中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

SRF Activities in China

Jiyuan Zhai (IHEP)

14th Workshop of France China Particle Physics Laboratory (FCPPL2023)
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Acknowledgement

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- **USTC** (HALF): Prof. Yelong Wei
- **PKU**: Prof. Jiankui Hao, Prof. Fang Wang
- **CAEP** (CTFEL): Prof. Xing Luo

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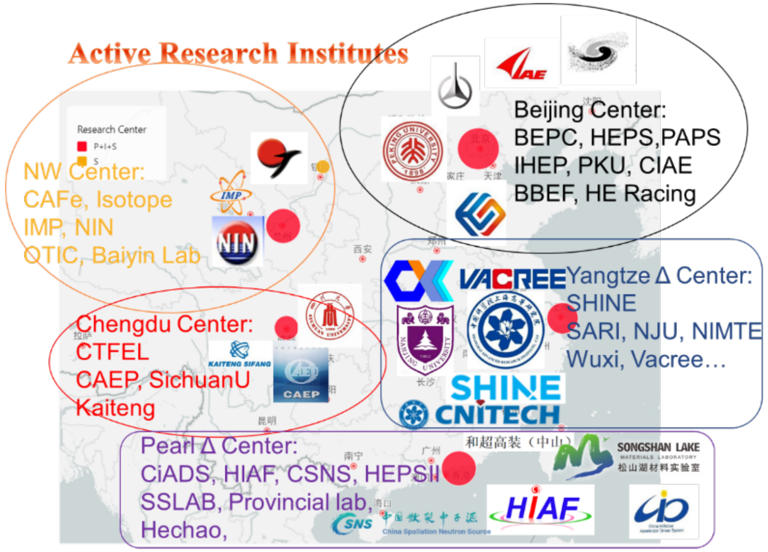
Introduction: SRF Accelerator Research Institutes, Infrastructures, Projects and Industry in China



Teng Tan, TTC2020

Part of CIPC members'

SRF Accelerator Projects in China

	Operation	Construction	Design & R&D	Sum
Collider	**BEPCII** (1.89 GeV, 2 CAV, since 2006)	**BEPCII upgrade** (2.35 GeV, 4 CAV, complete in 2024)	**CEPC** (45.5-180 GeV, 288 ~ 980 CAV) …	**2 circular colliders** tau-charm, Z, W, Higgs, ttbar
Synchrotron Light Source	**BSRF** (2.5 GeV, 2 CAV, since 2006) **SSRF** (3.5 GeV, 3 CAV, since 2009)	**HEPS** (6 GeV, 10 CAV, complete in 2025) **HALF** (2.2 GeV, 1 CAV, complete in 2028)	**SAPS** (3.5 GeV, 4 CAV) …	**5+ light sources** 3^{rd} & 4^{th} generations 2.2 ~ 6 GeV
FEL	**PKU FEL & DC-SRF Gun** (30 MeV, 3 CAV) **CTFEL** (10 MeV, 2 CAV, since 2017)	**SHINE** (8 GeV, 616 CAV, complete in 2027) **S3FEL** (2.5 GeV, 224 CAV, complete in 2031) **CTFEL upgrade** (50 MeV)	**DALS** (1 GeV, 96 CAV) **CAEP XFEL** (pulsed hard X-ray, 16 GeV) …	**7+ FELs** 2 hard X-ray 1 soft X-ray 1 EUV, 1 IR, 2 THz
Proton & Heavy Ion	**ADS injector I** (10 MeV, 14 CAV, since 2016) **CAFe** (25 MeV, 23 CAV, since 2017)	**CiADS** (0.5 GeV, 151 CAV, complete in 2025) **HIAF** (4.25 GeV/u, 96 CAV) **CSNS-II** (300 MeV, 54 CAV, complete in 2028)	**CSNS-III** (1 GeV) **ADS** (1 GeV) **CIAE proton linac** (1 GeV) …	**6+ proton & heavy ion SRF accelerators**
Sum	**Operating 6 facilities ~ 50 cavities**	**Constructing 9 projects ~ 1200 cavities by 2028 ~ 40 billion CNY**	**Proposing 6+ projects 2000+ cavities**	

Superconducting RF Systems at IHEP

Light Sources & FELs

BSRF, HEPS, CW FEL, ERL

166 MHz (HEPS)
World's first very low freq
β=1 module

1.3 GHz (FEL, CEPC, ILC)
World's first mid-T high Q module

HEP Colliders

BEPCII&U, CEPC, ILC

500 MHz (BEPC-II&U, HEPS)
In-house-made, long-term operation
in large scientific facility

650 MHz (CEPC, ADS, CSNS)
World's first 650 MHz cryomodule

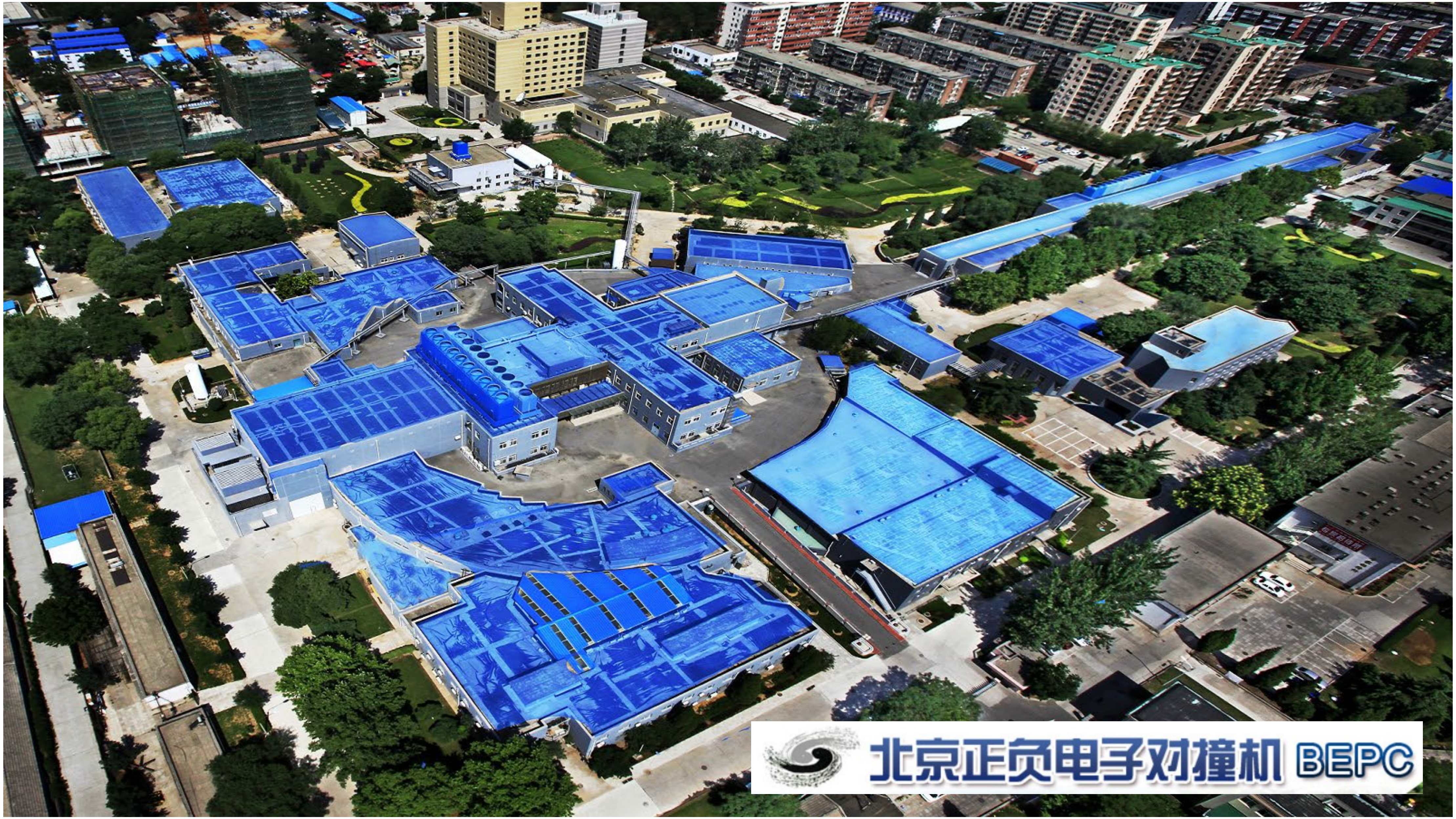
High Intensity Proton Linacs

ADS, CSNS-II, *v* factory

325 MHz (ADS)
World's first spoke cavity linac

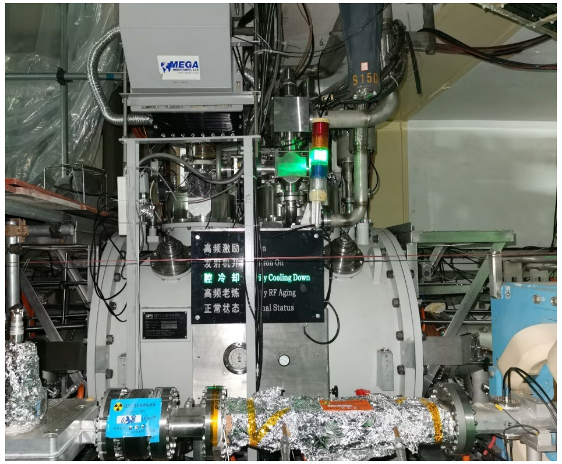
324 MHz (CSNS-II)
China's first double-spoke module

IHEP BEPCII and Upgrade



BEPCII SRF System

- BEPCII SRF system stable operation since 2006 with two imported cavities from Japan and in collaboration with KEK, reached design luminosity of $1 \times 10^{33}\ cm^{-2}s^{-1}$ (910 mA @ 1.89 GeV) in 2016.
- In 2017, east cavity replaced with in-house-made cavity and module, stable operation till now.
- Three imported sub-systems (SRF cavity and module, LLRF, RF power source) have been replaced with in-house-made ones.



In-house-made 500 MHz cavity and module

made in 2011, stable operation since 2017

Digital LLRF system

Stable operation since 2019

200 kW SSA

Operation since Oct. 2023

BEPCII-Upgrade SRF System

Table 1: Main parameters of BEPCII and BEPCII-U.

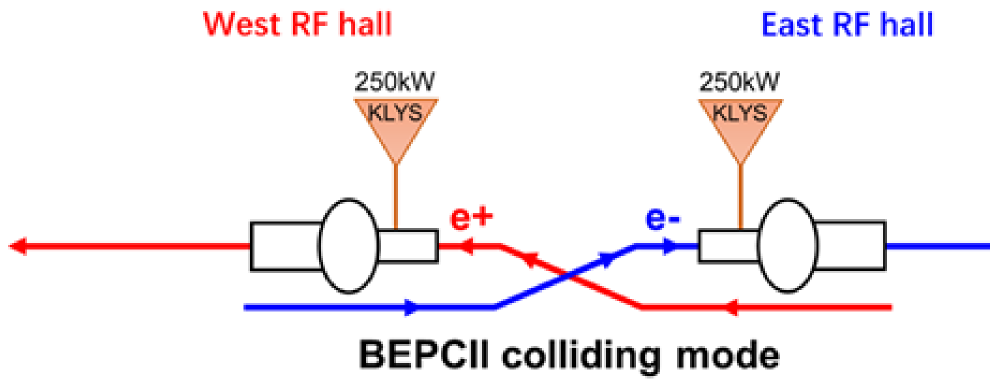
Parameter	Symbol	BEPCII	BEPCII-U	Unit
Circumference	C	237.53	237.53	m
Beam energy	E_0	1.89	2.35	GeV
Beam current	I_0	910	900	mA
Bunch number	N_b	120	120	-
Total energy loss per turn	U_{tot}	0.116	0.277	MeV
Total power loss to SR	P_{SR}	106	250	kW
Parasitic loss	P_{HOM}	7.7	30	kW
Total beam power	P_b	114	290	kW
Revolution frequency	f_{rev}	1262.1	1262.1	kHz
Synchrotron tune	ν_s	0.03	0.04	-
Bunch length	σ_z	14	12	mm
Momentum compaction factor	α_p	0.018	0.017	-
RF frequency	f_{rf}	499.8	499.8	MHz
Total RF voltage	V_{rf}	1.6	3.3	MV
Radiation damping time (x)	τ_x	24.2	12.6	ms
Radiation damping time (y)	τ_y	25.8	13.4	ms
Radiation damping time (z)	τ_z	13.4	6.9	ms
β function at straight section	β_x	15	20	m
β function at straight section	β_y	15	20	m

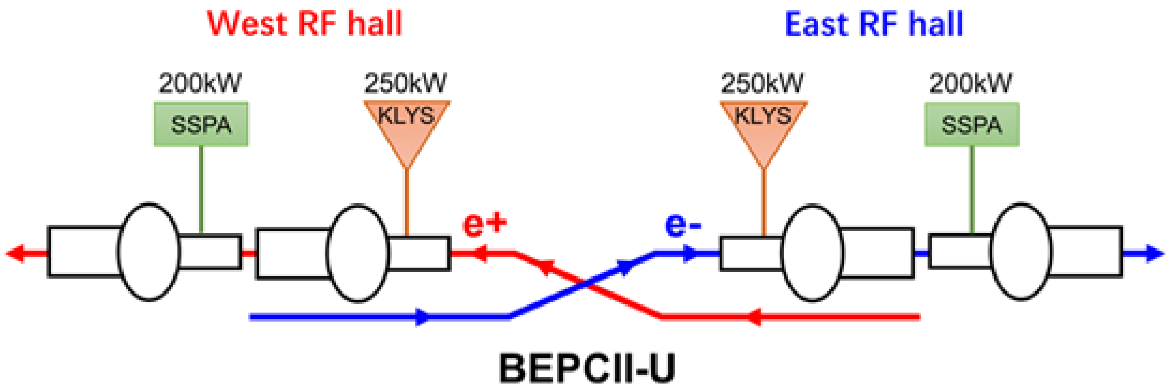
Table 3: RF parameters for BEPCII-U (breakdown).

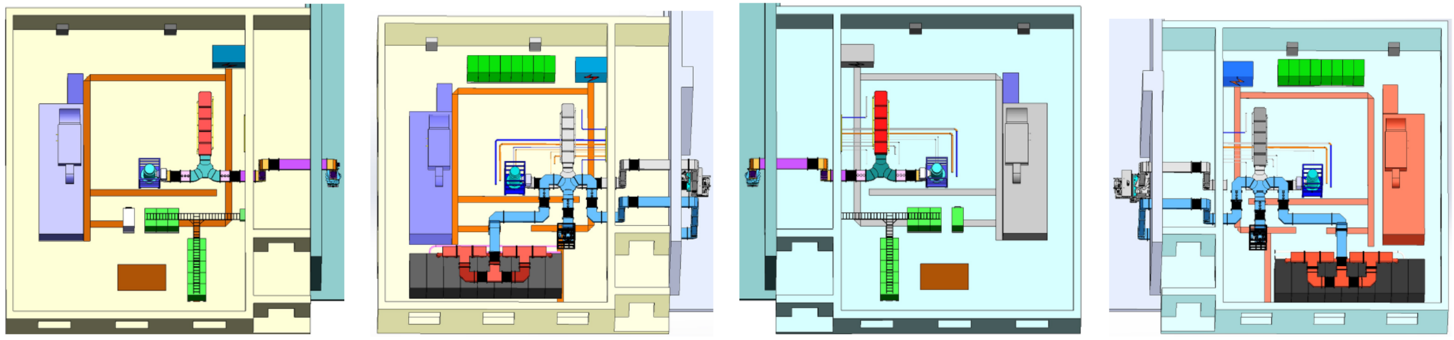
Parameter	Existing	To be added	Unit
RF frequency	499.8	499.8	MHz
Number of cavities	2(+1)	1	-
RF voltage per cavity (V_c^{op})	1.65	1.75	MV
Cavity unloaded Q at V_c^{op}	$\geq$5e8	$\geq$1e9	-
Operating temperature	4.2	4.2	K
Nominal RF power per cavity	145	145	kW
Loaded Q	2e5	2e5	-
Cavity loaded bandwidth	2.5	2.5	kHz
Number of RF stations	2	2	-
Number of transmitters	2	2	-
Transmitter type	Klystron	SSA	-
Nominal power per transmitter	250	200	kW
Min. output power per transmitter (including 15% transmission loss)	165	165	kW
FPC designed power (CW)	200	200	kW
Number of LLRF	2	4	-
Specified amplitude noise (pk-pk)	± 1	± 0.5	%
Specified phase noise (pk-pk)	± 1	± 0.5	°

BEPCII-Upgrade SRF System

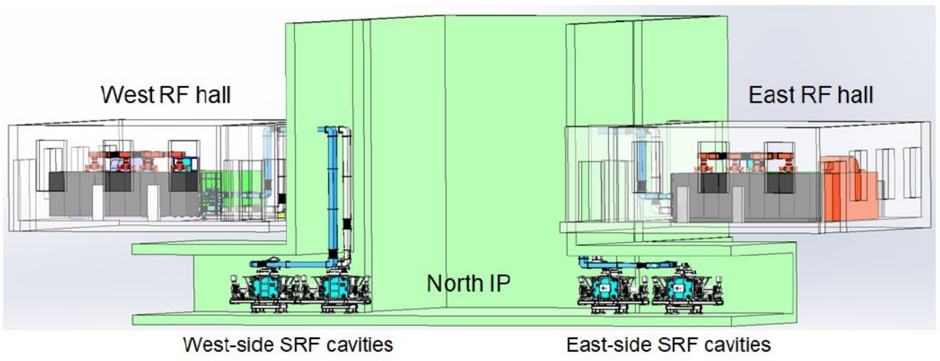
- BEPCII-U：Add two cavities and SSAs in 2024.
- Further R&D in 500 MHz cavity, LLRF and SSA.







(a) West RF hall (BEPCII) (b) West RF hall (BEPCII-U) (c) East RF hall (BEPCII) (d) East RF hall (BEPCII-U)



BEPCII-U and HEPS 500 MHz Cavity and Cryomodule

- One 500 MHz cavities for BEPCII-U and two 500 MHz third hormonic cavities for HEPS.
- Prevent cavity buckling by thicker Nb sheet (2.5 mm to 3.7 mm), deep drawing instead of spinning, adding stiffening rings.
- First CM assembly complete soon.

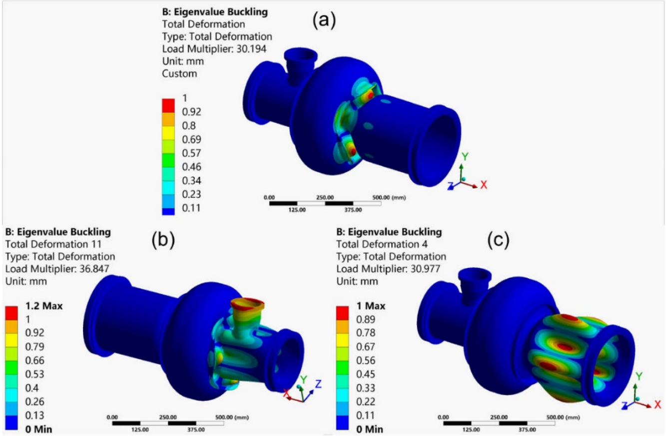
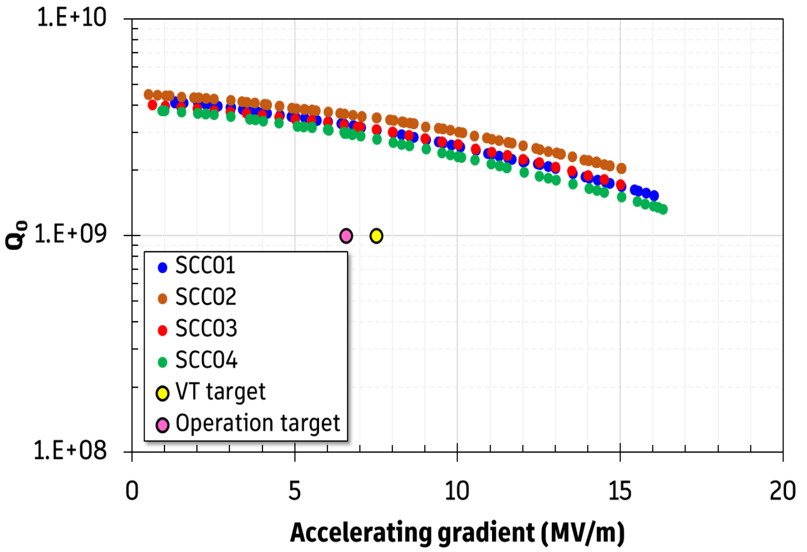
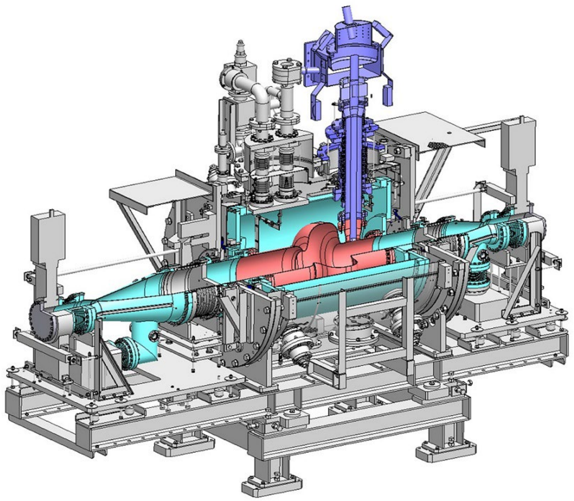


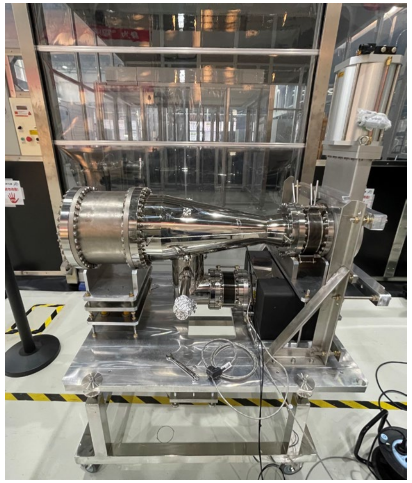
TABLE V
BUCKLING PERFORMANCE OF THE CAVITY UNDER TWO DIFFERENT BOUNDARIES

	Conditions	Φ (Bare)	Φ (Stiff.)	Φ_{cr}
Cell (LBP side)	BPs fixed	29.3	83.7	16.1
	LBP LF	10.5	30.2	
Cell (SBP side)	BPs fixed	29.4	85.1	16.1
	LBP LF	12.8	36.9	
LBP tube	BPs fixed	33.2	33.2	2.5
	LBP LF	17.2	31.0	

"BPs fixed" stands for both beam pipes are fixed, "LBP LF" stands for the cavity LBP side is free to move longitudinally while the SBP side is fixed, "Bare" stands for bare cavity without any stiffening rings, and "Stiff." stands for cavities with one pair of stiffening rings added on the cell.

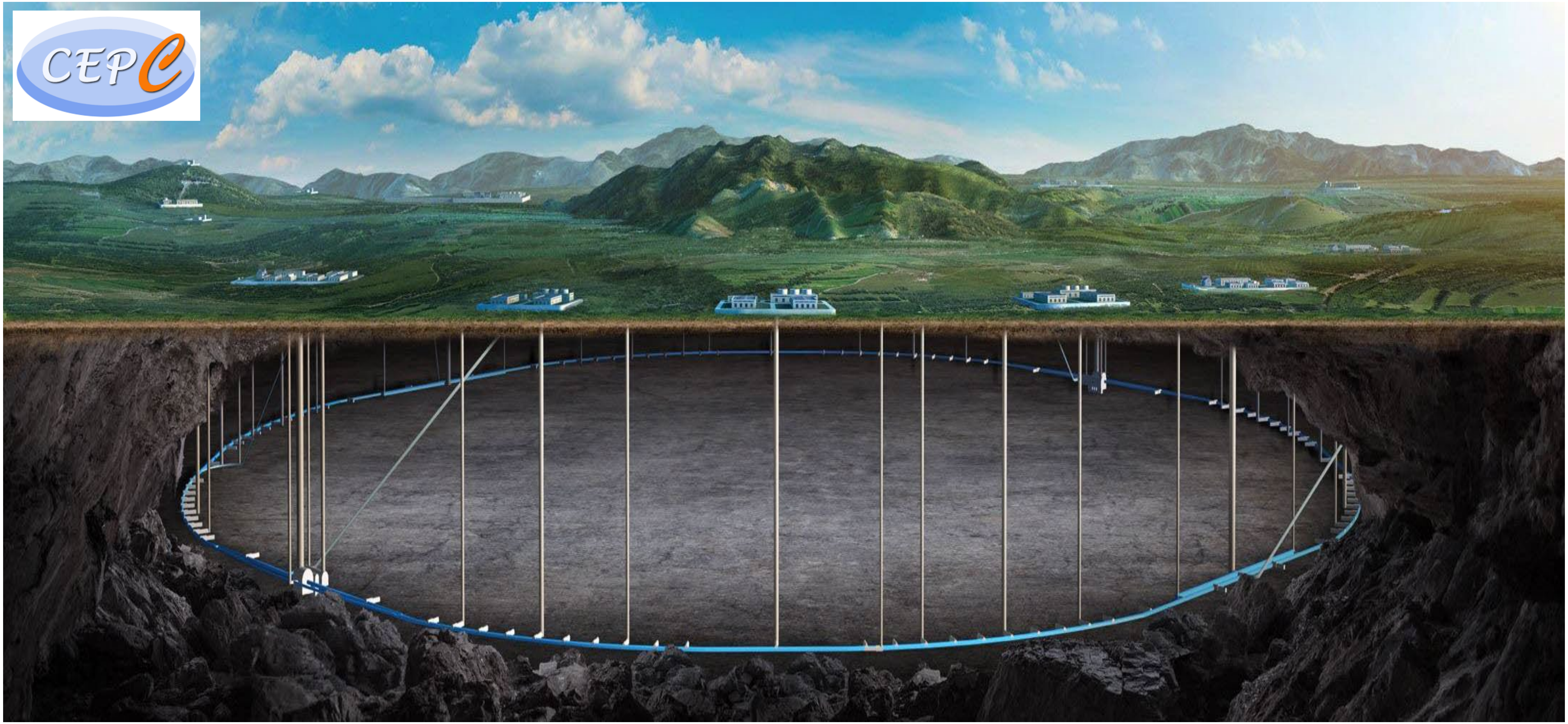






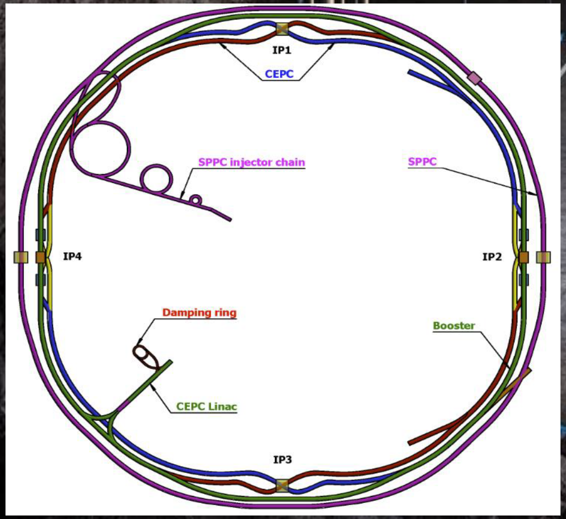
500 MHz KEKB-type single-cell SC cavity module

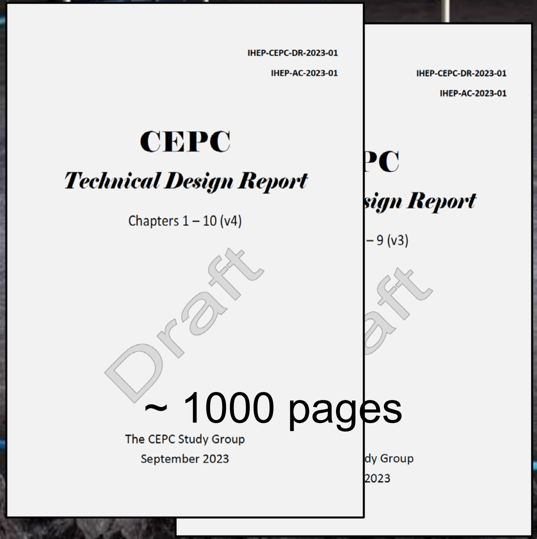
IHEP CEPC



IHEP CEPC

- 100 km circular collider, Higgs (Z / W / ttbar) factory, in China. Run at $\sqrt{s}$ ~ 90, 160, 240, 360 GeV. Possible *pp* collider (SppC) of $\sqrt{s}$ ~ 50 - 100 TeV in the far future.
- CEPC CDR published in 2018, TDR will publish in late 2023. Will propose to the government to begin construction around 2028 during the 15th 5-year-plan period.
- CEPC SRF system has unprecedented challenges in high RF voltage (20 GV) , high current (1.4 A), high power (100 MW RF power, Z-pole 1 MW per cavity) , high HOM power and beam-cavity interaction issues, with requirement of mode switching. State-of-the-art technology in high gradient, high Q and high power.



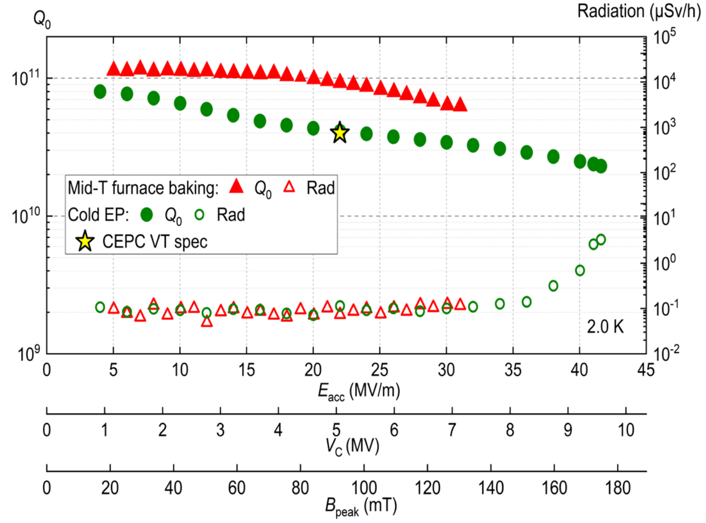


~ 1000 pages

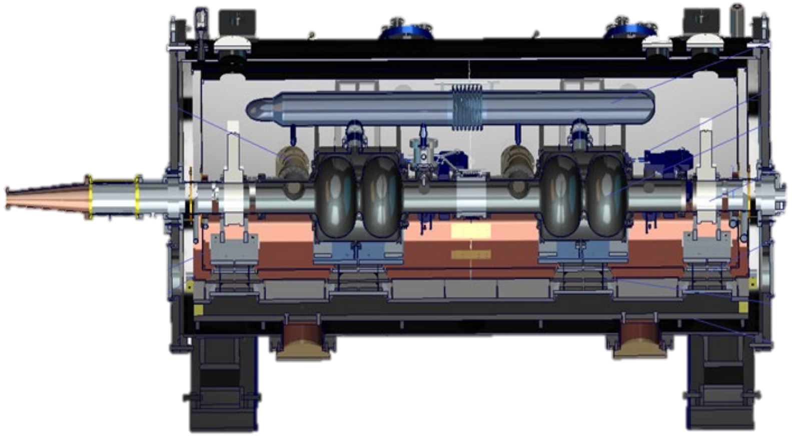
CEPC TDR Review, June 12-16 2023

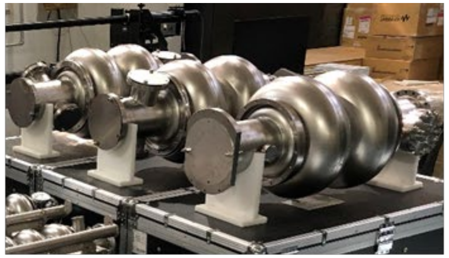
CEPC 650 MHz SRF System R&D

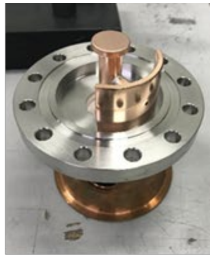
650 MHz test cryomodule with 2x2-cell cavities. Beam test soon.

