RF Developments for HEPS

Pei Zhang

(Institute of High Energy Physics, CAS)

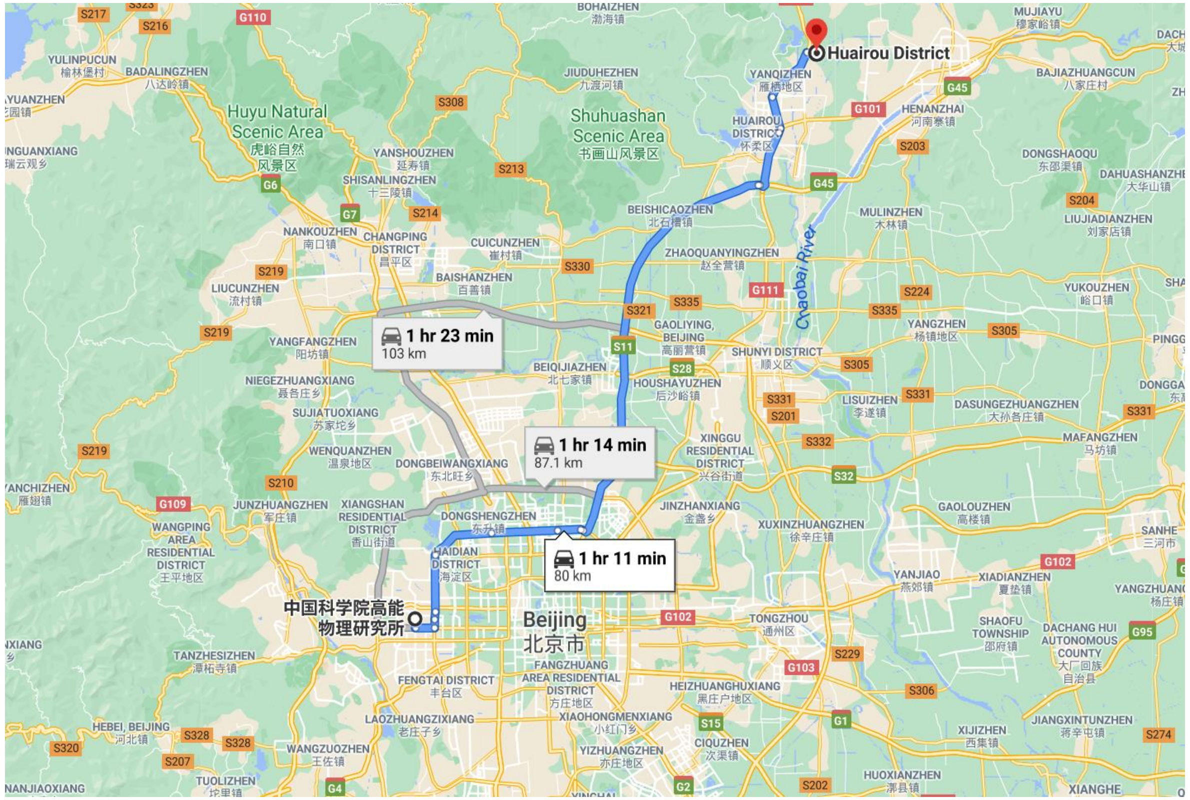
eeFACT2022, 12-15 Sep 2022, INFN-LNF, Frascati, Italy

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

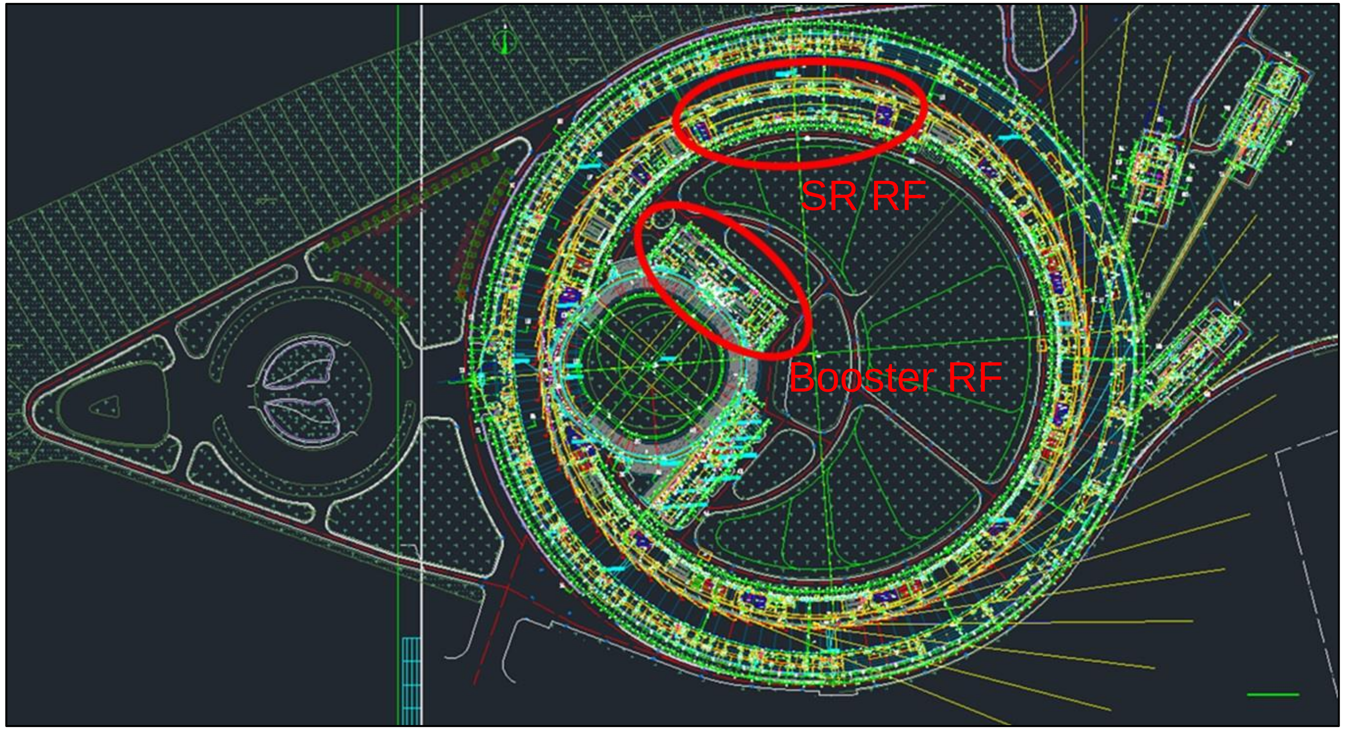
- HEPS civil construction in good shape
- Platform of Advanced Photon Source Technology R&D (PAPS) completed in 05.2021
- First accelerator component installation in 07.2021
- Linac commissioning started in 07.2022 (underway)

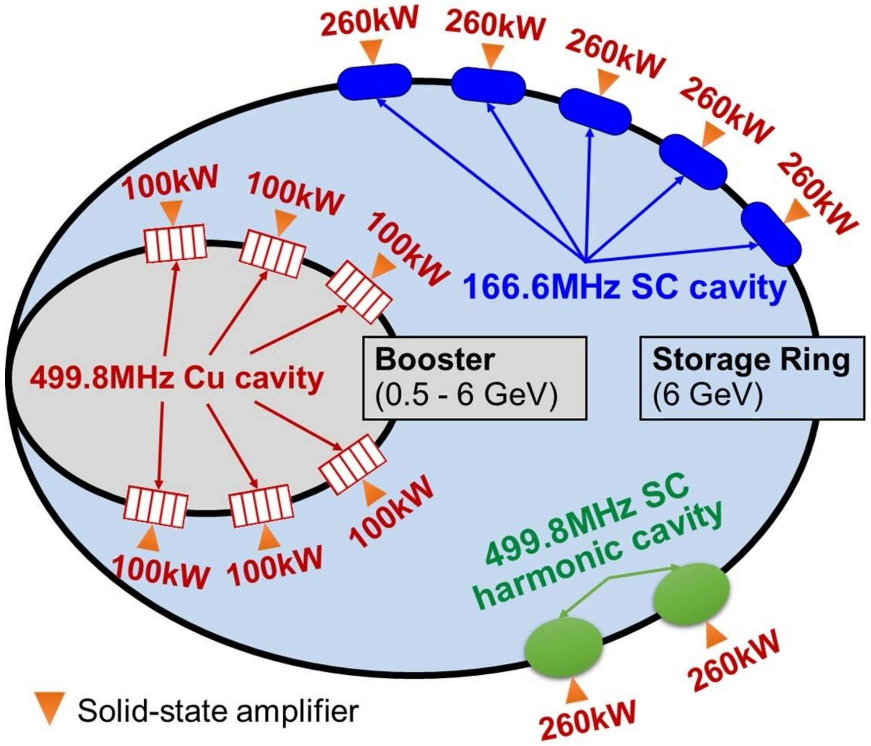
HEPS main parameters

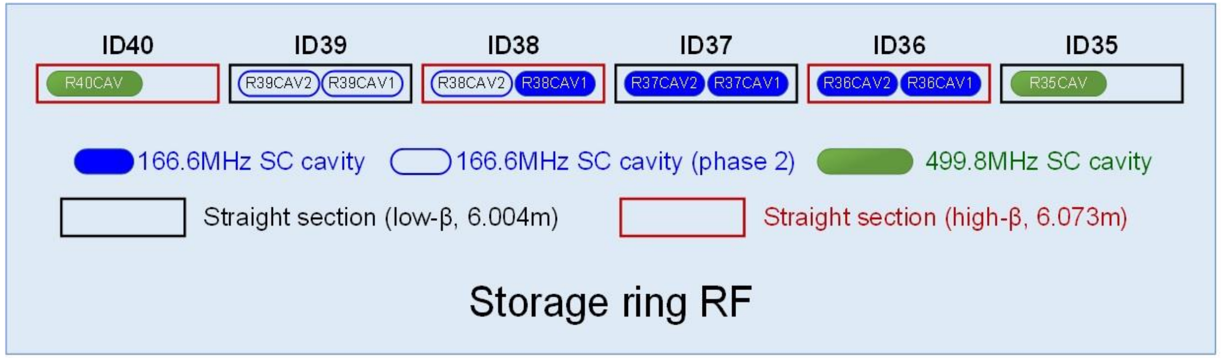
Parameter	Value	Unit
Beam energy	6	GeV
Circumference	1360.4	m
Beam current	200	mA
Lattice type	7BA	-
Number of sectors	48	-
Natural emittance	34.2	pm·rad
Natural bunch length	5.06	mm
Energy loss (bare lattice)	2.64	MeV
Total no. of IDs (Phase I)	14	-
Total beam power	850	kW
Radiation damping time (x/y/z)	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

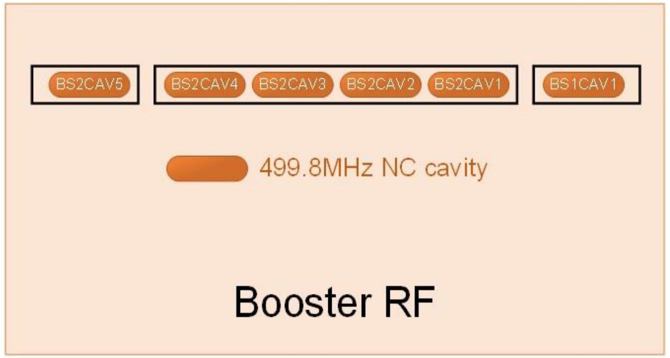
Y. Jiao et al., *Journal of Synchrotron Radiation* 25, 1611 (2018).

