

# CEPC Superconducting RF System

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On behalf of CEPC SRF team



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# Outline

- Design requirements and challenges
- SRF layout and parameters
- Technology R&D

# CEPC-SPPC Project

## Reminder about the CEPC-SppC

### $e^+e^-$ Higgs (Z) factory

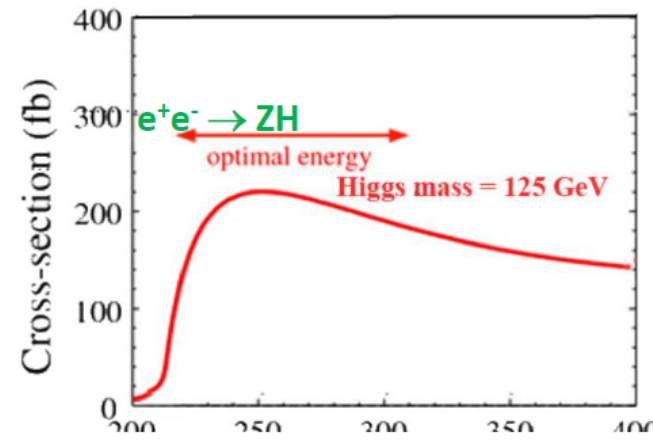
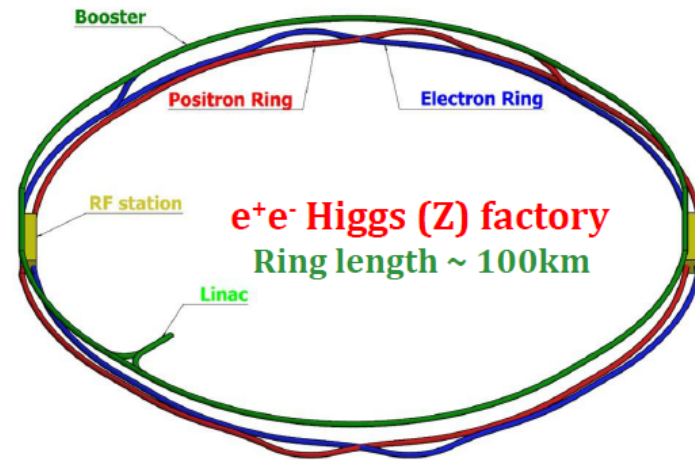
$E_{\text{cm}} \approx 240 \text{ GeV}$ , luminosity  $\sim 2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ , 2IP, 1M H in 10 years  
at the Z-pole  $10^{10}$  Z bosons/yr

Higgs precision  
1% or better

Precision measurement of the Higgs boson (and the Z boson)

Upgradable to pp collision with  $E_{\text{cm}} \approx 50\text{-}100 \text{ TeV}$  (with ep, HI options)

A discovery machine for BSM new physics

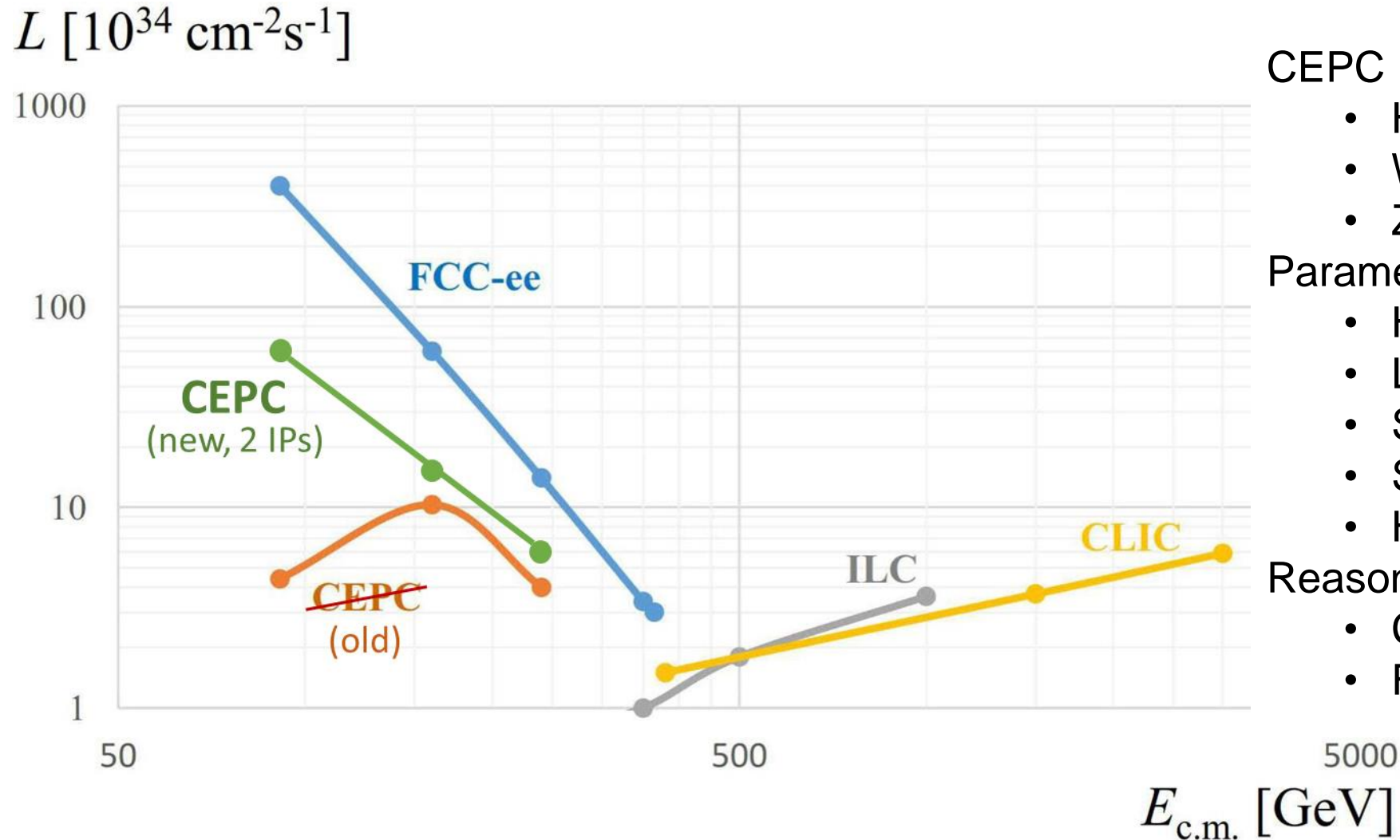


BEPCII will likely complete its mission  $\sim 2020$ s;

CEPC – possible accelerator based particle physics program in China after BII

X. Lou, IAS HEP 2018

# CEPC Luminosity



CEPC luminosity (per IP):

- H:  $3 \times 10^{34}$
- W:  $7 \times 10^{34}$
- Z:  $4 \times 10^{35}$

Parameter changes (from the old):

- Higher bunch intensity
- Lower  $\beta(y)^*$
- Smaller x-y coupling
- Shorter bunch spacing (for Z)
- Higher RF voltage (for Z)

Reason for difference from FCC-ee:

- CEPC: 60 MW rf
- FCC-ee: 100 MW rf



# CEPC SRF Design Requirements

## 1. Higgs long operation first

- One-time full installation of all Higgs cavities
- Cavity optimized for Higgs, with operation margin (higher voltage and current)

## 2. W and Z use part of the Higgs cavities

- Baseline W and Z luminosity not limited by Higgs cavity
- W limited by SR power
- Z limited by beam-beam (bunch charge) , x-y coupling ( $\beta_y^*$ ), e-cloud (bunch spacing)

# CEPC SRF Design Requirements

3. Cavity and cryogenics cost reduction (by half)
  - Common H cavities, separate W/Z cavities
4. Upgradable (to 50 MW SR per beam etc.)
  - Margin for power source, RF distribution and input coupler
  - Variable coupler to save power
  - Independent KEKB/BEPCII type cavity for high luminosity Z
  - Longer RF tunnel reserved for upgrade

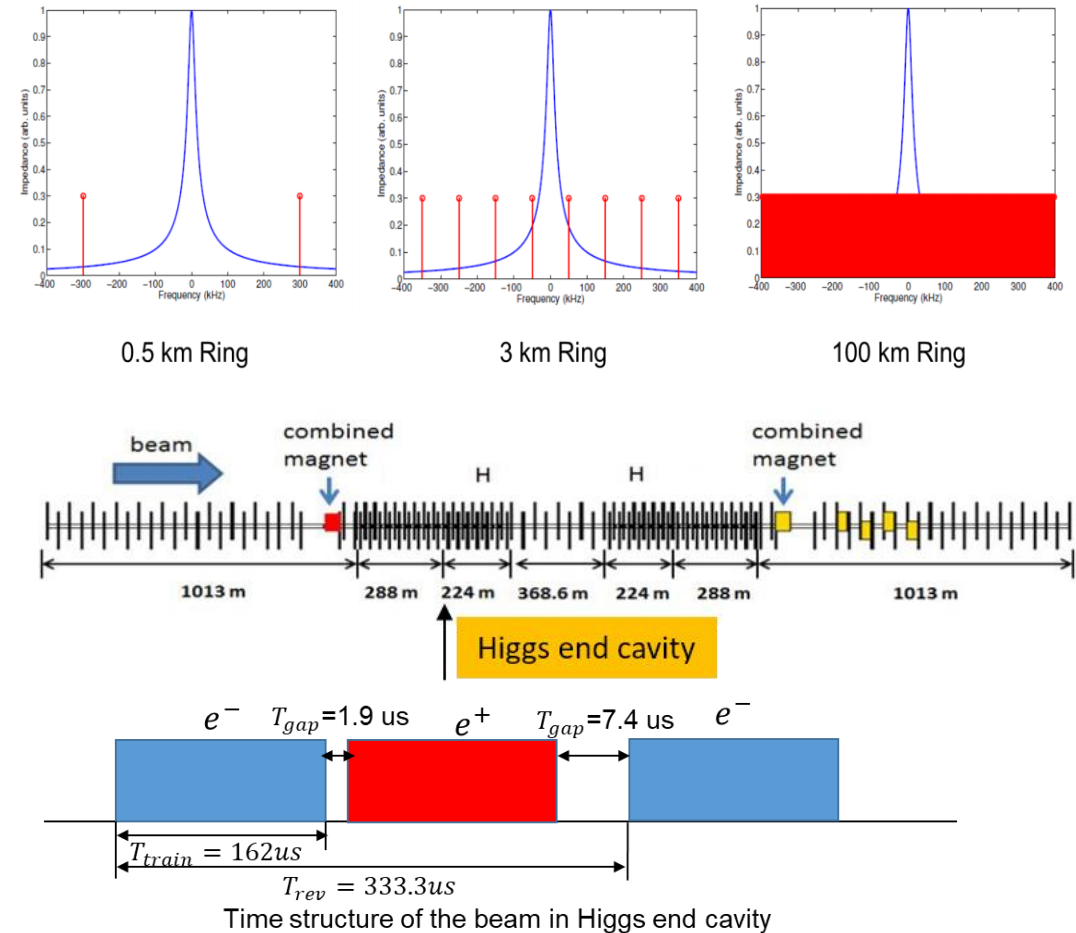
# CEPC SRF Design Challenges

	H	W	Z
<b>Collider Ring</b>	<b>650 MHz 2-cell cavity</b>		
Lumi. / IP ( $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ )	2.9	7.3	4.1
RF voltage (GV)	2.17	0.47	0.054
Beam current (mA)	17.4 x 2	87.8	160
Cavity number	336	108 x 2	24 x 2
SR power (MW)	30	30	5.7
2 K cavity wall loss (kW)	6.6	1.9	0.1
<b>Booster Ring (extraction)</b>	<b>1.3 GHz 9-cell cavity</b>		
RF voltage (GV)	1.84	0.75	0.39
Beam current (mA)	0.52	0.66	0.53
Cavity number	96	64	32
RF input power (MW) avg.	0.14	0.04	0.06
2 K wall loss (kW) avg.	0.37	0.1	0.1

- **Higgs: high energy (voltage), low current**
  - High gradient for less cavity (also limited by coupler power)
  - High Q for less cryogenics (but should be realistic)
  - Narrow bandwidth operation (microphonics, multi-cavity feedback, extra power, especially for higher energy)
- **W & Z: low energy (voltage), high current**
  - HOM coupled-bunch-instabilities (CBI)
  - Fundamental mode CBI
  - HOM power per cavity (not a limit for baseline)
  - Parasitic loss (significant luminosity loss for high current)

# CEPC SRF Design Challenges

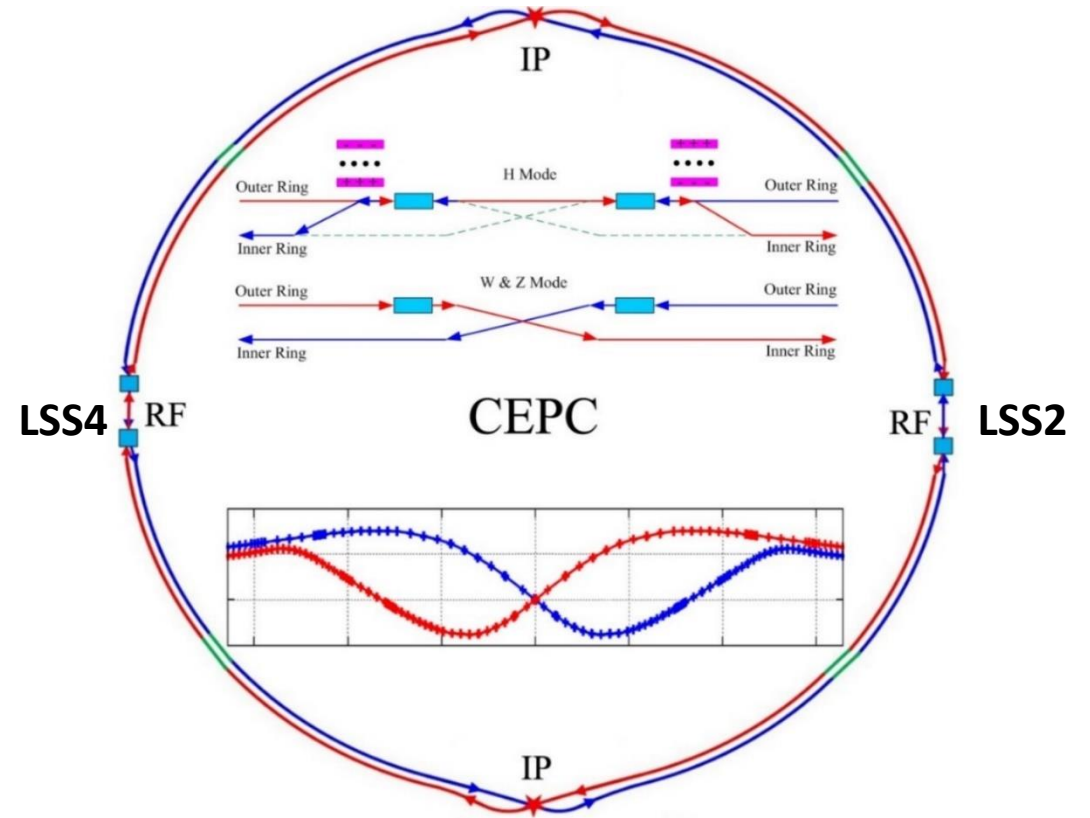
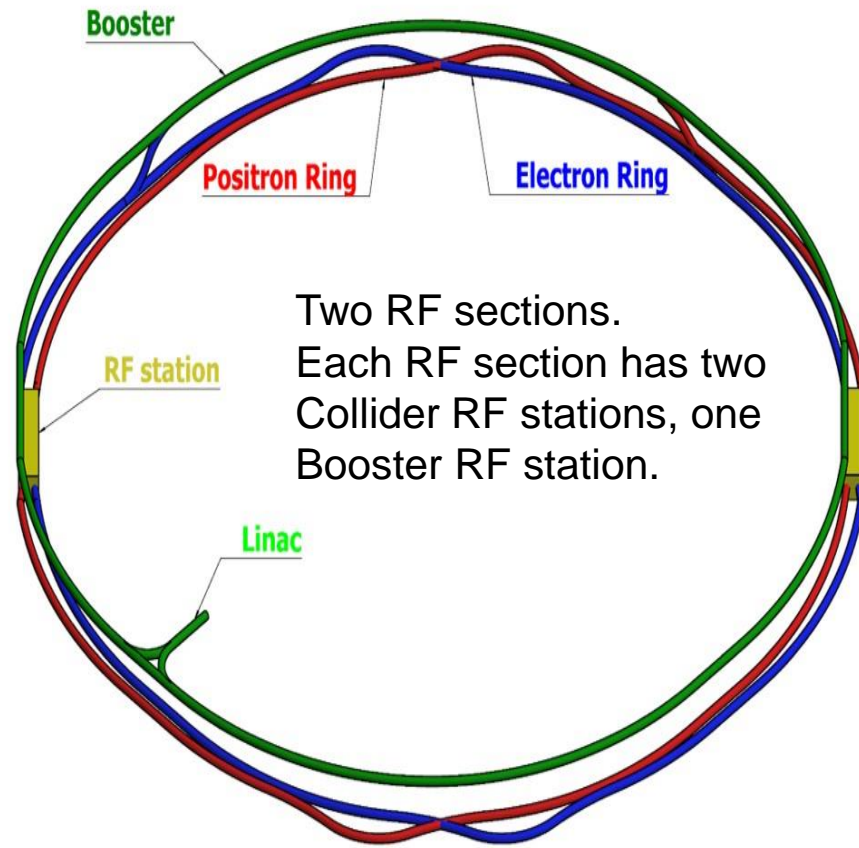
- **Large ring issues**
  - beam gap transient (mitigate by bunch trains)
  - dense beam spectrum (make HOM and FM CBI worse).
- **Special issues with CEPC**
  - parking cavities for W and Z (cure by symmetry detuning)
  - different gap transient at different position for Higgs less than half-fill
- **Booster cavity fast voltage ramp**
  - narrow bandwidth ramping operation (piezo feedforward, RF power margin)



# Outline

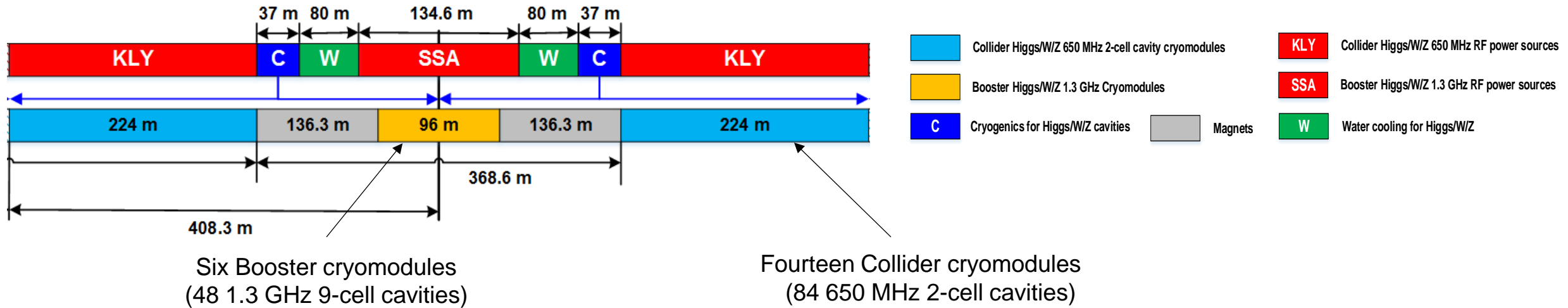
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# CEPC Layout



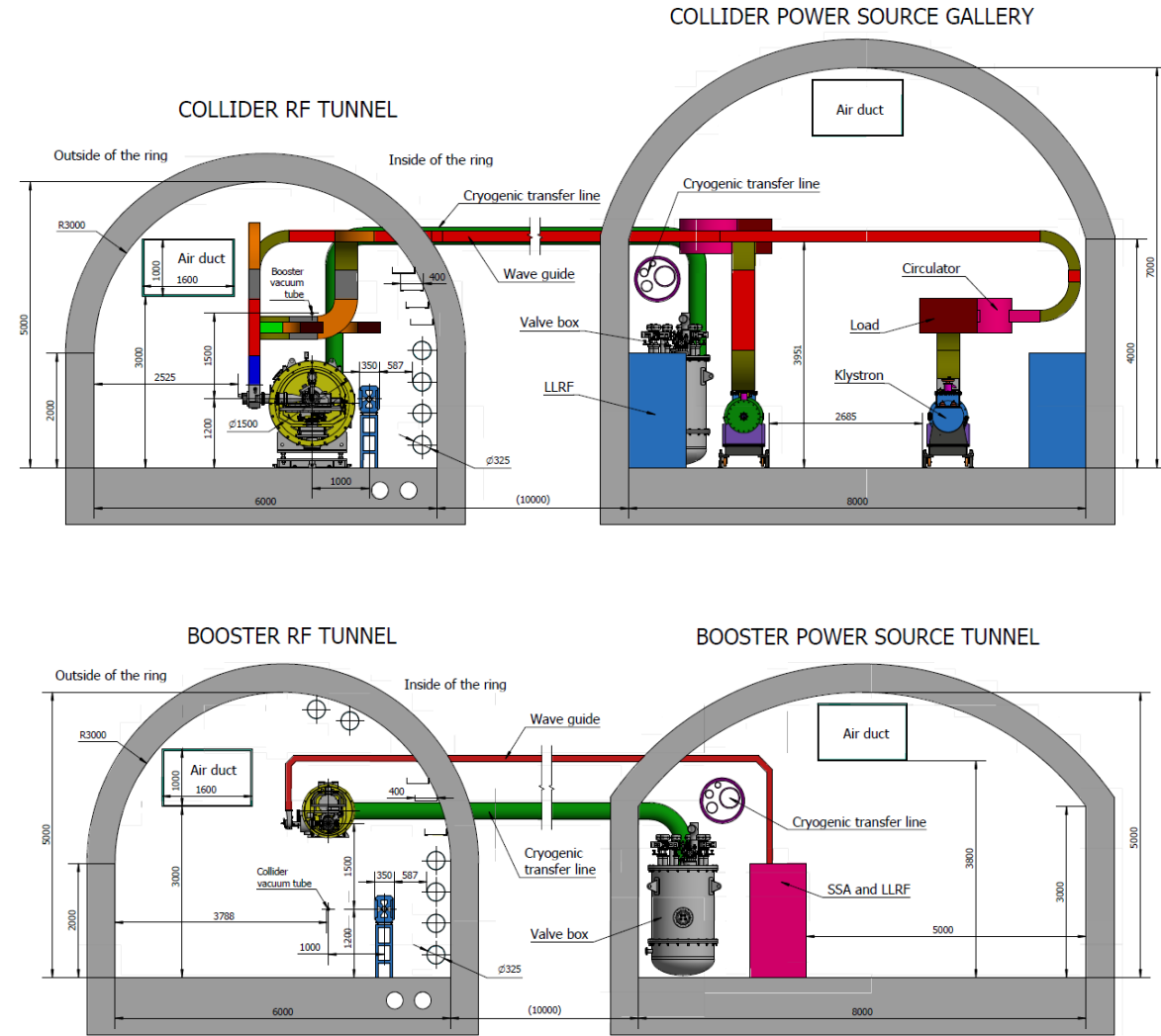
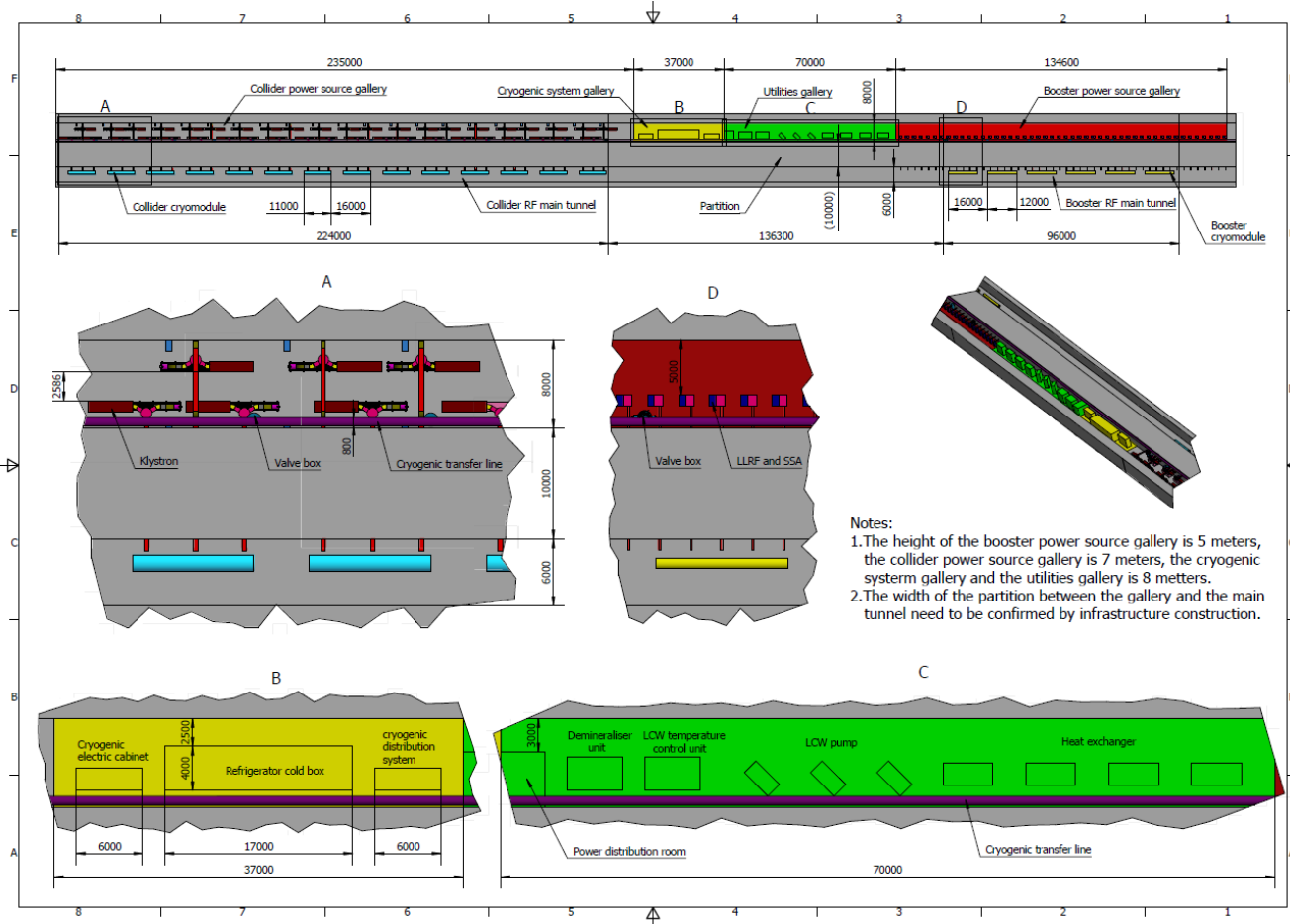
# CEPC RF Section

RF Section A @ IP2 / LLS2 (length 1948.6 m)



One 11~12 m long cryomodule between two quadrupoles in the Collider or Booster.

# CEPC RF Tunnel





# CEPC Collider Ring SRF Parameters

Collider parameters: 20180109	<b>H</b>	<b>W</b>	<b>Z</b>
SR power / beam [MW]	30	30	5.7
RF voltage [GV]	2.14	0.47	0.054
Beam current / beam [mA]	17.4	87.7	160
Bunch charge [nC]	24	8.6	6.4
Bunch length [mm]	3.26	3.43	6
Cavity number (650 MHz 2-cell)	336	216	48
Gradient [MV/m]	14	9.5	4.9
Input power / cavity [kW]	179	278	239
Klystron power [kW] (2 cavities / klystron)	800	800	800
HOM power / cavity [kW]	0.48	0.33	0.11
Optimal $Q_L$	1E6	3.2E5	1E5
Optimal detuning [kHz]	0.22	1.0	3.7
$Q_0$ @ 2 K at operating gradient (long term)	1E10	1E10	1E10
Total cavity wall loss @ 2 K [kW]	6.6	1.9	0.1
RF length [m]	896	576	128

Optimized for the Higgs mode of 30 MW SR power per beam, with enough operating margin and flexibility.

Cavity number determined by coupler power capacity, less is better for W and Z to reduce the detuning. 2-cell is a balance of gradient, beam loading and HOM power and damping.

Input coupler power limit 300 (500) kW, variable, low heat load, be short to reduce cryomodule diameter.

HOM power per cavity in the level of LEP2/LHC, but much wider freq.

