CDR Design of CEPC Superconducting RF System

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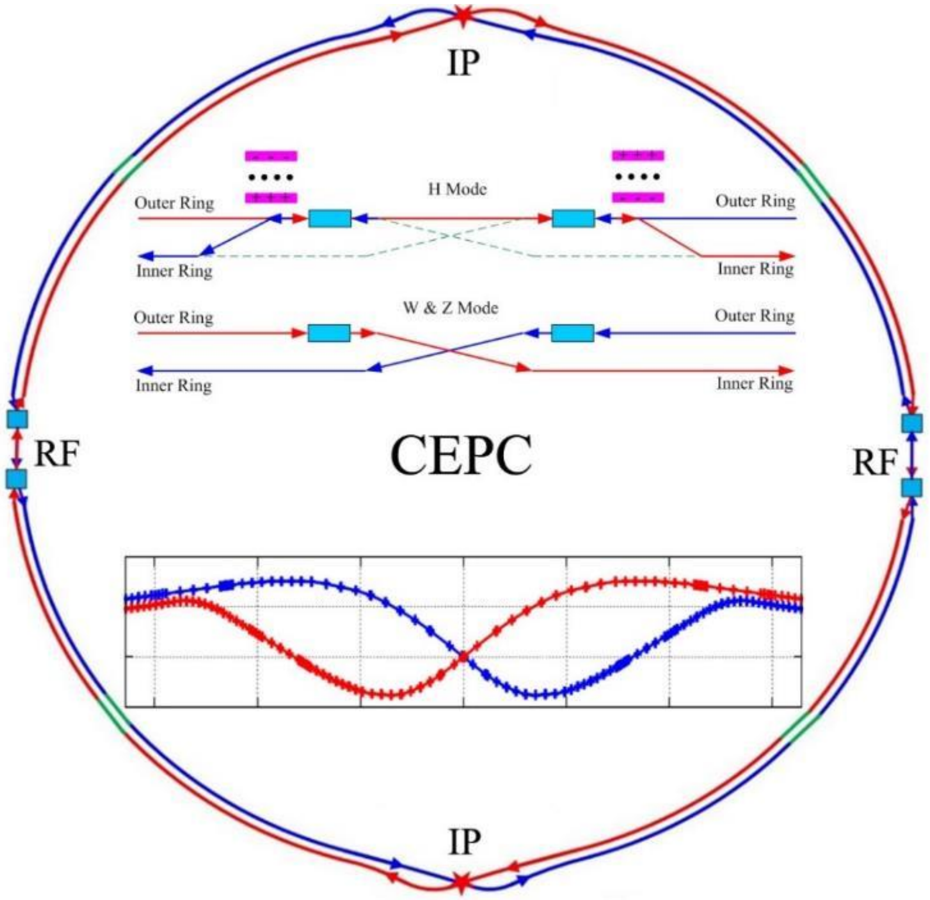
Outline

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

CEPC SRF Design Requirements



- Higgs long operation first:
  one-time full installation of all the same cavities for H, W, Z. Use part of the Higgs cavities for W and Z. Park the idle cavities (not off beamline).
- Cavity and cryogenics cost reduction:
  common H cavities, separate W/Z cavities.
- Upgradable to 50 MW SR per beam:
  longer tunnel, add cavities, variable coupler, RF configuration and cavity suitable for higher power.

CEPC SRF Design Challenges

	H	W	Z
Collider Ring	**650 MHz 2-cell cavity**		
Lumi. / IP (10^{34} $cm^{-2}s^{-1}$)	2.93	10.1	16.6 / 32.1
RF voltage (GV)	2.17	0.47	0.1
Beam current (mA)	17.4 x 2	87.7	460
Cavity number	240	108 x 2	60 x 2
SR power (MW)	30	30	16.5
2 K cavity wall loss (kW)	6.1	1.3	0.1
Booster Ring (extraction)	**1.3 GHz 9-cell cavity**		
RF voltage (GV)	1.97	0.585	0.287
Beam current (mA)	0.52	2.63	6.91
Cavity number	96	64	32
RF input power (MW) avg.	0.07	0.02	0.02
2 K wall loss (kW) avg.	0.17	0.01	0.02

- High energy, low current: high gradient, high Q, more cells, narrow bandwidth
- Low energy, high current: HOM power (less cells), parasitic loss, HOM CBI, FM CBI (low voltage, large detuning)
- Large ring: gap transient, dense beam spectrum
- Special issues with CEPC: parking cavities for W and Z, gap transient for Higgs half-fill, transient beam loading of bunch swapping for on-axis injection
- Booster cavity voltage ramp: narrow bandwidth

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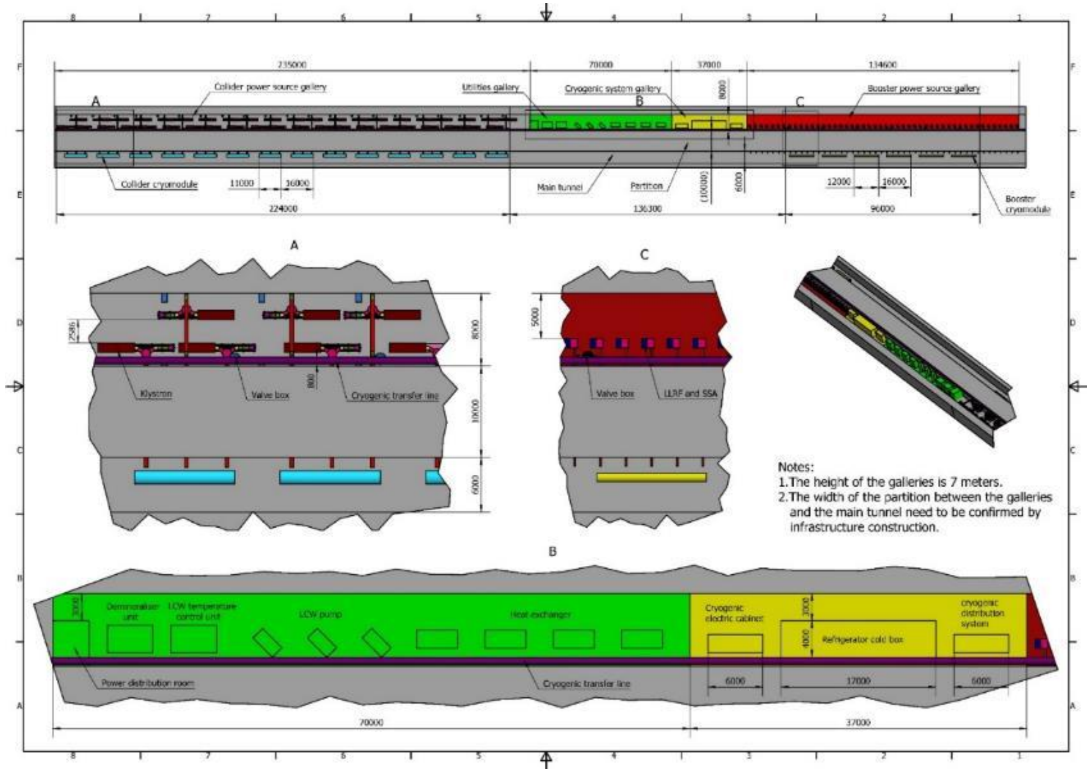
CEPC RF Layout

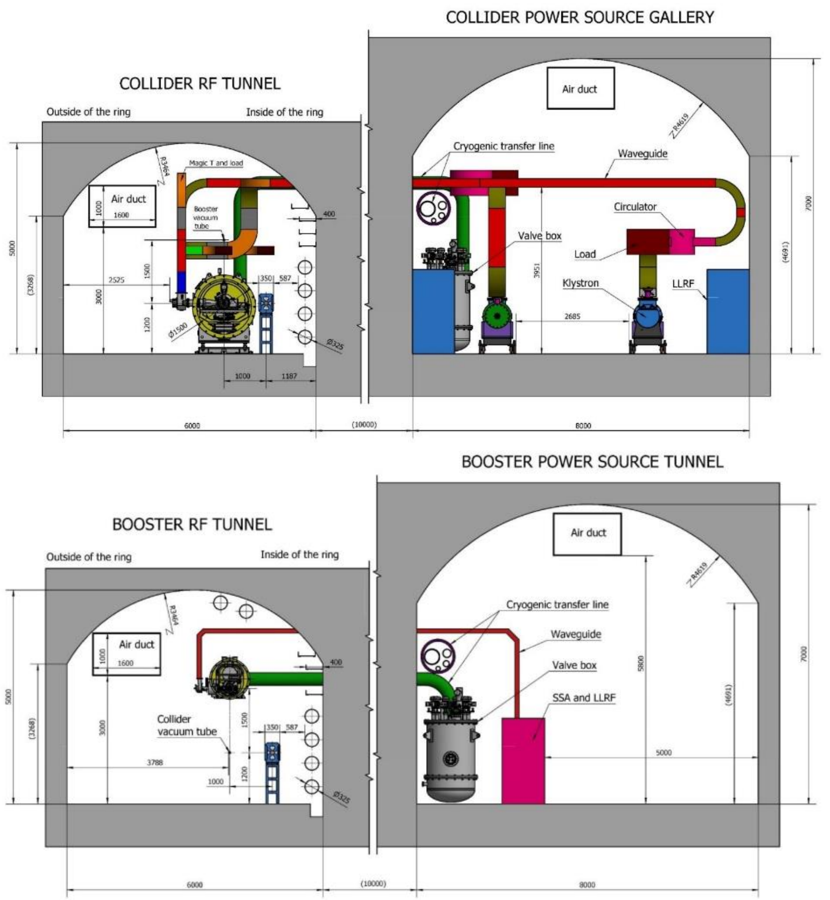
For 30 MW Higgs:

Collider: 240 650 MHz 2-cell cavities in 40 cryomodules (6 cav./ module).

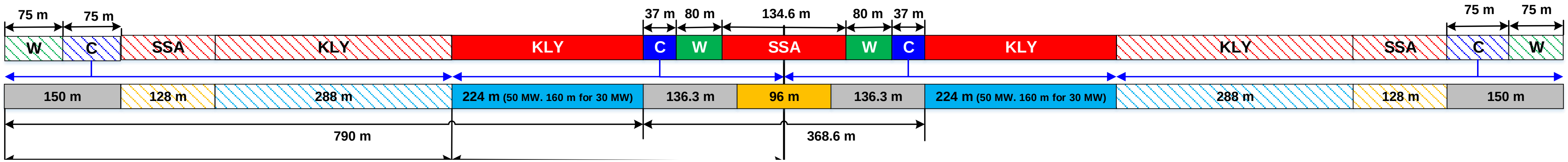
Booster: 96 1.3 GHz 9-cell cavities in 12 cryomodules (8 cav. / module).

For 50 MW Higgs: add 16 Collider modules.