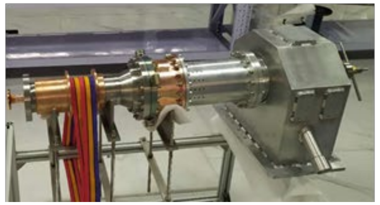


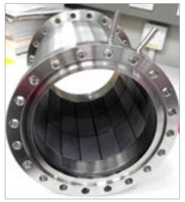
High G High Q 650 MHz 1-cell Cavity
EP treated: 2.3E10@41.6 MV/m@2 K
Mid-T treated: 6.3E10@31 MV/m@2 K











IHEP 1.3 GHz SRF R&D

2003-2015

Early research
Technology R&D



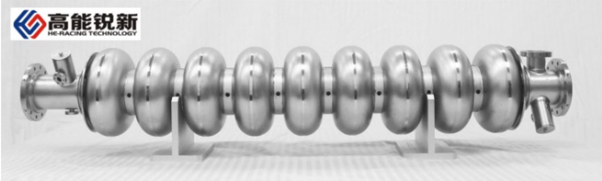

1-cell and 9-cell cavities

ILC test cryomodule

Important collaboration with PKU, KEK, INFN-LASA, FNAL, JLAB, DESY …

2016-2020

Technology transfer
Performance breakthrough



HERT 11 TESLA 9-cell cavities

EP 36 MV/m (reach ILC spec)

Mid-T 5E10@21 MV/m (world record)

4 BCP + 4 mid-T high Q cavities delivered to SHINE

2021-2025

Cavity mass production
Cryomodule prototyping

SHINE

88 9-cell cavities by HERT

DALS 1.3 GHz high Q cryomodule

2026-2035

Cavity and cryomodule mass production

Engage in these projects:

SHINE (600 CAV, 75 CM)

S^3FEL (208 CAV, 26 CM)

Other CW FELs

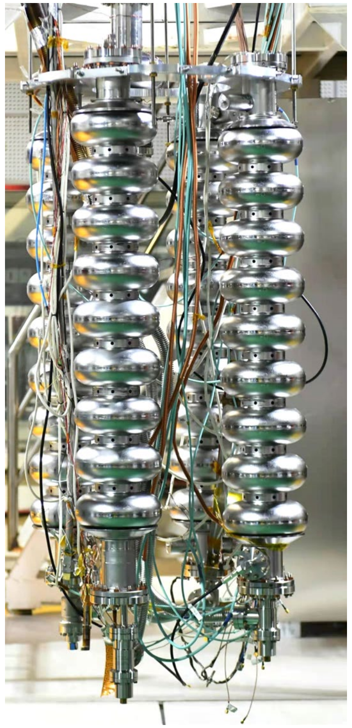
CEPC booster (352 cavities)

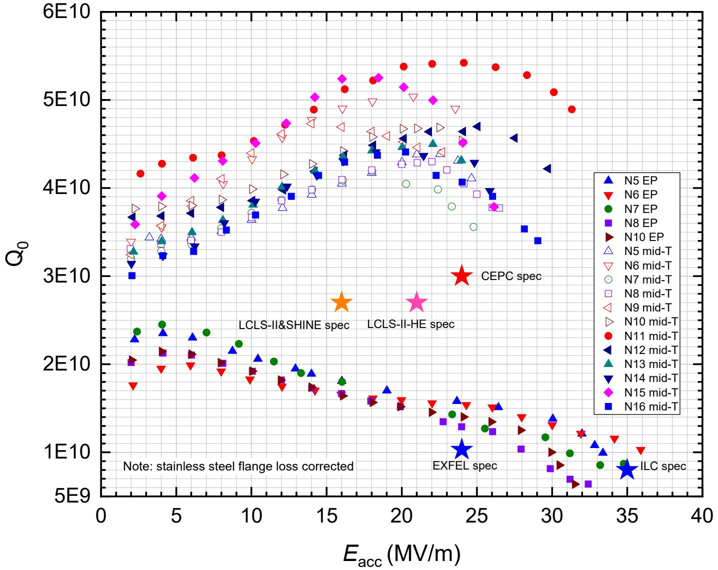
ILC (8000+8000 cavities)

…

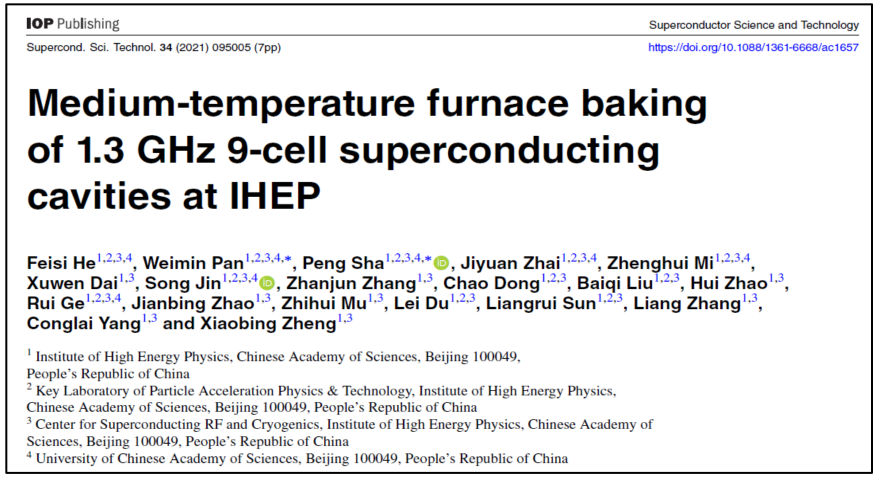
High Q high gradient and new material R&D

IHEP 1.3 GHz SRF R&D





High average Q_0 of 4.5E10 at 16 ~ 21 MV/m.
Mid-T bake recipe has distinct advantages over nitrogen-doping



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https://doi.org/10.1088/1361-6668/ac1657

Medium-temperature furnace baking of 1.3 GHz 9-cell superconducting cavities at IHEP

Feisi He[1,2,3,4], Weimin Pan[1,2,3,4,*], Peng Sha[1,2,3,4,*], Jiyuan Zhai[1,2,3,4], Zhenghui Mi[1,2,3,4], Xuwen Dai[1,3], Song Jin[1,2,3,4], Zhanjun Zhang[1,3], Chao Dong[1,2,3], Baiqi Liu[1,2,3], Hui Zhao[1,3], Rui Ge[1,2,3,4], Jianbing Zhao[1,3], Zhihui Mu[1,3], Lei Du[1,2,3], Liangrui Sun[1,2,3], Liang Zhang[1,3], Conglai Yang[1,3] and Xiaobing Zheng[1,3]

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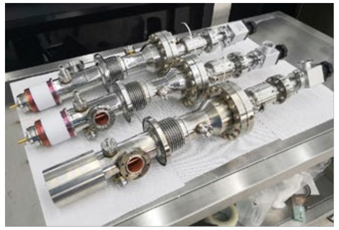
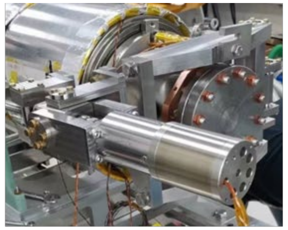
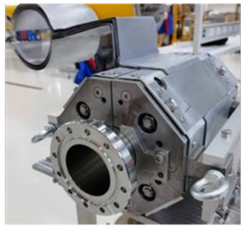


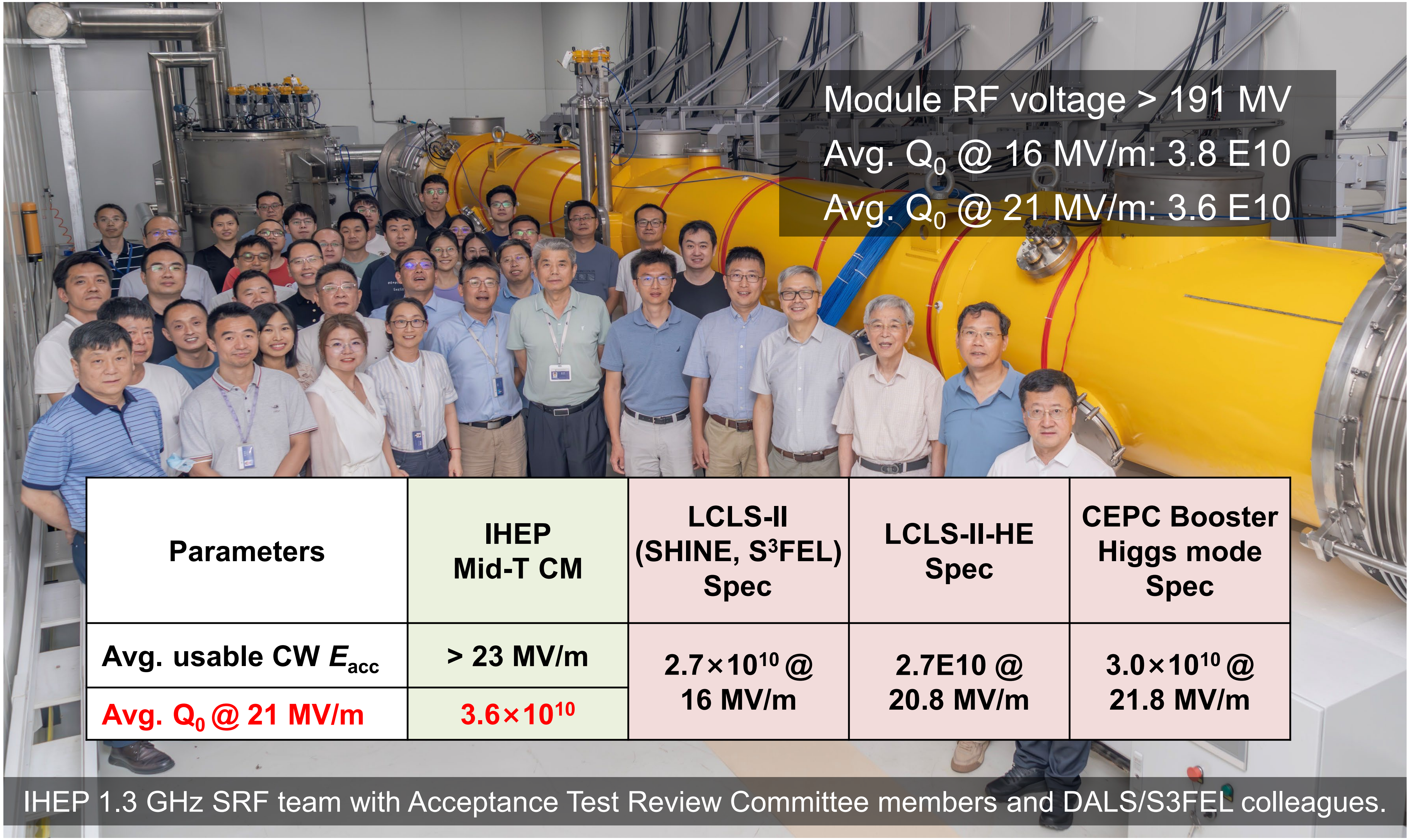




World's first Mid-T 1.3 GHz Cryomodule with Record High Q_0

IHEP 1.3 GHz SRF team with Acceptance Test Review Committee members and DALS/S3FEL colleagues.

World's first Mid-T 1.3 GHz Cryomodule with Record High Q_0



Module RF voltage > 191 MV

Avg. Q_0 @ 16 MV/m: 3.8 E10

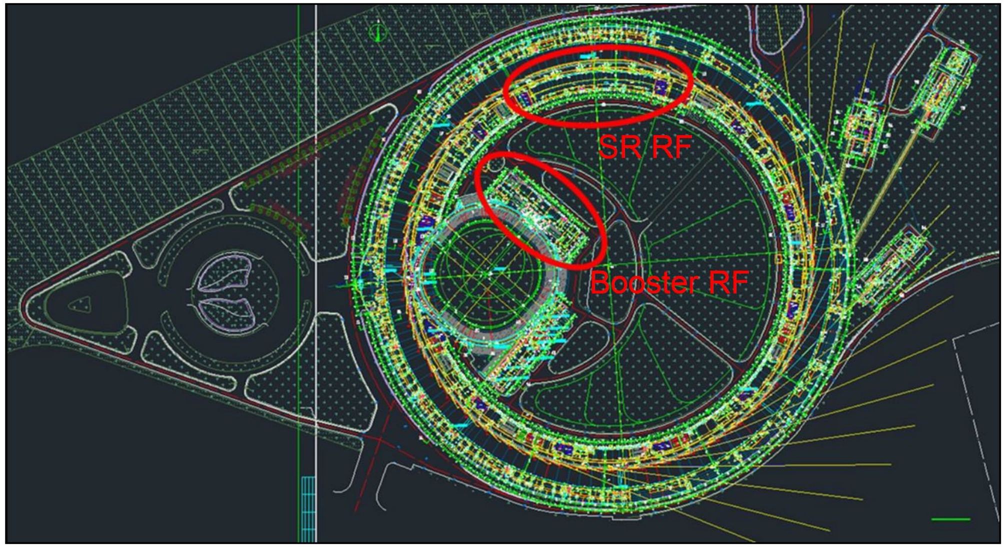
Avg. Q_0 @ 21 MV/m: 3.6 E10

Parameters	IHEP Mid-T CM	LCLS-II (SHINE, S3FEL) Spec	LCLS-II-HE Spec	CEPC Booster Higgs mode Spec
Avg. usable CW E_{acc}	**> 23 MV/m**	**2.7×10^{10} @ 16 MV/m**	**2.7E10 @ 20.8 MV/m**	**3.0×10^{10} @ 21.8 MV/m**
Avg. Q_0 @ 21 MV/m	**3.6×10^{10}**			

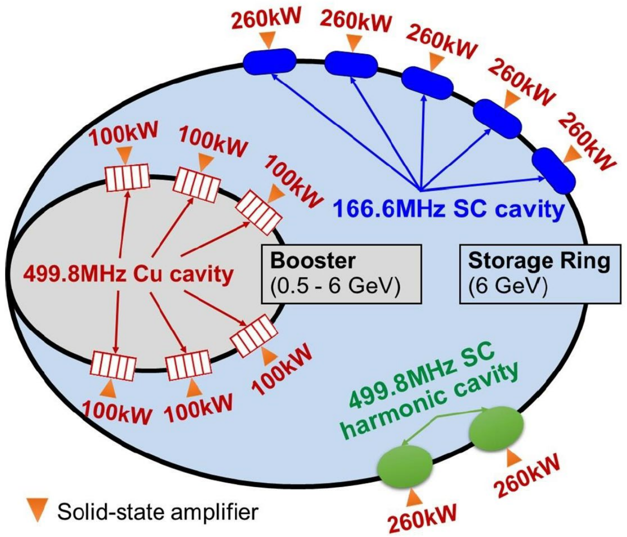
IHEP 1.3 GHz SRF team with Acceptance Test Review Committee members and DALS/S3FEL colleagues.

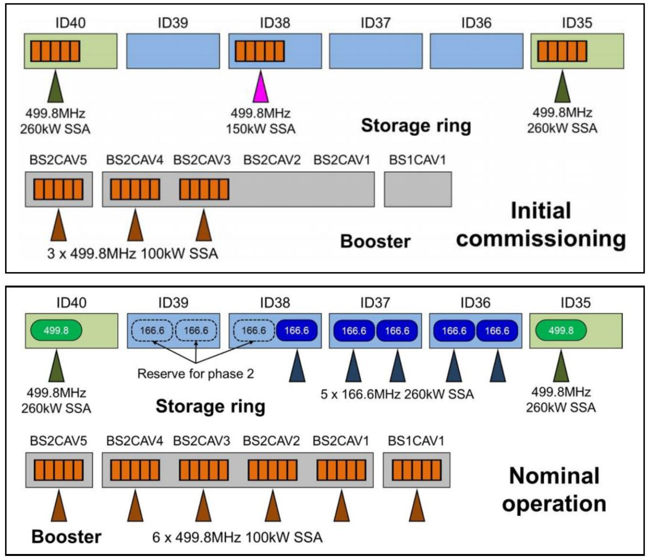
IHEP HEPS

HEPS RF System



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

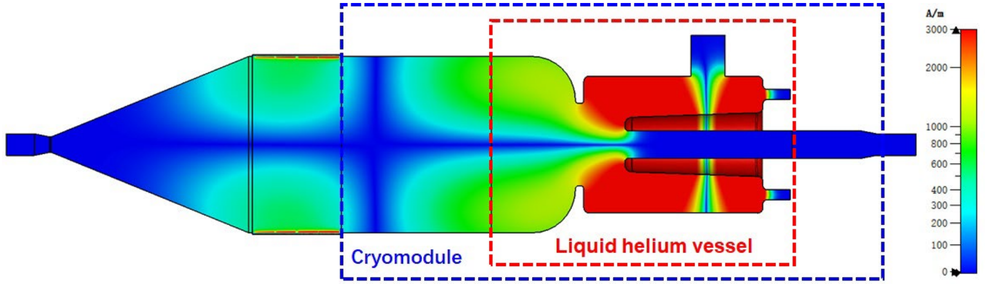


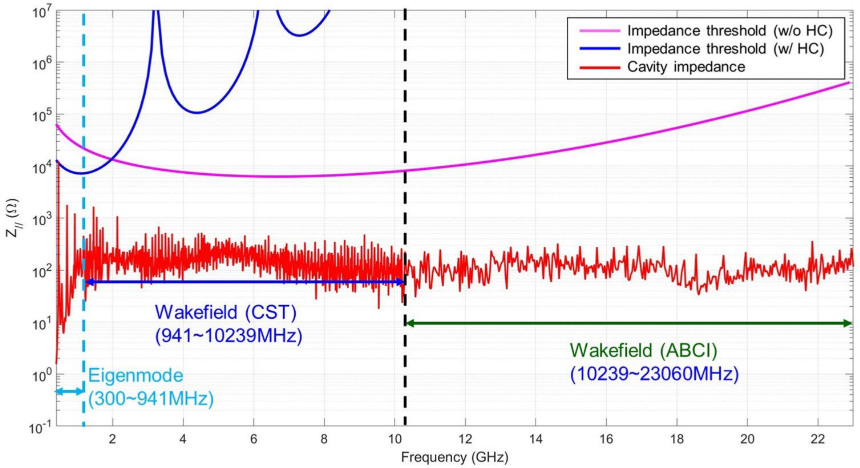


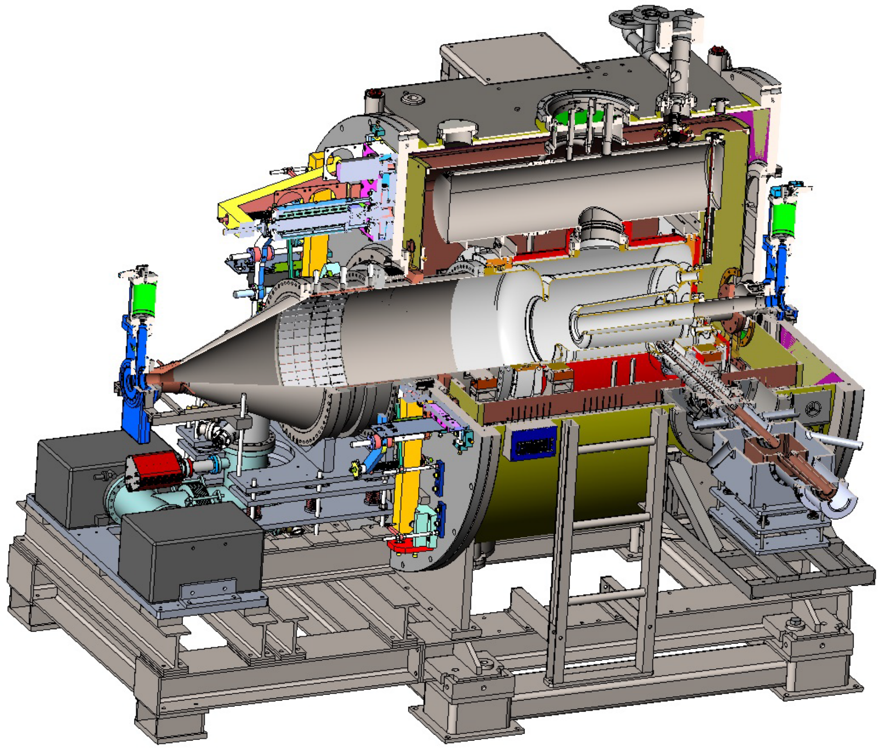
Parameter	Value	Unit
Circumference	1360.4	m
RF frequency (f_0)	166.6	MHz
Total energy loss per turn (U_0)	4.14	MeV
Total beam power (P_b)	850	kW
Total RF voltage (V_{RF})	5.16	MV
Number of main RF cavities	5	-
RF power per main cavity	170	kW
Cavity type	SRF cavity	-
HOM control	Heavy damping	-
Harmonic 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°	-

IHEP HEPS 166 MHz Cavity and Cryomodule

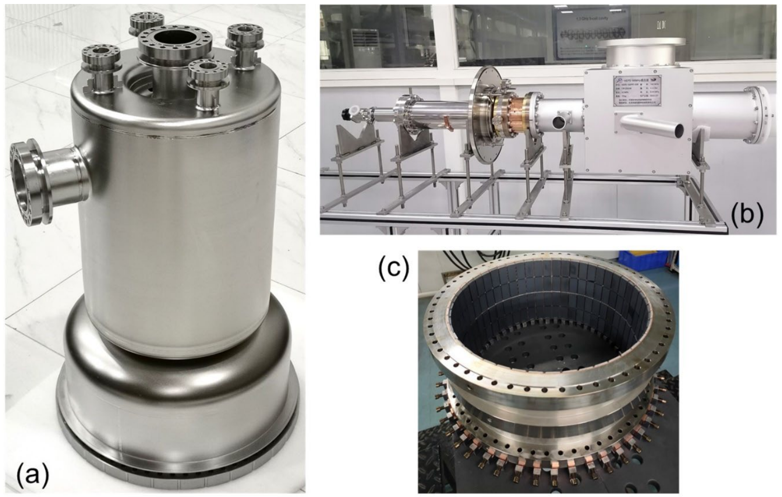
- Low frequency: 166.6 MHz, β=1
- High RF power: 180 kW per cavity
- High current: 200 mA → heavy HOM damping: Q_L< 1000
- Compactness: limited space of the straight section (6 m for 2 cavs)
- Stable operation (user facility): large margin in RF parameters

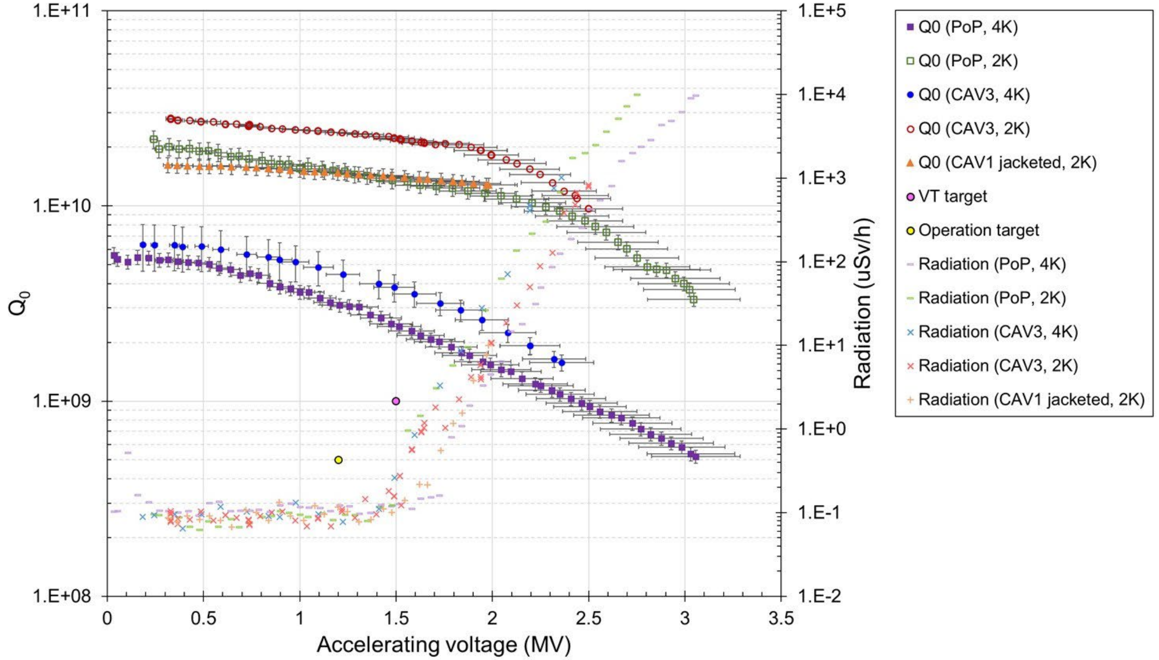




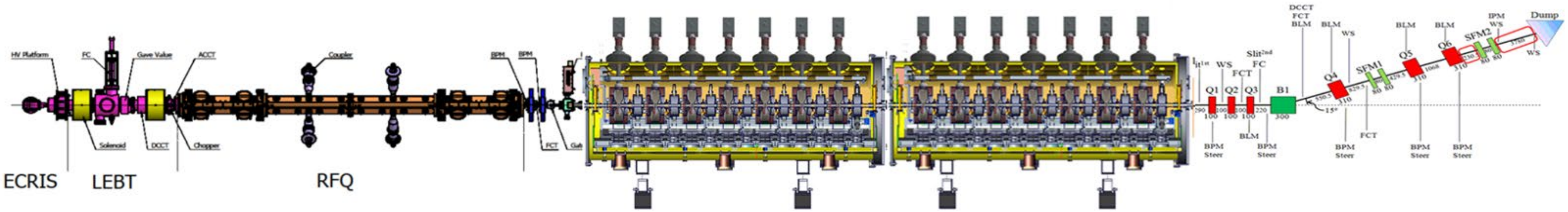


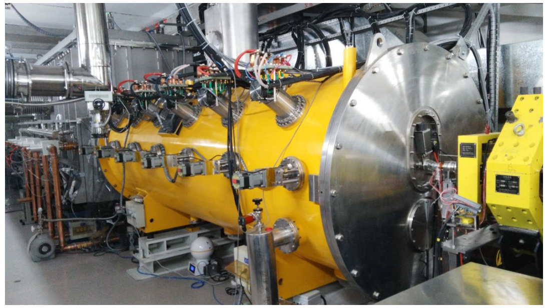
IHEP HEPS 166 MHz Cavity and Cryomodule

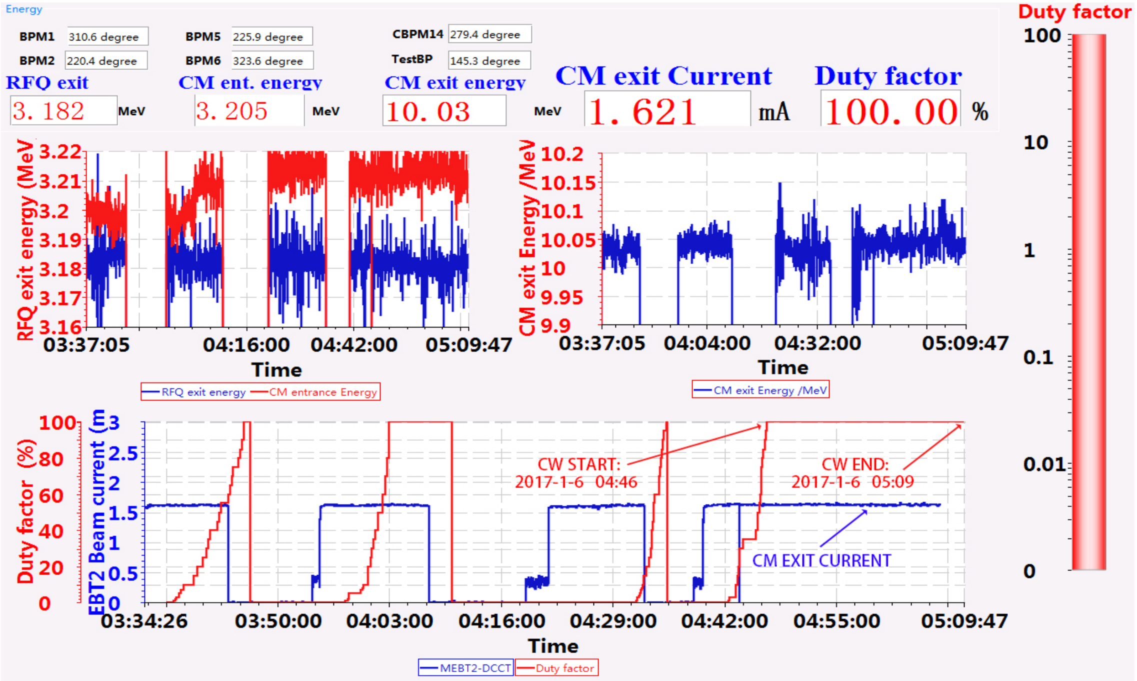




IHEP ADS Injector SRF System







14 spoke012 cavities accelerate 2 mA CW proton beam to 10 MeV in Injector-I at IHEP.

6 spoke021 cavities increase CW proton beam to 25 MeV in Injector-II at IMP.

