RF Developments for HEPS

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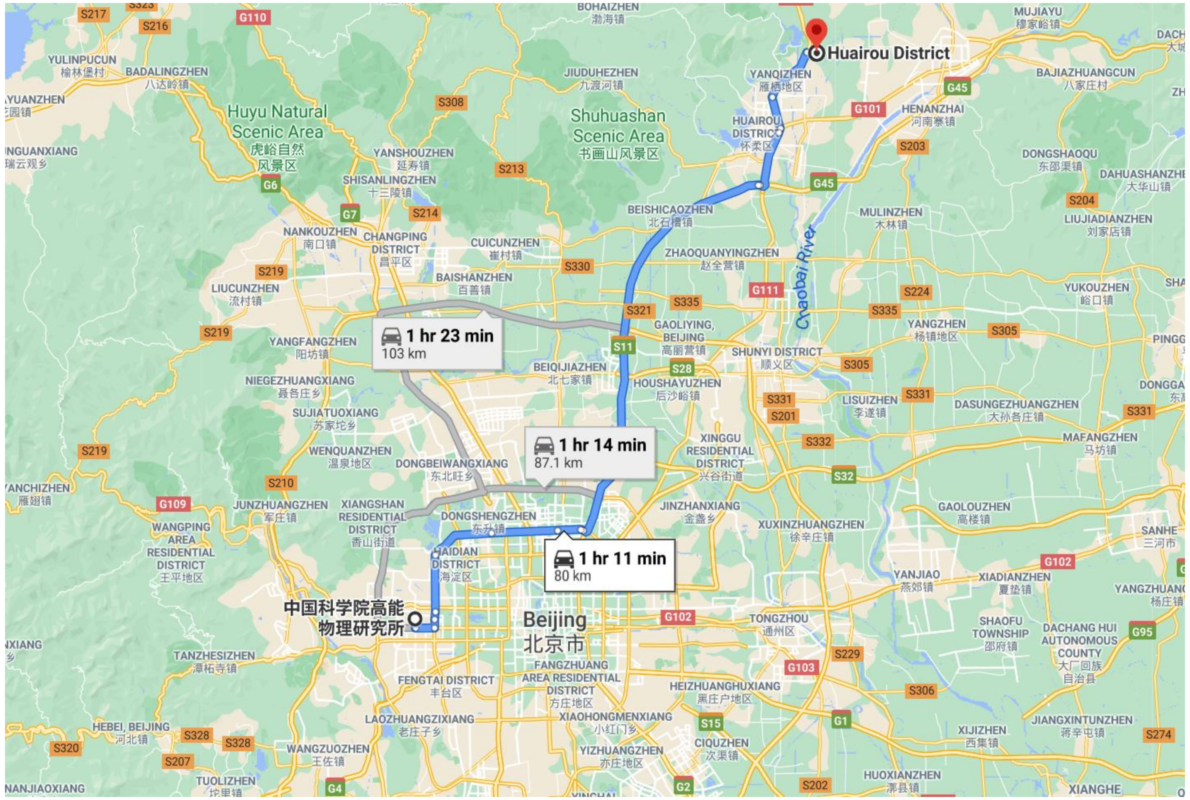
Outline

- Introduction to HEPS
- Booster RF system
- Storage-ring RF system
- Summary

High Energy Photon Source (HEPS)

- HEPS is a 6 GeV diffraction-limited synchrotron light source
- Location: 80 km from IHEP main campus, 70 km from the forbidden city
- Construction schedule: Jun. 2019 – Dec. 2025



Civil construction

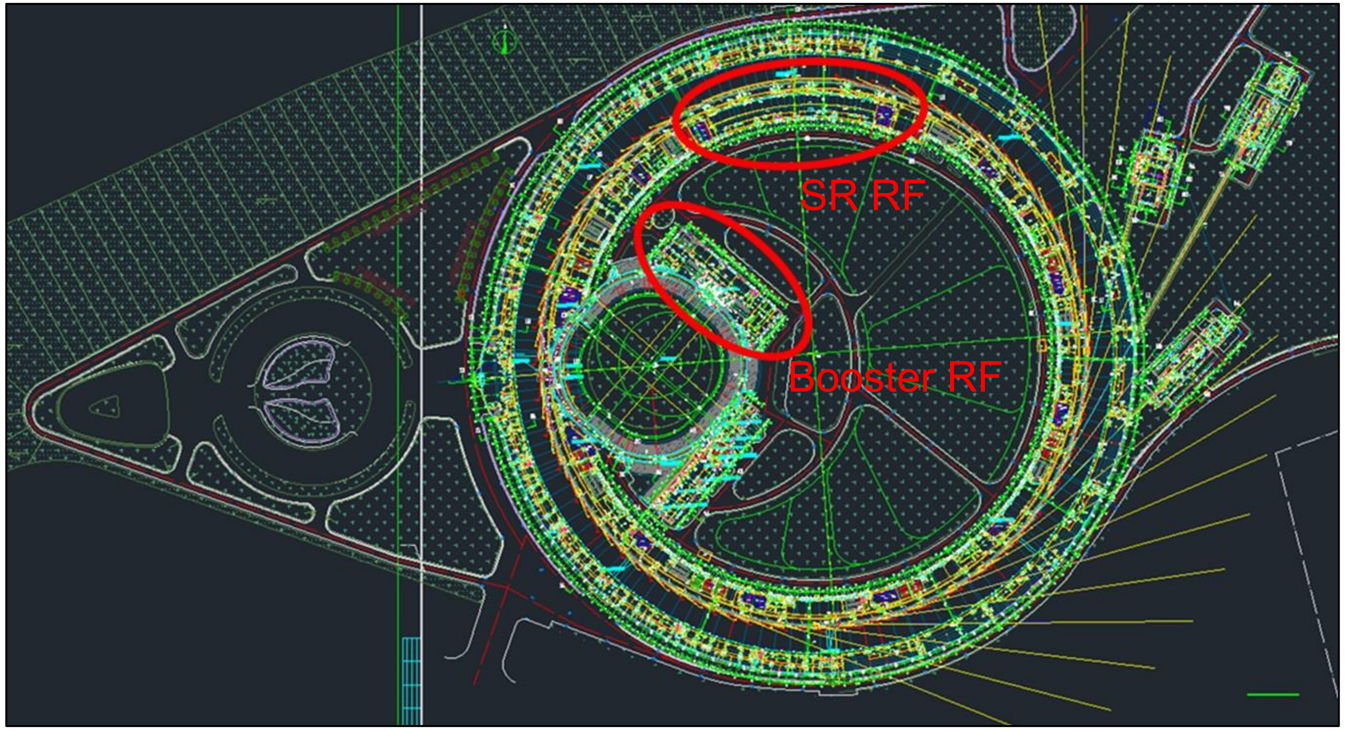
- HEPS civil construction in good shape
- Platform of Advanced Photon Source Technology R&D (PAPS) completed in 05.2021
- First accelerator component installation in 07.2021
- Linac commissioning started in 07.2022 (underway)

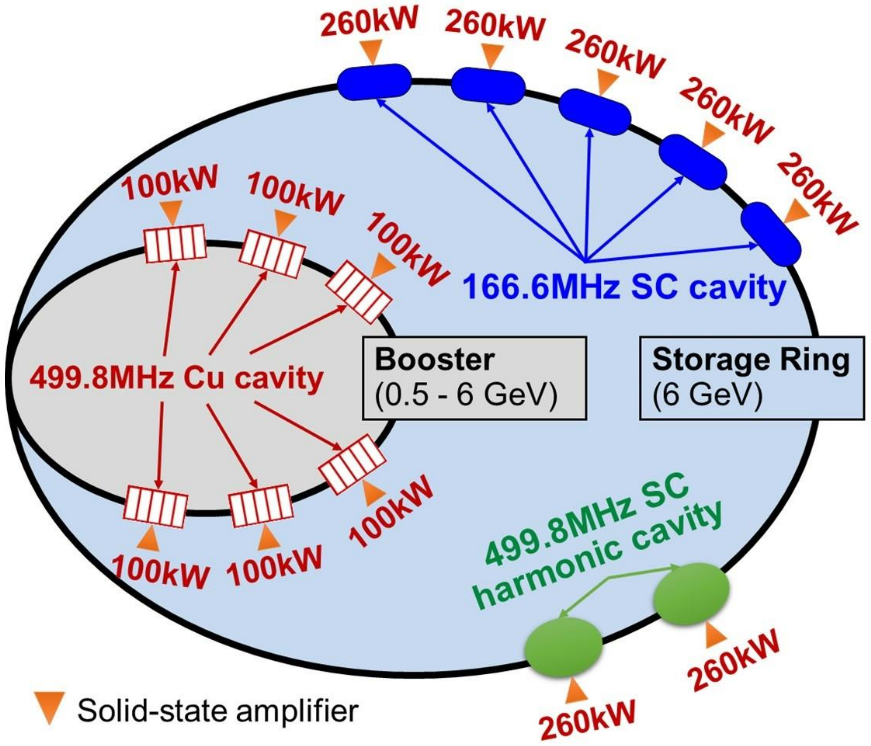
HEPS main parameters

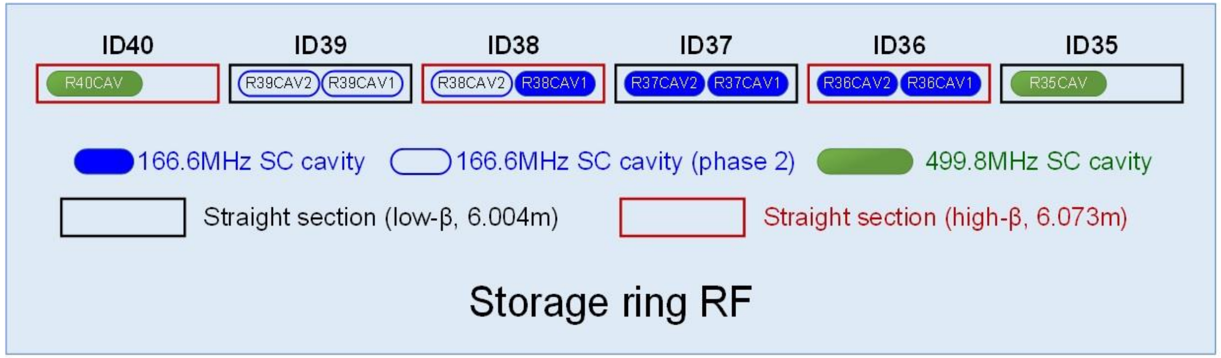
Parameter	Value	Unit
Beam energy	6	GeV
Circumference	1360.4	m
Beam current	200	mA
Lattice type	7BA	-
Number of sectors	48	-
Natural emittance	34.2	pm·rad
Natural bunch length	5.06	mm
Energy loss (bare lattice)	2.64	MeV
Total no. of IDs (Phase I)	14	-
Total beam power	850	kW
Radiation damping time (x/y/z)	10.85/20.62/18.76	ms
RF frequency (main, 3^{rd} harm.)	166.6, 499.8	MHz
Main RF voltage (w/ harm. cav.)	5.16	MV

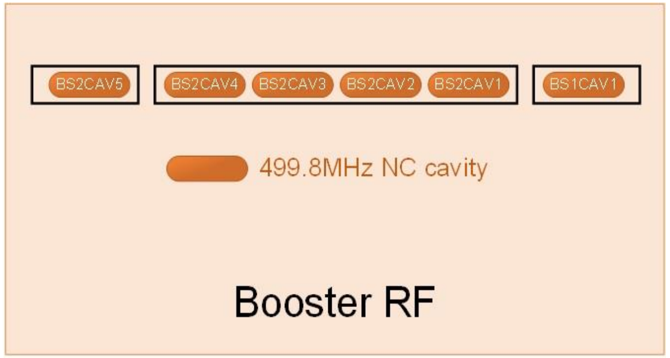
Y. Jiao et al., *Journal of Synchrotron Radiation* 25, 1611 (2018).