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



CEPC Collider Ring SRF Parameters

Collider parameters: 20180330	**H**	**W**	**Z**
SR power / beam [MW]	30	30	16.5
RF voltage [GV]	2.17	0.47	0.1
Beam current / beam [mA]	17.4	87.7	460
Bunch charge [nC]	24	19.2	12.8
Bunch number / beam	**242**	1524	12000
Bunch length [mm]	3.26	5.9	8.5
Cavity number (650 MHz 2-cell)	**240**	2 x 108	2 x 60
Idle cavities on line / ring	0	12	60
Cavity gradient [MV/m]	**19.7**	9.5	3.6
Q_0 for long term operation	1.5E10	1E10	1E10
Input power / cavity [kW]	250	278	275
Klystron power [kW] (2 cavities / klystron)	800	800	800
HOM power / cavity [kW]	0.57	0.75	1.94
Optimal Q_L	1.5E6	3.2E5	4.7E4
Optimal detuning [kHz]	0.2	1.0	17.8

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

- **FM and HOM impedance and power, heat load**
- **Gradient (stored energy) as high as possible**

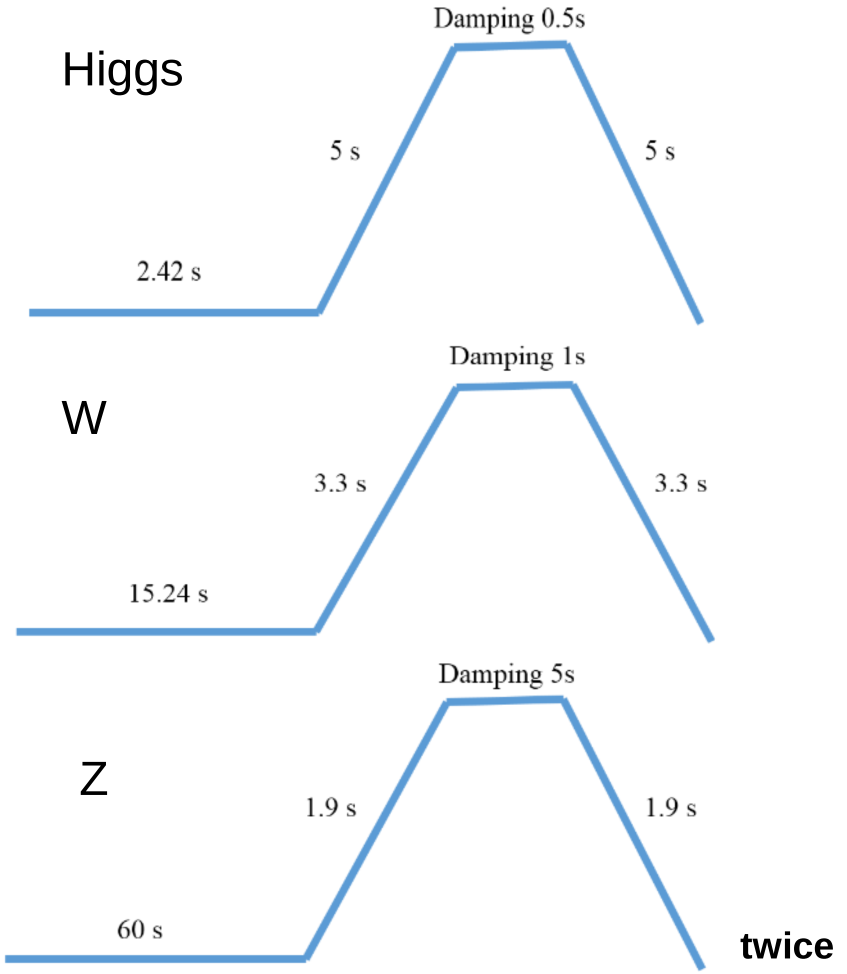
- **Input coupler power limit 300 kW (high risk)**
- **Keep power level and RF distribution**
- **HOM power per cavity limit 2 kW**
- **Input coupler variable**
- **Revolution frequency: 3 kHz (FM CBI)**

CEPC Booster SRF Parameters

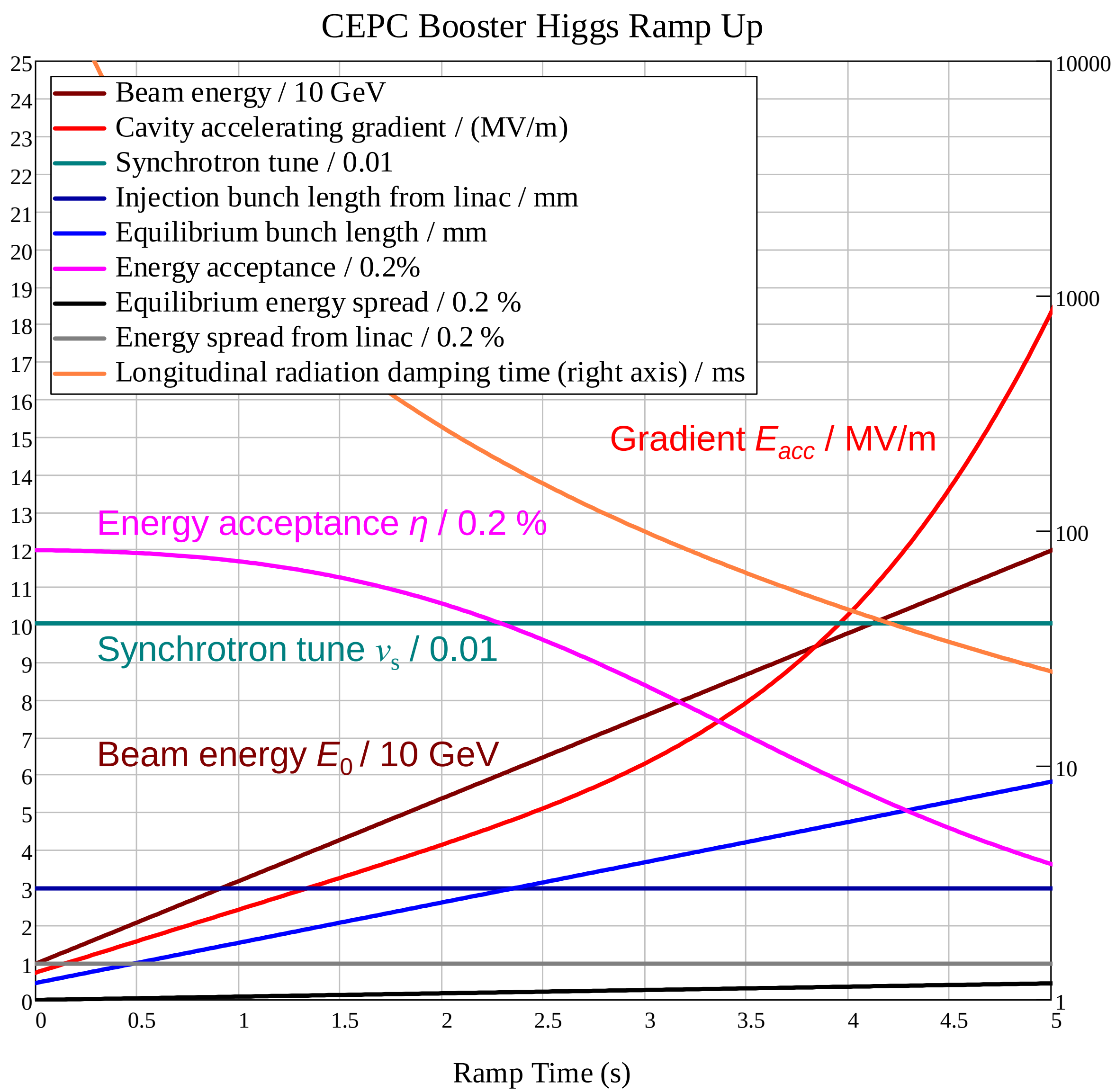
10 GeV injection	**H**	**W**	**Z**
Extraction beam energy [GeV]	120	80	45.5
Bunch number	242	1524	6000
Bunch charge [nC]	0.72	0.576	0.384
Beam current [mA]	0.52	**2.63**	**6.91**
Extraction RF voltage [GV]	1.97	0.585	0.287
Extraction bunch length [mm]	2.7	2.4	1.3
Cavity number in use (1.3 GHz TESLA 9-cell)	96	64	32
Gradient [MV/m]	19.8	8.8	8.6
Q_L	1E7	6.5E6	1E7
Cavity bandwidth [Hz]	130	200	130
Beam peak power / cavity [kW]	8.3	12.3	6.9
Input peak power per cavity [kW] (with detuning)	18.2	12.4	7.1
Input average power per cavity [kW] (with detuning)	0.7	0.3	0.5
SSA peak power [kW] (one cavity per SSA)	25	**25**	**25**
HOM average power per cavity [W]	0.2	0.7	**4.1**
Q_0 @ 2 K at operating gradient (long term)	1E10	1E10	1E10
Total average cavity wall loss @ 2 K eq. [kW]	0.2	0.01	0.02

Booster Time Structure (off-axis injection)

	H	W	Z
Injection from linac [s]	2.42	15.24	60.00
Ramp-up or down [s]	5.00	3.30	1.90
Damping [s]	0.5	1.00	5.00
Extraction [ms]	0.3	0.3	0.3
One injection duration for top-up (e+ and e-) [s]	25.8	45.7	137.6
Number of injection times	1	1	2
Total injection duration [s]	25.8	45.7	275.2
Injection interval for top-up [s]	73	153	438
Booster duty factor	35%	30%	63%
SR duty factor	4.4%	2.3%	5.1%
RF power duty factor	3.8%	2.4%	7.4%
Cryogenic dynamic duty factor	4.3%	2.9%	7.9%
HOM power duty factor	18.4%	15.6%	33.7%



