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

CEPC SRF System Design and Challenges

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On behalf of CEPC SRF Study Team

SRF2017 Conference, 17 July 2017, Lanzhou, China

An Unexpected National and Global Debate

Should China build CEPC or not?

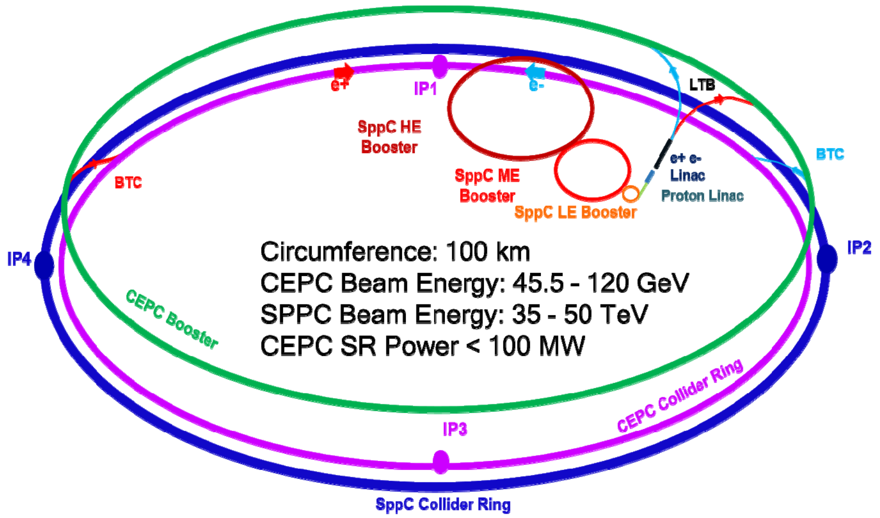
- Since August 2016
- Widely spread and discussed
- Debate Book:

  14 papers (C.N. Yang, Y. F. Wang, D. Gross …)

Outline

- CEPC introduction
- RF system design and parameters
- RF transient and instability
- R&D plan and status

CEPC-SPPC Project



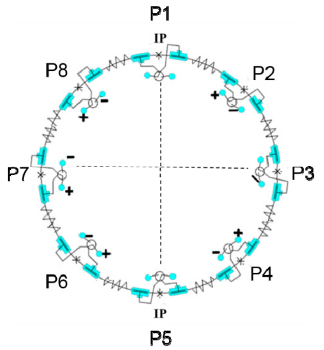
Luminosity Goal (per IP): Higgs > 2.0×10^{34} $cm^{-2}\,s^{-1}$, W & Z > 1.0×10^{34} $cm^{-2}\,s^{-1}$

SR power / beam: < 30 (50) MW

- Low mass Higgs discovery in 2012
- **2022-2040**: 240 GeV circular e+e- collider (CEPC) to explore Higgs, the keystone of the SM.
- **2040-2070**: 100 TeV pp collider (SPPC) for new physics in the same tunnel.
- **China's top priority accelerator based HEP program.**
- Similar to FCC. Concurrent and complimentary to ILC.

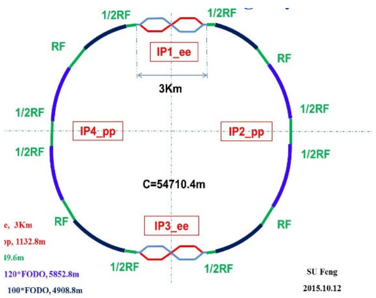
The Evolving Ring

Oct 2012



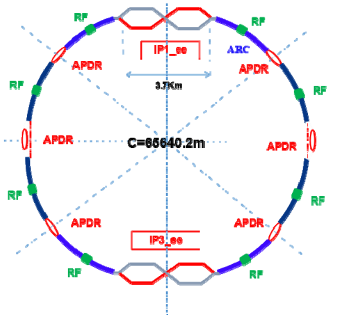
Single Ring

May 2015



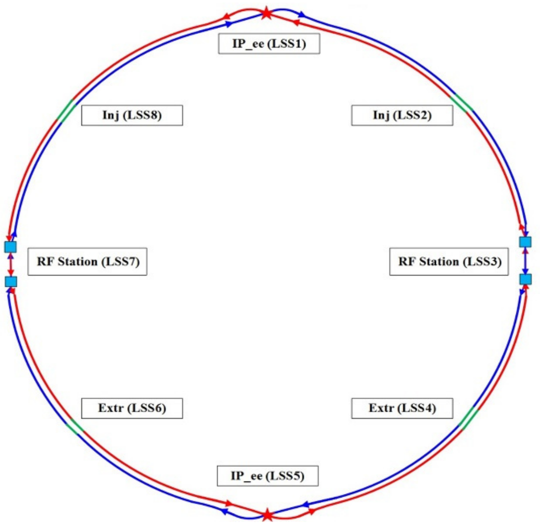
Partial Double Ring (PDR)

May 2016



Advanced PDR (APDR 6 or 8)

Jan 2017



Double Ring with common cavity
(K. Oide design for FCC-ee)

pretzel, DA, sawtooth, beam loading, COD correction, collision tuning …

Machine Parameters of CEPC Main Ring

	Higgs *Wang Dou 20170607*	***W*** *Wang Dou 20170306*	***Z*** *Wang Dou 20170607*	***Z-high lumi*** *Wang Dou 20170306*
Number of IPs	2	2	2	2
Energy (GeV)	120	80	45.5	45.5
SR loss/turn (GeV)	1.67	0.33	0.034	0.034
Half crossing angle (mrad)	16.5	16.5	16.5	16.5
Piwinski angle	3.19	5.69	11.8	4.29
N_e/bunch (10^{11})	0.968	0.365	0.22	0.455
Bunch number	412	5534	5100	21300
Beam current (mA)	19.2	97.1	53.9	465.8
SR power /beam (MW)	32	32	1.9	16.1
Bending radius (km)	11	11	11	11
Momentum compaction (10^{-5})	1.14	1.14	1.14	4.49
β_{IP} x/y (m)	0.171/0.002	0.171 /0.002	0.171 /0.002	0.16/0.002
Emittance x/y (nm)	1.31/0.004	0.57/0.0017	0.18/0.0037	1.48/0.0078
Transverse σ_{IP} (um)	15.0/0.089	9.9/0.059	5.6/0.086	15.4/0.125
ξ_x/ξ_y/IP	0.013/0.083	0.0055/0.062	0.004/0.039	0.008/0.054
RF Phase (degree)	128	126.9	135	165.3
V_{RF} (GV)	2.1	0.41	0.049	0.14
f_{RF} (MHz) (harmonic)	650	650 (217800)	650	650 (217800)
Nature σ_z (mm)	2.72	3.37	3.9	3.97
Total σ_z (mm)	2.9	3.4	4.0	4.0
HOM power/cavity (kw)	0.41(2cell)	0.36(2cell)	0.11(2cell)	1.99(2cell)
Energy spread (%)	0.098	0.065	0.037	0.037
Energy acceptance (%)	1.5	/	/	/
Energy acceptance by RF (%)	2.1	1.1	0.65	1.1
n_γ	0.26	0.15	0.16	0.12
Life time due to beamstrahlung (min)	52	/	/	/
F (hour glass)	0.96	0.98	0.99	0.96
L_{max}/IP ($10^{34}cm^{-2}s^{-1}$)	2.0	5.15	1.03	11.9

