SRF 2023 GRAND RAPIDS

Development of 3.9 GHz 9-cell cavities at SHINE

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on behalf of SHINE 3.9 GHz working group
30 June, 2023

25–30 June 2023
AMWAY GRAND PLAZA HOTEL
Grand Rapids, Michigan, USA

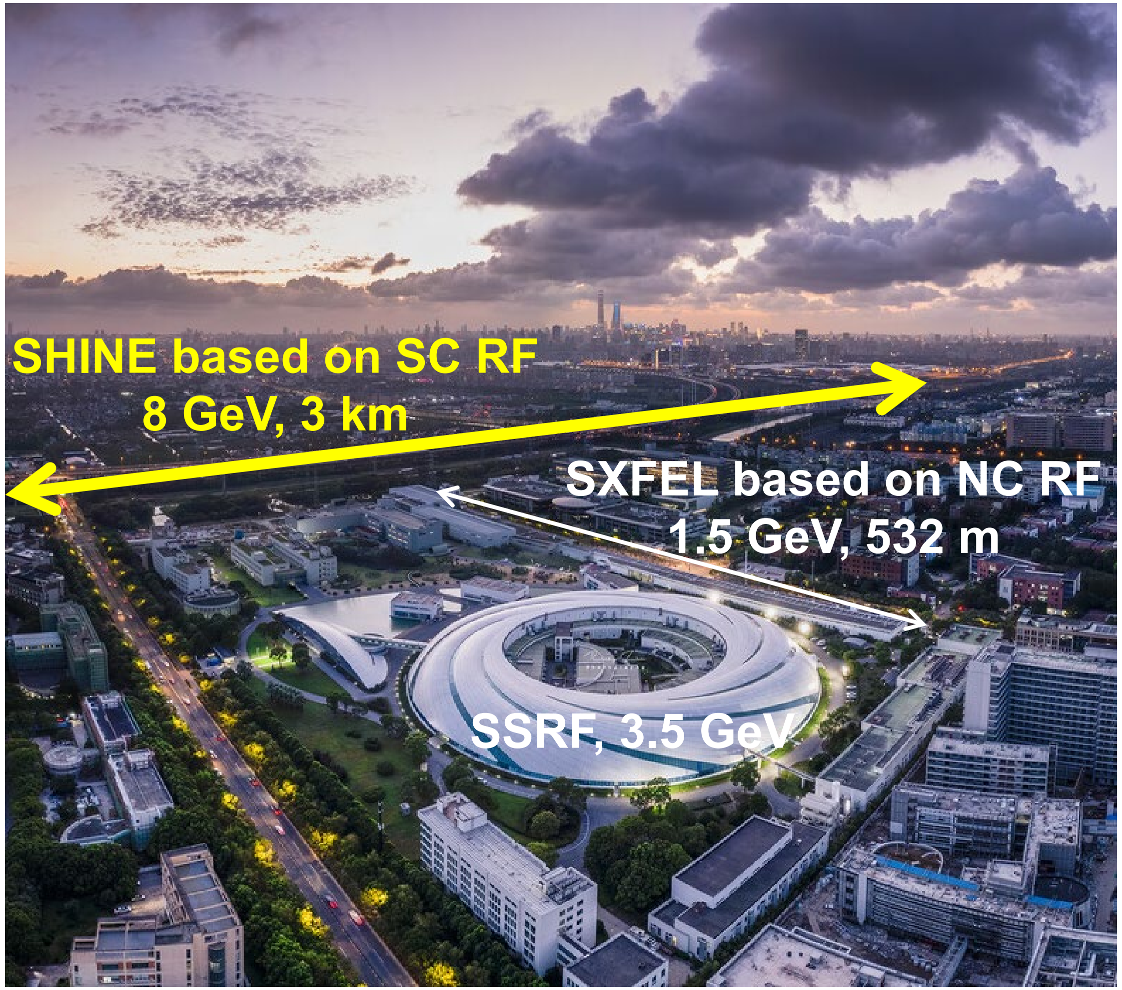
SHINE

Outline

- Introduction to SHINE and 3.9 GHz cavity
- Design of SHINE 3.9 GHz 9-cell cavity
- Fabrication of the 3.9 GHz prototypes
- Test the 3.9 GHz prototype
- Summary

Introduction to SHINE

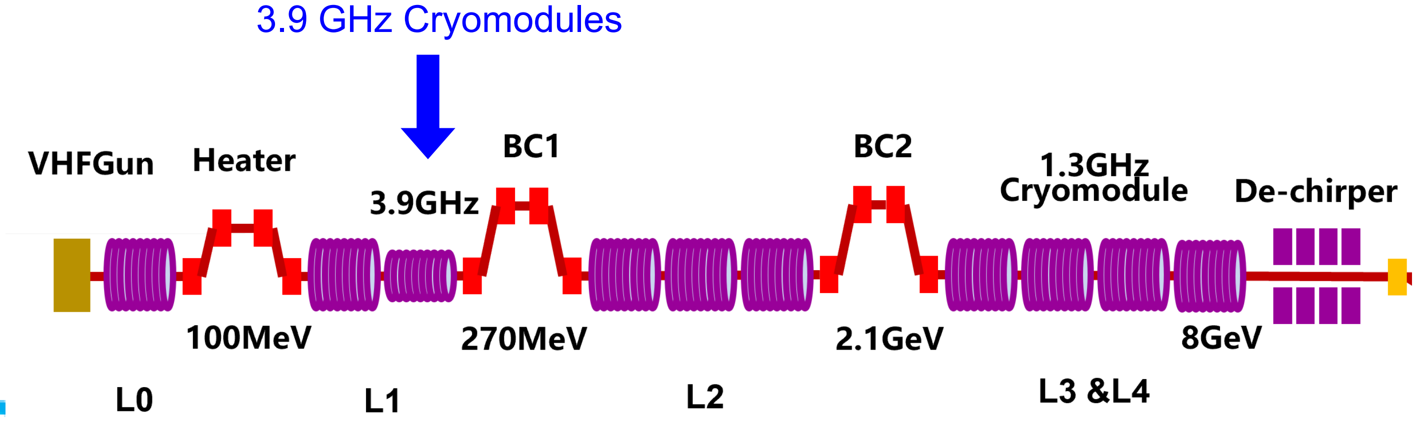
- **SHINE: Shanghai HIgh repetitioN rate XFEL and Extreme light facility**
- Launched in April 2017, groundbreaking in April 2018, aiming at the first light in 2025



Introduction to SHINE

MOIXA01
Jinfang Chen et al.

- SHINE is a CW machine which consists of 75 CMs of 1.3 GHz cavities and 2 CMs of 3.9 GHz cavities
- 3 km tunnel with 1.5 km Linac



Linac parameters	Value	
Cavity	1.3 GHz Tesla	3.9 GHz SHINE
Operating mode	CW	
Frequency [MHz]	1300	3900
Eacc [MV/m]	16.0	13.1
Q0	2.7×10^{10}	2.0×10^{9}
Number of cavity	600	16

