Specifics of Electron Dynamics in High Energy Circular e^+e^- Colliders

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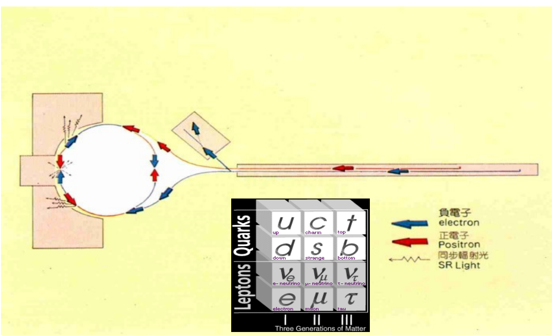
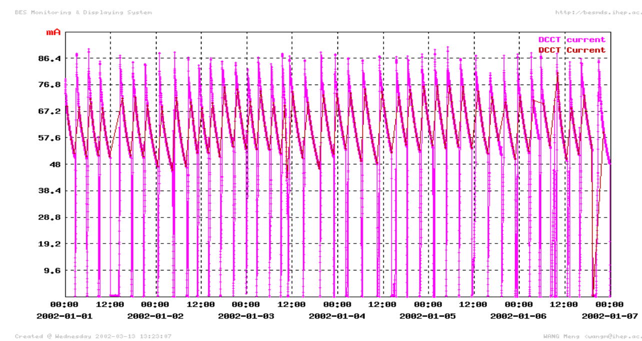
Outline

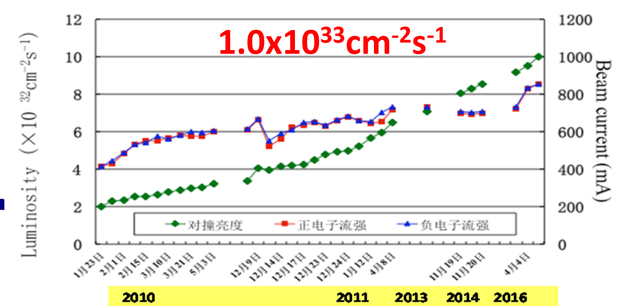
- Introduction
- Lattice Design
  - Pretzel Scheme
  - Sawtooth effect
  - Interaction region & Dynamic Aperture
- Beam-Beam Interaction
- Collective Instability
- Conclusion

1. Introduction

- **From BEPC → BEPCII, 1980's → 2010's**

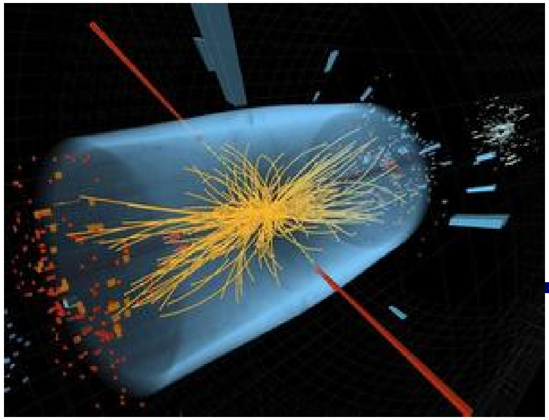




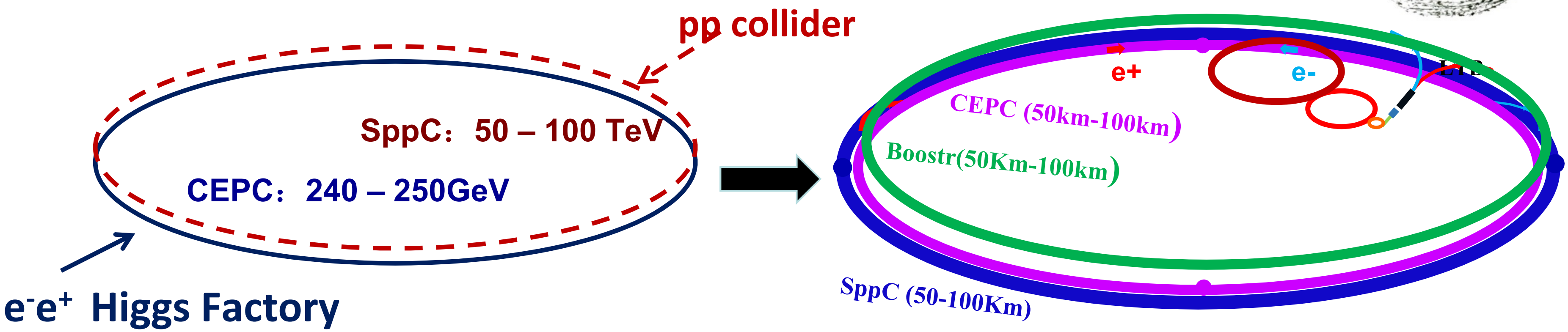


CEPC+SppC, proposed as

- Higgs Boson was discovered in 2012, with a lower energy than expected, ~126GeV/c^2
- Circular collider seems more mature and promising
- More high energy physics hide in a possible pp collider converted by electron machine



CEPC+SppC：


pp collider
SppC：50 – 100 TeV
CEPC：240 – 250GeV
e-e+ Higgs Factory
e+
e-
CEPC (50km-100km)
Boostr(50Km-100km)
SppC (50-100Km)

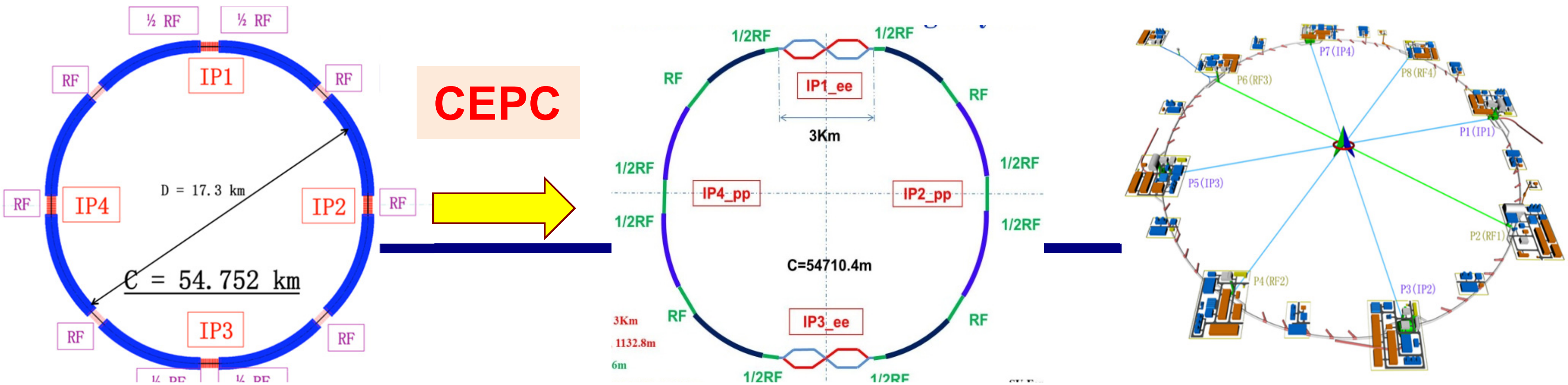

½ RF
½ RF
RF
RF
IP1
IP4
IP2
IP3
D = 17.3 km
C = 54.752 km
CEPC
1/2RF
RF
IP1_ee
3Km
IP4_pp
IP2_pp
C=54710.4m
IP3_ee
3Km
1132.8m
6m
P7(IP4)
P6(RF3)
P8(RF4)
P1(IP1)
P5(IP3)
P2(RF1)
P4(RF2)
P3(IP2)

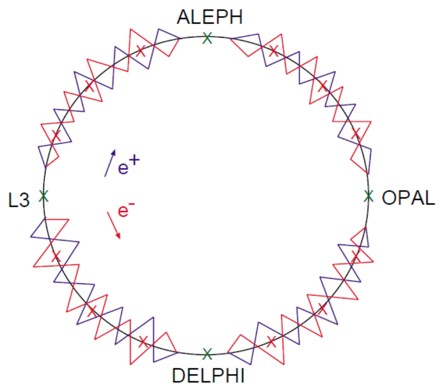
Table 1: Main Parameters of LEP2, FCC-ee and CEPC

	LEP2	FCC-ee (h)	CEPC (pre-CDR)
Max. E_b (GeV)	104.5	175	120
Circumference (km)	26.7	100	54
Beam current (Ma)	4	6.6	16.6
Bunch No. /beam	4	98	50
Particles/beam (10^{11})	23	1.4	3.79
Hori. Emit. (nm-rad)	48	2	6.12
Verti. Emit. (nm-rad)	0.25	0.002	0.018
Bending radius (km)	3.1	11	6.1
Mom. Compact. (10^{-5})	18.5	0.5	3.36
SR power/beam (MW)	11	50	51.7
β^*_x (m)	1.5	1	0.8
β^*_y (mm)	50	1	1.2
E^{SR}_{loss}/turn (GeV)	3.41	7.55	3.1
$V_{rf,tot}$ (GV)	3.64	11	6.87
$\delta_{max,RF}$(%)	0.77	7.1	5.99
$\delta_{SR,rms}$(%)	0.22	0.14	0.13
ξ_x/IP	0.025	0.092	0.118
ξ_y/IP	0.065	0.092	0.083
L/IP (10^{32}cm^{-2}s^{-1})	1.25	180	204
No. of Ips	4	4	2
Beam lifetime (min)	360	21	47

In Sept. 2012, two months later than the discovery of Higgs boson, IHEP announced a plan of building a circular electron positron collider (CEPC) as a Higgs factory in the next decade to study the features of Higgs, and some precise measurements on the Higgs particle. The CEPC can be converted to a super proton proton collider (SppC) in the same tunnel of CEPC. Meanwhile, TLEP, which was re-organized as FCC-hh, and –ee, were proposed by CERN as a future project after the LHC.

