SRF Status of the SHINE Project at Shanghai

Hou Hongtao for the SHINE Project Team

SRF2019 Conference, Dresden, Germany

July, 2019

Outline

- Introduction of SHINE
- SHINE progress
- SRF R&D and prototypes Progress
- Infrastructures progress
- Summary

SHINE

Introduction

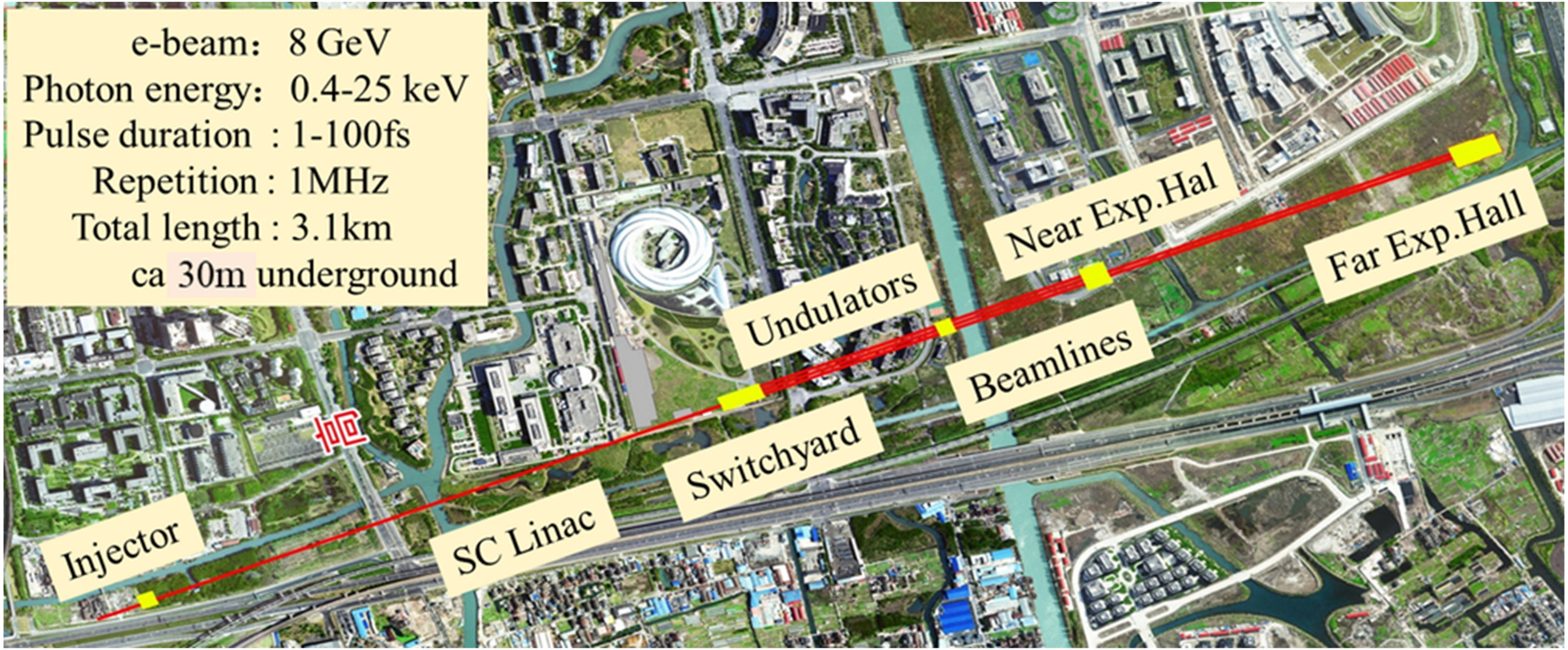
Shanghai Hard X-ray FEL Facility (SHINE)

- SHINE is a high rep-rate XFEL facility, based on an 8 GeV CW SCRF linac, under development in Shanghai;
- This facility will be built in a 3.1 km long tunnel underground at Zhang-Jiang High Tech Park, across the SSRF campus;
- This XFEL facility has 3 undulator lines and 10 experimental stations in phase-I, it can provide the XFEL radiation in the photon energy range of 0.4 -25 keV.
- This XFEL project was approved by the central government in 2017, and its groundbreaking was made in April, 2018, aiming at starting user experiments in 2025.

This facility will be developed by Shanghai-Tech Univ., SARI and SIOM of Chinese Academy of Sciences.

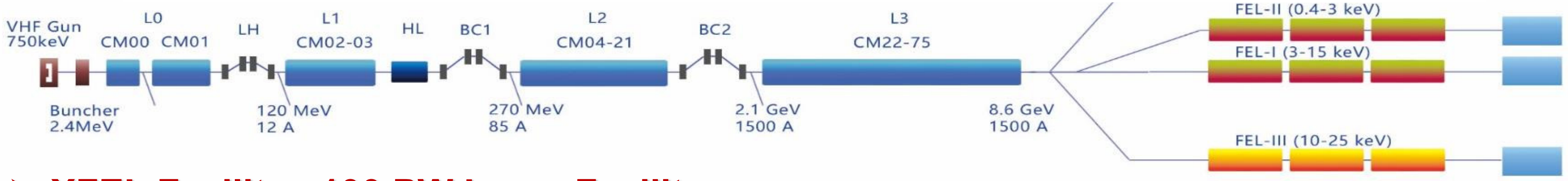
SHINE

Shanghai Hard X-ray FEL Facility (SHINE)



SHINE

SHINE: A high-rep rate XFEL based on SCRF

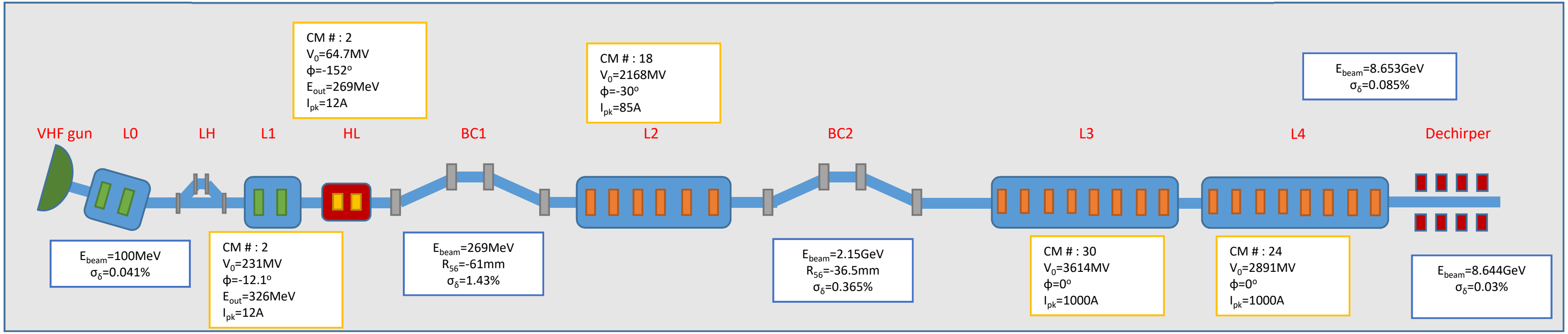


- **XFEL Facility +100 PW Laser Facility**

	Nominal	Range
Beam energy/GeV	8.0	4-8.6
Bunch charge/pC	100	10-300
Max rep-rate/MHz	1	up to 1
Beam power/MW	0.8	0 - 2.4
Photon energy/keV	0.4-25	0.4-25
Pulse length/fs	20-50	5-200
Peak brightness	5×10^{32}	1×10^{31}-1×10^{33}
Average brightness	5×10^{25}	1×10^{23}-1×10^{26}
Total facility length/km	3.1	3.1
Tunnel diameter/m	5.9	5.9
2K Cryogenic power/kW	12	12
RF Power/MW	2.28	3.6