ADS Injector SRF System

- Batch production of Spoke012 and Spoke021, meet spec
- SSR024/040, HWR325, MB082 prototypes

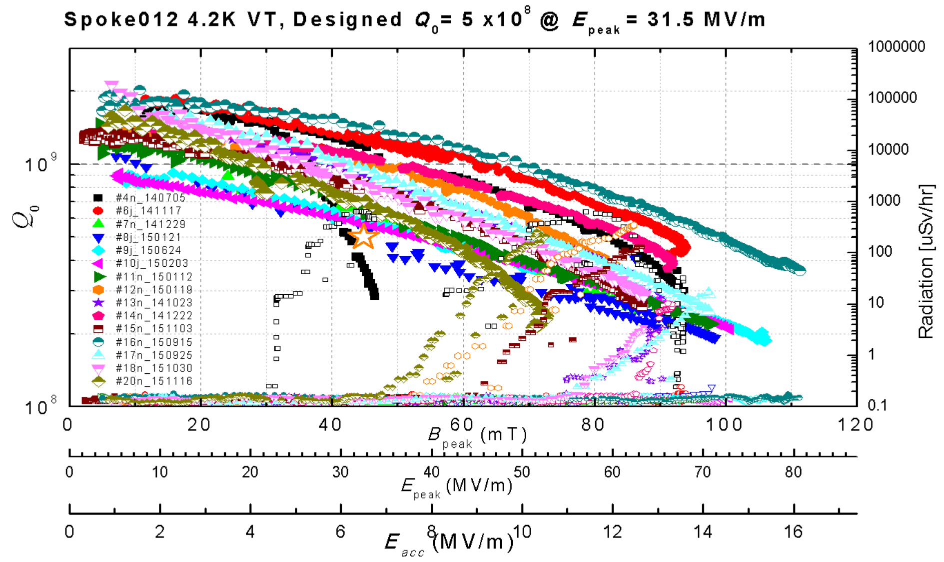
Spoke012 cavity string

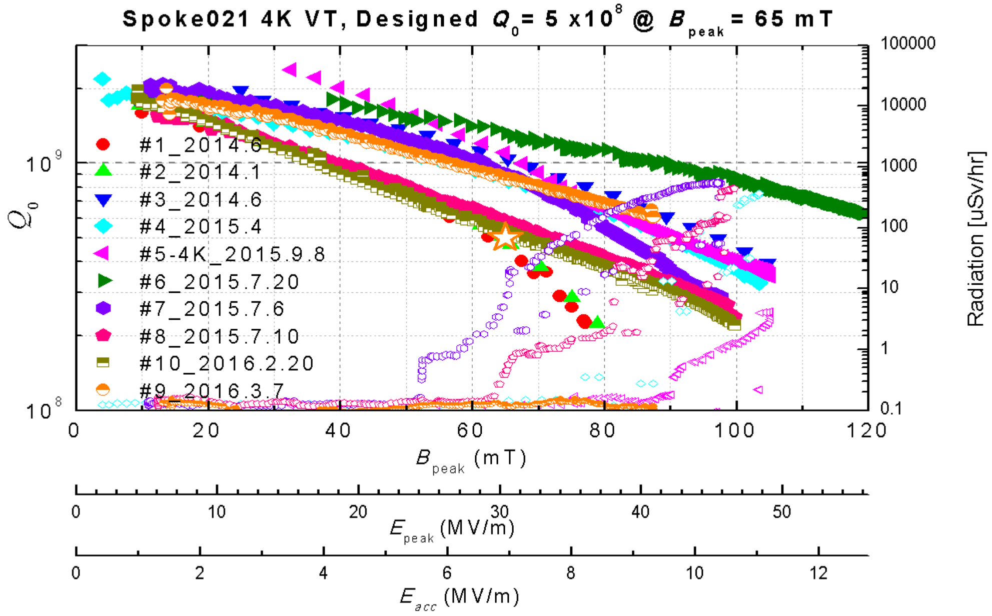
650 MHz 5-cell cavity (beta 0.82)

325 MHz Spoke cavity (beta 0.21)

325 MHz Spoke cavity (beta 0.40)

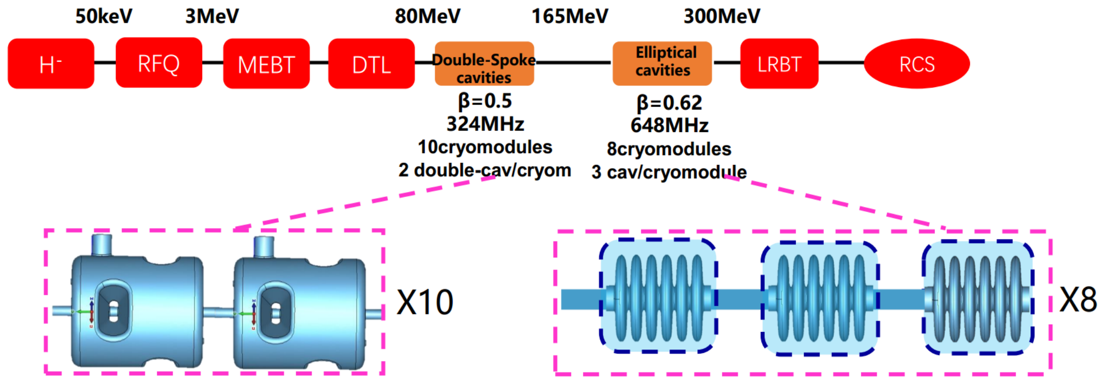
325 MHz HWR cavity (beta 0.14)

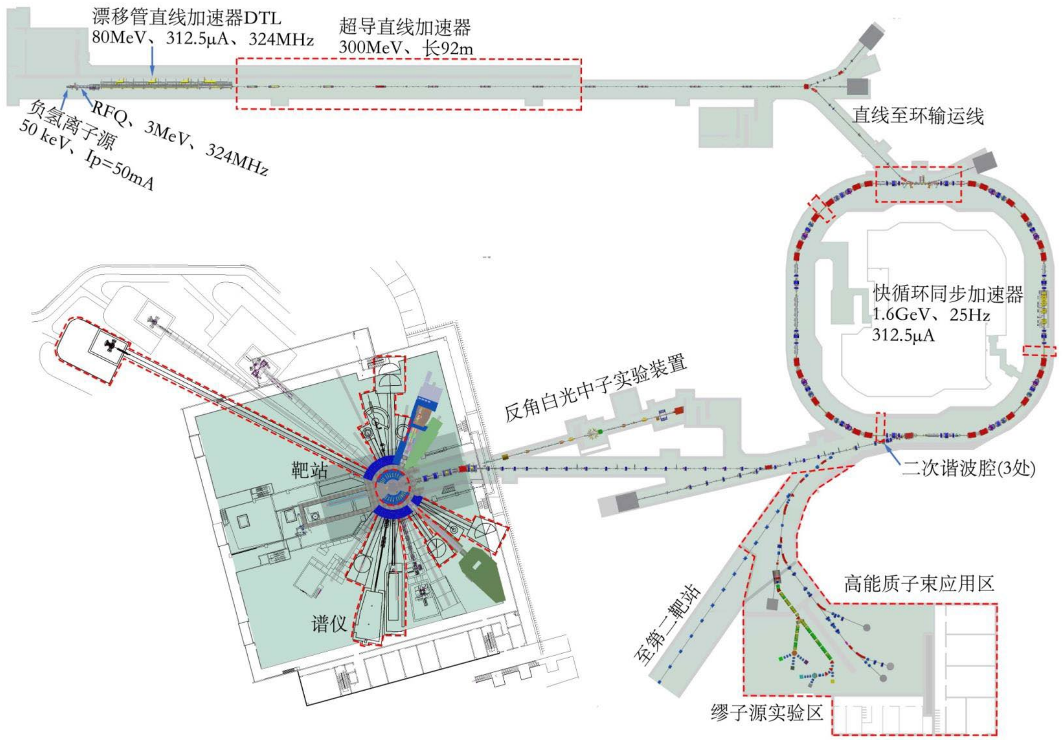


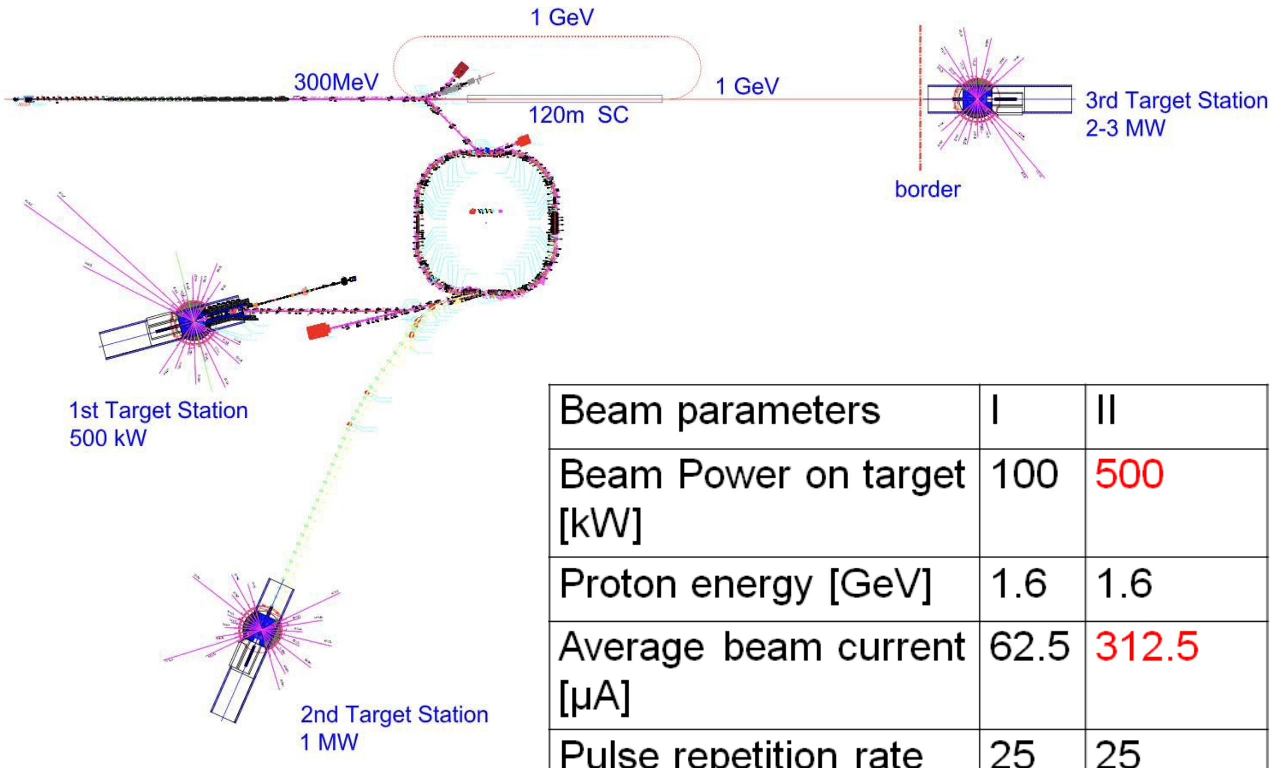


IHEP CSNS

CSNS-II and Future Plan

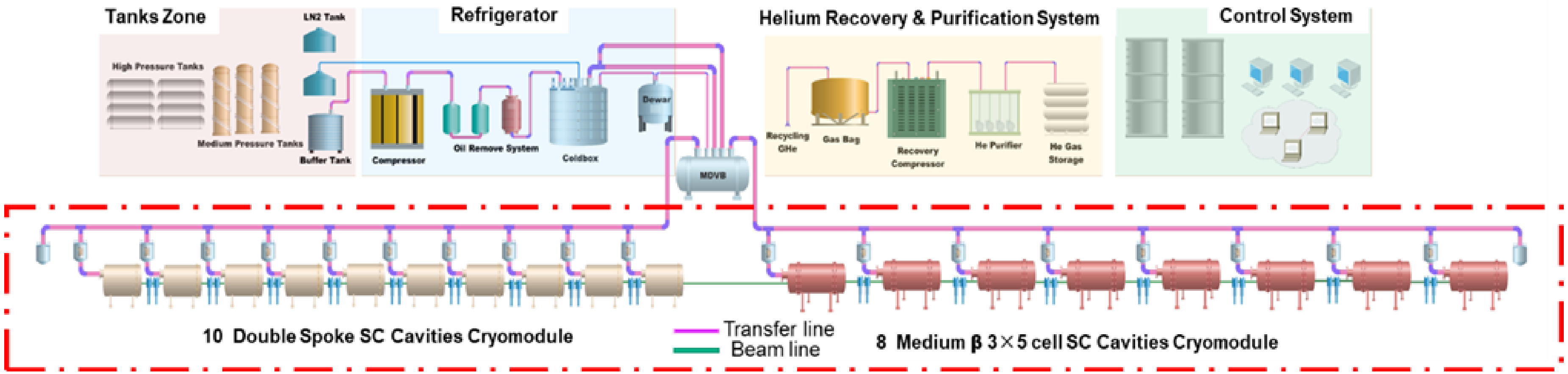


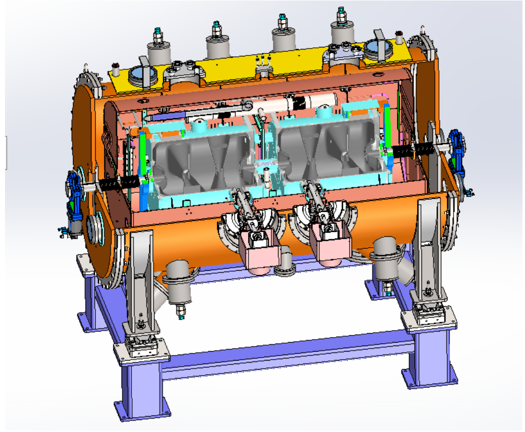




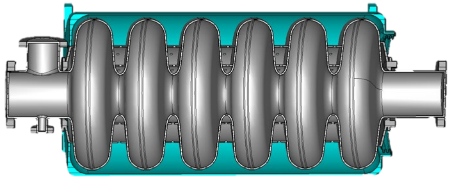
Beam parameters	I	II
Beam Power on target [kW]	100	500
Proton energy [GeV]	1.6	1.6
Average beam current [μA]	62.5	312.5
Pulse repetition rate [Hz]	25	25
Linac energy [MeV]	80	300
Macropulse. ave current [mA]	15	40
Linac RF frequency (MHz)	324	324/648
Linac beam width(μs)	400	600

CSNS-II SRF System





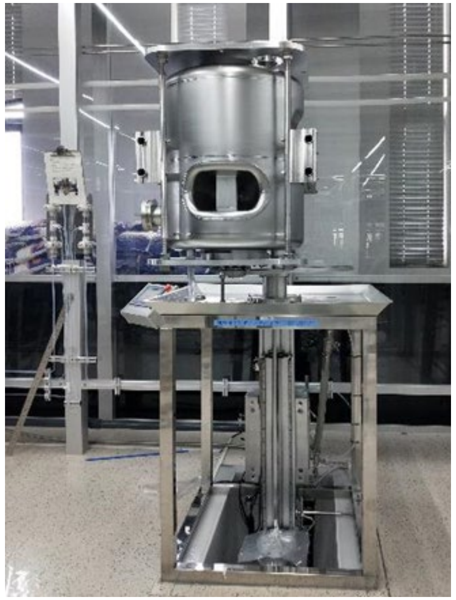
- **CSNS-II upgrade (2023-2028)**
  - Linac energy: 80 MeV → 300 MeV
  - Linac beam current: 15 mA → 40 mA
  - Linac beam pulse length: 400 μs → 600 μs
- **20 324 MHz β=0.5 double-spoke cavities**
  - Prototype cavities meet design spec
  - Prototype cryomodule under assembly at PAPS
- **24 648 MHz β=0.62 6-cell cavities**
  - Prototype cavity in fabrication, module in design

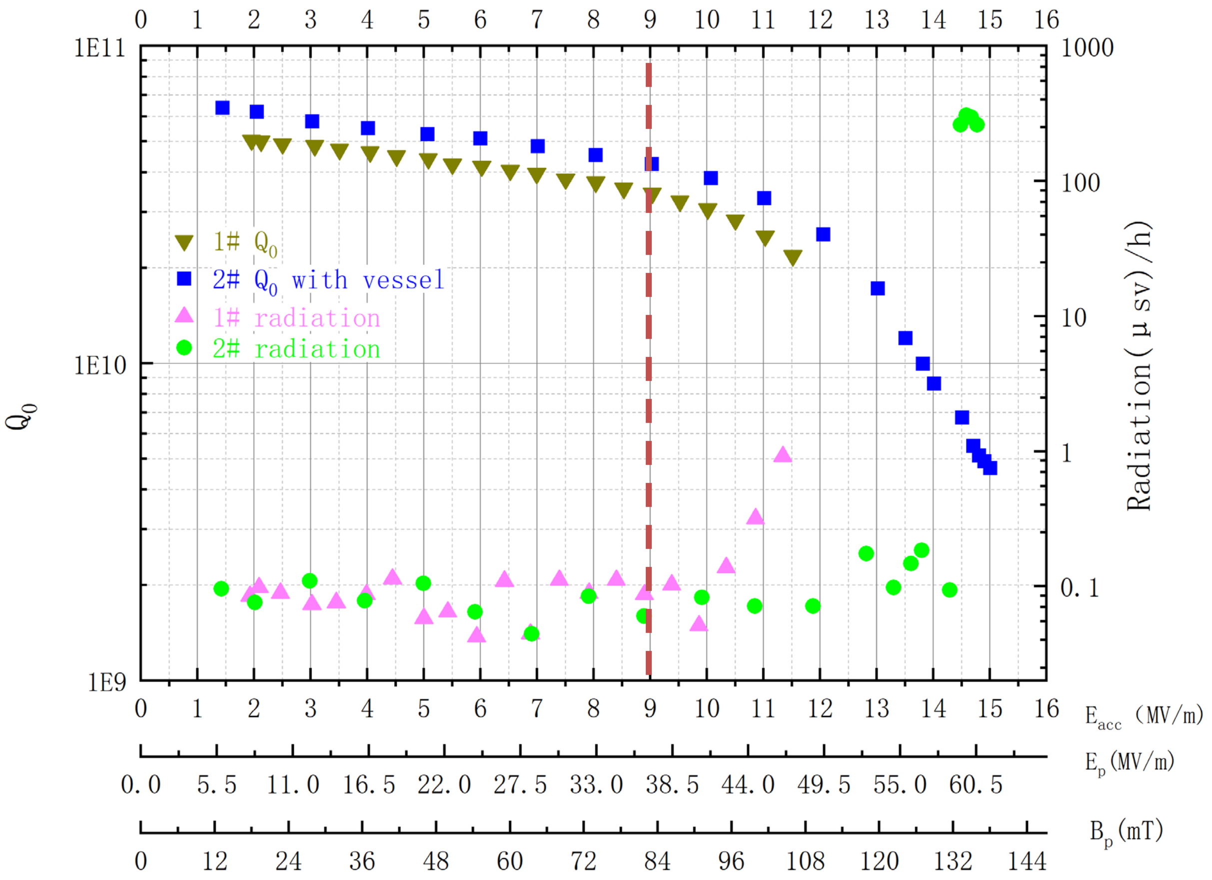


Parameter	Value
f (MHz)	324
TTF	0.79
β_0	0.5
Eacc (MV/m)	7.3 (9)
Ep/Eacc	3.44
Bp/Eacc mT/(MV/m)	8.86
R/Q (Ω)	401.8
G (Ω)	118.6

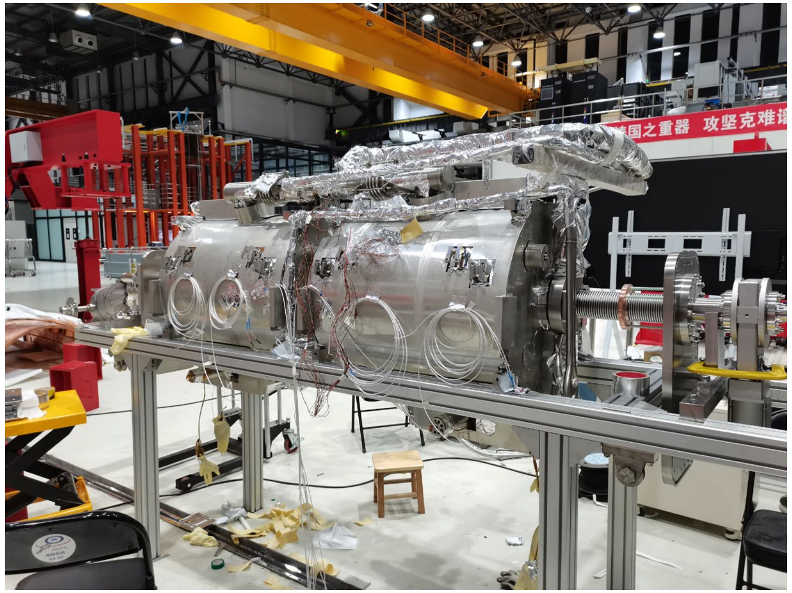
Parameter	Value
f (MHz)	648
TTF@βg	0.7
βg	0.62
Eacc (MV/m)	14
Ep/Eacc	2.53
Bp/Eacc mT/(MV/m)	5.45
R/Q (Ω)	309
G (Ω)	177
Beam tube diameter (mm)	105/120
Cell-cell coupling (%)	1.35

CSNS-II Double-Spoke Cavities





CSNS-II Double-Spoke Module Prototype Assembly



IHEP SAPS

- **Southern Advanced Photon Source (SAPS)**
  - SAPS, a mid-energy fourth generation storage ring photon source, is planned to be built adjacent to the China Spallation Neutron Source (CSNS)
  - Modified H-7BA magnetic focusing structure
  - 350 mA high brightness mode
  - 500 mA high-throughput mode

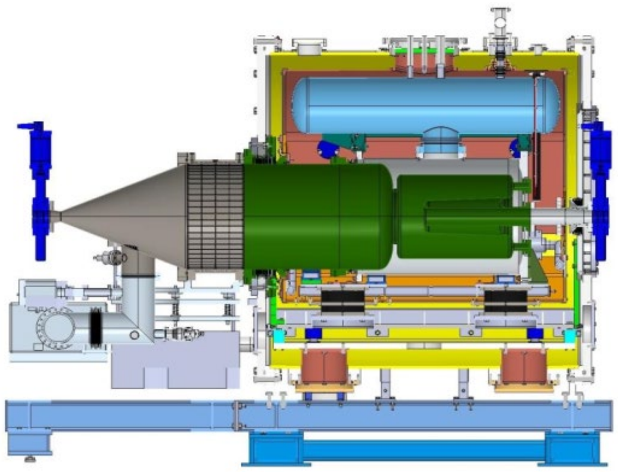
Parameters	Value	Unit
Beam energy E_0	3.5	GeV
Current	500	mA
Circumference	810	m
Nature emittance	26.3	pm·rad
Cell number	32	-
Long straight section	6	m

IHEP SAPS RF System

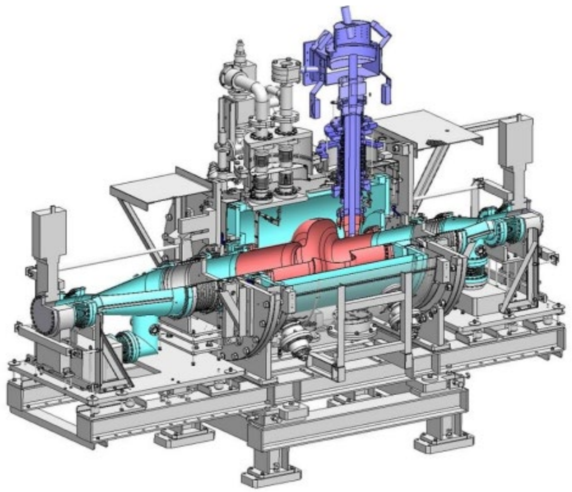
- **RF system**
  - 500 MHz/5-cell Normal conducting cavities for booster RF
  - Superconducting cavities for storage ring RF
  - 166.6 MHz SC cavity + 499.8 MHz SC cavity

Parameters of the storage-ring rf system for SAPS

Parameter	Fundamental RF	HHC	Unit
RF frequency	166.6	499.8	MHz
Total energy loss (w/ IDs)	1.55	-	MeV
Total power loss to radiation	800	-	kW
Total RF voltage	2	0.36	MV
Number of cavities	4	1	-
Cavity type	SCC	SCC (active)	-
RF voltage per cavity	>0.5	>0.36	MV
Max. power per cavity	200	120	kW
Nominal transmitter power per RF station	260	150	kW



166.6 MHz SC cavity



499.8 MHz SC cavity

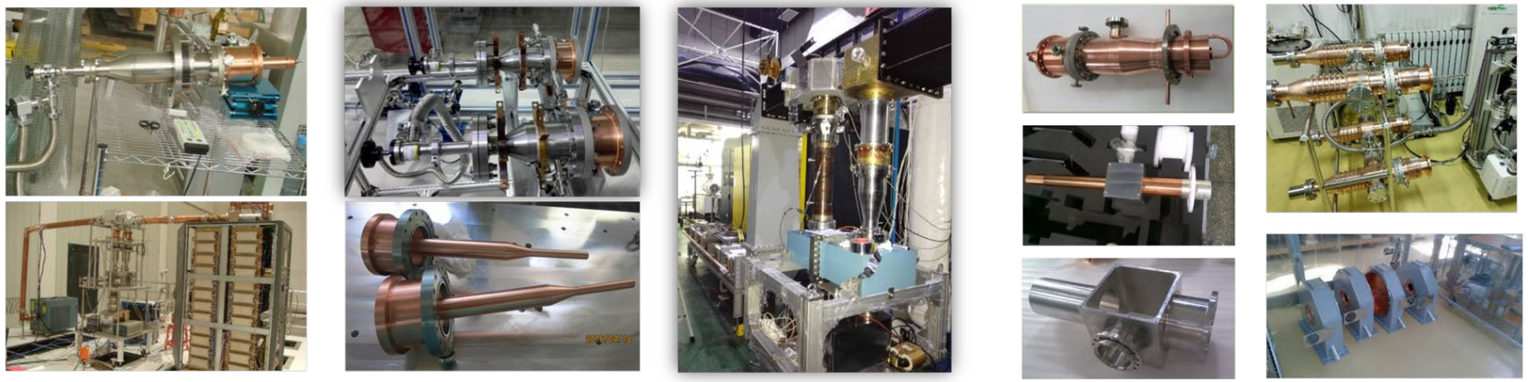
[1] P. Zhang et al., Radio-frequency system of the high energy photon source, Radiation Detection Technology and Methods (2023) 7:159–170.

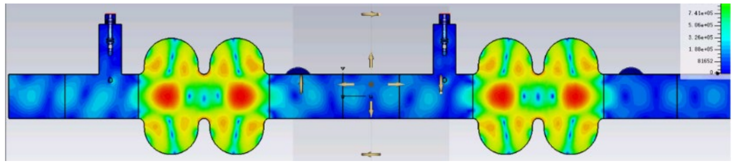
IHEP High Power Input Couplers and HOM Damper

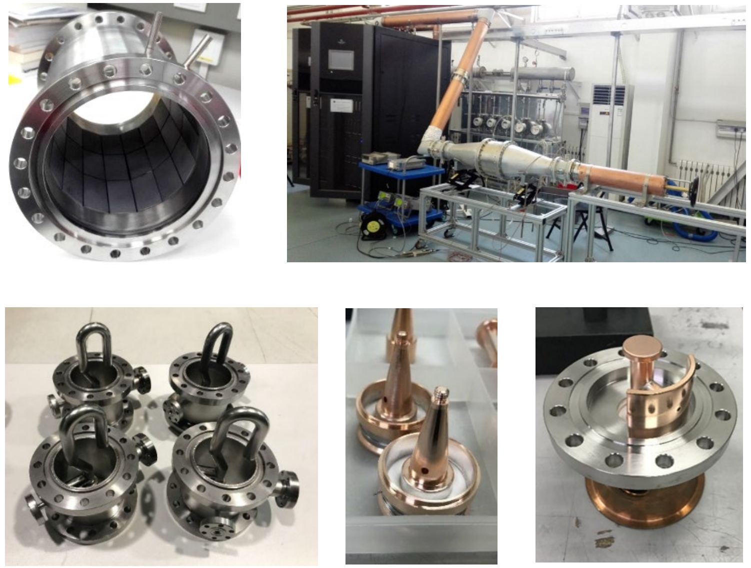
Input power: BEPC 100 kW, HEPS 200 kW, CEPC Higgs 300 kW, CEPC Z-pole 500 kW (1 MW)

500MHz-CW 420kW 166.6MHz-CW 200kW 650MHz-CW 300kW 1.3GHz-CW,70kW 1.3GHz-Pulse 1MW

162.5MHZ-CW,20kW 325MHZ-CW,25kW 650MHZ-CW,150kW 162.5MHZ-CW,80kW 325MHZ-CW,100kW



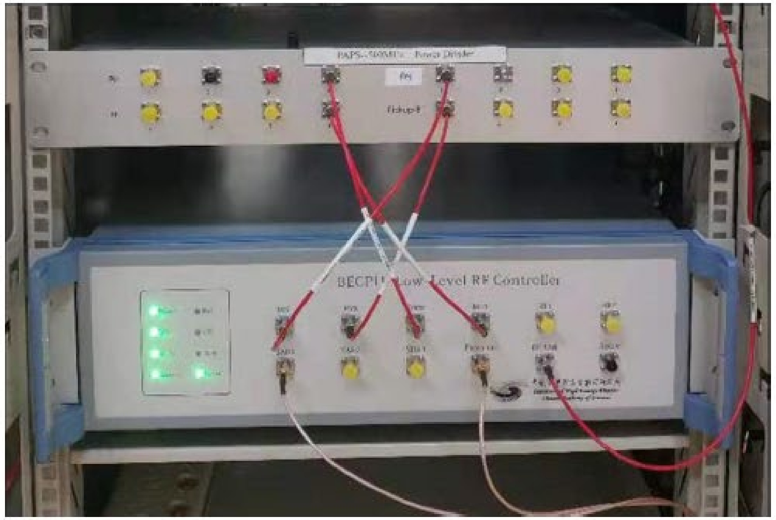




IHEP BEPCII LLRF

(a) Analog LLRF (since 2005)

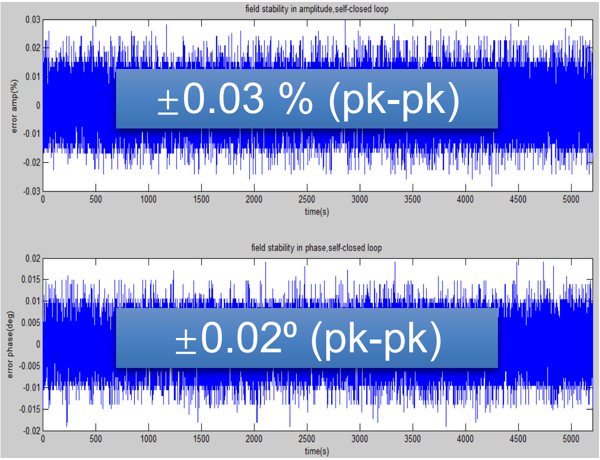
(b) Digital LLRF (2017)



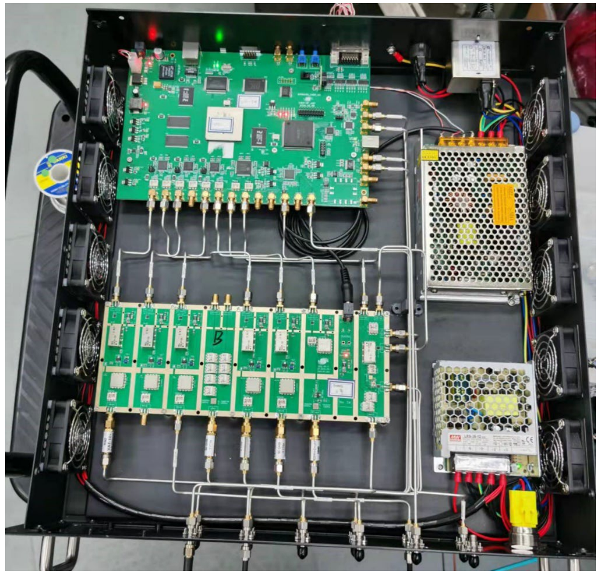
(c) Digital LLRF (2019)

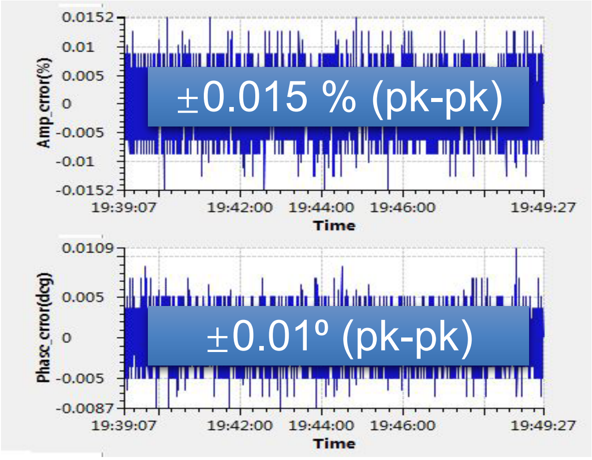
(d) Digital LLRF (2021)

