduced after implementing logic-based arc discrimination, though still occasional occurrence
- **Cavity vacuum trips:** occasional, some linked to beam loss

# Open issues

#	Name	Impact	Planned actions
1	Beam-loss-induced arc events	Trigger MPS	<ul style="list-style-type: none"><li>• Logic-based arc discrimination (impl.)</li><li>• Plastic optical fiber to be installed</li></ul>
2	SSA temp. & interlock signal interference (EMI)	Trigger MPS	Shielded closure to be installed in summer shutdown in 2026
3	Higher FPC temperature for two booster NC cavities	Risk of failure	<ul style="list-style-type: none"><li>• Coupling elements in procurement</li><li>• Reduced cavity voltage in operation</li></ul>
4	SSA PSM high failure rate	Not yet affecting operation	Under investigation
5	One 166MHz circulator returned to vendor for improvement	Not yet affecting operation	SAT to be completed, reinstallation for operation in summer shutdown in 2026
6	Piezo broken	Not yet affecting operation	Experiments on low-voltage piezo underway

# Summary

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- Vacuum scrubbing phase using 500MHz RF system completed
- Booster RF and Storage-ring RF systems in nominal configuration and fully operational
  - Newly developed 166MHz SRF cavities in beam operation, **demonstrated success**
  - First active SRF harmonic cavity operational in the first week, routinely elongating bunch by a factor of 3
- Key issues identified and analyzed, countermeasures developed and being implemented

Commitment of RF WP to HEPS project success fulfilled.

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# Thank you!



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