2. Lattice design

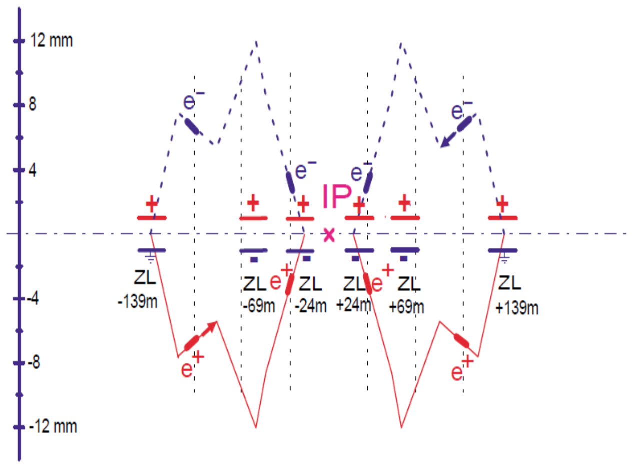
- **Single ring scheme tested in LEP: Pretzel scheme**



Schematic layout of the pretzel scheme used in LEP

- ➢ Electrons and positrons travel in opposite directions in the same beam pipe
- ➢ The orbit is generated by electrostatic separators
- ➢ Horizontal separation is used
- ➢ The distances between bunches are equal
- ➢ The maximum bunch number is: 8 bunches/beam

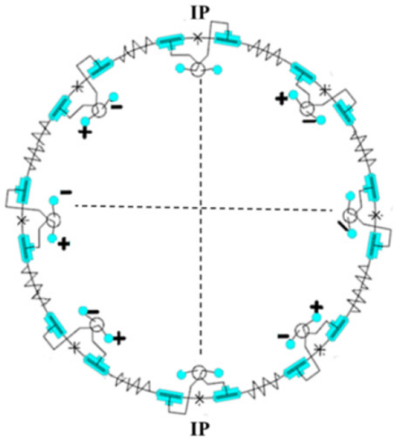
Single ring scheme tested in LEP: Bunch train scheme

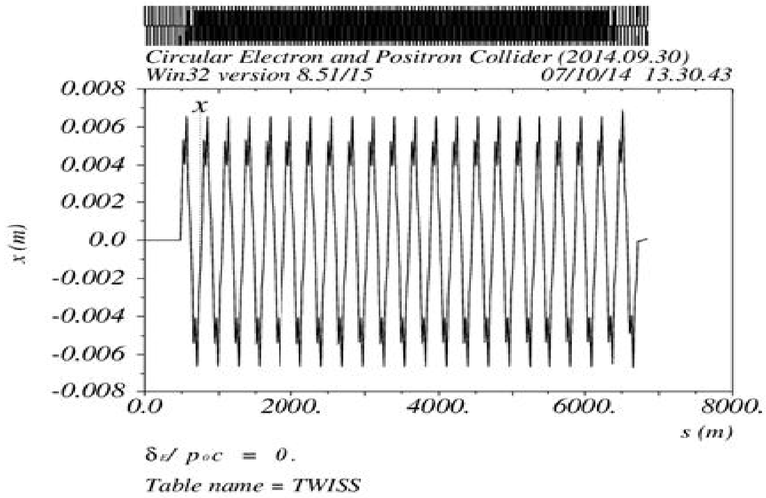


Schematic layout of the bunch train scheme used in LEP.

- Bunches are stringed together as a train
- Vertical separation is used
- The distances between bunches are equal
- The maximum bunch number: 2 bunches/train and 4 trains/beam

Single ring design for CEPC





- Pretzel scheme is used for single ring design of CEPC
- 60/60 degree FODO cells are used in arcs
- Horizontal separation is used
- Orbits will be generated by electrostatic separators
- Maximum separation distance between two beams are $10\sigma_x$

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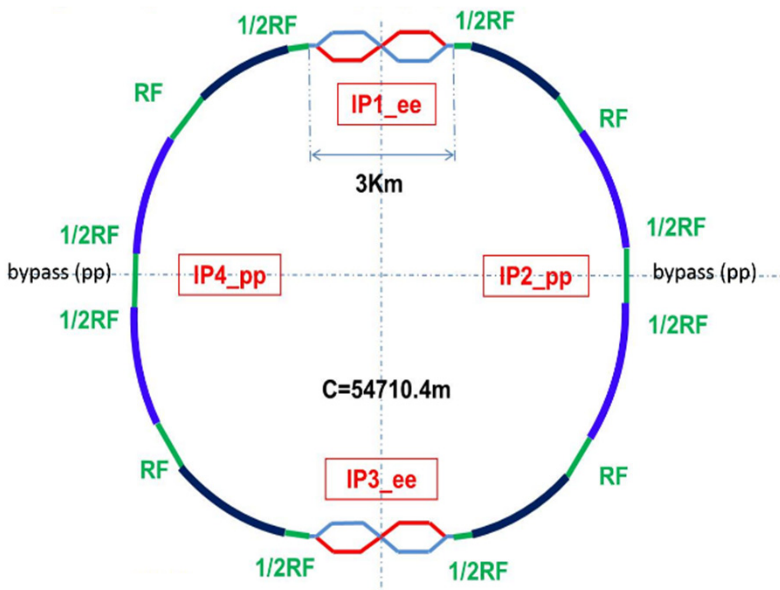
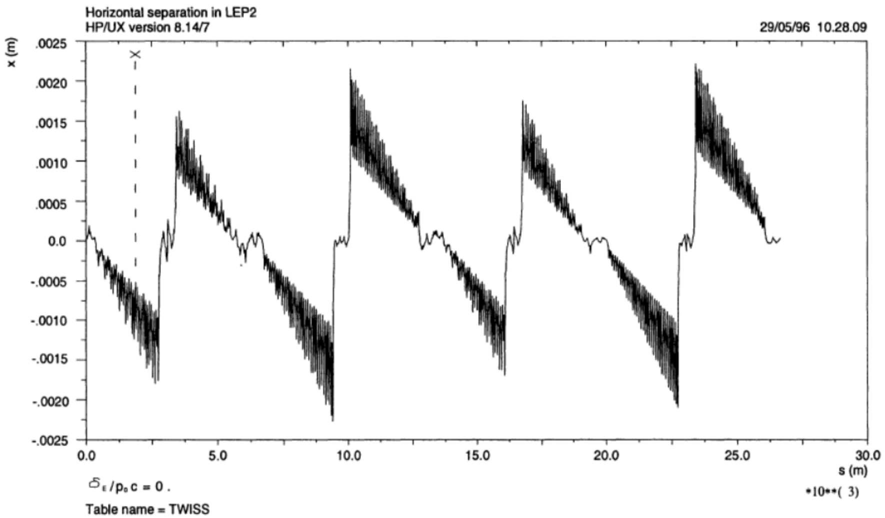
Partial double ring design for CEPC



