Status of HEPS RF System

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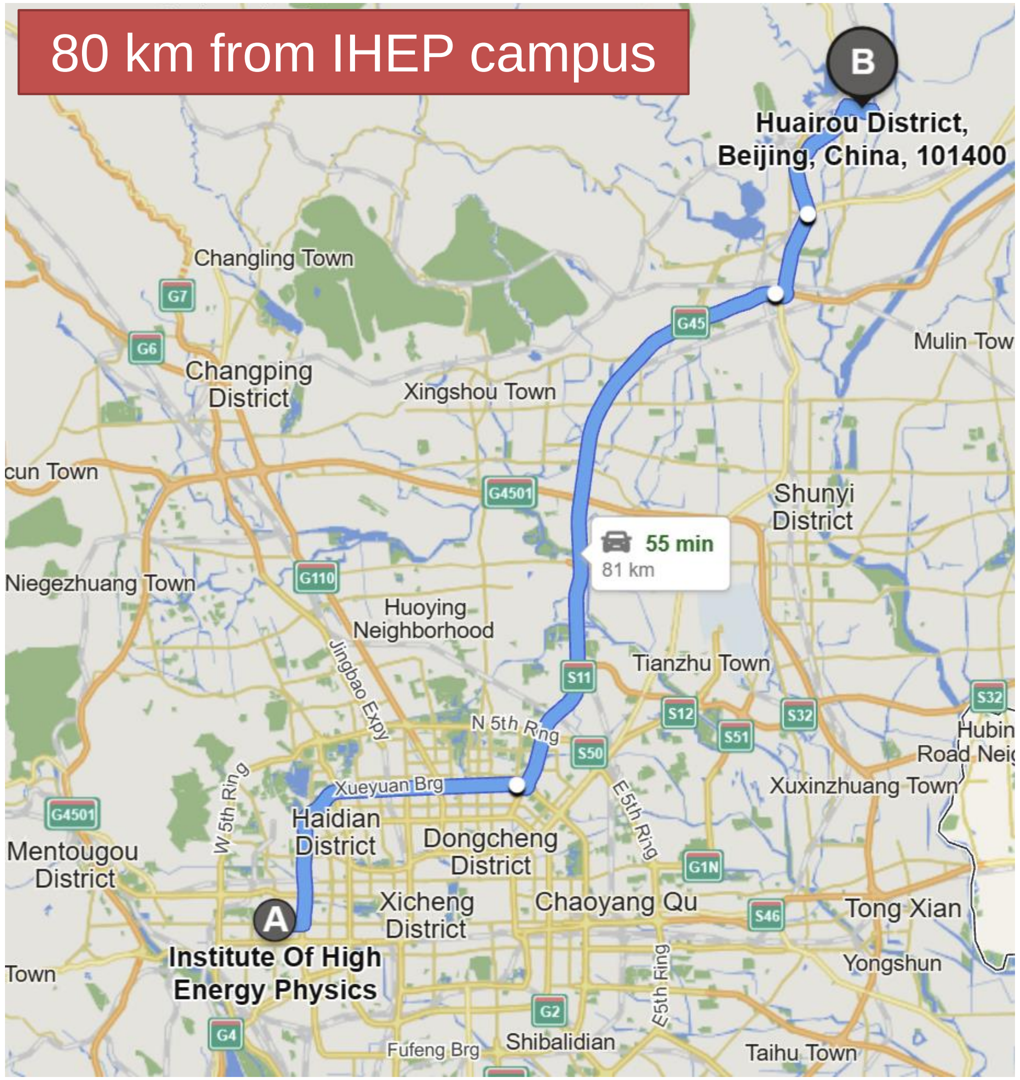
Outline

- Introduction to HEPS
- HEPS RF System
- Booster RF
- Storage-ring RF

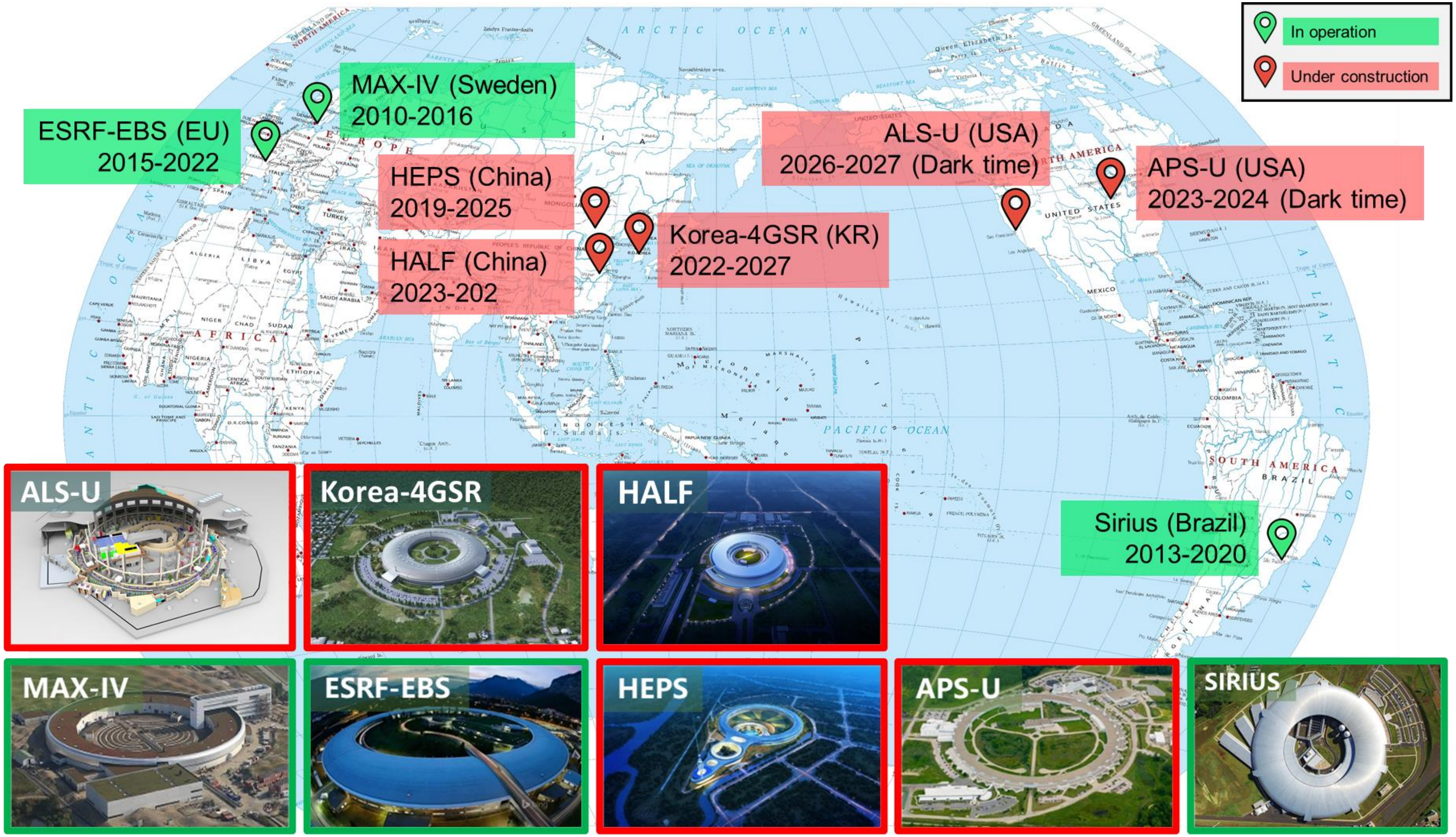
High Energy Photon Source

- **High Energy Photon Source (HEPS)**
  - A diffraction-limited SR light source (4th-gen)
  - The 1st high-energy SR light source in China
- **Main facts**
  - Circumference: 1360.4 m
  - Beam energy: 6 GeV
  - **Location**: Huairou Science City, Beijing
  - **Construction time**: 06.2019 – 12.2025
  - **Budget**: 4.76B CNY (~$652M)(including materials, civil construction & commissioning, excluding labor costs)
  - **Support**: Central government + Local government + Chinese Academy of Sciences



SR: Synchrotron Radiation

Landscape of the 4th-gen SR facilities



Light sources in mainland China

Beijing Synchrotron Radiation Facility (1st-gen)

Hefei Light Source (2nd-gen)

Shanghai Synchrotron Radiation Facility (3rd-gen)

- In operation: 5 light sources (3 SRs + 2 Linacs)
- Under constr.: 3 light sources (2 SRs + 1 Linacs)
- Planning, R&D: 4 light sources (3 SRs + 1 Linacs)

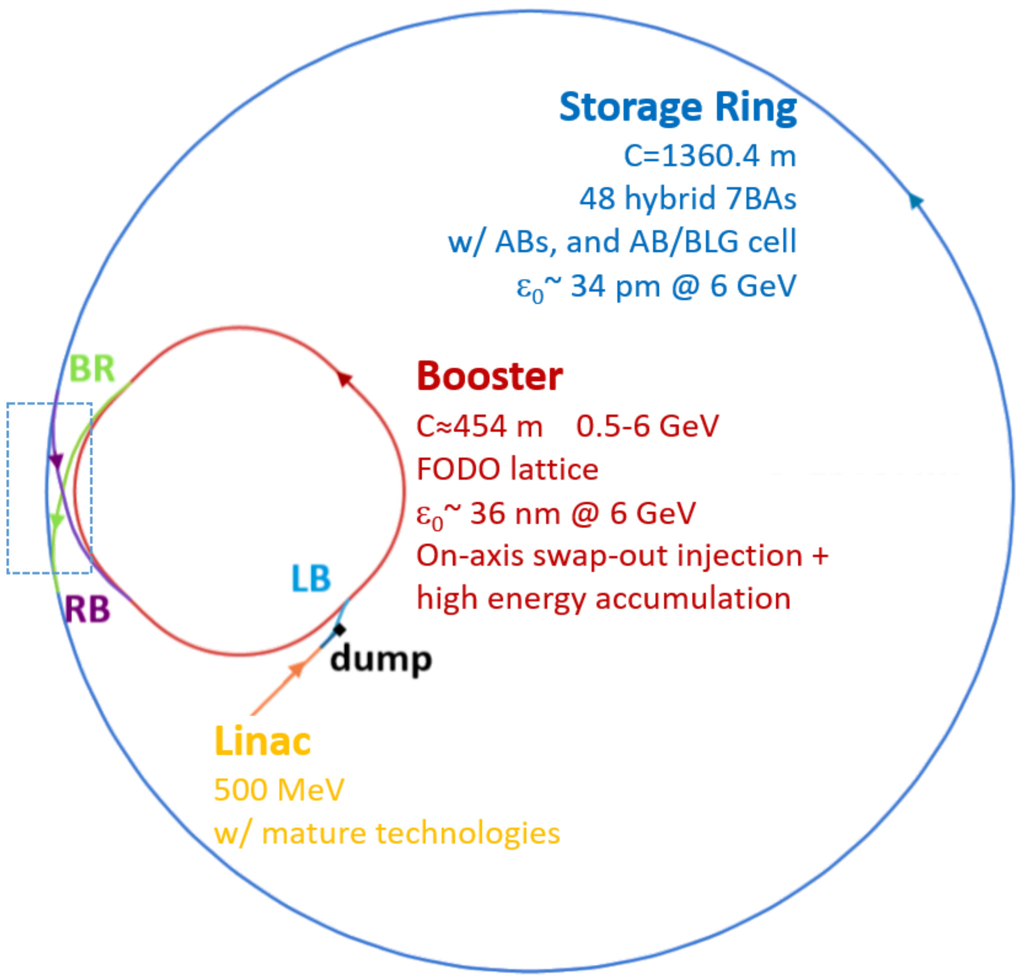
High Energy Photon Source

Hefei Adv. Light Facility

Southern Adv. Photon Source

HEPS in Huairou Science City (Beijing)

Main parameters



[1] Y. Jiao *et al.*, *J. Synchrotron Rad.* 25, 1611–1618 (2018).
[2] H. Xu *et al.*, *RDTM* 7, 279–287 (2023).
[3] C. Meng *et al.*, *RDTM* 4, 497–506 (2020).

