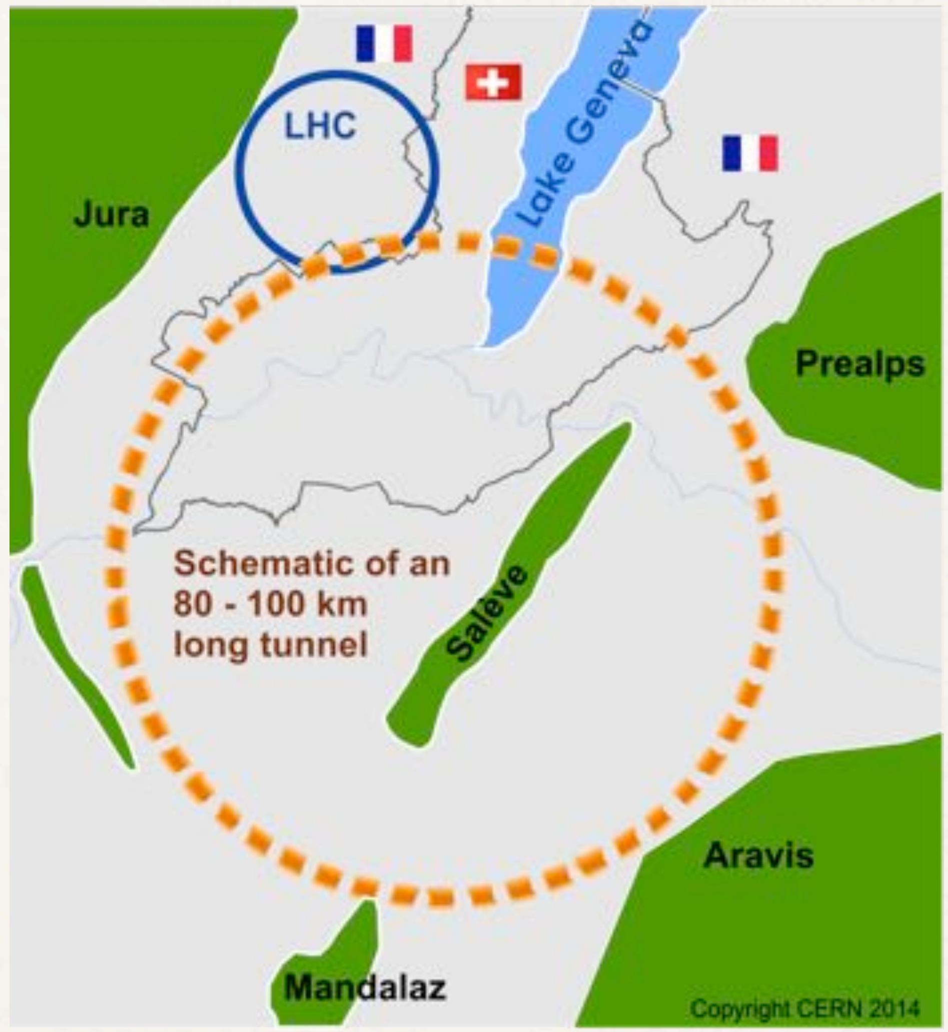
High Energy e^+e^- Factories (FCC-ee & CEPC)

Accelerator Seminar

@ KEK



Dec. 21, 2016

K. Oide (KEK)

Many thanks to J. Gao, H. Geng, Qing Qin, Dou Wang, Yiwei Wang, Yuan Zhang for providing materials of CEPC.
Contributions for FCC-ee: M. Aiba, S. Aumon, M. Benedikt, A. Blondel, A. Bogomyagkov, M. Boscolo, H. Burkhardt, Y. Cai, A. Doblehammer, B. Haerer, B. Holzer, J.M. Jowett, I. Koop, M. Koratzinos, E. Levitchev, L. Medrano, S. Ogur, K. Ohmi, Y. Papaphilippou, P. Piminov, D. Shatilov, S. Sinyatkin, M. Sullivan, J. Wenninger, U. Wienands, D. Zhou, F. Zimmermann.

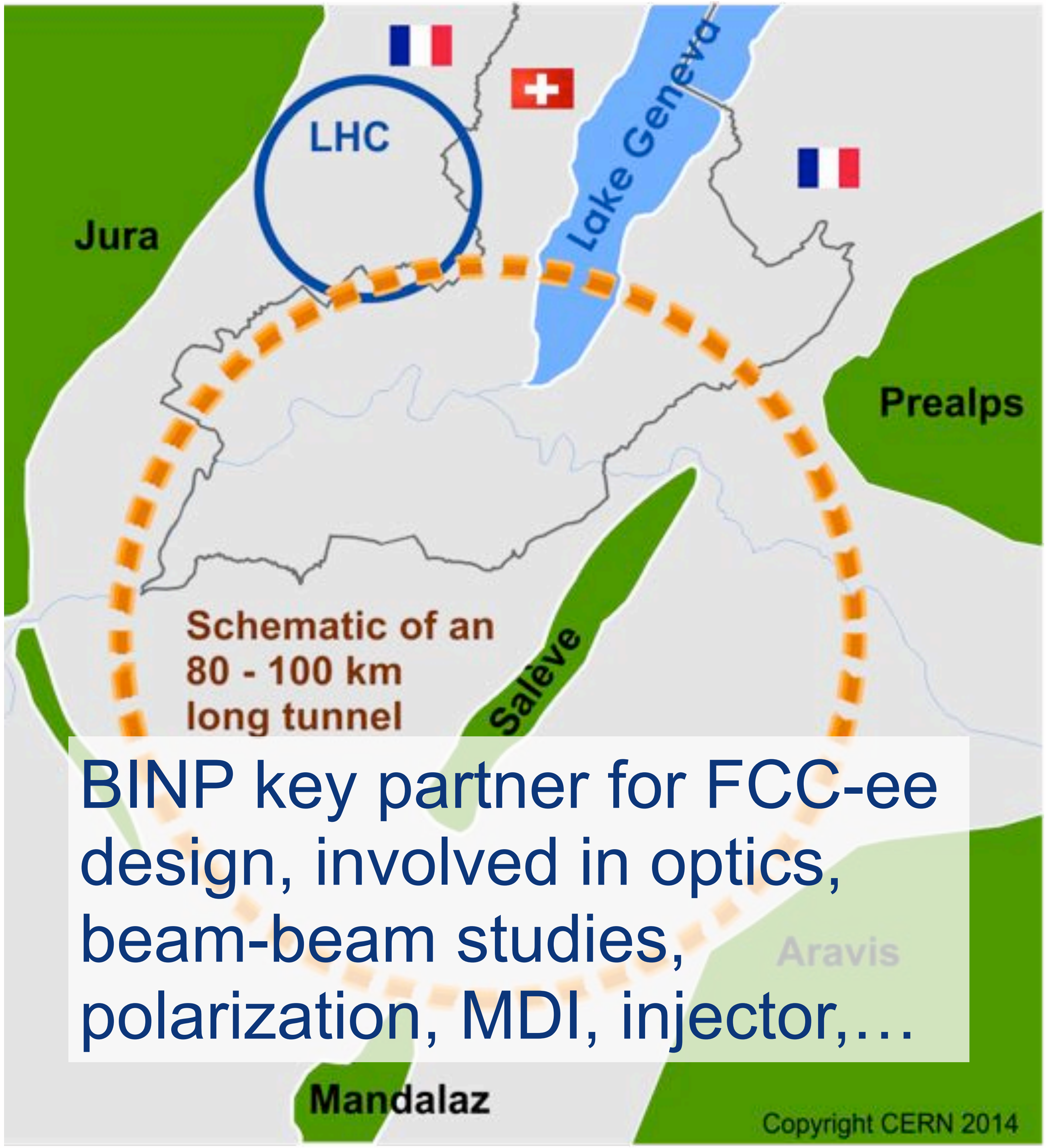
Future Circular Collider Study
GOAL: CDR and cost review for the next ESU (2018)

International FCC collaboration (CERN as host lab) to study:

- ***pp*-collider (*FCC-hh*)**
  → main emphasis, defining infrastructure requirements

~16 T ⇒ 100 TeV *pp* in 100 km

- **80-100 km infrastructure** in Geneva area
- **e^+e^- collider (*FCC-ee*) as potential intermediate step / as a possible first step**
- *p-e* (*FCC-he*) option, HE-LHC …



BINP key partner for FCC-ee design, involved in optics, beam-beam studies, polarization, MDI, injector,…

CEPC – Site Investigation

A good example is 秦皇岛:

300 km from Beijing

3 hours by car; 1 hours by high speed train

- Circular Higgs factory (phase I) + super pp collider (phase II) in the same tunnel

possible physics requirements

A. Blondel, J. Ellis, C. Grojean, P. Janot

- **physics programs / energies:**

  ***Z* (45.5 GeV) *Z* pole,** *'TeraZ' and high precision M_Z & Γ_Z*

  ***W* (80 GeV) *W* pair production** *threshold, high precision M_W*

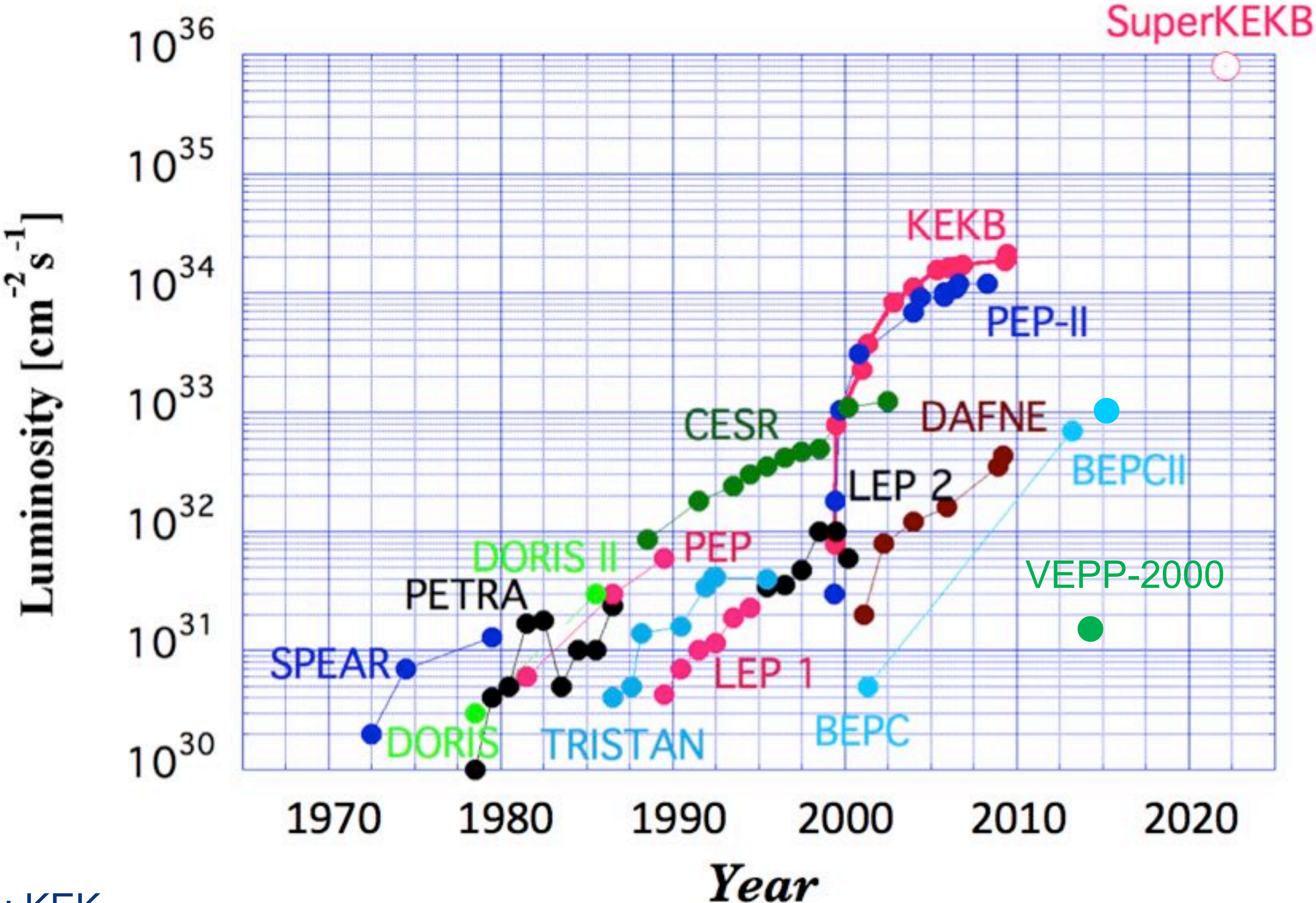
  ***H* (120 GeV) *ZH* production** *(maximum rate of H's)*

  ***t* (175 GeV): $t\bar{t}$ threshold**, *H studies*

- **beam energy range from 35 GeV to ≈200 GeV**
- **highest possible luminosities** *at all working points*
- possibly ***H* (63 GeV) direct *s*-channel** production with **monochromatization**

