Overview of SRF projects for Synchrotron Light Sources in China

Pei Zhang

(Institute of High Energy Physics, CAS)

TTC2023 Meeting, December 5-8, 2023, Fermilab

Acknowledgement

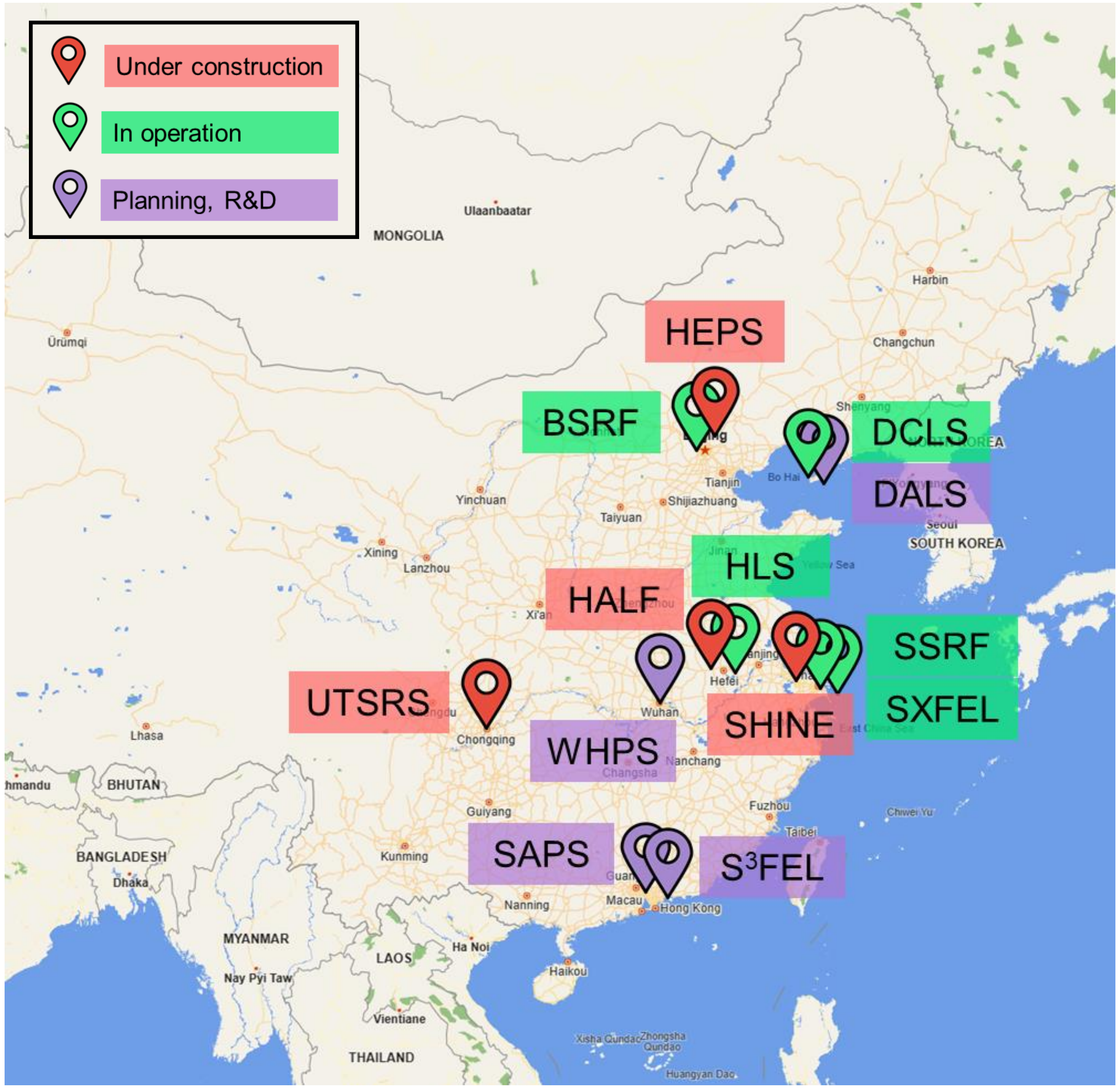
Thanks to colleagues from the following institutes for providing materials and information.

- Shanghai Advanced Research Institute (SARI), CAS
- Institute of High Energy Physics (IHEP), CAS
- University of Science and Technology of China (USTC), CAS

Outline

- Introduction
- Existing projects: BSRF, SSRF
- New projects: HEPS, HALF, SAPS
- SRF infrastructures
- Summary

Major light sources in mainland China



Beijing

Beijing Synchrotron Radiation Facility (BSRF)
High Energy Photon Source (HEPS)

Shanghai

Shanghai Synchrotron Radiation Facility (SSRF)
Shanghai soft X-ray Free-Electron Laser facility (SXFEL)
Shanghai High Repetition Rate X-ray FEL and Extreme Light Facility (SHINE)

Hefei

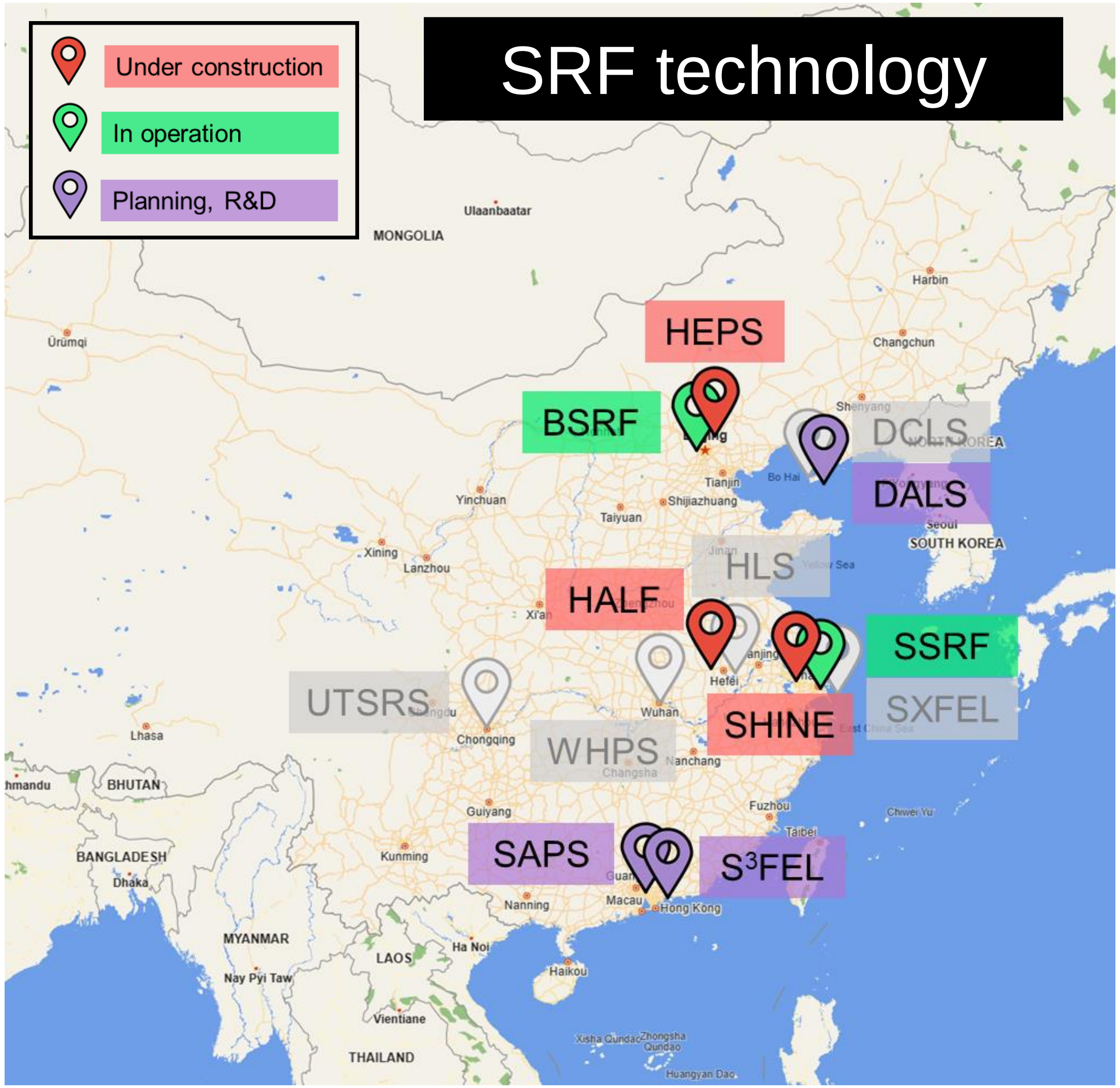
Hefei Synchrotron Radiation Facility (HLS)
Hefei Advanced Light Facility (HALF)

Others

Dalian Coherent Light Source (DCLS)
Dalian Advanced Light Source (DALS)
Ultrafast Transient Synchrotron Radiation Facility
Shenzhen Superconducting Soft X-Ray FEL (S3FEL)
Southern Advanced Photon Source (SAPS)
Wuhan Photon Source (WHPS)

Not an exhaustive list.

Major light sources in mainland China



Beijing

Beijing Synchrotron Radiation Facility (BSRF)

High Energy Photon Source (HEPS)

Shanghai

Shanghai Synchrotron Radiation Facility (SSRF)

Shanghai soft X-ray Free-Electron Laser facility (SXFEL)

Shanghai High Repetition Rate X-ray FEL and Extreme Light Facility (SHINE)

Hefei

Hefei Synchrotron Radiation Facility (HLS)

Hefei Advanced Light Facility (HALF)

Others

Dalian Coherent Light Source (DCLS)

Dalian Advanced Light Source (DALS)

Ultrafast Transient Synchrotron Radiation Source

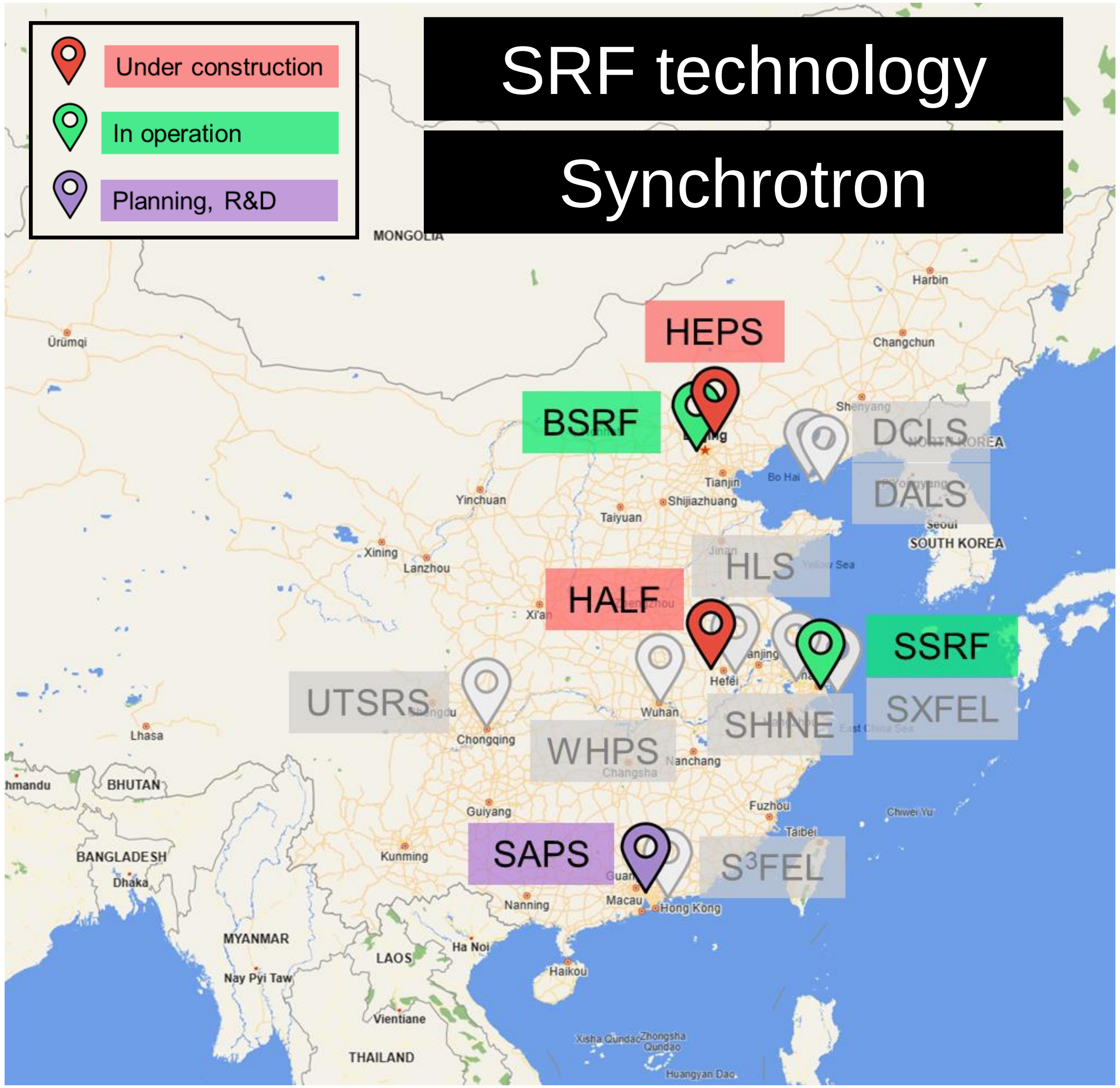
Shenzhen Superconducting Soft X-Ray FEL (S3FEL)

Southern Advanced Photon Source (SAPS)

Wuhan Photon Source (WHPS)

Not an exhaustive list.

Major light sources in mainland China



Beijing

Beijing Synchrotron Radiation Facility (BSRF)

High Energy Photon Source (HEPS)

Shanghai

Shanghai Synchrotron Radiation Facility (SSRF)

Shanghai soft X-ray Free-Electron Laser facility (SXFEL)

Shanghai High Repetition Rate X-ray FEL and Extreme Light Facility (SHINE)

Hefei

Hefei Synchrotron Radiation Facility (HLS)

Hefei Advanced Light Facility (HALF)

Others

Dalian Coherent Light Source (DCLS)

Dalian Advanced Light Source (DALS)

Ultrafast Transient Synchrotron Radiation Source

Shenzhen Superconducting Soft X-Ray FEL (S3FEL)

Southern Advanced Photon Source (SAPS)

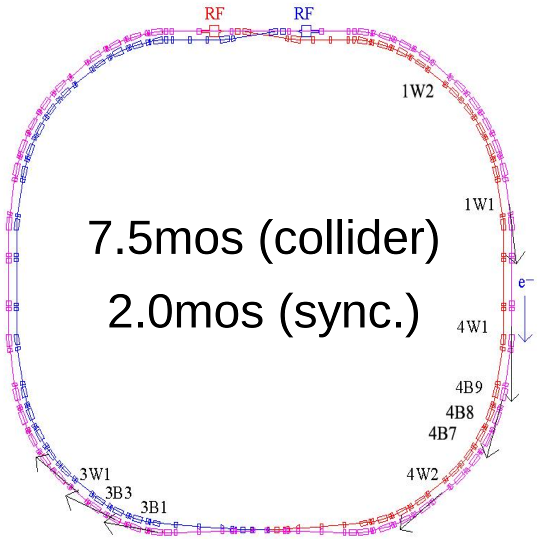
Wuhan Photon Source (WHPS)

Not an exhaustive list.