SHINE

3.9 GHz cyromodule in SHINE

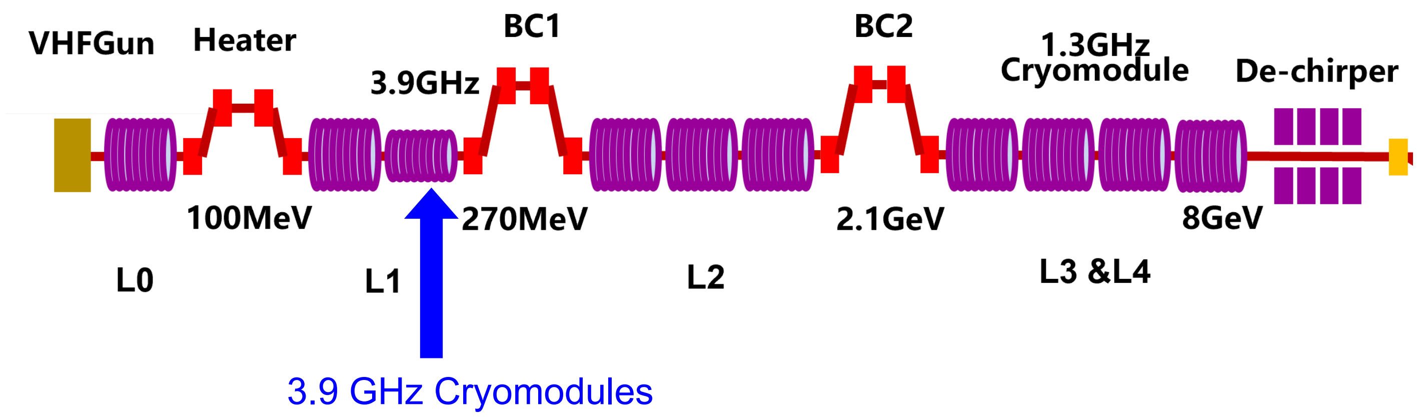
Two 3.9 GHz CMs are required in SHINE

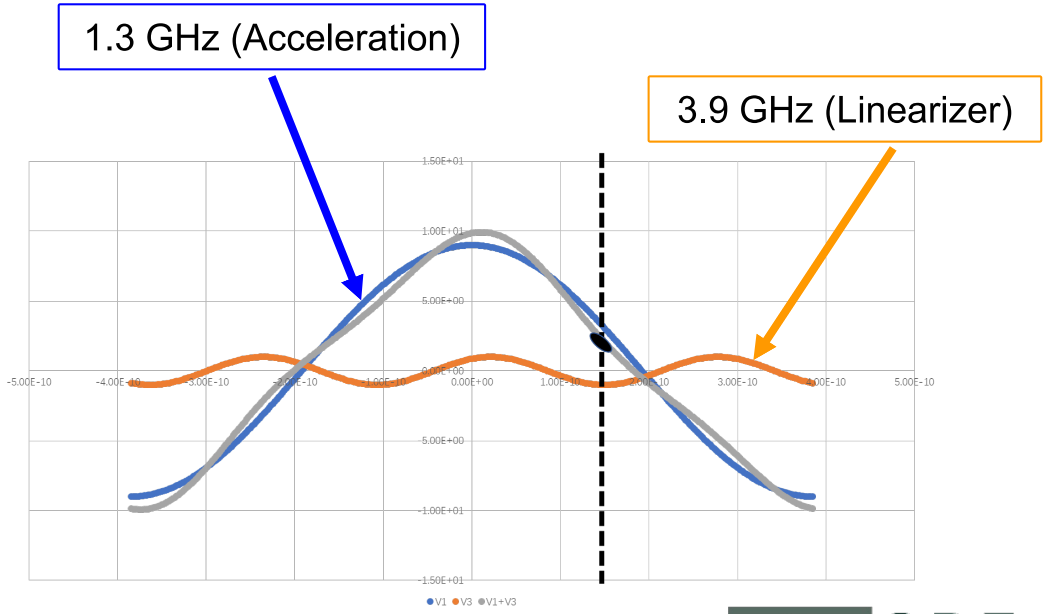
- 8 cavities per CM
- In L2 before BC1

Cavities in front of BC1 are decisive to the beam performance

- Uniformly compressed cluster increases beam peak current
- 3.9 GHz CMs linearizes longitudinal phase space of electron beam

SHINE Linac L1=1.3 GHz CM × 2 + 3.9 GHz × 2

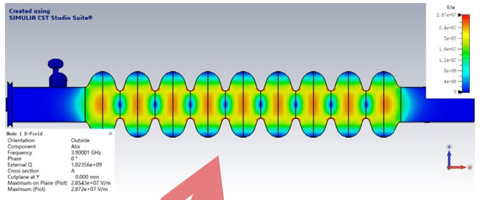




Timeline of 3.9 GHz study at SHINE

Two prototypes + Two batches of cavities (16 cavities for 2 CMs)

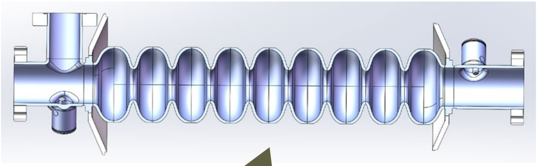
2017 — Started from 2017



2018 — Single-cell study and fabrication

2019

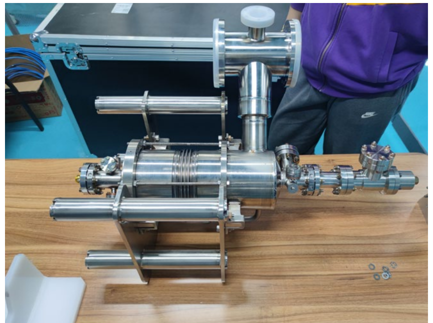
2020 — Started 1# fabrication



2021

2022 — 1# fabricated and tested

2023 — 1# integrated and tested



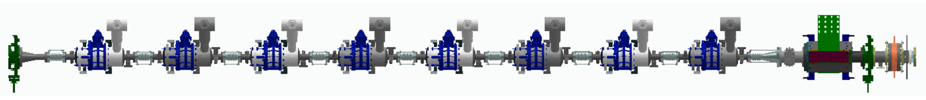
2023 — #1 horizontal test

First batch started

2024 — First cryomodule

Second batch fabrication

2025 — Cryomodule operation



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SHINE 3.9 GHz cavity design

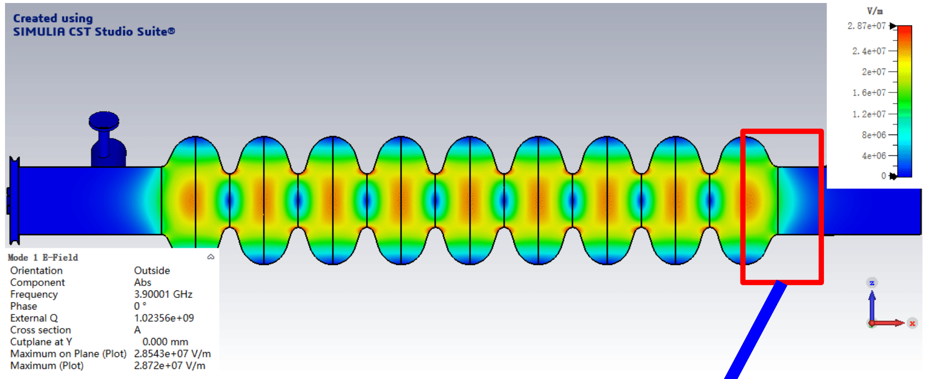
3.9 GHz Cavity Design

- Optimize end cell and the pipe size
- Frequency difference between the lowest dipole mode and fundamental mode is increased to 265 MHz
- Middle cell has the same design as EXFEL and LCLS-II
- Reduce power loss on HOM antenna

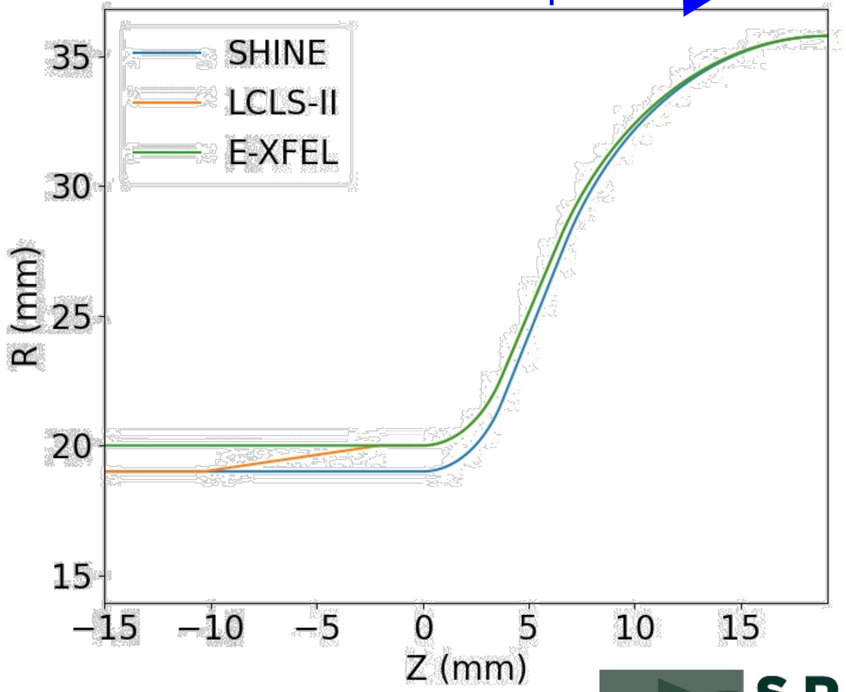
Technical Specifications

- $Q_0 > 2.0e9$ @ $E_{acc} = 13.1$ MV/m
- Max $E_{acc} \geq 16.5$ MV/m
- HOM $Q_e < 1e6$ for high R/Q modes (HOM suppression)
- Field flatness> 95%
- Eccentricity < 0.4 mm

SHINE 3.9 GHz cavity



End cell shape

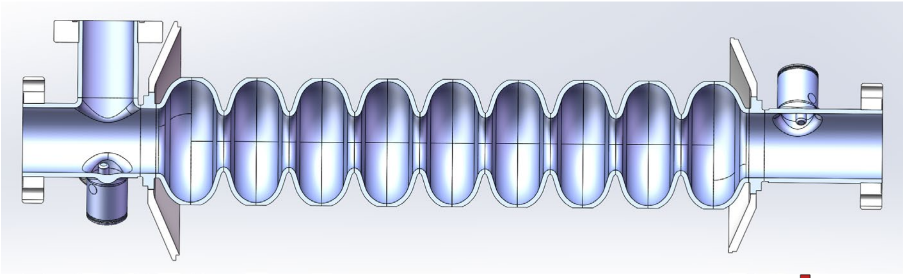


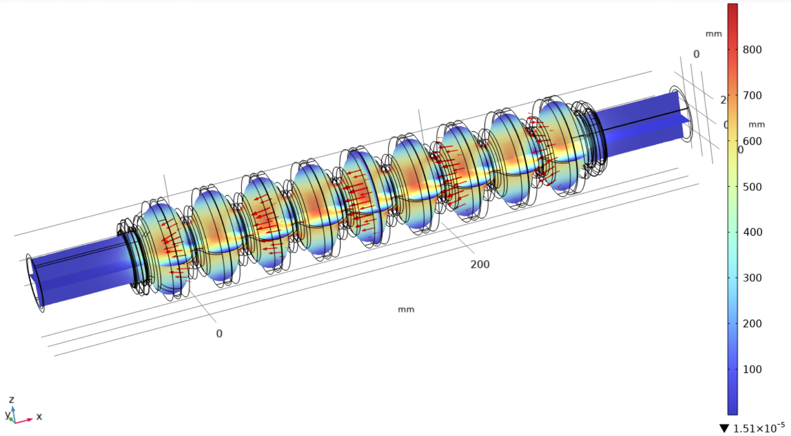
[1] Zhang Yuxin et al, *Nuclear Science and Techniques*, 2020.
[2] Lunin, A., et al. *Physical Review Accelerators and Beams* 21.2 (2018): 022001.
[3] Pierini, P., et al. *Physical Review Accelerators and Beams* 20.4 (2017): 042006.

