Radio-Frequency System of the High Energy Photon Source

Pei Zhang

(IHEP, CAS)

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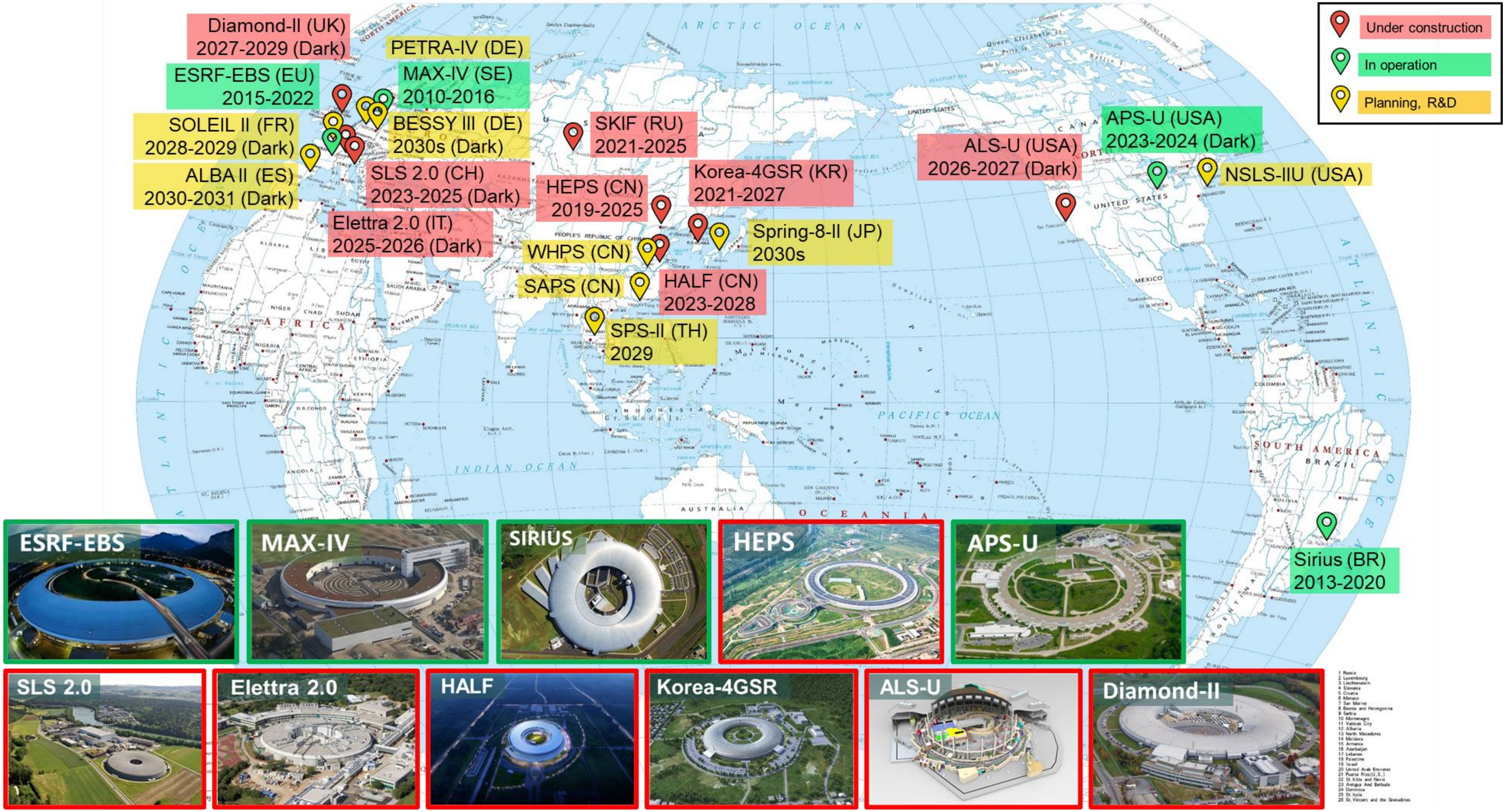
Outline

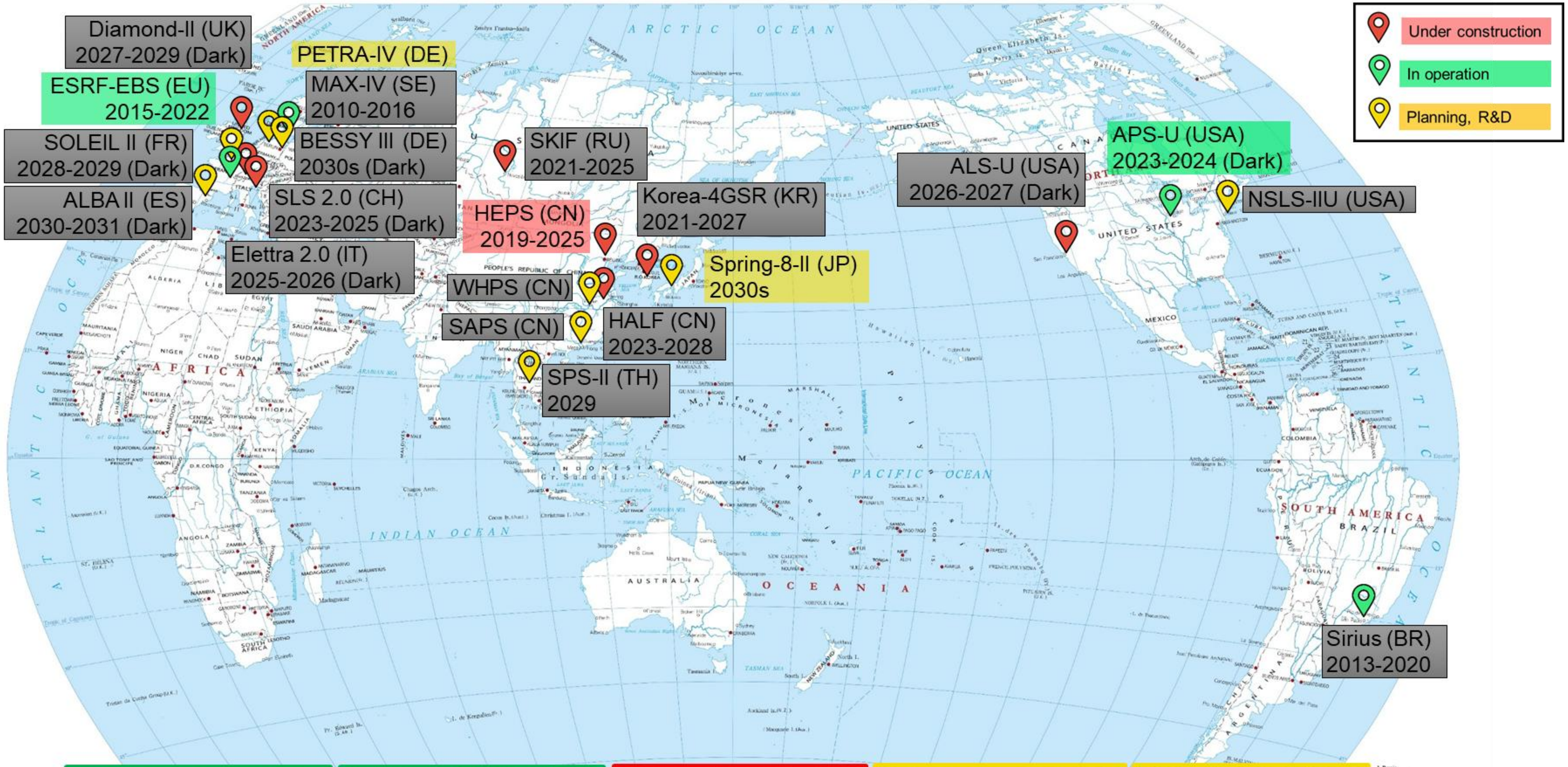
- Introduction to HEPS
- RF system design
- Development highlights
- Installation & commissioning
- Summary

Introduction to HEPS

Landscape of the 4th-gen SR facilities

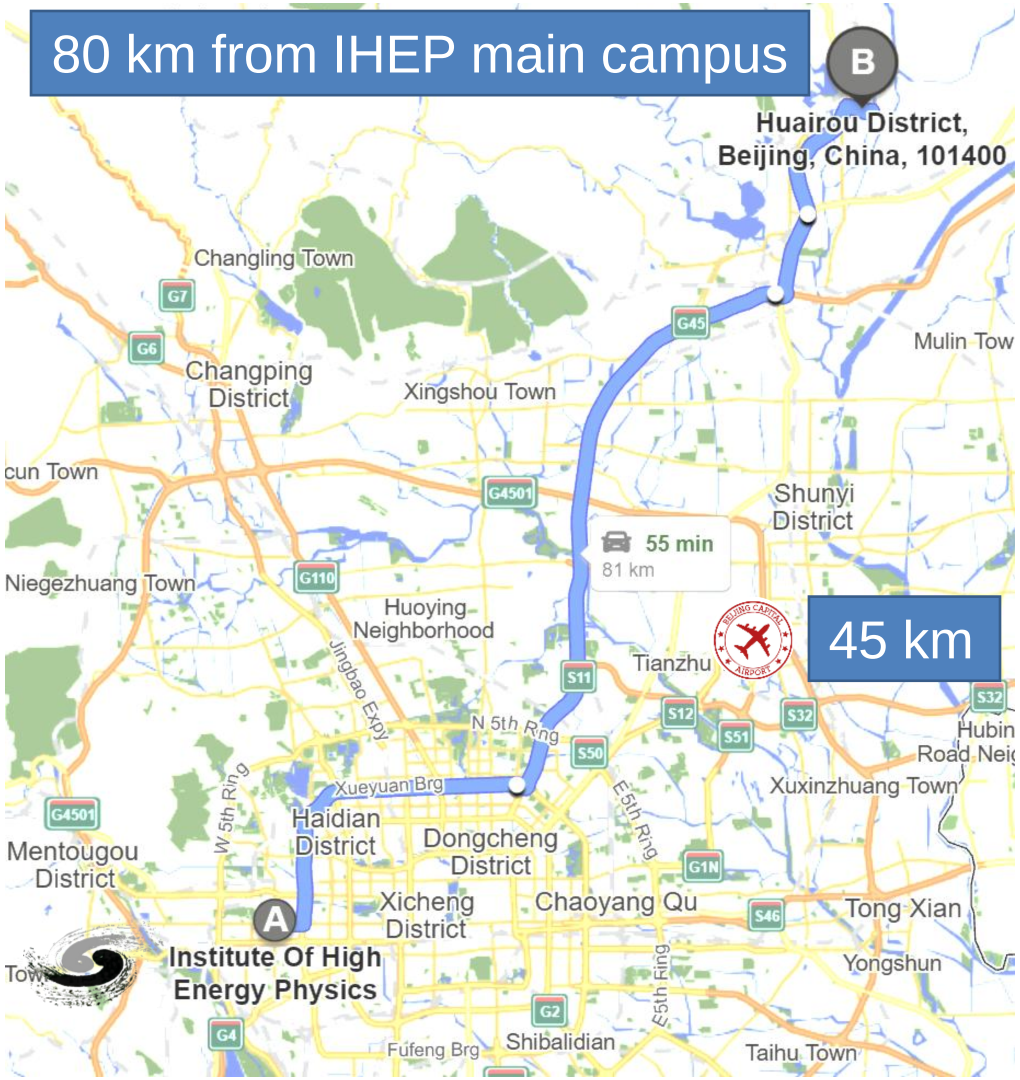


High-energy 4th-gen SR facilities



High Energy Photon Source (HEPS)

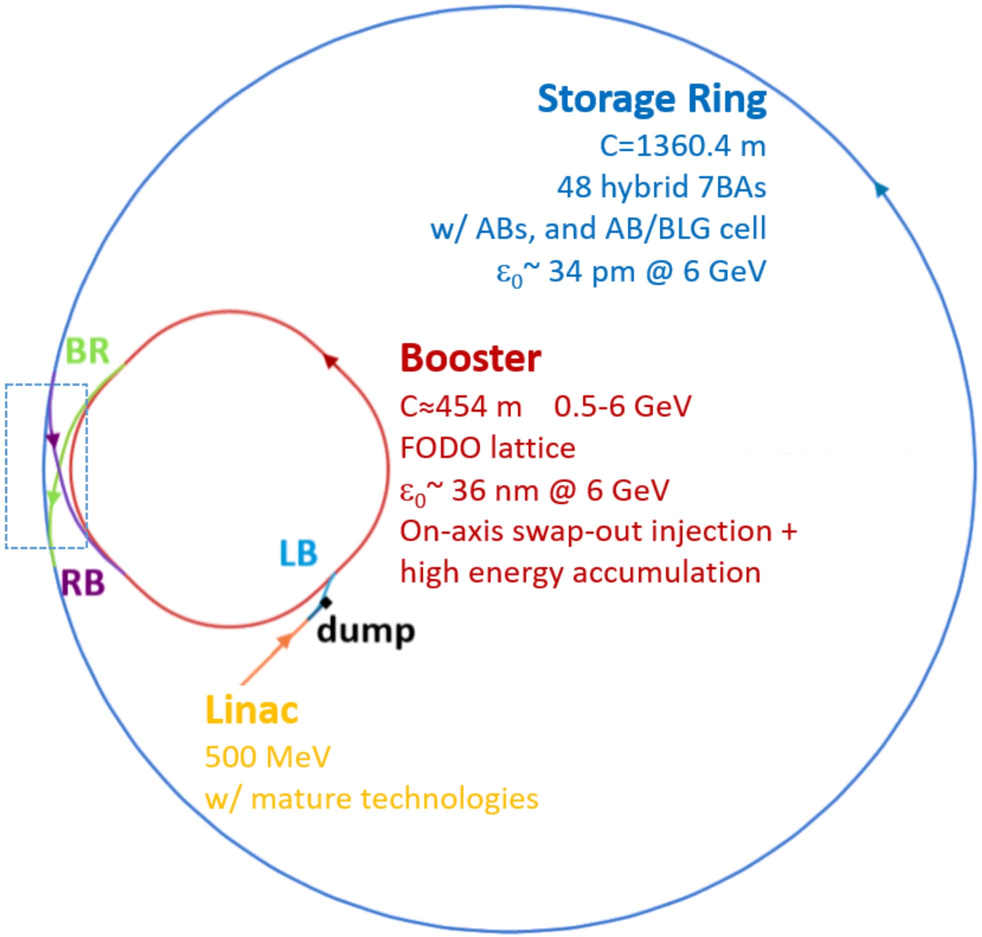
- **Project outline**
  - A diffraction-limited SR light source (4^{th}-gen)
  - **The 1^{st} high-energy SR light source in China**
  - **Location**: Huairou Science City, Beijing
  - **Construction time**: 06.2019 – 12.2025
  - **Land**: 650,667 m^2, **Building**: 125,000 m^2
  - **Budget**: 4.76B CNY (~$652M)(incl. materials, civil constr. & commissioning, excl. labor costs)
  - **Funding**: Central government + Local government + Chinese Academy of Sciences



HEPS in Huairou Science City (Beijing)

100.9 km^2 **5** large science facilities

Main parameters: accelerator



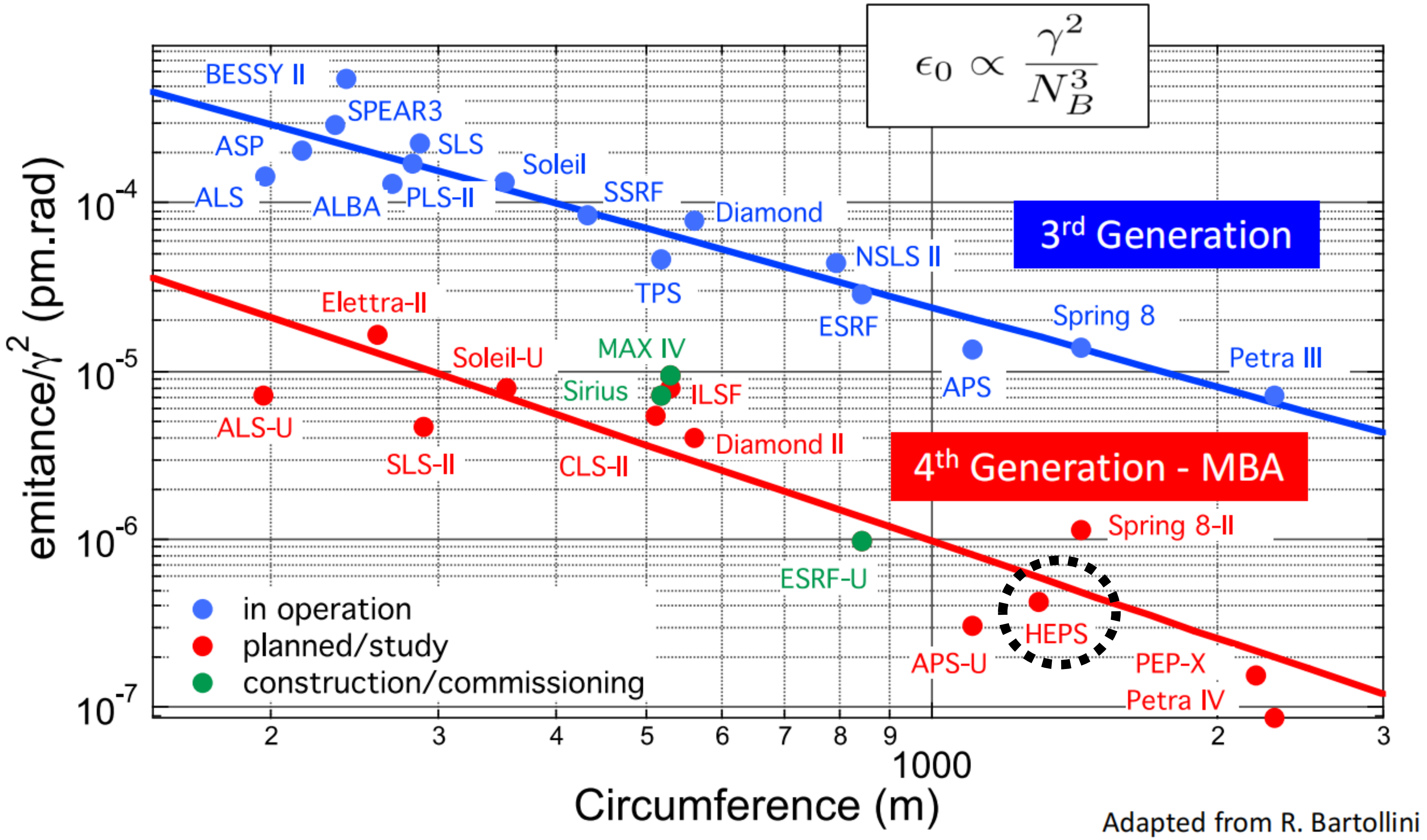
[1] Y. Jiao *et al.*, *J. Synchrotron Rad.* 25, 1611–1618 (2018).
[2] H. Xu *et al.*, *RDTM* 7, 279–287 (2023).
[3] C. Meng *et al.*, *RDTM* 4, 497–506 (2020).