IHEP HEPS LLRF

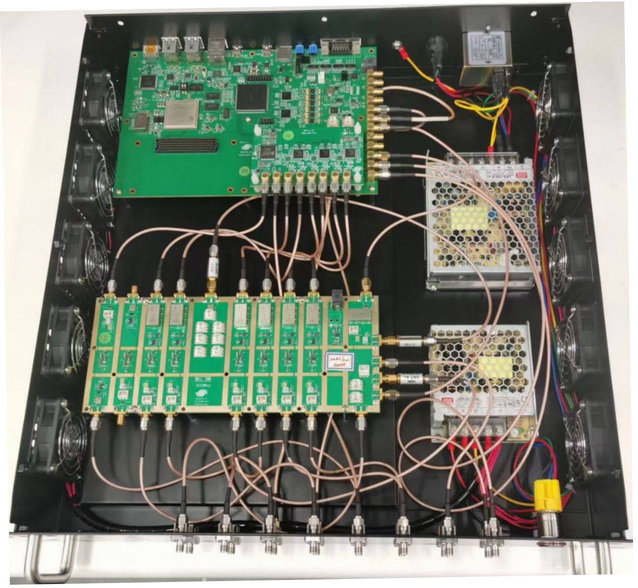


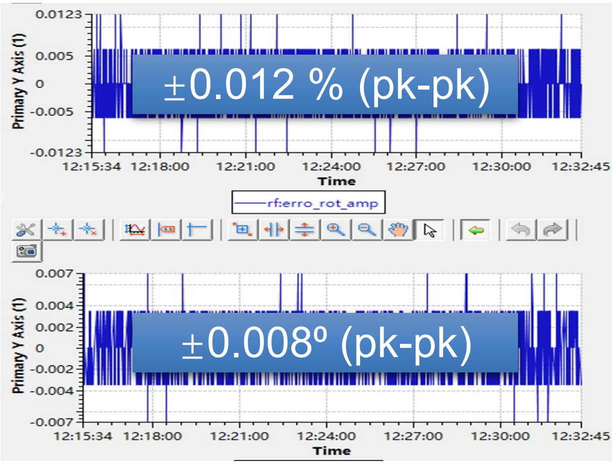
1st-gen LLRF
(166.6 MHz cavity horizontal test,
Vc = 1.2 MV, 4.2 K)





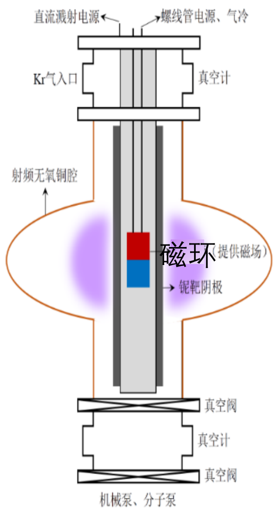
2nd-gen LLRF
(lab test, self closed-loop)

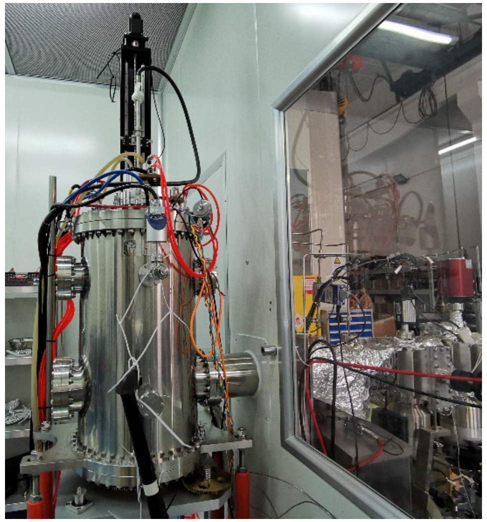


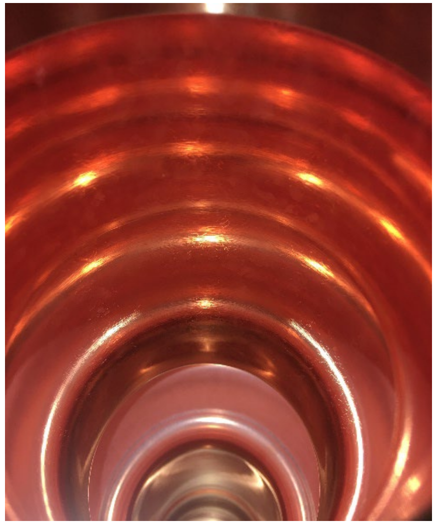


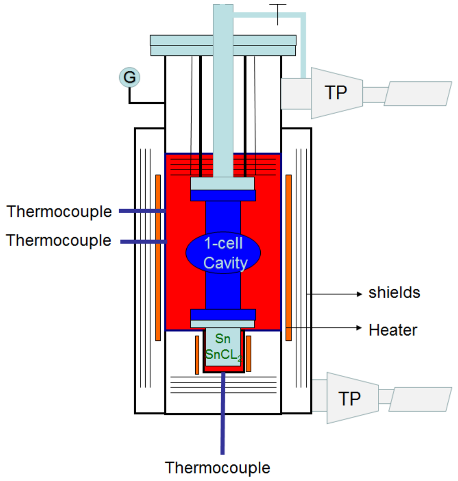
3rd-gen LLRF
(lab test, self closed-loop)

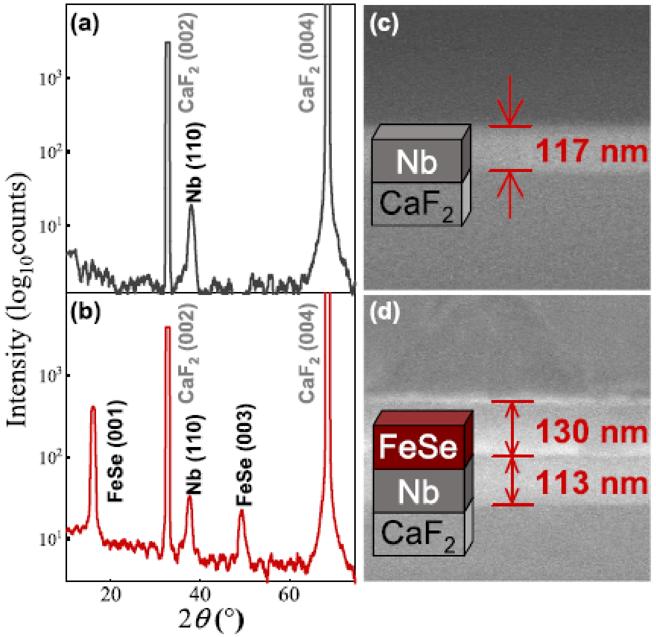
IHEP Thin Film Cavity R&D (Nb/Cu sputtering, Nb_3Sn, Iron-based)



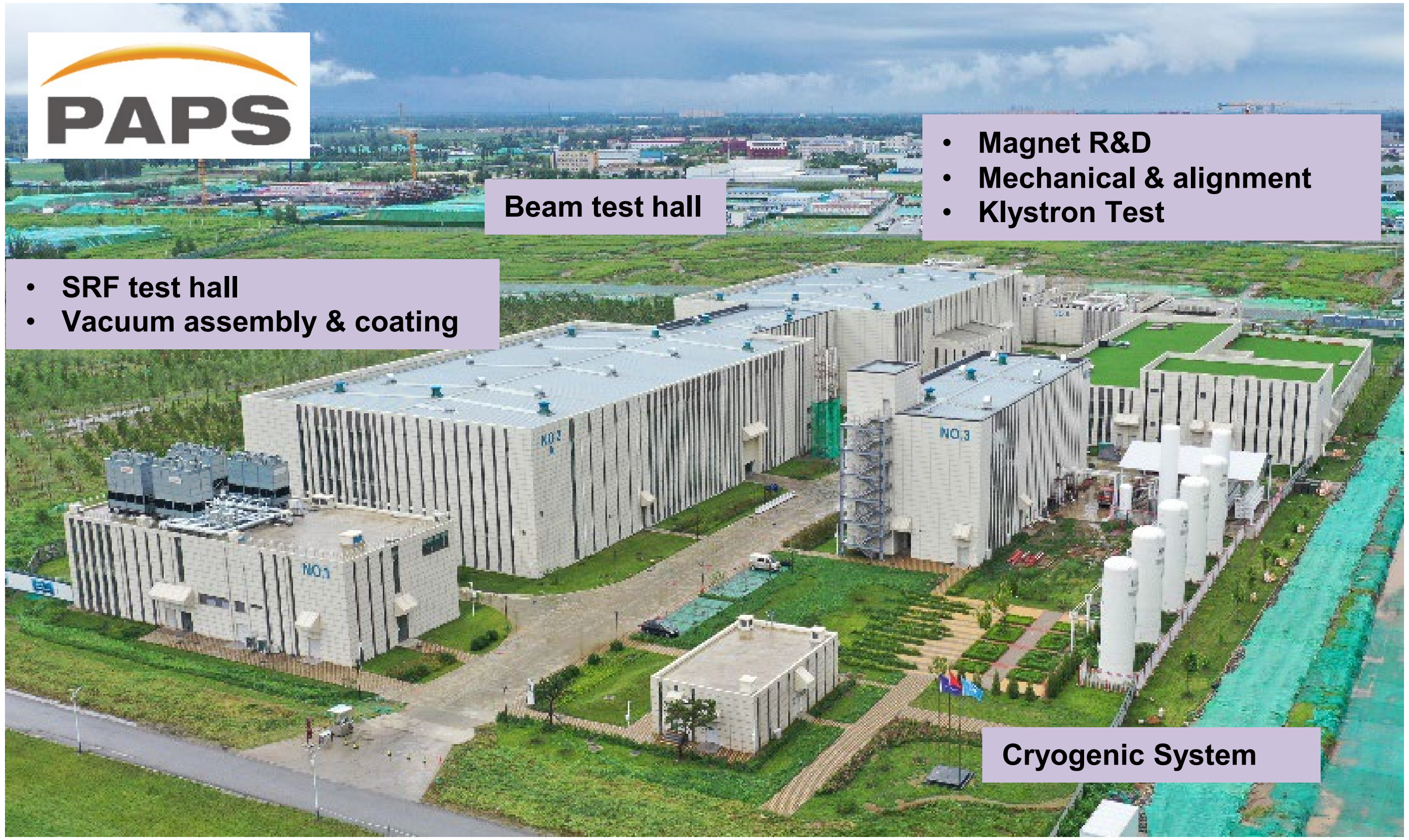


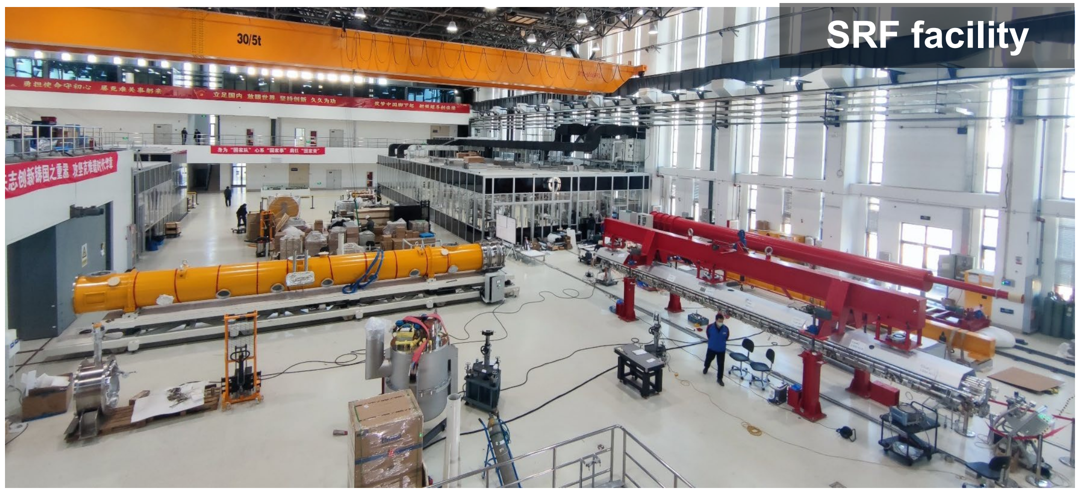


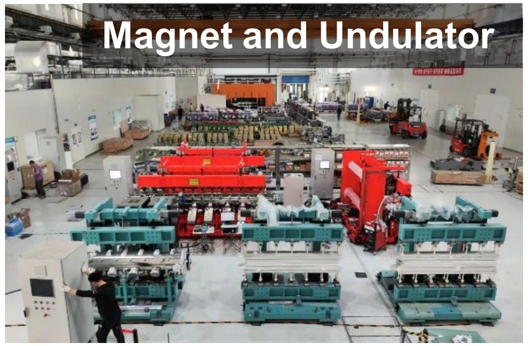


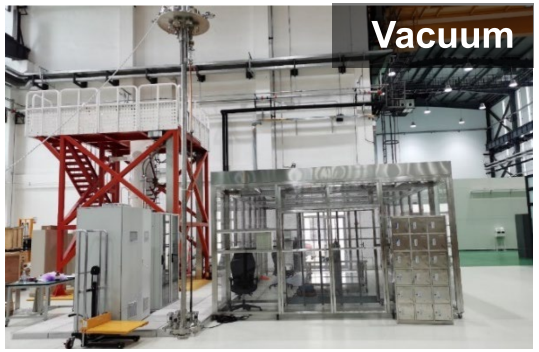


IHEP PAPS SRF Infrastructure in Huairou, Beijing





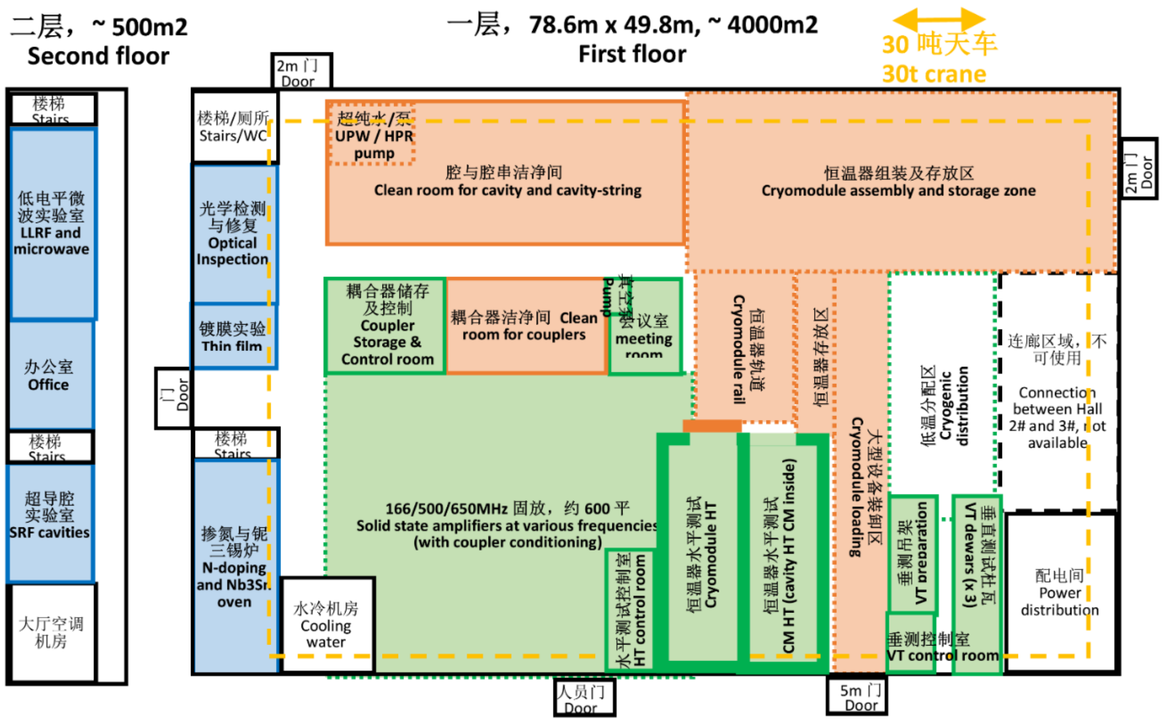


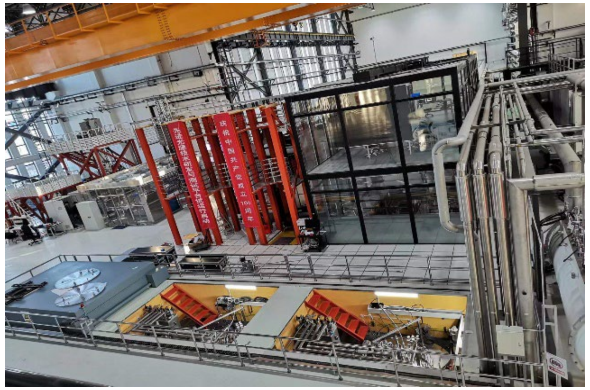


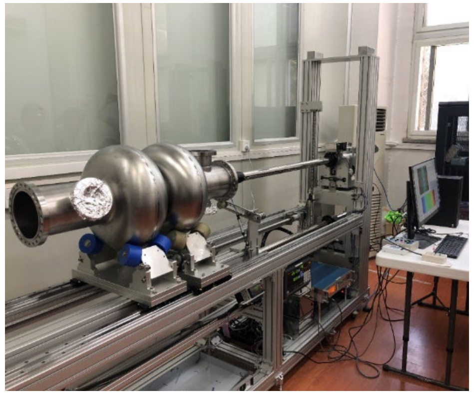
Accelerator key technology R&D and Testing platform:

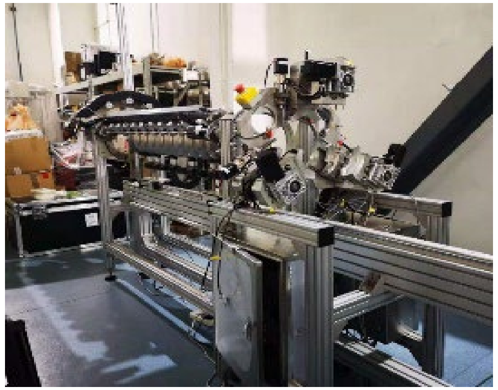
- SRF cavity and module
- High precision magnet
- Vacuum assembly & coating
- High efficiency Klystron
- Mechanics and alignment
- Beam test facility

IHEP PAPS SRF Infrastructure Fully Operational



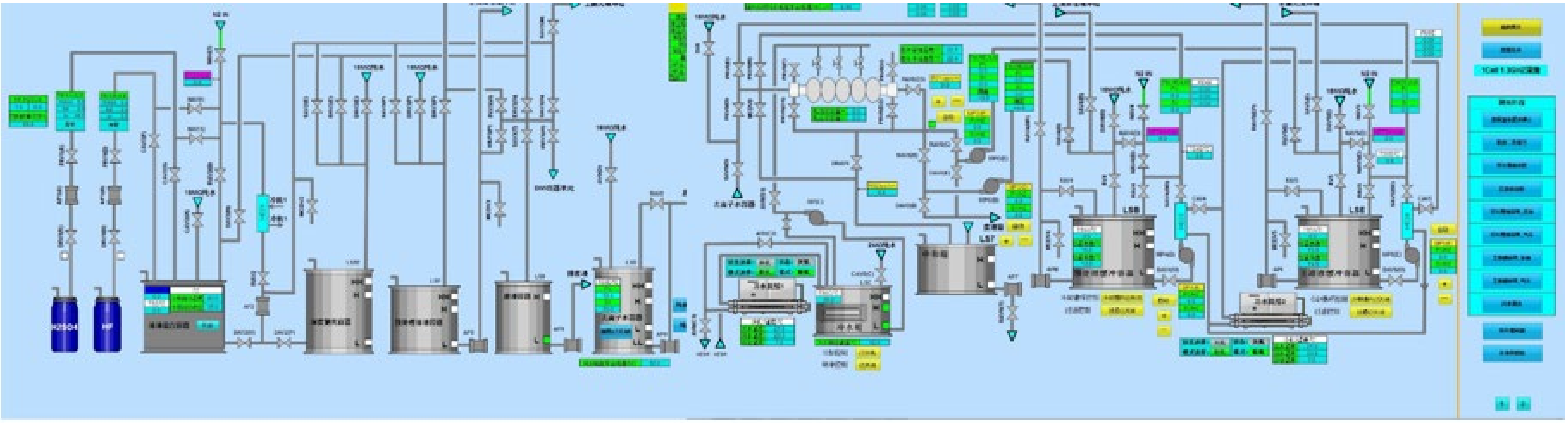


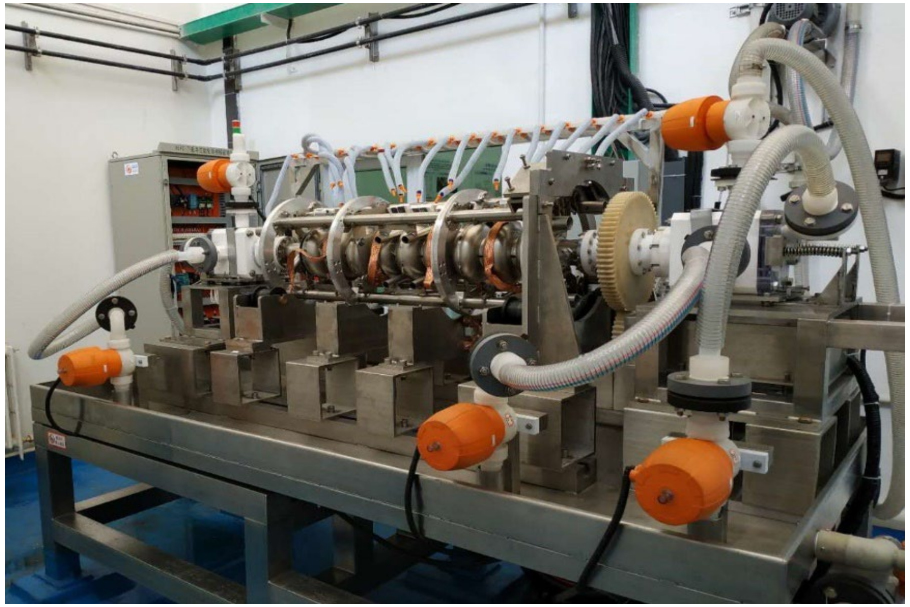


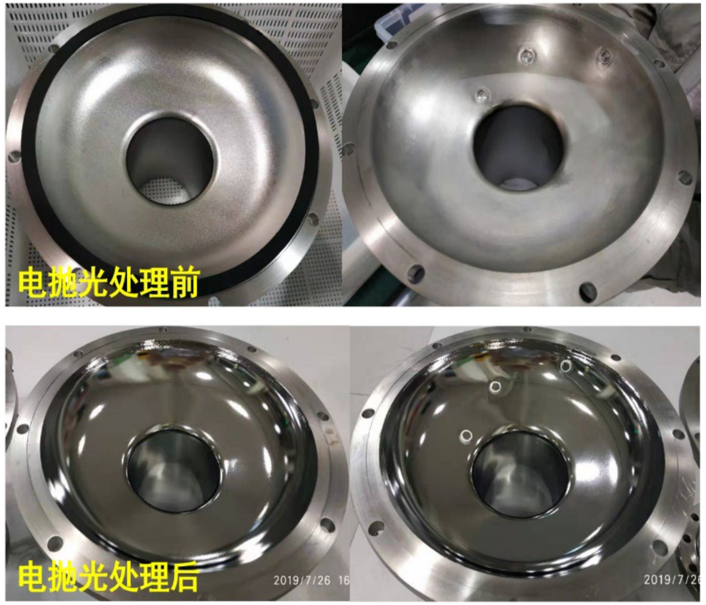


IHEP Cavity Electro-Polishing System at OTIC Ningxia

China's first 9-cell cavity EP system, key tool for high gradient and high Q cavity.



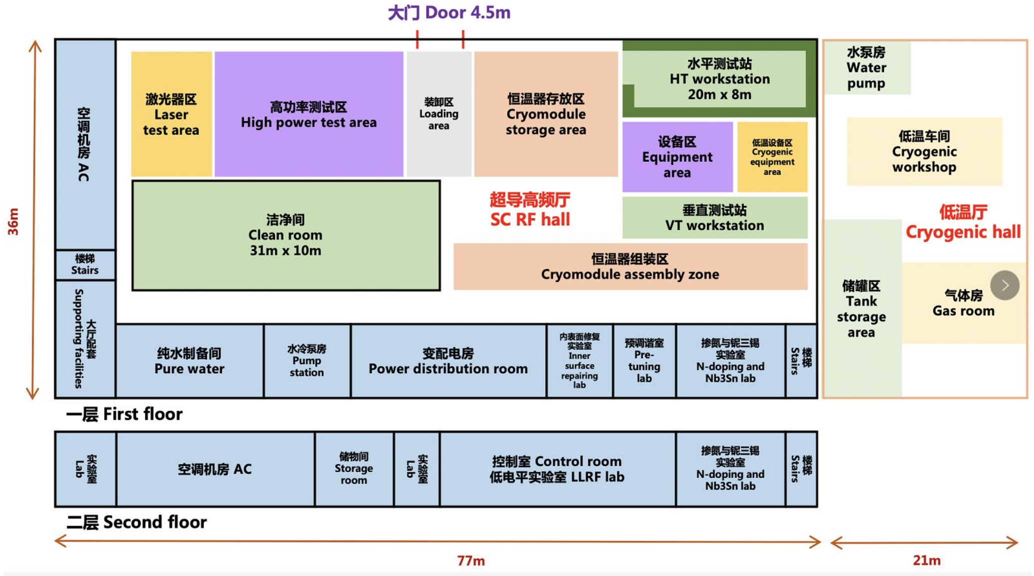




IHEP PAPS SRF Infrastructure Operation Status

Facilities (capability per year)	Devices	Tests since 2021	Related Projects
VT stand (400 cavities)	166 MHz / 325 MHz / 500 MHz / 650 MHz / 1.3 GHz CAV	~ 160	HEPS/BEPCII-U/CEPC/CSNS-II/SHINE/DALS/HALF/(CiADS)
HT stand (20 modules, including assembly)	1.3 GHz CAV	~ 20	CEPC/SHINE/DALS/HEPS/(BEPCII-U/CSNS-II)
High power test stand (200 couplers)	Coupler / Circulator / RF load / Copper cavity	~ 20	HEPS/SHINE/DALS/CSNS-II/(HALF)
Clean assembly and HPR	166MHz / 325MHz / 500MHz / 650MHz / 1.3 GHz CAV	~ 160	HEPS/CEPC/CSNS-II/SHINE/DALS/BEPCII-U/(HALF)
Vacuum furnace	650 MHz / 1.3 GHz CAV	~ 50	CEPC/CSNS-II/SHINE/DALS

IHEP Dongguan SRF Infrastructure



IMP HIAF and CiADS

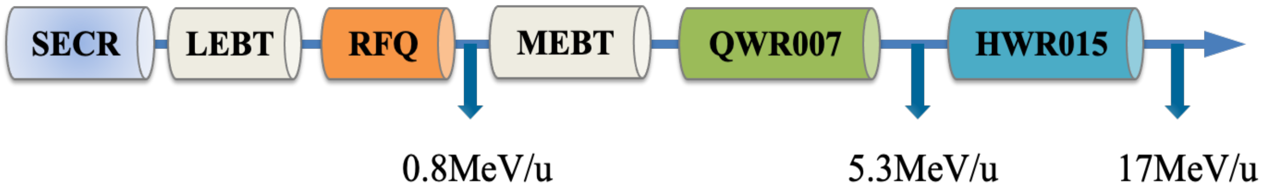
IMP HIAF and CiADS

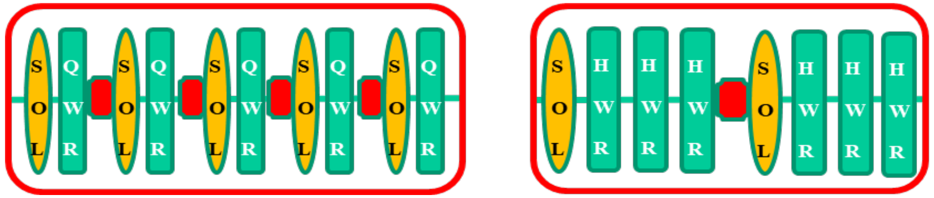
- **HIAF: High Intensity heavy ion Accelerator Facility**
- **CiADS: China Initiative Accelerator Driven System**
- **Being built by IMP in Huizhou of Guangdong Prov.**
- **Two large-scale scientific infrastructure facilities approved by China Government hosted by IMP**

- **HIAF:** Nuclear physics research
- **Total budget:** 2.8 B CNY ¥ (424 M USD $)
- **Schedule:** 2018-2025
- Construction started officially Dec. 2018

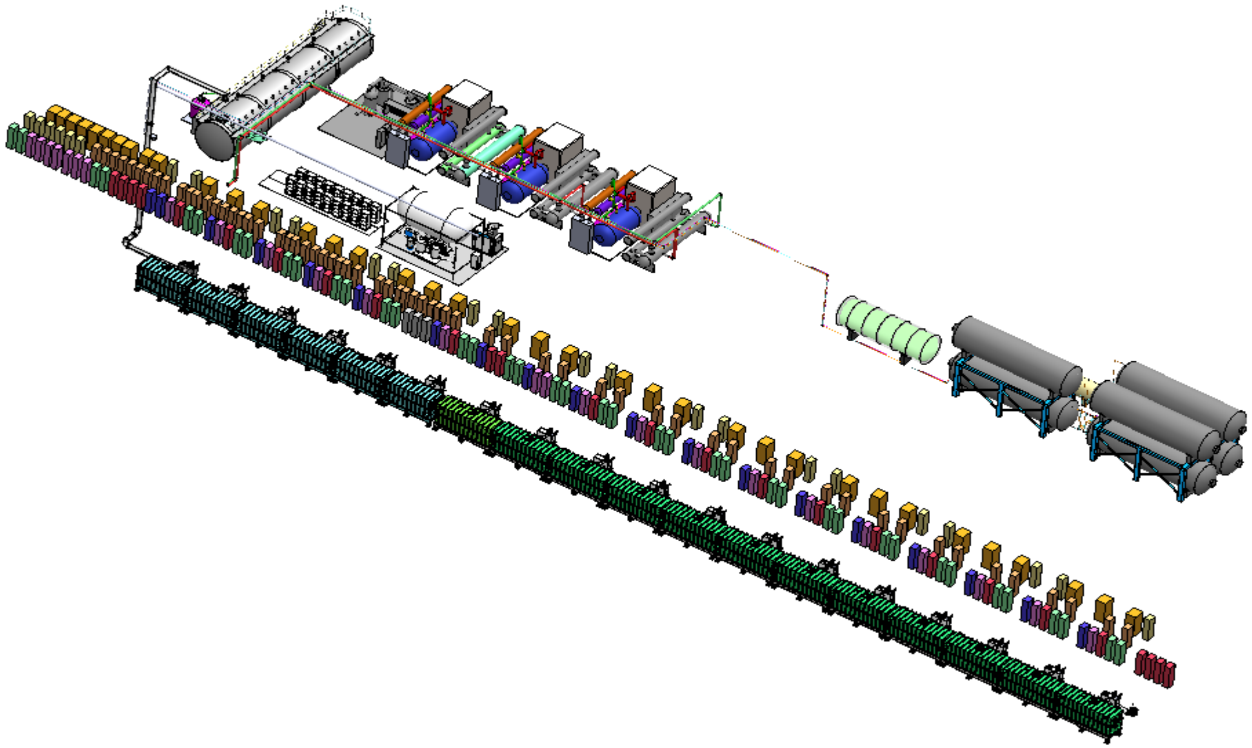
- **CiADS:** Nuclear waste transmutation
- **Total budget:** 4.0 B CNY ¥ (606 M USD $)
- **Schedule:** 2021-2027
- Construction started officially July. 2021

