Status of SHINE Cryomodule and Infrastructure

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On behalf of SHINE Cryomodule Group

2022.03.03

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- Cryomodules
- Key components R&D
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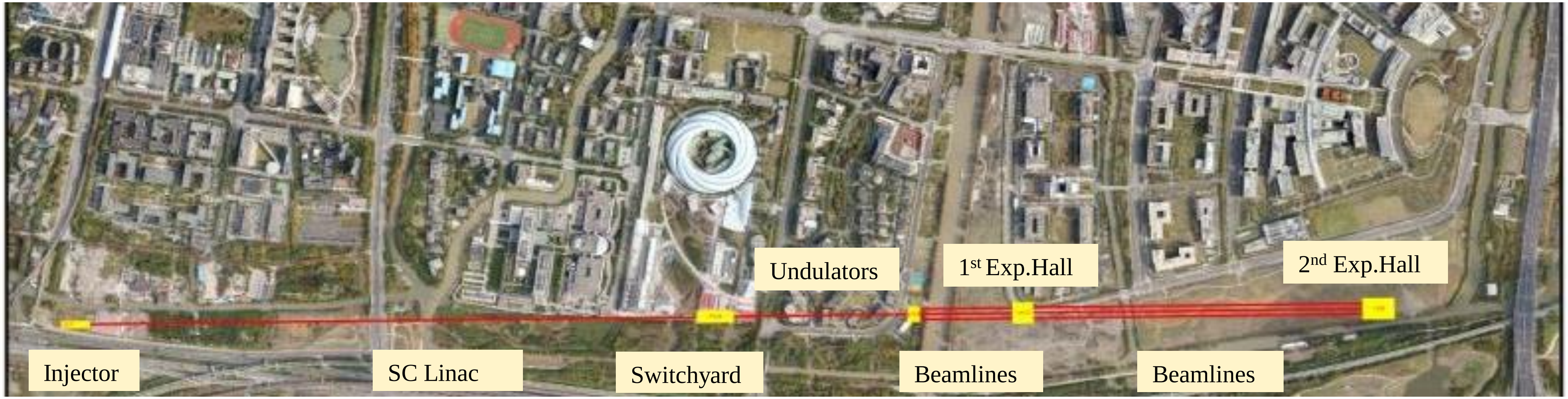
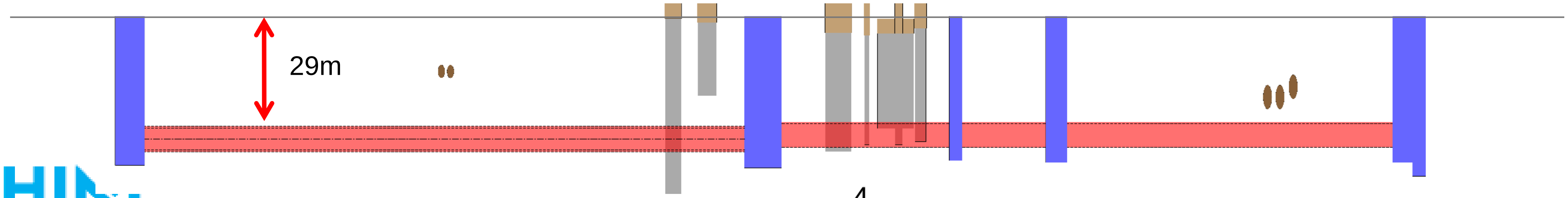
Introduction of SHINE

Layout and schedule of SHINE project

- SHINE (Shanghai HIgh repetitioN rate XFEL and Extreme light facility)
- Total length 3.1km, 29m underground
- 8GeV CW Linac, 3 FEL undulator lines, 3 beamlines ,10 stations, PWs laser
- Construction schedule: 2018.04 ~ 2025.03

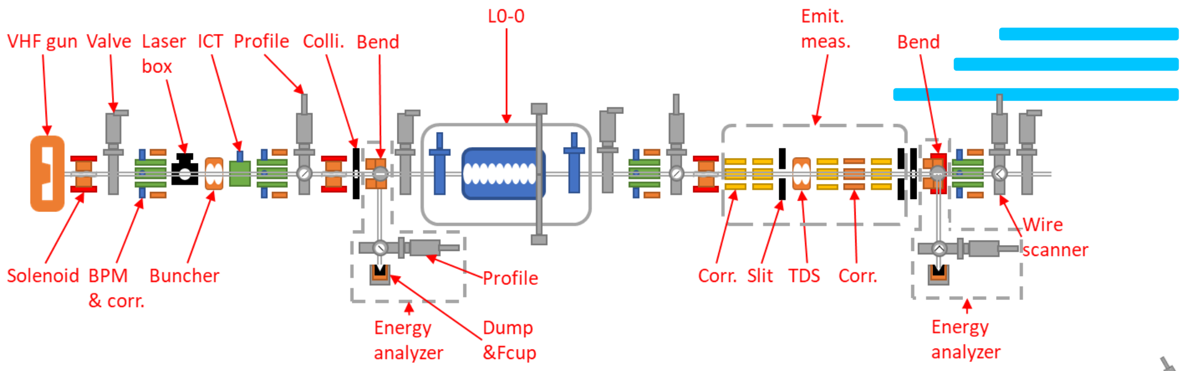


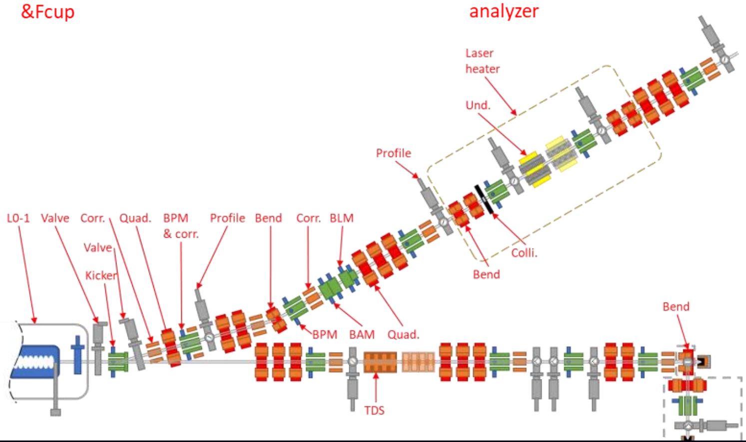


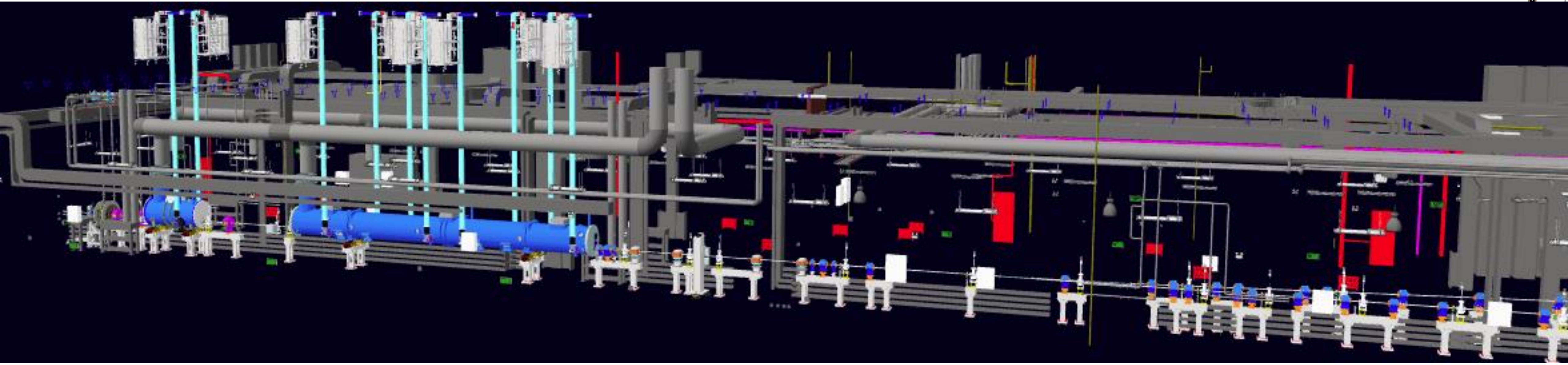
Injector

- **750kV VHF gun**
- **Single cavity CM**
- **8-cavity CM**
- **DBA bending section**

Parameters	Value
Bunch charge (pC)	10~300
Repetition Rate (MHz)	0~1
Beam energy (MeV)	90~120
Slice energy spread (10^{-4})*	0.1~1
Peak current (A)	5~20
Normalized emittance (95%, um·rad)	0.2~0.6



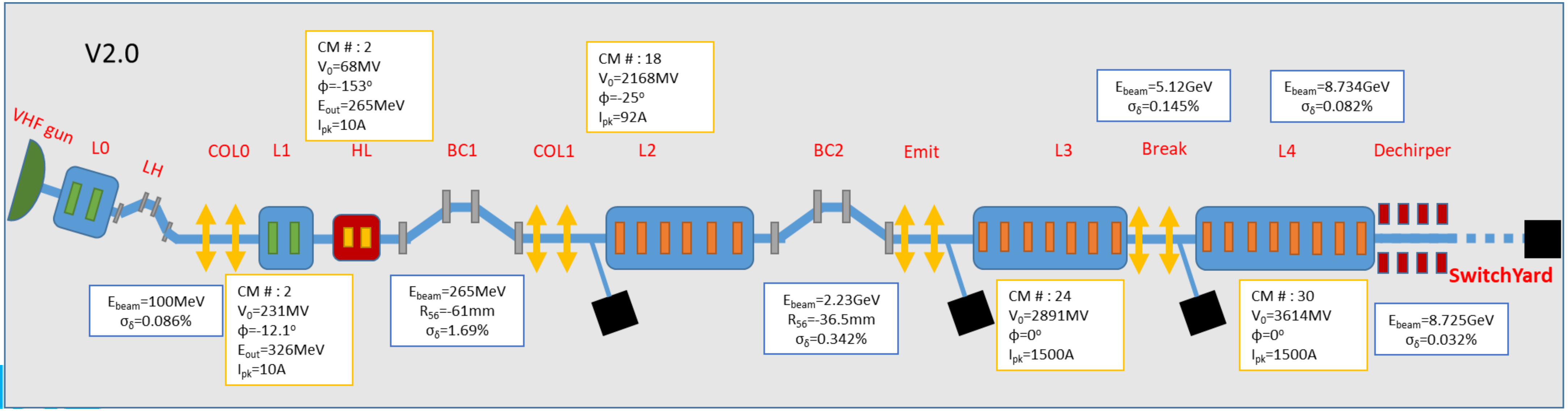




Linac

- **SHINE Linac design is based on TELSA technology, with CW operation.**
- **The linac consists of 75 1.3GHz cryomodules for beam accelerating, and two 3.9GHz cryomodules for non-linear correction.**
- **Dedicated sections for beam diagnostics are arranged at critical locations (after laser heater and two BCs), together with collimator systems for beam halo control.**
- **Corrugated structure to 'de-chirp' the energy spread is adopted.**
- **Tuning dumps are adopted to facilitate beam commissioning stage by stage.**