Beijing **S**ynchrotron **R**adiation **F**acility

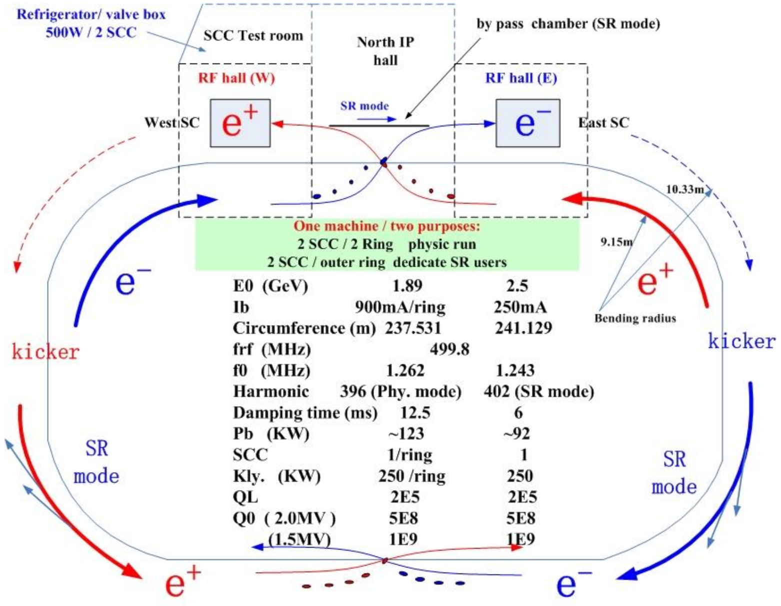
Beijing Synchrotron Radiation Facility

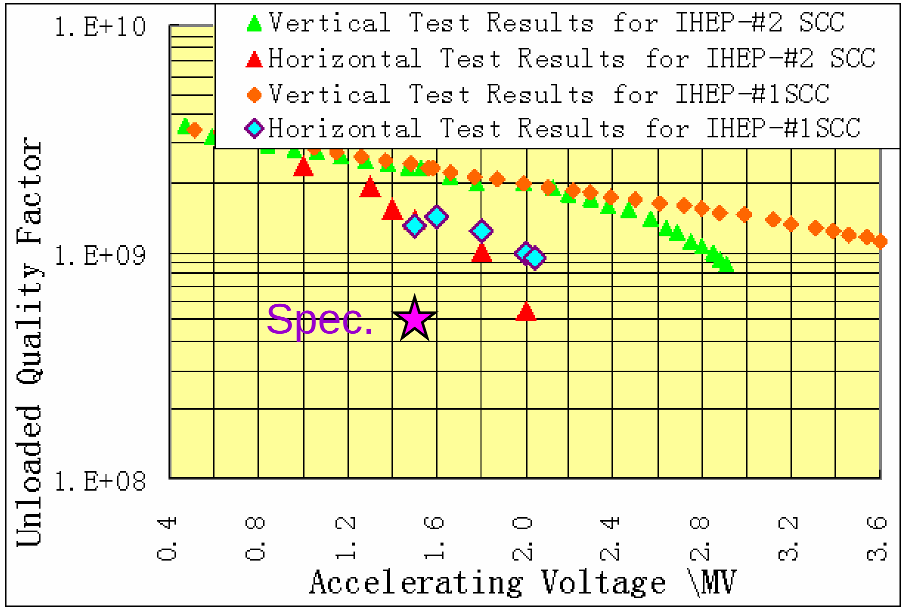
- Location: IHEP campus, Beijing city
- First synchrotron light source in China (first generation)
- Parasitic use of synchrotron on an electron-position collider (BEPC)
- Operation time: 1991-2004, 2009-now (2004-2008, upgrade to BEPCII)
- Parameters: 2.5GeV full energy injection, 250mA, 242m circumference
- Beamlines: 5 IDs, 14 beamlines, vacuum ultraviolet to hard X-ray
- SRF cavities: 2×500MHz single-cell (2 additional cavities in 2024)
- Upgrade in 2024 abandons dedicated sync. mode, keeping the parasitic exp.



500MHz SRF at BEPCII/BSRF

- Two 500MHz SRF cavity modules (KEKB-type) procured from Mitsubishi in 2004
- Collaboration between KEK and IHEP
- Assembled in IHEP, horizontal tests performed in 2006, passed acceptance
- Beam operation since 2009
- SR mode: 1.6 MV, 110 kW, heavy HOM damping, 4K

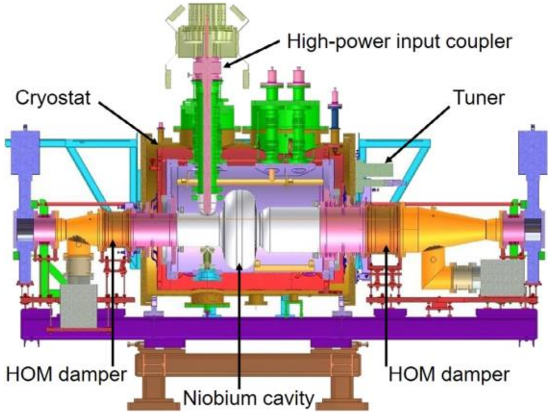




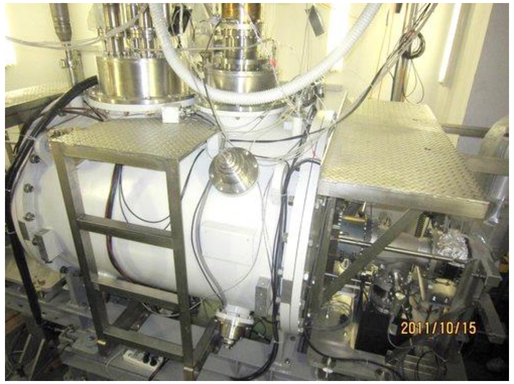
Z. Li *et al.*, *SRF2007*, WEP23.

500MHz spare cavity for BEPCII

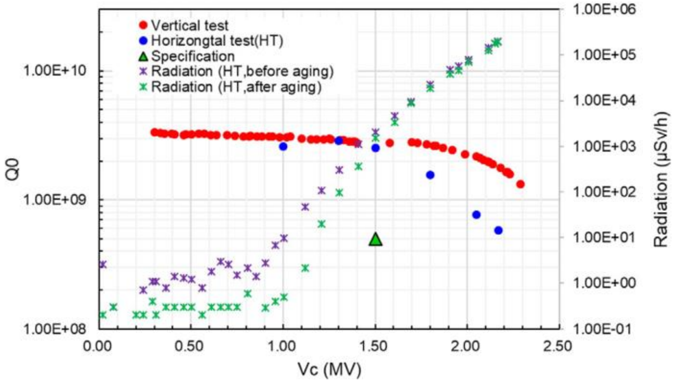
- Spare cavity module in-house development launched in 2006
- Help received from KEK colleagues, for example: FPC tests both at KEK and IHEP
- Horizontal test in 2011, passed acceptance
- Installation at BEPCII in 2017 (replaced one MHI cavity), taking beam since 2017



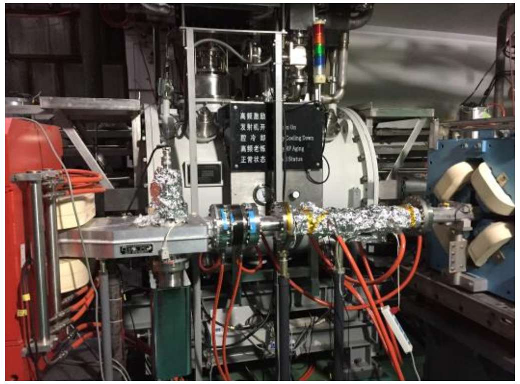
Horizontal test



Cryogenic results

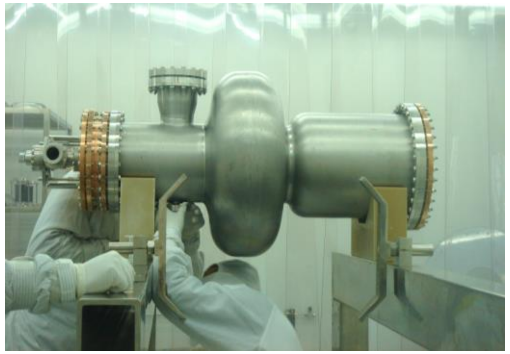


Installed in BEPCII



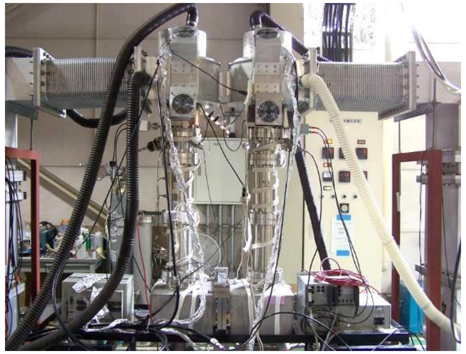
Cavity fabrication

Cavity clean assembly

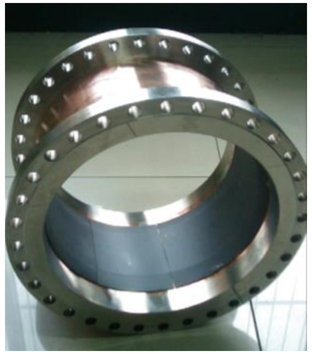


Vertical test

Power couplers



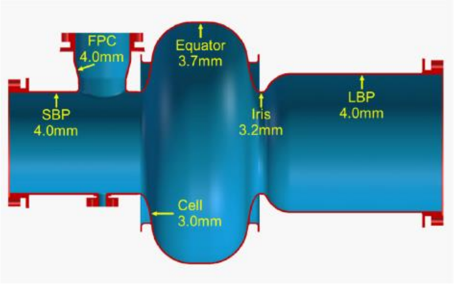
HOM absorber

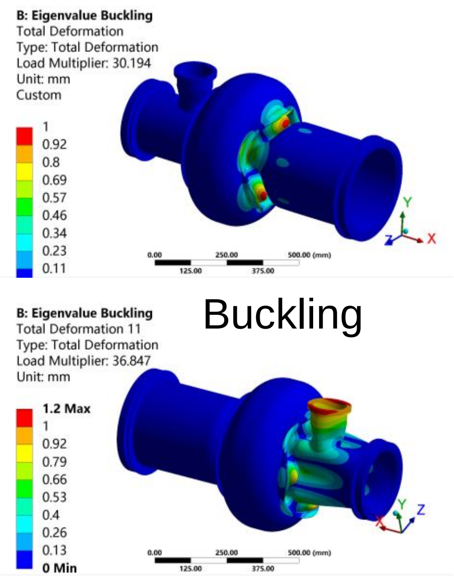


T. Huang *et al.*, *NIM-A* 1013, 165649 (2021).

500MHz cavities for BEPCII upgrade

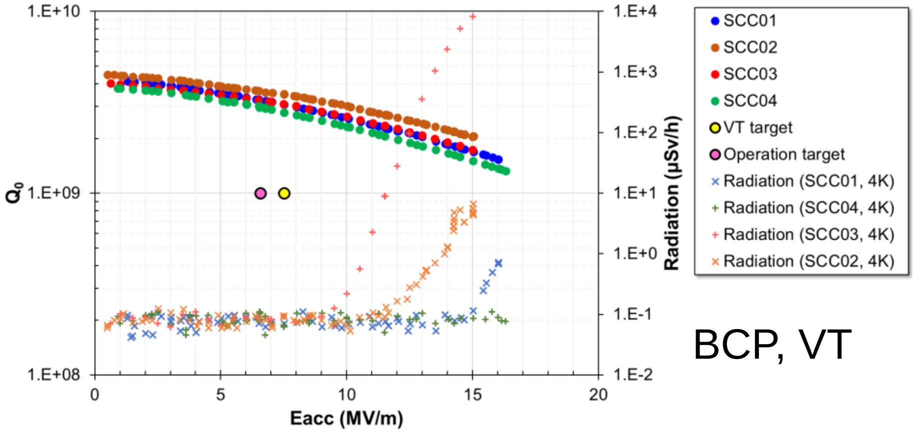
- New development for BEPCII upgrade and HEPS launched in 2020
- Mechanically improved cavity geometry to reserve larger operational margin
- Cryomodule is currently being assembled (1 gate valve under repairment)





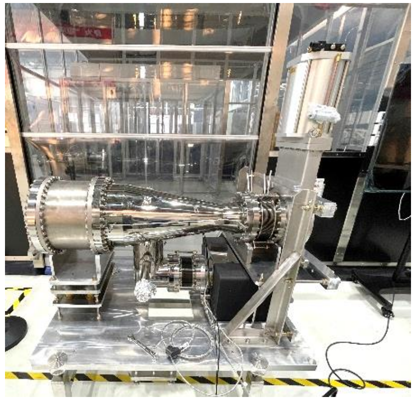
Buckling

Cavity string



BCP, VT

Taper + damper



Cryomodule

FPC mounting

H. Zheng *et al.*, *IEEE Trans. Appl. Supercond.* 31, 3500109 (2021).

Shanghai **S**ynchrotron **R**adiation **F**acility

Shanghai Synchrotron Radiation Facility

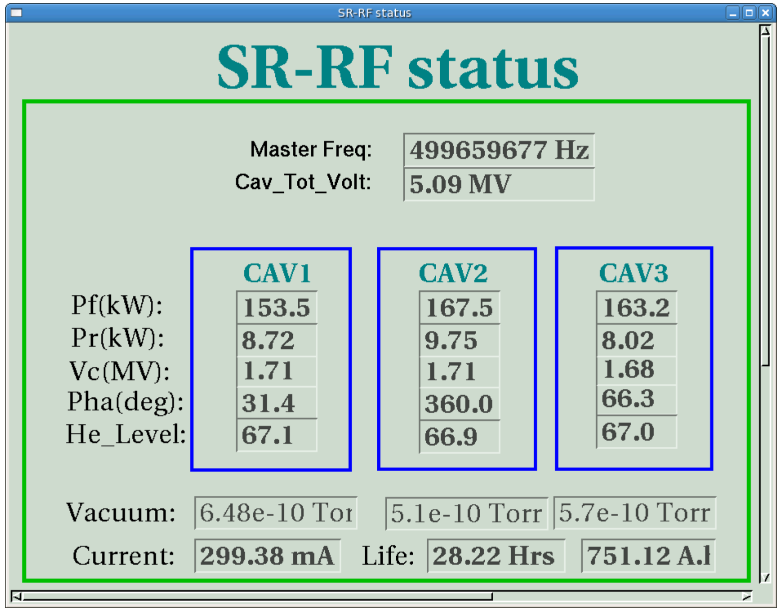
- Third-generation light source in China (Shanghai city)
- Construction time: 2004-2009, Operation time: 2009-now
- Parameters: 3.5GeV, 300mA, 432m circumference (main ring)
- Upgraded in 2016-2023 for additional beamlines and third harmonic cavity
- Beamlines: 34 beamlines, 46 experimental stations
- SRF cavities: 3×500MHz CESR-type single-cell, 1×1.5GHz 2-cell

500MHz cavities at SSRF

- Three 500MHz SRF cavity modules (CESR-type) from ACCEL in 2008
- Beam operation since 2009
- Nominal operation: >1.6MV per cavity, >170kW per cavity, heavy HOM damping, 4K

Horizontal test (SAT)

