Protype cryomodule for the SHINE Free Electron Laser at shanghai

Yiyong Liu
SHINE Cryomodule Group

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Introduction of SHINE

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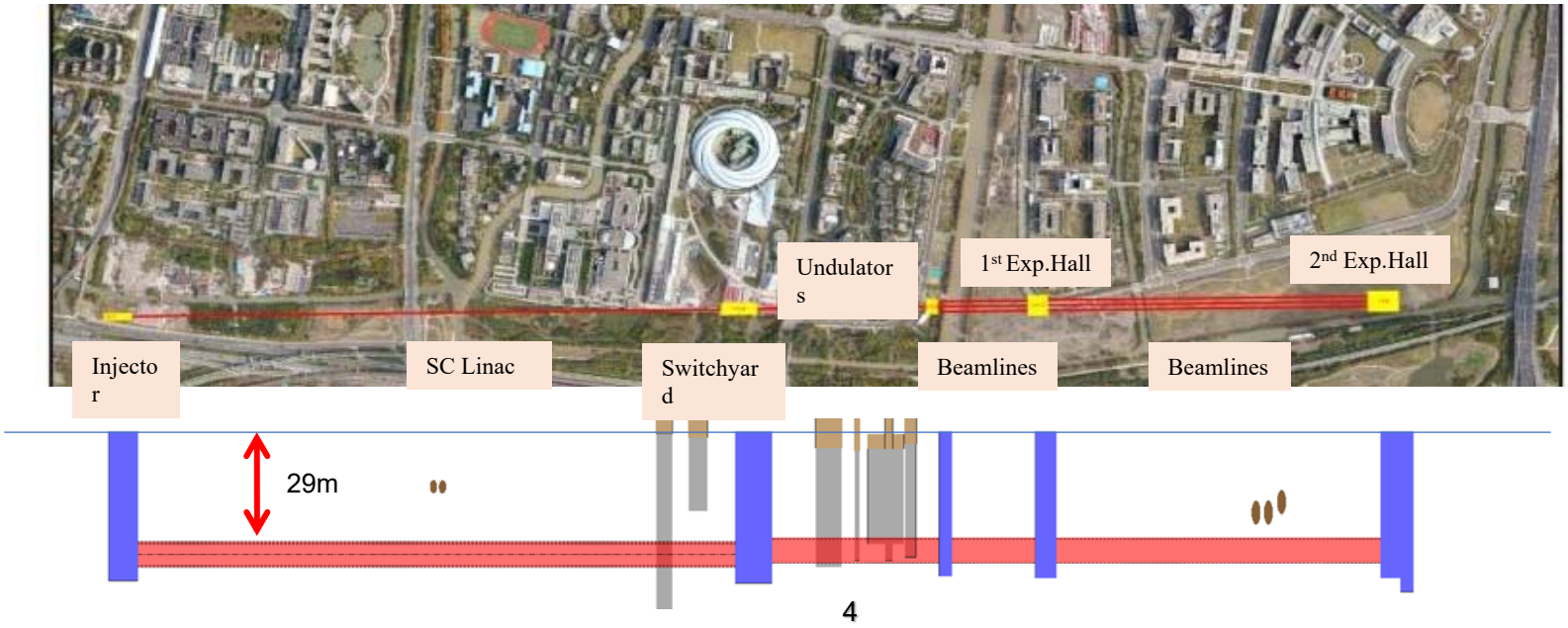
Layout and schedule of SHINE project

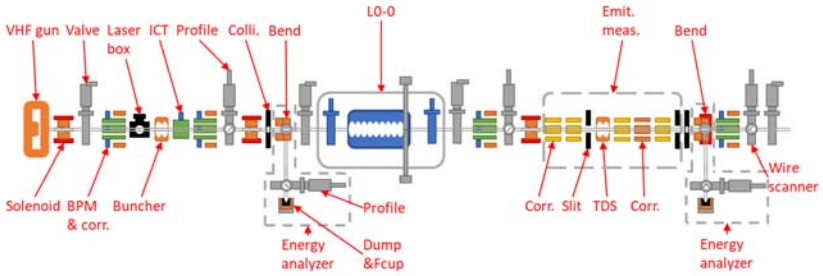
- **SHINE (Shanghai HIgh repetitioN rate XFEL and Extreme light facility)**
- **Total length 3.1km, 29m underground**
- **8GeV CW Linac, 3 FEL undulator lines, 3 beamlines ,10 stations, PWs laser**
- **Construction schedule: 2018.04 ~ 2025.03**