Parameters	Value
Electron beam energy (GeV)	8
Bunch charge (pC)	10-300
Rep. rate (MHz)	0-1
Normalized slice emittance in transverse (mm·mrad)	0.2-0.7
Peak current (A)	500-3000
Slice energy spread in rms	< 0.01%

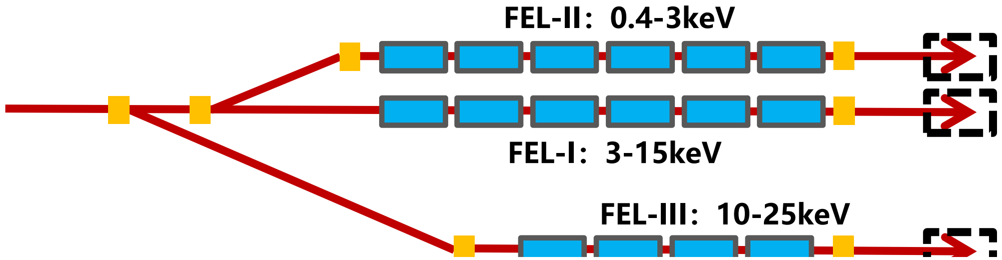


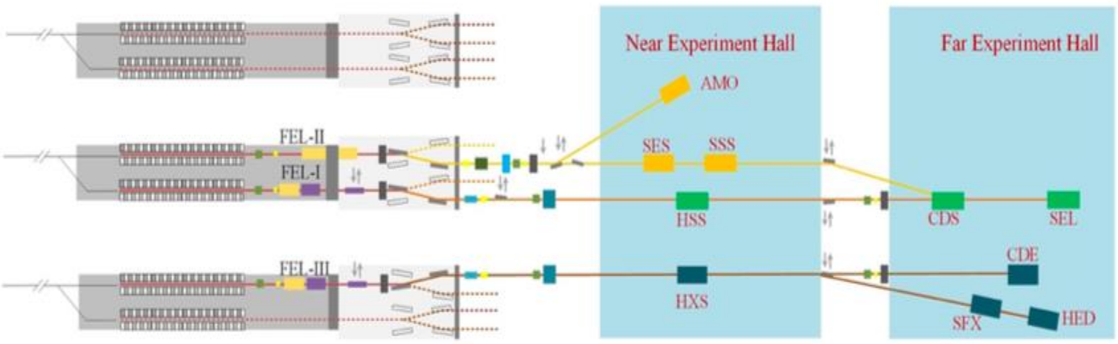
SHI

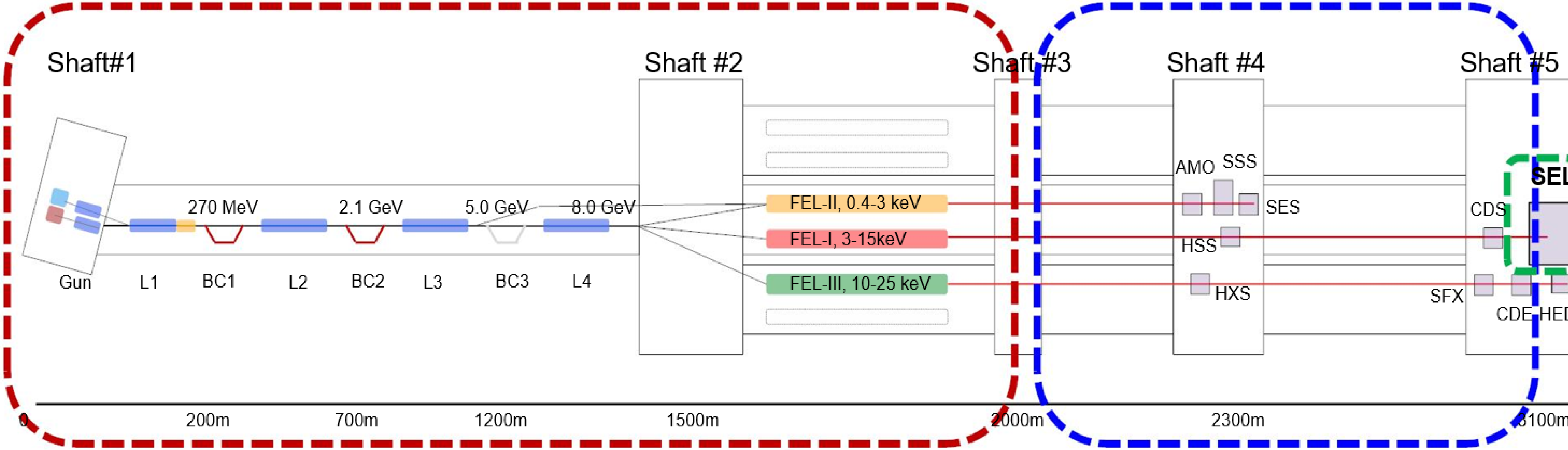
FEL Lines

Phase-I beamlines and stations

- There will be **118 undulators**, including 74 **planar undulators**, 4 **elliptical undulators** and 40 **superconducting undulators**. The total effective length is about 506 meters.







Civil construction

- Tunneling machine reached shaft #2 on August 5, 2021.

2022.06， shaft #1 & accelerator tunnel (Injector and Linac) will be ready , utilities (water，gas，electricity…) installation will be started.

2022.12，civil construction will be completed, injector begin on-site installation.

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Cryogenic hall

- Cryogenic hall for the first 4 KW cryo-plant are ready now , installation for cryo-plant will start in the first half of the year.

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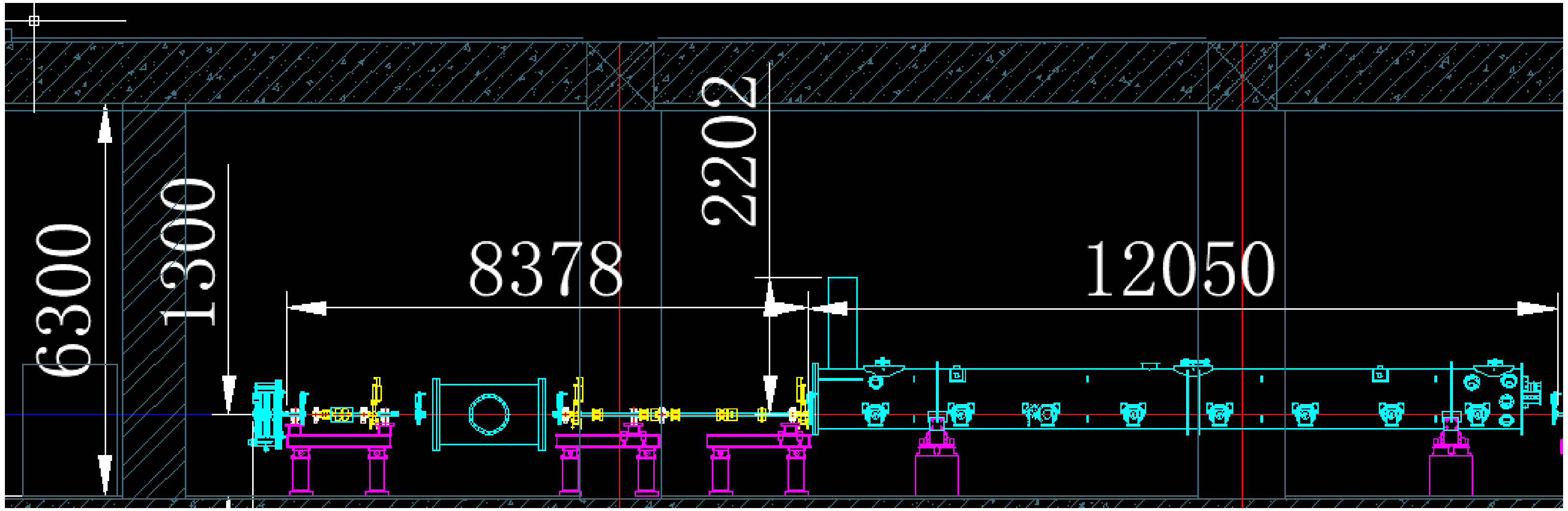
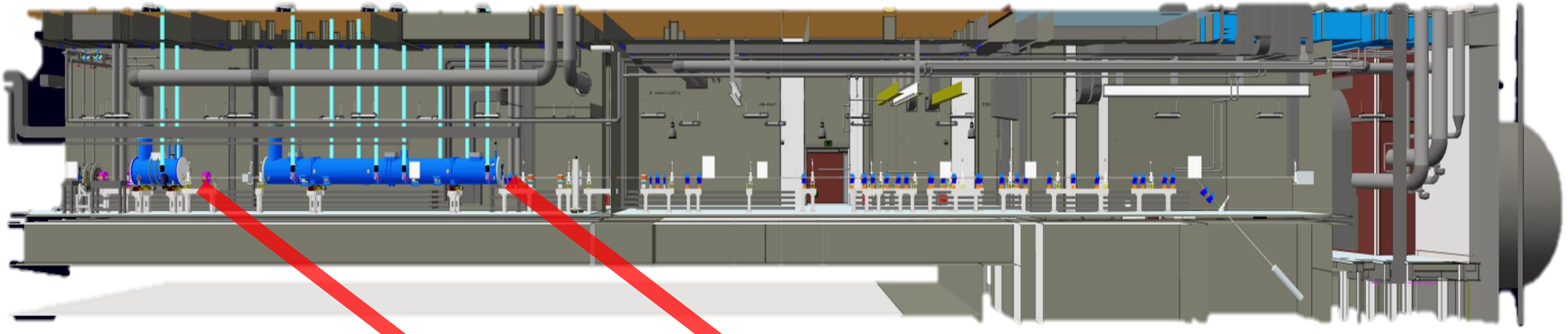
Cryomodules