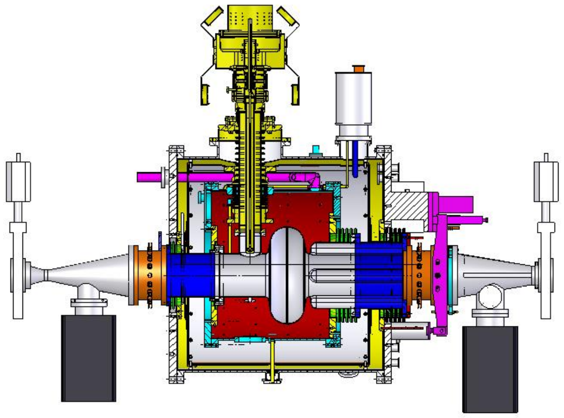
300mA operation

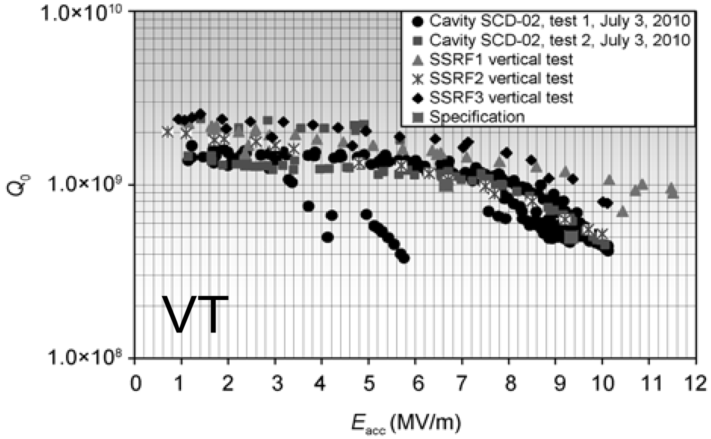


Modules in the tunnel

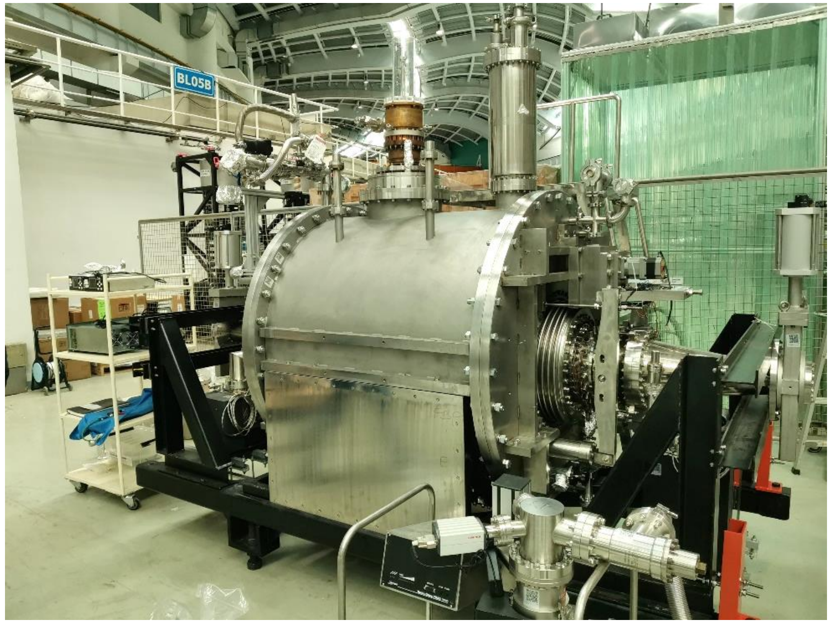
500MHz spare cavity for SSRF

- Spare cavity module in-house development launched in 2009
- New design: Cavity fluted beam pipe and coaxial power coupler
- Vertical tests in 2010, horizontal test in 2020, passed acceptance
- VT: Q_0=1.0e9 @ 1.5 MV and Q_0 = 7.7e8 @ 2.1 MV





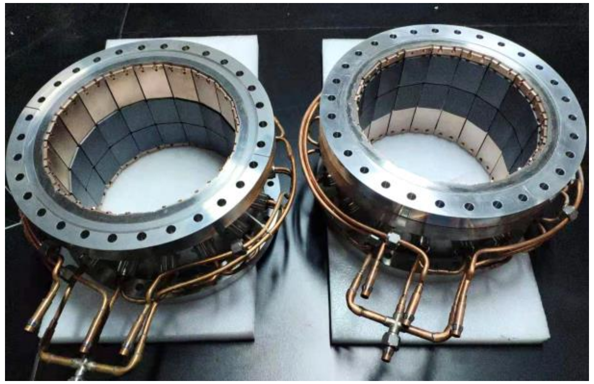
Cryomodule



Bare cavity

FPC

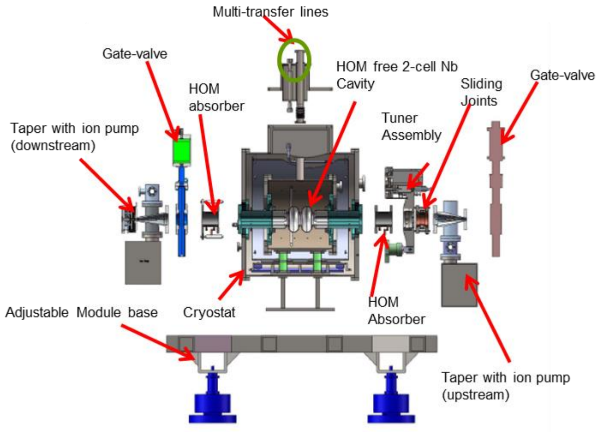
HOM absorber

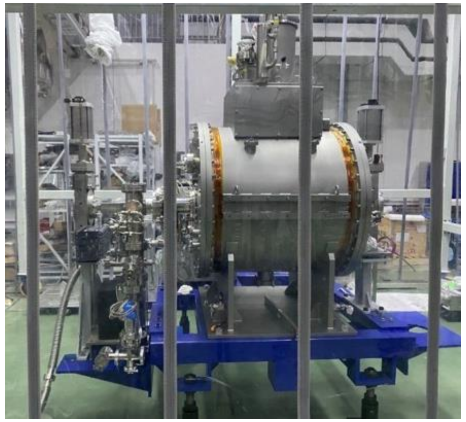


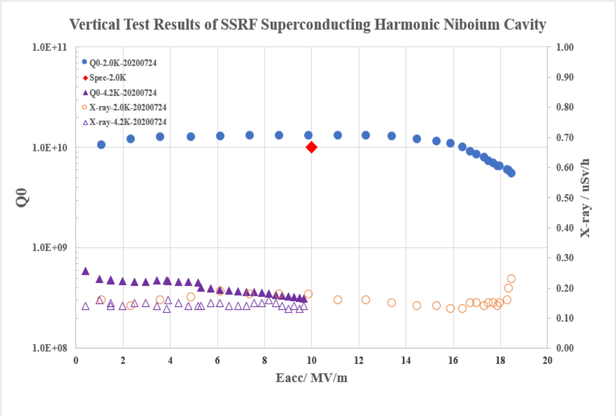
J. Liu *et al.*, *Sci. China Phys. Mech. Astron.* 54 (Suppl 2), 169-173 (2011).

1.5GHz harmonic cavity at SSRF

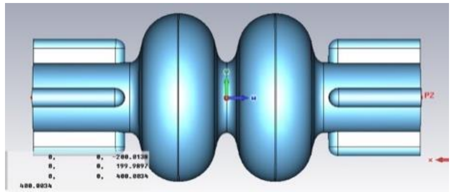
- 1.5GHz 2-cell cavity module in-house development launched in 2016
- Horizontal test in 2021, beam operation since 2021 (passive cavity)
- Operation parameters: Vc>1.8MV, Q_0>2e8 (4K), bunch lengthening factor > 2



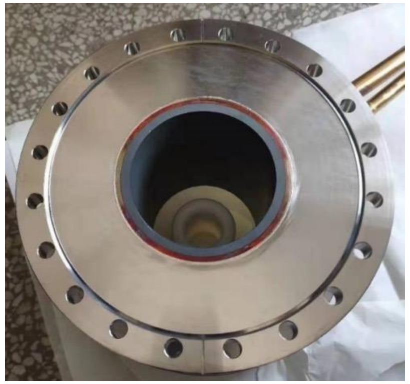




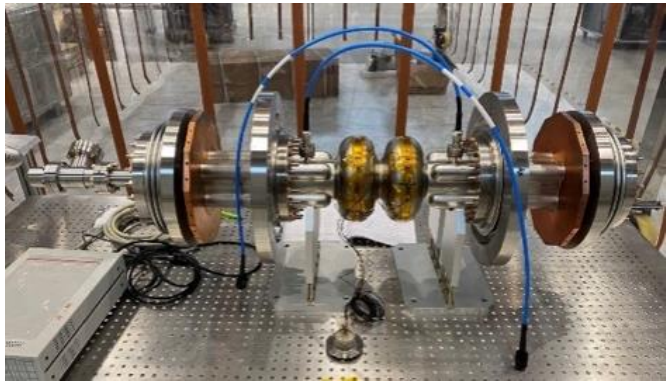
Cryomodule in SSRF tunnel



HOM absorber (SiC)



Cavity string



H. Hou, *National Workshop on Microwave and RF Technology of Particle Accelerators*, 09.2023, Yunnan, China.

Synchrotron light sources in China

Beijing Synchrotron Radiation Facility (BSRF)

1st generation | SRF

Hefei Synchrotron Radiation Facility (HLS)

2nd generation | NCRF

Shanghai Synchrotron Radiation Facility (SSRF)

3rd generation | SRF

High Energy Photon Source (HEPS)

SRF

Construction: 2019-2025

4th-generation DLSR

Hefei Advanced Light Facility (HALF)

SRF

Construction: 2023-2028

<u>H</u>igh **<u>E</u>**nergy **<u>P</u>**hoton **<u>S</u>**ource

(Beijing)

High Energy Photon Source (two phases)

HEPS project milestones

- 28.09.2016, Project settle in Huairou (Beijing)
- 15.12.2017, Project proposal approved by NDRC (CD0 equivalent)
- 28.12.2018, Feasibility study approved by NDRC (CD1 equivalent)
- 22.05.2019, Preliminary design and budget approved by NDRC (CD2 equivalent)
- 29.06.2019, Construction start in Huairou (CD3 equivalent)
- 31.12.2025, Construction completed, national acceptance (CD4 equivalent)

HEPS-TF (R&D project before HEPS)

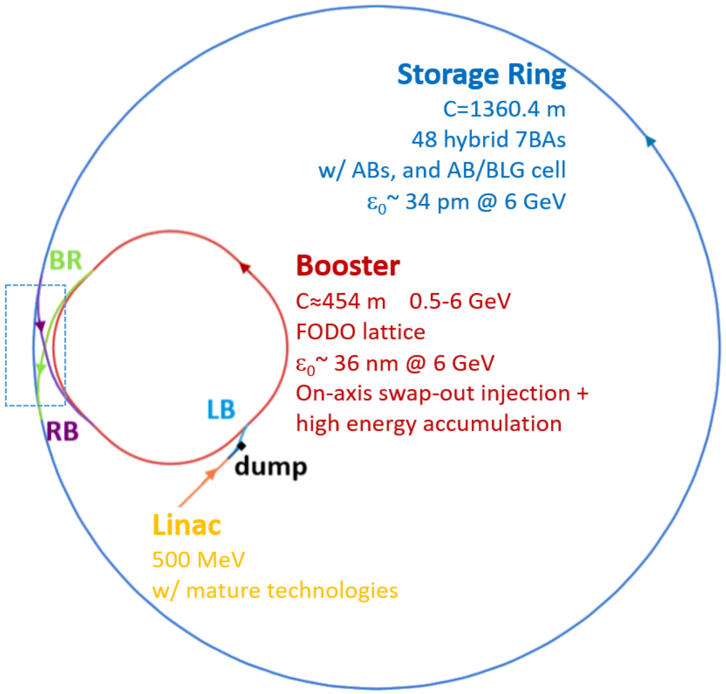
- Schedule：04.2016 - 10.2018
- Budget: 321.6 M RMB (~48 M USD)
- Objective: Key components R&D for HEPS

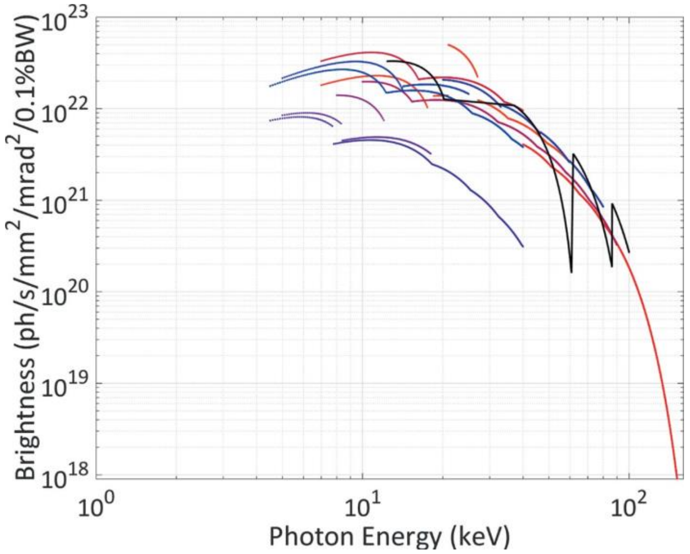
NDRC: National Development and Reform Commission

Main facts

- **High Energy Photon Source (HEPS)**
  - A diffraction-limited SR light source (4th-gen)
  - One of the brightest 4th-gen SR in the world
  - The 1st high-energy SR light source in China
- **Main facts**
  - 1360.4m circumference, linac + booster + SR
  - **Beam**: 6 GeV, 200 mA
  - **Location**: Huairou Science City, Beijing
  - **Construction time**: 06.2019 – 12.2025
  - **Budget**: 4.76 B CNY (~652 M USD)(including materials, civil construction & commissioning, excluding labor costs)
  - **Support**: Central government + Local government + Chinese Academy of Sciences

Main parameters





- 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, maximum capacity of 90 BLs

Parameter	Value	Unit
Beam energy	6	GeV
Circumference	1360.4	m
Lattice type	7BA	-
Hori. Natural emittance	<60	pm·rad
Brightness	$>1\times10^{22}$	*
Beam current	200	mA
Injection mode	Top-up	-
Total energy loss to bare lattice	2.64	MeV
Total beam power	850	kW
Number of sectors	48	-
Bunch length (w/o, w/ HC)	5.06, 29.8	mm

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

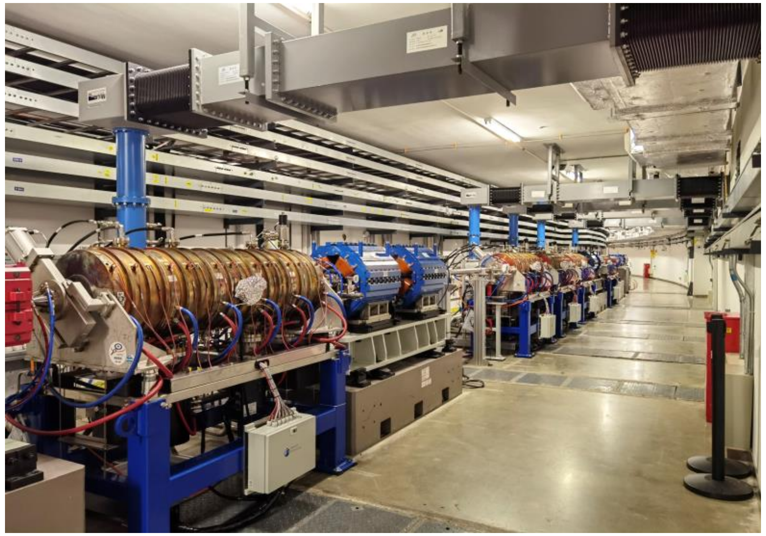
[1] Y. Jiao *et al.*, *J. Synchrotron Rad.* 25, 1611–1618 (2018).
[2] H. Xu *et al.*, *RDTM* 7, 279–287 (2023).