FEL Line	Nominal	Objective
FEL-I		
Photon energy/keV	3-15	3-15
Photon number per pulse @12.4keV	$>10^{10}$	$>10^{11}$
Max pulse repetition rate/MHz	0.66	1
FEL-II		
Photon energy/keV	0.4-3	0.4-3
Photon number per pulse @1.24keV	$>10^{12}$	$>10^{13}$
Max pulse repetition rate/MHz	0.66	1
FEL-III		
Photon energy/keV	10-25	10-25
Photon number per pulse @15keV	$>10^{9}$	$>10^{10}$
Max pulse repetition rate/MHz	0.66	1

Layout of the SHINE accelerator



Injector Parameters	Value
Beam energy (MeV)	**100**
Bunch charge (pC)	**100**
Normalized emittance (95%, um·rad)	**0.4**
Slice energy spread (10^{-4})*	**0.1/0.5**
Bunch length, rms (mm)	**1**
Peak current (A)	**12**

Linac	No. of CM's	Avail. Cavities	Powered. Cavities*	Gradient (MV/m)	Eout (MeV)
L0	1	8	7	16.3	100
L1	2	16	15	14.8	326
HL	2	16	15	12.5	269
L2	18	144	135	15.5	2148
L3	30	240	225	15.5	5762
L4	24	192	180	15.5	8653

- **750kV VHF gun +Single cavity CM + 1.3GHz SCRF cryomodules: 75 + 3.9GHz SCRF cryomodules: 2**

SHINE Progress

- Groundbreaking was made on April 27, 2018. Construction of shafts is in good progress;
- Accelerator engineering design, technical infrastructure development, key technology R&D, component prototyping and long-lead equipment procurements are underway ；
- Beamline design optimization are being carried out, R&D of key optics component, and Pixel array detector started;
- Technical and engineering design of high energy OPCPA, R&D of key laser technologies for SEL are in progress;
- …

SHINE

SHINE

Outline

- ➢Introduction of SHINE
- ➢SHINE progress
- ➢**SRF R&D and prototypes Progress**
- ➢Infrastructures progress
- ➢Summary

SRF R&D and prototypes progress

- Accelerator engineering design, technical infrastructure development, key technology R&D, component prototyping and long-lead equipment procurements are underway
- Three years on R&D and prototypes: 2018-2021
- Wide collaboration in China on SRF prototypes
- Hope and Welcome worldwide collaboration with Labs / Institutes / Companies on SRF technologies

SHINE SRF system

- 8.0 GeV 1MHz repetition rate, CW SC Linac based on TESLA / E-XFEL 1.3 GHz technology
- Totally, 600 1.3GHz SC cavities, 16 3.9GHz SC cavities

Parameter	Length	Cell shape accuracy	Straightness	f @ RT, Vacuum	f @ 2K,Vacuum	Field flatness (bare cavity)	Field flatness (dressed cavity)
SHINE	mm	mm	mm	MHz	MHz	/	/
	1283.4±3.0	±0.2	<0.4	1298.2±0.1	1300.2±0.1	>95%	>90%

- High-Q0 cavities required, Q0=(2.0~3.0) e10 @ Eacc=14 ~ 18 MV/m; **Baseline: EP+N2 doped fine grain cavities or traditional EP-ed large grain cavities**
- Worldwide Industrial mass production for 1) dressed cavities (ready for VT); 2) cryostats ;3) couplers ;4) HOM absorbers
- Prototype collaboration in China, R&D on cavity fabrication, surface treatment and vertical test
- Construction of a surface treatment platform for cavities and a Workshop for VT, clean assembly, cryomodule integration and horizontal test, is underway
- Digital LLRF with solid state power source: one source one cavity

SHINE

Cavity prototype

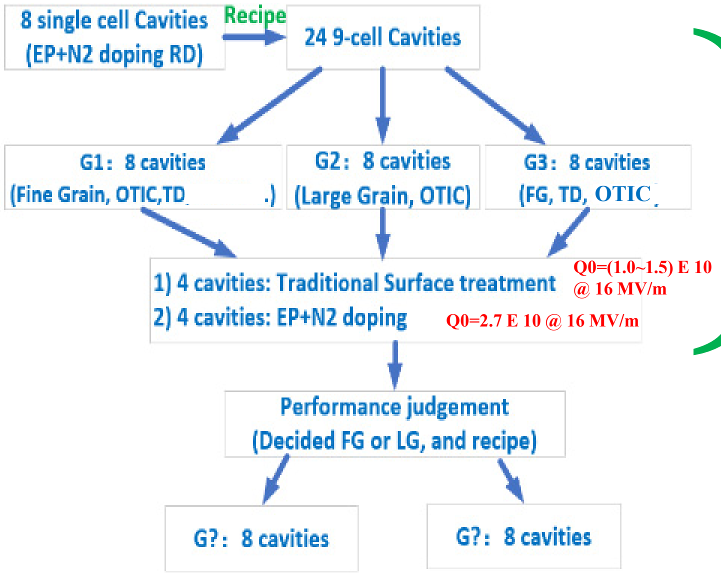
three groups for cavity fabrication and high Q0 studies (EP & N-doping)

G1

G2

OSTEC Ningxia

G3



Totally, 48 prototype dressed cavities

Phase-I — In parallel →

- 4 LG cavities with DESY (OTIC Nb material)
- 4 FG cavities from companies outside China

Phase-II Meet specification and fix doping recipe

SHINE

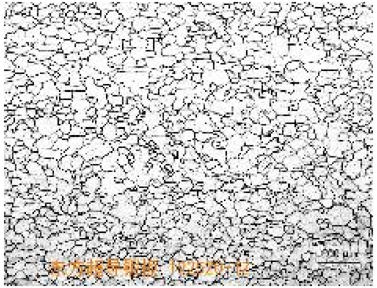
Key technology and techniques

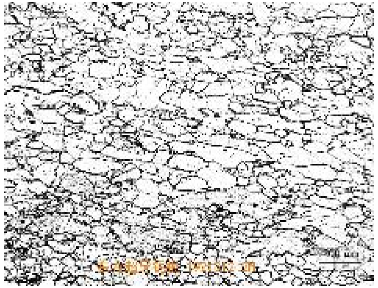
- **Frequency & length control:** half cell, dumb-bell, End-groups, whole 9-cell pre-tuning, HOM tuning; helium vessel welding;
- **Surface treatment**
  - Electro-polishing (EP): adopting EP to obtain fine inner surface, EP instrument and operating parameters; acid temperature and voltage control;
  - Nitrogen doping: high temperature annealing and N2 doping, find optimal N2 pressure, lasting time and following slight EP thickness; (LCLS-II: N2-A6-EP5)
  - High Pressure Rinsing (HPR): important to cure field emission
- **Clean room assembly** techniques: crucial for high performance cavity
- **Fast cooldown and flux expulsion:** to obtain low earth magnetic field for high Q0 performance;