Layout of injector cryomodules





Single-cavity CM

8-cavities CM

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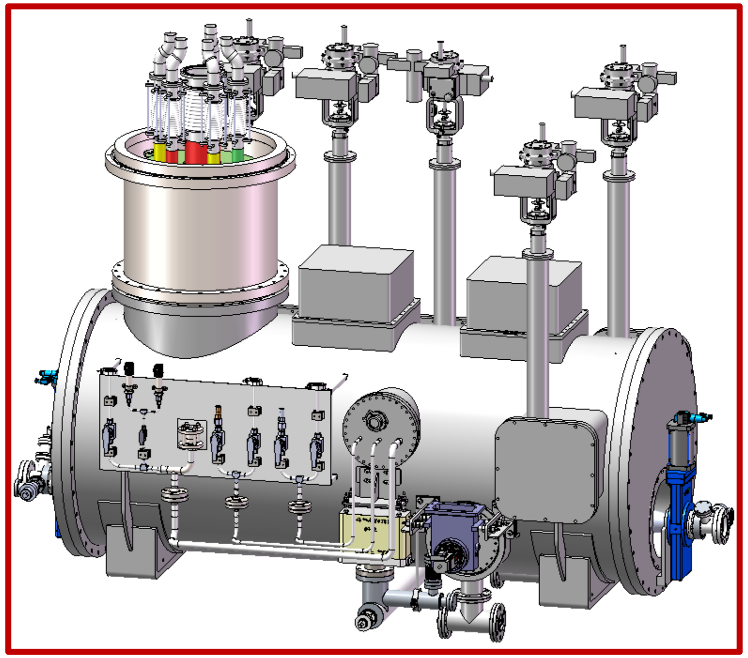
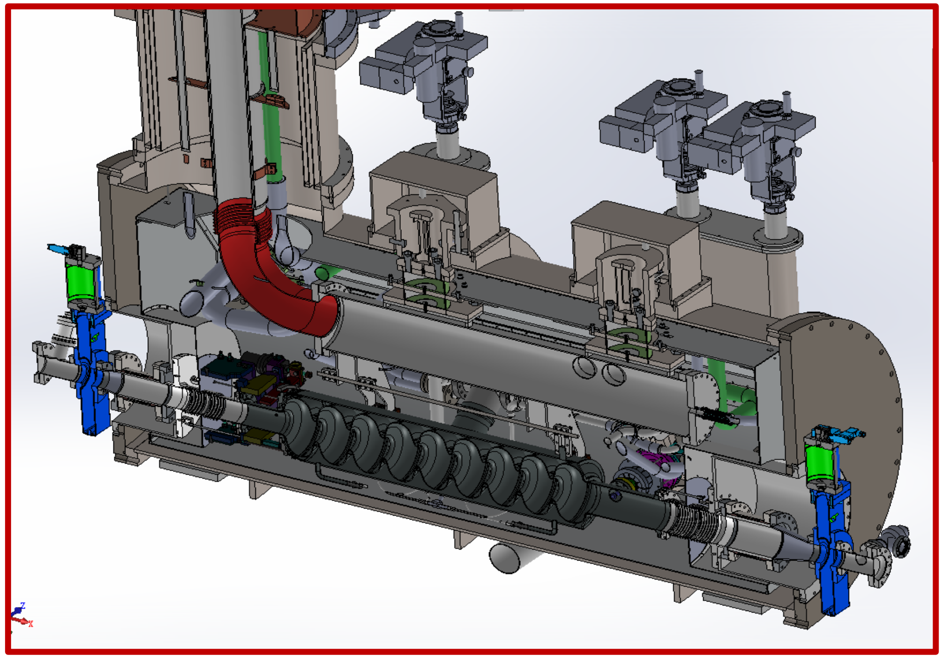
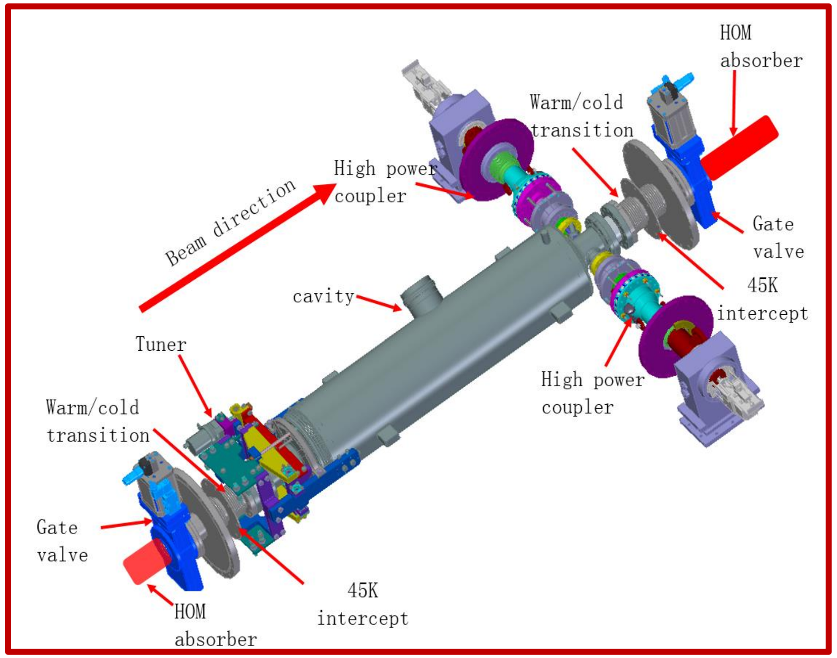
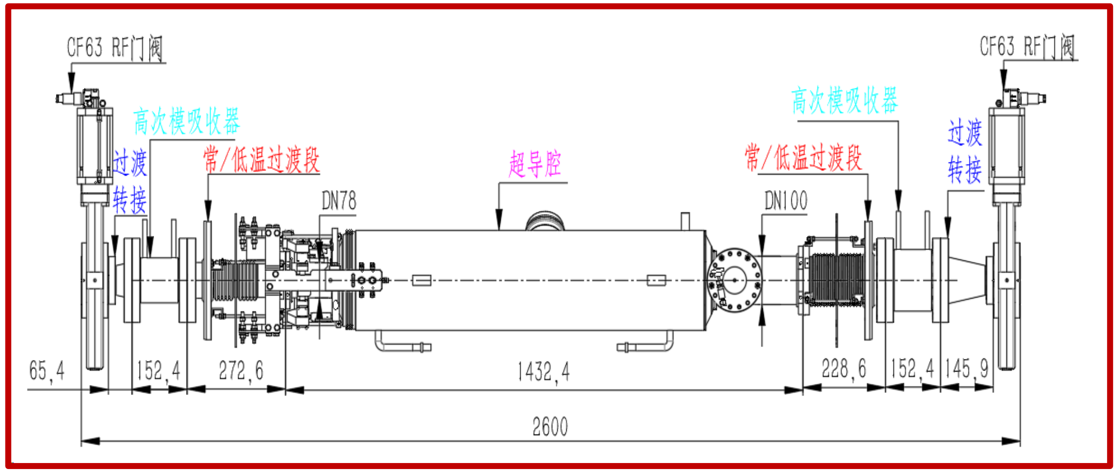
General structure of Single-cavity CM



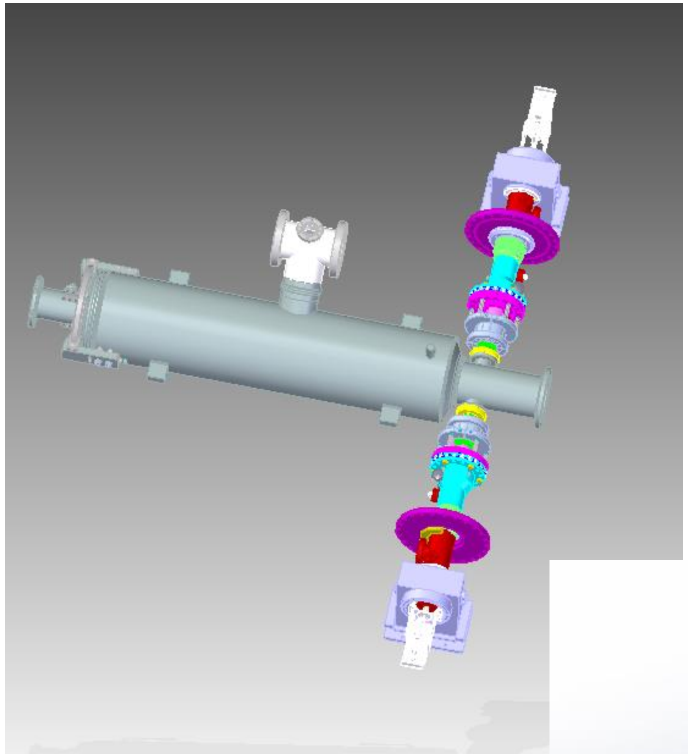


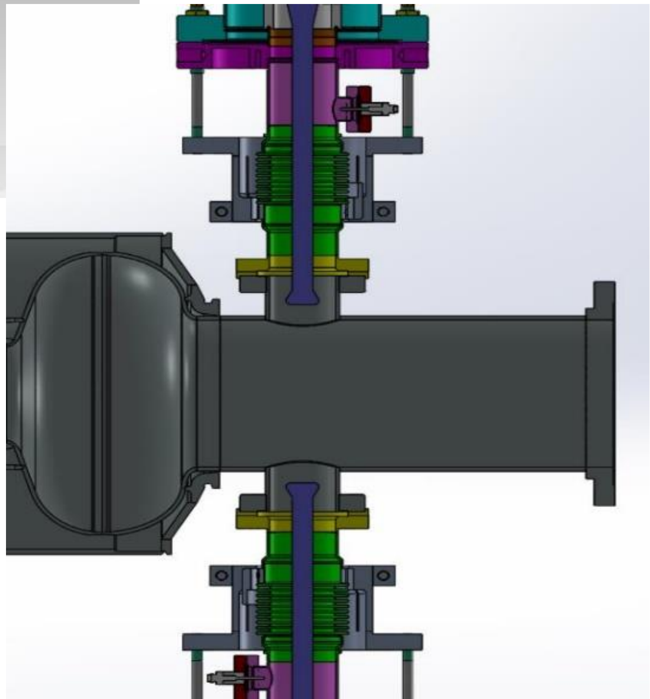




- **Twin-FPC structure adopt to decrease beam emmitance**
- **Independent vacuum isolation section （separate TL and CM)**
- **HOM absorber located at warm section(out of Cryomodule)**
- **NO vacuum gate valve arranged at cryogenic side**
- **NO feed cap& end cap , space saved**

Special cavity with Twin-FPC for injector





Twin-FPC without HOM coupler

- Symmetrical structure
- Twin-FPC at downstream
- Without HOM couplers
- Enlarge BP diameter at downstream for HOM propagation （78mm ⟶ 110mm)
- Penetration depth of FPC is 25.5 mm shorter compared to standard type by shorten the length of inner conductor
- The total length of cavity is 149mm longer than the standard cavity
- Position/Length of HOM absorber is optimized

Specification

- Q0>1.5e10 @ Eacc=12 MV/m
- E2/E0<1e-4, E1/E0<1e-4
- Qe_HOM < 1e6 for high r/Q modes

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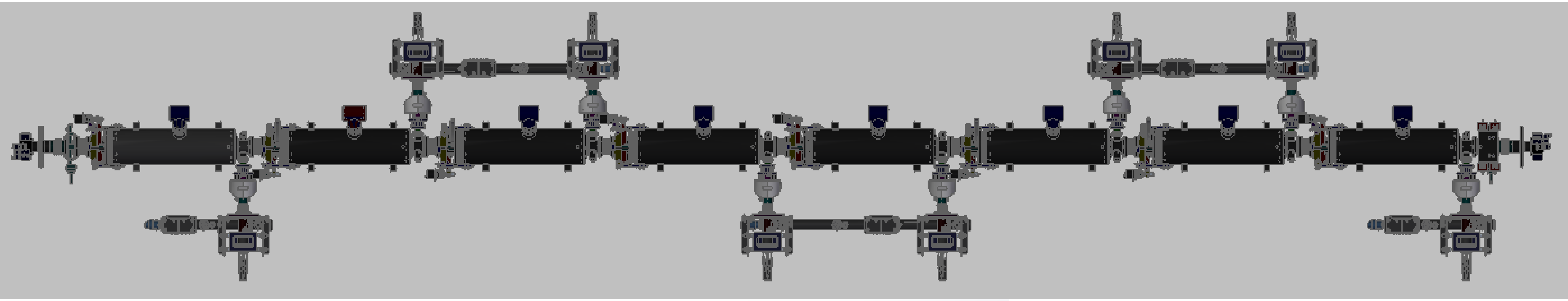
8-cavities CM for Injector

