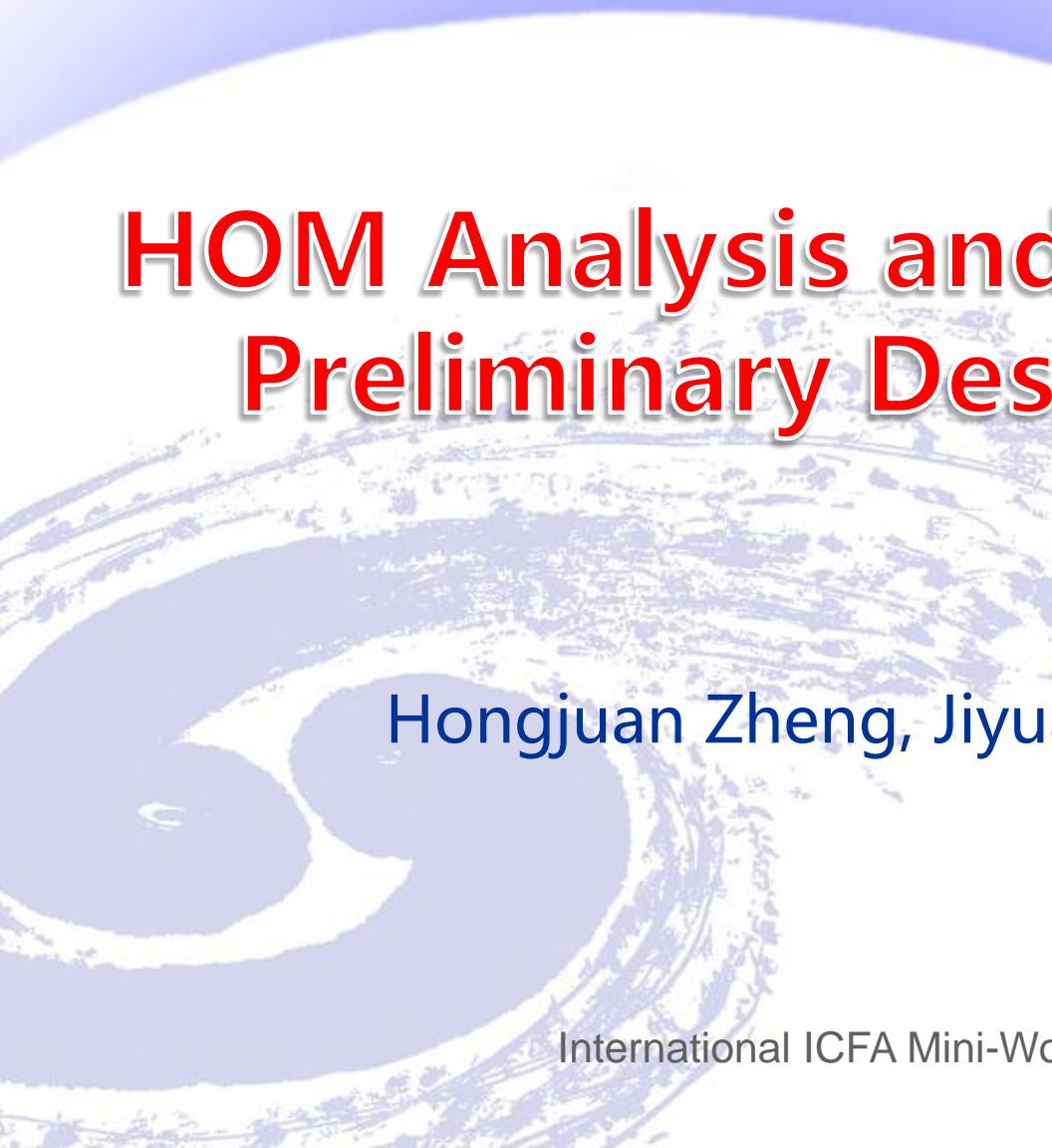


HOM Analysis and HOM Coupler Preliminary Design for CEPC



Hongjuan Zheng, Jiyuan Zhai, Jie Gao



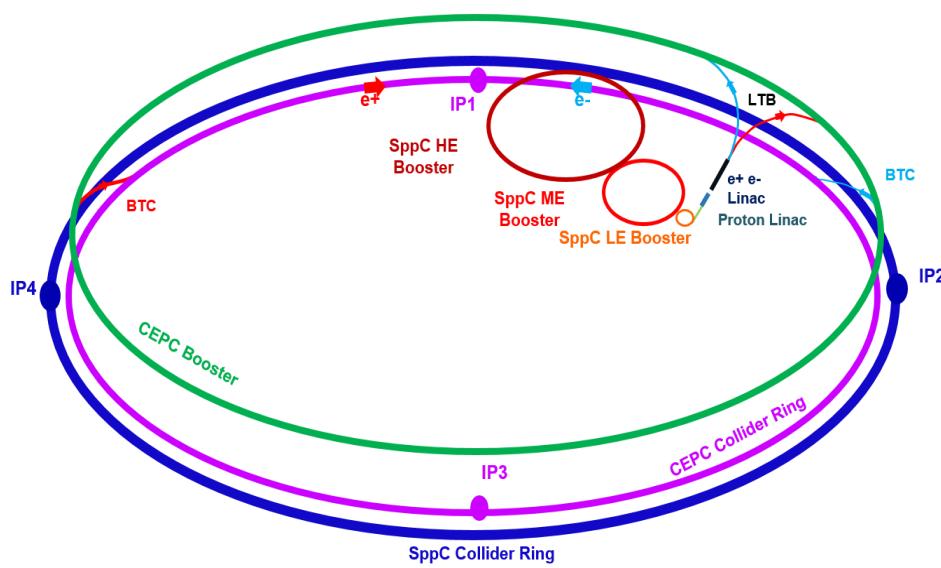
Outline

- CEPC SRF introduction
- HOM analysis for CEPC main ring (MR)
 - Eigenmode analysis
 - HOM power spectrum
 - HOM impedance of MR cavity
 - HOM damping scheme and damping results
- SOMs analysis
- Summary



CEPC Project

- CEPC is a Circular Electron Positron Collider operating at 240 GeV center-of-mass energy as a Higgs factory (also run at W and Z-pole energy), proposed by the Chinese HEP community in 2012.
- SPPC (Super Proton Proton Collider) will be installed in the same tunnel.
- CEPC Pre-CDR published in 2015, CDR in 2017, TDR in 2021