HEPS RF system



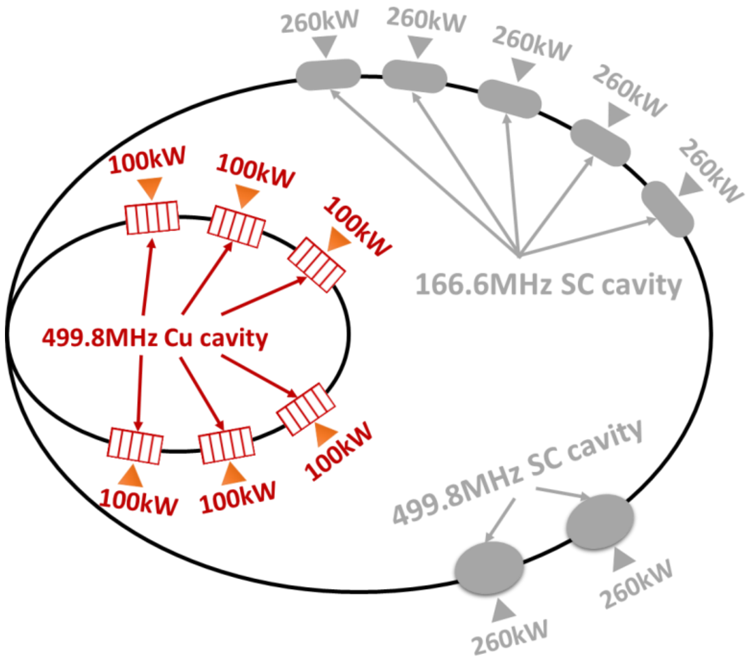




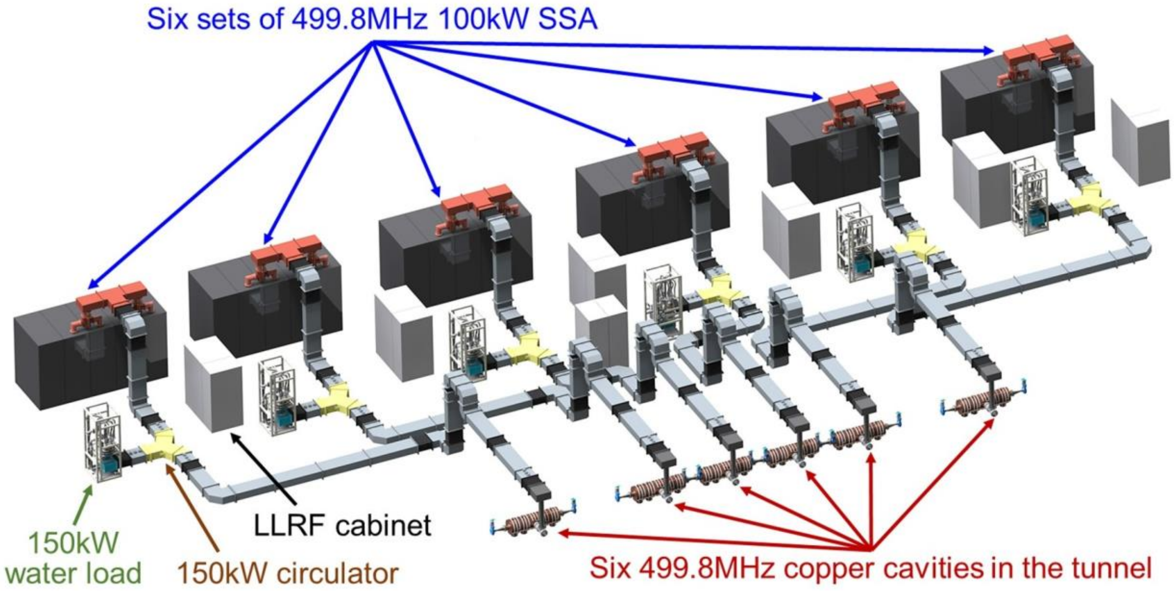


P. Zhang et al., *IPAC2021*, MOPAB380.

RF system for the booster



Booster RF: parameters

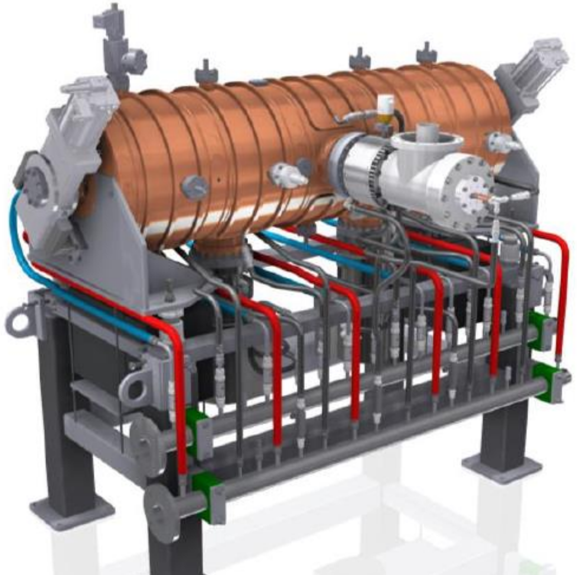


Parameter	Value	Unit
Circumference	454.066	m
Beam energy	0.5-6	GeV
Beam current	13	mA
Energy loss	4.02	MeV
Beam power	52.26	kW
Rep. rate	1	Hz

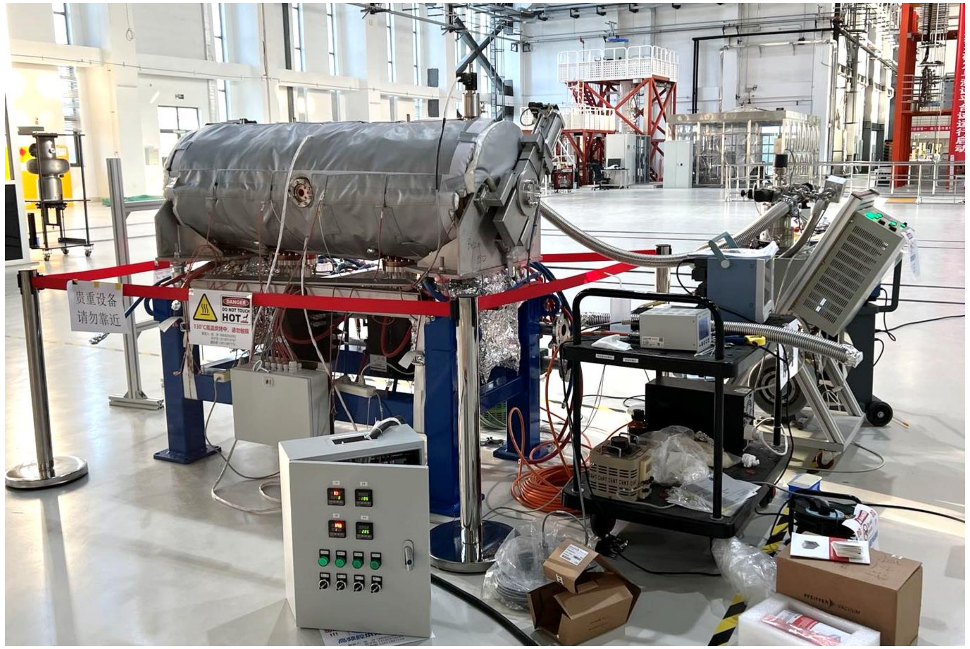
Parameter	Value	Unit
RF frequency	499.8	MHz
Total RF voltage	8	MV
No. of cavities	6	-
RF voltage per cav.	1.35	MV
Cavity type	5-cell, copper	
Wall loss per cav.	61	kW
Beam power per cav.	9	kW
Total RF power per cav.	70	kW
Coupling factor	1.17	-
RF transmitter	SSA	-
RF power per source	100	kW
No. of RF stations	6	-
No. of transmitter per station	1	-
Field noise (pk-pk)	±1%, ±1°	-

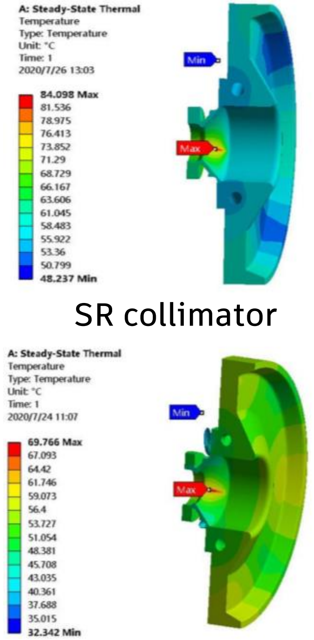
Booster RF: cavities

- Contract of 6 PETRA-type 5-cell cavities signed with RI GmbH in 03.2020
- 4 out of 6 cavities delivered (5 months delayed due to COVID-19)
- Several design changes implemented for HEPS
  - Synchrotron light collimator at beampipe (w/ modified cooling channels)
  - Additional monitoring for power coupler (camera, arc, LED)
  - Fiducial targets added, gate valves rotated
- Two cavities passed high-power conditioning to 120kW CW (4 more cavities)

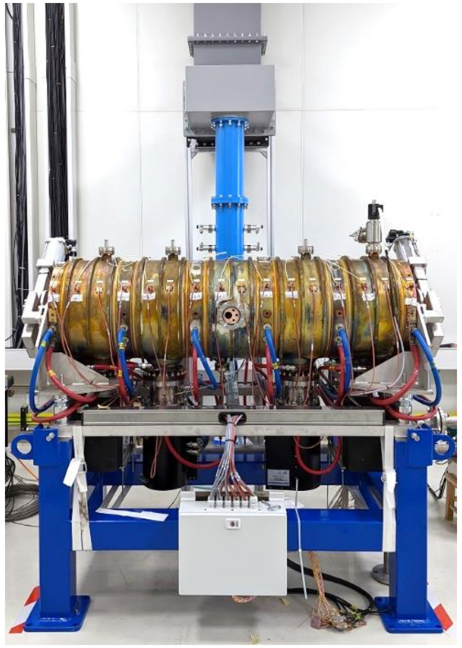


From RI.





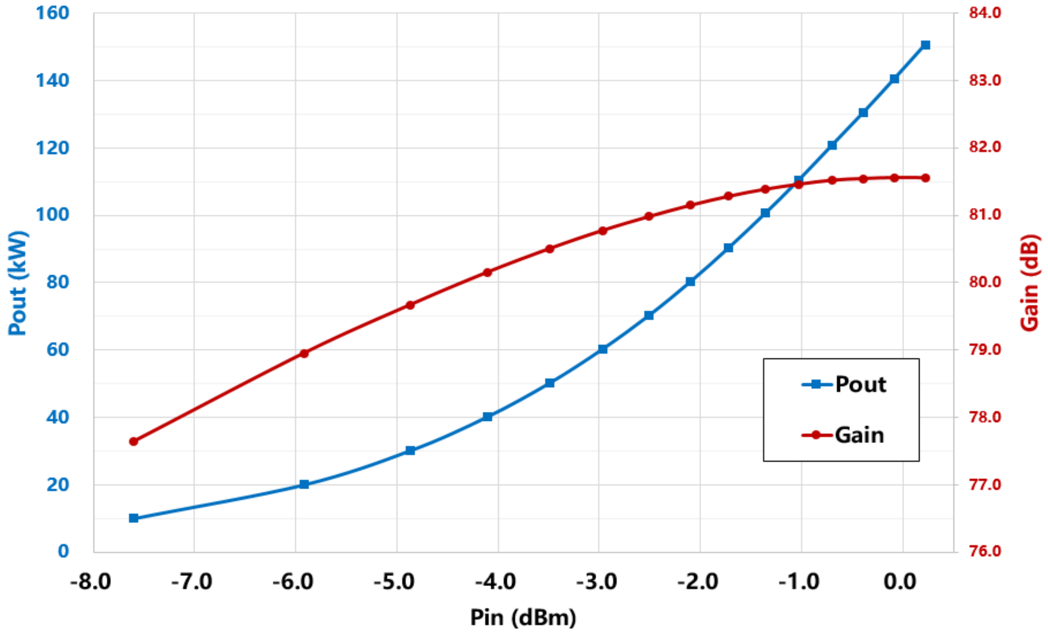
SR collimator



Booster RF: RF sources

- Contract of one 150kW and five 100kW SSAs signed in 03.2020
- 150kW SSA passed SAT in 10.2021 (9 mos. delayed D/T COVID)
  - Accumulated on-site aging time: ~150 hours (0 module failed)
  - Accumulated run time: >1600 hours (2 modules failed)
- Five 100kW series SSAs passed FAT in Q2.2022
- Installation on HEPS booster scheduled in Q4.2022

2kW unit
(600W × 4)

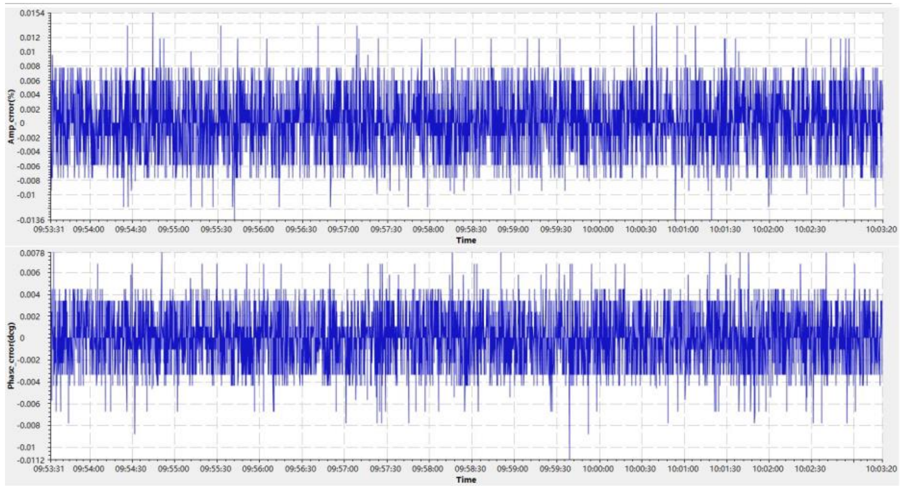


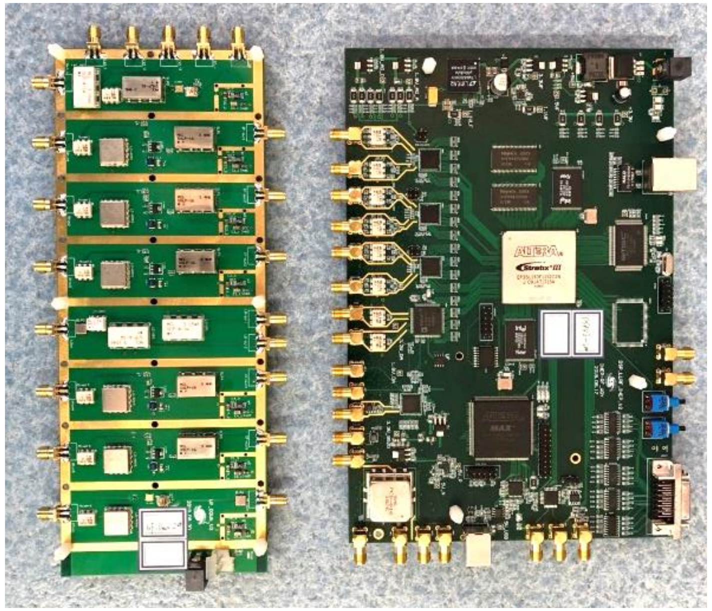
Y.L. Luo et al., *IPAC2021*, TUPAB346.