- **Accelerator complex**
  - Linac (500 MeV)
  - Booster (500 MeV to 6 GeV, 1 Hz)
  - Storage ring (6 GeV, top-up)

Parameter	Value	Unit
Beam energy	6	GeV
Circumference	1360.4	m
Lattice type	Hybrid 7BA	
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

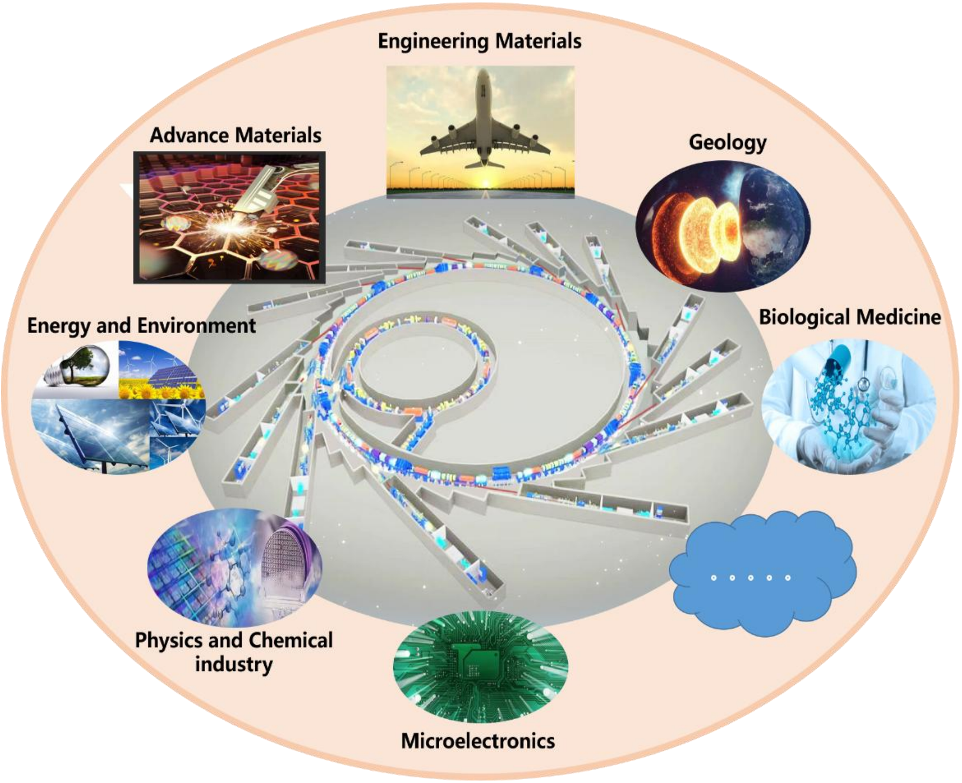
Main parameters: accelerator

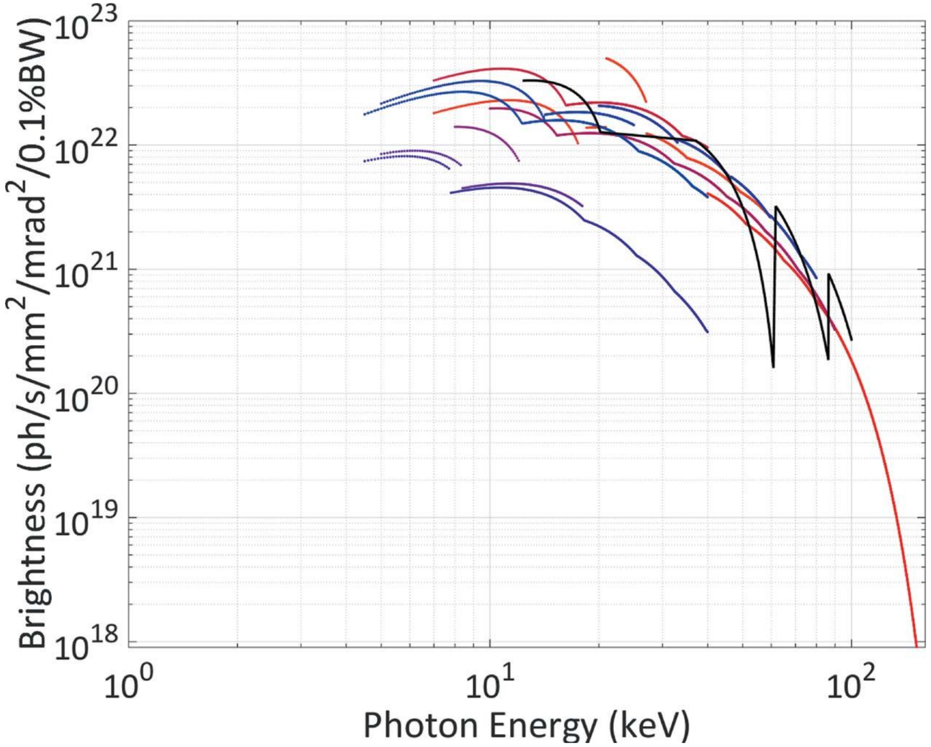


L. Liu, H. Westfahl Jr., IPAC2017, TUXA1.

Main parameters: beamlines

- 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 1, HEPS can accommodate up to 90 beamlines





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

Milestones

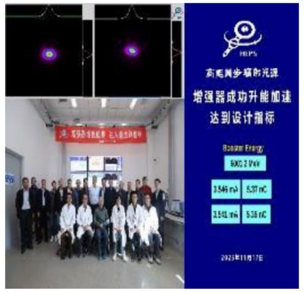
- 2025.03 ~ 2025.05, joint commissioning of accelerator and BLs
- 2025.05 ~ 2025.08, installation of SRF cavities and IDs, re-alignment of BS and SR
- 2025.09 ~, beam current ramp up to 100mA, reaching KPPs

May 12, 2022
The Linac Vacuum-sealing in the tunnel completed

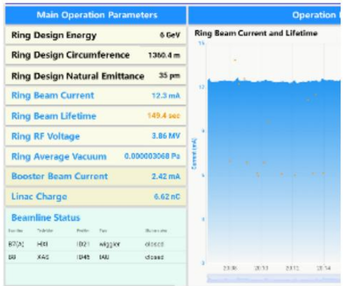
Jan. 13, 2023
The Booster Vacuum-sealing in the tunnel completed

Feb. 1,2023
The first girder was installed in the storage ring tunnel

Mar. 14, 2023
The first electron beam



Nov. 17, 2023
Electron Beam Ramped Up to 6 GeV

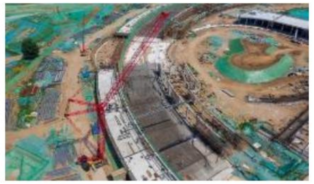


Aug. 18, 2024
Electron beams with currents higher than 10mA were successfully stored.

Oct. 12, 2024
the SR X-ray emitted from the R21 wiggler was successfully transmitted to the end station.

June 29, 2019
Groundbreaking ceremony

July 1, 2020
The first steel beam was installed



Apr. 13, 2021
Utility installation in NO.2 Hall commenced

June 27, 2021
Roof-sealing work for the main ring building completed

June 28, 2021
HEPS Installs First Piece of Accelerator Equipment in Linac Tunnel.

Nov. 3, 2023
Civil Construction for ancillary buildings completed

RF system design

RF-related beam parameters

Parameter (SR)	Value	Unit
Circumference	1360.4	m
Beam energy	6	GeV
Beam current	200	mA
Energy loss per turn (bare)	2.64	MeV
Total energy loss per turn	4.14	MeV
Total power loss to radiation	828	kW
Momentum compaction	1.88×10^{-5}	-
Natural bunch length	5.06	mm
Bunch length with HC	29.8	mm
Radiation damping time (x/y/z)	10.85/20.62/18.76	ms
No./Length of straights	24/6.086	m
Total CBI threshold (x/y)	3.4E+6/1.87E+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

Parameter (BS)	Value	Unit
Circumference	454.066	m
RF frequency	499.8	MHz
Harmonic number	757	-
Electron beam energy	0.5 – 6	GeV
Electron beam current	13	mA
Total SR loss @ 6GeV	4.02	MeV/turn
Total power loss to SR	52.3	kW
Total RF voltage	2 – 8	MV
Repetition rate	1	Hz

Parameter (SR)	Value	Unit
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

RF work package definition

- **Goal**: The design, construction and commissioning of the radio-frequency system for the **booster ring** and the **storage ring** of the High Energy Photon Source (HEPS).
- **Objectives**

  - Complete the integration and commissioning of 6 sets of 499.8 MHz normal-conducting RF system with the following specifications fulfilled.
  - Complete the development, integration and commissioning of 5 sets of 166.6 MHz SRF systems and 2 sets of 499.8 MHz SRF systems with the following specifications fulfilled.

Parameter	BS	SR (main)	SR (HC)
RF frequency	499.8 MHz	166.6 MHz	499.8 MHz
Number of cavities	6	5	2
RF technology	NCRF	SRF	SRF
RF voltage per cavity (Vc)	≥ 1.35 MV	≥ 1.1 MV	≥ 1.7 MV
Cavity Q0 (at Vc)	≥ 29000	$\geq 5\times10^8$	$\geq 1\times10^9$
Cavity field amplitude stability (pk-pk)	±1%	±0.1%	±0.1%
Cavity field phase stability (pk-pk)	±1°	±0.1°	±0.1°
RF power per transmitter	≥ 90 kW	≥ 200 kW	≥ 200 kW

RF work package scope

- **System A9 Radio Frequency** — P. Zhang
  - **A9.1 Cavity** — P. Zhang
    - **A9.1.1 166MHz SRF Cavity** — X.Y. Zhang, L. Guo
    - **A9.1.2 500MHz SRF Cavity** — H.J. Zheng
    - **A9.1.3 500MHz NCRF Cavity** — T.M. Huang
    - **A9.1.4 Ancillaries: Tuner** — Z.H. Mi
    - **A9.1.5 Ancillaries: HOM Damper** — F.B. Meng
  - **A9.2 High-Power RF** — T.M. Huang
    - **A9.2.1 166MHz SSA** — H.Y. Lin, Y.L. Luo
    - **A9.2.2 500MHz SSA** — J. Li, Y.L. Luo
    - **A9.2.3 Power Transmission** — T.M. Huang
    - **A9.2.4 Power Coupler** — T.M. Huang
  - **A9.3 RF Control** — Q.Y. Wang
    - **A9.3.1 Low-level RF** — Q.Y. Wang
    - **A9.3.2 RF Interlock** — H.Y. Lin
    - **A9.3.3 DAQ & Database** — D.B. Li
    - **A9.3.4 Diagnostics** — Q.Y. Wang, D.B. Li
  - **A9.4 INTG & CX** — Q. Ma, Q.Y. Wang
    - **A9.4.1 Cryomodule Assembly** — Q. Ma, J. Dai
    - **A9.4.2 Cryomodule Testing** — X.Y. Zhang, H.J. Zheng
    - **A9.4.3 RF System Integration** — F.C. Zhao, H.Y. Lin
    - **A9.4.4 RF System Commissioning** — Q.Y. Wang, T.M. Huang
  - **A9.5 Interface** — F.C. Zhao
    - **A9.5.1 Acc. Physics** — H.J. Zheng, Q.Y. Wang
    - **A9.5.2 Cryo. & Vacuum & Mech.** — Q. Ma, X.Y. Zhang
    - **A9.5.3 Acc. Control** — D.B. Li, Q.Y. Wang
    - **A9.5.4 Radiation Protection** — F.C. Zhao
    - **A9.5.5 Civil const. & Utilities** — F.C. Zhao
    - **A9.5.6 Installation & Alignment** — F.C. Zhao, Q. Ma

RF: Radio Frequency, **SRF**: Superconducting RF, **NCRF**: Normal-conducting RF
HOM: Higher Order Mode, **SSPA**: Solid-State Power Amplifier
INTG: Integration, **CX**: Commissioning

Version: 2023.08.22

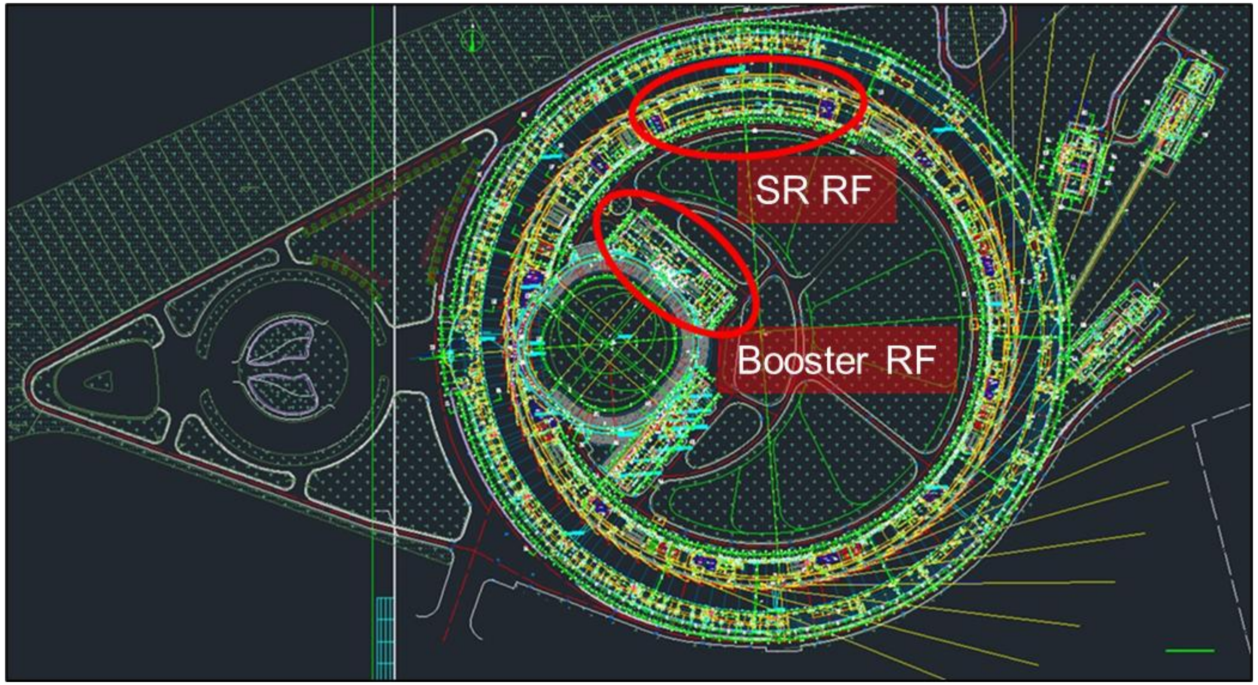
Main deliverables of RF WP

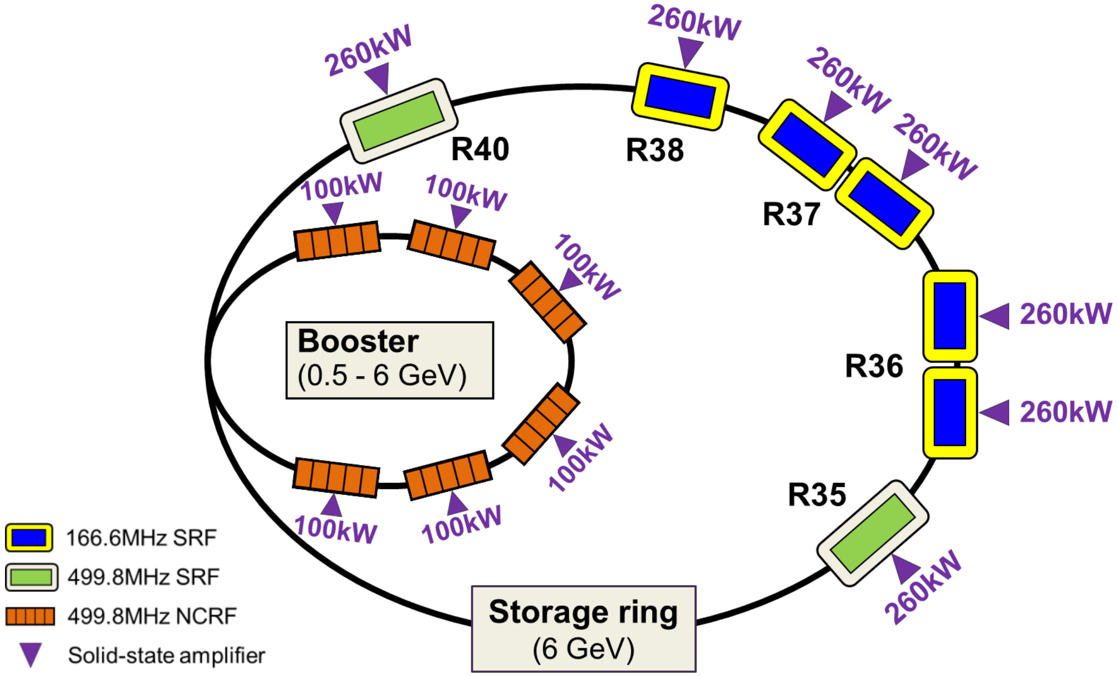
- **Cavities**
  - 5 sets of 166.6 MHz SRF cavity modules
  - 2 sets of 499.8 MHz SRF cavity modules
  - 6 sets of 499.8 MHz NCRF cavities
- **High-power RF**
  - 5 sets of 166.6 MHz 260 kW solid-state power amplifiers
  - 2 sets of 499.8 MHz 260 kW solid-state power amplifiers
  - 6 sets of 499.8 MHz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