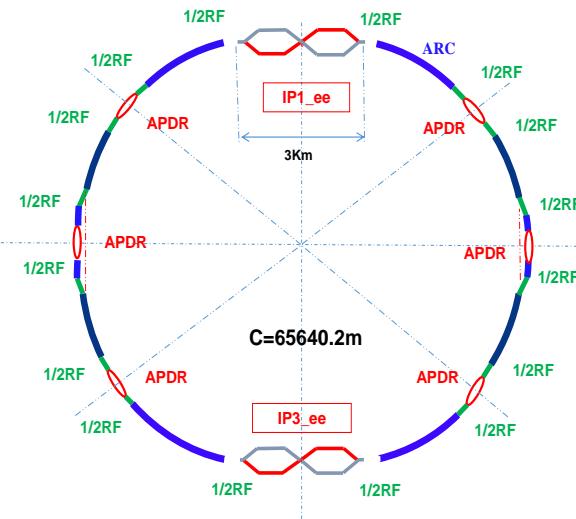
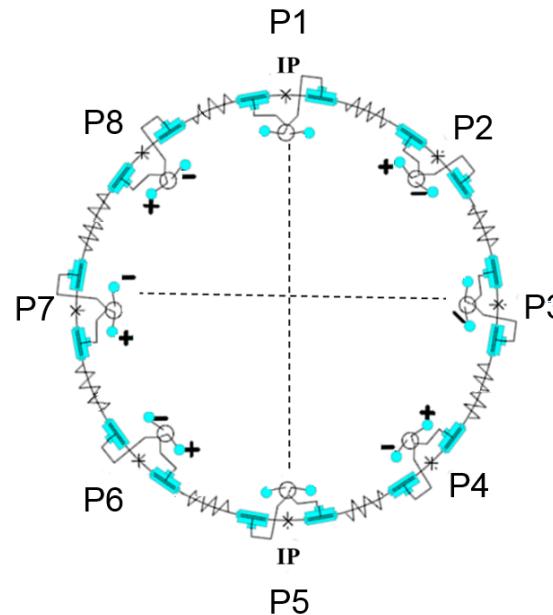
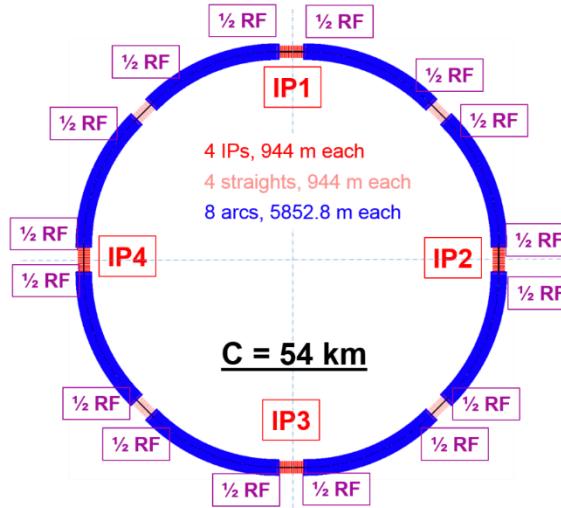
<http://cepc.ihep.ac.cn/>



Circumference: 50-70 (100) km
CEPC Beam Energy: 45.5 – 120 GeV
SPPC Beam Energy: 35 - 50 TeV
CEPC SR Power < 100 MW



CEPC Layout and RF System



Pre-CDR: Single Ring (e^+ and e^- in the same vacuum tube) with pretzel to separate bunches (equal spacing) at parasitic crossing, Head-on Collision => Higgs luminosity $2E34 \text{ cm}^{-2}\text{s}^{-1}$, W & Z lumi. limited by bunch number => 8 straight sections for RF, High RF voltage

CDR: Bunch train (1~4 bunch trains per beam) with partial double ring (PDR) separation, or full double ring (DR), Crab-waist Collision => Higgs, W & Z luminosity $\sim 2E34 \text{ cm}^{-2}\text{s}^{-1}$ =>

PDR: RF sections symmetry to the 2~8 crossing points, DR: two common RF sections with max half-fill buckets and magnet tapering, Low RF voltage.

CEPC MR Parameters (54 km)

	H (Pre-CDR)	H (HL)	H (LP)	W	Z
Energy (GeV)	120	120	120	80	45.5
Circumference (km)	54.793	54	54	54	54
Luminosity per IP ($10^{34} \text{ cm}^{-2}\text{s}^{-1}$)	2.1	2.94	1.96	3.1	3.1
Total power loss per beam (MW)	52.9	51.5	31.6	15.8	2.96
Synchrotron radiation loss per turn (GeV)	3.11	3.01	3.01	0.594	0.062
Parasitic loss per turn (GeV)	0.071	0.03	0.02	0.008	0.004
Total energy loss per turn (GeV)	3.18	3.03	3.03	0.594	0.062
RF voltage (parasitic loss included) (GV)	7.03	3.65	3.56	0.82	0.13
Momentum compaction factor (10^{-5})	3.36	2.5	2.2	2.4	2.5
RF frequency (MHz)	650	650	650	650	650
Harmonic number	118800	117081	117081	117081	117081
Bunch synchrotron phase (off-crest) (deg)	63.1	33.8	31.5	42.8	58.8
Bunch length (mm)	2.65	4.1	4.1	3.35	4.0
Bunch charge (nC)	60.8	45.6	42.7	11.8	7.4
Bunch number	50	67	44	400	1100
Beam average current (one beam) (mA)	16.6	17.0	10.4	26.3	45



CEPC MR Parameters (54 km)

	H (Pre-CDR)	H (HL)	H (LP)	W	Z
Single bunch current (mA)	0.33	0.25	0.24	0.07	0.04
Beam pulse current (PDR) (mA)	/	286.2	176.1	443.7	758.5
Revolution frequency (kHz)	5.5	5.6	5.6	5.6	5.6
Revolution time (μs)	182.8	180.1	180.1	180.1	180.1
Bunch train length (PDR) (μs)	/	10.62	10.63	10.46	10.15
Bucket number in bunch train	/	6798	6751	6783	6594
Bunch spacing (SR or DR) (μs)	3.66	2.7	4.1	0.5	0.2
Bunch spacing in train (PDR) (ns)	/	158.5	241.5	26.2	9.2
Beam gap length (PDR) (μs)	/	0.33 ~ 90	0.33 ~ 90	0.33 ~ 90	0.33 ~ 90
Energy spread total (%)	0.16	0.171	0.171	0.09	0.05
Energy acceptance (RF) (%)	6.1	2.1	2.0	1.7	1.2
Synchrotron tune	0.18	0.09	0.08	0.06	0.04
Transverse damping time (ms/turn)	14/75	14/79	14/79	48/266	249/1381
Longitudinal damping time (ms/turn)	7/38	7/40	7/40	24/133	124/691

CEPC MR SRF Parameters (54 km)