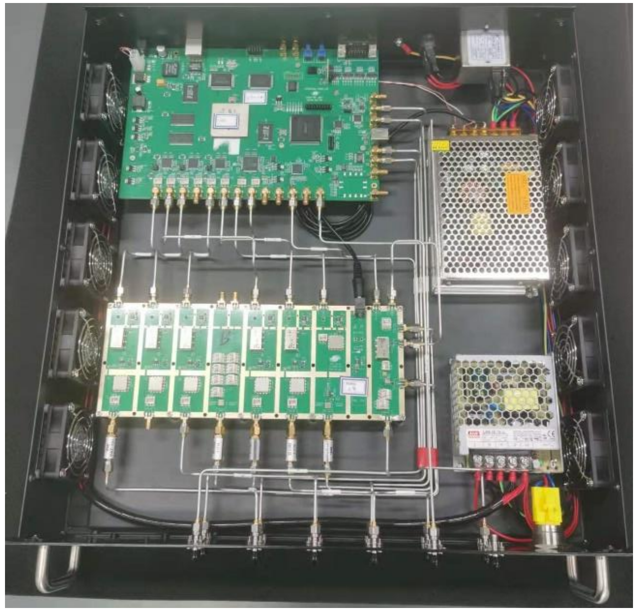
Booster RF: LLRF

- 1st- and 2nd-gen LLRF in-house developed
  - Up-/down-conversion, Altera FPGA
  - Lab test (pk-pk): ±0.02% (amp.), ±0.01° (phase)
  - 1st-gen in beam operation at BEPCII since 09.2019
  - Noise suppression algorithms implemented

Lab test

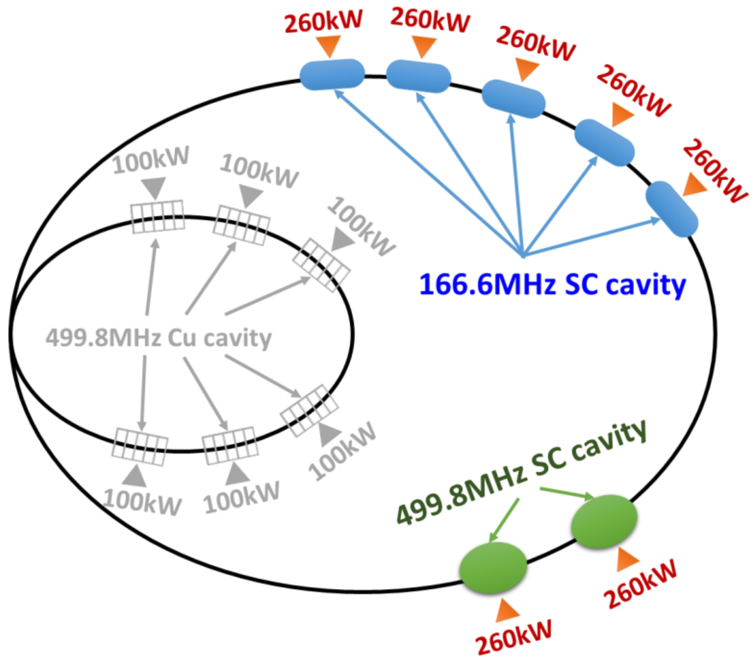






[1] Q.Y. Wang et al., *SRF2019*, THP075. [2] Q.Y. Wang et al., *Radiat. Detect. Technol. Methods* 5, 220–227 (2021).

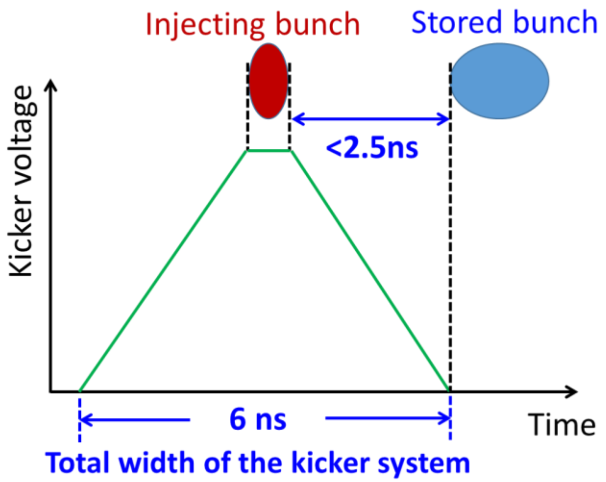
RF system for the storage ring



Storage-ring RF: main parameters

Parameter	Value	Unit
Circumference	1360.4	m
RF frequency (f_0)	166.6	MHz
Total energy loss per turn (U_0)	4.14	MeV
Total beam power (P_b)	850	kW
Total RF voltage (V_{RF})	5.16	MV
Number of main RF cavities	5	-
RF power per main cavity	170	kW
Cavity type	SRF cavity	-
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°	-

Why 166.6MHz?



Physics drive

Low emittance

On-axis beam accumulation injection

Two RF frequencies to make two RF buckets

Technology limitation

Kicker system total width ~6ns

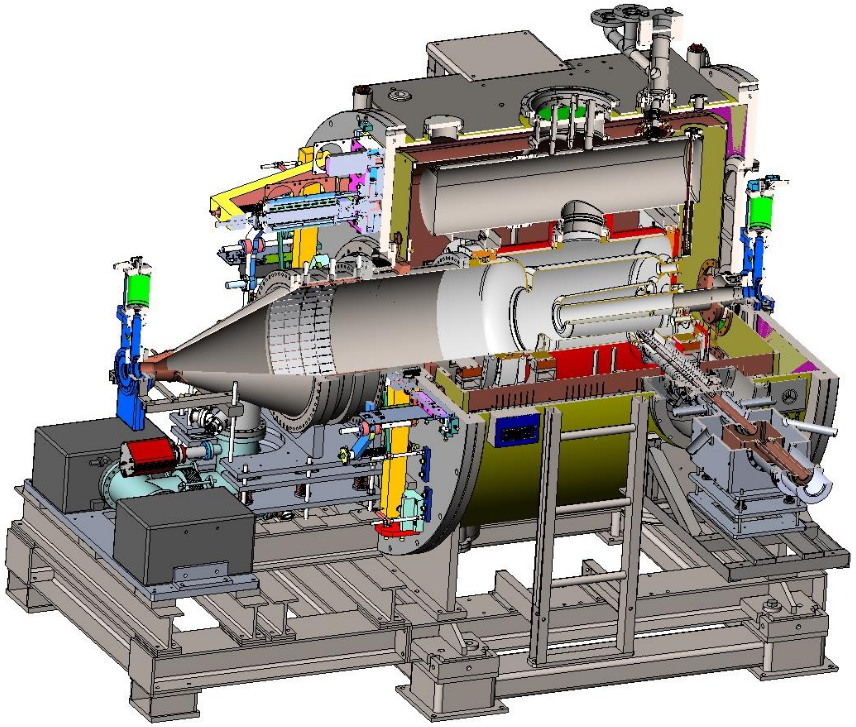
Technology readiness

Use 500MHz as harmonic RF

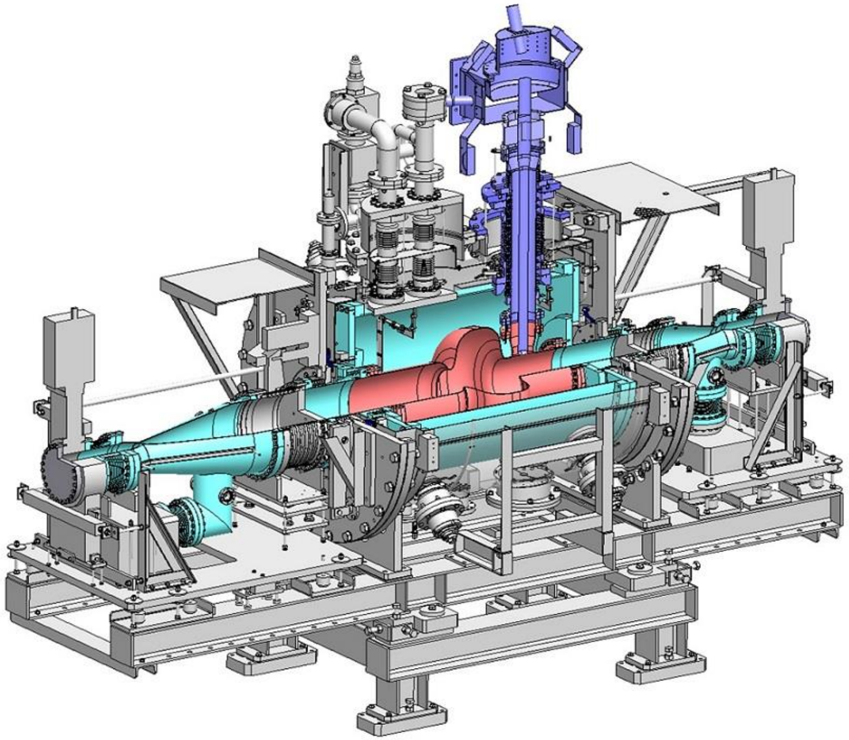
166.6 MHz (fundamental RF)
499.8 MHz (harmonic RF)

[1] G. Xu *et al.*, *IPAC2016*, WEOAA02.
[2] D. Zhe *et al.*, *eeFACT2016*, TUT2H4.

Storage-ring RF: cavities



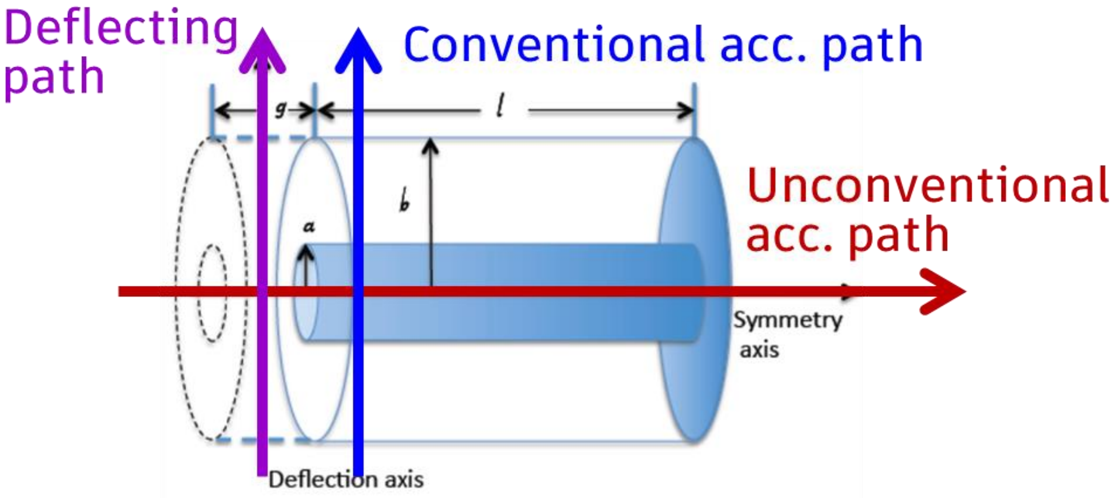
166.6MHz quarter-wave
β=1 SRF cavity
(New development)



499.8MHz KEKB-type
single-cell SRF cavity

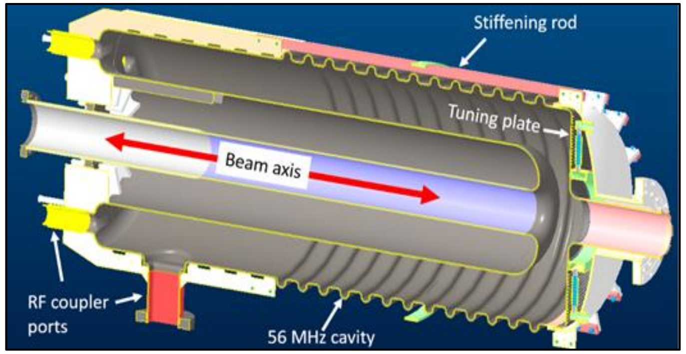
Cavity design features (166.6MHz)