7 SRF modules
6 NCRF cavities
2.4MW CW SSAs
13 LLRF controls

Main features of the RF system

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



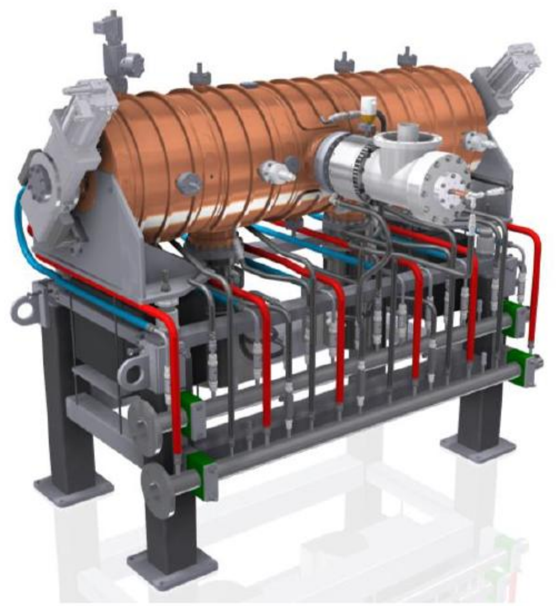


P. Zhang *et al.*, ”Radio-frequency system of HEPS”, *Radiation Detection Technology and Methods* 7, 159-170 (2023).

Main RF parameters

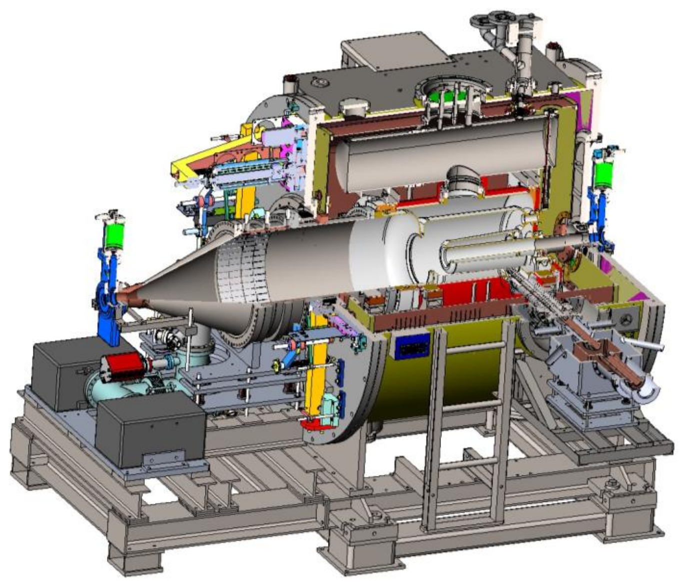
Parameter	BS	SR (main)	SR (HC)	Unit
RF frequency	499.8	166.6	499.8	MHz
Total RF voltage	2 – 8	5.4	0.91	MV
Cavity technology	Normal-conducting	Superconducting	Superconducting	-
Cavity type	5-cell	β=1 quarter-wave	1-cell elliptical	-
Technology readiness	Mature product	In-house new dev.	In-house dev.	-
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)	190	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)	±1%, ±1°	±0.1%, ±0.1°	±0.1%, ±0.1°	-
LLRF technology	Digital LLRF (in-house dev.)			-

RF cavities



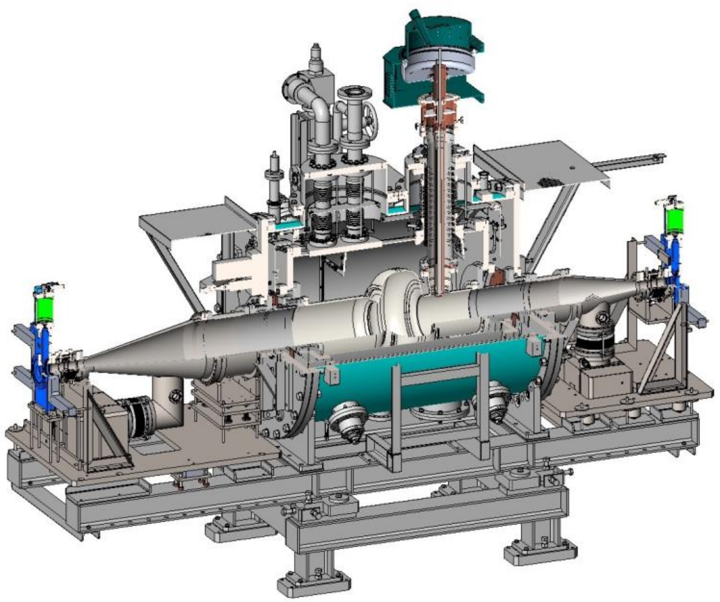
500MHz PETRA-type
5-cell copper cavity
(Booster)

Procured from RI
(Modifications)



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

In-house development
(New)



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

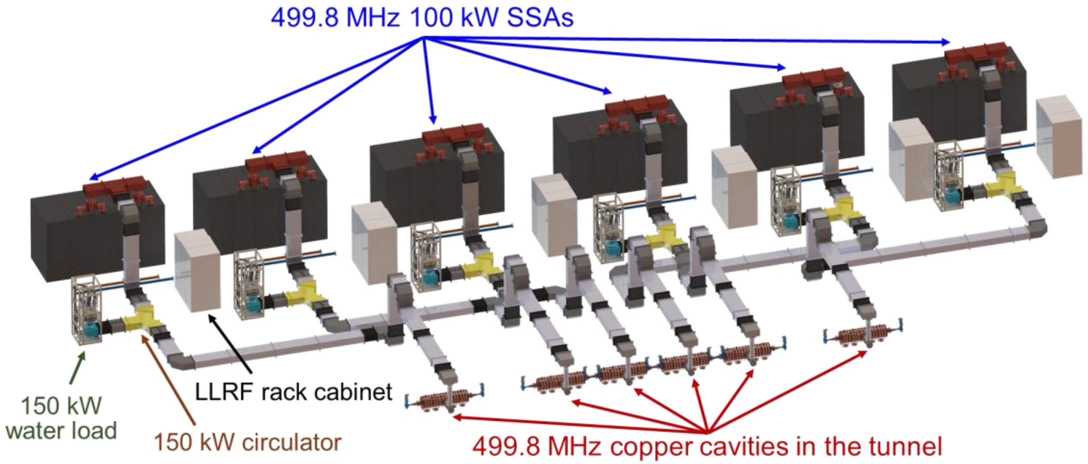
In-house development
(Mechanically-improved)

[1] P. Zhang *et al.*, “Development and vertical tests of a 166.6 MHz proof-of-principle superconducting quarter-wave beta = 1 cavity”, *Rev. Sci. Instrum.* 90, 084705 (2019).
[2] L. Guo *et al.*, “Development of a 166.6 MHz β = 1 higher-order-mode-damped superconducting cavity”, *Rev. Sci. Instrum.* 95, 074702 (2024).
[3] H. Zheng *et al.*, “Development and tests of the 499.8 MHz srf cryomodules for HEPS”, *JINST* 19, P10031 (2024).
[4] 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).

High-power RF

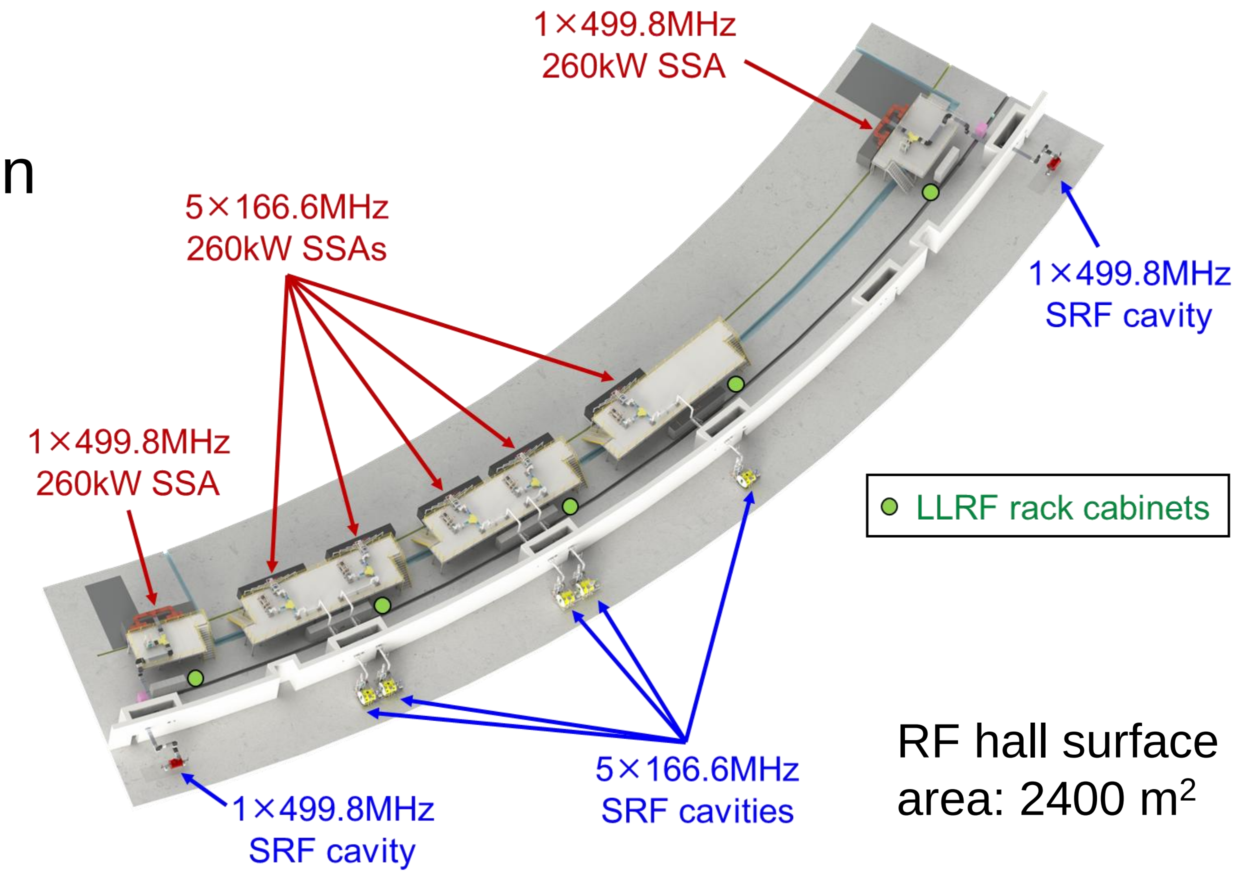
- Transmitter type: SSA
- Power transmission
  - 9-3/16” coaxial rigid lines for 166MHz
  - WR1800 rectangular waveguide for 500MHz
- High-power circulator for each RF station