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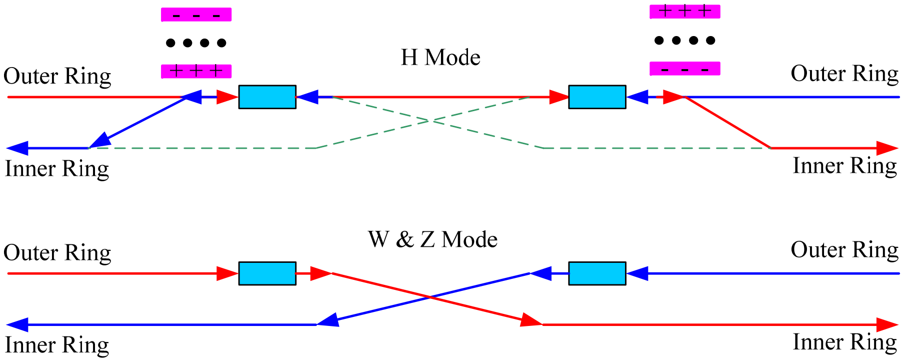
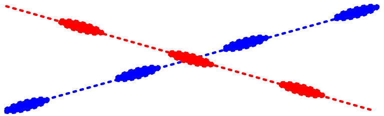
Yiwei Wang, Chenghui Yu

CEPC RF Layout (one RF section)

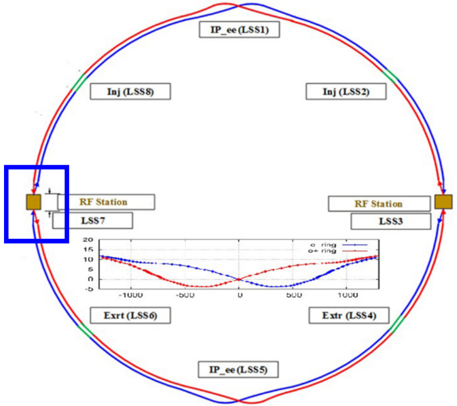


- H: high RF voltage, low current
- W & Z: low RF voltage, high current
- Two RF sections in total
- Two RF stations per RF section
- 14 modules per RF station
- Six 2-cell cavities per module



Horizontal Crossing
Longitudinal separation

Park (detune) the unused cavities for W & Z operation (or use lattice by-pass, or push the unused cavities off-line for Z).



H: shared cavities for two rings (half fill). W & Z: separate cavities for two rings ("uniform" fill). Fewer cavities for H, lower current seen by the W & Z cavity, lower impedance for W & Z.

CEPC Main Ring SRF Parameters (1)

ZJ20170410 Main Ring parameter: WD20170306	H	W	Z-HL
Luminosity / IP [10^{34} $cm^{-2}s^{-1}$]	**2**	**5**	**12**
SR power / beam [MW]	**32**	**32**	**16**
RF voltage [GV]	2.1	0.41	0.14
Beam current / beam [mA]	**19.2**	**97.1**	**466**
Bunch charge [nC]	15.5	5.8	7.3
Bunch length [mm]	2.9	3.4	4
Cavity number in use / beam (650 MHz 2-cell)	**336**	96	48
Gradient [MV/m] (with margin for HV-H)	14	9.3	6.3
Input power / cavity [kW] (with margin for HL-H)	190	333	335
Klystron power [kW] (2 cavities / klystron)	800	800	800
HOM power / cavity [kW]	0.4	0.3	**1.8**
Cryomodule number (6 cavities / module)	56	32	16
Q_0 @ 2 K at operating gradient (long term)	1E10	1E10	1E10
Total wall loss @ 4.5 K eq. [kW]	23	6	1

- **No staging (except super-Z and higher energy).**
- **Same RF cavity for H, W, Z.**
- **No cavity push-pull.**

Challenging input power, low heat load, input coupler short to reduce module diameter

Cavity acceptance Q_0 > 4E10 (N-doping), Module horizontal test > 2E10 (clean assembly and magnetic hygiene)

CEPC Main Ring SRF Parameters (2)

ZJ20170410 Main Ring machine parameter: WD20170306	H	W	Z-HL
Optimal Q_L	1.0E6	2.7E5	1.2E5
Relative optimal Q_L (to H)	1.0	0.1	0.12
Extra power (if fixed optimal coupling for H)	0	209 %	155 %
Cavity bandwidth [kHz]	0.7	2.4	5.3
Optimal detuning [kHz]	0.2	0.9	10.5
Cavity time constant [μs]	488	130	60
Cavity stored energy [J]	46	22	10
Max relative voltage drop for **1 %** beam gap	0.9 %	3.3 %	23.2 %
Max phase shift for **1 %** beam gap [deg]	0.8	3.2	13.7
Max relative voltage drop for 4+4 APDR	10 %	77 %	decelerate
Max bunch train phase shift for 4+4 APDR [deg]	9.8	74	decelerate

Variable coupler needed for W&Z, and even for Higgs itself to save power.

Heavy beam loading → damp acceleration mode CBI instability during injection and top-up operation

Even 1 % beam gap will have large bunch phase shift → change fill pattern from one long gap to many small gaps

Alternative APDR (4+4 trains) scheme may not work unless phase shift corrected by beat cavity or other method.

CEPC Booster SRF Parameters (preliminary)

ZJ20170410. 10 GeV injection. Booster machine parameter: CX20170401	**H**	**W**	**Z-HL**
Extraction beam energy [GeV]	120	80	45.5
Bunch charge [nC]	0.77	0.2	0.3
Beam current [mA]	**0.37**	**0.33**	**0.96**
Extraction RF voltage [GV]	**2.8**	**1**	**0.4**
Extraction bunch length [mm]	4.7	2.8	1
Cavity number in use (**1.3 GHz TESLA 9-cell**)	**160**	64	32
Gradient [MV/m]	16.9	15.1	12.0
Q_L	2E+07	2E+07	2E+07
Cavity bandwidth [Hz]	**65**	**65**	**65**
Input power per cavity [kW] (remained detuning 10 Hz)	5.8	4.0	2.5
SSA power [kW] (one cavity per SSA)	**10**	**10**	**10**
HOM power per cavity [W]	0.4	0.2	1.6
Cryomodule number in use (8 cavities per module)	20	8	4
Q_0 @ 2 K at operating gradient (long term)	**2E+10**	**2E+10**	**2E+10**
Total wall loss @ 4.5 K eq. [kW] (assume CW)	8.4	2.7	0.9