- **ABBA-FPC structure for emittance control**
- **Independent vacuum isolation section**
- **HOM absorber located at warm section(out of Cryomodule)**
- **NO feed cap& end cap , space saved**



FPC layout-ABBA

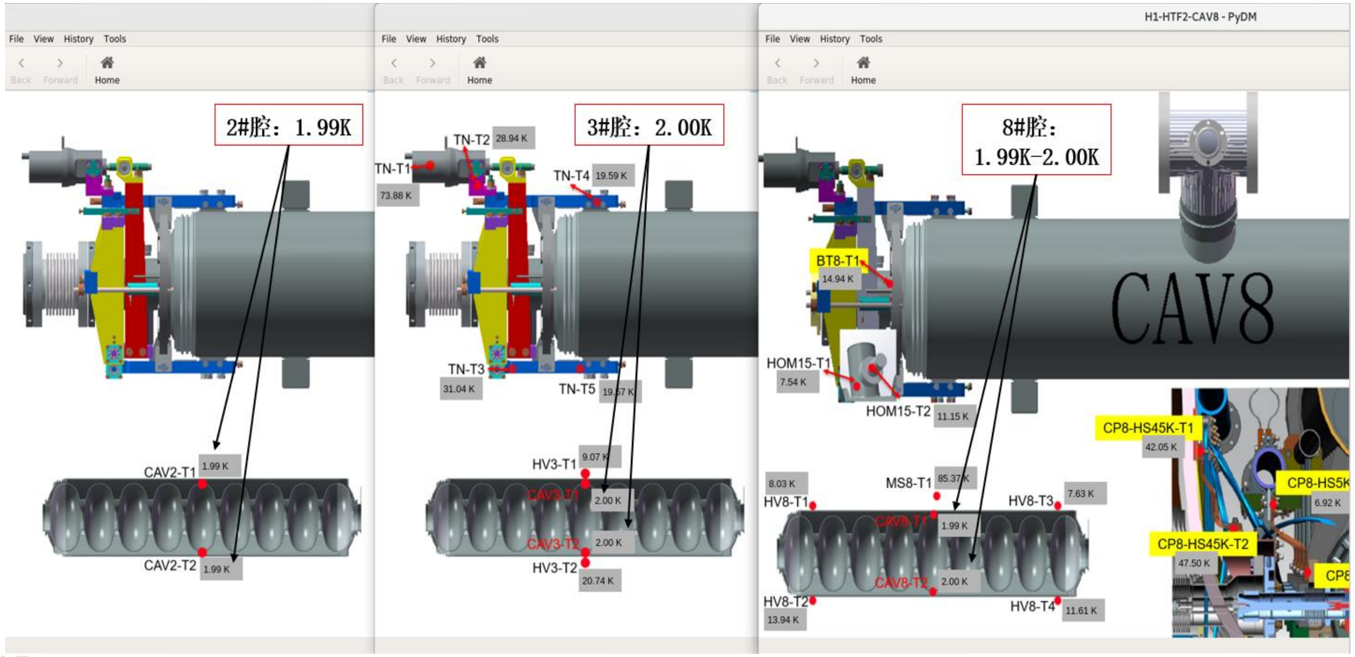
The first Standard 1.3GHz CM for Linac（prototype）

2021.01
CM assembly start

2021.03
CM assembly completed

2021.04
Cool down of TL

2021.07.14
First CM cool down to 2K successfully!!!



CM prototype RF test

- All the cavities were tuned to 1.3GHz
- Three of eight cavities achieved 16MV/m, total gradient of CM~93MV (megavolt)
- Q_0 not successfully measured: Helium level gauge broken

Possible reasons:
1. Vacuum is not so good(~ 200Pa) when we received these cavities, maybe small leaks on the flange、angle valve for some cavities,.
2. 4 cavities from IHEP take part in trial assembly procedure before formal assembly: they are suffered more times backfill than the other cavities.

Treatment : Re-HPR ,Re-vertical test for 8 cavities!

	#1	#2	#3	#4	#5	#6	#7	#8	模组 (MV)
腔	BJ001	BJ004	BJ003	BJ002	GJ003	GJ002	GJ001	GJ004	
耦合器	HJ002	HJ001	HJ004	HJ003	HJ006	DJ002	GJ001	GJ002	
目前梯度	**16.01**	**16.01**	**16.02**	**8.60**	**9.48**	**12.88**	**6.86**	**4.20**	93.3
目前梯度时间	07月22日	7月27日	07月24日	07月24日	07月27日	07月27日	07月27日	07月25日	
辐射起始(MV/m)[注1]	9/10	11/11	9/12	7/-	5.69/-	5.8/-	5.8/-	-/-	
16MV/m辐射[注2]	24499/20631	1361/692	6520/20631						
quench梯度	13.5	15.12 15.63 15.7	15.8	8.6 8.6	8.89	12.56 13.17 13.38	5.79 6.82 6.85 6.87		

[注1]-模组测试数据/垂测数据
[注2]-模组测试数据(多探头中最大值)/垂测数据

Cavity conditioning result

first BCP 8-cavities module in MTF2 tunnel

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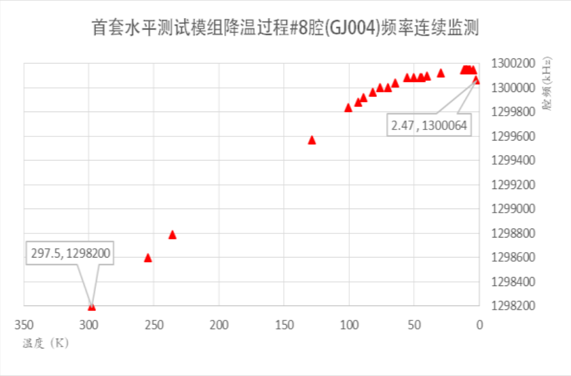

#8 cavity frequency monitoring during cooling down

1#	初始腔频	丝杠转6圈	丝杠转6.72（final）	频偏Δf（Hz）	慢调分辨率（Hz/Step）
	1300.094361	1300.011399	1300.000701	701	1.39
2#	初始腔频	丝杠转14.8圈	丝杠转14.9圈（final）	频偏Δf（Hz）	慢调分辨率（Hz/Step）
	1300.210407	1300.001067	1300.000375	375	1.4
3#	初始腔频	丝杠转6圈	丝杠转7.58（final）	频偏Δf（Hz）	慢调分辨率（Hz/Step）
	1300.108142	1300.023498	1300.000386	386	1.42
4#	初始腔频	丝杠转20圈	丝杠转23.9圈（final）	频偏Δf（Hz）	慢调分辨率（Hz/Step）
	1300.336865	1300.055788	1300.000906	906	1.4
5#	初始腔频	丝杠转3圈	丝杠转3.88（final）	频偏Δf（Hz）	慢调分辨率（Hz/Step）
	1300.051888	1300.013008	1300.000036	36	1.33
6#	初始腔频	丝杠转3圈	丝杠转3.36圈（final）	频偏Δf（Hz）	慢调分辨率（Hz/Step）
	1300.045802	1300.006442	1300.000582	582	1.35
7#	初始腔频	丝杠反转9.8圈	丝杠反转10圈（final）	频偏Δf（Hz）	慢调分辨率（Hz/Step）
	1299.880122	1300.000162	1300.000242	242	1.2
8#	初始腔频	丝杠转4圈	丝杠转4.24圈（final）	频偏Δf（Hz）	慢调分辨率（Hz/Step）
	1300.058222	1300.004482	1300.000042	42	1.37

Tuner test

VT and Ultra clean assembly

VT results after re-HPR

Parameter/No.	Threshold value	HJ002	BJ001	GJ002	BJ004	BJ003	GJ004	BJ002	GJ001	GJ003
frequency@16MV/m@2K MHz [1]	1300.2 +/- 0.1	1299.858	1300.089	1299.954	1300.243	1300.102	1300.005	1300.363	1299.869	1300.073
Q0 @ 16 MV/m	> 1.0e10	1.37e10	1.49e10	1.47e10	1.88e10	1.56e10	1.54e10	1.44e10	1.21e10	1.68e10
Xray @ 16 MV/m µSv/h	free	0.80	0.29	0.17	0.25	0.15	0.12	0.12	0.12	1.31
Q0 @ 19 MV/m	/	1.03e10	1.45e10	1.30e10	1.84e10	1.54e10	1.44e10	1.41e10	0.89e10	1.59e10
Xray @ 19 MV/m µSv/h	/	10.4	2.97	0.61	11.4	0.13	0.23	1.04	0.16	25.9
Eacc_FE_onset MV/m	/	7.9	16.0	21.1	17.0	none	none	19.0	none	11.0
Qt_pickup	/	1.14e10	3.17e11	1.21e11	1.24e12	1.09e12	5.73e11	2.41e11	1.14e11	4.57e11
Qe_HOM_FPC	> 2.7e11	7.50e11	9.05e11	8.85e11	4.24e11	7.70e12	2.77e11	3.40e12	5.35e12	1.27e12
Qe_HOM_PU	> 2.7e11	3.12e12	1.81e12	1.01e12	1.21e11	3.90e12	1.07e12	4.52e11	2.32e10	2.35e12
Eacc_max MV/m	> 19.0	22.5	26.1	23.0	20.4	28.1	22.3	25.8	20.4	24.8
Q0 @ Eacc_max	/	0.66e10	0.89e10	0.84e10	1.59e10	1.04e10	1.13e10	1.26e10	0.63e10	0.67e10
Xray @ Eacc_max µSv/h	/	356	1284	6.15	19804	0.13	0.13	235	0.13	903
Remarks	/	位置 1	位置 2	位置 3	位置 4	位置 5	位置 6	位置 7	位置 8	单腔模组
FPC-No.	/	HJ006	HJ002	DJ002	HJ001	CJ001	GJ002	HJ003	GJ001	HJ007

Ultra clean assembly for cavities string

Ultra clean assembly procedure: No problem!