Parameters	H (Pre-CDR)	H (High L)	H (Low P)	W	Z
650 MHz cavity (bulk Nb)	5-cell	2-cell	2-cell	2-cell	1-cell
Cavity number	384	384	384	128	32
V_{RF} (GeV)	7	3.65	3.56	0.82	0.13
E_{acc} (MV/m)	15.9	20.6	20.1	13.9	17.2
Q_0 @ 2 K	4E10	2E10	2E10	5E9	5E9
Cryomodule number	96	64	64	32	16
Input power / cav. (kW)	276	268	164.8	247.3	185.1
HOM power / cav. (kW)	3.6	0.8	0.5	0.4	0.2
Total RF power (MW)	106	103	63	32	6
Total cav. wall loss@4.5K eq. (kW)	22.2	30	28.5	18.2	3.5



HOM Challenges of CEPC

- Extract large HOM power (1~3.5 kW per cavity) with wide spectrum
 - Waveguide or coaxial HOM coupler
- HOM issues of bunch train operation
 - HOM power spectrum for bunch train scheme
 - high pulsed peak power (4~7 kW, RF breakdown, not thermal effect)
 - special instabilities (higher instability threshold, linac-like BBU?)
- HOM heat load in multi-cavity cryomodule
 - high Q_0 and large machine scale require small HOM heat load
 - HOM power propagation through cavities
 - heat load on the normal-conducting bellows and connections (copper-plating or superconducting bellow?)
 - cable heat load
- HOM damping of the booster ring (in the same tunnel with MR)
 - 1.3 GHz 9-cell cavity
 - small radiation damping at low energy (6 ~ 120 GeV ramp for Higgs)

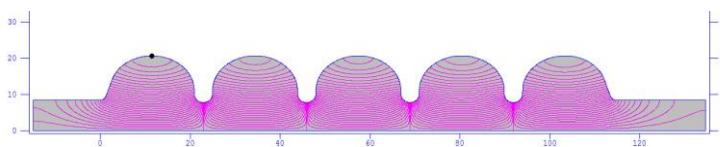


HOM Heat Load Budget

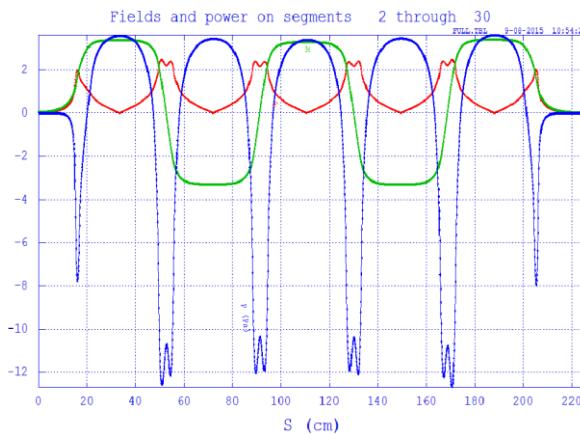
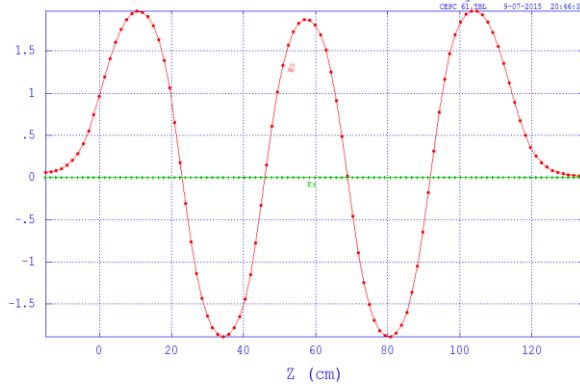
	Main Ring	Booster
HOM power / cavity	3.5 kW	5.3 W
HOM power / module	21 kW	56 W
HOM 2K heat load / module	13 W (0.06 %)	5.9 W
HOM 5K heat load / module	39 W (0.18 %)	3 W
HOM 80K heat load / module	390 W (1.8 %)	43.8 W
Percent of total cryogenic load	22 %	11 %

- Main Ring heat load: design upper limit (estimated to have enough margin)
- Booster heat load: scaled from ILC TDR (DF 50 % for continuous injection)

CEPC Cavity for MR Pretzel Scheme



Electromagnetic field data from file CEPC 650MHZ CAVITY.AF
Problem title line 1: CEPC 650MHz cavity



Parameter	Unit	Main Ring
Cavity frequency	MHz	650
Number of cells	-	5
Cavity effective length	m	1.154
Cavity iris diameter	mm	156
Beam tube diameter	mm	170
Cell-to-cell coupling	-	3 %
R/Q	Ω	514
Geometry factor	Ω	268
$E_{\text{peak}}/E_{\text{acc}}$	-	2.4
$B_{\text{peak}}/E_{\text{acc}}$	$\text{mT}/(\text{MV/m})$	4.23
Cavity longitudinal loss factor $k_{\parallel \text{ HOM}}^*$	V/pC	1.8
Cavity transverse loss factor k_{\perp}^*	V/pC/m	2.4
Acceptance gradient	MV/m	20
Acceptance Q_0	-	4E10

* collider bunch length 2.65 mm



Eigenmode Analysis

Two separate eigenmode simulations for just a single cell, with **periodic boundary conditions (PBC)**, were computed. 34 modes up to 1.8 GHz were calculated.

Results:

0 mode and π mode frequency for every passband.

Number of modes within one passband depends on number of cells in the cavity.