Milestones of HEPS construction

- Groundbreaking in 06.2019
- Civil construction completed in 11.2021
- First accelerator equipment installed in 07.2021
- Booster installation completed in 01.2023
- Storage-ring installation started in 02.2023
- Linac commissioning completed in 03.2023
- Booster commissioning completed in 11.2023

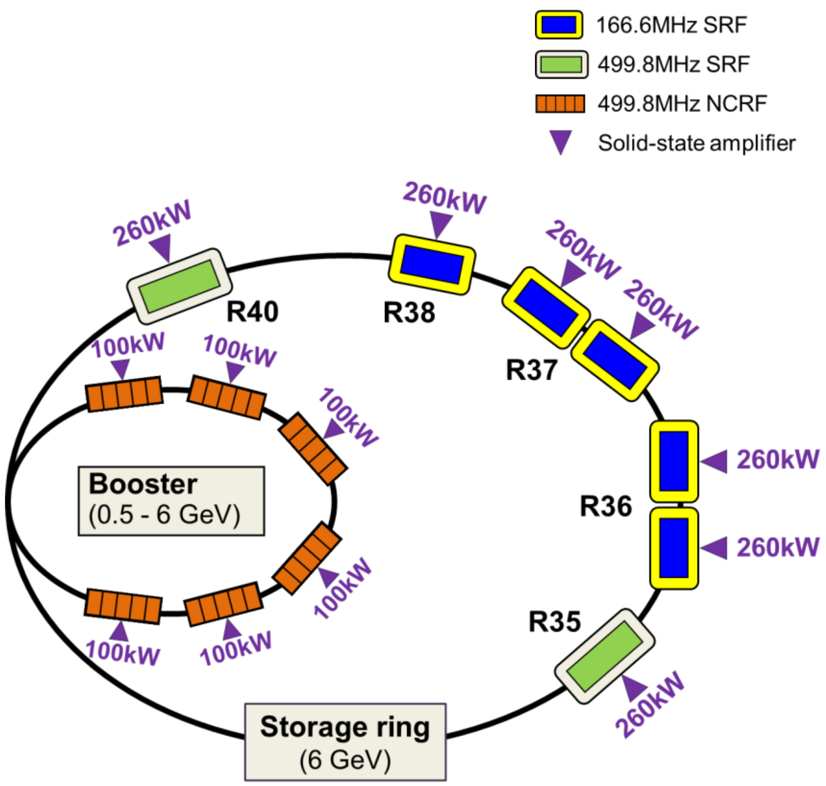
SSAs in booster RF hall

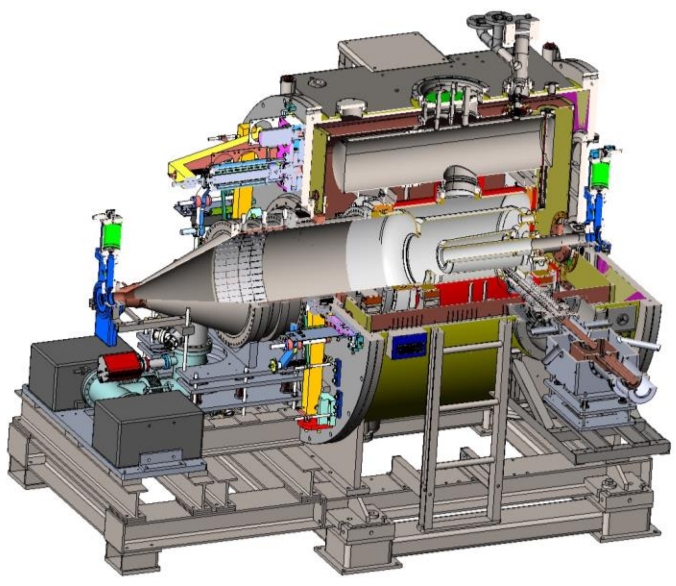
Booster tunnel (RF section)



Linac tunnel

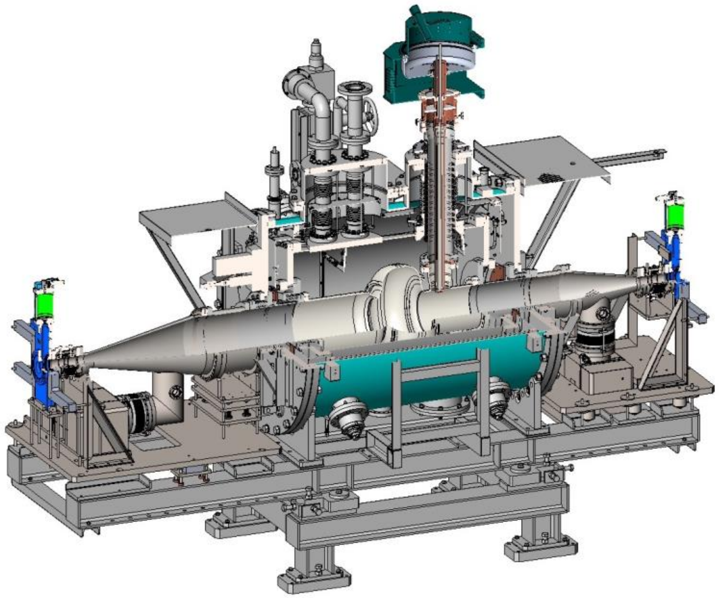
SRF for HEPS





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

In-house development
(**New**)

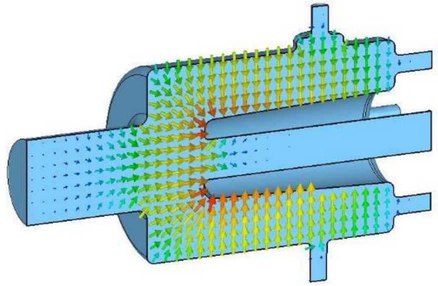


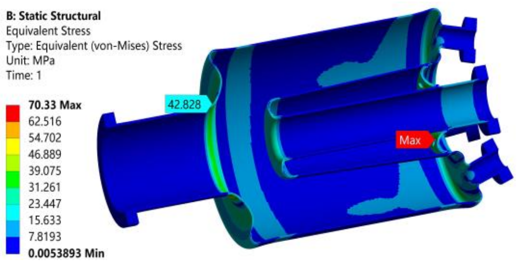
500MHz KEKB-type
single-cell elliptical SRF cavity
(Storage ring)

In-house development
(Synergy w/ BEPCII-U)

[1] P. Zhang *et al.*, *Radiation Detection Technology and Methods* 7, 159-170 (2023).
[2] X. Zhang *et al.*, *SRF2021*, MOPCAV010.
[3] H. Zheng *et al.*, *IEEE Trans. Appl. Supercond.* 31, 3500109 (2021).

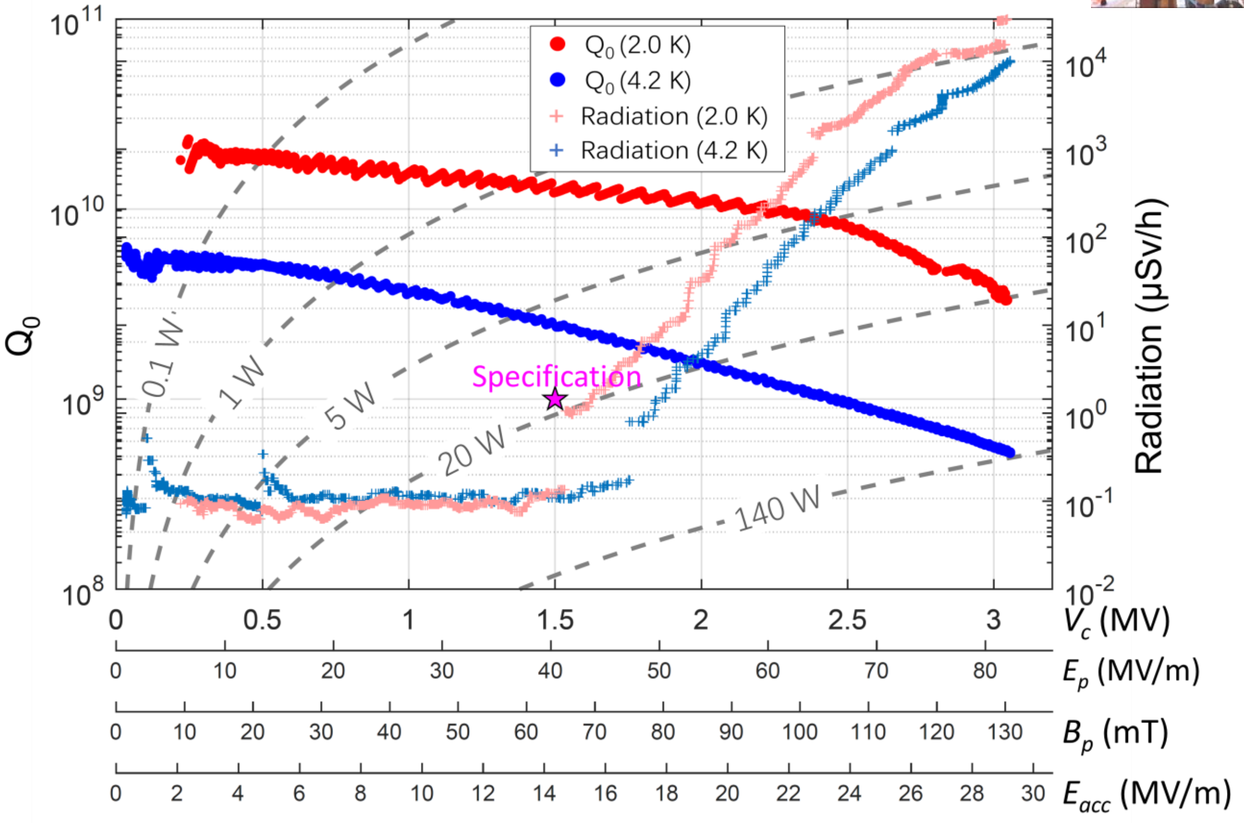
166MHz Proof-of-Principle cavity





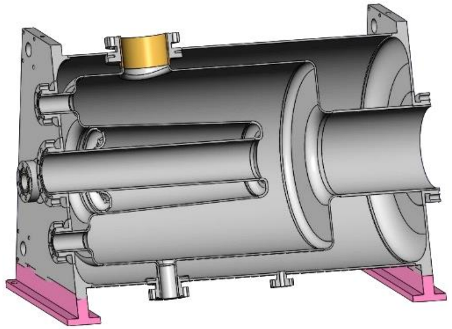
- Q_0 (4K) at design Vc (1.5MV): 2.4×10^9
- Maximum Ep: 82 MV/m
- Maximum Bp: 132 mT
- FE onset: Ep = 48 MV/m
- Residual resistance: 2.2 nΩ

Parameter	Value	Unit
Frequency	166.6	MHz
Cavity length (main)	530	mm
Cavity diameter (no ports)	397	mm
Aperture (small side)	80	mm
R/Q	136	Ω
Geometry factor	54.5	Ω
Design voltage (Vc_d)	1.5	MV
Design gradient	12.5	MV/m
Q0 at Vc_d	>1e9	-
Epeak at Vc_d	40.1	MV/m
Bpeak at Vc_d	63.9	mT
Stored energy	15.8	J



[1] P. Zhang *et al.*, *Rev. Sci. Instrum* 90, 084705 (2019). [2] X. Zhang *et al.*, *NIM-A* 947, 162770 (2019).

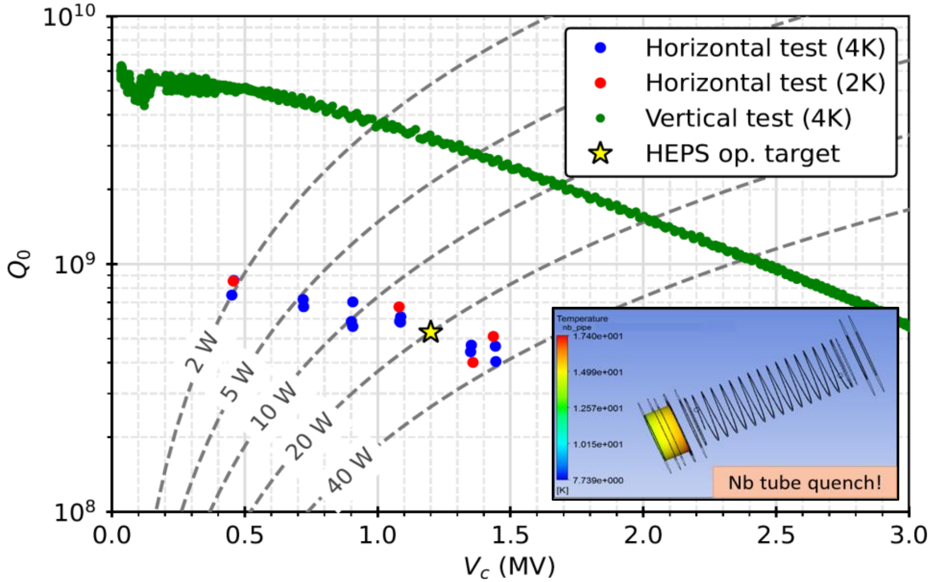
166MHz Proof-of-Principle cavity (dressed)



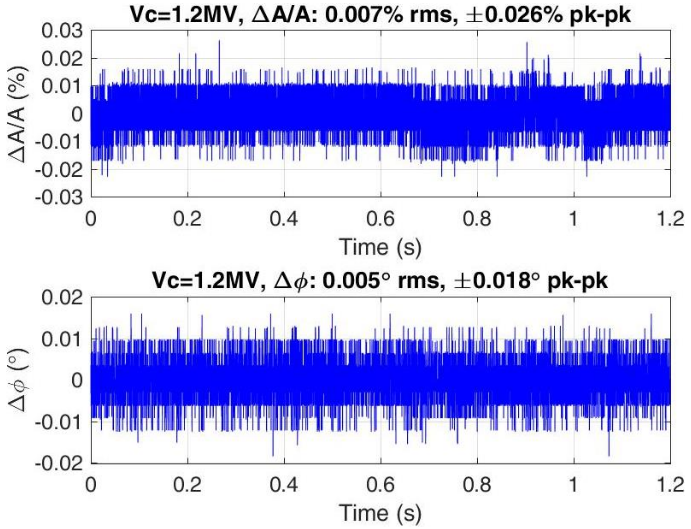




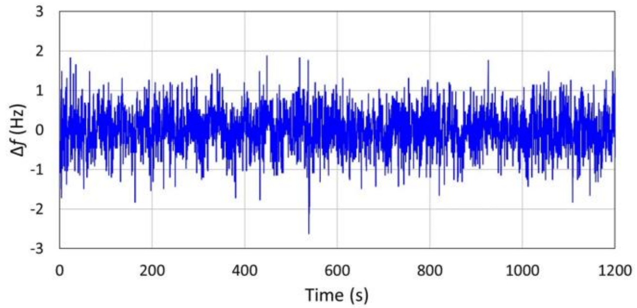
- Large performance degradation observed from VT to HT
  - Cause: overheating on FPC Nb tube extension, 80mm -> 120mm
  - Relocate the pickup to simplify helium jacket design



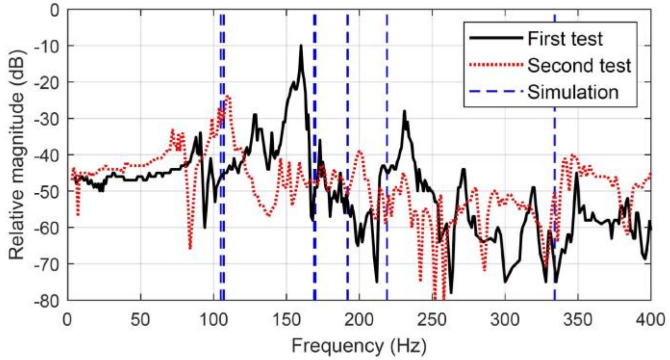
A/P loop closed



Freq. loop closed



Microphonics spectrum



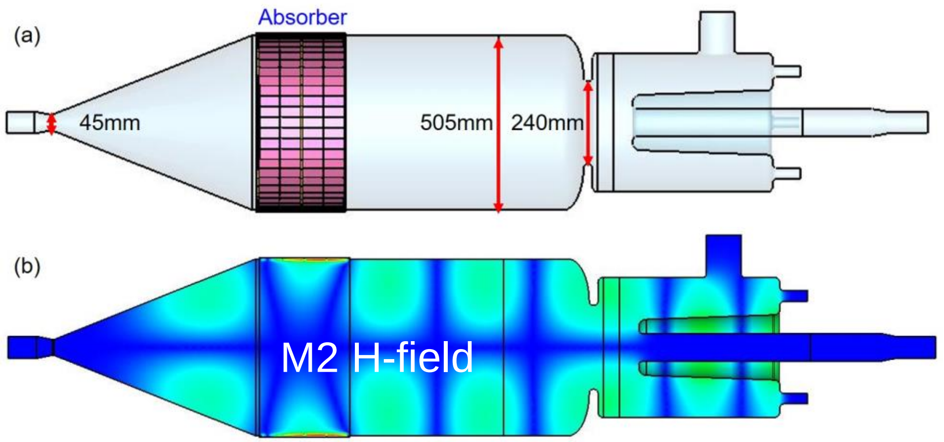
[1] X. Zhang *et al.*, *IEEE Trans. Appl. Supercond.* 30, 3500208 (2020). [2] T. Huang *et al.*, *AIP Advances* 11, 045024 (2021).