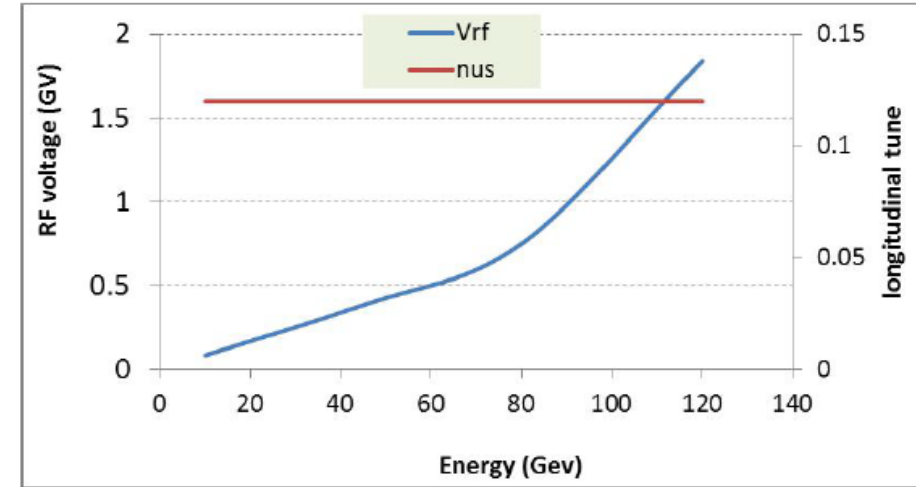
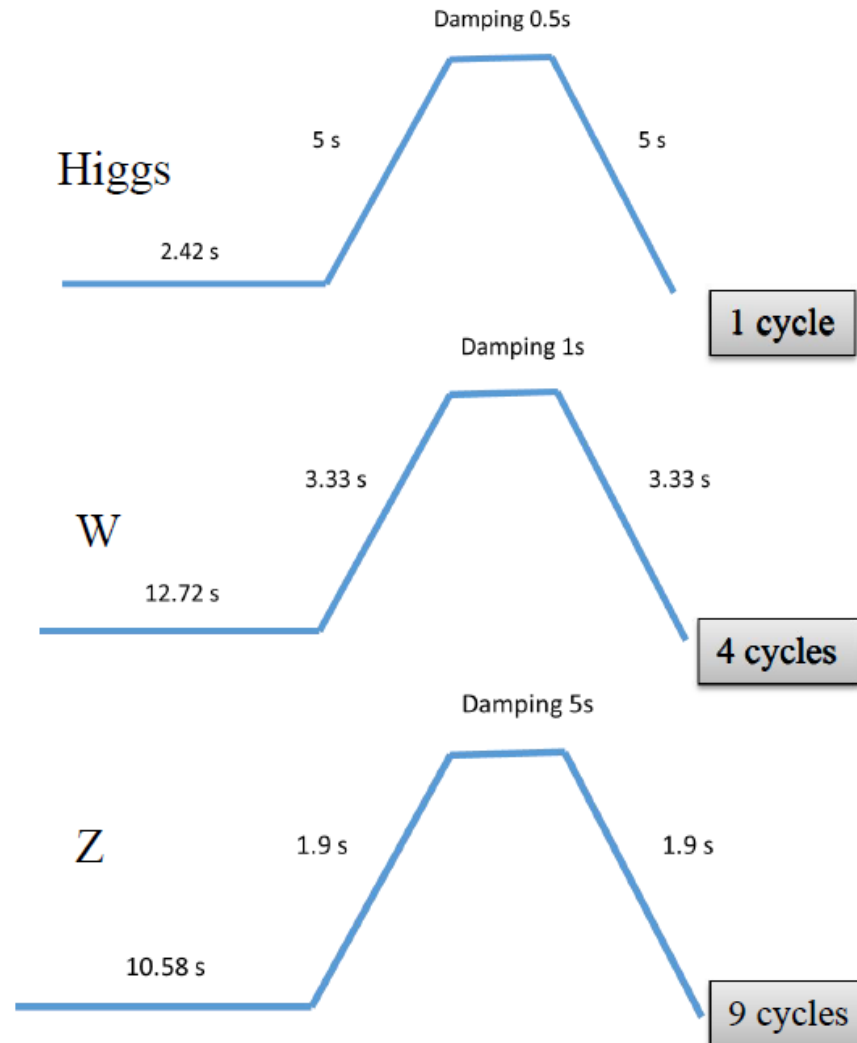
Cavity acceptance  $Q_0 > 4E10$  (N-doping), module horizontal test  $> 2E10$  (clean assembly and magnetic hygiene)

# CEPC Booster SRF Parameters

10 GeV injection	<b>H</b>	<b>W</b>	<b>Z</b>
Extraction beam energy [GeV]	120	80	45.5
Bunch charge [nC]	0.62	0.17	0.078
Beam current [mA]	0.53	0.53	0.51
Extraction RF voltage [GV]	1.83	0.7	0.36
Extraction bunch length [mm]	2.9	2.0	1.1
Cavity number in use (1.3 GHz TESLA 9-cell)	96	64	32
Gradient [MV/m]	18.4	10.5	10.8
$Q_L$ (over-coupled)	1E7	1E7	1E7
Cavity bandwidth [Hz]	130	130	130
Beam peak power / cavity [kW]	8.8	2.6	0.5
Input peak power per cavity [kW] (with detuning)	14.1	4.4	3.4
Input average power per cavity [kW] (with detuning)	1	0.4	0.3
SSA peak power [kW] (one cavity per SSA)	25	25	25
HOM average power per cavity [W]	0.4	0.15	0.10
$Q_0$ @ 2 K at operating gradient (long term)	1E10	1E10	1E10
Total average cavity wall loss @ 4.5 K eq. [kW]	0.8	0.3	0.1

# Booster Injection Time Structure

D. Wang



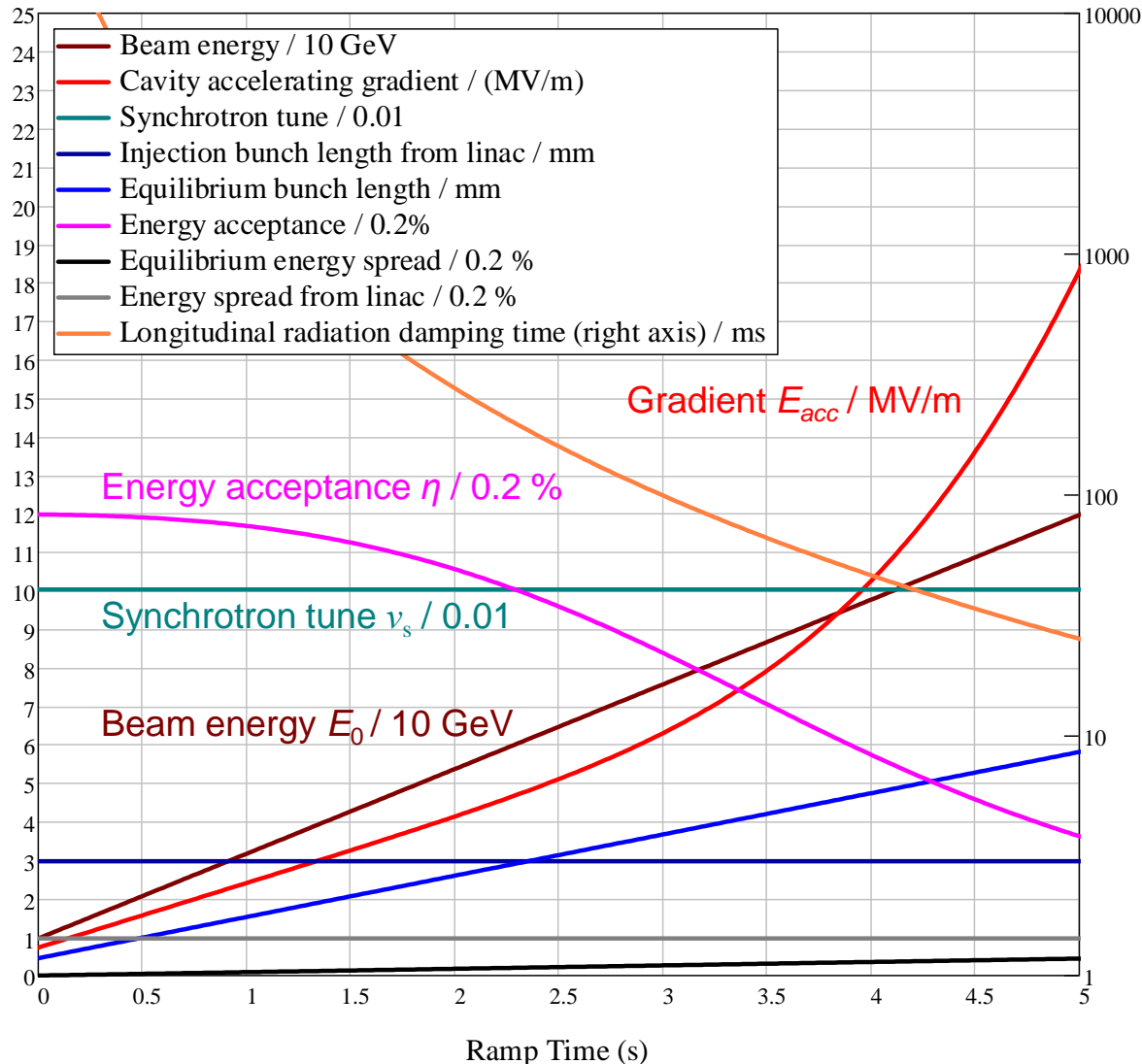
30Gauss @ 10GeV

Eddy current effect

- Transverse quantum lifetime@10GeV:  
 **$1.65 \times 10^8 \text{ s}$  ( $\epsilon_{\text{inj}}=120 \text{ nm}$ )**
- Beam loss due to lifetime  $\ll$  **1%**

# Booster Voltage Ramp

CEPC Booster Higgs Ramp Up



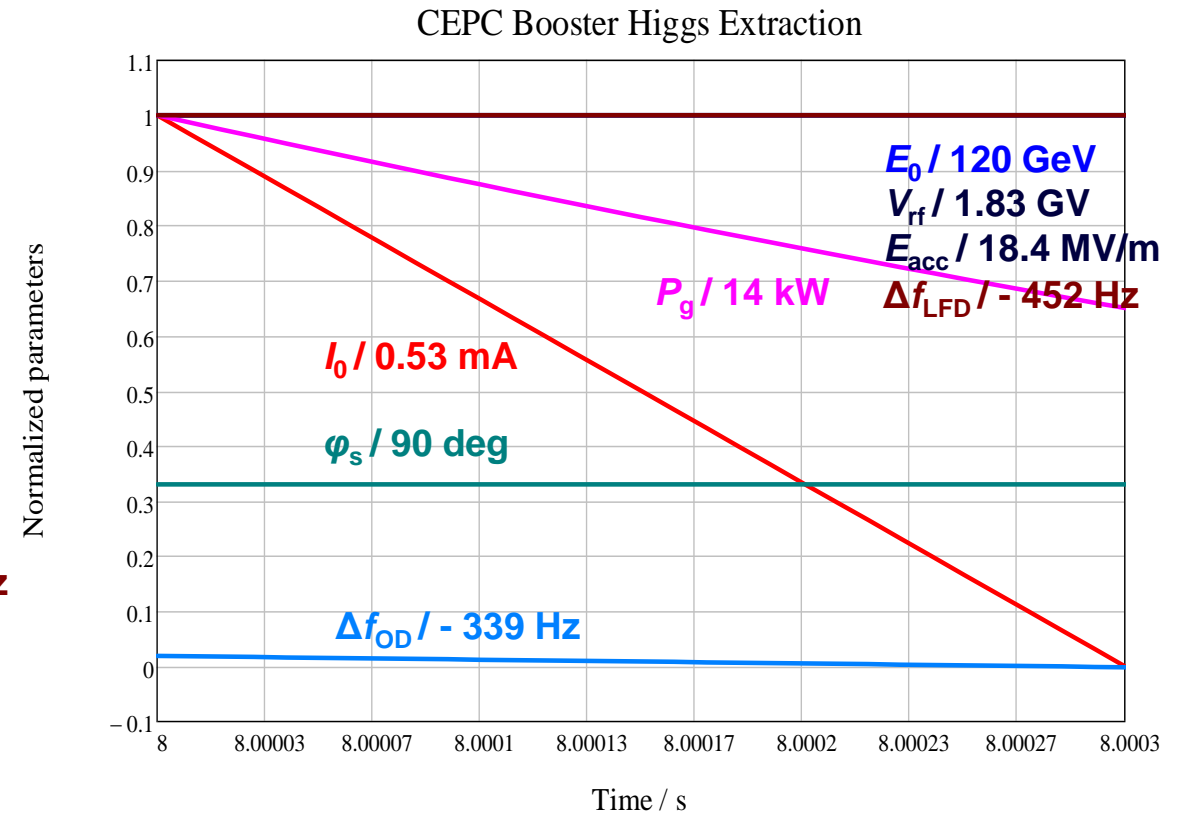
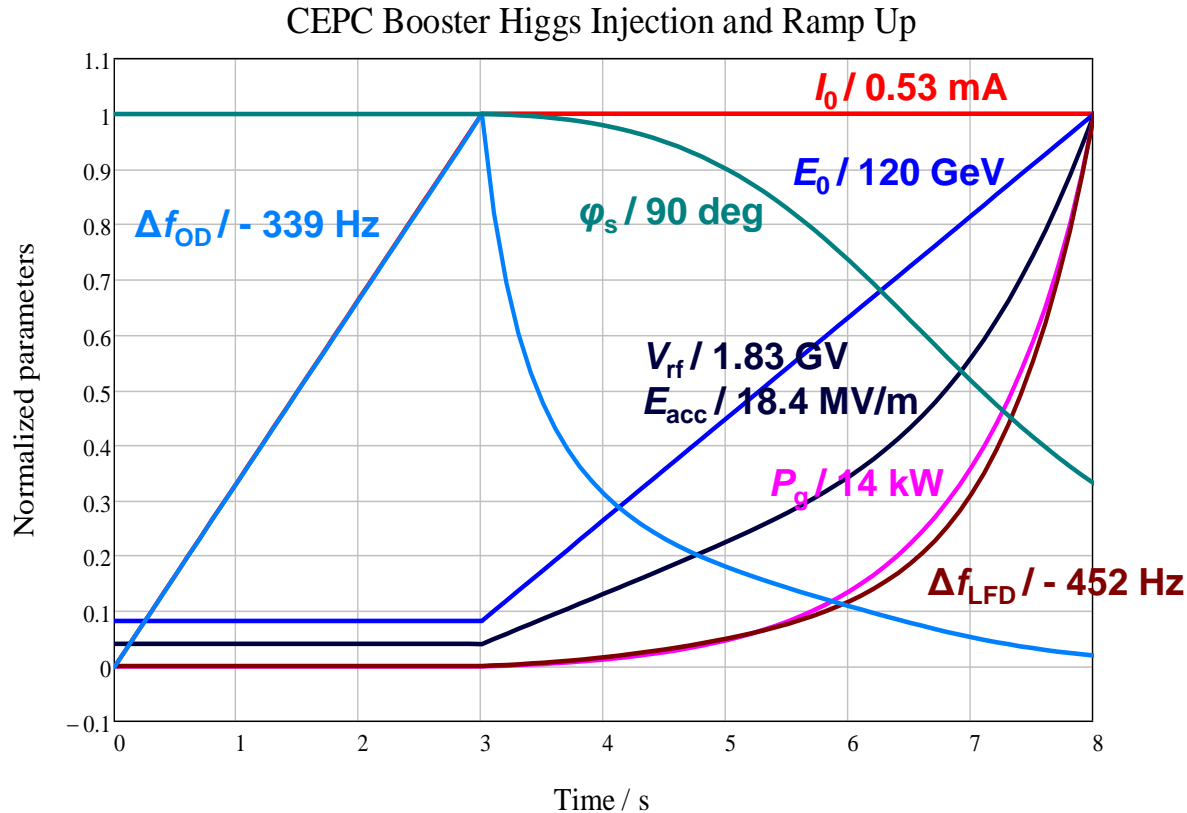
- Beam energy increase linearly with time.
- RF voltage ramp with constant synchrotron tune to avoid synchrotron-betatron oscillation.

$$V_{rf}(t) := \sqrt{\left(\frac{\nu_s^2 \cdot 2 \cdot \pi}{\alpha \cdot h \cdot e_0} \cdot E_0(t)\right)^2 + \left(\frac{U_0(t)}{e_0}\right)^2}$$

- Equilibrium bunch length and quantum lifetime not too short.
- Multipacting during voltage ramp?
- Counter-phasing can be used to ramp the effective RF voltage?

Very narrow bandwidth SRF cavity operation with microphonics and Lorentz detuning in a fast ramp synchrotron. Challenging but doable.

# Booster Voltage Ramp



- Assume 10 % Lorentz force detuning (LFD) remains not compensated by piezo actuators, 40 Hz peak-to-peak microphonics (not hard, but need careful cryomodule design and quiet operation condition). LFD factor for TESLA 9-cell cavity with helium vessel and tuner:  $1 \text{ Hz} / (\text{MV/m})^2$
- Ensure the detuning not to cause Robison instability during injection and ramping.
- With detuning, forward power 14 kW / cavity for + 20 Hz microphonics, 20 kW for - 20 Hz microphonics.

# Outline

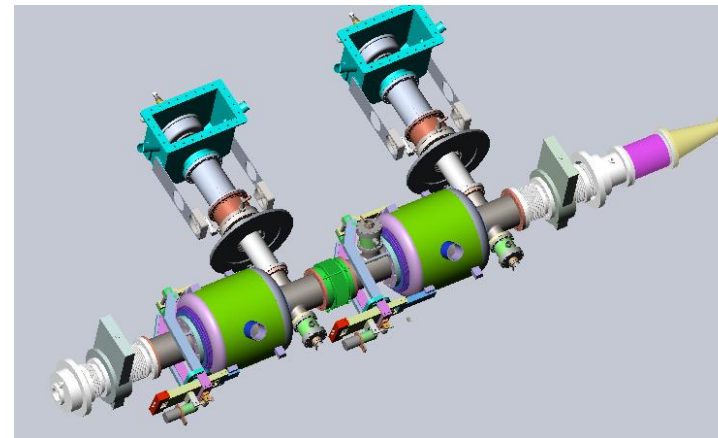
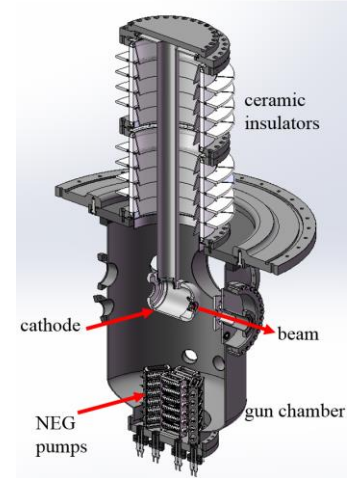
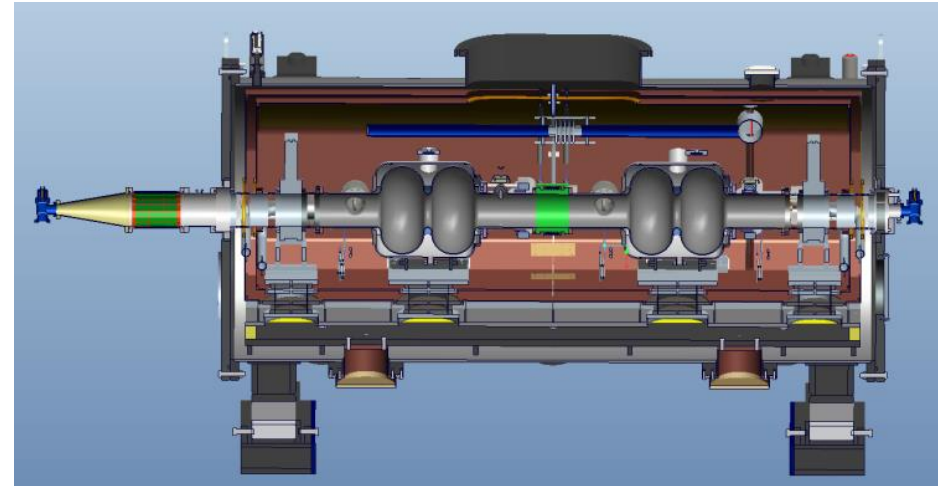
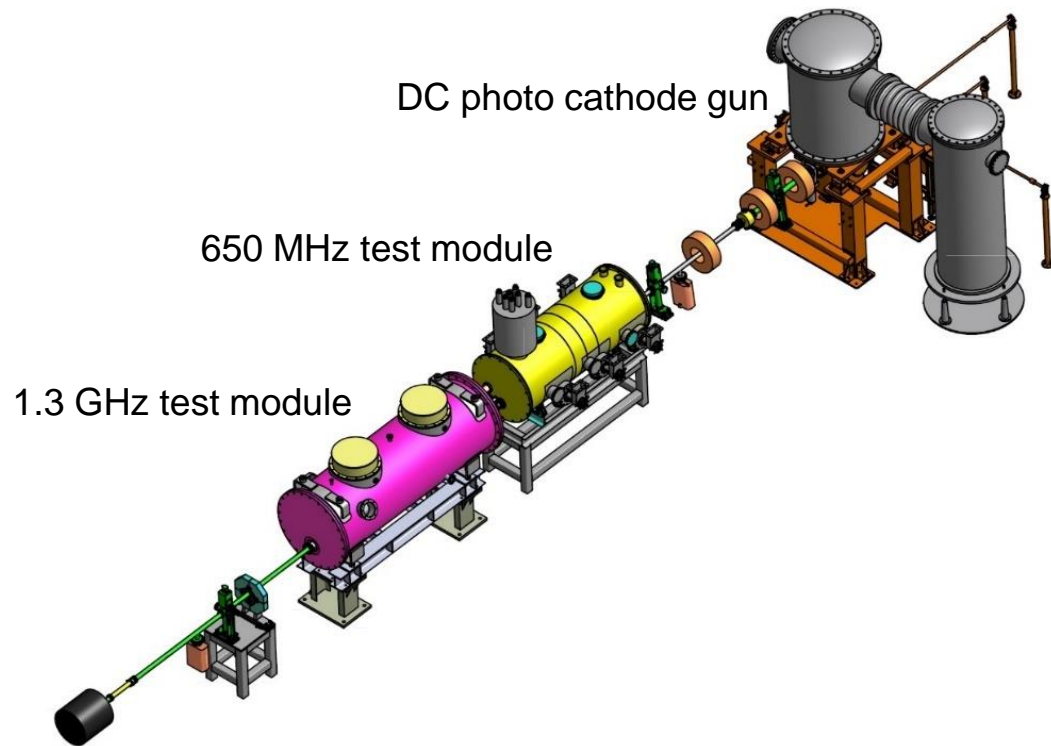
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# CEPC SRF R&D Plan (2017-2022)

- **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)

# Test Cryomodules

- CW 10 mA, 50 MeV
- 350 keV beam commissioned with GaAs
- New  $K_2CsSb$  cathode





# Choice of Cavity Freq., Temp. & Material

- Frequency

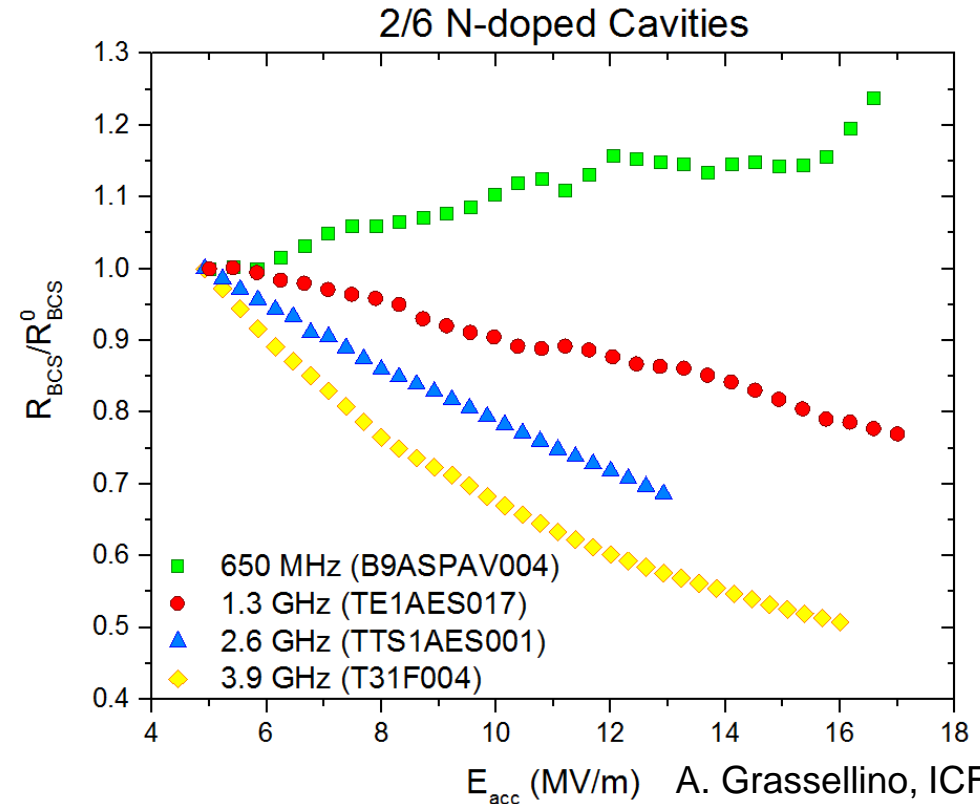
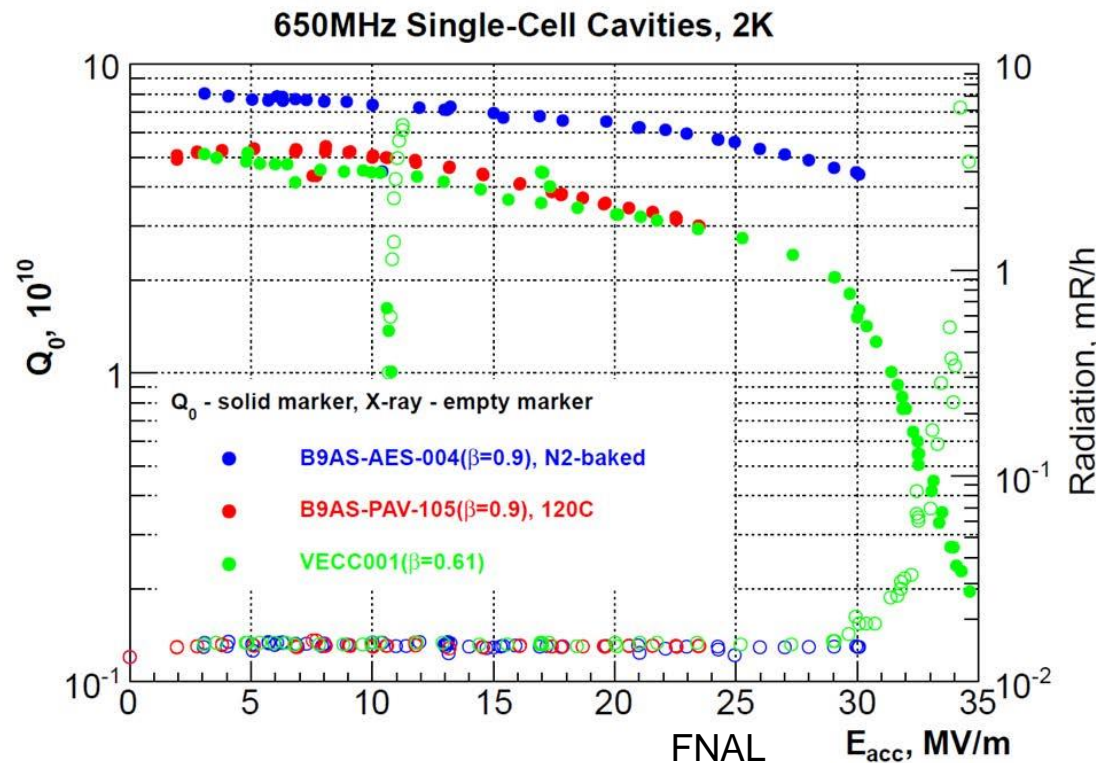
- Booster (low current with low duty factor): 1.3 GHz (matured technology and widely used in Euro-XFEL, ERLs, LCLS-II, Shanghai-SCLF, PIP-III, ILC ...)
- Collider: CW high current: 650 MHz (second harmonic, fulfill beam dynamics requirement, used in CADS, PIP-II, eRHIC ...)