Narrow bandwidth, microphonics

Voltage ramp 12 times in 1 s

LLRF challenge

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Beam Gap Transient

- **Phase shift caused by beam gap in DR or APDR**
  - A bunch extracts cavity stored energy when passing through, and power source will recover the cavity voltage when the next bunch comes. When the bunch spacing is much smaller, cavity stored energy and voltage will drop continuously due to lack of power. The latter bunch will move towards voltage peak by auto-phasing, resulting in less longitudinal focusing, smaller energy acceptance, lifetime and luminosity, and possible other dynamical problem. Small phase shift can be estimated by (K. Bane, etc., EPAC96):

$$\Delta\theta_{1N} \approx \frac{-2kq}{V_{c0}\sin\phi_0}\left[\frac{T_{\mathrm{t}}T_{\mathrm{g}}/T_{\mathrm{b}}}{T/N_{\mathrm{t}}}\right] \approx \frac{-2kI_0 T_g}{V_{c0}\sin\phi_0} \approx \frac{-2kqN}{V_{c0}\sin\phi_0}$$

Max phase variation proportional to number of bunches in a bunch train, or number of bunch trains (for fixed total bunch number) or the gap length.

- **Correction methods**

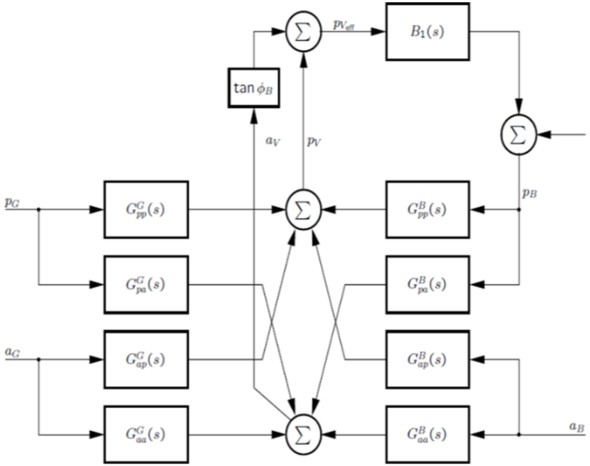
1. **Increase cavity stored energy** (less cell number, higher RF voltage, low RF freq)
2. **More uniform distribution** (increase bunch train number or length)
3. **Pulsed power** (power source hardware limit and low RF-to-beam efficiency)
4. **Beat cavity** (small frequency shift of part of RF sources and cavities, beating)

Refer to talks in the CEPC-SPPC Workshop, Apr. and Sept. 2016
http://indico.ihep.ac.cn/event/5277/session/9/contribution/45/material/slides/
http://indico.ihep.ac.cn/event/6149/session/2/contribution/55/material/slides/

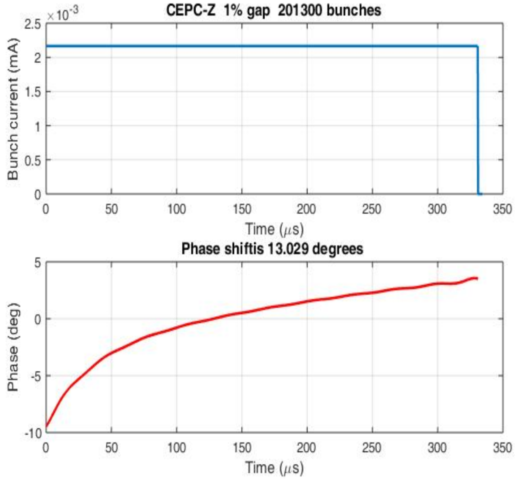
Phase shift not trivial for double ring W & Z with 1 % ~ 5 % gap to mitigate ion-trapping and fast beam ion instability (FBII) → Cure by using many short bunch trains. APDR phase shift → Cure by beat cavity

Phase Shift of Z-pole Beam Gap

D. Gong
MOPB069

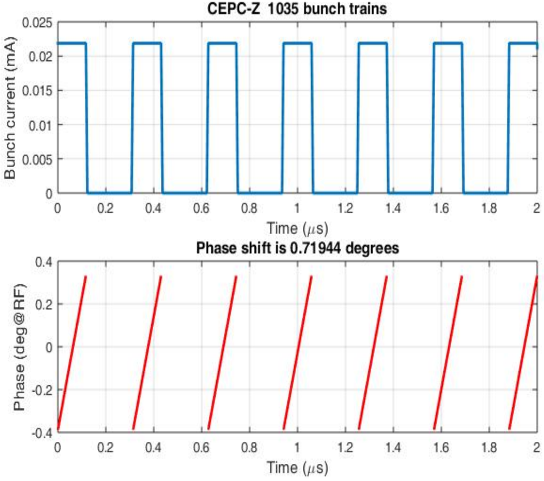


Transfer functions
(Pedersen Model)