Booster Voltage Ramp



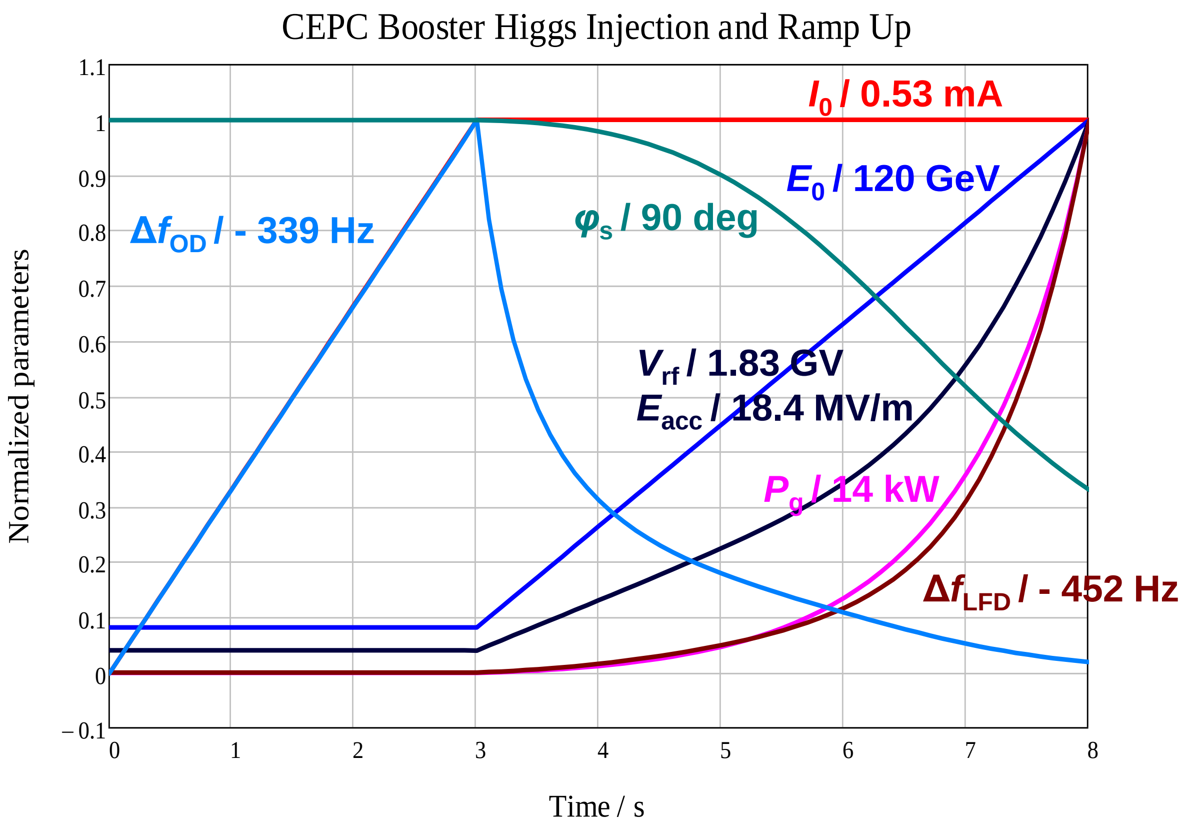
- Beam energy increase linearly with time.
- RF voltage ramp with constant synchrotron tune to avoid synchrotron-betatron oscillation.

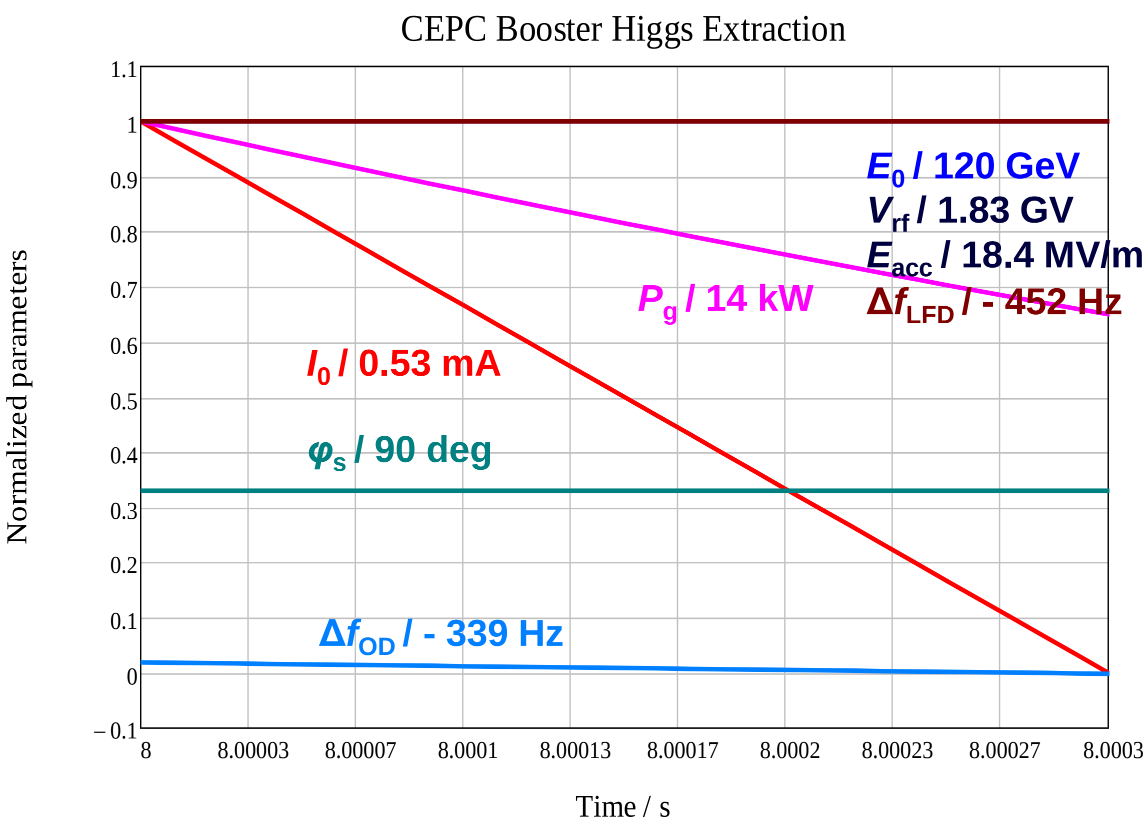
$$V_{rf}(t) := \sqrt{\left(\frac{\nu_s^2 \cdot 2 \cdot \pi}{\alpha \cdot h \cdot e_0} \cdot E_0(t)\right)^2 + \left(\frac{U_0(t)}{e_0}\right)^2}$$

- 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 Hz / $(MV/m)^2$
- 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.

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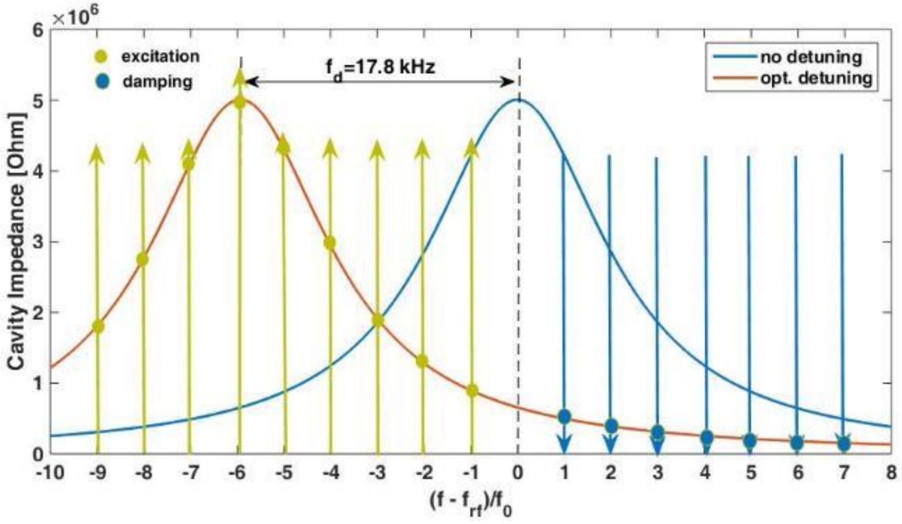
Fundamental Mode CBI of Z

Mode number	Impedance / cavity (Ω)	Growth Time (ms)	Growth Time/ Damping Time	Growth Rate/ Syn. Freq.
-28	3.11E+04	411.3	0.98	0.03
-27	3.49E+04	366.6	0.87	0.03
-26	3.94E+04	325.2	0.77	0.04
-25	4.46E+04	286.9	0.68	0.04
-24	5.08E+04	251.7	0.60	0.05
-23	5.83E+04	219.5	0.52	0.05
-22	6.74E+04	190.0	0.45	0.06
-21	7.84E+04	163.2	0.39	0.07
-20	9.21E+04	139.0	0.33	0.09
-19	1.09E+05	117.2	0.28	0.10
-18	1.31E+05	97.8	0.23	0.12
-17	1.59E+05	80.5	0.19	0.15
-16	1.96E+05	65.3	0.16	0.18
-15	2.45E+05	52.1	0.12	0.23
-14	3.14E+05	40.8	0.10	0.29
-13	4.11E+05	31.1	0.07	0.38
-12	5.55E+05	23.1	0.05	0.52
-11	7.75E+05	16.5	0.04	0.72
-10	1.13E+06	11.4	0.03	1.05
-9	1.71E+06	7.5	0.02	1.59
-8	2.67E+06	4.8	0.01	2.49
-7	4.01E+06	3.2	0.01	3.73
-6	4.82E+06	2.7	0.01	4.49
-5	4.05E+06	3.2	0.01	3.77
-4	2.65E+06	4.8	0.01	2.46
-3	1.57E+06	8.1	0.02	1.46
-2	8.74E+05	14.6	0.03	0.81
-1	3.87E+05	33.1	0.08	0.36



Longitudinal coupling-impedance

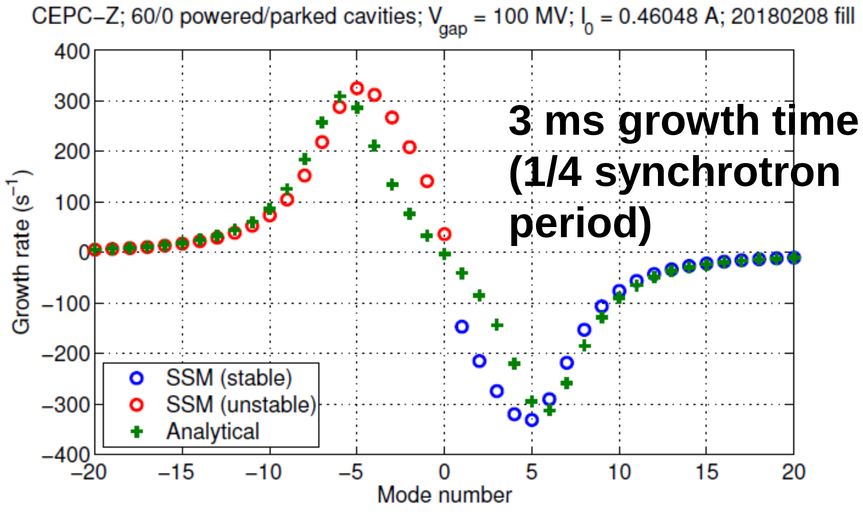
$$Z^{||}(f) = \frac{1}{\beta}\frac{R_{sh}/2}{1 + iQ_L\left(\frac{f}{f_{res}} - \frac{f_{res}}{f}\right)}$$