HEPS RF system



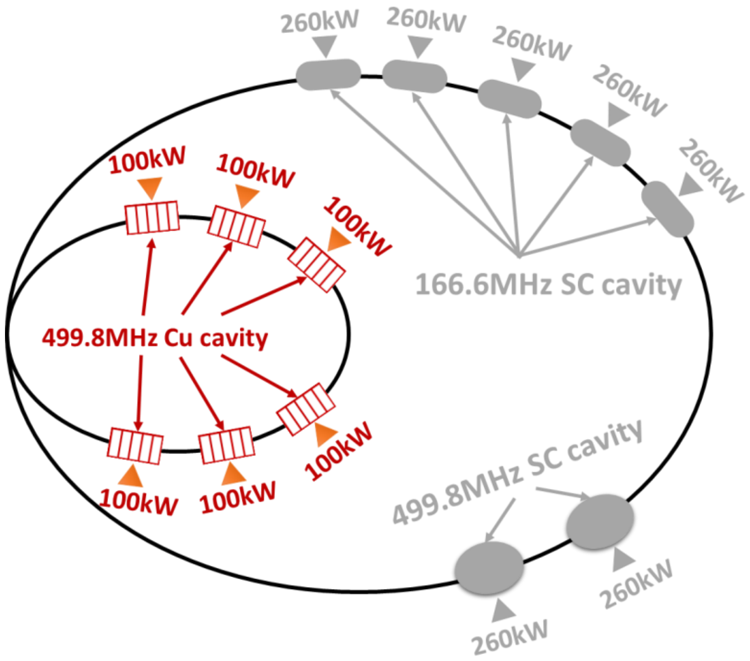




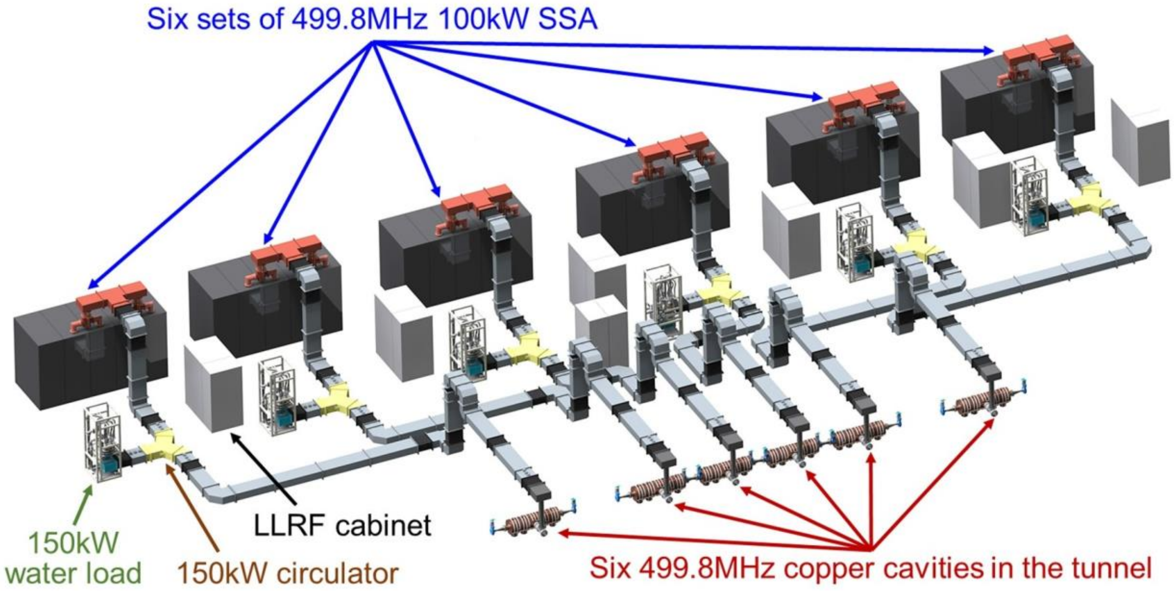


P. Zhang et al., *IPAC2021*, MOPAB380.

RF system for the booster



Booster RF: parameters

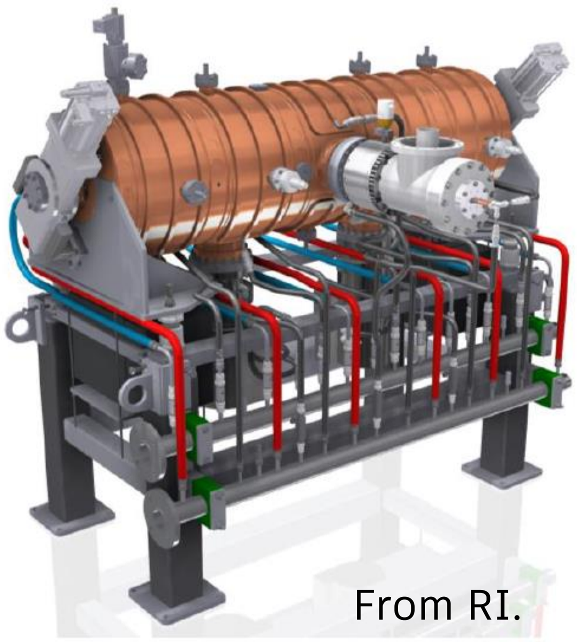


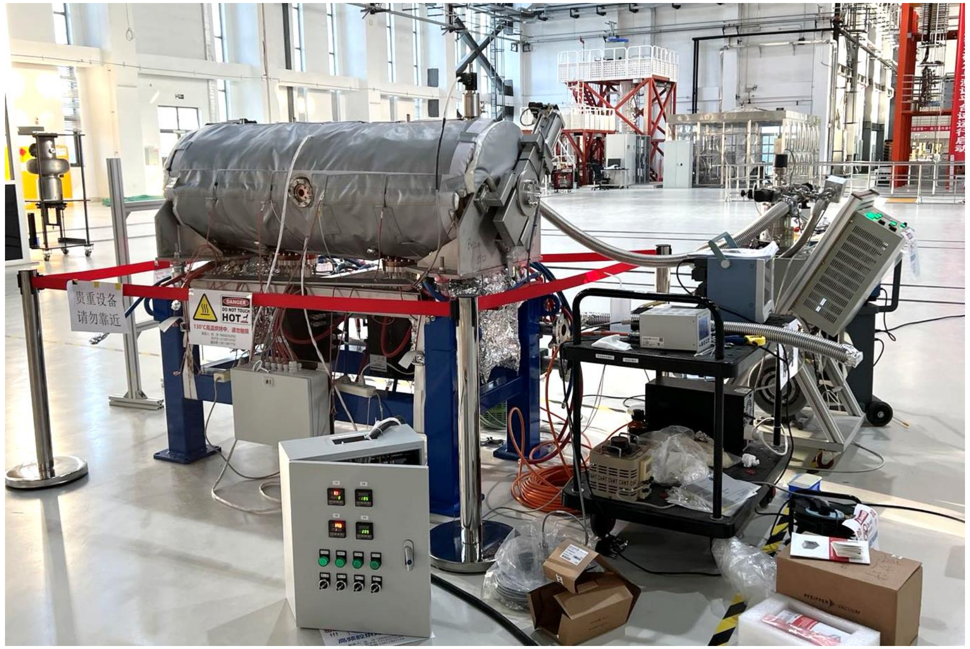
Parameter	Value	Unit
Circumference	454.066	m
Beam energy	0.5-6	GeV
Beam current	13	mA
Energy loss	4.02	MeV
Beam power	52.26	kW
Rep. rate	1	Hz

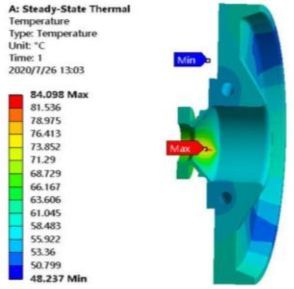
Parameter	Value	Unit
RF frequency	499.8	MHz
Total RF voltage	8	MV
No. of cavities	6	-
RF voltage per cav.	1.35	MV
Cavity type	5-cell, copper	
Wall loss per cav.	61	kW
Beam power per cav.	9	kW
Total RF power per cav.	70	kW
Coupling factor	1.17	-
RF transmitter	SSA	-
RF power per source	100	kW
No. of RF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

Booster RF: cavities

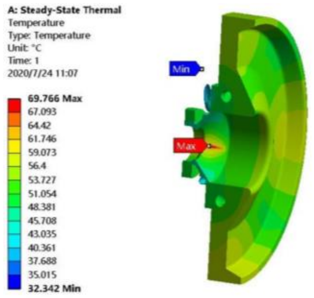
- Contract of 6 PETRA-type 5-cell cavities signed with RI GmbH in 03.2020
- 4 out of 6 cavities delivered (5 months delayed due to COVID-19)
- Several design changes implemented for HEPS
  - Synchrotron light collimator at beampipe (w/ modified cooling channels)
  - Additional monitoring for power coupler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

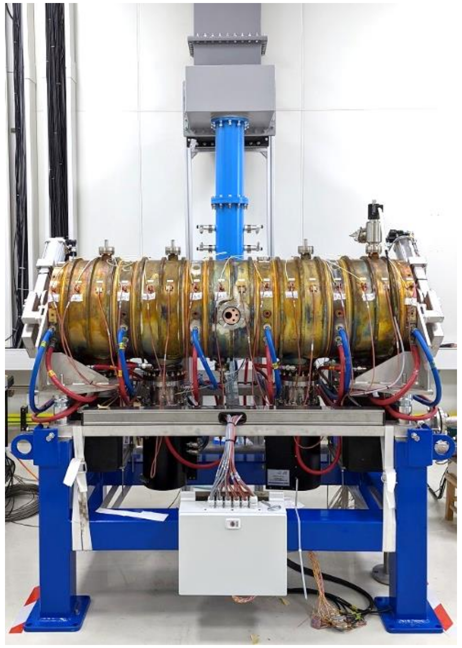

From RI.





SR collimator

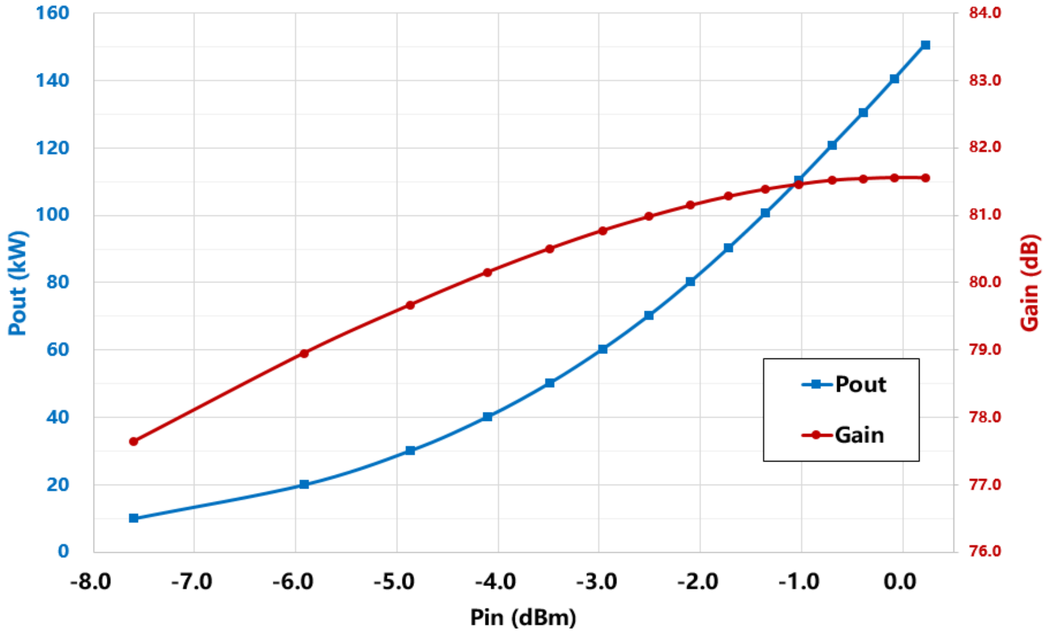




Booster RF: RF sources

- 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)

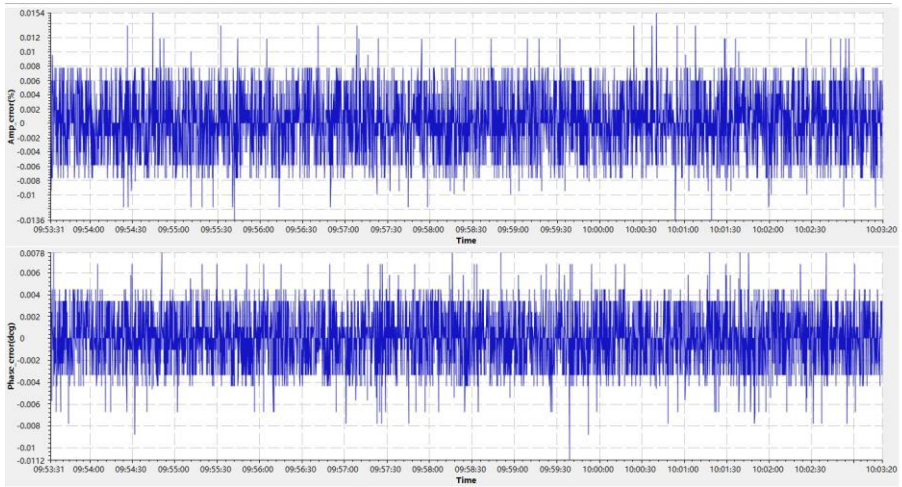


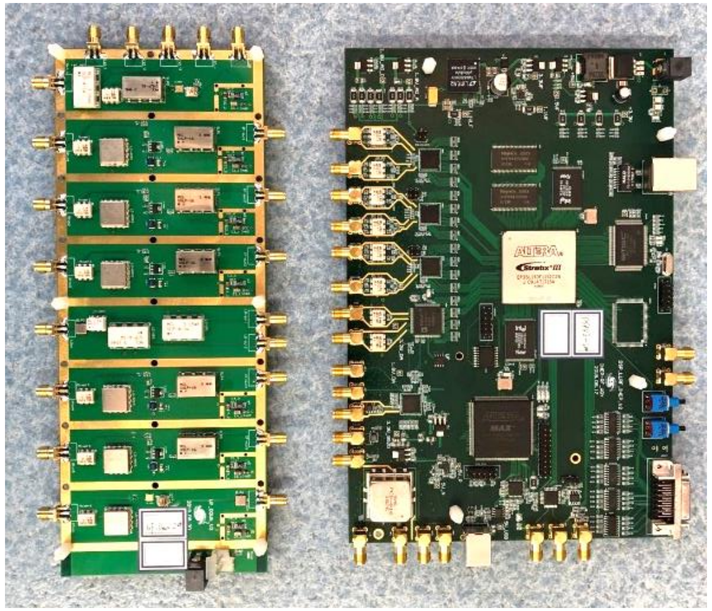
Y.L. Luo et al., *IPAC2021*, TUPAB346.