1% long gap

$$\Delta\theta_{max} = 13.82\,\text{deg}$$

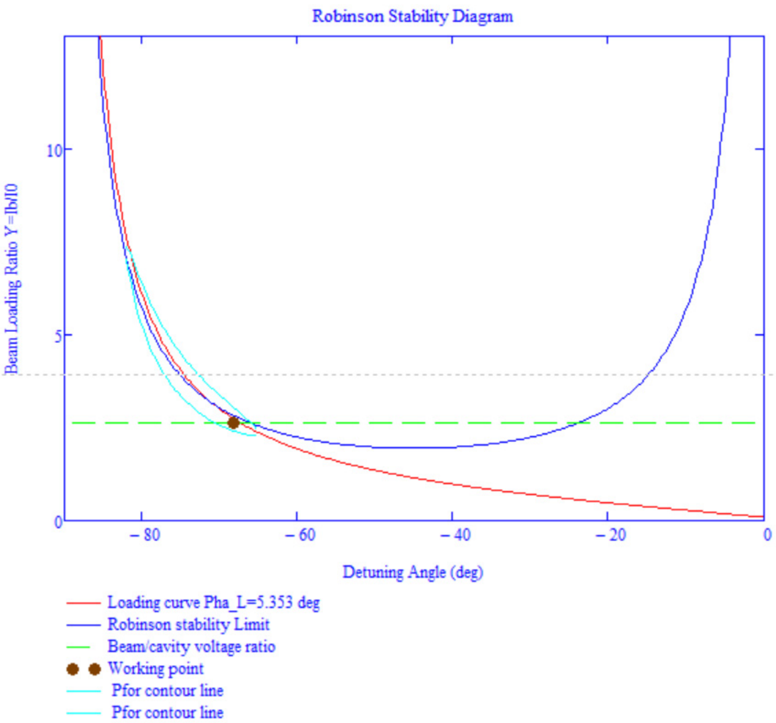


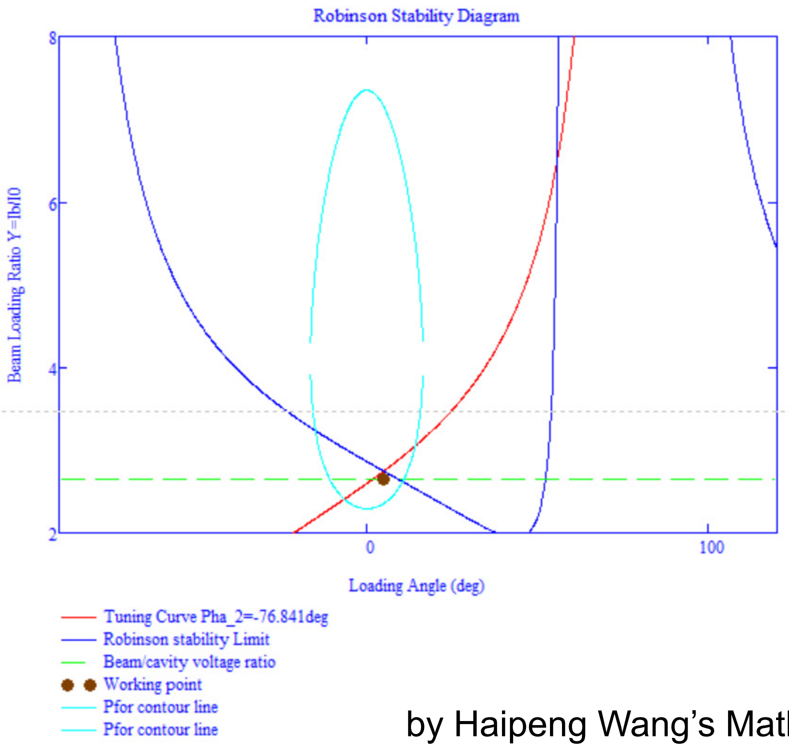
1065 trains, 20 bunches each
(T_g = 195.7 ns, T_b = 6.15 ns)

$$\Delta\theta_{1N} = 0.76\,\text{deg}$$

Simulation based on D. Teytelman's MATLAB code
Analytical formula from K. Bane EPAC'96 and P.B. Wilson SLAC-PUB-6062

Robinson Stability (CEPC DR Z mode)





by Haipeng Wang's Mathcad code

- Fast direct feedback (group delay 2 us, loop gain 22).
- ~ 10 % more power to have Robinson stable operation of high current Z-pole.

Fundamental Mode Instability of Z-pole

D. Gong
MOPB069

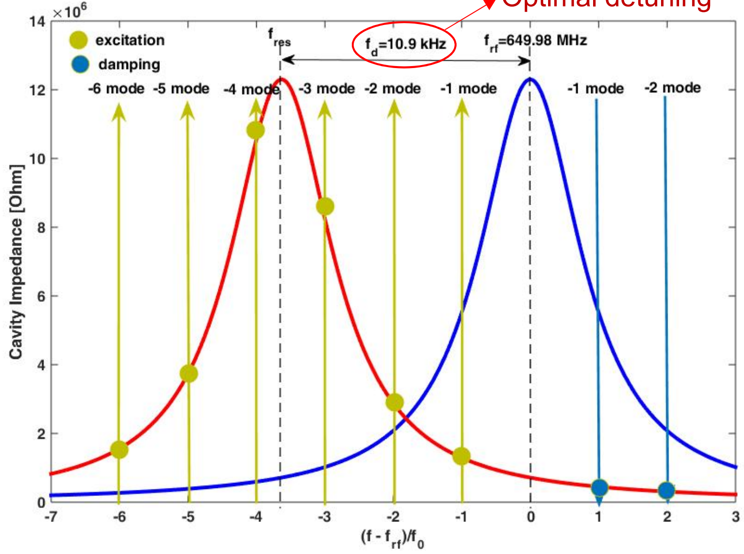
Longitudinal coupling-impedance

$$Z^{||}(f) = \frac{1}{\beta}\frac{R_{sh}/2}{1 + iQ_L(\frac{f}{f_{res}} - \frac{f_{res}}{f})}$$

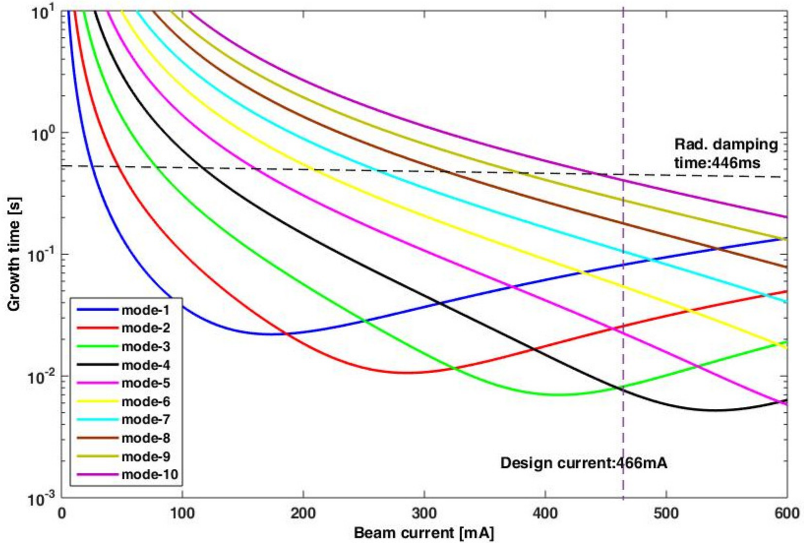
Cavity resonance frequency

$$f_{res} = f_{rf} + \Delta f \qquad \Delta f_{opt} = -\frac{I_b \sin\phi_s \frac{R}{Q} f_{RF}}{2V_c}$$

Optimal detuning



Cavity acceleration mode impedance and beam spectrum of CEPC Z-pole mode



Growth time of CBI due to acceleration mode of CEPC Z operation (10 modes to be damped)

Main Ring HOM CBI and Feedback

Machine parameter: wangdou20170222	H	W	Z
Cavity number (total)	336	240	96
Beam feedback time [ms]	**3.3**	**3.3**	**3.3**
Average beta_x,y in RF cavity [m]	30	30	30
***Qe* limit**	**1×10^4**	**1×10^4**	**1×10^4**
H cavity 336, W&Z cavity 168, with feedback, Ib limit [mA]	**580.14**	**1547.05**	**673.07**
Lmax / IP [10^{34} $cm^{-2}s^{-1}$]	**60.19**	**81.59**	**17.23**
Unused cavity off-line for W&Z, with feedback, Ib limit [mA]	580.14	2165.87	2355.75
Lmax / IP [10^{34} $cm^{-2}s^{-1}$]	**60.19**	**114.23**	**60.29**
H, W, Z all 336 cavities, with feedback, Ib limit [mA]	580.14	386.76	168.27
Lmax / IP [10^{34} $cm^{-2}s^{-1}$]	60.19	20.40	4.31
H cavity 336, W&Z cavity 168, without feedback, Ib limit [mA]	**39.94**	**31.57**	**3.25**
Lmax / IP [10^{34} $cm^{-2}s^{-1}$]	**4.14**	**1.66**	**0.08**
Unused cavity off-line for W&Z, without feedback, Ib limit [mA]	39.94	44.19	11.38
Lmax / IP [10^{34} $cm^{-2}s^{-1}$]	4.14	2.33	0.29
SR power limit [MW]	**50**	**50**	**50**
Ib limit from SR power limit [mA]	**29.9**	**151.1**	**1470.6**
Lmax/IP limit from SR power limit [10^{34} $cm^{-2}s^{-1}$]	**3.1**	**8**	**37.6**