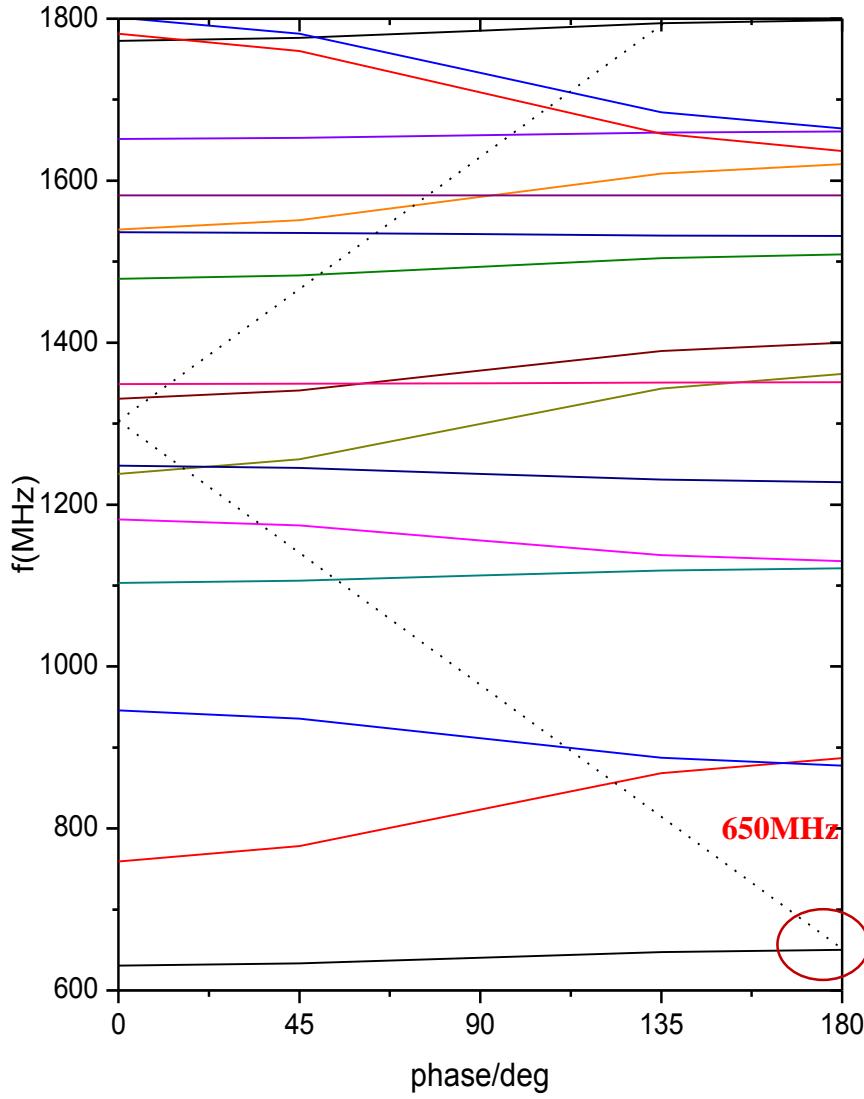
The cell to cell coupling factor is

$$k_{cc} = 2 \cdot \frac{f_\pi - f_0}{f_\pi + f_0}$$

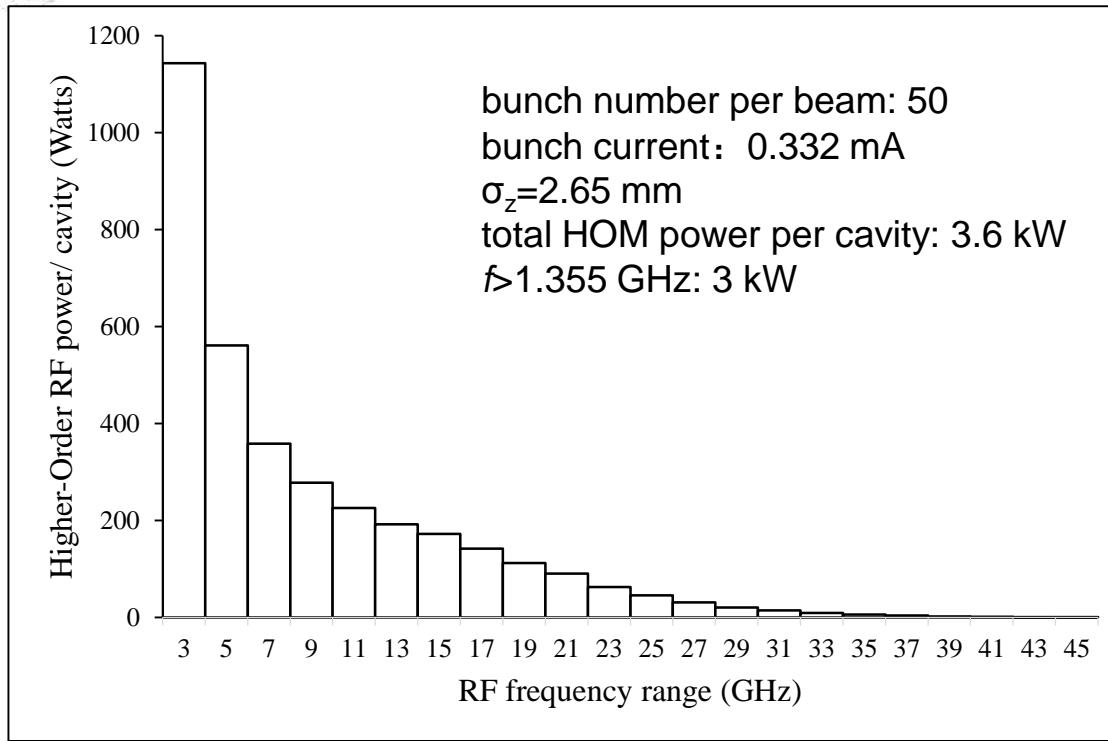
For small k_{cc} values there is a danger that if that given mode is excited by the beam, it will propagate and decay very slowly.

➤ Analysis results:

There is no trap mode till 1.8 GHz.



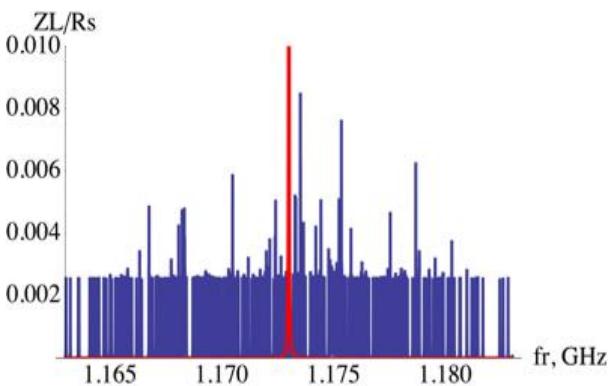
HOM Power



- Average power losses calculated as single pass excitation. HOM power damping of **3.6 kW** for each 650 MHz 5-cell cavity.
 - In ideal case, only 600 W (TM011 and TM020) is confined in one cavity, 80 % above cut-off frequency of the 170 mm beam pipe and they will propagate through cavities and finally absorbed by the two HOM absorbers at RT outside cryomodule.
 - Each absorber has to damp about 10 kW HOM power, can't be in the cryogenic region.
- LEP:
 - 4 cavity/module
 - HOM power in a module: 1720 W
 - above cut off (2.2 GHz): 620 W
 - Question:
 - How much of the HOM power is extracted by the HOM damper (coaxial or waveguide)?
 - How much power is propagating through the beam pipe and among the cavities?
 - Local damping or almost propagating and absorb at RT?