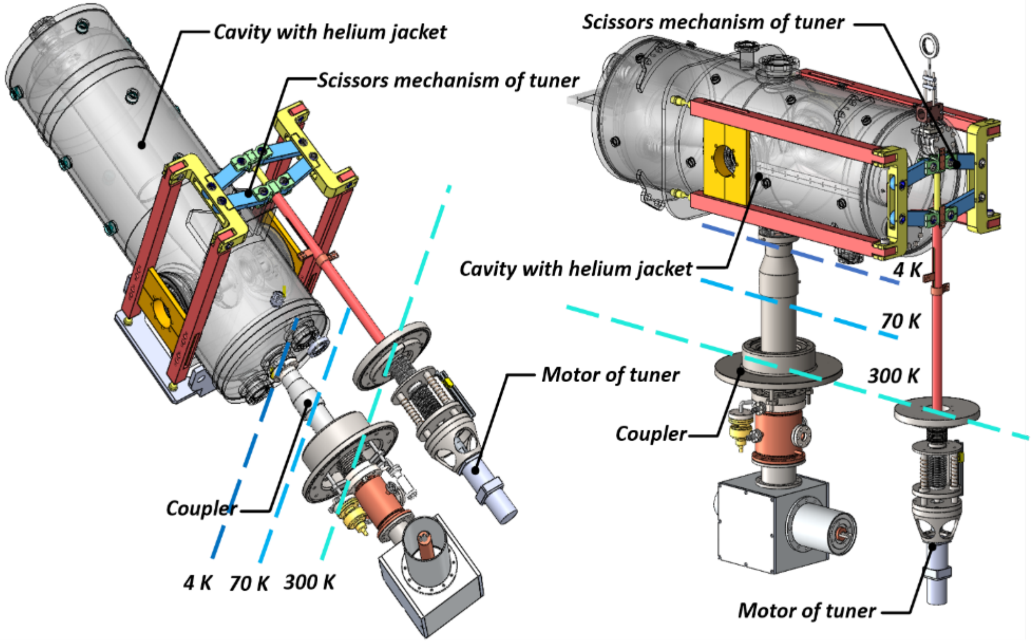
IMP HIAF SRF Cavities





from p to $^{238}U^{35+}$



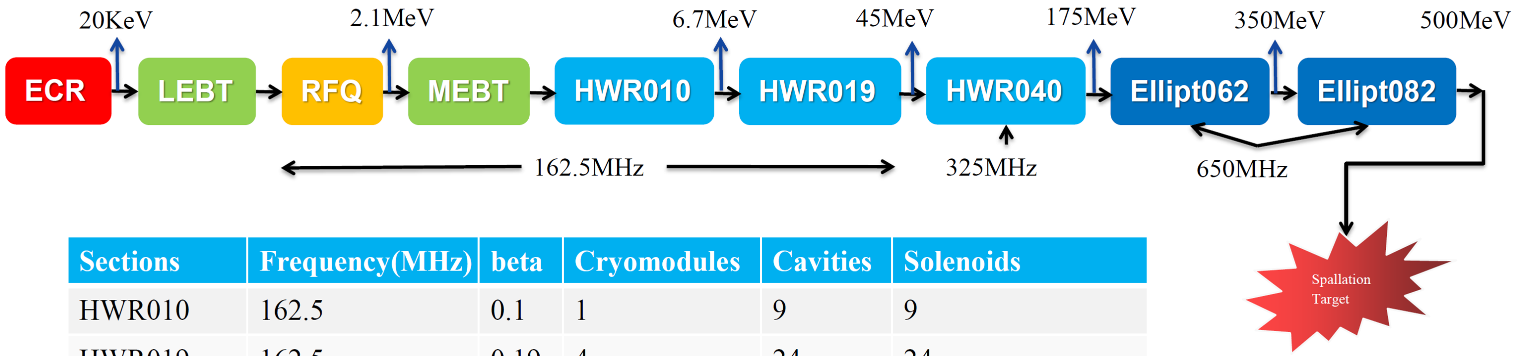


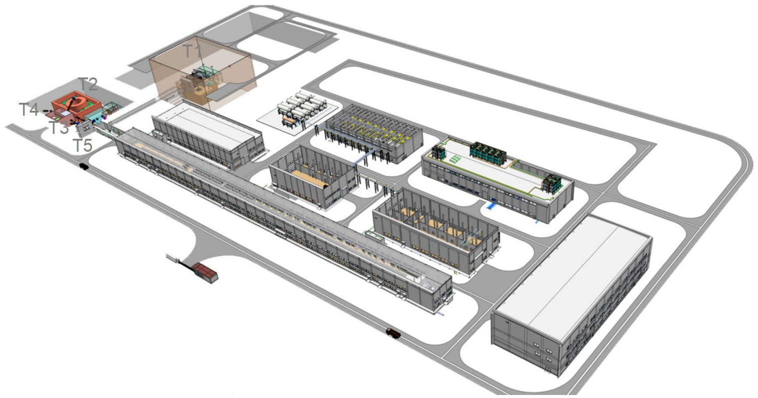
81.25 MHz QWR007
(30 in 6 CMs)

162.5 MHz HWR015
(66 in 11 CMs)

IMP CiADS SRF Cavities

CiADS Linac Design





Sections	Frequency(MHz)	beta	Cryomodules	Cavities	Solenoids
HWR010	162.5	0.1	1	9	9
HWR019	162.5	0.19	4	24	24
HWR040	325	0.4	10	60	20
Ellipt062	650	0.62	10	30	0
Ellipt082	650	0.82	7	28	0
Totals			32	151	53

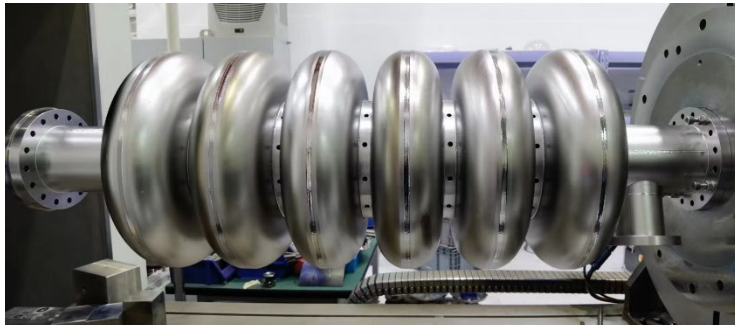
Particle	proton	
Energy	500	MeV
current	5/10	mA
Beam power	2.5	MW
RF freq	162.5/325/650	MHz
Epeak	26/28/29/29/29	MV/m
Num of CM	32	-
Num of cavity	151	-

The strongest *p* machine for spent fuel processing and other nuclear technologies.

Featured with Cu/Nb technology.

HWR010

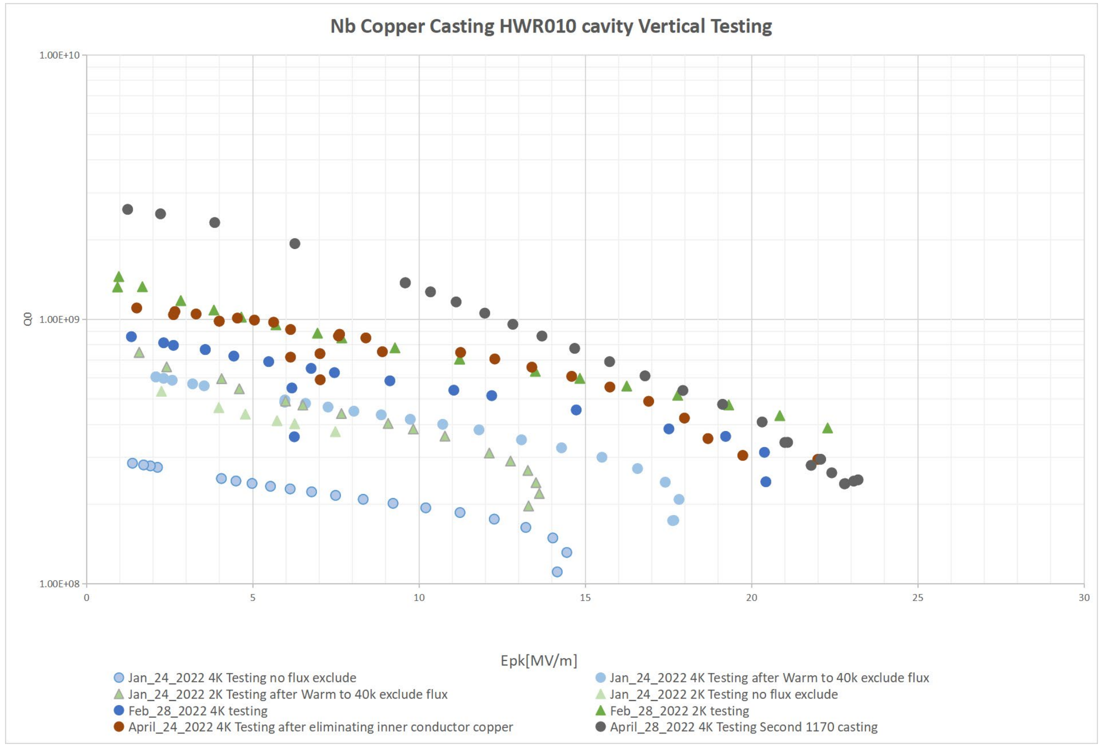
HWR040



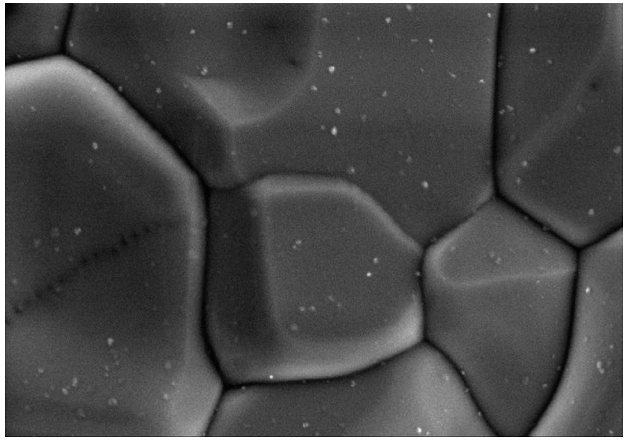
Ellip-062

IMP Cu/Nb Casting and Coating Cavities

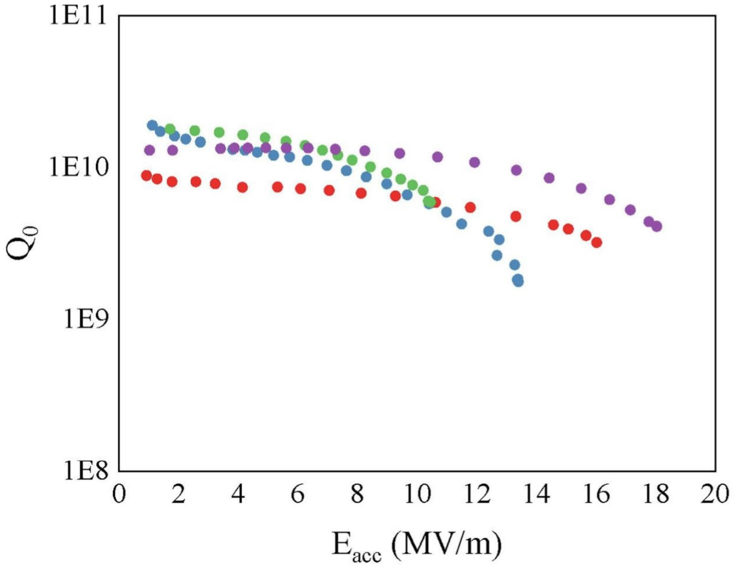
- Batch production of Cu/Nb cavities of HWR type.
- First all-Cu/Nb-cavity cold mass was successfully assembled and will be installed in CiADS linac.
- Performance is improving with verified high-stability

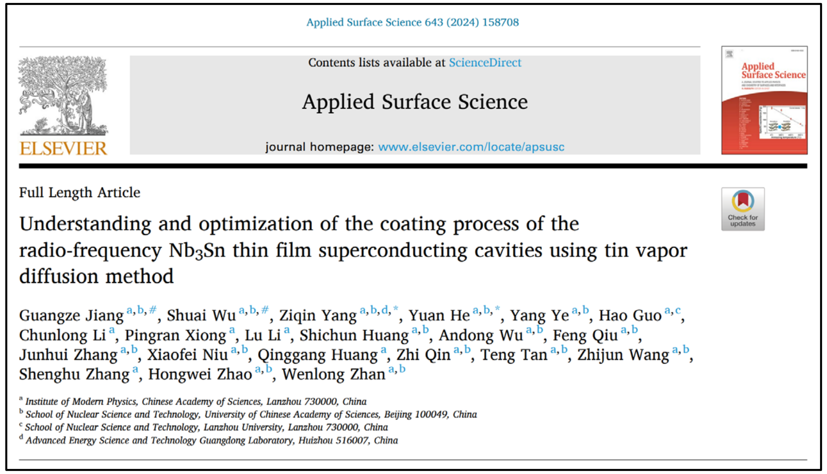


IMP Nb_3Sn Cavity and LHe-Free Linac



- Systematic study about Nb3Sn thin film growth mechanism and cavity optimization.
- Maximum E_{acc} reaches 18 MV/m





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ELSEVIER

Full Length Article

Understanding and optimization of the coating process of the radio-frequency Nb_3Sn thin film superconducting cavities using tin vapor diffusion method

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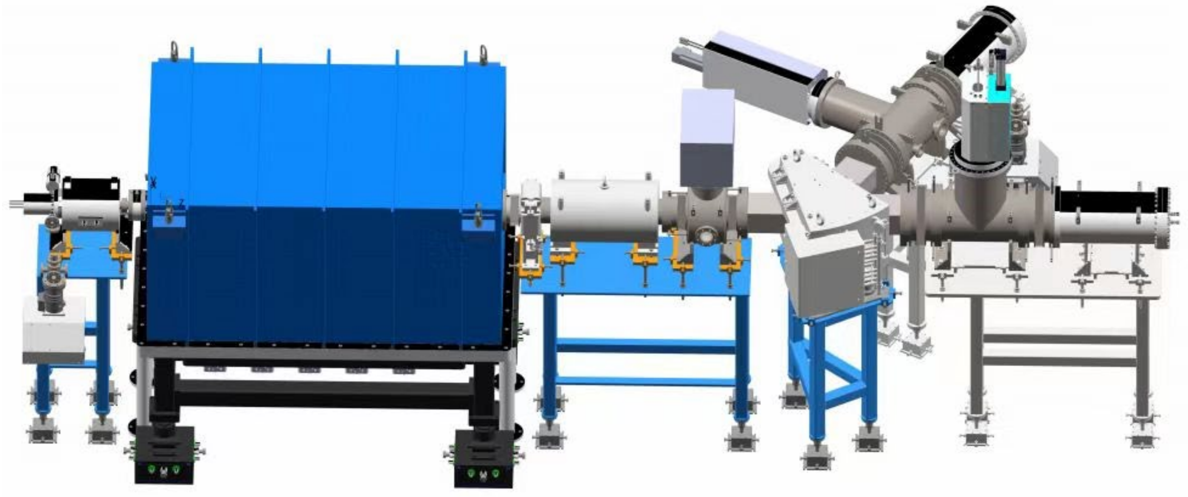
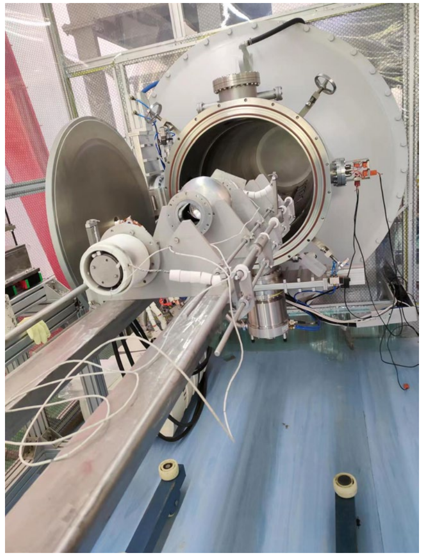
IMP Nb_3Sn Cavity and LHe-Free Linac

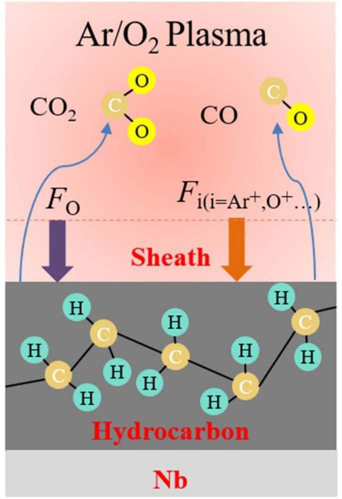


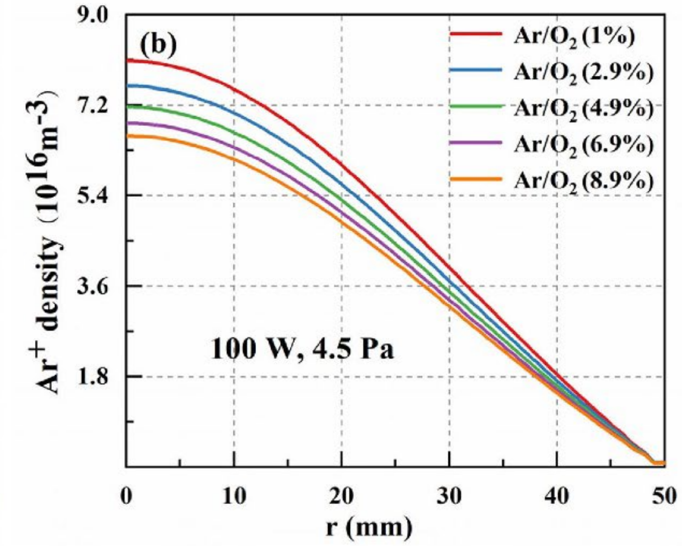
- The first cryocooler-driven SRF e-machine for various industrial applications will be commissioned in this Dec.
- One optimized Nb_3Sn cavity with 10 cryocoolers produce 5 MeV 10 mA e-beam, suitable for clean-water project, e-beam manufacturing, etc.

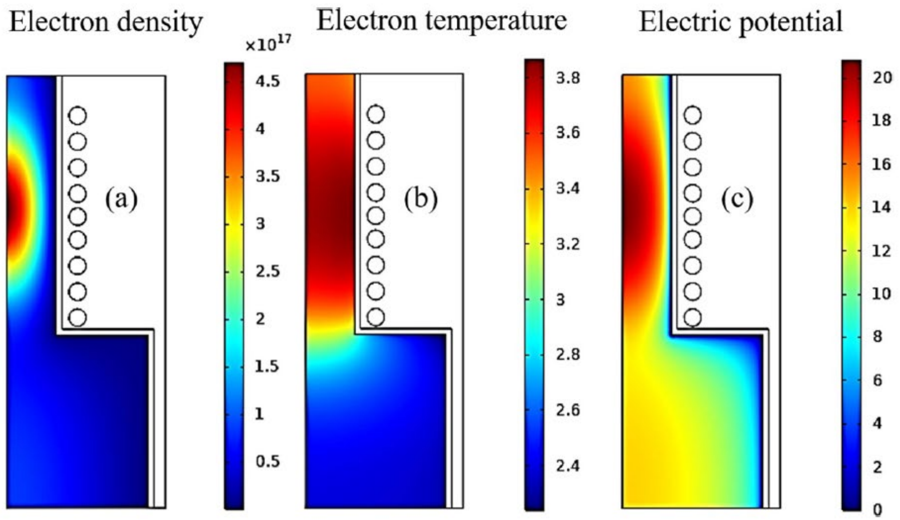


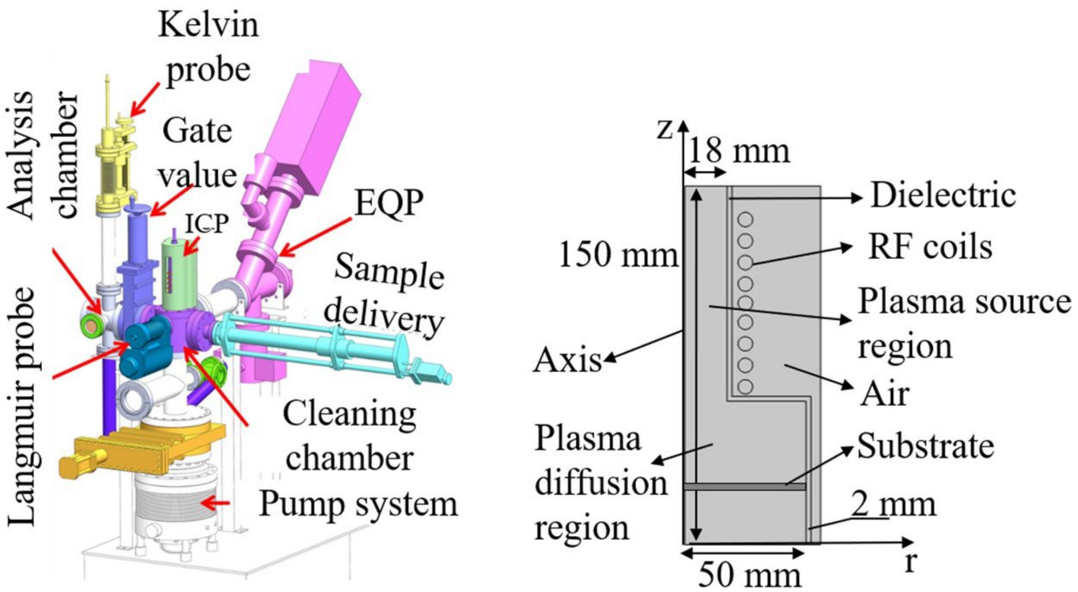
IMP Reactive Plasma Cleaning

- Reaction mechanism between reactive oxygen plasma and hydrocarbon was studied.
- Test platform and commercialized machine were developed for plasma cleaning technique.









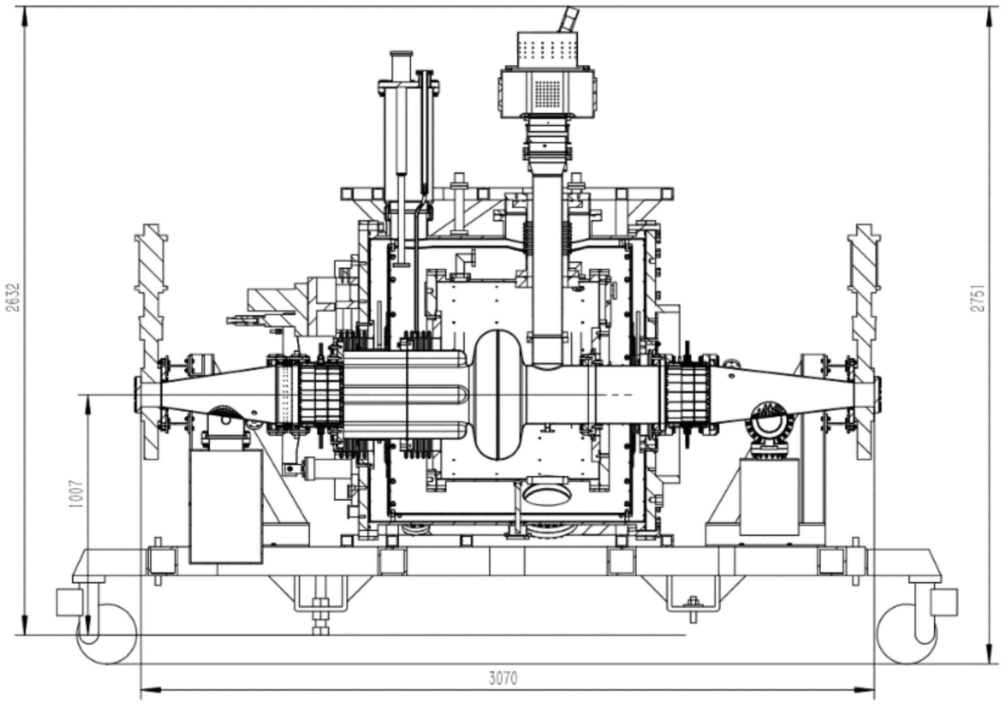
Plasma Sources Sci. Technol. **32** (2023) 115002

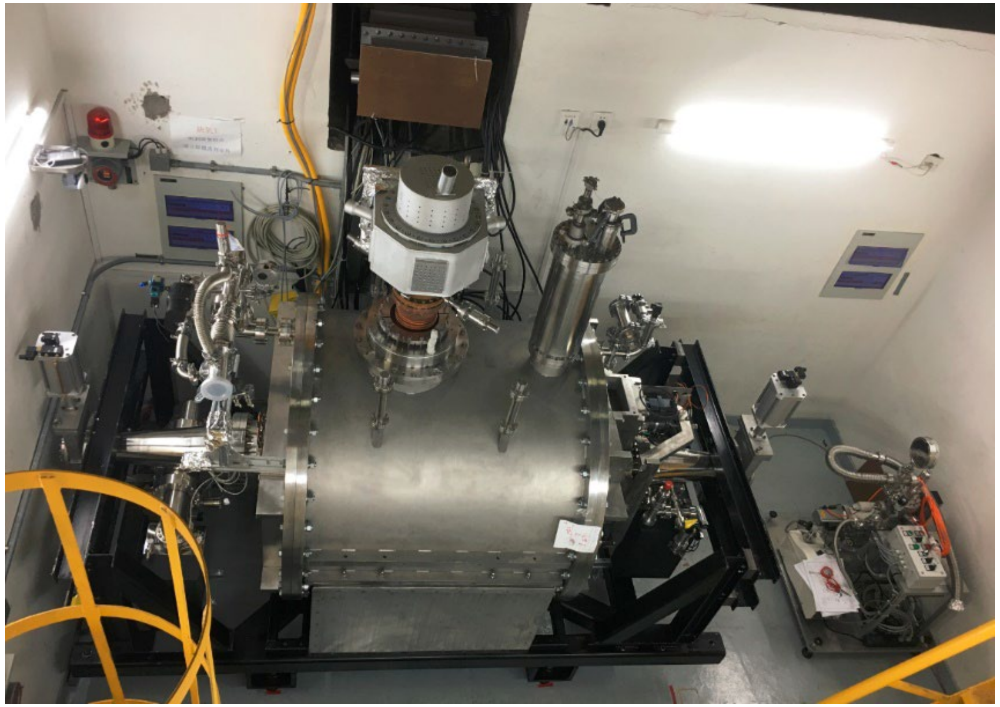
Shanghai SARI SSRF

Spare 500 MHz Cryomodule for SSRF

One 500 MHz cryomodule has been horizontal tested successfully in April 2021:

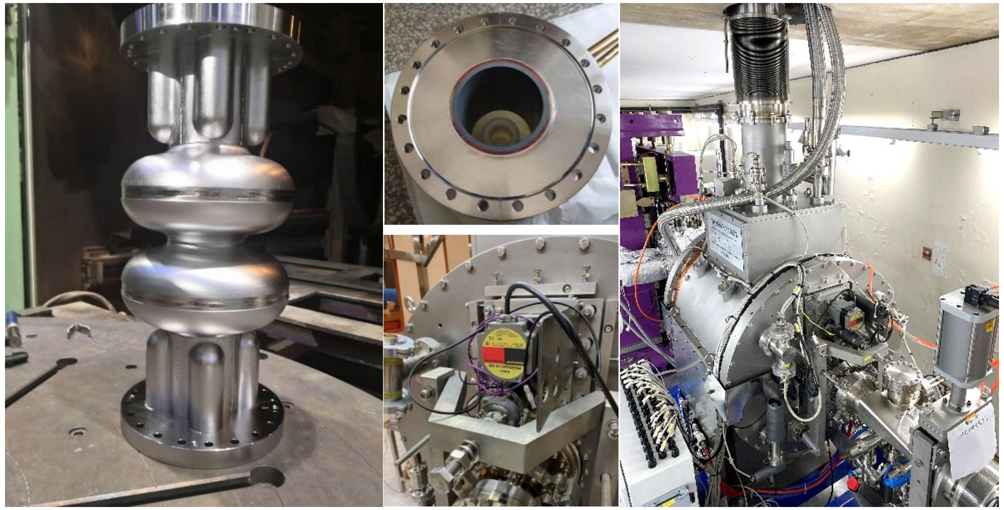
- New design: fluted beam pipe and coaxial input coupler are combined
- Q0=1.0e9 @ 1.5 MV and Q0 = 7.7e8 @ 2.1 MV;
- Helium pressure stability < +/- 1.5 mbar and helium level stability < +/- 1.0%
- Input coupling is adjustable: (1.5+/-0.3)e5





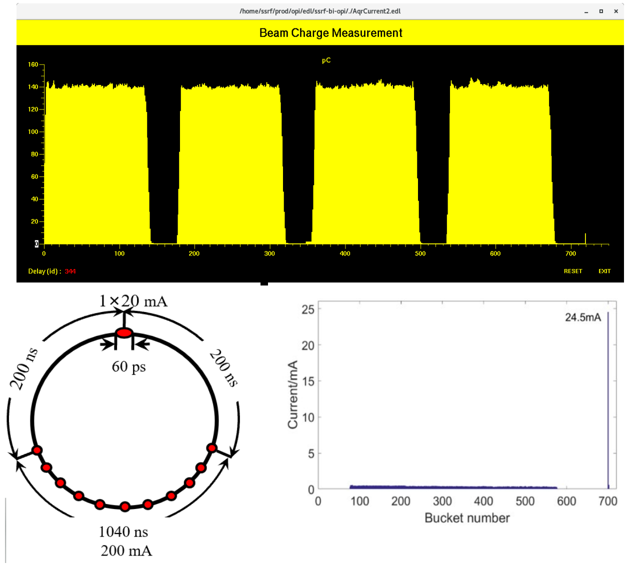
SARI Superconducting Harmonic Cryomodule for SSRF

- **Function:** bunch size lengthen, improve beam quality and lifetime, increase single bunch beam current threshold……
- **Key components:** In-house developed, including Nb Cavity, cryostat, HOM absorber, Tuner, Monitor & Interlock controller, Digital LLRF controller
- **Operation** with 200 mA top-up beam: lengthen factor is 2.24 at four bunch train filling pattern, 2.98 at hybrid filling pattern with current in single bunch is higher than 24 mA. Lifetime increased factor is about 2.



3HC cryomodule in tunnel

Monitor & Interlock and LLRF

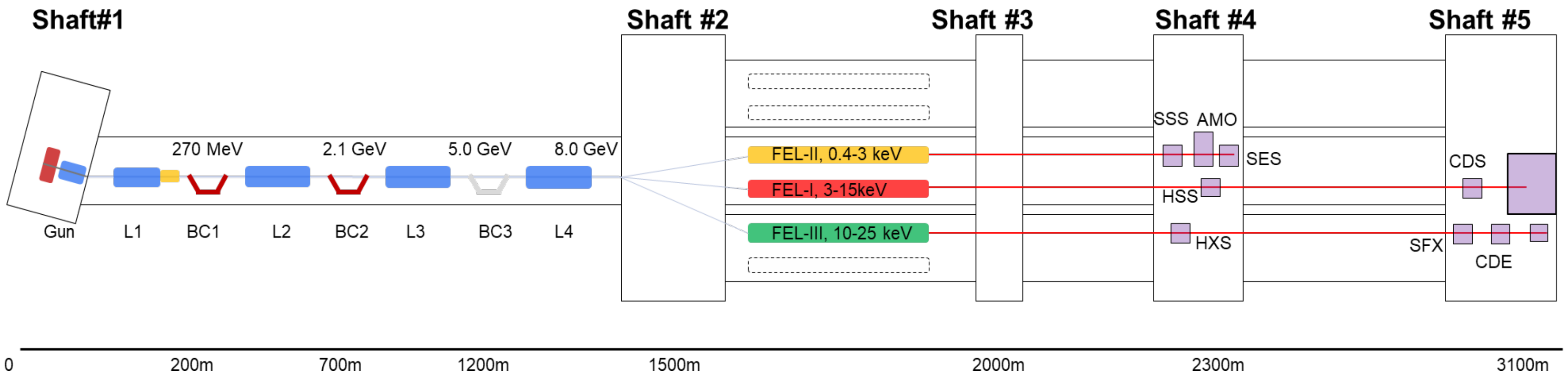


Beam Operation

Shanghai SARI SHINE

SHINE: Shanghai HIgh repetitioN rate XFEL and Extreme light facility (600 9-cell cavities, 75 modules)

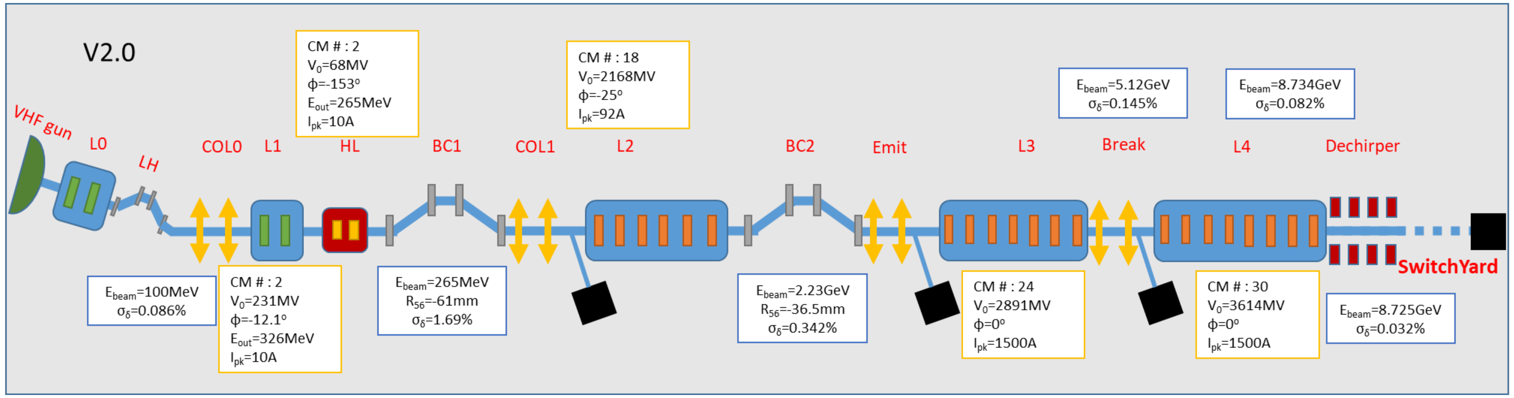
- Launched in April 2017, groundbreaking in April 2018, aiming at the first lasing in 2025.