Cavity resonance frequency

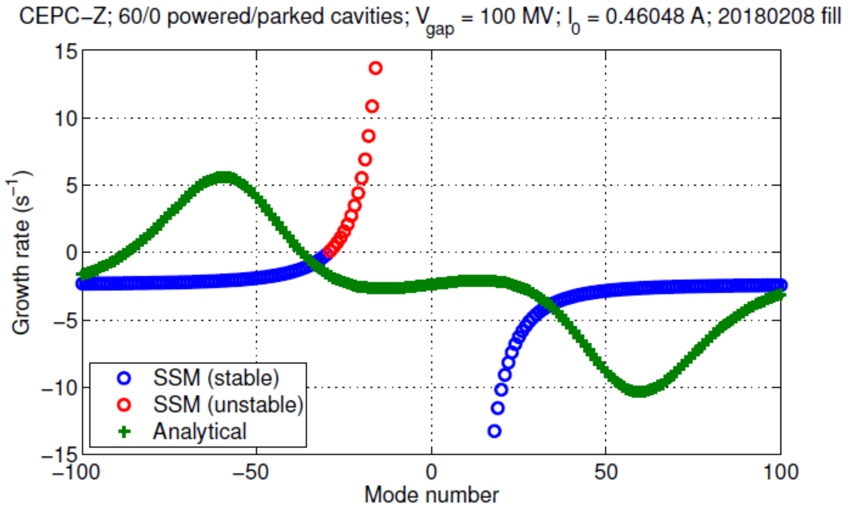
$$f_{res} = f_{rf} + \Delta f \qquad \Delta f_{opt} = -\frac{I_b \sin\phi_s \frac{R}{Q} f_{RF}}{2V_c}$$

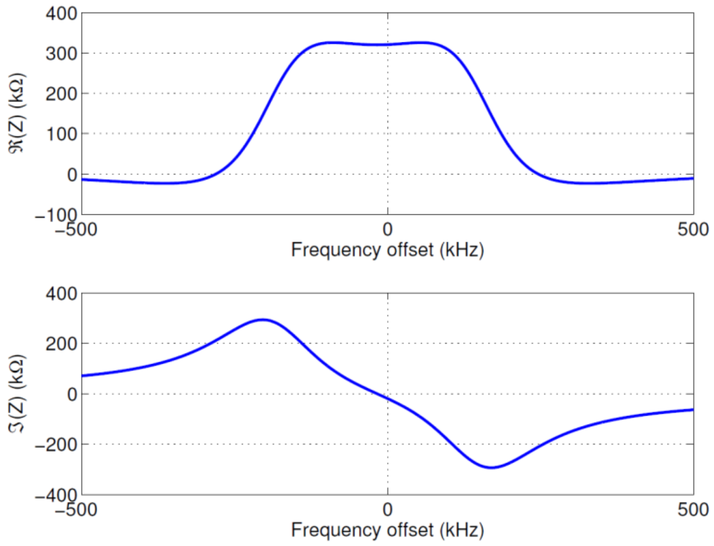
Simulation of Growth Rate and Direct RF Feedback

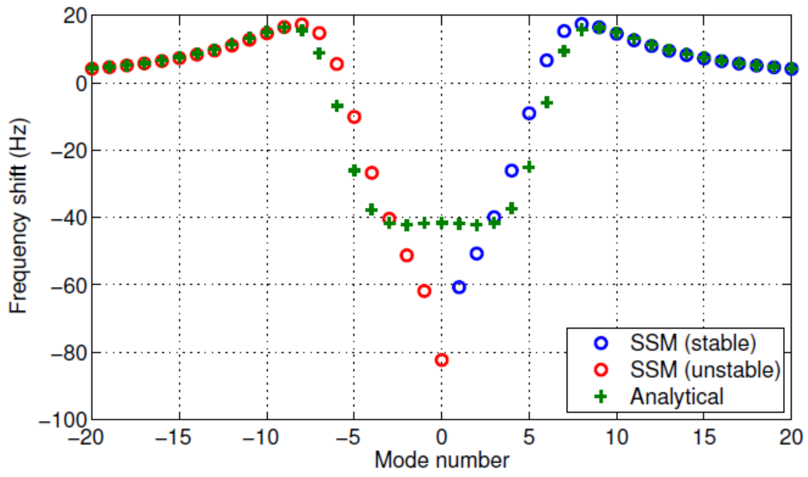
D. Teytelman.

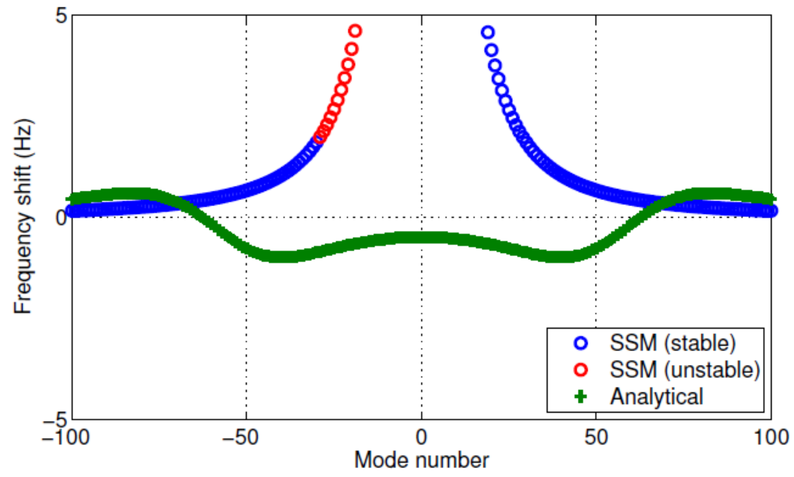


3 ms growth time (1/4 synchrotron period)



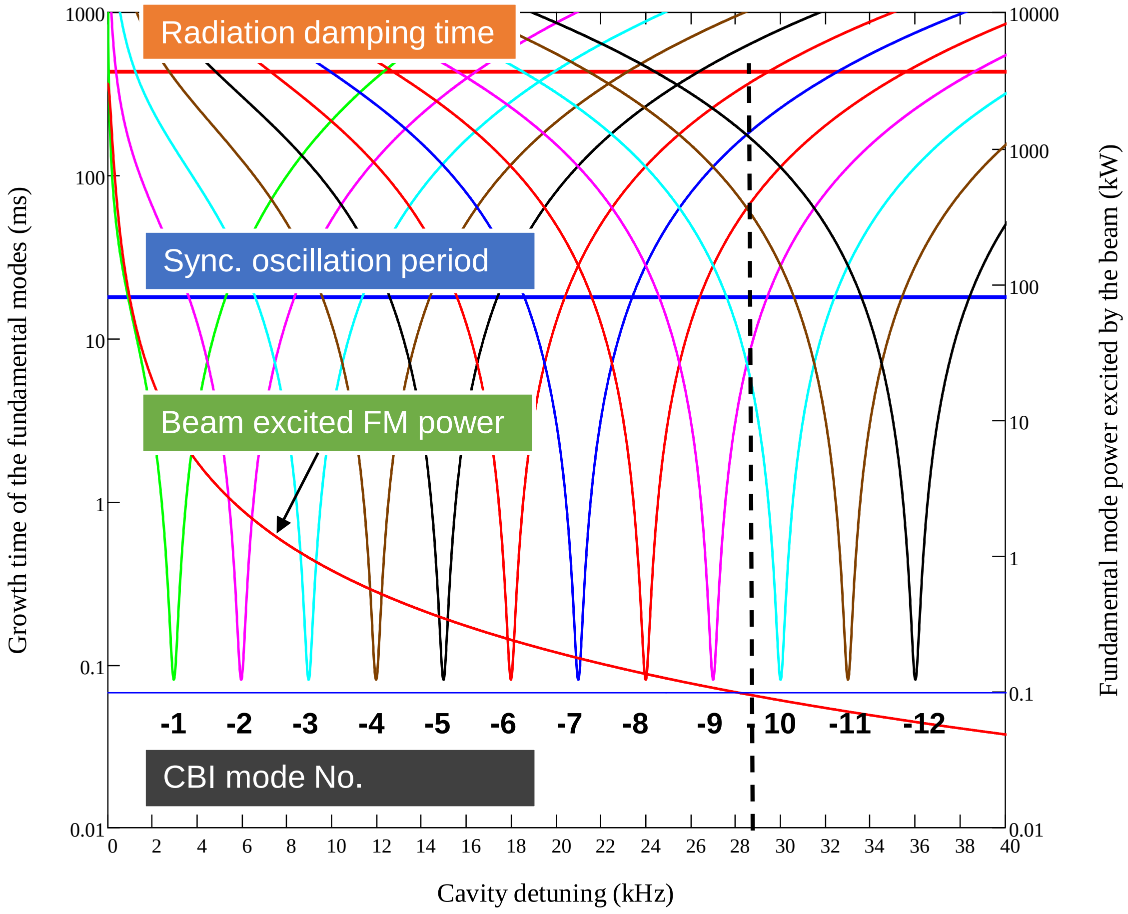






Optimal direct loop gain of 14 the growth rates are reduced to a very reasonable 7.2 1/s (139 ms growth time, 11.6 synchrotron periods). That residual growth rate should be easy to control with standard bunch-by-bunch feedback.

FM CBI and Power of Parked Cavities

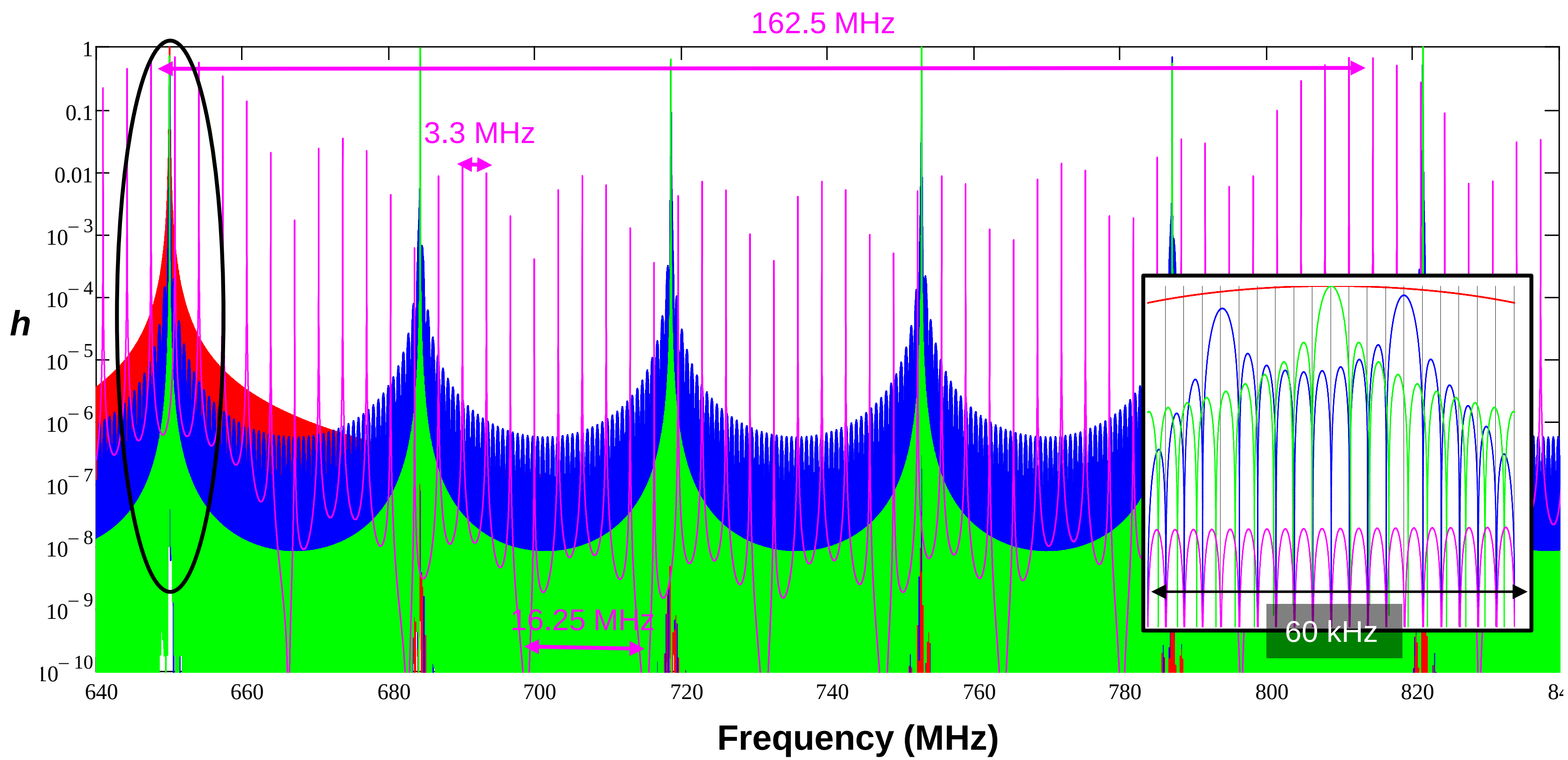


CEPC baseline Z mode FM CBI and beam excited power per cavity of the 156 parked cavities (reduce FM coupling to Q_e = 2E6)