HOM Impedance of MR Cavity

- Frequency spread between cavities
 - Large HOM frequency spread from cavity to cavity **relaxes the Q requirement.**
 - The frequency of TM011 is 1.173 GHz and Q_{limit} for this mode is 5.76×10^5 . If the frequency spread is **5 MHz**, the impedance threshold increase about two orders of magnitude.
 - The frequency is normal distribution after we consider the frequency spread.



$$Z_L = \frac{R_s}{1 + iQ(\frac{f_0}{f} - \frac{f}{f_0})}$$

Monopole Mode	f (GHz)	$R/Q(\Omega)^*$	Q_{limit} $\sigma_{fr}=0\text{MHz}$	Q_{limit} $\sigma_{fr}=0.5\text{MHz}$	Q_{limit} $\sigma_{fr}=5\text{MHz}$
TM011	1.173	84.8	5.76×10^5	2.9×10^7	5.8×10^7
TM020	1.427	54.15	7.72×10^6	3.7×10^7	7.5×10^7
Dipole Mode	f (GHz)	$R/Q(\Omega/\text{m})^{**}$	Q_{limit} $\sigma_{fr}=0\text{MHz}$	Q_{limit} $\sigma_{fr}=0.5\text{MHz}$	Q_{limit} $\sigma_{fr}=5\text{MHz}$
TE111	0.824	832.23	2.35×10^4	1.2×10^6	2.4×10^6
TM110	0.930	681.15	2.87×10^4	1.5×10^6	3.0×10^6
TE122	1.232	544.5	5.4×10^5	1.9×10^6	3.7×10^6
TM112	1.440	101.53	1.93×10^5	1.0×10^7	2.0×10^7

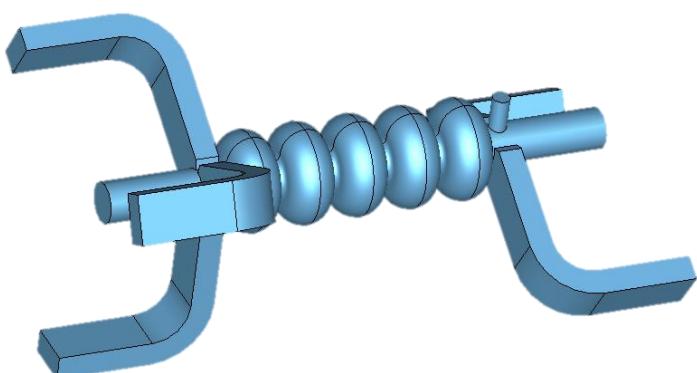
$$* k_{\parallel \text{mode}} = 2\pi f \cdot (R/Q) / 4 \text{ [V/pC]}$$

$$** k_{\perp \text{mode}} = 2\pi f \cdot (R/Q) / 4 \text{ [V/(pC·m)]}$$

- DESY TESLA cavity measured spread: TM011 9 MHz, TE111 5 MHz, TM110 1~6 MHz, TE121 2 MHz.

CEPC Main Ring 5-Cell Cavity with Waveguide HOM Couplers

- 5-cell cavity with two asymmetrical end groups + JLab HOMs waveguide couplers.
- HOM couplers
 - The structure of waveguide HOM coupler is simple.
 - Cutoff is natural rejection filter for fundamental mode.
 - HOM power can be dissipated in loads located at ambient temperature.
 - High power handling capability.
- Higher Order Modes
 - HOM power for 2 beam is 3.63 kW/cavity
 - Q_e as low as possible
 - Identification of dangerous modes
- Impedance budget
 - To keep the beam stable, the radiation damping time should be less than the rise time of any of the oscillation modes.
 - In the resonant condition, the threshold shunt impedances are

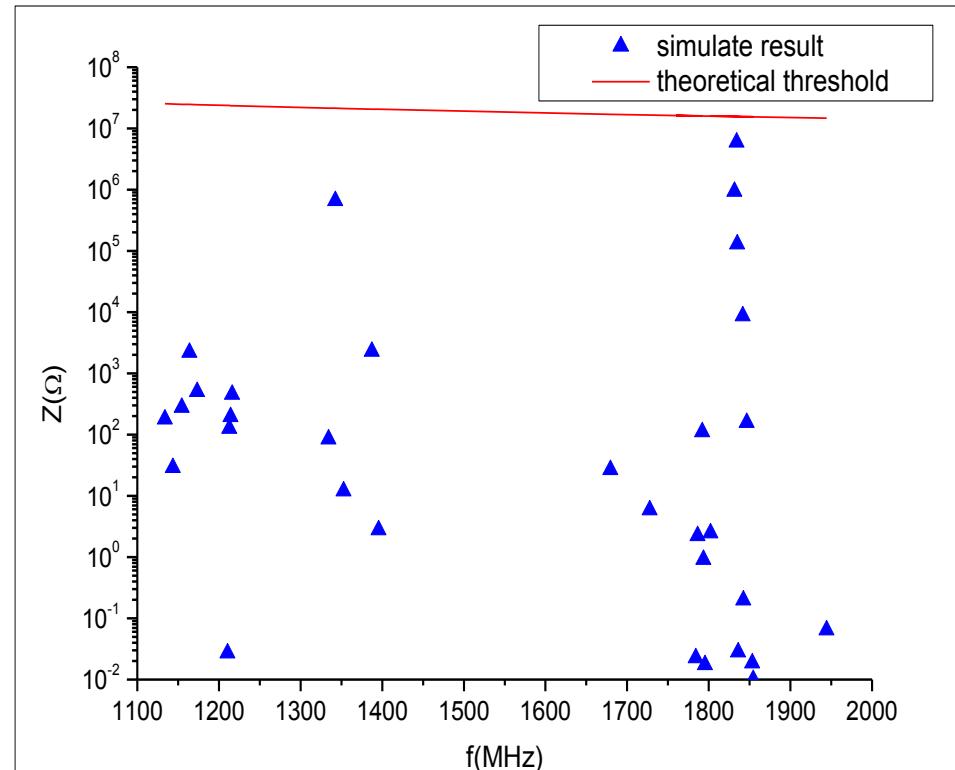


$$R_L^{\text{thresh}} = \frac{2(E_0 / e)\nu_s}{N_c f_L I_0 \alpha_p \tau_z} = \frac{28.7 \text{M}\Omega \text{GHz}}{f_L (\text{GHz})}$$

$$R_T^{\text{thresh}} = \frac{2(E_0 / e)}{N_c f_{rev} I_0 \beta_{x,y} \tau_{x,y}} = 9.77 \text{M}\Omega/\text{m}$$

