Design Issues of CEPC SRF System

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- Main parameter choices
- HOM and SOM damping
- Booster RF transients
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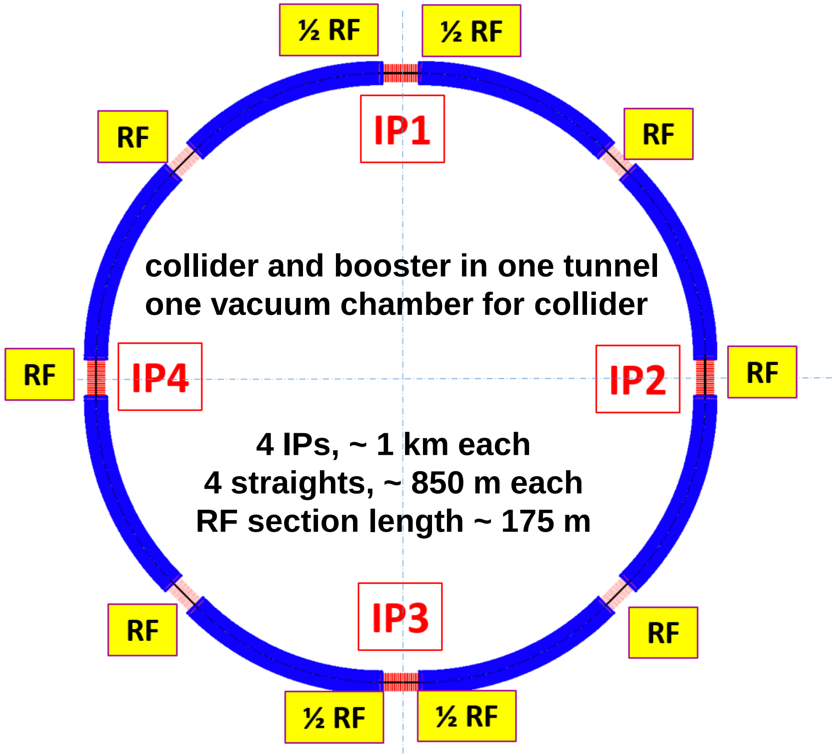
CEPC Top-level Parameters related to SRF System (1)

Parameter	**Unit**	**Main Ring**	**Booster Injection**	**Booster Extraction**
Beam energy	GeV	120	6	120
Circumference	km	54.752	54.752	54.752
Luminosity / IP	$cm^{-2}s^{-1}$	2.04E+34	-	-
Energy loss / turn	GeV	3.11	17.6 keV	2.81
SR power	MW	103.42	16.2 W	2.46
Revolution period	s	1.83E-04	1.83E-04	1.83E-04
Revolution frequency	kHz	5.4755	5.4755	5.4755
Bunch charge	nC	60.56	3.35	3.2
Bunch number	-	100	50	50
Beam current (total)	mA	33.2	0.92	0.87
Bunch spacing	μs	1.825	3.65	3.65
Beam spectrum spacing	MHz	0.55	0.274	0.274

CEPC Top-level Parameters related to SRF System (2)

Parameter	Unit	Main Ring	Booster Injection	Booster Extraction
Momentum compaction	-	3.36E-05	7.69E-05	7.69E-05
Energy spread	%	0.1629	0.1 (linac)	0.127
Bunch length	mm	2.65	1.5 (linac)	2.66
RF voltage	GV	6.87	0.213867	5.12
RF frequency	GHz	0.65	1.3	1.3
Harmonic number	-	118800	237423	237423
Synchrotron tune	-	0.180	0.32076	0.32076
Energy acceptance (RF)	%	5.99	17.307	2.091
Transverse damping time	turns	77.05	682122 (125 s)	85.2 (15.56 ms)
Longitudinal damping time	turns	38.52	341219 (62 s)	42.7 (7.789 ms)
Lifetime Bhabha	min	51.77	-	-
Lifetime BS (sim.)	min	47	-	-