3.9 GHz cavity design

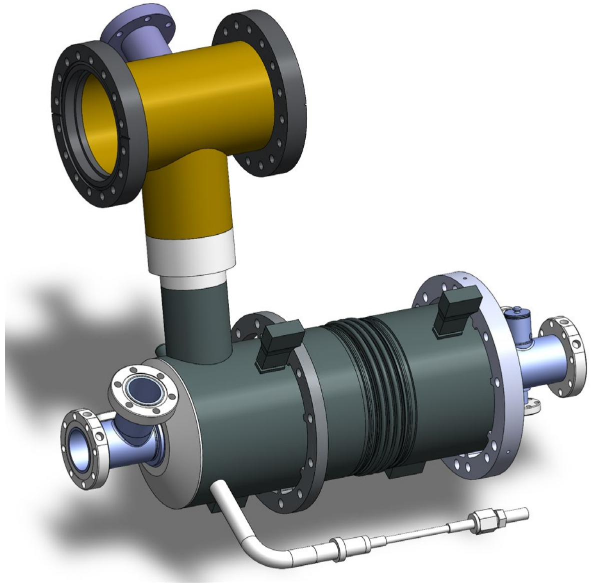
- Mechanical design of bare and dressed cavity
- Chimney design (Φ56.3→76 mm) for dressed cavity
- Inner and external magnetic shield

3.9 GHz bare cavity





3.9 GHz dressed cavity



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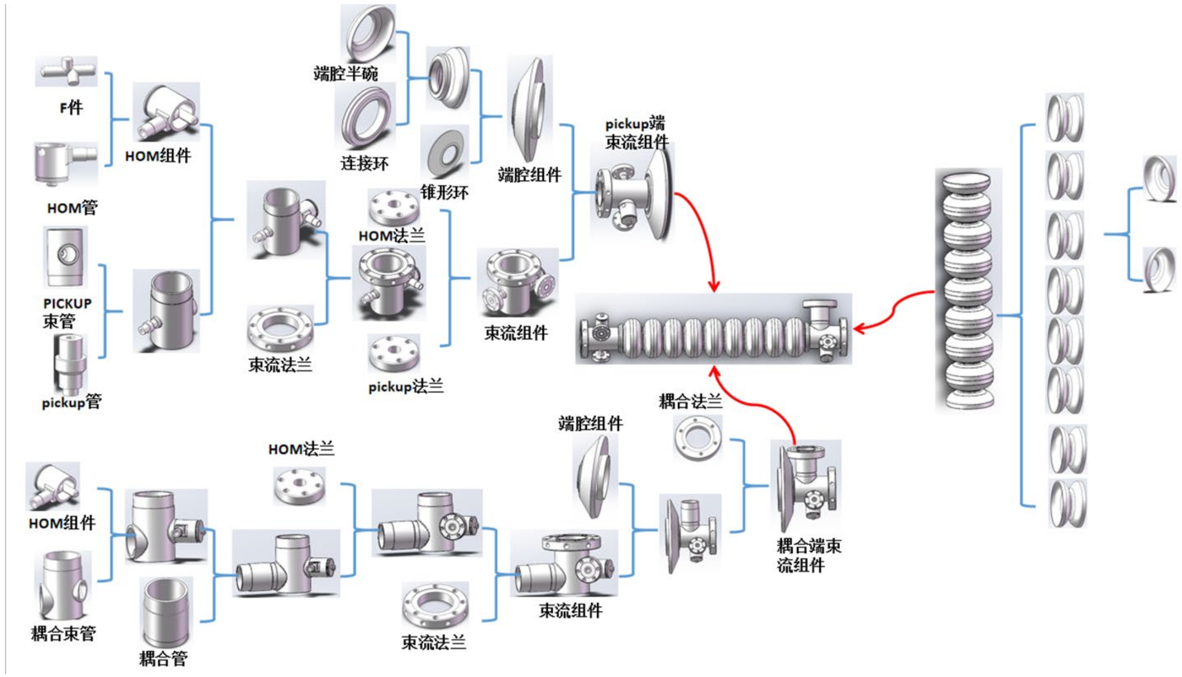
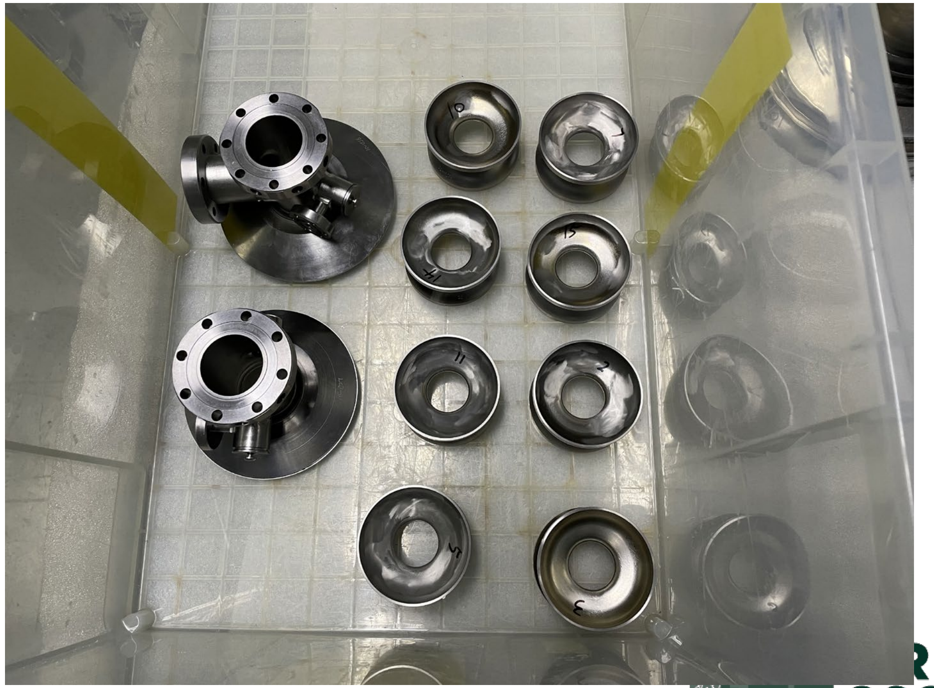
Fabrication of the prototypes

- Two prototypes were fabricated by domestic company (OSTEC)
- Materials provided by OSTEC, NX
- Followed by the standard fabrication procedures

Fabrication procedures



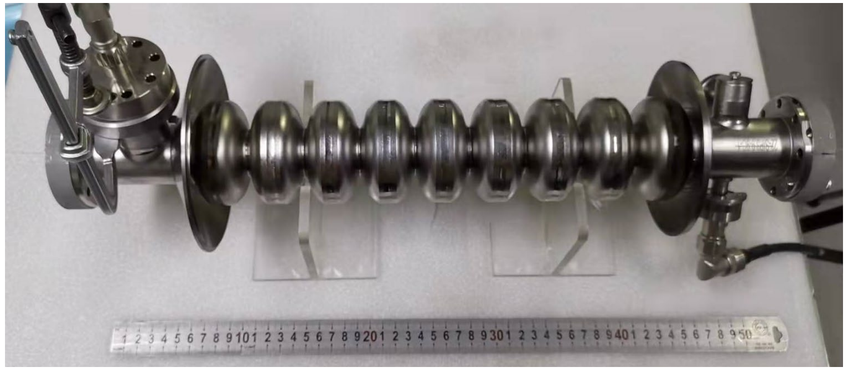
Prototype components



Fabrication of the prototypes

- Two prototypes were fabricated in 2022 and 2023
- Frequency/length met the goal
- Field flatness is good after fabrication