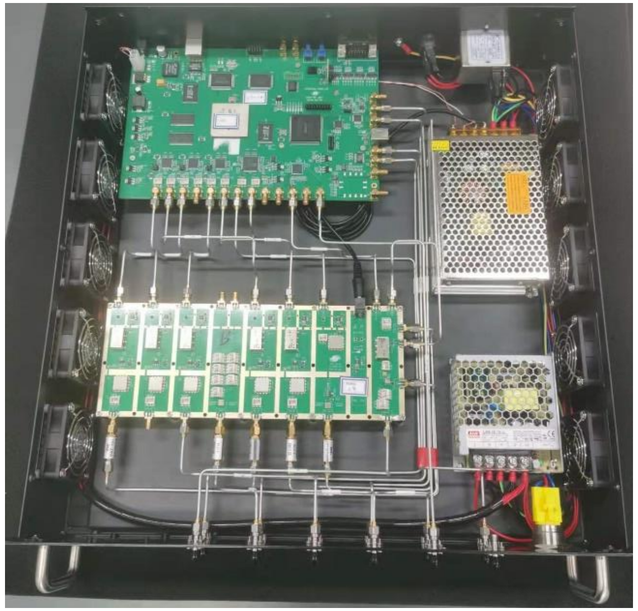
Booster RF: LLRF

- 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

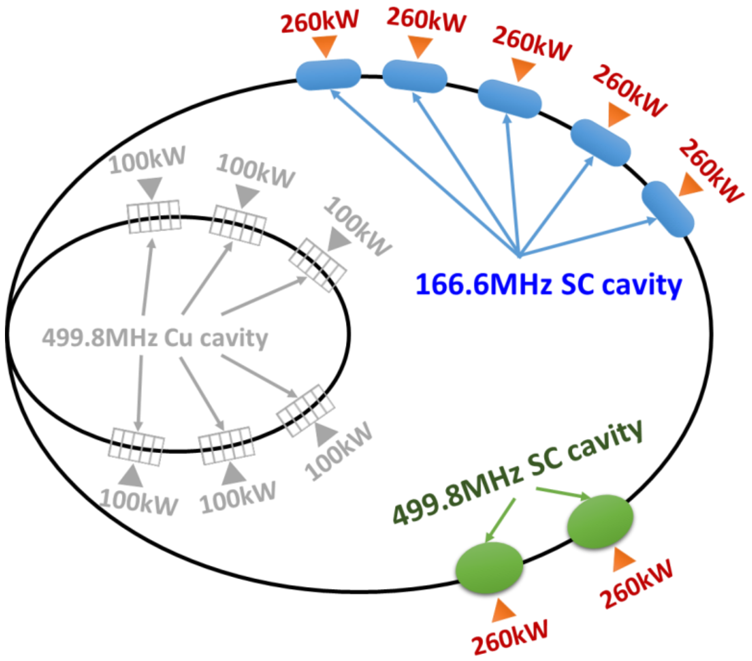






[1] Q.Y. Wang et al., *SRF2019*, THP075. [2] Q.Y. Wang et al., *Radiat. Detect. Technol. Methods* 5, 220–227 (2021).

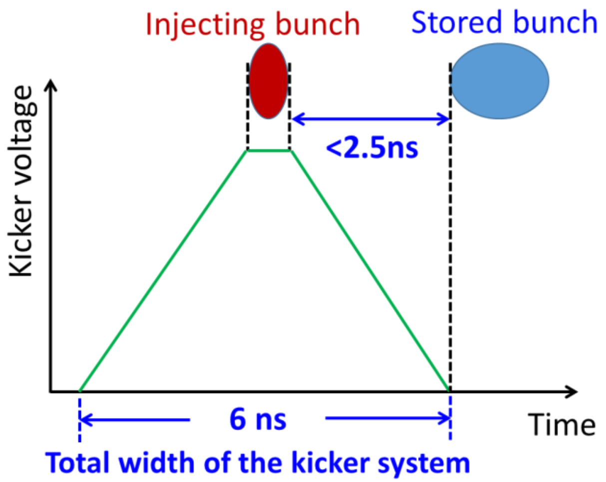
RF system for the storage ring



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

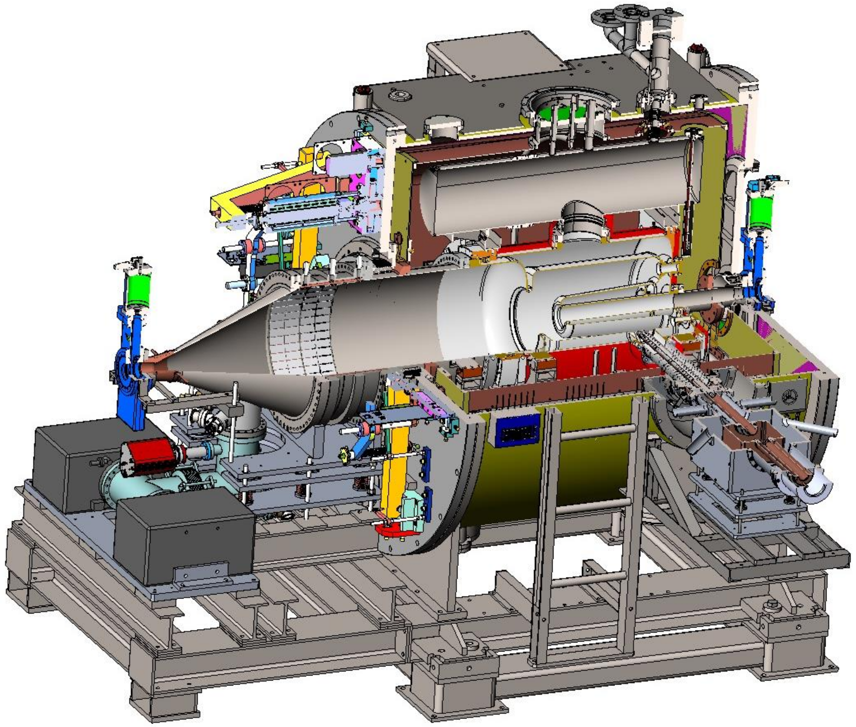
Technology readiness

Use 500MHz as harmonic RF

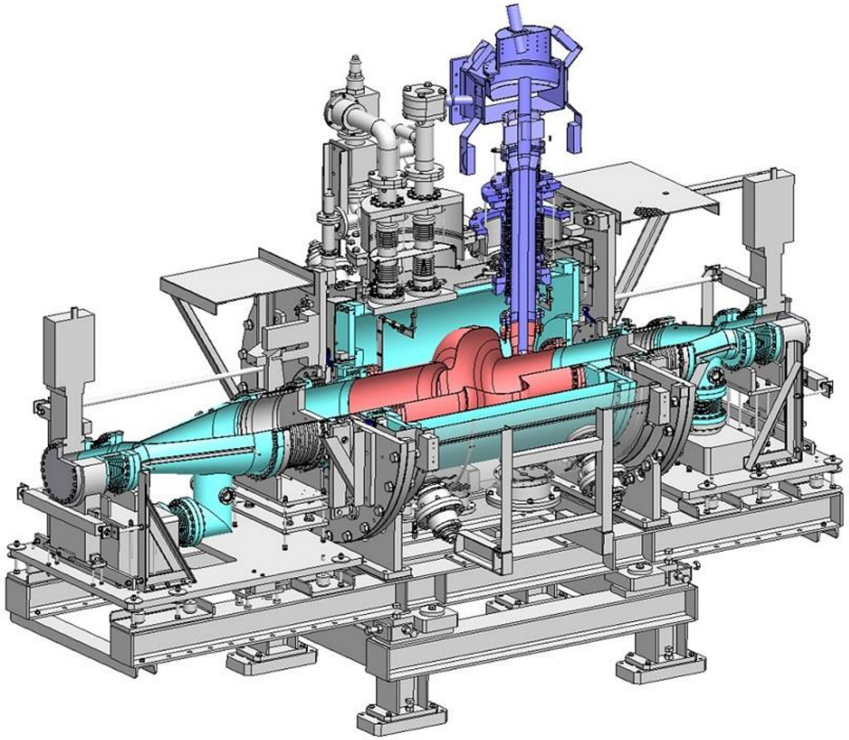
166.6 MHz (fundamental RF)
499.8 MHz (harmonic RF)

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

Storage-ring RF: cavities



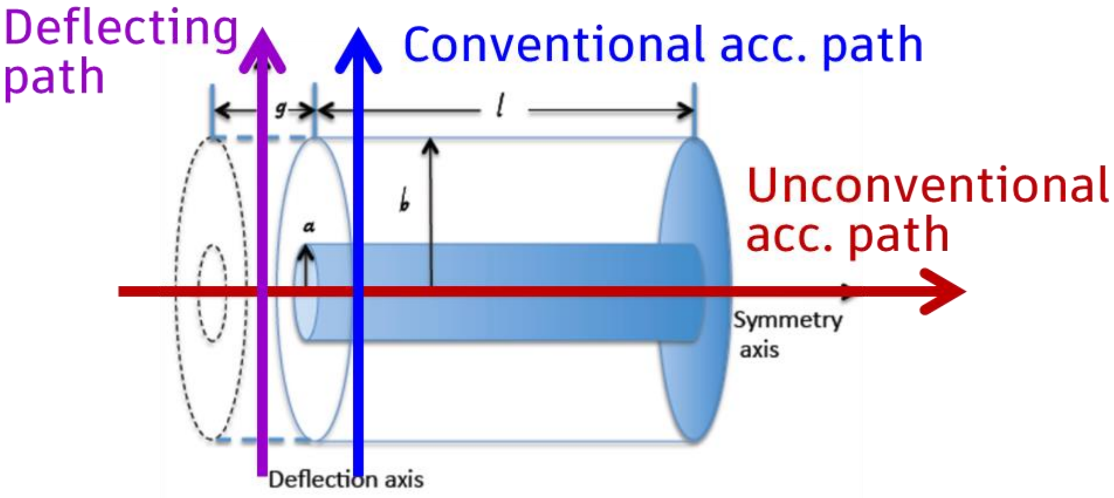
166.6MHz quarter-wave
β=1 SRF cavity
(New development)



499.8MHz KEKB-type
single-cell SRF cavity

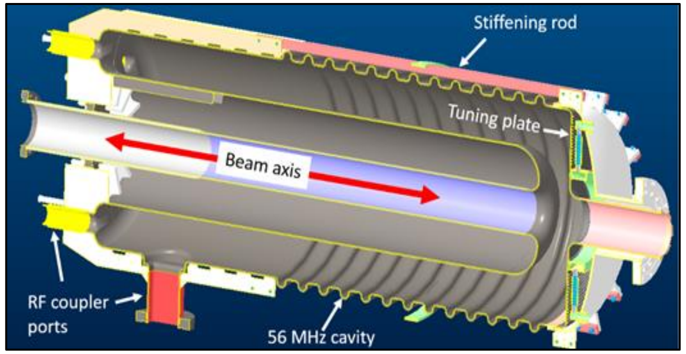
Cavity design features (166.6MHz)