CEPC SRF System Layout

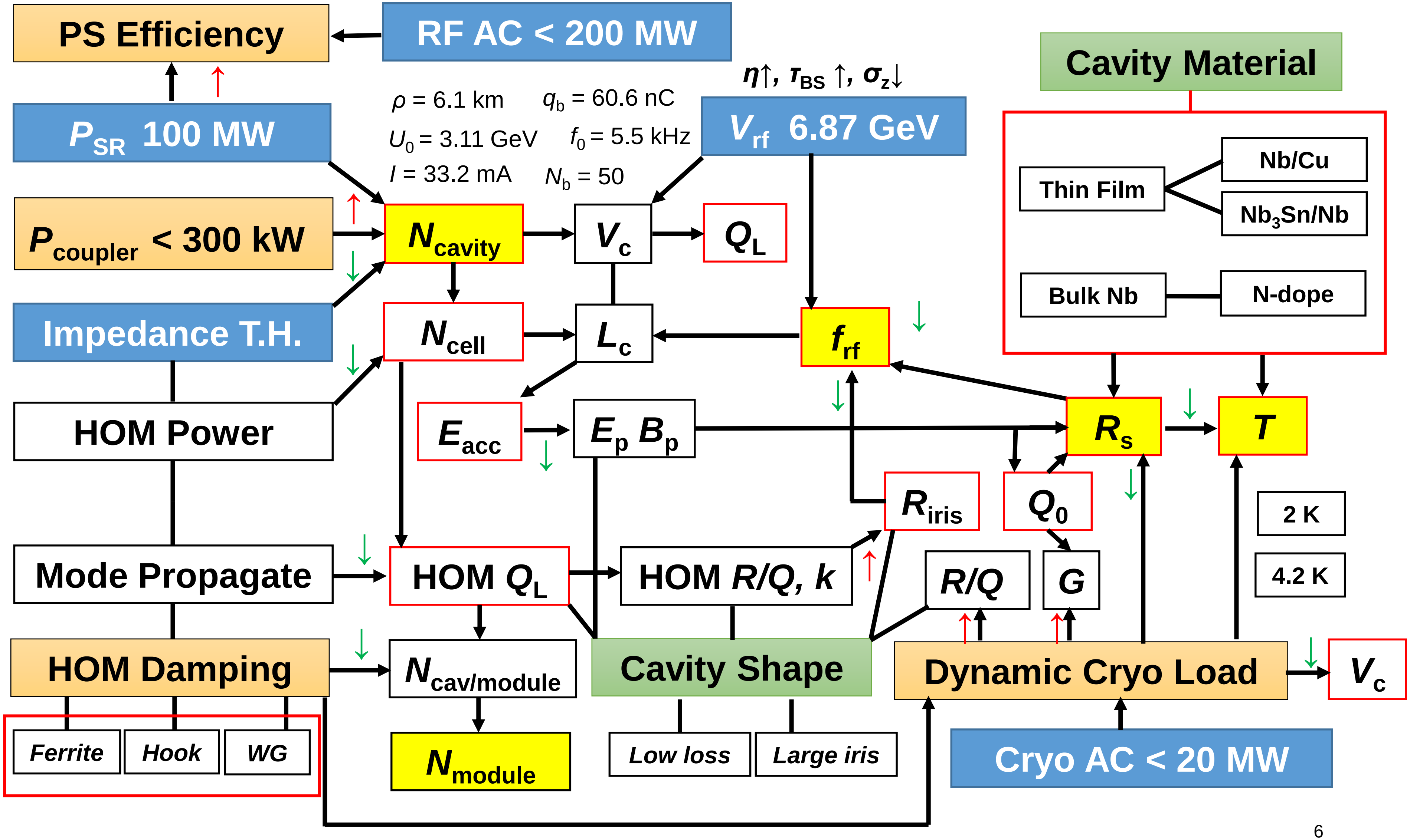


Collider: 120 GeV, 54 km, 50+50 bunches, 60.6 nC, 33.2 mA (CW)

Booster: 6 - 120 GeV, 54 km, 50 bunches, 3.2 nC, 0.87 mA (quasi-CW)