#01 at OSTEC

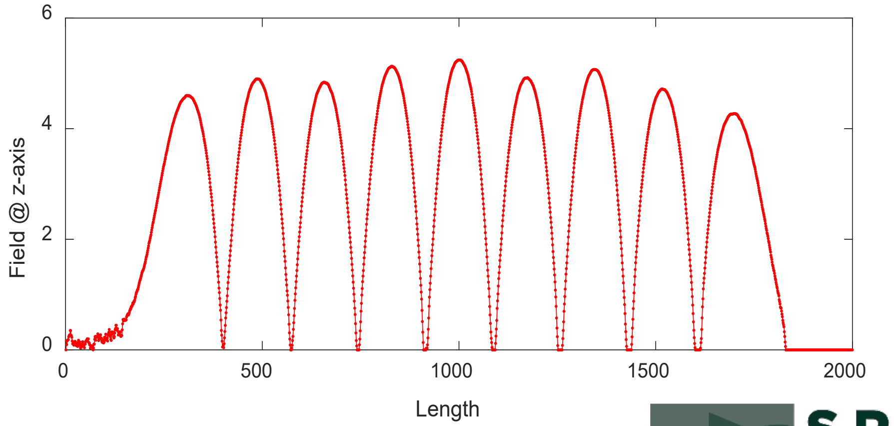


Parameters after fabrication

	#01	#02	Goal
Length	508.8	509.5	506.0±4
Freq [MHz]	3903.0	3902.8	3898.5±5
Eccentricity [mm]	1.0	0.46	<1.0
Field Flatness [%]	89.0	86.6	>50

*Measured in room temp and air

#01 field distribution after fabrication



Surface treatment of #01

- Surface treatment was conducted at SHINE facility at Wuxi Creative
- BCP and heat treatment
  - 120 μm heavy BCP + 900℃ + 20 μm light BCP
  - SHINE BCP process
- Smooth and bright, no obvious defects

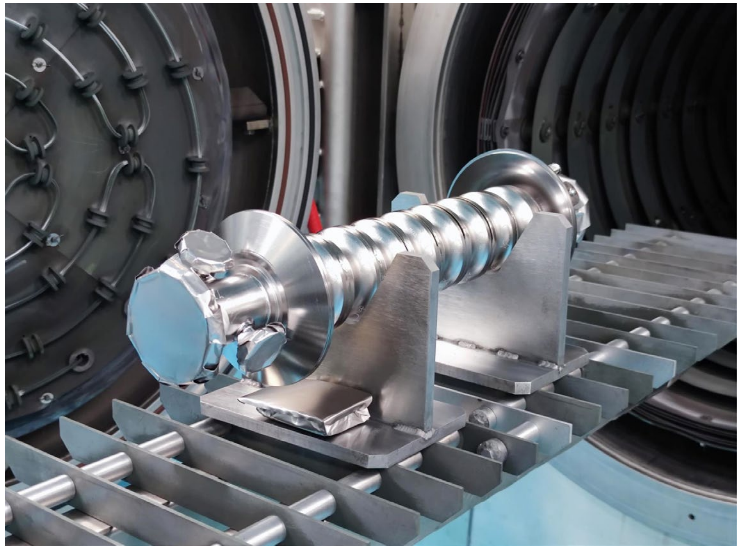
Wuxi Creative

BCP of #01

Equator before BCP

Equator after BCP

Heat treatment



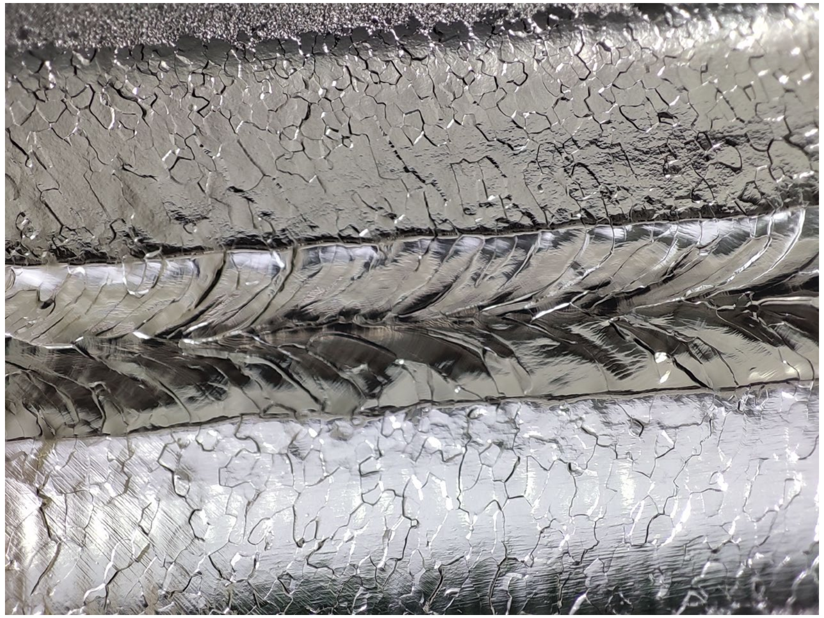
[1] Pierini, P., et al. *Physical Review Accelerators and Beams* 20.4 (2017): 042006.

SHI

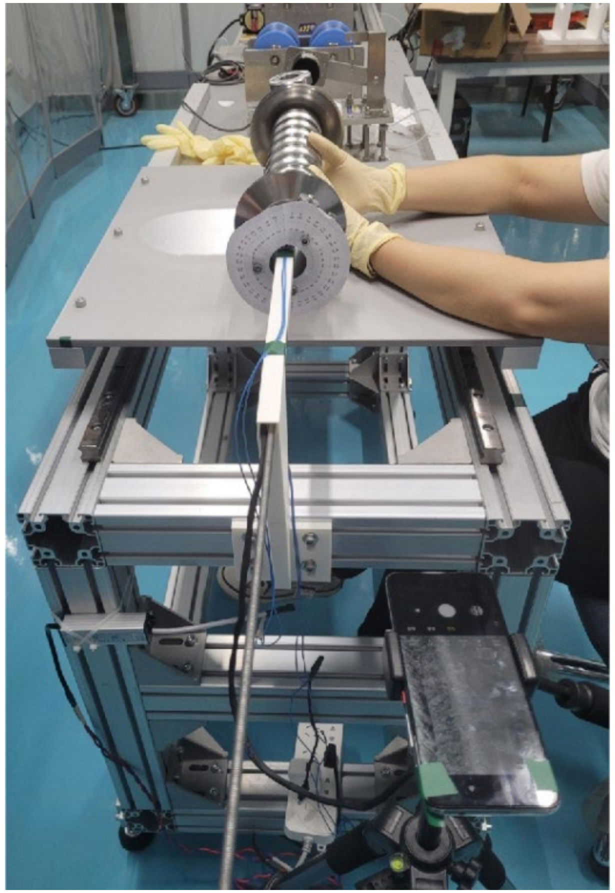
Borescope system

- The iris size (15 mm) of 3.9 GHz cavity is smaller than that of 1.3 GHz cavity
  - Kyoto camera could be used for 3.9 GHz cavity directly
- A self-made borescope system was developed
  - movable support
  - insertion probe
  - macro camera module
- Good results achieved by the borescope system

Equator of #01 after BCP



Borescope system



Dimensional check and tuning

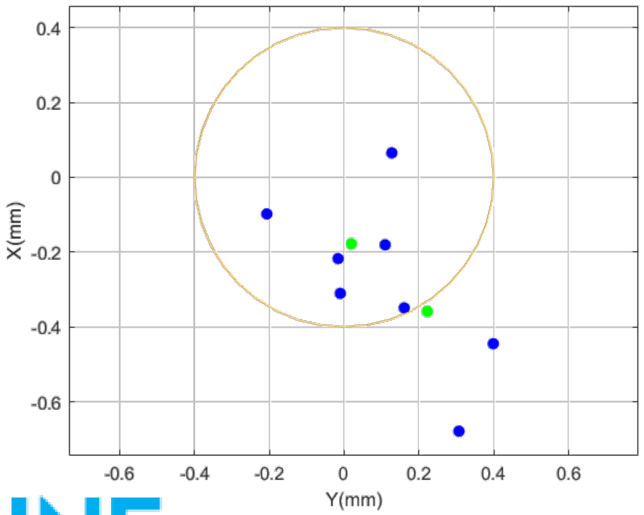
- Mechanical measurement and tuning were conducted
- Frequency, length, field flatness met the goal at same time

Quantity at room temperature	Goal	Measured
Length [mm]	505.98	506.18
Eccentricity [mm]	< 1.0	Satisfied
Field flatness [%]	> 95	95.9
Frequency [MHz]	3893.0	3893.1