Booster RF



RF hall surface area: 1600 m^2

Storage-ring RF

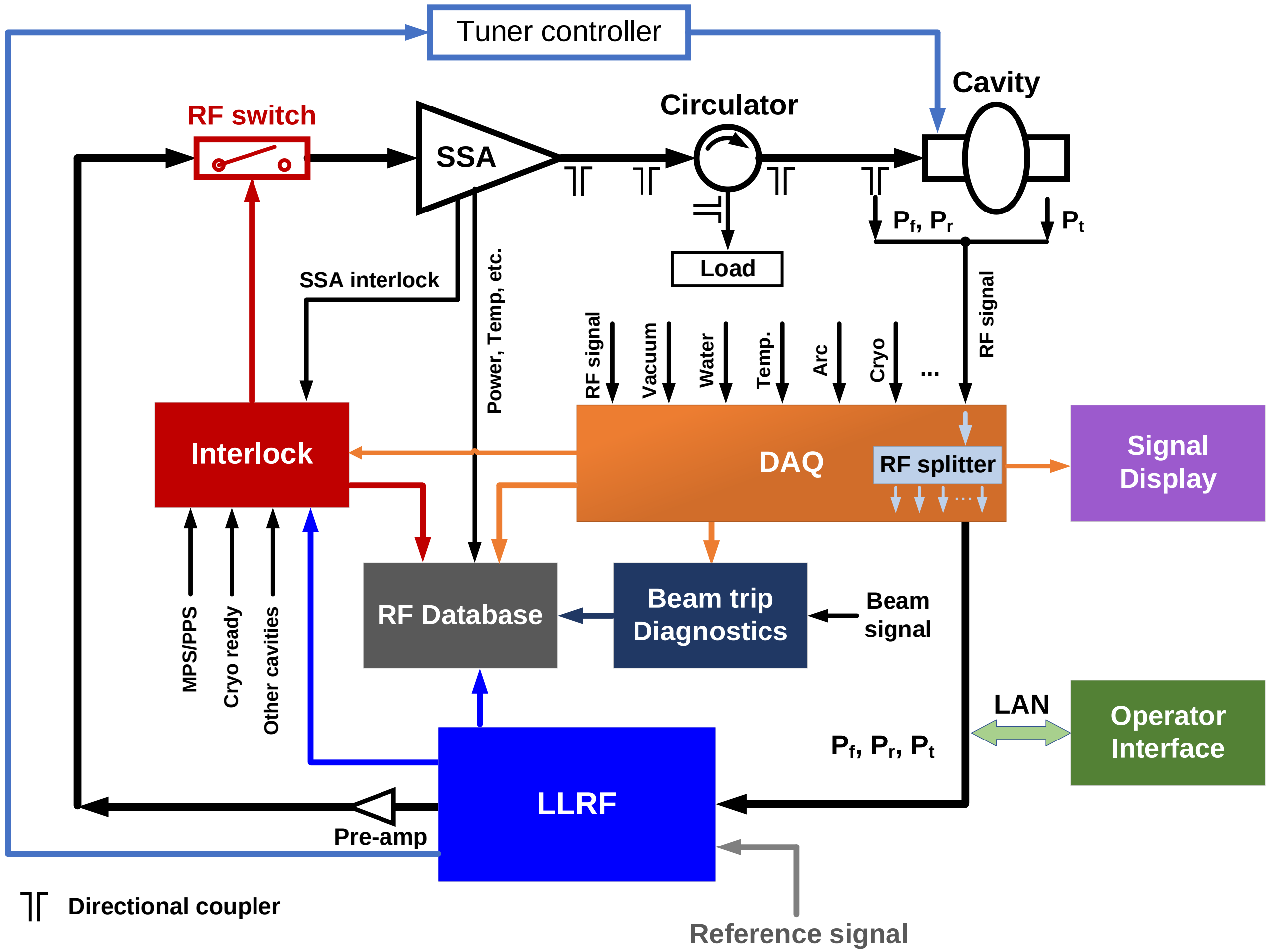


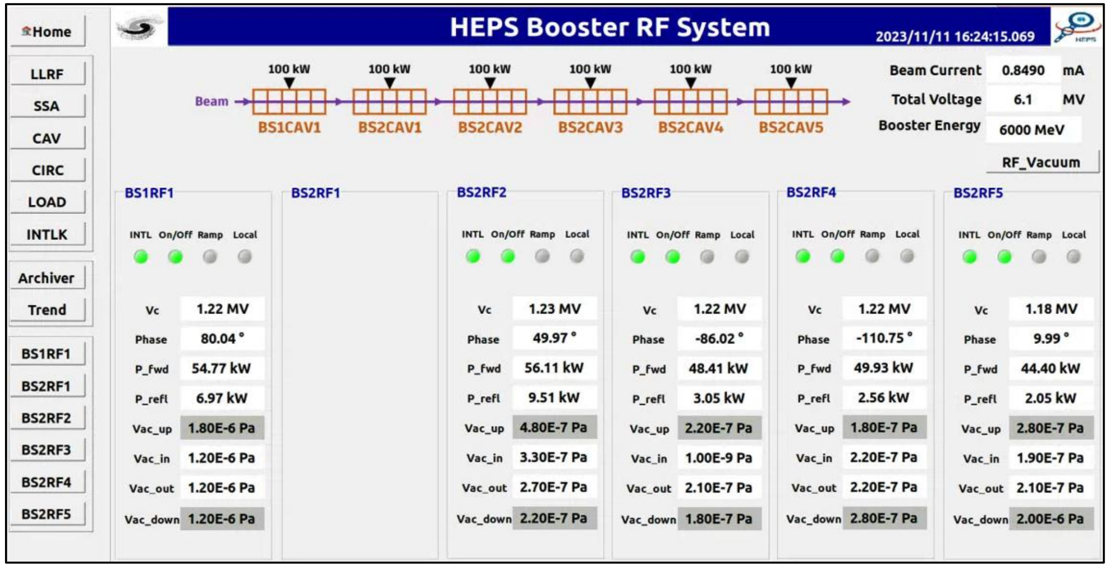
RF hall surface area: 2400 m^2

Y. Luo *et al.*, *IPAC2023*, WEPM014.

RF control

- In-house development: LLRF and Interlock hardware, OPI, RF local database

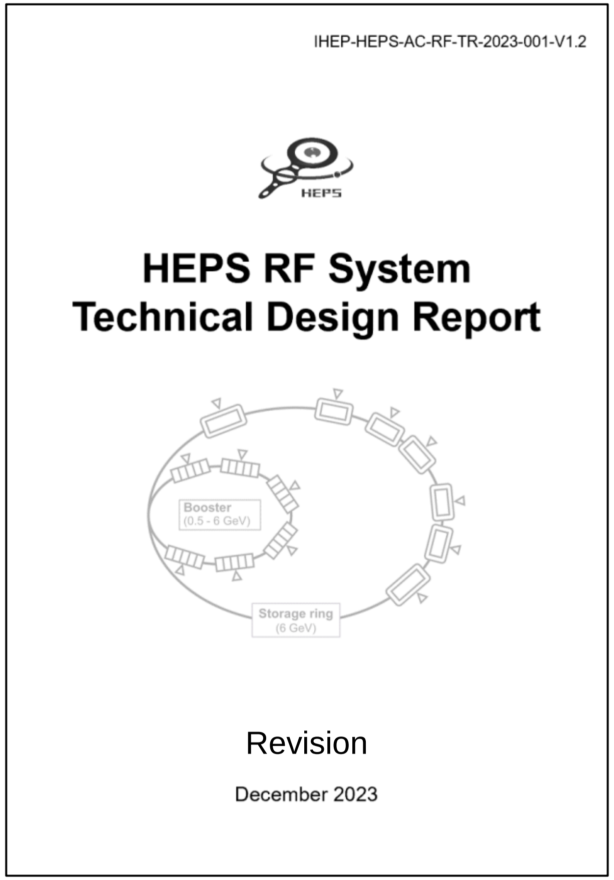


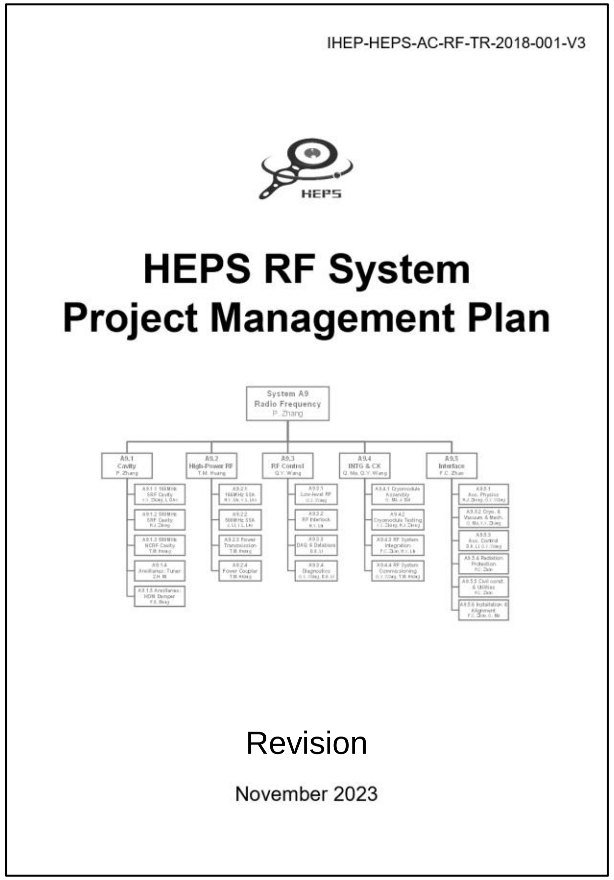


Q. Wang *et al.*, *IPAC2023*, THPA088.

TDR, PMP and international review

- Technical Design Report released in 2019, revised in 2021 and 2023
- Project Management Plan released in 2018, revised in 2020 and 2023
- International review meeting on RF in 2016 and 2023 (first post-pandemic review at HEPS)
- HEPS International Advisory Committee Meeting in 2016, 2017, 2018, 2019, 2025



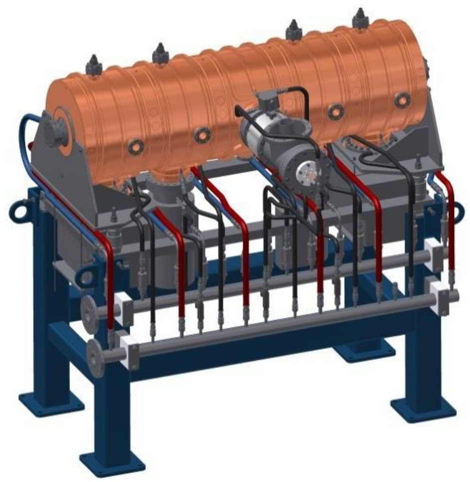


Rama CALAGA (Chair), CERN
Zheqiao GENG (Co-chair), PSI
Eiji KAKO, KEK
Denis KOSTIN, DESY
Hiroshi SAKAI, KEK
Daniel VALUCH, CERN
Yingchao DU, Tsinghua University
Qiang GU, SARI, CAS
Senlin HUANG, Peking University

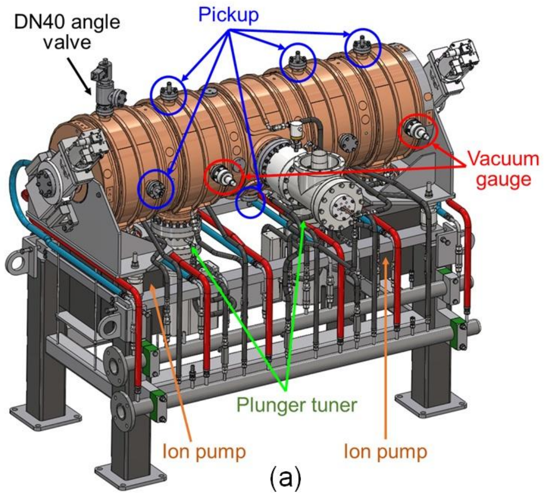
Development highlights

500MHz NCRF cavities: modified for HEPS

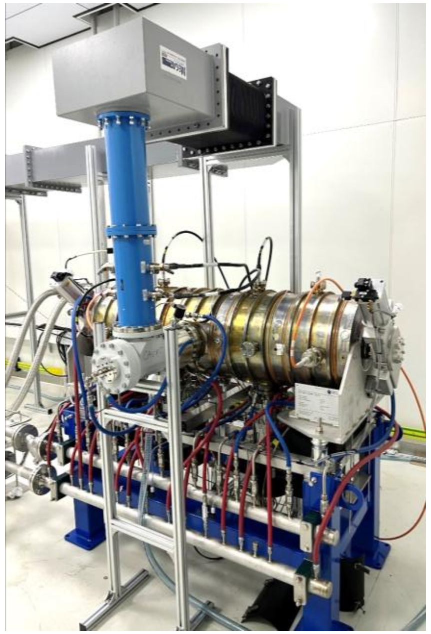
- Contract of 6 cavities signed with RI GmbH in 2020, batch delivery in 2022, SAT in 2022
- Several design modifications implemented to accommodate HEPS requirement
  - Sync. light collimation, diagnostics for power couplers (DESY approach), additional & relocated pickups, etc.
- Procedures for cavity reception and high-power tests developed by IHEP RF team
- Several non-conformities identified and resolved with RI
- High-power tests of all 6 cavities completed up to 120kW except for CAV06 (limited to 100kW)
  - Automatic conditioning system in-house developed to improve efficiency considerably



RI original design



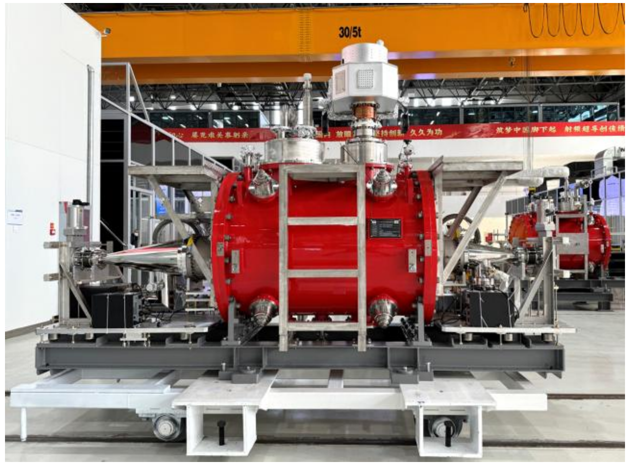
HEPS final design



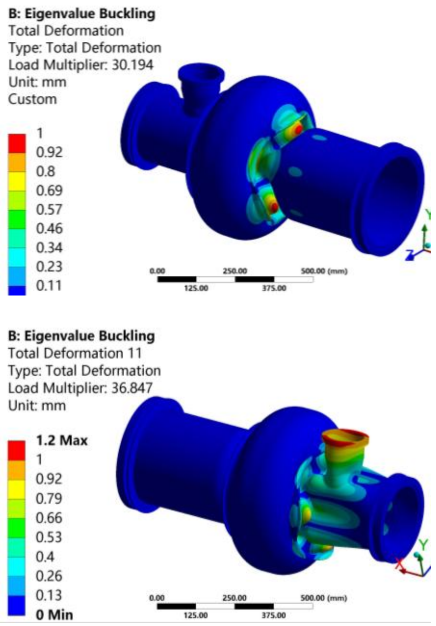
[1] T. Huang *et al.*, *JINST* 19, P06031 (2024). [2] Z. Deng *et al.*, *JINST* 16, P07027 (2021).

500MHz SRF cavities: optimized design

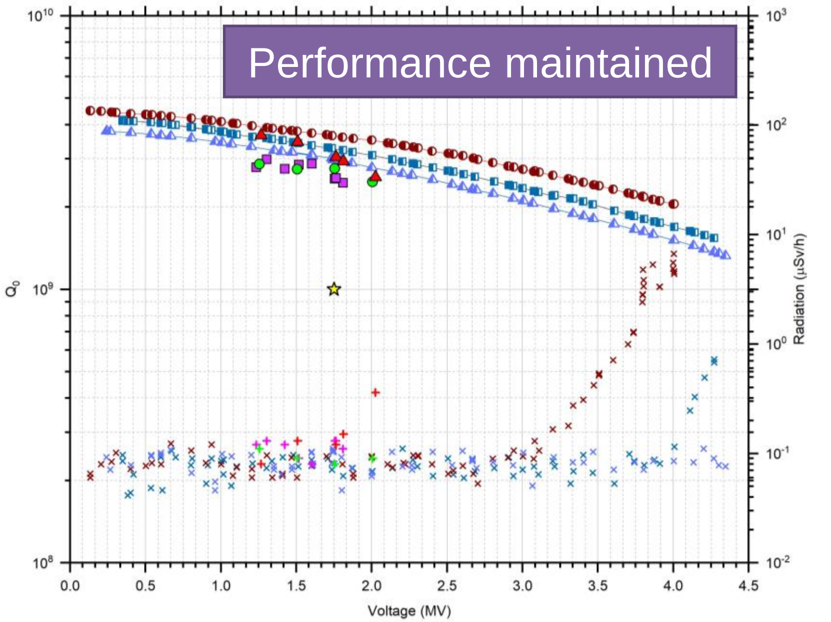
- Cavity geometry mechanically improved by adding a pair of stiffeners
- **Synergy with BEPCII-U, same cavity & same module**, different taper aperture (63mm vs. 150mm)
- Four cavities produced, BCP treated, all met VT specs., demonstrated excellent performance: Vc > 4MV with mild or no field-emission (FE)
- Three modules (incl. 1 BII-U module) assembled, **excellent performance achieved in VT preserved in HT, no FE onset**, demonstrated cavity treatment and module assembly procedures



Parameter	Value	Unit
Frequency	499.8	MHz
Operating temp.	4.4	K
Design Vc	2.0	MV
Operating Vc	0.91	MV/m
Ep/Eacc	2.08	-
Bp/Eacc	4.63	mT/(MV/m)
R/Q (=$V^2/\omega U$)	95	Ω
External Q	8e4	-



Static HL: 20~23W, Q0@1.75MV: 2.5e9
Dynamic HL: 11~13W, no FE onset

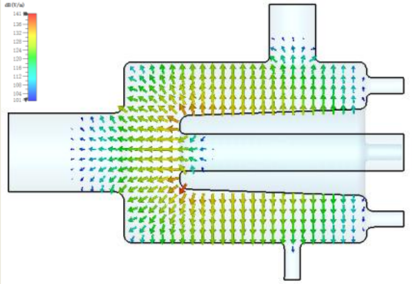
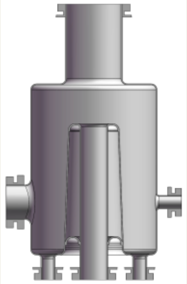


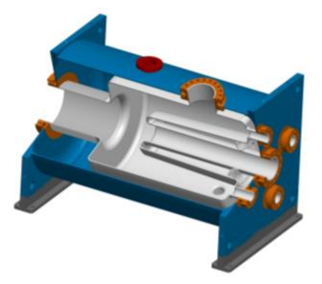
[1] H. Zheng *et al.*, *IEEE TAS* 31, 3500109 (2021)
[2] H. Zheng *et al.*, *JINST* 19, P10031 (2024).

166MHz SRF cavities: original innovation

- **First of its kind in the world**: low-frequency, β=1, high input power, heavy HOM damping, quarter-wave structure, compact geometry -> **require innovative design & development**
- In-house, two-step approach, **9 years of continuous development & innovation**
- A total of 8 bare cavities and 5 jacketed cavities produced and tested, met specifications

Proof-of-Principle (PoP) cavity, 2016-2019, demonstrate prod. technics and surface treatment

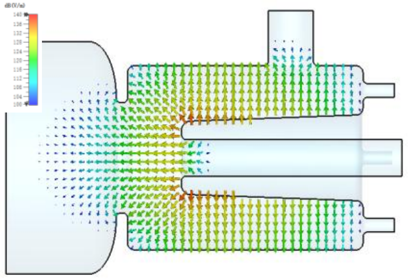
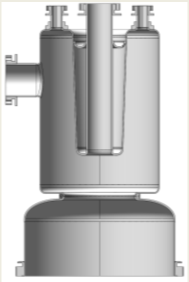



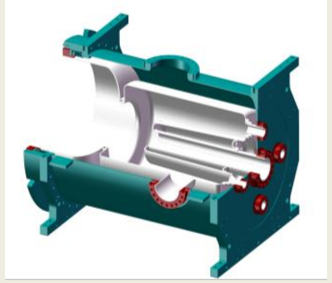
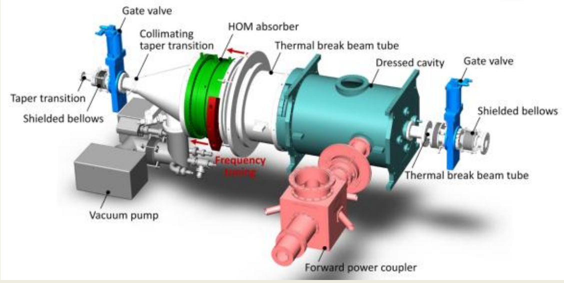


- **Optimization proposed**
  - Replace pin PU w/ loop PU
  - Elongate FPC niobium tube
  - Improve FPC cooling
  - Strengthen HPR ports

World's first SRF quarter-wave cavity to accelerate ultra-relativistic beam !