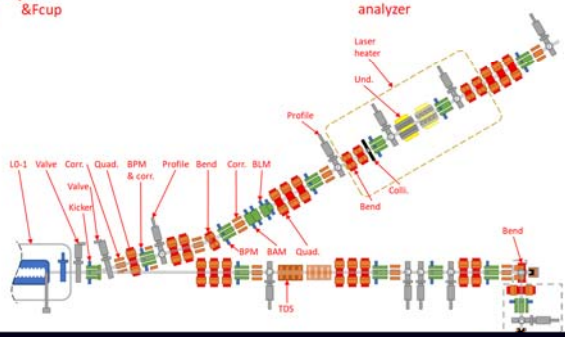


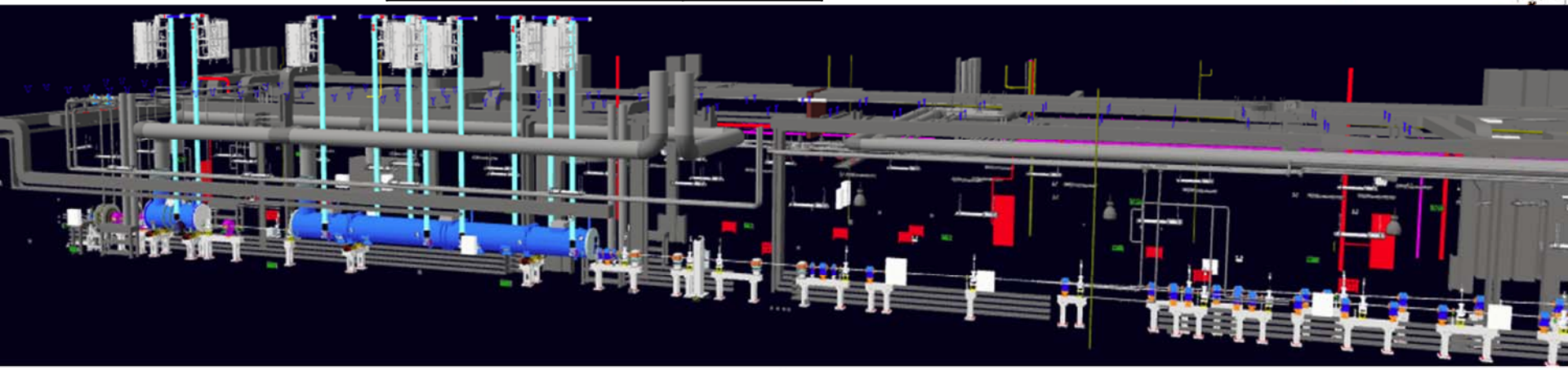
Injector

- **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







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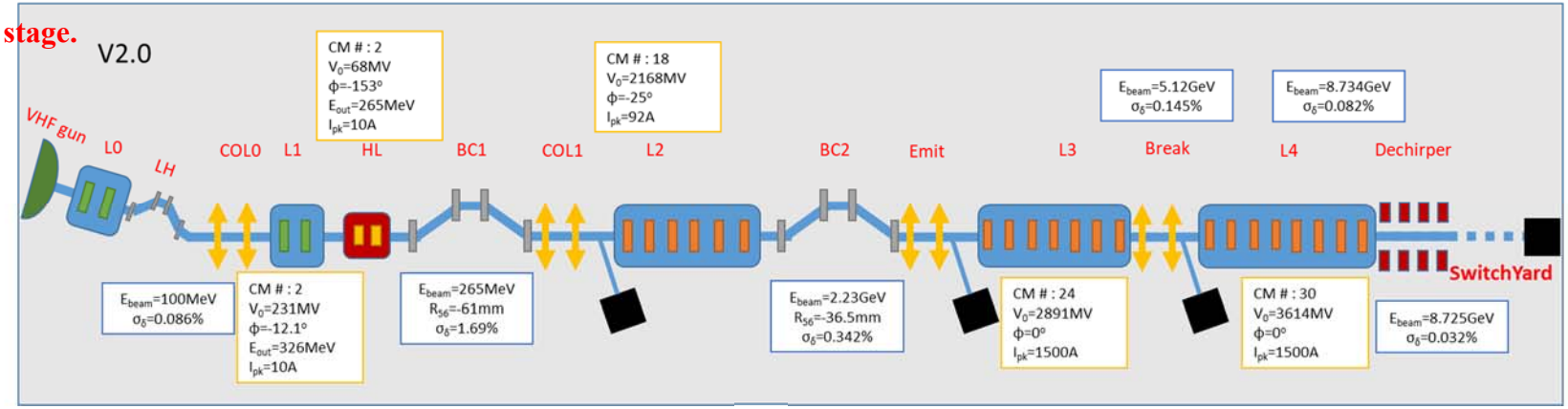
Linac

- **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%



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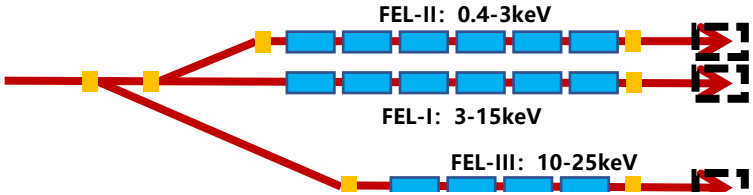
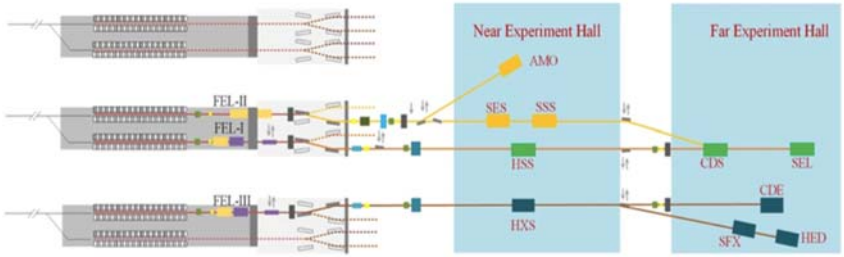
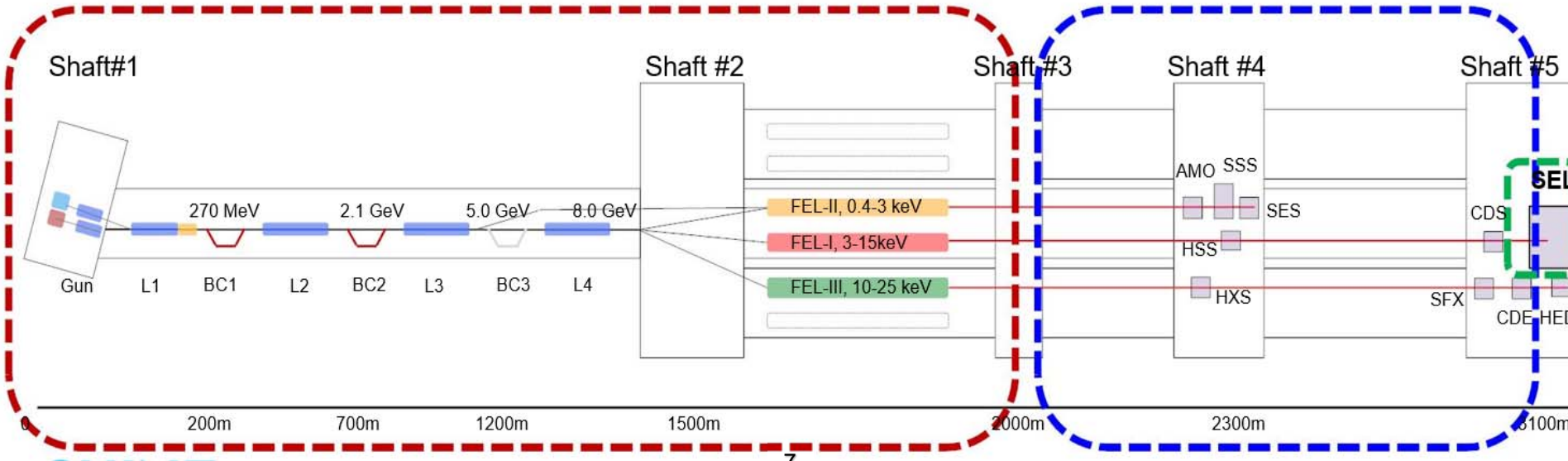
FEL Lines

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



Phase-I beamlines and stations





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Linac tunnel

2022.07， shaft #1 & accelerator tunnel (Injector and Linac) has been ready , utilities (water，gas，electricity…) installation will be started.