- Large detuning and narrow BW to reduce FM power excited by the beam (limit?), but fast-growing CBI modes. Alternating 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 exited 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 bunches], 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 ~ $1 / (M_b n_t)^2$
Bunch structure dominates when $M_b >> n_t$
Train structure dominates when $n_t >> M_b$

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.

N. Wang, IHEP

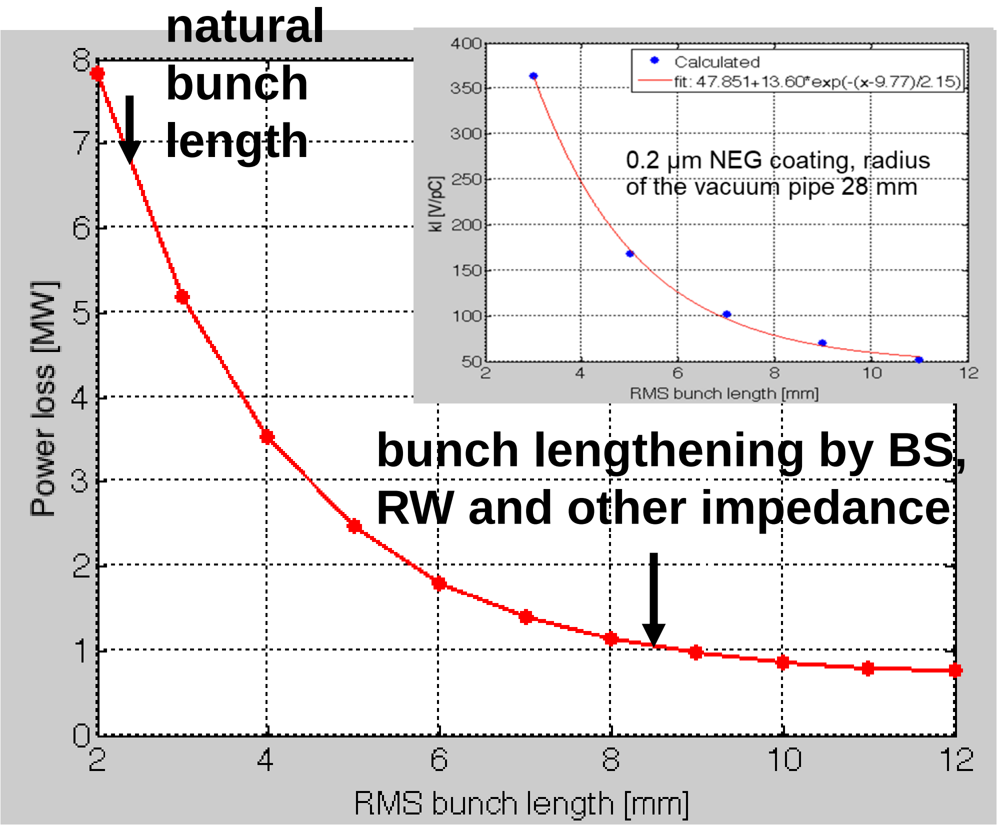
Parasitic Loss

CEPC Z (460 mA, 12.8 nC)

- SR loss: 33 MW
- Cavity HOM loss: 0.5 MW (8.5 mm), 1.3 MW (2.4 mm)
- Resistive wall loss: 1 MW (8.5 mm), 6.8 MW (2.4 mm)
- And other loss: …

RF system must compensate the energy and power loss by increasing RF voltage and power.

Bootstrapping and bunch lengthening is necessary for stable RF operation.



Resistive wall power loss of CEPC Z

HOM Damping Requirement for Z

Monopole mode	*f* (MHz)	*R*/*Q* (Ω)	Q_e (with feedback)	Q_e (without feedback)
TM011	1165.574	65.2	9.2×10^3	2.6×10^2
TM020	1383.898	1.29	3.9×10^5	1.1×10^4
TM021	**1717.475**	19.88	2.0×10^4	5.8×10^2
TM012	1832.801	17.26	2.2×10^4	6.2×10^2
Dipole mode	***f* (MHz)**	***R*/*Q* (Ω/m)**	**Q_e (with feedback)**	**Q_e (without feedback)**
TE111	844.738	279.82	4.0×10^4	1.6×10^2
TM110	907.592	420.05	2.6×10^4	1.0×10^2
TE121	**1475.553**	**125.79**	8.8×10^4	3.5×10^2
TM120	1662.599	18.80	5.9×10^5	2.3×10^3

← Cut off frequency: 1471MHz

← Cut off frequency: 1126 MHz

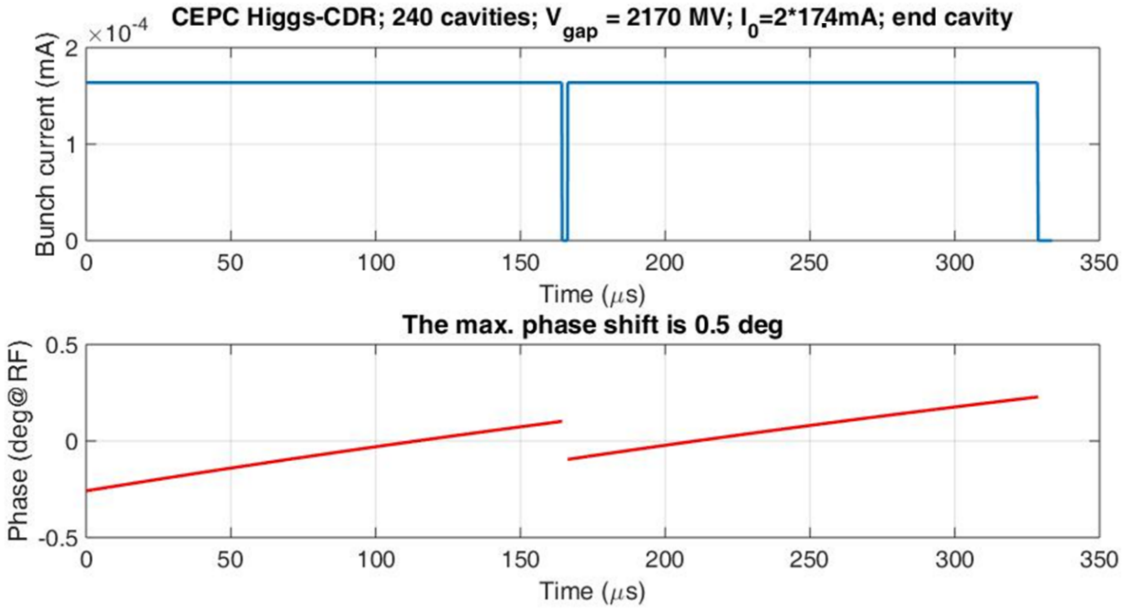
- Z: 120 2-cell cavity/beam
- Average beta_x,y in RF cavity ~ **30 m**
- No frequency spread included
- **Shortest longitudinal feedback time: 11.9 ms (synchrotron oscillation period)**
- **Feedback time for transverse mode: 3.3 ms (10 turns), could be shorter.**

Beam Gap Phase Shift

Gap for beam abort and mitigate ion-trapping and fast beam ion instability (FBII), and avoid collision in RF section (Higgs).

~ 10 % total gap needed for Z. But one gap will have too large phase shift and beam loss. Use many bunch trains with short gaps.

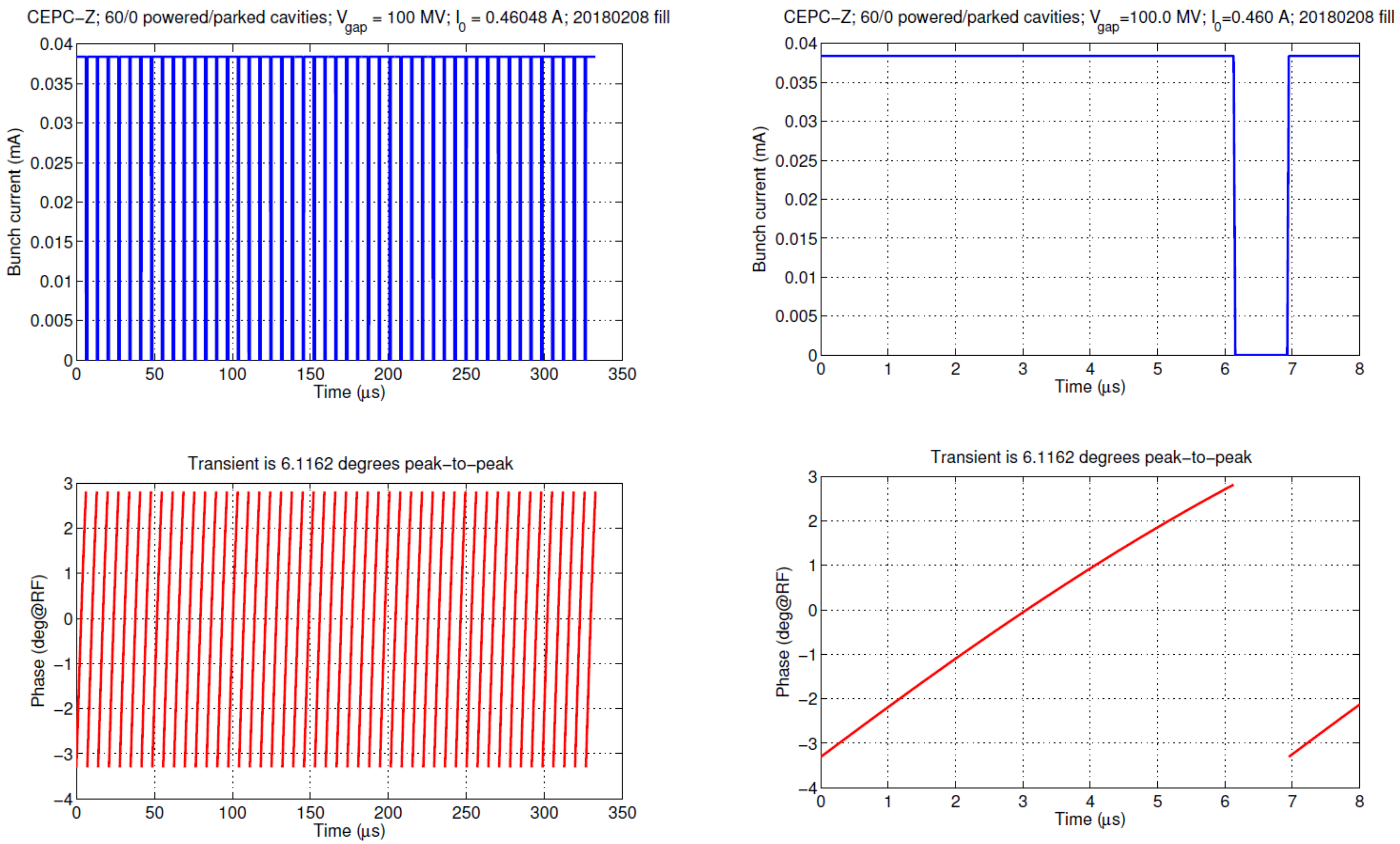
	H	W	Z
Beam gap in number of buckets	3091	550	24832
Beam gap length [us]	4.76	0.85	38.20
Max relative voltage drop	0.5%	0.7%	460%
Max bunch train phase shift [deg]	0.5	0.6	/