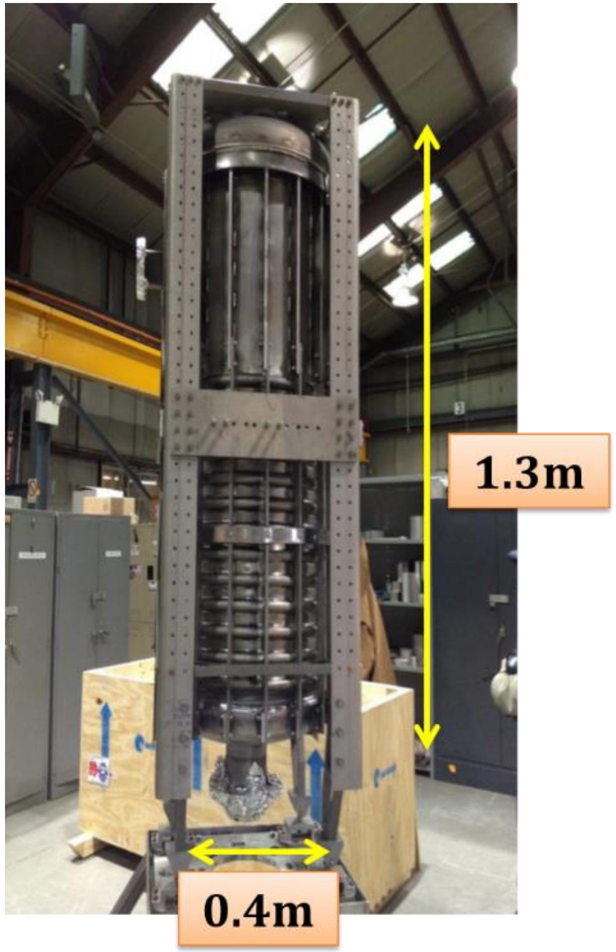
- **Low frequency**: 166.6MHz, β=1
- High current: 200mA → **heavy HOM damping**: Q_L<1000
- **High RF power**: 170kW CW per cavity
- **Compactness**: limited space of the straight section (6m for 2 cavs)
- Stable operation (user facility): **large margin** in RF parameters
- **Risks: no time or facilities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



β=1 quarter-wave cavities

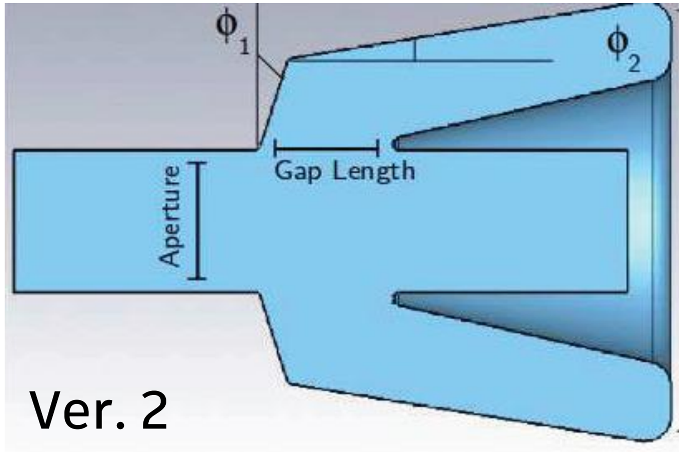
BNL 56MHz QW cavity

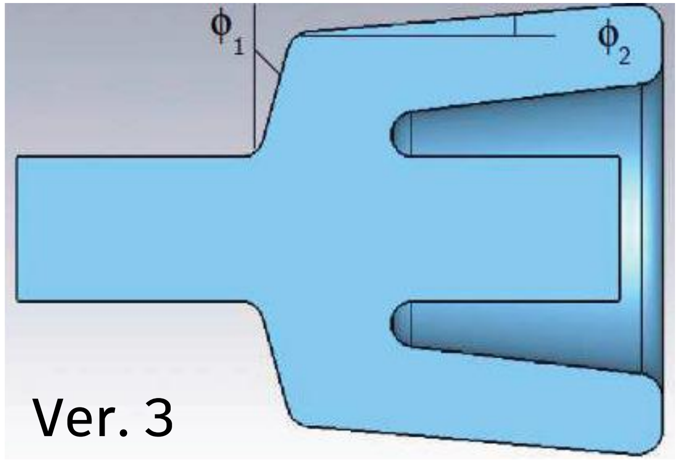




Q. Wu et al., *SRF2015*, WEBA07.
Q. Wu et al., *Phys. Rev. Accel. Beams* 22, 102001 (2019).

CERN 200MHz QW for HL-LHC





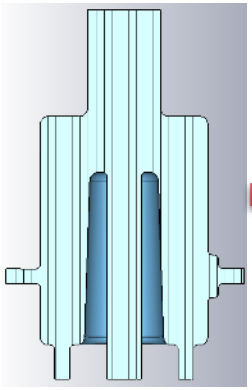
R. Calaga et al., *IPAC2016*, TUPMW034.

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

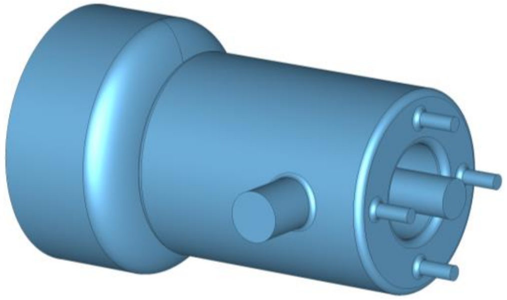

Bare cavity

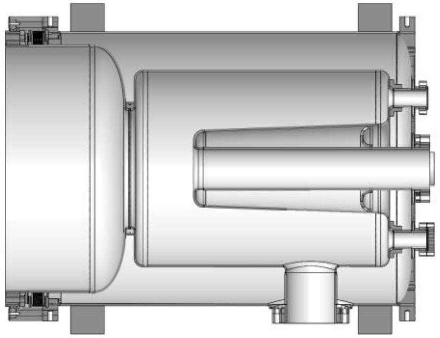

VT

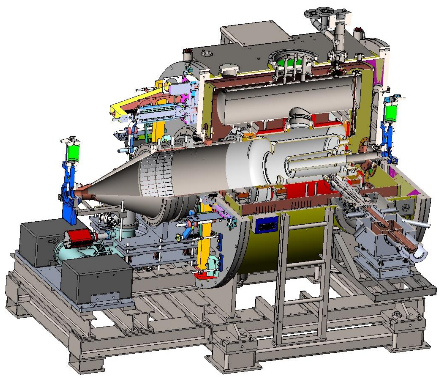

Dressed cavity


HT

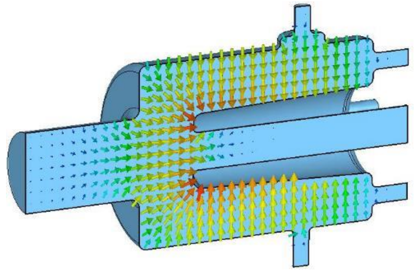
HOM-damped cavity (2019-now)

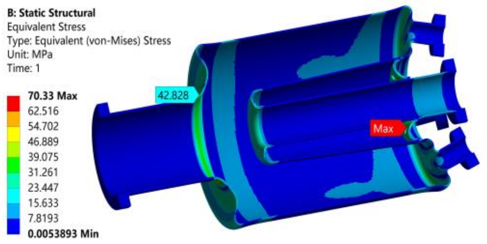

Bare cavity


Jacketed cavity


Module

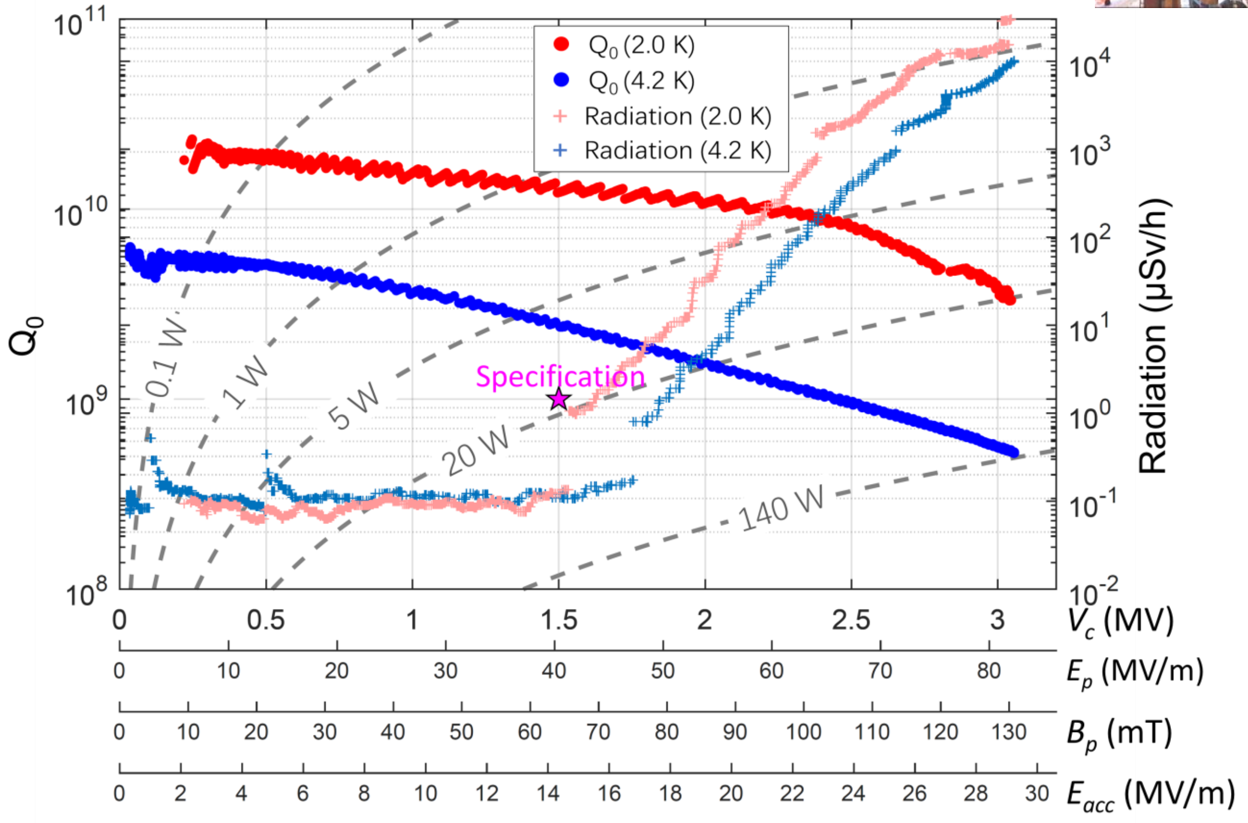
PoP bare cavity development





- 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

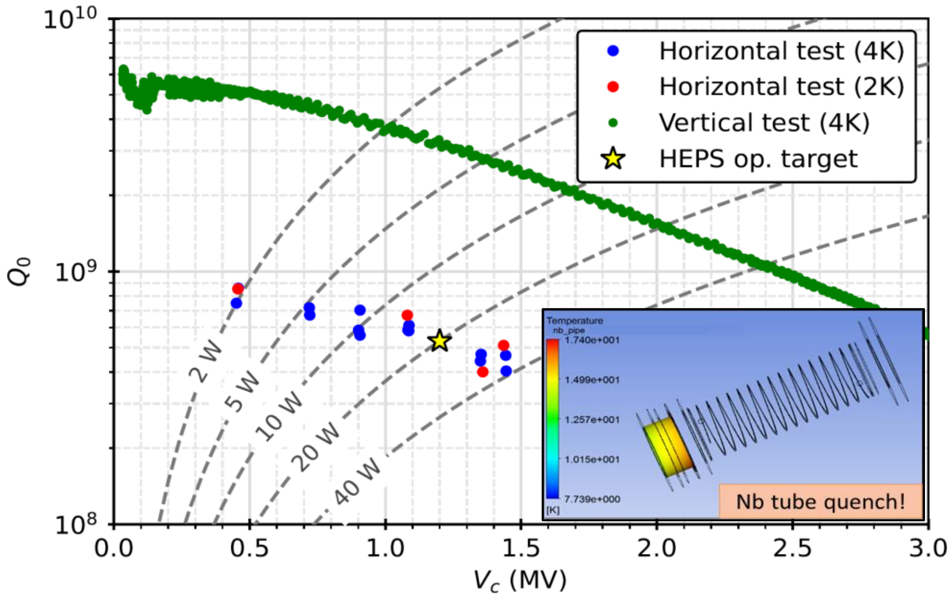
Parameter	Value	Unit
Frequency	166.6	MHz
Cavity length (main)	530	mm
Cavity diameter (no ports)	397	mm
Aperture (small side)	80	mm
R/Q	136	Ω
Geometry factor	54.5	Ω
Design voltage (Vc_d)	1.5	MV
Design gradient	12.5	MV/m
Q0 at Vc_d	≥1e9	-
Epeak at Vc_d	40.1	MV/m
Bpeak at Vc_d	63.9	mT
Stored energy	15.8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



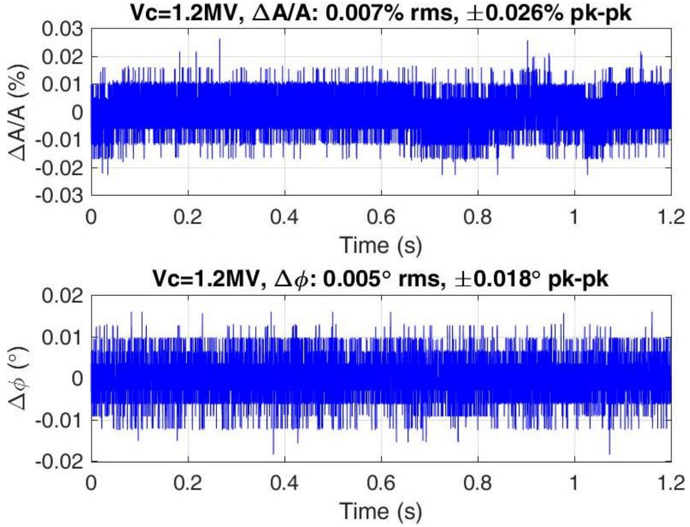
[1] P. Zhang et al., *Rev. Sci. Instrum* 90, 084705 (2019). [2] X.Y. Zhang et al., *NIM-A* 947, 162770 (2019).

