Beam parameters at CEPC ttbar runs

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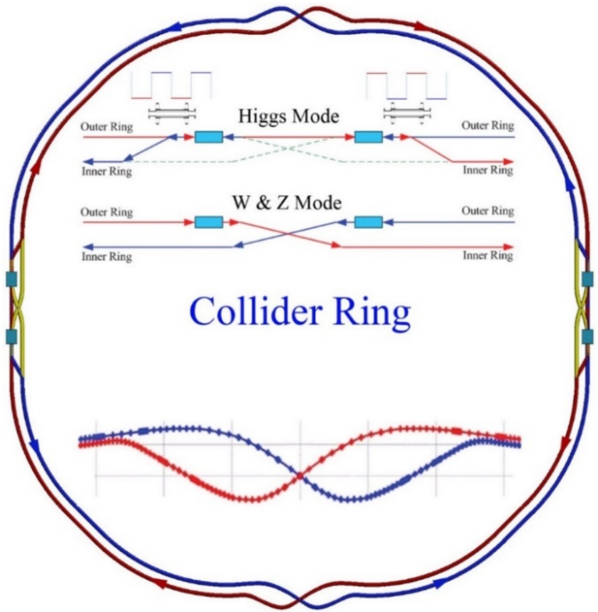
Design requirement of the CEPC collider ring

- **SR power 30MW** (50 MW upgradable), 100km, 2 IPs
- Crab waist collision
- Local chromaticity correction for the interaction region
- Non-interleaved sextupoles
- Correction of sawtooth orbit
- **Shared cavities for two beam @ tt, Higgs and W**
- Dual aperture dipole and quadrupole magnets
- Spin polarized beam @ Z
- Asymmetric interaction region
- **Compatible of $t\bar{t}$/H/W/Z modes**
- Compatible with SPPC

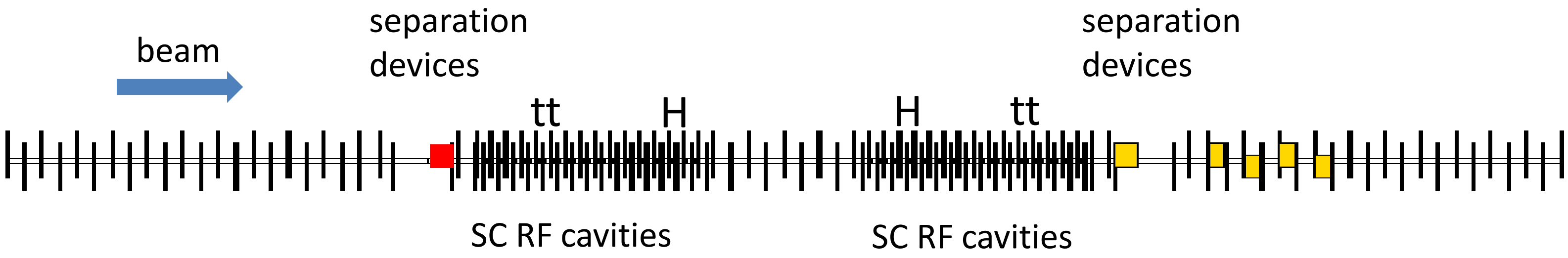


Machine running at ttbar

- CEPC is optimized at Higgs energy.
- The ttbar running will be based on the hardware for Higgs
  - except adding high gradient RF cavities and separation devices.
- No bottle neck on the accelerator physics design **if not high luminosity is required at tt bar for CEPC**.