- Temperature and Cavity Material

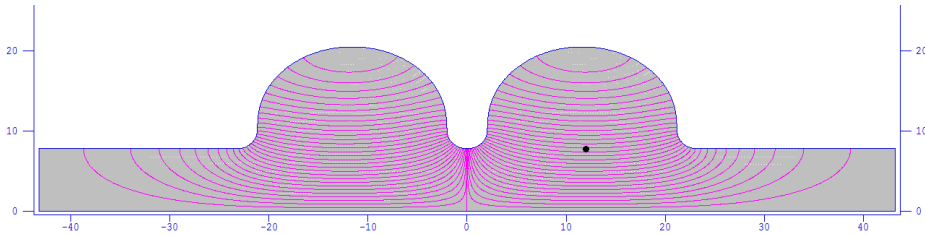
- 1.3 GHz Nitrogen-doped fine grain bulk Nb at 2 K
  - BCS resistance should be reduced to the level of residual resistance (several nΩs): at least 2 K
  - 1.8 K saves ~ 15 % of overall cryo-efficiency, large grain cavity has higher Q, but Nitrogen-doped cavity is much more efficient (2 times)
- 650 MHz Nitrogen-doped fine grain bulk Nb at 2 K
  - 2~4 times cryo-efficient than at 4.5 K
  - Nb<sub>3</sub>Sn has similar Q<sub>0</sub> at 4.5 K, 4 times efficient than bulk niobium at 2 K

# Choice of Cavity $Q_0$

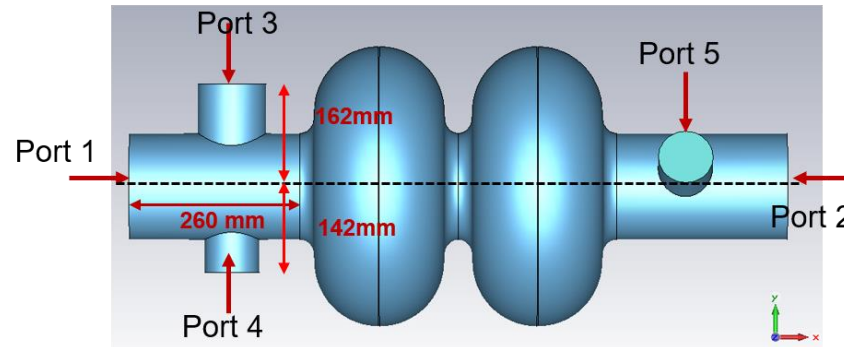
- Nitrogen-doping allows large  $Q$  margin from cavity acceptance test to long-term operation ( $Q$  degradation in dirty environment)
- Nitrogen doping not so effective at low frequency (650 MHz)



# RF Design of 650 MHz 2-cell Cavity



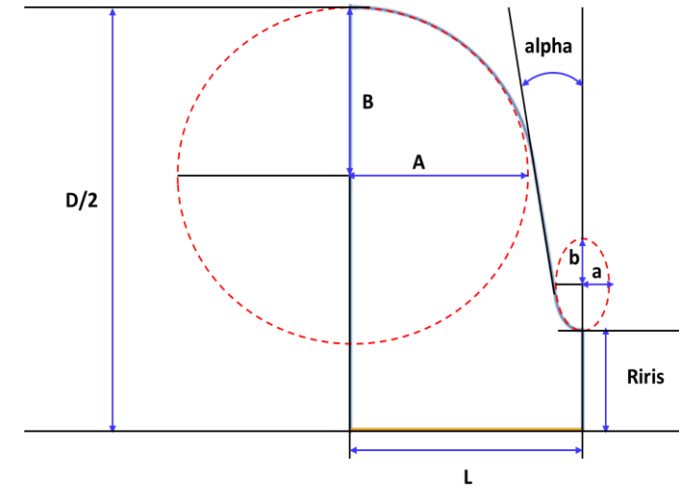
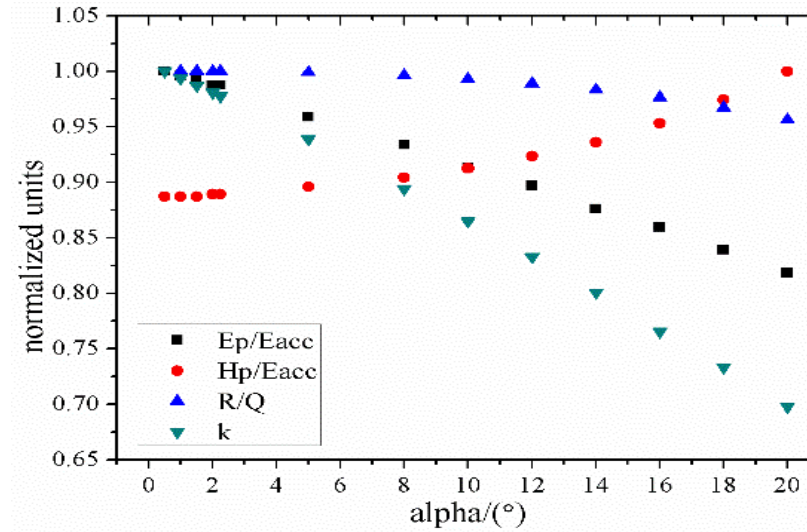
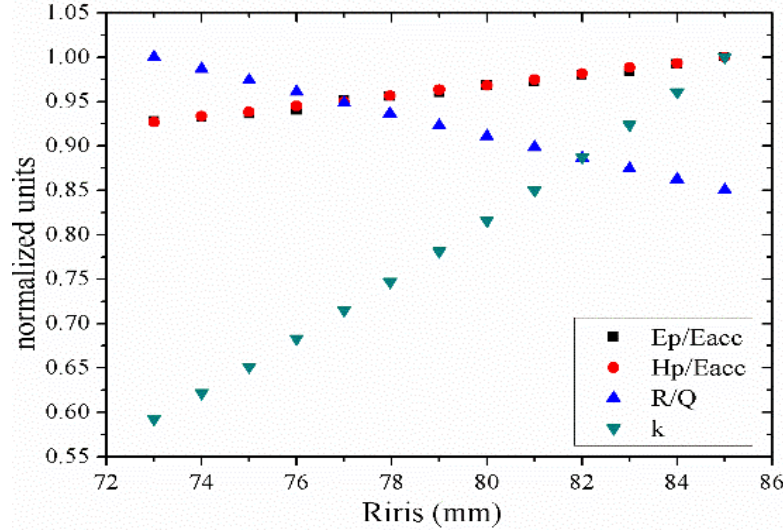
Parameter	Unit	Value
Cavity frequency	MHz	650
Number of cells	-	2
Cavity effective length	m	0.46
Cavity iris diameter	mm	156
Beam tube diameter	mm	156
Cell-to-cell coupling	-	3%
R/Q	$\Omega$	213
Geometry factor	$\Omega$	284
$E_{\text{peak}}/E_{\text{acc}}$	-	2.4
$B_{\text{peak}}/E_{\text{acc}}$	mT/(MV/m)	4.2



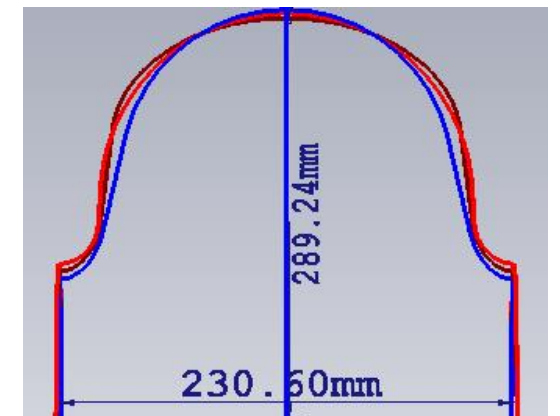
	P (W) (U = 1J)	Qe
Port 1	0.001867	2.19E12
Port 2	0.001352	3.02E12
Port 3	0.005441	7.51E11
Port 4	0.003435	1.19E12
Port 5	0.003320	1.23E12

- The length of the cavity beam pipes and ports should be long enough to ensure negligible power dissipation on the gaskets and flanges surface, but cannot be too long to go beyond the critical temperature of Nb.
- Special gapless gaskets will be considered to avoid the additional dissipation at different joints.
- Cooling of cavity ports by extended helium vessel could be considered especially for the power coupler.
- Copper plating is necessary for the bellows between cavities. RF shielded bellow might be needed.

# Cell Optimization



	$f$	$B/A$	$b/a$	$Riris$	$D$	$L$	$\alpha$	$Ep/Eacc$	$Hp/Eacc$ (mT/(MV/m))	$R/Q$	$G$	$k$ (%)
CEPC	650	1	1.1	78	204.95	115.3	3.2	2.38	4.17	105.5	284	3.05
TESLA	650	1	1.58	70	206.6	115.3	13.2	2	4.16	113.7	271.1	1.89
FCC- eeH	650	0.7	1.42	74	202.43	115.3	7.5	2.2	4.07	110.6	278.5	2.54

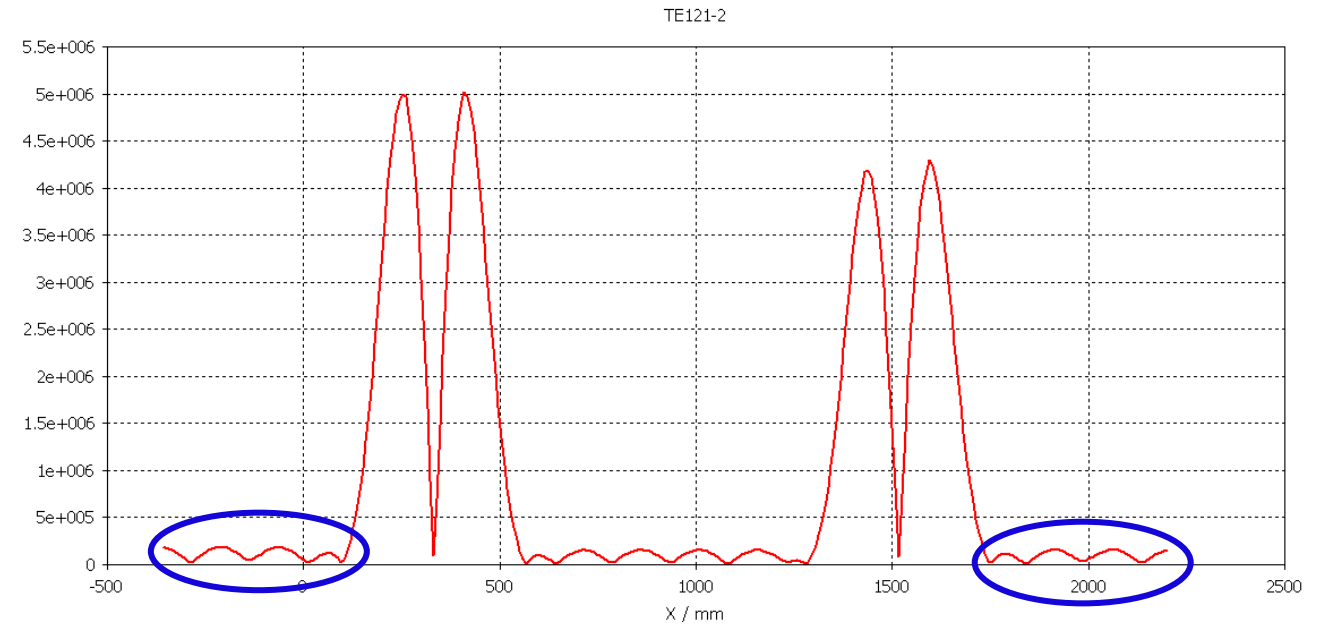
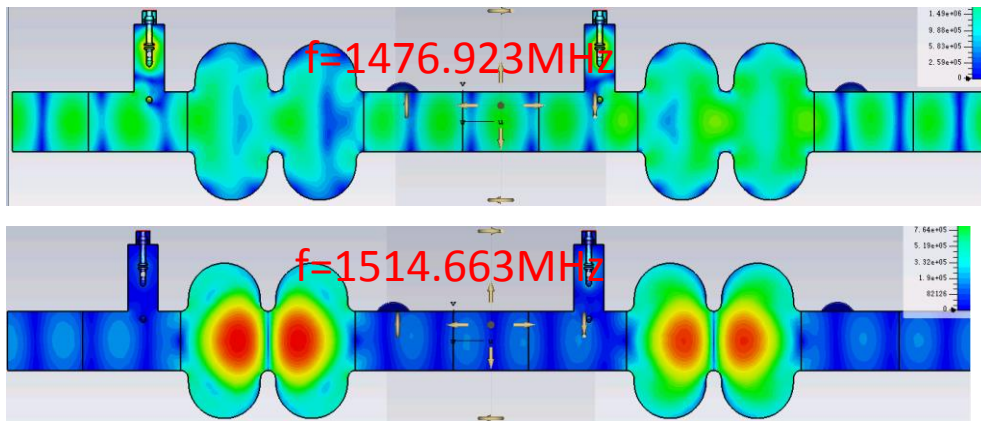
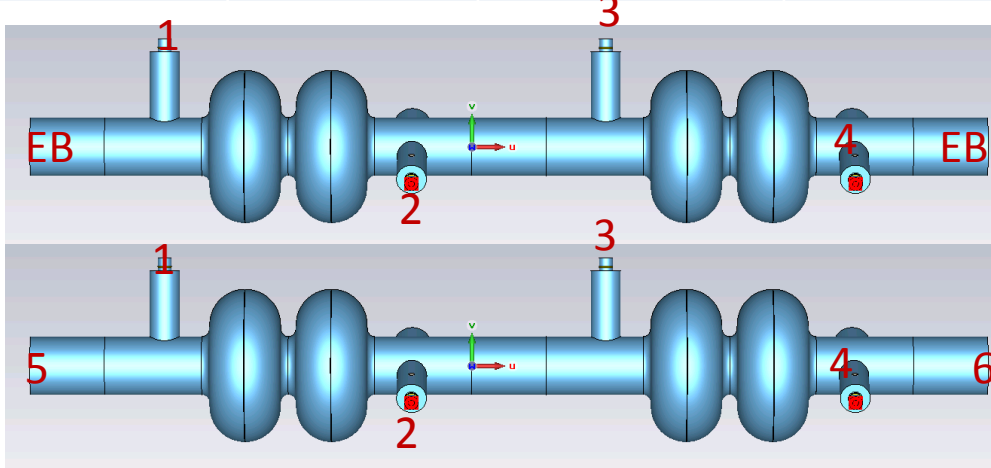


\* All geometrical parameters are scaled to 650 MHz

Red: CEPC, Blue: TESLA, Brown: FCC-eeH

# TE121

f (MHz)	R/Q ( $\Omega/\text{m}$ )	Qe (4 ports)	Qe (6 ports)
1476.923	126	5441	19
1514.663	13	3.75e+6	2E+4

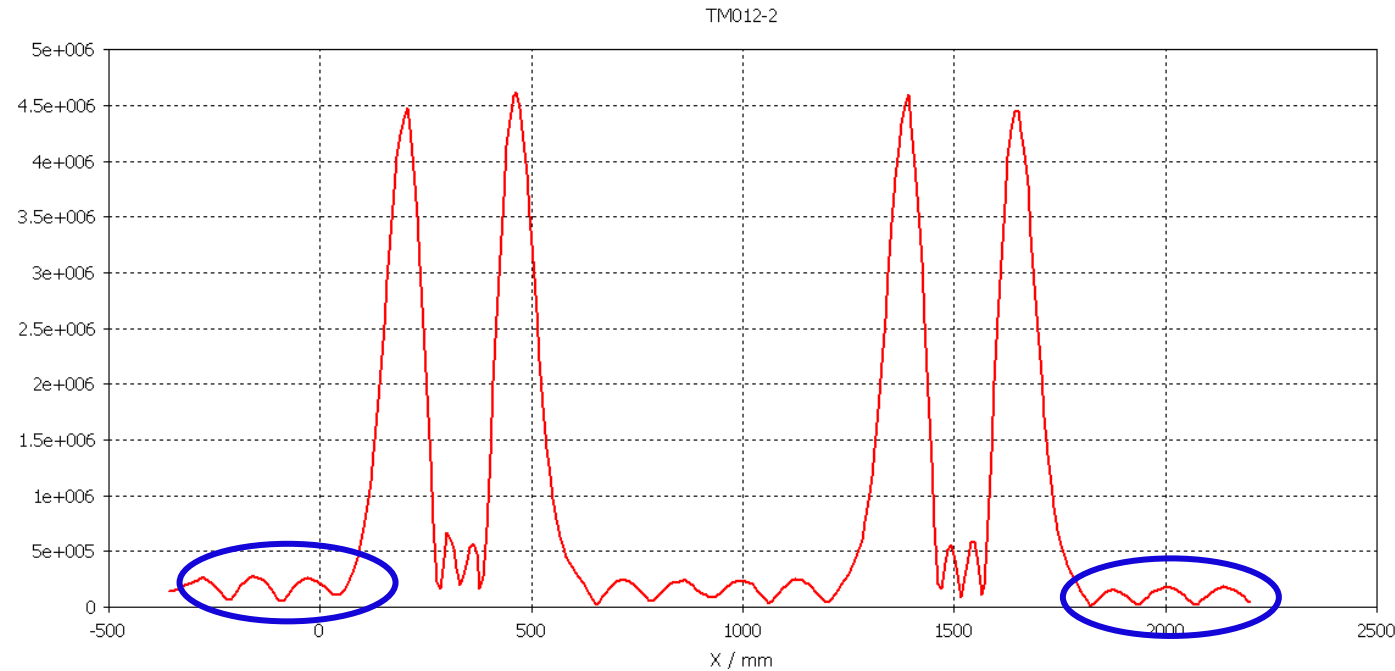
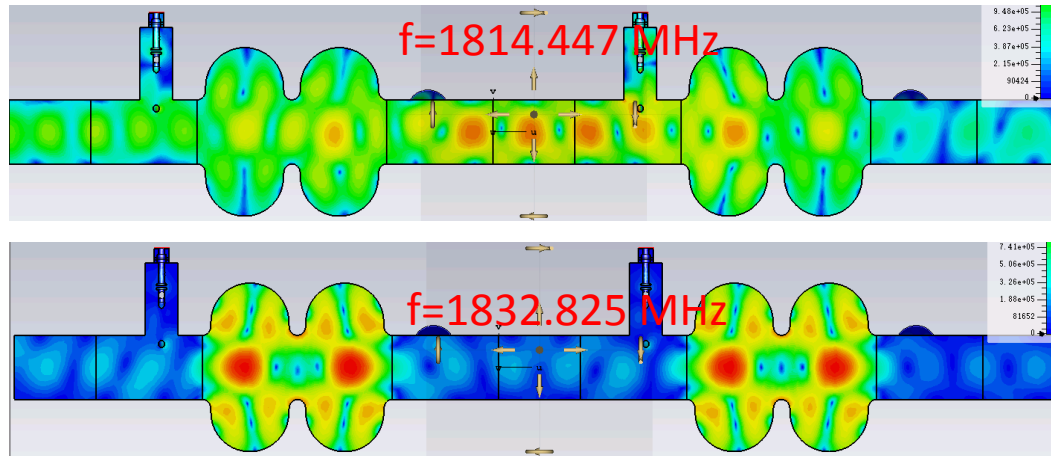


- For TE121-2 mode, only a small amount of HOM power come out from HOM coupler.
- A large amount of stored energy concentrate in the middle cell. The field values in the beam pipe is low. **Even so it can meet the CBI requirement.**



# TM012

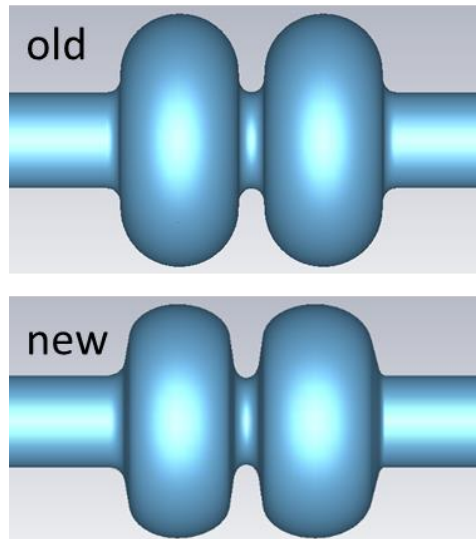
f (MHz)	R/Q ( $\Omega$ )	Qe (4 ports)	Qe (6 ports)
1814.447	0.07	3.07e+4	1095
1832.825	17	2.14e+7	2.8E+4



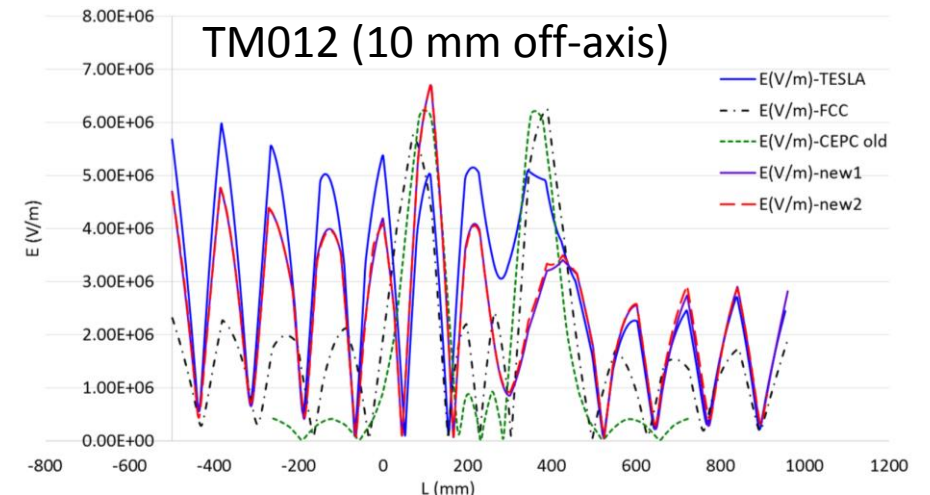
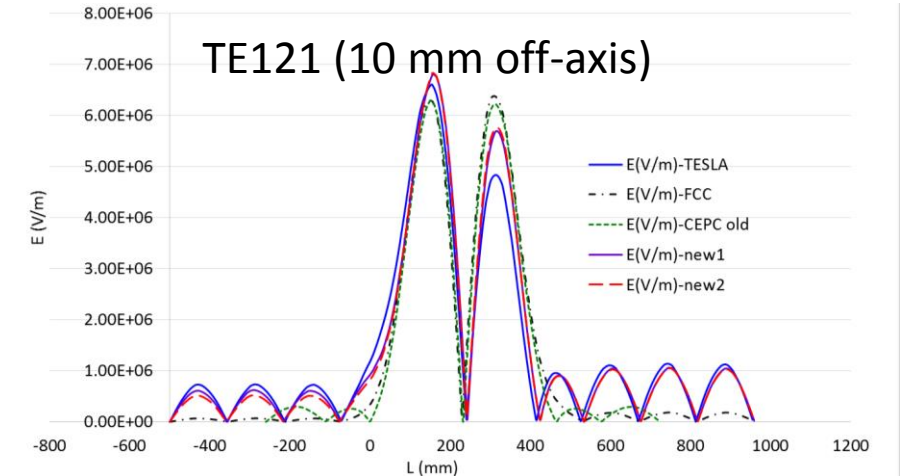
- For TM012-2 mode, a large amount of stored energy concentrate in the middle cells.
- Both end cells are distorted by the presence of the beam pipe on either end of the cavity.
- **Tuning the end cells** for the "trapped modes" is one way to improve the field profile.
- Compared with the symmetric end cell design, an asymmetric end cell design is better.
- Modify the curve from equator to iris, the iris ellipsis to untrap the TE121 and TM012 mode, but still have the TM010 flat.
- **Even so it can meet the CBI requirement.**

# New Cavity Design with Asymmetry End Cell

- To untrap TE121 and TM012 mode, as well as TM011
- Larger wall angle for mechanical stability and cleaning



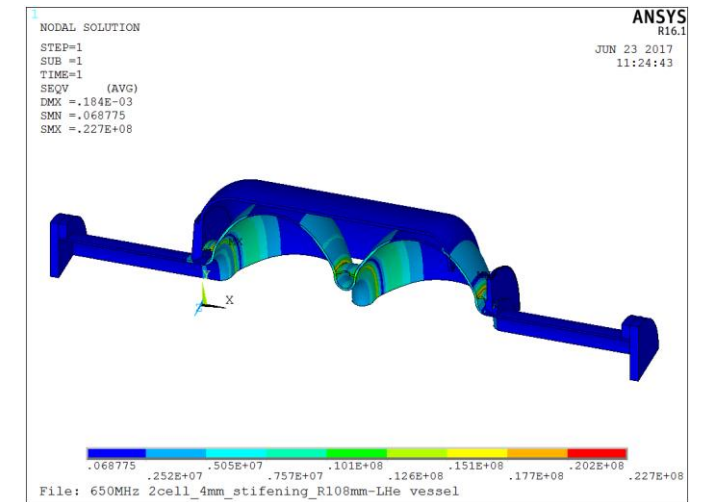
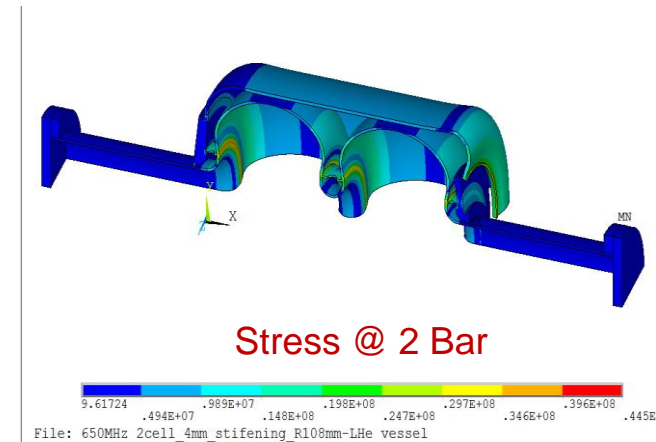
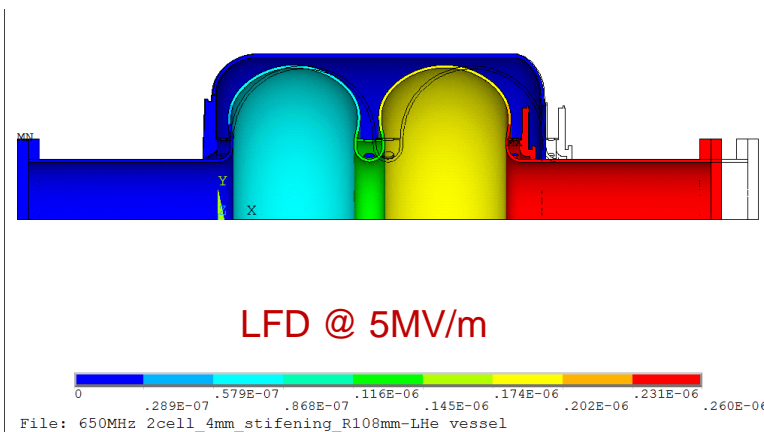
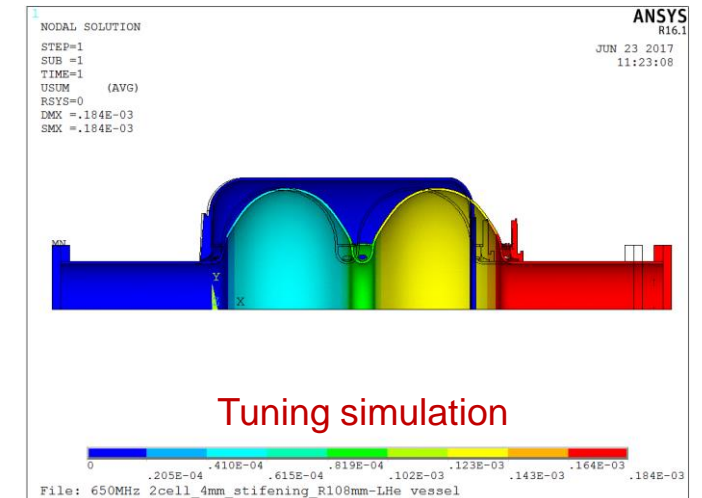
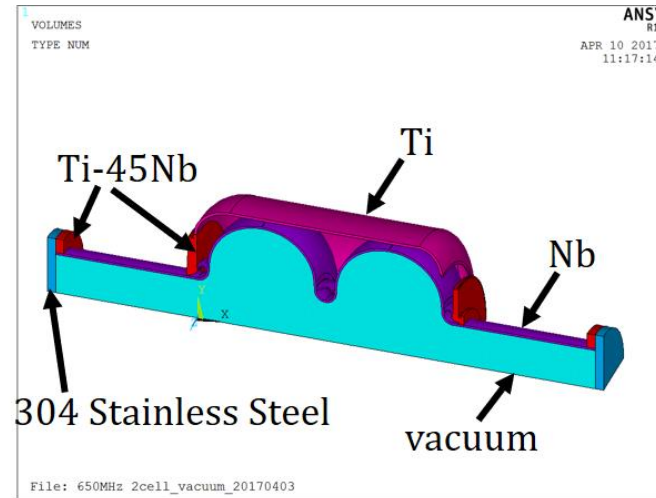
Parameters	mid cell	end1	end2
Riris (mm)	75	80	80
Alpha (deg)	8	9.56	14.12
A (mm)	88	81	95
B (mm)	60	60	73
a (mm)	20.97	25.85	10.92
b (mm)	28	26	27
L (mm)	115.3	114	115.3
D (mm) -dia.	405.13	405.13	405.3
K (%)	2.65		
R/Q ( $\Omega$ )	212.8		
G ( $\Omega$ )	281		
$E_p/E_{acc}$	2.27		
$B_p/E_{acc}$	4.21		



# Cavity Mechanical Analysis

Without tuner and bellow

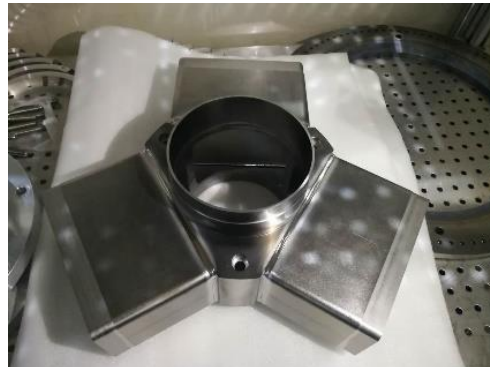
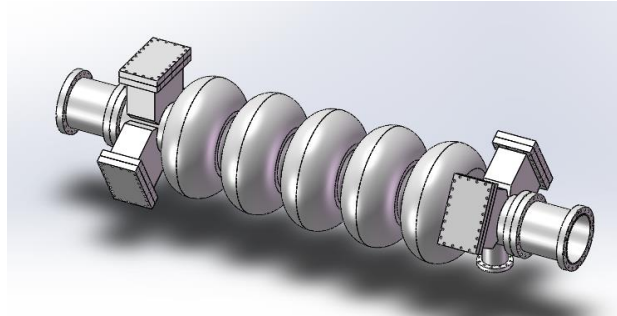
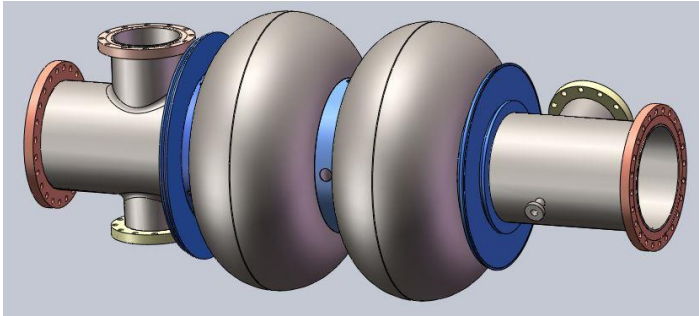
- $df/dp$ 
  - -68.7 Hz/mbar
  - The stress under 2 bar (44.5 MPa)
- Tuning
  - Tuning sensitivity: 310 kHz/mm
  - Stiffness: 16001 N/mm
- LFD
  - LFD coefficient= - 4.16 Hz/(MV/m)<sup>2</sup>





# Cavity Fabrication

Three 2-cell cavities with coaxial HOM coupler, one 5-cell cavity with waveguide HOM coupler.