- Maximal acceleration gradient for seven of 8 cavities are more than 19 MV/m after re-HPR (except GJ001)
- GJ001 re-BCP treatment on WUXI platform , VT again , Eacc is 20.4MV/m, satisfied the requirement for assembly.
- BJ003 test at PKU

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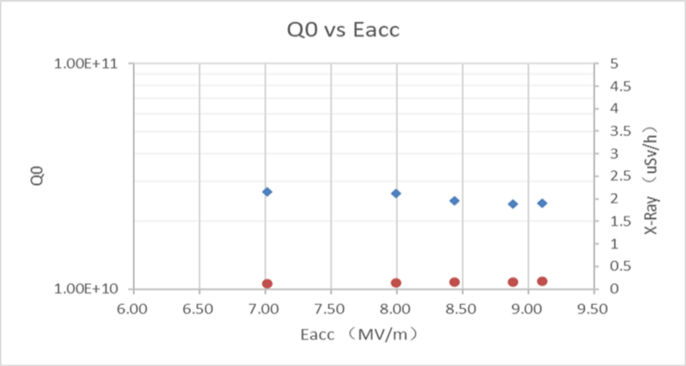
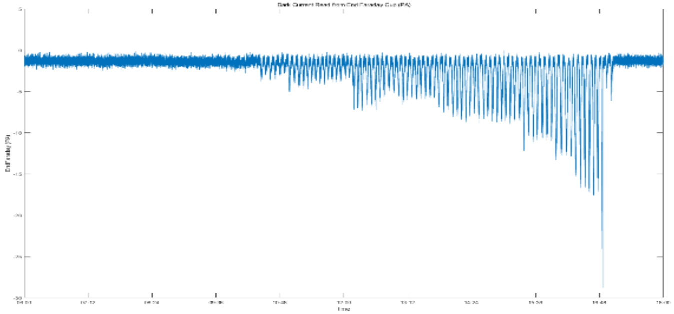
A short test CM

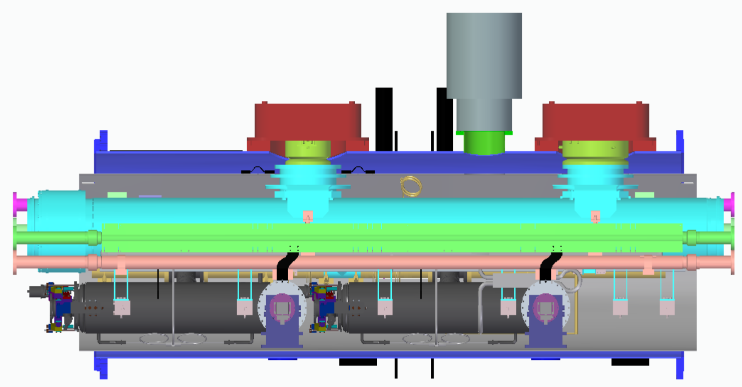
- **A short test cryomodule(available for 2 cavities and 1 SC magnet at a time) was developed to improve assembly and test efficiency;**
- **In Dec 2021, the short CM with 1 BCP cavity (GJ003) was successfully cooled to 2K, followed by a 13 days cooling test;**
- **Q_0 test carried out this time with dissipation power measured by heater compensation;**
- **Microphonic, piezo precision, dark current , etc have been tested successfully;**
- **Significant microphonic are measured , we need search for noise source .**

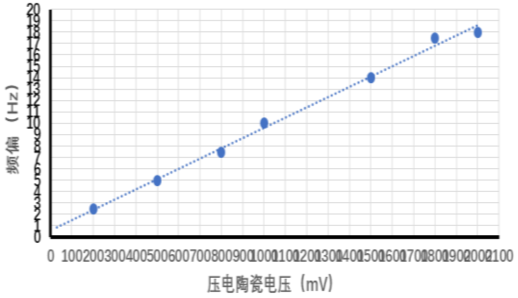


Q0 vs Eacc

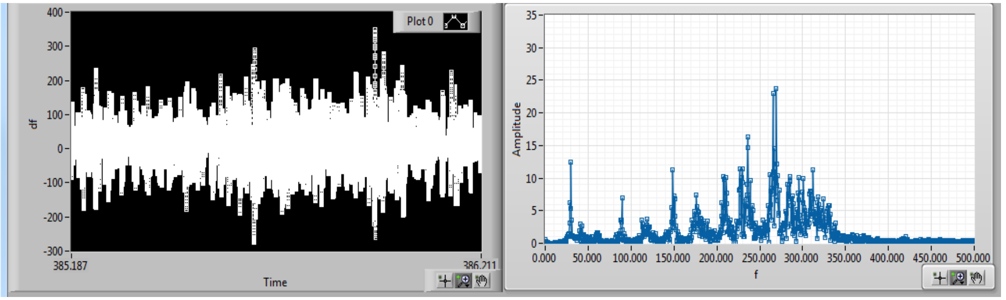


Dark current during condition





Piezo precision test

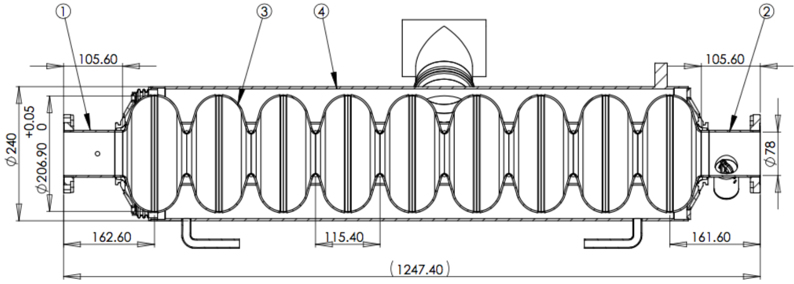


Microphonic test

Key Components R&D

1.3GHz superconducting RF cavity

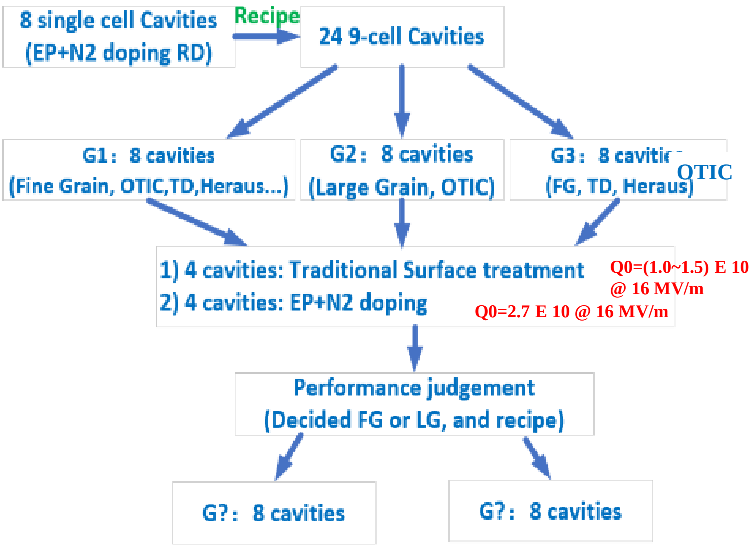
- TESLA type nine cell cavity, equipped with two higher order modes coupler, one pickup and one fundamental input coupler.
- Q_0=2 ~ 3E10 @ E_{acc}=14 ~ 18MV/m @ 2.0K.
- Dynamic power loss : ~ 10W/cavity.
- Surface treatment: Nitrogen doping / infusion / Mid-T with EP to obtain high Q_0.
- Low residual magnetic field: < 5mGauss.
- Q_e = 4.12E7 with 10Hz peak microphonics with 0.3mA current.



G1 中国科学院高能物理研究所 Institute of High Energy Physics Chinese Academy of Sciences
高能锐新 HE-RACING TECHNOLOGY

G2 OSTEC

G3 中国科学院上海应用物理研究所 Shanghai Institute of Applied Physics, Chinese Academy of Sciences
哈尔滨工业大学 HARBIN INSTITUTE OF TECHNOLOGY



In parallel

4 LG cavities, RI collaboration with DESY (2020-)

16 FG cavities from international suppliers ZANON 8, RI 8 (2021-2022)

Zanon RESEARCH & INNOVATION

KEK

- Annual meeting on SRF technology
- Supervision on facilities developed in Japan

INFN LASA

- 3.9GHz single-cell cavity test and CM design

DESY under CHILFEL

- Training for young engineers
- Materials specification for Nb discs
- LG cavity prototype R&D in Germany

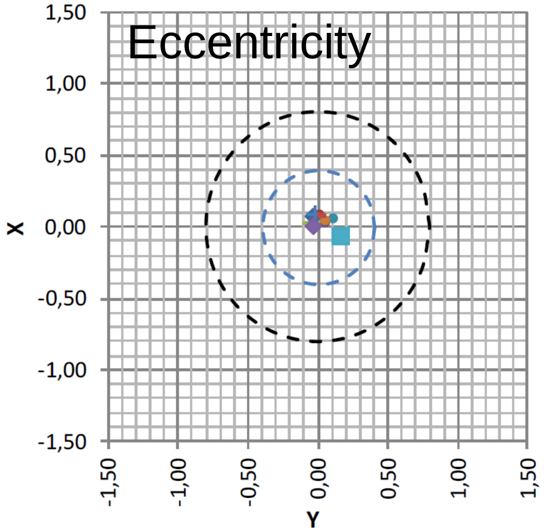
1.3GHz cavities - E.ZANON line

1.3 GHz cavity fabrication for SHINE project
Production Report

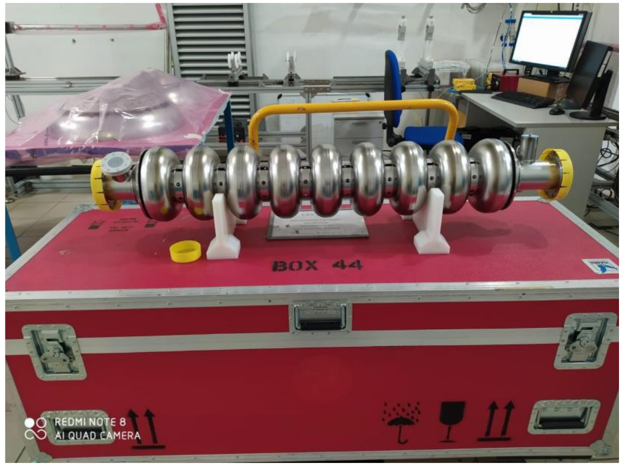
- The first two of 8 eight FG cavities have been fabricated. Good result.

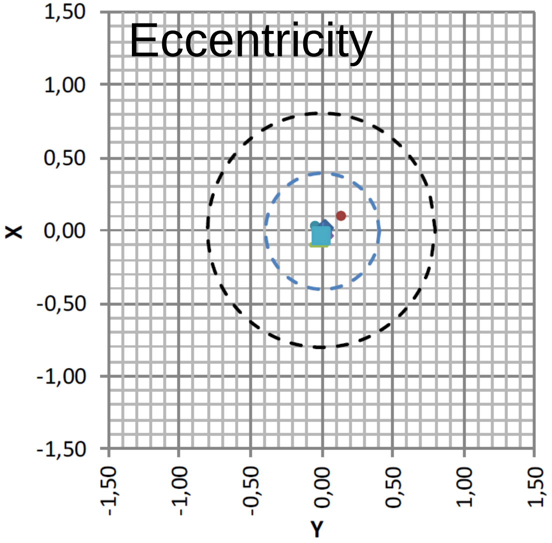
N. Cavity	Length (mm)	Frequency(MHz)	Eccentricity (mm)
Spec	1283.4 ± 3.0	~1299	<0.4
ZJ001	1281.71	1299.274	<0.2
ZJ002	1281.92	1299.277	<0.2