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

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 next year.

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Cryomodules

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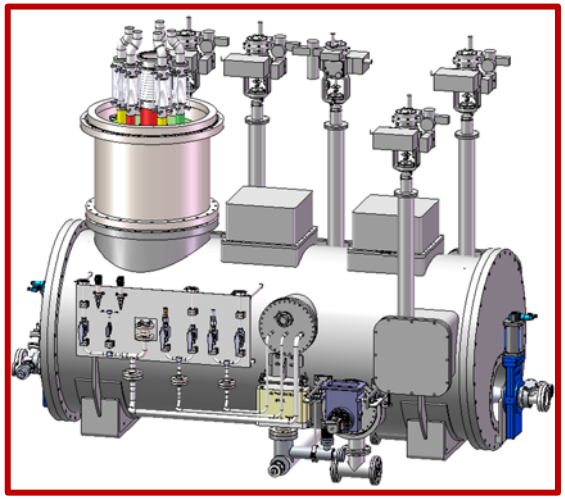
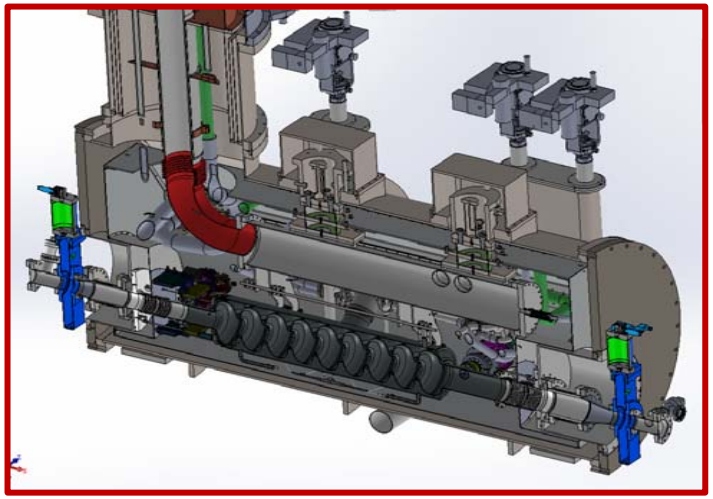
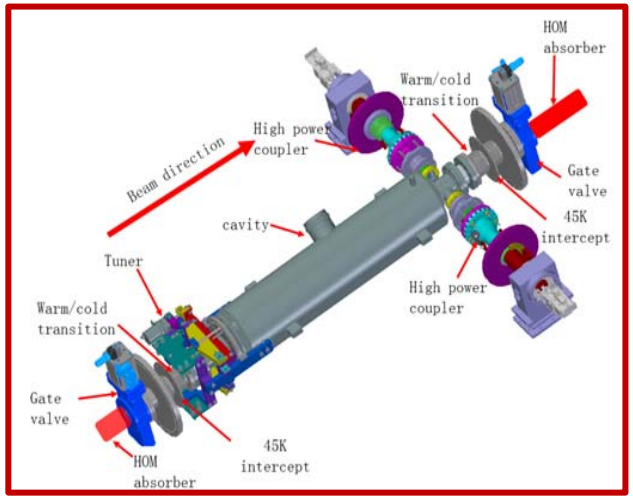
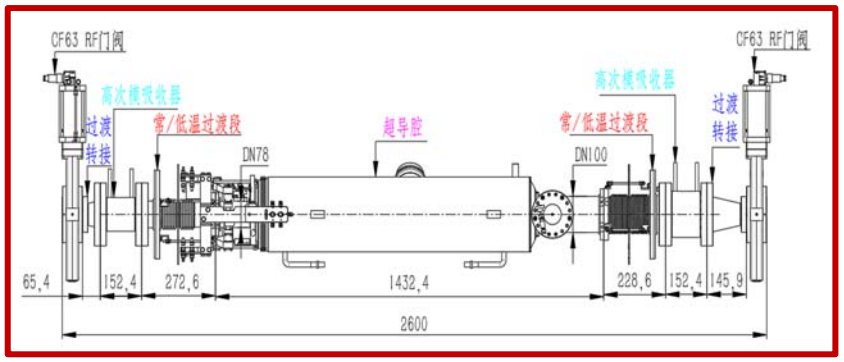
General structure of Single-cavity CM









- Twin-FPC structure adopt to decrease beam emittance
- Independent vacuum isolation section （separate TL and CM)
- HOM absorber located at warm section(out of Cryomodule)

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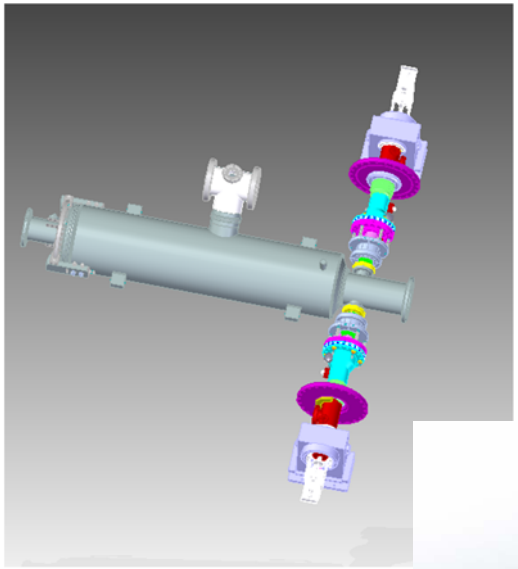
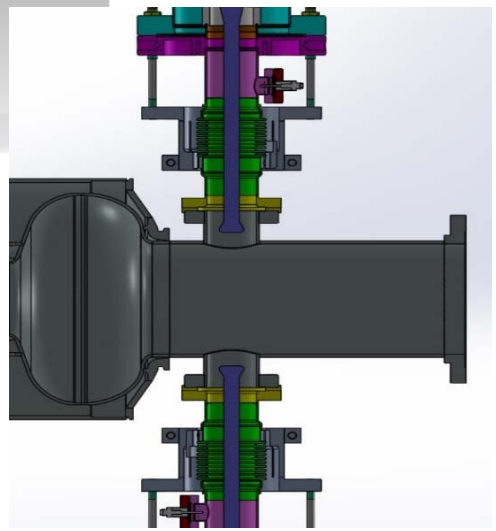
Special cavity with Twin-FPC for injector