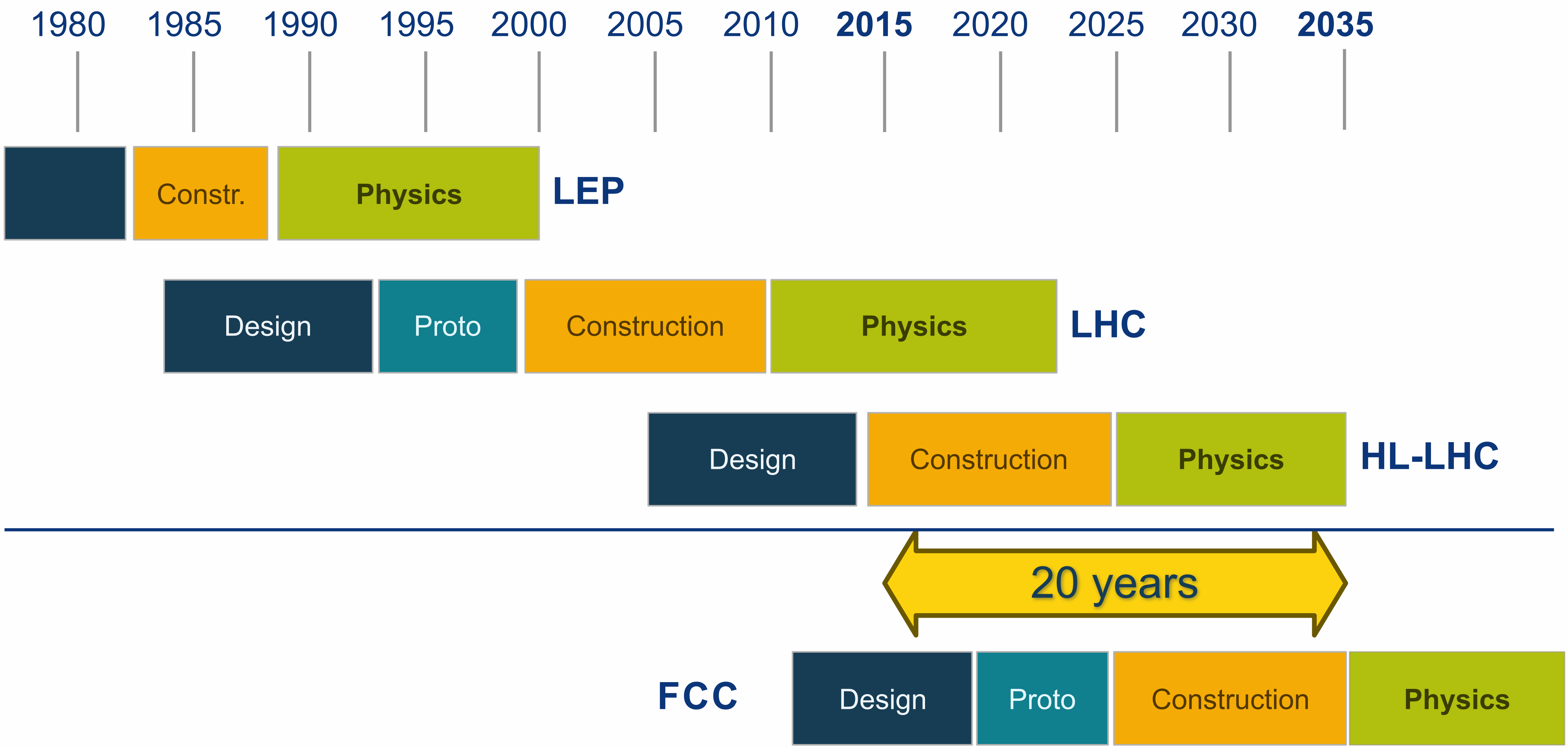
  (**c.m. energy spread <6 MeV**, presentation at IPAC'16)
- **beam polarization up to ≥80 GeV** for beam energy calibration

luminosity trends of circular e⁺e⁻ colliders



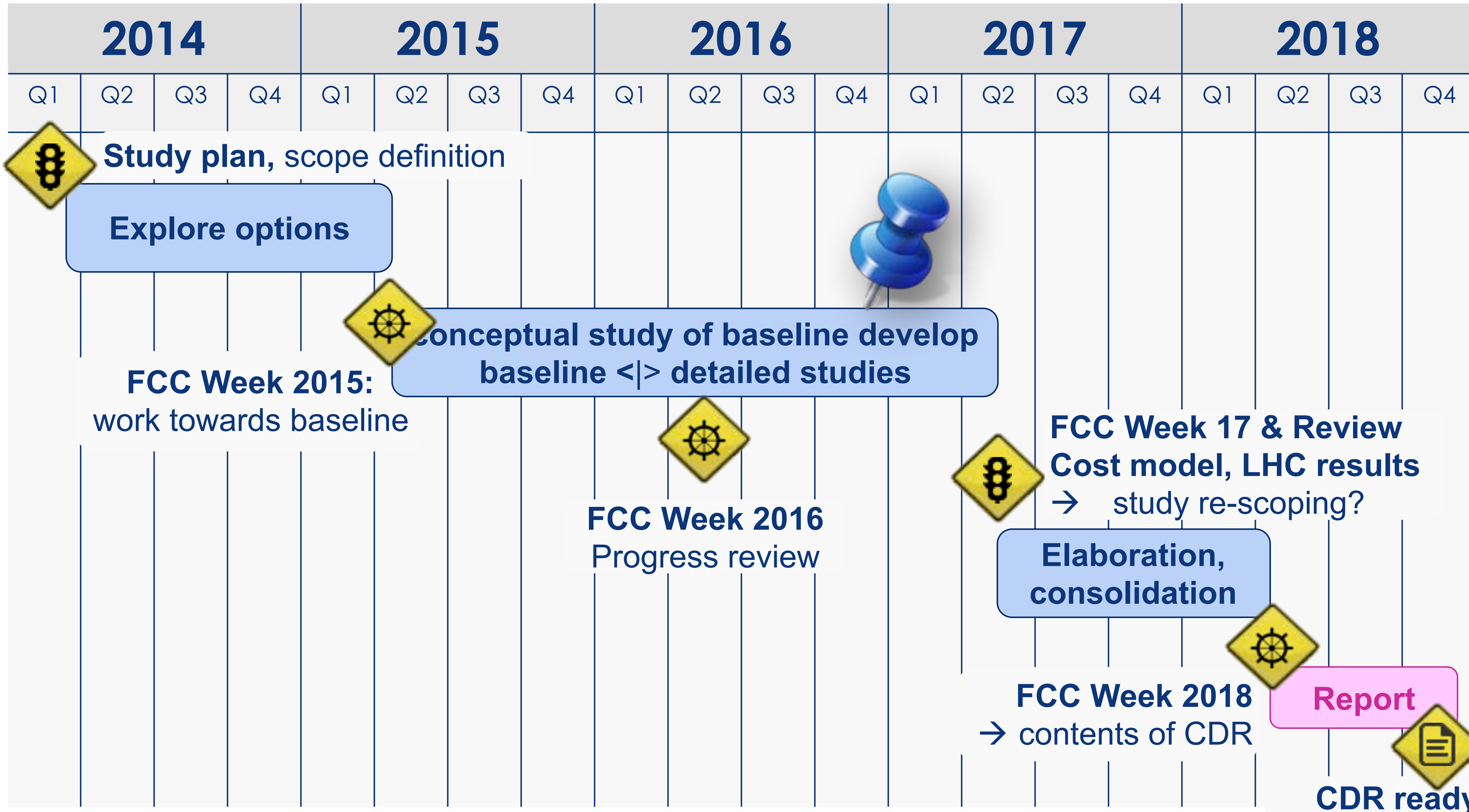
source: KEK

CERN Circular Colliders & FCC



Now is the time to plan for the period 2035 – 2040

CDR Study Time Line



CEPC-SPPC Timeline (preliminary)

CEPC

2015 | 2020 | 2025 | 2030 | 2035

Pre-studies
(2013-2015)

R&D
Engineering Design
(2016-2022)

Construction
(2022-2030)

Data taking
(2030-2040)

1st Milestone: Pre-CDR (by the end of 2014) ;2nd Milestone: R&D funding from MOST (in Mid 2016); 3rd Milestone: CEPC CDR Status Report (by the end of 2016); 4th Milestone: CEPC CDR Report (by the end of 2017);5th Milestone: CEPC TDR Report and Proto (by the end of 2022);6th Milestone: CEPC construction (by the end of 2030);

SPPC

2020 | 2030 | 2040

R&D and CDR
(2014-2030)

Engineering Design
(2030-2040)

Construction
(2040-2050)

Data taking
(2050)

J. Gao

2016 Parameters

parameter	FCC-ee				CEPC		LEP2
energy/beam [GeV]	**45**		**120**	**175**	**45**	**120***	105
bunches/beam	91500	30180	770	78	1100	67	4
beam current [mA]	1450		30	6.6	45.4	16.9	3
energy loss/turn [GeV]	0.03		1.67	7.55	0.062	2.96	3.34
synchrotron power [MW]	100				2.8	100	22
RF voltage [GV]	0.2	0.4	3.0	10	0.12	3.6	3.5
rms bunch length (SR,+BS) [mm]	1.6, 3.8	1.2, 6.7	2.0, 2.4	2.1, 2.5	3.9, 4.0	3.1, 4.1	12, 12
rms emittance $\varepsilon_{x,y}$ [nm, pm]	0.1, 1	0.2, 1	0.6, 1	1.3, 2.5	0.62,2.8	2.45,7.4	22, 250
$\beta^*_{x,y}$ [m, mm]	1, 2	0.5, 1	1, 2	1, 2	0.1, 1	0.25, 1.4	1.5, 50
long. damping time [turns]	1320		72	23	726	41	31
crossing angle [mrad]	30				30		0
beam lifetime [min]	185	94	67	57	79	20	434
luminosity/IP x 10^{34} $cm^{-2}s^{-1}$	**70**	**207**	**5.1**	**1.3**	**3.6**	**2.96**	0.0012

FCC-ee: 2 separate ring **CEPC: Partial double ring (PDR), 120*: high-lumi version**

parameter for CEPC partial/full double ring

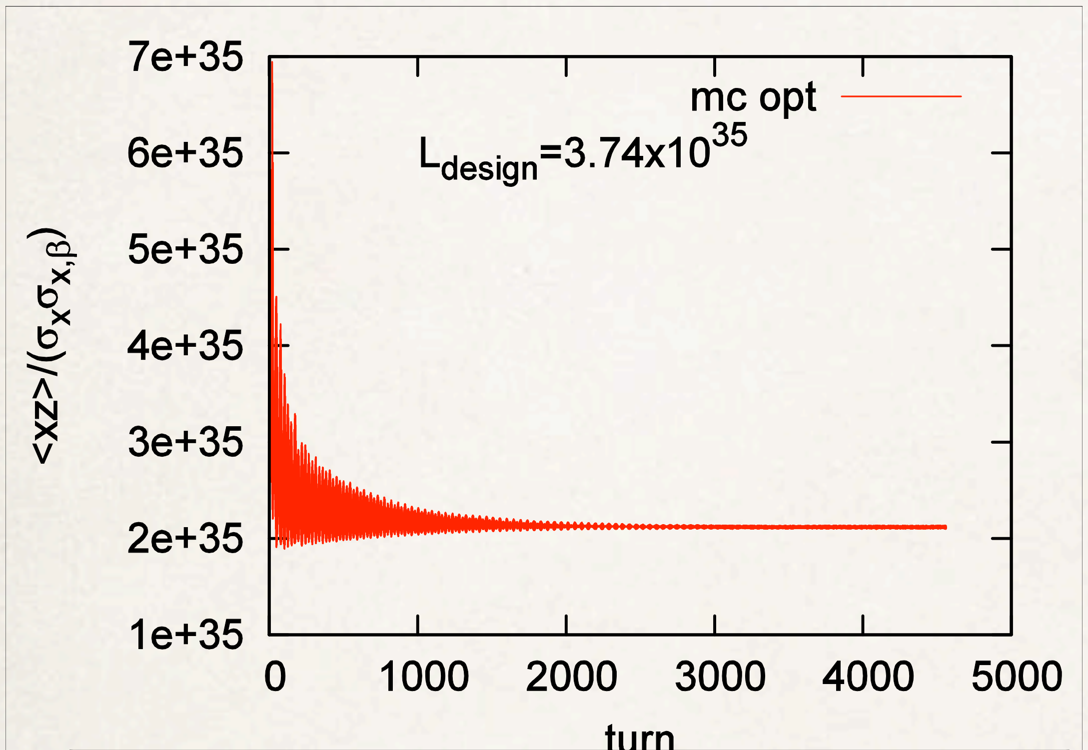
(wangdou20161123-100km)