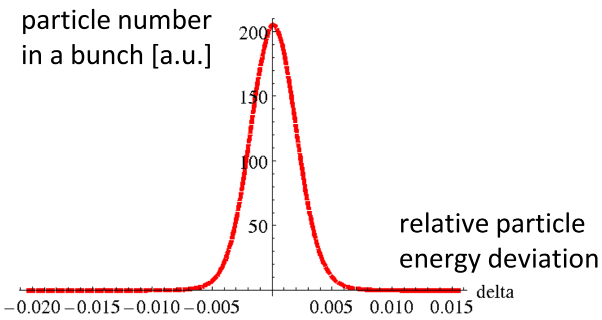
Hardware at ttbar

- RF cavity
  - 240 two cell cavities (for higgs) + 347 cavities five cell cavities (extra cavities for tt)
- Separation devices
  - Higgs: electro-static separator
  - ttbar: electro-static separator + septum without more impedance
  - The design of scheme with kicker + septum with smaller impedance is undergoing.
- Magnets
  - Field maximum: “tt” operation field used
  - Good field region: In all regions except final doublet, Max[Rgf(tt), Rgf(higgs)] used for ttbar



Lattice design at ttbar

- Lattice design
  - magnets strength margin reserved for running at tt bar except two additional normal conducting quadrupoles in IR
- Error correction
  - same scheme as normalized strength is the same with Higgs running
- Dynamic aperture
  - asymmetric momentum acceptance to match the beam energy distribution due to very strong beamstrahlung at ttbar.



by Y. Zhang, CEPC day Feb. 2021

Beam-beam at ttbar

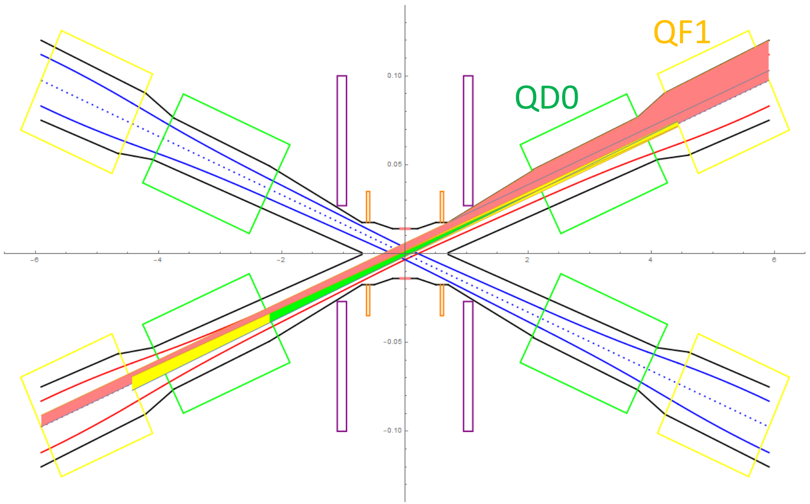
Y. Zhang, CEPC day Feb. 2021

- Different from H/W/Z
  - Very strong SR damping (longitudinal damping time: 20 turns)
  - Medium Piwinski angle CEPC-ttbar~1, BEPCII/KEKB~0.5, CEPC-Z~8
    - Beam-beam resonance could not be suppressed well by Crab-Waist
  - Horizontal beam-beam parameter: 0.07, still very large

Synchrotron radiation in the interaction region at ttbar

by S. Bai et al

- Last bending magnet generates a fan of SR with power 65.8W contributed by e+ will go through the IP.
- The critical energy of photons is about 146.3keV.
- No SR hits directly on the detector beryllium pipe.
- The synchrotron radiation power before the entrance of QD0 is 2.23W, on QD0 is 0.18W, the region between QD0 and QF1 is 2.42W. SR on QF1 is 0.22W.



Beam parameters evolution from CEPC CDR

by C. Yu, Y. Wang, Y. Zhang, S. Bai, Y. Zhu, D. Wang et al

Key parameters of CDR scheme for Higgs

- **L*=2.2m, θc=33mrad, βx*=0.36m, βy*=1.5mm, Emittance=1.2nm**
  - Strength requirements of anti-solenoids B_z~7.2T
  - Two-in-one type SC quadrupole coils (Peak field 3.8T & 136T/m)

Key parameters of high luminosity scheme for Higgs

- **L*=1.9m, θc=33mrad, βx*=0.33m, βy*=1.0mm, Emittance=0.68nm**
  - Strength requirements of anti-solenoids B_z~7.2T
  - Two-in-one type SC quadrupole coils (Peak field 3.8T & 141T/m) with room temperature vacuum chamber & Iron yoke