- # Cavity: 640
- # Module: 128
- Module length: 1.4 km
- RF voltage: 12 GeV
- Beam power: 104.5 MW
- HOM power: 2 MW
- Installed RF power: ~ 160 MW
- Installed cryogenics: ~ 100 kW @ 4.5 K

Main Ring SRF System Design Criteria



PS Efficiency

RF AC < 200 MW

Cavity Material

P_{SR} 100 MW

ρ = 6.1 km q_b = 60.6 nC

U_0 = 3.11 GeV f_0 = 5.5 kHz

I = 33.2 mA N_b = 50

$\eta\uparrow$, $\tau_{BS}\uparrow$, $\sigma_z\downarrow$

V_{rf} 6.87 GeV

Thin Film

Nb/Cu

Nb_3Sn/Nb

Bulk Nb

N-dope

$P_{coupler}$ < 300 kW

N_{cavity}

V_c

Q_L

Impedance T.H.

N_{cell}

L_c

f_{rf}

HOM Power

E_{acc}

E_p B_p

R_s

T

R_{iris}

Q_0

2 K

4.2 K

Mode Propagate

HOM Q_L

HOM R/Q, k

R/Q

G

HOM Damping

$N_{cav/module}$

Cavity Shape

Dynamic Cryo Load

V_c

Ferrite

Hook

WG

N_{module}

Low loss

Large iris

Cryo AC < 20 MW

CEPC SRF Main Parameters

Parameters	CEPC-Collider	CEPC-Booster	LEP2
Cavity Type	650 MHz 5-cell Nitrogen-doped Nb	1.3 GHz 9-cell Nitrogen-doped Nb	352 MHz 4-cell Nb/Cu sputtered
Cavity number	384	256	288
V_{cav} / V_{RF}	17.9 MV / 6.87 GeV	20 MV / 5.12 GeV	12 MV / 3.46 GeV
E_{acc} (MV/m)	15.5	19.3	6 ~ 7.5
Q_0	4E10 @ 2K	2E10 @ 2K	3.2E+9 @ 4.2K
Cryomodule number	96 (4 cav. / module)	32 (8 cav. / module)	72 (4 cav)
RF input power / cav. (kW)	280	20	125
RF source number	384 (400 kW)	256 (25 kW)	36 (1.2 MW/8 cav)
HOM damper (W)	10k ferrite +1k hook	50 (hook+ceramic)	300 (hook)

Cavity Design Parameters

Parameter	Unit	Main Ring	Booster
Cavity frequency	MHz	650	1300
Number of cells	-	5	9
Cavity effective length	m	1.154	1.038
Cavity iris diameter	mm	156	70
Beam tube diameter	mm	170	78
Cell-to-cell coupling	-	3 %	1.87 %
R/Q	Ω	514	1036
Geometry factor	Ω	268	270
$E_{\mathrm{peak}}/E_{\mathrm{acc}}$	-	2.4	2
$B_{\mathrm{peak}}/E_{\mathrm{acc}}$	mT/(MV/m)	4.23	4.26
Cavity longitudinal loss factor* $k_{/\!/ \mathrm{HOM}}$	V/pC	1.8	3.34
Cavity transverse loss factor* $k_{\perp}$	V/pC/m	2.4	35.3
Acceptance gradient	MV/m	20	23
Acceptance Q_0 at acceptance gradient	-	4E10	2E10