ZJ001



ZJ002



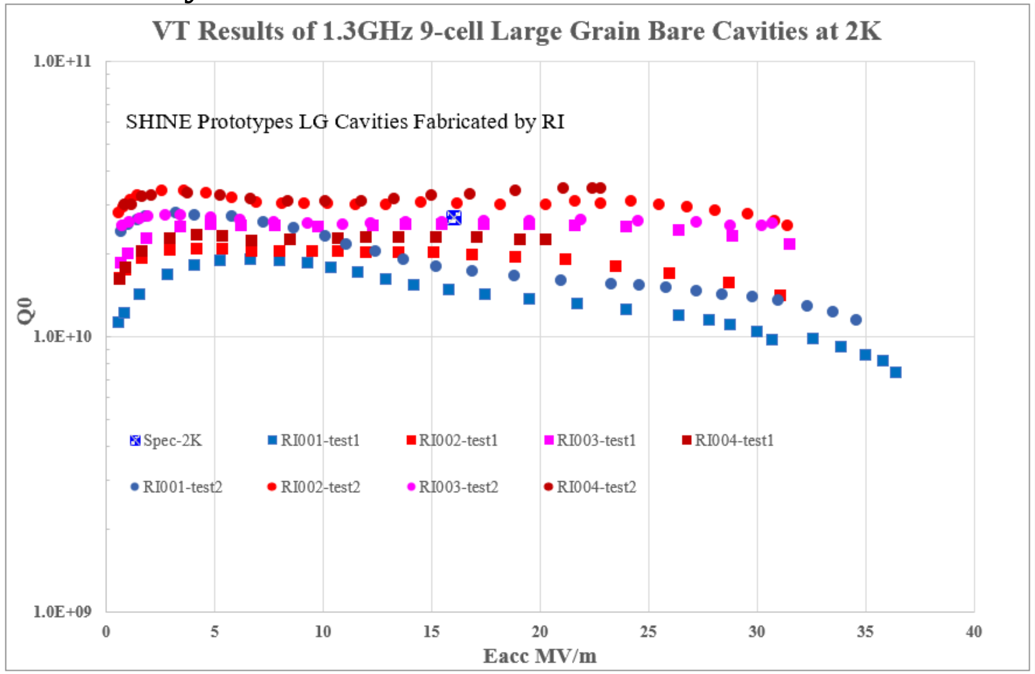


SHINE

1.3GHz 9-cell cavities-RI

Four LG Cavities

- LG Nb materials from NX, inspected by DESY. Cavity performance supervised by DESY
- Specs of SHINE prototypes are satisfied, including Shape accuracy, Field flatness, Straightness , Frequency, Cavity length
- Delivery will be scheduled



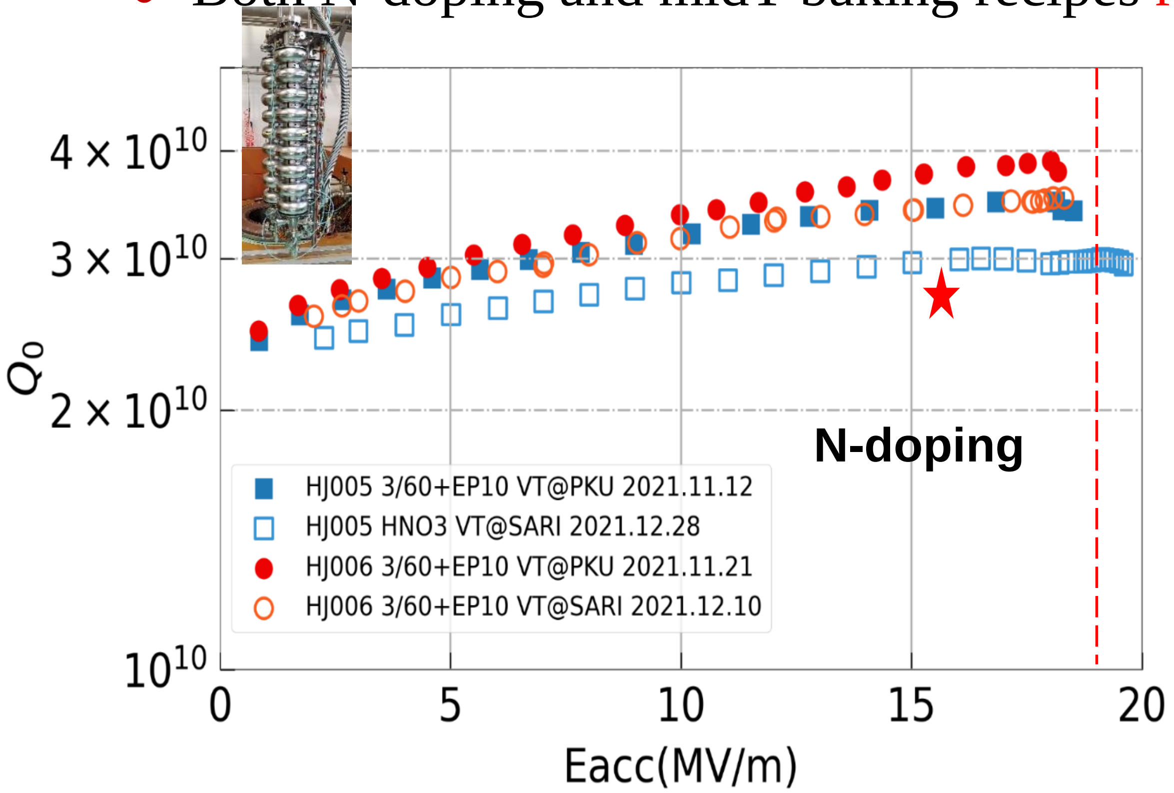
Parameter	unit	RI001	RI002	RI003	RI004
Q0@~16 MV/m	/	~1.7e10	~3.0e10	~2.7e10	~3.3e10
Q0@~19 MV/m	/	~1.5e10	~3.0e10	~2.6e10	~3.4e10
Xray@~16 MV/m	uSv/h	none	none	none	none
Eacc_max	MV/m	34.6	31.4	30.7	22.8
Limited by	/	quench	quench	quench	quench
Frequency@16MV/m	MHz	1300.290	1300.280	1300.300	1300.270

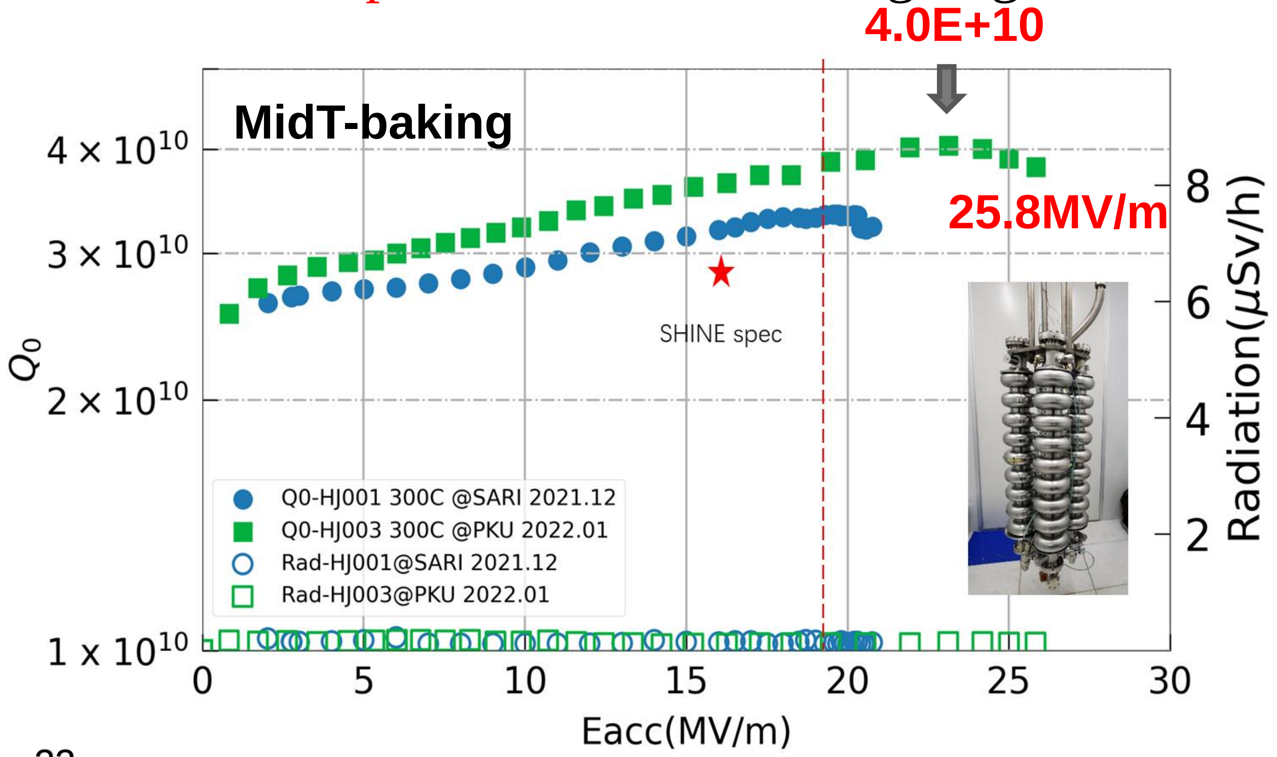
Eight FG Cavities

- Two of them are welded
- Surface treatment is in progress
- Nb material from NX, inspected by DESY

High-Q R&D on 9-cell cavities

- **Surface treatments at Wuxi platform**
  - **N-doping :** Bulk BCP + EP 100um+900C/3h + 3/60@800°C + EP10 um
  - **midT-baking:** BCP baseline +EP 50um + 900C/3h + air exposure/3days + 300C/3h
  - Q_0 difference likely due to different fast cooling at PKU and SARI
  - Both N-doping and midT-baking recipes reached SHINE specs; more studies on going.





1.3 GHz Fundamental Power Couplers

- 28 1.3 GHz FPC prototypes have been fabricated and all of them passed the RF conditioning :14kW CW in Traveling wave mode and 7kW CW in standing wave mode.
- The maximum RF power can reach 20kW in TW mode and 10kW in SW mode (maintaining stable for 12 hours).
- 9 FPC prototypes have been assembled in the eight-cavity cryomodule prototype and the single-cavity cryomodule respectively, and been RF conditioned of 5.2kW both at room temperature and 2K temperature.
- The FPCs for double-fed SC cavity have been designed and in process. The difference from the standard SHINE 1.3GHz FPCs is that the length of antenna is shorten 25.5mm to achieve the 7.0E+7 of Q_{ext}.