SHINE

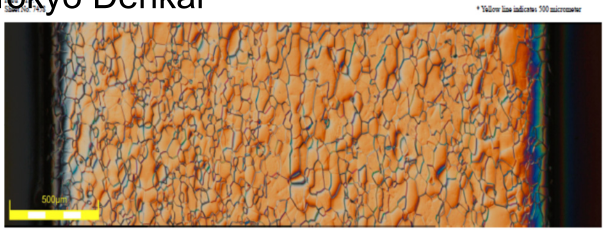
Nb sheets for prototypes

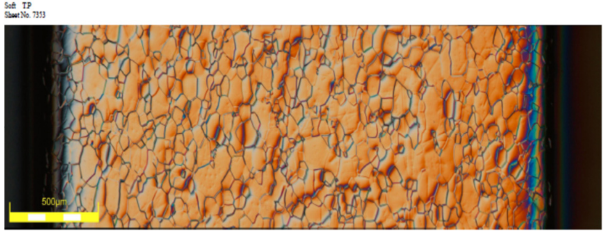
OTIC NX





Tokyo Denkai





SHINE

- Define grain size: ASTM 6, no smaller than ASTM 7.
- Hope to find the relation between grain size and the doping cavity performance.
- NX material: RRR> 300, in average, grain size= ASTM4.5 ~ 5.5, HV10=56.9 , elongation= 58.8~62.8,
- TD material: RRR> 300, in average grain size= ASTM 5~6. HV=38.7~51.6, elongation ~ 60
- Single cells have been welded, surfaced treated and some of them vertical tested.
- Quality control of sheets——EXFEL 007 as reference
- Re-test of Nb material by SHINE are in process

Spec.

- RRR value: ≥300
- Tensile strength –Rm>140 MPa
- Yield strength Rp 0.2= (50 ~ 100) MPa
- Elongation AL 30 ≥ 30%
- Hardness ,HV≤ 60

Substitutional elements 杂质成分	Content（ppm） 含量(ppm)	Interstitial elements 杂质成分	Content (weight ppm) 含量（质量 ppm）
Ta / 钽	≤ 500	H / 氢	≤ 2
W / 钨	≤ 70	N / 氮	≤ 10
Ti / 钛	≤ 50	O / 氧	≤ 10
Fe / 铁	≤ 30	C / 碳	≤ 10
Mo / 钼	≤ 50		
Ni / 镍	≤ 30		

Recent results of cavity prototypes

- **Group-1: 4 FG cavities fabricated, BCP treated, 2 was vertical test; one dressed cavity vertical tested**
- **Group-2: 2 LG cavities fabricated, BCP treated, vertical test**

See also H.T.HOU et al., MOP049
F. S. He et al., FRCAA5

Table 2: Performance of fabricated FG and LG cavities

Cavity number	FG#1	FG#2	LG#1	LG#2
Cavity length @ RT & 1.0 bar (mm)	1284.55	1283.59	Not measured	Not measured
Field flatness (%)	95.0	98.0	98.4	97.4
Freq. @ RT & 1.0 bar (MHz)	1298.22	1298.17	1298.11	1298.07
Freq. @ 2K vacuum (MHz)	1300.25	1300.20	1300.38	1300.44
Q_0 @ 16 MV/m @ 2.0K	1.50×10^{10}	1.15×10^{10}	1.75×10^{10}	1.89×10^{10}
Q_0 @ 16 MV/m @ 1.8K	/	1.31×10^{10}	3.00×10^{10}	3.20×10^{10}
Maximum gradient (MV/m)	20.0	19.6	25.3	26.0
Gradient limited by	N-connector broken	quench	LHe	quench

- FG cavities met the specification on length, frequency, flatness, and Q0 ~ Eacc met the requirement of BCPed cavity .
- As LG cavities, length is not measured yet, frequency is a little higher, Q0 ~ Eacc met the requirement of BCPed cavity.

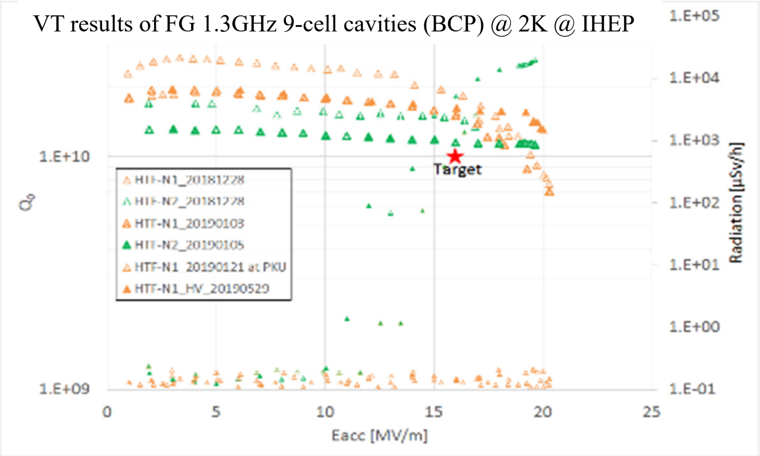
Latest news: #3 and #4 cavities (BCPed, NX sheets) have been vertical tested, max gradient reaches 25 MV/m and 26 MV/m, respectively. Q0~ 1.8×10^{10} @ E_{acc}=16 MV/m. See more detail **in FRCAA5.**

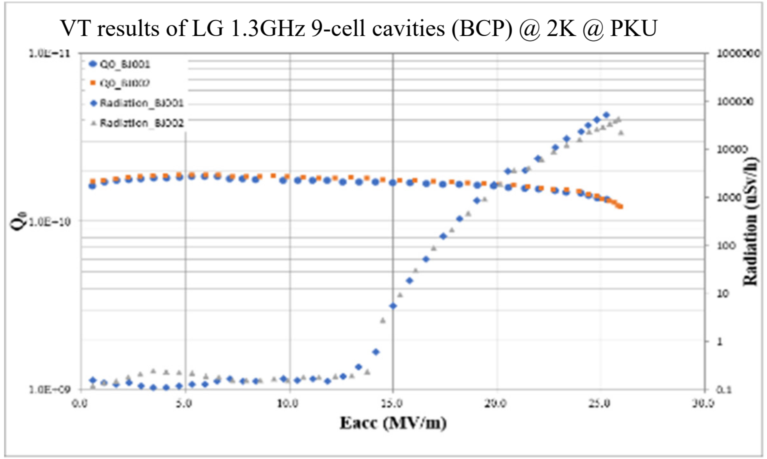
1st FG cavity, Dec. 2018

LG cavity, Feb. 2019

SHINE

Recent results of cavity prototypes





- Gradient limited, difficult to tell the defects, lack of diagnostic instrument such as T mapping and X-ray mapping.
- #1 and #2 FG cavities' gradient is limited to 20 MV/m, #2 has X-ray radiation, FE arose ~10 MV/m
- LG cavities' gradient is limited to ~26 MV/m, both have X-ray radiation, FE arose ~ 14 MV/m
- Clean (surface and assembly) is always a big challenge!