* main ring bunch length 2.65 mm, booster bunch length 2.66 mm

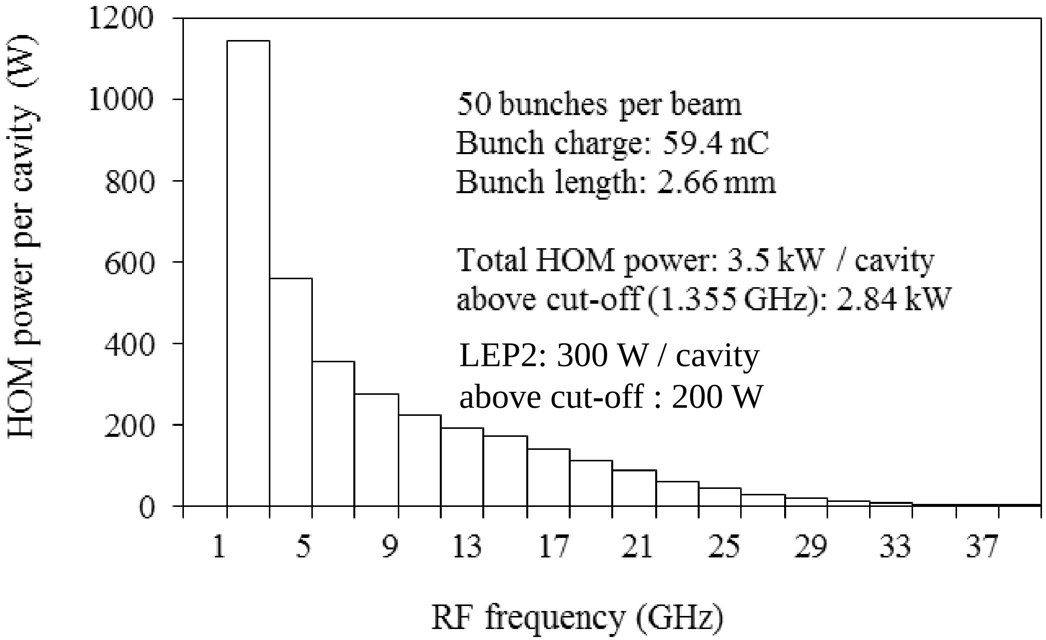
Input Coupler Power and Cavity Number

- When the input coupler power and total synchrotron radiation power are fixed, the total number of cavities is determined.
- Reducing the total RF voltage will only reduce the cavity RF voltage, not the total cavity number.
- Main ring coupler power 280 kW => 384 cavities => 18 MV each
  - coupler should be compatible to cavity clean assembly (two windows)
  - balance SRF capital cost and coupler operational risk
  - if BEPCII coupler power level (~ 130 kW), 384 more cavities
  - if higher than 300 kW, risk (KEKB 380 kW, LHC 300 kW, ~ 10-20 pieces)

CEPC HOM Power

- Very small beam spectral line spacing: main ring 0.55 MHz, booster 0.275 MHz.
- Impossible to detune HOM modes away from beam spectral lines with large HOM frequency scattering from cavity to cavity
  - by fabrication tolerances and RF tuning of the fundamental mode
  - DESY TESLA cavity measured spread: TM011 9 MHz, TE111 5 MHz, TM110 1~6 MHz, TE121 2 MHz
- Average power losses calculated as single pass excitation. HOM power damping of 3.5 kW for each 650 MHz 5-cell cavity and 21 kW for each cryomodule of the CEPC main ring.

HOM Power Spectrum and Damping



80 % above cut-off frequency , propagate through cavities and finally absorbed by the two HOM absorbers at room temperature outside the cryomodule.

Each absorber has to damp about 10 kW HOM power, can't be in the cryogenic region.

- LEP/LHC-type HOM coupler for the kW level power capacity. BNL also developing new kW class coaxial HOM couplers.
- KEKB and SuperKEKB ferrite HOM absorbers 20 kW.
- Waveguide at the cavity beam pipe is also a possible solution for the main ring cavity HOM power extraction.
- XFEL/ILC type HOM coupler and absorber can easily handle the booster HOM power. Ceramic HOM absorber at 70 K in the cryomodule beam line.