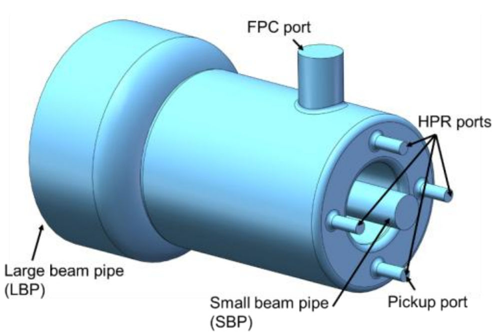
HOM-damped cavity, 2019-2023, prototyping of complete module prior to series production

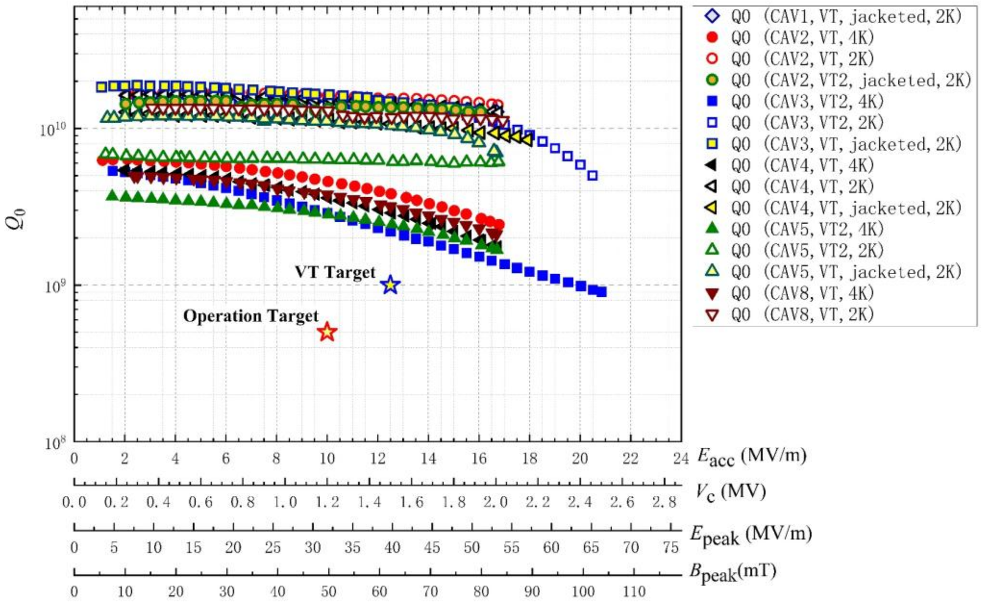




166MHz SRF cavities: performance

- Established BCP recipes for bare cavities, no chemistry required for jacketed cavities, excellent cryogenic performance demonstrated, optimized procedures ensuring no field-emission onset & considerably reduced multipacting, 6 out of 7 series cavities **outperform qualification criteria**



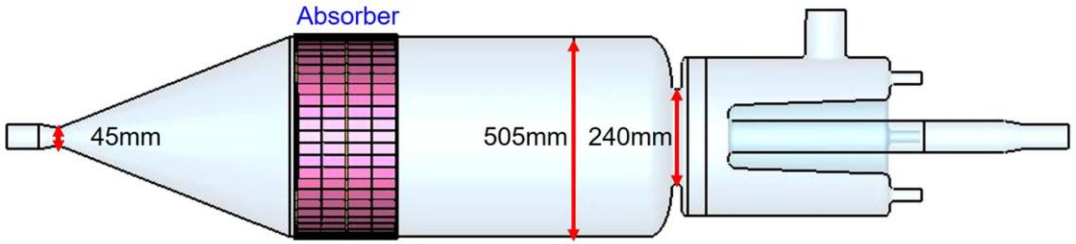
Parameter	Value	Unit
Frequency	166.6	MHz
Operating temp.	4.4	K
Design Vc	1.5	MV
Operating Vc	1.2	MV
R/Q (=$V^2/\omega U$)	139	Ω
Q0 at Vc_d (VT)	1e9	-
Q0 at Vc_op (HT)	5e8	-
Ep at Vc_op	32	MV/m
Bp at Vc_op	50	mT
Input power	190	kW

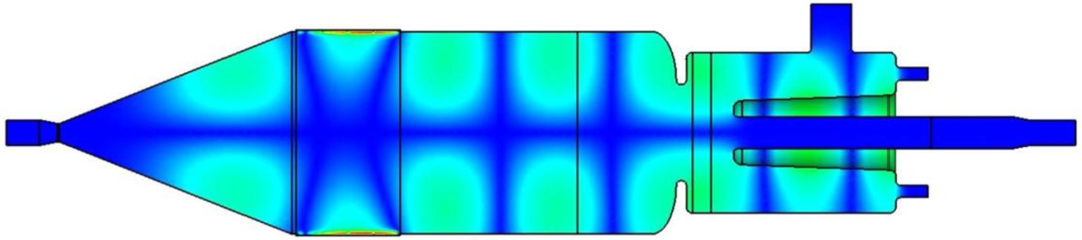


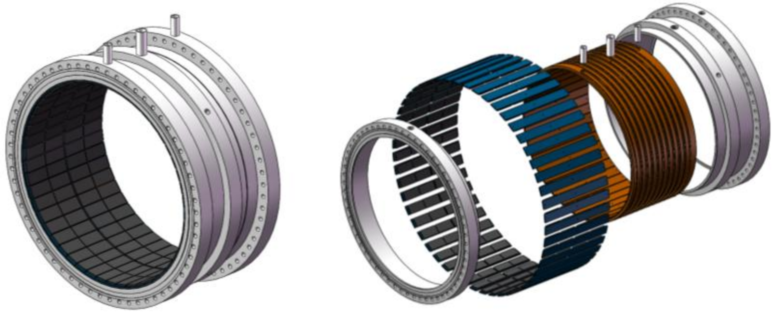
L. Guo *et al.*, *Rev. Sci. Instrum.* 95, 074702 (2024).

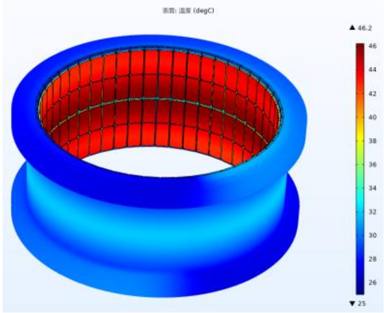
166MHz SRF modules: HOM absorber

- **Heavy higher-order-mode damping** realized by enlarged beam pipe and ferrite absorber at room temperature
- Power capacity of 10kW, **505mm** inner diameter



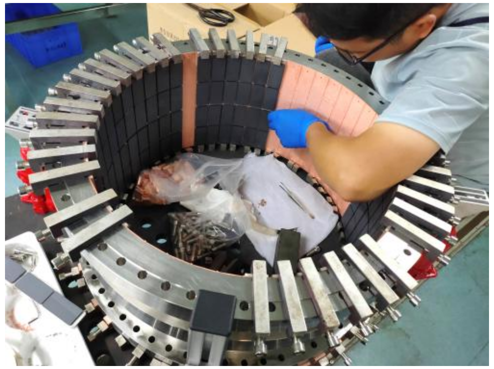


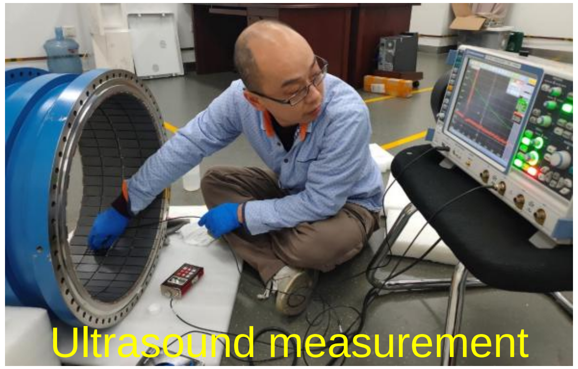




Nickel-Zinc ferrite materials

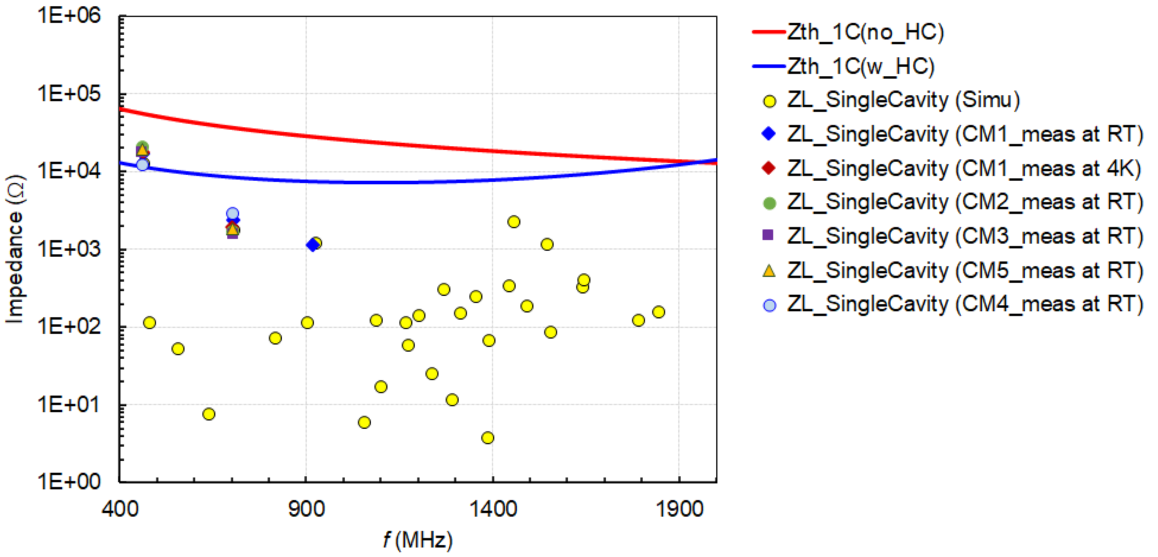
Parameter	High charge	High brightness
Bunch rms length (σ_z) [mm]	5.06	5.06
Loss factor for HOM (k_{HOM}) [V/pC]	2.54	2.54
Beam current [mA]	200	200
Bunch number	**63**	**680**
Bunch charge [nC]	**14.41**	**1.33**
Average HOM power [kW]	**7.32**	**0.68**

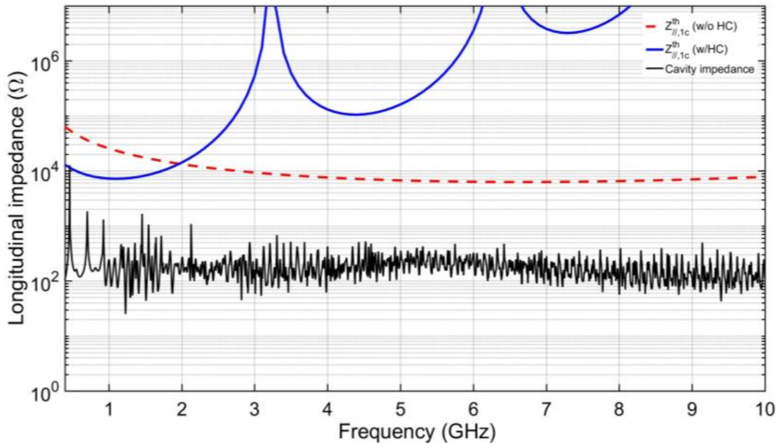


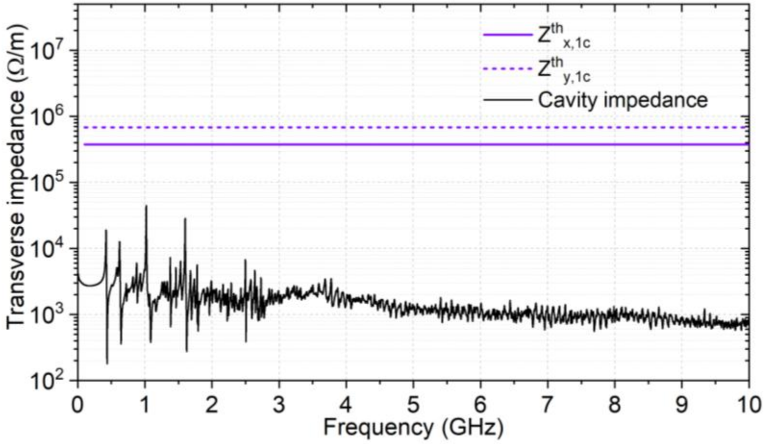


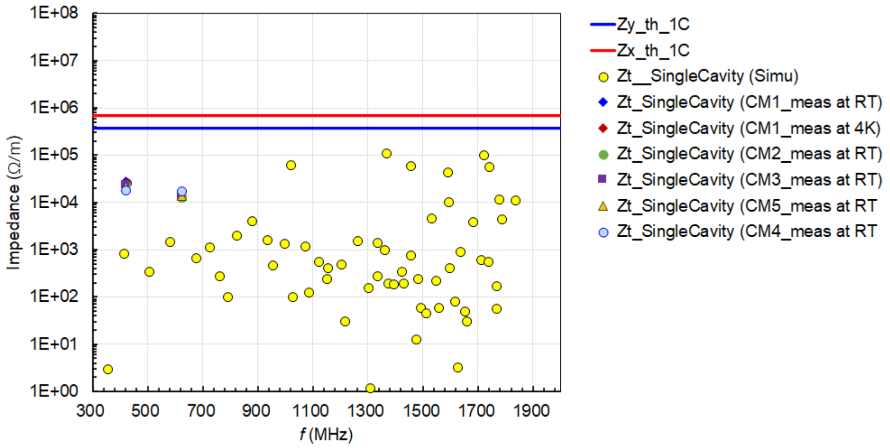
166MHz SRF modules: HOM damping

- HOM impedance of 166MHz SRF cavities fulfills CBI thresholds (equally distributed)
- The most dangerous mode (1st monopole HOM, 464MHz) marginally fulfills the most stringent requirement
  - Series absorbers obtained stable performance
  - Relocate ferrite tiles may further reduce impedance at a price of lower power capacity





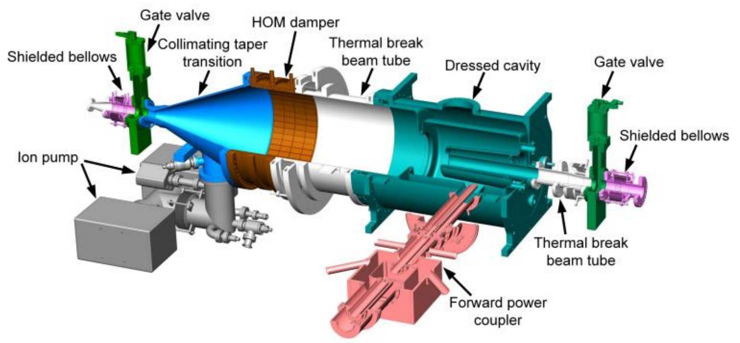


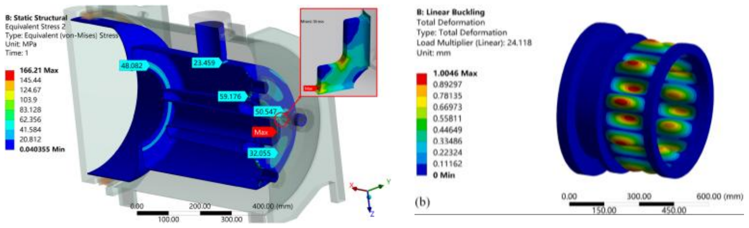


H. Zheng *et al.*, *IEEE-TAS* 34, 3500309 (2024).

166MHz SRF modules: development

- **Cavity string and cryomodule development**
  - Extremely limited longitudinal space to fit 2 CMs in one 6m straight section -> **compact design**
  - Heavy damping of HOM -> **large-dimension ferrite absorber**, high-power handling capability
  - Developed an optimized cleaning & assembly procedures to minimize contamination due to large aperture (505mm), VT & HT demonstrated
- 11.2023, first 166MHz module successfully assembled, excellent performance demonstrated in horizontal test, **outperform HEPS specifications**, series modules launched
- 08.2024 ~ 06.2025, four 166MHz modules assembled & tested, **all CMs exceed specifications**





[1] L. Guo *et al.*, *Rev. Sci. Instrum.* 95, 074702 (2024). [2] X. Zhang *et al.*, *NIM-A* 1059, 168972 (2024). [3] R. Han *et al.*, *NIM-A* 1070, 170000 (2025).