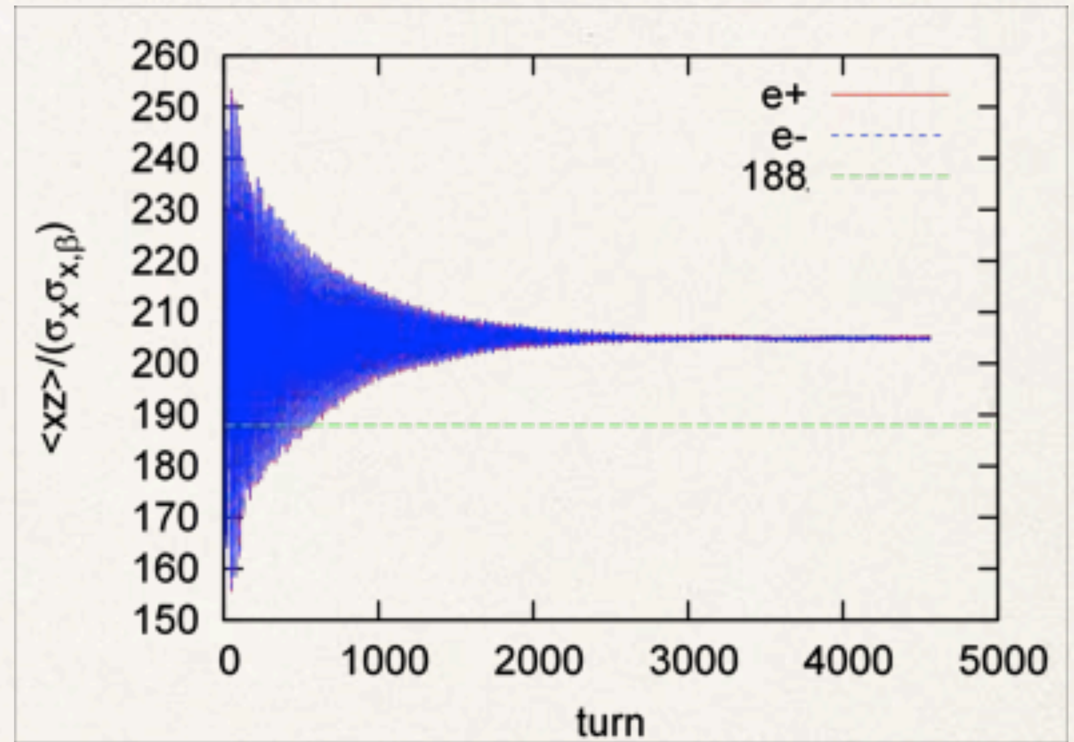
Dou Wang

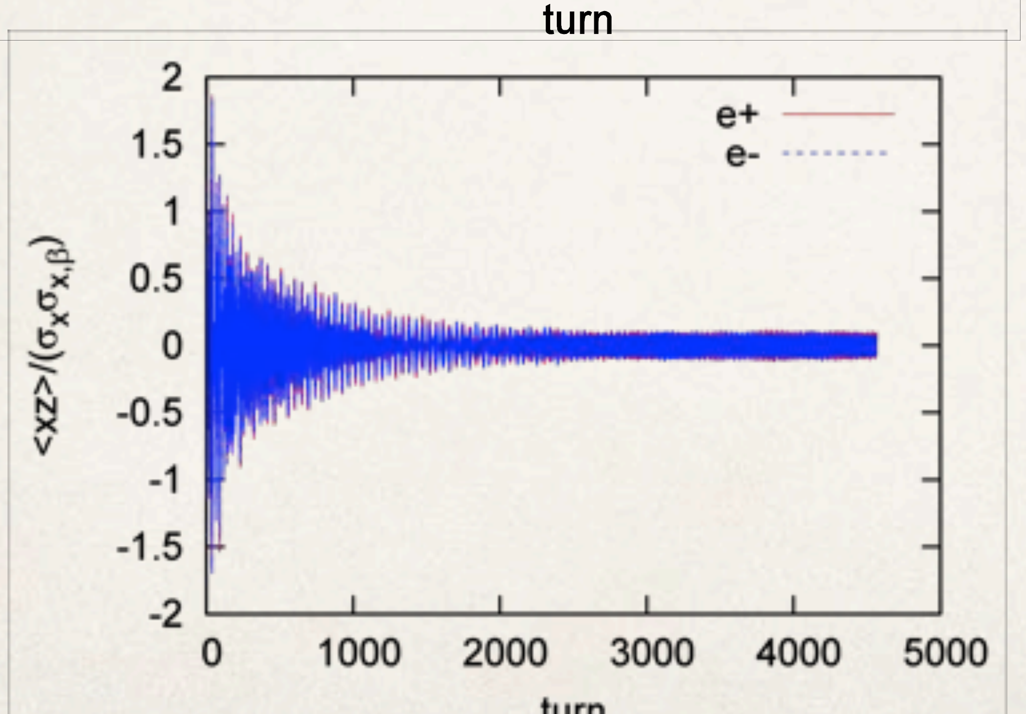
	Pre-CDR	*W*	*Z*	Full double ring
Number of IPs	2	2	2	2
Energy (GeV)	120	80	45.5	45.5
Circumference (km)	54	100	100	100
SR loss/turn (GeV)	3.1	0.33	0.034	0.034
Half crossing angle (mrad)	0	15	15	15
Piwinski angle	0	3.57	5.69	5.69
N_e/bunch (10^{11})	3.79	1.05	0.46	0.46
Bunch number	50	1100	1100	**65716**
Beam current (mA)	16.6	55.7	24.3	**1449.7**
SR power /beam (MW)	51.7	18.3	0.84	50
Bending radius (km)	6.1	11	11	11
Momentum compaction (10^{-5})	3.4	3.1	3.3	3.3
β_{IP} x/y (m)	0.8/0.0012	0.1 /0.001	0.12/0.001	0.12/0.001
Emittance x/y (nm)	6.12/0.018	2.68/0.008	0.93/0.0049	0.93/0.0049
Transverse σ_{IP} (um)	69.97/0.15	16.4/0.09	10.5/0.07	10.5/0.07
ξ_x/ξ_y/IP	0.118/0.083	0.0082/0.055	0.0075/0.054	0.0075/0.054
RF Phase (degree)	153.0	149	160.8	160.8
V_{RF} (GV)	6.87	**0.63**	**0.11**	**0.11**
f_{RF} (MHz)	650	650	650	650
Nature σ_z (mm)	2.14	**3.8**	**3.93**	**3.93**
Total σ_z (mm)	2.65	3.9	4.0	4.0
HOM power/cavity (kw)	3.6 (5cell)	1.1 (2cell)	0.11 (1cell)	6.25(1cell)
Energy spread (%)	0.13	0.065	0.037	0.037
Energy acceptance (%)	2			
Energy acceptance by RF (%)	6	1.5	1.1	1.1
n_γ	0.23	0.26	0.18	0.18
Life time due to beamstrahlung_cal (minute)	47			
F (hour glass)	0.68	0.84	0.91	0.91
L_{max}/IP (10^{34}cm^{-2}s^{-1})	2.04	4.49	1.19	**70.97**

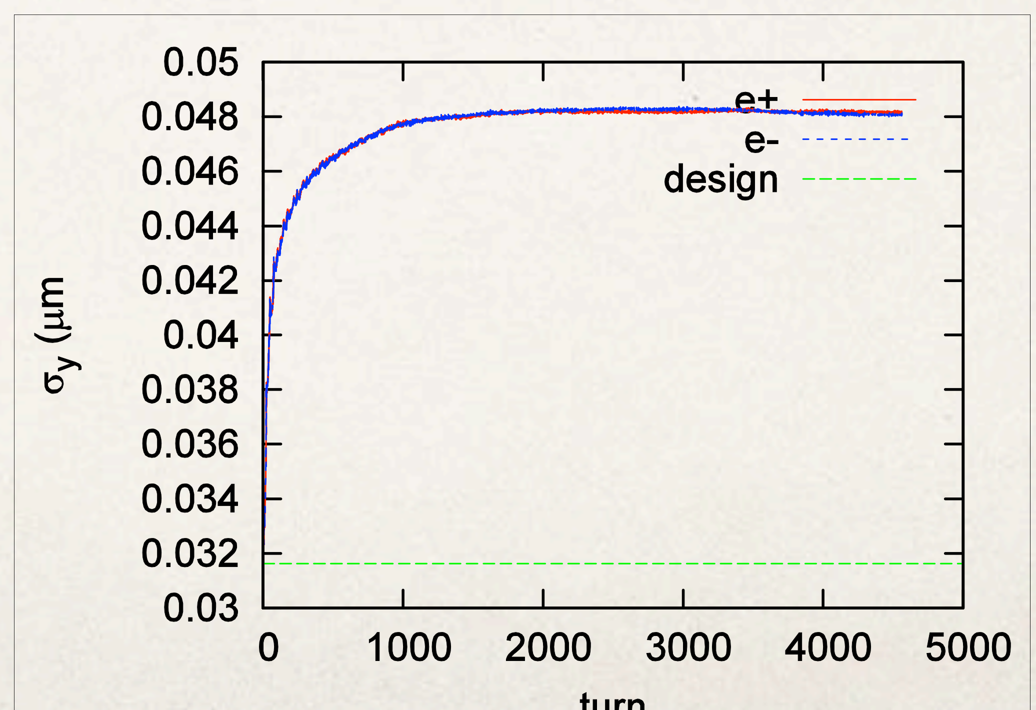
Strong-Strong beam-beam instability (FCC-ee @ Z)

- x-z coherent instability is seen in early stage and beam size blow up.
- Residual x-z motion remains.
- Luminosity is reduced to 60% of the design.









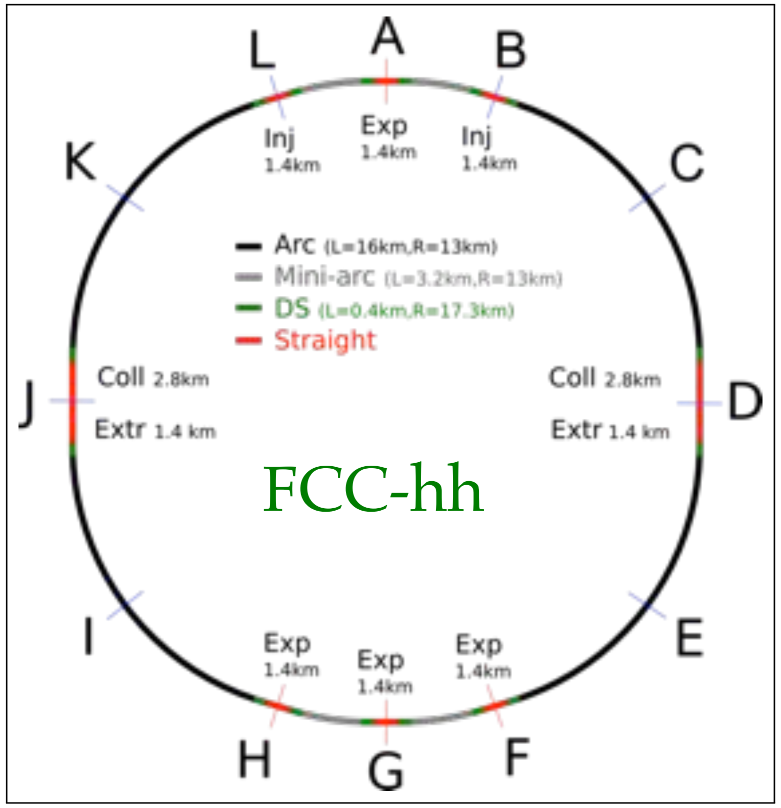
K. Ohmi

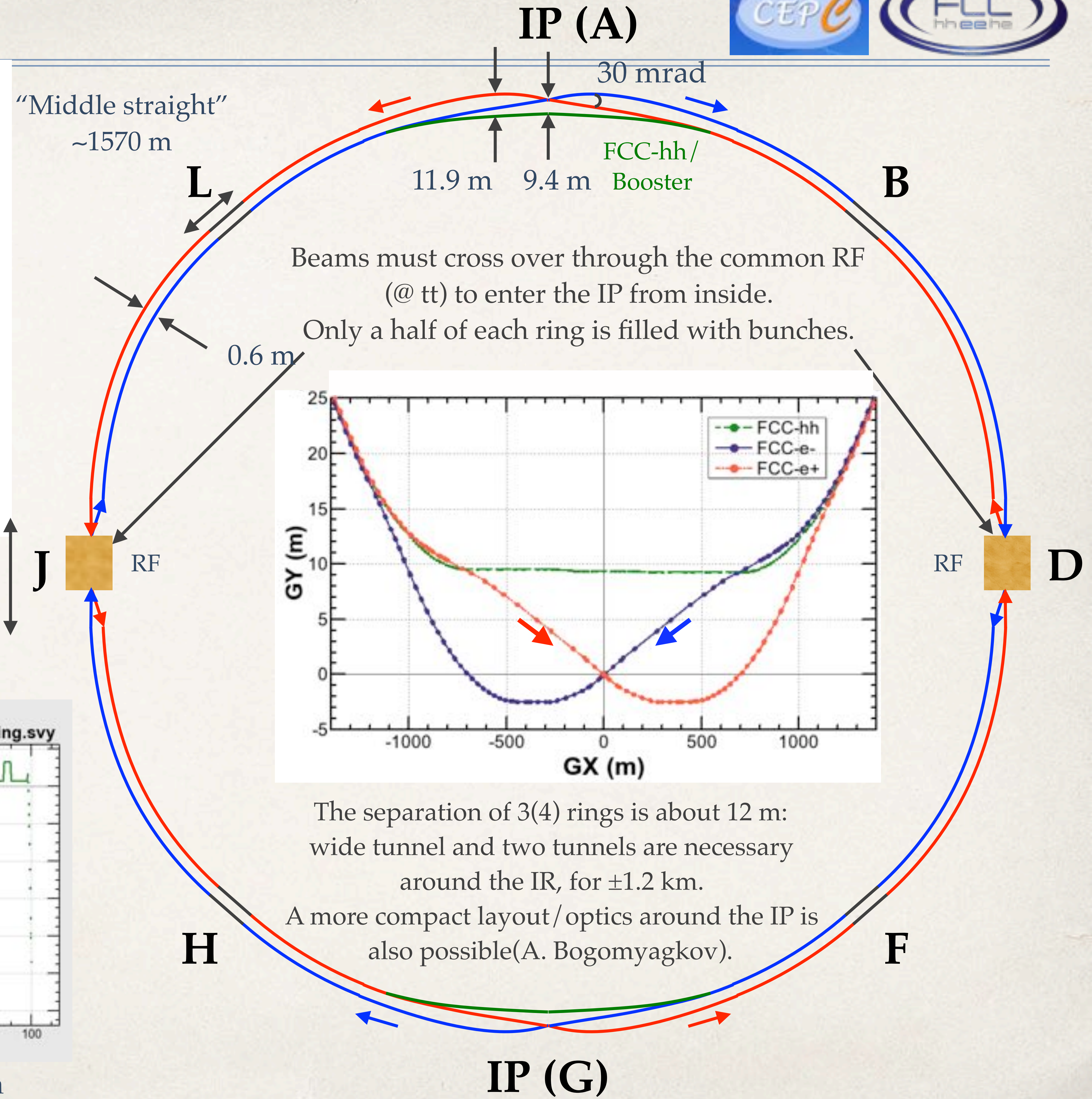
Design constraints & assumptions (FCC-ee)

- C = 100 km, fits to the FCC-hh tunnel and footprint as much as possible.
- 2 IPs / ring.
- 30 mrad crossing angle at the IP with crab waist.
- Common lattice for all energies, except for the detector solenoid.
- $\varepsilon_x \leqq 1.3$ nm @ 175 GeV, basically scaling with energy.
- ±2% momentum acceptance at 175 GeV to hold the large energy spread caused by beamstrahlung.
- Vertical emittance less than 2.5 pm at 175 GeV before collision.
- $\beta_{x,y}^* = (1\text{ m}, 2\text{ mm})$ at 175 GeV, (0.5 m, 1 mm) at 45.6 GeV as the baseline.
- Suppress the critical energy of the synchrotron radiation to the IP below 100 keV, up to 500 m upstream. No dipole magnets 100m upstream from the IP.
- "tapering" to cure the sawtooth at high energy.