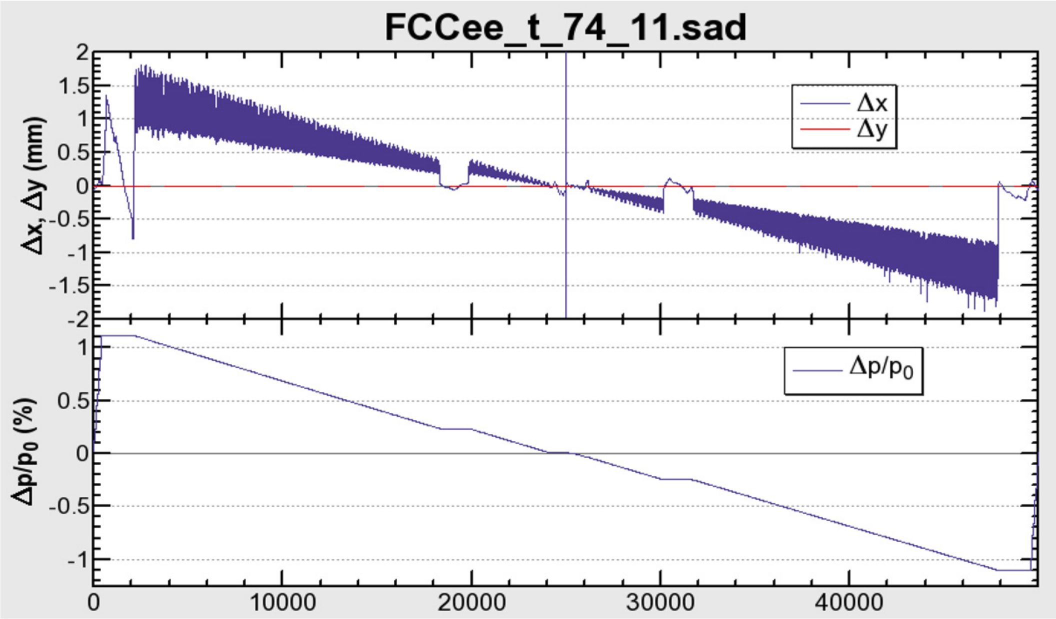
- The ring is partially doubled near the IPs
- Pretzel scheme could be avoided
- Bunch train scheme will be used
- FODO cells with 90 degree phase advances in both planes are used
- The full crossing angle of the PDR scheme is 30 mrad.

Energy sawtooth effect in LEP



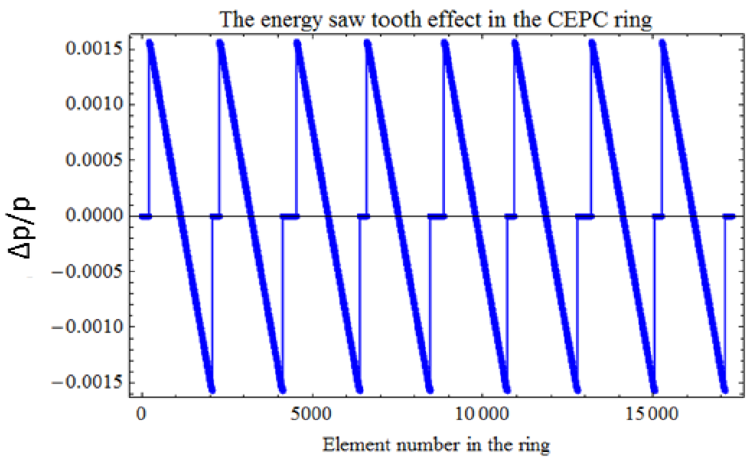
- ➢ Energy sawtooth effect at LEP2 had been calculated at 87GeV
- ➢ All RF units on, but RF voltages are distributed asymmetrically
- ➢ The horizontal orbit shift due to the energy sawtooth could be as large as 2.5mm

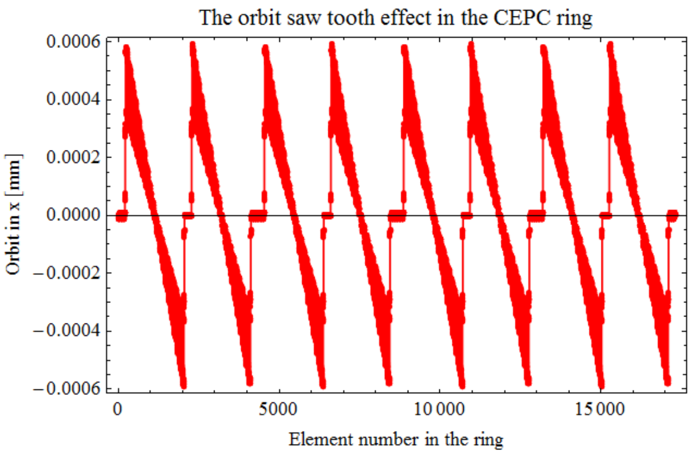
Energy sawtooth effect in FCC-ee



- Energy sawtooth effect at FCC-ee had been calculated at 175GeV
- The momentum spread due to this effect is as big as 1.1%
- The horizontal excursion due to this effect can be as large as 1.8mm
- Can be mitigated by tapering

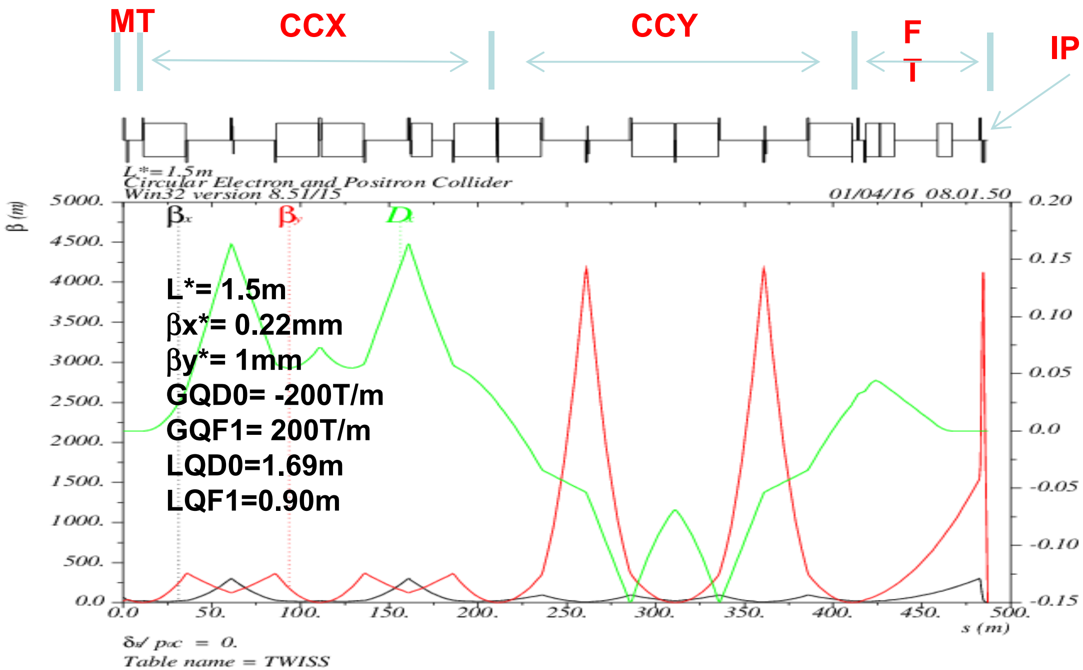
Energy sawtooth effect in CEPC





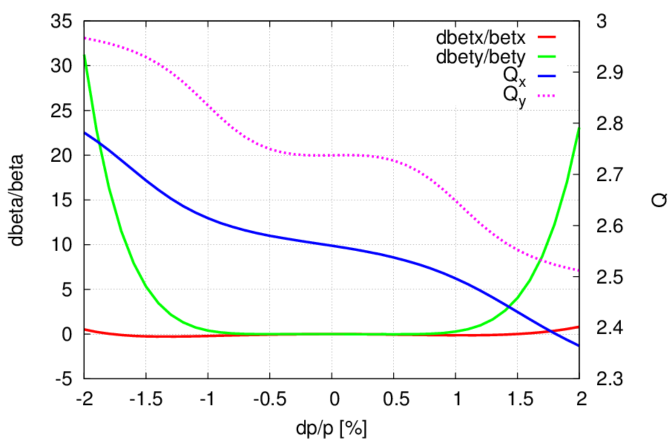
- Energy sawtooth effect at CEPC had been calculated at 120GeV
- the momentum spread due to this effect is only about 0.15%
- The horizontal orbit shift due to the energy sawtooth is 0.6mm
- Primary study shows no obvious reduction in dynamic aperture

Lattice of Interaction Region (CEPC)