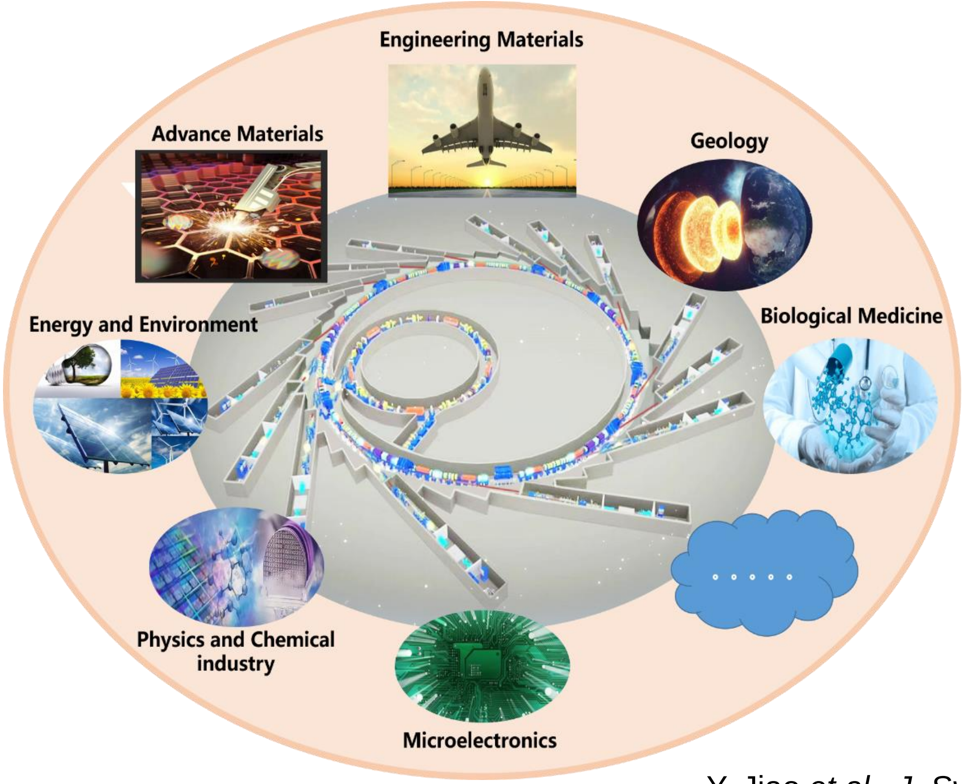
Parameter	Value	Unit
Beam energy	6	GeV
Circumference	1360.4	m
Lattice type	7-bend achromat	
Hori. Natural emittance	<60	pm·rad
Brightness	$>1\times10^{22}$	*
Beam current	200	mA
Injection mode	Top-up	-

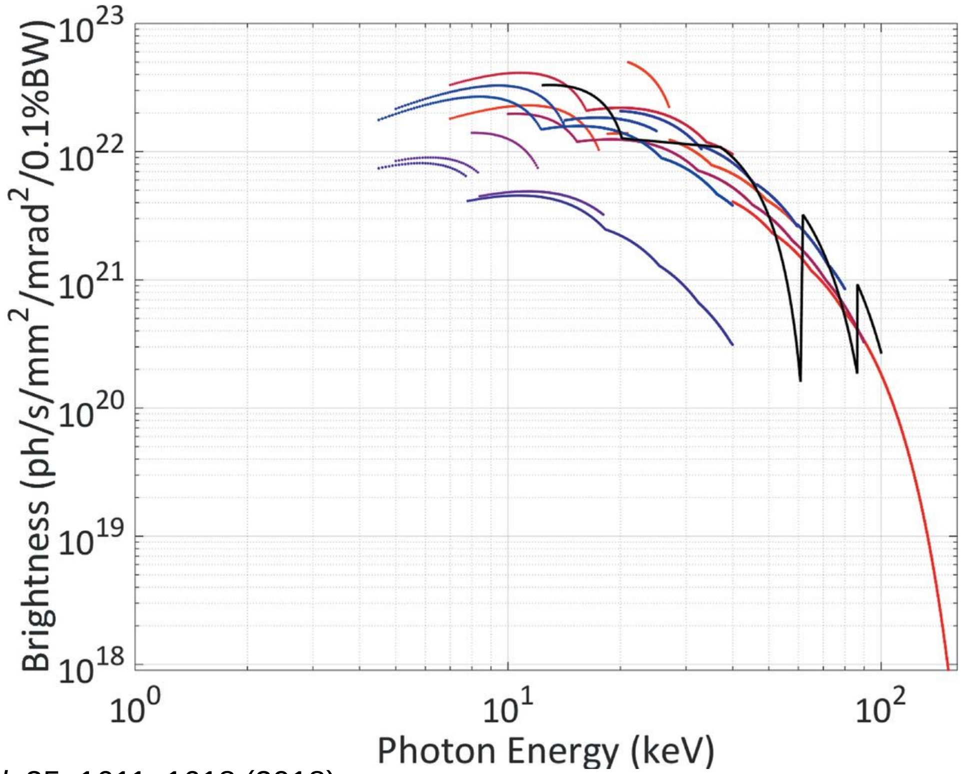
*: phs/s/mm^2/mrad^2/0.1%BW

Detailed parameters refer to:
Design Report of the HEPS RF System, IHEP-HEPS-AC-RF-TR-2023-001.

Main parameters

- One of the brightest 4th-gen SR facilities in the world
- Brightness of 5×10^{22} phs/s/mm^2/mrad^2/0.1%BW at the photon energy of 21 keV, can provide X-ray with energy up to 300 keV
- 14 public beamlines in Phase I, HEPS can accommodate up to 90 beamlines





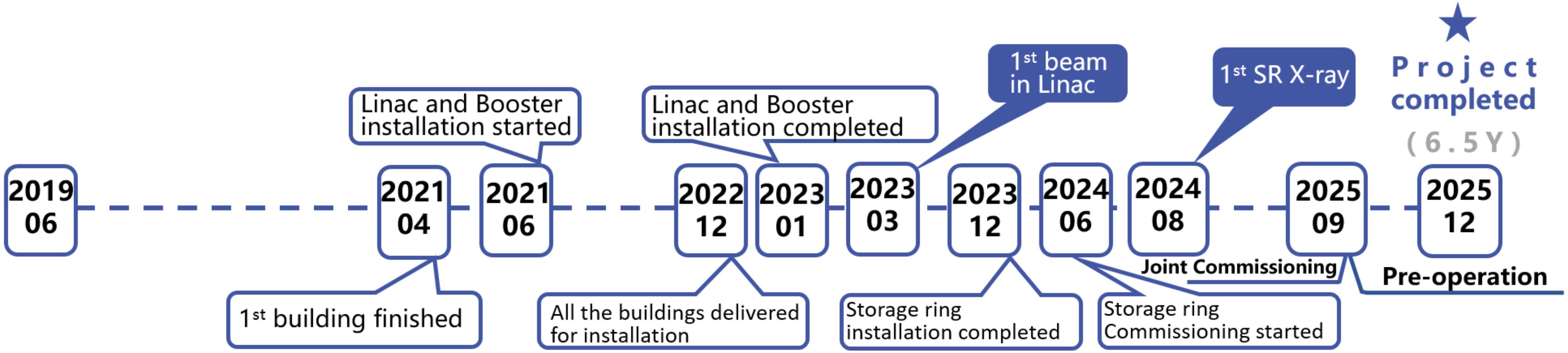
Y. Jiao *et al.*, *J. Synchrotron Rad.* 25, 1611–1618 (2018).

HEPS-TF and HEPS

- **HEPS - Test Facility (HEPS-TF) project**

  - R&D phase for HEPS, Apr. 2016 – Oct. 2018

  - Funding: 321M CNY (25M CNY for RF)



Milestones of HEPS

- Groundbreaking in Jun. 2019
- Civil construction completed in Nov. 2021
- PAPS completed in May 2021, currently in operation
- First accelerator component installation in Jul. 2021
- Booster installation completed in Jan. 2023
- Storage-ring installation started in Feb. 2023
- Linac commissioning completed in Mar. 2023
- Booster commissioning completed in Nov. 2023

Platform of Advanced Photon Source Technology R&D

Jul. 2019

Aug. 2023

RF system

HEPS-RF deliverables

- **Cavities**
  - 5 sets of 166.6 MHz SRF cavity modules
  - 2 sets of 499.8 MHz SRF cavity modules
  - 6 sets of 499.8 MHz NCRF cavities
- **High-power RF**
  - 5 sets of 166.6 MHz 260 kW solid-state power amplifiers
  - 2 sets of 499.8 MHz 260 kW solid-state power amplifiers
  - 6 sets of 499.8 MHz 100 kW solid-state power amplifiers
- **RF controls**
  - 5 sets of 166.6 MHz RF control systems
  - 8 sets of 499.8 MHz RF control systems

Main parameters of the booster

Parameter	Injection	Extraction	Unit
Circumference	454.066		m
RF frequency	499.8		MHz
Harmonic number	757		-
Electron beam energy	0.5	6	GeV
Electron beam current	11	13	mA
Total SR loss	1.94e-4	4.02	MeV/turn
Total power loss to SR	2.134e-3	52.26	kW
Radiation damping time (x, y, z)	7.8e3, 7.8e3, 3.9e3	4.5, 4.5, 2.3	ms
Total RF voltage	2	8	MV
RF bucket height	3.02	1.02	%
Bunch length	1.5	11.0	mm
Repetition rate	1		Hz
Max. straight section length	8.8		m

[1] HEPS Interface Control Document, HEPS-PM-CD-2018-003-V0 (in Chinese).
[2] P. Zhang *et al.*, ”Radio-frequency system of HEPS”, *Radiation Detection Technology and Methods* 7, 159-170 (2023).

Main parameters of the storage ring

Parameter	Value	Unit
Circumference	1360.4	m
Beam energy	6	GeV
Beam current	200	mA
Energy loss per turn (bare)	2.64	MeV
Energy loss per turn to IDs	1.5	MeV
Total energy loss per turn	4.14	MeV
Total power loss to radiation	828	kW
Momentum compaction	1.88×10^{-5}	-
Synchrotron frequency (w/o HC)	181	Hz
Energy acceptance (ΔE/E)	4	%
Natural bunch length	5.06	mm
Bunch length with HC	29.8	mm
Radiation damping time (x/y)	10.85/20.62	ms
Radiation damping time (z)	18.76	ms