Phys. Rev. Accel. Beams 19, 111005 (2016)

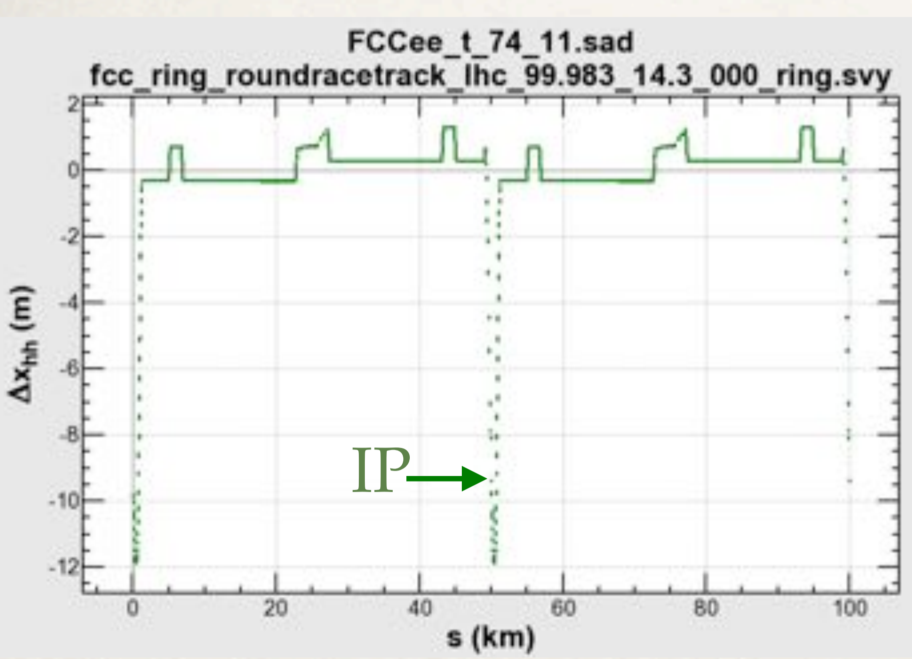
Layout of FCC-ee





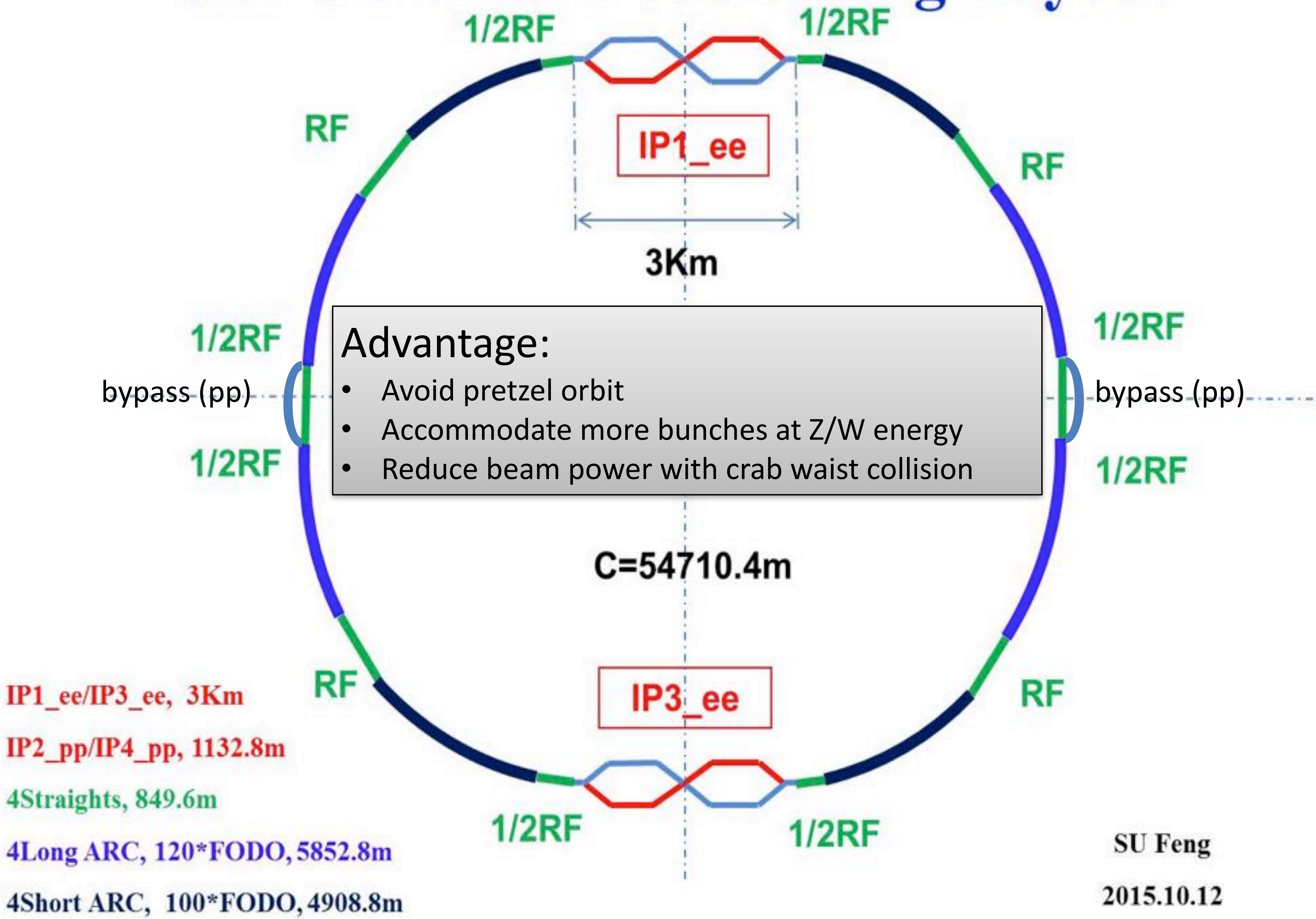
Beams must cross over through the common RF (@ tt) to enter the IP from inside.
Only a half of each ring is filled with bunches.

The separation of 3(4) rings is about 12 m: wide tunnel and two tunnels are necessary around the IR, for ±1.2 km.
A more compact layout/optics around the IP is also possible(A. Bogomyagkov).



Relative distance to FCC-hh

CEPC Partial Double Ring Layout



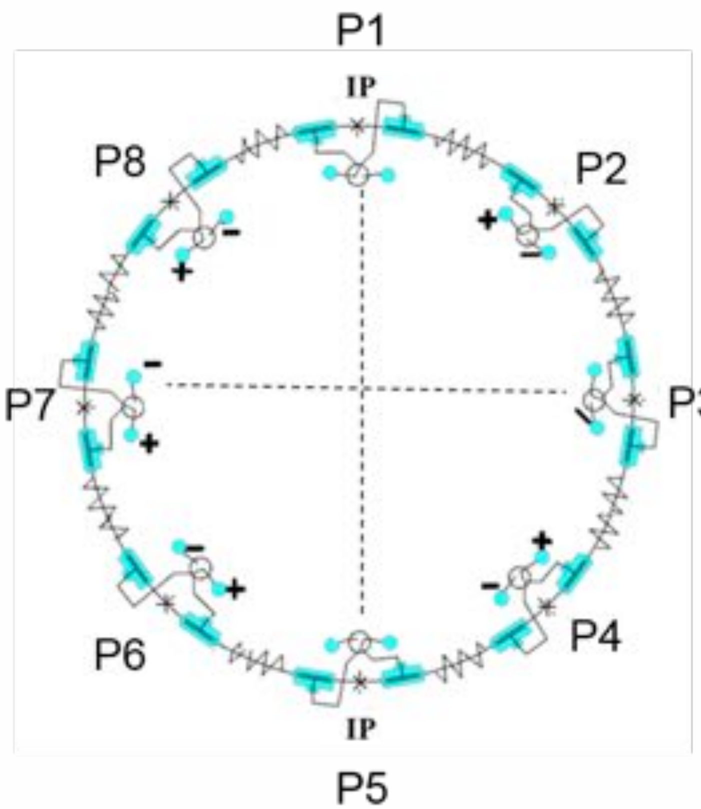
Advantage:

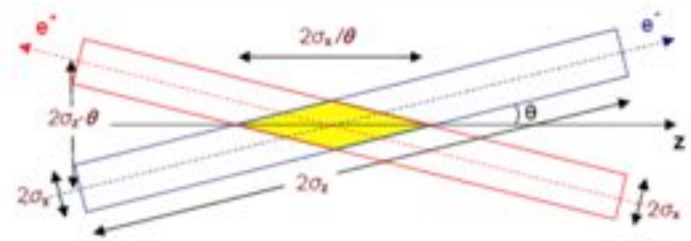
- Avoid pretzel orbit
- Accommodate more bunches at Z/W energy
- Reduce beam power with crab waist collision

SU Feng

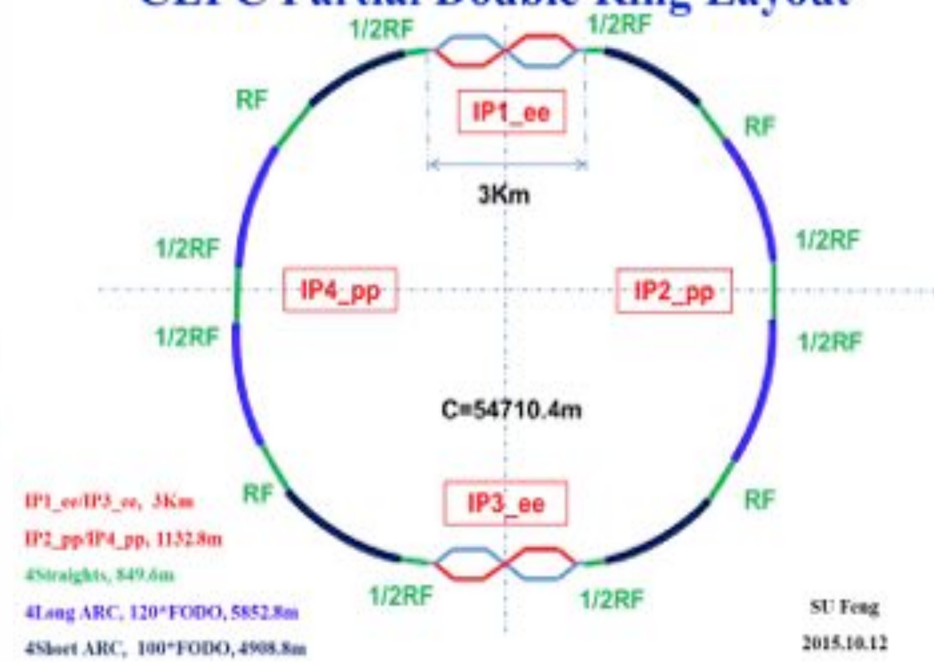
2015.10.12

CEPC for options for twoards CDR





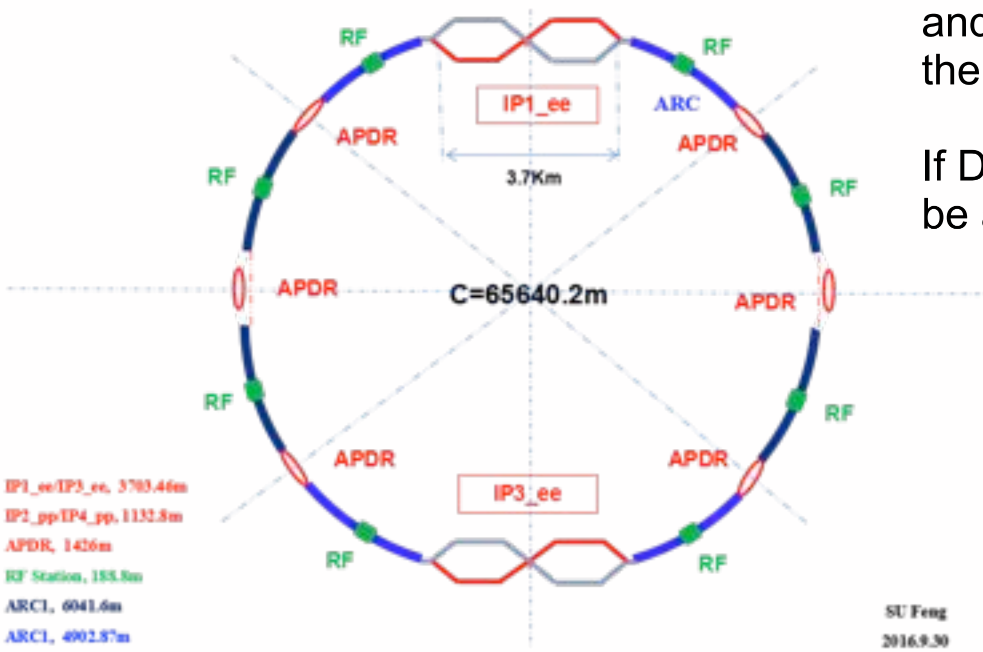
CEPC Partial Double Ring Layout



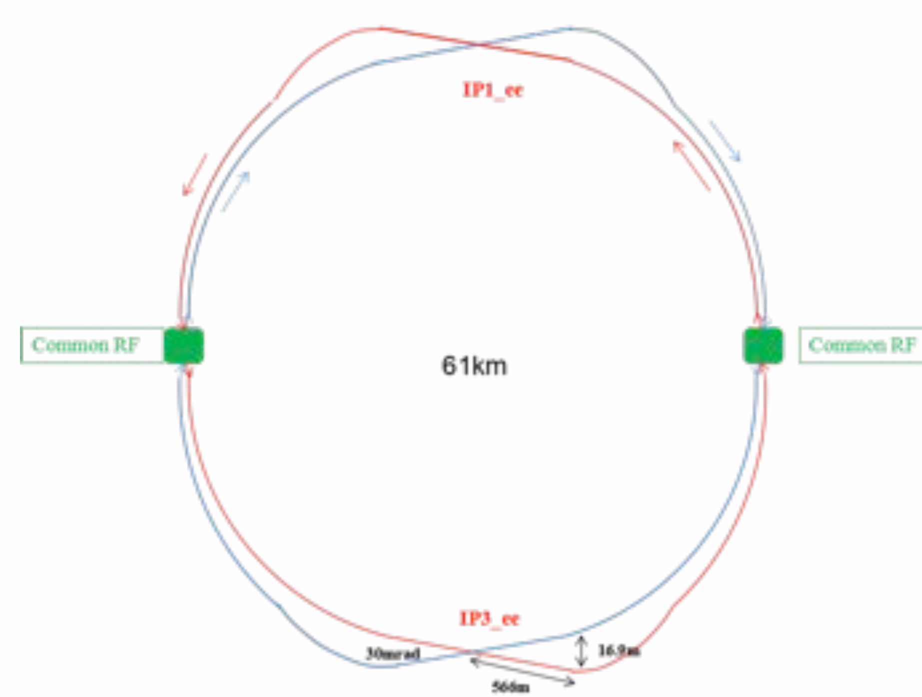
The choice will come from the fact that CEPC luminosity is far more advanced compared with LEPII (1000 times)
and is reaching the design limit of on the on sing and partial double rings