PoP dressed cavity development

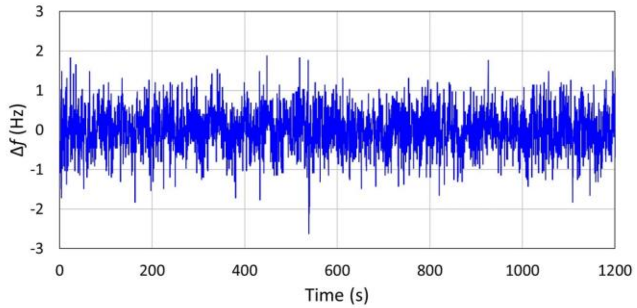
- Large performance degradation observed from VT to HT
  - Cause: overheating on FPC Nb tube extension, 80mm -> 120mm
  - Relocate the pickup to simplify helium jacket design



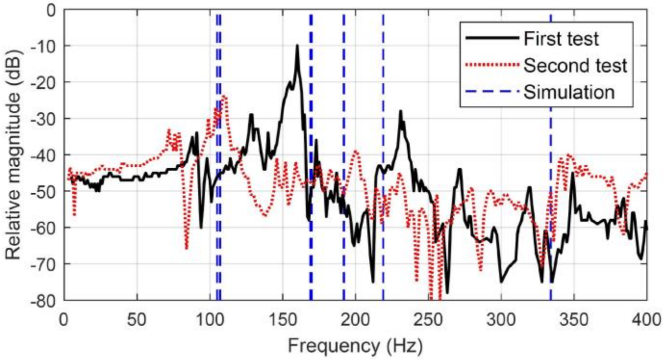
A/P loop closed



Freq. loop closed



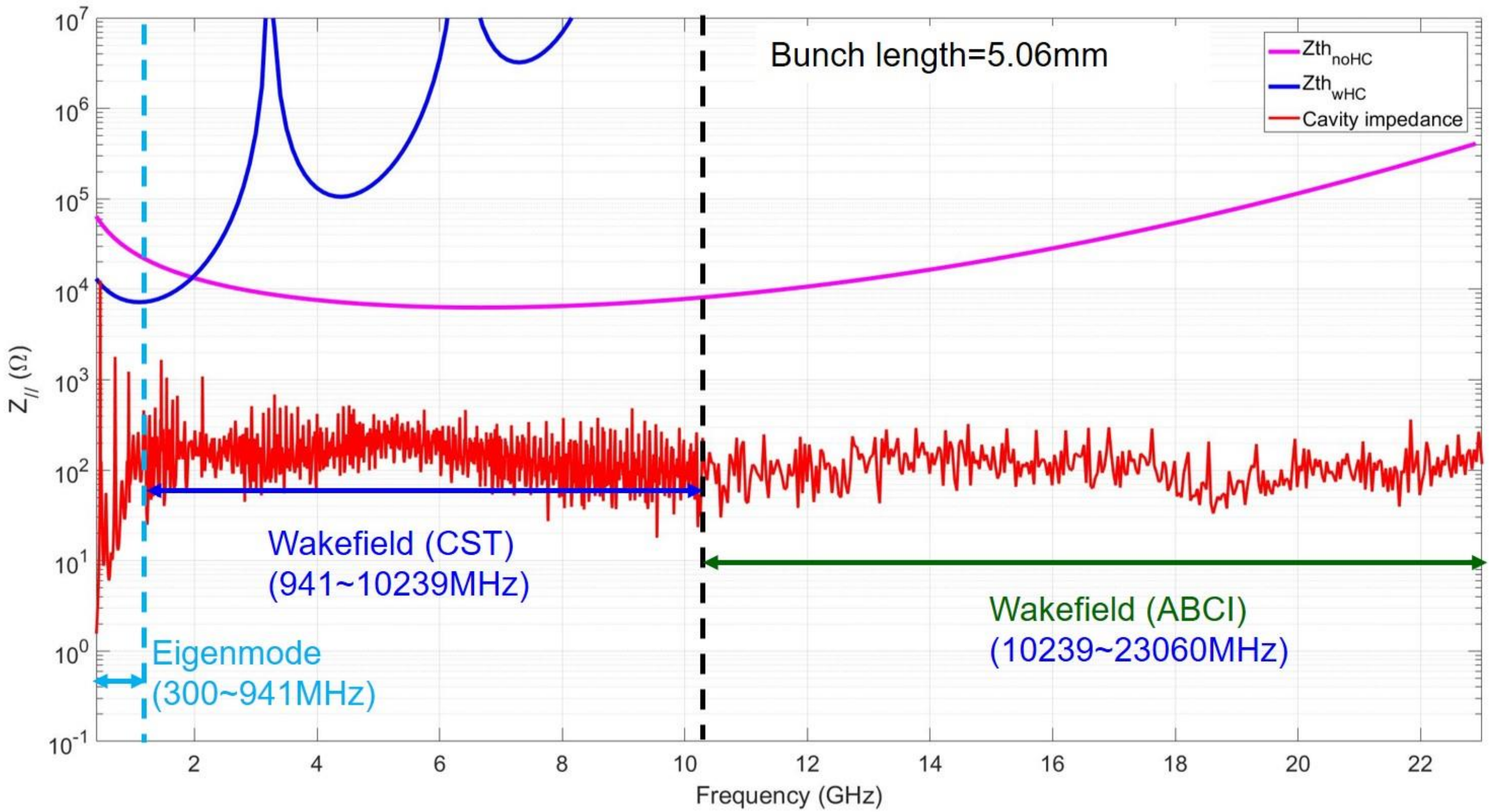
Microphonics spectrum

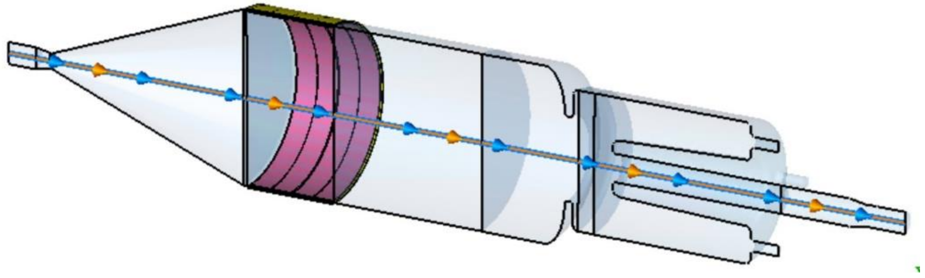


[1] X.Y. Zhang et al., *IEEE Trans. Appl. Supercond.* 30, 3500208 (2020). [2] T.M. Huang et al., *AIP Advances* 11, 045024 (2021).

HOM damping

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

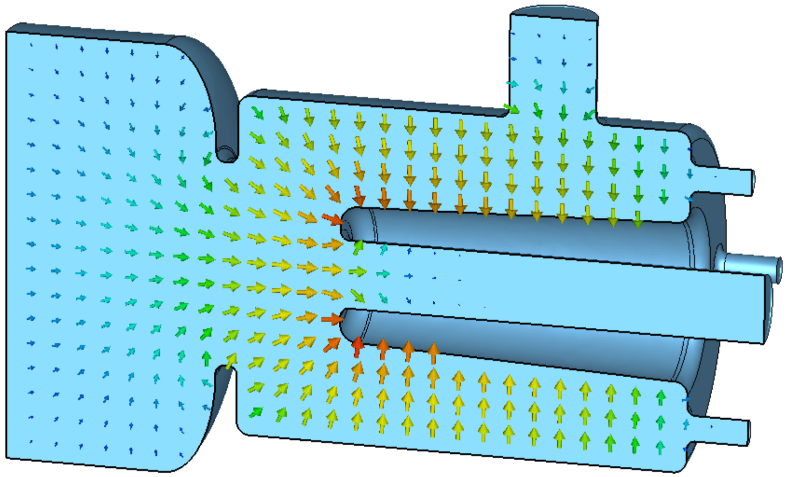


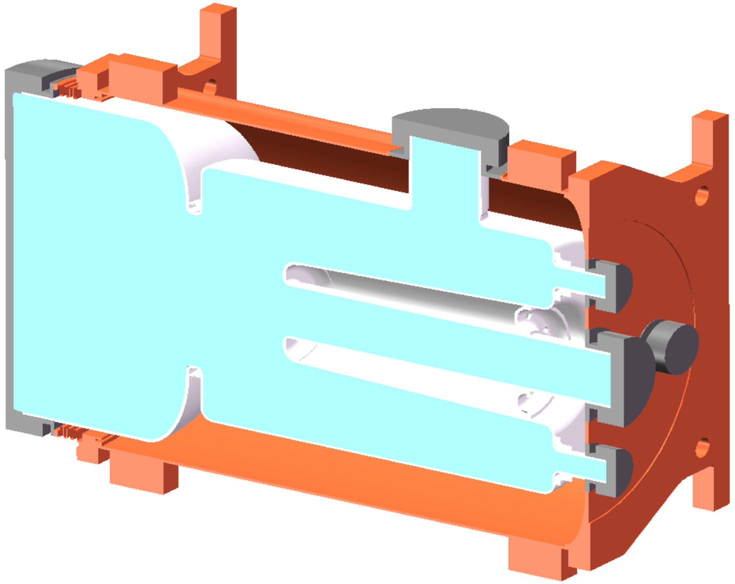


- **HOM power**
  - 7kW in high-charge mode
  - 700W in high-luminosity mode

[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)



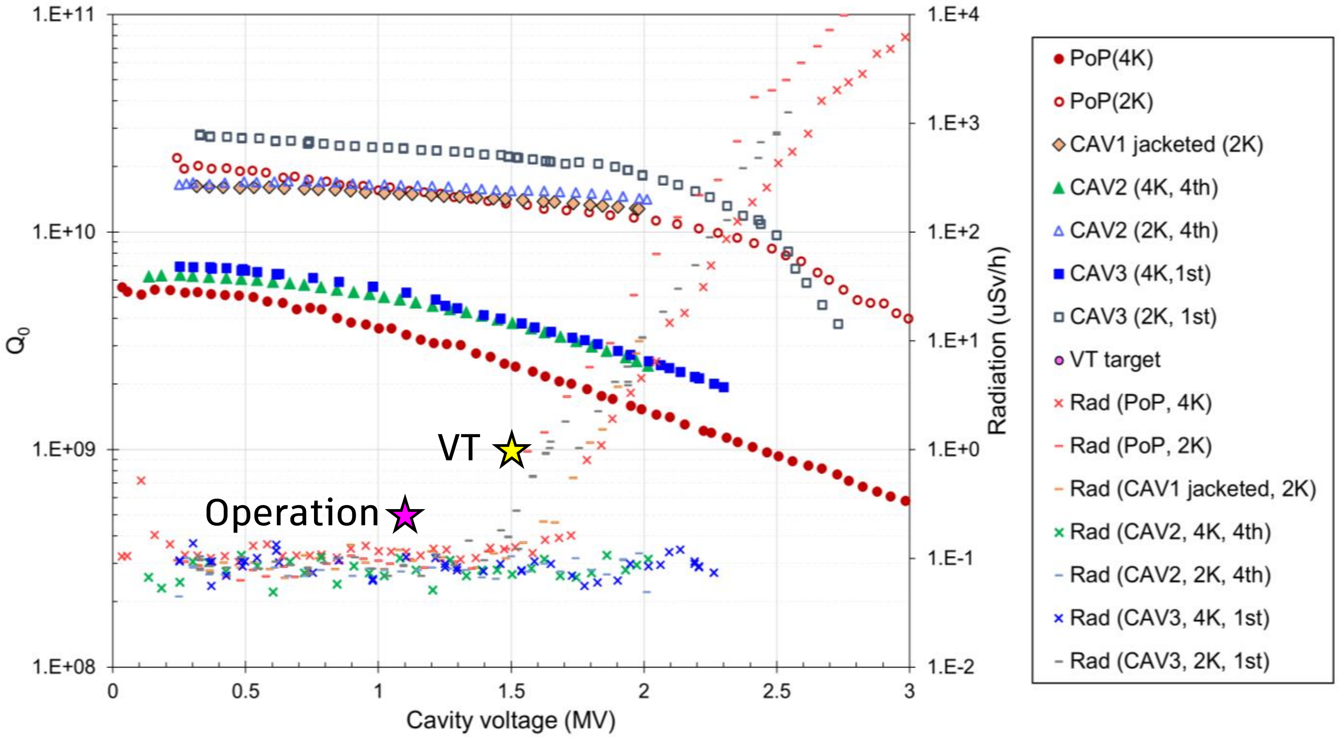


Parameter	Value	Unit
Frequency	166.6	MHz
Operating Temperature	4.2	K
R/Q	139	Ω
Geometry factor	56	Ω
Cavity VT voltage (Vc_VT)	1.5	MV
Q0 at Vc_VT	≥1e9	-
Cavity op. voltage (Vc_op)	1.1	MV
Q0 at Vc_op during operation	≥5e8	-
Epeak at Vc_op	29	MV/m
Bpeak at Vc_VT	46	mT
df/dp	39.2	Hz/mbar
Tuning range	+/-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