HOM damping design

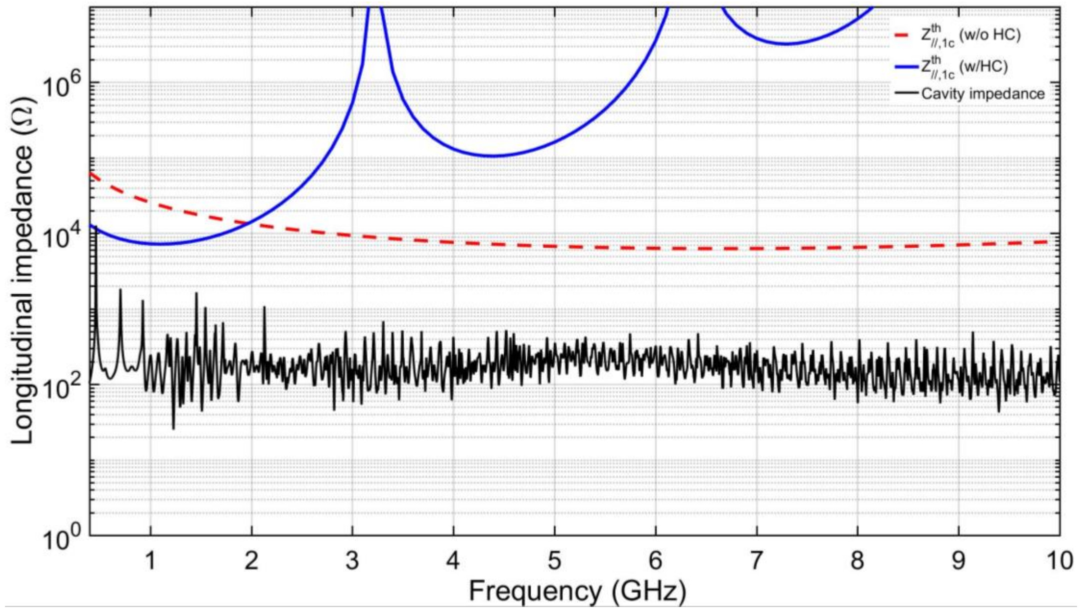
- Various damping schemes investigated (HOM coupler, C-waveguides, hybrid)

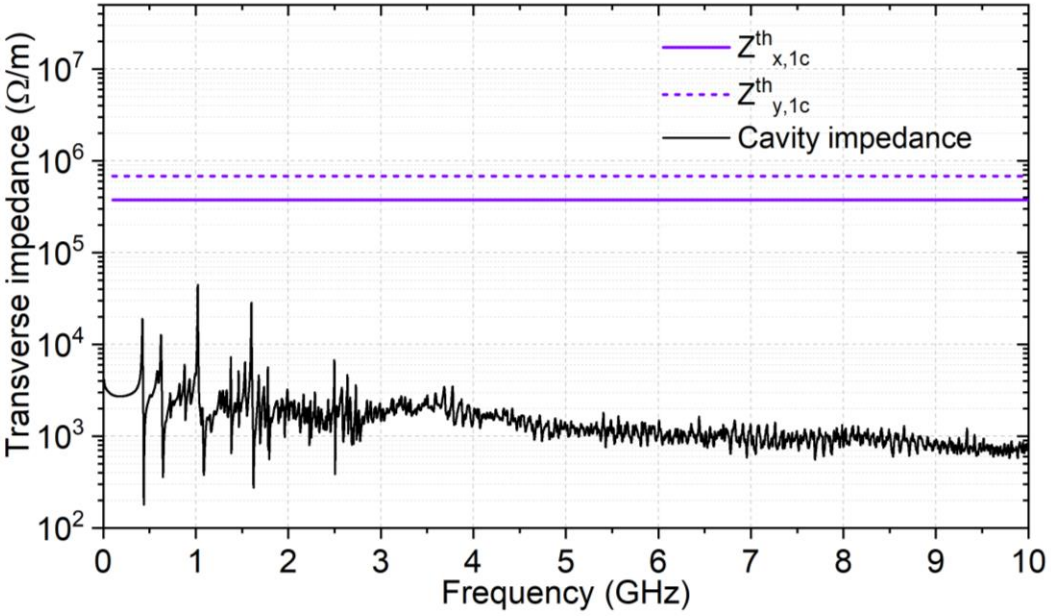
  - Enlarged-beam-pipe option was chosen

- Maximum HOM power: 7kW per cavity
- Challenges: large HOM absorber, impedance, SR light collimation



M2: 464 MHz, R/Q=45 Ω, Q_L=576



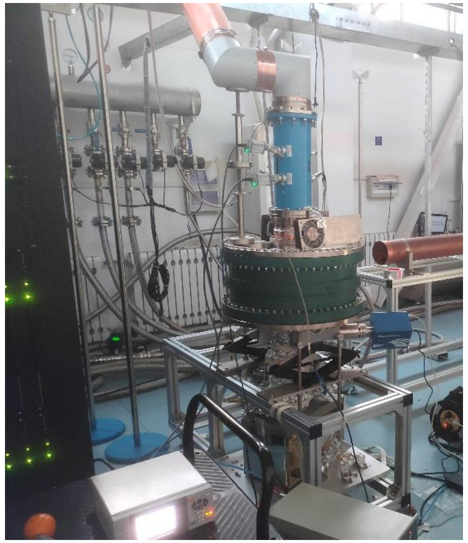


H.J. Zheng *et al.*, *IPAC2021*, WEPAB090.

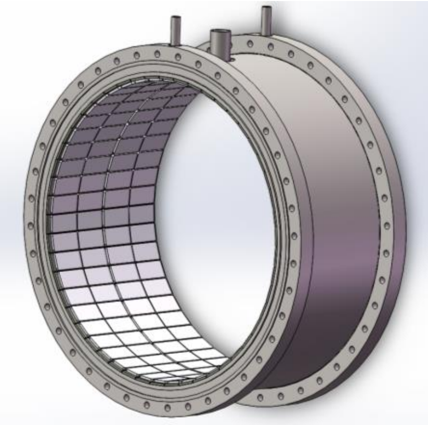
HOM Absorber

- In-house development launched in 2020
  - Inner diameter of the beam pipe: 505 mm, 200 ferrite tiles, 4 tiles/coupon
- Peeling of ferrite tiles due to brazing fixtures moved during the final brazing (optimized)
  - 1 tile peeled off after the 10 kW power test
  - 2 tiles peeled off after pure water cleaning and stored in humid air at cleanroom rinsing section for over 6 months (aggravated oxidation for the two already compromised tiles)
- Additional baking + extensive examinations by applying shear forces (30 N) on all tiles
- Optimized cleaning procedure, particle-free achieved before assembling with cavity

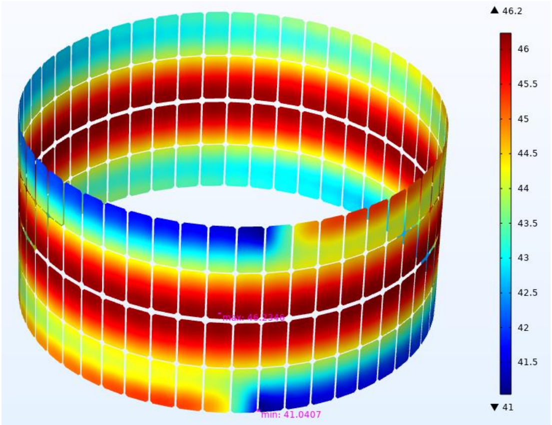
10kW test under vacuum



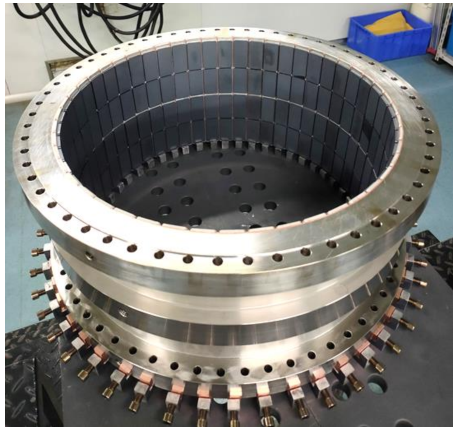
Design

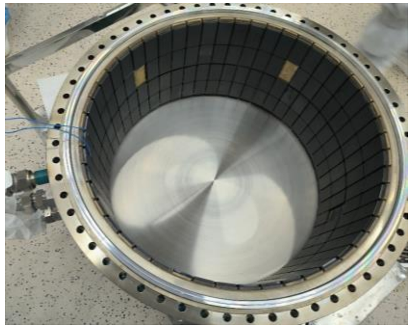


Ferrite Temp. (7kW RF power w/ water cooling)



After final brazing



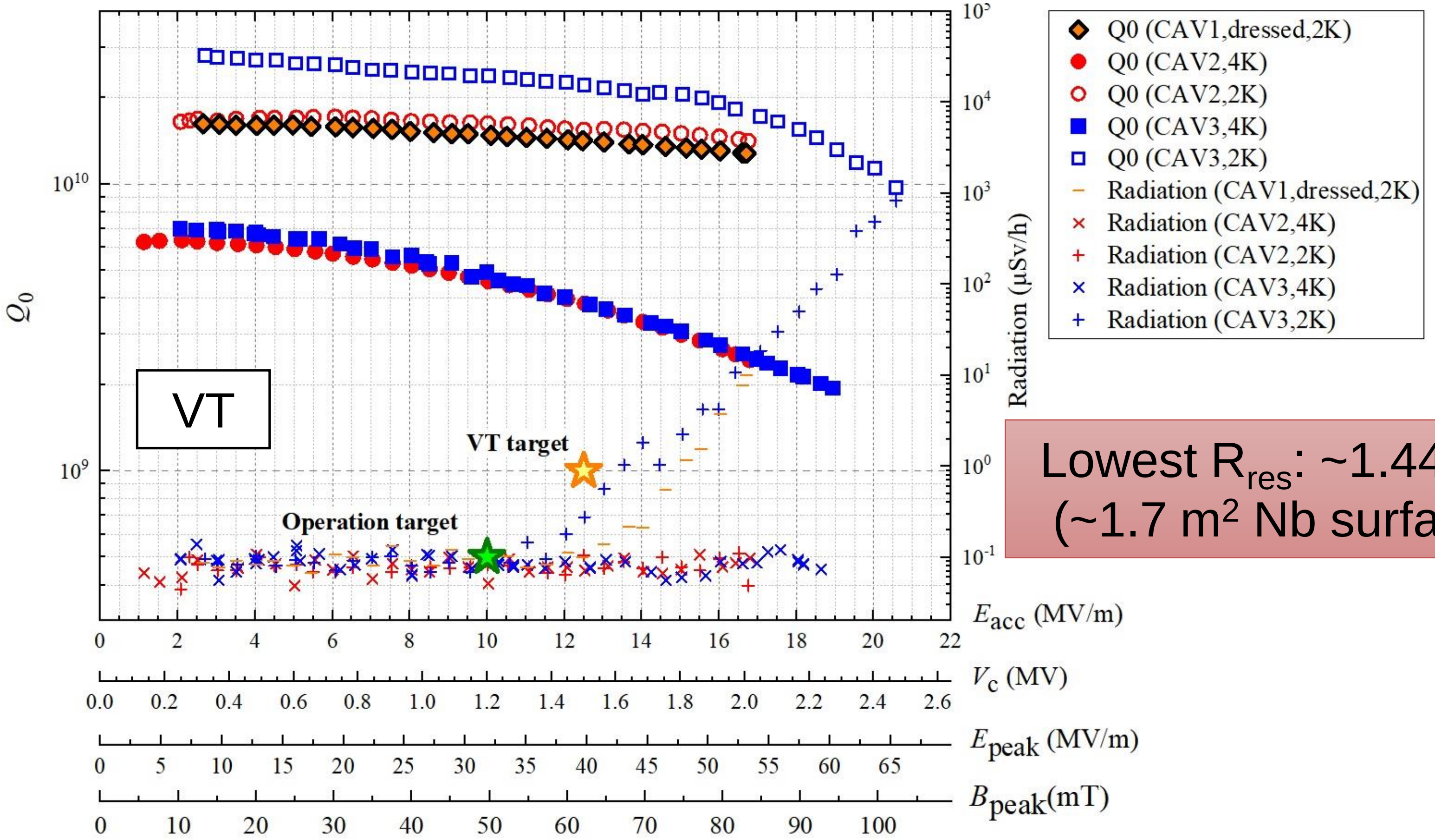


HOM-damped 166MHz cavity

Parameter	Value	Unit
RF frequency	166.6	MHz
Operation T.	4.4	K
Designed V_d	1.5	MV
Operation V_o	1.2	MV
Ep at V_d	40	MV/m
Bp at V_d	62	mT
Q0 at V_d (VT)	>1e9	-
R/Q	139	Ω
G	56	Ω

X. Zhang *et al.*, *SRF2021*, MOPCAV010.

- First batch of bare cavities developed and met design goal
- First jacketed cavity performance preserved: no chemistry after LHe vessel welding, only HPR
- Optimized procedure ensure no FE onset up to Ep=60MV/m

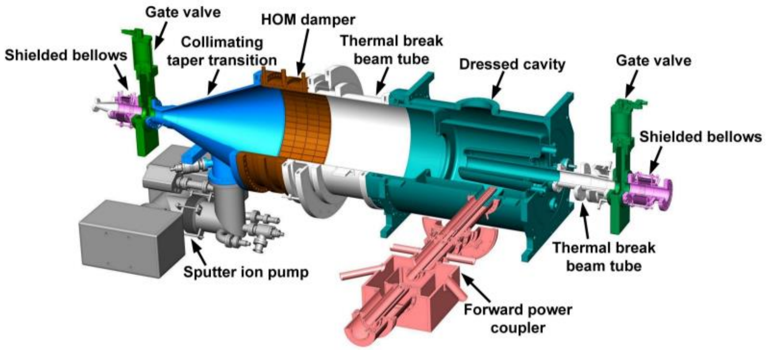


Lowest R_{res}: ~1.44 nΩ
(~1.7 m^2 Nb surface)