HOM Heat Load Budget

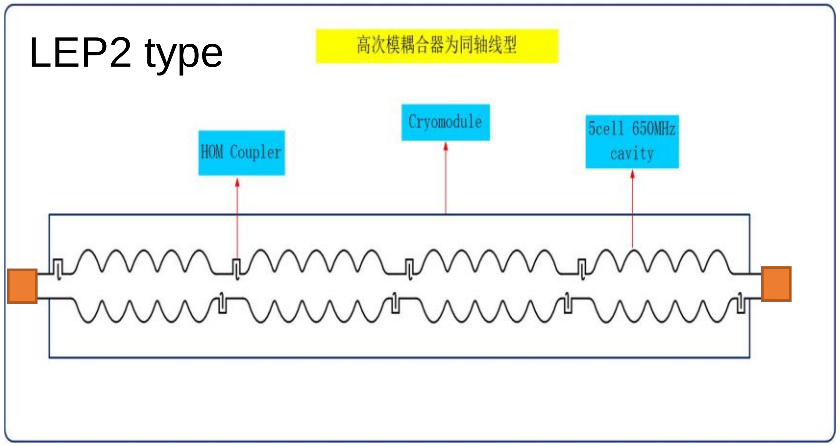
	Main Ring	**Booster**
HOM power / cavity	3.5 kW	5.3 W
HOM power / module	21 kW	56 W
HOM 2K heat load / module	13 W (0.6 %)	5.9 W
HOM 5K heat load / module	39 W (1.8 %)	3 W
HOM 80K heat load / module	390 W (18 %)	43.8 W
Percent of total cryogenic load	22 %	11 %

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

HOM Heat Load Estimation

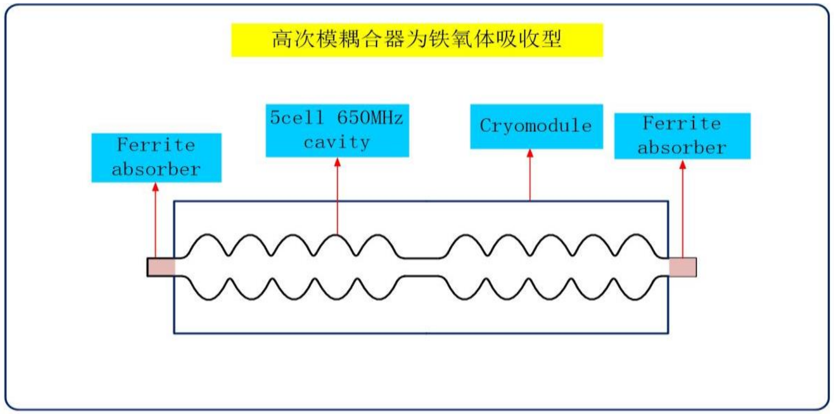
- Assume 10 kW HOM power propagating through the beam tubes and bellows (thin copper film RRR=30, in abnormal skin effect regime), power dissipation < 2 W/m @ 2K.
  - Even RRR=1 for copper plating (normal skin effect regime), power dissipation < 10 W/m
- HOM power loss in cavity at 2 K less than 0.3 W (all modes $Q_{ext} < 10^6$)
- 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 …

HOM Damping Scheme



Inter-cavity beam pipe (and bellow) diameter will determine the fraction of HOM power propagating out of the cryomodule.

Let most HOMs confine in one cavity and extract them out or let them go through cavities? How much will trap, especially the grey zone?



Conservative scheme: two cavities in one module.

Another possible solution is hybrid module with water cooled HOM absorber inside.

Need further study. Critical issue.

HOM Impedance of Main Ring 650 MHz Cavity

Monopole Mode	f (GHz)	R/Q (Ω)	Q_{limit} $\sigma_f = 0$ MHz	Q_{limit} $\sigma_f = 0.5$ MHz	Q_{limit} $\sigma_f = 5$ MHz	
TM011	1.173	84.8	5.1E+5	2.9E7	5.8E7	
TM020	1.350	5.5	6.8E+6	3.7E7	7.5E7	cut-off
Dipole Mode	f (GHz)	R/Q (Ω/m)	Q_{limit} $\sigma_f = 0$ MHz	Q_{limit} $\sigma_f = 0.5$ MHz	Q_{limit} $\sigma_f = 5$ MHz	
TE111	0.824	832.2	2.3E+4	1.2E6	2.4E6	
TM110	0.930	681.2	2.8E+4	1.5E6	3.0E6	cut-off
TE112	1.225	36.2	5.2E+5	1.9E6	3.7E6	
TM111	1.440	101.5	1.9E+5	1.0E7	2.0E7	