Twin-FPC without HOM coupler

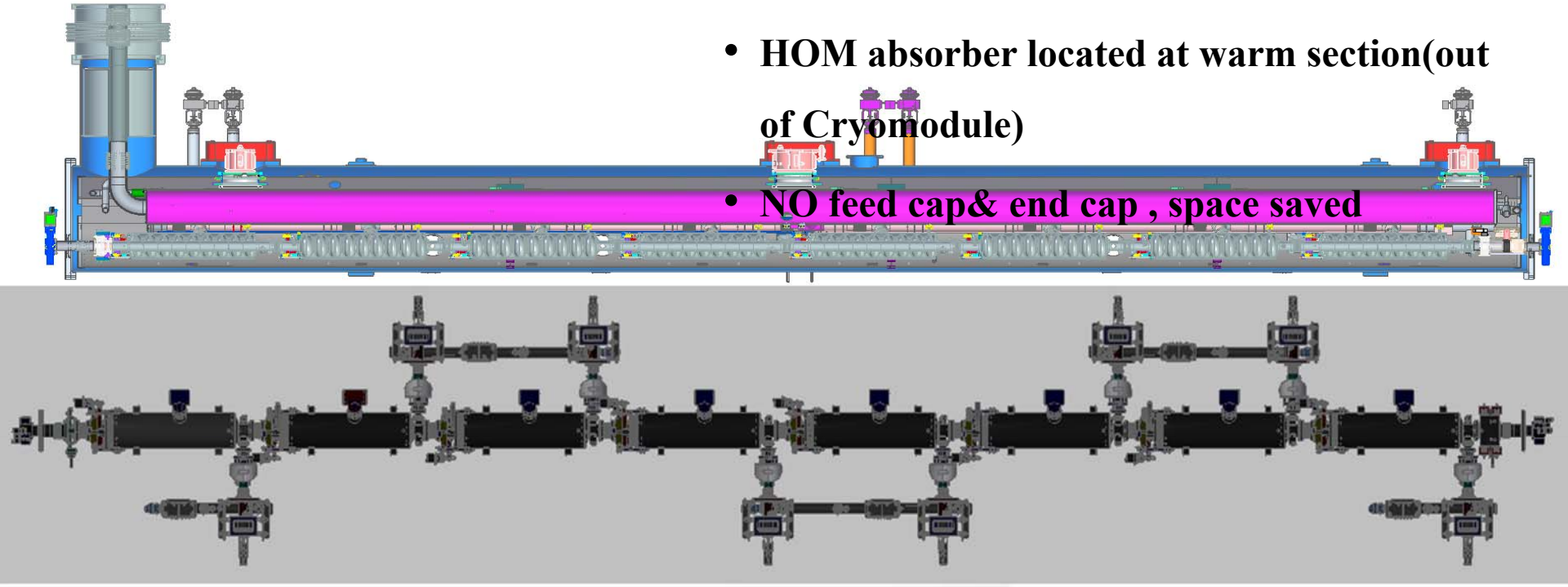
- Symmetrical structure
- Twin-FPC at downstream
- Without HOM couplers
- Enlarge BP diameter at downstream for HOM propagation **(78mm → 110mm)**
- Penetration depth of FPC is 25.5 mm shorter compared to standard type by shorten the length of inner conductor
- The total length of cavity is 149mm longer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

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

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The first Standard 1.3GHz CM for Linac（prototype）

2021.01
CM assembly start

2021.03
CM assembly completed

2021.07.14
First CM cool down and RF test successfully!!!

2022.06
First CM RF test @ 2K completed.

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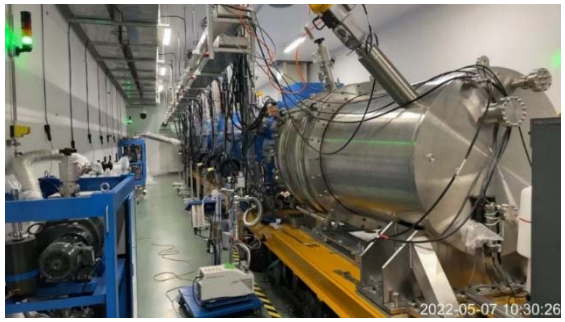
CM prototype RF test

- **First standard 8-cavity (BCP refurbished) CM,** RF tested in June 2022, has reached its basic goal (V_{tot}>:128 MV, average Q_0>1.0E+10, I_d<1 nA).
- **More standard 8-cavity (High Q) CMs,** in preparation, include mid T-baked and N-doped cavities

CM with 8 BCP'ed cavities under testing



BCP 8腔模组Q0 vs CW Voltage-20220613

腔位置	腔	耦合器	OG (MV/m)	CW Volt (MV)	CW Volt (MV)	Pdiss (W)	Pdiss (W)	Q0	Q0	暗电流 (nA)	暗电流 (nA)
#1	HJ002	HJ006	15.24	59.2		75.5		1.12E+10		0.40	
#3	GJ002	DJ002	18.67								
#5	BJ003	CJ001	17.88								
#7	BJ002	HJ003	5.23		130.4		194.0		1.06E+10		0.96
#2	BJ001	HJ002	17.66	71.2		118.5		1.03E+10		0.56	
#4	BJ004	HJ001	15.41								
#6	GJ001	GJ001	19.55								
#8	GJ004	GJ002	15.99								