166MHz SRF modules: performance

Parameter	Spec.	Test	Unit
Vc_op	≥ 1.2	1.5~1.6	MV
Q_0 @ Vc_op	≥ 5e8	1.5~2.1e9	-
Radiation @ Vc_op	< 500	0.08~84	μSv/h
Static HL @ 4K	< 40	33~36	W
Dyn. HL @ 4K	< 21	5~7	W

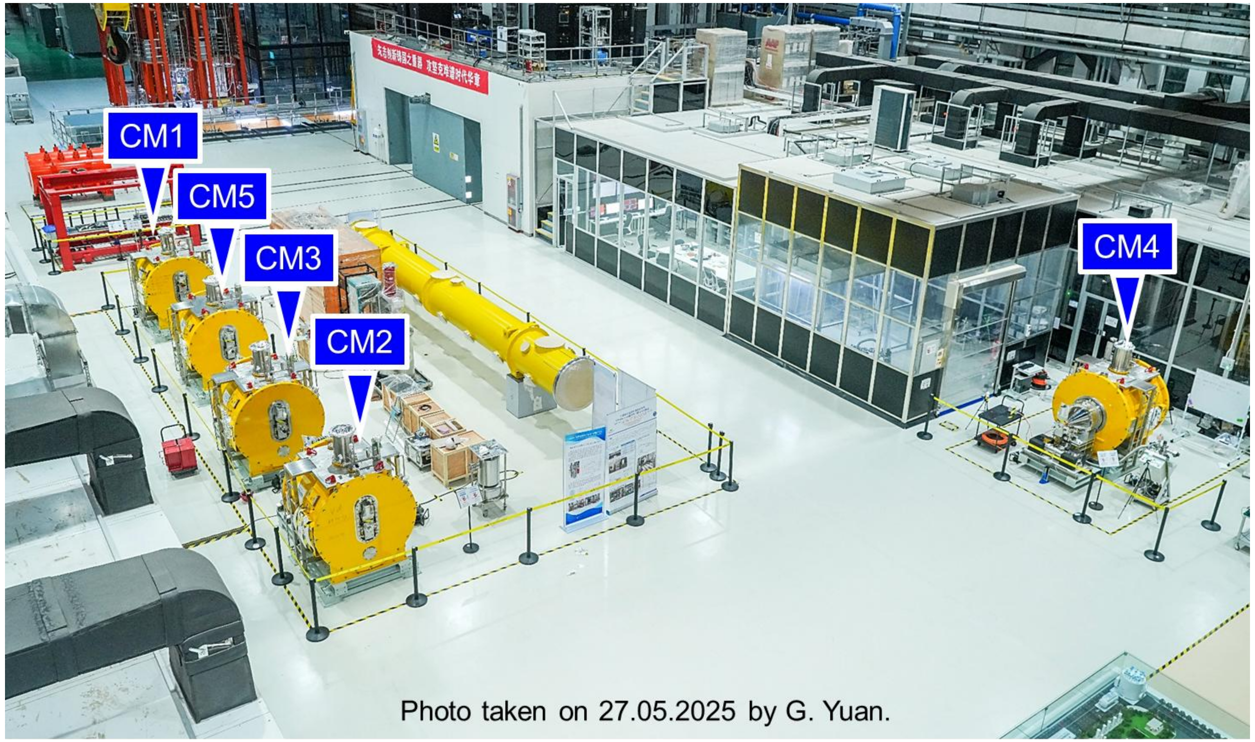
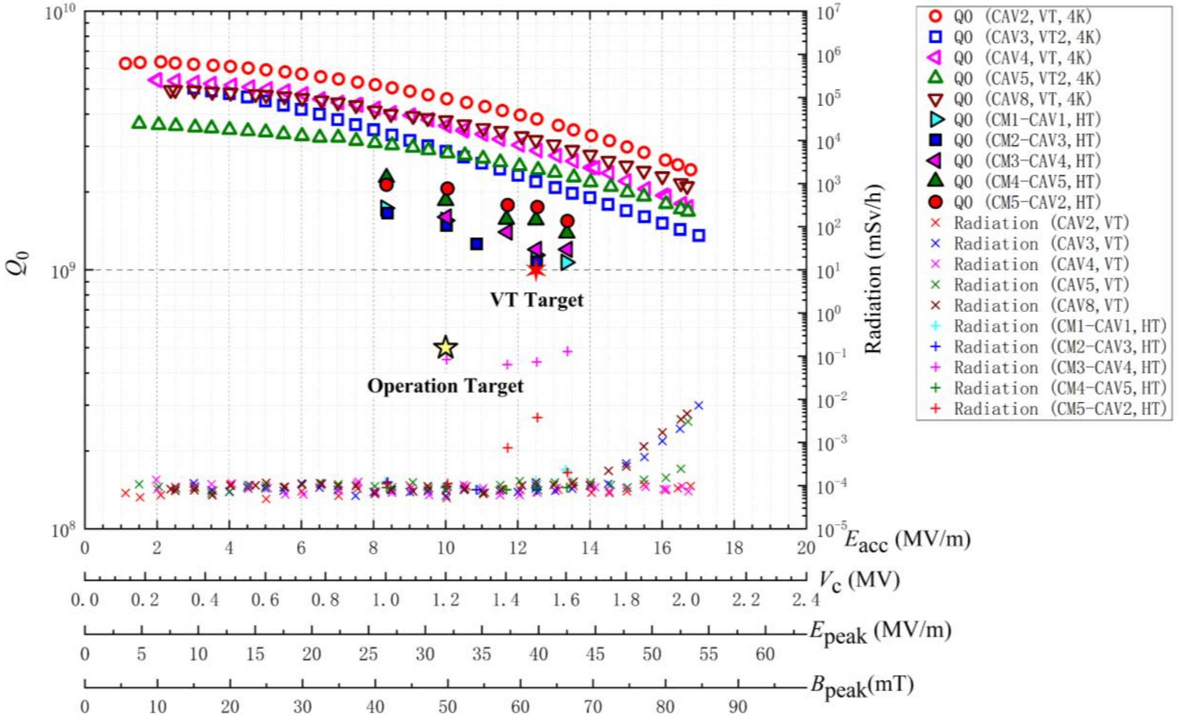


Photo taken on 27.05.2025 by G. Yuan.

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

166CMs horizontal tests at 4K



Solid-state amplifiers (SSAs)

- Three types of SSAs: 500MHz-100kW, 500MHz-260kW, 166MHz-260kW
- **Total power: 2.42MW (cw), 13 sets**
- 166MHz-50kW prototype developed in 2017 during HEPS-TF phase
- 166MHz-260kW and 500MHz-150kW prototype developed in 2019-2021, passed SAT in Oct. 2021, used for high-power testing of various RF components

  - Optimized thermal design of amplifier modules, N-way direct power comb., improved monitoring, etc.
- Series SSAs delivered and passed SAT in Jul. 2023 (BS) and Sep. 2024 (SR)
- Synergy with BEPCII upgrade (shared spares)

166MHz 260kW prototype (PAPS)

500MHz 150kW prototype (PAPS)

SSA operation status

BS SSA	Freq-Power	Total op. time (hour)	No. of modules damaged	
			Amp. transistor	PS module
BS1SSA1	500MHz-100kW	6993	**6** out of 224	5 out of 20
BS2SSA2	500MHz-100kW	2896	0 out of 224	0 out of 20
BS2SSA3		9071	0 out of 224	7 out of 20
BS2SSA4		8955	0 out of 224	8 out of 20
BS2SSA5		9062	0 out of 224	8 out of 20

Booster-RF SSA

- A few amplifier modules replaced due to malfunction during SAT

9 out of 4336 transistors damaged (~0.2%)

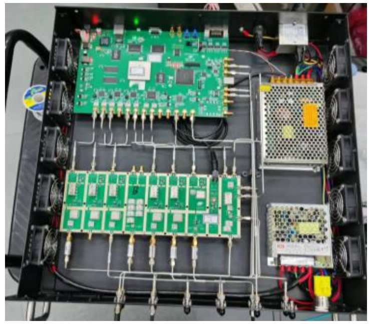
SR SSA	Freq-Power	Total op. time (hour)	No. of modules damaged	
			Amp. transistor	PS module
R35SSA2	500MHz-260kW	2830	**3** out of 576	2 out of 24
R38SSA2	500MHz-150kW	7640	0 out of 384	0 out of 16
R40SSA2	500MHz-260kW	2920	0 out of 576	5 out of 24
PAPS-prototype	166MHz-260kW	2286	0 out of 336	0 out of 24
HEPS	166MHz-260kW*4	~300	0 out of 336×4	1 out of 24×4

SR-RF SSA (part)

RF control

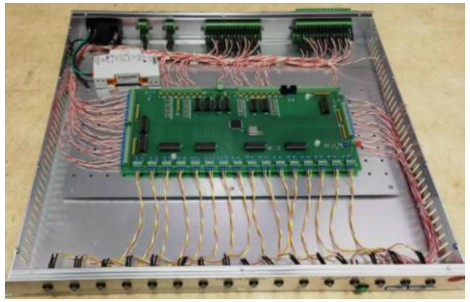
- **RF control system for booster and storage ring, in-house development**
- Constituents: Digital LLRF controller (3rd gen), RF interlock (2nd gen), RF fast data acquisition, beam trip diagnostics (prototype), RF EPICS database (450TB capacity), RF control interfaces
- HL functions: amp. & phase & freq. loops, field-flatness loop, reflected power protection, quench protection, amp. & phase modulation, phase jump, automatic start-up, etc.
- Synergy with BEPCII and BEPCII-U (lower dev. cost & maintenance overhead, shared spares)

1st-gen LLRF
(Altera) 2018



2nd-gen LLRF
(Altera) 2021

3rd-gen LLRF
(XILINX SoC) 2023



1st-gen RF Interlock
(CPLD, 32ch) 2015

2nd-gen RF Interlock
(XILINX, 54ch) 2021

3rd-gen RF Interlock
(XILINX, 54ch) 2022

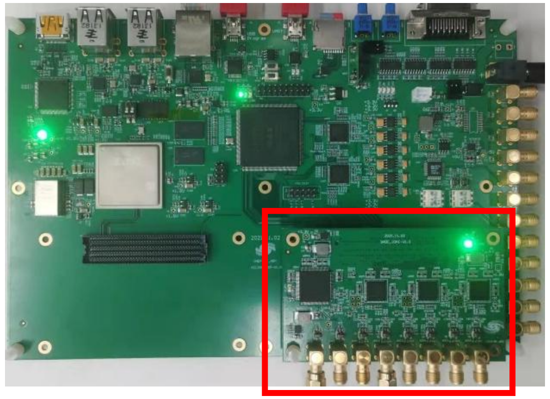
BS-RF Control

DB

Low-level RF controller

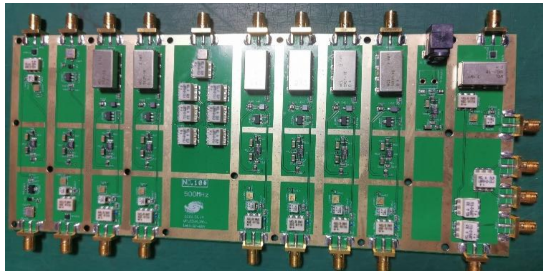
- In-house development of LLRF controller since 2016, currently on 3rd generation
- Excellent performance demonstrated in BEPCII operation and HEPS commissioning
- Continuous optimization of both hardware and functions, series production completed
- **Performance (rms, 18mA): 0.012% in amplitude and 0.012° in phase**

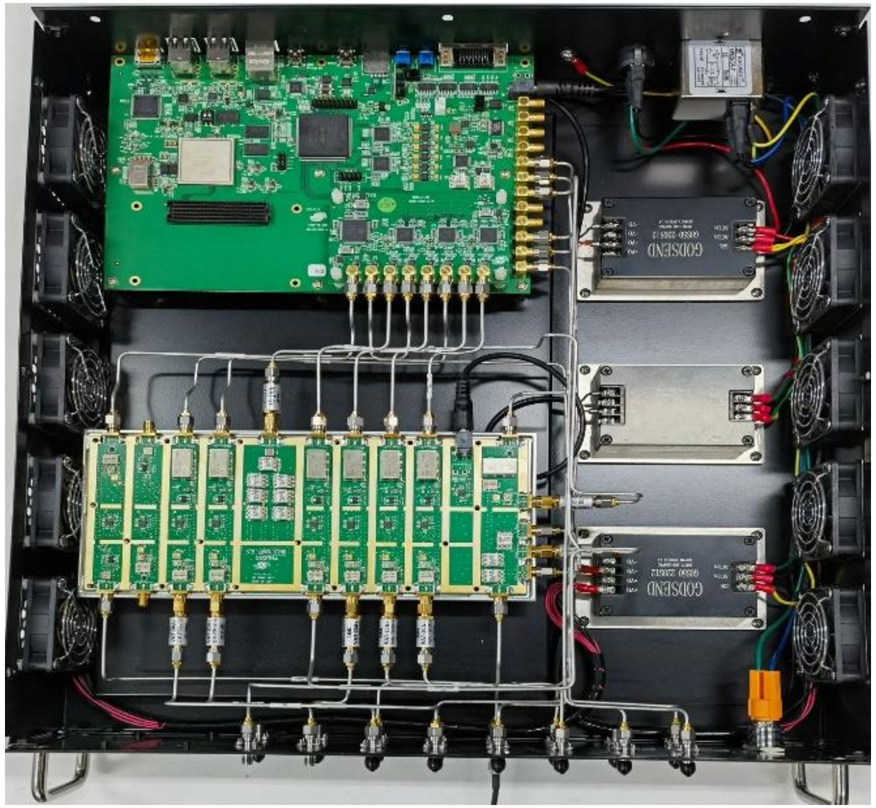
DSP board V1.1

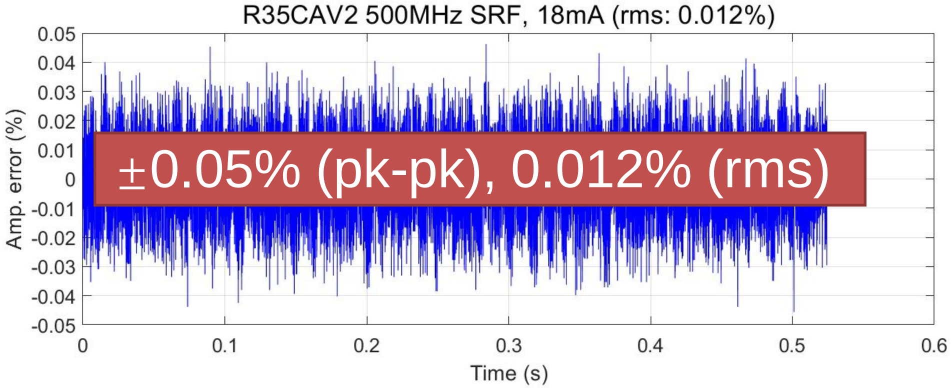


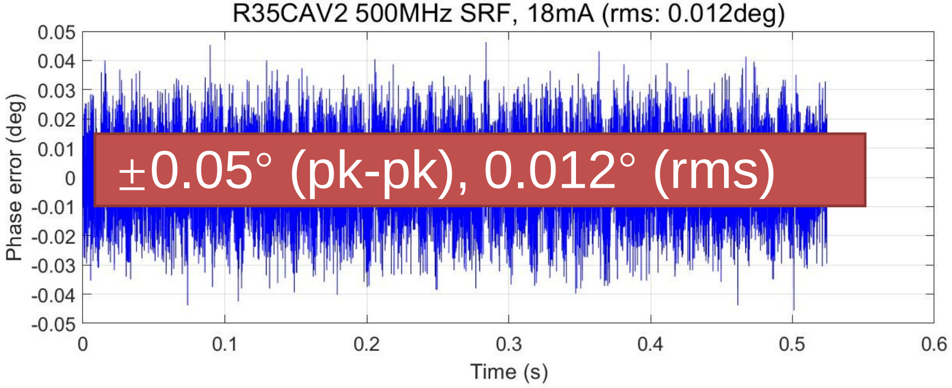
FMC board V1.0

RF front-end board V8.2



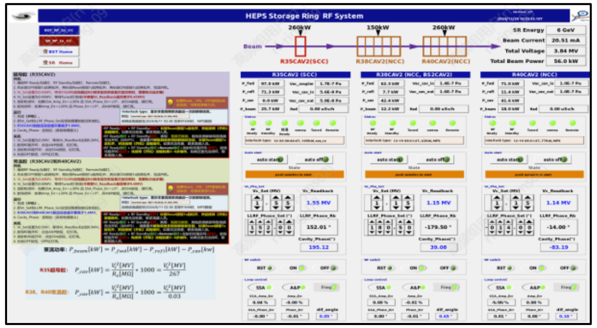




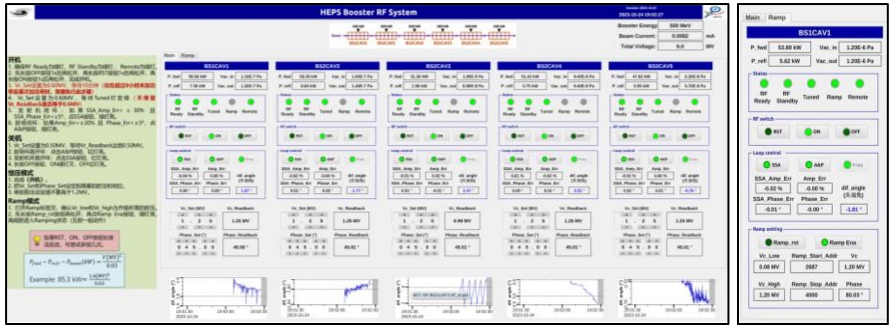


Control interface: in-house dev. (local + CC)

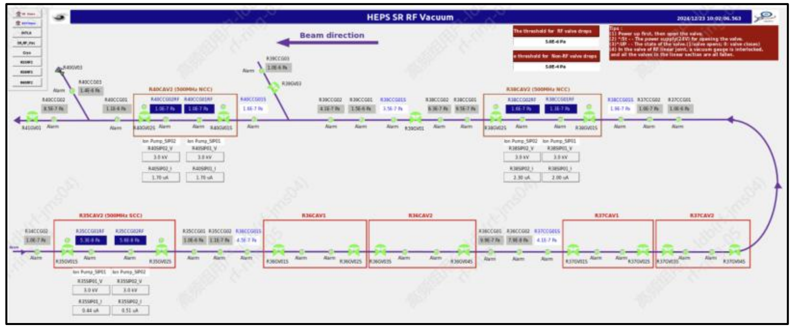
SR RF (CC)



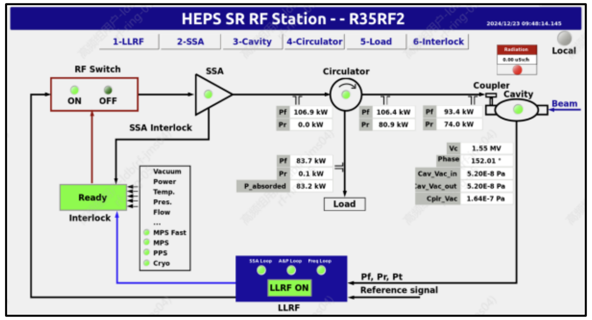
Booster RF (CC)