Cavities

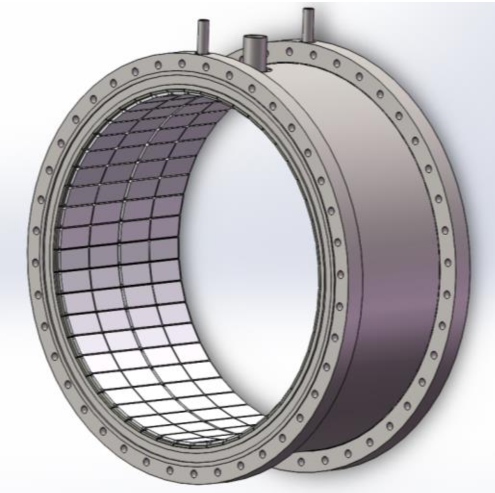
- In-house developed, contract of 10 bare cavities signed in 10.2020
- Pre-series (3 cavities) production completed in Q1.2022
  - All 3 bare cavities passed VT tests, Cav#1-jacketed VT at 2K
  - Modified BCP implemented to eliminate unwanted traces on the LBP transition

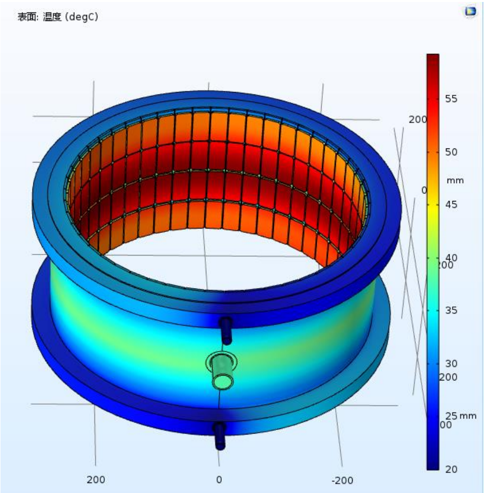
Lowest Rres: ~1.44 nΩ (~1.7 m^2 Nb surface)



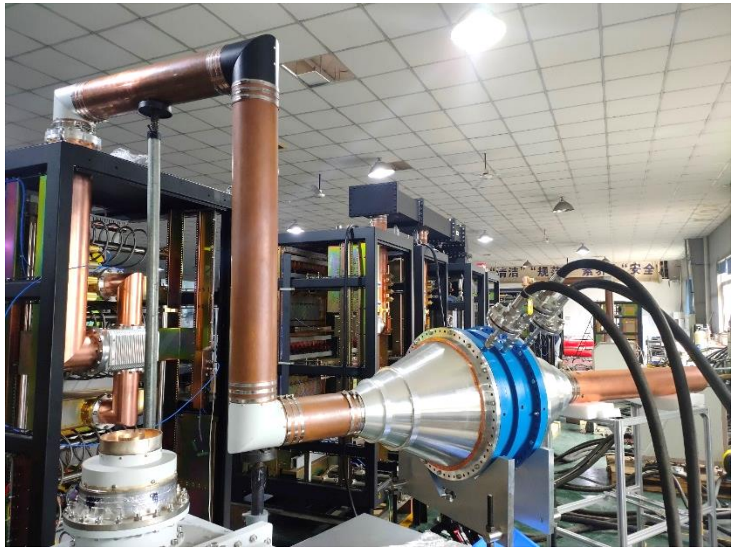
Ferrite HOM absorber

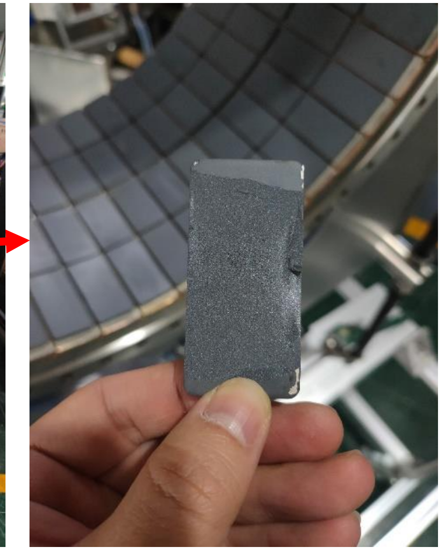
- In-house developed
  - Inner diameter: 505mm
  - 200 tiles, 4 tiles/coupon
- 1 tile peeled off after the 10kW power test
- Brazing fixtures optimized



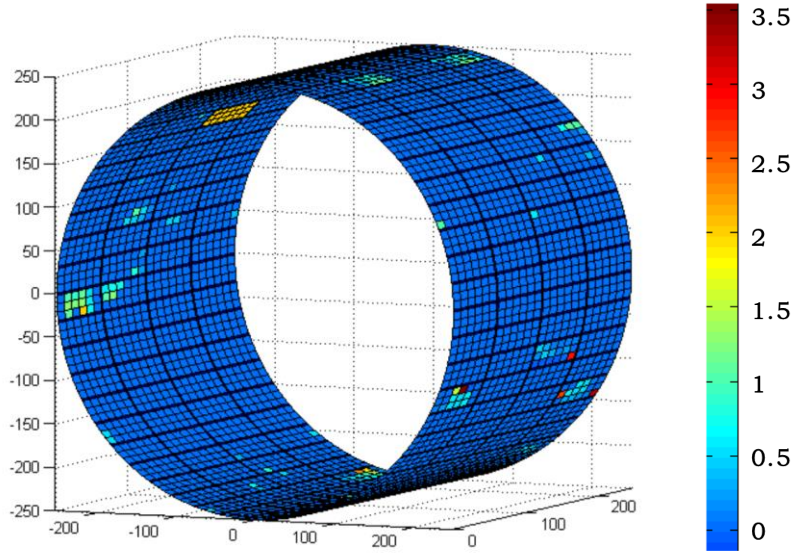


10kW test





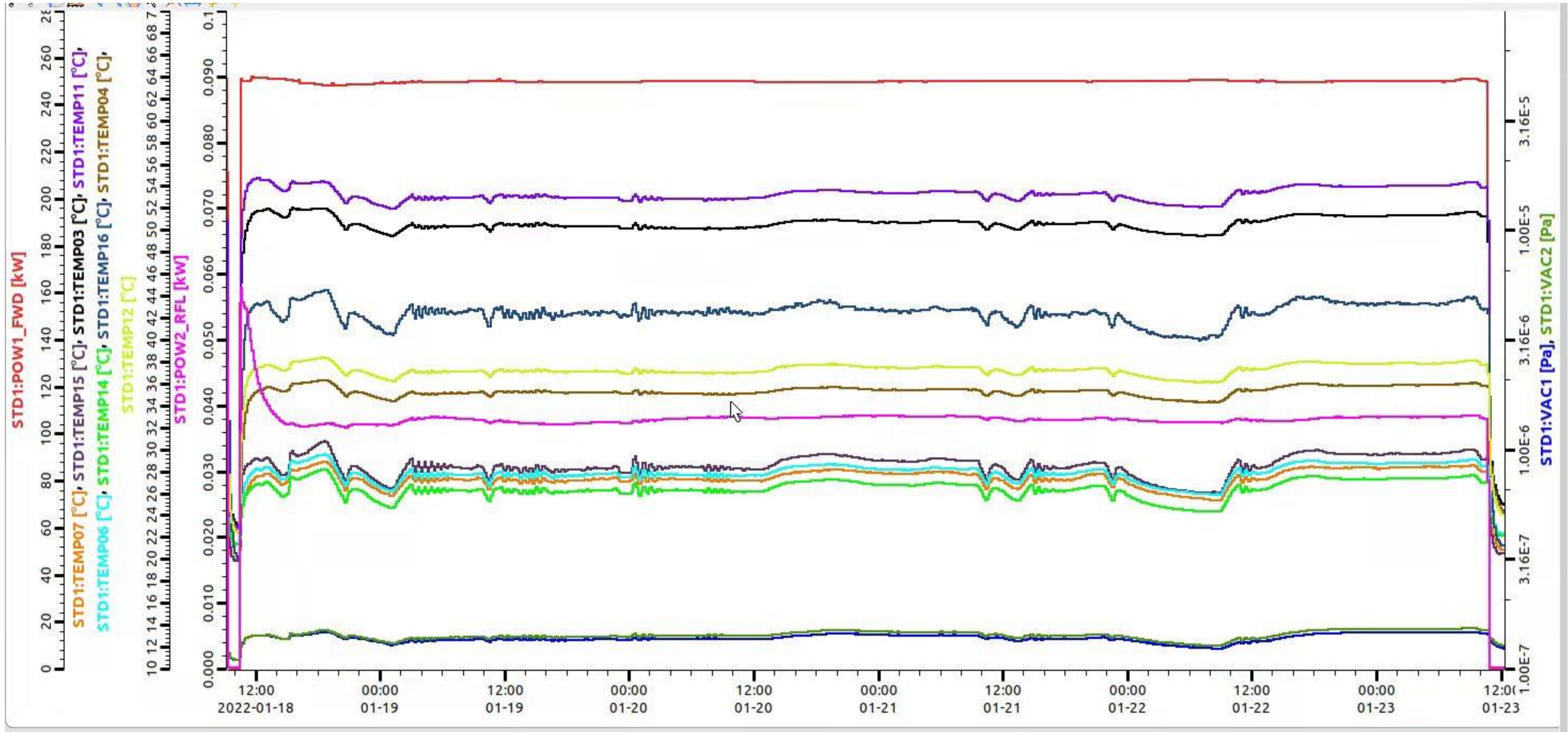
Distance to defects



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

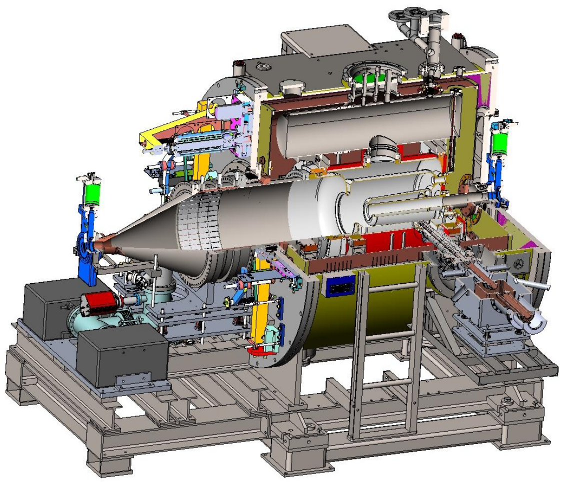
High-power aging for 120 hours at 250kW CW

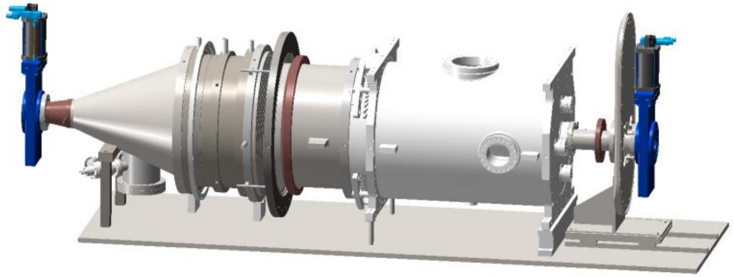


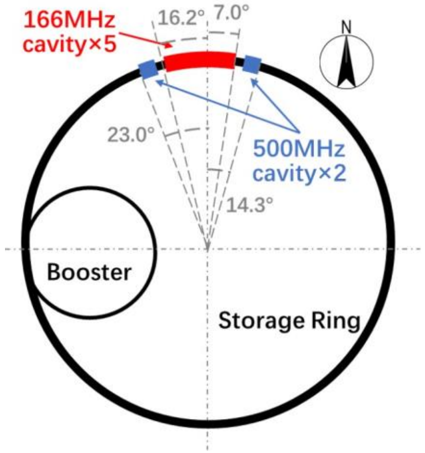
T.M. Huang et al., *Review of Scientific Instruments* 91, 063301 (2020).