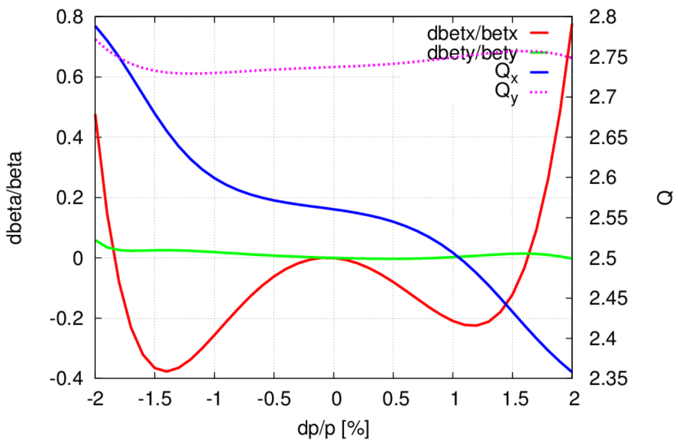


- An FF optics similar to the linear collider is adopted for the CEPC
- As a telescopic transfer line including a **final telescopic transformer** (FTT), **chromaticity correction section** on the horizontal and vertical planes (CCX and CCY), and the **matching telescopic transfer** (MT)

Chromaticity correction of IR (CEPC)



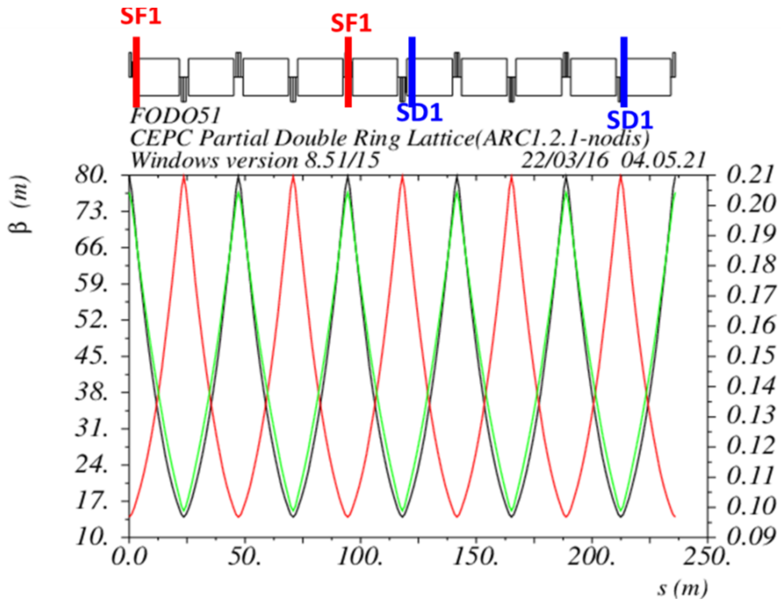
Correct 1st and 2nd order chromaticity



Correct 3rd order chromaticity

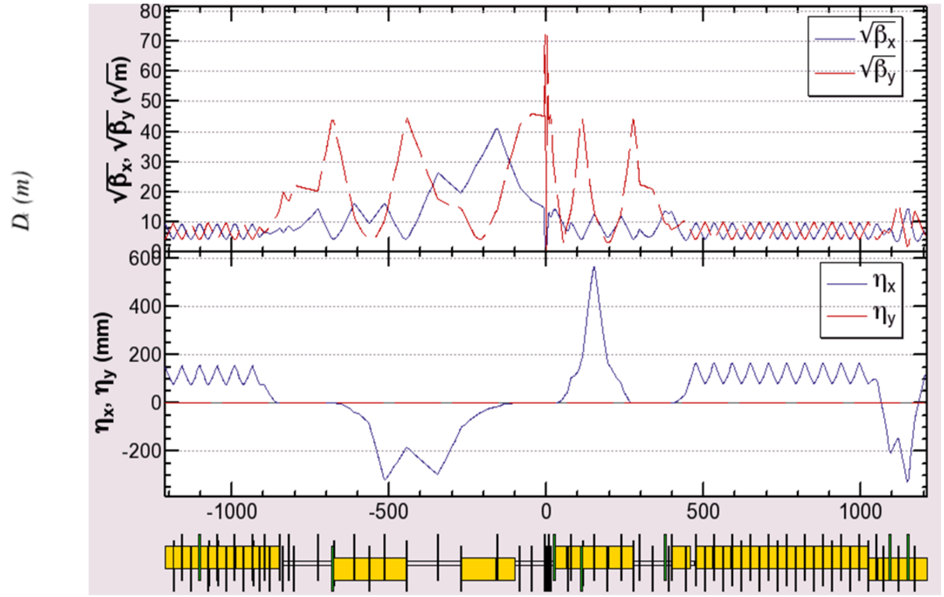
- 3rd order chromaticity in the horizontal plane could be corrected with an additional sextupole at second image point or ARC sextupoles

Lattice design of CEPC



Non-interleave sextupoles in arc,(90°/90° FODO)

Beam optics for FCC-ee IR



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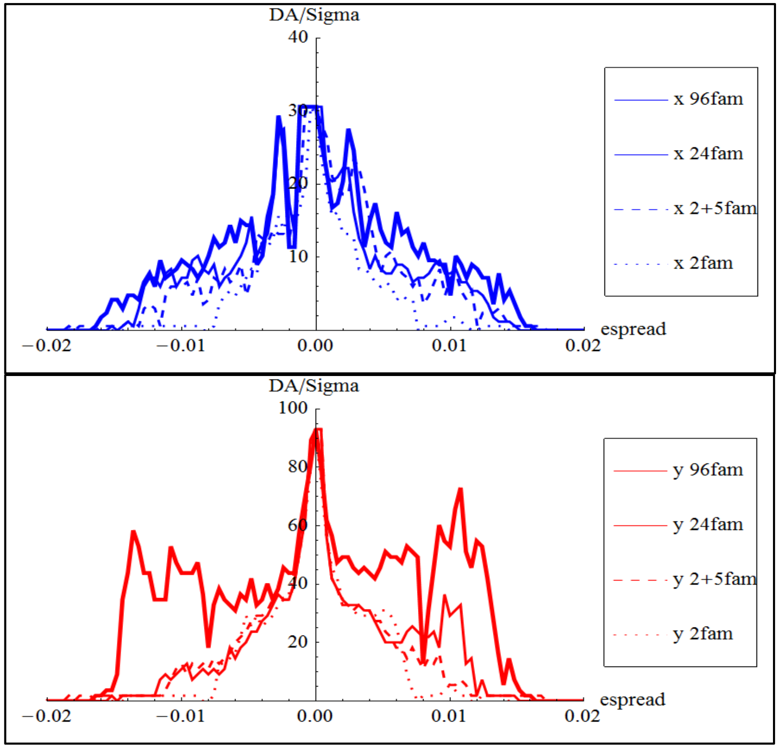
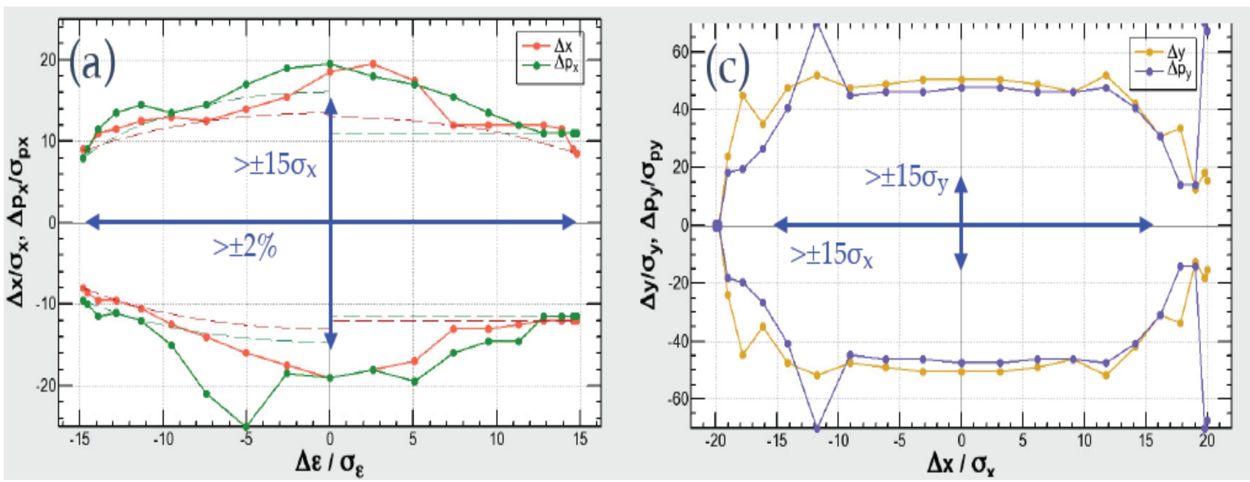
Dynamic aperture optimization (CEPC)