- Large HOM frequency spread from cavity to cavity relaxes the Q requirement
- Easy to reach these Q values with HOM couplers on beam tubes for the modes below cut-off frequency
- Some modes above cut-off may trap in the cavity and cryomodule

HOM Impedance of Booster 1.3 GHz Cavity

Monopole Mode	*f* (GHz)	*R/Q* (Ω)	$Q_{measured}$ *	σ_f (MHz) *	τ^{**} (ms)
TM011	2.450	156	5.9E4	9	1500
TM012	3.845	44	2.4E5	1	472
Dipole Mode	*f* (GHz)	*R/Q* (Ω/m)	$Q_{measured}$ *	σ_f (MHz) *	τ (ms)
TE111	1.739	4283	3.4E3	5	218
TM110	1.874	2293	5.0E4	1	44
TM111	2.577	4336	5.0E4	1	22
TE121	3.087	196	4.4E4	1	497

cut-off

cut-off

* TESLA cavity measurement data ** at 6 GeV. Note: Booster longitudinal damping time: 62 s @ 6 GeV, 8 ms @ 120 GeV, transverse damping time: 125 s @ 6 GeV, 16 ms @ 120 GeV

- Feedback system is needed to mitigate multi-bunch instabilities.
- Single bunch instability is dominated by the vacuum pips, not the cavity.
- 650 MHz cavity is a little better for the Booster beam instability but still need the bunch feedback system (Q limit in the same order with the 1.3 GHz cavity)

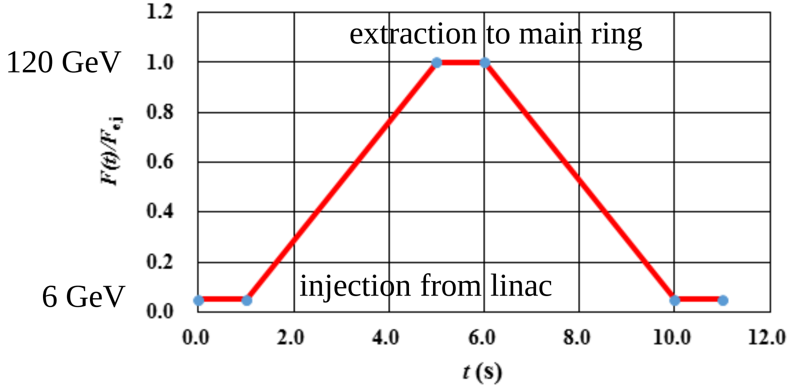
SOM Damping

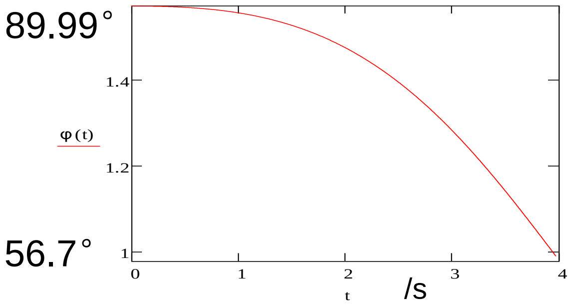
- Same Order Modes (SOM, other pass-band modes of operating mode) may drive instabilities or extract RF power from the beam
- Input coupler as the natural SOM damper (HOM couplers not work)
- Total SOM power quite small for real passband modes frequencies and CEPC bunch spacing.
- SOM power 1 kW for resonant excitation. Power dissipated on cavity wall is negligible (~ 0.1 W)