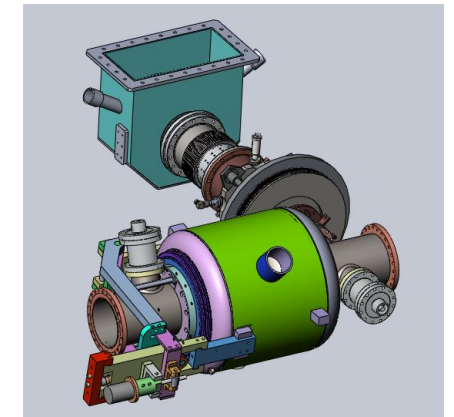
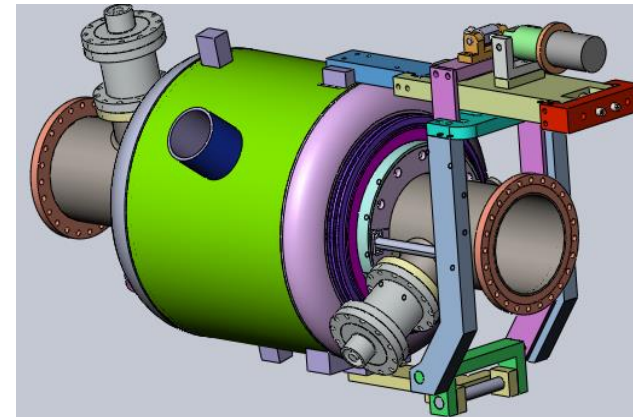
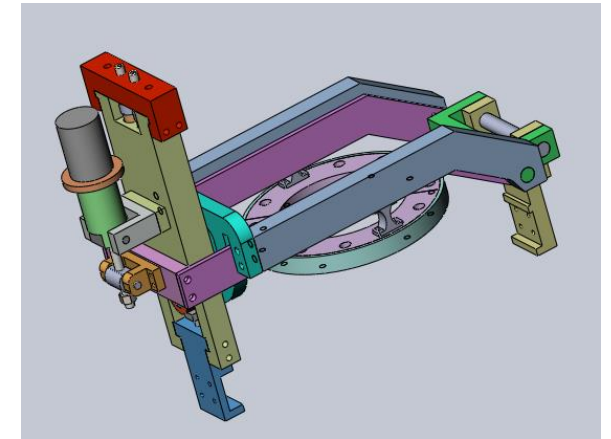
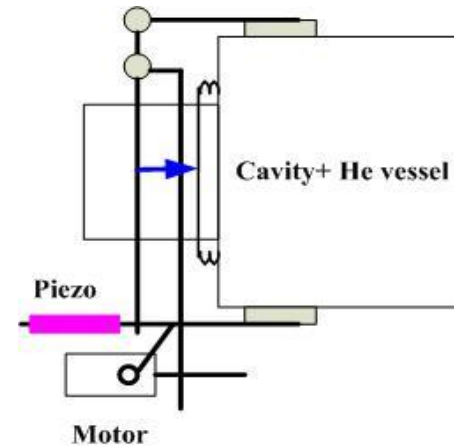
## Cavity with more cells (4 or 5-cell)

- **A must for higher energy operation**, and low HOM power (due to low current)
- **Possible for H with shared cavity** if the input coupler power capacity could be increased to 500 ~ 800 kW or use two couplers per cavity for same gradient. If same coupler power, the gradient will be too low and cost more, beam loading effect ... But 1.5 times more HOM power, HOM damping and trapping, cavity pretuning, handling and infrastructure...
- **Not suitable for high current W and Z**

# Helium Vessel and Tuner

Parameters	Unit	Value
Cavity tuning sensitivity	kHz / mm	310
Cavity spring constant	kN / mm	16
Coarse (slow) tuner frequency range	kHz	340
Coarse tuner frequency resolution	Hz	< 20
Fine (fast) tuner frequency range	kHz	> 1.5
Fine tuner frequency resolution	Hz	3
Motor and piezo temperature	K	5~10
Motor number		1
Piezo number		2
Operating pressure	Torr	< 5E-5
Operating lifetime	year	20

- Must have high reliability, access port on the cryomodule
- Installed at the end of cavity, piezo always compressed
- The installation space is limited by HOM coupler



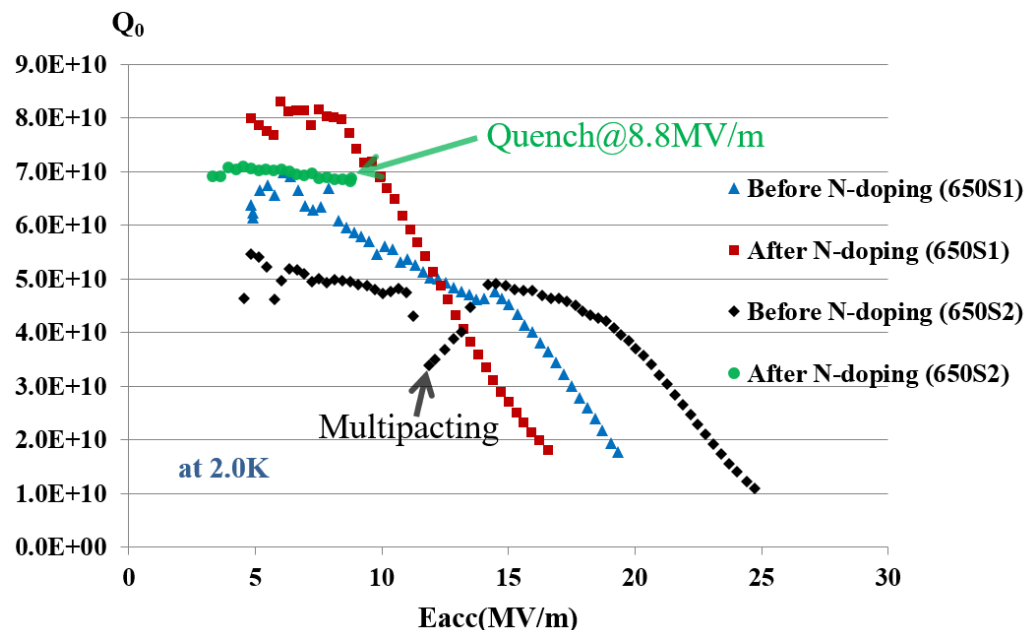
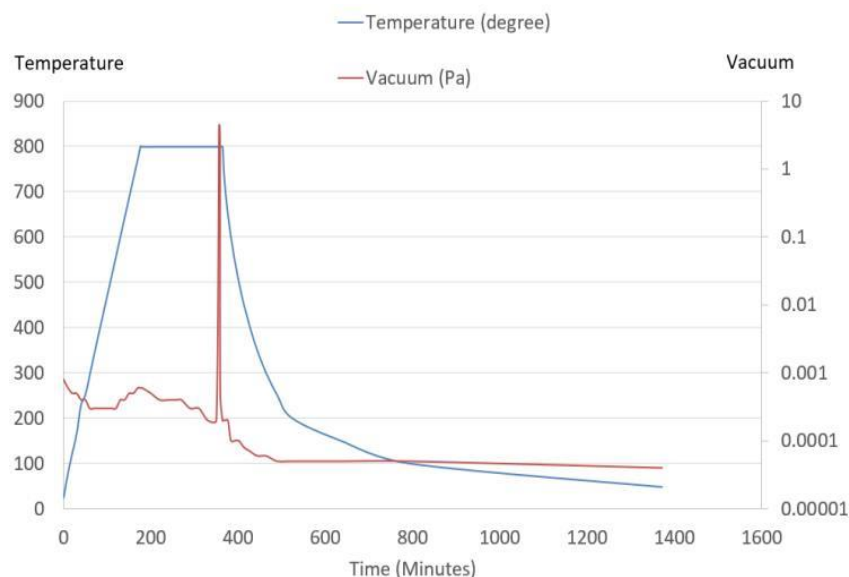
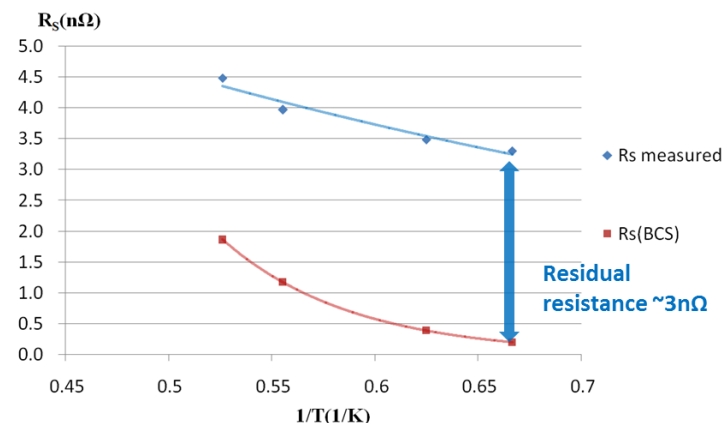
# N-doped 650 MHz Single-cell Cavity

After N-doping of two 650 MHz single cell cavities (BCP treated),  $Q_0$  increased obviously at low field for both cavities.

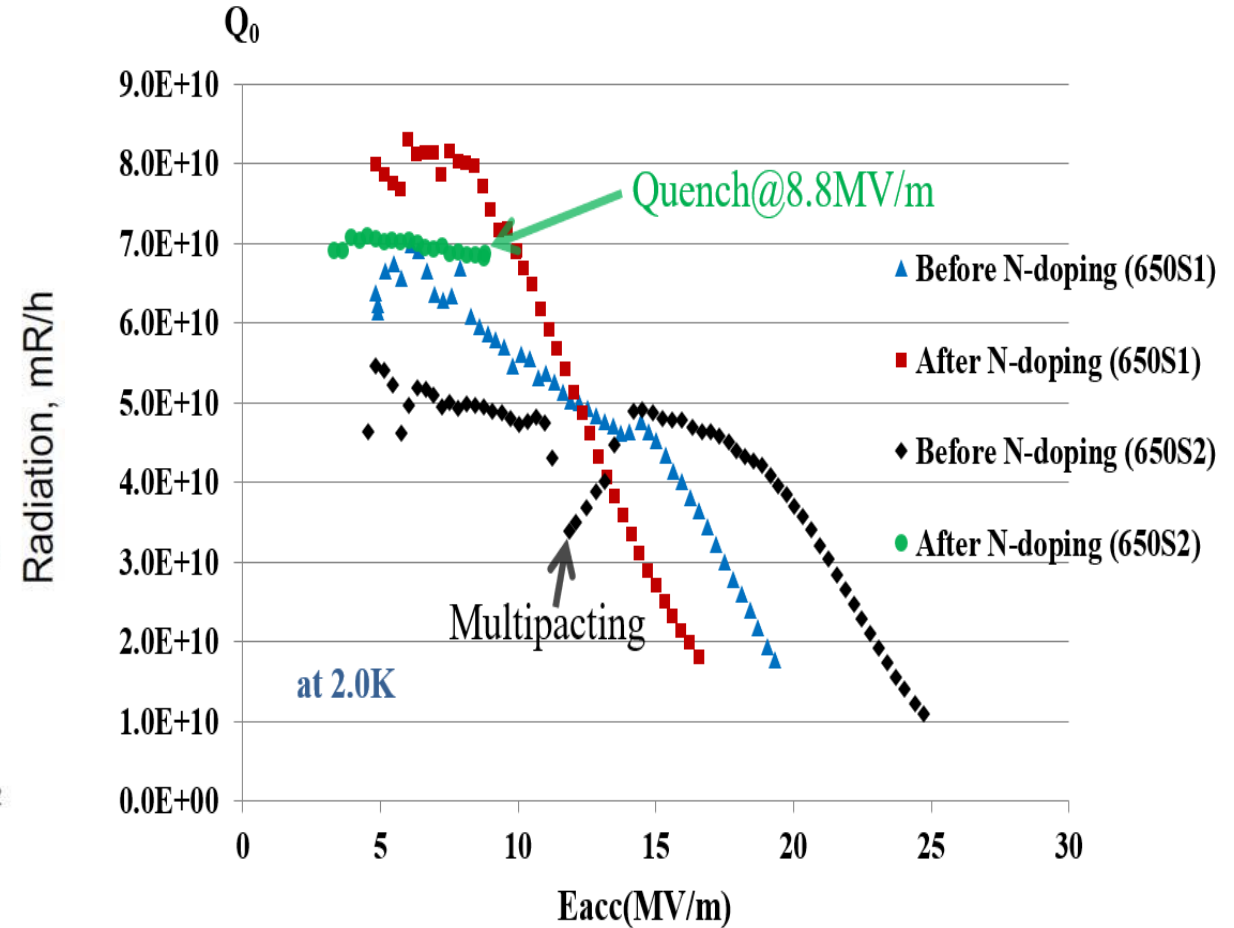
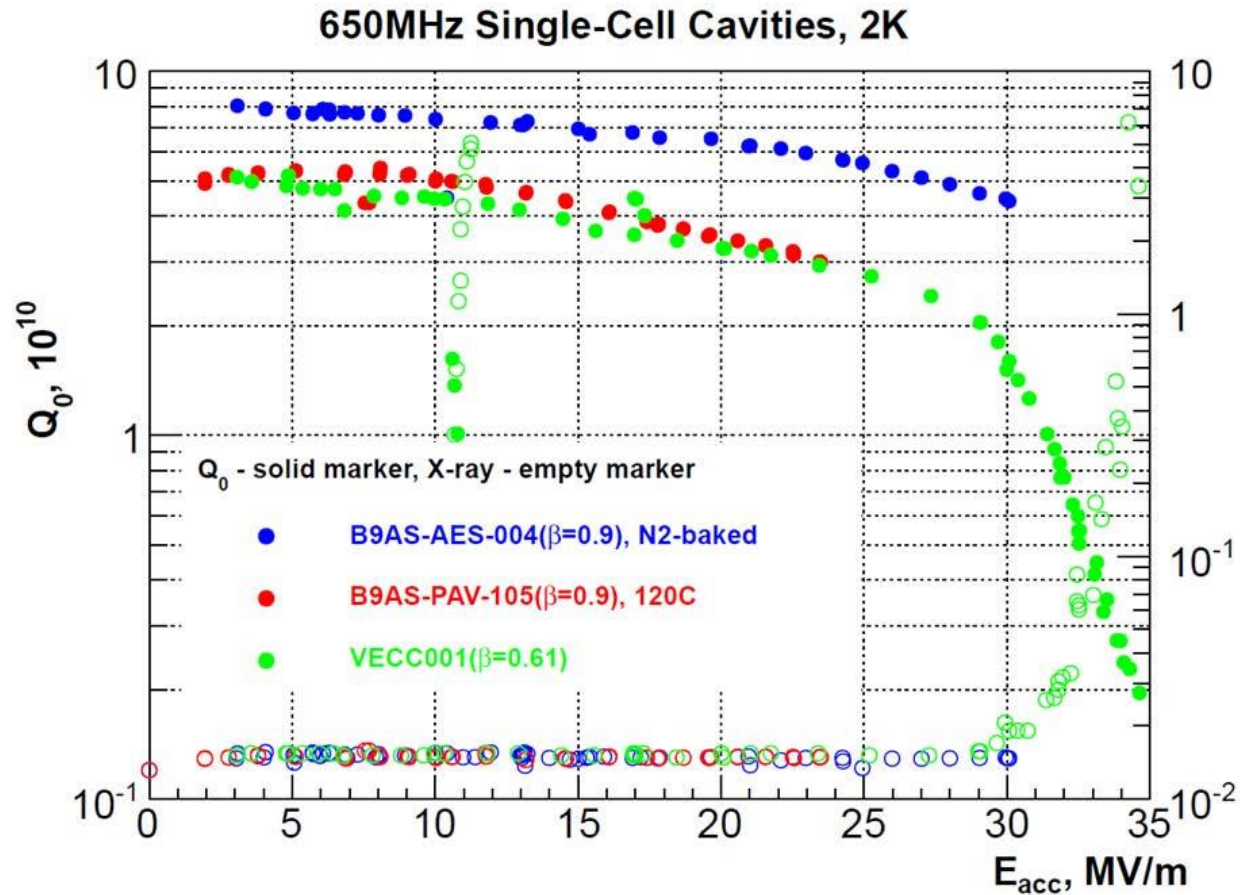
- 650S1:  $Q_0=7e10$  @  $E_{acc}=10$  MV/m. But  $Q_0$  decreased quickly at high field ( $>10$  MV/m).
- 650S2: Quench at  $Q_0=6.9e10$  @  $E_{acc}=8.8$  MV/m.

Flux gate and Helmholtz coil will be added soon for demagnetization.

EP facility will be ready to use in mid 2018.



# N-doped 650 MHz Single Cell Cavity



FNAL PIP-II

A. Rowe. LINAC2016



# Furnaces for N-doping/infusion and Nb<sub>3</sub>Sn

## 1) Old Furnace at IHEP

- Diffusion pump, not oil free
- N-doping failed
- not suitable for high Q



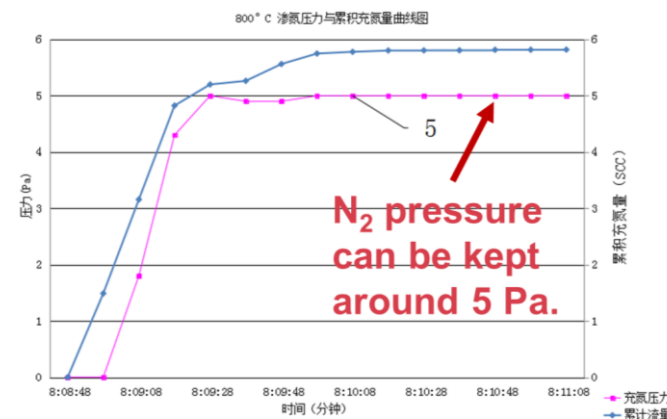
## 2) Furnace at OTIC

- Cryo-pump
- Successful N-doping
- Tantalum heater (not molybdenum). N-infusion not allowed



## 3) New Furnace at PAPS

- Ordered and will deliver in mid 2018
- for N-doping & N-infusion
- Maximum operation temperature: 1200 °C
- Effective heating zone: Φ 600 mm x 1500 mm
- Vacuum pressure at 900 °C: < 1e-4 Pa
- Oil-free pump system with two cryo-pumps (CTI OB400)
- N<sub>2</sub> injected with feedback controller

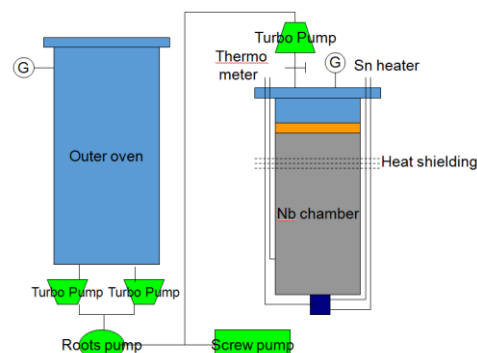


## 4) New Small Furnace at IHEP (just delivered)

- For N-doping and infusion of Nb sample and 1.3 GHz single-cell cavity
- Φ300 mm × 500 mm
- Outside heating
- Cryopump 2500 L/s for H<sub>2</sub>
- MFC vent controlling
- Ultimate vacuum
- 25 °C : 6E-7Pa, 850 °C : 2.4E-5Pa

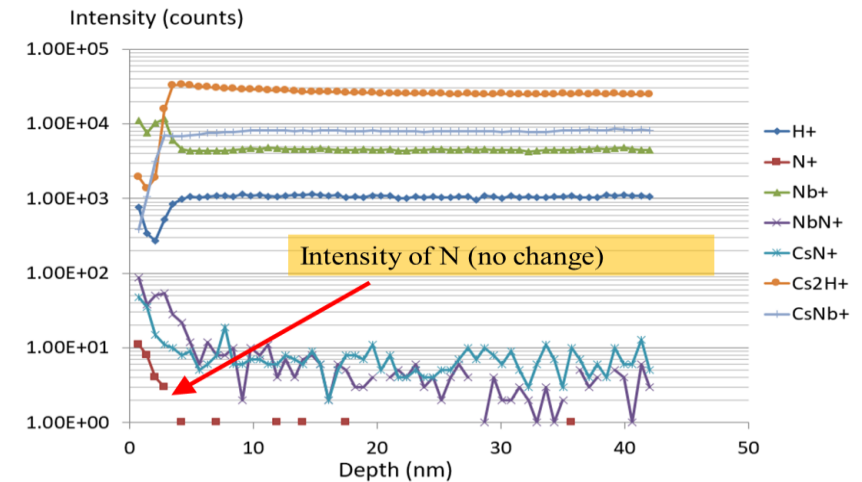
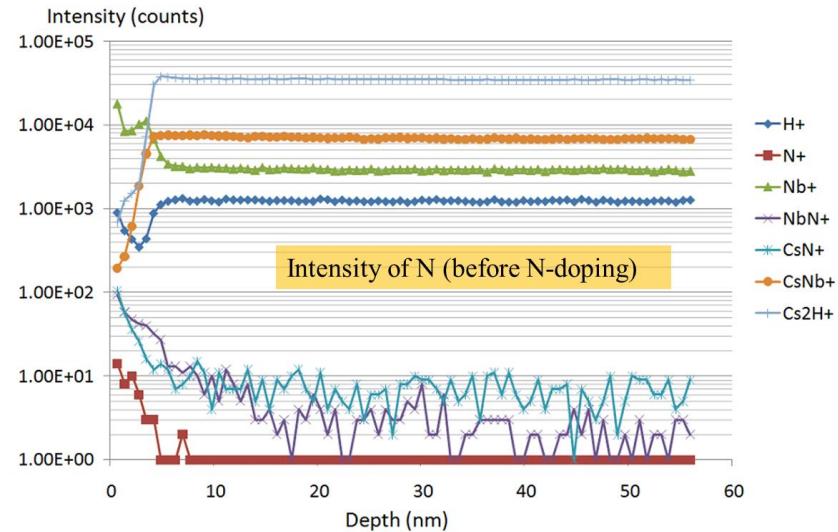


## 5) Nb<sub>3</sub>Sn Furnace at PAPS

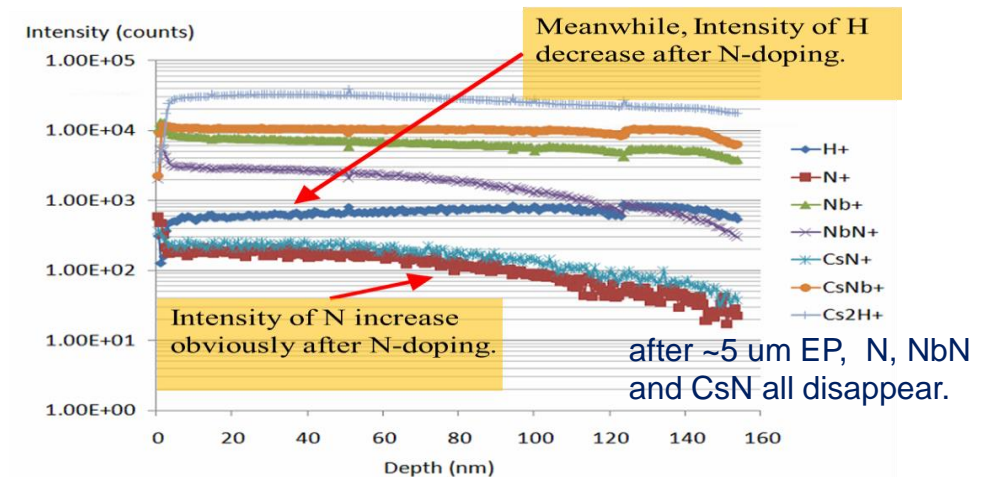
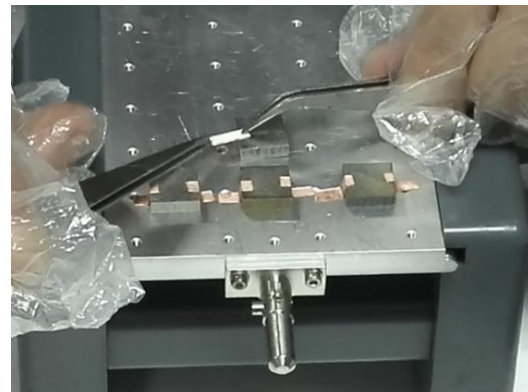


# SIMS Results of N-doping Samples

## Doping with Furnace at IHEP

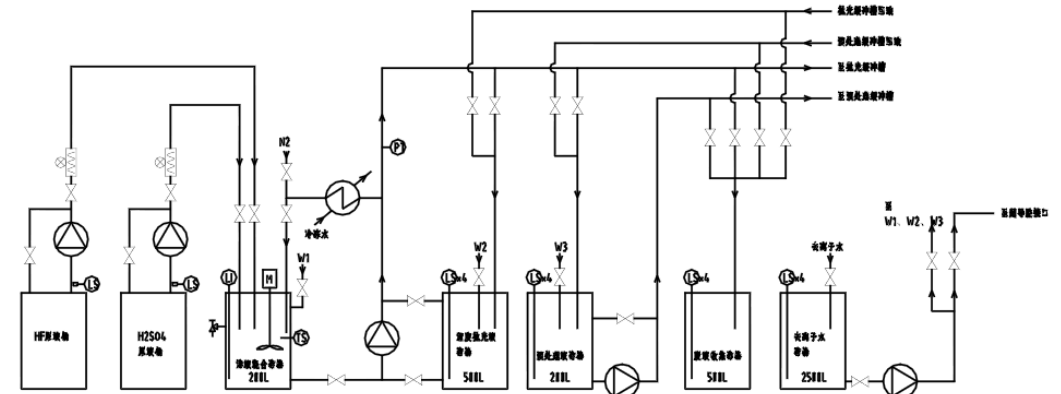
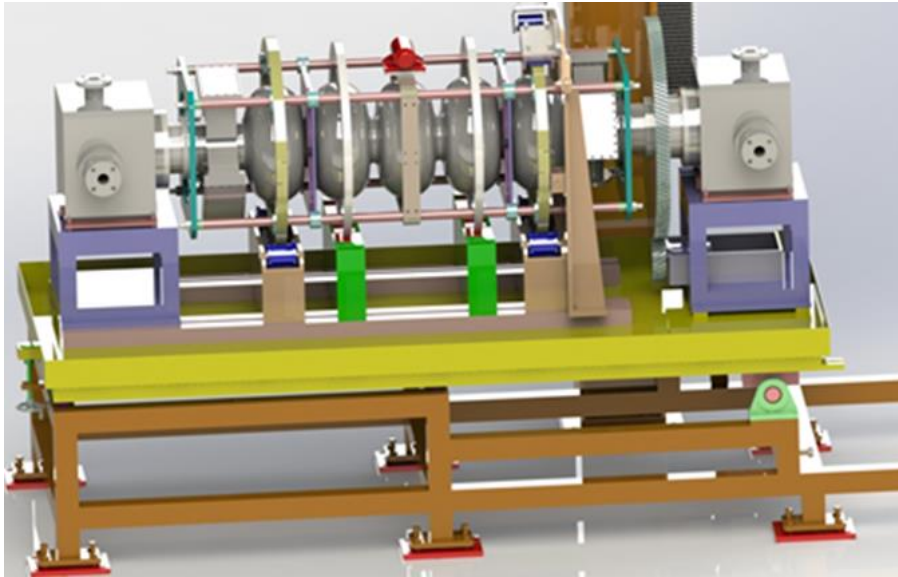