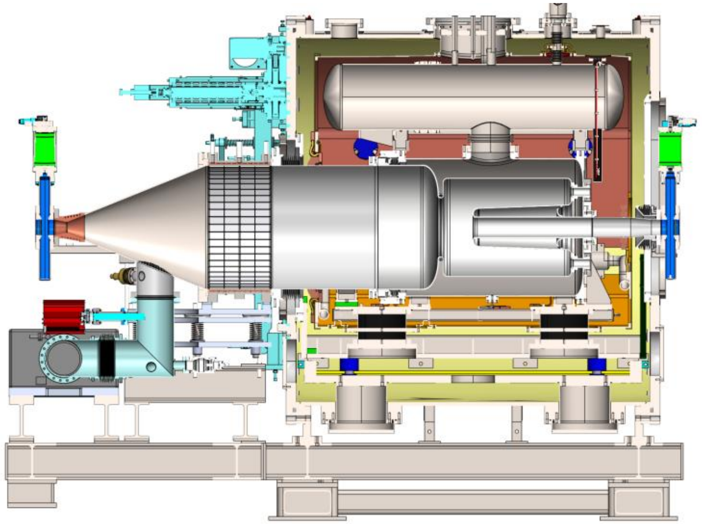
166MHz cryomodule

- Cavity string designed to ensure compactness, sync. light collimation, impedance, etc.
- First cryomodule successfully assembled and horizontal tests performed in Nov. 2023

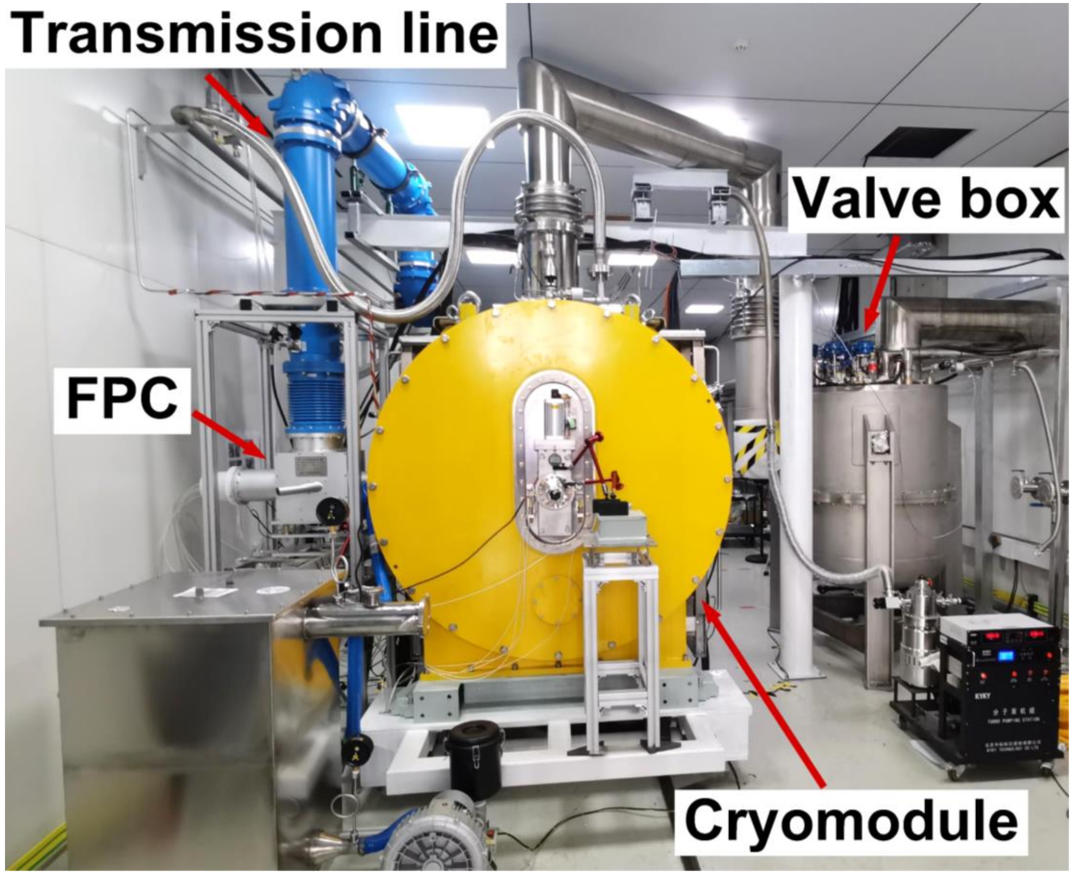
Cavity string



Cryomodule

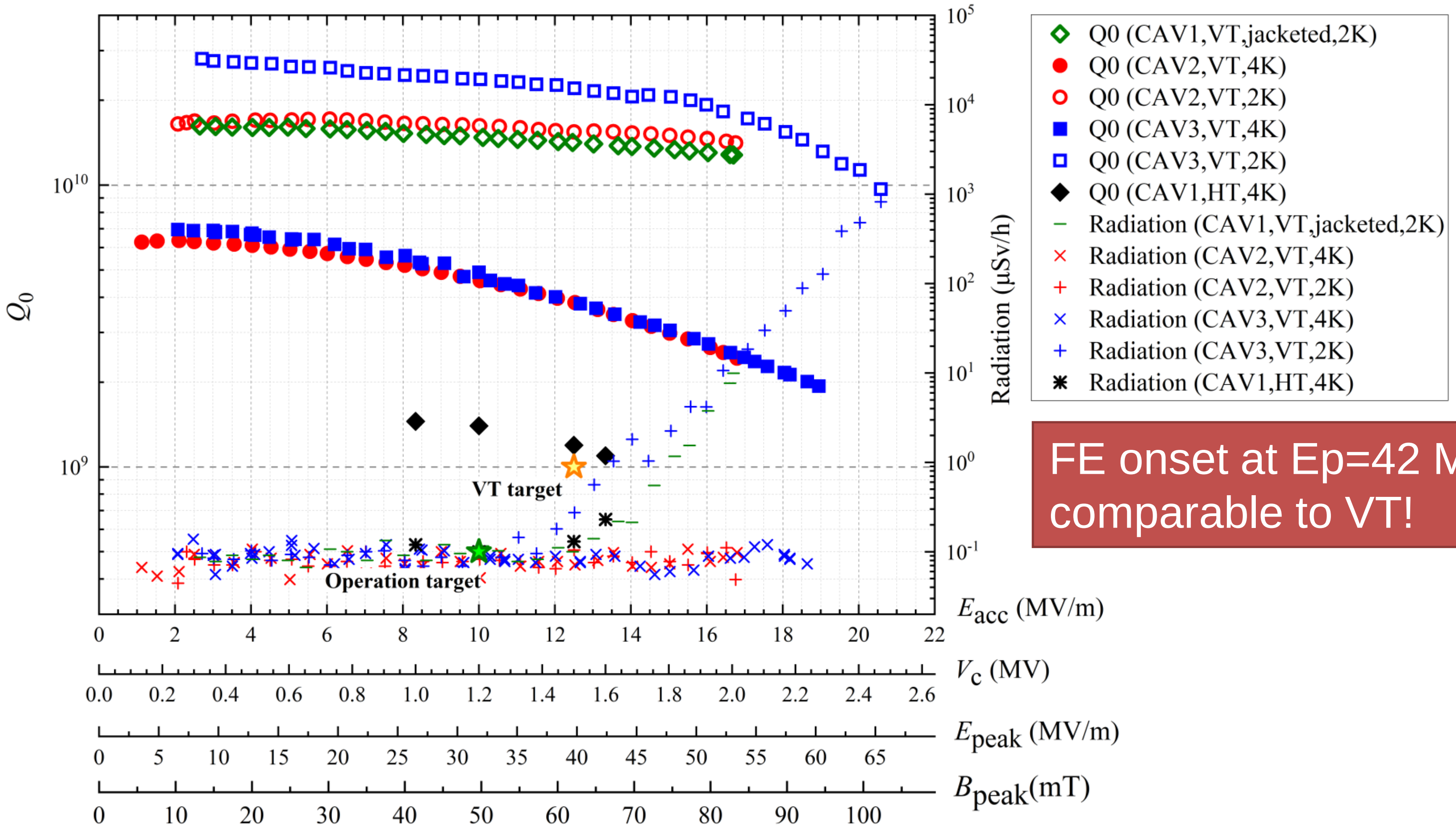


Cryomodule at horizontal test bench



166MHz cryomodule horizontal test

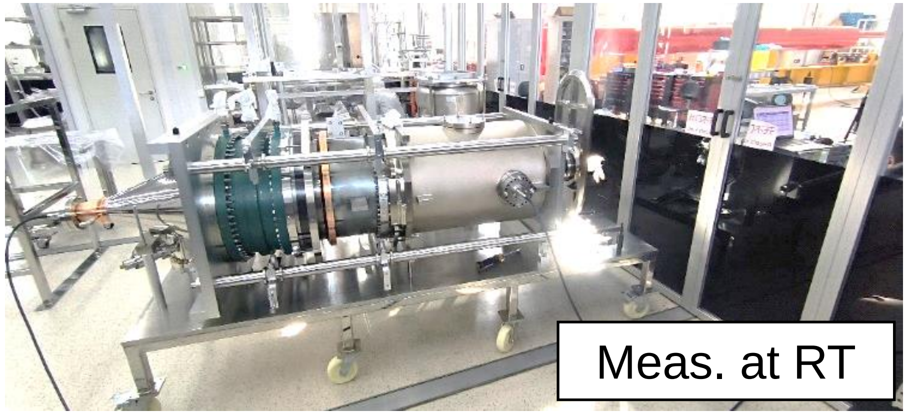
- Performance demonstrated: assembly procedure, processing, cooldown
- Vc=1.2 MV, $Q_0=1.4\times10^9$, dynamic heat loss=7.4 W, radiation=0.1 μSv/h

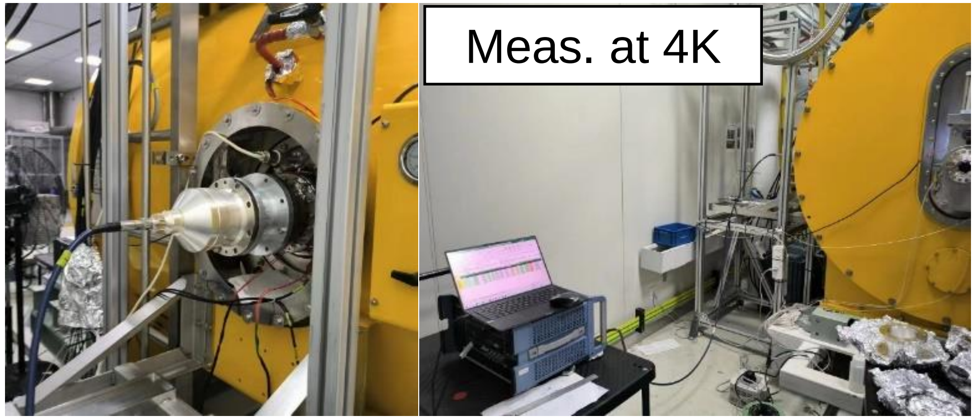


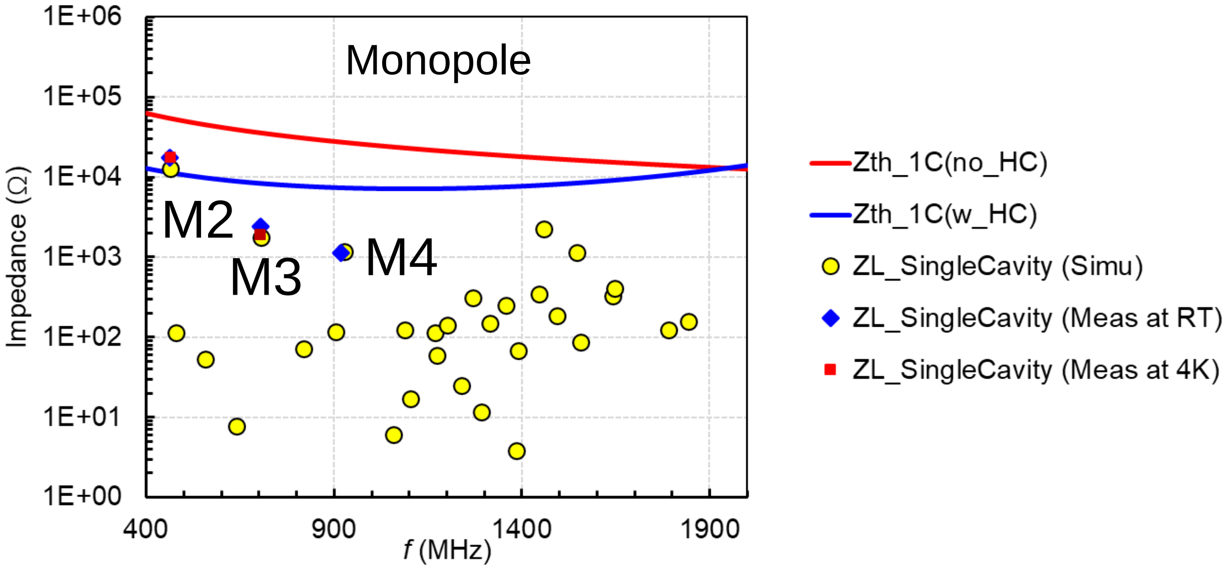
FE onset at Ep=42 MV/m comparable to VT!