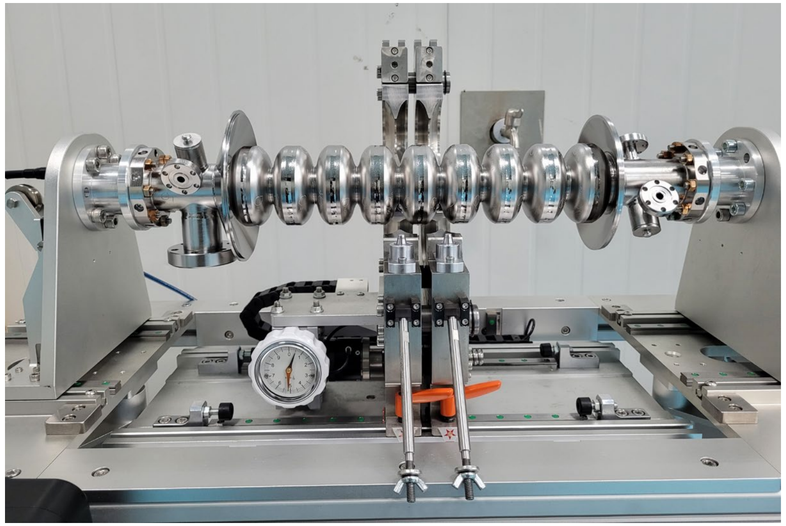
*Measured in room temp and vacuum

**Eccentricity has been improved by lip-weld geometry in #02

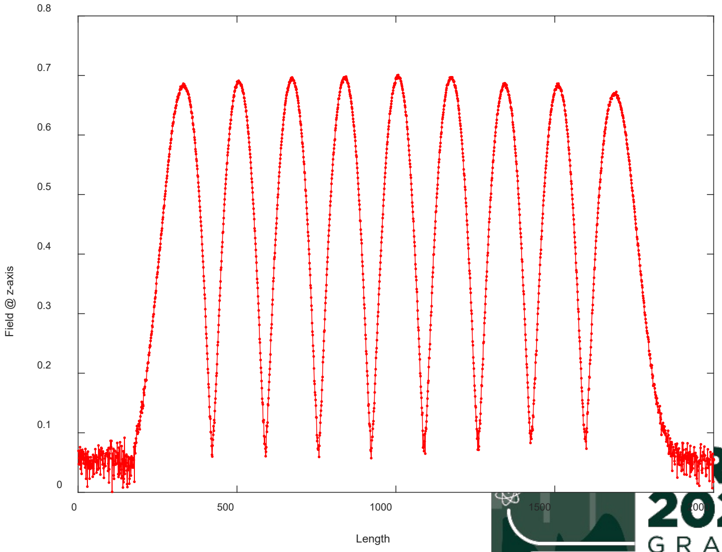
Eccentricity of #01



Tuning of #01



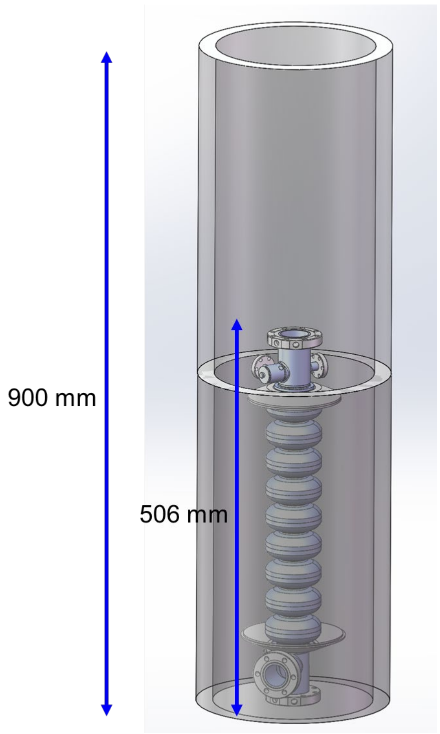
#01 field distribution after tuning



2-step low temperature baking

- 2-step low-T baking (75/120℃) was conducted after the first vertical test
  - 75℃ (4 hours) +120℃ (48 hours)
- Temperature of the bottom part was low and not uniform→ will be improved soon

2-step low temperature baking layout



[1] A Grassellino, et al. arXiv preprint arXiv:1806.09824, 2018

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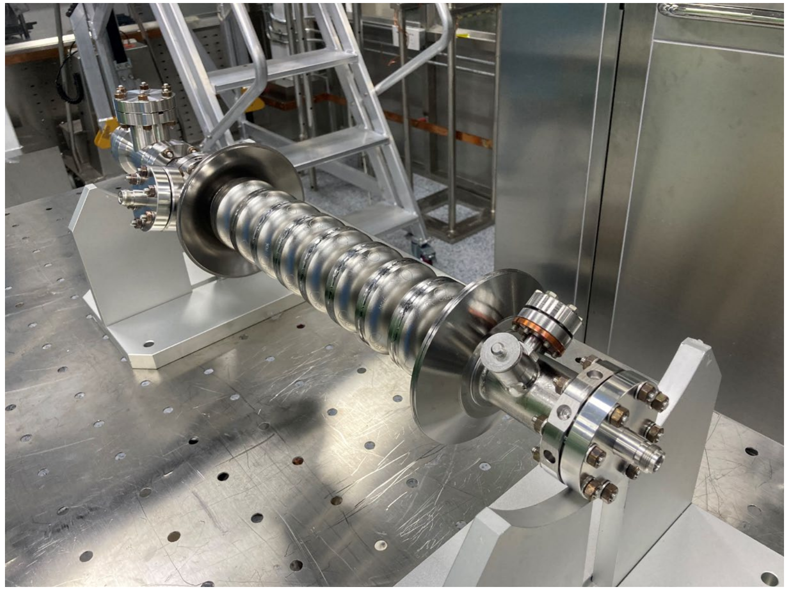
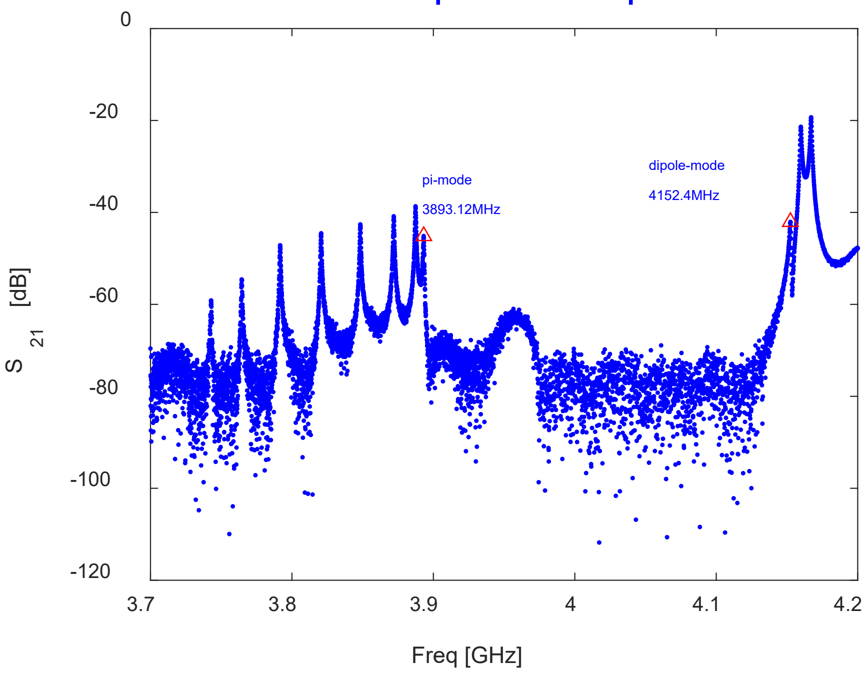
Rf spectrum of #01

- Rf measurements performed at SHINE facility at Shanghai
- 3983.1 MHz→3899.5 MHz in vertical test
- First dipole mode ~260 MHz away from fundamental mode