- HOM Qe limit ~ **1×10^4** (including frequency spread)
- Beam feedback time ~ **3.3 ms** (damping time: 5 turns and margin)
- Average beta_x,y in RF cavity ~ **30 m**

$$Lmax \propto I_0 \propto \frac{1}{\tau \cdot Q_e}$$

CEPC Booster HOM CBI Instability and Feedback

Modes	*f* (GHz)	R/Q (Ω)	Q_{ext} measured	CBI Growth Time (ms)		
				H-extraction	W-extraction	Z-extraction
TM011	2.45	156	5.90E+04	3758	2157	363
TM012	3.845	44	2.40E+05	2087	1198	202
TE111	1.739	4283	3.40E+03	6159	4594	906
TM110	1.874	2293	5.00E+04	782	583	115
TM111	2.577	4336	5.00E+04	414	309	61
TE121	3.087	196	4.40E+04	10400	7757	1530
				H-injection	W-injection	Z-injection
TM011	2.45	156	5.90E+04	313	270	80
TM012	3.845	44	2.40E+05	174	150	44
TE111	1.739	4283	3.40E+03	513	574	199
TM110	1.874	2293	5.00E+04	65	73	25
TM111	2.577	4336	5.00E+04	34	39	13
TE121	3.087	196	4.40E+04	867	970	336

- All larger than beam feedback time limit ~ **3.3 ms** (5 turns and margin)
- Cavity HOM frequency spread will have more margin
- Average beta_x,y in RF cavity ~ **30 m**

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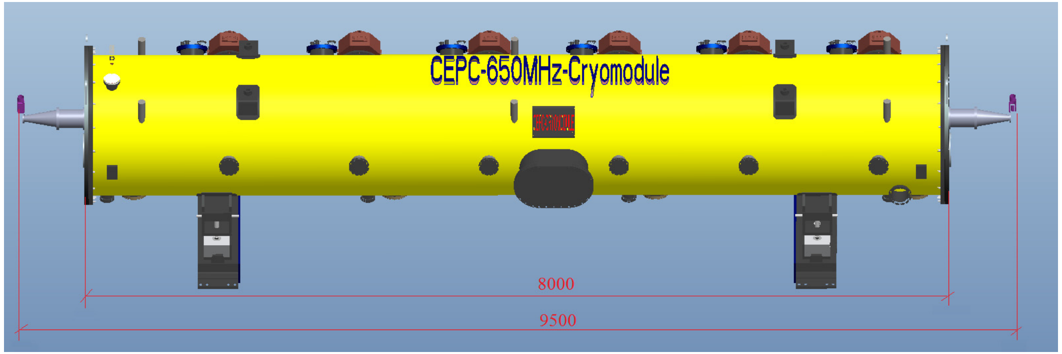
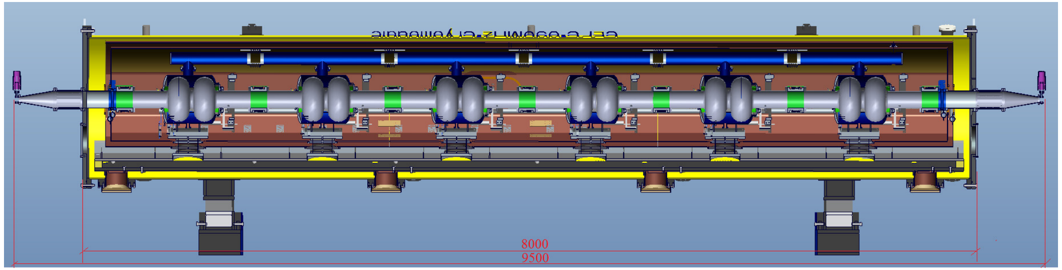
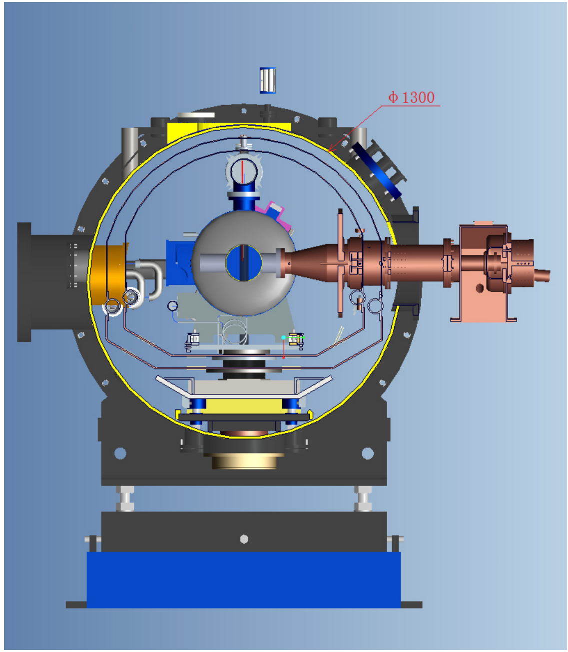
CEPC SRF R&D Plan (2017-2022)

- **Two small Test Cryomodules** (650 MHz 2 x 2-cell, 1.3 GHz 2 x 9-cell)
- **Two full scale Prototype Cryomodules** (650 MHz 6 x 2-cell, 1.3 GHz 8 x 9-cell)
- **Schedule**
  - 2017-2018 (key components, IHEP Campus)
    - high Q 650 MHz and 1.3 GHz cavities, N-doping + EP
    - 650 MHz variable couplers (300 kW)，1.3 GHz variable couplers (10 kW)
    - high power HOM coupler and damper, fast-cool-down and low magnetic module, reliable tuner
  - 2019-2020 (test modules integration, Huairou PAPS)
    - Horizontal test 16 MV/m, Q_0 > 2E10
    - beam test 1~10 mA
  - 2021-2022 (prototype modules assembly and test, Huairou PAPS)