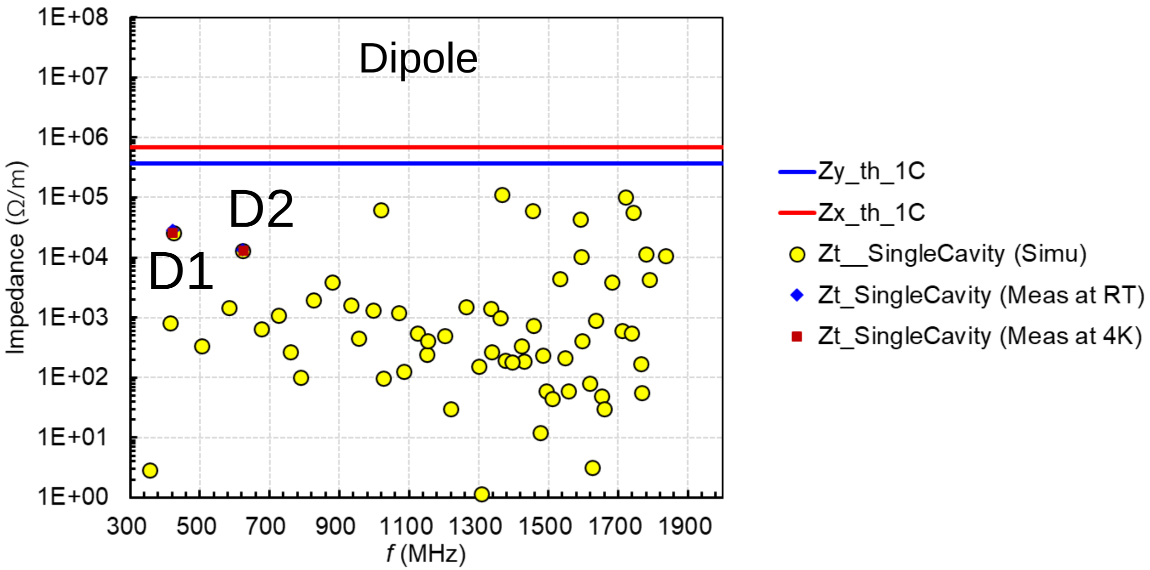
HOM measurement

- Measurement of HOMs conducted both at room-temperature and at 4K
- Measurement and simulation consistent, M2 impedance slightly higher than threshold
  - simulations suggested removing one quarter of ferrite ring will help, under careful investigation



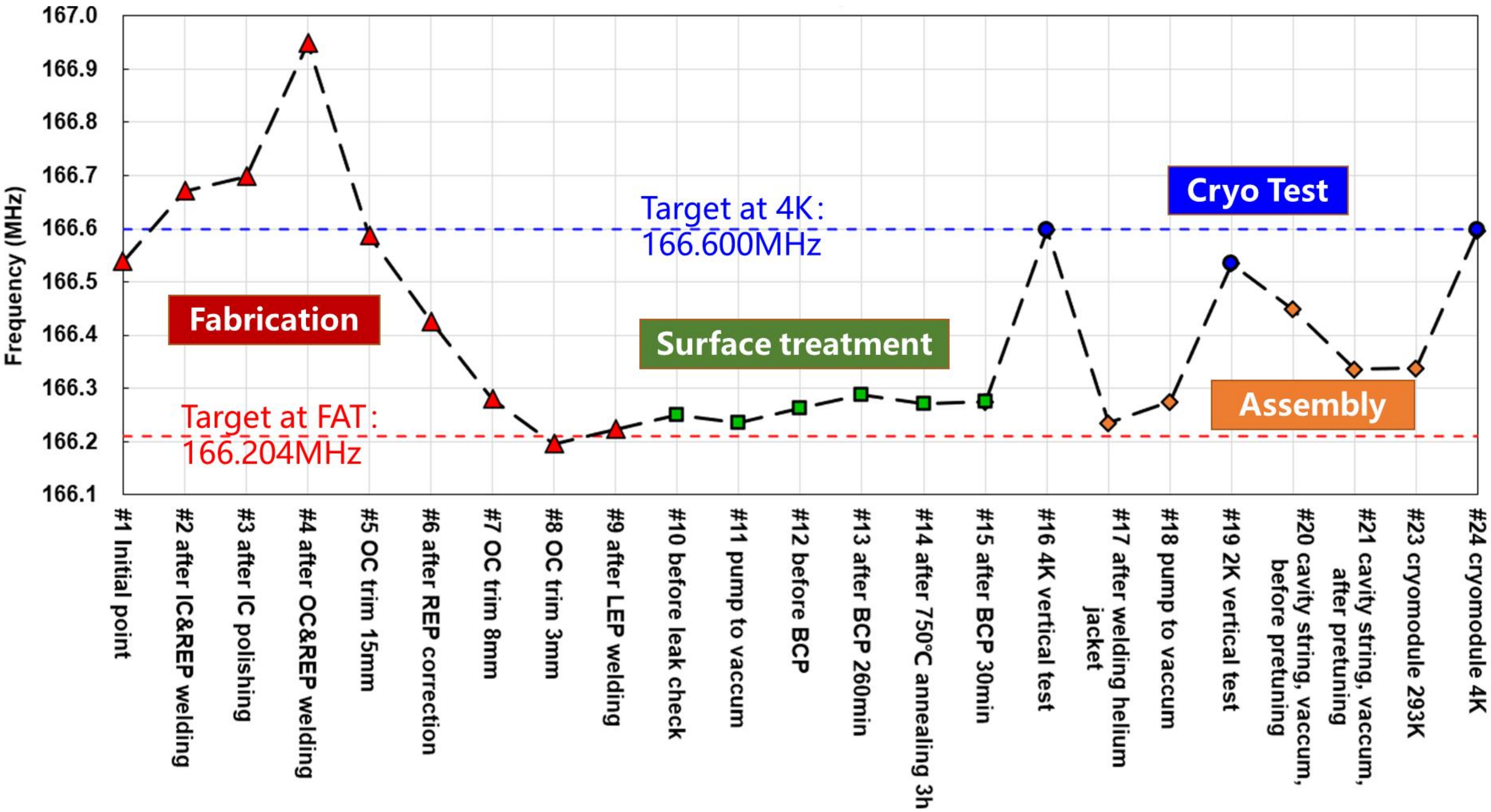






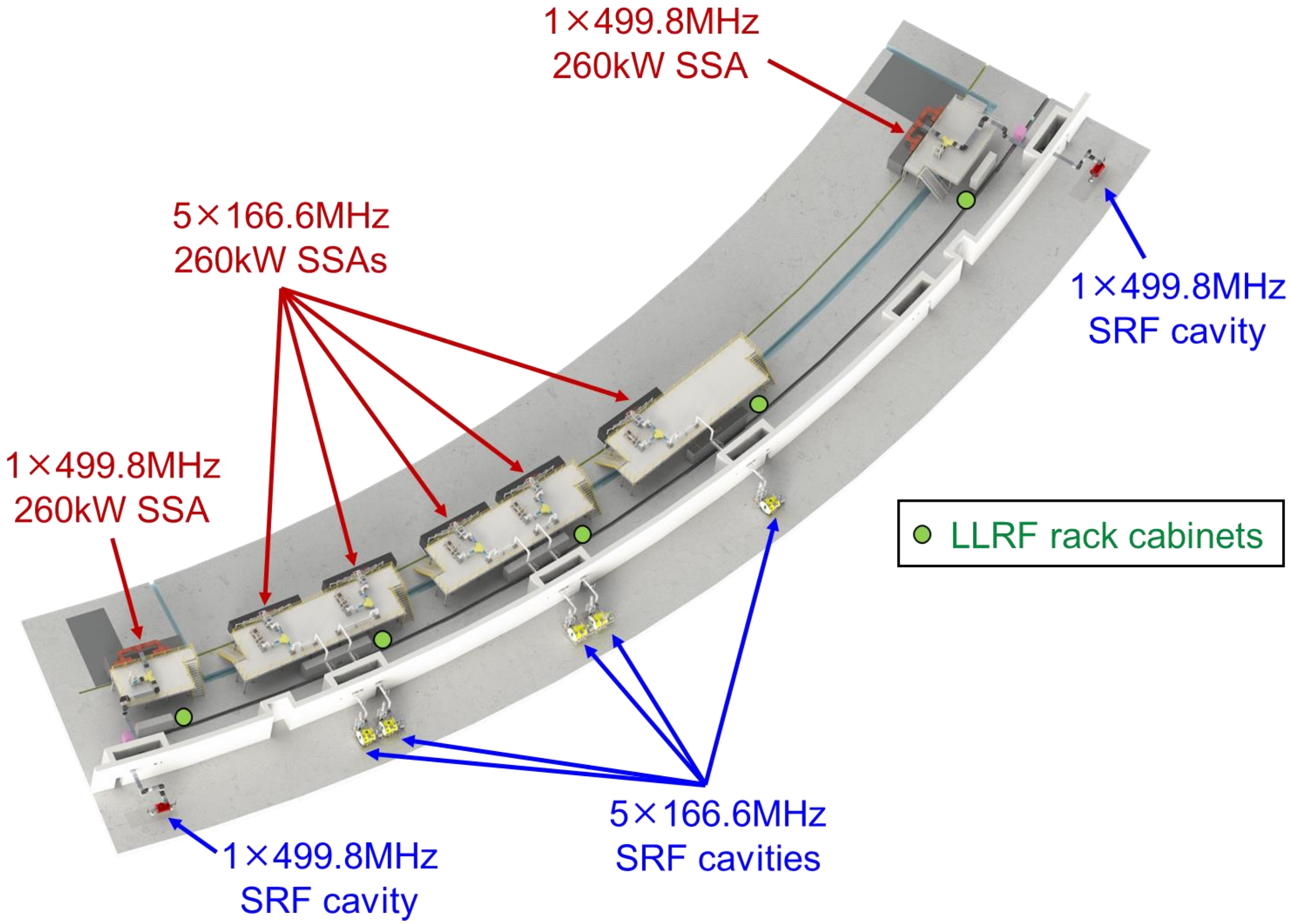
Frequency control

- A comprehensive frequency control plan developed and applied
- CM01 successfully reached the target frequency of 166.6 MHz at 4 K



L. Guo *et al.*, *IPAC2023*, WEPA192.

Series 166MHz modules under production



HEPS SSAs

- Two frequencies, three power levels, total RF power ~2.4MW

500MHz 100kW (BS RF Hall)

166MHz 260kW prototype (PAPS)

500MHz 150kW prototype (PAPS)

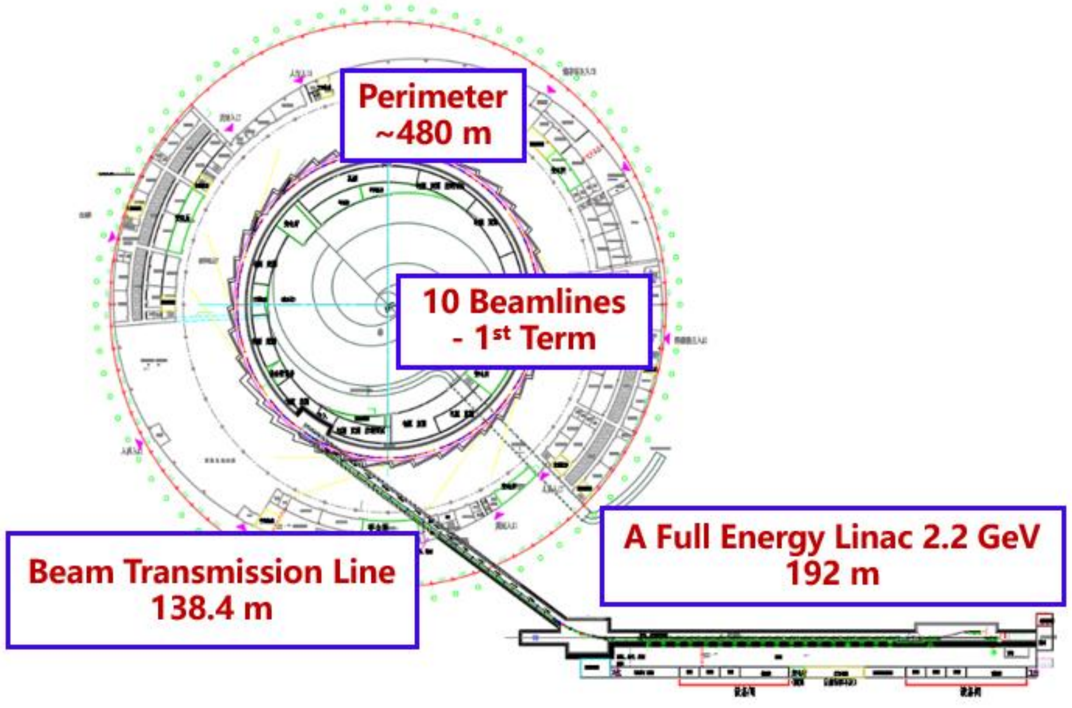
500MHz 260kW (FAT)

Hefei Advanced Light Facility

(Hefei, Anhui)

Hefei **A**dvanced **L**ight **F**acility

- A low-energy 4th-gen storage ring light source in Hefei, Anhui
- Collaboration between USTC and IHEP on SRF, magnets, cryogenics, etc.
- Construction time: 09.2023 - 12.2028, Budget: ~400 M USD
- Beam: 2.2GeV, 350mA, ~480m circumference, full energy linac
- Beamlines: 10 beamlines in Phase I
- SRF cavities: 1×500MHz KEKB-type single-cell, 1×1.5GHz single-cell

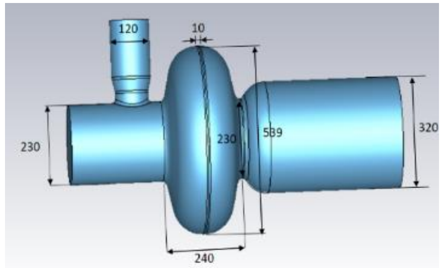


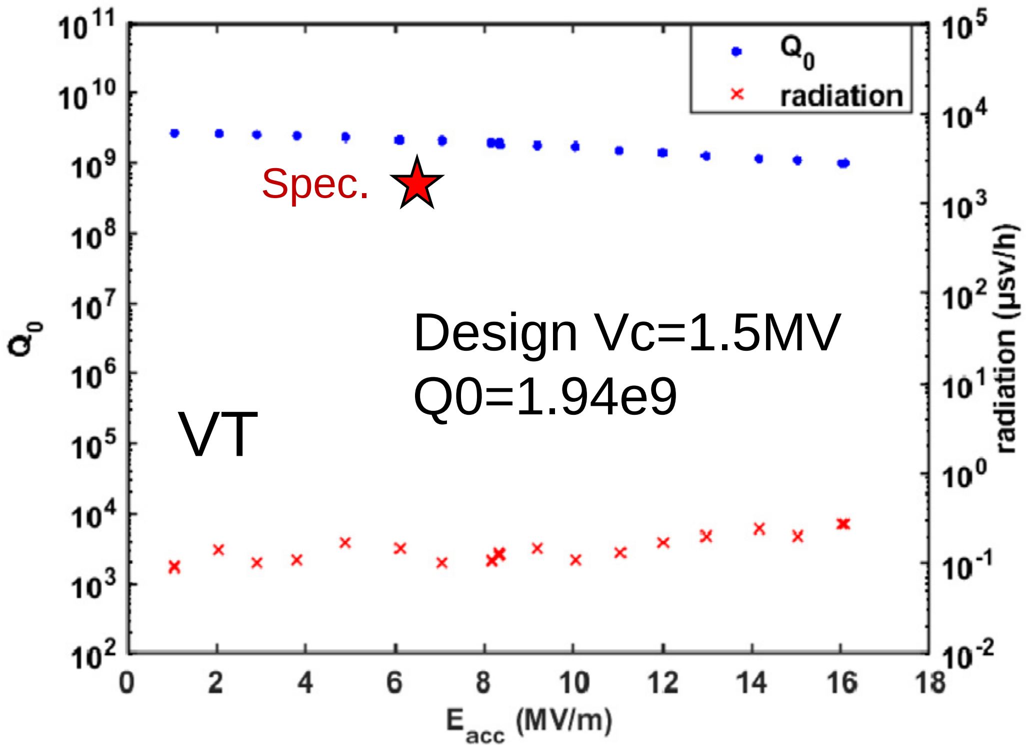
HALF storage-ring parameters

Parameters	Symbol	Value
Beam energy	E_0 [GeV]	2.2
Average current	I_0 [mA]	350
Harmonic number	h	800
Circumference	C [m]	~480
Energy spread	σ_p	0.00062
Nature emittance	ε_e	85 pm·rad
Momentum compaction	α	0.00009
Energy loss per turn (Phase I)	U_{s1} [MeV]	~0.4
Energy loss per turn (Phase II)	U_{s2} [MeV]	~0.6

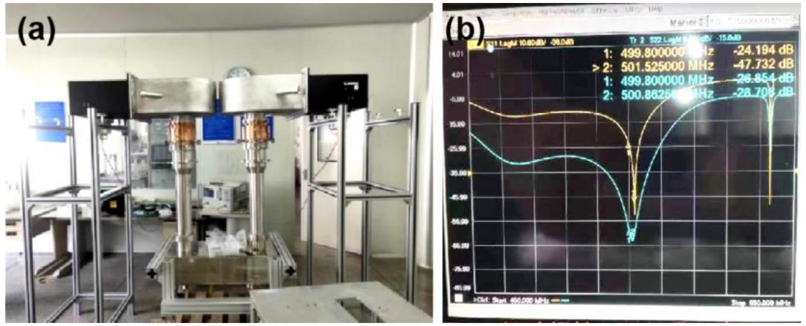
500MHz main SRF at HALF

- Two bare cavities (KEKB-type) developed and vertical tested
- Two FPCs (210kW) developed, high-power tests planned
- Ferrite HOM absorber (5kW) developed and cold tested
- Cryomodule is being developed