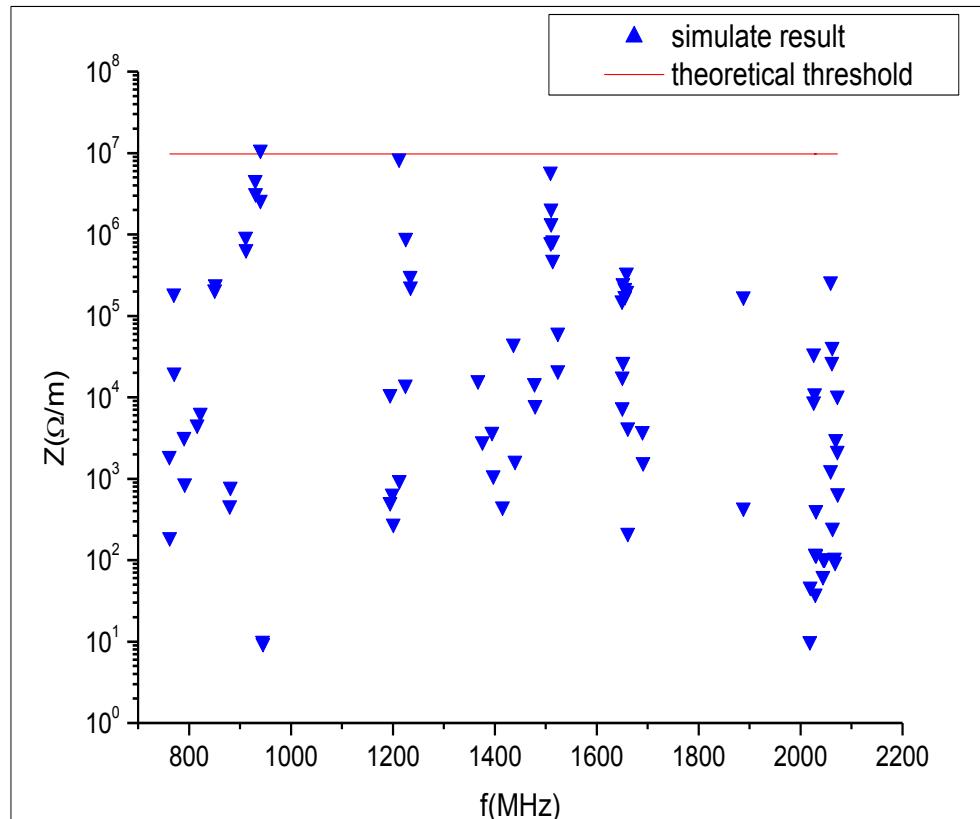
Monopole Modes Damping Results

- The cutoff frequency of the beam tube for TM01 mode is 1.355 GHz.
- Q_e for fundamental mode is 4E11.
- For $f < 2$ GHz, all of the monopole modes damping results are under the longitudinal impedance threshold.
- The Q_e for most of monopole modes is below 10^3 , a few of them is about 10^5 .
- If the Q_0 for the monopole modes is 10^{10} . The HOM power loss on cavity is only a few milliwatts.

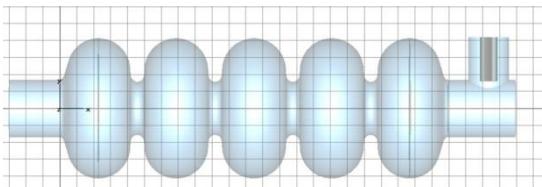


Dipole Modes Damping Results

- The cutoff frequency of the beam tube for TE11 mode is 1.04 GHz.
- For $f < 2$ GHz, most of the dipole modes damping results are under the transverse impedance threshold.
- If the frequency spread is 0.5 MHz, the impedance threshold can increase 1~2 orders of magnitude. So, the design can meet the damping requirements.



Same Order Modes (SOMs) Damping



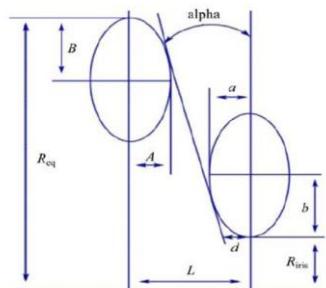
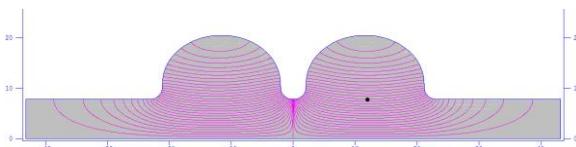
- Use the input coupler as the SOM coupler.
- The external quality factor (Q_e) of the input coupler for the fundamental mode is 2.2×10^6 .
- The damping for the SOMs by the input coupler is very efficient!

mode	f (MHz)	R/Q (Ω)	Q_{limit}	$Q_{\text{input coupler}}$	P_{SOM} (W)	$P_{\text{SOM-res}}$ (W)
$\pi/5$	632.322	0.02	4.5E+9	1.2E+07	1.3E-5	268.9
$2\pi/5$	637.099	0.00017	5.4E+11	3.3E+06	8.7E-7	0.6
$3\pi/5$	643.139	0.341	2.6E+8	1.7E+06	9.31E-3	638.9
$4\pi/5$	648.146	0.078	1.1E+9	1.2E+06	2.92E-4	105.8

The analysis results show that the total SOM power is quite small when we consider the real cavity passband modes frequencies and the bunch time spacing of the collider. Even assuming resonant excitation, the total SOM power is about 1 kW and with the input coupler damping, the power dissipated on the cavity wall is negligible (~ 0.1 W).

2-cell Cavity for Crab Waist Scheme

- 5-cell cavity was designed for pretzel scheme. However, it is not suitable for crab waist scheme.
- 2-cell cavity is chosen for crab waist scheme. The selection basis are
 - Accelerating gradient
 - HOMs
 - HOM power
 - HOM power coupler
 - Impedance
 - Cryogenic
 - Transient beam loading
 - Cost
 -