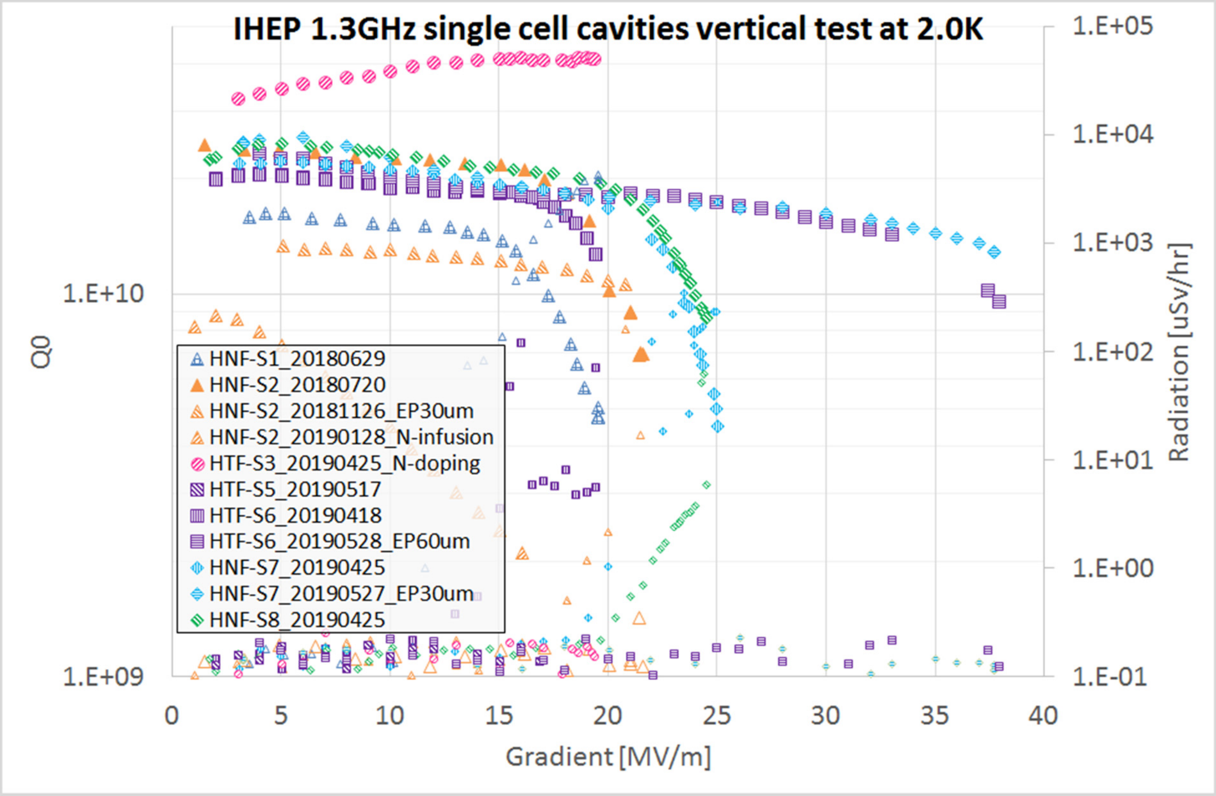
Recent results of cavity prototypes

- Camera was used to inspect the inner surface on #3 FG cavity
- No obvious defect at the equator welding area.
- However, some suspected spots at the welding area. Are these defects?
- #3 FG cavity: Vertical testing is completed on June 30. Maximum gradient reaches 25 MV/m, Q_0~ 1.8×10^{10} @ E_{acc}=16 MV/m. It seems these kinds of spots didn't bring much limitation to gradient.
- **How to qualify the welding joints is another challenge.**

See also H.T.HOU et al., MOP049
F. S. He et al., FRCAA5

SHINE

EP and N-doping studies with IHEP and PKU

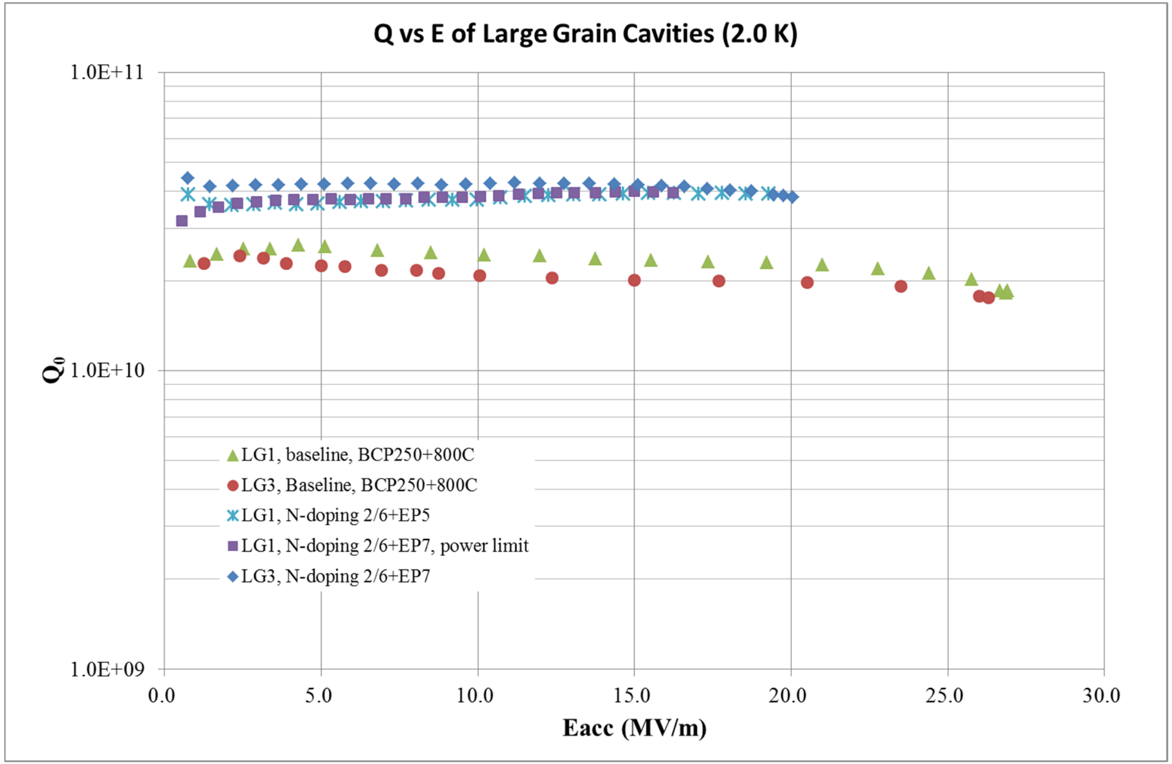


FG single cell cavity @ IHEP

- N-doping studies: S3, Q-inverse, Q0~ 4e10 @ 16 MV/m
- EP studies on FG material from NX and TD: S6_TD, S7_NX, gradient has been improved to ~ 38 MV/m
- See more detail in F. S. He, FRCAA5.