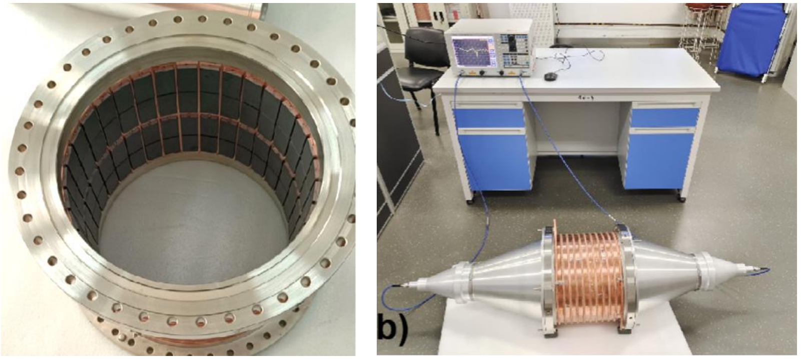




Power couplers



Ferrite HOM absorber

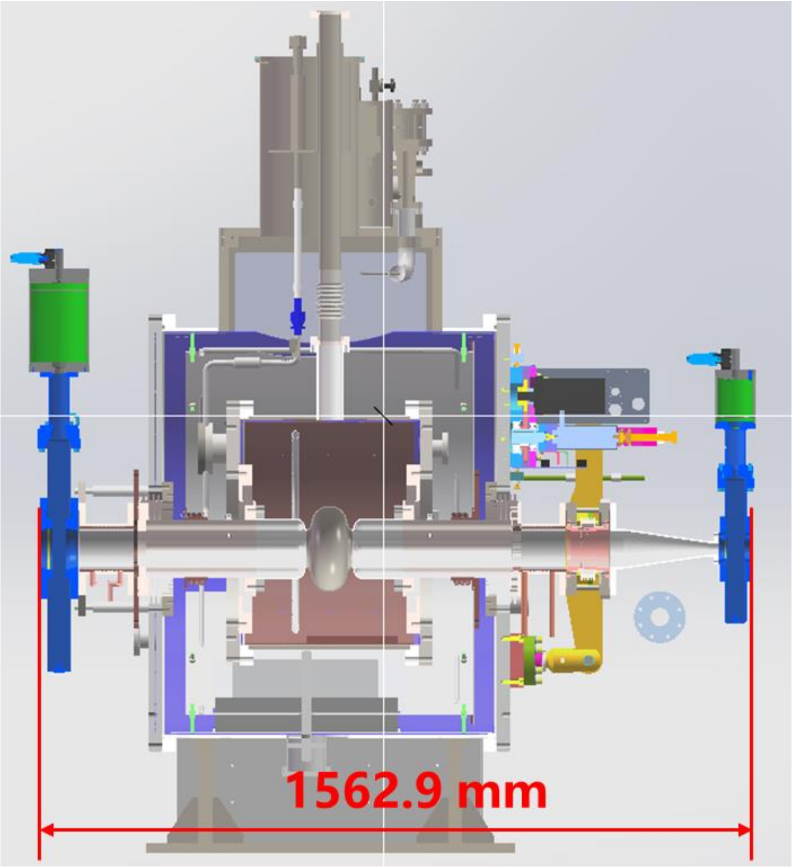


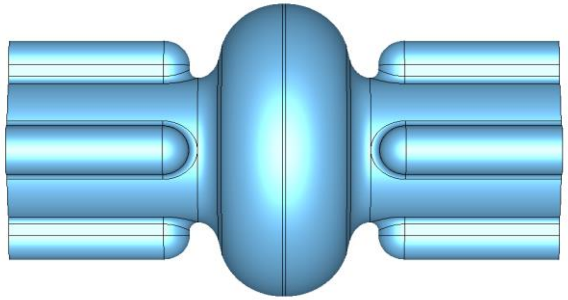
C. Wu *et al.*, *NIM-A* 1050, 168176 (2023).

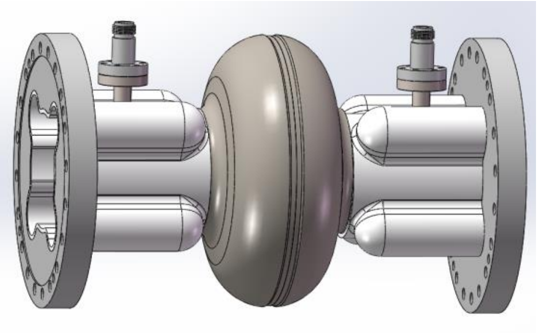
1.5GHz harmonic SRF at HALF

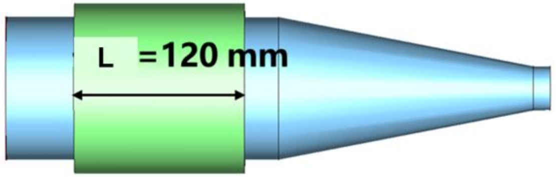
- 1499.4MHz SRF cryomodule under development

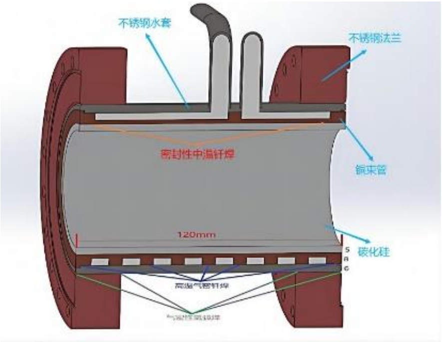
  - Cavity voltage: 0.5 MV
  - SiC HOM absorber: 0.5 kW
  - Bunch lengthening factor: ~6

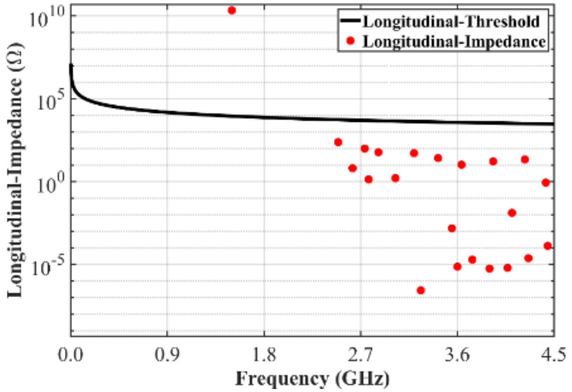


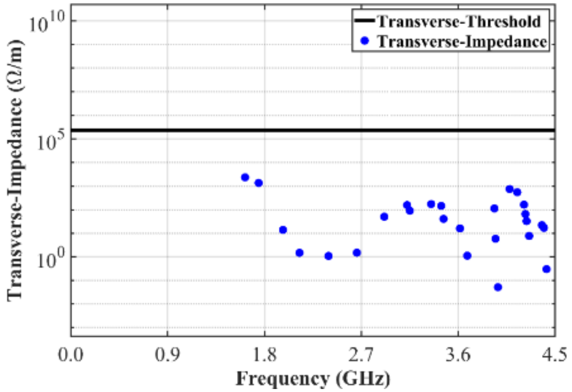












Southern **A**dvanced **P**hoton **S**ource

(Dongguan, Guangdong)

SAPS parameters

- A mid-energy 4th-gen storage ring light source, in planning by IHEP Dongguan Branch
- Location: close to the China Spallation Neutron Source (CSNS)
- Beam: 3.5GeV, 810m circumference (main ring)
- Operation mode: 350mA high brightness mode, 500mA high-throughput mode
- RF cavity technology under evaluation: superconducting and normal conducting

IHEP Dongguan campus, Guangdong

Parameter	Main	HHC	Unit
RF frequency	166.6	499.8	MHz
Total energy loss (w/ IDs)	1.55	-	MeV
Total power loss to radiation	800	-	kW
Total RF voltage	2	0.36	MV
Number of cavities	4	1	-
Cavity type	SCC	SCC (active)	-
RF voltage per cavity	>0.5	>0.36	MV
Maximum power per cavity	200	120	kW
Nom. transmitter power per RF station	260	150	kW

SRF infrastructures for synchrotron light sources

PAPS (Beijing)

Platform of Advanced Photon Source Technology R&D

- **Construction**: 2017 - 2020 (500 M CNY)
- **Operation**: 2021 - now
- **SRF infrastructure**
  - 4000m^2 hall, 500m^2 clean room (ISO4-7)
  - HPR, FPC baking oven, Nb3Sn oven, Nb/Cu, etc.
  - 2.5kW @ 4.5K or 300W @ 2K cryogenic system
  - 3 VT Dewar, 2 HT bunkers, 1 single-cavity cryostat
- **Test capabilities**
  - 200-400 cavities (couplers)/year, 20 CMs/year

SRF hall

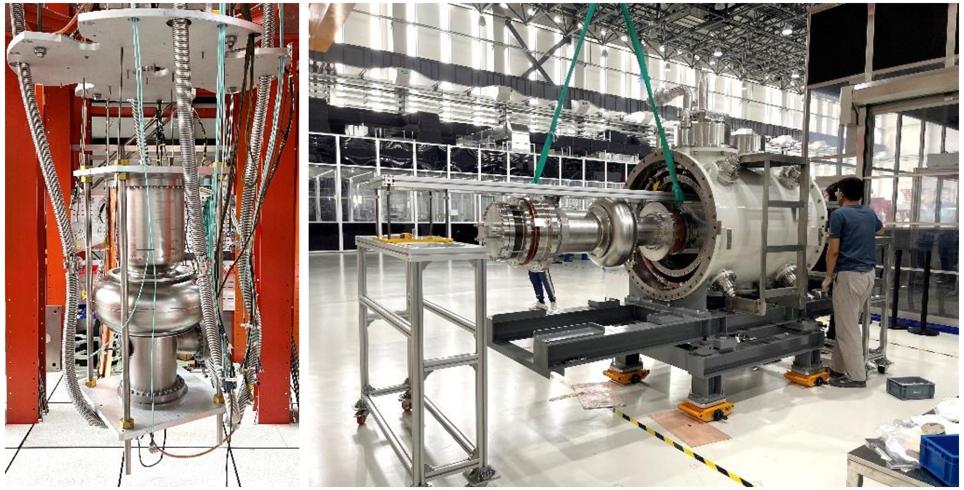
Cryogenics hall

Vertical test stand

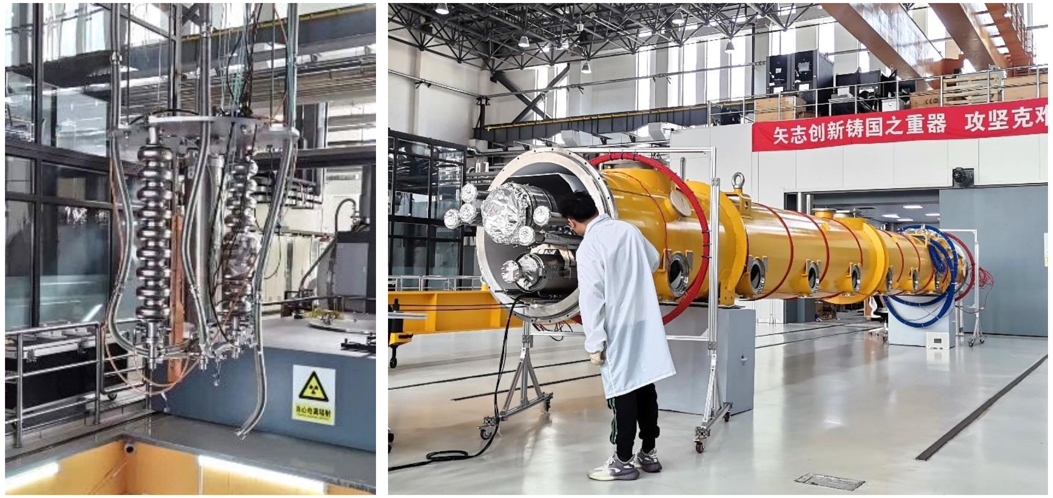
PAPS (Beijing)

166MHz cavity and cryomodule

500MHz cavity and cryomodule



1.3GHz cavity and cryomodule



650MHz cavity

324MHz double-spoke

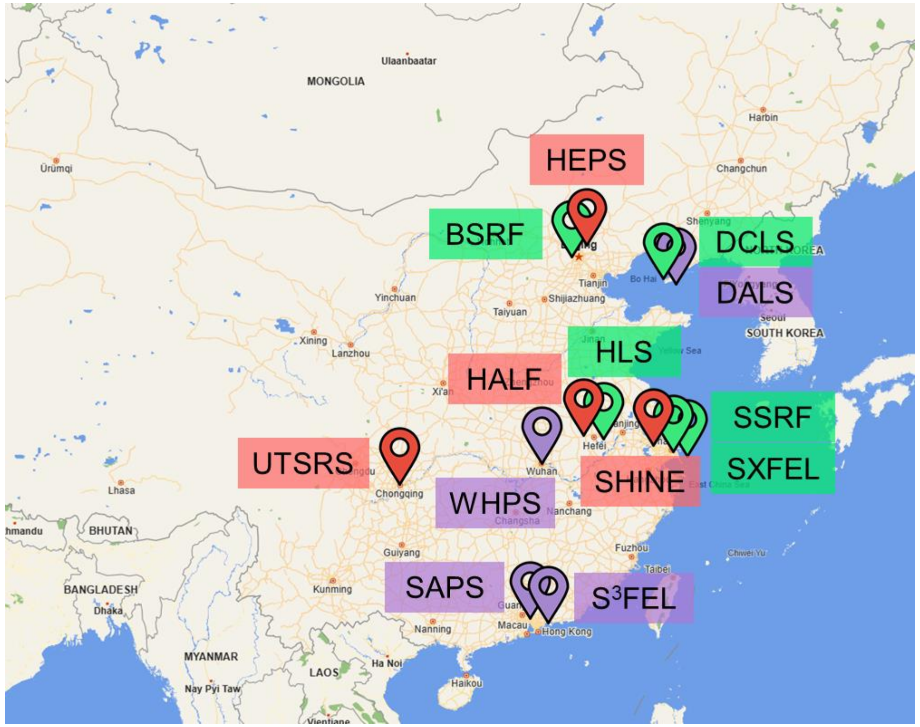
SAPS-TP (Guangdong)

Southern Advanced Photon Source – Test Platform

- **Construction**: 2019 - 2022 (600 M CNY)
- **Operation**: 2022 - now
- **SRF infrastructure**
  - 4520m^2 hall, 315m^2 clean room (ISO4/6)
  - 850W @ 4.5K or 100W @ 2K cryogenic system
  - 2 VT Dewar, 1 HT bunkers, 1 single-cavity cryostat

Summary

- Both synchrotron light sources and FELs are booming in China
- SRF technology adopted by most new projects
- 500MHz SRF remains a popular choice for synchrotrons, with HEPS developed a new 166MHz SRF module



List of synchrotrons adopted SRF technology

Existing machine under upgrade

- Beijing Synchrotron Radiation Facility (BSRF)
- Shanghai Synchrotron Radiation Facility (SSRF)

New projects

- High Energy Photon Source (HEPS)
- Hefei Advanced Light Facility (HALF)

SRF as one possible option, under assessment

- Southern Advanced Photon Source (SAPS)