## Doping with Furnace at OTIC

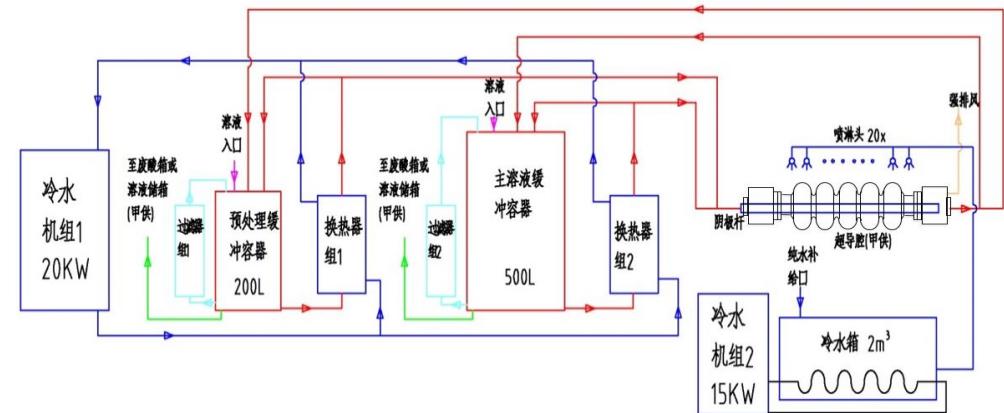


# IHEP EP Facility

- In construction, located at OTIC Ningxia
- Commission in mid 2018
- In collaboration with KEK



Flow chart of acid mixing and storage unit



Flow chart of circulation unit

# Iron-based Superconductor Research for SRF Cavity

- High Tc Superconductivity Collaboration of China
- Find the suitable iron-based superconducting material for SRF cavity
- Set up a surface resistance test system
- Optimize the growth condition and successfully grow high-quality iron-based thin films
- Try to get a cavity coated by the iron-based thin film

## Path to 70-120-200 MV/m

### Maximum screening field $H_m$ at optimal thickness

#### Dirty Nb layer on Nb:

$H_c = 200$  mT,  $H_s = 170$  mT,  $l = 2$  nm, and  $\lambda = \lambda(\xi_0/l)^{1/2} = 180$  nm

$H_m = 288$  mT,  $E_{acc} = 70$  MV/m,  $d_m = 0.44\lambda = 79$  nm.  
20% gain as compared to  $H_s = 240$  mT of clean Nb

#### Nb<sub>3</sub>Sn on Nb: $H_s = 0.84H_c = 454$ mT and $\lambda = 120$ nm (moderately dirty):

$H_m = 507$  mT,  $E_{acc} = 120$  MV/m,  $d_m = 1.1\lambda = 132$  nm  
doubles the superheating field of clean Nb

#### Fe-pnictides on Nb: $H_s = 0.84H_c = 840$ mT and $\lambda = 200$ nm:

$H_m = 872$  mT,  $E_{acc} = 206$  MV/m,  $d_m = 1.78\lambda = 356$  nm  
quadruples the superheating field of clean Nb

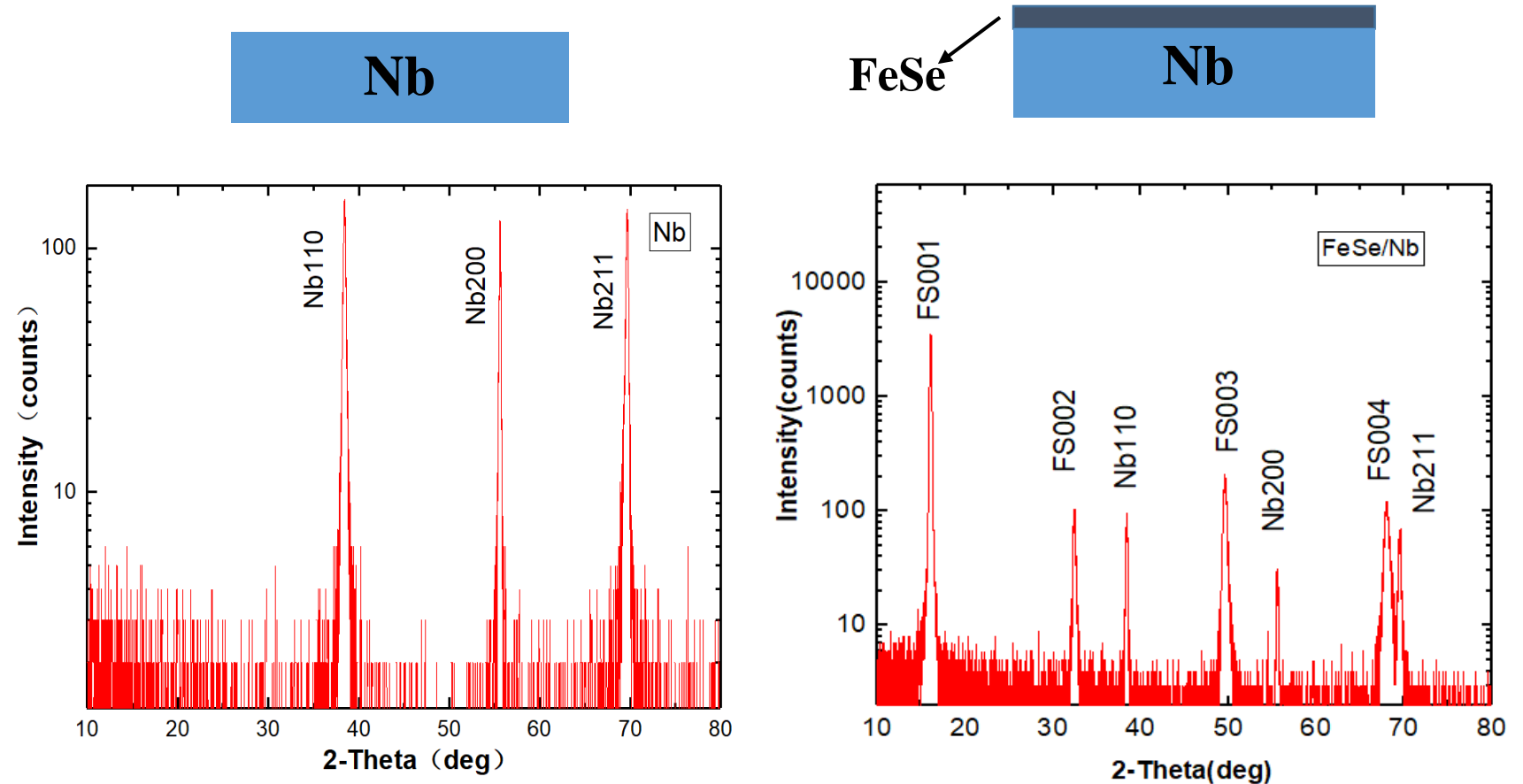
A. Gurevich, GARD-RF Research Roadmap Workshop, Washington DC, March 8-9, 2017



# Fabrication of FeSe thin films on Nb substrates by PLD

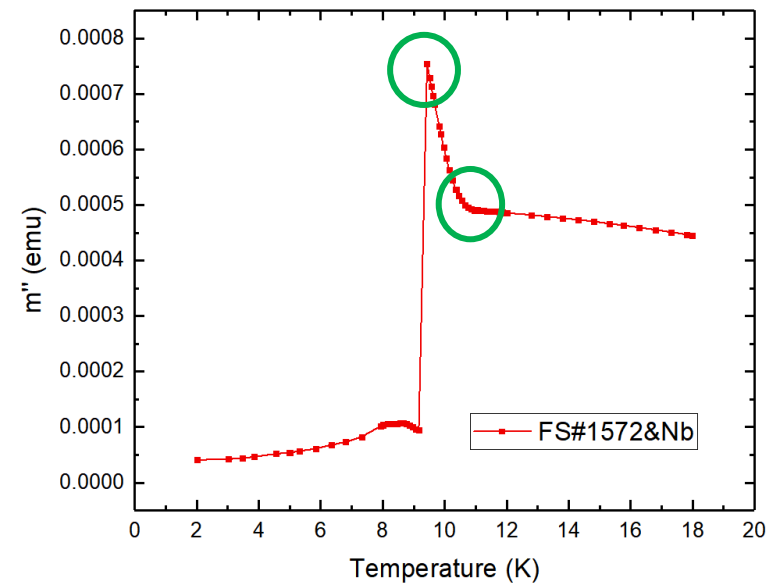
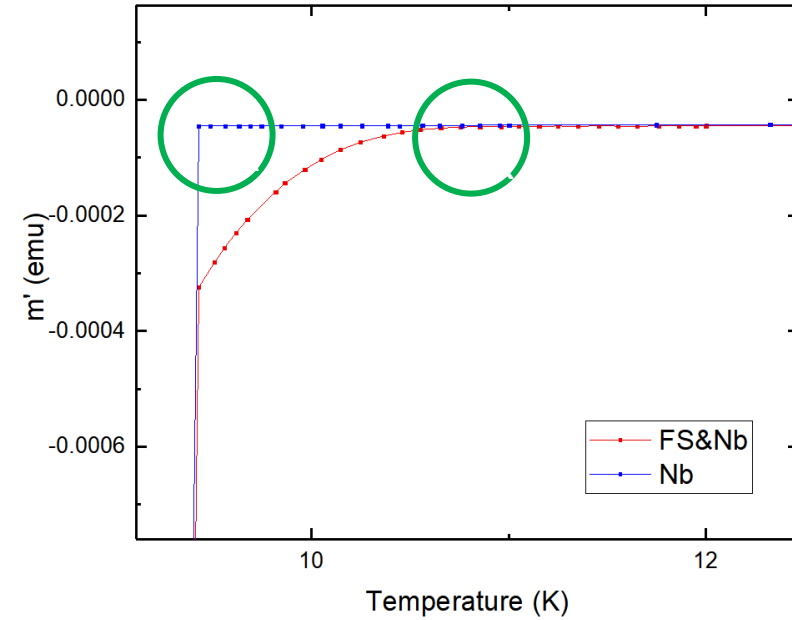
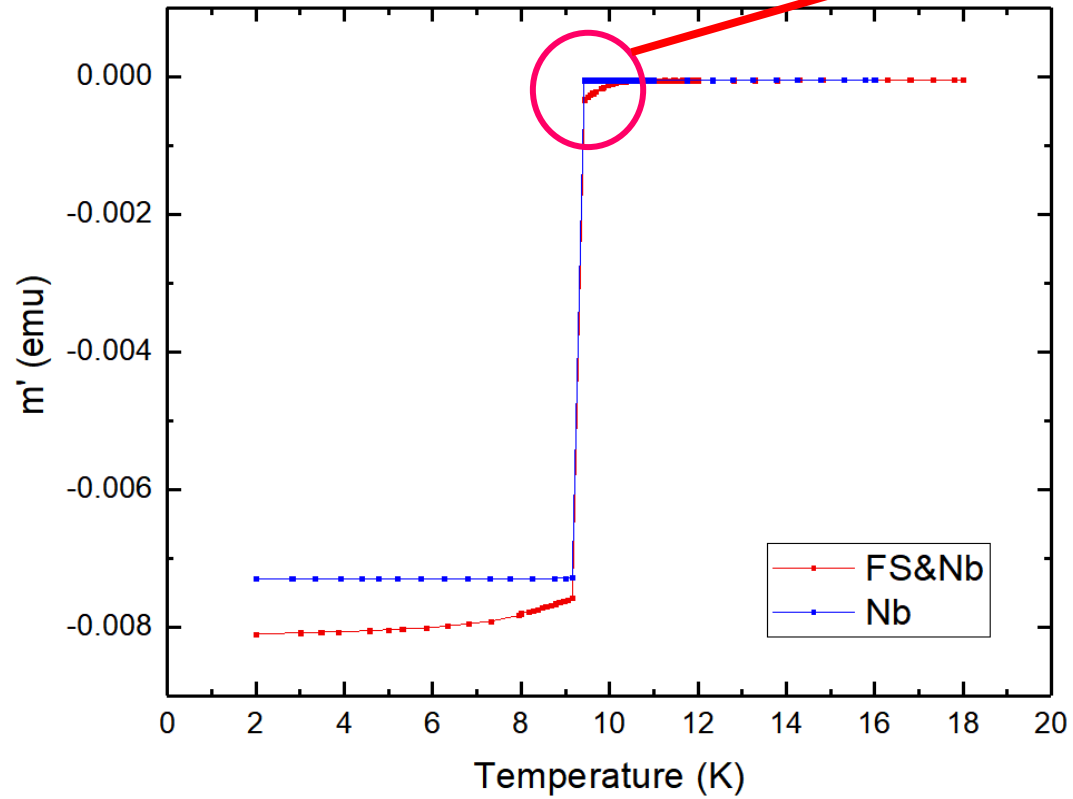


Photo of  
PLD



In collaboration with Institute of Physics, CAS

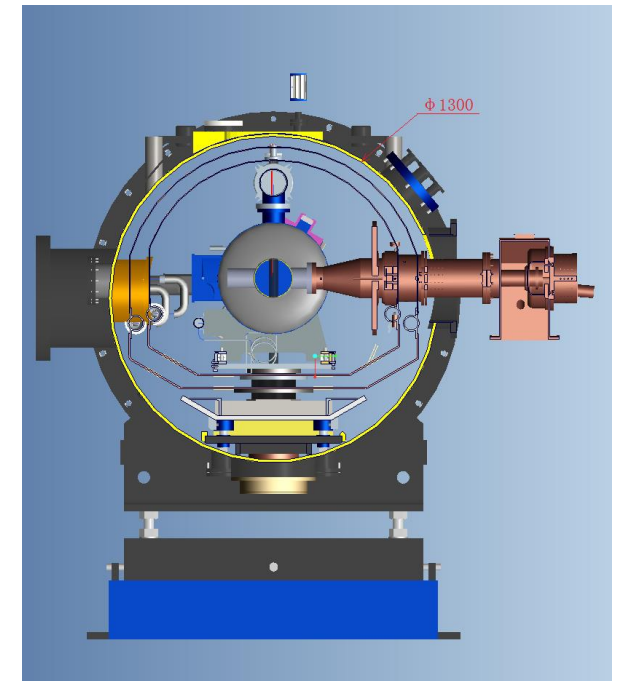
# Magnetic Property Measurement



# CEPC Input Coupler Challenges

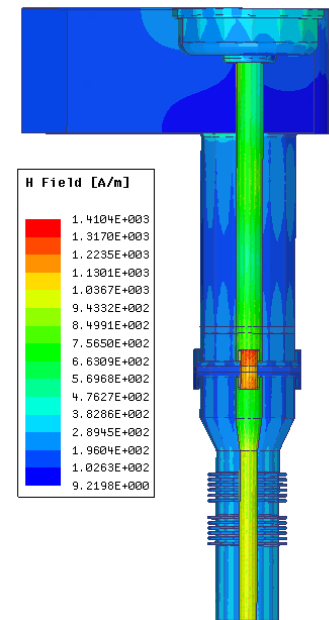
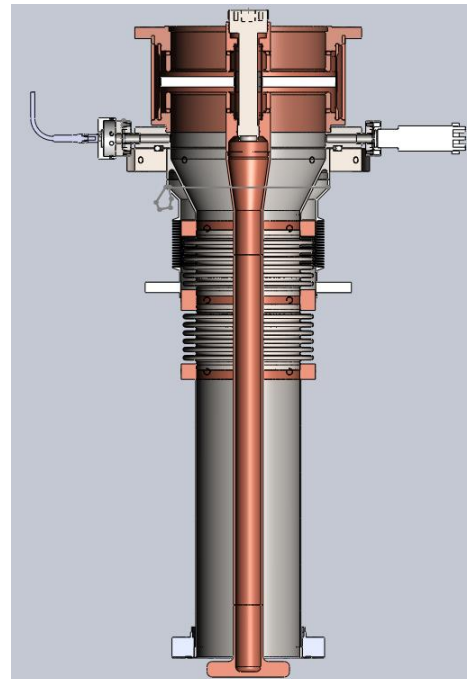
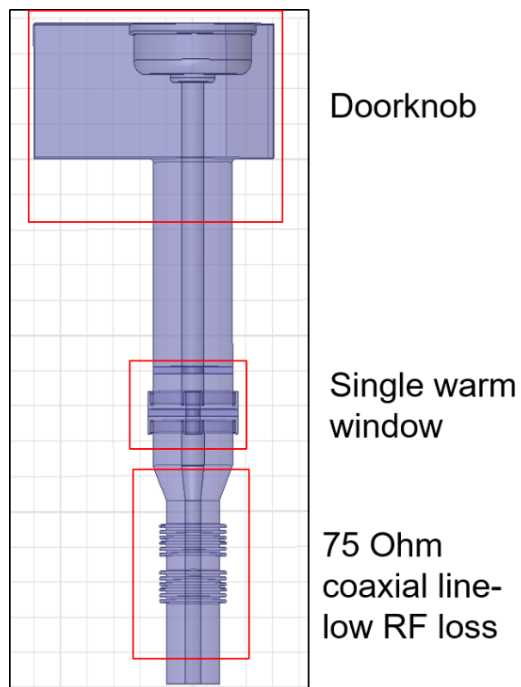
- **High power handling** capability: CW, 300 kW ( > 400 kW, update).
- **Wide-range variable** coupler with **low heat load** to save power.
- Clean assembled with cavity in class 10 clean room
- Balance **coupler vacuum part length** (cryomodule diameter size) and heat load.

Frequency (GHz)	0.65
Power (kW)	300
Coupling (Qext)	Variable: 1E5~2E6
Heat load spec (dynamic 300 kW, TW, CW)	Dynamic: 1 W / 6 W / 10 W @ 2 K / 5 K / 80 K Static: 0.3 W / 3 W / 6 W @ 2 K / 5 K / 80 K



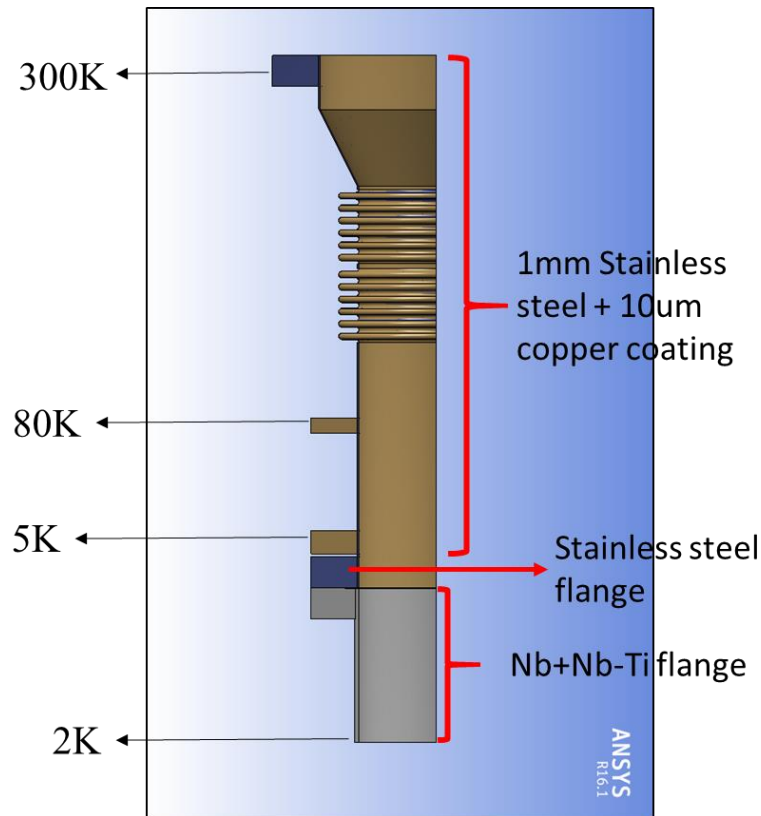
# CEPC Variable 650 MHz Input Coupler Design

- RF design complete, thermal and mechanical design ongoing.
- Thermal anchor or helium gas cooling of outer conductor. Water or gas cool of inner conductor.
- Start fabrication in end 2017.

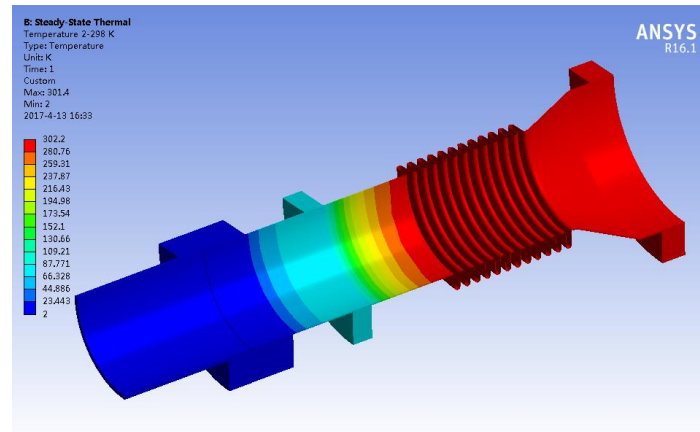


Component	Power loss at 300 kW, CW, TW (W)
Ceramic	113
Inner window	70.4
Outer window	15.8
Inner coaxial of vacuum part	103.4
Outer coaxial of vacuum part (Bellow)	50 (29.2)
Inner coaxial of air part	102.6
Outer coaxial of air part	23.1
Doorknob	77.0
Total	555

# Input Coupler Heat Load



The heat load calculation model



Component	Power dissipation
Stainless steel of gap	2.28 W
Al-Mg alloy sealing gasket	0.02 W
SS outer conductor of FPC	48.4 W

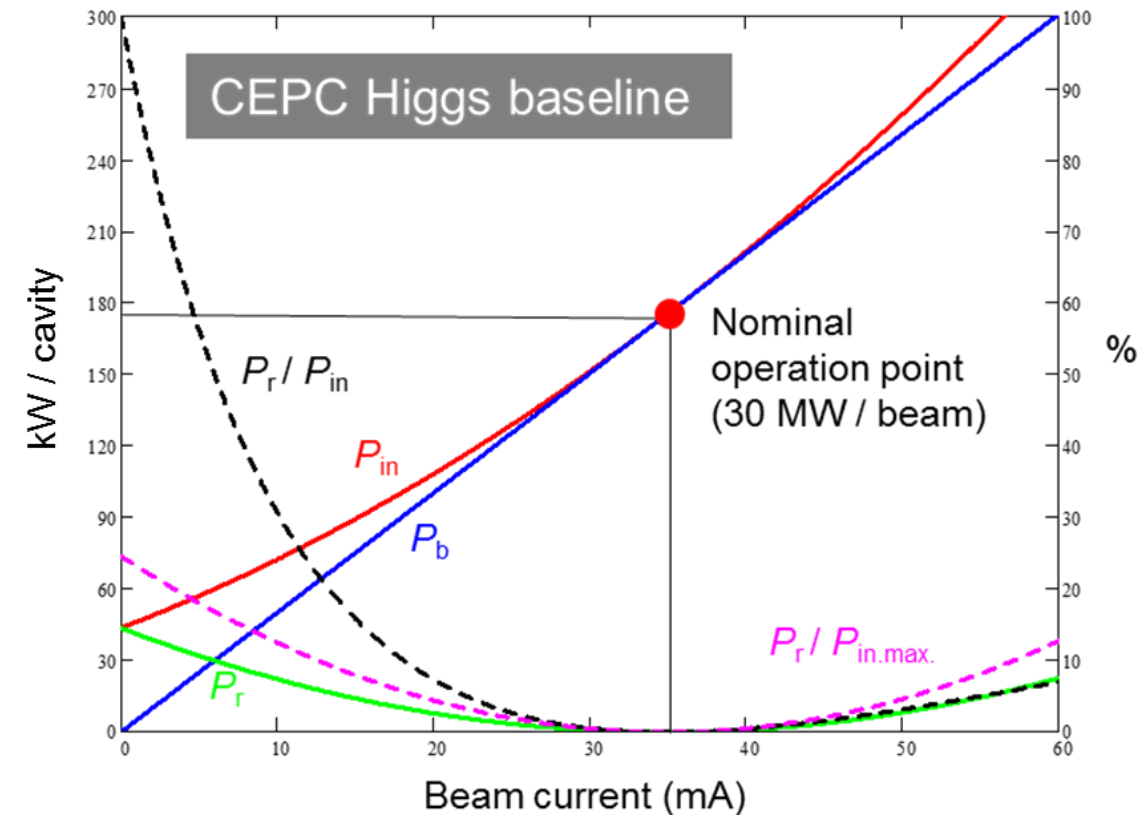
	No gap	With gap
2 K heat load	-0.99 W	-2.74 W
5 K heat load	-8.17 W	-8.94 W
80 K heat load	-30.68 W	-30.32 W
300 K heat load	-8.09 W	-0.16W

- Water cooling of the outer bellow is a must.
- RF shielding of the **gap between the coupler and cavity** connecting flange is very important, since which made great contributions to the 2K heat load.
- Try helium gas cooling for next step

# Variable Coupling and Power Saving

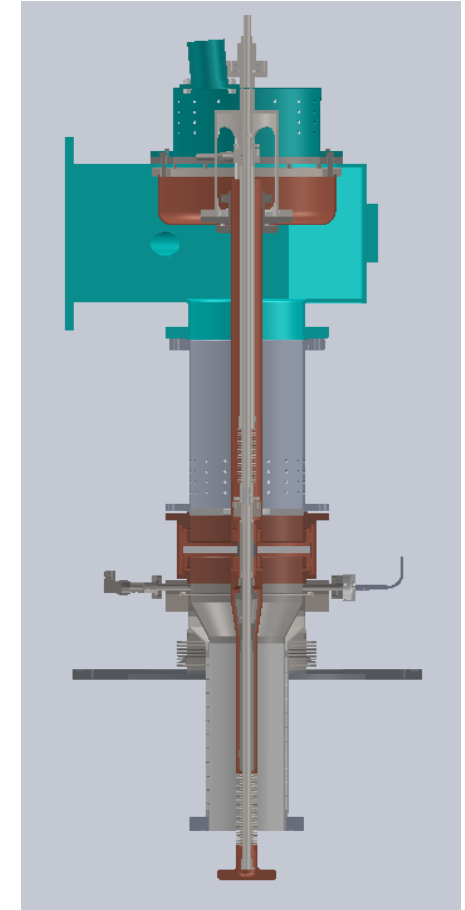
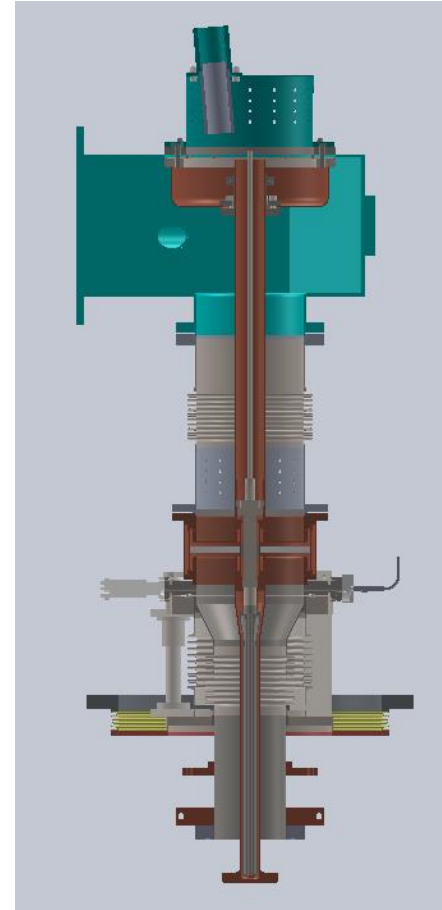
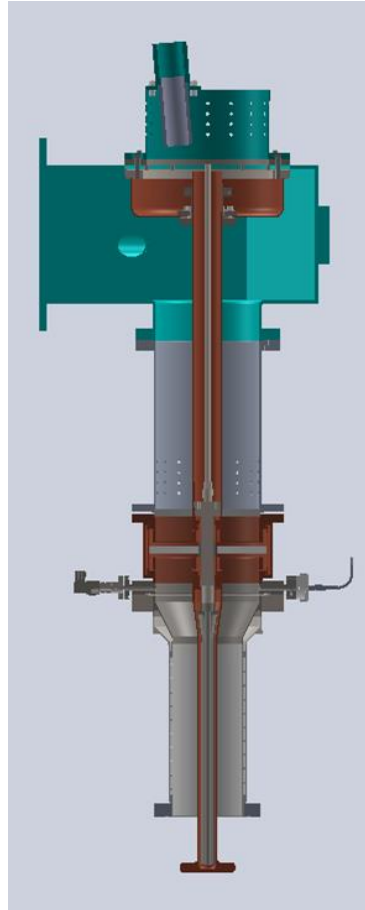
Variable coupling ( $Q_e$ :  $1E5 \sim 2E6$ ) of power coupler is necessary especially with “high efficiency klystron”:

- Collider Ring: same mode, different beam current
  - Not so significant, but 10 % is  $\sim 20$  MW AC power (and lower efficiency for lower klystron operation power)
  - Compensate Qext scattering
  - Enable matching for higher current
- Collider Ring: different modes at max design current
  - 46 % and 32 % more RF power for W and Z with fixed H coupling. Under coupling not good for stability
- Booster
  - cavity BW change (easy control or power saving)



# Coupling Adjusting Mechanism

- Two bellows on outer or inner conductor.
- Method other than changing the penetration depth of the antenna tip : RF short plunger on the doorknob waveguide (standing wave, frequency change, adjusting range ...)