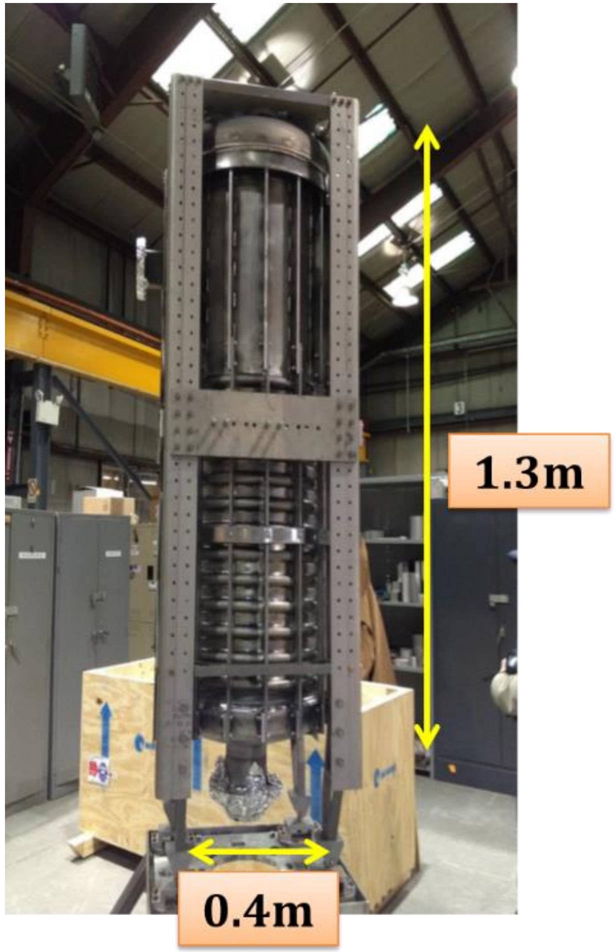
- **Low frequency**: 166.6MHz, β=1
- High current: 200mA → **heavy HOM damping**: Q_L<1000
- **High RF power**: 170kW CW per cavity
- **Compactness**: limited space of the straight section (6m for 2 cavs)
- Stable operation (user facility): **large margin** in RF parameters
- **Risks: no time or facilities for beam demonstration**
- Design quickly converged to β=1 quarter-wave geometry



β=1 quarter-wave cavities

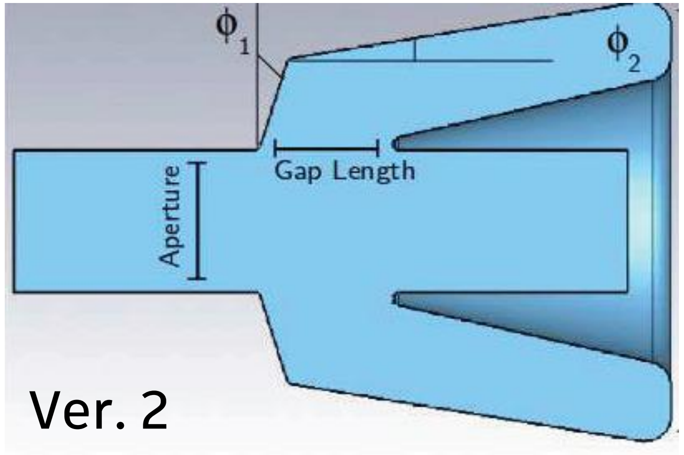
BNL 56MHz QW cavity

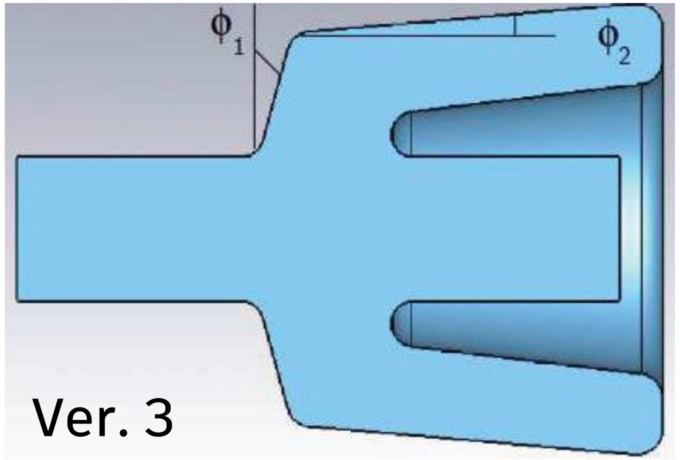




Q. Wu et al., *SRF2015*, WEBA07.
Q. Wu et al., *Phys. Rev. Accel. Beams* 22, 102001 (2019).

CERN 200MHz QW for HL-LHC





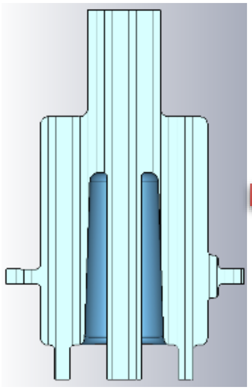
R. Calaga et al., *IPAC2016*, TUPMW034.

Development strategy

Two-step approach

1. Proof-of-Principle (PoP) cavity: production technics, surface treatment, maximize learning, with no HOM damping
2. HOM-damped cavity: cavity, ancillaries, integration

PoP cavity (2016-2019)



Design

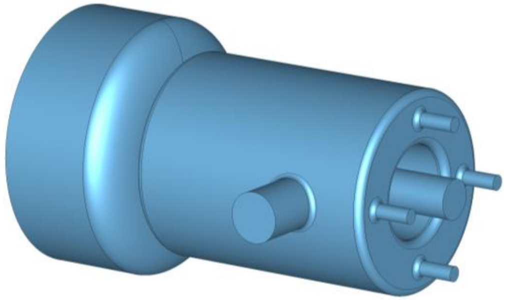
Bare cavity

VT

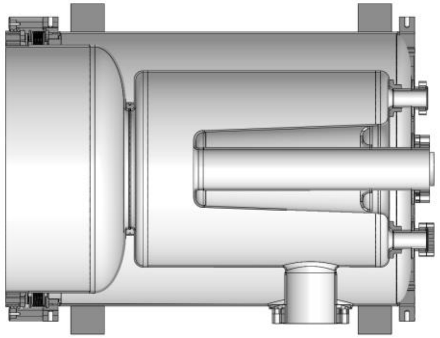
Dressed cavity

HT

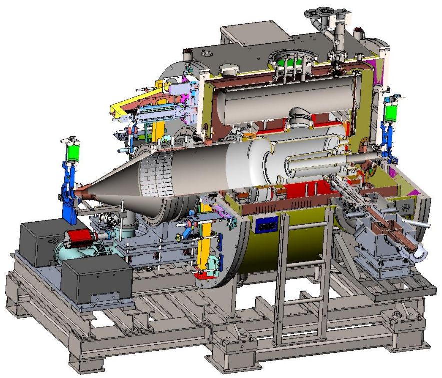
HOM-damped cavity (2019-now)



Bare cavity

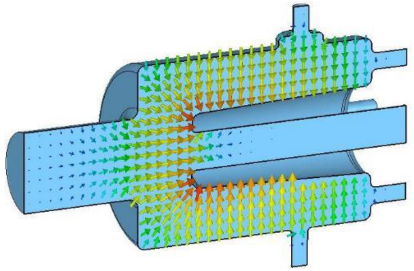


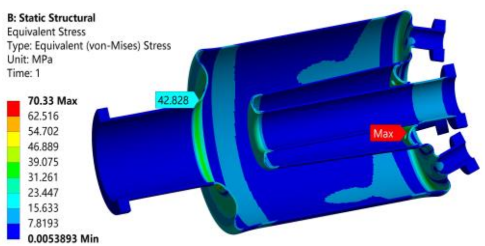
Jacketed cavity



Module

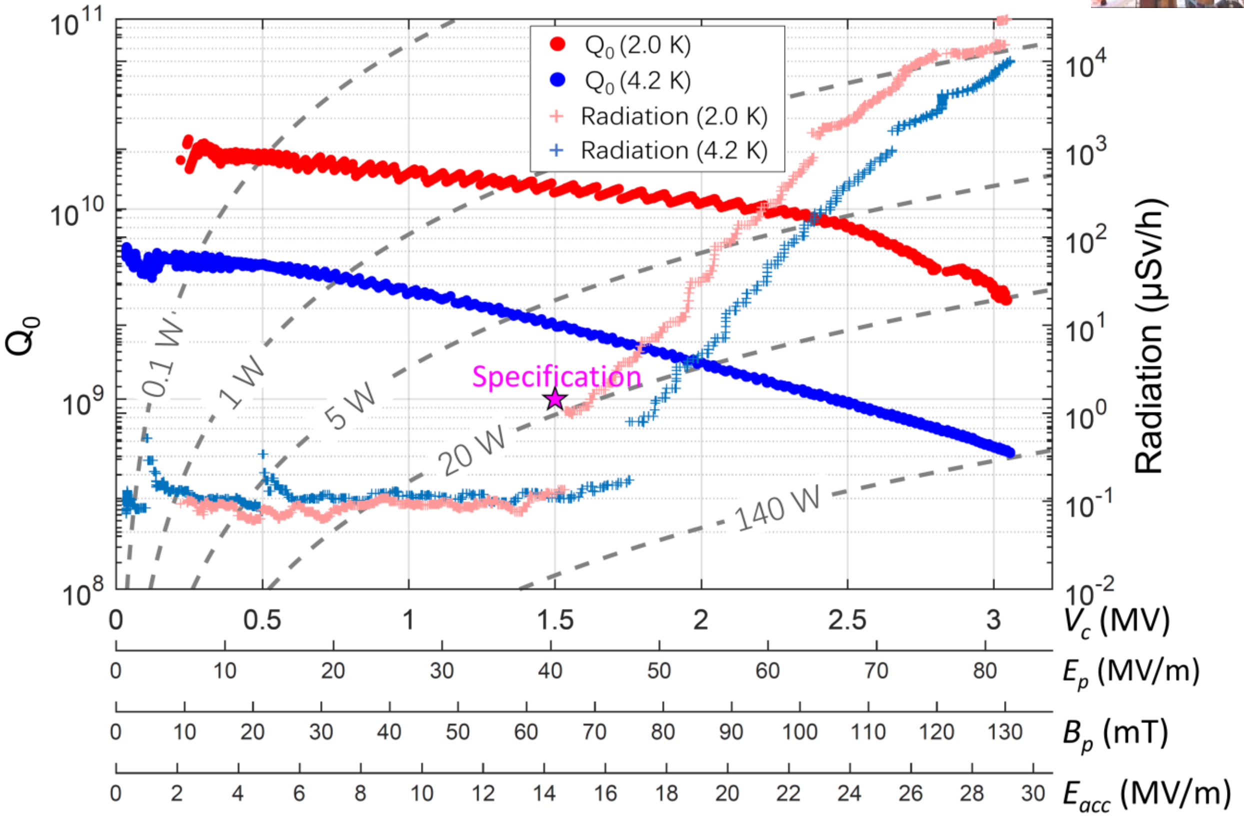
PoP bare cavity development





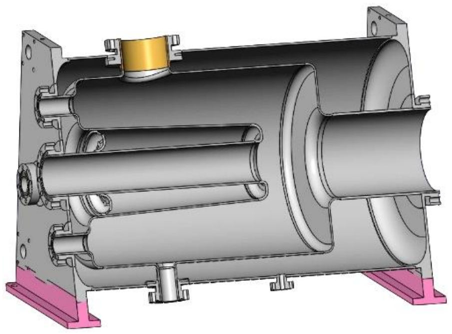
Parameter	Value	Unit
Frequency	166.6	MHz
Cavity length (main)	530	mm
Cavity diameter (no ports)	397	mm
Aperture (small side)	80	mm
R/Q	136	Ω
Geometry factor	54.5	Ω
Design voltage (Vc_d)	1.5	MV
Design gradient	12.5	MV/m
Q0 at Vc_d	≥1e9	-
Epeak at Vc_d	40.1	MV/m
Bpeak at Vc_d	63.9	mT
Stored energy	15.8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

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

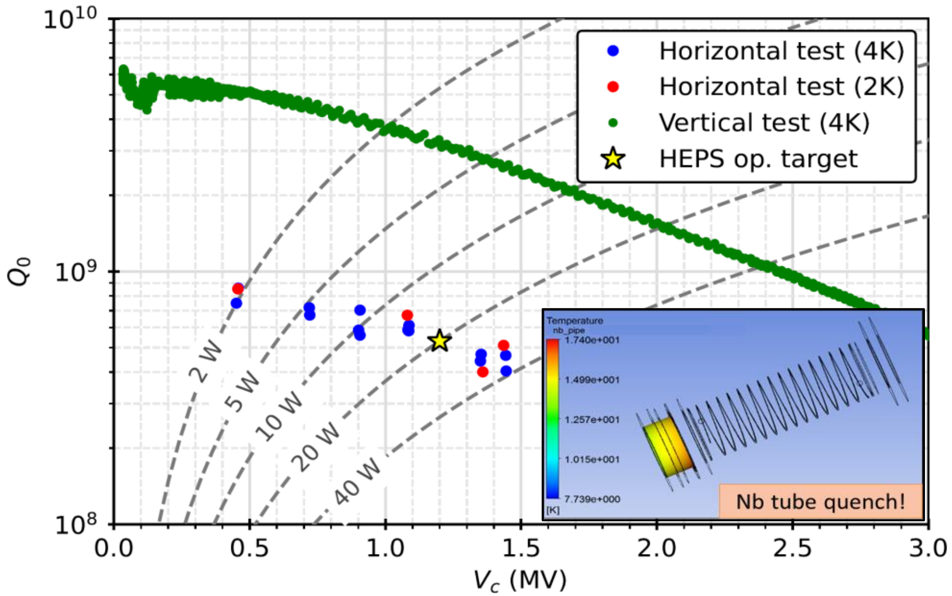


[1] P. Zhang et al., *Rev. Sci. Instrum* 90, 084705 (2019). [2] X.Y. Zhang et al., *NIM-A* 947, 162770 (2019).