Phase shift for Higgs end cavity

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

Phase Shift of Z with Bunch Trains



48 trains of 250 bunches located symmetrically in the ring. Bunch spacing is 24.6 ns (16 RF buckets), gaps are 820 ns (533 buckets).

D. Teytelman.

RF Issues for Z

CEPC CDR Z is challenging for RF hardware and beam operation with Higgs cavity, but feasible:

1. HOM CBI is OK with deeper TM011 mode damping (and large cavity frequency spread and fast bunch-by-bunch feedback), but critical. Better to have idle cavities off-line.
2. HOM power (1 kW per coupler) is within the current coaxial HOM coupler technology reach.
3. FM CBI is manageable by direct RF feedback.
4. Phase shift is moderate for small gaps (what is the beam dynamics limit?)
5. Parking cavities FM CBI can be mitigated by symmetry detuning.

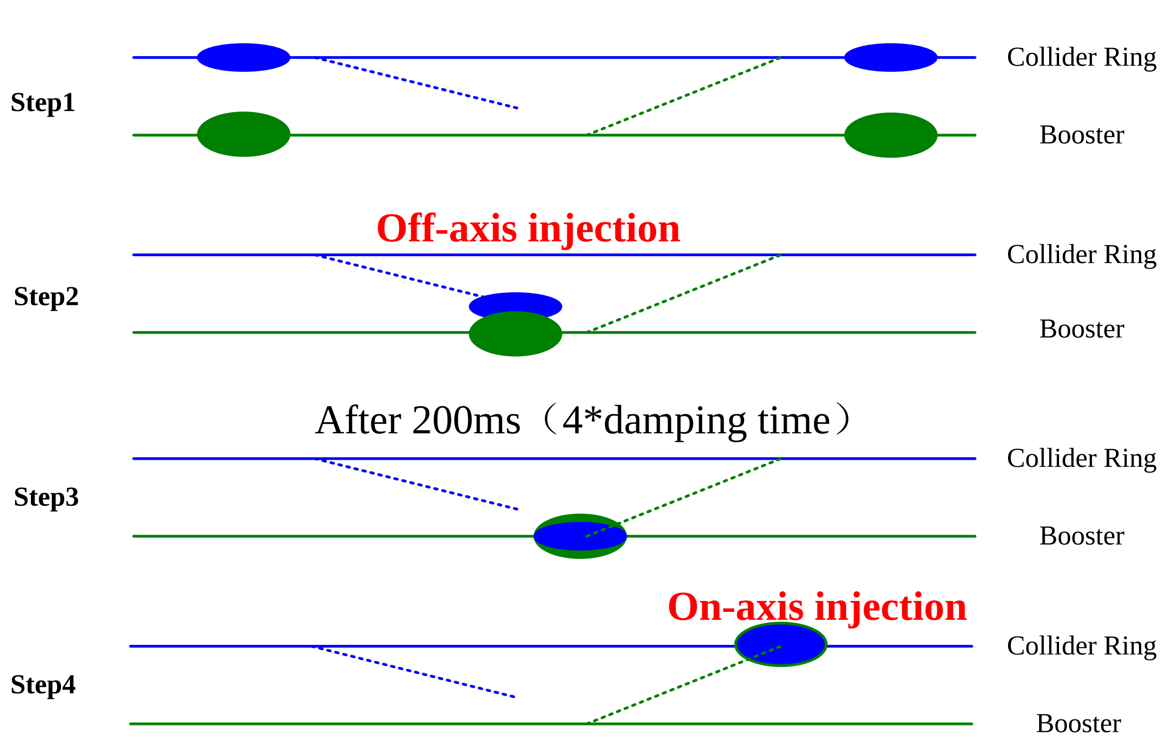
Push RF limitation beyond Z baseline for higher current and luminosity:

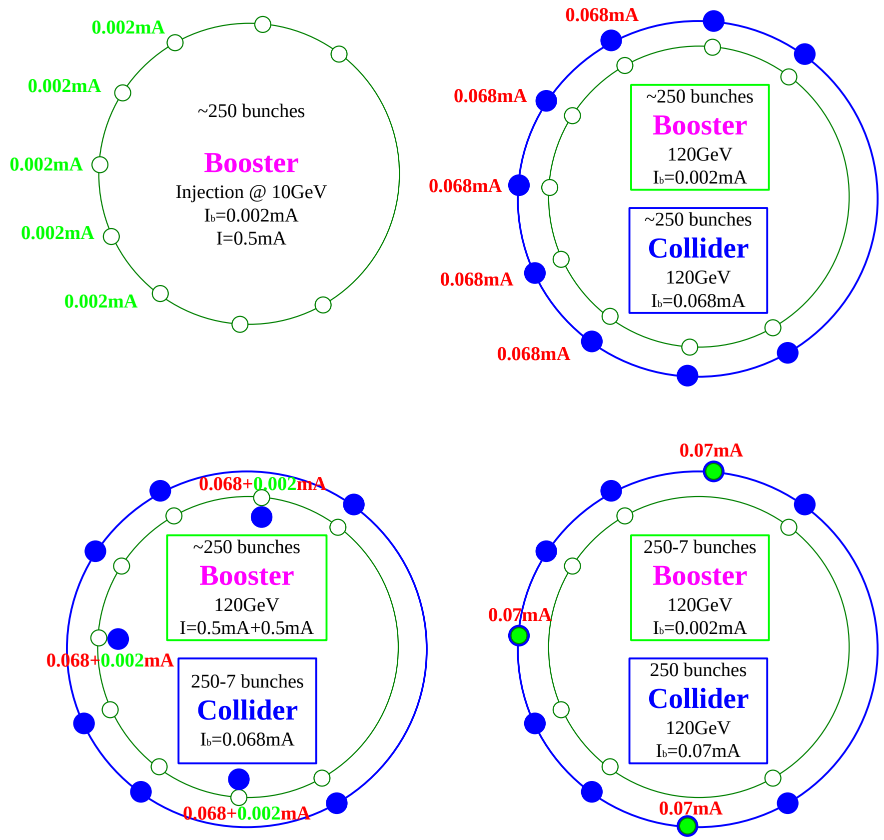
1. Novel HOM coupler design with larger power capacity.
2. Very high power input coupler (> 500 kW) and wide variable range (or two couplers per cavity).
3. BEPCII type cryomodules (but cost …).

Higgs On-axis Injection and Bunch Swapping

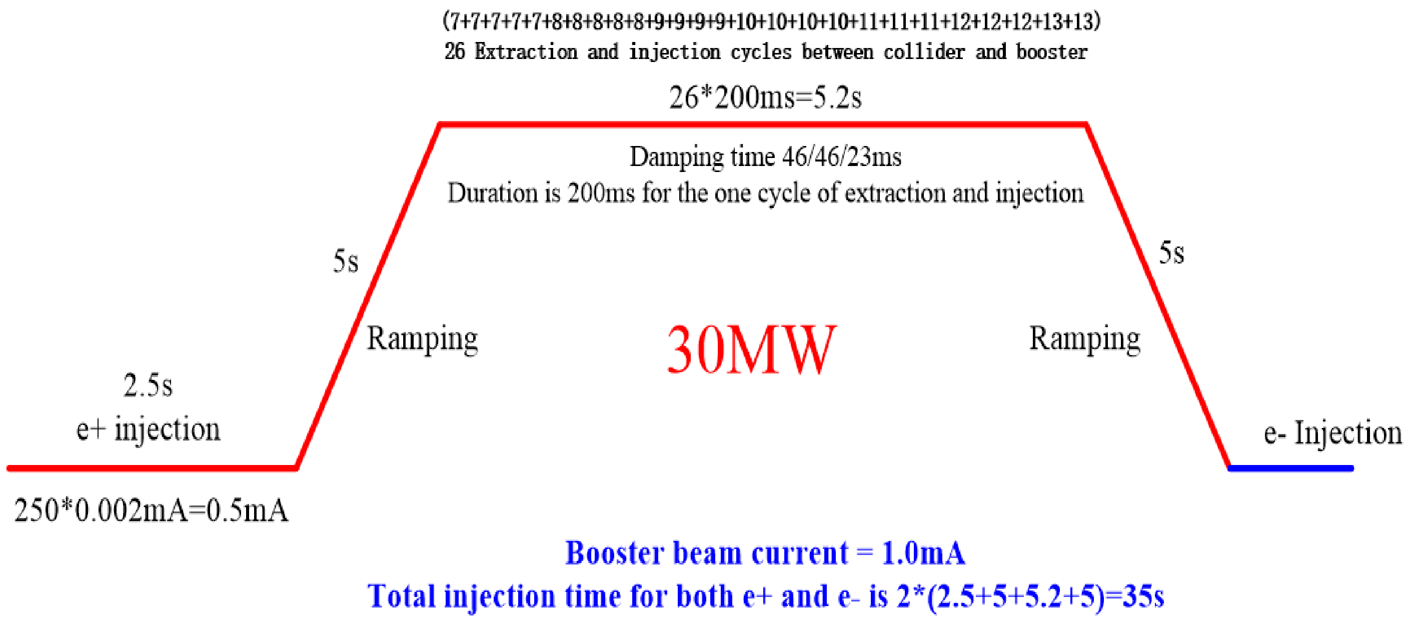
Reduce the requirement of the Collider dynamic aperture of the Higgs mode. Acceptance (40 min beam lifetime): **$13\sigma_x$** * $12\sigma_y$ (off-axis injection) , **$8\sigma_x$** * $12\sigma_y$ (**on-axis injection**).