If DR scheme is chosen, Z-liuminosity will be above 10^35 towards 10^36/cm^2s

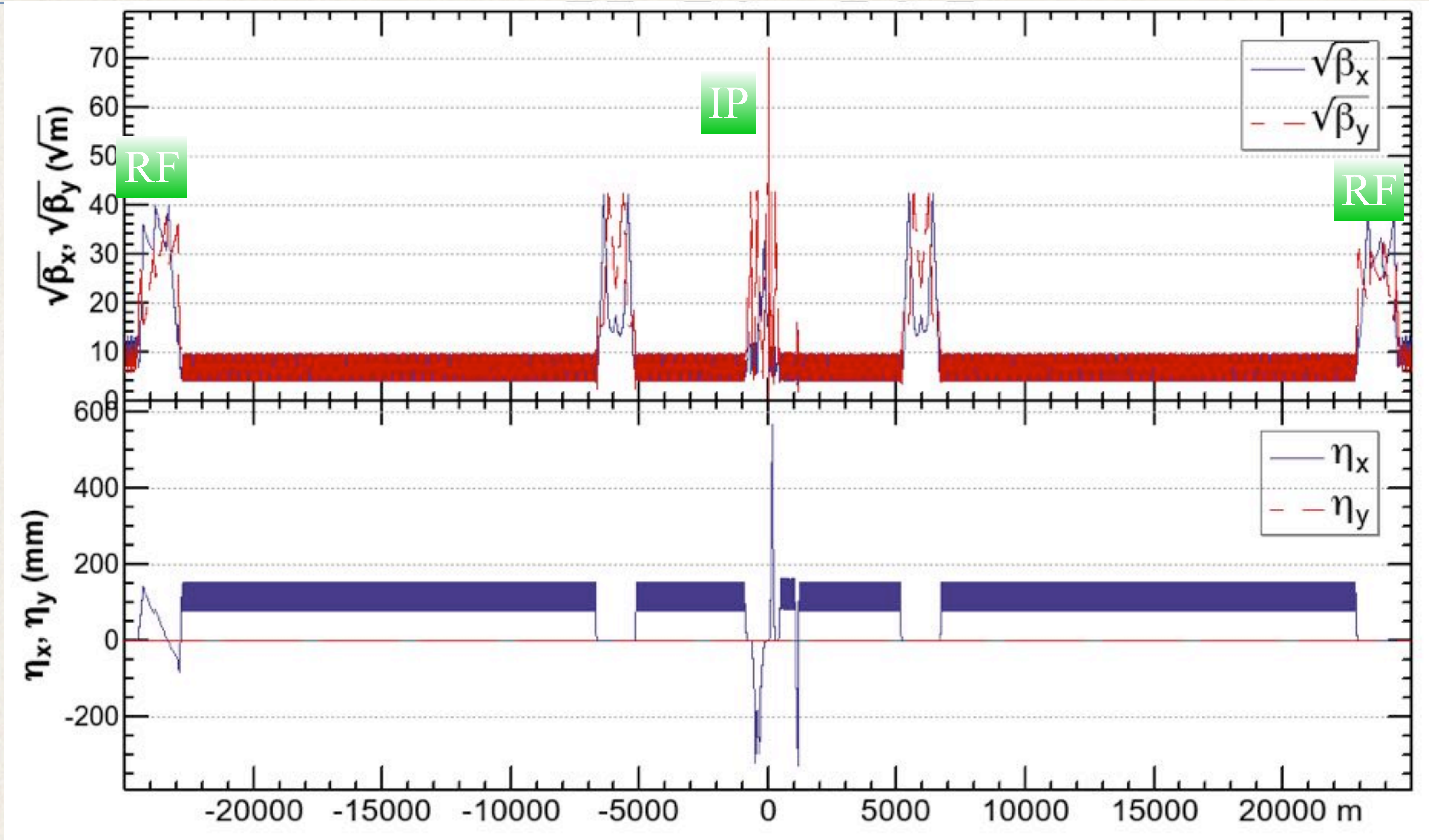
CEPC Advanced Partial Double Ring Option II



CEPC Double Ring Scheme Layout

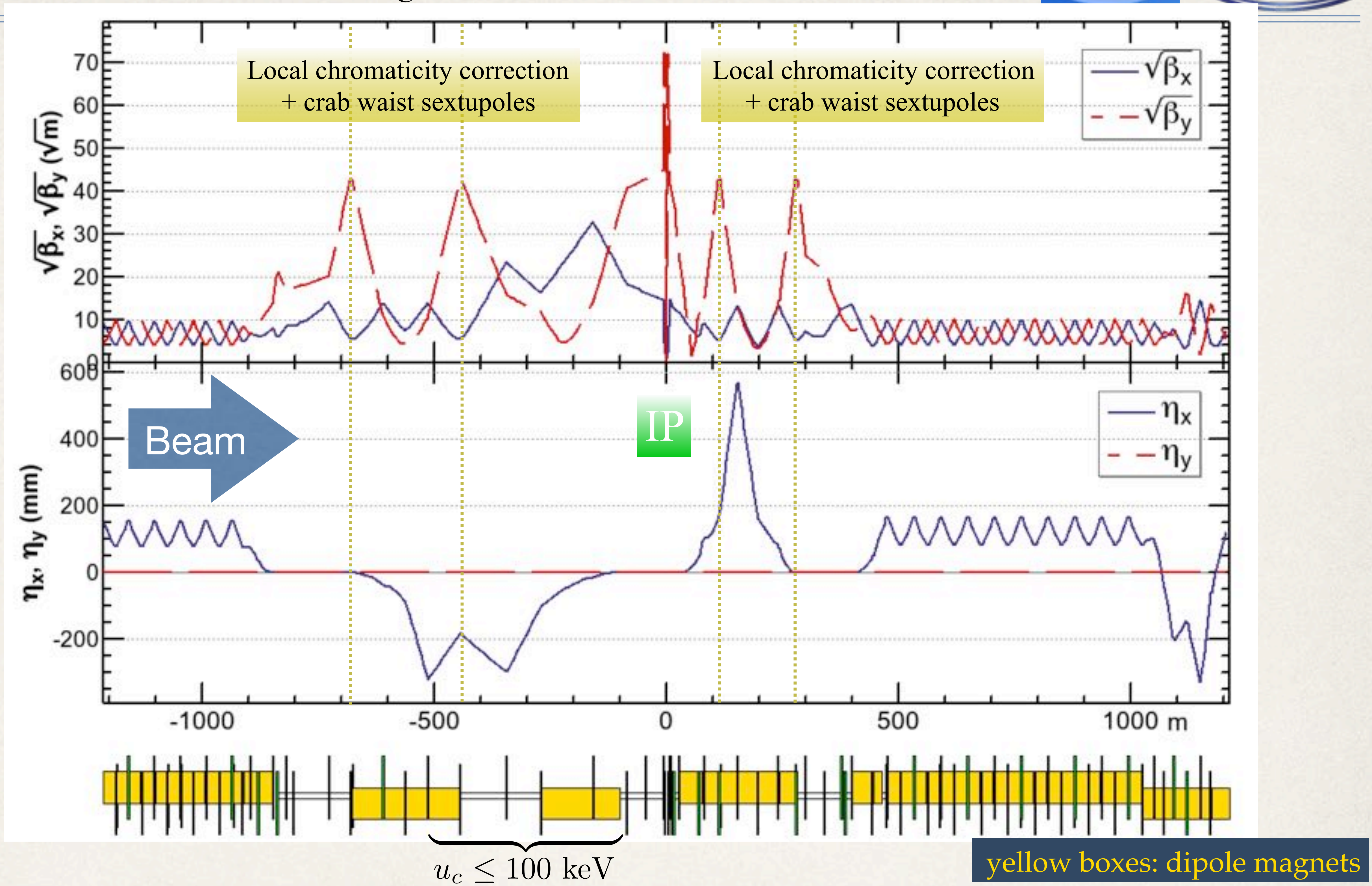


Half Ring Optics



- Above are the half optics $\beta^*_{x/y}$ = 1 m / 2 mm.
- 2 IP/ring.
- The optics for straight sections except for the IR are tentative, to be customized for infection/extraction/collimation/beam instumentation, etc.

FCC-ee Interaction Region



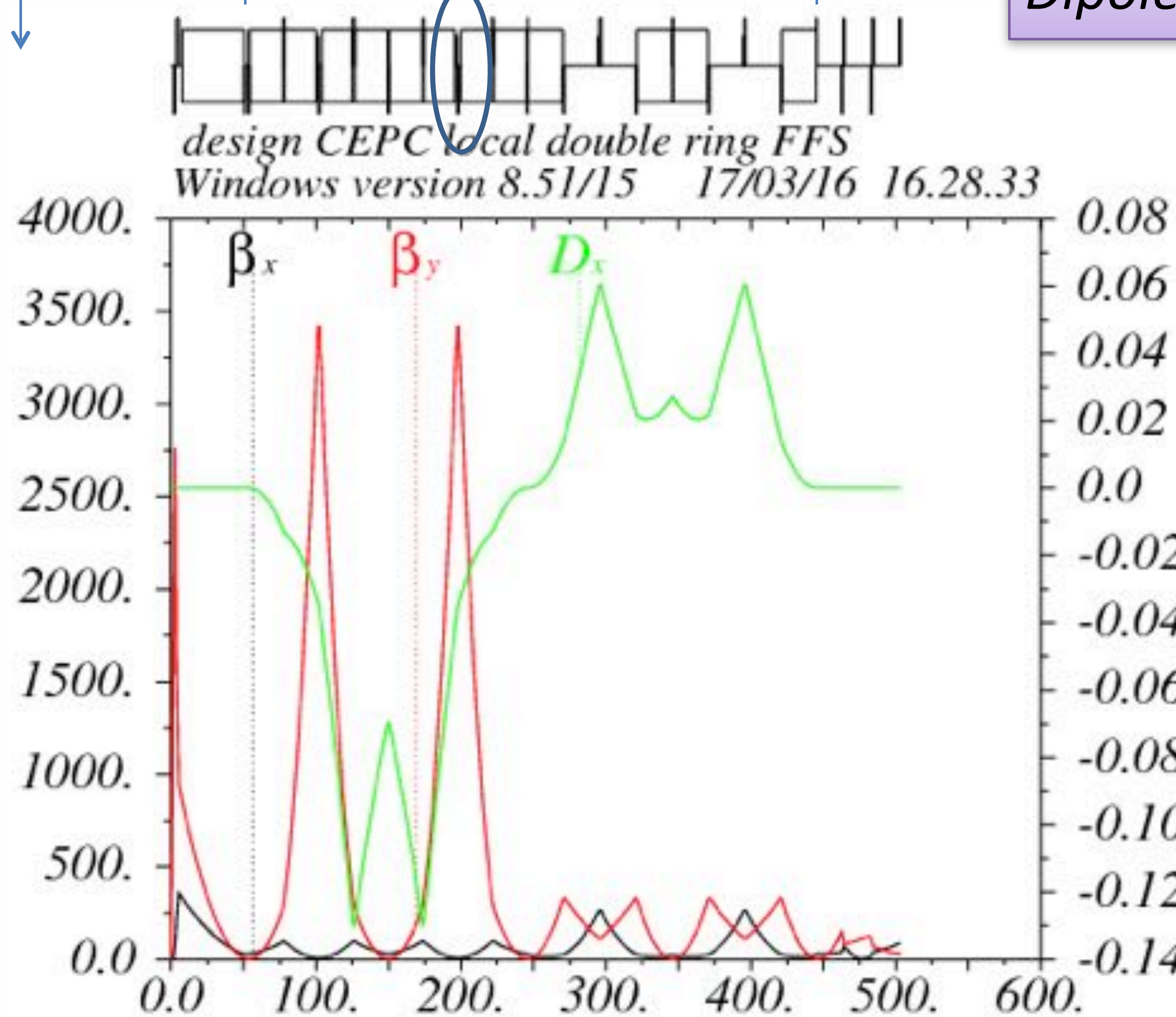
- The optics in the interaction region are asymmetric.
- The synchrotron radiation from the upstream dipoles are below 100 keV up to 450 m from the IP.
- The crab sextuples are integrated in the local chromaticity correction system in the vertical plane.

Partial double ring FFS design with crab sextupoles

Betax=0.25m
Betay=0.00136m
K2hs=26.8 m^{-3}
K2vs=32.2 m^{-3}

IP

Crab sextupole



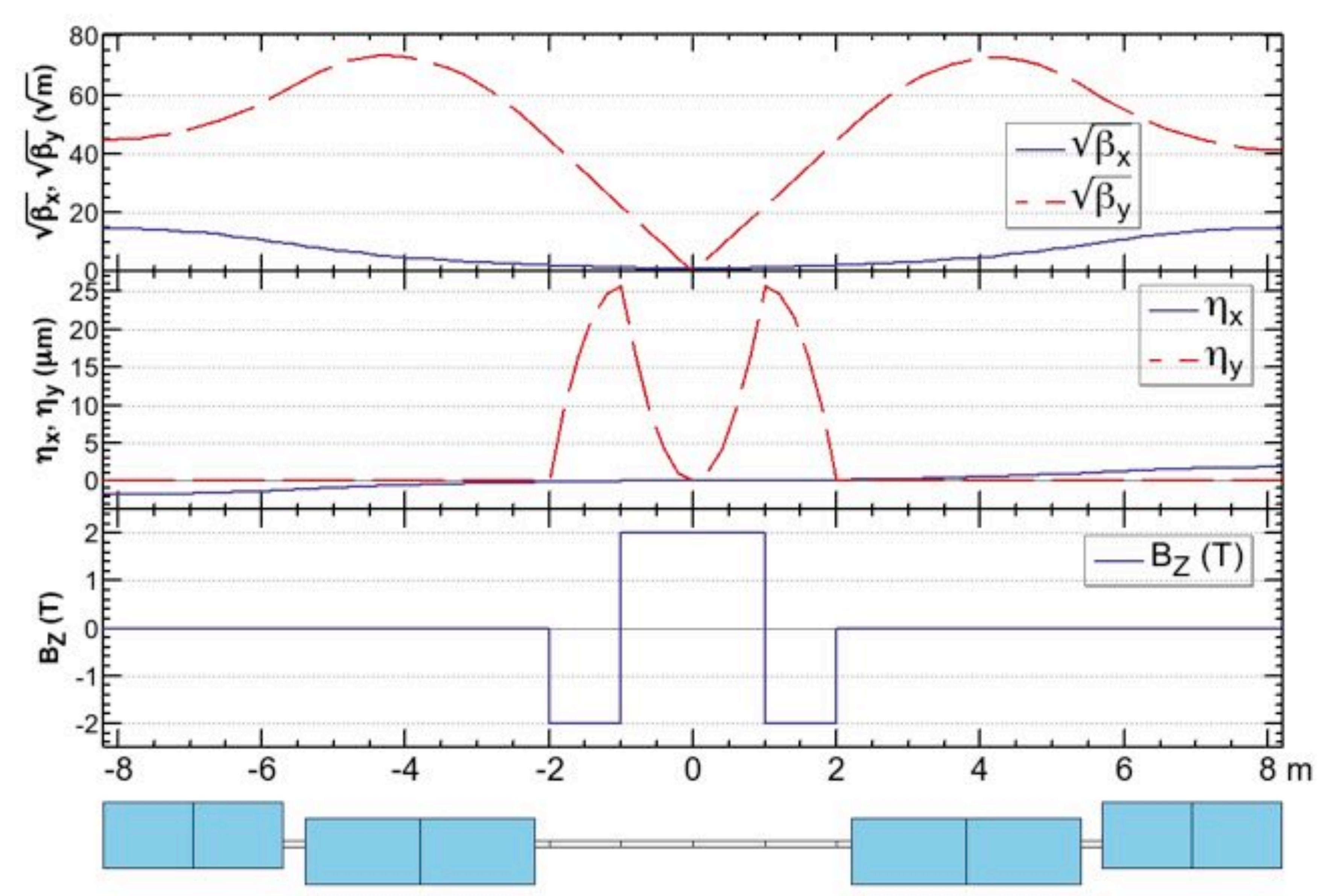
Critical energy: E*c*=190 keV
Dipole strength: B=0.019 T

Dou Wang

➢ The second FFS sextupoles of the CCS-Y section work as the crab sextupoles.