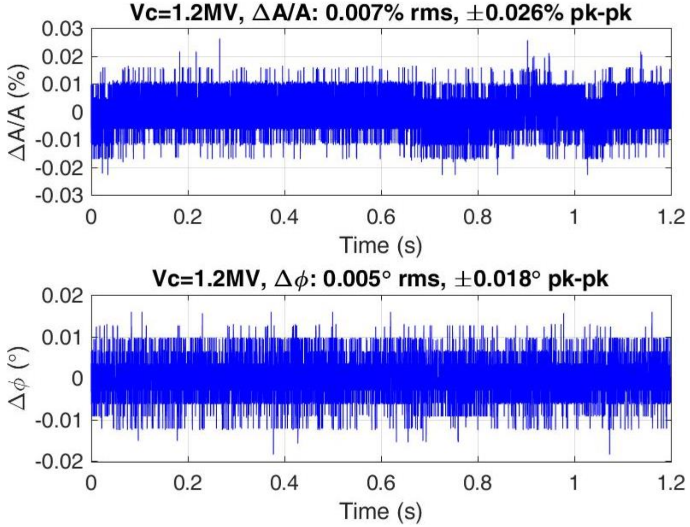
PoP dressed cavity development



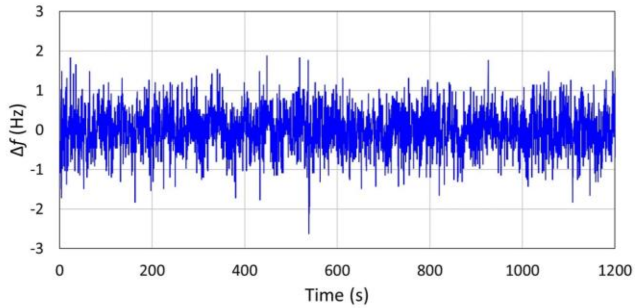
- Large performance degradation observed from VT to HT
  - Cause: overheating on FPC Nb tube extension, 80mm -> 120mm
  - Relocate the pickup to simplify helium jacket design



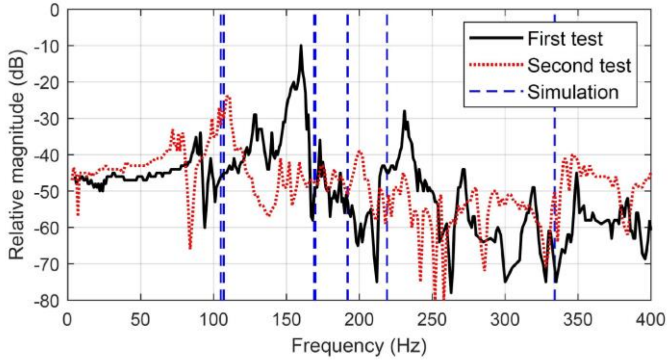
A/P loop closed



Freq. loop closed



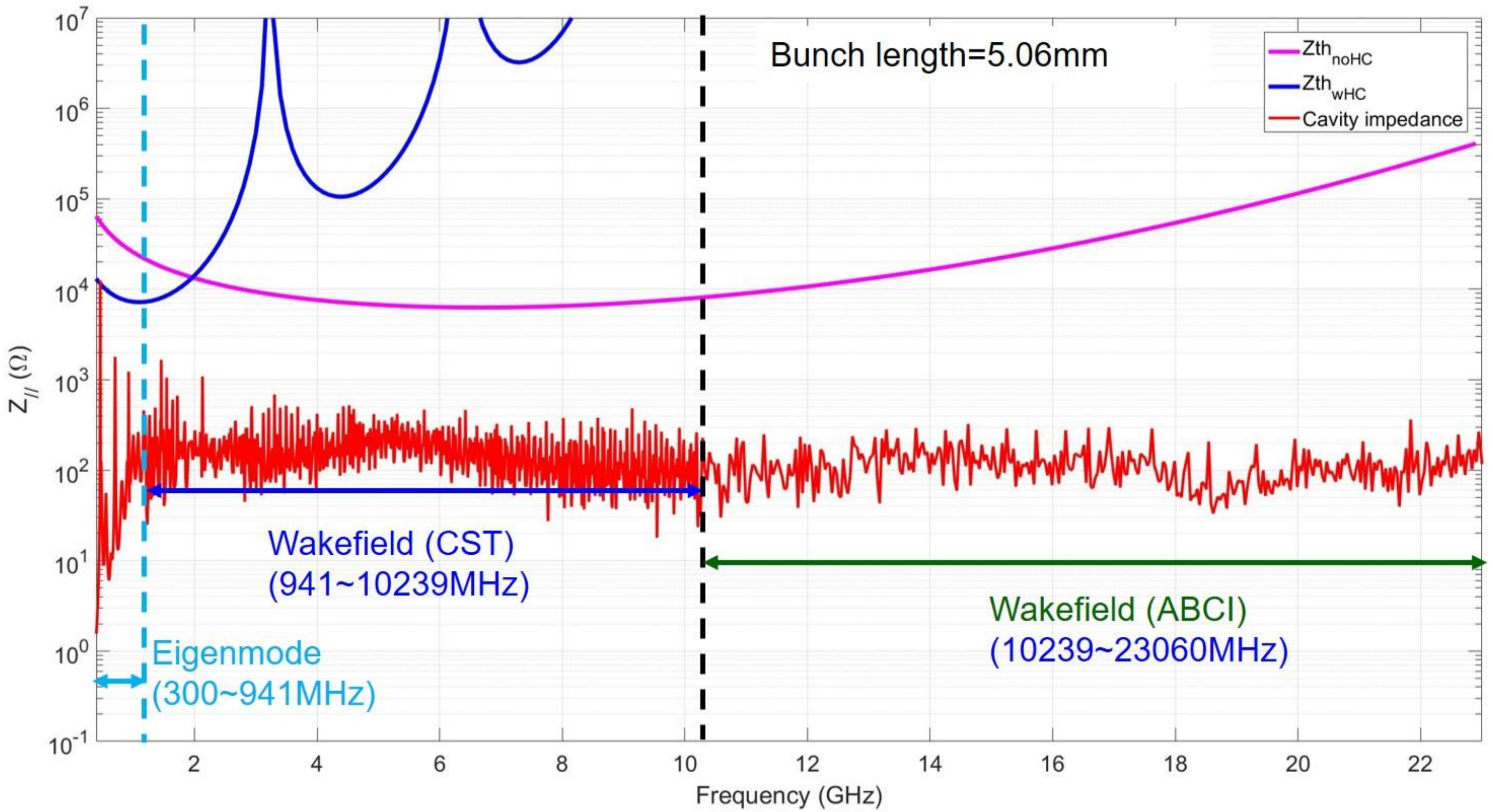
Microphonics spectrum

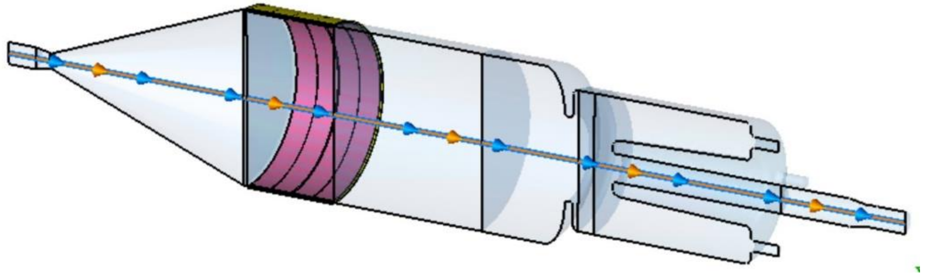


[1] X.Y. Zhang et al., *IEEE Trans. Appl. Supercond.* 30, 3500208 (2020). [2] T.M. Huang et al., *AIP Advances* 11, 045024 (2021).

HOM damping

- Various damping schemes investigated (HOM coupler, waveguides, hybrid)
  - Enlarged-beam-pipe option won out
- Challenges: large HOM absorber, impedance, SR light collimation

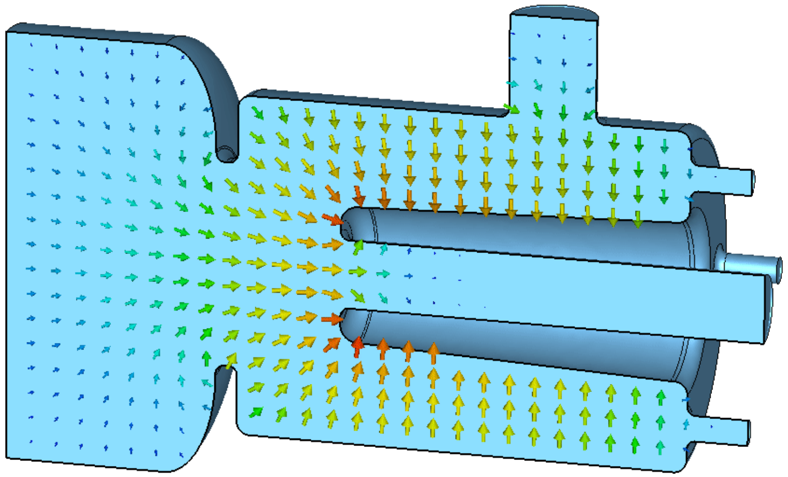


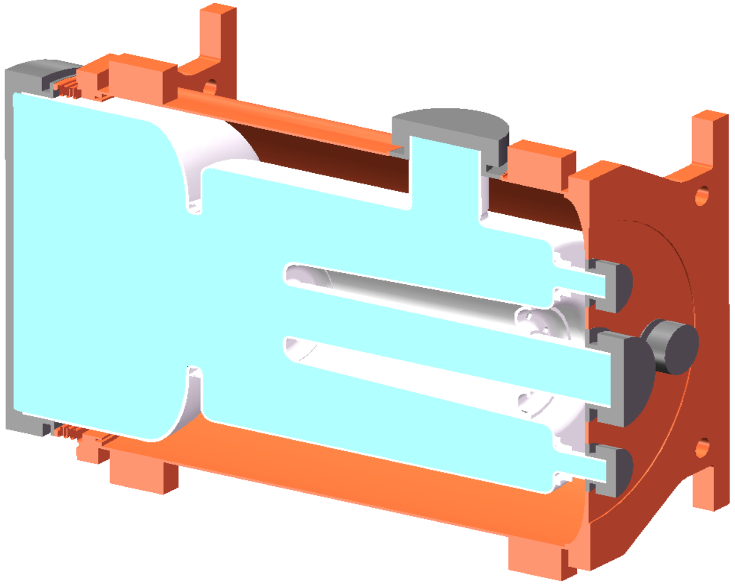


- **HOM power**
  - 7kW in high-charge mode
  - 700W in high-luminosity mode

[1] H.J. Zheng et al., *IPAC2021*, WEPAB090. [2] H.J. Zheng et al., "Design evolution of HOM damping …", to be submitted to NIM-A.

Cavity parameters (166.6MHz)



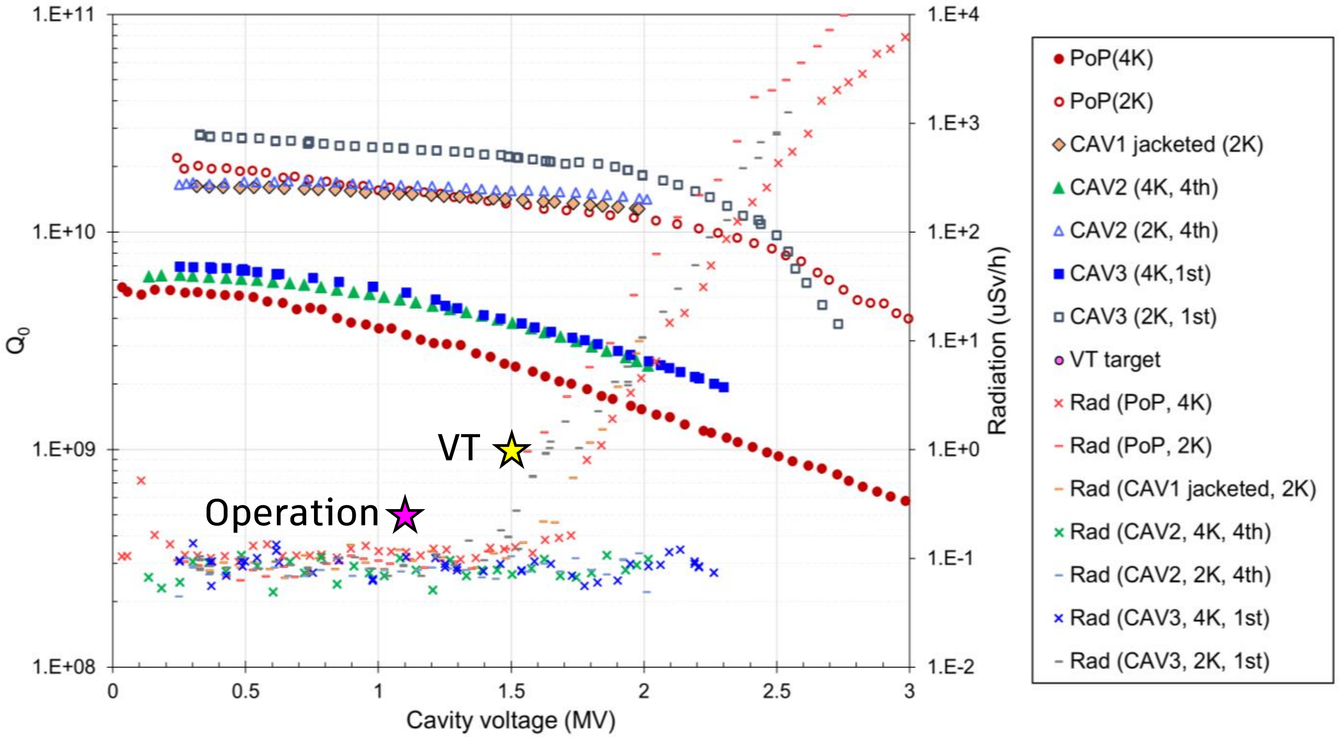


Parameter	Value	Unit
Frequency	166.6	MHz
Operating Temperature	4.2	K
R/Q	139	Ω
Geometry factor	56	Ω
Cavity VT voltage (Vc_VT)	1.5	MV
Q0 at Vc_VT	≥1e9	-
Cavity op. voltage (Vc_op)	1.1	MV
Q0 at Vc_op during operation	≥5e8	-
Epeak at Vc_op	29	MV/m
Bpeak at Vc_VT	46	mT
df/dp	39.2	Hz/mbar
Tuning range	+/- 36	kHz
RF power/cavity	170	kW
Loaded Q	5e4	-
HOM control	Heavy damping	