CEPC Main Ring 650 MHz Cryomodule

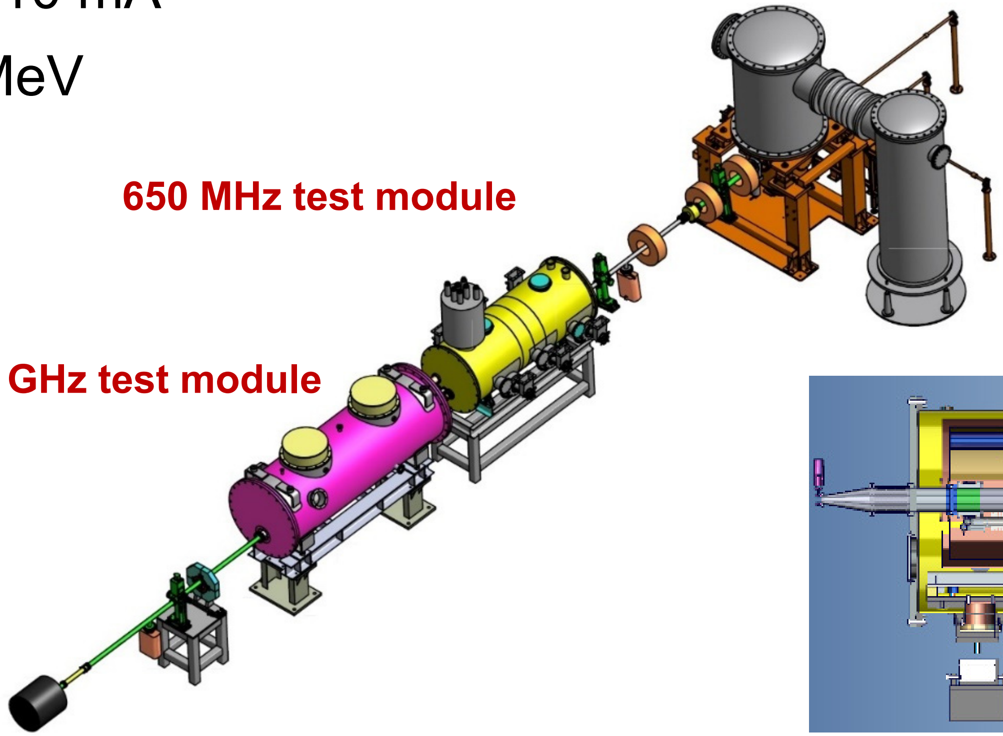


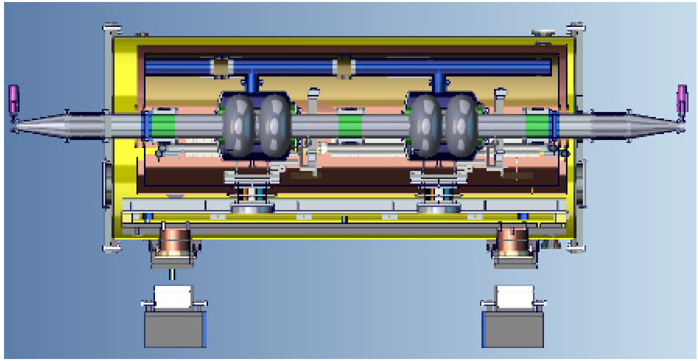




Module Beam Test

- CW 10 mA
- 50 MeV

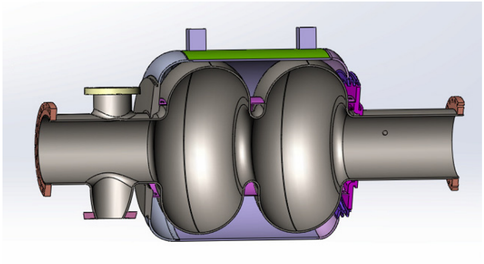


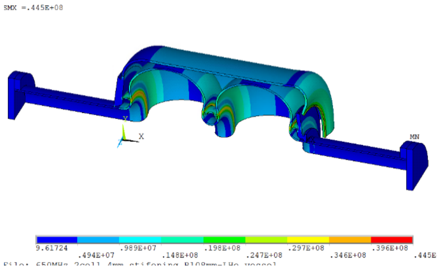


650 MHz Cavity & Sample N-dope

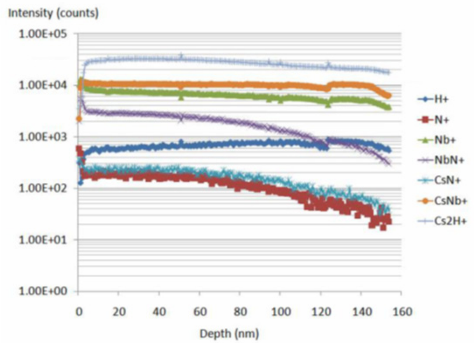
S. Peng
TUPB036

X. Zhang
TUPB038

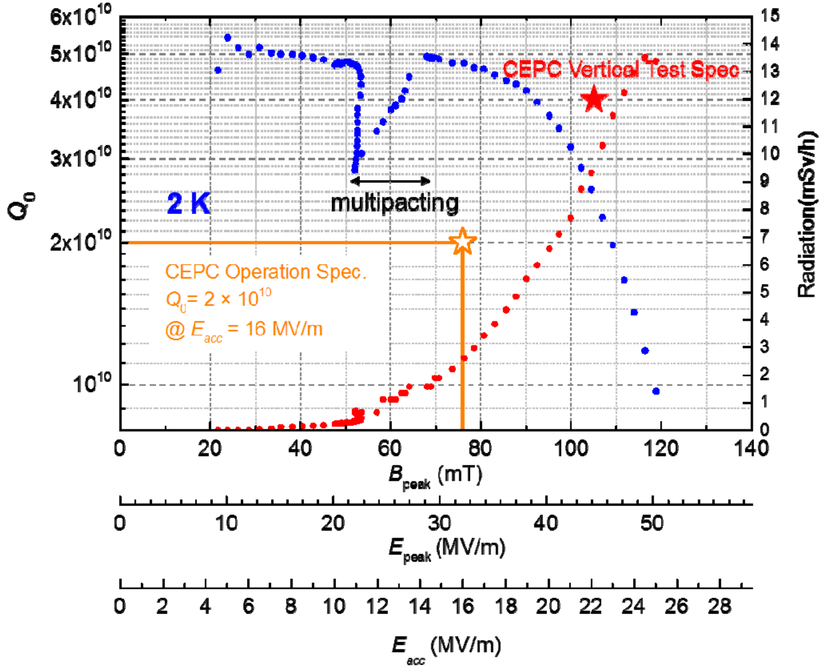




RF and mechanical design



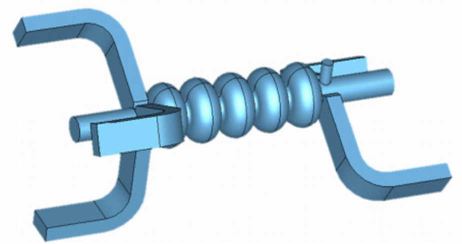
Sample N-doping and SIMS analysis

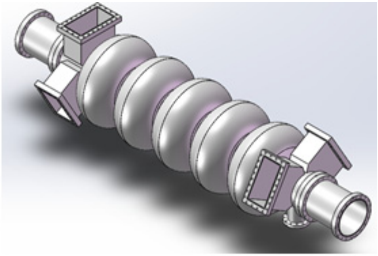


650 MHz single cell test w/o N-dope

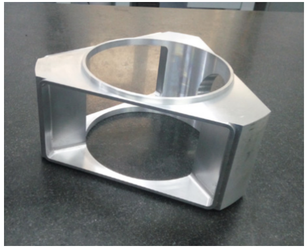
S. Jin
TUPB032

5-cell Cavity with WG HOM Coupler

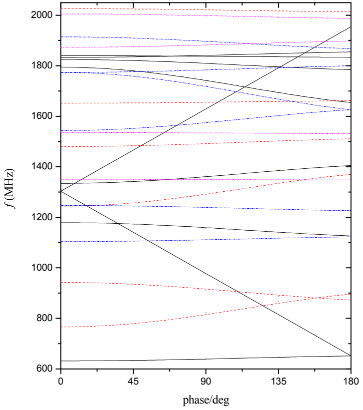


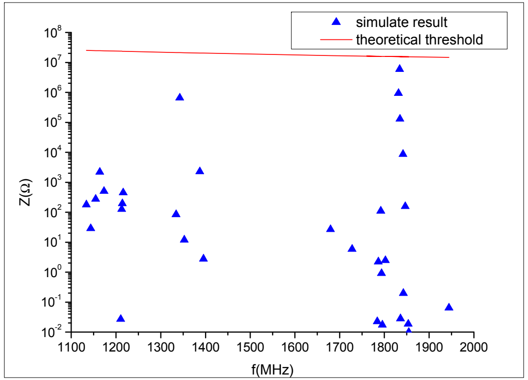