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Key Components R&D

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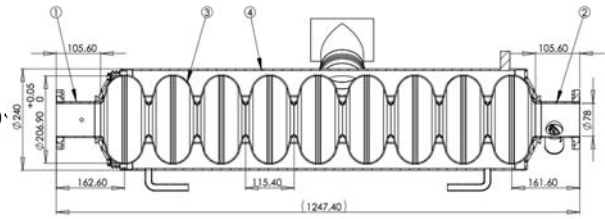
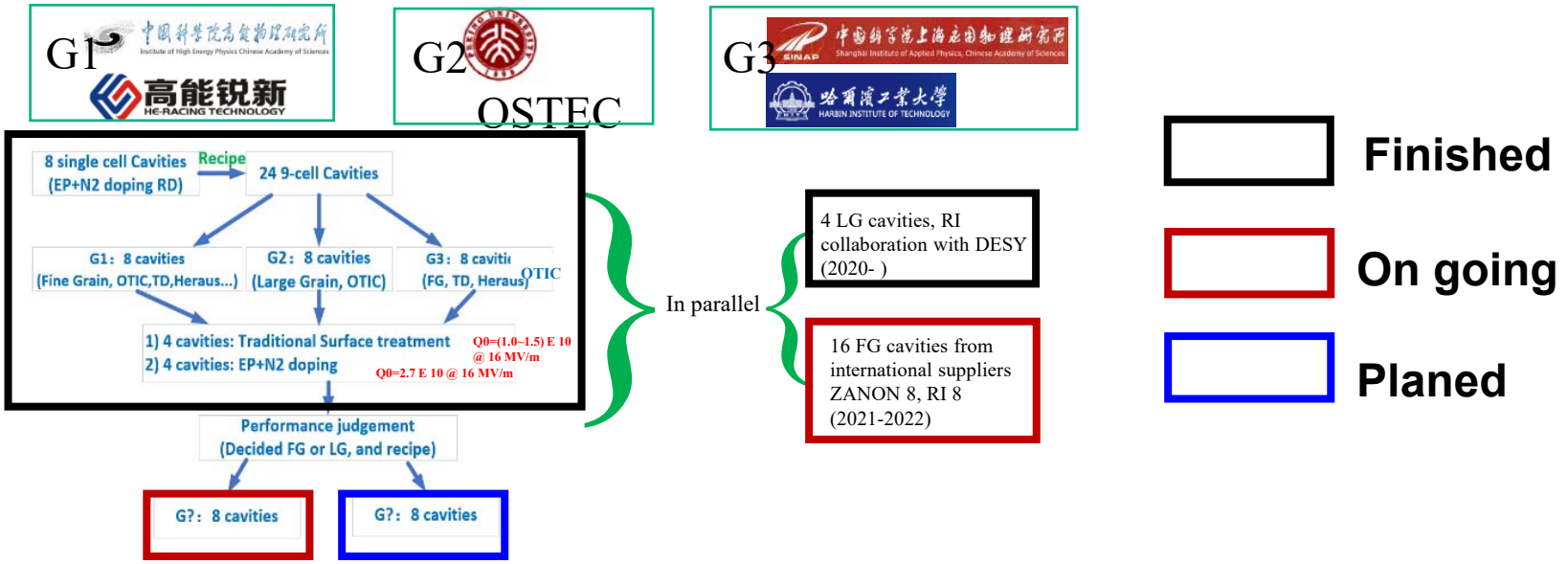
1.3GHz superconducting RF cavity

- 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.





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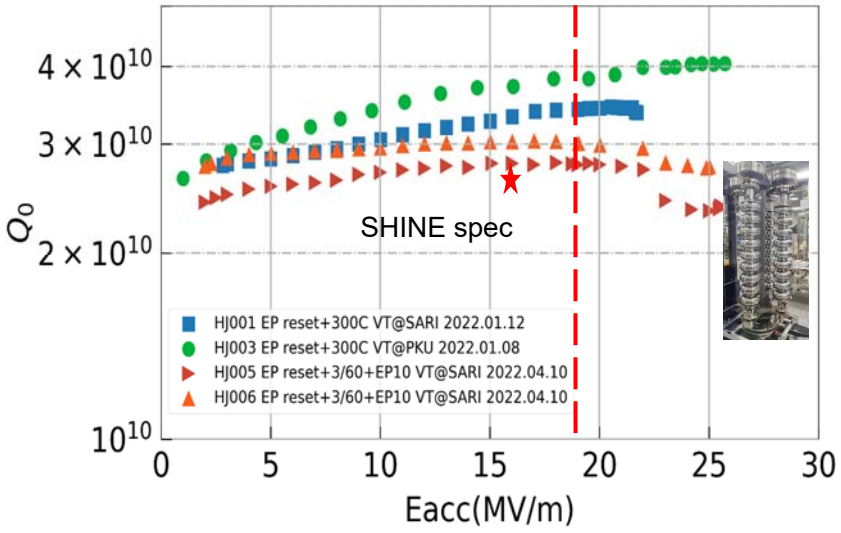
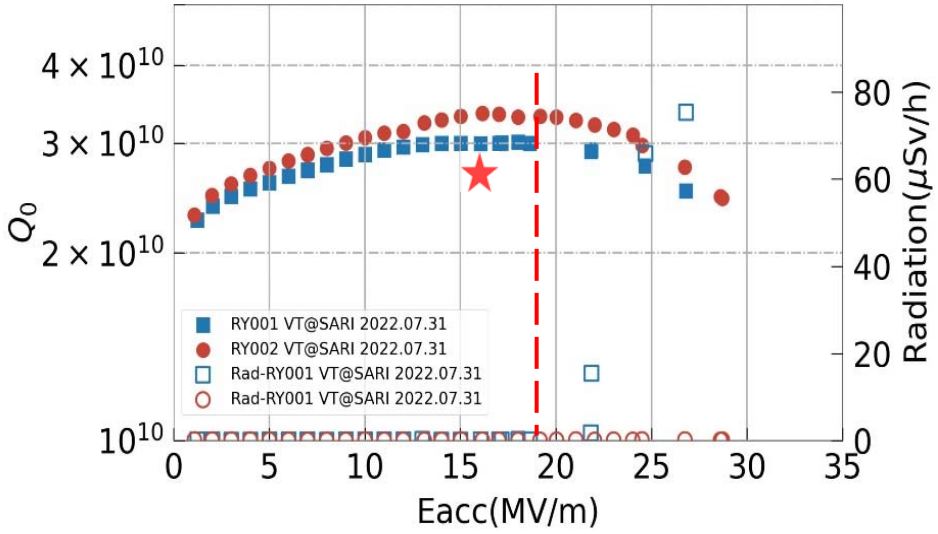
High-Q R&D on 9-cell cavities

- **High-Q technologies** (both N-doping& midT-baking) have been achieved on SHINE 1.3 GHz 9-cell cavities, with Q_0>2.7E+10 @16MV/m and max Eacc>25 MV/m in average.