Cavities

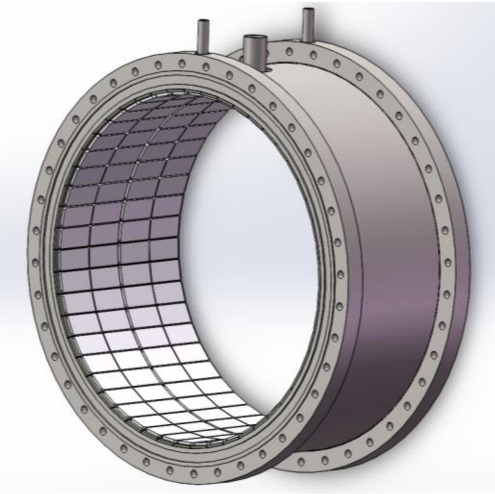
- In-house developed, contract of 10 bare cavities signed in 10.2020
- Pre-series (3 cavities) production completed in Q1.2022
  - All 3 bare cavities passed VT tests, Cav#1-jacketed VT at 2K
  - Modified BCP implemented to eliminate unwanted traces on the LBP transition

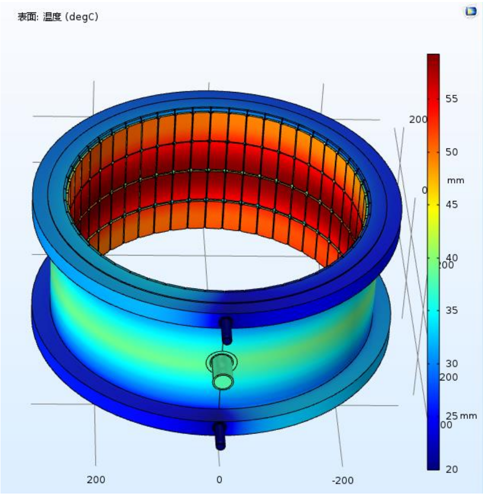
Lowest Rres: ~1.44 nΩ (~1.7 m^2 Nb surface)



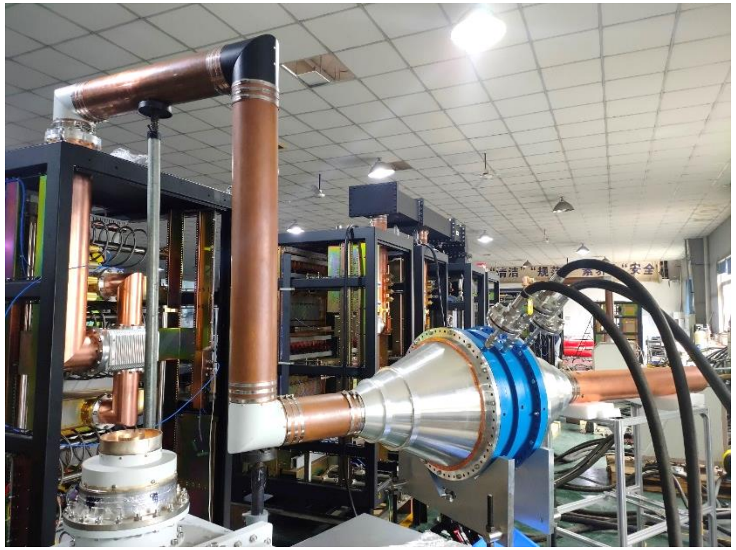
Ferrite HOM absorber

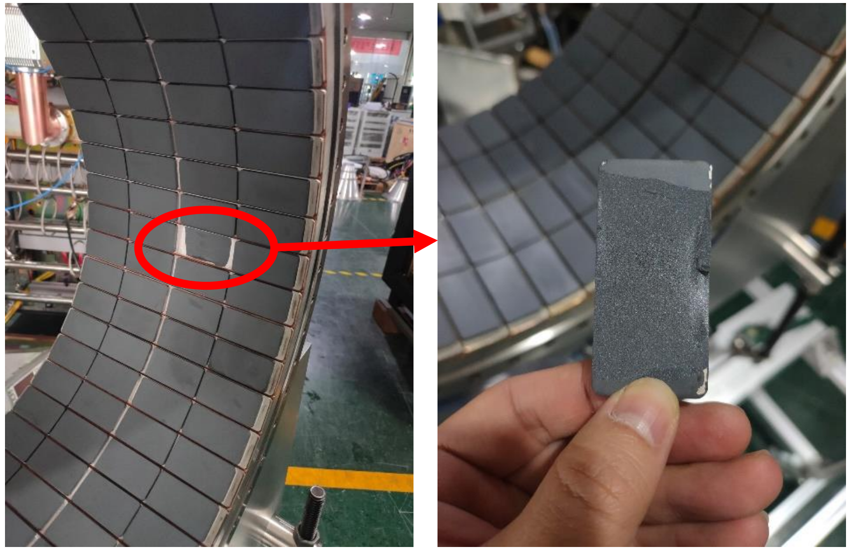
- In-house developed
  - Inner diameter: 505mm
  - 200 tiles, 4 tiles/coupon
- 1 tile peeled off after the 10kW power test
- Brazing fixtures optimized



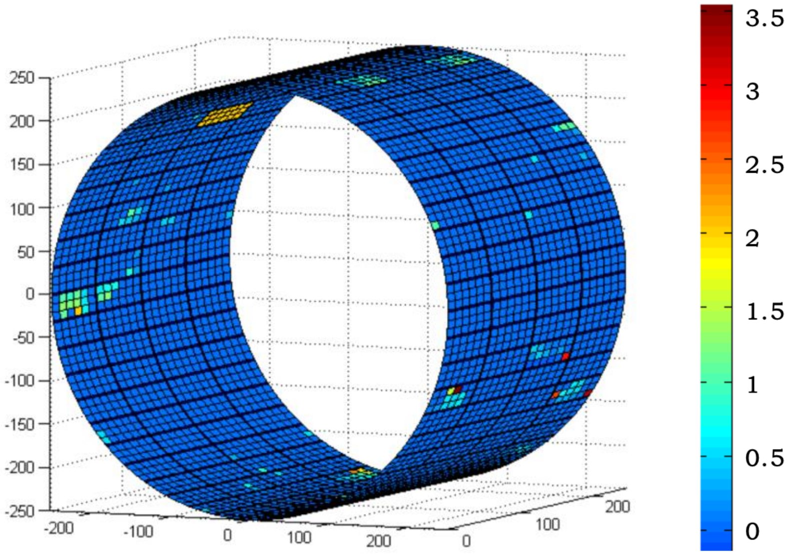


10kW test





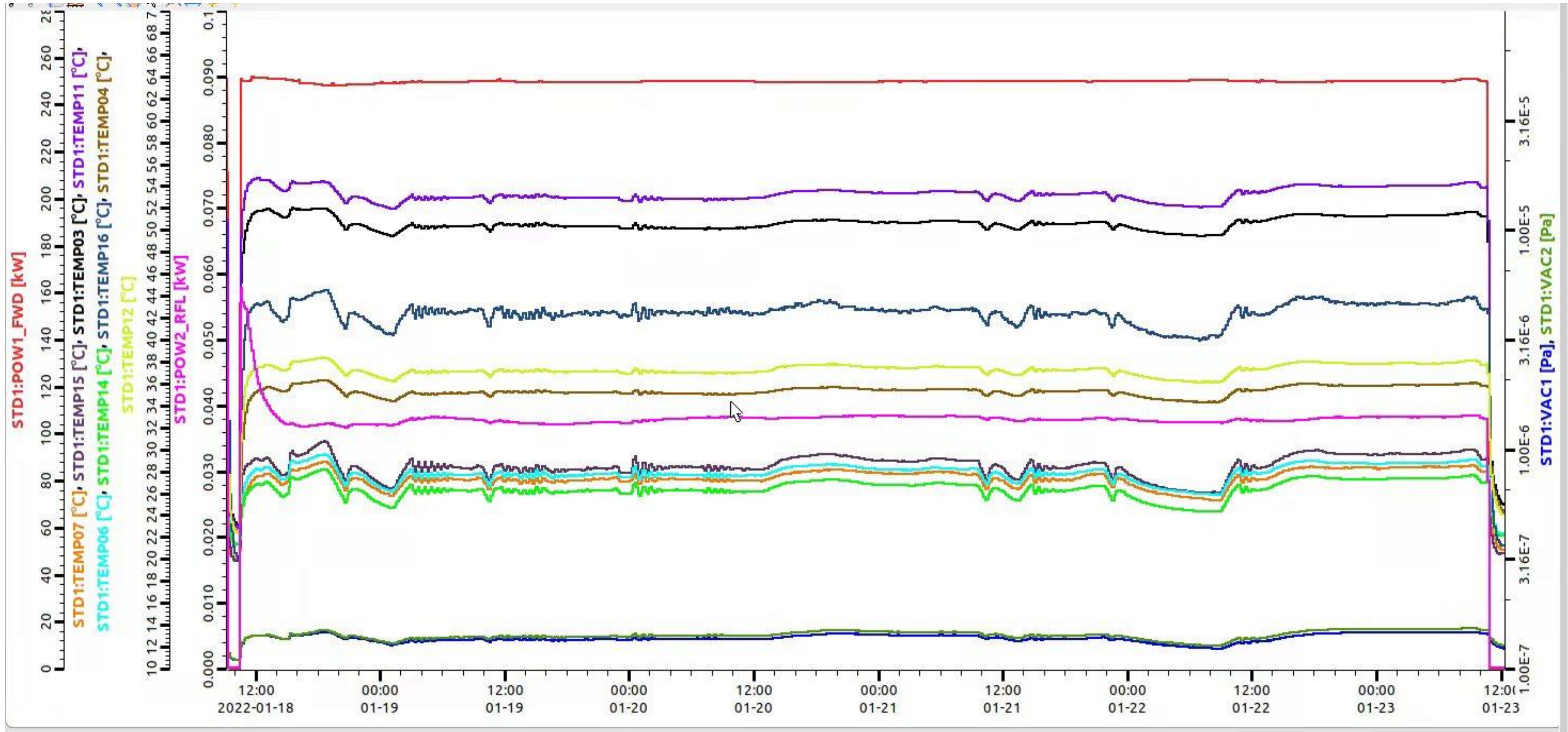
Distance to defects



Fundamental power couplers

- In-housed developed, contract of 10 FPCs signed in 11.2020
- Pre-series (2 couplers) delivered in 07.2021
- High-power conditioning to 250kW CW passed in Q1.2022

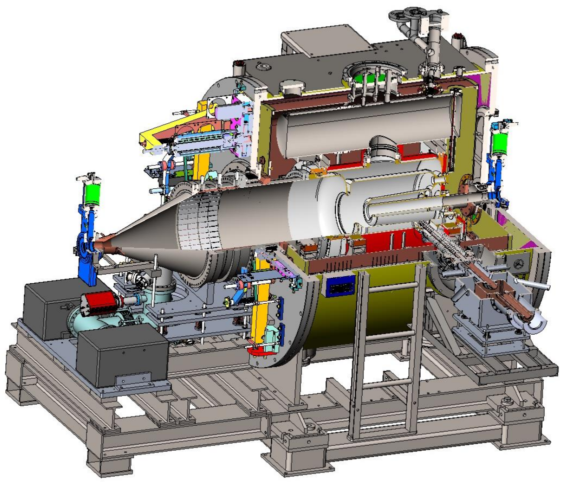
High-power aging for 120 hours at 250kW CW

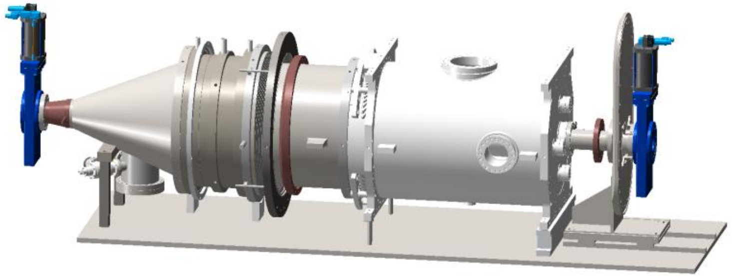


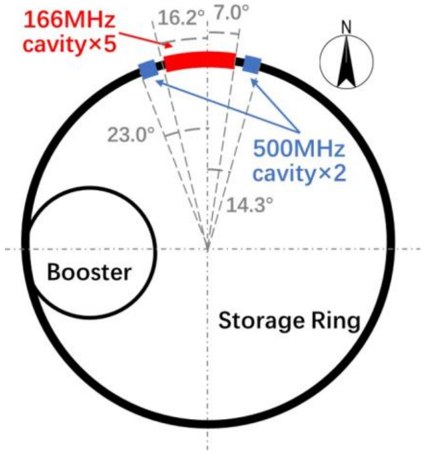
T.M. Huang et al., *Review of Scientific Instruments* 91, 063301 (2020).