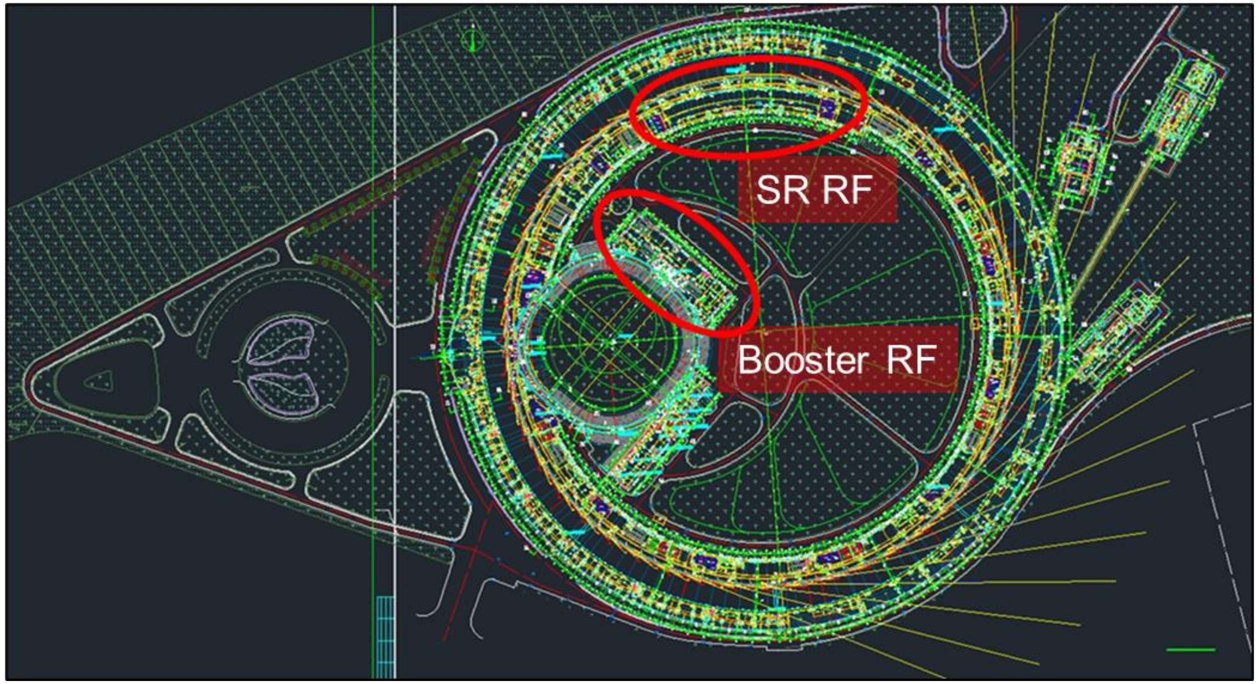
Parameter	Value	Unit
β function at high-β straight (x/y)	8.18/5.0	m
β function at low-β straight (x/y)	2.56/2.31	m
No./Length of straights	24/6.086	m
Total CBI threshold (x)	3.4E+6	Ω/m
Total CBI threshold (y)	1.87E+6	Ω/m
Total LCBI threshold @1 GHz		
(w/o HC, 200 mA)	1.27E+5	Ω
(w/ HC, 200 mA)	3.63E+4	Ω
RF frequency (fund. rf)	166.6	MHz
Harmonic number	756	-
RF frequency (HC)	499.8	MHz
Touschek lifetime (680 bunches)	3.8	hour
Total RF voltage (fund. rf)(w/ HC)	5.16	MV
Total RF voltage (HC)	0.91	MV

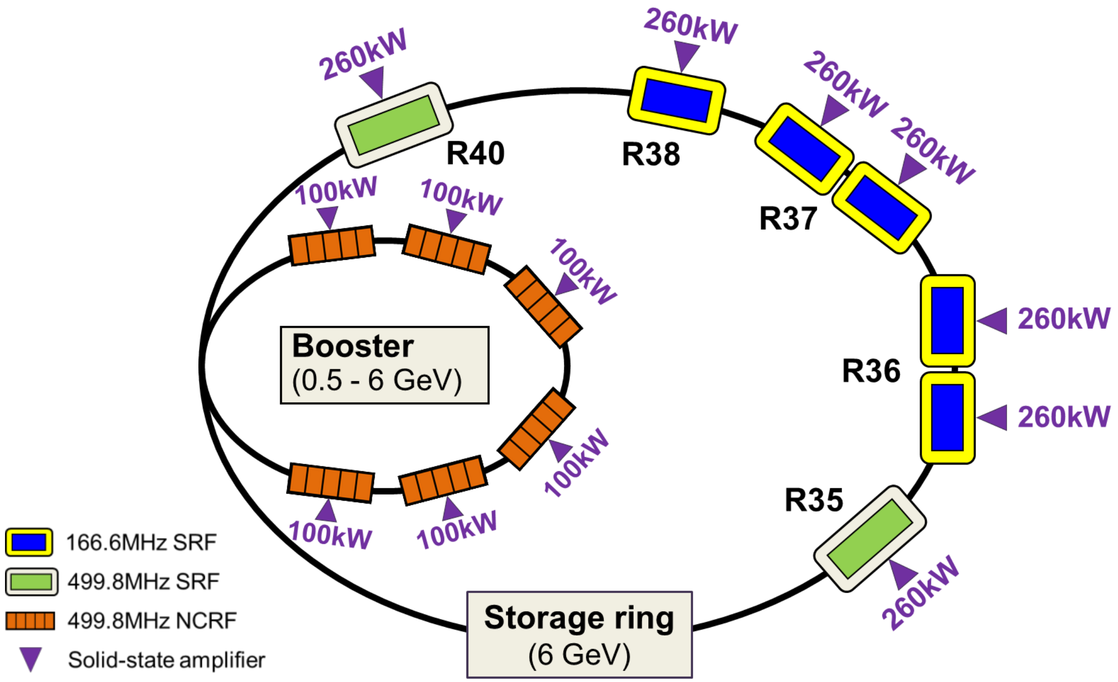
[1] HEPS Interface Control Document, HEPS-AC-CD-2019-007-V0 (in Chinese).
[2] P. Zhang *et al.*, "Radio-frequency system of HEPS", *Radiation Detection Technology and Methods* 7, 159-170 (2023).

HC: Harmonic Cavities

Main features of the RF system

- Double-frequency RF system: 166.6 MHz + 499.8 MHz
- Active harmonic RF compatible for on-axis swap-out & on-axis accumulation injections
- SRF for the storage ring, normal-conducting RF for the booster
- Heavy damping of higher order modes for storage-ring SRF cavities
- Solid-state power amplifiers for all RF transmitters, digital low-level RF controllers

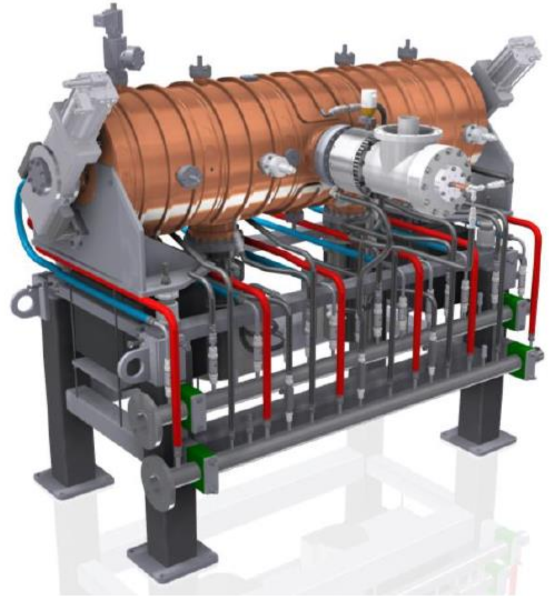




Main RF parameters

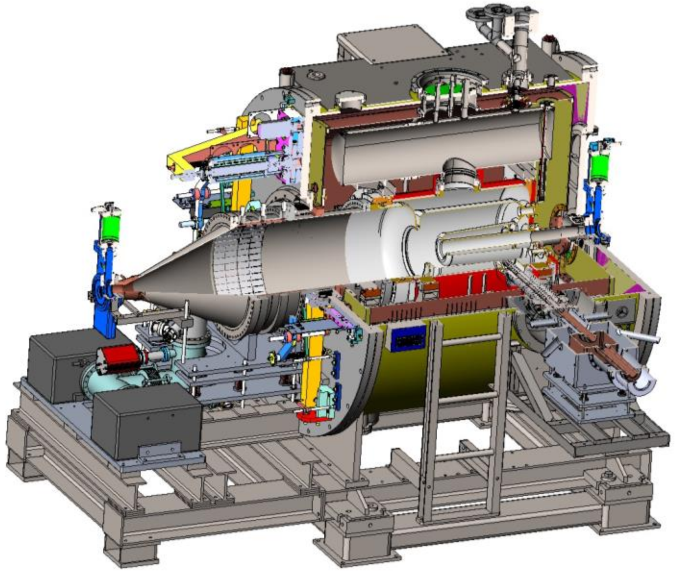
	BST	SR (main)	SR (HC)	Unit
RF frequency	499.8	166.6	499.8	MHz
Total RF voltage	2 – 8	5.4	0.91	MV
Cavity technology	Normal-conducting	Superconducting	Superconducting	-
Cavity type	5-cell	β=1 quarter-wave	1-cell elliptical	-
Technology readiness	Mature product	In-house new dev.	In-house exp.	-
No. of cavities	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)	170	105	kW
No. of transmitters	6	5	2	-
RF power per transmitter	100 (cw)	260 (cw)	260 (cw)	kW
Transmitter technology	SSA	SSA	SSA	-
LLRF control stability (p-p)	±1%, ±1°	±0.1%, ±0.1°	±0.1%, ±0.1°	-
LLRF technology	Digital LLRF (in-house development)			-

RF cavities for HEPS



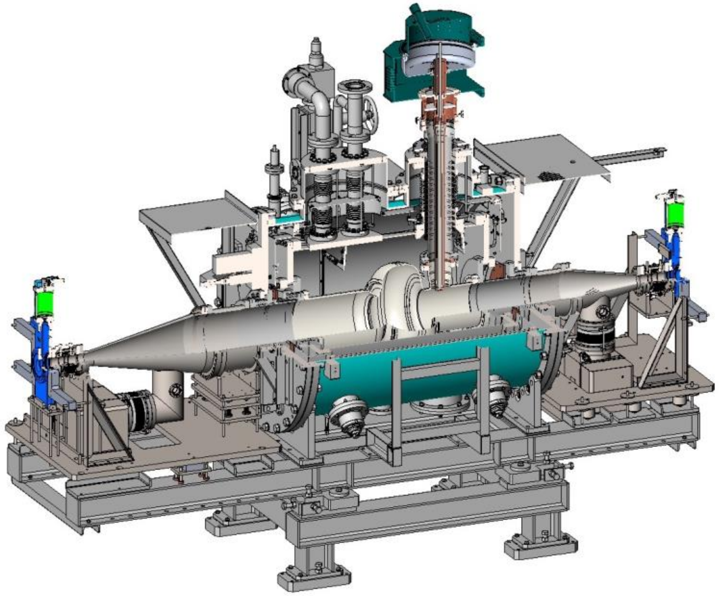
500MHz PETRA-type
5-cell copper cavity
(Booster)

Procured from RI
(Minor modifications)



166MHz Quarter-wave
β=1 SRF cavity
(Storage ring)

In-house development
(**New**)



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

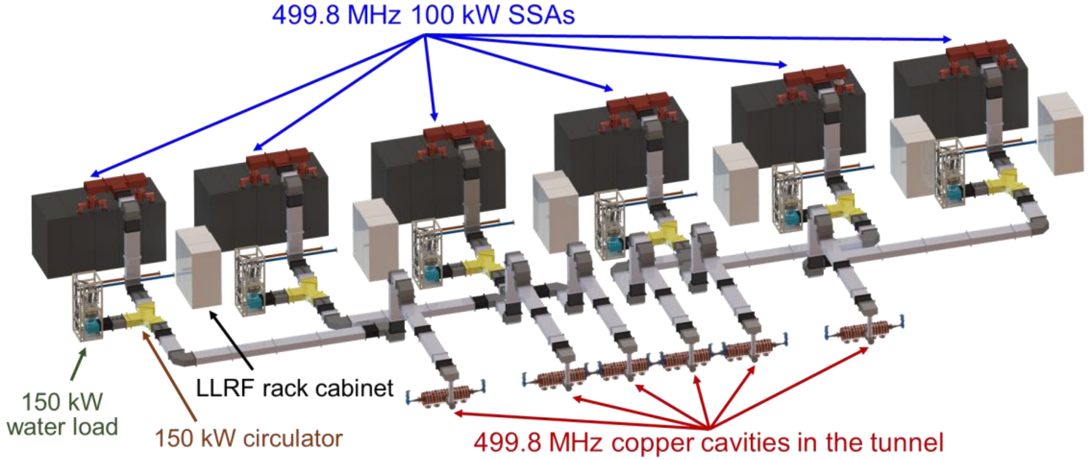
In-house development
(BEPCII experience)

[1] T. Huang *et al.*, "Normal-conducting 5-cell cavities for HEPS booster RF system", *IPAC2023*, MOPA184.
[2] X. Zhang *et al.*, "Design of a HOM-Damped 166.6 MHz Compact Quarter-Wave β=1 SC Cavity for HEPS", *SRF2021*, MOPCAV010.
[3] H. Zheng *et al.*, "Design optimization of a mechanically-improved 499.8 MHz single-cell SC cavity for HEPS", *IEEE TAS* 31, 3500109 (2021).