# ADS 650 MHz Input Coupler (fixed)

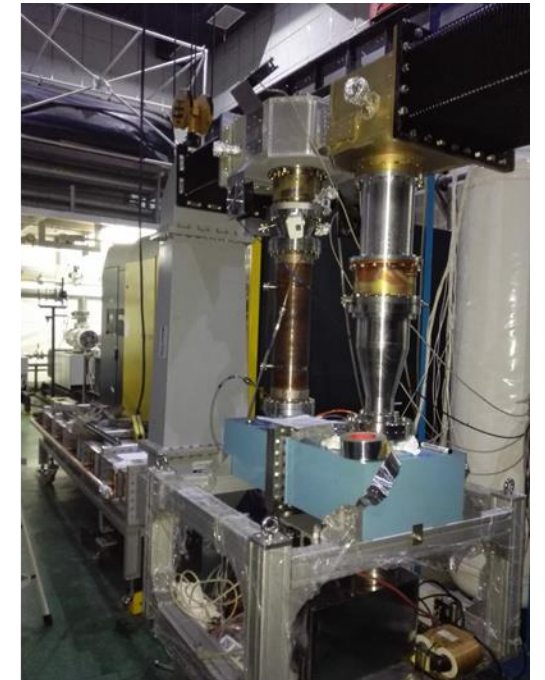
- RF, mechanical and thermal design.
- ADS 650 MHz input coupler **tested up to 130 kW CW** (limited by the power source).



Cold test



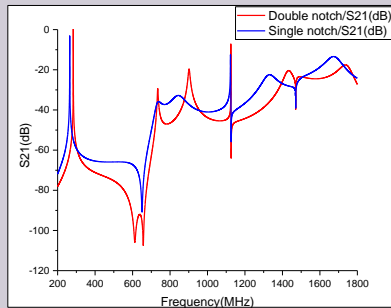
Clean and assembly



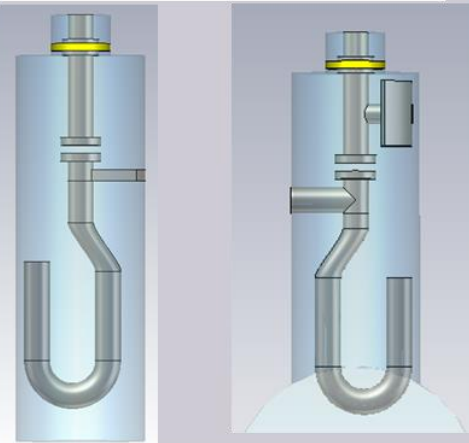
High power test

# 650 MHz Cavity HOM Coupler Design

## RF design



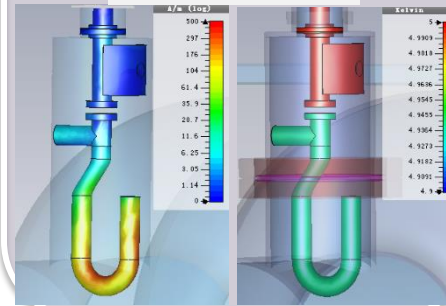
## Design approach for HOM coupler



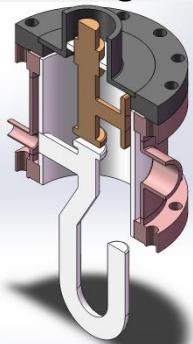
Single notch coupler

double notch coupler

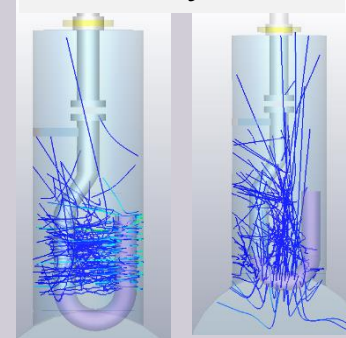
## Thermal Design



## Mechanical designs



## Multipacting analysis



**> 1 kW power**

Report from the International Review Committee of the CEPC HOM Coupler Design

August, 2017

### Objectives:

With the discovery of the Higgs boson at the LHC in 2012, the Institute of High Energy Physics (IHEP) in Beijing, China, in collaboration with a number of other domestic and international institutions, launched a study of a 100 km Circular Electron-Positron Collider (CEPC) as a Higgs factory. CEPC Conceptual Design Report (CDR) will be published at the end of 2017.

CEPC will require two large Superconducting RF (SRF) systems: 336 2-cell 650 MHz cavities in 56 cryomodules for the Main Ring and 160 1.3 GHz 9-cell cavities in 20 cryomodules for the Booster. The HOM coupler is a challenging and key component of the Main Ring cavity. Up to 1 kW CW power should be extracted via each of the two coaxial HOM couplers on a cavity. The CEPC SRF hardware design and R&D has been started since 2016. HOM coupler prototypes will be fabricated in 2018 and installed in a test cryomodule with the cavity in 2019 for high power and beam test. The International review of the CEPC HOM coupler design was held on July 18, 2017 at Lanzhou University during the SRF2017 conference, Lanzhou, China.

### Members of the International Review Committee:

Bob Rimmer (Chair), JLAB  
Carlo Pagani, INFN  
Jacek Sekutowicz, DESY  
Kai Papke, CERN  
Wencan Xu, BNL  
Qiong Wu, BNL  
Gary Cheng, JLAB  
Subashini De Silva, ODU  
Marco Garlasche, CERN  
James Mitchell, CERN/Lancaster U.

### Charges to the committee:

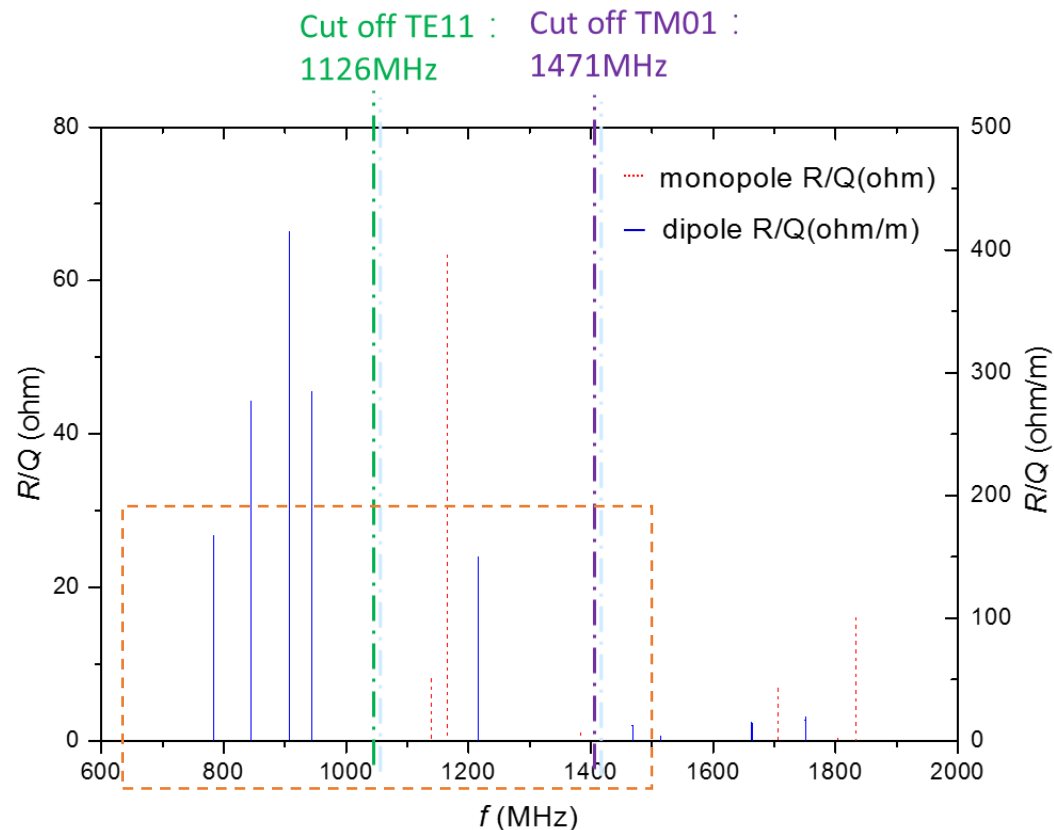
The review committee was invited to review on the CEPC Main Ring HOM coupler design with the following questions:

1. Does the design of the HOM couplers in terms of RF design, thermal analysis, mechanical design meet the CEPC requirement?
2. Are there any important aspects ignored or without adequate consideration?
3. Can any design be optimized according to current design, either to have more simplicity or reduce risk?
4. Is the current design ready to fabricate? If not, what is suggested before manufacture?

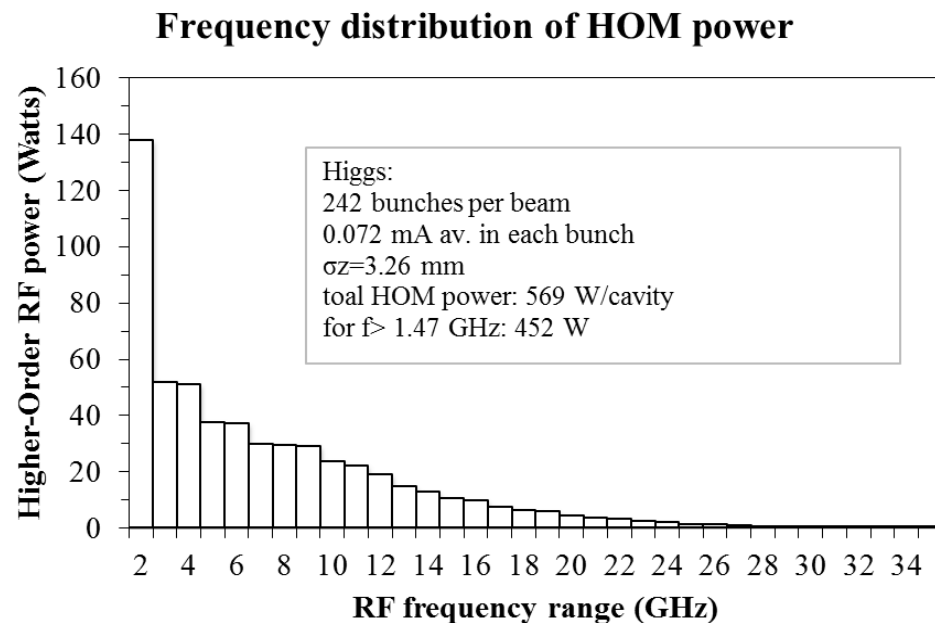
### Findings:

Five-pages report from the International Review Committee of the CEPC HOM Coupler Design chaired by Bob Rimmer (JLAB), July 18, 2017.

# Collider Cavity HOM Spectrum and Power



- Dangerous monopole: around 1200MHz
- Dangerous dipole: 800 MHz ~ 900 MHz, 1200 MHz



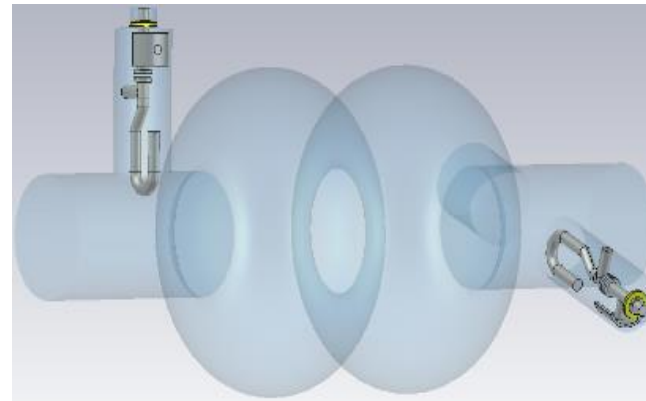
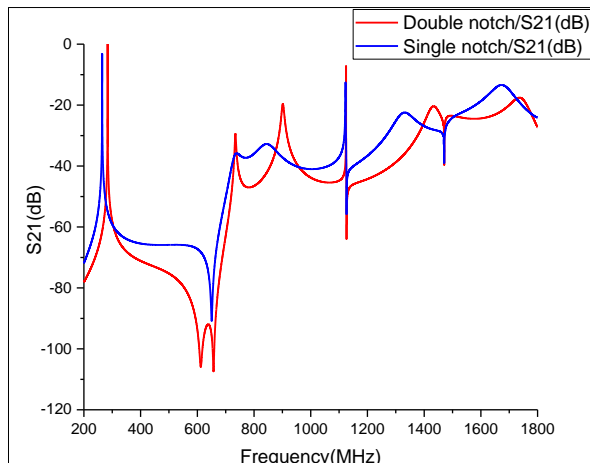
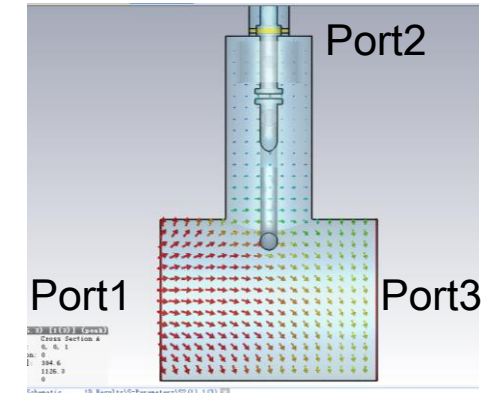
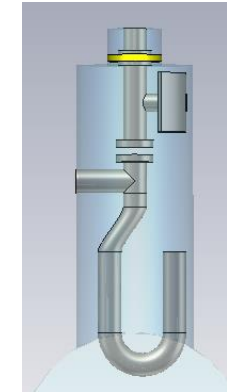
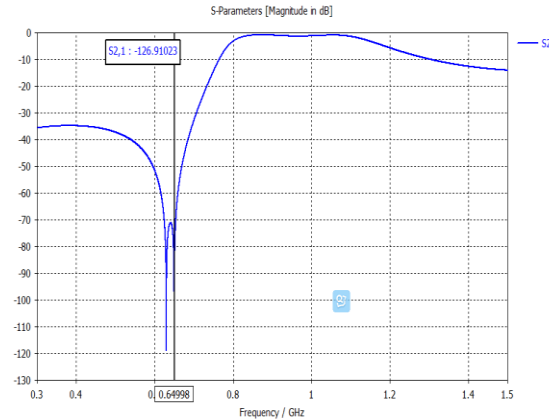
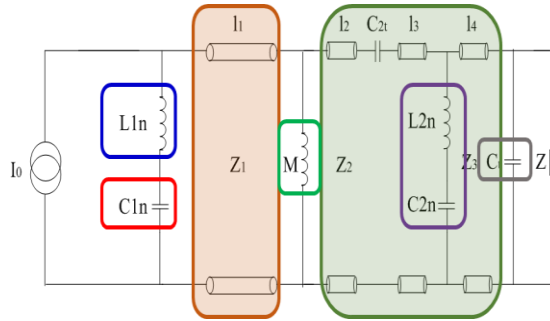
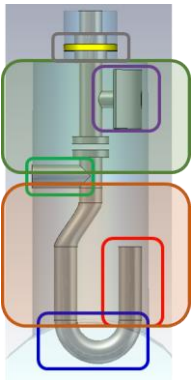
$f$ (GHz)	1~10	10~20	20~30	30~40
$P$ (W)	339.38	103.19	20.73	2.22
percentage	72.9%	22.17%	4.45%	0.48%

HOM coupler: 800~1400 MHz

HOM absorber: operating frequency > 1.4 ~ 20 GHz

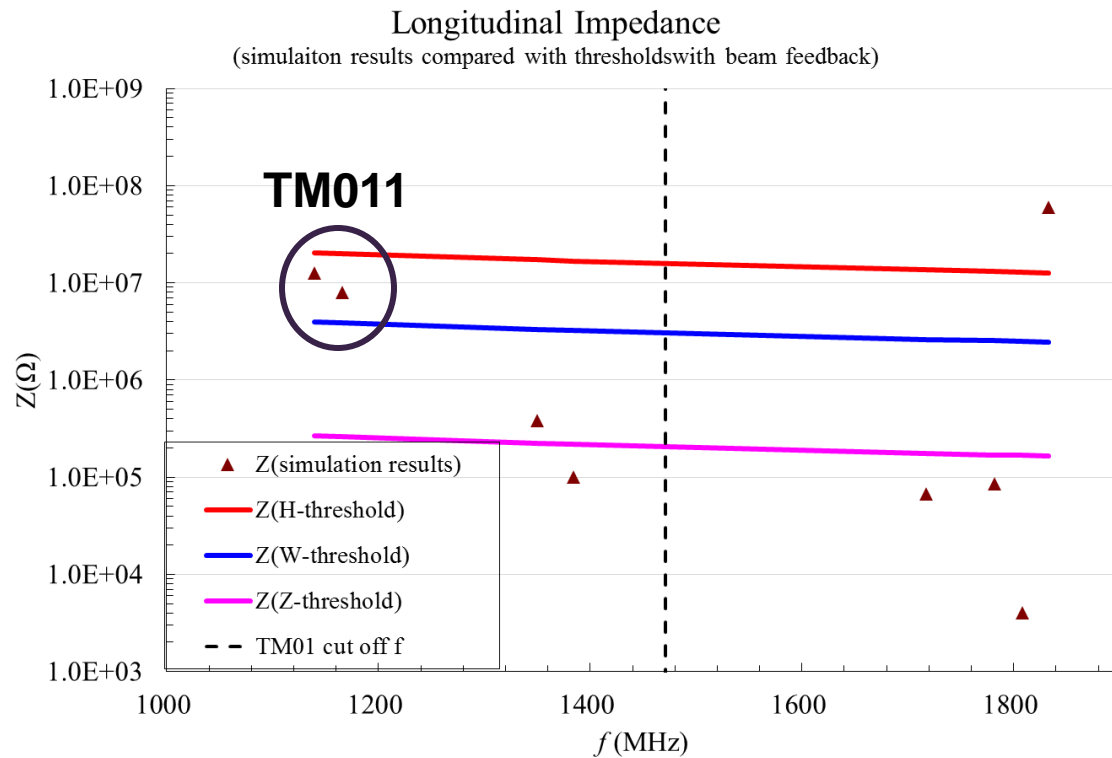
# HOM Coupler Damping Design

equivalent circuit (transmission line model) → optimize each part according to  $S_{21}$  curve  
 → change to 3D model → electromagnetic optimization

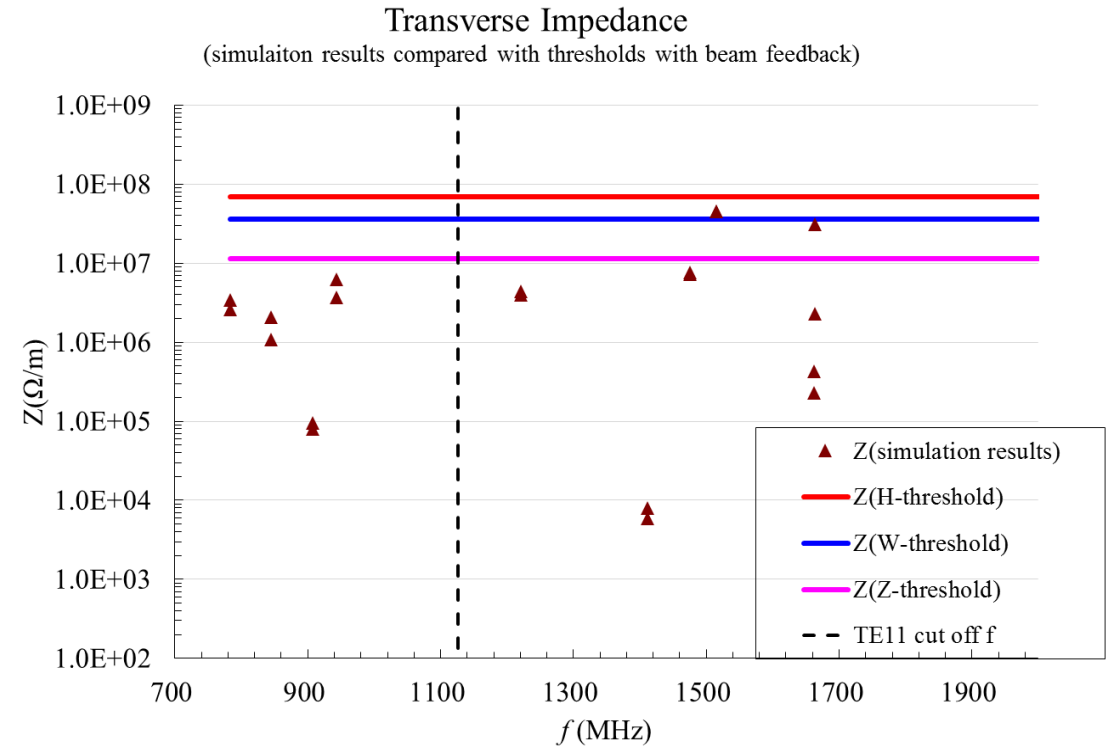


Modes	f (GHz)	R/Q (monopole $\Omega$ , dipole $\Omega/m$ )	$Q_e$ simulation
TM011	1165.574	65.2	2.46E+05
TM020	1383.898	1.3	1.55E+05
TE111	844.738	279.8	1.50E+04
TM110	907.592	420.1	4.58E+02

# HOM Damping Result



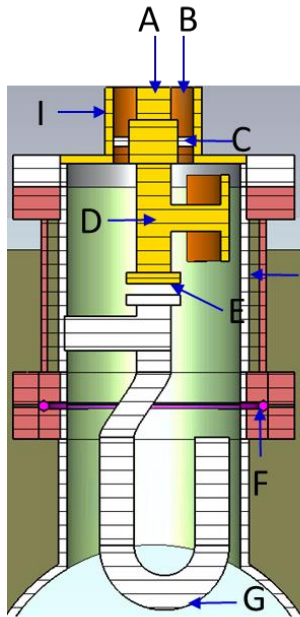
- Monopole modes impedance per cavity (cavity impedance thresholds with feedback and parking cavities in beamline)
- Without frequency spread
- **Optimize the geometry of the HOM coupler, increase TM011 field in one side and reduce Qext by asymmetric end cells, push idle cavities off-line.**



- Dipole modes impedance per cavity (cavity impedance thresholds with feedback and parking cavities in beamline)
- Without frequency spread

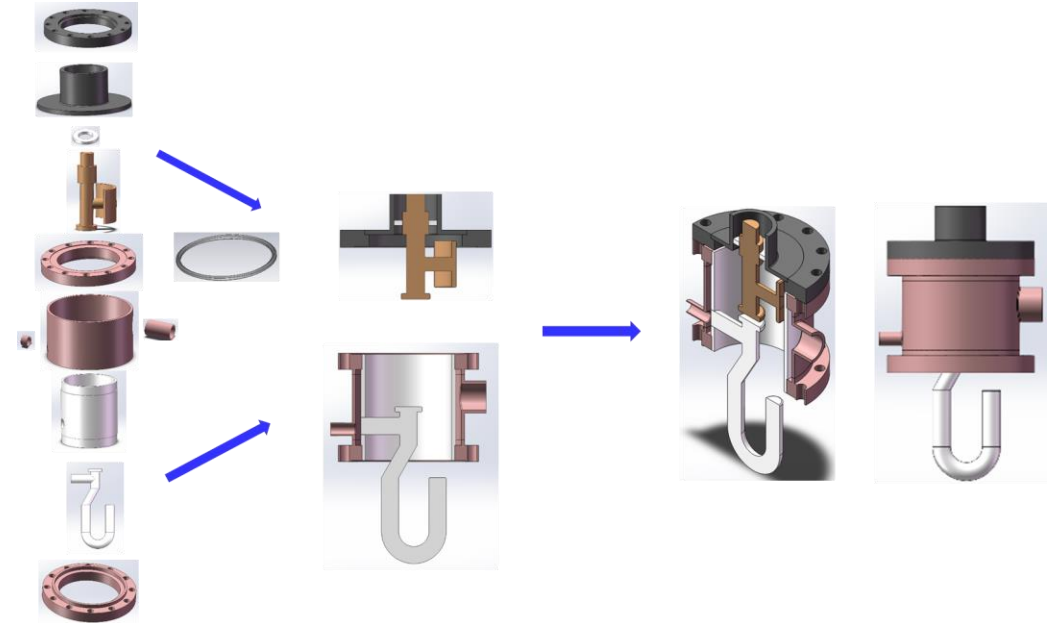
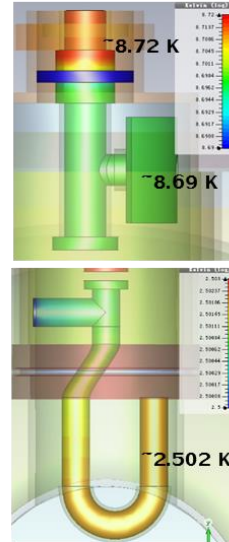
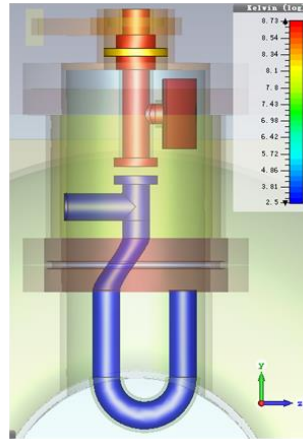


# Thermal Analysis and Mechanical Structure



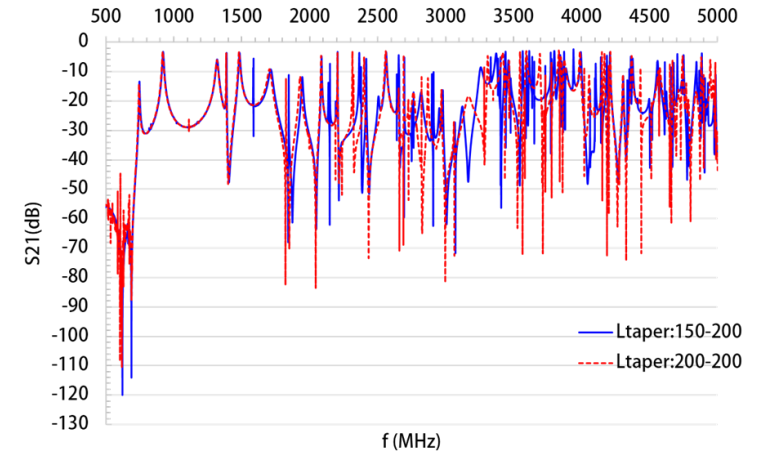
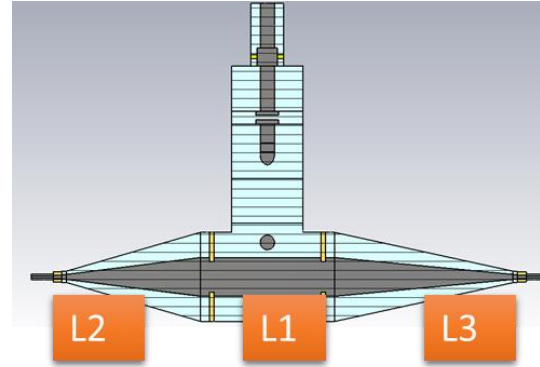
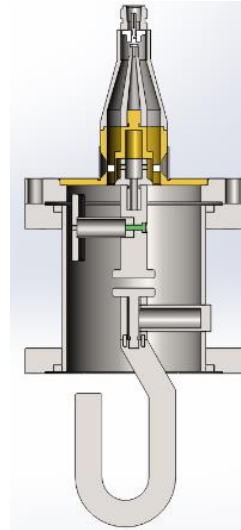
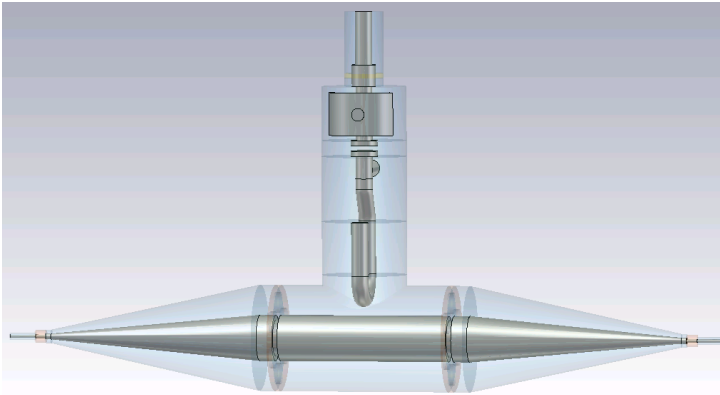
Boundary conditions:

- A Heat: 1 W
- B Heat: 1 W
- C Heat: 0.03 W
- D Heat: 0.553E-3 W
- E Heat: 1.108E-3 W
- F Heat: 0.271E-3 W
- G Heat: 0.217E-3 W
- H Temperature: 2.5K
- I Temperature: 5K



- Power dissipation caused by the fundamental mode and 1 kW HOM is in the mW range.
- A helium tank outside the HOM coupler is needed.
- No active cooling by liquid helium inside the loop.