CEPC Collider Ring Lattice Design and injection scheme. Oral tomorrow afternoon.





Transient Beam Loading of On-axis Injection

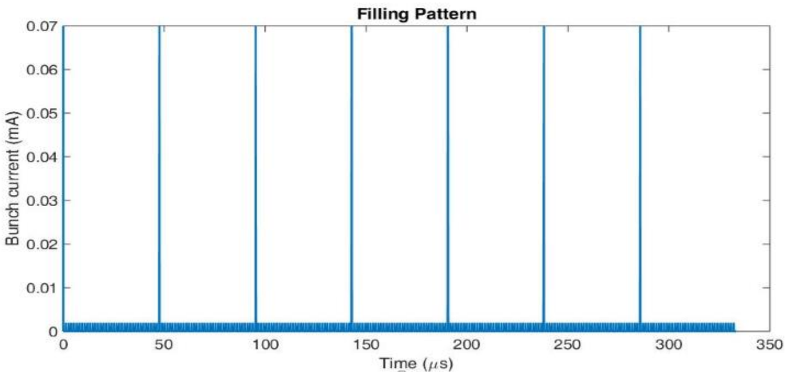


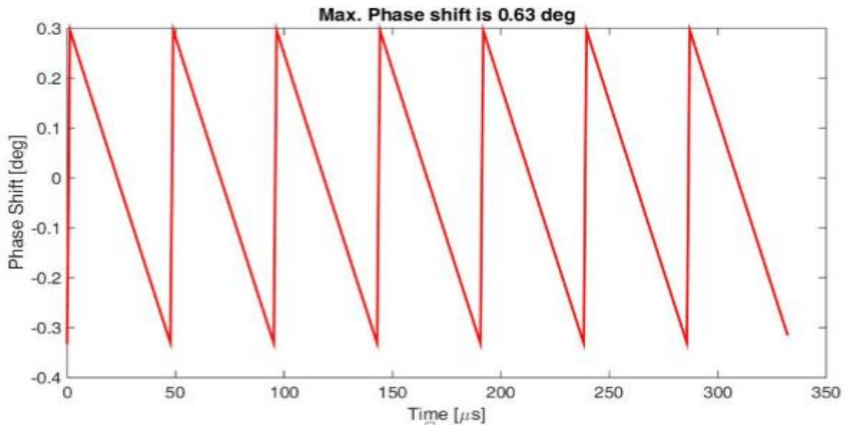
Transient beam loading in both Collider and Booster:

- Bunch gap in the Collider Ring
- Large bunch charge (x 33 up to 13 bunches) and larger total beam current (x 2) in the Booster
- Max HOM power x 33 (peak) in the Booster 1.3 GHz 9-cell cavity. Peak HOM power and DF of off-axis injection is 1 W and 18 %. Peak HOM power and DF of off-axis injection is 34 W and ~ 7 % (2.4 W average, manageable by HOM coupler of the TESLA cavity).

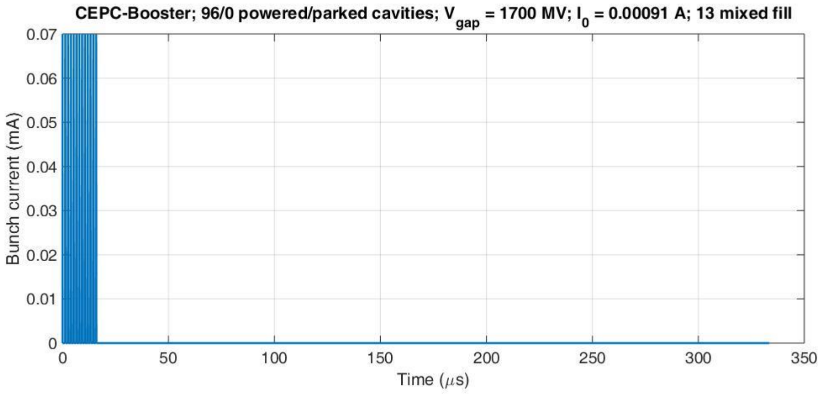
Booster Phase Shift of On-axis Injection

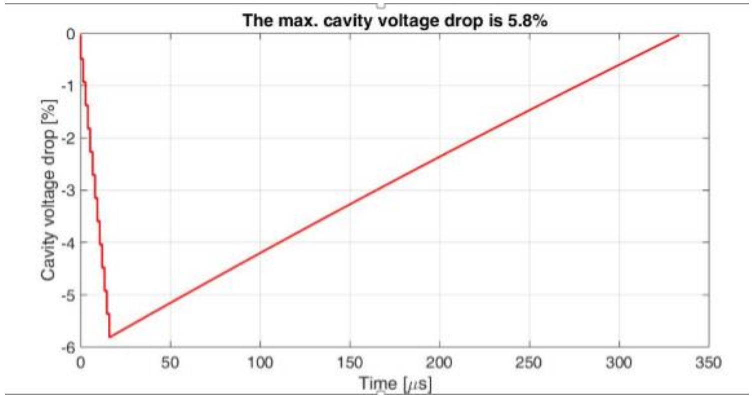
Best case: In first injection，7 large bunches (0.07mA) evenly distributed among the other small bunches. Max cavity voltage drop is 0.48 %. Max phase shift is 0.63 deg





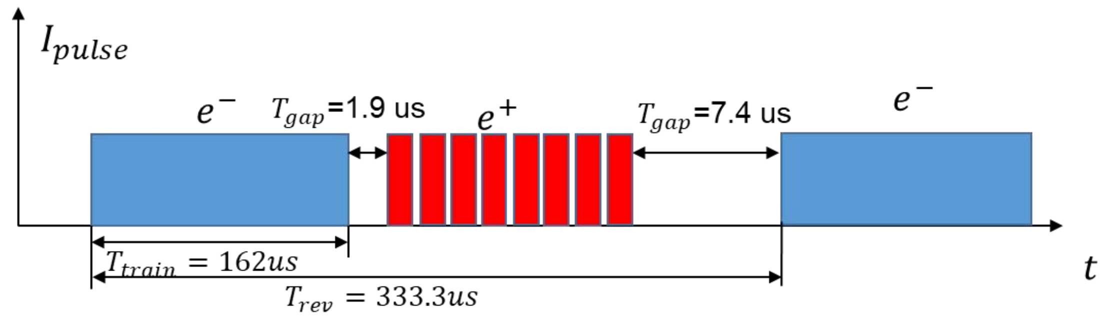
Worst case: After last injection, only 13 large bunches. Assume they are in a very short bunch train. Max cavity voltage drop is 5.8 % . The maximum phase shift is 7.7 deg.



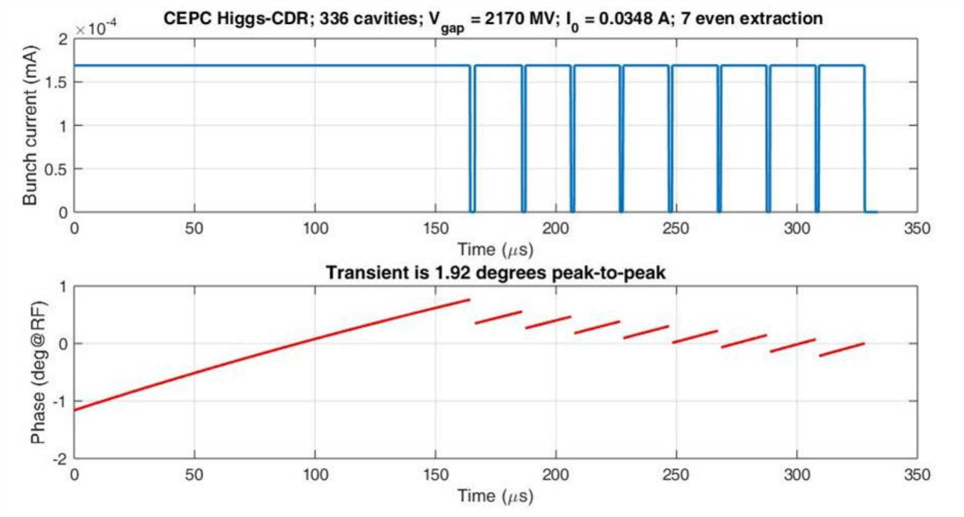


Collider Ring Phase Shift of On-axis Injection

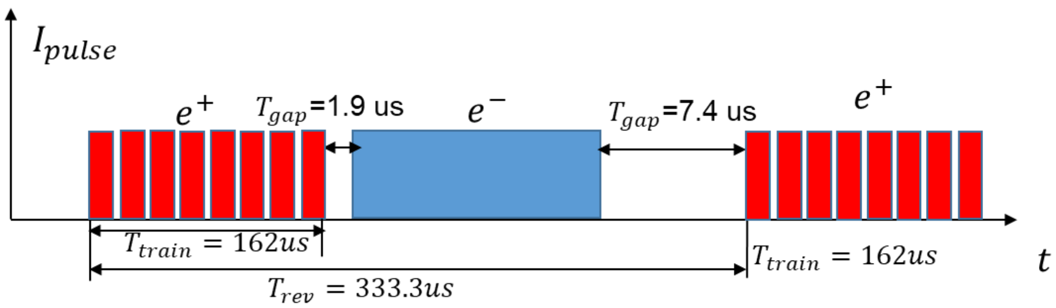
Total phase shift of e- beam is not equal to e+ (?)