High-power RF

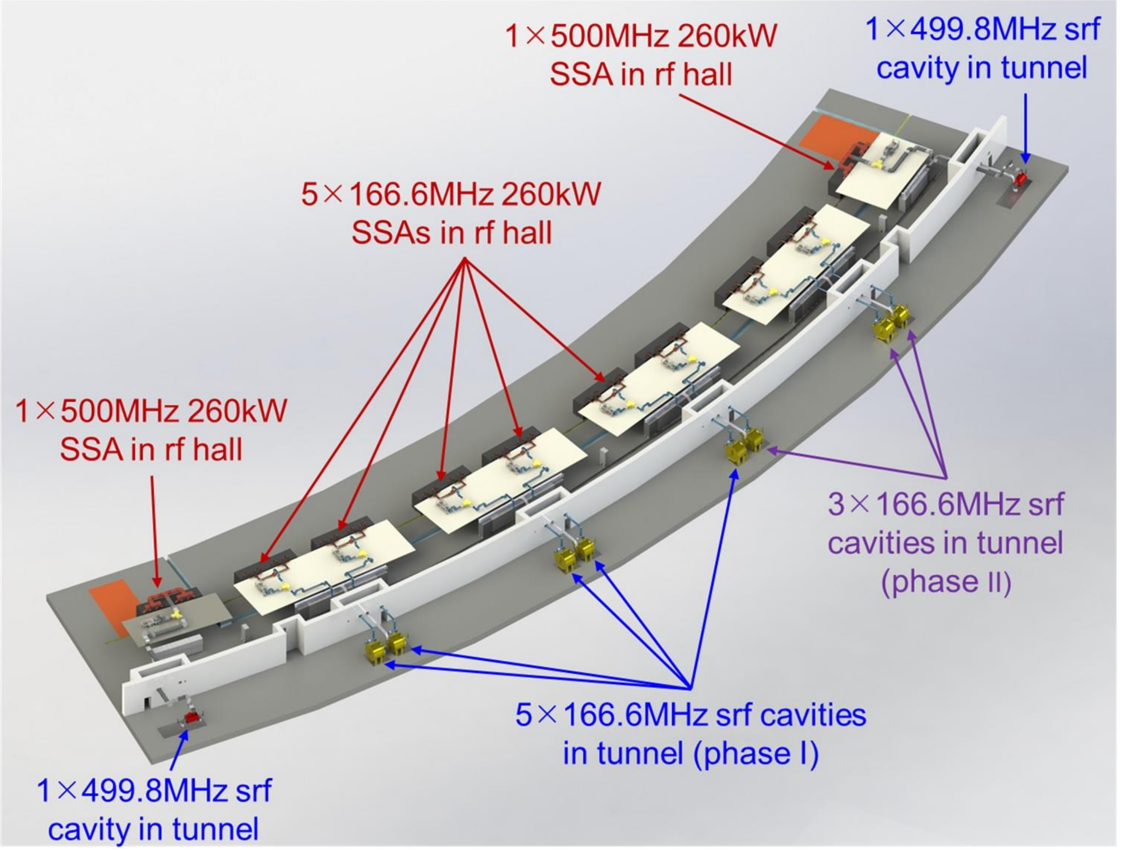
- Transmitter type: SSA
- Power transmission
  - 9-3/16” coaxial rigid lines for 166MHz
  - WR1800 rectangular waveguide for 500MHz
- High-power circulator for each RF station