# Low Power Test Bench and Model Cavities

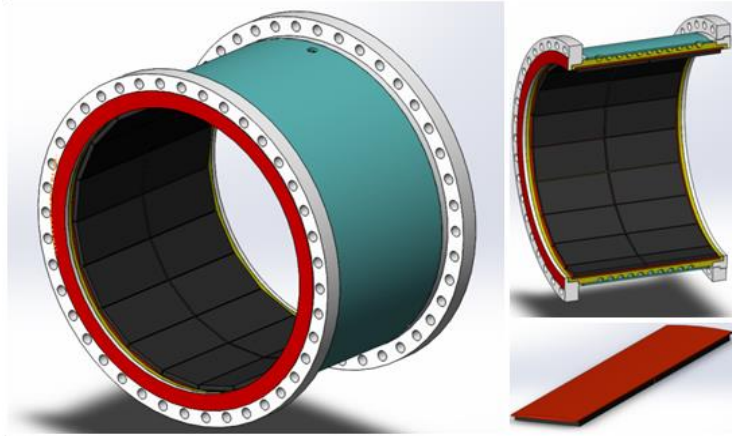


Ra=21.73mm, Rb=50mm, rin=20mm, S21

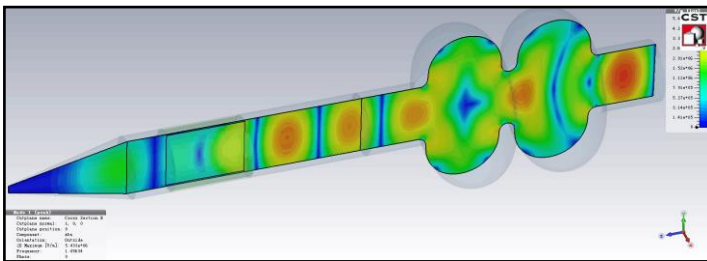
- Coaxial transmission line with HOM coupler model used to measure the transmission properties of the coupler
- Symmetry cone & asymmetry cone (200-150-200)
- **Fabricate two 2-cell aluminum cavities**
  - Measure damping performance of HOM couplers
  - Check the actual spread of the HOM spectrum due to mechanical tolerance



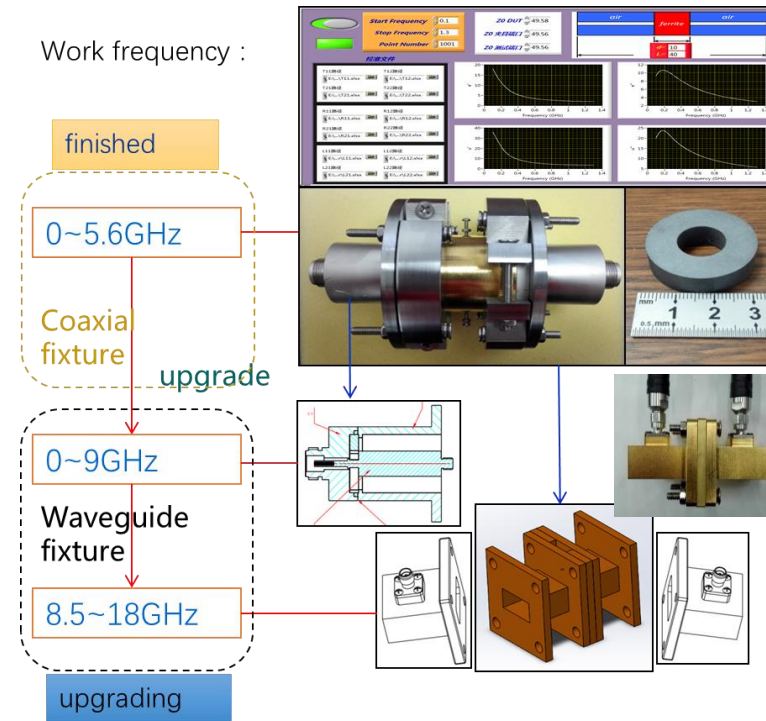
# HOM Absorber (Ferrite and SiC)



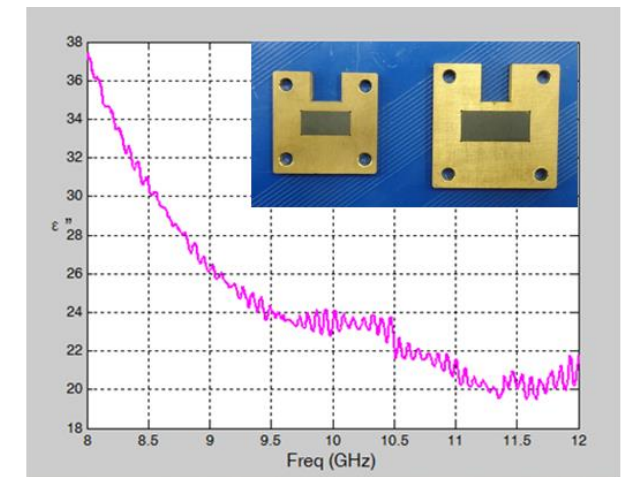
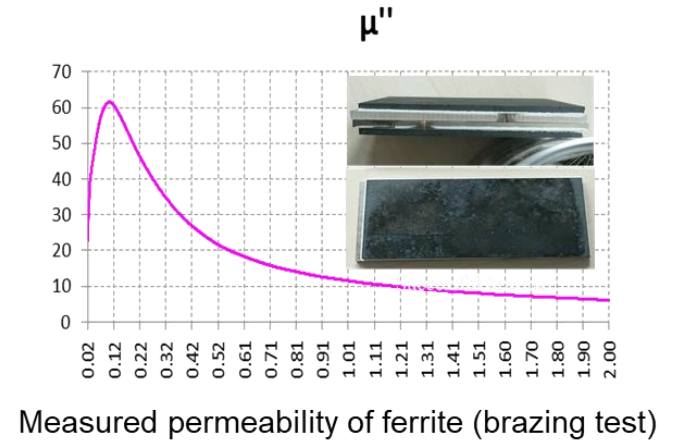
Brick structure to reduce the fabrication cost



Work frequency :

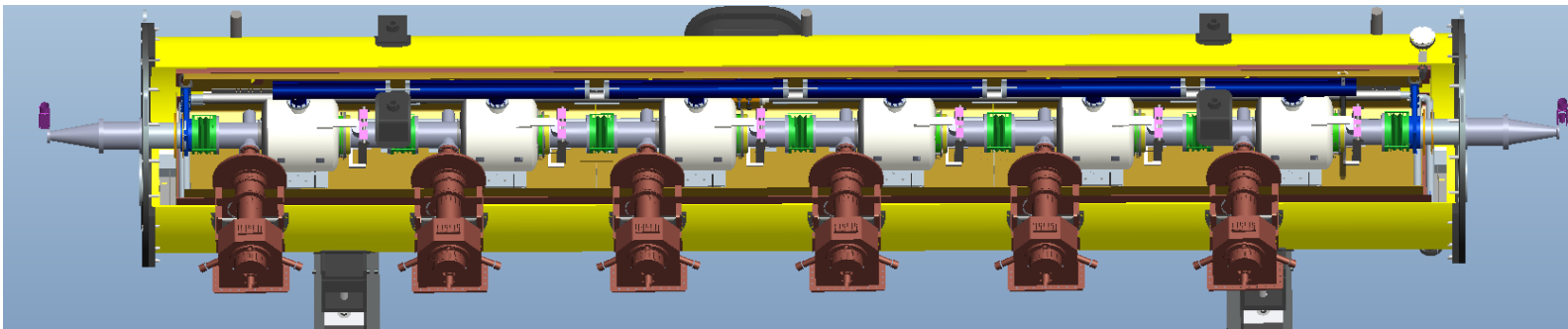
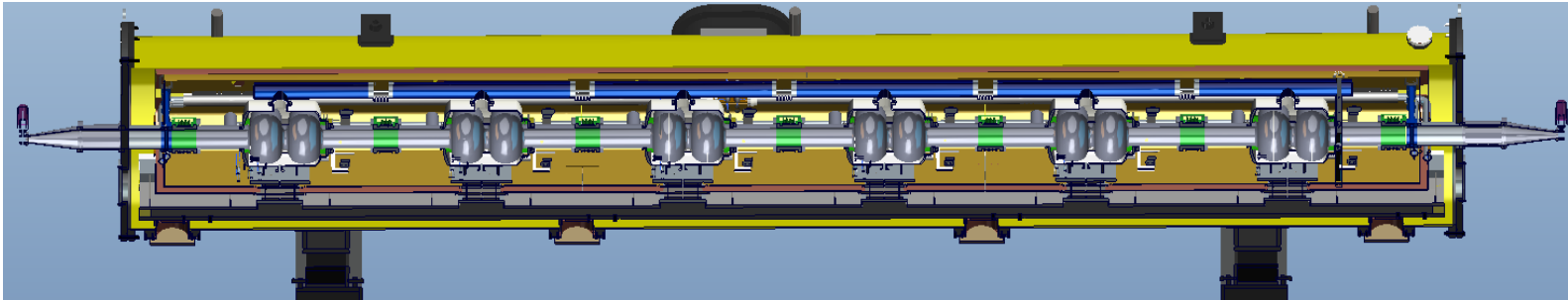


Microwave absorbing material test system



# CEPC 650 MHz Cavity Cryomodule

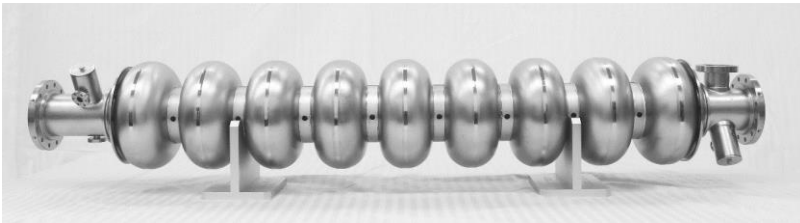
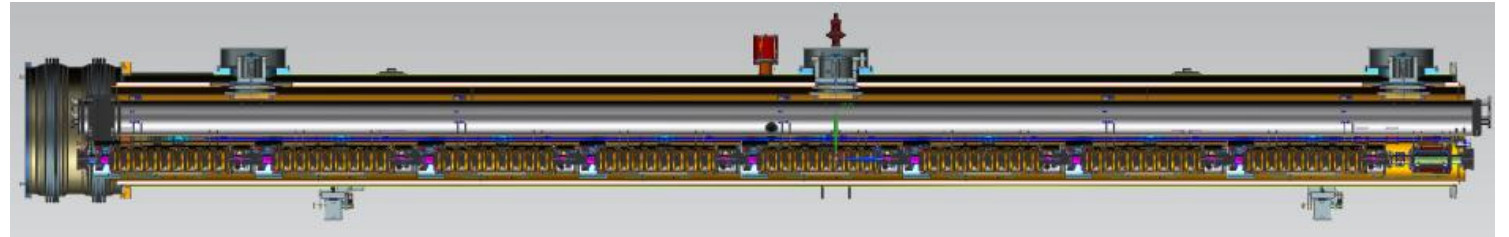
- Structure based on ADS cryomodule. High Q requirement drives new design features (fast cool down and magnetic hygiene).
- Fast cool down rate is supposed to be 10 K/min during 45 K to 4.5 K.
- Ambient magnetic field at cavity surface should be less than 5 mG. Magnetic shielding and demagnetization of parts and the whole module should be implemented for the magnetic hygiene control.



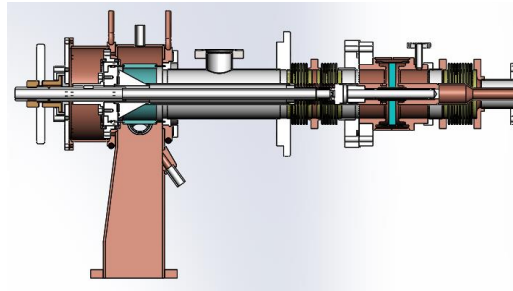
Overall length (flange to flange, m)	8.0
Diameter of vacuum vessel (m)	1.3
Beamline height from floor (m)	1.2
Cryo-system working temperature (K)	2
Number of cavities and tuners	6
Number of couplers	6
Number of RT HOM absorbers	2
Number of 200-POSTs	6
Static heat loads at 2 K (W)	5
Alignment x/y (cavities) (mm)	0.5
Alignment z (mm)	2

# 1.3 GHz SRF Technology for CEPC Booster

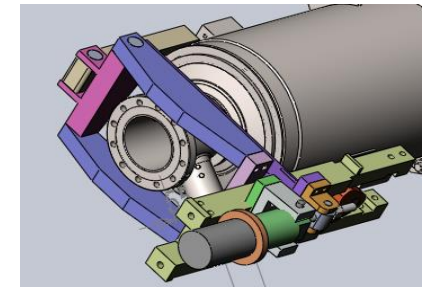
**XFEL and LCLS-II type cryomodule,** without SCQ. Technology R&D in synergy with Shanghai XFEL (SCLF). No big challenge.



**TESLA cavity.** Nitrogen-doped bulk niobium and operates at 2 K.  $Q_0 > 3 \times 10^{10}$  at 24 MV/m for the vertical acceptance test.  $Q_0 > 1 \times 10^{10}$  up to 20 MV/m for long term operation.



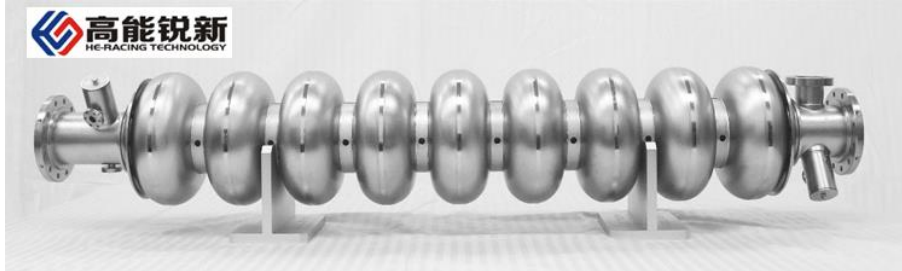
XFEL/ILC/LCLS-II or other type **variable power coupler.** **Peak power 30 kW, average 4 kW,**  $Q_{\text{ext}} 1\text{E}7\text{-}5\text{E}7$ , two windows.



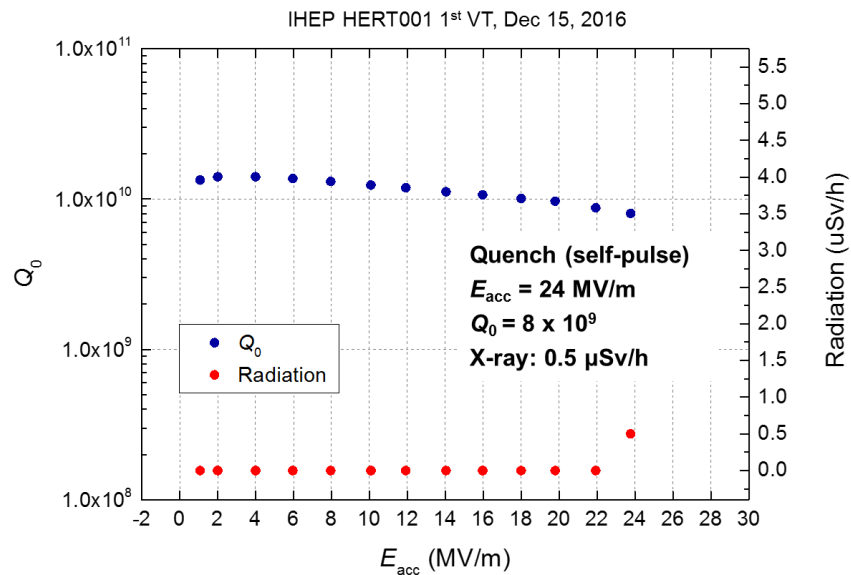
XFEL/LCLS-II type **end lever tuner.** Reliability. Large stiffness. Piezos abundance, radiation, overheating. Access ports for easy maintenance.



# SRF Industrialization



TESLA FG 9-cell cavity by HERT (new vendor).  
Processed and tested at KEK. Two more TESLA  
cavities in fabrication by HERT (material delivered).  
High gradient and N-doping / infusion study.



# CEPC Industrial Promotion Consortium (CIPC)



**Established in Nov. 7 , 2017**



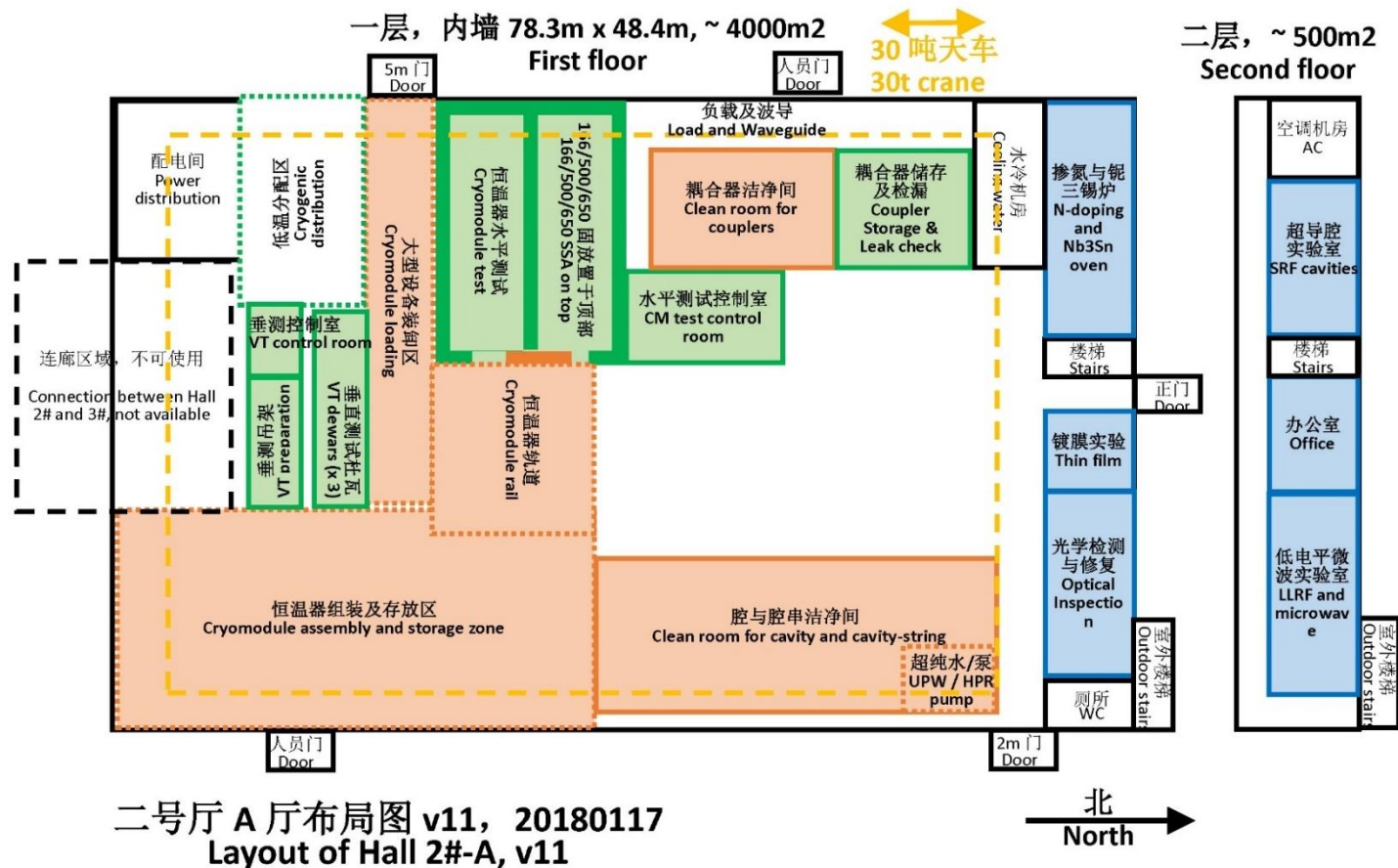
- 1) Superconducting materials (for cavity and for magnets)
- 2) Superconducting cavities
- 3) Cryomodules
- 4) Cryogenics
- 5) Klystrons
- 6) Vacuum technologies
- 7) Electronics
- 8) SRF
- 9) Power sources
- 10) Civil engineering
- 11) Precise machinery.....

More than 50 companies joined in first phase of CIPC,  
and more will join later....

J. Gao, IAS HEP 2018



# IHEP New Large SRF Facility



**4500 m<sup>2</sup> SRF lab** in the Platform of Advanced Photon Source Technology R&D (PAPS), Huairou Science Park, north Beijing.

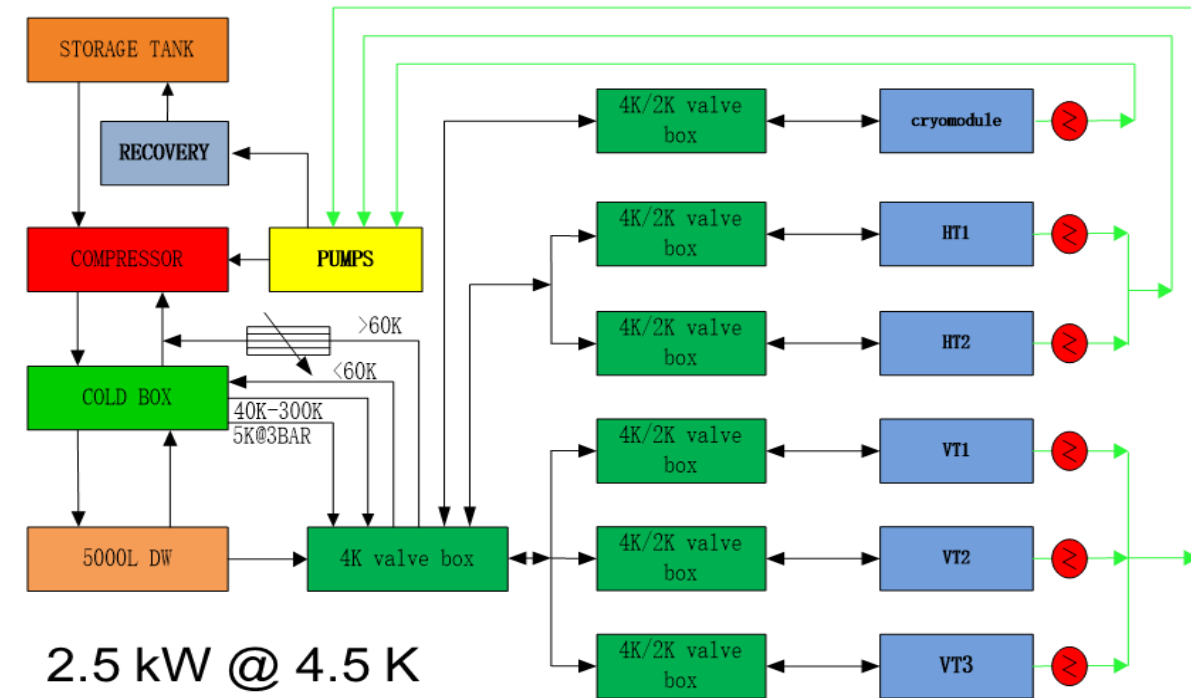
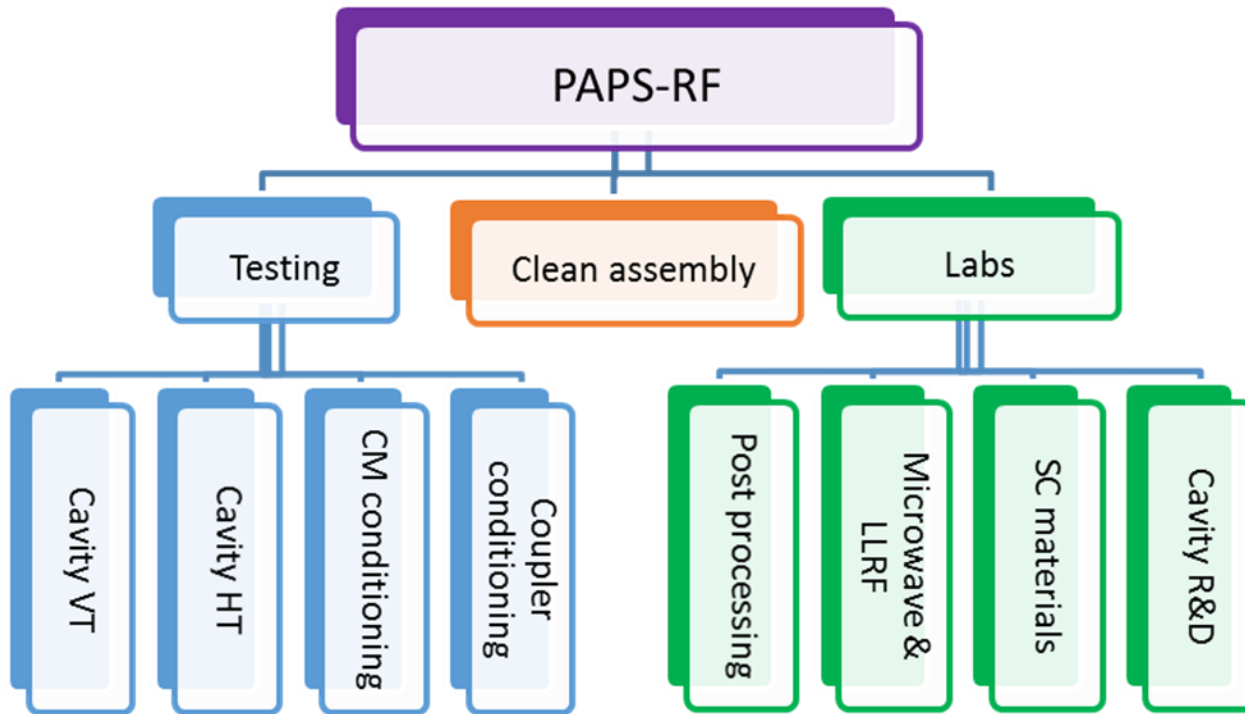
**Mission:** World-leading SRF Lab for Superconducting Accelerator Projects and SRF Frontier R&D.

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

**International Review:** chaired by Carlo Pagani on July 14. Seven-page report.

**Construction and facility commission:**  
**2017 - 2020**

# PAPS SRF Lab and Cryogenics





# PAPS in Construction



# Summary

- CEPC baseline SRF layout and parameters established. Challenges:
  - Unprecedented cavity high  $Q_0$ , large number of very high power variable input couplers, high HOM power in a multi-cavity cryomodule, fast SRF cavity voltage ramp with narrow bandwidth in a storage ring.
  - Coupled bunch instabilities and RF transient manageable for baseline. High-L Z needs more investigation.
- SRF key components design and R&D launched, with support of PAPS SRF facility.
- CEPC SRF industrialization synergy with SCLF, ADANES, HIAF, HEPS (~ 1000 cavities in next five years), FCC-ee and ILC.
- Welcome more international collaboration.

Thank you.