Cavities treated with SHINE facilities in Wuxi



Cavities produced by RI with SHINE High-Q recipe



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Fundamental Power Couplers

- 30 1.3 GHz FPC prototypes have been manufactured and RF high power tested on the room temperature test bench: CW 14kW in traveling-wave (TW) mode and CW 7kW in standing-wave (SW) mode. Even higher power levels have been demonstrated with TW 20 kW and SW 10 kW.
- Two 1.3 GHz FPCs for double-fed SC cavity have been fabricated and RF power tested with CW 14kW in TW mode and CW 7kW in SW mode.
- Two 3.9 GHz FPC prototypes have been designed and fabricated at SARI. Both of them have passed the RF power tests with a CW power of 2.2 kW in the TW mode and power of 2 kW in the SW mode.

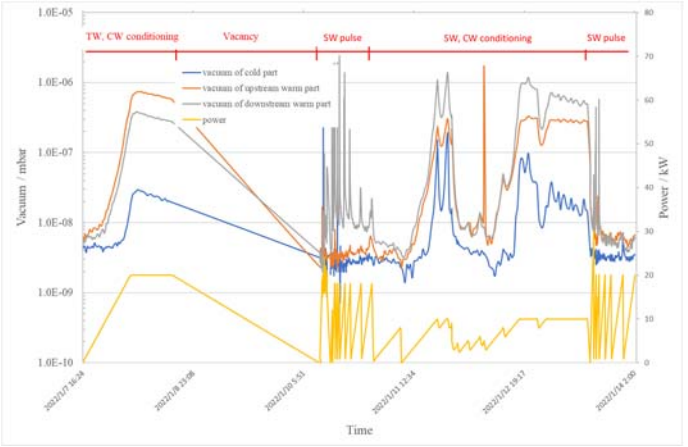

Fig. RF high power tests of 1.3 GHz FPCs

Fig. Fabricated sub-assemblies of 3.9 GHz FPCs

Fig. Test bench for 3.9 GHz FPCs

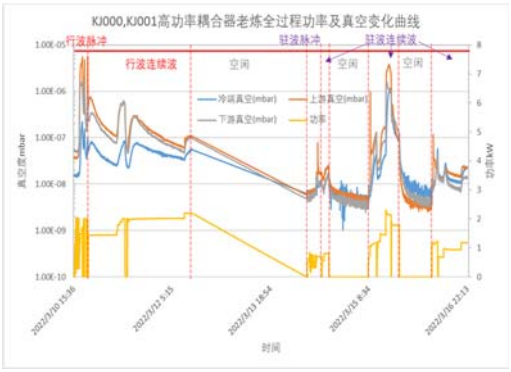

Fig. RF high power tests of 3.9 GHz FPCs

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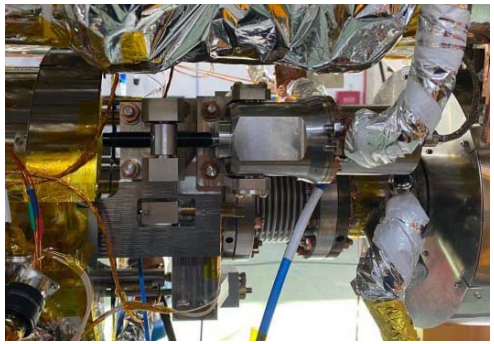
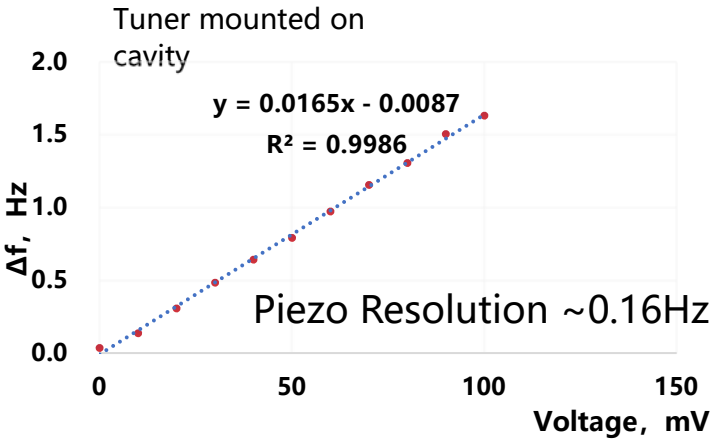
1.3GHz Cavity Tuner





	Design Value	Measured Value
Slow tuner frequency range（Nominal）	≥250 kHz	316kHz~350kHz
Slow tuner frequency range（Maximum）	≥450 kHz	525kHz~560kHz
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	2.7kHz
Fast Tuner tuning resolution	~1 Hz	<1Hz
Tuner stiffness	~30N/μm	34.6N/μm
Operating conditions	Insulating vacuum 1.3E-4Pa ,T=20-60K，Radition doses $5*10^8$rad	
Lifetime	20years	

- **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.**

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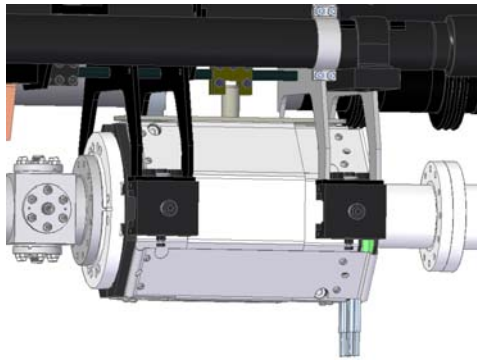
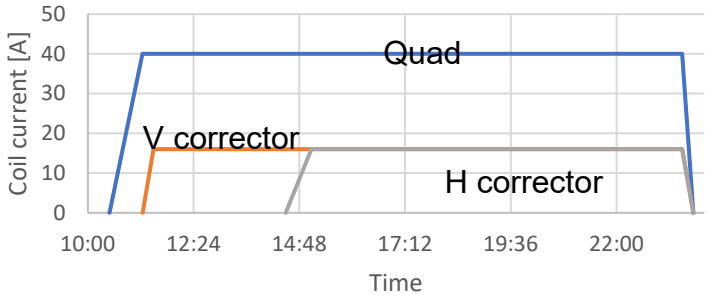
Superconducting quadrupole magnet