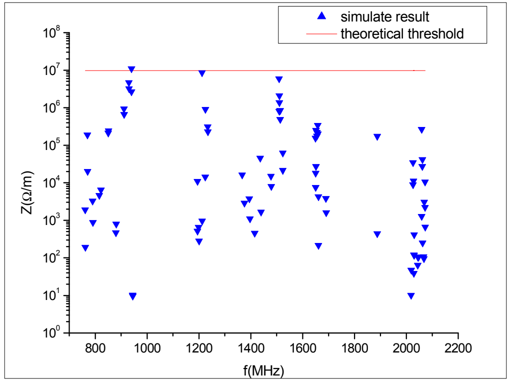
Nb prototype cavity in fabrication



Aluminum test piece





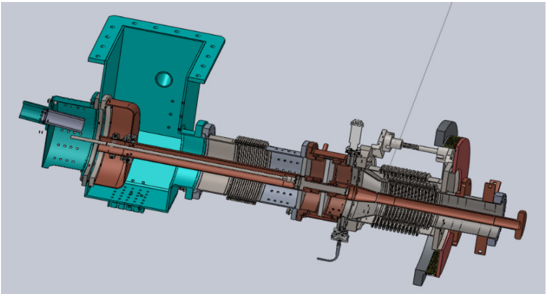


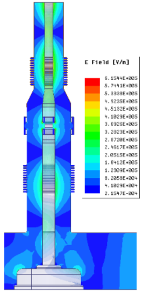
Dispersion curve, monopole impedance, dipole impedance

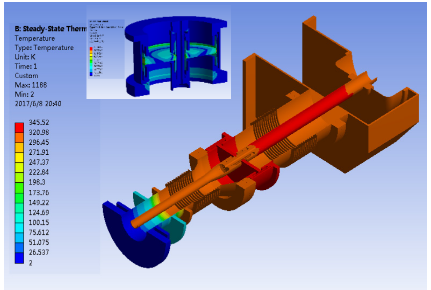
650 MHz Input Coupler

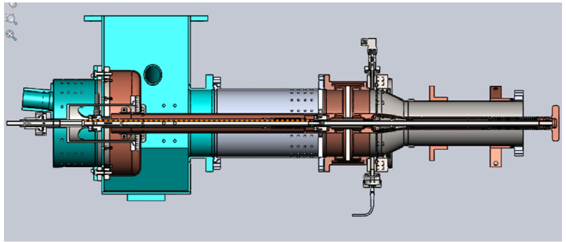
Q. Ma, T. Huang
MOPB069

- **High power handling**: CW > 300 kW, one window only
- **Clean assembled** with cavity in class 10 clean room
- Wide-range **variable coupling** to save huge CEPC AC power.
- Balance coupler length (**cryomodule size and type**) and **heat load**.









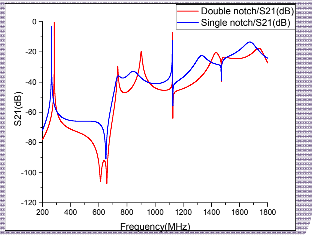
Bellow on outer conductor
RF, thermal and mechanical design