- Dynamic aperture for whole ring (PDR scheme)
  - Bare lattice
  - Synchrotron motion included, w/o damping
  - Tracking with around 1 times of damping time
  - Coupling factor κ=0.003 for εy
  - Working point (0.08, 0.22)
- Many cases of sextupole families tried
  - Downhill Simplex algorithm applied
  - Further optimization is possible
    - Further optimization with these families
    - More families in IR
    - βy*= 1mm -> 1.36mm (new parameter)
    - Larger dispersion for IR sextupoles
  - work on with SR damping and excitation, magnetic errors, crab sextupoles and solenoid field, is still on the way



Dynamic aperture optimization for FCC-ee



- DA has been optimized by the downhill simplex method scripted in SAD
- 50 turns were tracked
- Synchrotron radiation is on and tapering has been applied
- No errors has been applied yet
- Satisfies the requirements

3. Beam-beam interaction

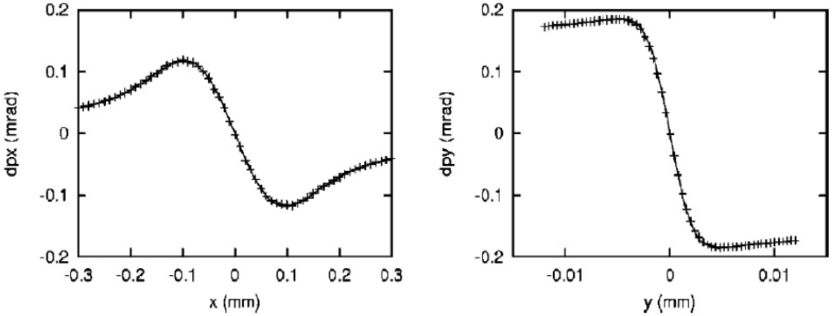
For the case of flat Gaussian beams in e- e+ circular collider, the deflection angle can be expressed analytically in terms of the complex error function:

$$\Delta p_y + \Delta p_x = \frac{2N_b r_e}{\gamma}\sqrt{\frac{2\pi}{\sigma_x^2-\sigma_y^2}}\left[w\left(\frac{x+iy}{2(\sigma_x^2-\sigma_y^2)}\right)-\exp\left(-\frac{x^2}{2\sigma_x^2}-\frac{y^2}{2\sigma_y^2}\right)w\left(\frac{\frac{\sigma_y}{\sigma_x}x+\frac{\sigma_x}{\sigma_y}y}{\sqrt{2(\sigma_x^2-\sigma_y^2)}}\right)\right]$$

A typical transverse beam-beam deflection, the vertical deflection strongly depends on the horizontal offset, which excite transverse betatron resonance.

At small amplitudes, where the deflection increases approximately linearly with displacement, it resembles the effect of an additional quad, whose strength is characterized by the so-called beam-beam parameter

$$\xi_{x,y} = \frac{r_e \beta_{x,y} N_b}{2\pi\gamma\sigma_{x,y}(\sigma_x+\sigma_y)}$$

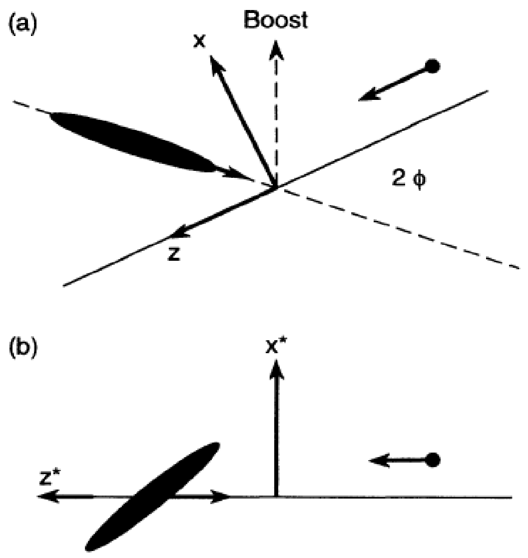


Bunch length effect

- The beam-beam force acts mainly in the transverse directions so that the longitudinal effects have scarcely been studied before 1990s, except for the cases of a collision with a crossing angle by Piwinski*[A. Piwinski, IEEE Trans. Nucl. Sci. NS-24 1408 (1977)*]
- When the beam are focused extensively at the interaction point, the beam sizes can vary significantly within the bunch length. Krishnagopal and Siemann [*S. Krishnagopal and R. Siemann, Phys. Rev. D41, 2312 1990*] have shown that we should not neglect the bunch length effect in this case.
- The transverse kick depends on the longitudinal position as well as on the transverse position. Hirata proposes the so-called synchro-beam map[*K. Hirata, H. Moshammer, and F. Ruggiero, Particle Accelerators 40, 205 (1993).*] for a particle-slice interaction, which provides us a 6*6 symplectic map.

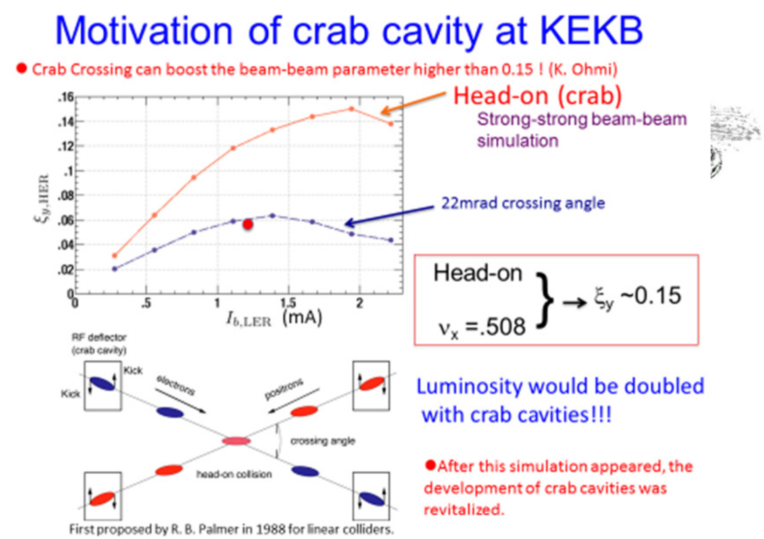
Crossing Angle

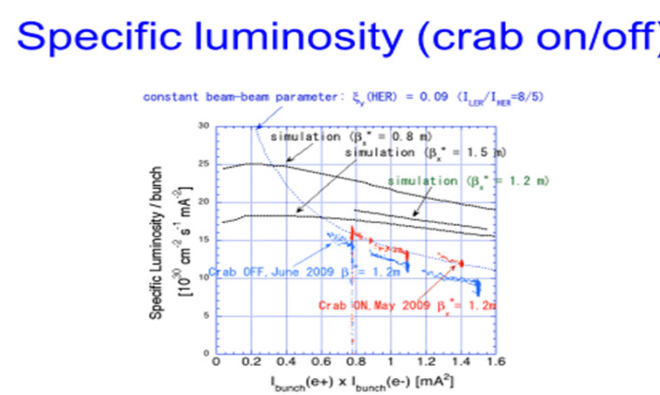
- In 1990s, high-luminosity e+e- colliding rings were being considered seriously. Small bunch spacing is useful because collisions occur more frequently. This causes the problem of parasitic collisions: Bunches may interact with each other not only at the interaction point but also at points around the IP.
- These can be avoided by collision with a crossing angle. This, however, leads to another difficulty. The collision with a crossing angle causes an instability due to the synchrobetatron resonances which are known to have limited the performance of the DORIS collider[A. Piwinski, DESY Report No. DESY 77/18, 1977]. It was widely believed that SB resonances become more serious for larger crossing angles at that time.
- Hirata develop a new method of calculation to simulate the effect of crossing angle: Synchro-beam mapping + Lorentz Boost.
- The simulation study shows that crossing with a large angle has less serious detrimental effects that is usually believed. The luminosity reduction is only of geometrical origin: Compared to the luminosity reduction factor is small, but reduction factor is even smaller, so that the beam blowup is less serious.
- With more simulation study, collision with crossing angle is popular. The kekb/dafne/bepcii all adopt a horizontal crossing scheme, with the Piwinski angle about 0.5-1.0.