Parameter	Unit	Value
Integrate field gradient	T	3
Integrate corrector field	T·m	0.009
pole tip bore diameter	mm	90
Clear bore aperture	mm	>85
Main coil current	A	25
Corrector current	A	10
NbTi superconductor diameter	mm	0.5
Quantity	-	77





Coil current Vs. time, tested in the Single-cavity CM

- Prototype R&D finished: physical requirements are met, major engineering problem solved
- Quantity production will be started this year

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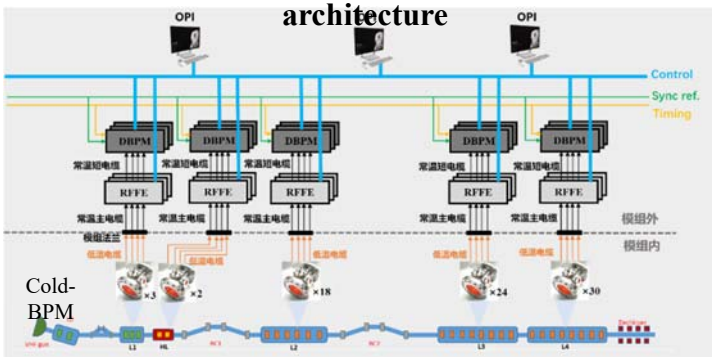
Cold-BPM System

- **A cold-BPM system:** Cold-BPM + RFFE + DBPM + Cables (warm & cold)
- **77** Cold-BPMs distributed in L1 (5), L2 (18), L3 (24), and L4 (30) sections;
- **19** Cold-BPMs (used for test) have been manufactured and 14 of them have been or are under cold-test;
- A special eight-button BPM has been designed and beam tested at SXFEL (warm section):

  32 μm@100pC & horizontal **33** μm@100pC & vertical

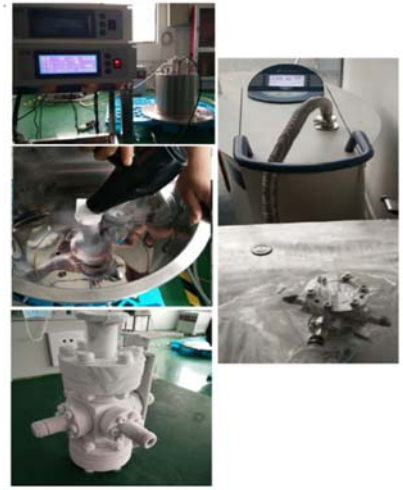
System architecture



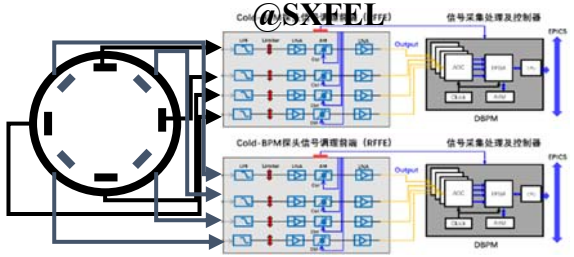

Cold-BPM

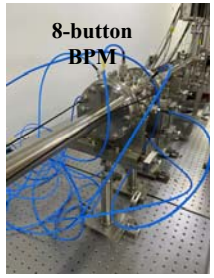

BPM body Feedthrough

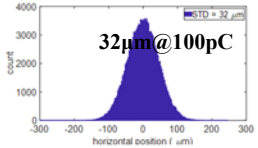
Photo of Cold test

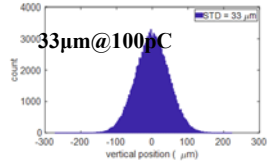


Beam test @SXFEL









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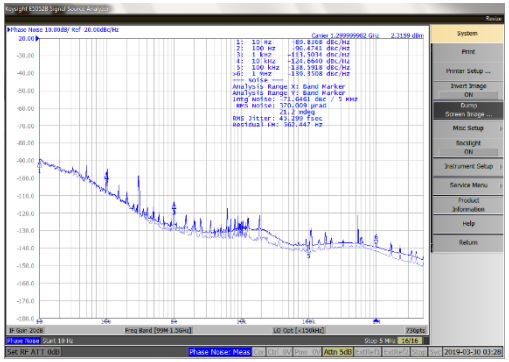
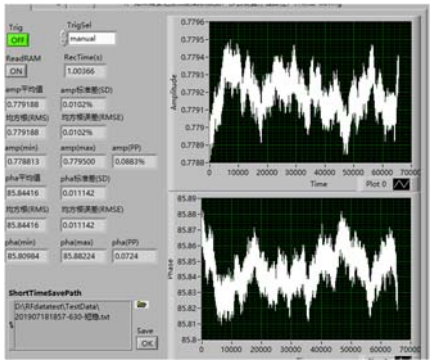
SSA &LLRF

- **4 manufactures develop the SSA in parallel since 2019.**
- **26 sets SSA have reached the specification.**
- **Long term conditioning is under performed in SARI.**

	Requirement	Acceptance test result
Frequency	1.3GHz	1.3GHz
Delay of small signal	<300ns	44ns
1 dB compression	5.2kW @0dBm	5.5kW
Bandwidth(1dB)	1MHz	2MHz@0.1dB
Phase noise	80dBc/Hz(10Hz offset @1.3GHz)	89dBc/Hz
Amplitude stability	0.1% @ 1 second	<0.1%
Phase stability	0.1° @ 1 second	<0.1°
Spur	<-70dBc	<-70dBc
Noise	<10 dB	2dB (90-88)
Harmonic	<-30 dBc	-38 dBc@5th
Efficiency	>40% (at 5.2kW)	45%