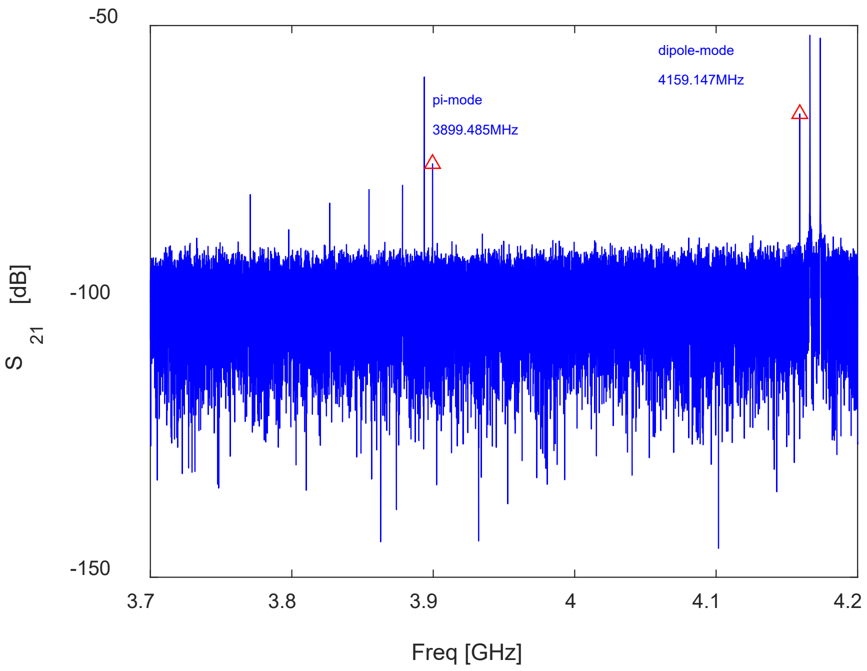
#01 before vertical test



Room temperature spectrum



2 K spectrum



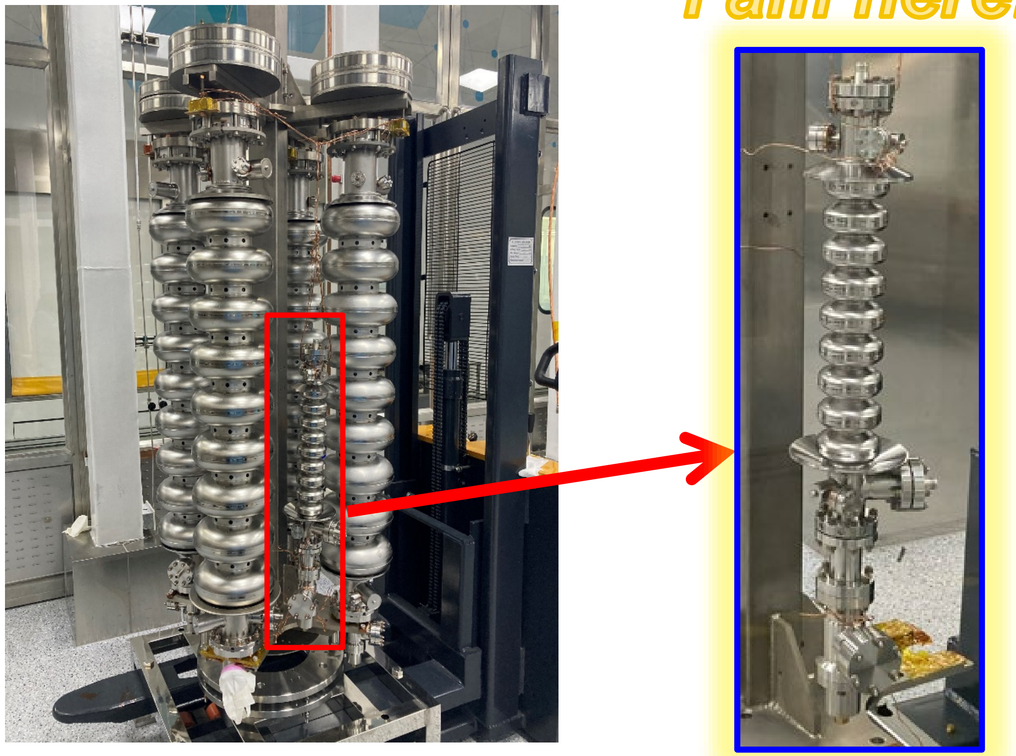
Vertical test results of #01 bare cavity

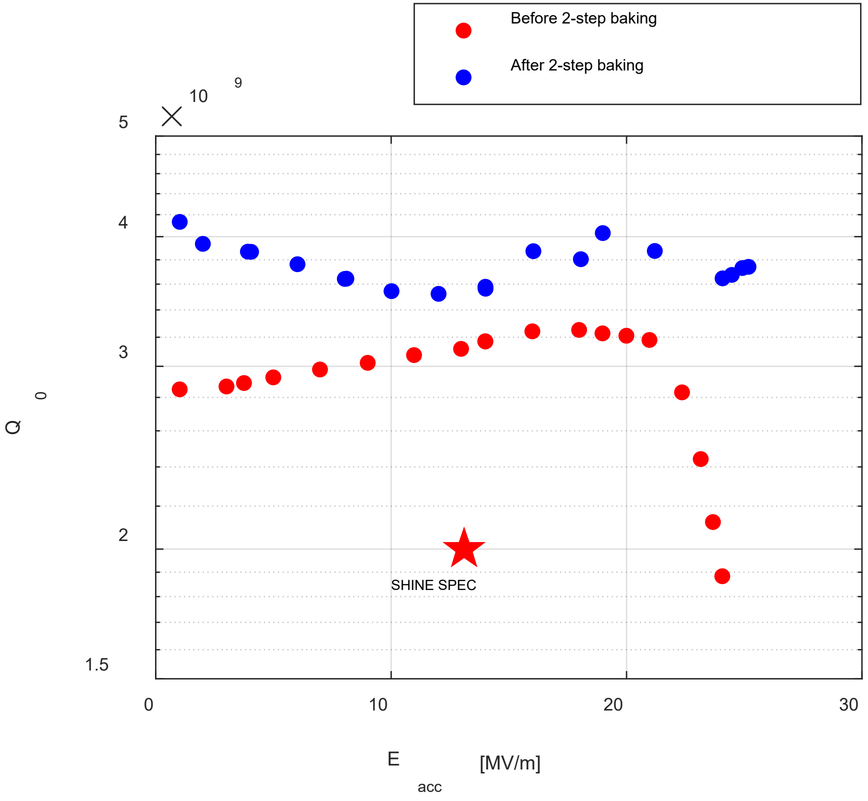
- Q0 = 3.5×10^9@13.1 MV/m
- Max Eacc = **24.0 MV/m**, FE free
- Excellent performance at 2 K

Quantity at 2 K	Goal	VT-NoBaking	VT-Baking
Nominal Gradient [MV/m]	13.1	Achieved	
Q0@13.1 MV/m	2.0×10^9	3.1×10^9	3.48×10^9
Max Eacc [MV/m]	> 16.5	24.0	25.0
Frequency [MHz]	3899.4	3899.5	

#01 at insert

"I am here!"



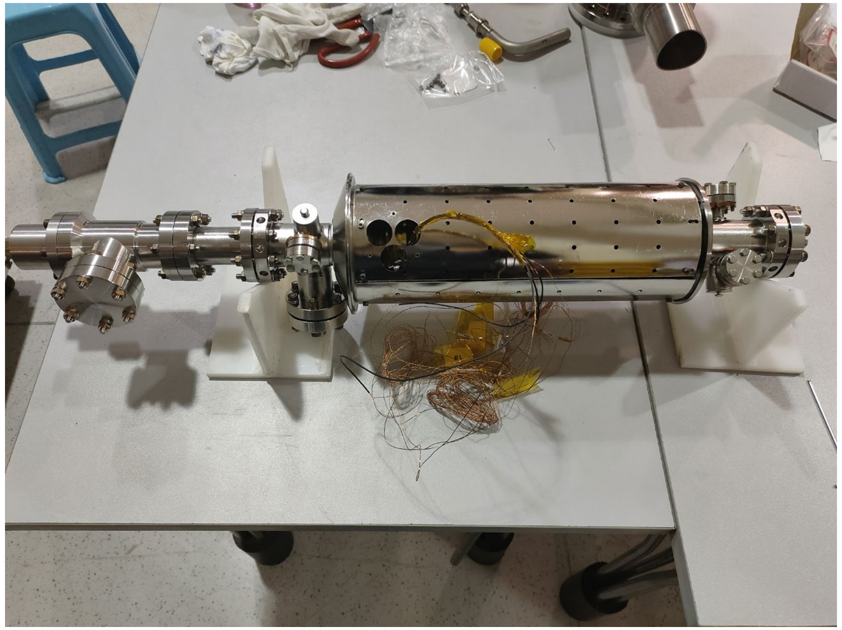


Integration of #01 cavity

- TIG welding for helium tank integration
- Inner magnetic shield was installed on #01 bare cavity
- Frequency controlled during the integration
- Helium tank pressure test performed