Crab Crossing

- **The Palmer idea of the beam-beam collision will make a large crossing angle possible without a loss of the luminosity and an excitation of synchrobetatron resonances[*R. B. Palmer, SLAC-PUB-4707(1988), K. Oide, Phys. Rev. A. 40, 315, 1989*]**
- **Finally two crab cavities were installed in KEKB, one for each ring in January 2007. After fine tuning, the highest luminosity with the crab cavities is about 23% higher than that before, which is larger than the geometrical loss of the luminosity due to the crossing angle (~11%). The achieved vertical beam-beam parameter was ~0.09. [*Y. Funakoshi, beam-beam workshop 2013*]**

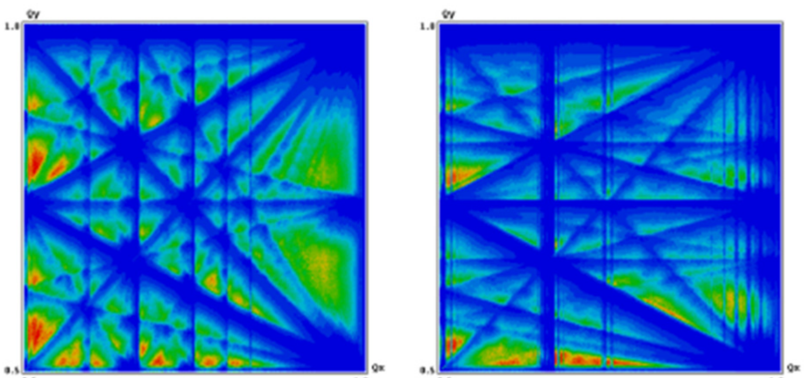




Luminosity improvement by crab cavities is about 20%.
Geometrical loss due to the crossing angle is about 11%.

More on Crossing Angle

- **The synchrobetatron resonance dominates for , while betatron resonances dominate for**



ϕ = 0.87 Mainly synchro-betatron resonances

ϕ = 3.5 Mainly betatron coupling resonances

Luminosity and emittances blowup vs. betatron tunes: 2D tune scans in the range from 0.5 to 1.0. "Geographical map" colors: **red** – "good", **blue** – "bad". The main working resonances can be easily seen on these plots. [D. Shatilov]

For small Piwinski angle, the particle's horizontal coordinate in "strong" frame is determined by its horizontal betatron coordinate and longitudinal position, so synchrobetatron resonances apprear. For large Piwinski angle, the collision point of vertical kick is located at the intersection with the central axis of the opposite bunch, where the particle's horizontal coordinate in "strong" frame is always zero, while the CP is determined by the horizontal beatatron coordinate, which induces strong betatron coupling resonance.

Crab Waist Collision

- The large Pinwinski scheme reduces the overlap area, allowing to squeeze betay* without hourglass effect.
- The Piwinski angle is increased by decreasing the horizontal beam size and increasing the crossing angle. This is called the nano scheme, which is adopted for SuperKEKB.
- Large Piwinski angle itself introduces new beam-beam resonances which may strongly limit the maximum achievable tune shifts.
- The crab sextupole strength should satisfy the following condition depending on the crossing angle and the beta functions at the interaction point (IP) (indicated with an asterisk) and the sextupole locations:

$$K = \frac{1}{\theta}\frac{1}{\beta_y^* \beta_y}\sqrt{\frac{\beta_x^*}{\beta_x}}$$

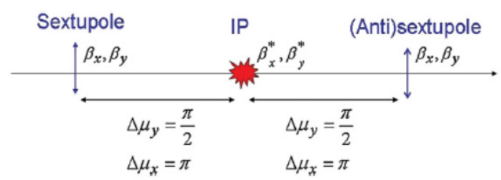


FIG. 2 (color). Crab sextupole locations.

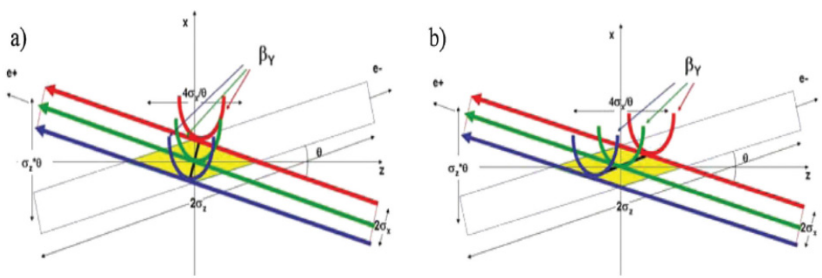
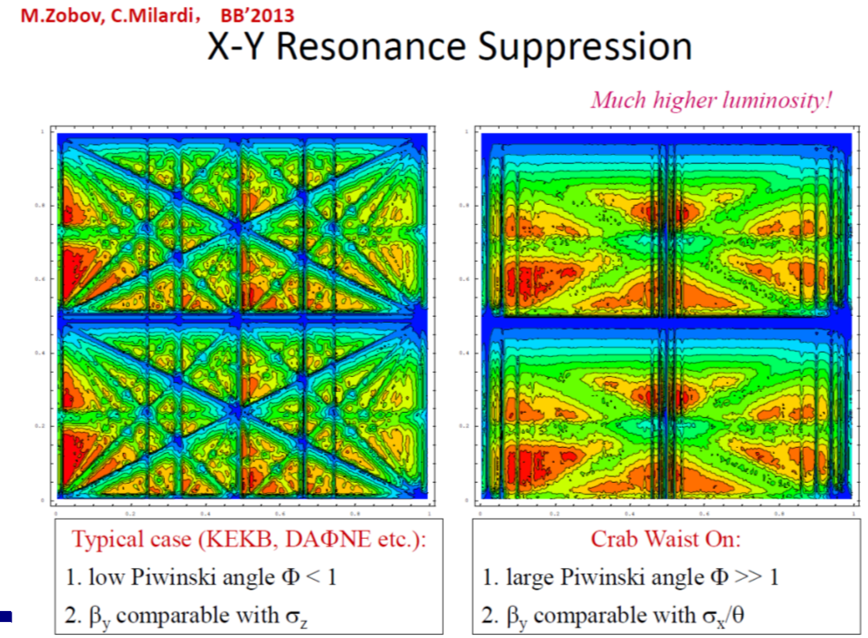


FIG. 1 (color). Crab-waist collision scheme. The color straight lines show directions of motion for particles with different horizontal deviations from the central orbit. The arrows indicate the corresponding β function variations along these trajectories.

Crab Waist Collision (Cont)

- **The dominating effect of the crab-waist transformation comes from the suppression of betatron (and synchrobetatron) resonances arising (in collisions without CW) from the vertical motion modulation by the horizontal betatron oscillations [*P. Raimondi, D. Shatilov, and M. Zobov, Report No. LNF-07/003; arXiv:physics/0702033*].**



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Test of Crab Waist at DAFNE

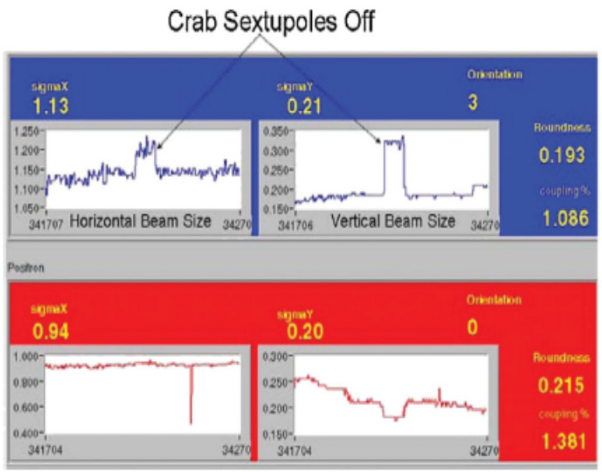


FIG. 3 (color). Transverse beam sizes at the synchrotron light monitors (electrons: blue windows, positrons: red windows).

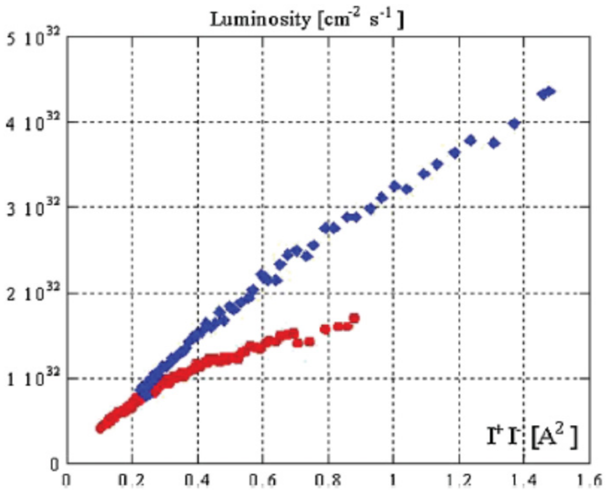


FIG. 4 (color). Measured luminosity as a function of beam current product for crab sextupoles on (blue) and off (red).