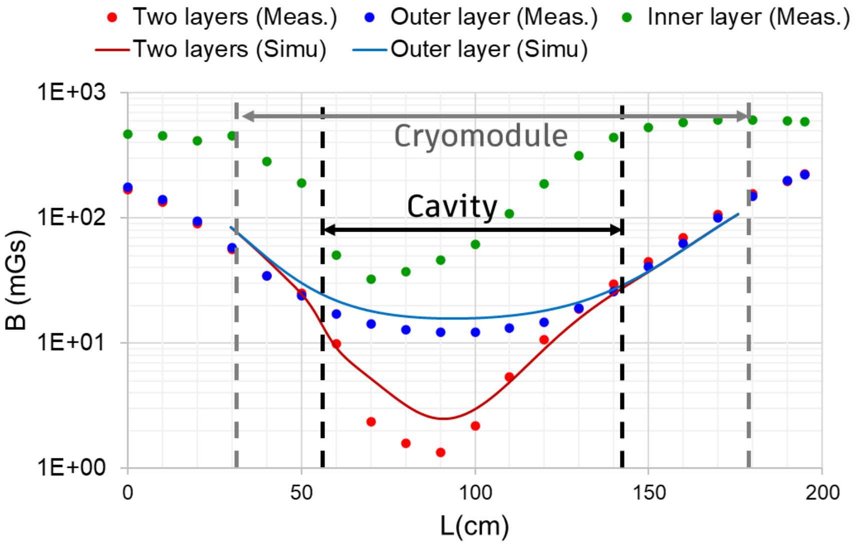
Cryomodule

- 166MHz cryomodule in-house developed
  - Two layers of magnetic field shielding (permalloy)
- 1st 166MHz cryomodule passed FAT
- First assembly scheduled in Q4.2022



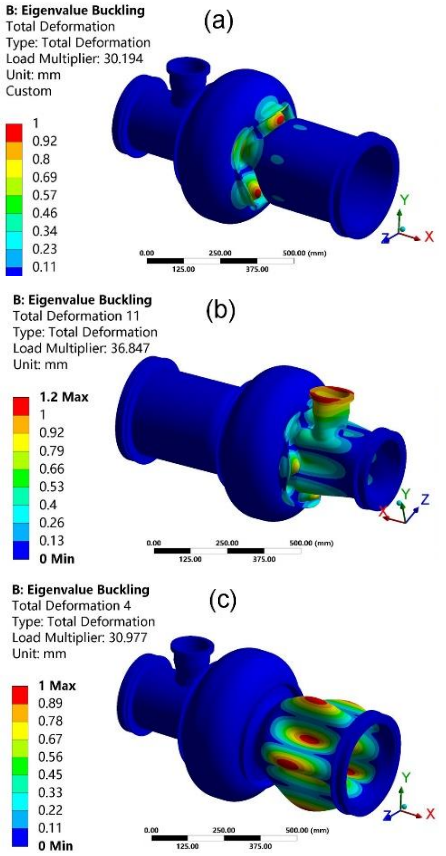


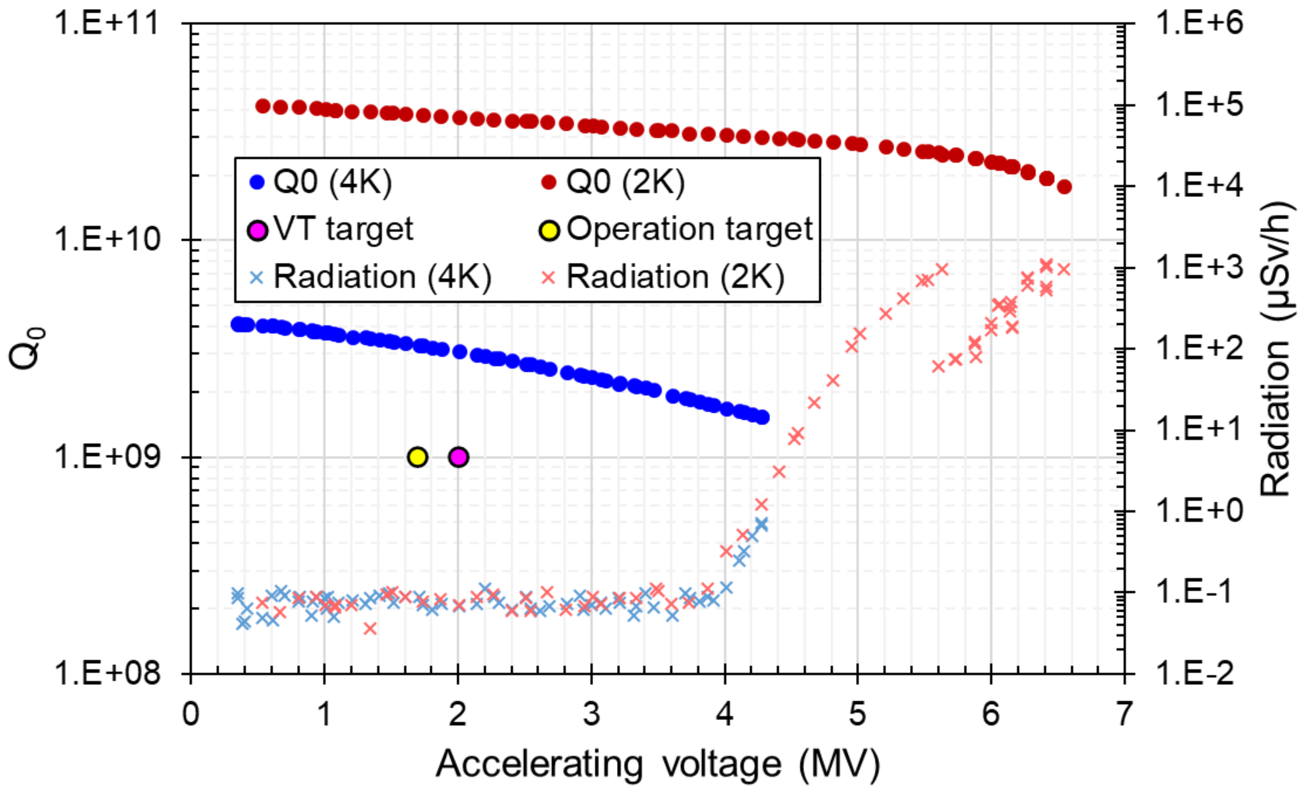




500MHz SRF cavities

- Based on BEPCII 500MHz cavity, improved mechanical properties
- All 4 bare cavities delivered in Q3.2022
- CAV#1 (BCP) passed VT

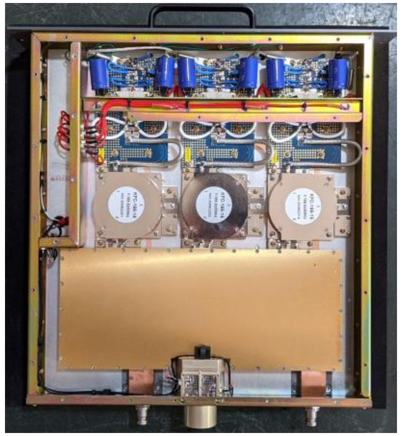




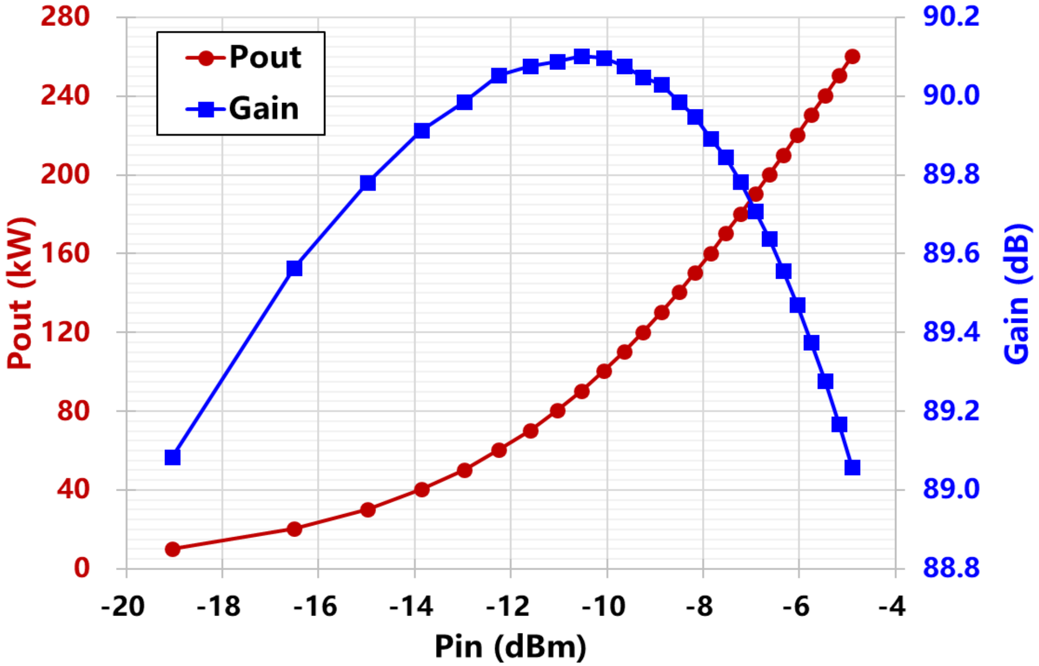
H.J. Zheng et al., *IEEE Trans. Appl. Supercond.* 31, 3500109 (2021).

166.6MHz 260kW SSA

- Contract of one prototype signed in 10.2019
  - Passed SAT in 10.2021 (6 mos. delayed D/T COVID)
  - Accumulated on-site aging time: ~400 hours (1/336 module failed)
- Contract of 4 series SSAs signed in 11.2021
  - Scheduled delivery in Q1.2023