Helium tank components

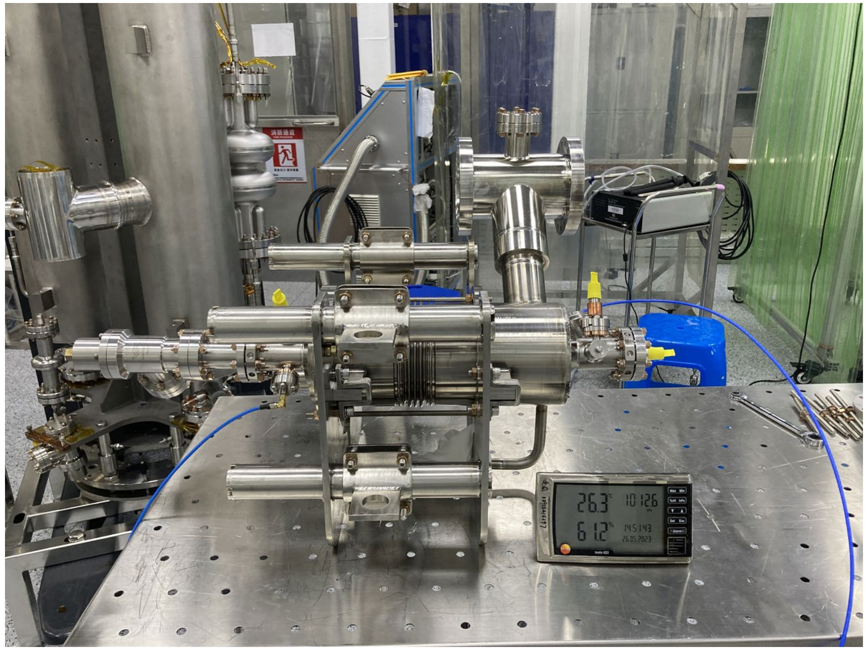
#01 during integration



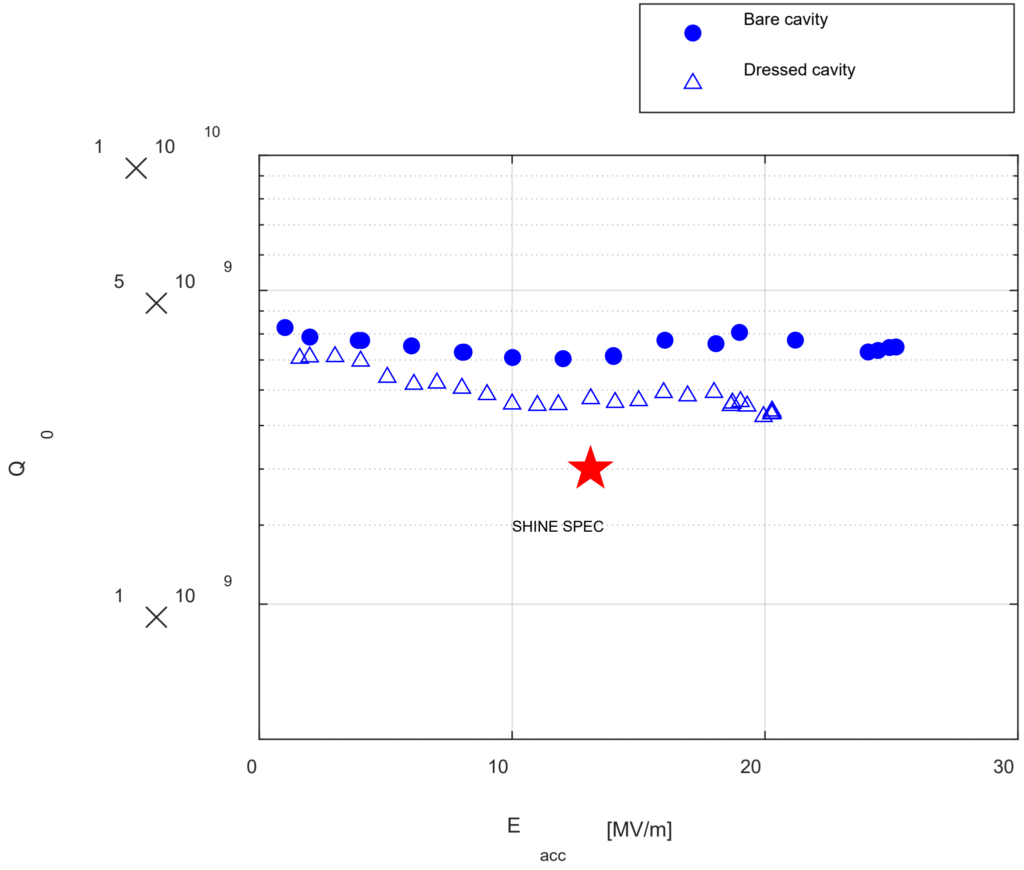
Vertical test of #01 dressed cavity

- Q0 = 2.9×10^9@13.1 MV/m
- Max Eacc = **20.3 MV/m**
- FE observed from 19.0 MV/m
- #01 now under HPR and will be re-VT

#01 dressed cavity under rf measurement

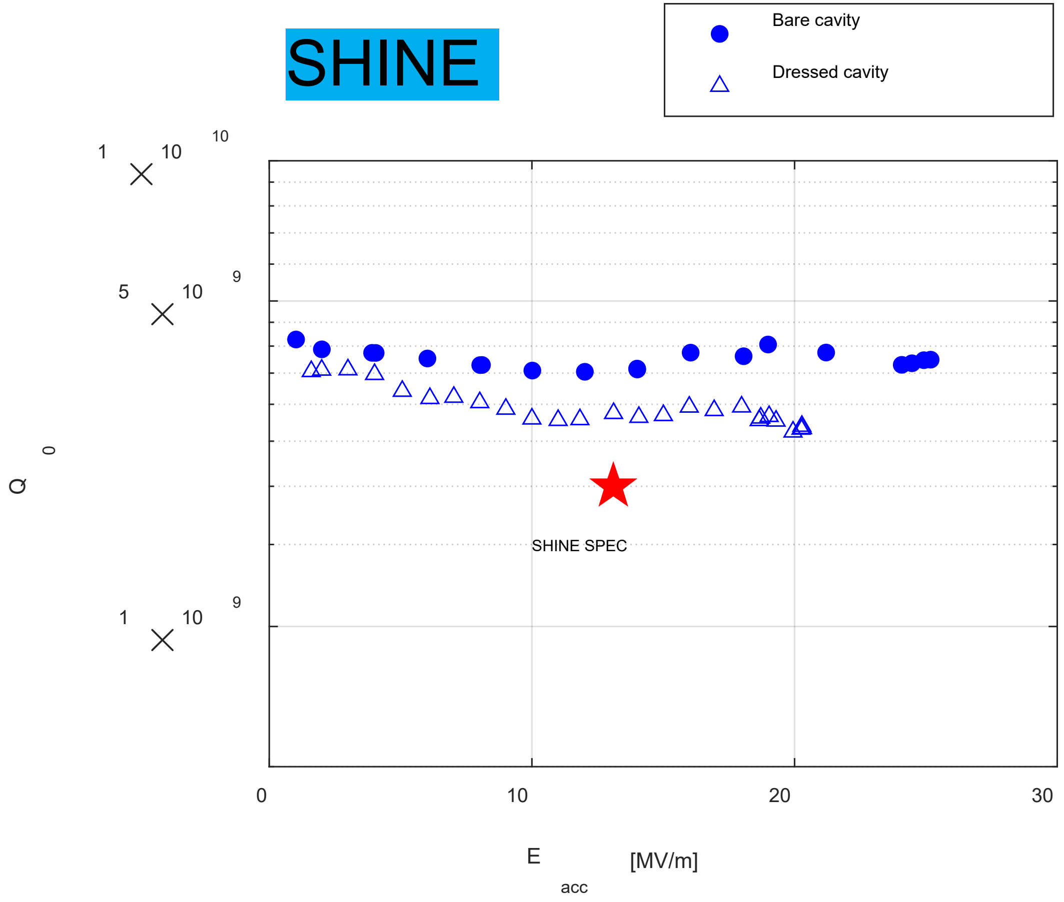


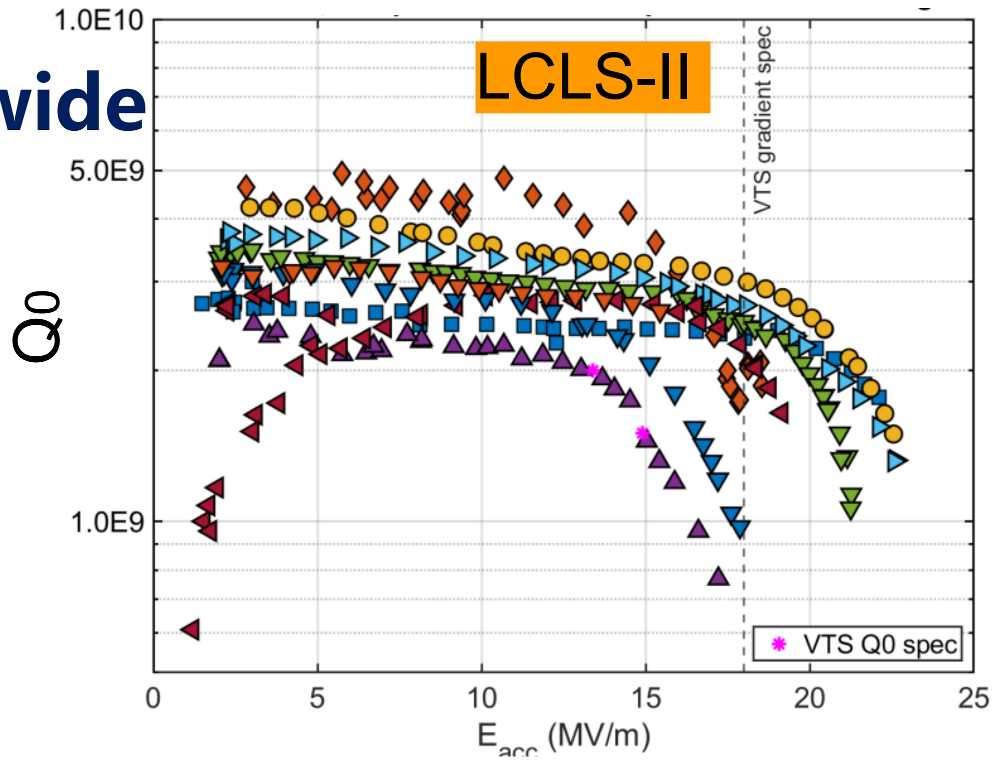
Quantity at 2 K	Goal	Bare cavity	Dressed cavity
Nominal Gradient [MV/m]	13.1	Achieved	
Q0@13.1 MV/m	2.0×10^9	3.48×10^9	2.9×10^9
Max Eacc [MV/m]	> 16.5	25.0	20.3