M. Zobov and et al., PRL 104, 174801 (2010)

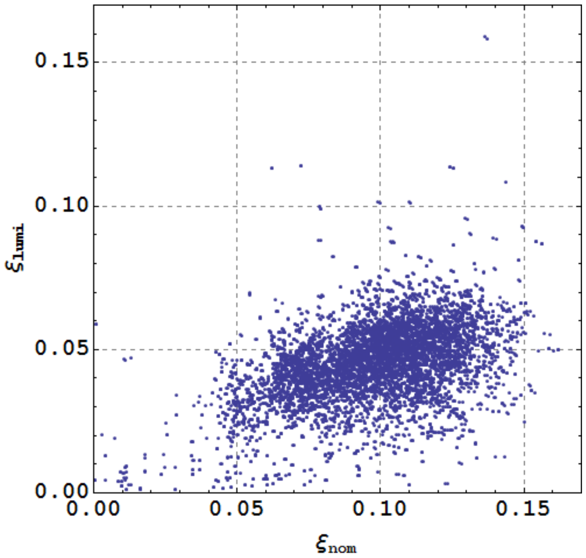
Round Beams (D. Shatilov)

Advantages:

- Geometrical factor of 2 in luminosity.
- If the bunch current is limited by beam-beam effects, one more factor of 2.
- Axial symmetry → angular momentum preservation → increase of ξ.

But:

- Small beta-function in both directions is more difficult to achieve, than only in one direction.
- In factories (many bunches → crossing angle, parasitic crossings) axial symmetry is broken.
- If Piwinski angle is not very small, geometric factors of luminosity gain vanish.



- Round colliding beams are implemented now at VEPP-2000 collider, Novosibirsk.
- The record high values of ξ were achieved (damping time ~ $5{\cdot}10^5$ turns!).

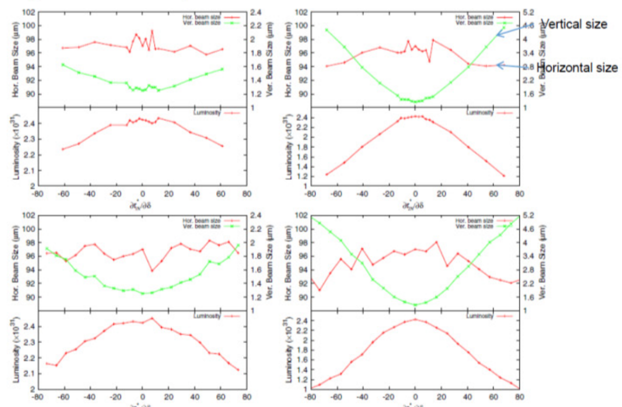
$$\xi_{nom} = \frac{N^- r_e \beta^*_{nom}}{4\pi\gamma\sigma^{*2}_{nom}} \qquad \xi_{lumi} = \frac{N^- r_e \beta^*_{nom}}{4\pi\gamma\sigma^{*2}_{lumi}}$$

Crosstalk between Beam-Beam and Lattice Nonlinearity

- **General chromaticity maybe important to luminosity: The tuning with skew-sextupole magnets were effective to increase the luminosity w/ crab (~15% gain).**

Scan of first-order chromatic coupling (WS, Crab on)

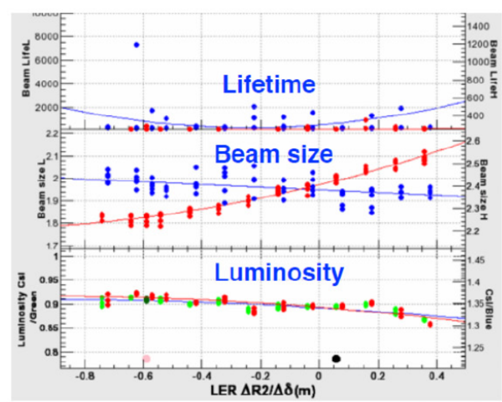
D. Zhou, et al., PRST--AB 13, 021001 (2010).

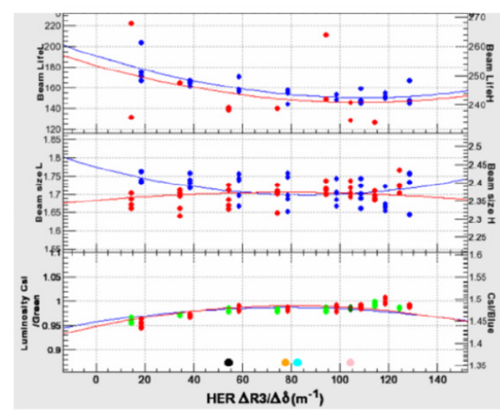


$$\begin{pmatrix} r^*_{1N} & r^*_{2N} \\ r^*_{3N} & r^*_{4N}\end{pmatrix} = \begin{pmatrix} r^*_1\sqrt{\beta^*_x/\beta^*_y} & r^*_2/\sqrt{\beta^*_x\beta^*_y} \\ r^*_3\sqrt{\beta^*_x\beta^*_y} & r^*_4\sqrt{\beta^*_y/\beta^*_x}\end{pmatrix}$$

G. 8 (Color) Scan of first-order chromaticity of X-Y couplings at the IP.

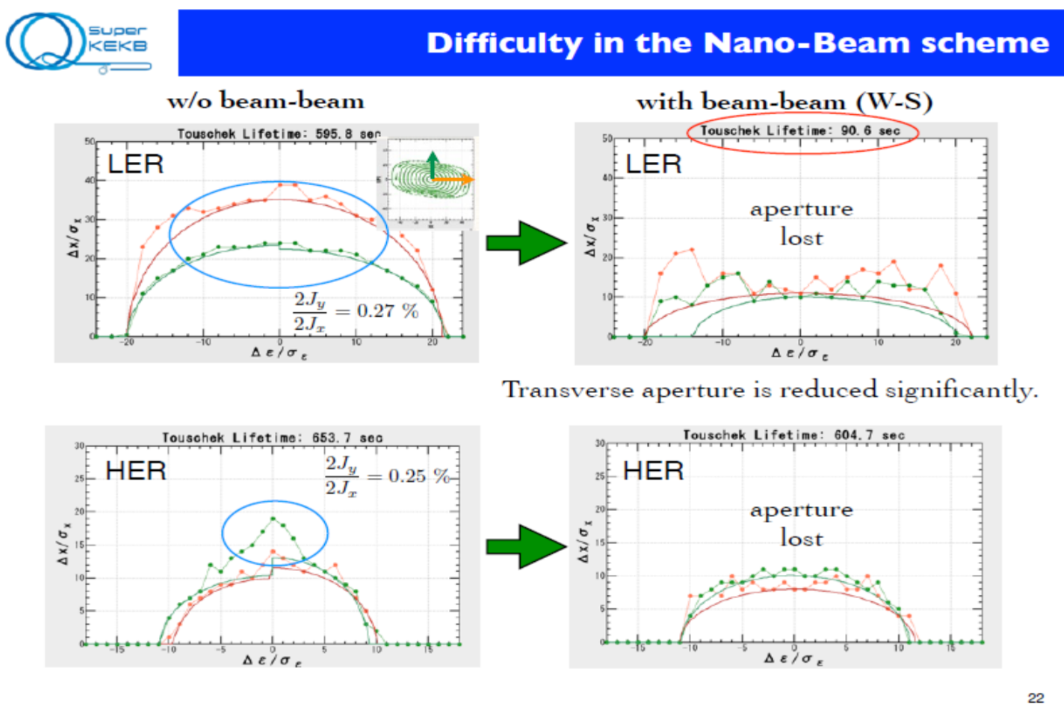
The first scans of chromatic coupling at IP during the KEKB operation:





Crosstalk between Beam-Beam and Lattice Nonlinearity (Cont)

- **Aperture loss due to beam-beam interaction**



Y. Ohnishi, 18th KEKB Review, 2014

Beamstrahlung: essential for Higgs factory

- **Increased energy spread and bunch lengthing due to the additional synchrotron radiation with large quantum fluctuation, which is described by [*K. Ohmi and F. Zimmermann, in Proc of IPAC 2014*]**

$$\sigma_{\delta,BS} \approx \delta_{BS}\left(0.333 + \frac{4.583}{N_\gamma}\right)^{\frac{1}{2}}$$

$$\sigma_{\delta,tot} = \left(\frac{1}{2}\sigma_{\delta,SR}^2 + \left(\frac{1}{4}\sigma_{\delta,SR}^4 + \frac{1}{4}\frac{\tau_z n_{IP}}{T_{rev}}\sigma_{\delta,BS}^2\frac{\sigma_{\delta,SR}^2}{\sigma_{z,SR}^2}\right)^{\frac{1}{2}}\right)^{\frac{1}{2}}$$

$$\delta_{BS} \approx 0.86\frac{r_e^3\gamma N_b^2}{\sigma_z\sigma_x^2}$$

$$N_\gamma \approx 2.1\frac{\alpha r_e N_b}{\sigma_x}$$

- **Reduction of the beam lifetime due to the emission of photons of so large an energy that emitting electron, or positron, falls outside of the ring momentum acceptance and is lost over subsequent turns. One approximate analytical formula for the beamstrahlung lifetime is [*V. Telnov, Phys. Rev. Letters 110 (2013) 114801*]**