Fig. SHINE 1.3 GHz FPC

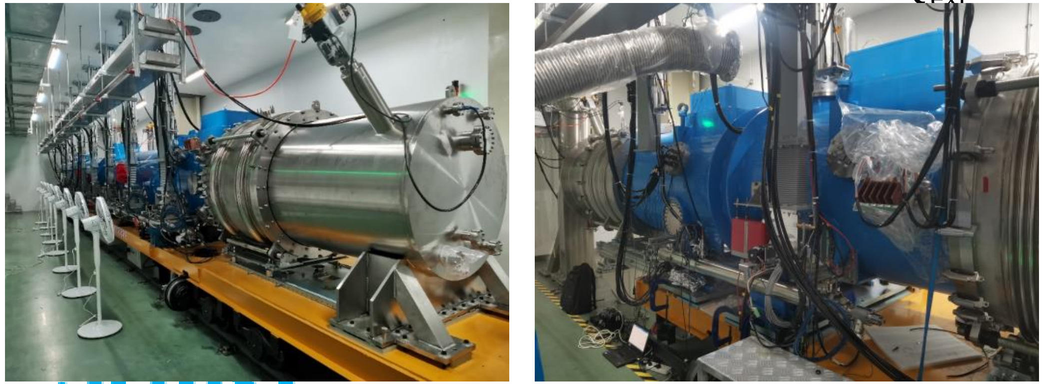


Fig. Eight-cavity and Single-cavity cryomodules

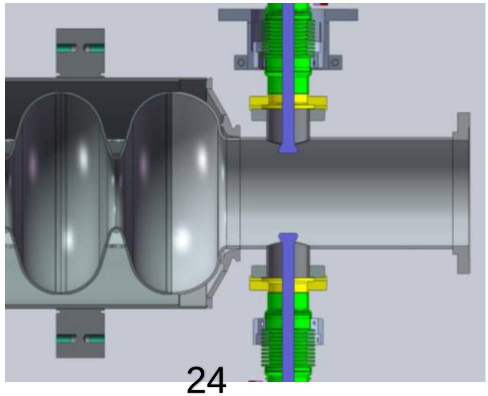


Fig. FPC for double-fed cavity

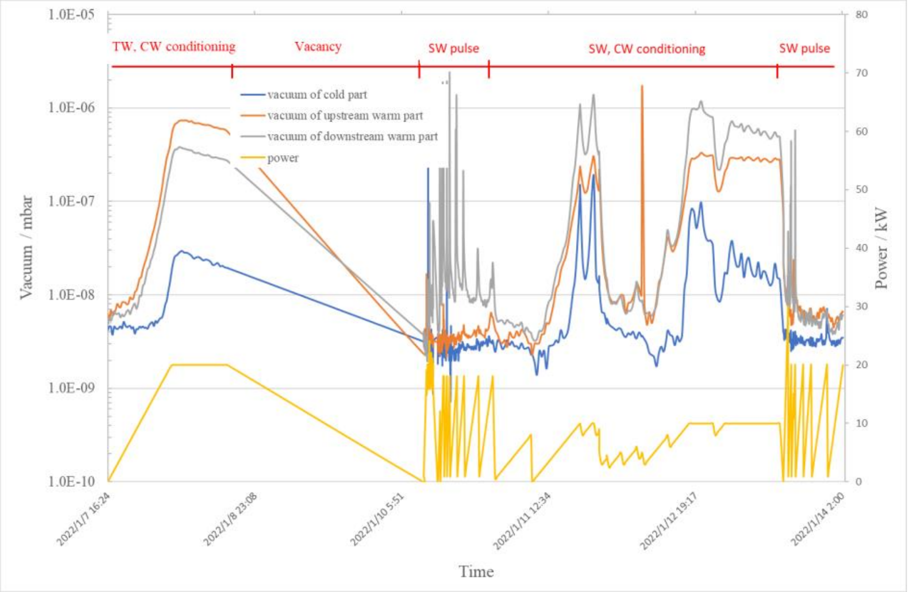
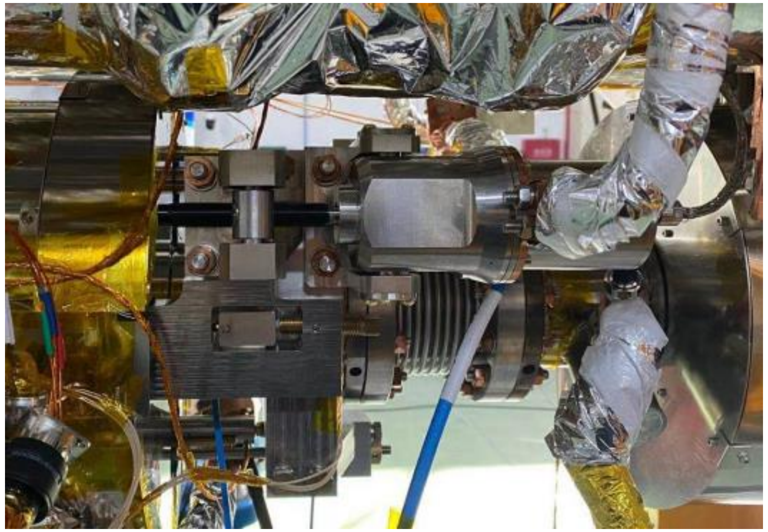


Fig. FPCs RF conditioning historical curves

1.3GHz Cavity Tuner



Tuner mounted on cavity

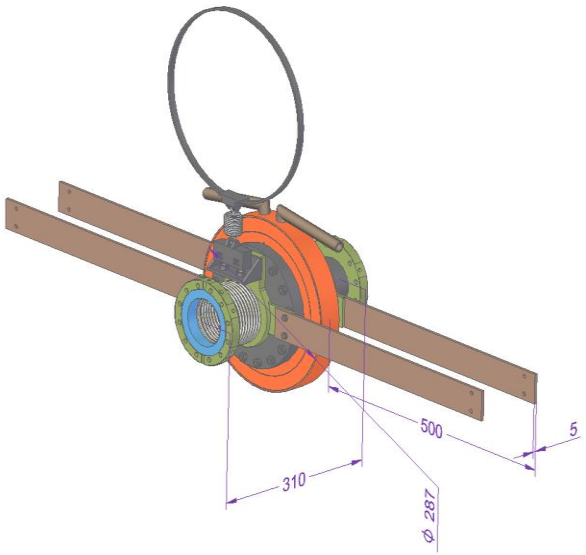
- **Several warm and cold tests have been carried out , all parameters meet or better than the design requirements.**
- **8 Tuners of the cryomodule prototype have passed the first round of horizontal test.**

	Design Value	Measured Value （*Estimated）
Slow tuner frequency range （Nominal）	≥250 kHz	330kHz~360kHz*
Slow tuner frequency range （Maximum）	≥450 kHz	525kHz~570kHz*
Slow tuner dimensional range （Nominal）	≥0.75mm	1.2mm
Slow tuner dimensional range （Maximum）	≥1.3mm	1.7mm
Slow Tuner sensitivity	1-2 Hz/step	1.2~1.55Hz/Step
Fast Tuner frequency range	≥1kHz	3~4kHz
Fast Tuner tuning resolution	~1 Hz	~1Hz*
Tuner stiffness	~30N/μm	34.6N/μm
Operating conditions	Insulating vacuum 1.3E-4Pa ,T=20-60K，Radiation doses $5*10^8$rad	
Lifetime	20years	

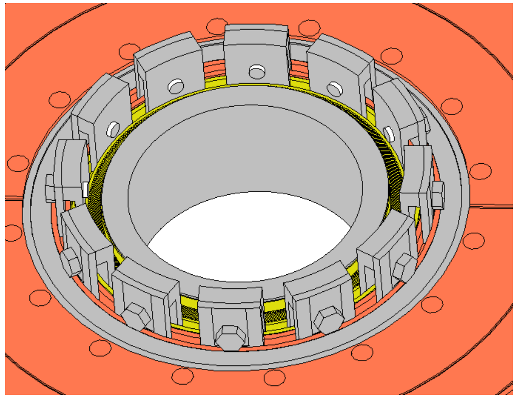
SHINE

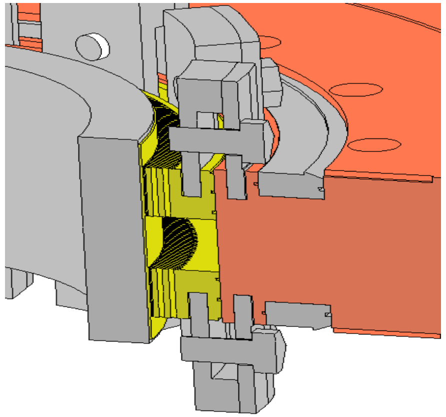
HOM absorber structure and welding process

Designed available absorb power
200W@45K
Under development

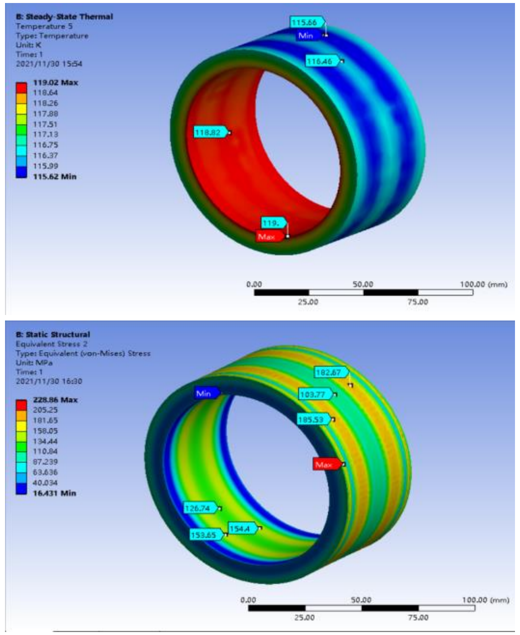


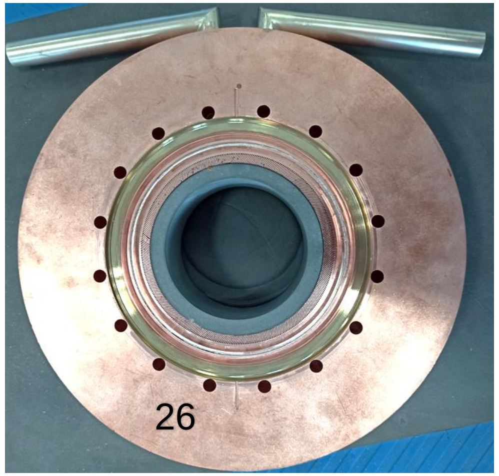
Welding profile



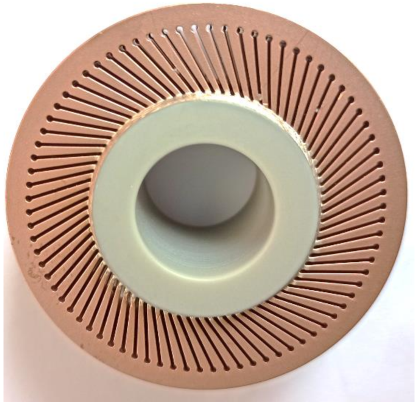


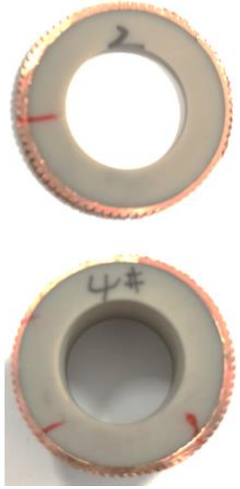
Temperature and Stress Analysis





Welding prototype



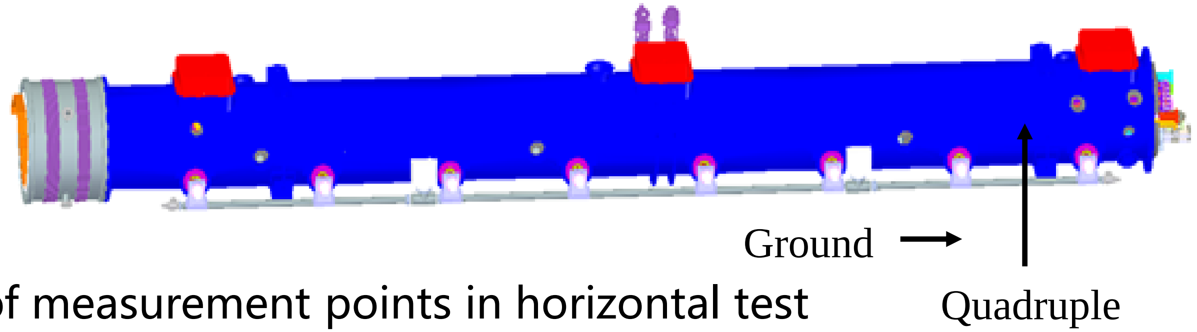


Two advantages of the comb structure :