RF vacuum

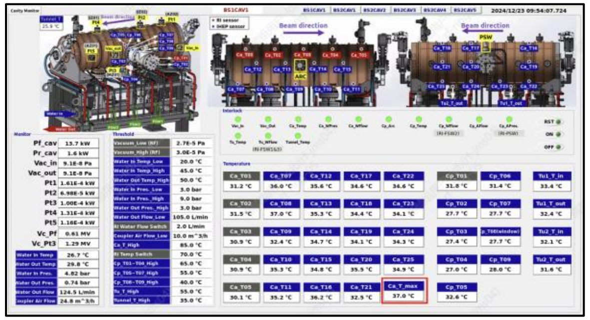


RF station



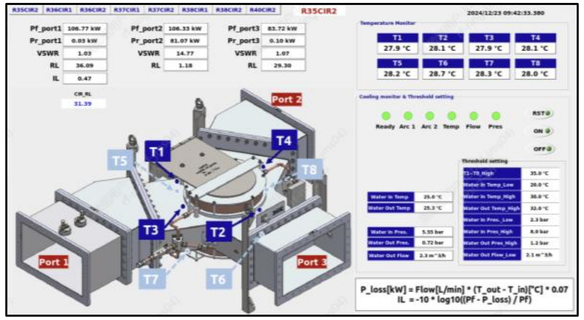
SRF cavity

NCRF cavity

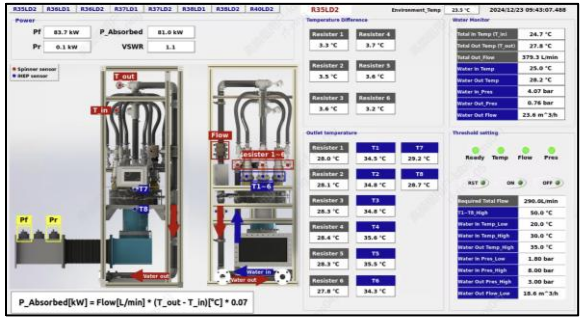


SSA

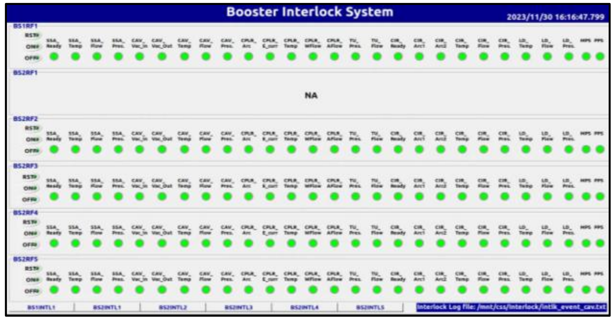
High-power circulator



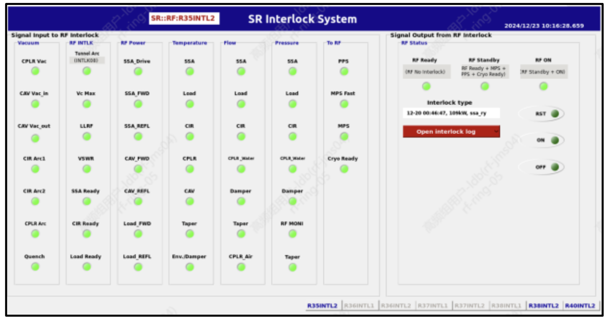
High-power load



Interlock (overview)



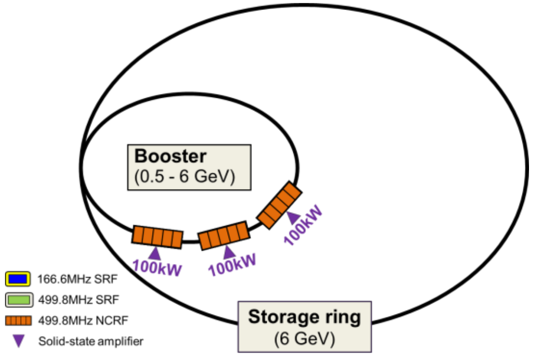
Interlock (individual station)



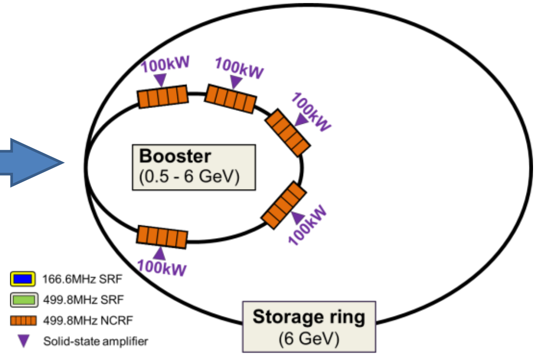
Installation & commissioning

Commissioning in stages

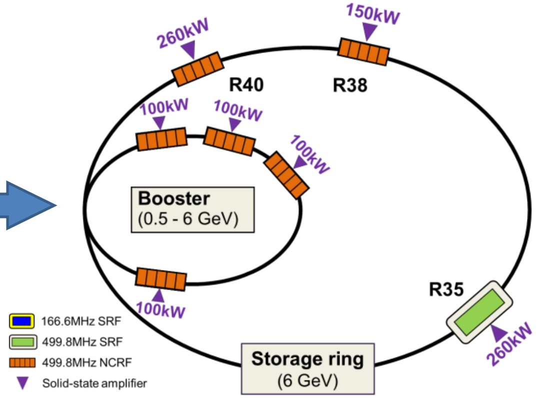
- **Commissioning plan**
  - Initial beam commissioning with normal-conducting cavities
  - Install SRF cavities after accumulating ~100 A·h beam dose in SR
- **Purpose**
  - Vacuum scrubbing of the SR: large outgassing by sync. light irradiation on vacuum chambers
  - Lower the potential contamination risk for the SRF cavities (vacuum incidents, gas absorption)
    > HEPS Mgmt. decided to add one 500MHz SRF cavity to provide higher RF voltage for SR CX
  - Reserve longer development time for the new 166MHz SRF cavities
  - **Pragmatic approach adopted**: RF setup of "NCC+SCC" used for vacuum scrubbing, install all SCCs after ~41 A·h accumulated beam dose



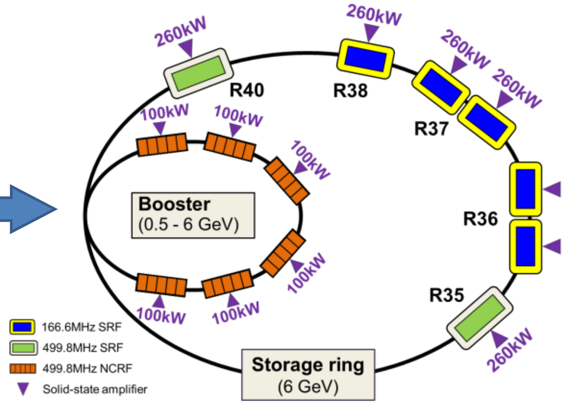
S1: BS CX (orig.)
(2023.07~2023.10)



S1b: BS CX (new)
(2023.10~2023.11)



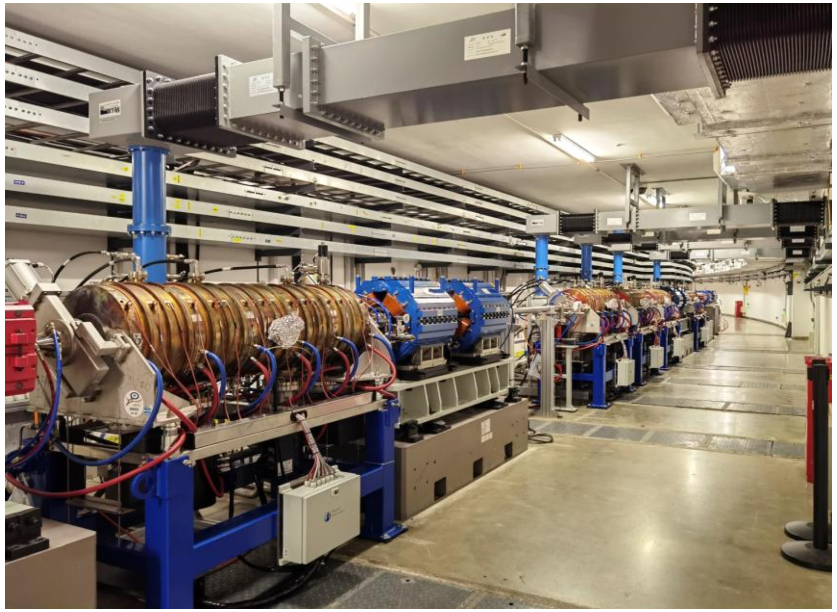
S1c: SR CX (new)
(2024.08~2025.05)



S2: Joint CX (orig.)
(2025.09~)

RF cavities: tunnel installation

- Jul. 2023, 3 NCRF cavities and 5 SSAs installed in BS
- Oct. 2023, 2 more NCRF cavities installed in BS (5 NCRF cavities in BS)
- Jun. 2024, 2 NCRF + 1 500MHz SRF cavities and SSAs installed in SR
- Nov. 2024, exchange 1 500MHz SRF cavity in SR tunnel
- May. 2025, 2 NCRF cavities removed from SR, back to BS
- May. ~ Jul. 2025, 5 166MHz SRF + 2 500MHz SRF cavities installed in SR

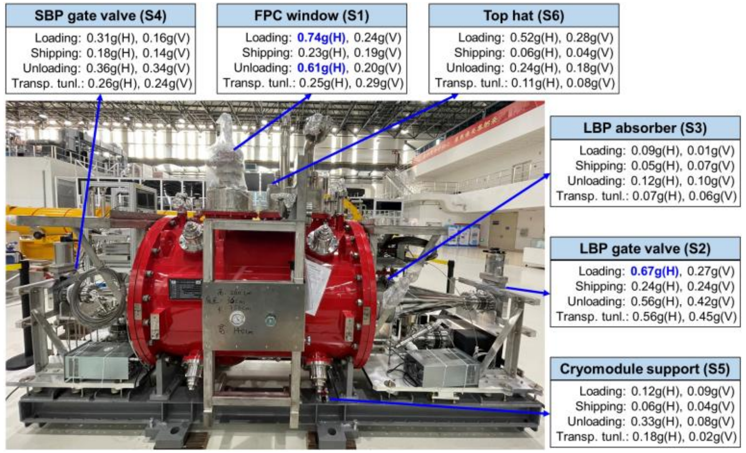


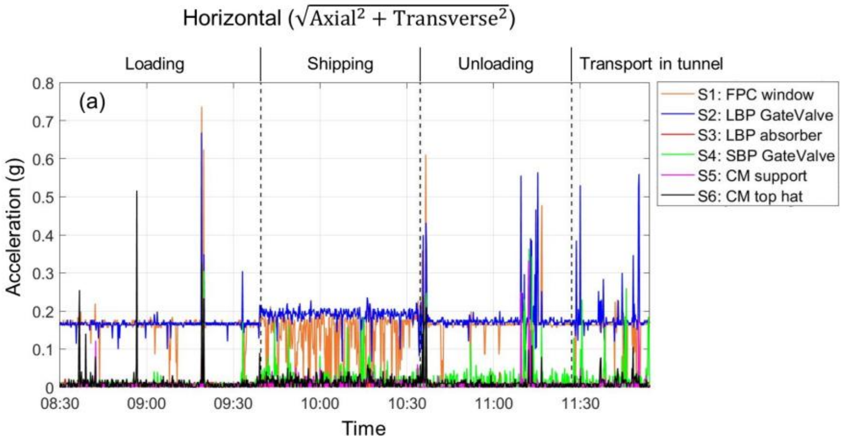
Booster tunnel

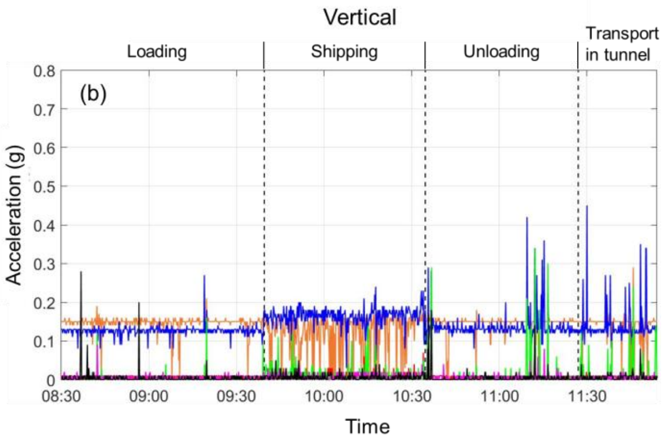
Storage ring tunnel

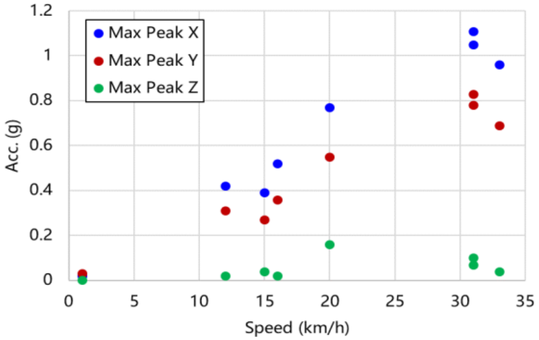
Transportation of 500MHz SRF modules

- Multiple road tests with dummy loads conducted before cav. transp.
- Short-distance (~5km, HEPS) and cross-city transportation (~80km, BEPCII-U) of the **complete modules under cavity vacuum**, shock of sensitive components and vacuum level monitored, **vacuum integrity well preserved**









FPC window req.

Acc_hor < 0.6 g

Acc_vert < 3 g

(safety margin: 2)

H. Zheng *et al.*, *JINST* 19, P10031 (2024).

Transportation of 166MHz SRF modules

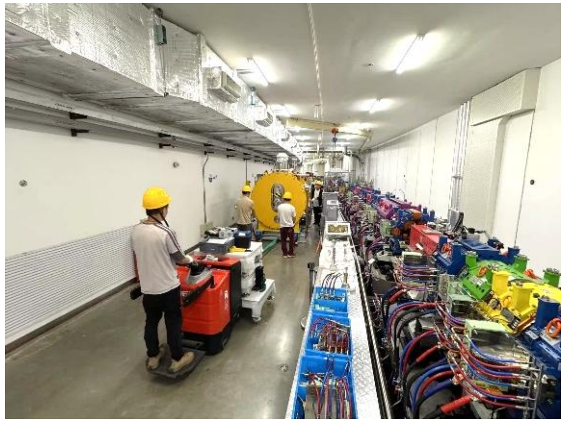
- Maximum recorded shock: < 0.5g in all directions for all 166MHz modules during the entire transportation & installation process
- All cavities transported under vacuum, cavity **vacuum integrity well preserved**

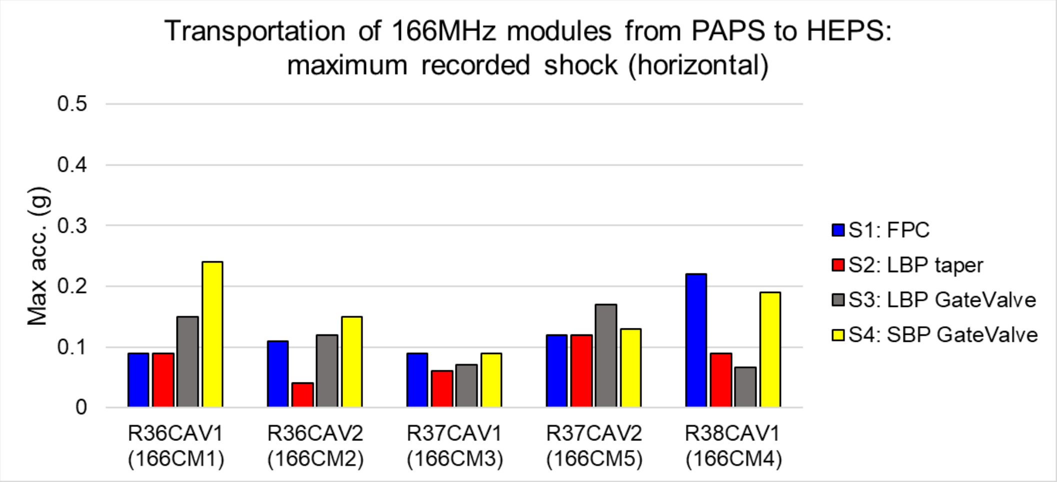
Loading on truck

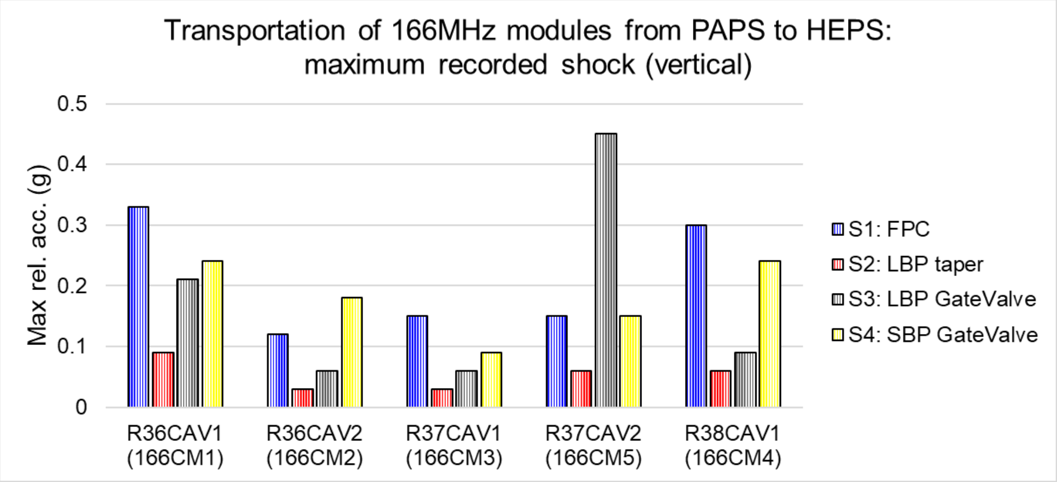
Freight transport

Unloading at tunnel entrance

Move to final position

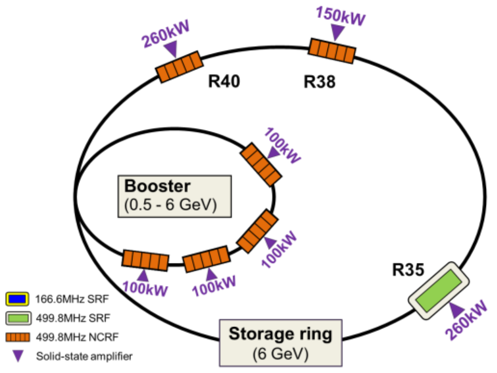






SR commissioning: stage 1 (11.2024~05.2025)