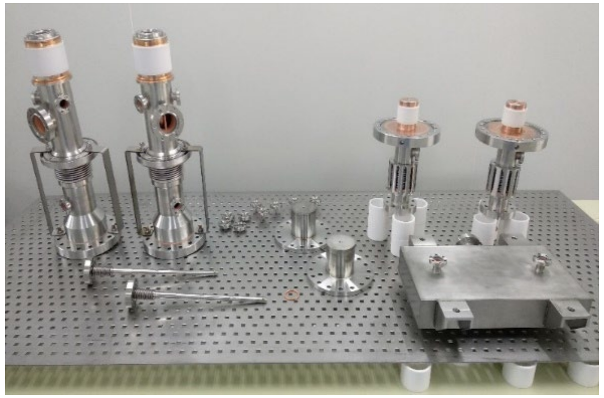


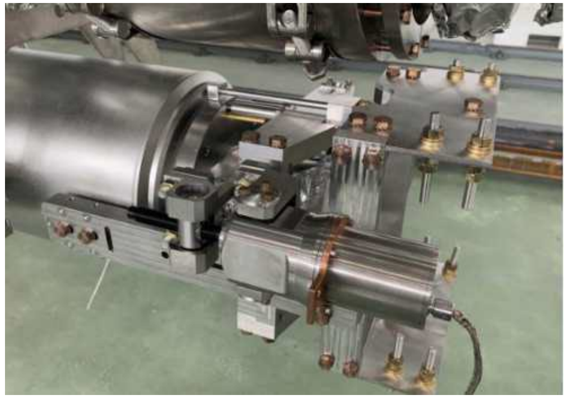
- 8 GeV SRF linac, total length: 3110 m -29.0 m underground
- 3 undulator lines, photons from 0.4-25 keV
- 3 X-ray beamlines, delivering up to 1MHz photon pulse
- 10 experimental stations
- A 100 PW laser facility

Superconducting Cryomodule for SHINE

- **Key components:** Nb Cavity, high power coupler, cryostat, HOM absorber, Tuner, BPM,
  - Both N-doping and midT-baking recipes reached SHINE specs: Q0> 2.7e10 @ 16 MV/m, Eacc_max>19 MV/m, FE free
- **Infrastructure:** Wuxi SRF Cavity post-processing platform (BCP, EP, Pre-tuning, HPR, Furnace, Cleanroom); Cryomodule HT & Cavity VT platform at Shanghai(Cleanroom, Assembly, Vertical test, Horizontal test)
- **Research:** high-Q & G study; high average coupler; cold BPM; tuner; Solid-State Power Source; Digital LLRF…



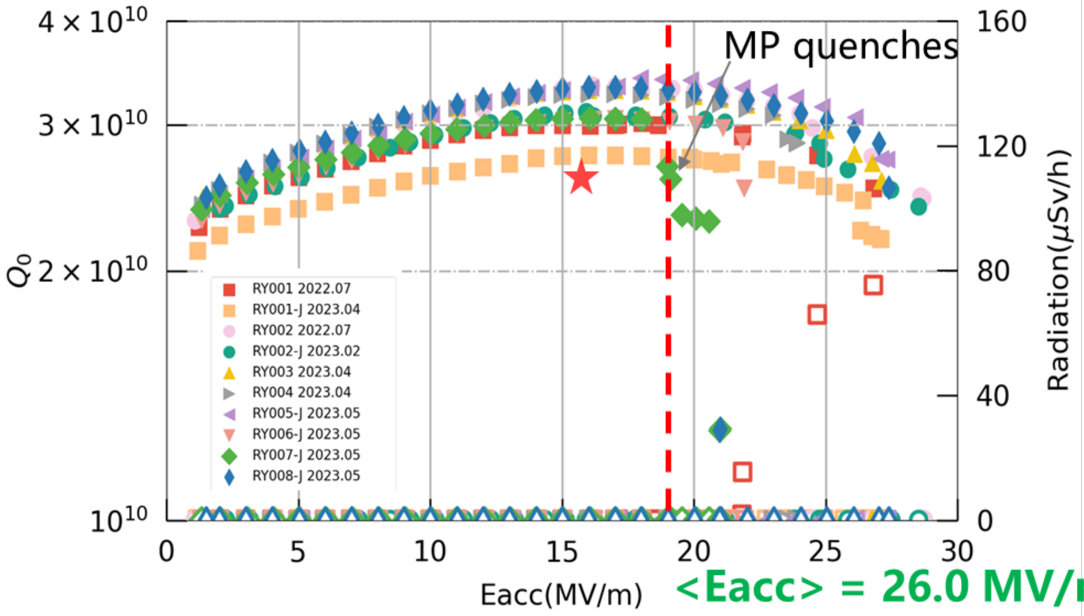




Status of small-batch high-Q cavities

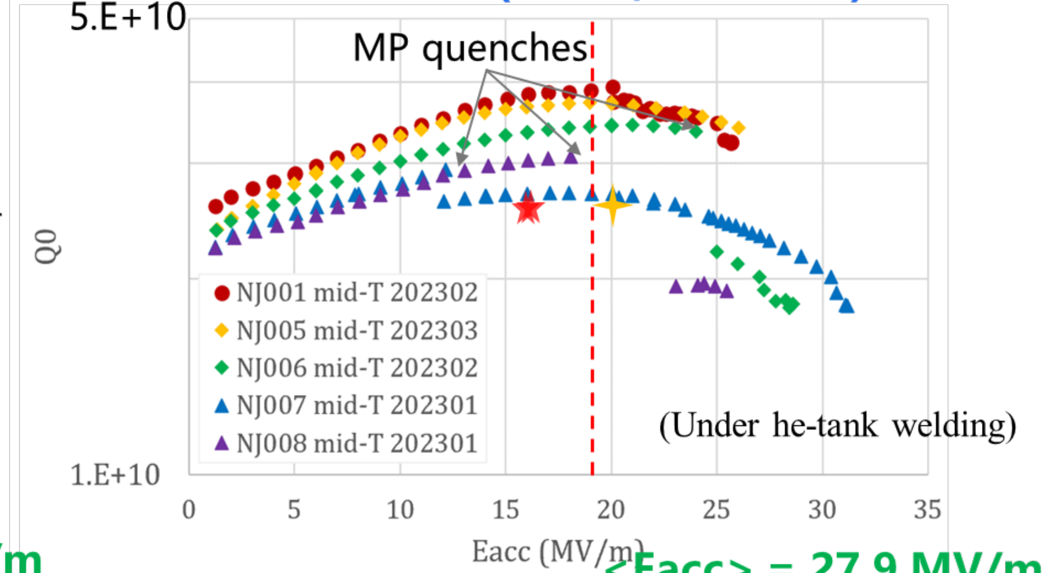
- International cavities (RI and ZANON): N-doping, 3/60 recipe applied
- Domestic cavities (~half half): N-doping and mid-T baking
- So far, **two production lines have been qualified** by small batch cavities: One international and one domestic.
- Cavities of the other two lines are underway (surface treatment and waiting for VT)

All the 8 N-doped dressed cavities (Line 1)



<Eacc> = 26.0 MV/m
<Q0>= 3.15 E+10

All the mid-T baked bare cavities tested so far (Line 2, domestic)

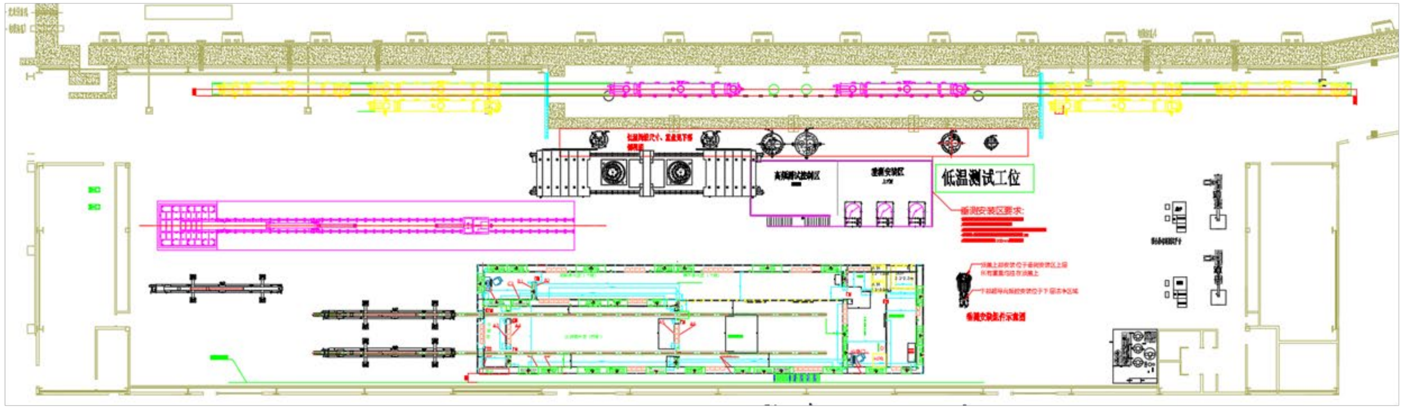


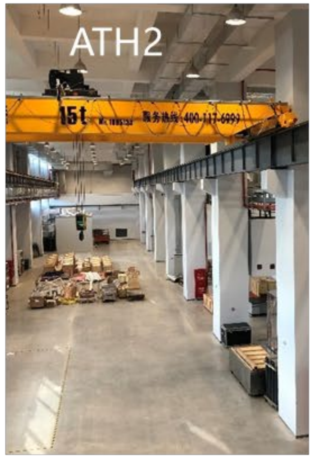
<Eacc> = 27.9 MV/m
<Q0> = 3.3 E+10

Infrastructure for CM assembly and test

S. Sun

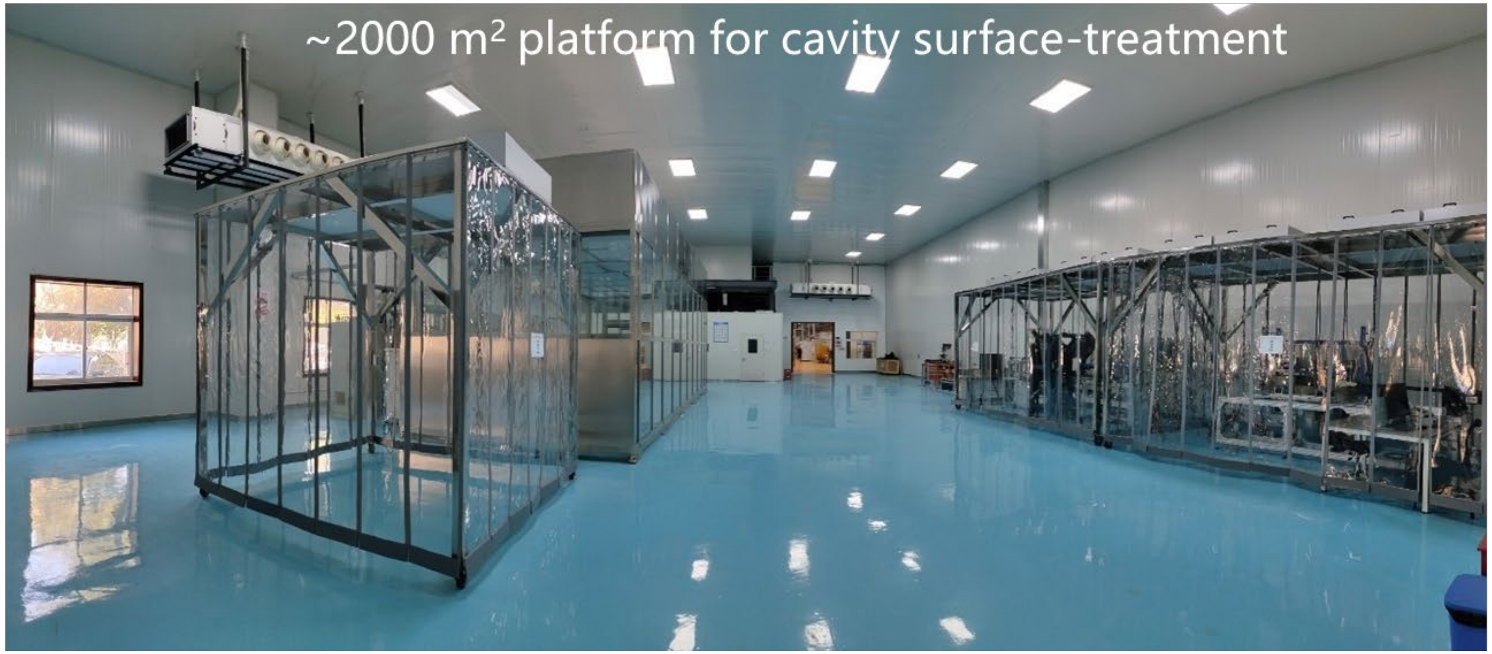
- Two 3000 m² for CM Assembly and Test Halls (ATH1 & ATH2)
- Commissioning and gradually put into operation since 2021
- 3 rounds of standard CM assembled and tested

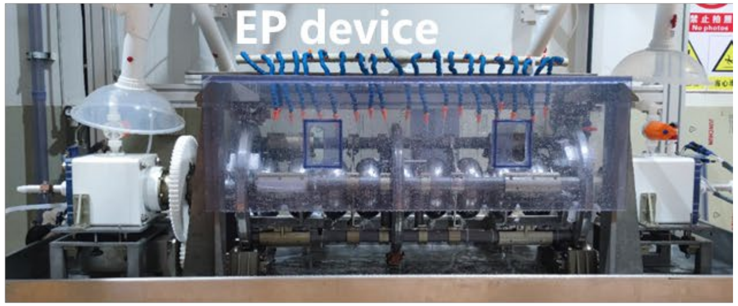


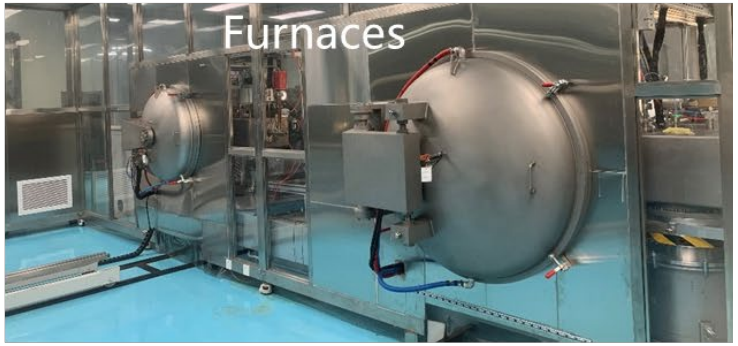


Infrastructure for cavity surface treatment

- **Cavity surface-treatment platform** (co-built): SHINE facilities at Wuxi Creative
- **Goal**: R&D and mass production for cavity surface-treatment
- **Design:** Dealing with all the procedures after cavity fabrication, and before vertical test
- **Status:** Commissioning and gradually put into operation since 2021, undertaking the surface-treatment of SHINE cavities from domestic companies



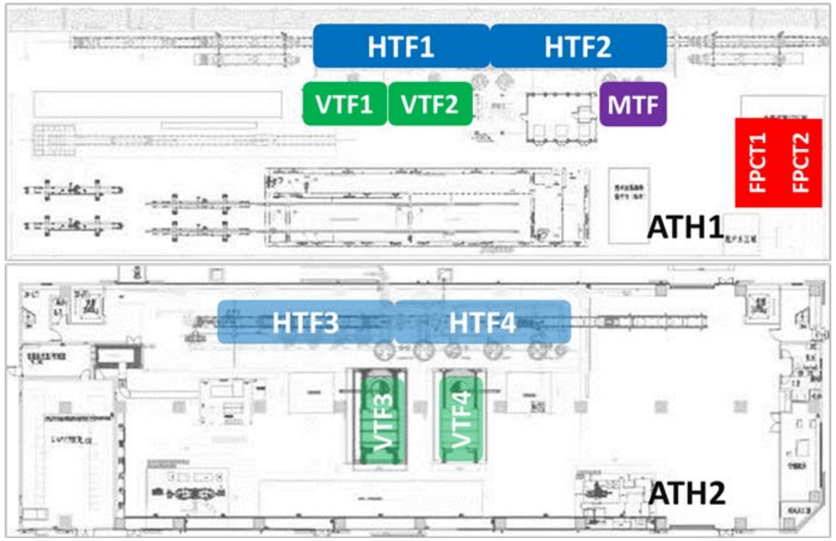




Test Stands for cavities and CMs

S.J. Zhao

- 4 vertical test stands and 4 horizontal test stands are designed in the two halls
- In ATH1(Assembly and Test Hall), 2 vertical test stands and 2 horizontal test stands, have been constructed and **put into operation**;
- The test stands in ATH2 are expected to be completed this year;
- The Cryo distribution will be optimized to allow more effective operation of multi-stands;
- The mass flow meters will be equipped to make the Q_0 test easier than the delta liquid level method used now.



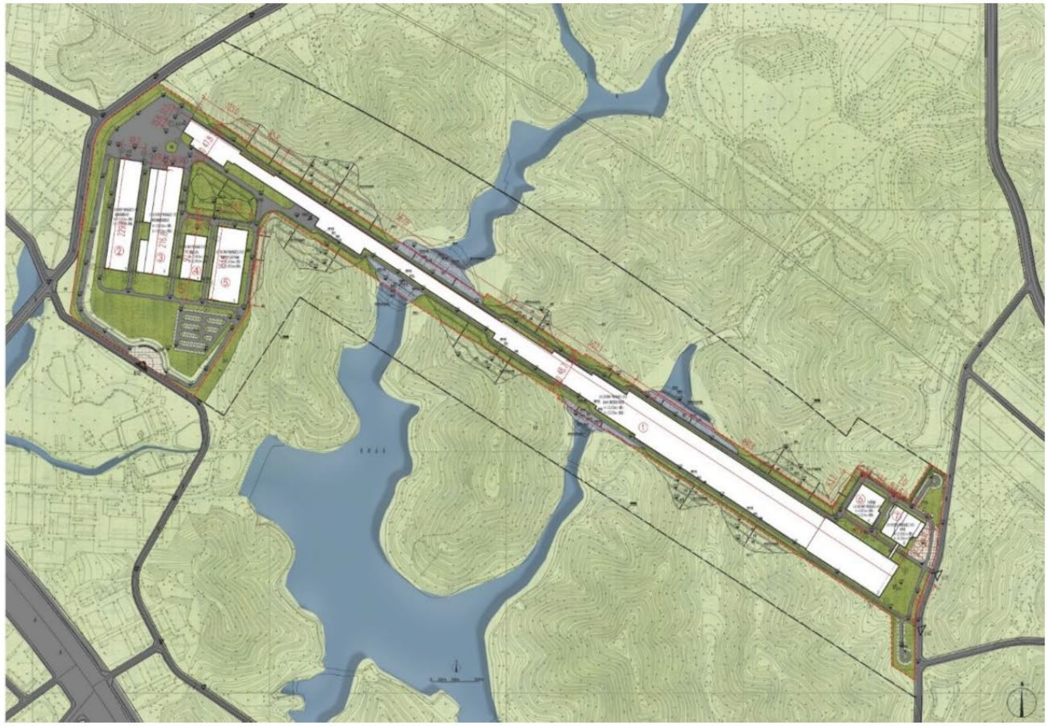
Shenzhen IASF S^3FEL

Worldwide FELs

Facility	Wavelength	Country	LINAC	Beam energy /GeV	Photon energy	Rep. rate/Hz	Staues
FLASH	Soft X-ray	DE	SRF	1.25	14 - 300 eV	5000	operation
European XFEL	Hard X-ray	EU	SRF	17.5	8.4 - 30 keV	27,000	operation
LCLS-II	Hard X-ray	US	SRF	4	0.2 - 5 keV	1,000,000	commissioning
SHINE	Hard X-ray	CN	SRF	8	0.4 - 25 keV	1,000,000	Under construction
S^3FEL	Soft X-ray	CN	SRF	2.5	0.04 - 1 keV	1,000,000	Approved

Shenzhen IASF S^{3}FEL

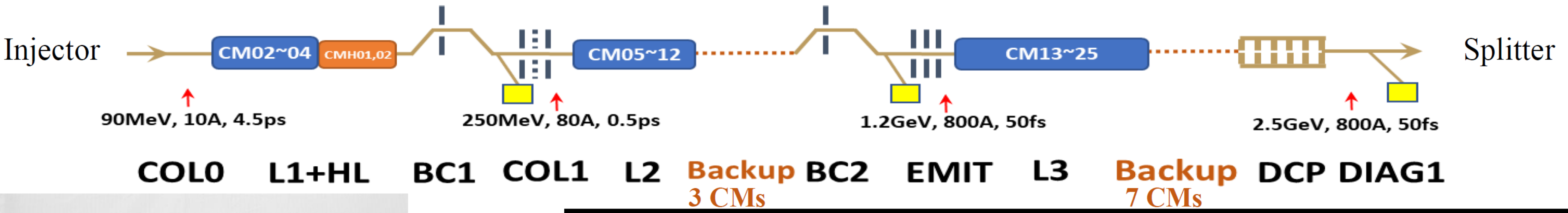
Location and Layout

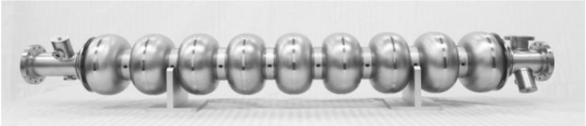


Shenzhen IASF S³FEL

LINAC design

Function: accelerate the electron beam, compress the beam length and increase the peak current intensity





1.3 GHz cryomodule:
26 sets, energy acceleration

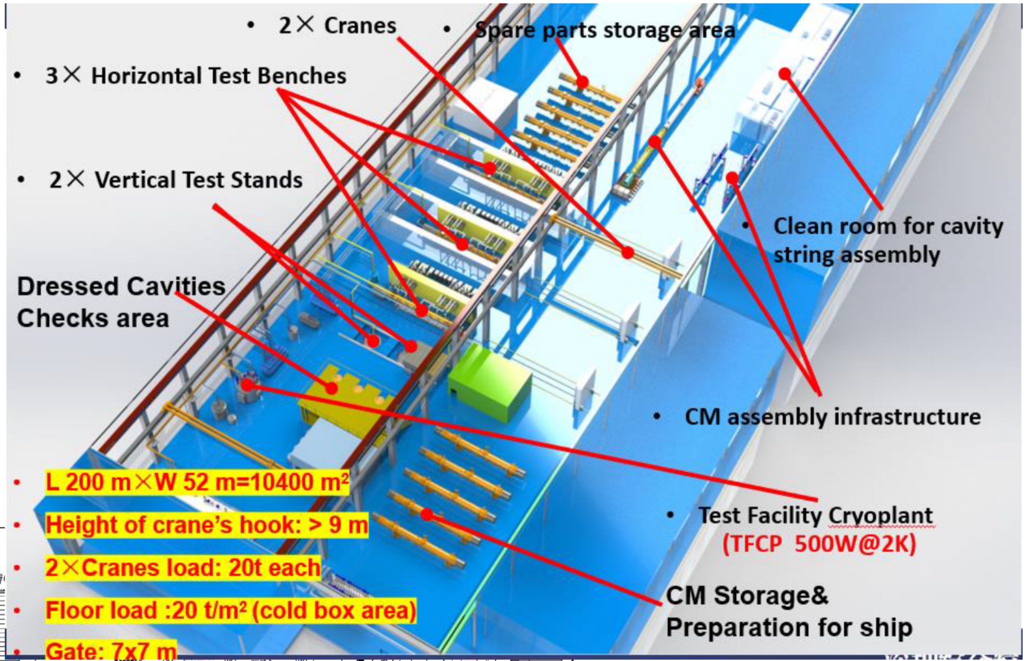
3.9 GHz cryomodule:
2 sets, linear compression compensation

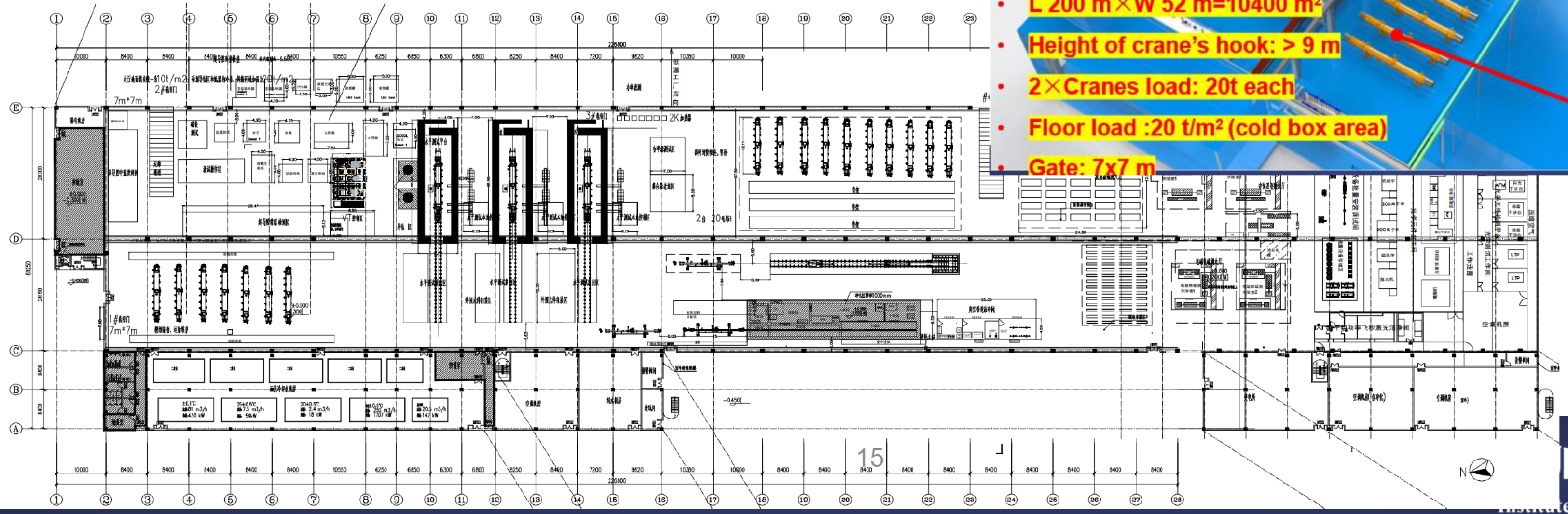
Parameter	Design	Range	Unit
energy	2.5	1.0-2.5	GeV
charge	100	10-300	pC
bunch length（rms)	50	10-100	fs
current	800	200-1000	A
emittance	0.5	0.2-1.0	mm·mrad
energy spread	400	250-500	keV
rep. rate	1	0-1	MHz

Shenzhen IASF S³FEL

SRF Module Test Facility (SMTF)

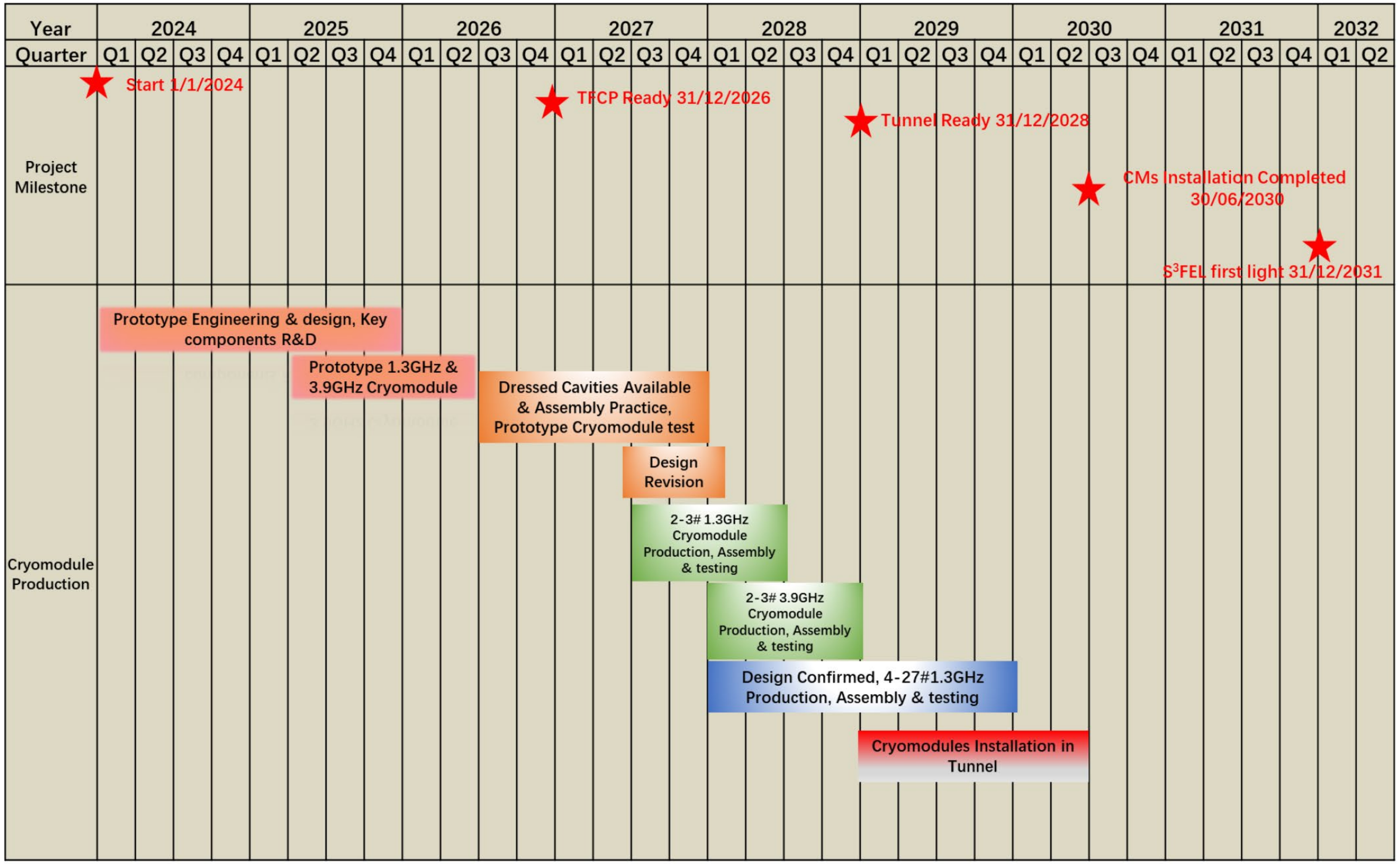
- 2 × Vertical Test Cryostats (VTC)
- 3 × Cryomodule Test Benches (CMTB)
- 1 × Magnet test bench
- 1 × Clean room infrastructure
- 1 × Multipurpose cryo-test Facility
- Cryomodule assembly and integration bench
- Dedicated RF test bench