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

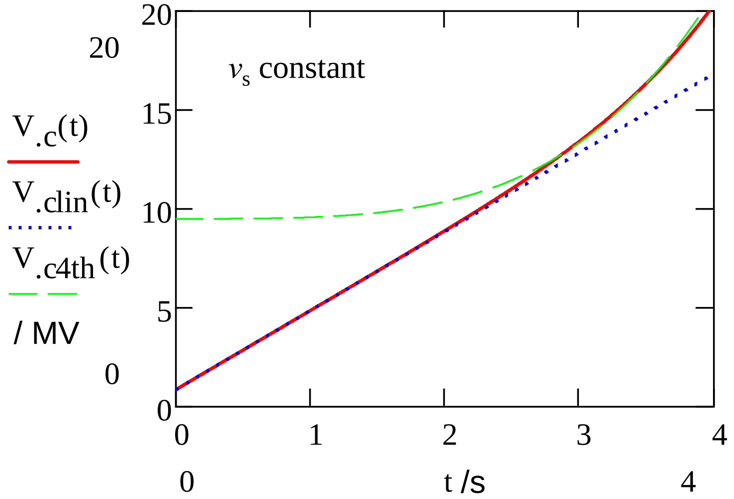
CEPC Booster RF Transients

Booster magnet field cycle

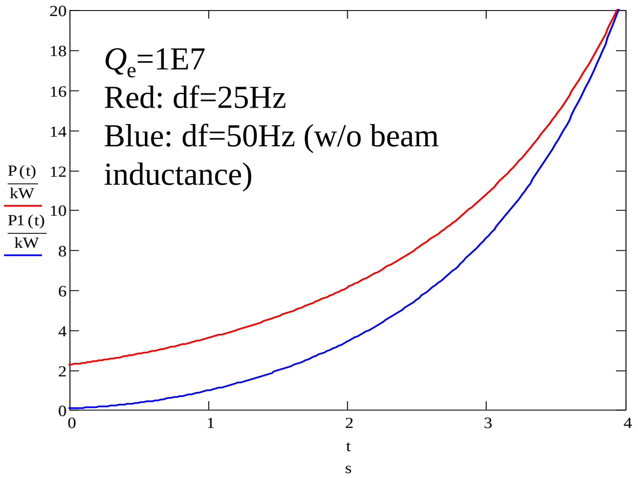




4s ramp beam phase change（off-crest）



4s ramp cavity voltage (red)



4s ramp RF power

Duty factor for continuous injection：Cavity wall loss: 21.2 % （Q_0 const.）；
HOM heat load: 50 %; Power Source：22.4 %

Booster Cavity Bandwidth

$$P_i(Q_L,\Delta f_c)=\frac{V_c^2}{4(R/Q)Q_L}\left[\left(1+\frac{I_b}{V_c}\frac{R}{Q}Q_L\cos\phi_b\right)^2+\left(2Q_L\frac{\Delta f_c}{f}+\frac{I_b}{V_c}\frac{R}{Q}Q_L\sin\phi_b\right)^2\right]$$

- Q_{opt} = 4E7 (BW 33 Hz, LCLS-II), df = 10 Hz, 10 kW input power, SSA 12.5 kW, hard for transient LLRF control (no existing machine).
- Baseline: over coupled (Q_{ext} =1E7, df = 50 Hz), 20 kW input power, SSA 25 kW
- If both amplitude and phase control (e.g. para-phasing) of the cavities are used for the energy ramp, assumptions for microphonics and transient control could be relaxed with more analysis. => Half the Solid State Amplifier power (30 MUSD less)

Summary

- The present CEPC SRF design is only for Higgs boson
  - One beam pipe, 120 GeV, 33.2 mA, 2×10^{34} $cm^{-2}s^{-1}$
  - Low energy, high current modes (e.g. at the Z-pole) will significantly change the design and add more challenges
- Three main challenges, especially the HOM power issue
  - HOM power extraction with low heat load (SOM no problem)
  - High power CW coupler (~ 300 kW)
  - Cavity with very high Q_0 at 15-20 MV/m in repeatable longtime operations of the real cryomodules (horizontal test stands) : new nitrogen-doping and flux expulsion technology, thin film (e.g. Nb_3Sn)
- Booster transient issue
- *CEPC-SPPC Pre-CDR* for more details