Reduction of the length from IP to 1st quadrupole without changing the front-end position of the FD cryo-module

- To make the lattice robust and provide good start point for DA

Luminosity comparison

- Luminosity of other modes are increased significantly from CDR.
- Further optimization of luminosity at ttbar and Z modes is possible
  - smaller βy*, emittance coupling and loose SR power limit

Luminosity [10^34/cm^2/s]	ttbar	H	W	Z
CEPC CDR	**0.38**	3.0	10	32
CEPC high lumi	**0.5**	**5.0**	**16**	**115**
FCC-ee CDR	1.55	8.5	28	230
FCC-ee CDR (30MW scaled)	**0.93**	**5.1**	**16.8**	**138**

	CEPC high lumi	*FCC*	*Lum. Factor*	*Upgrades Way*
Piwinski angle	1.21	1.0	1.21	
N_e/bunch (10^{10})	20	23		
Bunch number	35	48		
Beam current (mA)	3.3	5.4		
SR power /beam (MW)	30	50	1.67	loose SR power limit
β_{IP} x/y (m)	1.0/2.7	1.0/0.0016	1.30	decrease beta_y
Emittance x/y (nm)	1.44/0.0047	1.46/0.0029	1.26	decrease coupling
Energy acceptance (DA) (%)	-	-2.8,+2.4		
Energy acceptance by RF (%)	2.48	3.36		
Beamstruhlung/quantum lifetime (min)	60	18		
Lifetime (min)	42			
L_{max}/IP ($10^{34}cm^{-2}s^{-1}$)	0.5	1.55	3.1	

Y. Wang, D. Wang, Y. Zhang et al

Status of beam parameters for all modes

	ttbar	Higgs	W	Z
Number of IPs	2			
Circumference [km]	100.0			
SR power per beam [MW]	30			
Half crossing angle at IP [mrad]	16.5			
Bending radius [km]	10.7			
Energy [GeV]	180	120	80	45.5
Energy loss per turn [GeV]	9.1	1.8	0.357	0.037
Piwinski angle	1.21	5.94	6.08	24.68
Bunch number	35	249	1297	11951
Bunch population [10^10]	20	14	13.5	14
Beam current [mA]	3.3	16.7	84.1	803.5
Momentum compaction [10^-5]	0.71	0.71	1.43	1.43
Beta functions at IP (bx/by) [m/mm]	1.043/2.7	.33/1	.208/1	.125/.9
Emittance (ex/ey) [nm/pm]	1.444/4.693	.643/1.286	.865/1.73	.27/1.348
Beam size at IP (sigx/sigy) [um/nm]	38.815/112.56	14.575/35.855	13.417/41.594	5.805/34.833
Bunch length (SR/total) [mm]	2.198/2.857	2.307/3.929	2.47/4.94	2.481/8.683
Energy spread (SR/total) [%]	.152/.197	.101/.172	.067/.135	.038/.134
Energy acceptance (DA/RF) [%]	2.3/2.6	1.6/2.2	1.2/2.5	1.3/1.7
Beam-beam parameters (ksix/ksiy)	.071/.1	.015/.11	.012/.113	.004/.127
RF voltage [GV]	10.12	2.16	0.714	0.119
RF frequency [MHz]	650	650	650	650
HOM power per cavity (5/2/1cell)[kw]	0.4/0.2/0.1	1/0.4/0.2	-/1.8/.9	-/-/5.8
Qx/Qy/Qs	0.128/0.22/0.078	0.12/0.22/0.049		
Beam lifetime (bb/bs)[min]	80.9/103.9	39.2/18	59.7/716.5	79.8/182202
Beam lifetime [min]	45	12.3	55	80
Hour glass Factor	0.89	0.9	0.9	0.97
Luminosity per IP[1e34/cm^2/s]	0.5	5.0	16	115

Integrated luminosity

- The integrated luminosity is 0.13 ab^-1 per year for 2 IPs.
  - luminosity 0.5E34/cm^2/s/IP
  - 1.3 Snowmass units per year (running assumption in CEPC CDR 1.3*10^7 s/year)
- Need 7.7 years for 1 ab^-1
  - For FCC-ee need 2.5 years (smaller βy*=1.6mm, higher radiation power 50MW, align to 1.3 Snowmass units)
  - FCC-ee has pushed the luminosity to a quite aggressive number 1.55E34/IP. It's difficult to increase the luminosity/per IP by a big margin.