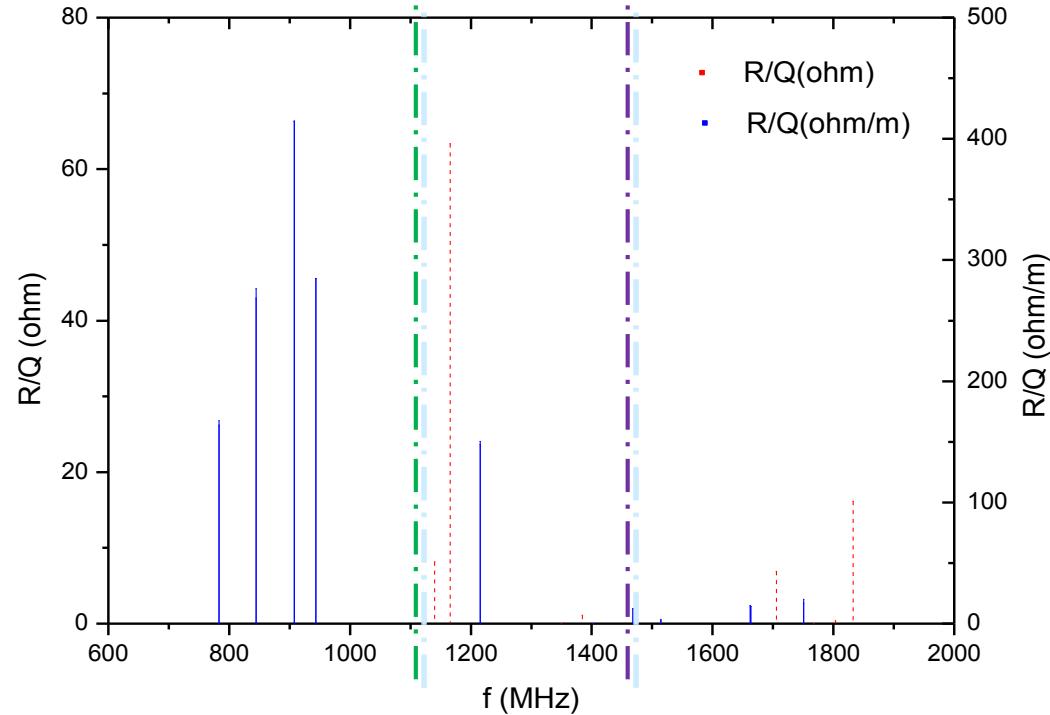


Parameters	Value
R_{iris} (mm)	78
Alpha (deg)	3.22
A (mm)	94.4
B (mm)	94.4
a (mm)	20.123
b (mm)	22.09
L (mm)	115.3
D (mm)	204.95
k	2.86%
R/Q (Ω)	212.731
G	284.113
E_p/E_{acc}	2.38
B_p/E_{acc} [mT/(MV/m)]	4.17
Total loss factor [V/pC]	$\sigma=4$ mm: 0.8111
Cut off frequency (MHz)	TE11: 1126 TM01: 1471



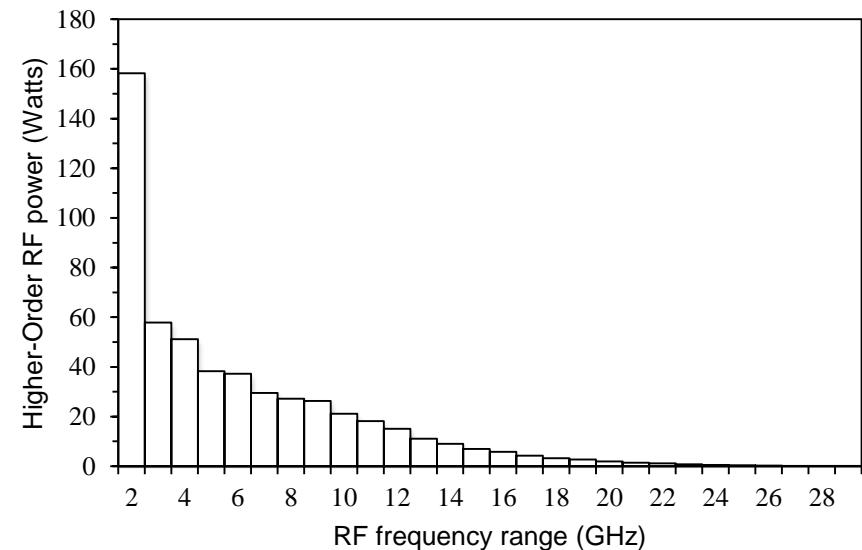
R/Q and HOM Power

cut off TE11: 1126 MHz cut off TM01: 1471 MHz



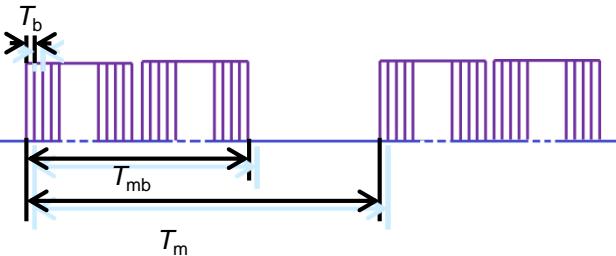
- The dangerous monopole modes are around 1200 MHz.
- The dangerous dipole modes are around 800 MHz~900 MHz and 1200 MHz.

Frequency distribution of HOM power

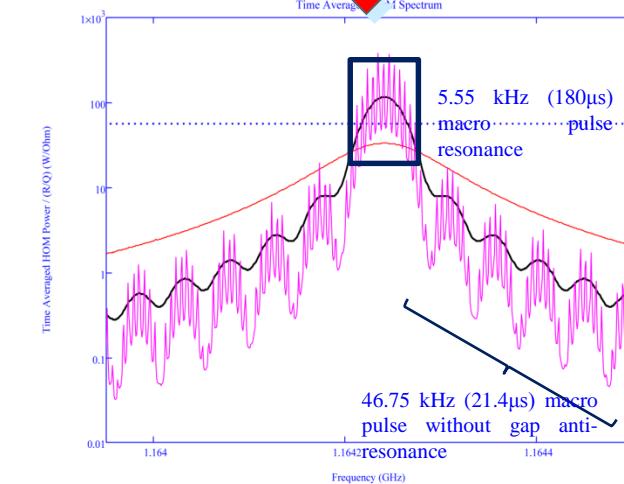
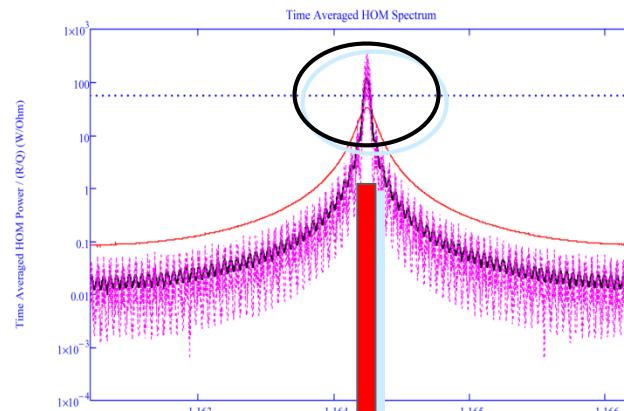
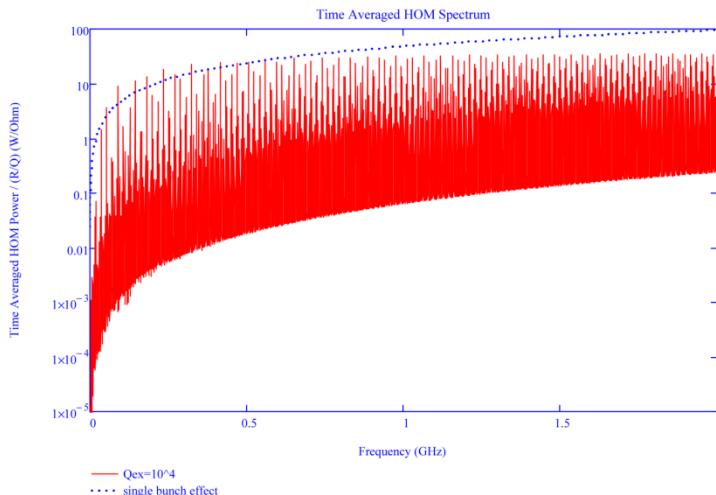


- 44 bunches per beam
- 0.238 mA av. in each bunch
- $\sigma_z=4$ mm
- total HOM power: 0.54 kW/cavity
- for $f > 1.47$ GHz: 0.42 kW