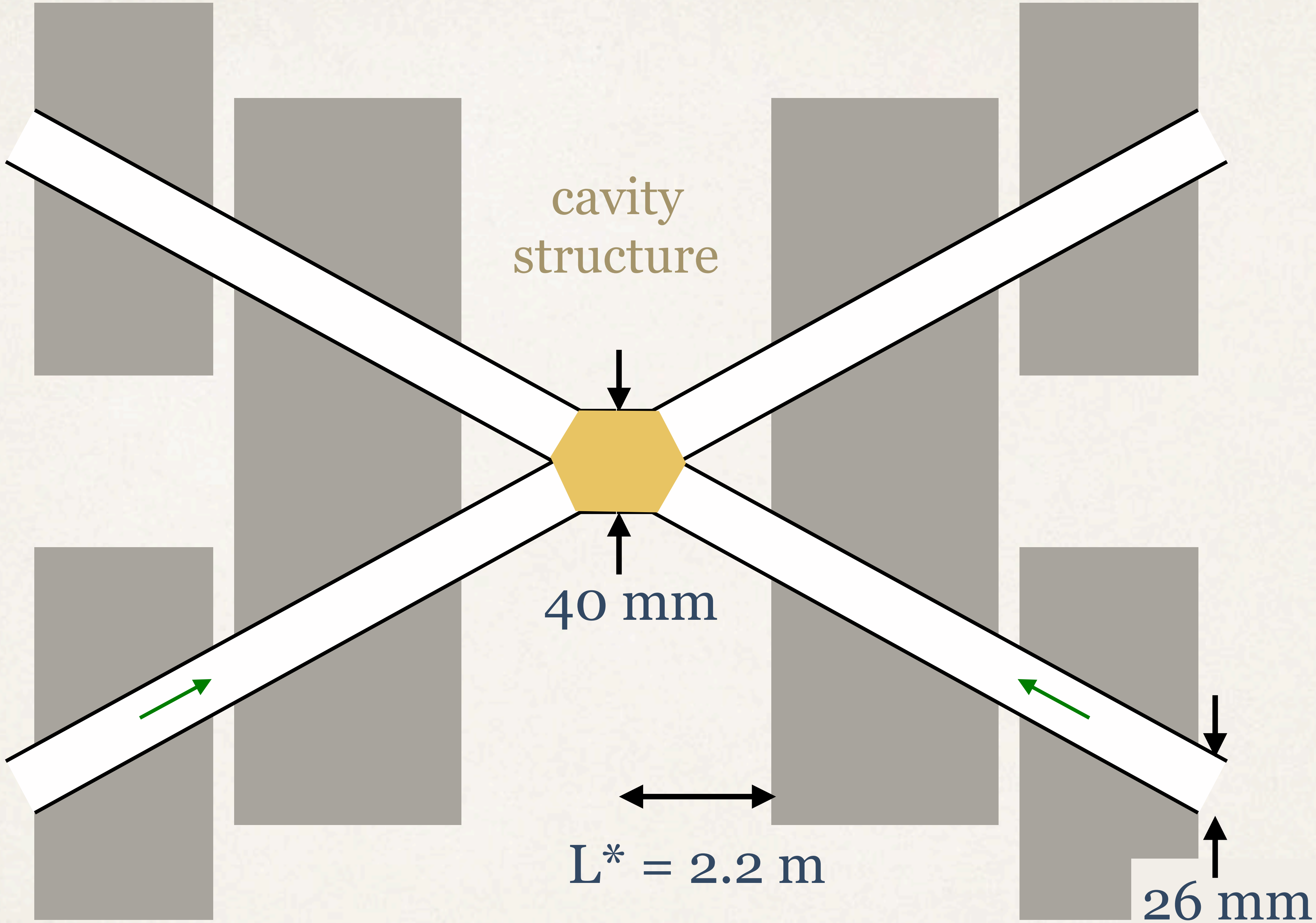
Optics at the FCC-ee IP

175 GeV, $\beta^*_{x,y}$ = (1 m, 2 mm)



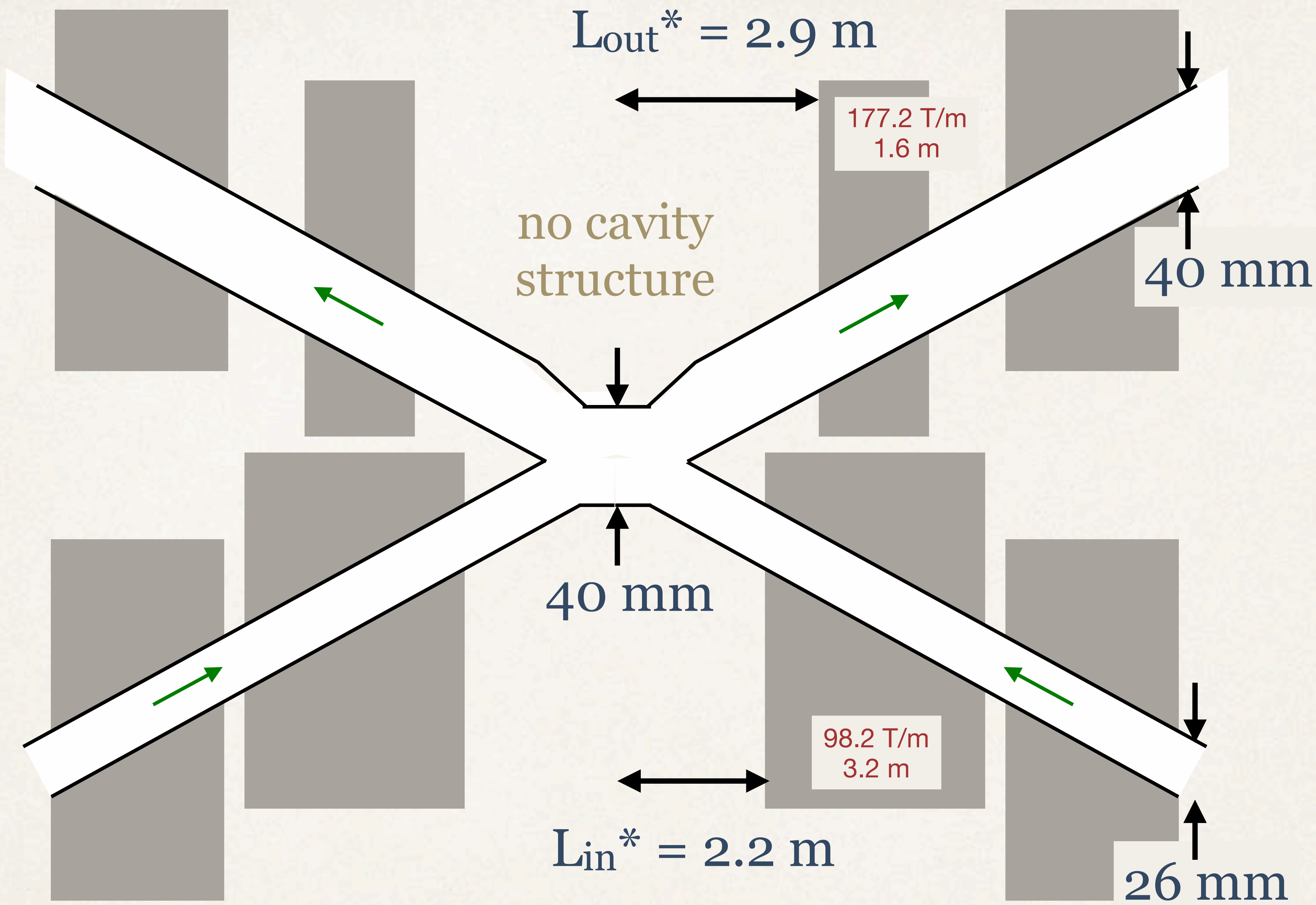
- The effect of detector solenoid field is locally compensated by counter solenoids.
- The solenoid field is shielded on the quadrupoles.
- If the compensation/shielding is perfect, their effects on the beam optics is minimal. No coupling, no vertical dispersion leak to the outside.

HOM trapping by the cavity structure at IP, FCC-ee



- HOM is trapped in the IP beam pipe, if all beam pipes are narrower than the IP, which needs to be larger that 40 mm (M. Sullivan).
- Heating, esp. at Z.
- Leak of HOM to the detector, through the thin Be beam pipe at the IP.

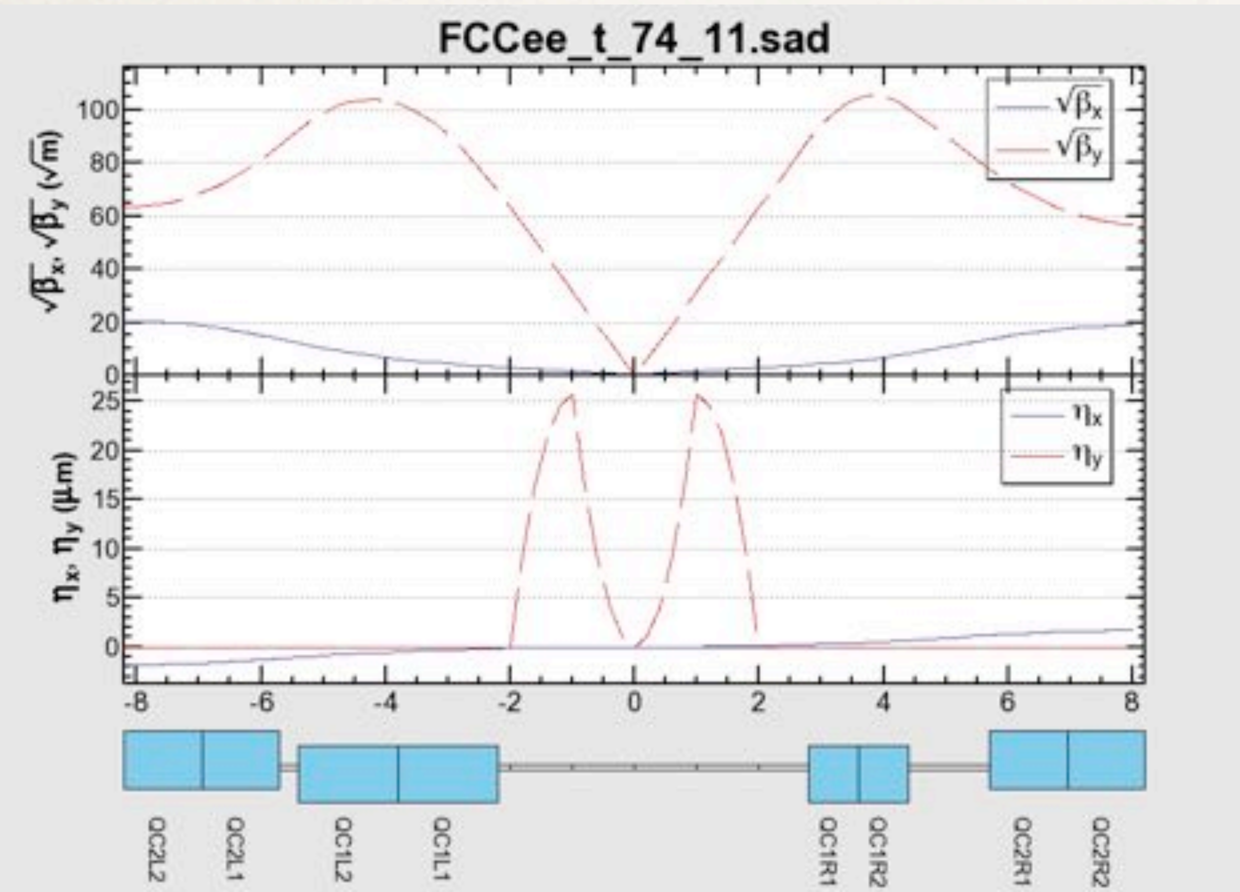
A solution: larger outgoing beam pipe & thinner final quads