Booster RF



RF hall surface area: 1600 m^2

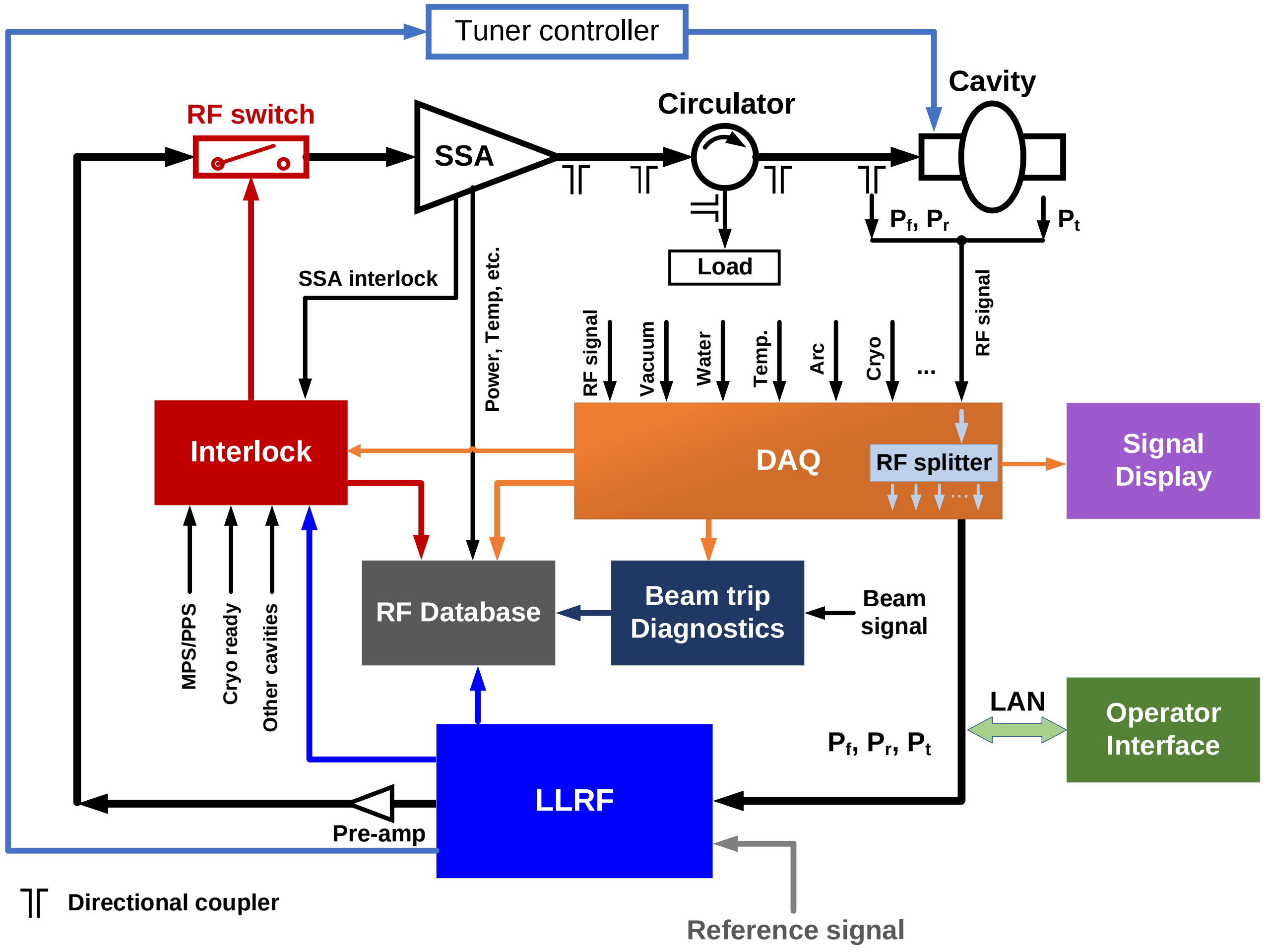
Storage-ring RF

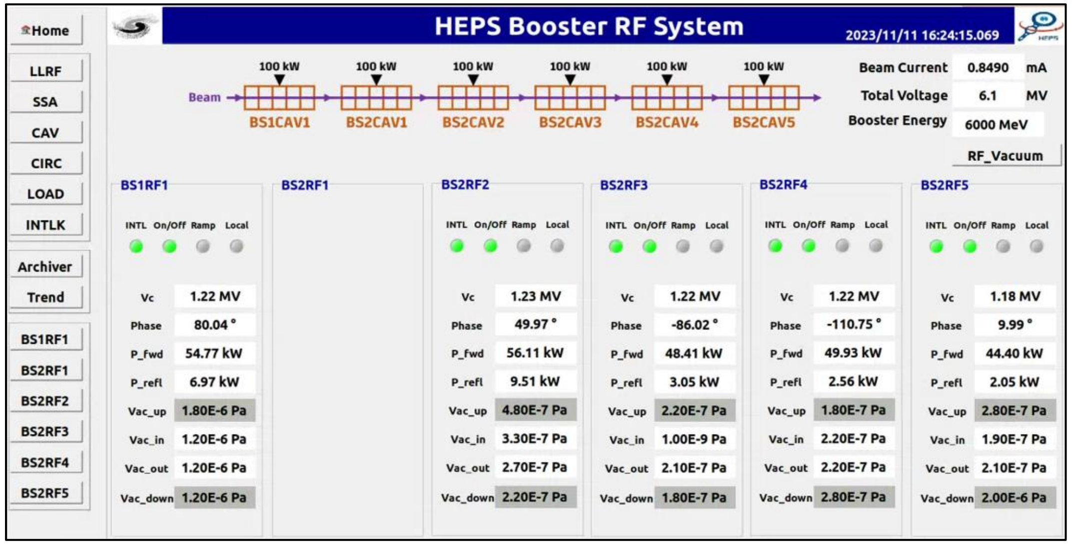


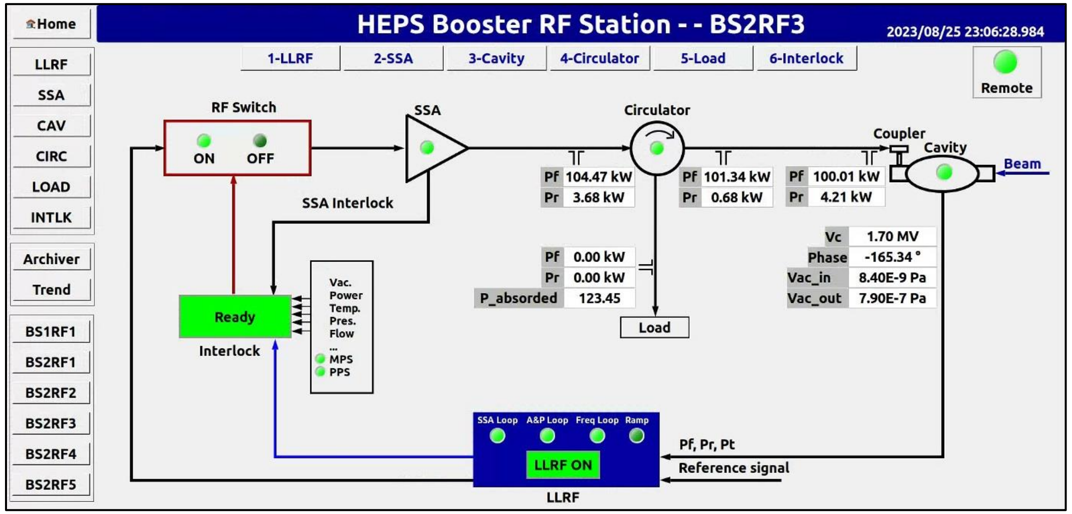
RF hall surface area: 2400 m^2

RF control

- In-house development

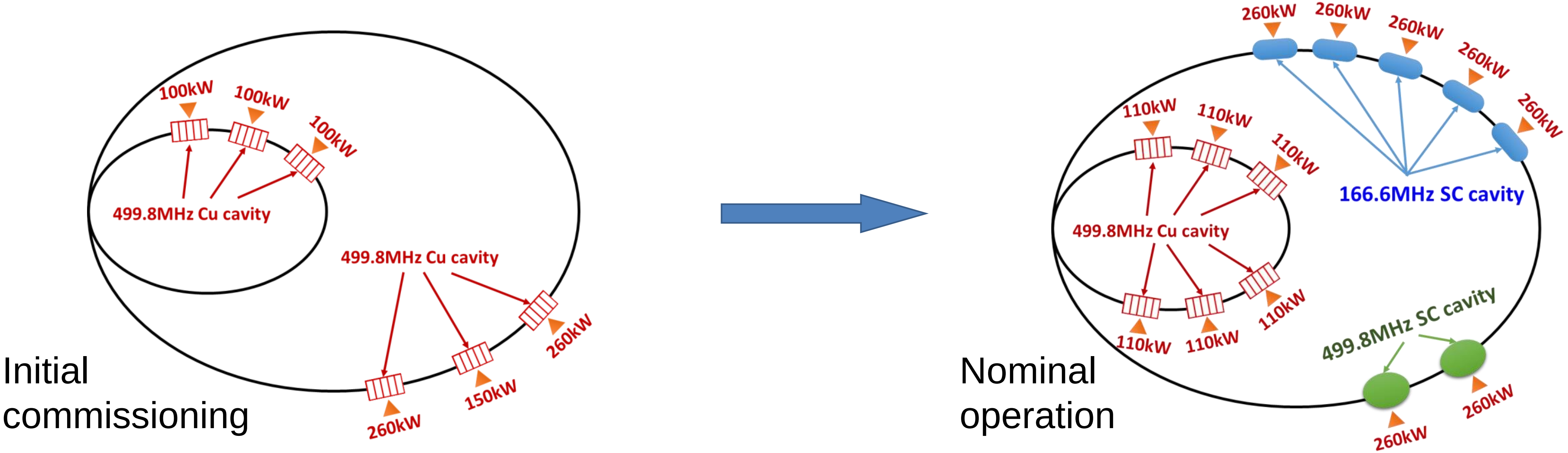






Commissioning in two stages (original plan)

- **Commissioning plan (original)**
  - Initial beam commissioning with normal-conducting cavities
  - Beam commissioning with SRF cavities after ~100 A·hour accumulated beam current
- **Purpose**
  - Vacuum cleaning of the SR: large outgassing by synchrotron light irradiation on vacuum chambers
  - Lower the potential contamination of the SRF cavities
  - Reserve longer development time for the new 166MHz SRF cavities



Initial commissioning with NC cavities

Parameter	Booster	Storage ring	Unit
Beam energy	6	6	GeV
Total energy loss (w/o IDs)	4.02	2.64	MeV/turn
Cavity type	5-cell, copper		
RF frequency	499.8		MHz
Number of cavities	3	3	-
Max. available power at cavity (incl. 10% transmission loss)	100	135	kW
Max. allowable power of FPC	120	120	kW
Forward power per cavity	100	120	kW
Beam current	4	70	mA
Total power loss to SR	16	185	kW
Wall loss per cavity	94	58	kW
Total RF voltage	5	3.96	MV
Limiting factor	SSA	FPC	-

Original plan

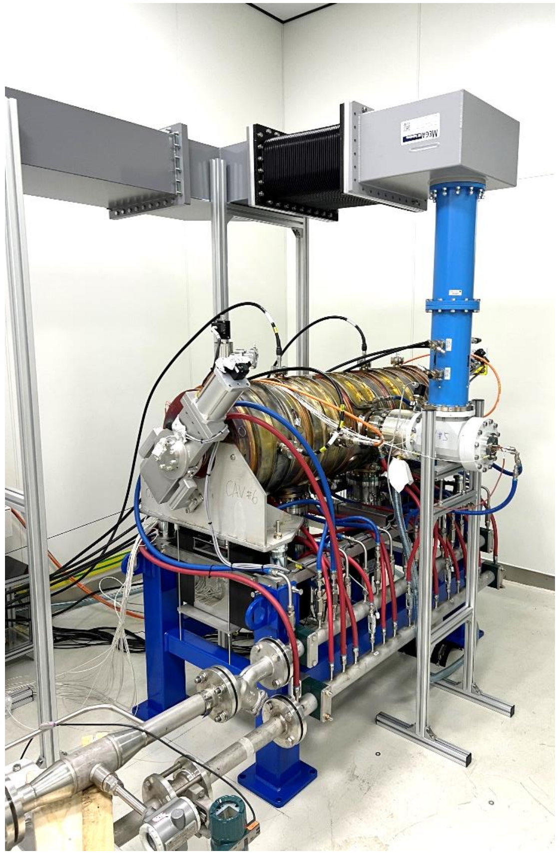
Normal booster operation: 70kW

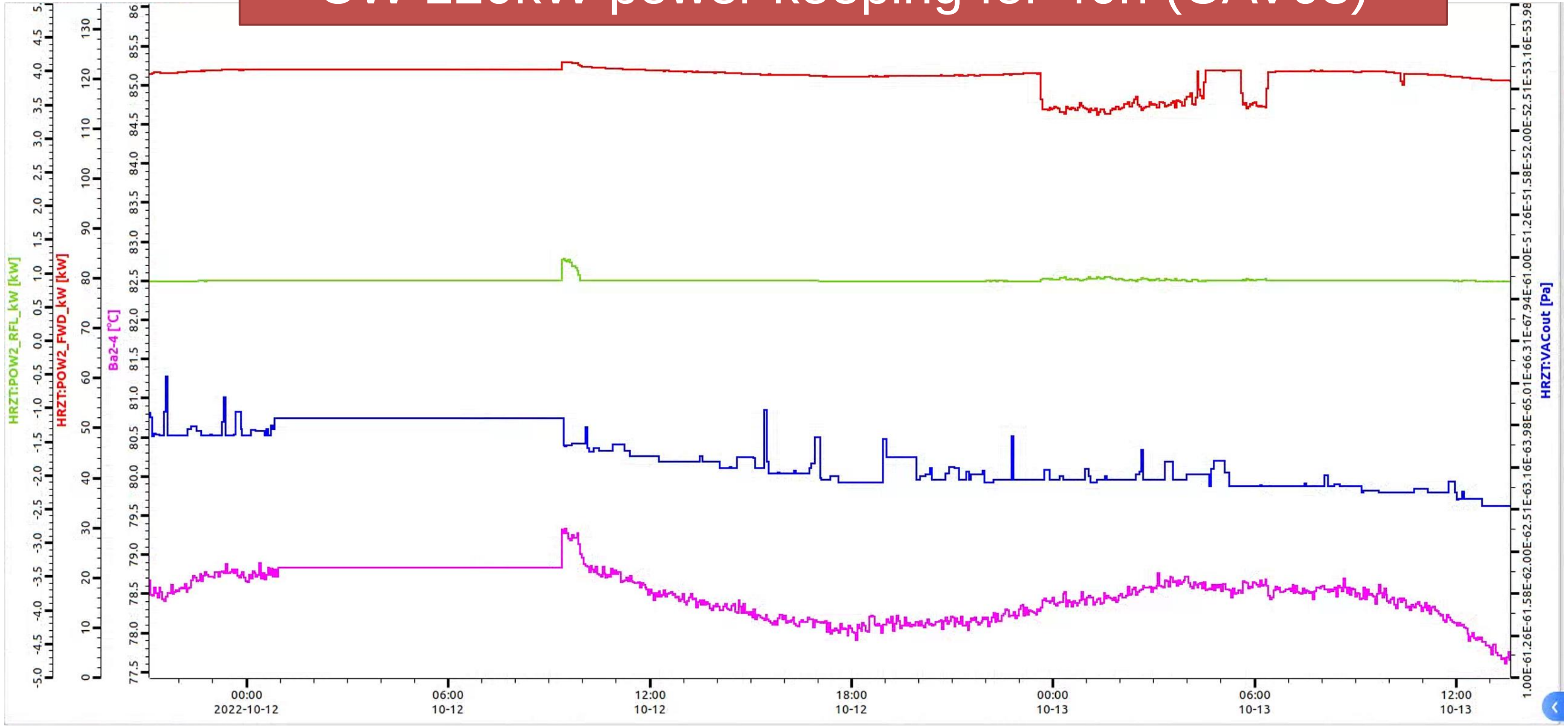
Booster RF

Normal-conducting cavities

- Contract of 6 cavities signed with RI GmbH in 03.2020
- Delivery of all 6 cavities in 11.2022, high-power tests complete in 12.2022

CW 120kW power keeping for 40h (CAV03)



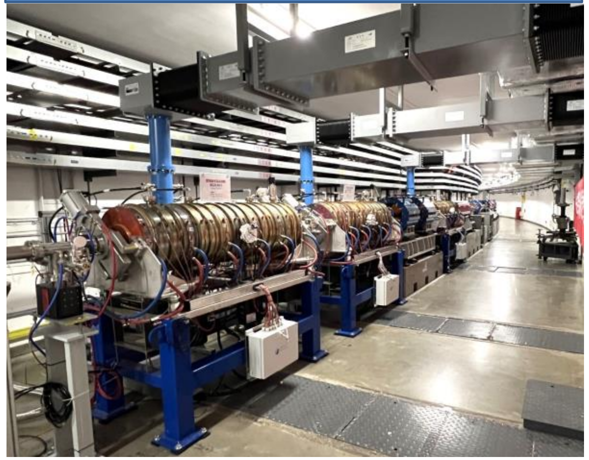


Booster RF installation & commissioning

- 30 Jun. 2022, handover of the BST RF hall
- 8 Oct. 2022, utilities completed installation in BST RF hall
- 24-28 Oct. 2022, 3 cavities installed in BST tunnel
- 16 Dec. 2022, BST-RF installation started
- 06 Jan. 2023, 100kW SSAs installed
- 10 Jan. 2023, waveguide installed
- 14 Apr. 2023, 100kW SSAs passed SAT
- 15 May. 2023, LLRF installation and cabling completed
- 20 Jul. 2023, RF conditioning and system commissioning completed
- 25 Jul. 2023, BST beam commissioning started
- 6 Oct. 2023, BST beam commissioning stopped