SHINE

EP and N-doping studies with IHEP and PKU

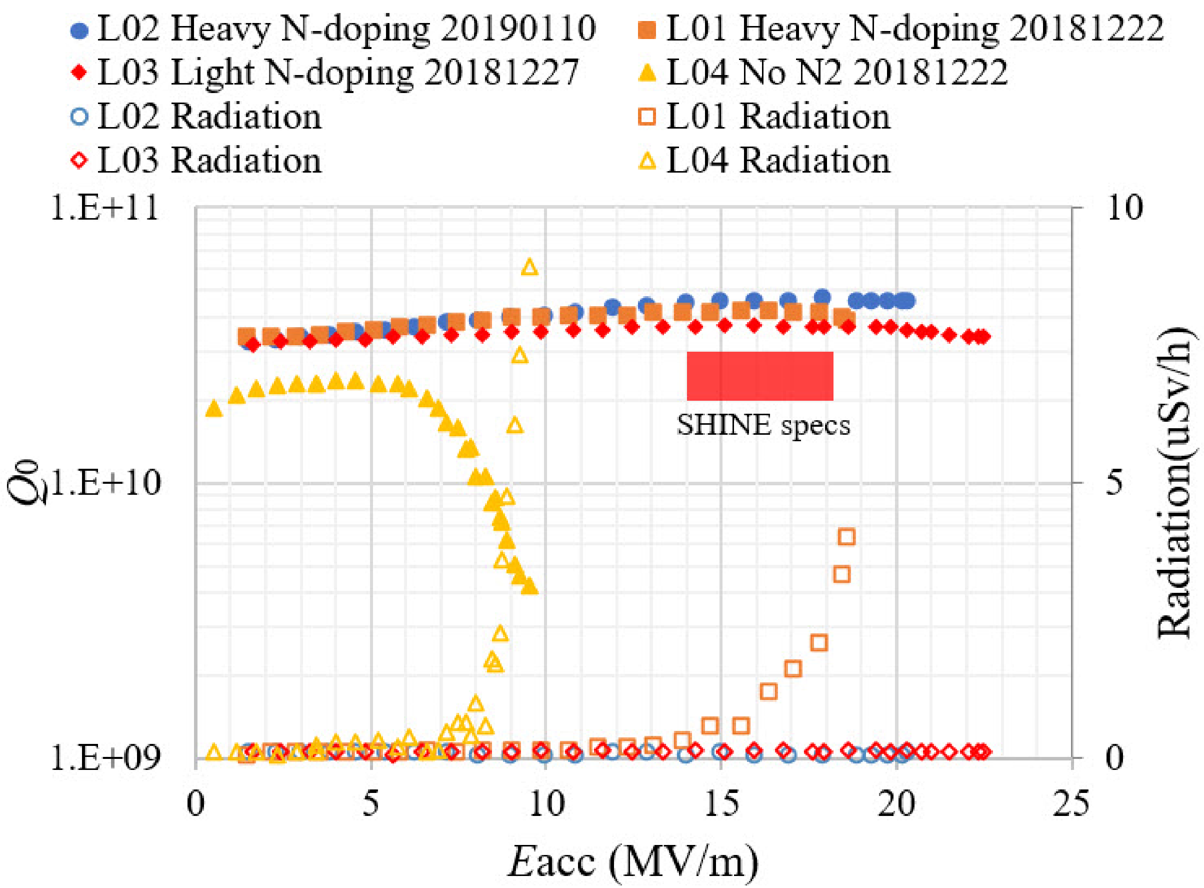


LG single cell cavity @ PKU

- LG material from NingXia
- Base line: BCP 250 μm + 800°C 3hr
- N-doping: N-doping 2 min/annealing 6 min + EP (different thickness)
- Q0= 3.8E10@20MV/m
- More detail in MOP039, Shu CHEN

SHINE

N-doping studies at SARI

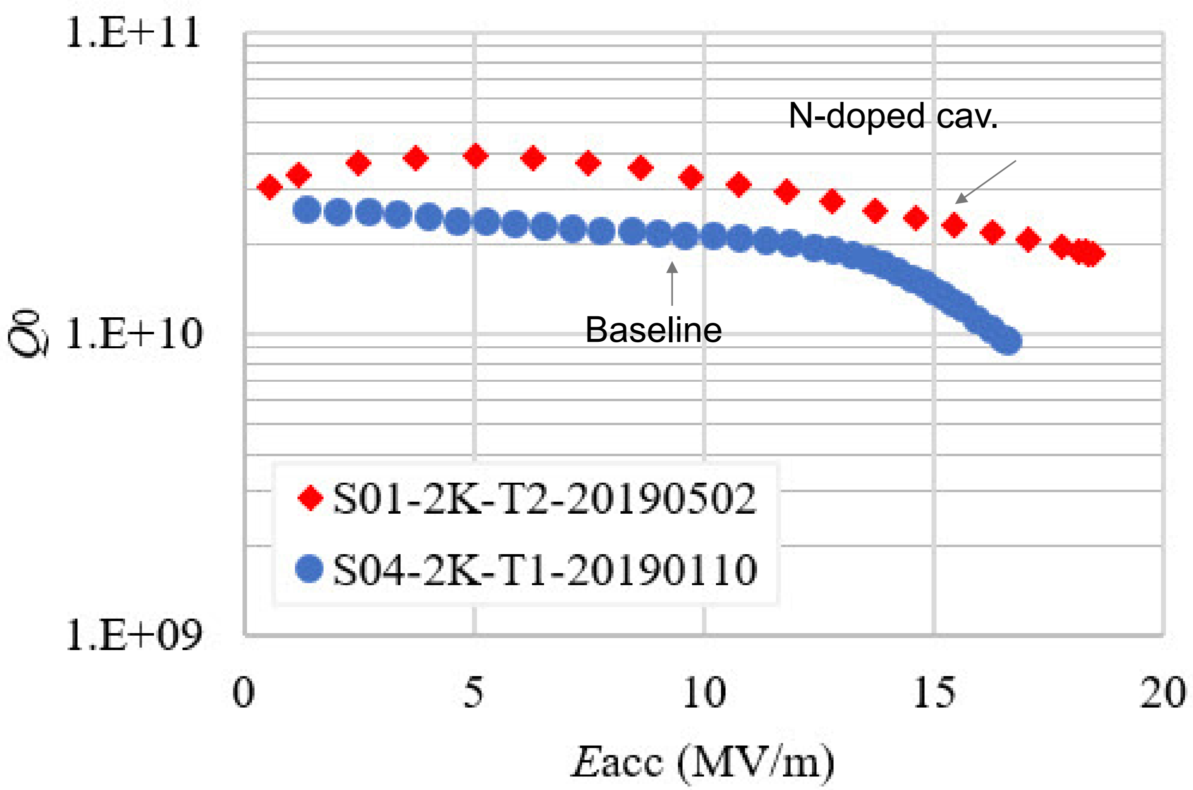


1.3 GHz large-grain single-cell cavities, fabricated from Ningxia Nb, vertical tested at PKU

- L01, L02 N-doping : 800℃ 3h + N20/A30@~3.3Pa+ EP15
- L03, N-doping: N-doping: 800℃ 3h + N2/A6@~3.3Pa+ EP5
- L04, Baseline: BCP250 + 800℃ 3h + BCP20