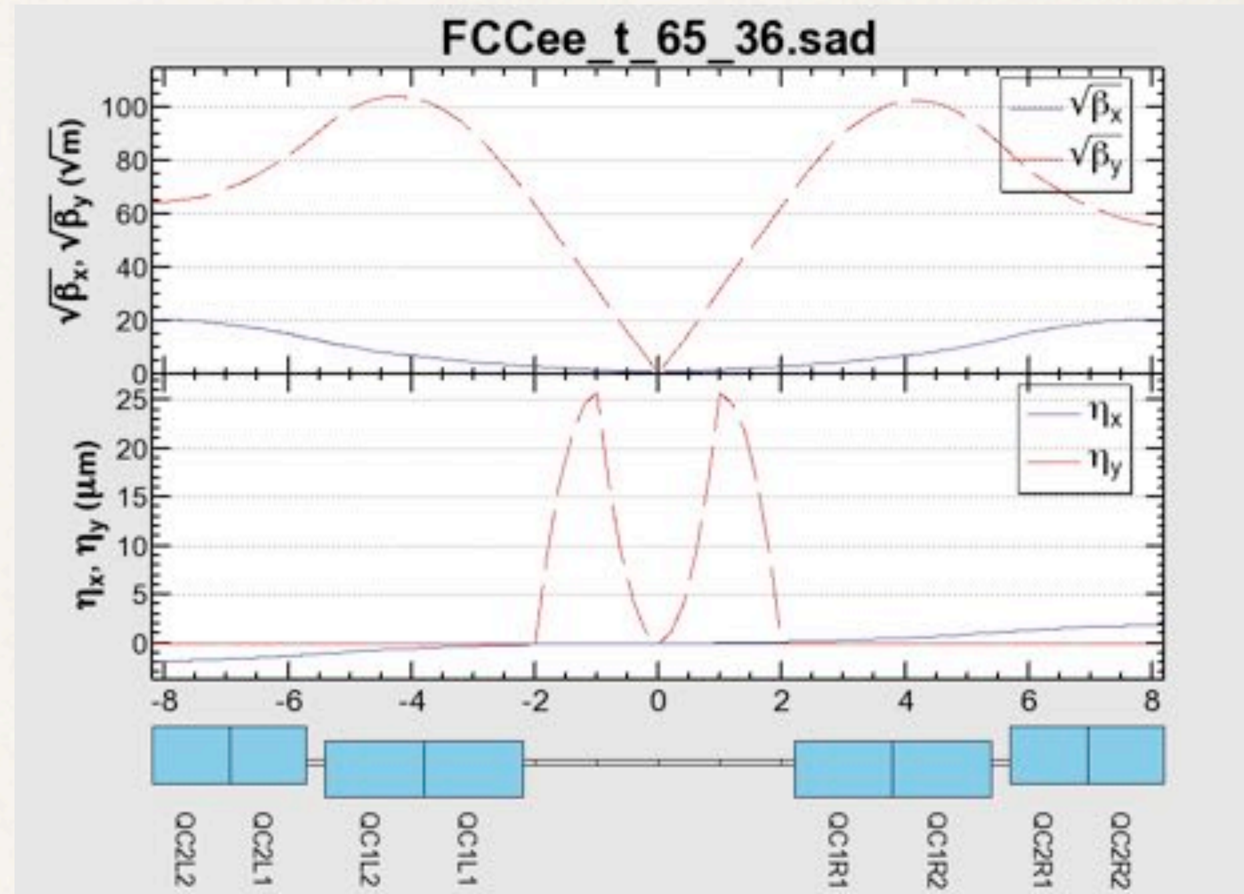
- The most of HOM can escape to the outside through the outgoing beam pipe, which has a diameter not smaller than IP.
- L* depends on the design of the final quadrupole.

Asymmetric L* at the FCC-ee IP

Asymmetric L*

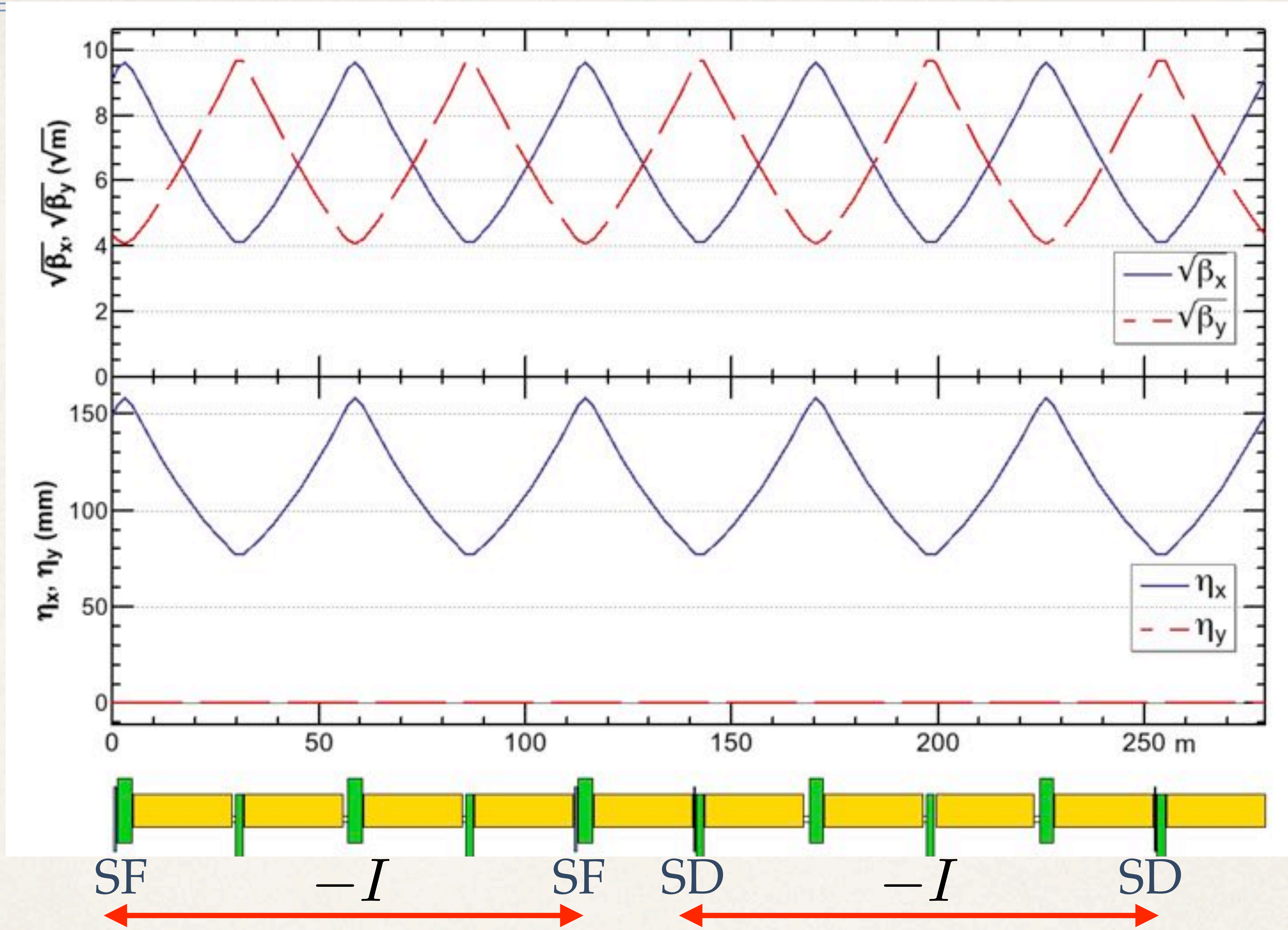


Symmetric L*



- Even with the asymmetric L*, the optics, so as the chromaticity, look similar.
- The solenoid compensation is unchanged: locally compensated up to 2.2 m from the IP.
- Longer L* downstream has no merit on the luminometer.

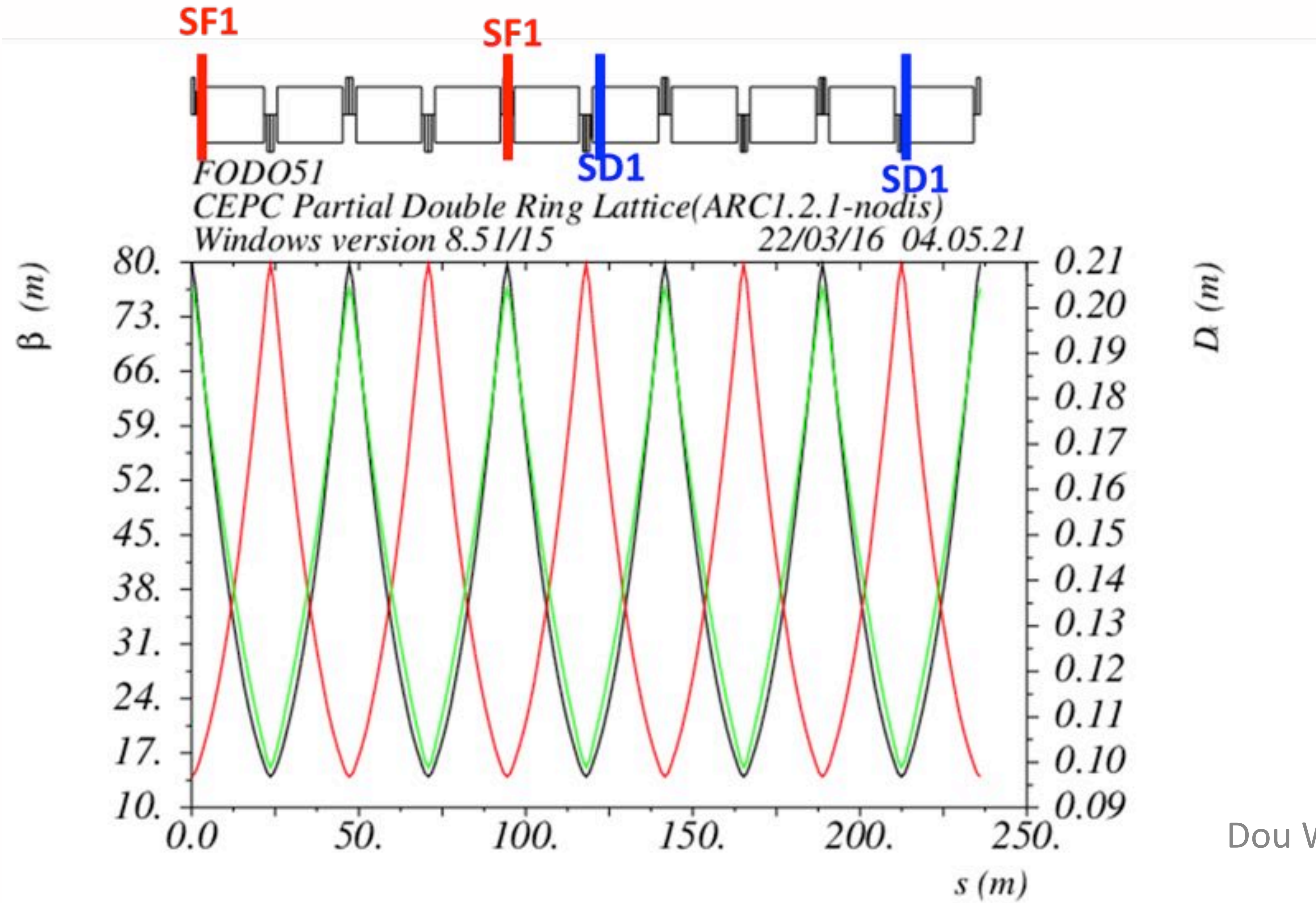
The Arc Cell (FCC-ee)



- Basically a 90/90 degree FODO cell.
- The quadrupoles QF/QD are 3.5 m/1.8 m long, respectively, to reduce the synchrotron radiation. They also depends on the design of quads and the beam pipe (A. Milanese, F. Zimmermann).
- All sextupoles are paired with -*I* transformation.
- 292 sextupole pairs per half ring.

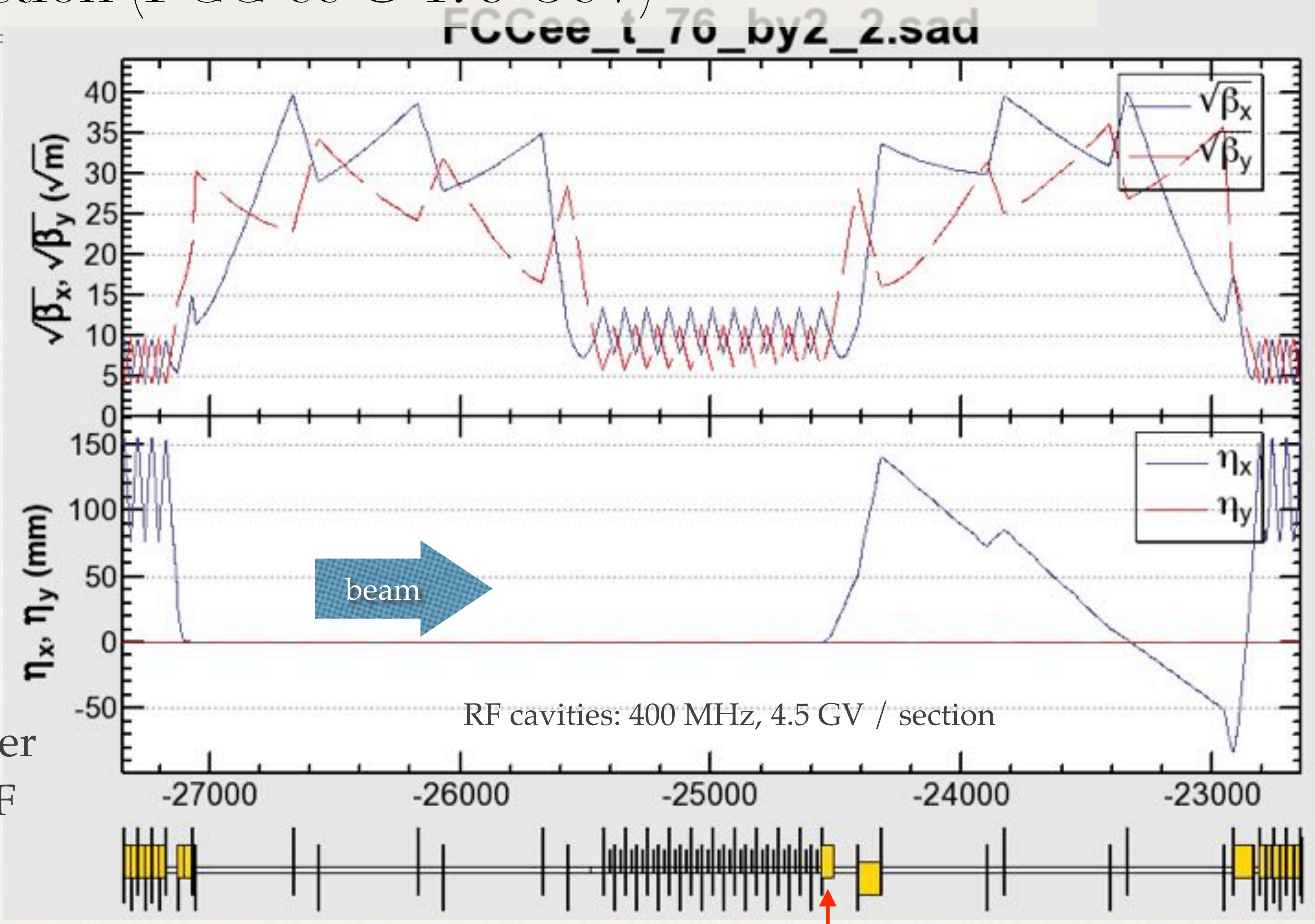
Non-interleave sextupoles in arc (CEPC)