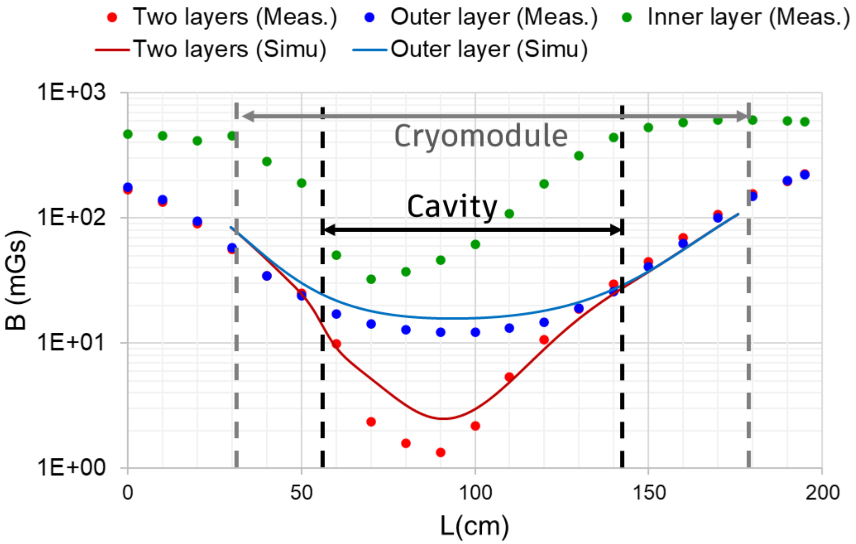
Cryomodule

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



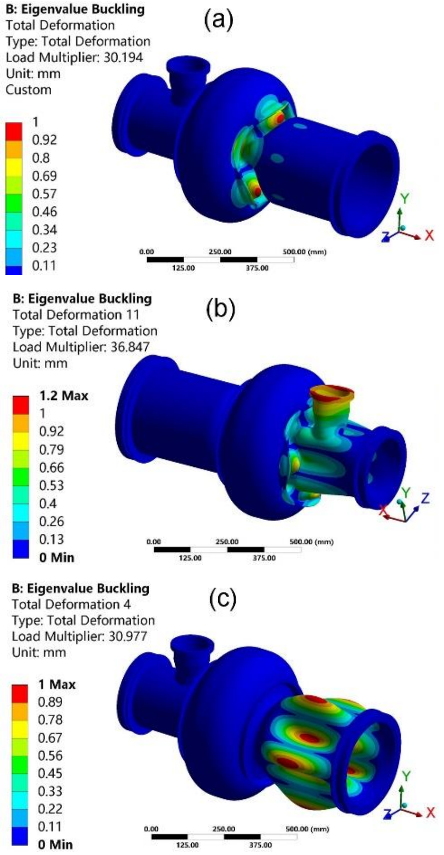


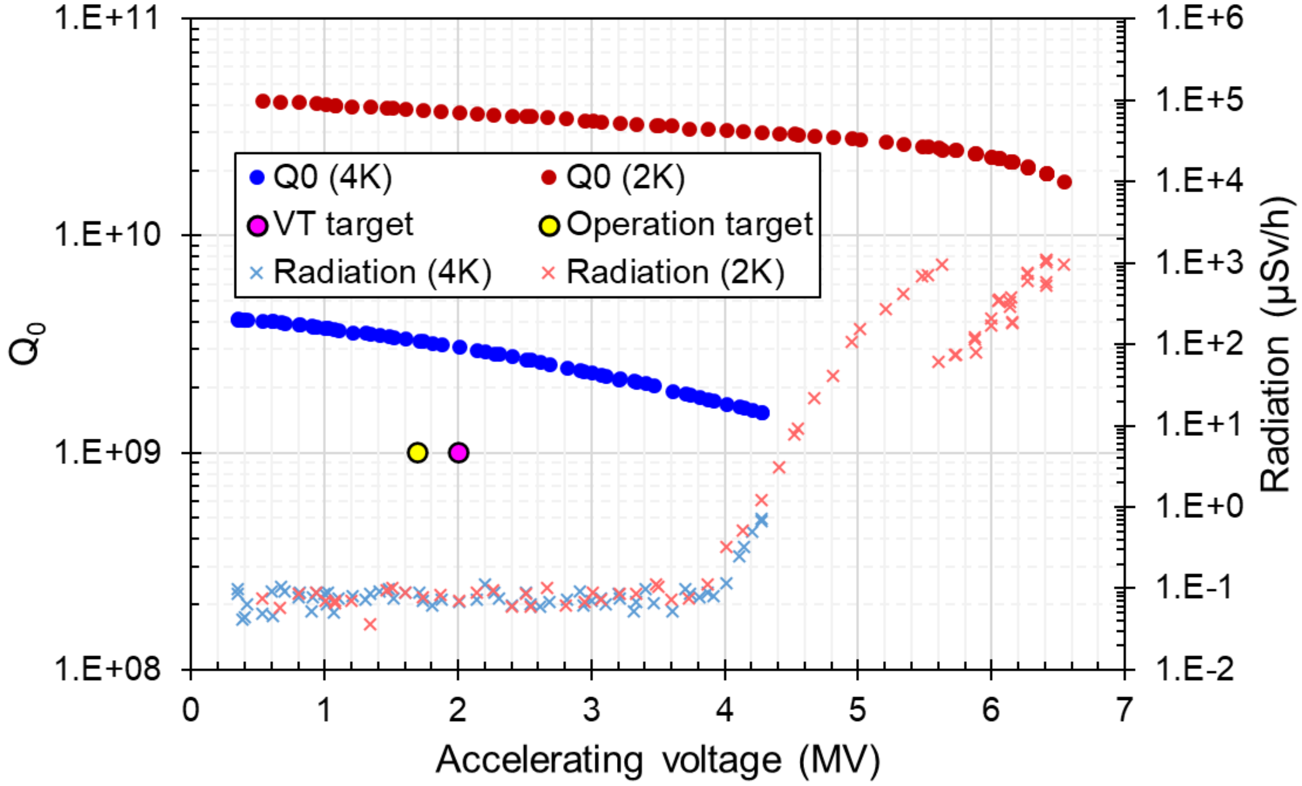




500MHz SRF cavities

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

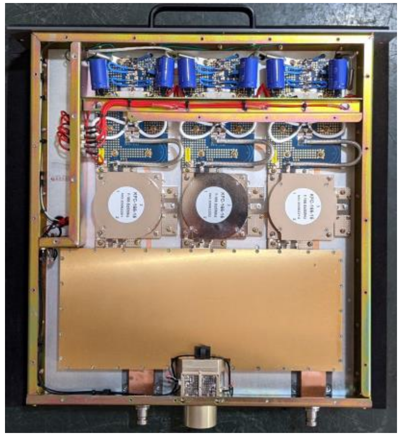




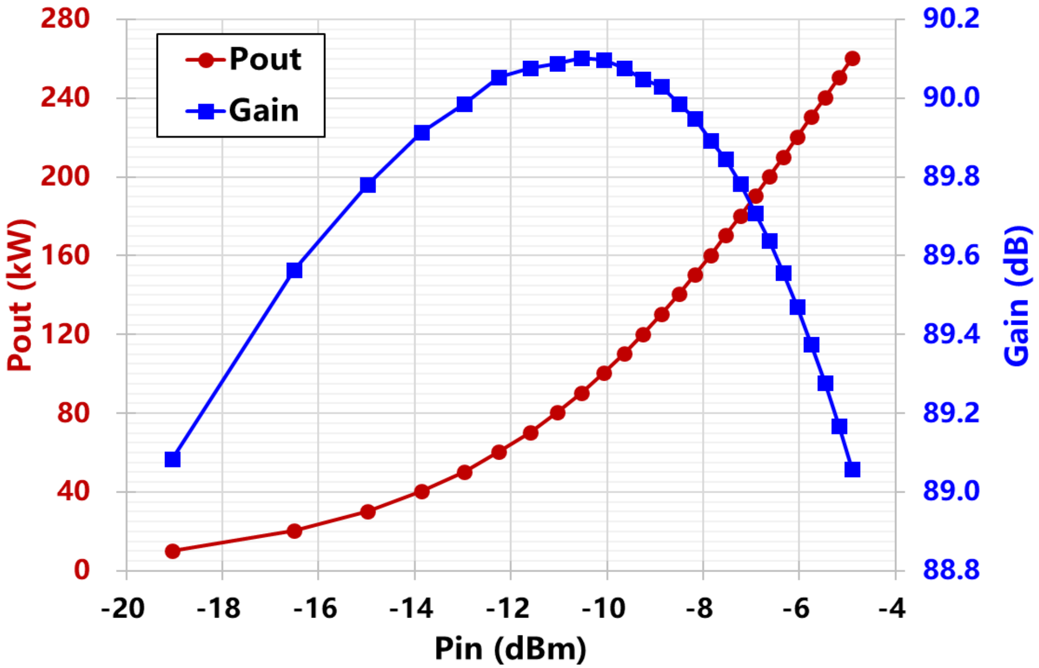
H.J. Zheng et al., *IEEE Trans. Appl. Supercond.* 31, 3500109 (2021).