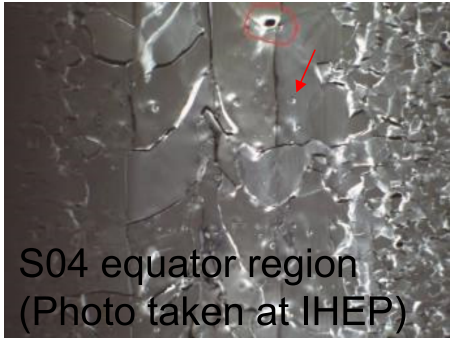
See also J.F. Chen et al., MOP029

N-doping studies at SARI



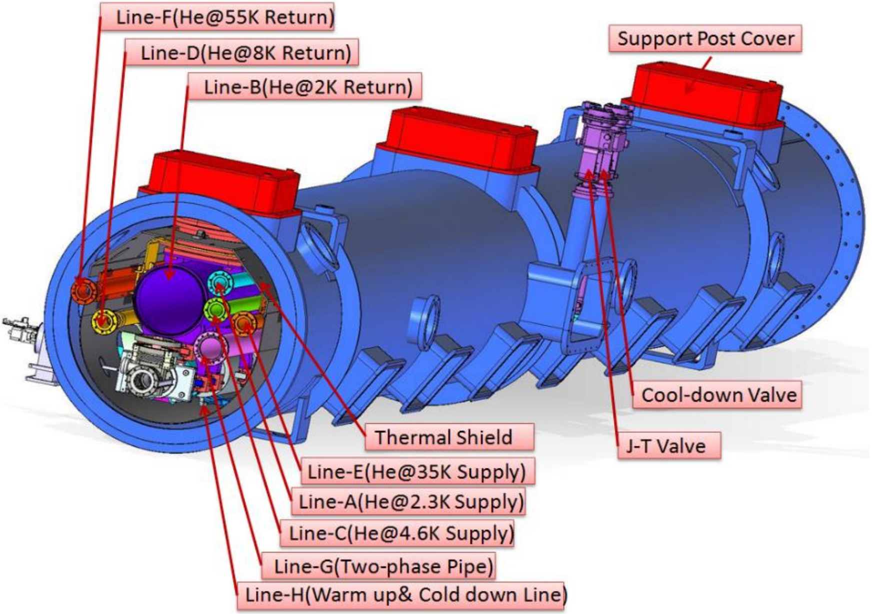
1.3 GHz fine-grain single-cell cavities, with NX Nb, tested at PKU

- S01 N-doping: 975℃ 3h + N20/A30@~3.3Pa + EP20
- S04 BCP baseline: quenched early, with spots/pits at the equator region after BCP.



SHINE

Cryostat Prototype



Insulation vacuum chamber

Cryogenic pipes

Thermal shield

Pipe	Description	Pipe ID [mm]	Design Pressure [bar]	Operating Temperature [K]
A	2K-Helium supply	55	20	2.3
B	2K-Helium gas return	300	4	2
C	Low temperature intercept supply	55	20	5
D	Low temperature intercept return	51	20	5
E	High temperature shield supply	55	20	40
F	High temperature shield return	53	20	40
G	Two phase pipe	98	4	2
	Chimney	98	4	2
H	Cool down/warm up Line	39	4	5

1. Fabrication completed
2. Arrive at SARI
3. Acceptance test
4. To be assembled with cavities, couplers, tuners, cold BPM and SC magnet.

SHINE

Coldmass integration training

- Integration has been completed twice.
- Functions of tools are verified.

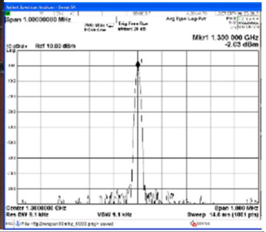

First integration

Cantilever


Second integration

SHINE

Solid-state power source and LLRF

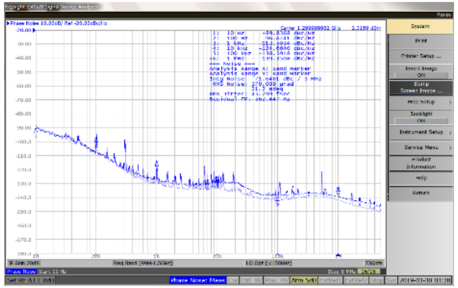


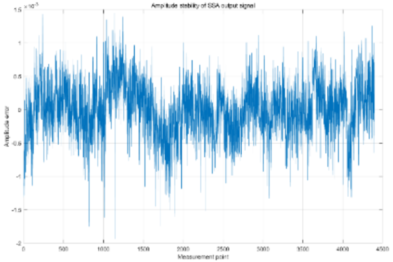
Frequency	1.3GHz
Delay of small signal	<300ns
1 dB compression	5.2kW @0dBm
Bandwidth(1dB)	1MHz
Phase noise	80dBc/Hz(10Hz offset @1.3GHz)
Amplitude stability	0.1% @ 1 second
Phase stability	0.1° @ 1 second
Spur	<-70dBc
Noise	<10 dB
Harmonic	<-30 dBc
Input voltage	3×380 V AC ± 5%
Efficiency	>40% (at 5.2kW)
RF output	WR650
Reliability	Modular design, keep operation if one module broken

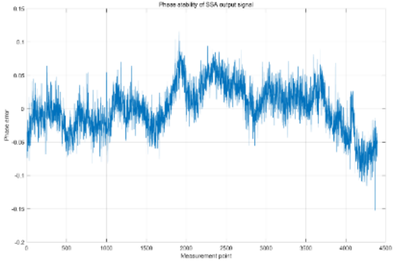
SHINE

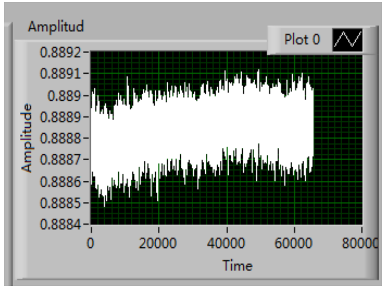
Performance:

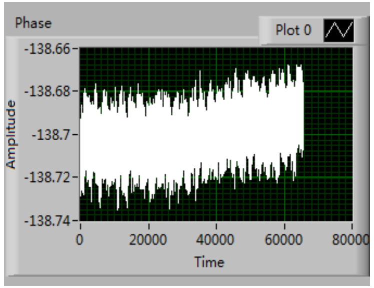
- 5.2 kW output power with 0dBm input signal
- Bandwidth (1dB): 1.0 MHz
- Modular design: plug in type; keep operation when one module broken;









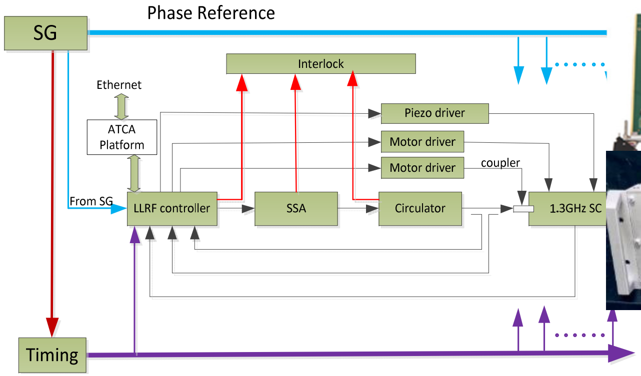


A & P stability in 1 second: < 1% and < 0.1 °

A & P stability in 20 mins: < +/- 2% and < +/-0.15 °

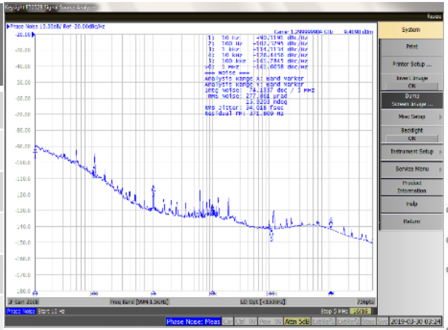
Solid-state power source and LLRF

- **Digital LLRF**
  - FPGA based technology
  - Feedback algorithm
  - Prototype developed, tested
  - Microphonics suppression is under design