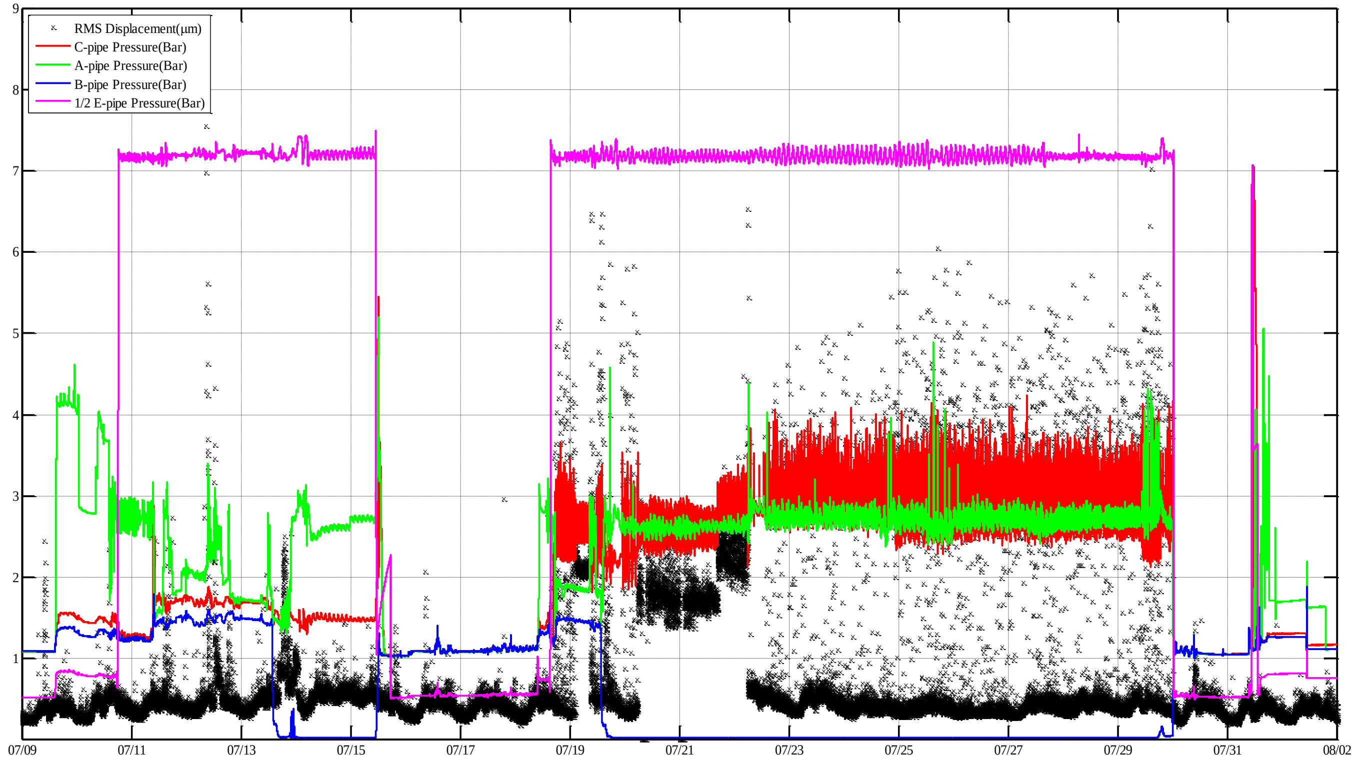
1. **Soft: absorb stress induced by different thermal expansion between different materials;**
2. **It is highly thermal conductive: transfer HOM power efficiently**

1st process prototype for absorber ceramic subunit (Copper TU0(High purity copper) + SS316LN + Aluminum Nitride)

Vibration stability studies of cryomodules



Layout of measurement points in horizontal test



1. **Vibration measurement sensors are located on Quadruple**
2. **Black points are RMS displacement.**
3. **BP distributed widely when the cryogenic pipe pressure fluctuated（red line).**
4. **Keep helium pressure stable in CM is important.**

Infrastructure

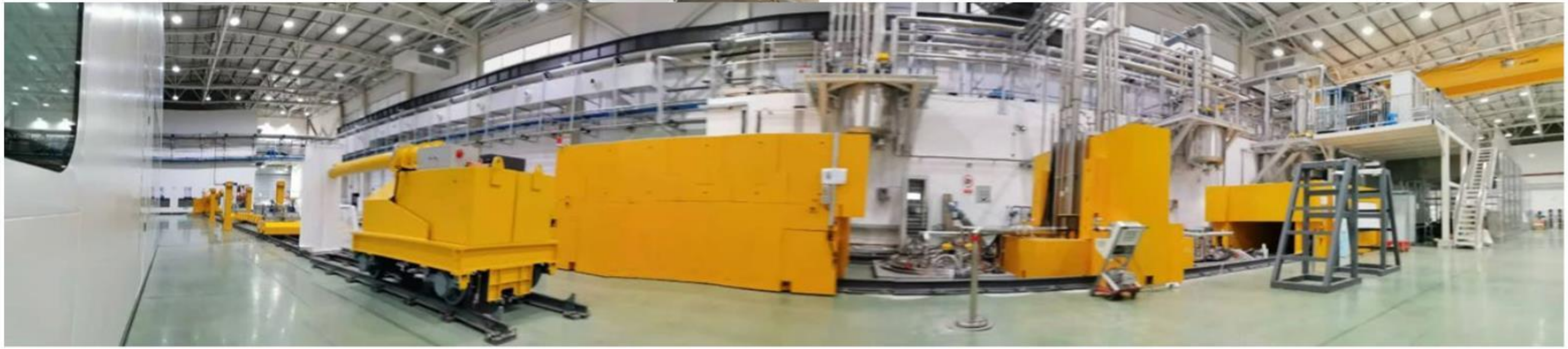
Cryoplant

1kW@2K Cryoplant

the largest superfluid helium cryogenic system in China with 1kW@2K has turned into operation to support the continuous RF test.

The largest superfluid helium cryogenic

Cryoplant for test with 1kW@2K has finished the SAT （site acceptance test) in July 2021, and has already supported five test benches among the HTB (Horizontal test BENCH),VTC(vertical test cryostat), MTC (multi functional test cryostat) to achieve 2K.



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Wuxi platform for SRF cavity surface-treatments

- **Main devices, gradually commissioned and put into operation since 2021.**

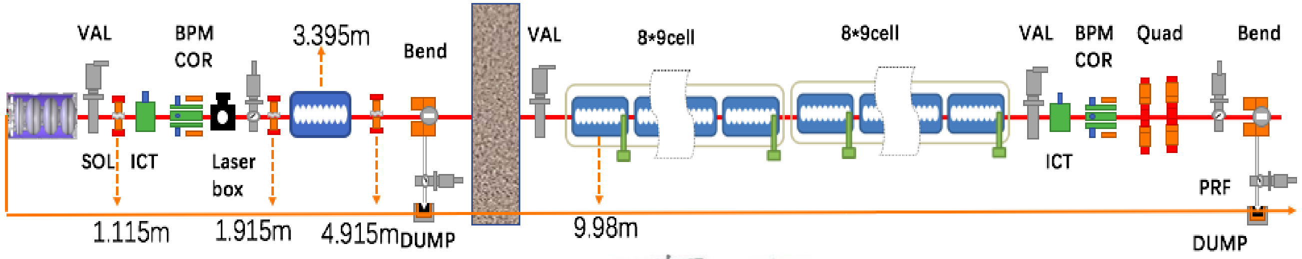
Beam test facility

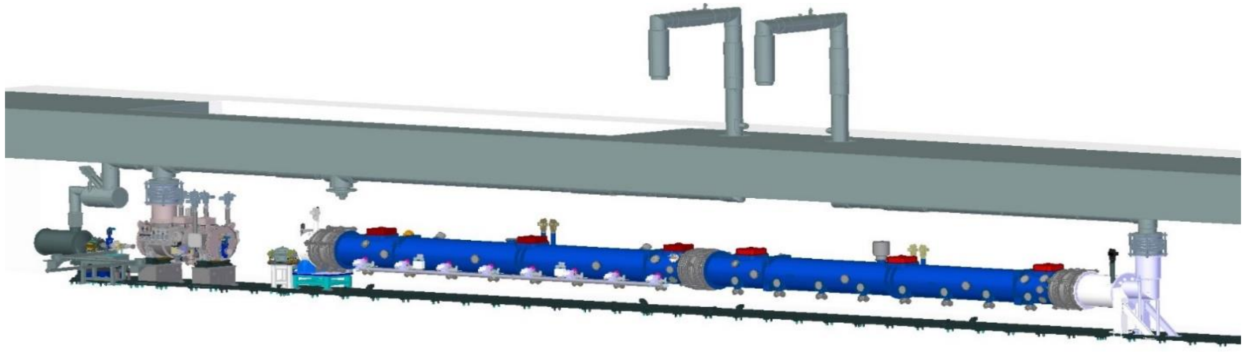
Objectives

- Confirm the CM dynamic performance
- Test CW related components, system and technology with beam
- Confirm operation reliability and safety of hardware
- Accumulate the operation experience for SC Linac

- Beam energy: 300MeV (Max)
- Beam charge: 300pC (Max)
- Average current: 0.1mA (Max)
- 20.03~22.05， Design and construction
- 22.05~23.03， Commissioning and beam test

Layout of the facility





Drawing of facility in #2 hall tunnel

Goals for 2022

Components R&D

- **Cavity: high Q process achieved and confirmed in VT, HT and BT**
- **Others: ready for mass production**

Infrastructure

- **installation and commissioning of beam test facility in 2# Hall completed**
- **Facilities in 2# Hall design and construction completed ,ready for mass production**

CM assembly and test

• **1st CM HT, 2022.04 ~05**	2 CMs must be HT by the end 1st half of the year – 06.30.2022-deadline
• **2nd ~ 5th CM HT, 2022.05 ~ 12**	of the pre-research project of SHINE
• **1st CM beam test , 2022.06 ~08**	3 other CMs~ 2nd half of the year
• **2ndCM beam test , 2022.11**	2 of 5 CMs finish beam test on beam test facility

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Summary

1. **Design for two injector CMs are completed, all the components are in production.**
2. **The first 1.3GHz CM prototype has been assembled , integration procedure has got confirmation.**
3. **HT has been carried out for the CM prototype, acceleration gradient~93MV, re-HPR treatment for all 8 cavities, VT result is good , now it is ready for HT again (2022.04).**
4. **A short CM just aimed for HT is designed, fabricated, assembled in 2021, HT for a cavity (GJ003) on this CM successfully.**
5. **Significant progress has been made in key components R&D, Q_0 for several 9 cell cavities can get to 4.0E10 @25 MV/m, better than specification.**
6. **Tunnel construction near completion , Cryo-plant for test (1 kw@ 2K) has been put into operation since 2021.06.**
7. **Main devices for the surface treatment platform in WUXI, gradually commissioned and put into operation since 2021, some research for single and 9 cell cavities are already carried out on the platform.**
8. **Beam test facility would be completed in 2022.05, and test work would be carried out with one CM at the first stage in 2022.06.**

Thank You!

SHINE