3kW unit

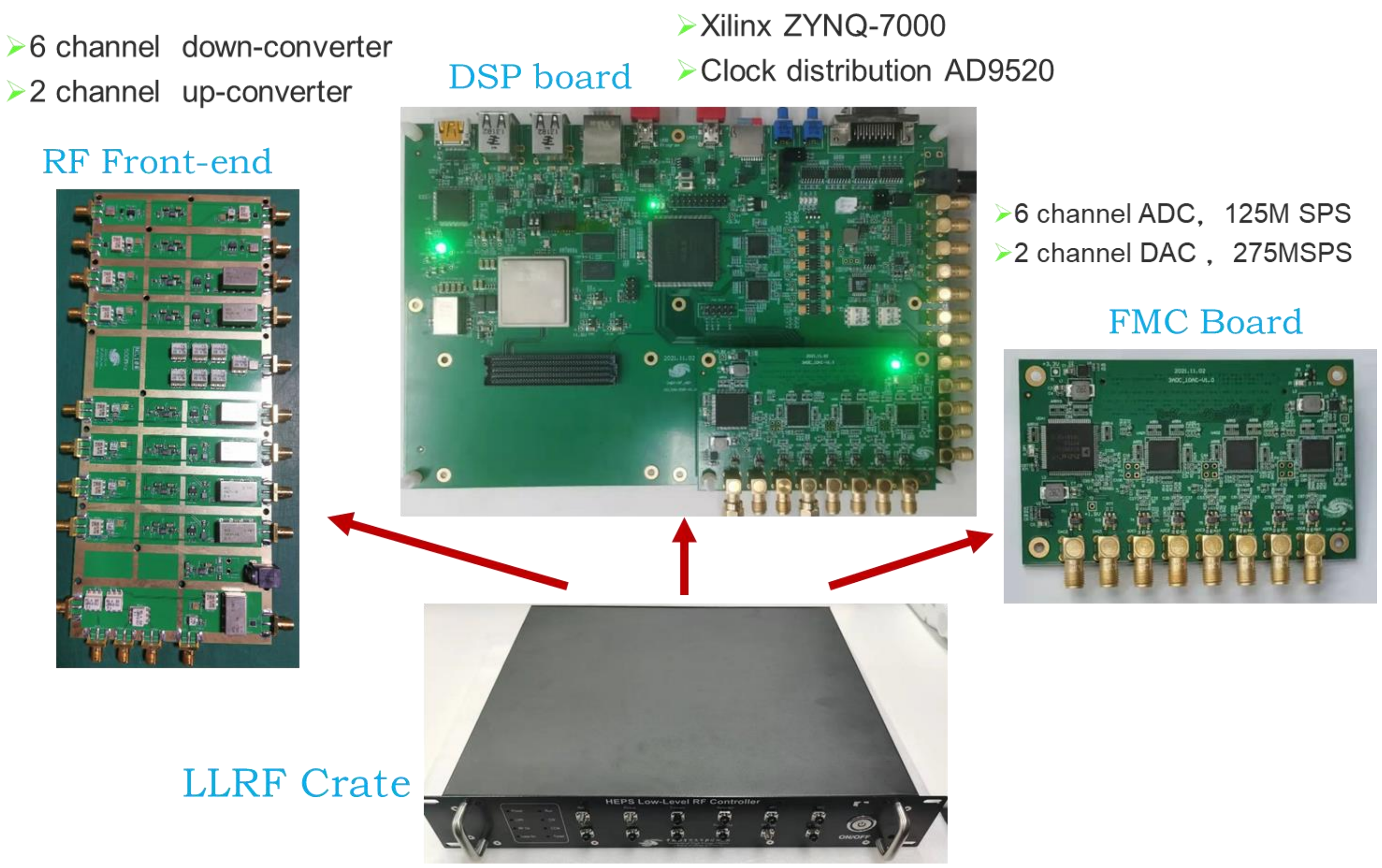


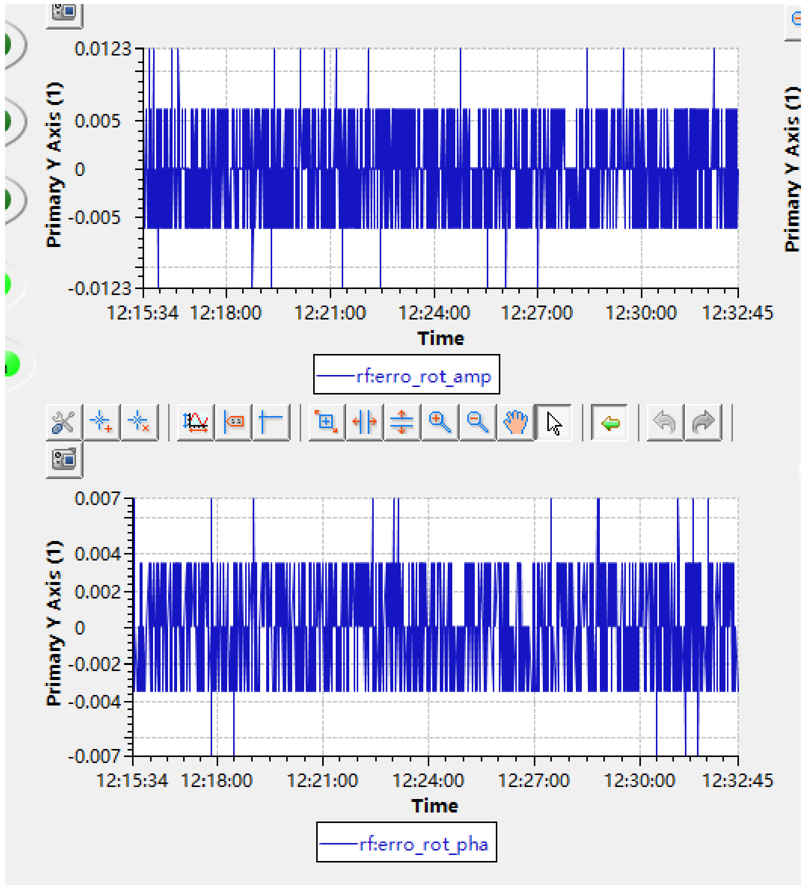
Y.L. Luo et al., *IPAC2021*, TUPAB347.

LLRF

- 3rd-gen LLRF (Xilinx-FPGA) being in-house developed
  - First prototype passed essential tests in Q4.2021
  - Second prototype under development
  - Pre-series launched in Q3.2022

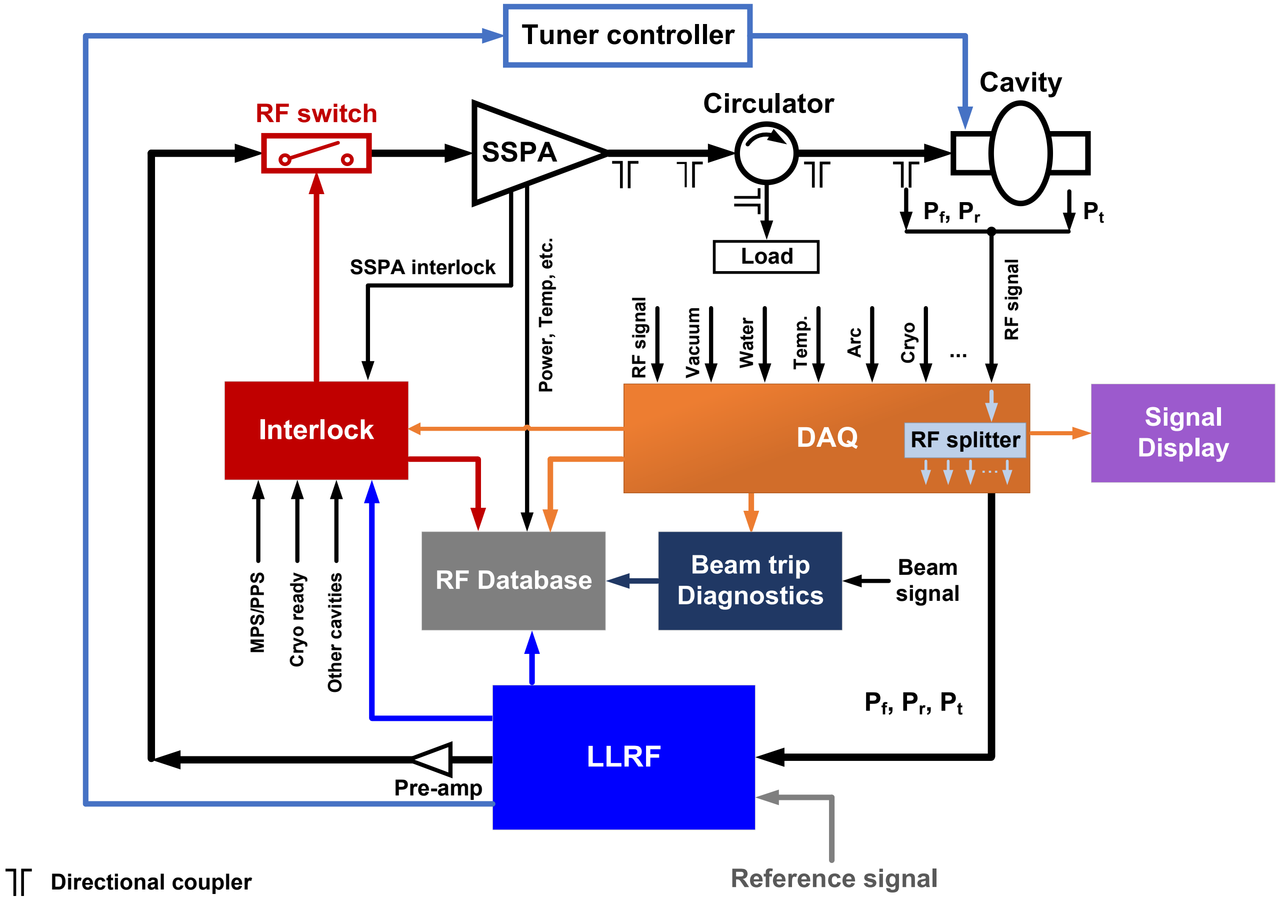
Lab test: ±0.015%， ±0.01°



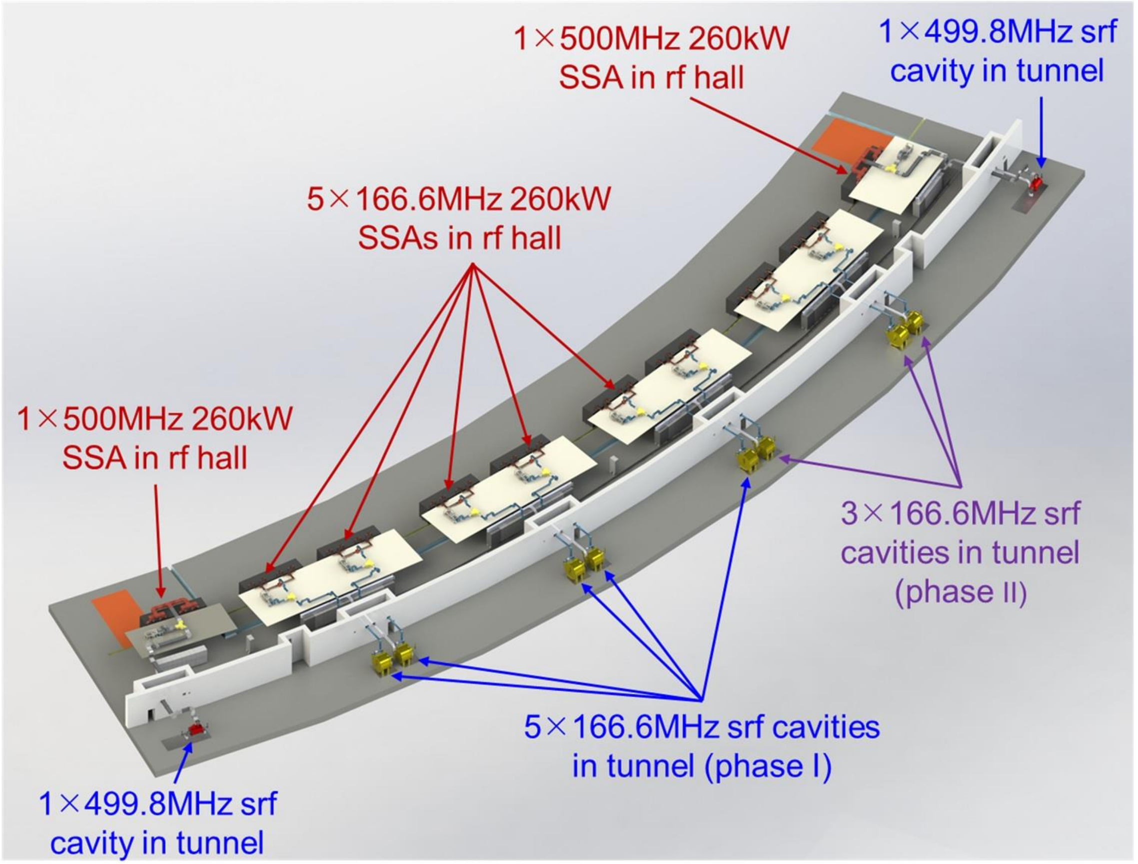


Integration

RF control layout

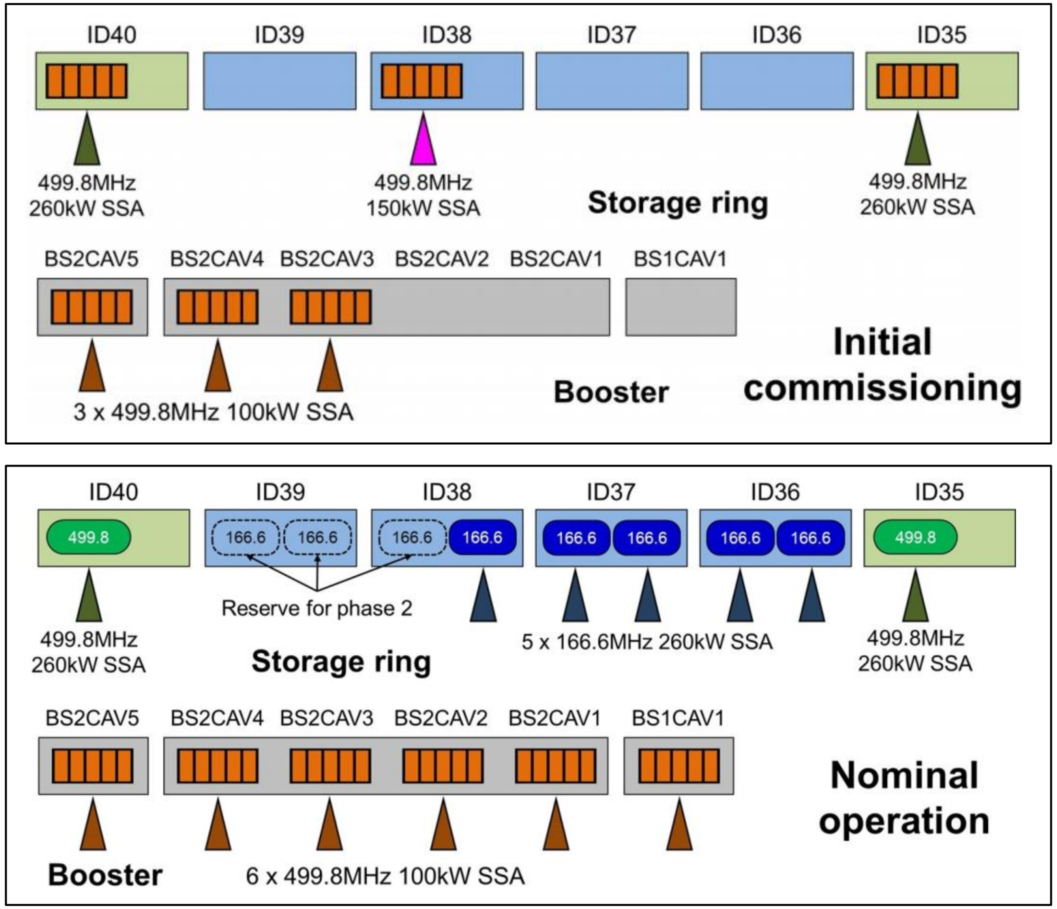


SR RF hall



Commissioning plan

- Initial commissioning of SR with 500MHz booster NC cavities
- Demanding RF power per cavity at SR (outgassing band at ~110kW)
- Switch to SRF cavities at later stage



Parameter	Booster	SR	Unit
Beam energy	6	6	GeV
Total energy loss (w/o IDs)	4.02	2.64	MeV
Cavity type	5-cell, copper		-
Number of cavities	3	3	-
Rf frequency	499.8	499.8	MHz
Max. available power at cavity (incl. 10% transmission loss)	100	135	kW
Max. FPC allowable power	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
Coupling factor	1.17	2	-
Limiting factor	SSA	FPC	-

Summary

- Construction of HEPS in good shape
- RF system for HEPS under active development
- Focusing on HOM-damped 166.6MHz SRF module
  - First 166.6MHz SRF module in Q4.2022
- RF power sources
  - Prototype SSAs passed acceptance tests, series production underway
  - Booster series SSAs passed FAT, to be installed in Q4.2022
- Low-level RF
  - 1st-gen (Altera FPGA) in beam operation
  - 2nd-gen (Altera FPGA) used in various tests
  - 3rd-gen (Xilinx FPGA) under development