Bellow on inner conductor

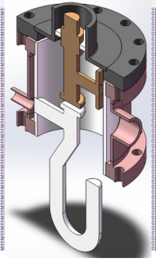
Main Ring HOM Coupler Design

H. Zheng
MOPB028

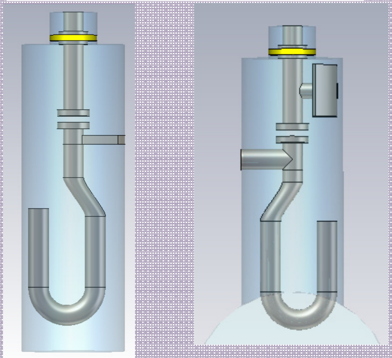
RF design



Mechanical designs



Design approach for HOM coupler

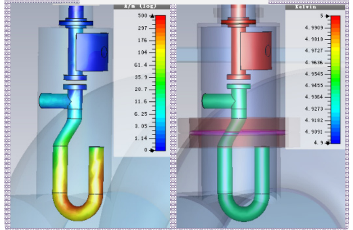


Single notch coupler

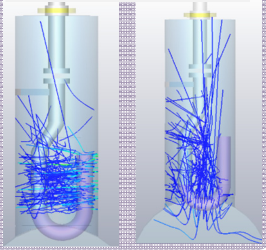
double notch coupler

> 1 kW power

Heat loss



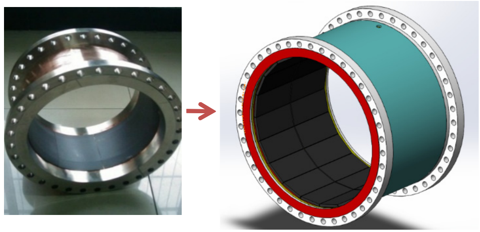
Multipacting analysis



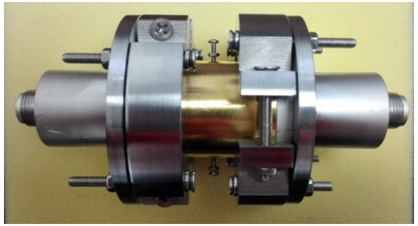
HOM Absorber

F. Meng
MOPB071

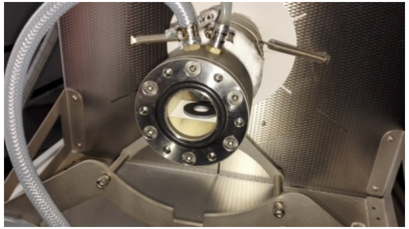
5 kW at RT
Up to 10 GHz



Brick shape

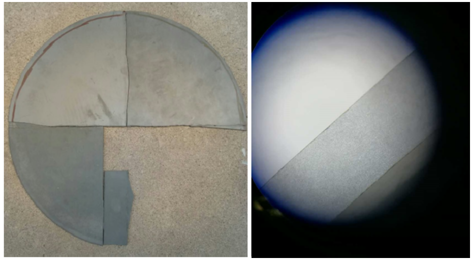


Material test

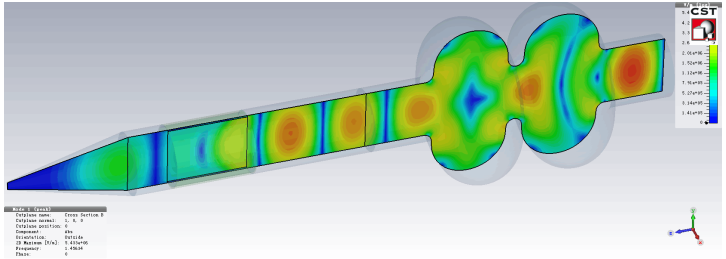


Ferrite brazing test

Ferrite

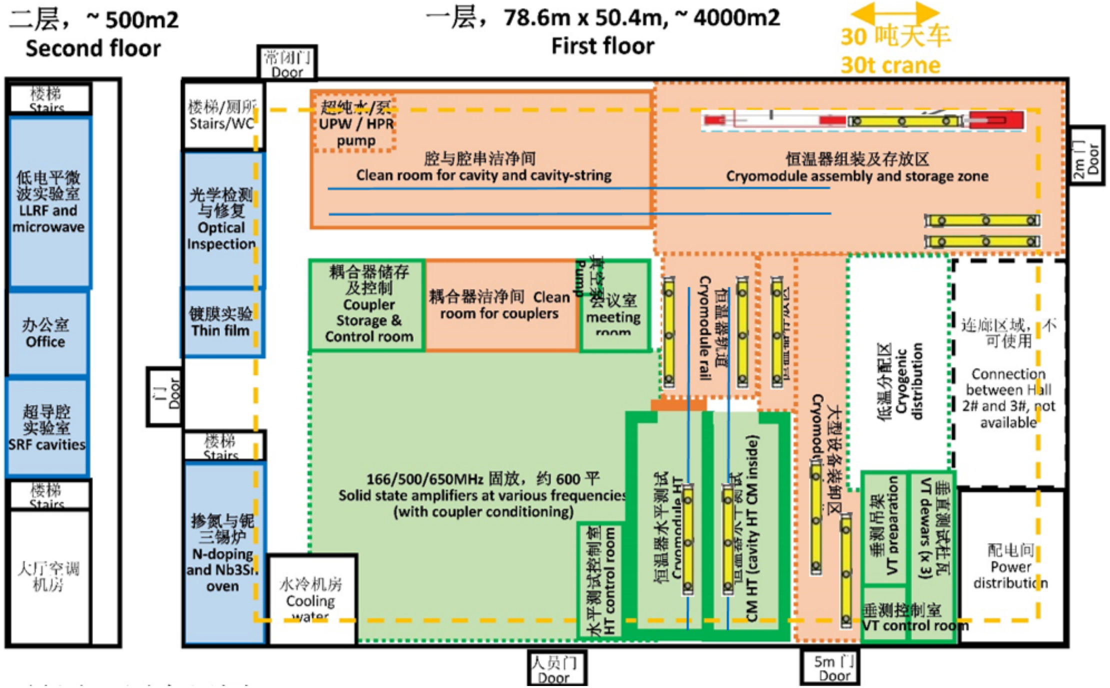


AlN+SiC composite



F. He
MOPB027

IHEP New Large SRF Facility



4500 m^2 SRF lab in the Platform of Advanced Photon Source Technology R&D (PAPS), Huairou Science Park, Beijing.

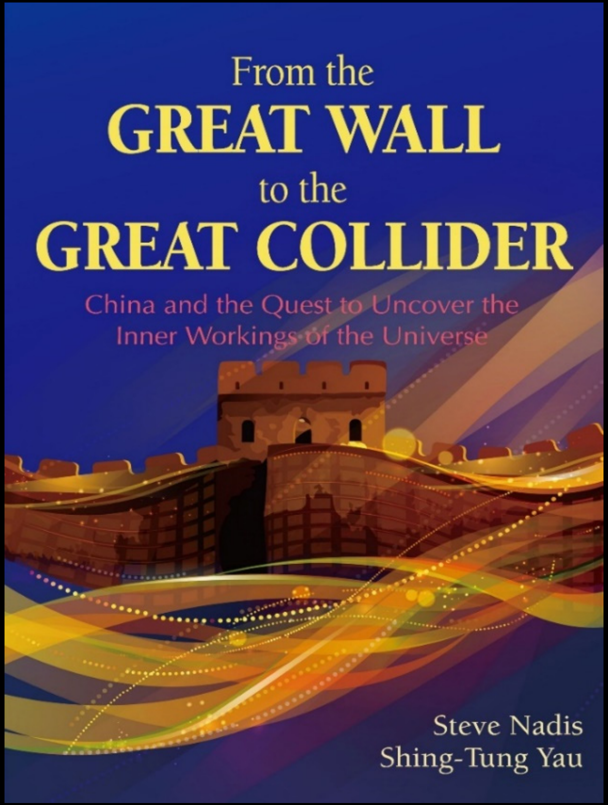
Mission: World-leading SRF Lab for Superconducting Accelerator Projects and SRF Frontier R&D.

Mass Production: 200 ~ 400 cavities (couplers) test per year, **20 cryomodules** assembly and horizontal test per year.

Construction: 2017 - 2020

Summary and Outlook

- Baseline layout and parameters for CEPC SRF system established. Plan to complete CDR in the end of 2017 and TDR in 2022.
- CEPC SRF technology R&D launched, with support of large PAPS SRF facility.
- CEPC SRF R&D and industrialization synergy with SCLF, CIADS, HIAF, HEPS (~ 1000 cavities in next five years), FCC and ILC.



And to me, the knowledge gained in the process would rank among humanity's greatest possible achievements. Frankly, I can't think anything higher to strive for.

Shing-Tung Yau（丘成桐）