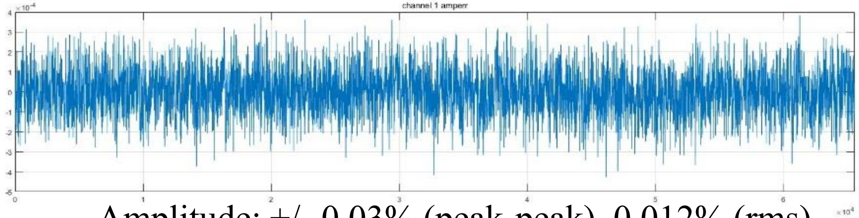


Specification

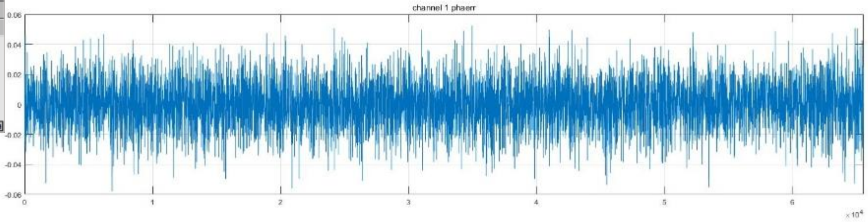
	CM number	Cavities	Amp. Stability %（rms）	Phase Stability deg（rms）
L0	1	8	0.01	0.015
L1	2	16	0.01	0.01
HL	2	16	0.01	0.01
L2	12	96	0.01	0.01
L3	60	480	0.01	0.015
Total	75+2	600+16		



Phase noise of LLRF output: 34 fs



Amplitude: +/- 0.03% (peak-peak), 0.012% (rms)



Phase: +/- 0.04° (peak-peak), 0.016° (rms)

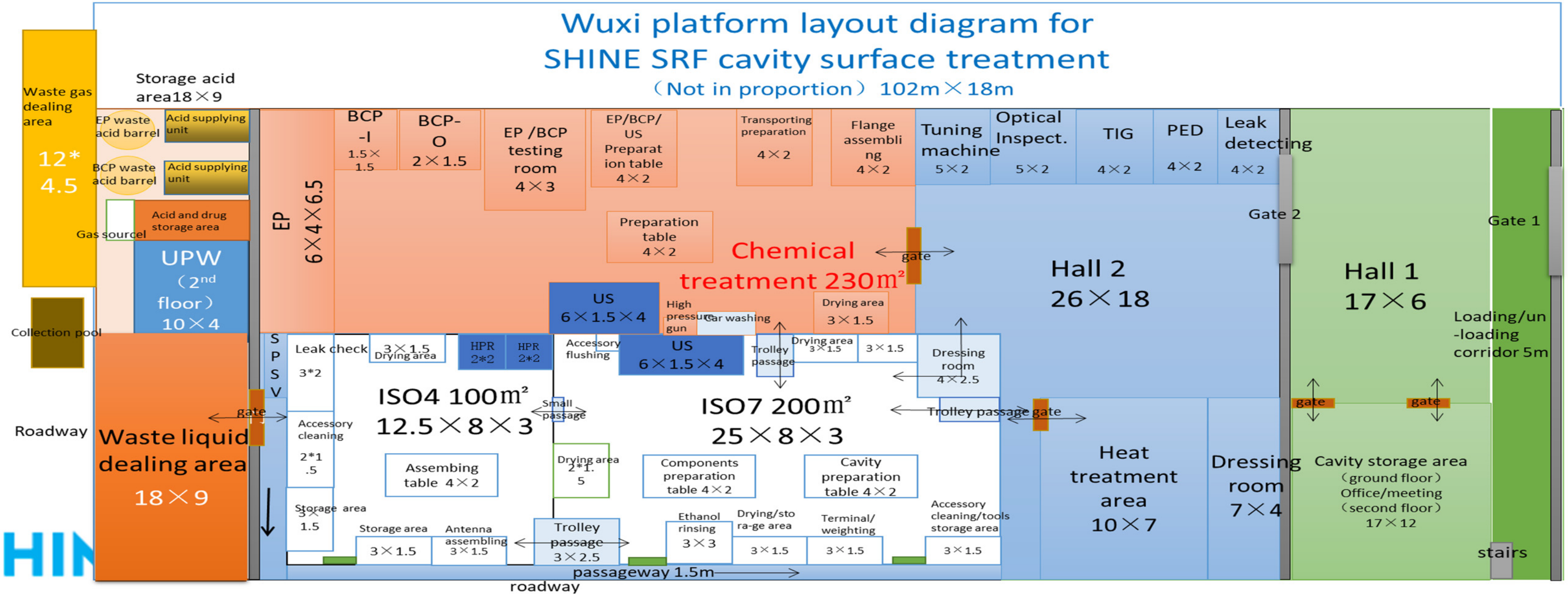
SHINE

Outline

- Introduction of SHINE
- SHINE progress
- SRF R&D and prototypes Progress
- **Infrastructures progress**
- Summary

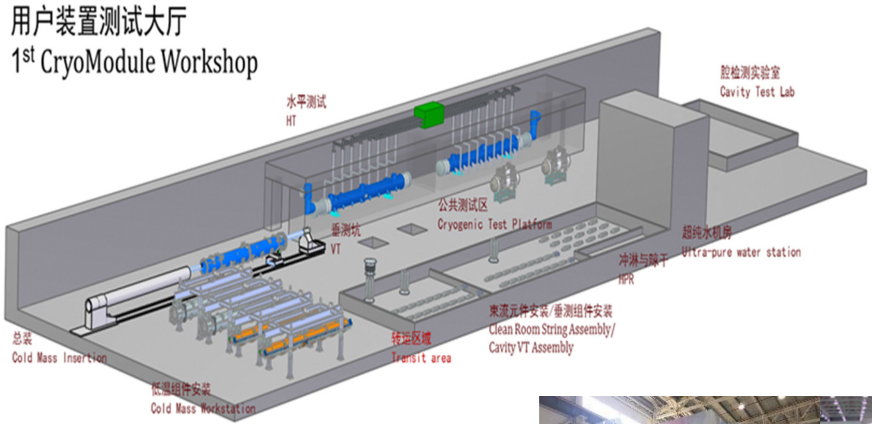
Infrastructures progress
Surface treatment platform

- **Main areas:** Clean rooms (ISO4-100m2, IOS7-200m2), Chemistry area, waste dealing area and normal area.
- **Main equipment: EP, BCP, Furnaces, HPR, Optical inspection device, Tuning machine etc.**
- **Present status:** Start renovation on the existing building.