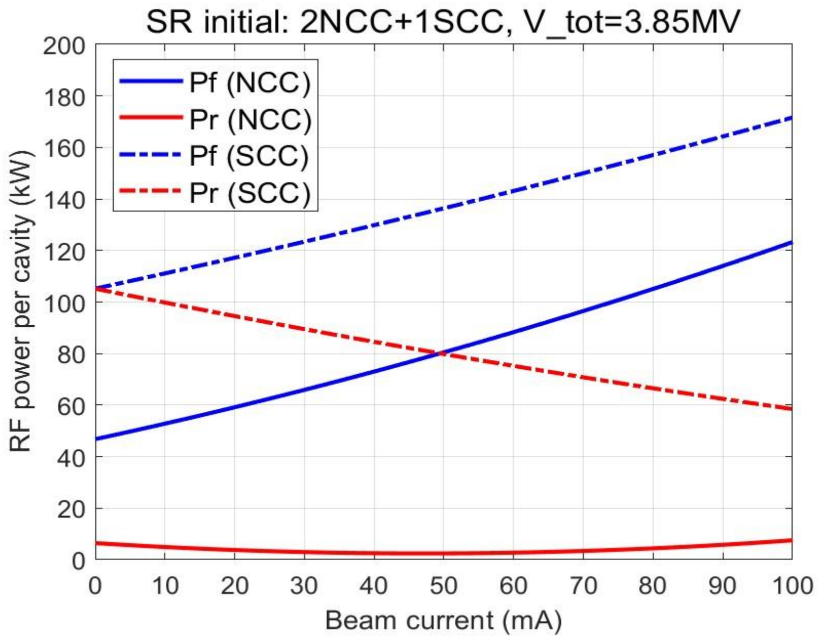
- Total RF voltage: 3.85MV
- Total beam power: 159kW, **max. beam current: 60mA**
- Stable op. for NCC (<90kW), limit for SCC (<180kW, 1.75MV)



SR cavity parameter	NCC	SCC
No. of cavities	2	1
Vc per cavity (MV)	1.1	1.65
Cavity wall loss	41 kW	~0 kW
Coupling	β=2	Qe=8e4
Beam current	60 mA	
U0 (w/o IDs)	2.64 MeV	
Synchronous phase (Φ_S)	46.7°	
Forward power per cavity	88 kW	143 kW
Reflected power per cavity	3 kW	**75 kW**
Cavity detuning (χ=-10°)	-32.6°	-20.9°
Beam power per cavity	44 kW	68 kW

High reflection

- **Vacuum admin. Limitation during CX**
  - SCC_vac < 1e-7 Pa, SCC_FPC < 4e-7 Pa
  - NCC_vac < 1e-6 Pa

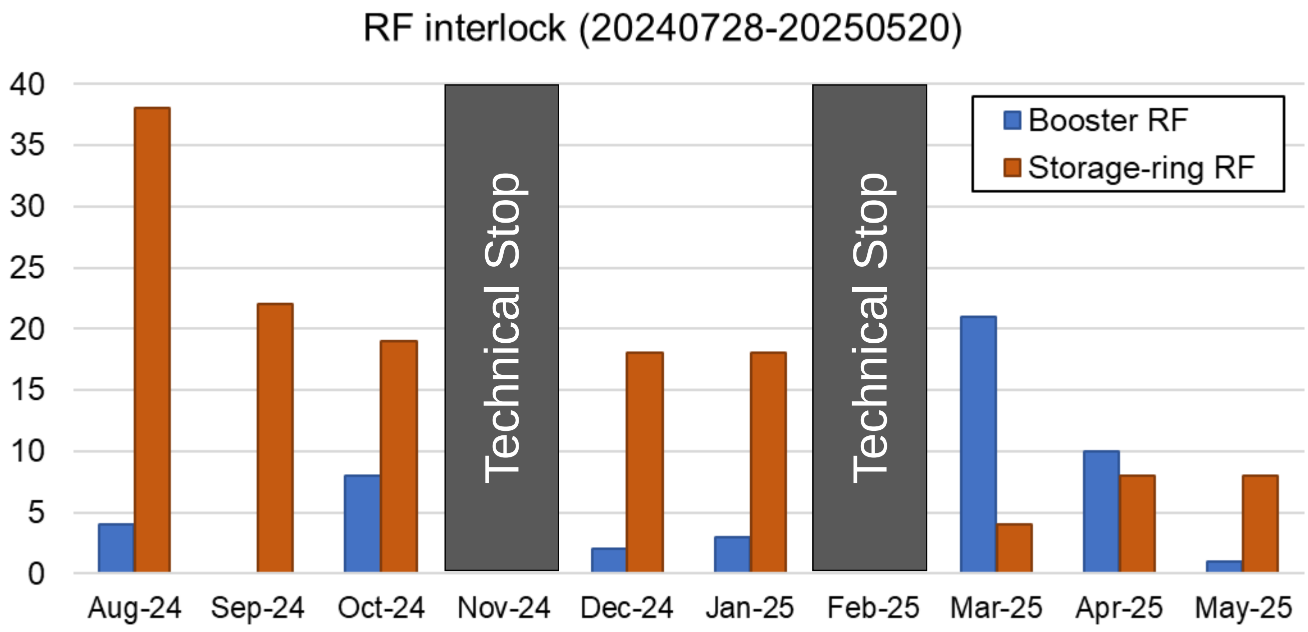


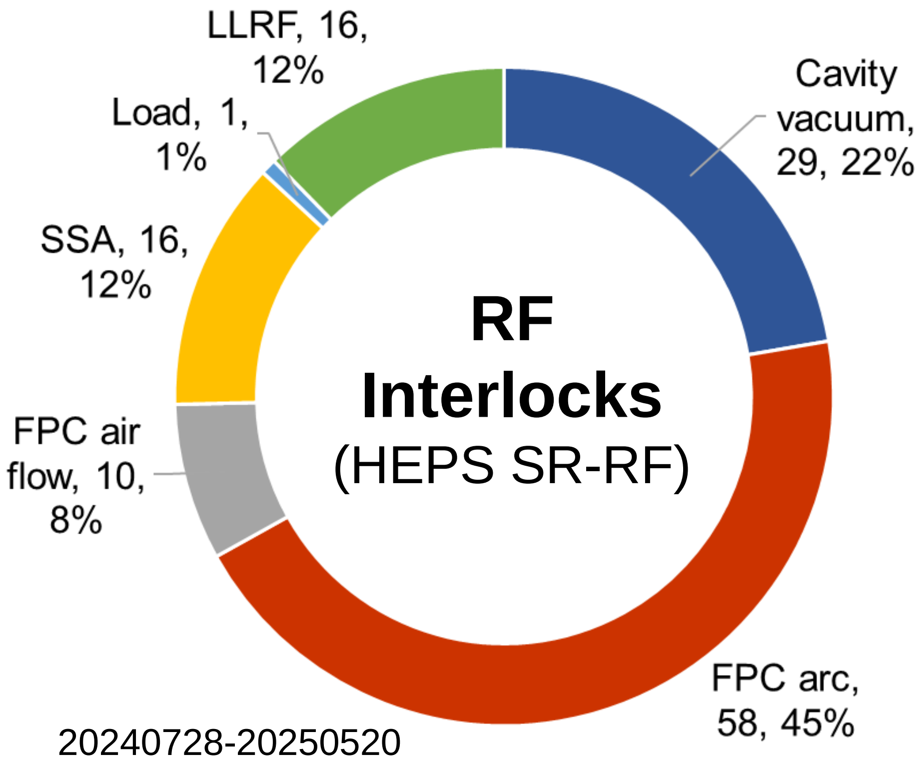
RF interlocks during beam CX stage 1

- Large number of arcing events recorded for SRF cavity, most of them accompanying no vacuum deterioration, very likely due to beam loss or synchrotron light
- One arc detector dismounted from the FPC to help distinguish false arc events

- In recent commissioning period, a total of 16 arc events triggered with 9 false arc

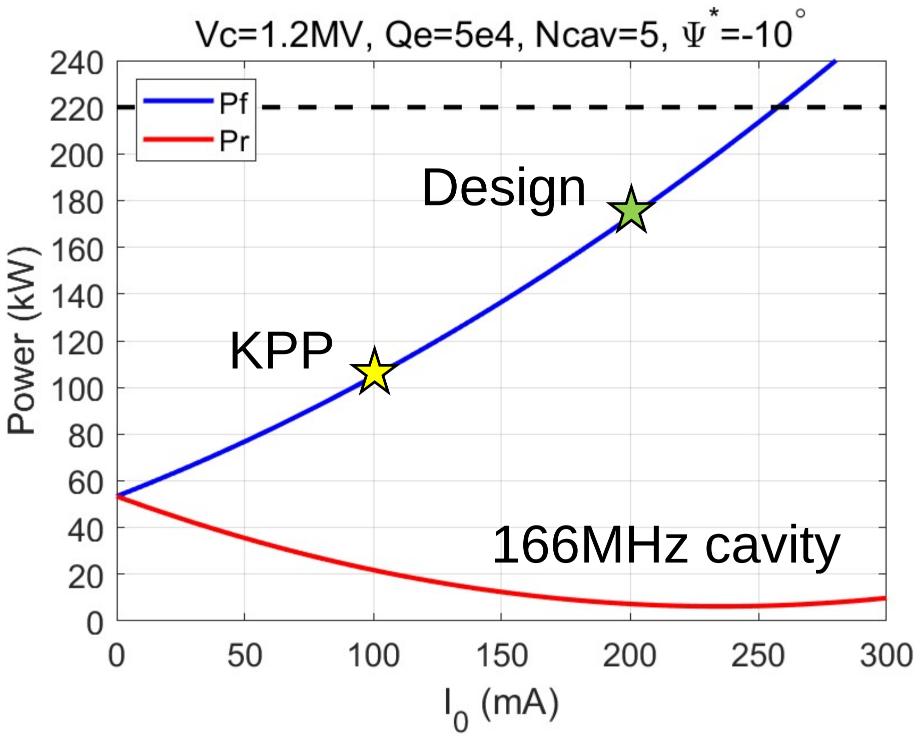
Vacuum threshold: 1e-6 Pa (SCC), 3e-5 Pa (NCC)



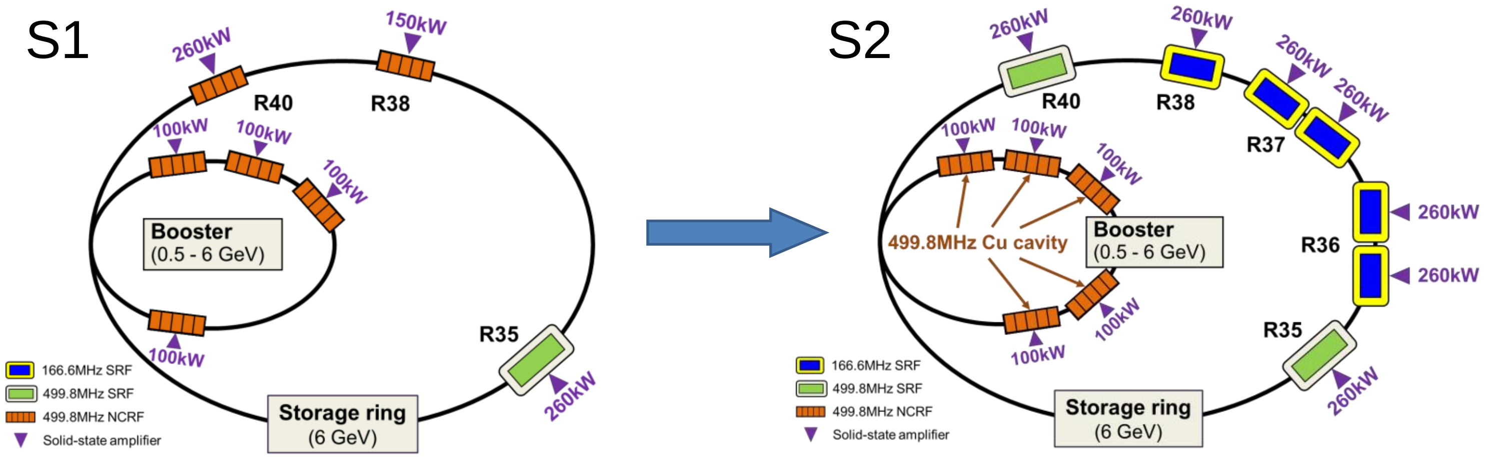


SR commissioning: stage 2 (09.2025~)

- Move two normal-conducting cavities from SR to BS, move one 150kW SSA from SR to BS
- Install five 166MHz cavities in SR to support 100mA beam current



Parameter	CX stage 1	CX stage 2	Nom. Op.
Booster	4*500NCC	5*500NCC	6*500NCC
SR	2*500NCC 1*500SCC	5*166SCC 2*500SCC	5*166SCC 2*500SCC
Beam current	60mA	100mA	200mA
RF voltage	500SCC: 1.65MV 500NCC: 1.10MV Total: 3.85MV	166SCC: 1.2MV Total: 6MV	166SCC: 1.2MV Total: 5.2MV
RF power	500SCC: 143kW 500NCC: 88kW Total: 319kW	166SCC: 105kW Total: 525kW	166SCC: 194kW Total: 970kW



Lessons learnt

- **Prototyping as much as possible at early stage of the project**

  - New development: 166MHz SRF cavity and module, 166MHz-300kW circulator

  - Existing in-house expertise: 166MHz HOM absorber, LLRF

- **Quality control is vital**

  - QC plan should be reviewed and updated from time to time, especially for R&D items

  - Non-conformities should be analyzed and documented in time

- **Vendor management**

  - Challenging during mask period, limited vendor visits, especially for oversea vendors

  - Communication plan should be revised accordingly and executed

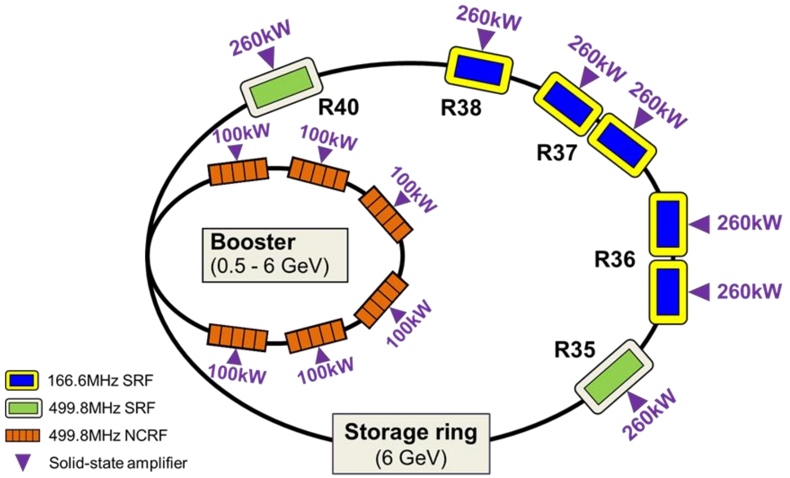
  - Working collaboratively with vendors for key components, e.g., 300kW circulator

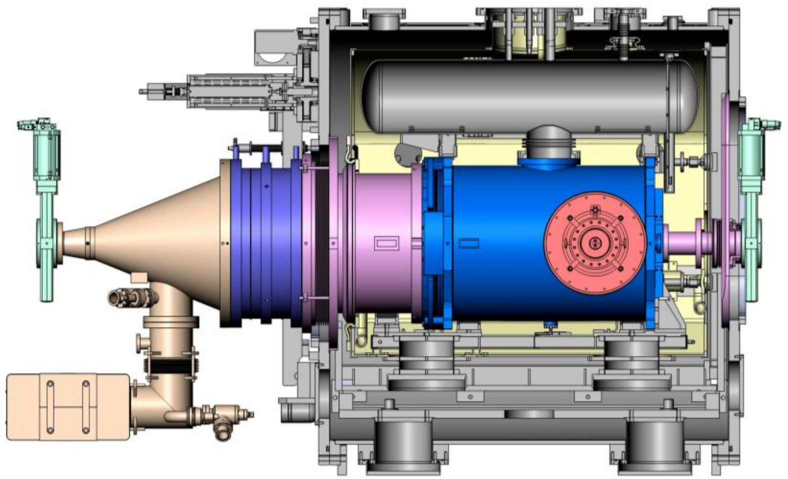
Summary

- Booster RF system commissioned w/ beam in Nov. 2023
- Storage-ring RF system (2NCCs + 1SCC, 500MHz) completed the 1st stage beam commissioning up to 40mA (Aug. 2024 ~ May. 2025)
- Storage-ring RF in nom. setup: all 7 SRF cavities (166MHz + 500MHz) installed with associated solid-state amplifiers and LLRF controls

  - World's first 166MHz SRF cavities to accelerate beam
- Beam commissioning of storage ring planned for early Sep., aiming for 100mA in 2025

Superconducting RF geared up for 100mA





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Thank you!