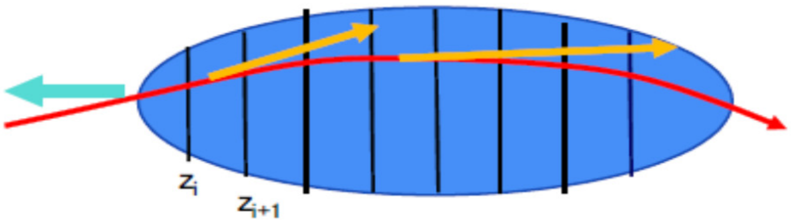
$$\tau_{BS} \approx \frac{1}{n_{IP} f_{rev}}\frac{4\sqrt{\pi}}{3}\sqrt{\frac{\delta_{acc}}{\alpha r_e}}\exp\left(\frac{2}{3}\frac{\delta_{acc}\alpha}{r_e\gamma^2}\frac{\gamma\sigma_x\sigma_z}{\sqrt{2}r_e N_b}\right)\frac{\sqrt{2}}{\sqrt{\pi}\sigma_z\gamma^2}\left(\frac{\gamma\sigma_x\sigma_z}{\sqrt{2}r_e N_b}\right)^{3/2}$$

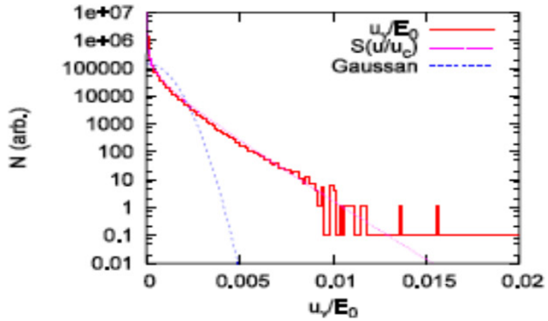
Beamstrahlung: essential for Higgs factory

K. Ohmi

- Synchrotron radiation during beam-beam collision
- Calculate trajectory interacting with colliding beam.
- Particles emit synchrotron radiation due to the momentum kick dp/ds.

ρ=23.5/19.7m<< ρ_{bend}= 6,094/11,000m (CEPC/TLEP)
u_c= 164/194 MeV, N_γ=0.21/0.092





$$ds = \frac{z_i - z_{i+1}}{2} \qquad \langle\delta\rangle = dn_\gamma\langle u\rangle = \frac{2r_e\gamma^3}{3\rho^2}ds$$

$$\frac{1}{\rho_{x,y}} = \frac{dp_{x,y}}{ds} \qquad \langle\delta^2\rangle = dn_\gamma\langle u^2\rangle = \frac{55}{24\sqrt{3}}\frac{r_e\hbar\gamma^5}{mc\rho^3}ds$$

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Collective effects

- In order to achieve the high luminosity, large efforts have been made to increase the beam intensity and decrease the bunch length.
  - High beam induced heating
  - More easily couple with the high frequency impedances
- High beam energy
  - Beneficial in general from the instability point of view
  - Instabilities are more critical for low energy operation (like Z-pole)
- Large circumference
  - Lower revolution frequency (~kHz) generates dense beam spectrum lines
  - Enhancement of the machine impedance
- Small momentum compaction factor due to large bending radius and small horizontal dispersion in dipoles.
  - Result in shorter bunch length and lower synchrotron frequency.
  - More sensitive to collective instabilities.

Single bunch instability

- **Coupling impedance dominated by**
  - Resistive wall impedance
  - Vacuum components with large numbers (RF cavities, flanges, BPMs, bellows, …)
  - Vacuum components with large impedances (IP duct, collimators, kickers, …)
- **Microwave instability**
  - Impedance threshold estimated by Boussard or Keil-Schnell criteria

$$I_{th} = \frac{\sqrt{2\pi}\alpha_p \frac{E}{e} \sigma_{e0}^2 \sigma_l}{R \left| \frac{Z_{\parallel}}{n} \right|_{eff}}$$

CEPC: 24 mΩ, FCC-ee: 13 mΩ (LEP measured: 30 mΩ)

  - Often believed to be too passive for short bunched beam
  - High frequency part of impedance may lead to turbulent distribution
  - Needed to be studied with macro-particle tracking or Vlasov solver

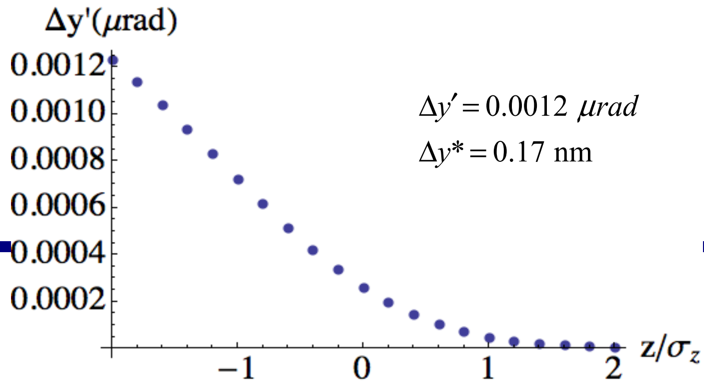
Single bunch instability

- **Transverse beam tilt**
  - **Tail particles will receive transverse kicks when a beam passes through a impedance with a transverse offset (Pretzel orbit in horizontal and close orbit in vertical)**

$$\Delta y'(z) = \frac{Ne^2}{E}\int_0^\infty dz'\rho(z'+z)W_\perp(y_b, z')$$

  - **May lead to transverse emittance increase and a transverse displacement of the bunch tail at IP.**

- Kick angle along the bunch due to single RF cavity in CEPC



As there are 384 cavities located in 8 positions in the ring, the displacements at IP are

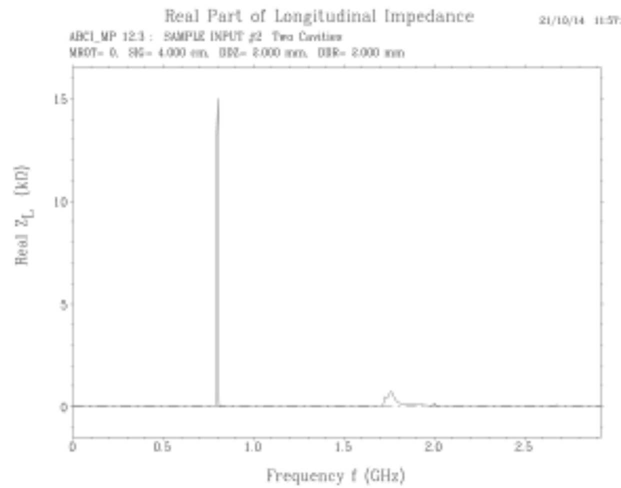
$\Delta y^* = 48 \quad {}^*0.17\text{nm} = 0.023\mu\text{m}$

About 1/5 of the beam size at IP

(beam size at IP: $\sigma_x^*/\sigma_y^* = 24.8/0.1\mu\text{m}$)

Simulation studies are under investigation.

Multi-bunch instability



- **Coupled bunch instability induced by RF HOMs**
  - Consider the whole RF system with large number of RF cavities, spread in resonant frequencies of HOMs will reduce the shunt impedance.
  - A single mode cavity design is an alternative option to avoid RF HOMs (M. Migliorati, FCC week 2015)
- **Transverse resistive wall instability**
  - **With high number of stored bunches, the RW instability can develop in several turns.**
  - **Positive chromaticity can help to shift the bunch mode away from the resistive wall resonance.**
- **Bunch-by-bunch feedback**
  - **Feedback system needed to suppress the resistive wall, HOMs and ion instabilities.**
  - **In general, feedback in ee collider can damp the instabilities in ~ 10 turns.**
  - **By implementing multiple and distributed feedback systems, it is possible to damp up to 1 revolution turn. (A. Drago, FCC week 2016)**

Summary & Discussion

- The pretzel scheme of LEP/CEPC are briefly introduced
- The energy sawtooth orbit could be mitigated by magnet tapering in double ring scheme
- The dynamic aperture of FCC-ee satisfies the requirement without error
- The beam-beam interaction study is briefly reviewed
- The collective effects in CEPC/FCC is briefly introduced

Thanks for your attentions !

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