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



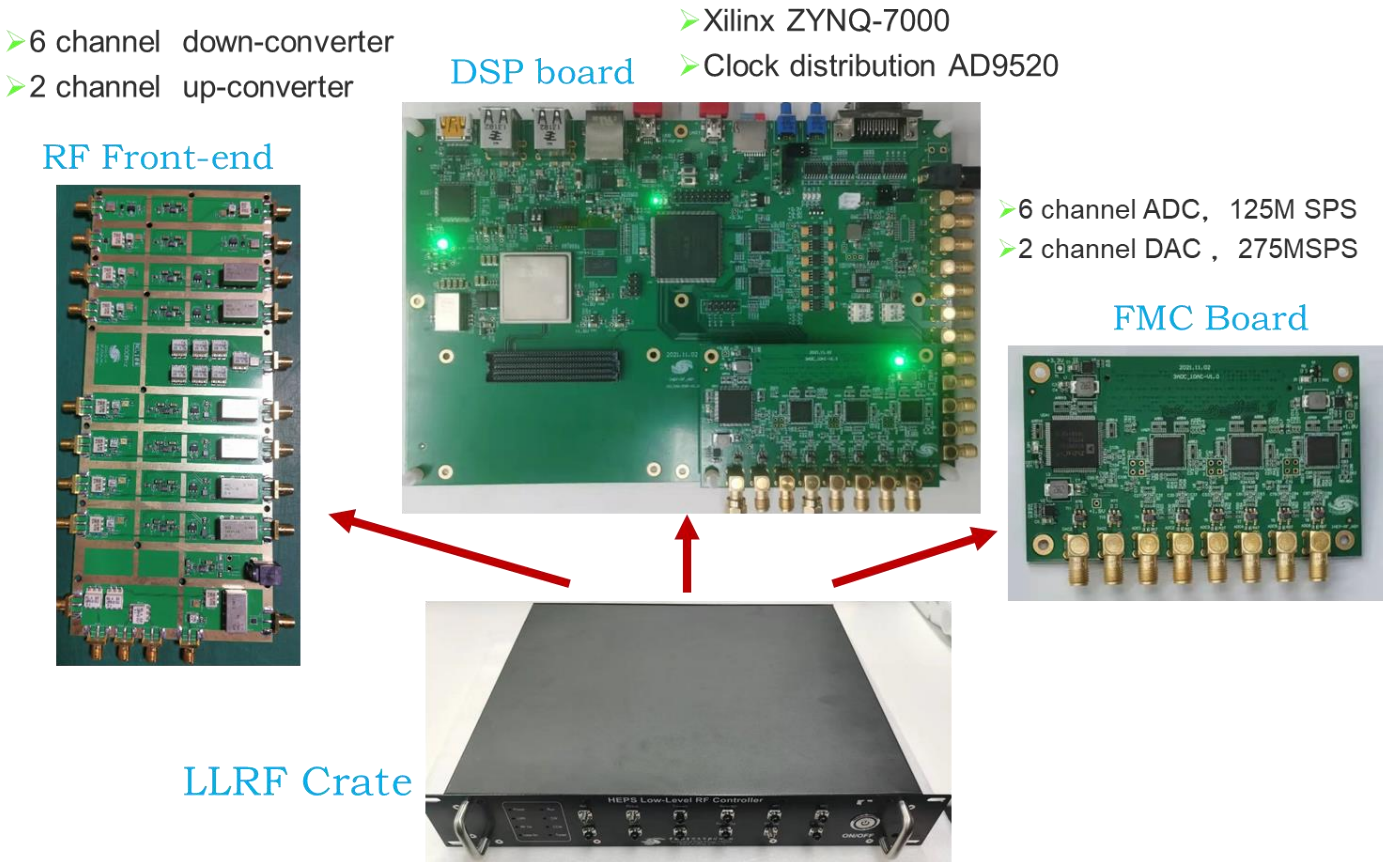
3kW unit



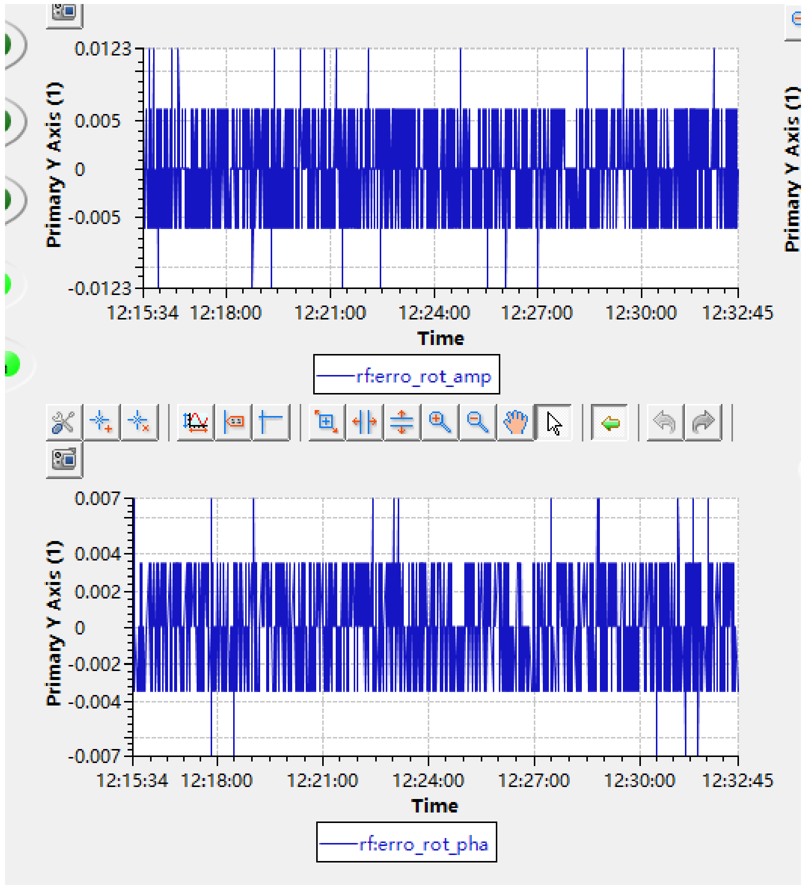
Y.L. Luo et al., *IPAC2021*, TUPAB347.

LLRF

- 3^{rd}-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

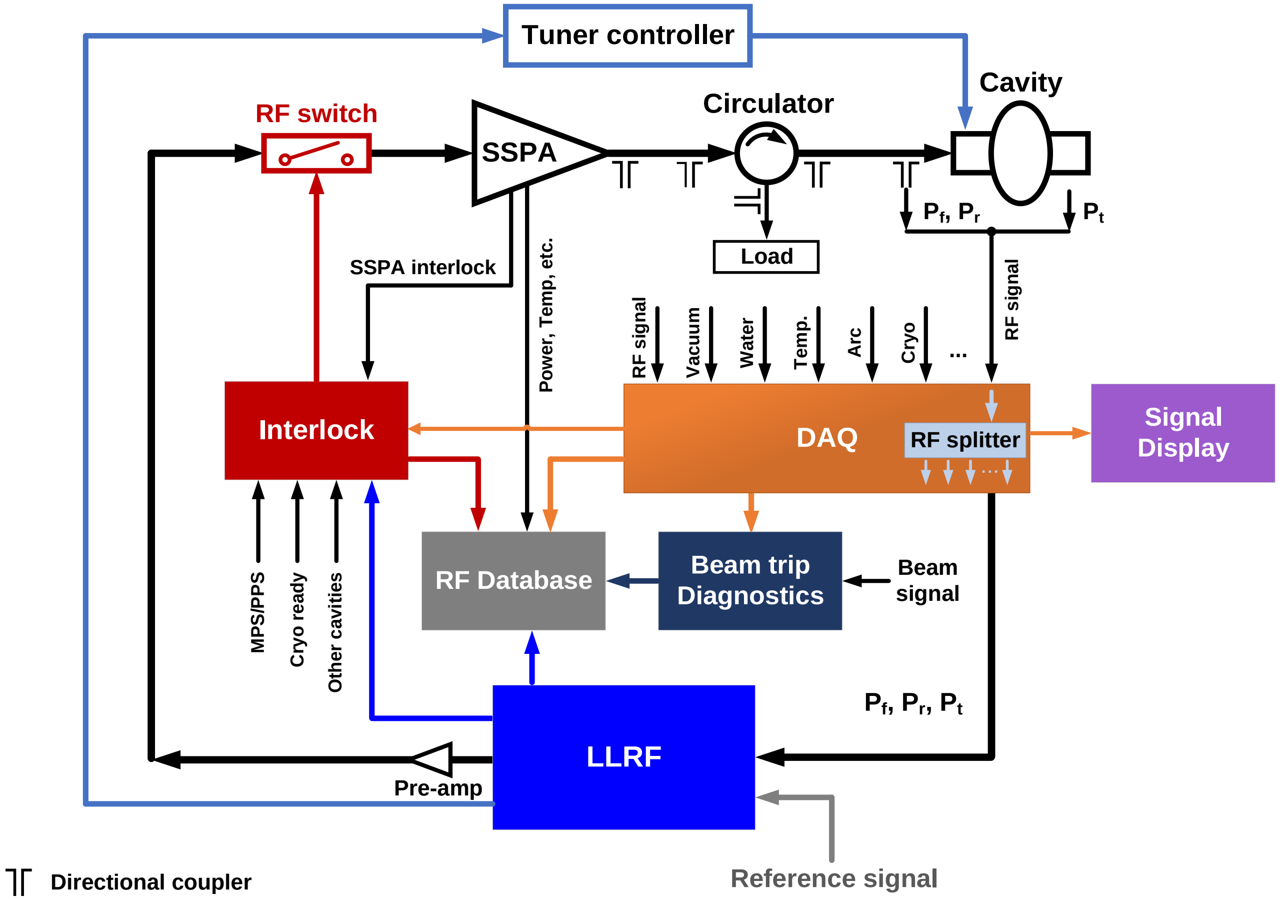


Lab test: ±0.015%, ±0.01°

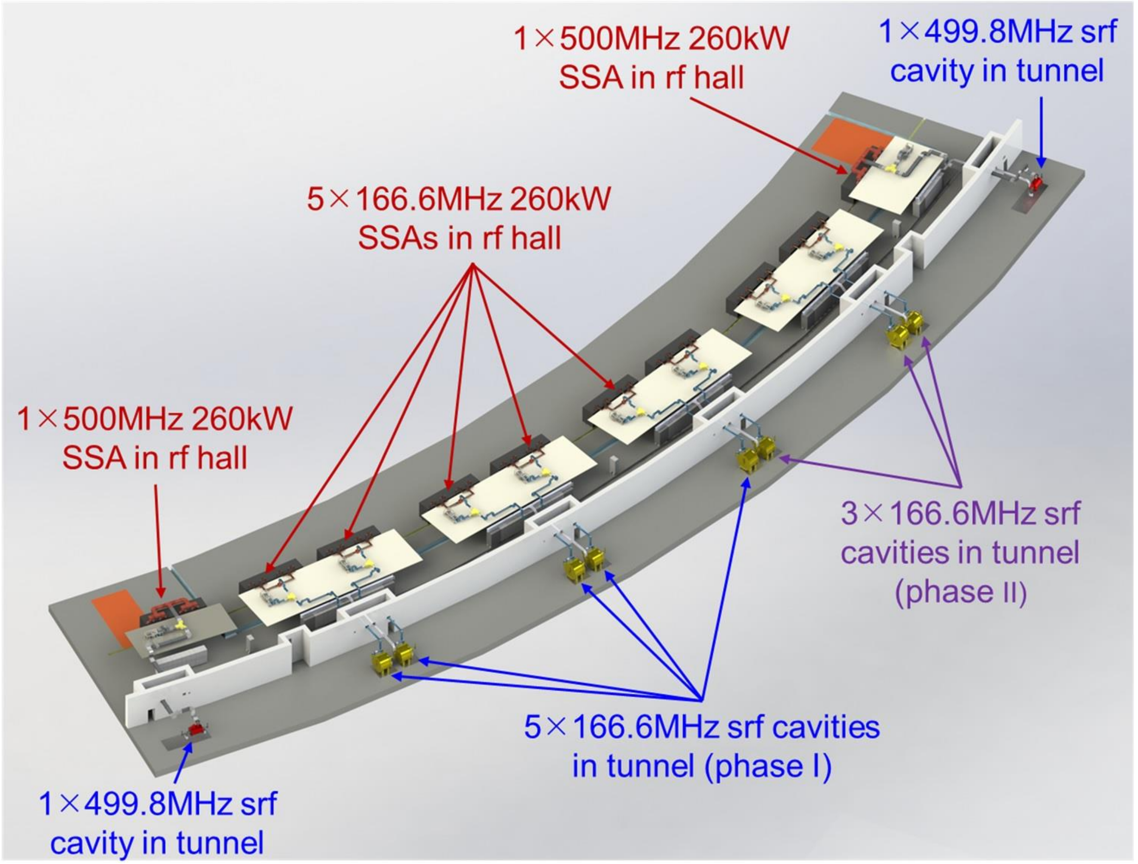


Integration

RF control layout

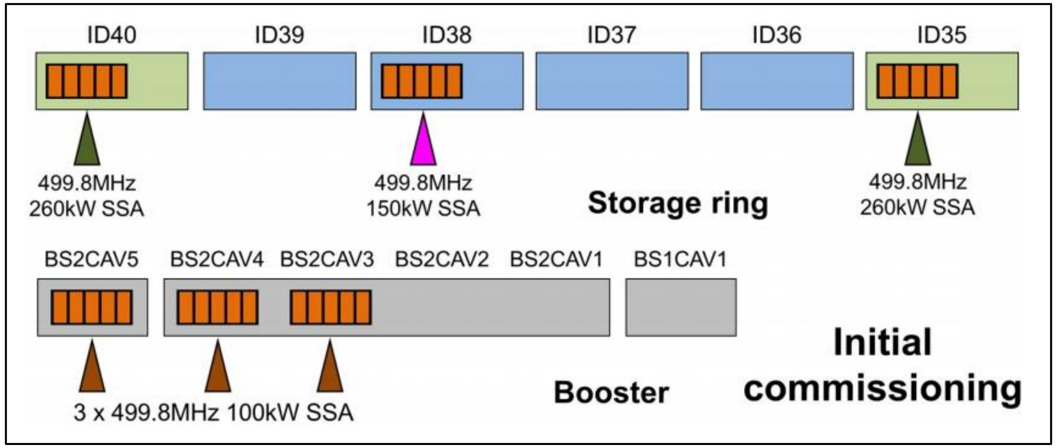


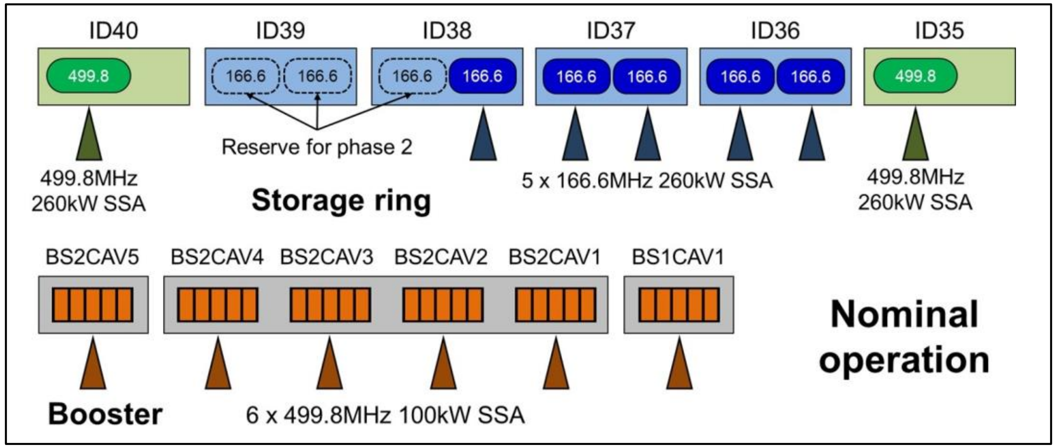
SR RF hall



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