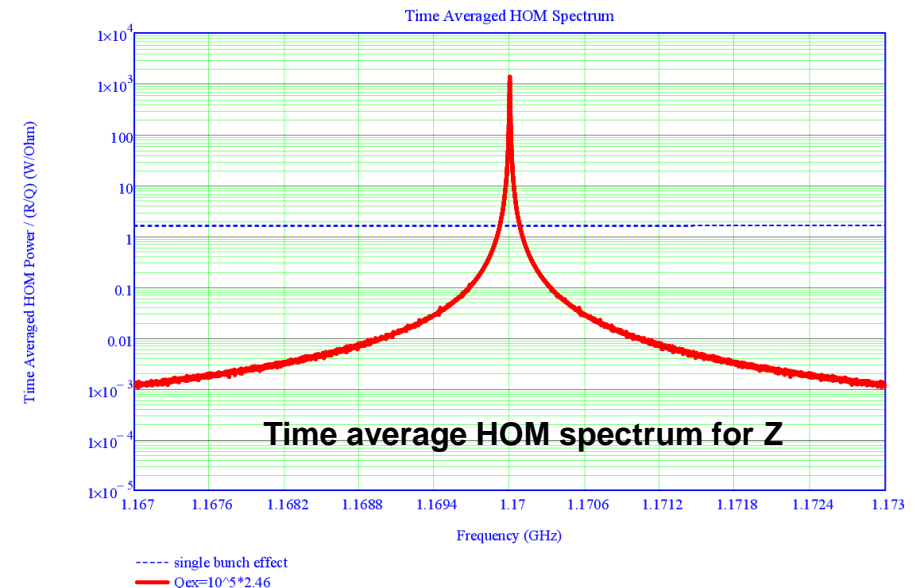
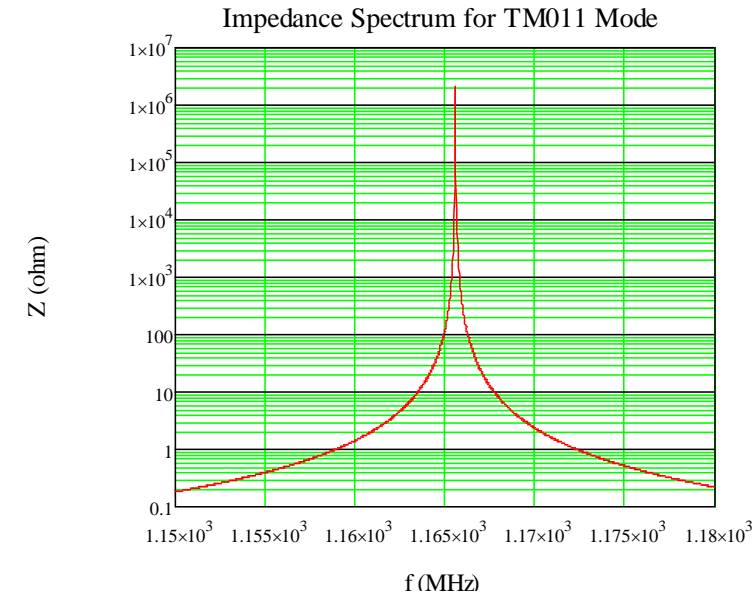
# HOM power-resonant case

Take TM011 mode for example

- $R/Q=65.2\Omega$ , the most dangerous monopole mode
- $Q_e=2.46E+5$

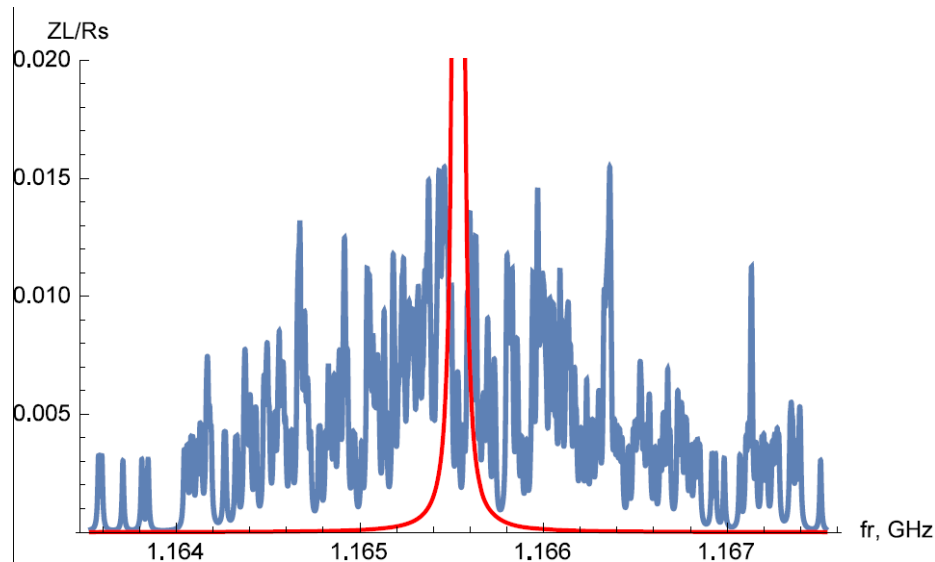
Resonant case	H	W	Z
HOM power (kW)	20.1	130.5	112.4

- If the HOM frequency is 26 kHz away from the beam spectrum for Z running, the HOM power will be less than 1 kW, while only 11 kHz for H running.



# Frequency Spread

- Considering the whole RF system, there will be finite tolerances in the cavity construction.
- To find the total effects of all the RF cavities, we need to take into account the spread in the resonance frequencies of different cavities.
- For small frequency spread, this will result in an “effective” quality factor  $Q$  of the whole RF system.



$$R_s (Z_L / R_s)_{\max} < R_L^{th} = \frac{2(E_0 / e) v_s}{N_{cav} f_L I_0 \alpha_p \tau_z}$$

A. Hofmann and J. R. Maidment, LEP note 168, 28.6.79.

N. Wang et al. Impedance and collective effects of CEPC, 55th ICFA Advanced Beam Dynamics Workshop on High Luminosity Circular e+e- Colliders – Higgs Factory (HF2014)

$f_R=1.1654\text{GHz}$ ,  $Q=1.10 \times 10^5$ ,  $\delta f=1\text{MHz}$ , 336 RF cavities

# Booster HOM CBI and Feedback

Modes	$f$ (GHz)	$R/Q$ (monopole $\Omega$ , dipole $\Omega/m$ )	$Q_e$ measured	CBI Growth Time (ms)		
				H-extraction	W-extraction	Z-extraction
TM011	2.45	156	5.9E4	2061.0	1314.9	788.5
TM012	3.845	44	2.4E5	1144.6	730.2	437.9
TE111	1.739	4283	3.4E3	6817.3	4465.1	2680.6
TM110	1.874	2293	5.0E4	865.9	567.1	340.5
TM111	2.577	4336	5.0E4	457.9	299.9	180.1
TE121	3.087	196	4.4E4	11511.5	7539.7	4526.4
				H-injection	W-injection	Z-injection
TM011	2.45	156	5.9E4	187.2	176.3	185.2
TM012	3.845	44	2.4E5	104.0	97.9	102.9
TE111	1.739	4283	3.4E3	568.1	558.1	589.2
TM110	1.874	2293	5.0E4	72.2	70.9	74.8
TM111	2.577	4336	5.0E4	38.2	37.5	39.6
TE121	3.087	196	4.4E4	959.3	942.5	994.8

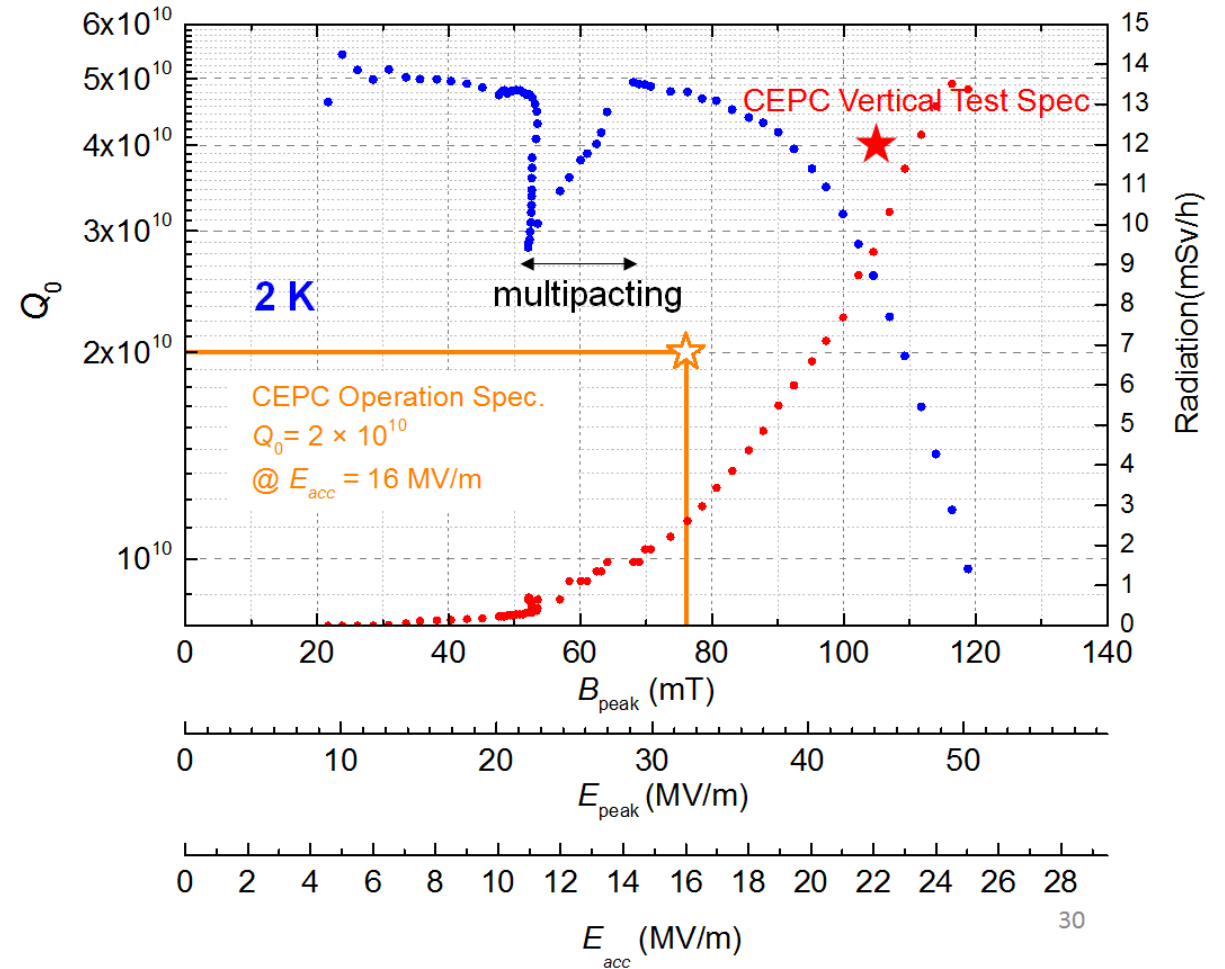
- All larger than beam transverse feedback time limit of **3.3 ms** (10 turns) and longitudinal feedback time limit of **3 ms** (synchrotron oscillation period)
- If the parked booster cavities are moved off beamline, the growth time will be increased to 1.5 and 3 times for the W and Z respectively.
- Cavity HOM frequency spread will have more margin
- Average  $\beta_{x,y}$  in RF cavity  $\sim 30$  m



# 650 MHz Single-cell Cavity (before N-doping)



- 130um BCP + 3 h 750 C annealing + 30um BCP + 120 C bake 48 h
- Shielded dewar, remnant magnetic field 20 mG. Additional magnetic shield around cavity.



# Collider HOM CBI $Q_{\text{ext}}$ Threshold

3 kHz beam spectrum lines, impossible to detune the HOMs (or just no damping?  $Q_{0\text{--}TM0mp} = Q_{0\text{--}TM010} \cdot f_{\text{rf}} / f_{\text{HOM}}$ )

Mode	$f$ (MHz)	$R/Q^*$ (monopole $\Omega$ , dipole $\Omega/\text{m}$ )	$Q_e$ (H)	$Q_e$ (W) idle cavities on-line	$Q_e$ (W) idle cavities off-line	$Q_e$ (Z) idle cavities on-line	$Q_e$ (Z) idle cavities off-line
TM011	1165.574	65.2	$1.4 \times 10^5$	$1.3 \times 10^4$	$2.0 \times 10^4$	$3.4 \times 10^2$	$2.4 \times 10^3$
TM020	1383.898	1.3	$5.8 \times 10^6$	$5.4 \times 10^5$	$8.5 \times 10^5$	$1.5 \times 10^4$	$1.0 \times 10^5$
TM021	1717.475	19.9	$3.0 \times 10^5$	$2.8 \times 10^4$	$4.4 \times 10^4$	$7.6 \times 10^2$	$5.3 \times 10^3$
TM012	1832.801	17.26	$3.3 \times 10^5$	$3.1 \times 10^4$	$4.8 \times 10^4$	$8.2 \times 10^2$	$5.8 \times 10^3$
TE111	844.738	279.8	$3.5 \times 10^4$	$5.5 \times 10^3$	$8.5 \times 10^3$	$3.2 \times 10^2$	$2.2 \times 10^3$
TM110	907.592	420.1	$2.4 \times 10^4$	$3.7 \times 10^3$	$5.7 \times 10^3$	$2.1 \times 10^2$	$1.5 \times 10^3$
TE121	1475.553	125.8	$7.8 \times 10^4$	$1.2 \times 10^4$	$1.9 \times 10^4$	$7.1 \times 10^2$	$5.0 \times 10^3$
TM120	1662.599	18.8	$5.3 \times 10^5$	$8.2 \times 10^4$	$1.3 \times 10^5$	$4.8 \times 10^3$	$3.3 \times 10^4$

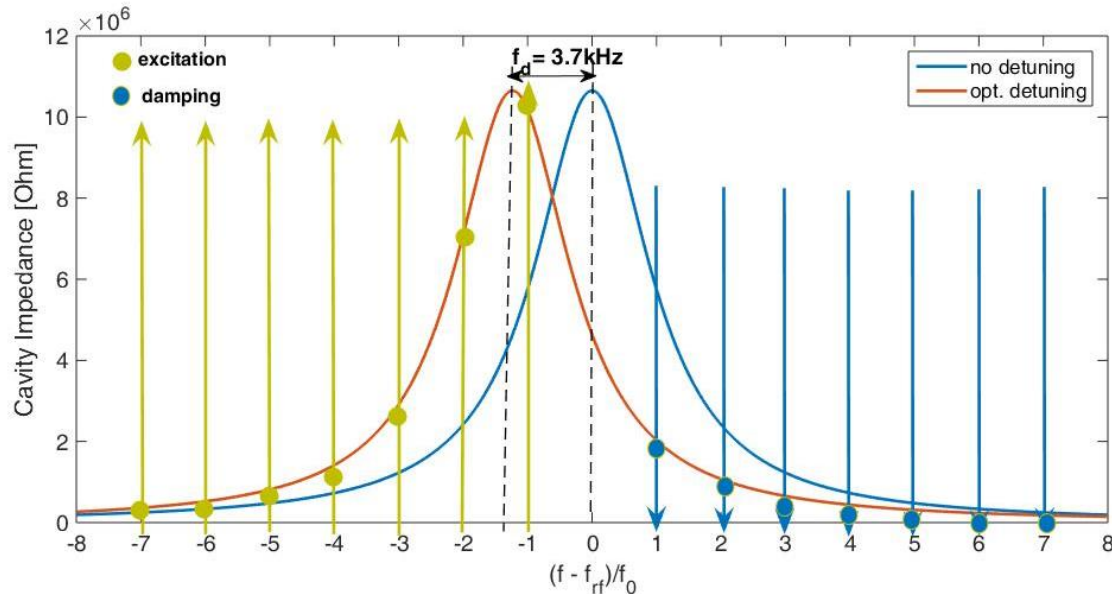
\* Longitudinal  $R/Q$  with the accelerator definition and  $k_{\parallel \text{mode}} = 2\pi f \cdot (R/Q) / 4$  [V/pC]. Transverse  $R/Q$ :  $k_{\perp \text{mode}} = 2\pi f \cdot (R/Q) / 4$  [V/(pC·m)]

Average beta<sub>x,y</sub> in RF cavity ~ 30 m

# Collider HOM CBI with all Effective $Q_{\text{ext}} = 2\text{E}3$

	H	W	Z
Cavity number in beam line	336	168	168
Shortest growth time of the HOM modes with parked cavities on-line [ms]	543 (TM110)	287 (TM110)	74 (TM011)
Shortest growth time of the HOM modes with parked cavities off-line [ms]	543 (TM110)	447 (TM110)	517 (TM011)
Radiation damping time [ms]	46.3 transverse	157 transverse	843 transverse
Beam feedback time for transverse mode (10 turns) [ms]	3.3	3.3	3.3
Beam feedback time for longitudinal mode [ms]	5.16	8.46	18.12
Beam current threshold with beam feedback [mA]	2865	5259	652
Corresponding $L / \text{IP}$ [ $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ ]	482	435	16.6
$L / \text{IP}$ limit from 50 MW SR power [ $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ ]	4.8	12.0	34.8

# Fundamental Mode Instability of W & Z



CEPC baseline Z FM-CBI (without parked cavities)

Mode number	Impedance / cavity ( $\Omega$ )	Growth Time (ms)	Growth Time / Damping Time	Growth Rate / Syn. Freq.
W / -1	5.50E+06	16.6	0.21	0.72
Z / -7	1.83E+05	322.7	0.77	0.06
Z / -6	2.92E+05	202.5	0.48	0.09
Z / -5	5.07E+05	116.7	0.28	0.16
Z / -4	9.91E+05	59.6	0.14	0.30
Z / -3	2.29E+06	25.8	0.06	0.70
Z / -2	6.12E+06	9.7	0.02	1.87
Z / -1	8.05E+06	7.3	0.02	2.46

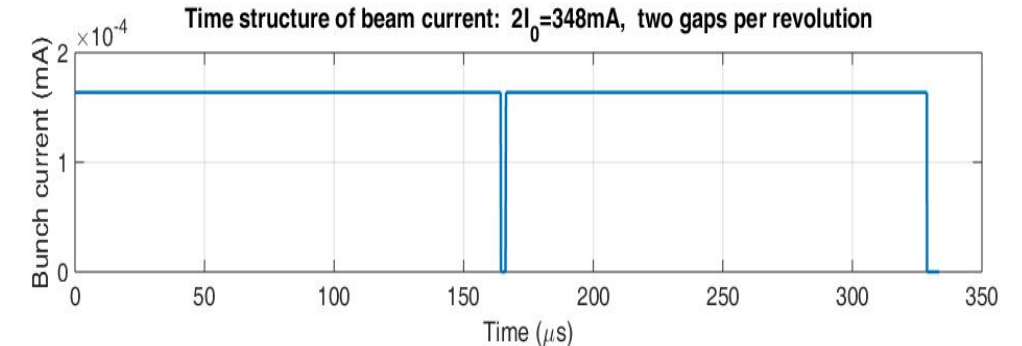
## Mitigation methods:

- Less running cavities (pushing the coupler power limit)
- Higher total RF voltage (but beam-beam instability)
- Direct (and comb) RF feedback loops to decrease the fundamental-mode impedance and the growth rates at least to the manageable level of the longitudinal bunch-by-bunch feedback system.

# Beam Gap Phase Shift

Gap for beam abort and ion-clearing or to avoid collision in the RF section for CEPC Higgs mode (each ring should be filled in less than half of the total buckets. Each cavity will see two gaps in one circulating period and the gap length seen by the cavities in different positions is different)

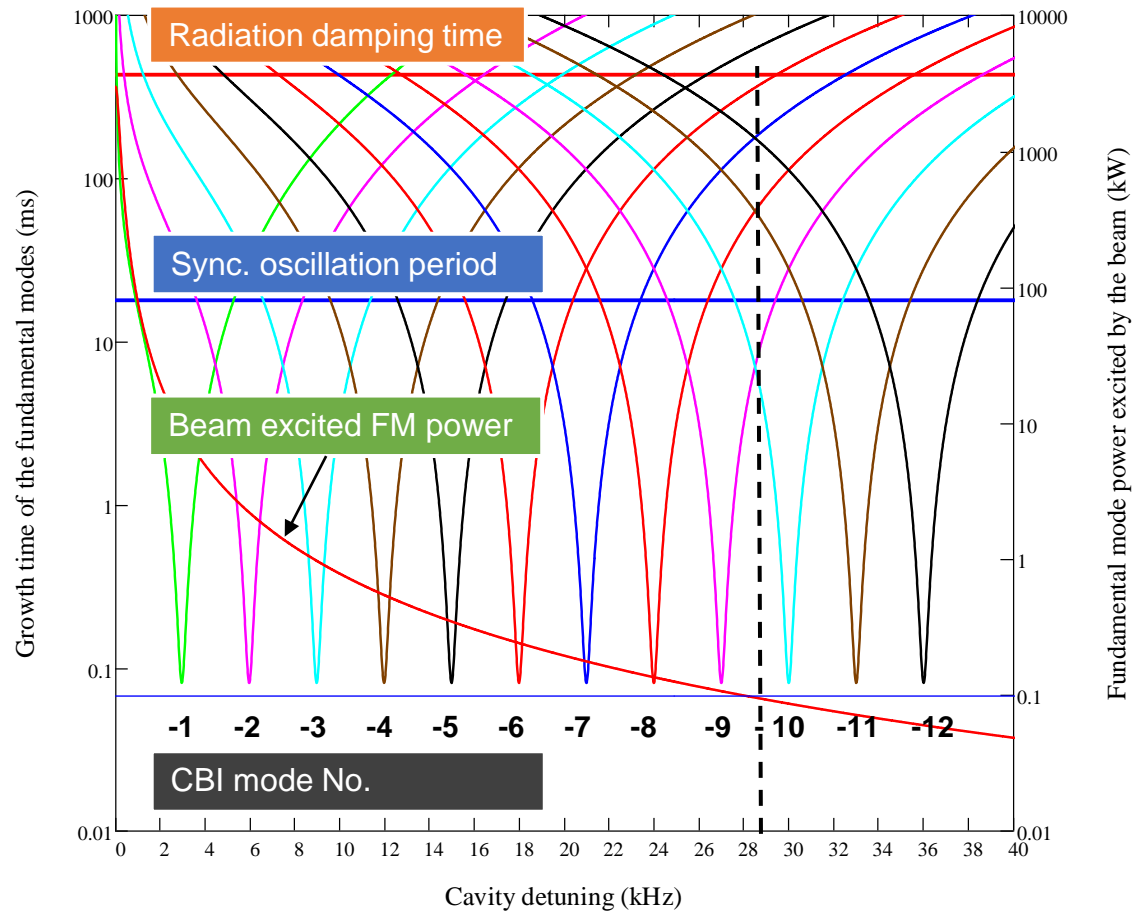
	H	W	Z
Beam gap in number of buckets	3091	3309	210
Beam gap length [ $\mu\text{s}$ ]	4.76	5.09	0.32
Max relative voltage drop	1.7 %	4.5 %	1.0 %
Max bunch train phase shift [deg]	1.6	3.7	0.8



Phase shift for Higgs end cavity

Simulation based on D. Teytelman's code with transfer functions.

# FM CBI and Power of Parked Cavities



CEPC baseline Z mode FM CBI and beam excited power per cavity of the 156 parked cavities (reduce FM coupling to  $Q_e = 2E6$ )

- Large detuning and narrow BW to **reduce FM power** excited by the beam (limit?), but fast-growing CBI modes. **symmetric detuning** (positive and negative detuned cavities cancel each other) will mitigate the instabilities.
- Small input power is required to have the signal to detune the cavity (?). Circulators and loads should keep working for the excited FM power. Cavities should be kept at 2 K to extract HOM power.
- Power increases with square of the beam current. Different fill pattern will change the excited power.
- Better to **move the large number of idle W and Z cavities off the beamline** (in the empty place of the future SPPC magnets) or with multi-by-pass (but needs lattice change and longer straight section), rather than parking (detune) them. **Similar for the Booster**. This will also reduce the HOM impedance significantly.

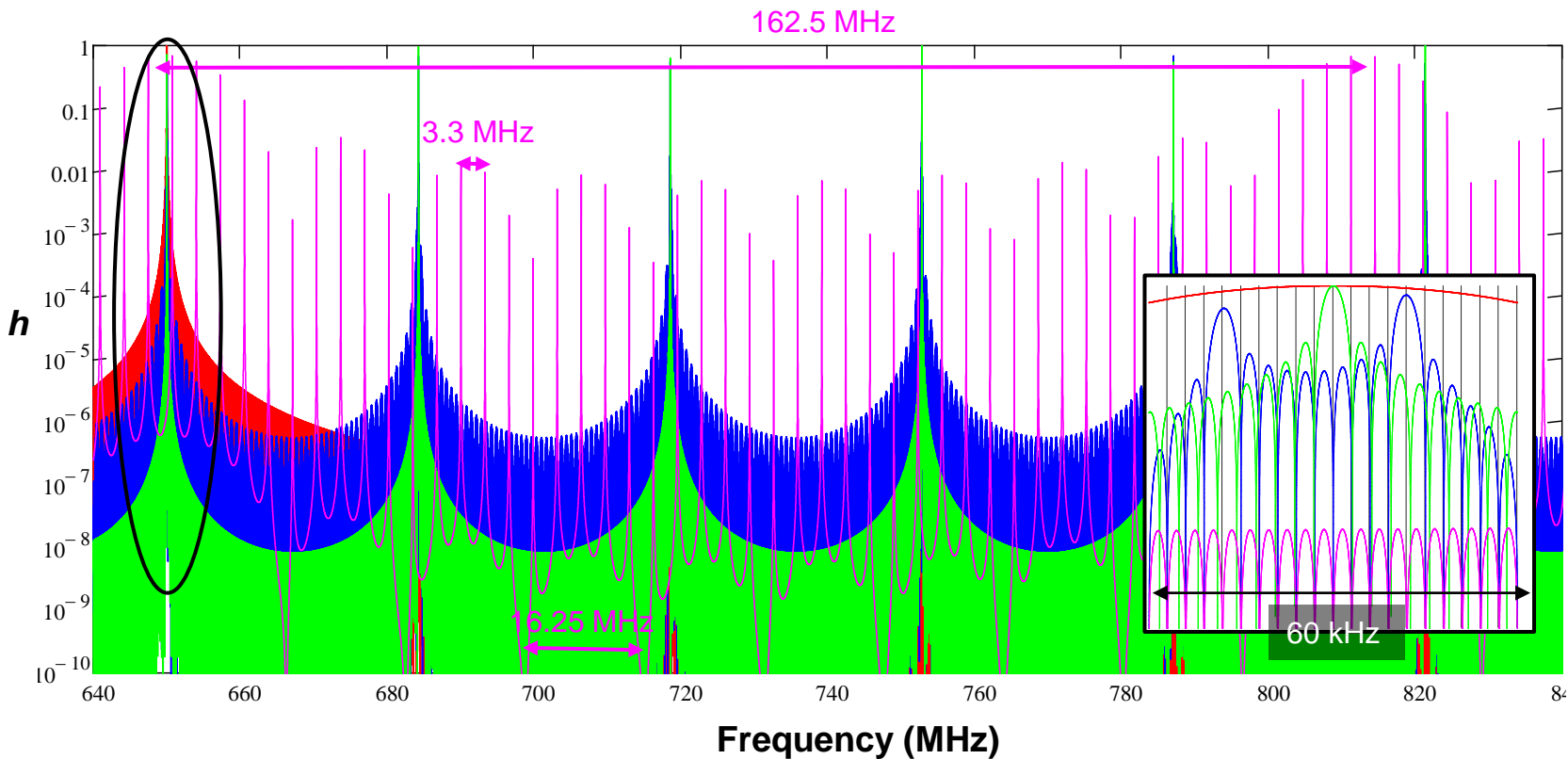


# Fill Pattern and Beam Power Spectrum

**Normalized beam power spectrum in terms of the fill pattern parameters:**

$h$  ( $f$  [frequency],  $n_t$  [number of bunch trains],  $n_b$  [bucket number between bunch],

$M_b$  [number of bunches in one train])



Train repetition:  $n_t f_0$

Fine structure repetition:  $f_0$

Bunch repetition:  $f_{rf} / n_b$

Fine structure repetition:  $f_{rf} / n_b / M_b$

Amplitude  $\sim 1 / (M_b n_t)^2$

Bunch structure dominates when  $M_b \gg n_t$

Train structure dominates when  $n_t \gg M_b$

Red:  $h(1, 1, 10900)$

Blue:  $h(10, 19, 1090)$

Green:  $h(1, 19, 10900)$

Pink:  $h(1090, 4, 10)$

**Detuned cavities are not always safe. Different fill pattern will move the beam spectrum peaks to generate large power. Slightly change the detune of each cavity to avoid resonance. Same attention should be paid to HOMs.**

# Parasitic Loss of High Current Z

- Beam energy loss by the cavity fundamental mode is compensated by input RF power
- Parasitic loss: cavity HOM loss + other ring components loss. Energy loss should be compensated by increasing RF voltage. Parasitic power loss should be compensated by increasing the total RF power. **A significant beam current and luminosity reduction for high luminosity Z** if keep the 50 MW “SR” power per beam.
- CEPC Z-pole baseline:
  - loss factor ~ **688 V/pC** (**bunch length dependent**), beam current 160 mA, bunch charge 6.4 nC
  - parasitic energy loss: 4.4 MV (8 % of the RF voltage, increase cavity gradient by 8 %)
  - parasitic power loss: 0.7 MW (12 % of the SR power, increase input power per cavity by 8 %)
- High current Z (with nominal 50 MW SR power per beam) :
  - e.g. bunch charge x 4, beam current x 9 → energy loss x 4, power loss x 36 (**25 MW !**)
  - total RF AC power and input coupler power per cavity will exceed the design.