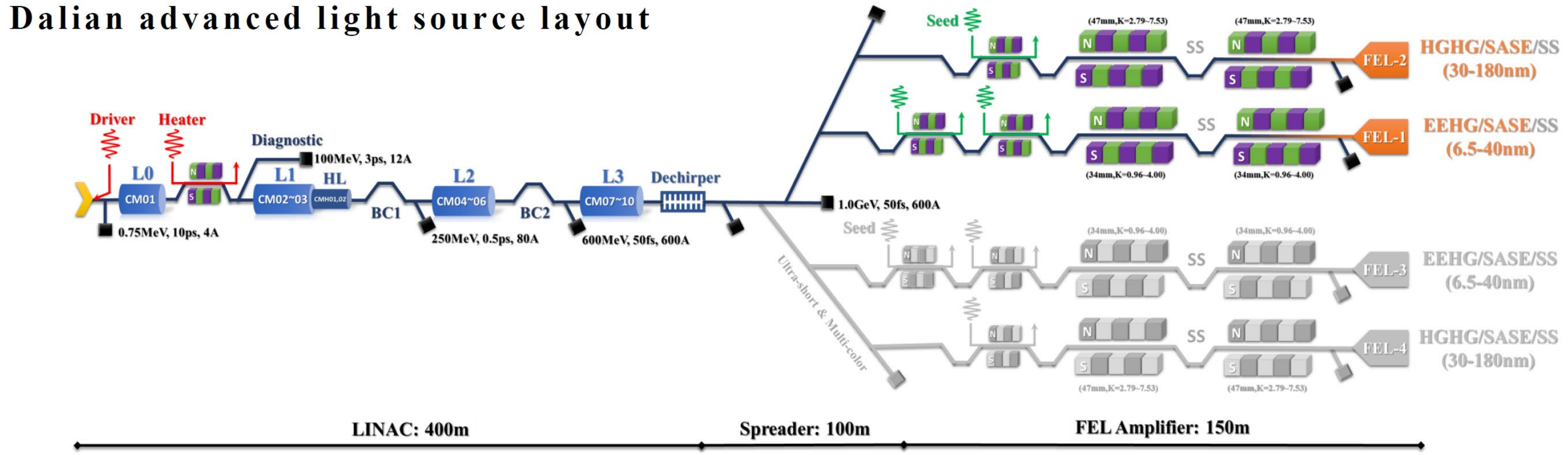
Shenzhen IASF S^{3}FEL

S^{3}FEL Project Schedule



Dalian DICP DALS

DALS Project overview

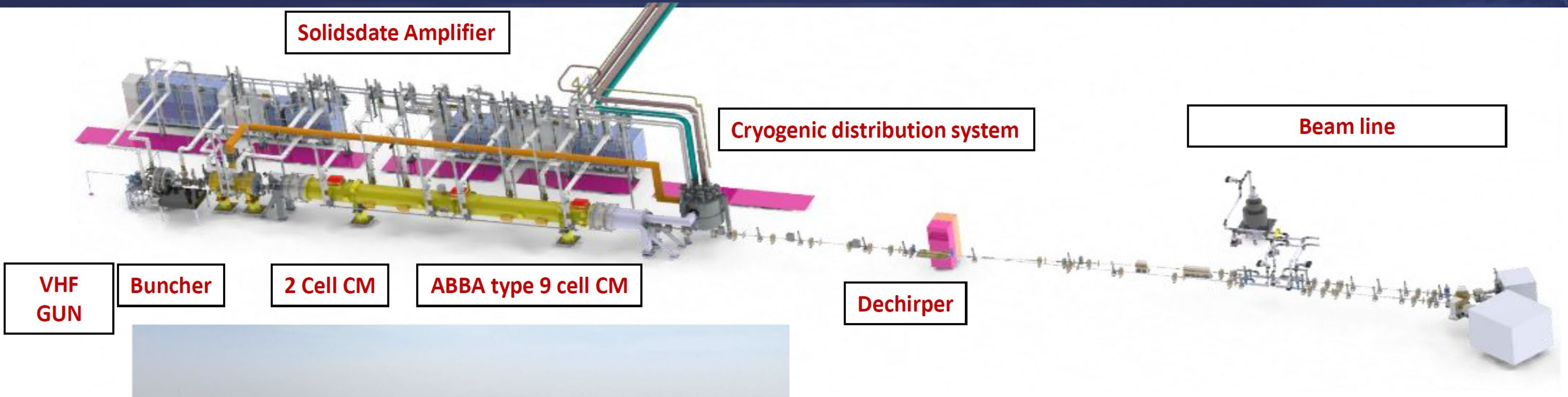


Parameter	design
beam energy/ GeV	1
charge/ pC	100
emittance/ mm-mrad	0.5
rep. rate/ MHz	1

CM type	Frequency [GHz]	Number of Cavities	Number of CM
9-cell cavity CM	1.3	80	10
9-cell cavity CM	3.9	16	2

Dalian DICP DALS

Current situation of injector test facility for DALS



Parameter	design
Beam energy/ MeV	90
Charge/ pC	100
Emittance/ mm-mrad	0.5-1.5
Rep. rate/ MHz	0.1-1
RMS pulse length/ps	4
Cooling capacity@ 2 K/W	370

Dalian DICP DALS

1.3 GHz prototype CM development
collaborate with HIPE

Kick-off meeting for 1.3 GHz prototype CM 01/03/2021

Cooperation with IHEP

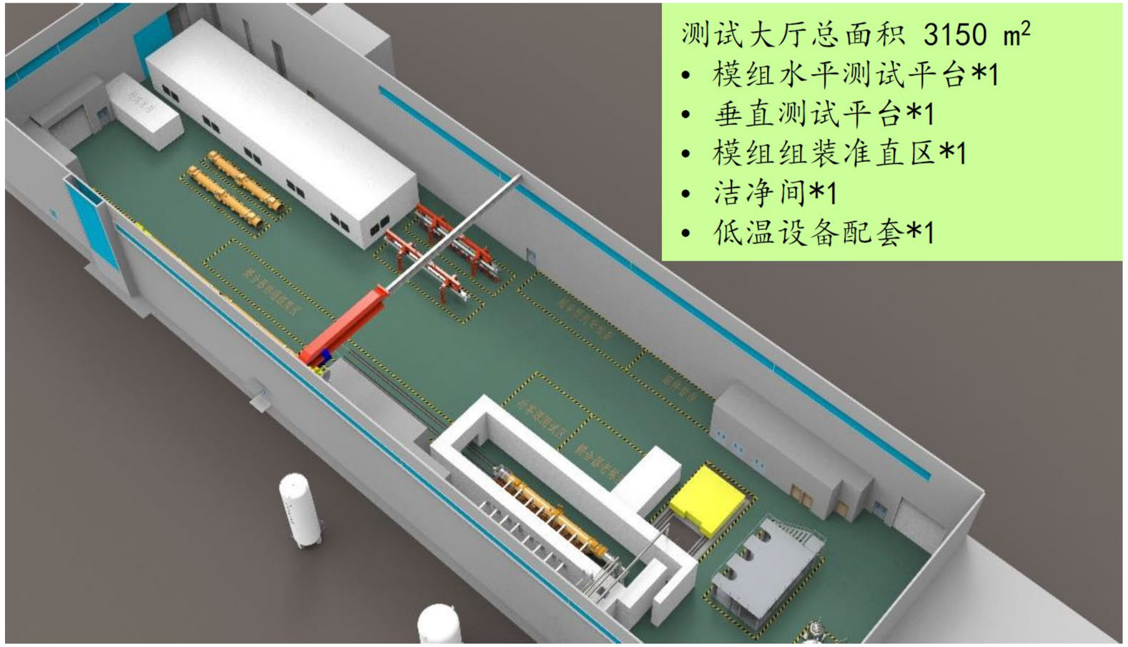
- IHEP made a 1.3 GHz cryomodule with 8 mid-T (medium-temperature furnace baking) 9-cell cavities for our project.
- Average usable gradient and Q_0 exceeds CW FEL projects and CEPC specs, and demonstrates excellent performance of mid-T cavities in a cryomodule for the first time.

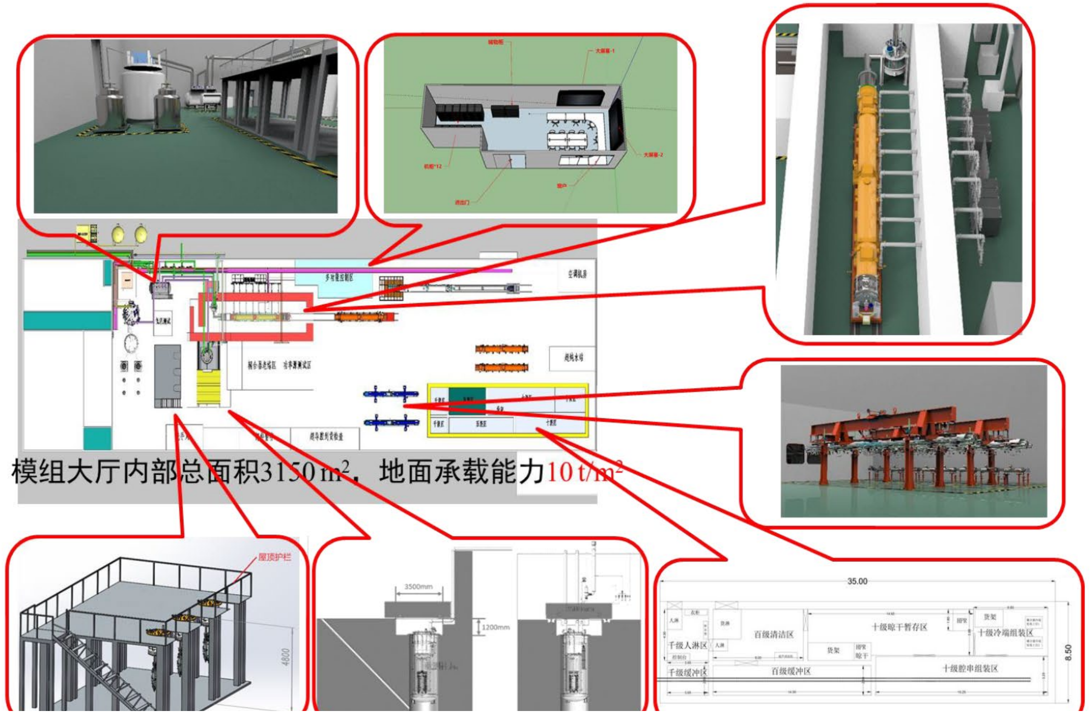
Parameters	IHEP Mid-T CM	LCLS-II (SHINE, S³FEL, DALS) Spec	LCLS-II-HE Spec	CEPC Booster Higgs mode Spec
Avg. usable CW E_{acc} (MV/m)	> 22	2.7×10^{10} @ 16 MV/m	2.7E10 @ 20.8 MV/m	3.0×10^{10} @ 21.8 MV/m
Avg. Q_0 @ 16 & 21 MV/m	3.6×10^{10}			

Dalian DICP DALS

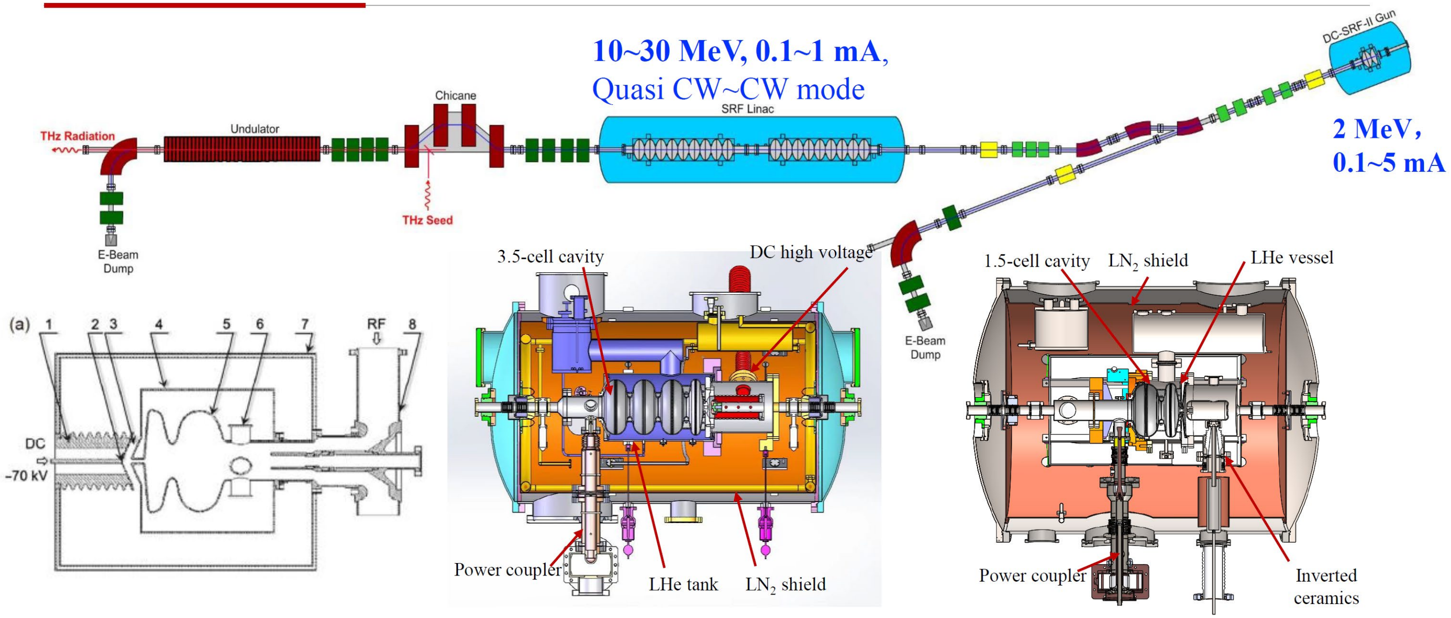
Current situation of SMTF for DALS

- 1 × Vertical Test Cryostats(VTC)
- 1 × Cryomodule Test Benche (CMTB)
- 1 × Clean room infrastructure
- Cryomodule assembly and integration bench





PKU SRF Linac



DC-SRF prototype （2001-2004）

DC-SRF-I 2007-2011,2012-2016，2020-

DC-SRF-II 2016-2020，2021-

Huang S L, Liu K X, Zhao K, et al. DC-SRF photocathode gun (in Chinese). Chin Sci Bull, 2023, 68: 1036–1046

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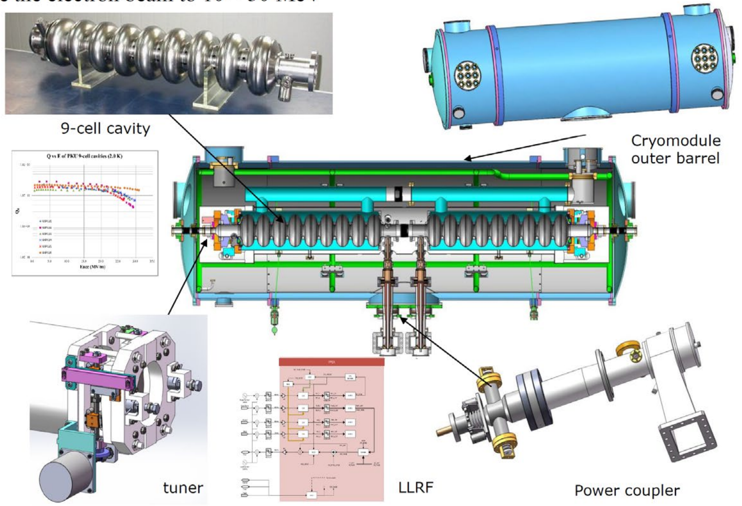
DC-SRF-II gun and beam line

1.3 The 2 × 9-cell cryomodule

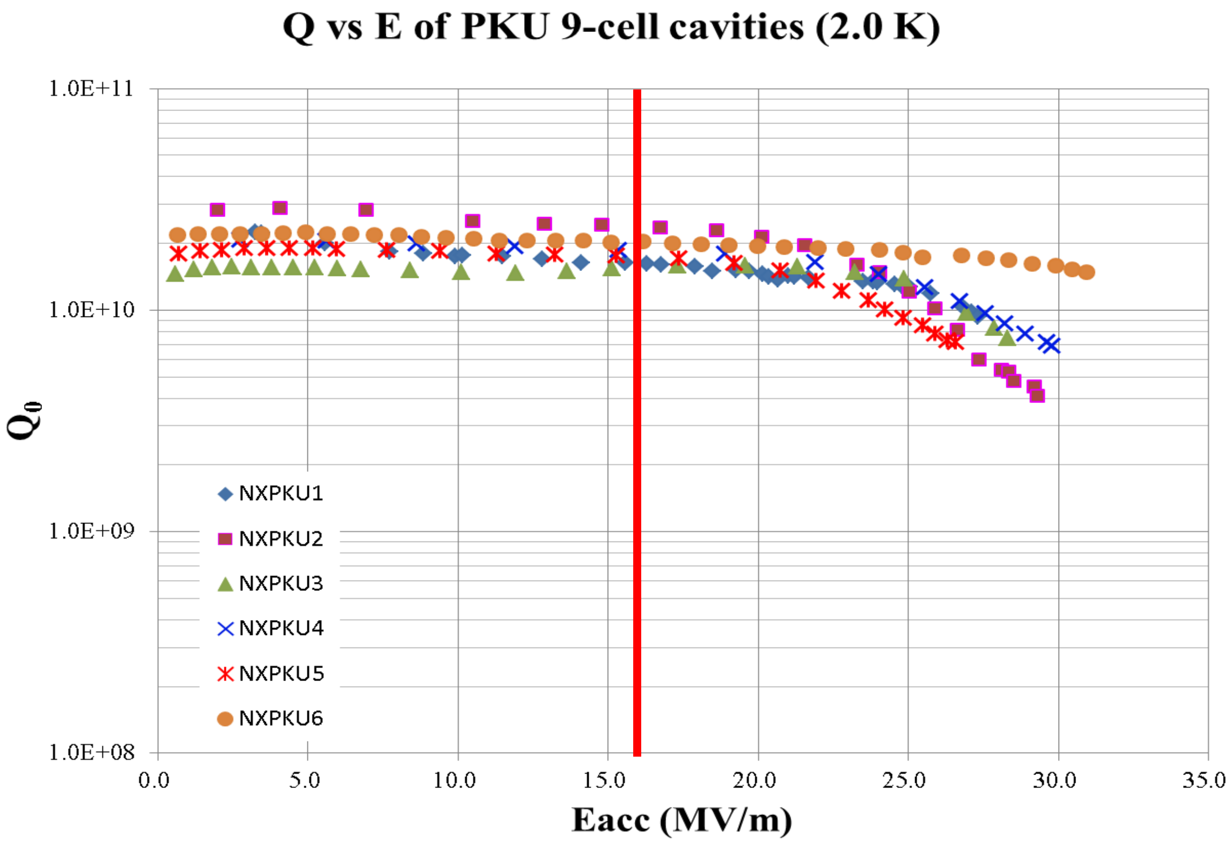
It can accelerate the electron beam to 10 ~ 30 MeV



PKU Large grain cavities

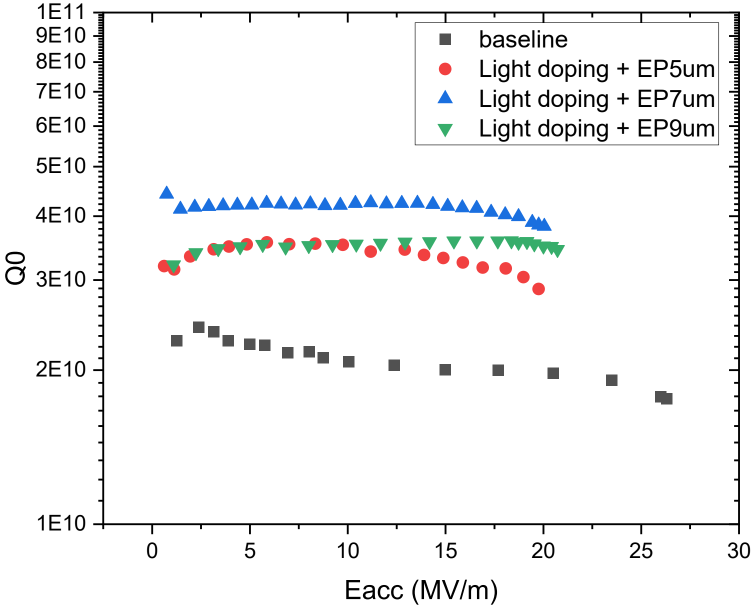
Large grain 9-cell cavities for XFEL

- 6 large grain 9-cell cavities were fabricated by PKU/OSTEC
- BCP 180μm + 800°C 3h + BCP 30μm
- Eacc > 25 MV/m
- Q_0~1.6-2.4E10 @ 16 MV/m @ 2.0 K



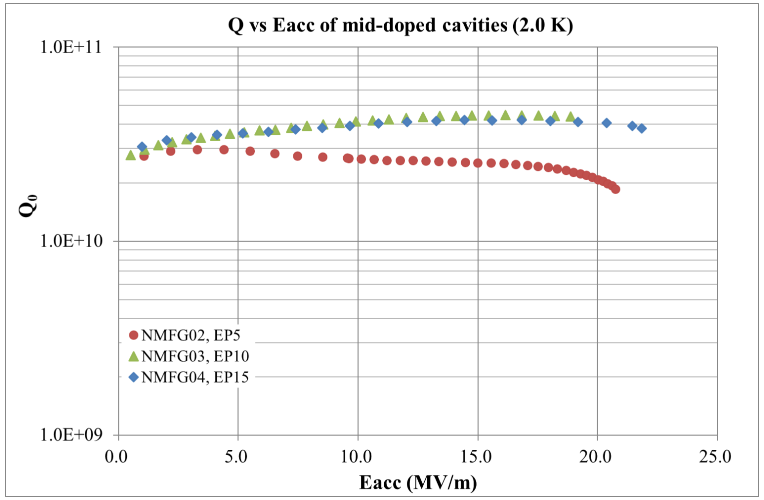
PKU High Q: N-doping

Light doping



Treatment	Q_0 (2K,16MV/m)	E_{acc}(MV/m)
Baseline(BCP200+800C+EP6)	2.0e10	26.3
BCP30+N2/A6+ EP5	3.2e10	19.8
+ EP2(totally EP7)	4.1e10	20.0
+ EP2(totally EP9)	3.6e10	20.7

Medium doping

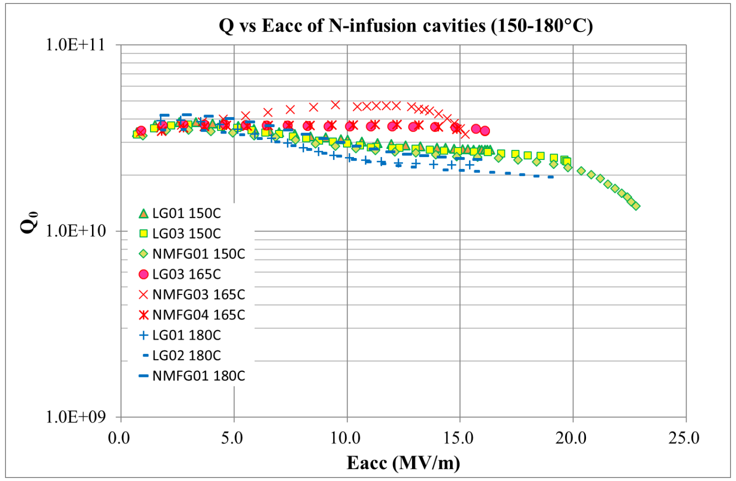


- BCP 200 μm + EP 50 μm + 900°C 3 h

Treatment	Q_0 (2K,16MV/m)	E_{acc} (MV/m)
NMFG02, EP5	2.5e10	20.7
NMFG03, EP10	4.2e10	18.9
NMFG04, EP15	4.4e10	21.8

PKU High Q: N-infusion

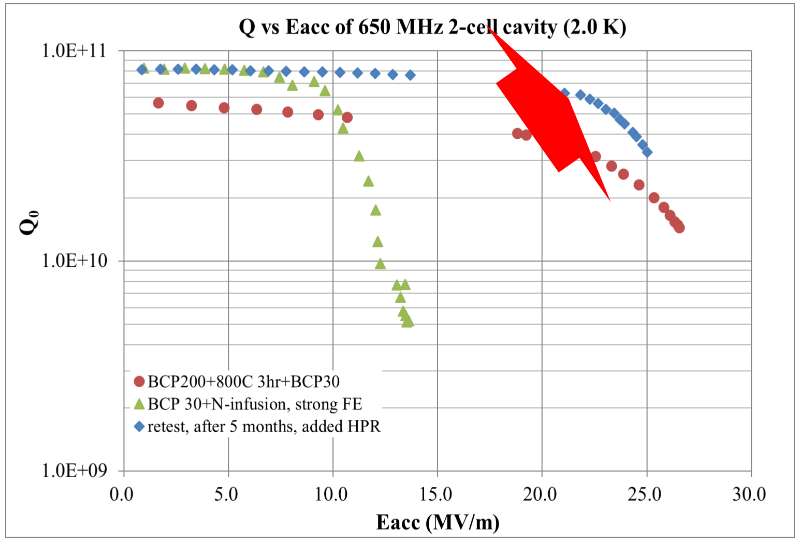
1.3 GHz 1-cell cavities



Q improvement: 165°C > 150 °C > 180 °C

Treatment	Q_0(2K)
LG03, 165°C	3.5e10@16.0MV/m
NMFG03, 165°C	3.3e10@15.2MV/m
NMFG04, 165°C	3.5e10@14.9MV/m

650 MHz 2-cell CEPC cavity
N-infusion, 165℃



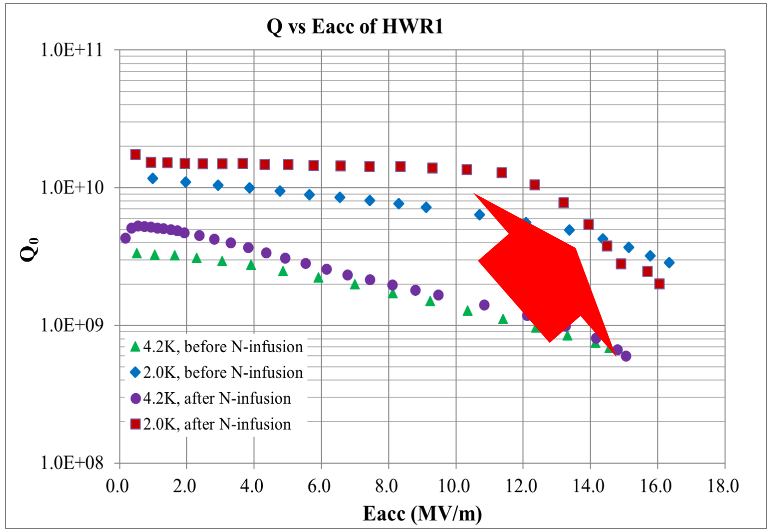
Baseline, BCP200+800C+BCP30

Q_0 ~ 3.8 × 10^{10} (2.0 K, 20 MV/m)

BCP30+N-infusion

Q_0 ~ 6.7 × 10^{10} (2.0 K, 20 MV/m)

162.5 MHz HWR
N-infusion, 160℃



Before infusion

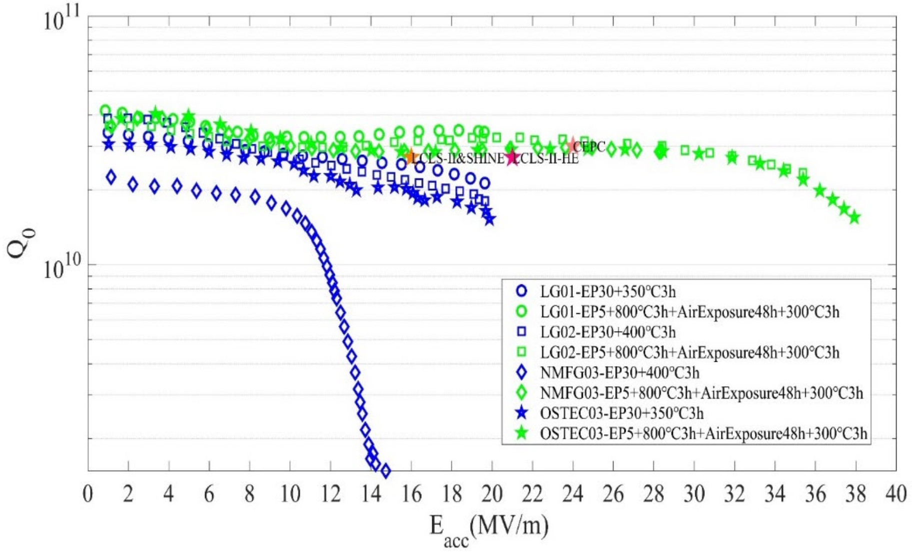
Q_0 ~ 7.9 × 10^9 (2.0K, 10 MV/m)
1.3 × 10^9 (4.2K, 10 MV/m)

After infusion

Q_0 ~ 1.4 × 10^{10} (2.0 K, 10 MV/m)
1.6 × 10^9 (4.2 K, 10 MV/m)

PKU High Q: Medium temperature baking

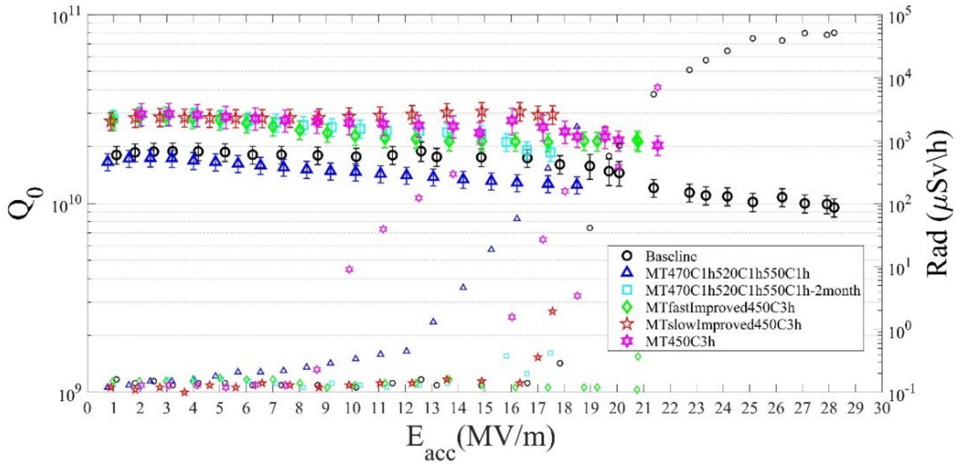
1-cell cavities



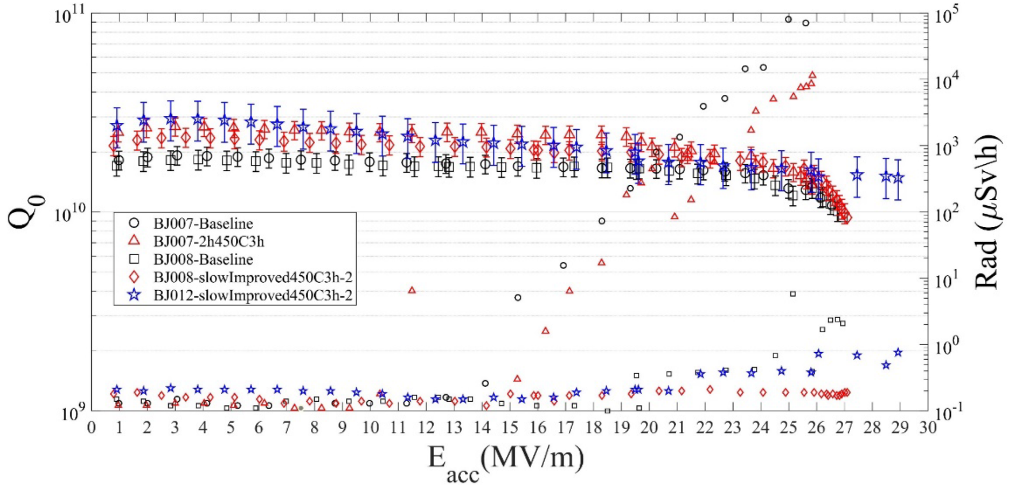
800°C3h+AirExposure48h+300°C 3h

Q_0: 2.8-3.4E10@16MV/m

9-cell cavities



9-cell cavities (EP)