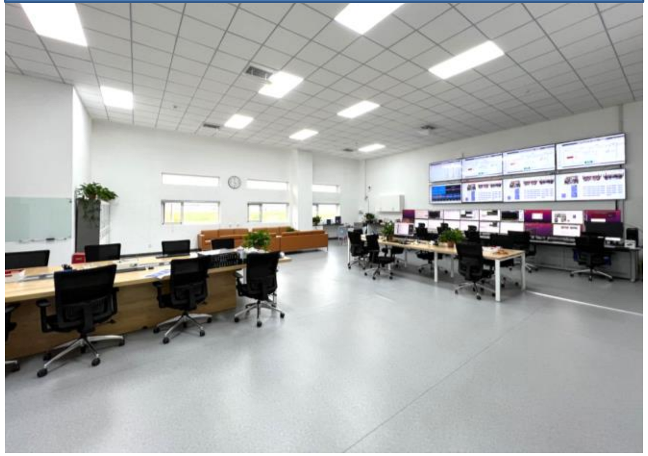
High-power RF

Cavities in BST tunnel



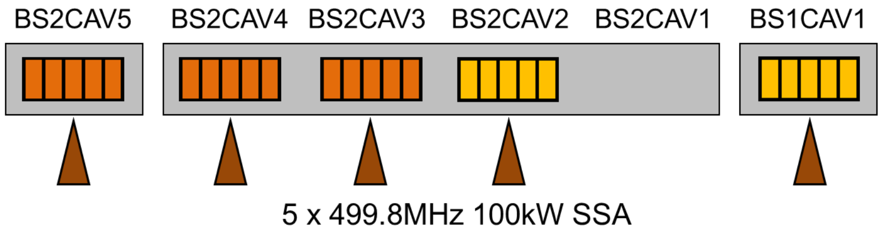
LLRF

BST-RF control room



Change of commissioning plan

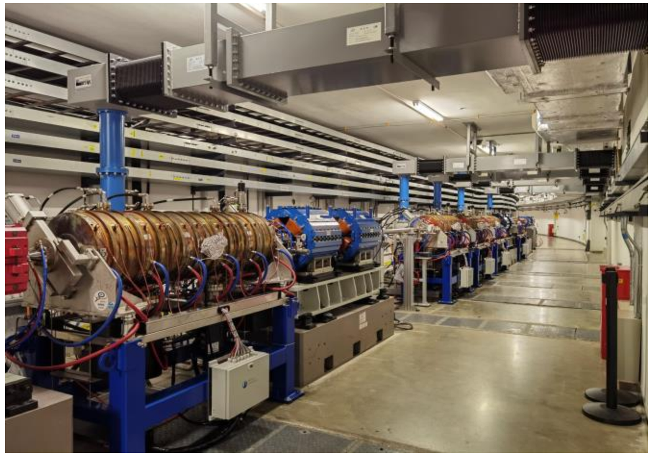
- **Change of plan (Sep 26, 2023)**
  - Acc. Phys. demands **higher RF voltage** for longer beam lifetime at 6 GeV, **higher RF power** for commissioning at 5 nC bunch charge, **ramp & stay** from 500 MeV to any energy up to 6 GeV in 1s
  - HEPS management decided to add 2 more NC cavities (5 cavs. in total) for booster commissioning
- **Impacts**
  - Resource & schedule: 5 pers., 1.5 mos. for installation & commissioning of 2 additional RF systems
  - Insufficient NCRF cavities for storage-ring commissioning (risk A9-R12)
- **Risk A9-R12:** Insufficient NCRF cavities for storage-ring commissioning
  - HEPS management suggested using SRF cavities for commissioning on Day1 (risk A9-R13)
  - Remove the 2 cavities after booster commissioning and stick to the original commissioning plan (require additional resources and time)
- **Risk A9-R13**: SRF cavity contamination due to storage-ring commissioning
  - Learn from other labs' experience: Diamond LS, Taiwan PS, etc.

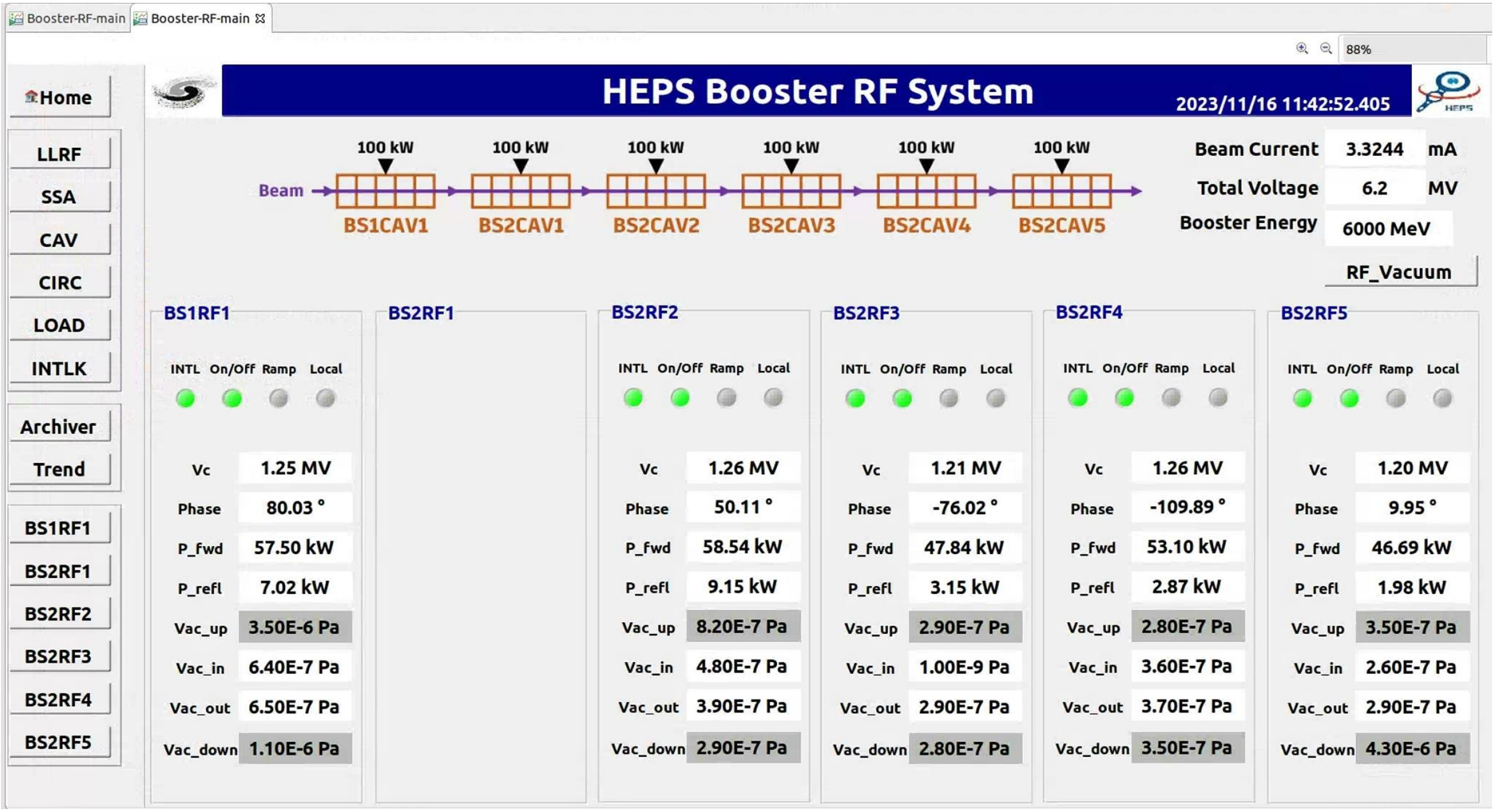


Booster Commissioning (New plan)

Booster RF installation & commissioning

- 7 Oct. 2023, 2 more cavities and RF systems start installation in BST
- 25 Oct. 2023, RF conditioning and commissioning (no beam) complete
- **17 Nov. 2023, BST beam commissioning complete**





Storage-ring RF

RF parameter (SR)

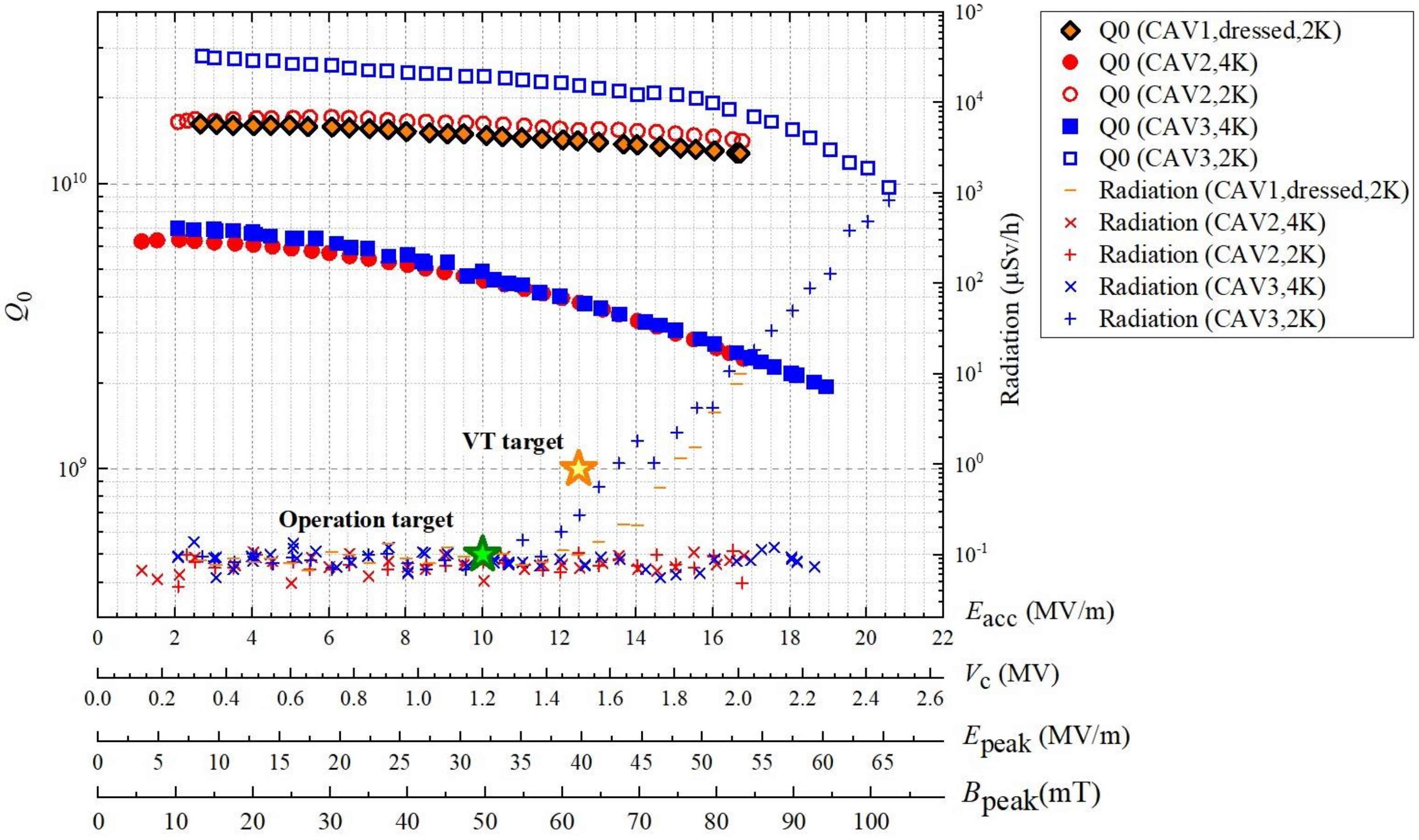
Parameter	Value	Unit
Circumference	1360.4	m
RF frequency (f_0)	166.6	MHz
Total energy loss per turn (U_0)	5.16	MeV
Total beam power (P_b)	850	kW
Total RF voltage (V_{RF})	5.4	MV
Number of main RF cavities	5	-
RF power per main cavity	170	kW
Cavity type	QW + Elliptical SCC	-
HOM control	Heavy damping	-
Harmonic RF frequency (f_{HC})	499.8	MHz
Number of RF stations	5 + 2	-
Transmitter power per RF station	260	kW
Field noise (pk-pk)	±0.1%, ±0.1°	-