HOM Power Spectrum for Bunch Train Scheme



- Time structure of IP1 & IP3
- Macro-pulse period: $T_m = 180 \mu\text{s}$
- Pulse length: $T_{mb} = 21.4 \mu\text{s}$
- Macro-pulse gap length : $T_G = T_m - T_{mb} = 158.4 \mu\text{s}$
- Time spacing between bunches: $T_b = 243.1 \text{ ns}$



Bandwidth: 0.55 MHz

HOM Impedance of 2-cell Cavity

monopole	f (MHz)	R/Q (Ω) (2 cell)	R/Q^* (Ω) (1 cell)	Q_e (H-low power)	Q_e (Z-2 cell)	Q_e (Z-1 cell)
TM011	1165.536	63.4	33.63	4.74×10^4	1.02×10^3	1.95×10^3
TM020	1384.302	1.128	0.095	2.24×10^6	4.83×10^4	5.85×10^5
dipole	f (MHz)	R/Q (Ω/m) (2 cell)	R/Q^{**} (Ω/m) (1 cell)	Q_e (H-low power)	Q_e (Z-2 cell)	Q_e (Z-1 cell)
TE111	844.666	276.62	131.03	5.86×10^3	4.13×10^2	8.72×10^2
TM110	907.469	414.84	353.04	3.91×10^3	2.75×10^2	3.23×10^2
TM111	1279.043	----	219.98	----	----	5.19×10^2
TE121	1468.139	12.61	0.749	1.29×10^5	9.06×10^3	1.52×10^5

$$^* k_{\parallel \text{mode}} = 2\pi f \cdot (R/Q) / 4 \text{ [V/pC]}$$

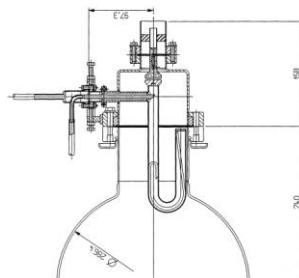
$$^{**} k_{\perp \text{mode}} = 2\pi f \cdot (R/Q) / 4 \text{ [V/(pC·m)]}$$

- Higgs: low power & 30 mrad crossing angle, 384 2-cell cavity
- Z: 32 2-cell or 1-cell cavity

Damping Scheme for Crab Waist Design

When the cavity and cryomodule configuration, HOM power and high frequency modes behavior are determined (which means how much power is to be extracted at the cavity beam pipe), we could choose the damper.

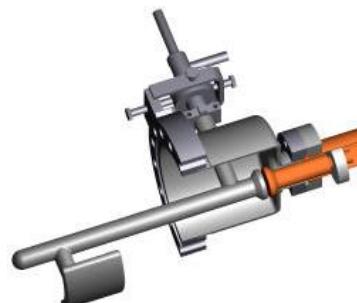
- In the crab waist case, only ~120 W per cavity confined in one cavity.
- Coaxial: notch filter BW and tuning, cooling, feedthrough antenna heating, RF connection heating, cable heating ...LEP/LHC-type, LHC-HL, BNL ERL& eRHIC HOM coupler for the kW level power capacity.
- KEKB and SuperKEKB ferrite HOM absorbers 20 kW at RT.



LEPII



LHC
(narrowband)



LHC
(broadband)



SOLEIL



Summary

- HOM power and heating are the main concerns for CEPC SRF design.
- 5-cell cavity with waveguide HOM coupler for pretzel scheme can meet the damping requirements.
- The damping for the SOMs by the input coupler is very efficient.
- 2-cell cavity with coaxial HOM coupler is the baseline for the future design.
- We hope to collaborate with more HOM experts.



Thank you for your attention !

CEPC MR SRF Parameters (54 km)

	H (Pre-CDR)	H (HL)	H (LP)	W	Z
RF section number (SR, PDR)	8	8	8	8	8
RF section number (DR common cavity)	/	2	2	2	2
Number of cells in a cavity	5	2	2	2	1
Number of cavities per module	4	6	6	4	2
Number of cryomodules per half RF section	6	4	4	2	1
Total number of cavities	384	384	384	128	32
Number of cryomodules	96	64	64	32	16
Cryomodule length (m)	10	10	10	8	5
Total module length (m)	960	640	640	256	80
Cavity operating voltage (MV)	18.3	9.5	9.3	6.4	4
Cavity operating gradient (MV/m)	16	20.6	20	14	17.2
Operating temperature (K)	2	2	2	2	2
Q ₀ at operating gradient	4E10	2E10	2E10	5E9	5E9
Cavity loss factor (HOM) (V/pC)	1.8	0.54	0.54	0.62	0.27

CEPC MR SRF Parameters (54 km)

	H (Pre-CDR)	H (HL)	H (LP)	W	Z
R/Q (Ω)	514	206	206	206	103
Geometry factor (Ω)	268				
Cavity effective length (m)	1.153	0.461	0.461	0.461	0.231
Cavity iris diameter (mm)	156				
$E_{\text{peak}} / E_{\text{acc}}$	2.4				
$B_{\text{peak}} / E_{\text{acc}}$ (mT / (MV/m))	4.2				
Cavity stored energy (J)	160	108	102	49	38
Q_L	2.4E6	1.6E6	2.5E6	8.1E5	8.3E5
Cavity bandwidth (kHz)	0.3	0.4	0.3	0.8	0.8
Cavity time constant (μ s)	1157	803	1241	396	406
Detuning frequency (kHz)	-0.27	-0.13	-0.08	-0.37	-0.65
RF average power / cavity (kW)	275.7	268	164.8	247.3	185.1
Total RF power (MW)	106	103	63	32	6
HOM power / cavity (SR, PDR, DR) (kW)	3.6	0.8	0.5	0.4	0.2
Pulsed HOM power per cavity (PDR) (kW)	/	7	4	3.3	1.6
Wall loss per cavity (W)	16.3	22	20.9	40	30.7
Total cavity wall loss (kW)	22.2	30	28.5	18.2	3.5



HOM Heat Load Estimation

- Assume 10 kW HOM power propagating through the beam tubes and bellows (thin copper film RRR=30, in abnormal skin effect regime), power dissipation < 2 W/m @ 2K.
 - Even RRR=1 for copper plating (normal skin effect regime), power dissipation < 10 W/m
- HOM power loss in cavity at 2 K less than 0.3 W (all modes $Q_{\text{ext}} < 10^6$)
- Heat load at 5 K and 80 K dominated by HOM cable heating.
Assume 0.1 dB/m power dissipation of the LEP/LHC-type rigid coaxial line (copper plated stainless steel) and 1 m length, total heat load is 10 W for the resonant excitation of TM011 mode.
- Further study: HOM propagating, heat load calculation, statistical approach to study heat load at 2 K (LCLS-II), trap mode ...