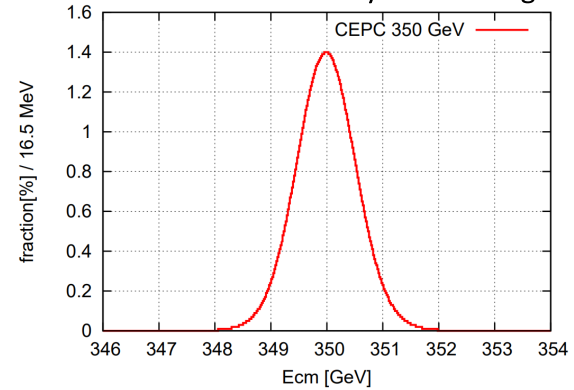
Luminosity spectrum

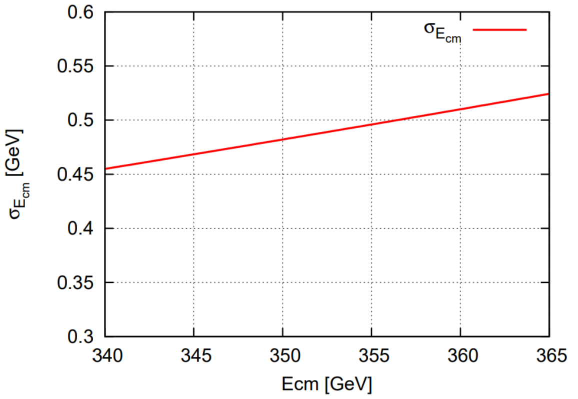
- Beam energy resolution of luminosity spectrum as large as 0.48 GeV at 350 GeV
- Resolution around 350 GeV estimated with

$$\sigma_{E_{\mathrm{cm}}} \approx \sqrt{2}\left(\frac{\sigma_{E_{\mathrm{beam}}}}{E_{\mathrm{beam}}}\right) E_{\mathrm{beam}} \propto E_{cm}^2$$

- Actual resolution may differ from this estimation due to the **limited beam tuning time for energy scan.**
  - lower resolution with lower integrated luminosity

by Yuan Zhang





Uncertainty of beam energy calibration

by Yongsheng Huang, Guangyi Tang et al

- The beam energy calibration of CEPC
  - **Inverse Compton Scattering**
  - Spin Resonance Depolarization (mainly at Z)
  - Microwave-beam Compton Back Scattering
- One dimension simulation results of ICS scheme shows an uncertainty **1.8 MeV at 350 GeV** (statistical uncertainties of the beam energy excluded).

	Higgs mode	Z mode	WW scan	$t\bar{t}$ scan
E_{beam}/GeV	120	45	80	175
X_{edge}/m	6.163 52	9.296 86	7.103 43	5.572 76
X_{beam}/m	1.879 35	5.011 78	2.819 03	1.288 68
δX_{edge}/m		2.6×10^{-5}		
δX_{beam}/m		6×10^{-8}		
δE_{beam}/MeV	1.0	0.3	0.6	1.8

G.Y. Tang et al, Rev. Sci. Instrum. 91, 033109 (2020)

More details of the energy calibration: Detector and Software - Session IV, Beam energy measurement, by Yongsheng Huang

Summary

- CEPC is optimized at Higgs energy.
  - The tt bar running will be based on the hardware for Higgs except adding high gradient RF cavities and separation devices.
  - No bottle neck on the accelerator physics design if not high luminosity is required at tt bar for CEPC.
- The integrated luminosity is 0.13 ab^-1 per year for 2 IPs with current design of CEPC –ttbar.
- Beam energy resolution of luminosity spectrum is as large as 0.48 GeV at 350 GeV.