Phase noise: 89.8dBc/Hz @offset 10Hz/1.3GHz 45fs(10Hz to 5MHz)



Amplitude: 0.088%, Phase: 0.072

Used in beam test

Used in cavity Horizontal test

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Infrastructure

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Cryoplant

1kW@2K Cryoplant

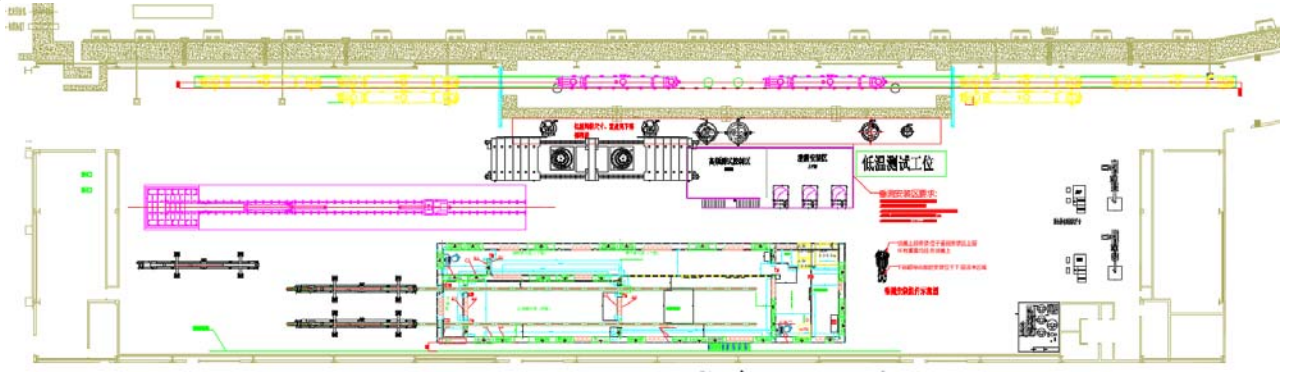
the largest superfluid helium cryogenic system in China with 1kW@2K has turned into operation to support the continuous RF test.

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.

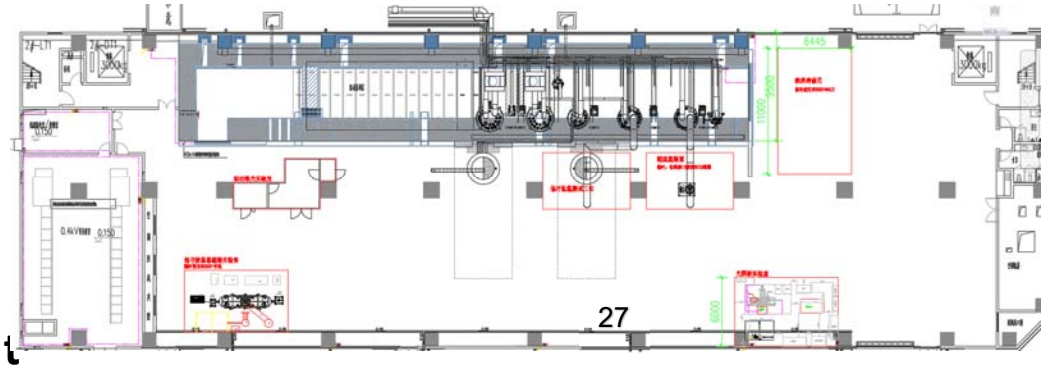
Assembly and test Halls for SHINE

- Two 3000m^2 halls for CM assembly and test ready.
- 1kW@2K He system under commissioning.
- Main facilities in workshop



Components inspection
Cavity vertical test
Coupler conditioning and test
Clean room

measurement
CM assembly
CM horizontal test



Wuxi platform for SRF cavity surface-treatments

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

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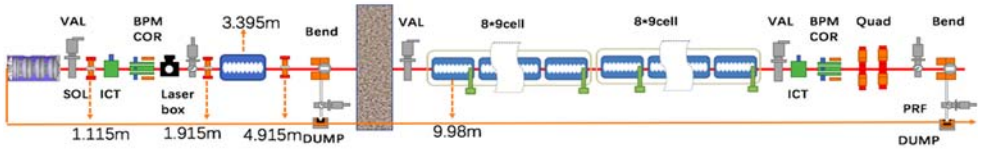
Beam test facility

Objectives

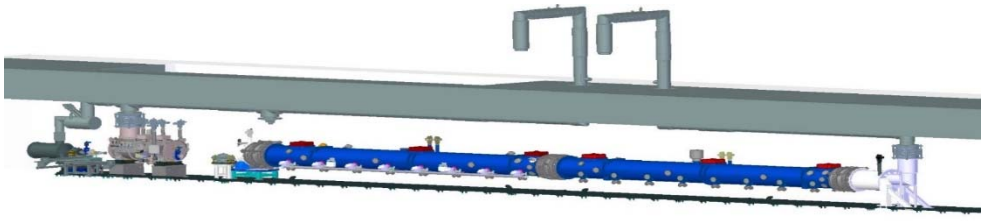
- Confirm the CM dynamic performance
- Test CW related components, system and technology with beam
- Confirm operation reliability and safety of hardware
- Accumulate the operation experience for SC Linac

- Beam energy: 300MeV (Max)
- Beam charge: 300pC (Max)
- Average current: 0.1mA (Max)
- 20.03~22.10，Design and construction
- 22.10~23.06，Commissioning and beam test

Layout of the facility



Drawing of facility in #2 hall tunnel



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Summary

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1. **Civil construction near completion , machine installation will begin in the next months.**
2. **Design for special CMs are completed, all the components are in production.**
3. **HT has been carried out successfully for 1.3GHz CM prototype:acceleration gradient~130MV, Q_0 is 1.06E10@16MV/m, dark current is 0.96 nA.**
4. **Some progress has been made on: high-Q R&D on 9-cell cavities, fundamental Power Couplers, HOM absorber ,microphonics and so on.**
5. **Signifcant progress have been made for infrastructure in the past 3 years: Wuxi cavity surface treatment platform, cryogenic-plant, CM assembly halls, beam test facility.**

Thank You!

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