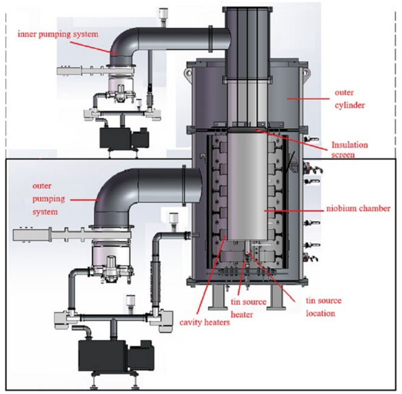


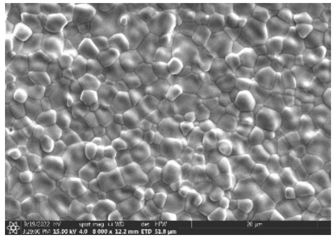
- 800℃ 3 h
- Air Exposure 48 h
- 450 ℃ 3 h
- $Q_0 \sim 2.7 \times 10^{10}$ @ 16 MV /m

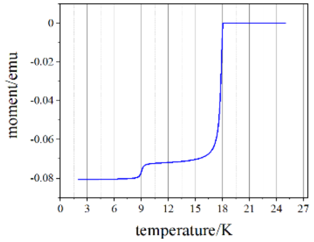
- Q_0 @ 16 MV/m
- ~ 2.7×10^{10} (BCP)
- ~ 2.3×10^{10} (EP)

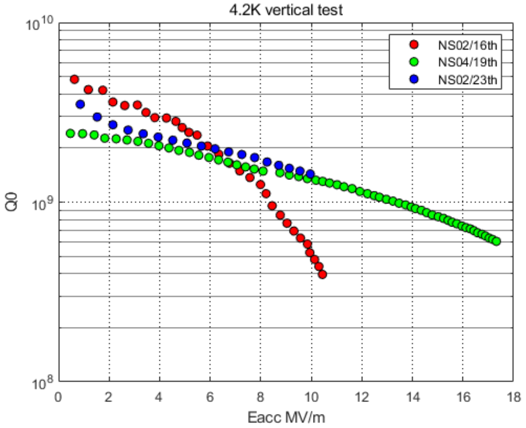
PKU Nb_3Sn cavities and conduction cooling accelerator

Tin vapor diffusion for Nb_3Sn coating



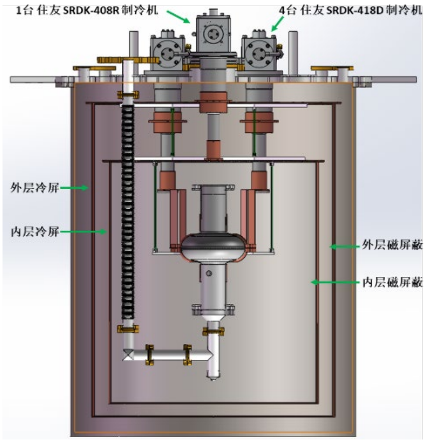


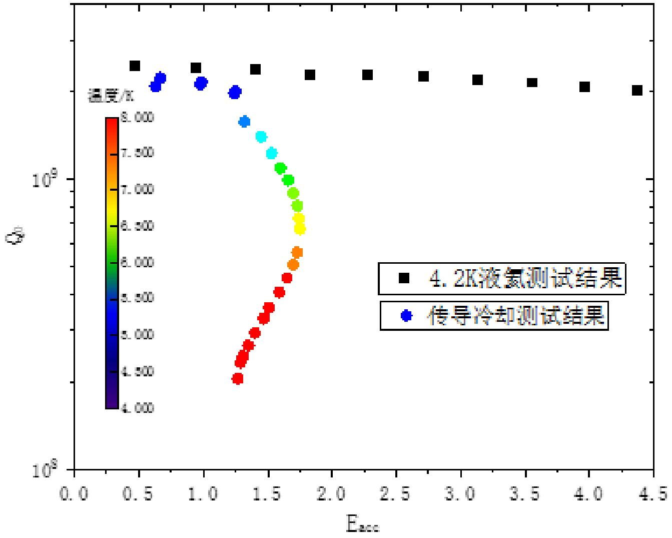




Q_0 ~ 4.8×10^9 @4.2K @ low field
max. E_{acc} ~ 17.3MV/m

Conduction cooling for Nb_3Sn cavity



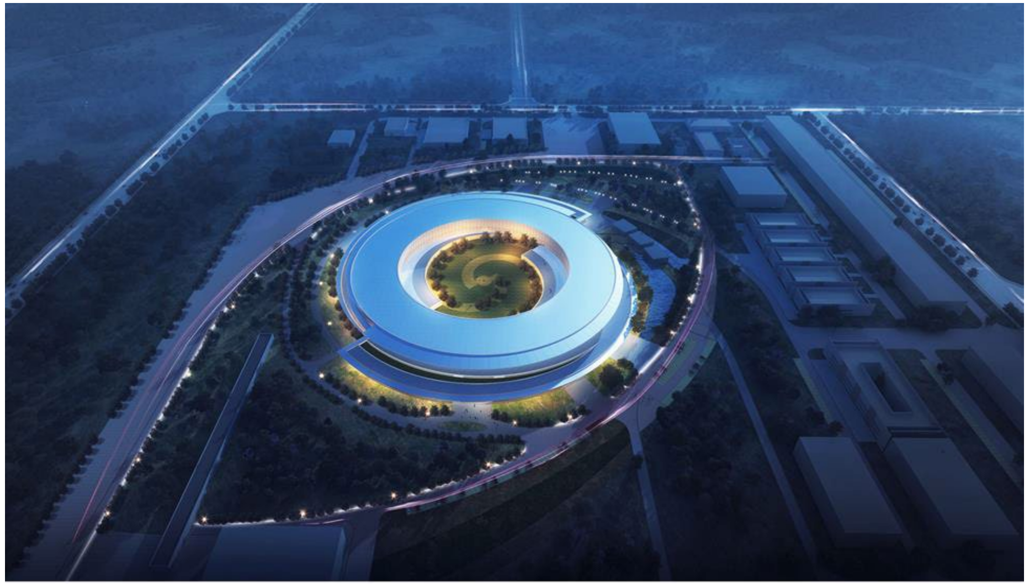


- CW running of Nb_3Sn cavity with conduction cooling

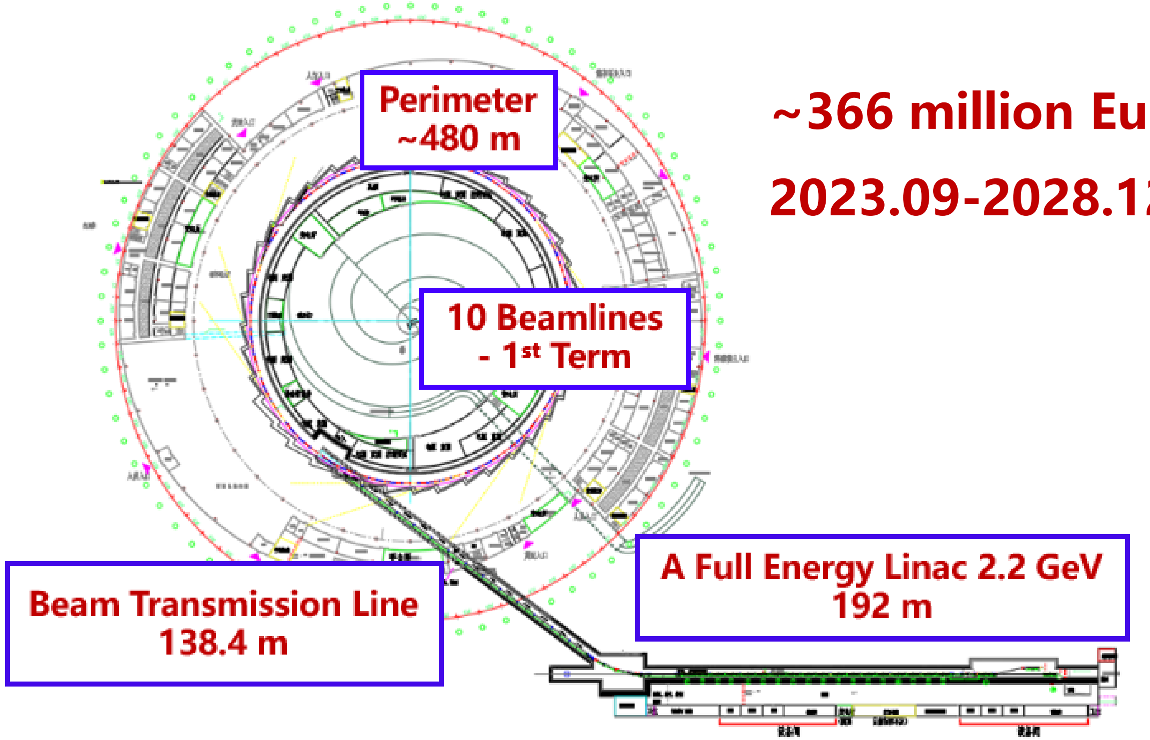
$$Q_0 = 6.7 \times 10^8$$
$$@E_{acc,max} = 1.75MV/m$$

- Cavity heat loss: 0.58W
- Ave. T of cavity ~ 7K

Hefei USTC HALF

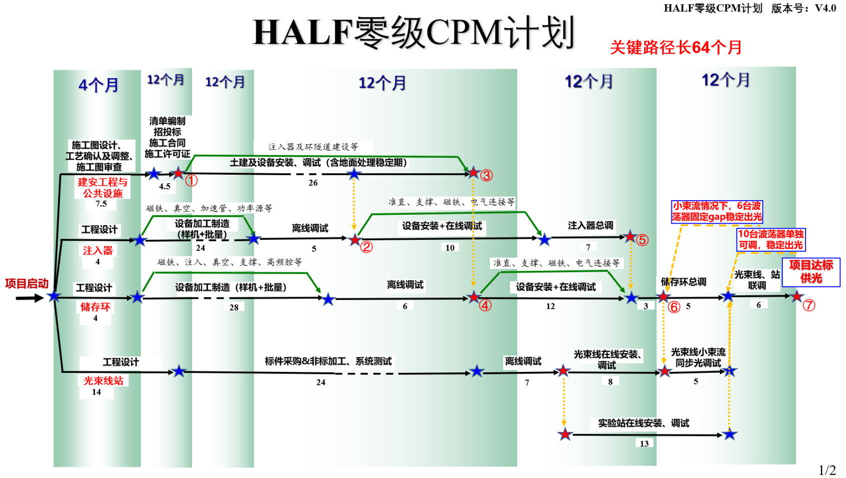


Hefei Advanced Light Facility（HALF）
4th generation synchrotron radiation source



~366 million Euros
2023.09-2028.12

参数	储存环要求	验收指标
能量 [GeV]	2.2	2.2
电荷量 [pC]	300	300
束流几何发射度 [nm·rad]	12	12
能量分散（rms）	≤0.2%	≤0.2%
能量稳定性（rms）	≤0.1%	≤0.1%
注入点位置偏差（rms）（dx，dy）	0.1 mm	---
注入点角度偏差（rms）（dx_p，dy_p）	0.1 mrad	---

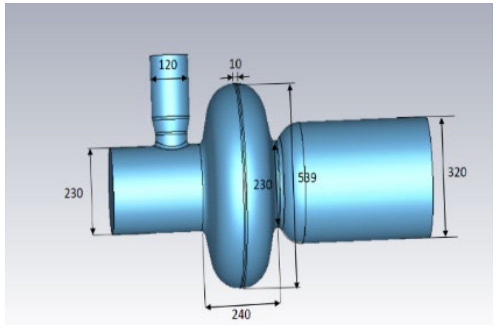


Hefei USTC HALF

499.8 MHz SRF cryomodule
(in collaboration with IHEP)

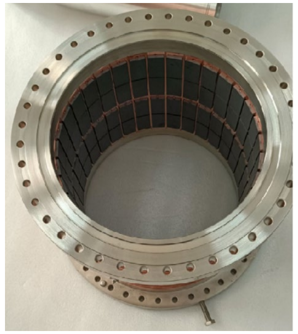
1. **SRF cavity ($V_a = 1.5$ MV)**
2. **Solid-state RF transmitter**
3. **HOM absorbers**
4. **High-power input coupler ($P_{\text{in}} = 140$ kW)**

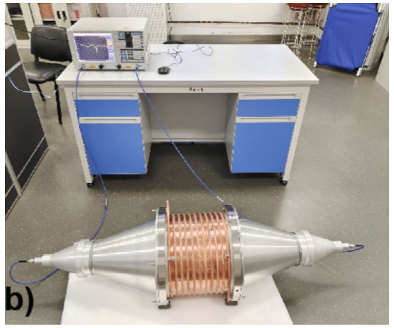
SRF cavity

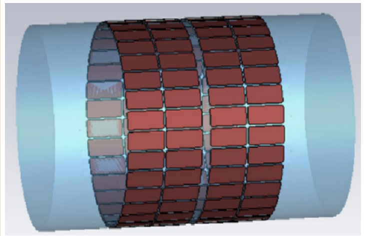


Vertical tests show that $Q_0 \geq 1 \times 10^9$ for an accelerating voltage = **3.84 MV**

HOM absorbers

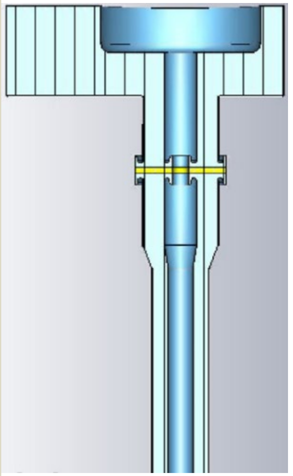


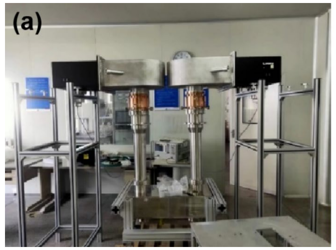


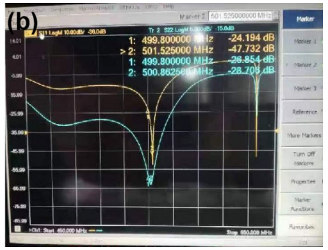


HOM absorbers has been fabricated and cold-tested.

High-power input coupler







High-power input coupler has been cold-tested and waiting for high-power tests.

Solid-state RF transmitter

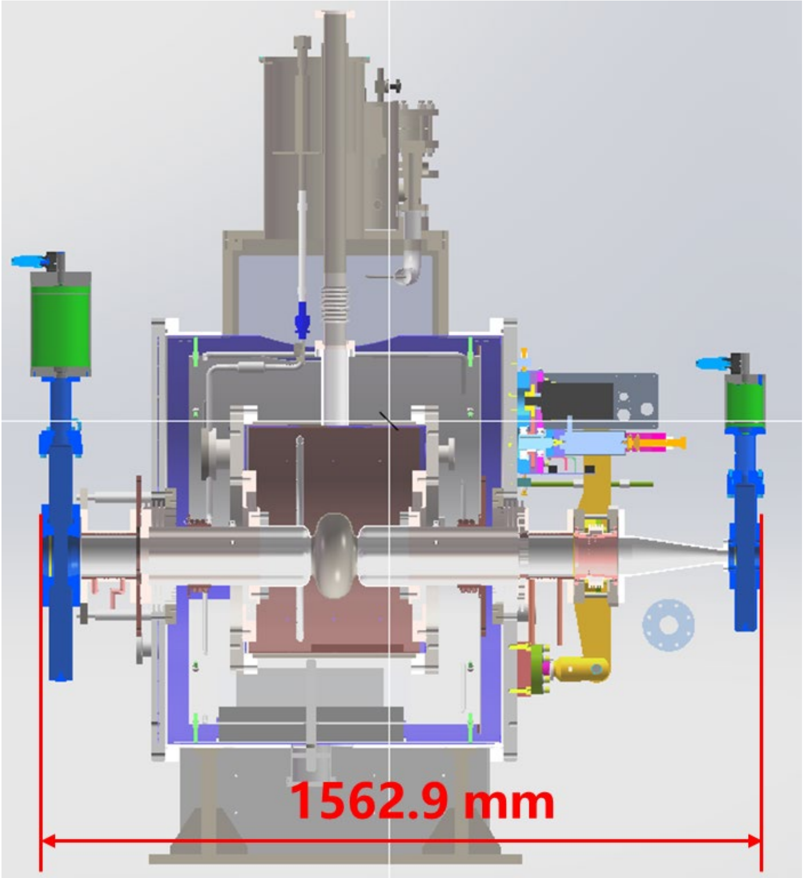
500 MHz / 250 kW solid-state RF transmitter has been manufactured and successfully tested.

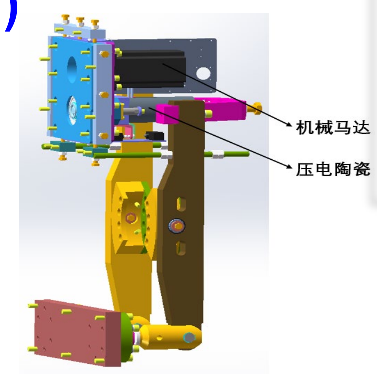
Hefei USTC HALF

1499.4 MHz SRF cryomodule
(in collaboration with SARI)

① **SRF cavity ($V_a = 0.5$ MV)**

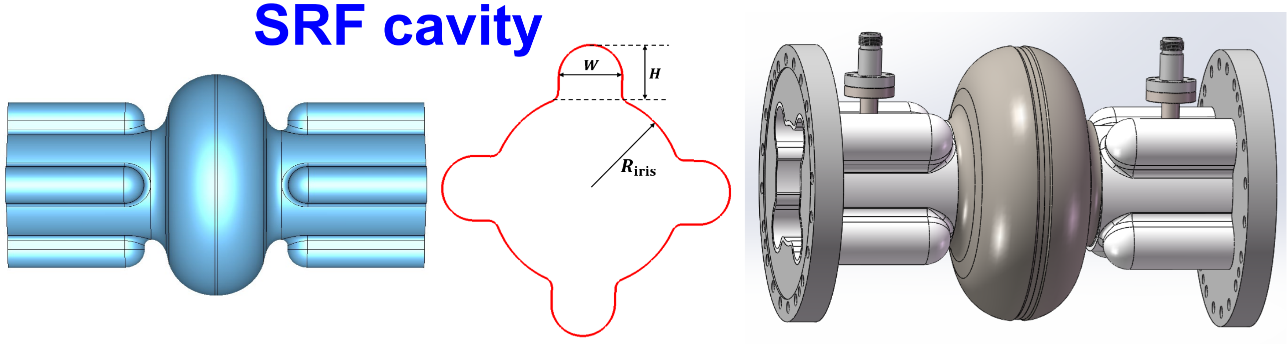
② **SiC HOM Absorbers**



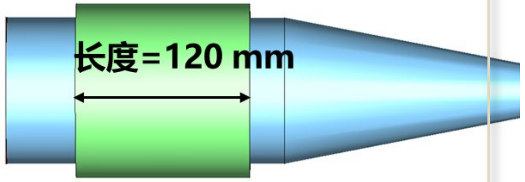


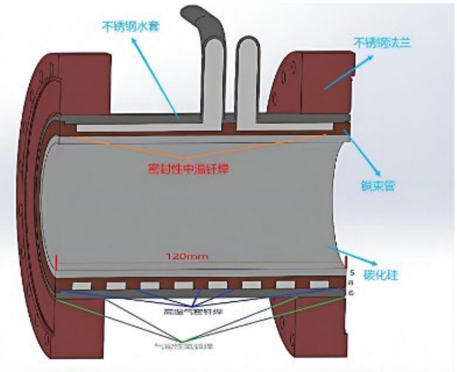
Parameters	Value
Mechanical tuning range	[-200 +500] kHz
Mechanical tuning sensitivity	3.153 MHz/mm
Mechanical tuning accuracy	20 Hz
Piezo tuning range	20 kHz
Piezo tuning accuracy	10 Hz

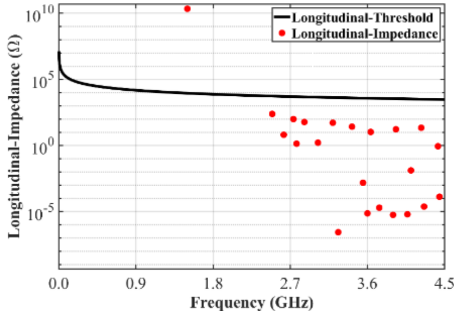
SRF cavity

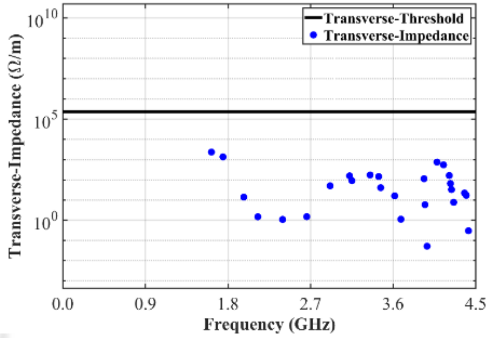


HOM Absorber

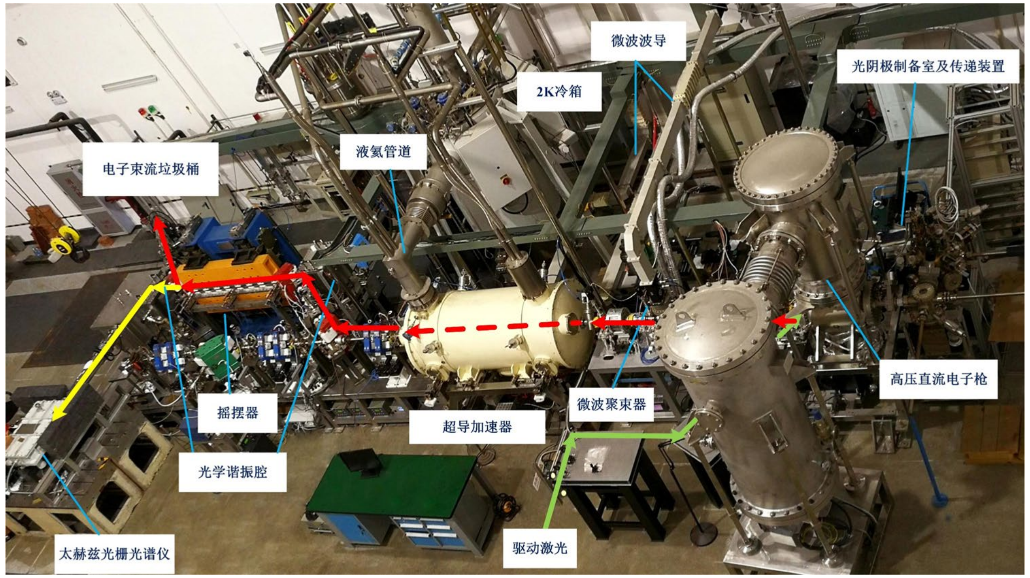


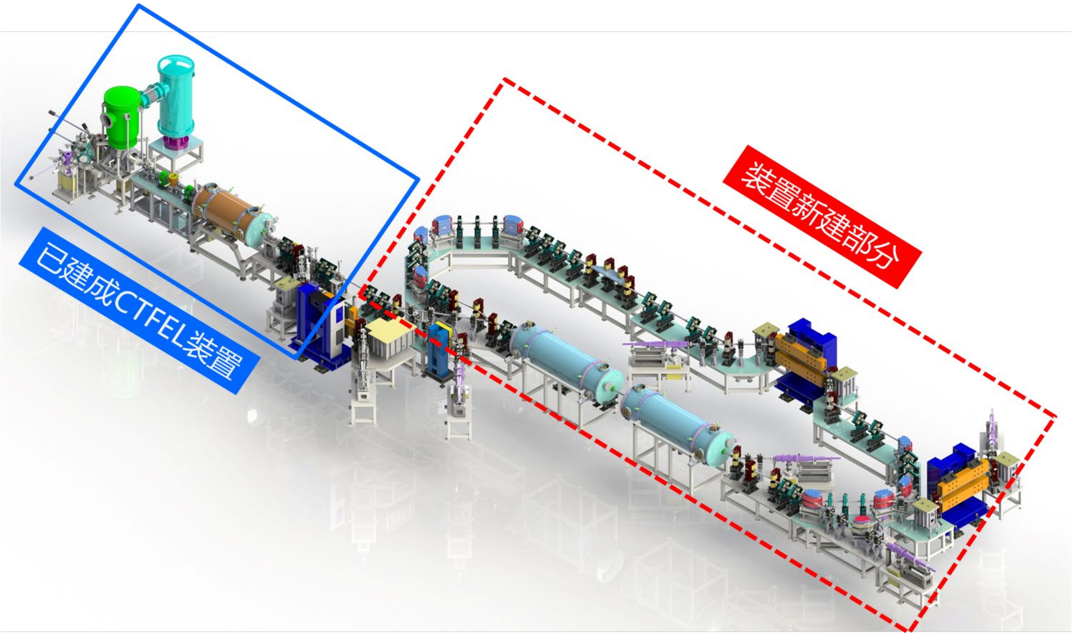


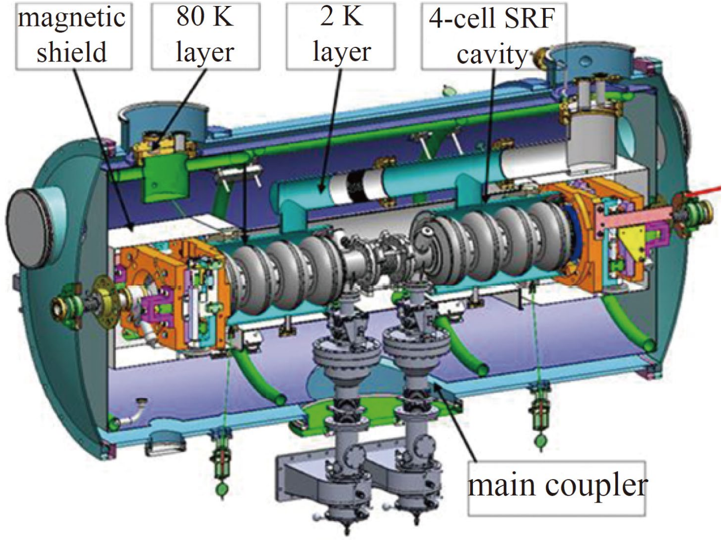




CAEP CTFEL







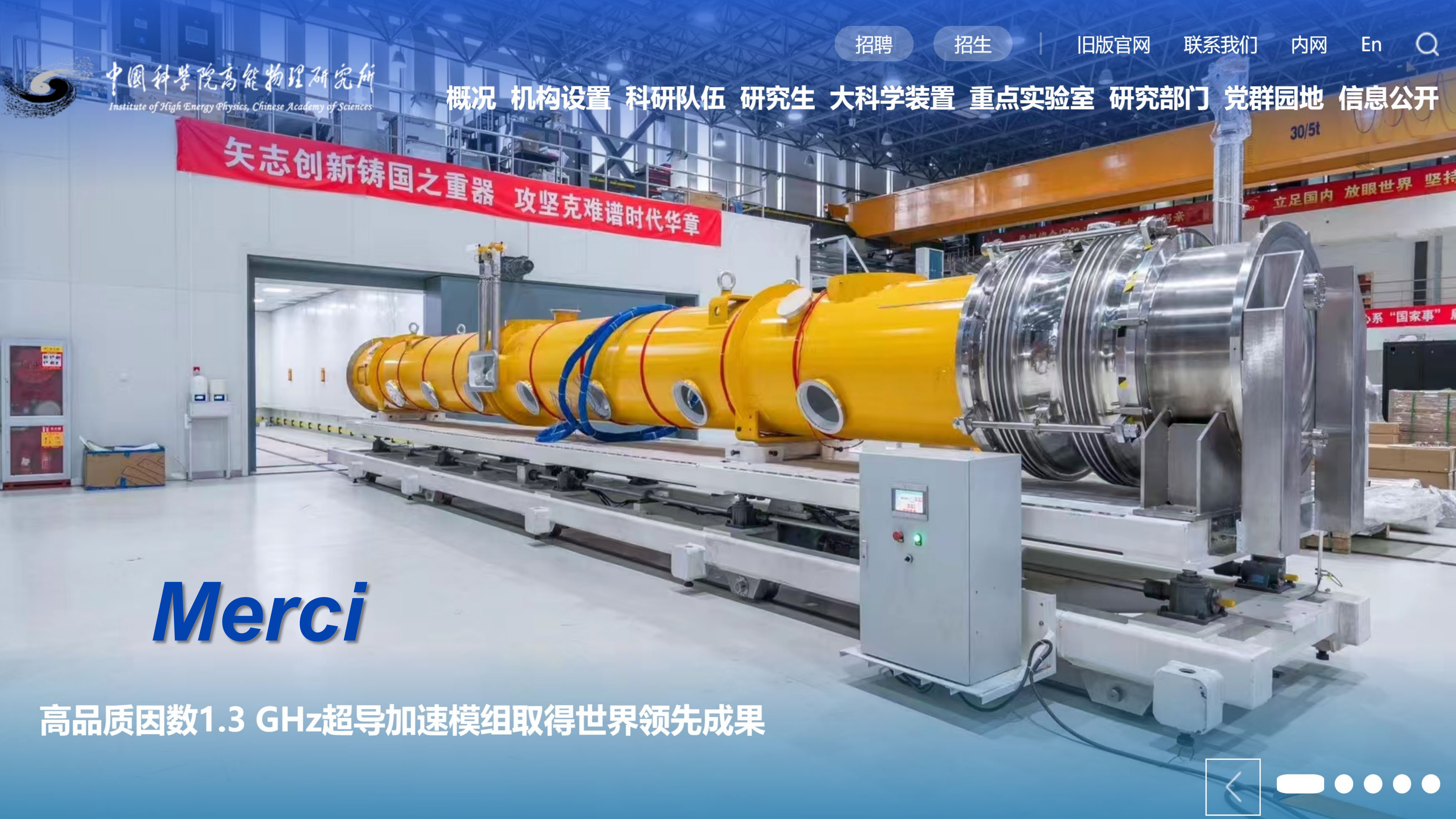
SRF accelerator

FEL设计参数				
频率调节范围	0.1 THz~125 THz			
波长调节范围	2.4 μm~3000 μm			
脉冲长度	500 fs~20 ps			
最大宏脉冲平均功率	＞100 W			
最大峰值功率	＞3 MW			
电子束设计参数				
电子束最高能量	~50 MeV			
电子束能散	<0.3% (FWHM)			
归一化发射度	<15 μm@100pC			
电荷量	50 pC~100 pC			
脉冲频率	宏脉冲重频1~10 Hz，宏脉冲长度100 μs~100 ms			
波荡器设计参数				
波荡器型号	U58	U38	U48	U35
	已有		新建	
周期长度	58 mm	38 mm	48 mm	35 mm
周期个数	10	42	40	40
对应出光频率	0.1~0.7 THz	0.7~4.2 THz	2~20 THz	15~125 THz

- THz and Infrared.
- SRF linac 8 MeV FEL to upgrade to 50 MeV ERL.

Summary

- 20 years blooming SRF R&D at IHEP and in China. We are in a golden era of large SRF accelerator facilities design and construction in China (2010-2035).
- Many challenges in the design, development, construction and operation of SRF systems for the colliders, light sources & FELs and proton linacs, as well as SRF application in industry.
- Domestic and international communications, exchanges and collaborations are always very important and will benefit to all.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