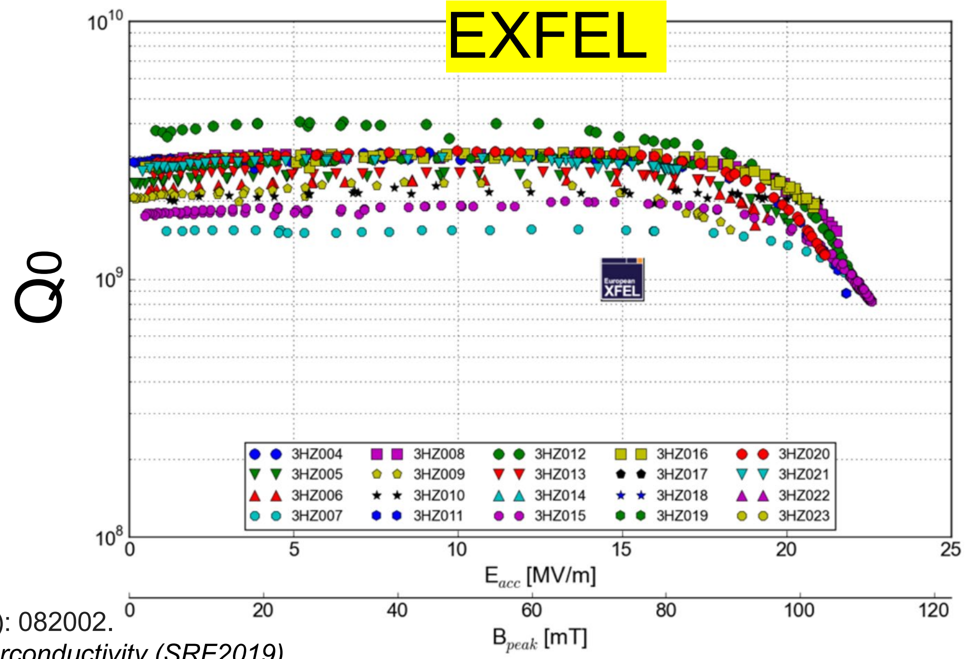


Compare with 3.9 GHz cavities worldwide

- **Bare cavity is as good as LCLS-II and EXFEL**
- Low T baking and Helium tank integration will be improved





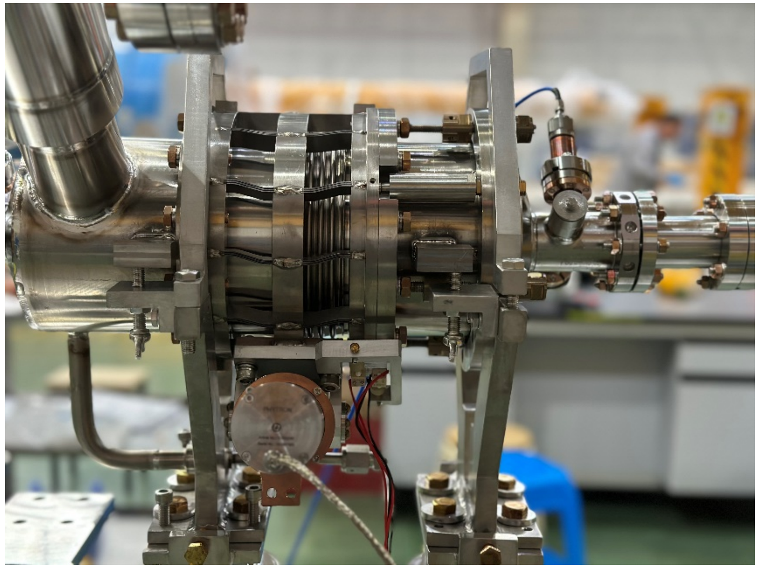


[1] Bertucci, M., et al. *Physical Review Accelerators and Beams* 22.8 (2019): 082002.
[2] Aderhold, S., et al. *Proceedings of International Conference on RF Superconductivity (SRF2019)*.

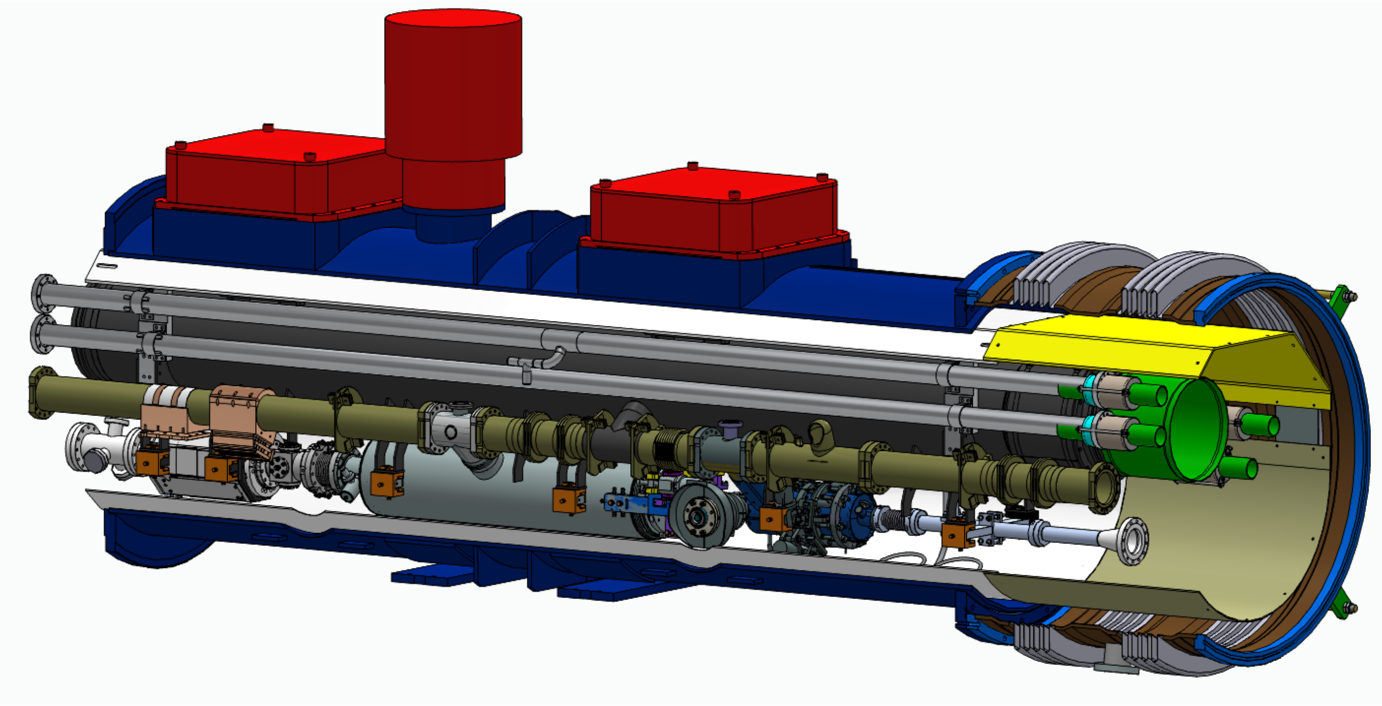
Horizontal test of #01

- The horizontal test will be conducted in a small cryostat with another 1.3 GHz 9-cell cavity

#01 with blade tuner



#01 in small cryostat



SHINE

Mass production of the first batch

- The first batch production started from beginning of 2023
- Components ready for welding
- First 3.9 GHz cryomodule expected in 2024

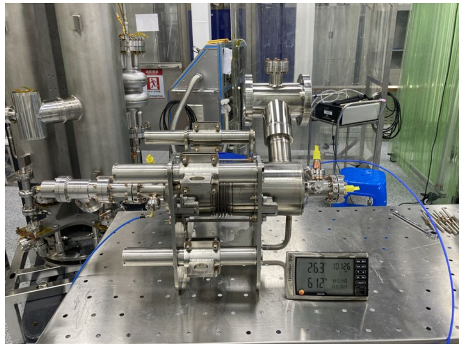
Dumbbells of the first batch

Components of the first batch

Summary

- First 3.9 GHz 9-cell prototype has been fabricated, treated, and verified
  - Gained experience, technology, and tools
  - Excellent performance in vertical test (900℃ + 2-step low-T baking)
  - Horizontal test in a small cryostat soon
- Second 3.9 GHz 9-cell prototype is under treatment
  - Vertical test around Aug 2023
- First batch of 3.9 GHz cavities is under fabrication
  - Domestic batch of 10 cavities
  - First cryomodule around 2024
  - Potential batch for a spare module

#01



#02

First batch

Acknowledgments

Thanks to SHINE 3.9 GHz working group for the efforts on the development of 3.9 GHz cavities

Collaboration of several institutes

- J.F. Chen, P.C. Dong, S.J. Zhao, X.H. Ouyang, Y.F. Liu, S. Sun, Y.L. Zhao, Y.X. Zhang, S. Xing, J.N. Wu from SARI, CAS
- Z. Wang, X, Huang, Y. Zong from SINAP, CAS
- R.Z. Xia, Y.W. Huang from Shanghai Tech University

Many thanks to the people of SHINE SRF cryomodule team

Thanks for the help from INFN-LASA

Thanks for your attention!

SHINE

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