166MHz SRF cavity: VT

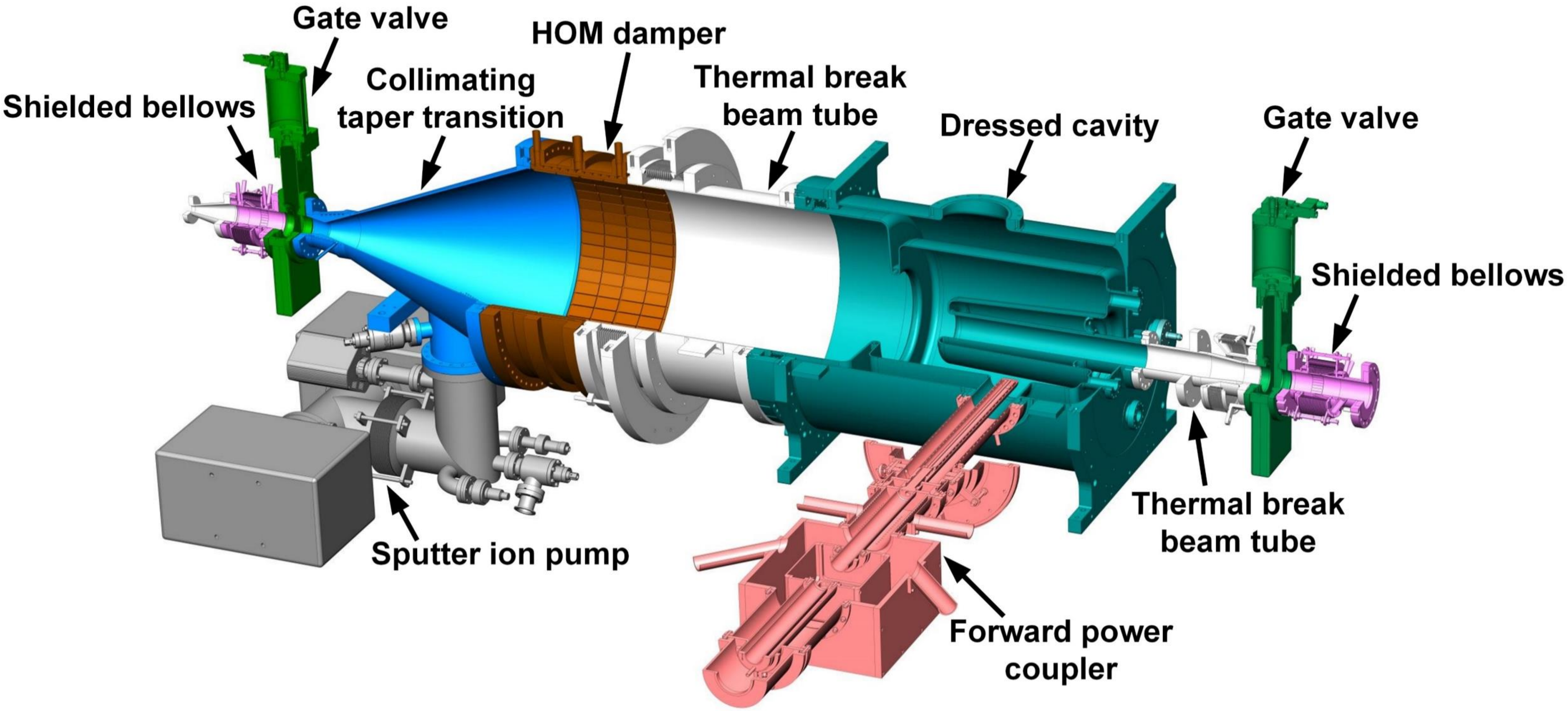
- First batch of cavities: 3 prototype bare cavities passed acceptance tests
- First jacketed cavity performance preserved: no chemistry aft. vessel welding

Bare cavity

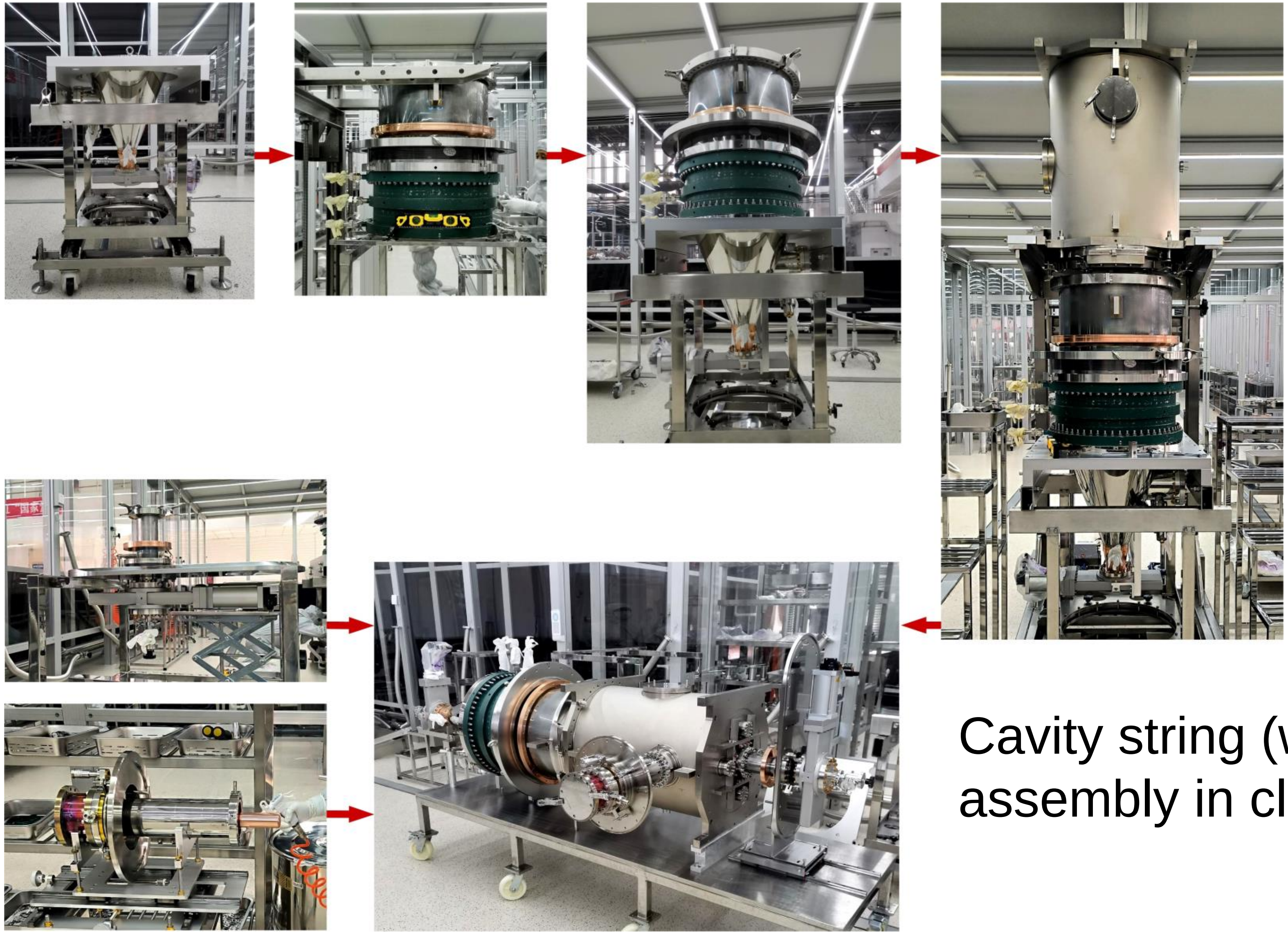
Jacketed cavity



Cavity string



Clean assembly



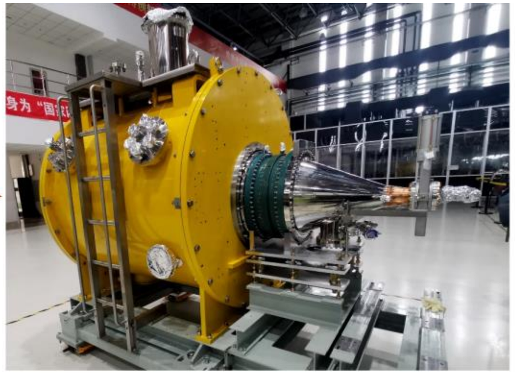
Cavity string (w/o ion pumps) assembly in class 10 clean room.