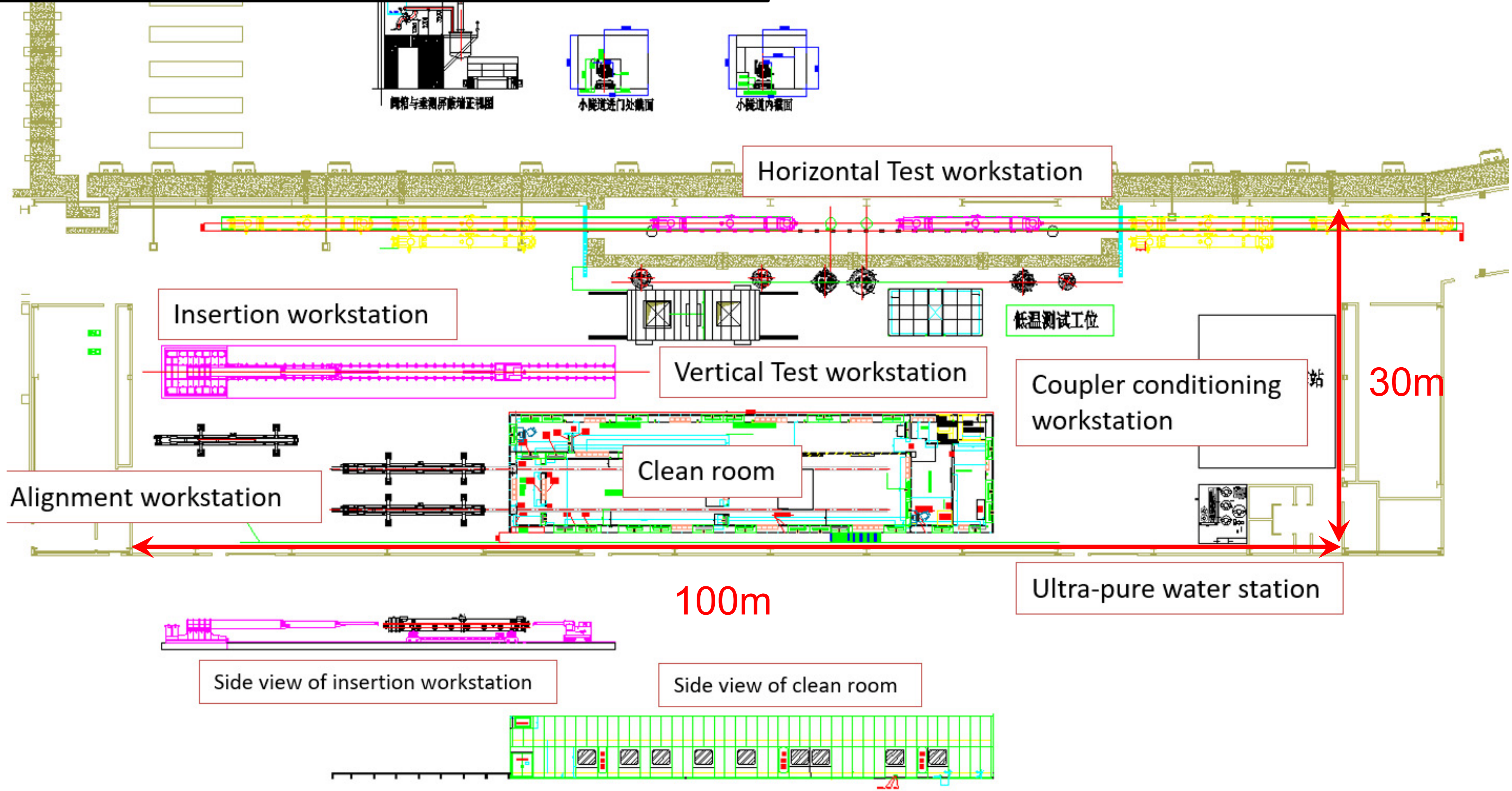
Construction of the CryoModule Workshop

- A 3000 m^2 cryomodule assembly and test workshop with an 1kW @ 2K cryogenic system is under construction at SSRF campus.



- Main capabilities
  - Components inspection
  - Cavity vertical test: 2 test stands
  - Coupler conditioning and test
  - Clean room assembly: cleanroom nearly ready, ISO 4> 200 m^2
  - Cold mass assembly
  - SC magnet measurement
  - CM assembly
  - CM horizontal test: 2 CMs in one tunnel

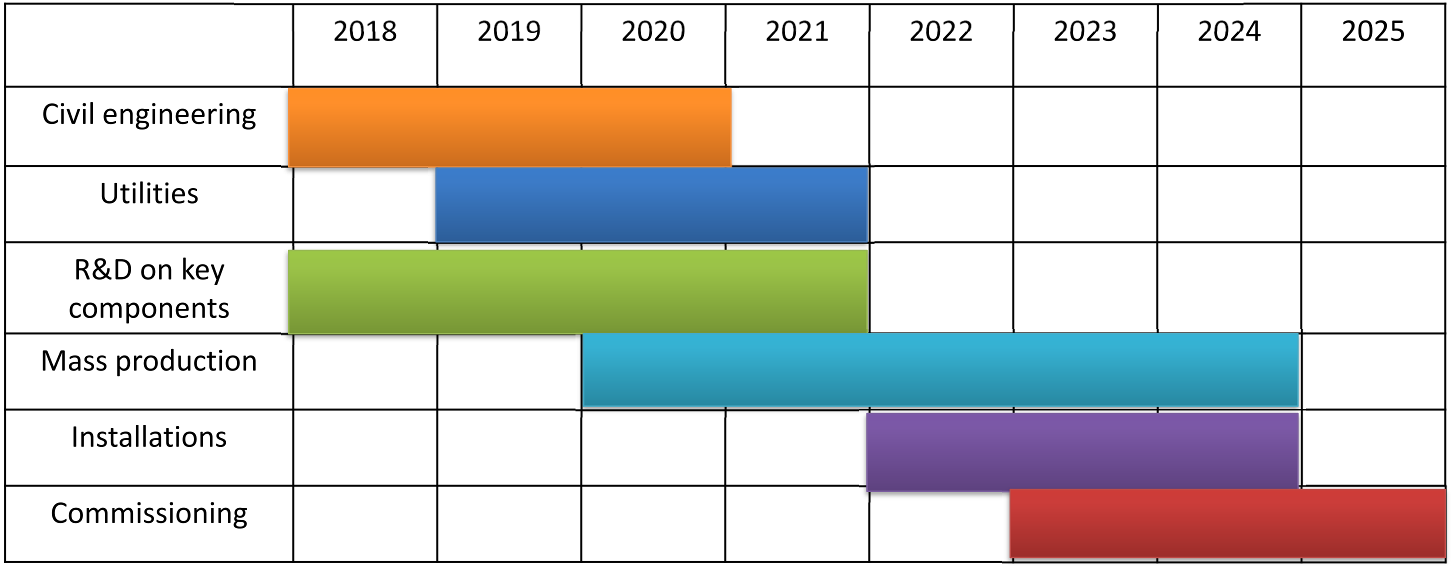
CryoModule Assembly Workshop



Estimated Construction Cost

Total Construction Cost	~1.5B US$
Central/Local Investment ratio	~20/80

Preliminary Construction Schedule



Groundbreaking was made in April, 2018, user experiments is expected to start in 2025.

Summary

- SHINE is a high rep-rate hard X-ray FEL facility, with an 8 GeV CW SCRF Linac, a 100PW laser system, 3 phase-I undulator lines and 10 end-stations, is going to be developed in Shanghai;
- This hard X-ray FEL project started its civil construction in April 2018, aiming to start user experiments in 2025.
- R&D and prototypes fabrication started from 2018, several TESLA type cavities (BCP treated) have been fabricated and vertical test; doping recipes are studied on both FG and LG material single cell cavities; one cryostat prototype fabricated; Solid-state power source and LLRF are in developing.
- Infrastructures, including a workshop and a surface treatment platform, are in construction

Thank You for Your Attention ！

SHINE