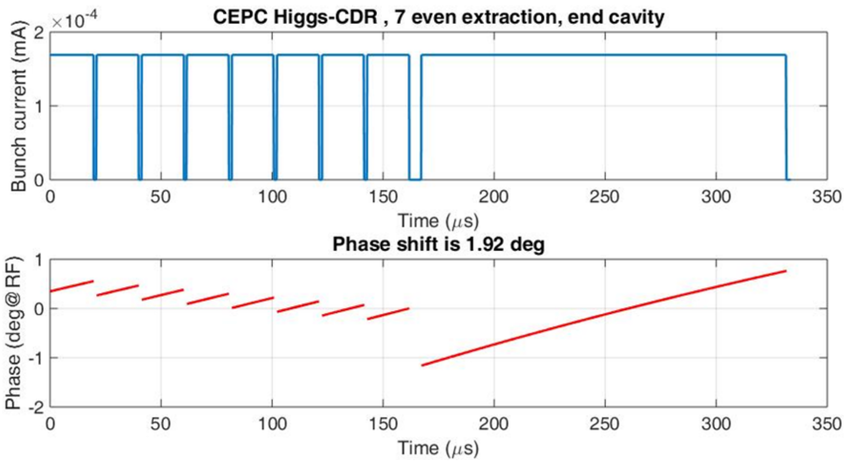
Time structure of the beam in Higgs end_1 cavity



First end cavity of one RF section



Time structure of the beam in Higgs end_2 cavity



Last end cavity of one RF section

Outline

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

CEPC SRF Hardware R&D

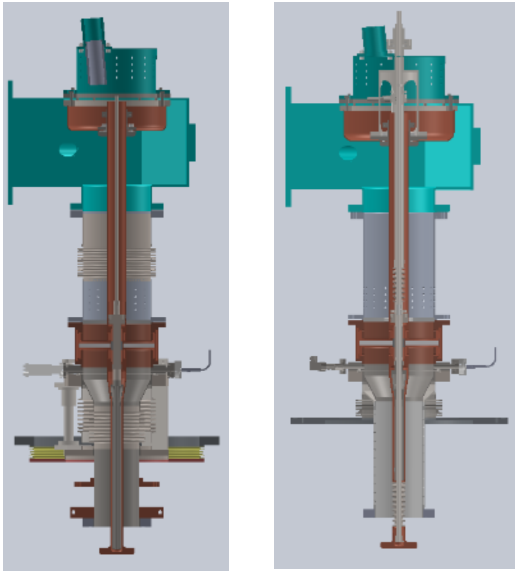
CEPC 650 MHz 2-cell cavity by OTIC

CEPC 650 MHz 2-cell cavity by HERT

- Nitrogen-doped and Fe-based superconductor cavity study, oral this afternoon.
- EP facility, poster 2AMSP12

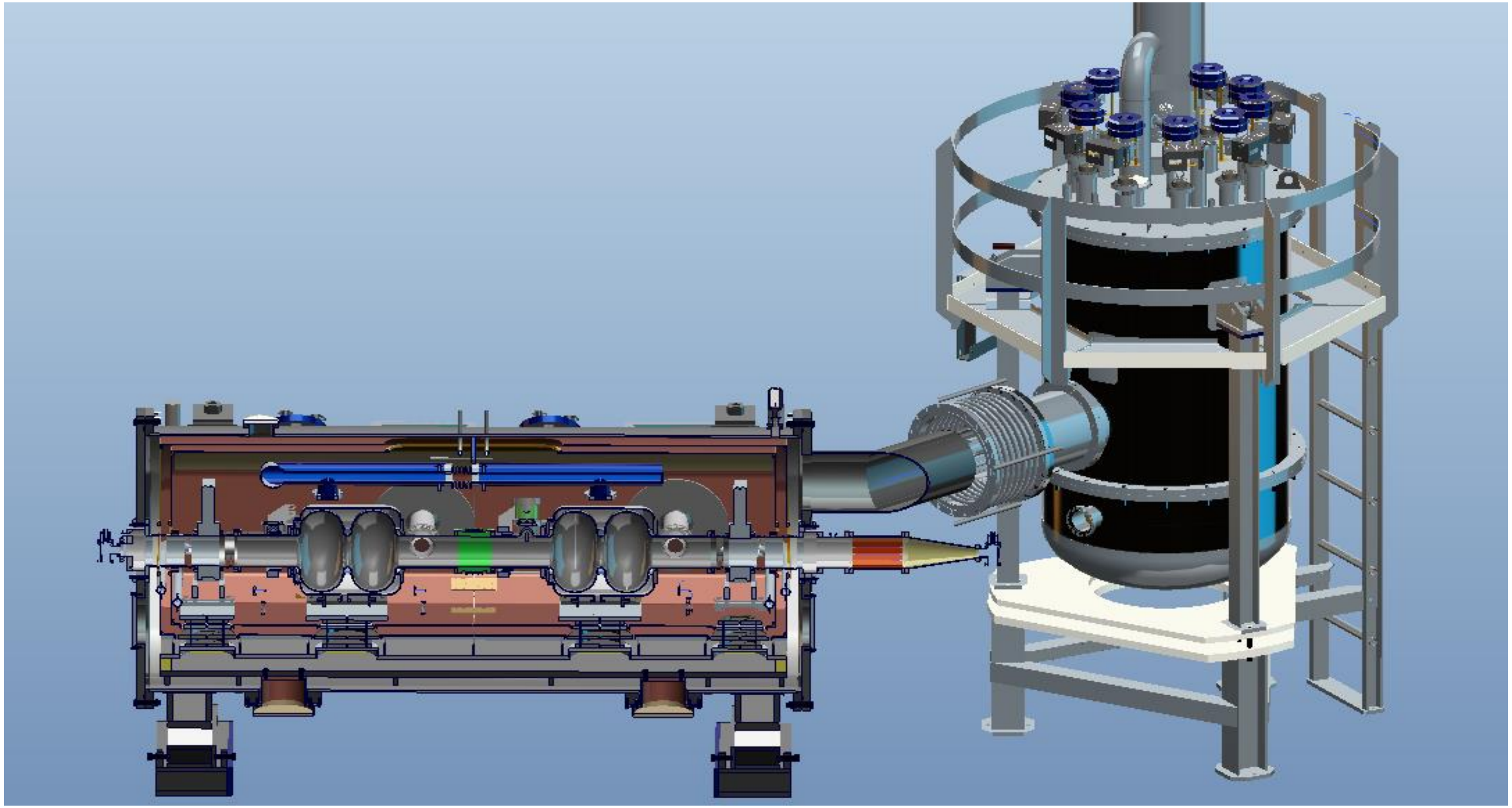
CEPC 650 MHz 5-cell cavity with waveguide HOM coupler by HERT (poster 2AMSP17)

CEPC Collider HOM coupler (SS and Nb)



CEPC 650 MHz 300 kW variable input coupler (in fabrication)

CEPC Collider Test Cryomodule



Summary

- CEPC CDR SRF parameters and layout have been established in view of high Higgs priority, low construction cost and upgradability.
- Beam cavity interaction issues (FM and HOM CBI, parking cavities, RF transients of bunch gap and swapping) are challenging but manageable.
- Technology R&D towards TDR is progressing.


Thank you

CEPC Collider Parameters

	Higgs	W	Z (3T)	Z (2T)
Number of IPs	**2**			
Beam energy (GeV)	**120**	**80**	45.5	
Circumference (km)	**100**			
Synchrotron radiation loss/turn (GeV)	1.73	0.34	0.036	
Crossing angle at IP (mrad)	16.5×2			
Piwinski angle	2.58	7.0	23.8	
Number of particles/bunch N_e (10^{10})	**15.0**	**12.0**	**8.0**	
Bunch number (bunch spacing)	**242 (0.68μs)**	**1524 (0.21μs)**	**12000 (25ns+10%gap)**	
Beam current (mA)	**17.4**	**87.9**	**461.0**	
Synchrotron radiation power /beam (MW)	**30**	**30**	**16.5**	
Bending radius (km)	10.7			
Momentum compact (10^{-5})	1.11			
β function at IP β_x^* / β_y^* (m)	0.36/0.0015	0.36/0.0015	0.2/0.0015	0.2/0.001
Emittance $\varepsilon_x/\varepsilon_y$ (nm)	1.21/0.0031	0.54/0.0016	0.18/0.004	0.18/0.0016
Beam size at IP σ_x/σ_y (μm)	20.9/0.068	13.9/0.049	6.0/0.078	6.0/0.04
Beam-beam parameters ξ_x/ξ_y	0.031/0.109	0.013/0.106	0.0041/0.056	0.0041/0.072
RF voltage V_{RF} (GV)	**2.17**	**0.47**	**0.10**	
RF frequency f_{RF} (MHz) (harmonic)	**650 (216816)**			
Natural bunch length σ_z (mm)	2.72	2.98	2.42	
Bunch length σ_z (mm)	**3.26**	**5.9**	**8.5**	
HOM power/cavity (2 cell) (kw)	**0.54**	**0.75**	**1.94**	
Natural energy spread (%)	0.1	0.066	0.038	
Energy acceptance requirement (%)	1.35	0.4	0.23	
Energy acceptance by RF (%)	2.06	1.47	1.7	
Photon number due to beamstrahlung	0.29	0.35	0.55	
Lifetime _simulation (min)	100			
Lifetime (hour)	0.67	1.4	4.0	2.1
F (hour glass)	0.89	0.94	0.99	
Luminosity/IP *L* ($10^{34}cm^{-2}s^{-1}$)	**2.93**	**10.1**	**16.6**	**32.1**

Collider HOM CBI Q_{ext} Threshold

3 kHz beam spectrum lines, impossible to detune the HOMs (or just no damping? $Q_{0\_TM0mp} = Q_{0\_TM010} * f_{rf} / f_{HOM}$)

Mode	*f* (MHz)	*R*/*Q** (monopole Ω, dipole Ω/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	1.9×10^5	1.8×10^4	2.0×10^4	**2.6×10^2**	**5.2×10^2**
TM020	1383.898	1.3	8.2×10^6	7.6×10^5	8.5×10^5	1.1×10^4	2.2×10^4
TM021	1717.475	19.9	4.3×10^5	4.0×10^4	4.4×10^4	**5.8×10^2**	1.2×10^3
TM012	1832.801	17.26	4.6×10^5	4.3×10^4	4.8×10^4	**6.2×10^2**	1.3×10^3
TE111	844.738	279.8	4.9×10^4	7.7×10^3	8.6×10^3	**1.6×10^2**	**3.1×10^2**
TM110	907.592	420.1	3.3×10^4	5.1×10^3	5.7×10^3	**1.0×10^2**	**2.1×10^2**
TE121	1475.553	125.8	1.1×10^5	1.7×10^4	1.9×10^4	**3.5×10^2**	**6.9×10^2**
TM120	1662.599	18.8	7.4×10^5	1.2×10^5	1.3×10^5	2.3×10^3	4.6×10^3

Average beta_x,y in RF cavity ~ 30 m, without feedback

Booster HOM CBI and Feedback

Modes	*f* (GHz)	*R*/*Q* (monopole Ω, dipole Ω/m)	Q_e measured	CBI Growth Time (ms)		
				H-extraction	W-extraction	Z-extraction
TM011	2.45	156	5.9E4	2307	236.7	51.3
TM012	3.845	44	2.4E5	1281.3	131.5	28.5
TE111	1.739	4283	3.4E3	7308.6	967.1	209.6
TM110	1.874	2293	5.0E4	928.3	122.8	26.6
TM111	2.577	4336	5.0E4	490.9	65	14.1
TE121	3.087	196	4.4E4	12341	1633	353.9
				H-injection	W-injection	Z-injection
TM011	2.45	156	5.9E4	149	29.6	11.3
TM012	3.845	44	2.4E5	82.7	16.4	6.3
TE111	1.739	4283	3.4E3	609	120.9	46.1
TM110	1.874	2293	5.0E4	77.4	15.4	5.9
TM111	2.577	4336	5.0E4	40.9	8.1	**3.1**
TE121	3.087	196	4.4E4	1028.4	204.1	77.8

- All larger than or near the beam transverse feedback time limit of **3.3 ms** (10 turns) and longitudinal feedback time limit of **2.5 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 ~ 30 m

Variable Coupling and Power Saving

Variable coupling (Qe: 1E5 ~ 2E6) of power coupler is necessary especially with “high efficiency klystron”:

- Collider Ring: same mode, different beam current
  - Not so significant, but 10 % is ~ 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)