Cryomodule assembly


Baking and leak check


Collimation, assembly with two-phase pipe


Integration of cavity string and cryomodule


Cryomodule installation completed


class 100 clean room


Assembly of ion pump and cryomodule

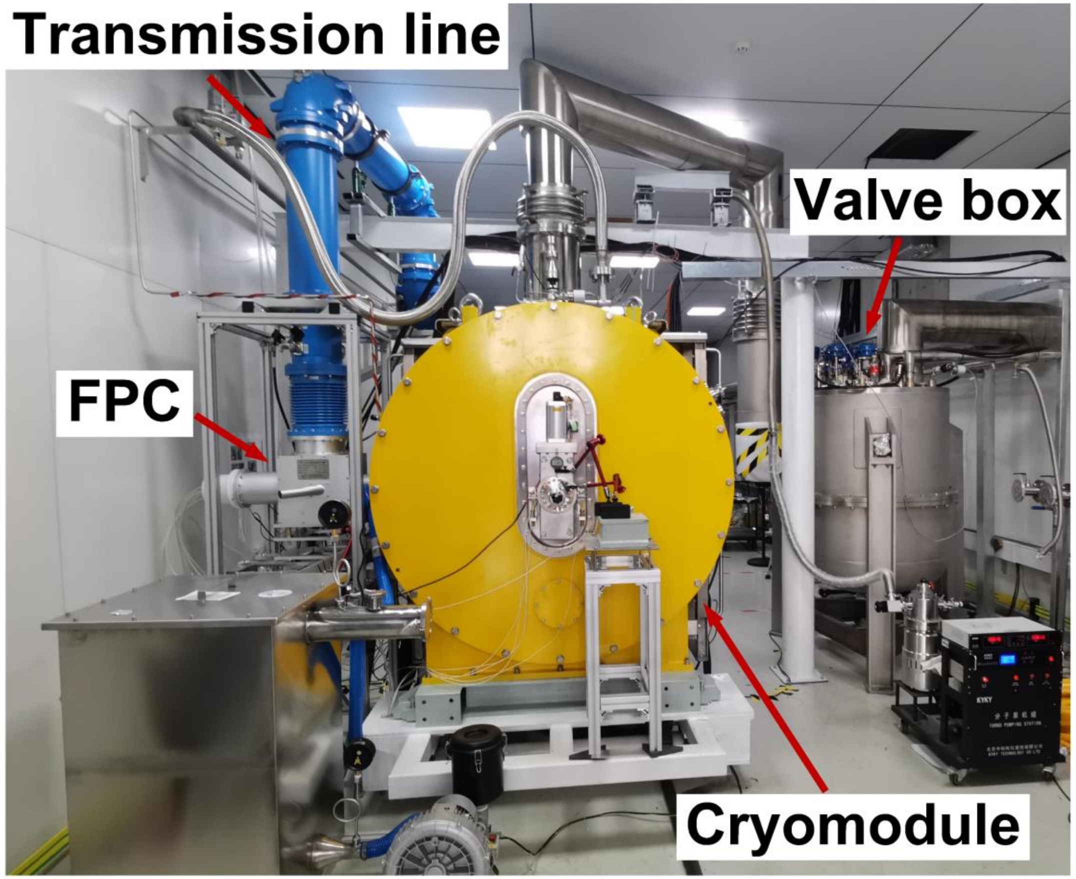
in Class 100 clean room


Ion pump installation completed

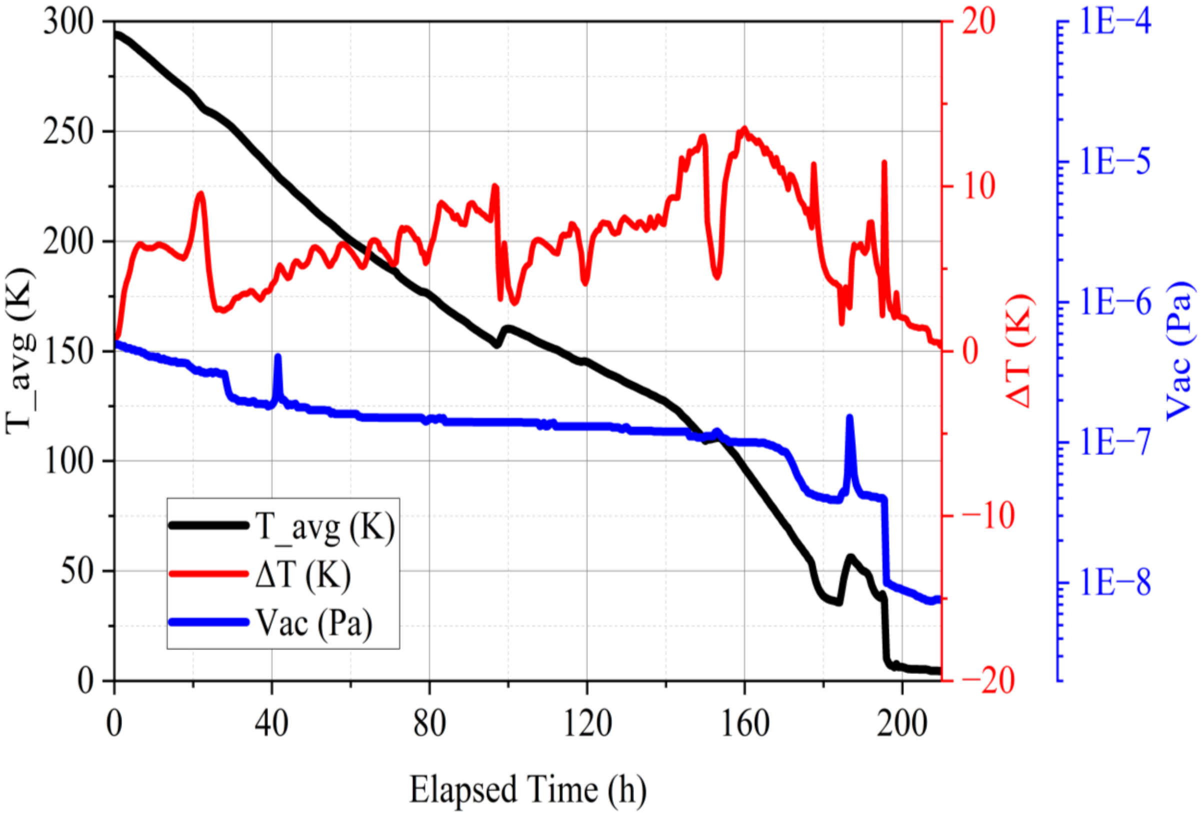
Assembly of tuner and cryomodule

in experiment hall

Module cooldown

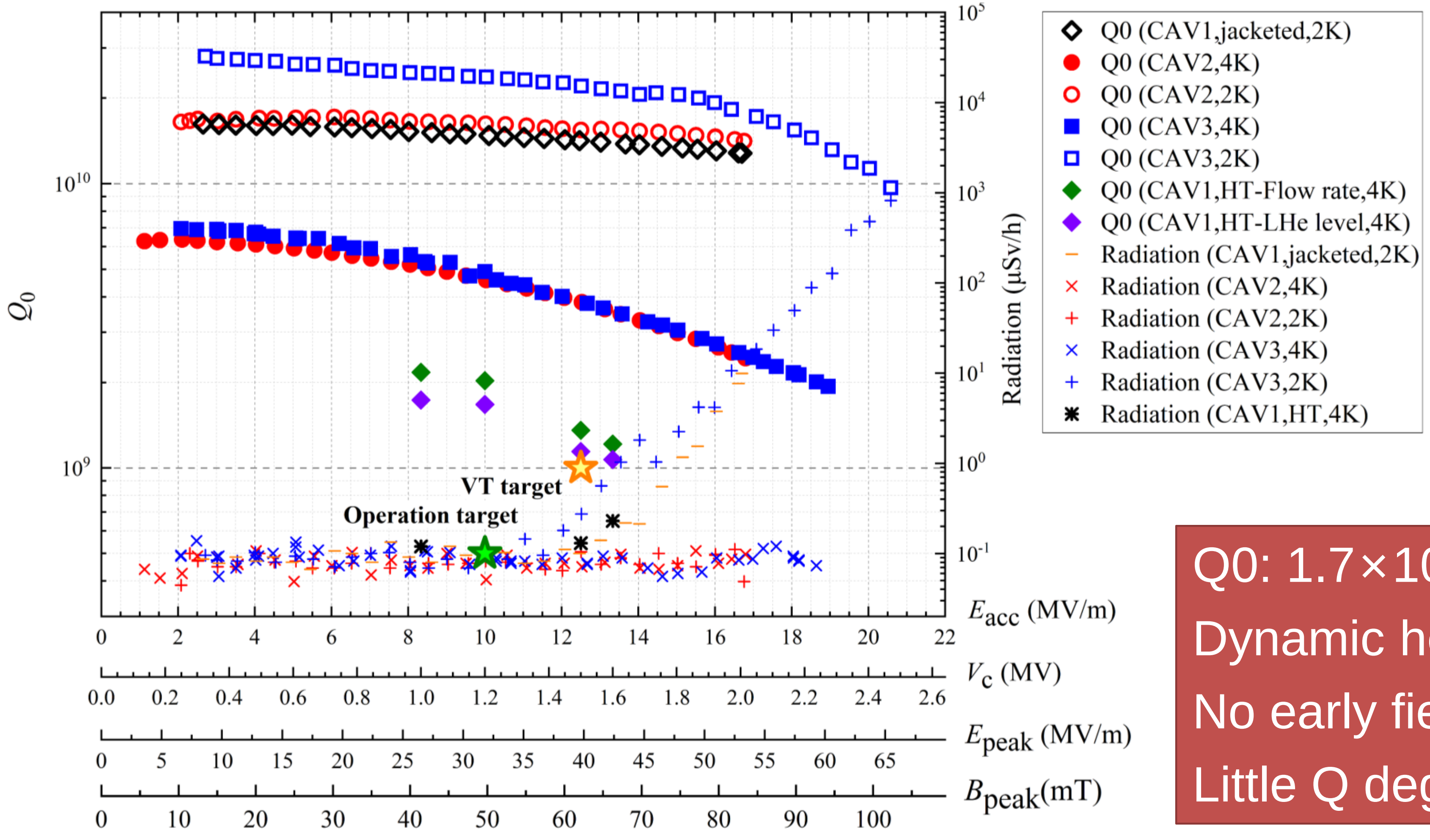


Cooldown



Horizontal test

- Performance demonstrated: assembly procedure, processing, cooldown



Q0: 1.7×10^9 @ 1.2MV

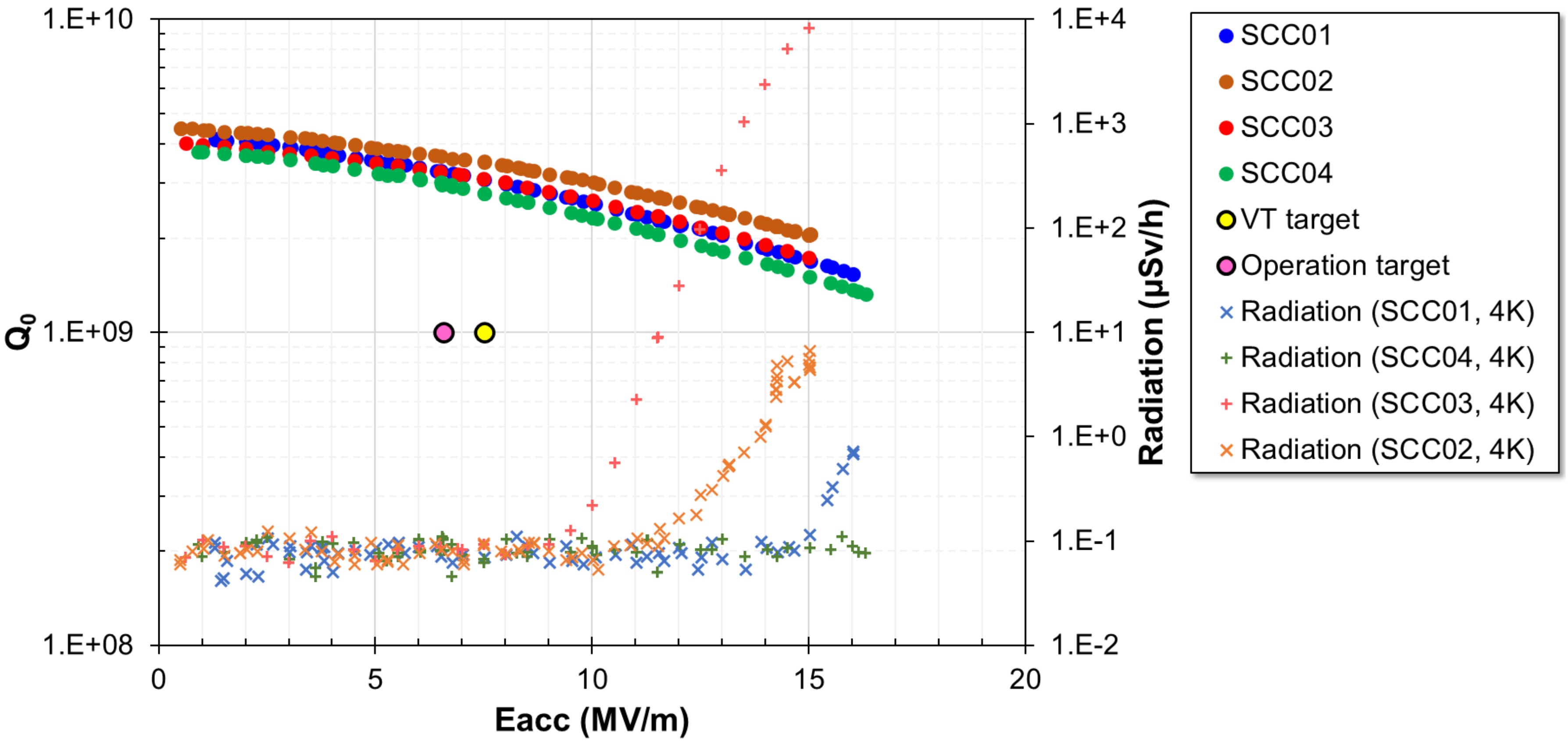
Dynamic heat loss: 6.2W @ 1.2MV

No early field emission

Little Q degradation

500MHz SRF cavity

- All 4 cavities BCP processed, VT complete, fulfill requirements
- Cryomodule assembly to be started by 2023

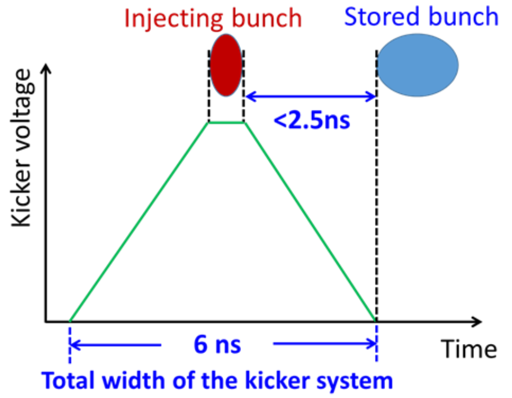


Summary

- **Booster RF system commissioned and in operation**
- **SRF cavity and module**
  - 166MHz SRF cavity module developed and performance demonstrated
  - 500MHz SRF bare cavities VT complete, module assembly to be started
- **RF power sources**
  - Booster SSAs installed and in operation (~3000 hours)
  - SR SSAs series production completed FAT in Q3.2023
  - SR SSAs installation in Q1.2024
- **Low-level RF**
  - In-house developed 2nd generation (Xilinx FPGA) in booster operation
  - Beam trip diagnostics under development


Photo taken in Sep. 2023

Choice of RF frequency



Physics drive

Low emittance

On-axis beam accumulation injection

Two RF frequencies to make two RF buckets

Technology limitation

Kicker system total width ~6ns

Technology readiness

Use 500MHz as harmonic RF

166.6 MHz (fundamental RF)
499.8 MHz (harmonic RF)

[1] G. Xu *et al.*, "On-axis Beam Accumulation Enabled by Phase Adjustment of a Double-frequency RF System for …", *IPAC2016*, WEOAA02.
[2] D. Zhe *et al.*, "Top-up injection schemes for HEPS", *eeFACT2016*, TUT2H4.
[3] S. Jiang and G. Xu, "On-axis injection scheme based on a triple-frequency rf system for …", *Phys. Rev. Accel. Beams* 21 (110701) 2018.