(90°/90° FODO)



Dou Wang

The RF section (FCC-ee @ 175 GeV)



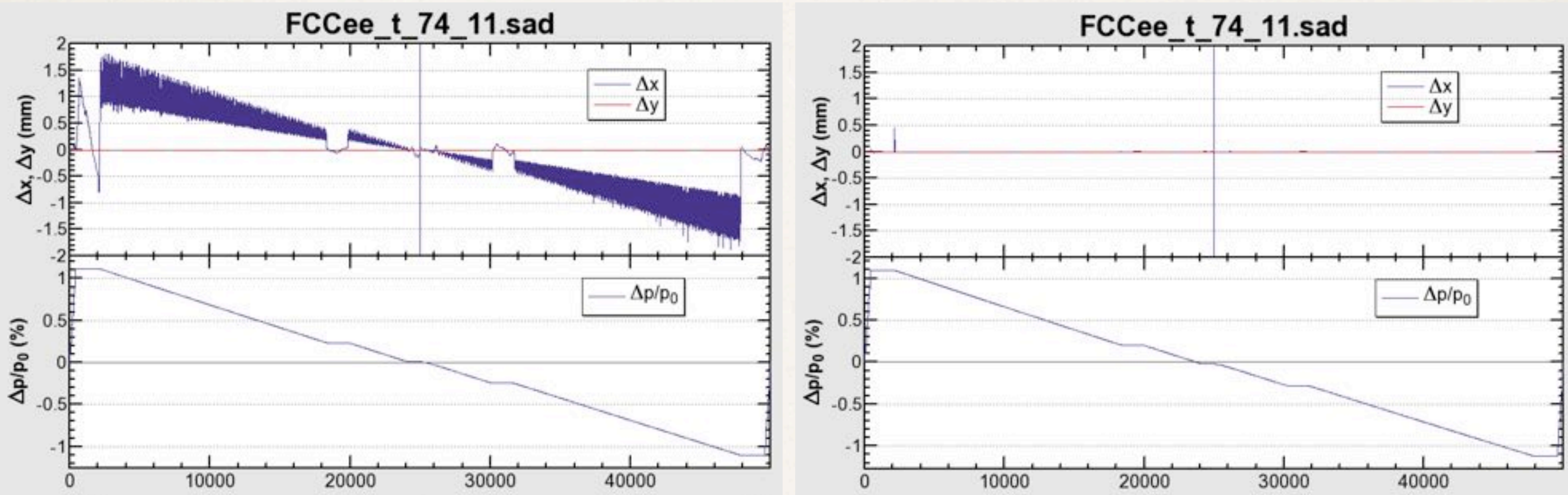
Beams cross over through the RF section.

An electrostatic separator, combined with a dipole magnet

- The usage of the straights on the both sides of the RF is to be determined.
- If the nominal strengths of quads are symmetrical in the common section, it matches to the optics of both beam.
- This section is compatible with the RF staging scenario. For lower energy, the common RF and cross over will not be necessary.

The Sawtooth & Tapering (FCC-ee @ 175 GeV)

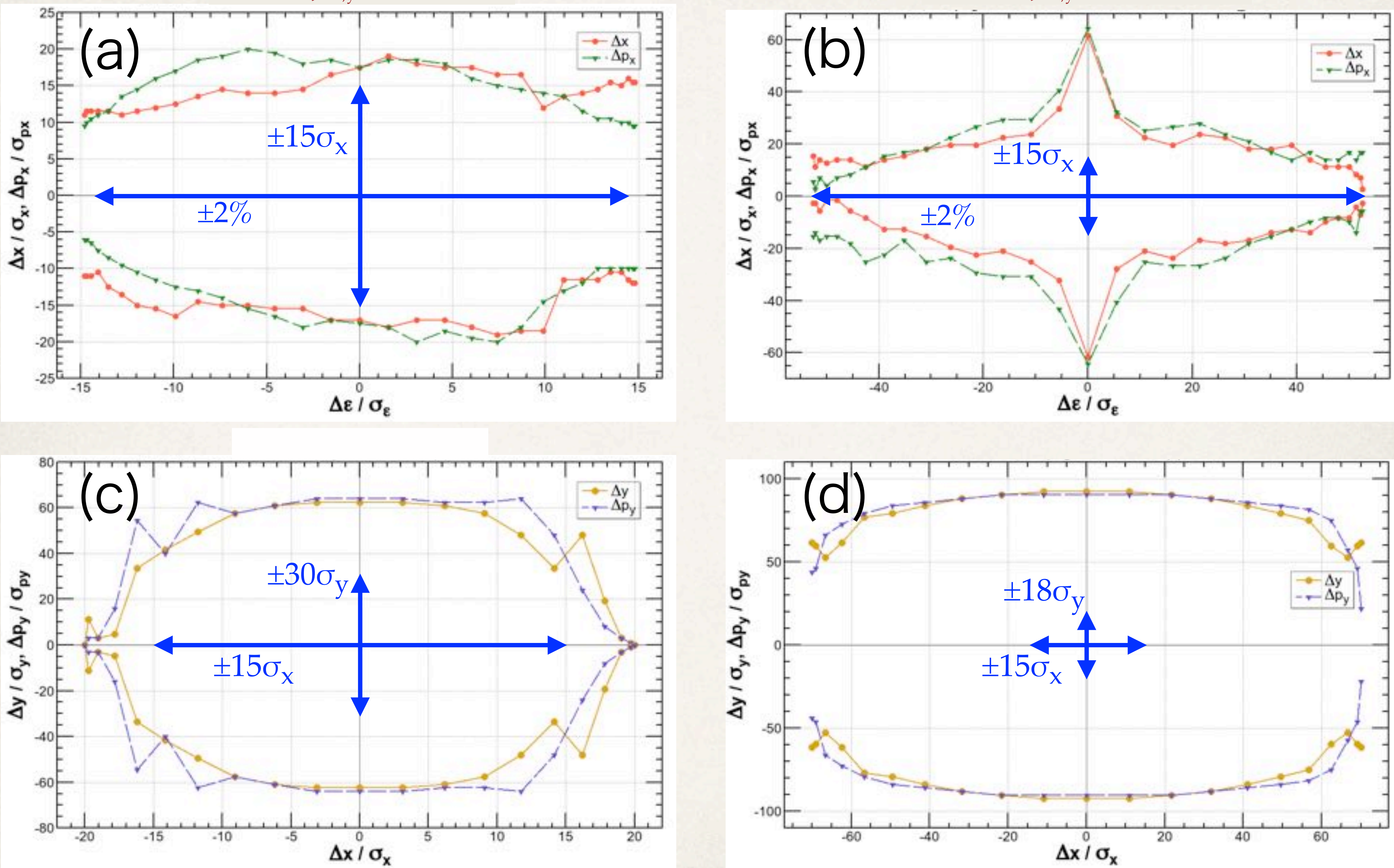
No Taper | Tapered



- The change of the orbit due to energy loss along the arc causes serious deformation on the optics, causing the loss of the dynamic aperture.
- Everything can be cured almost completely by “tapering”, i.e. scaling the strengths of all magnets along the local energy of the beam: this is one of the best merits of a double-ring collider (F. Zimmermann).

Dynamic Aperture satisfies the requirements (FCC-ee).

175 GeV, $\beta^*_{x,y}$ = (1 m, 2 mm) | 45.6 GeV, $\beta^*_{x,y}$ = (0.5 m, 1 mm)



All effects in the next slide are included except for radiation fluctuation and beam-beam.
Effects by the radiation fluctuation will be shown in the later slides.

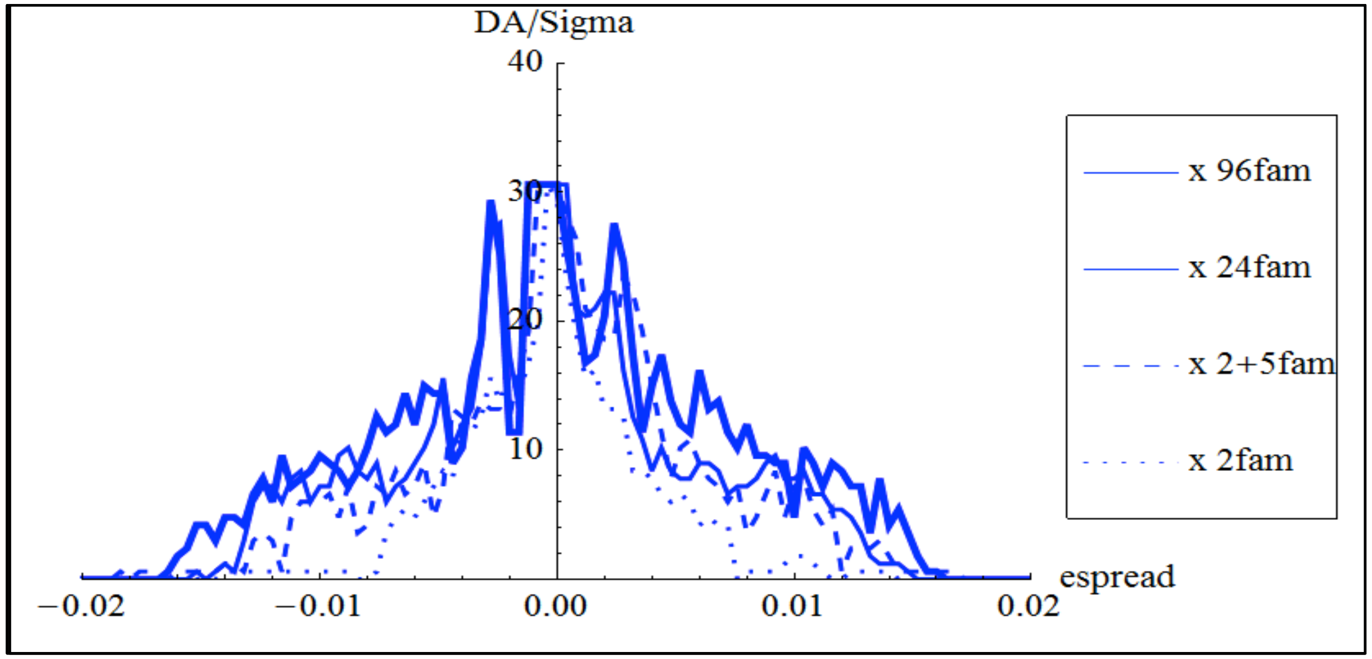
Effects included in the dynamic aperture survey

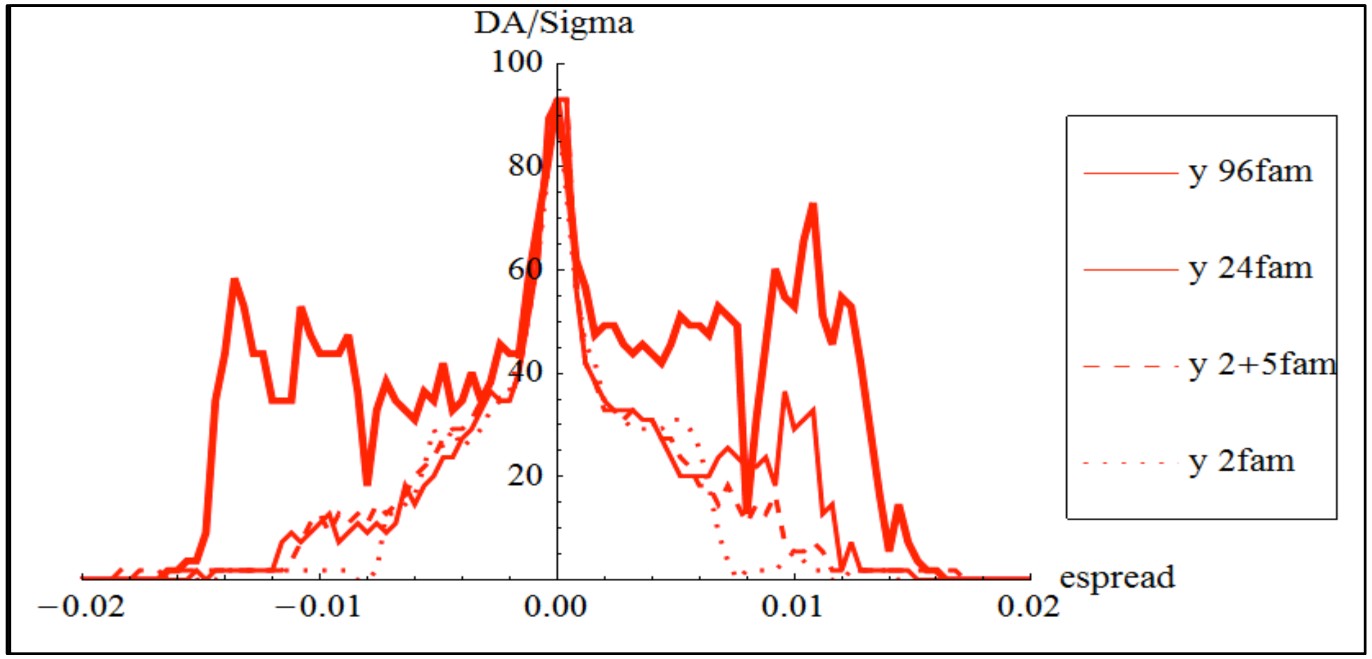
Effects	Included?	Significance at $t\bar{t}$
Synchrotron motion	Yes	**Essential**
Radiation loss in dipoles	Yes	**Essential** – improves the aperture
Radiation loss in quadrupoles	Yes	**Essential** – reduces the aperture
Radiation fluctuation	Yes	**Essential**
Tapering	Yes	**Essential**
Crab waist	Yes	transverse aperture is reduced by $\sim 20\%$
Solenoids	Yes	minimal, if locally compensated
Maxwellian fringes	Yes	small
Kinematical terms	Yes	small
Beam-beam effects (strong-weak model)	Yes (D. Zhou)	affects the lifetime for $\beta_y^* = 1$ mm
Higher order fields/errors/misalignments	No	**Essential**, development of correction/tuning scheme is necessary

Dynamic aperture optimization

CEPC PDR, IR + ARC

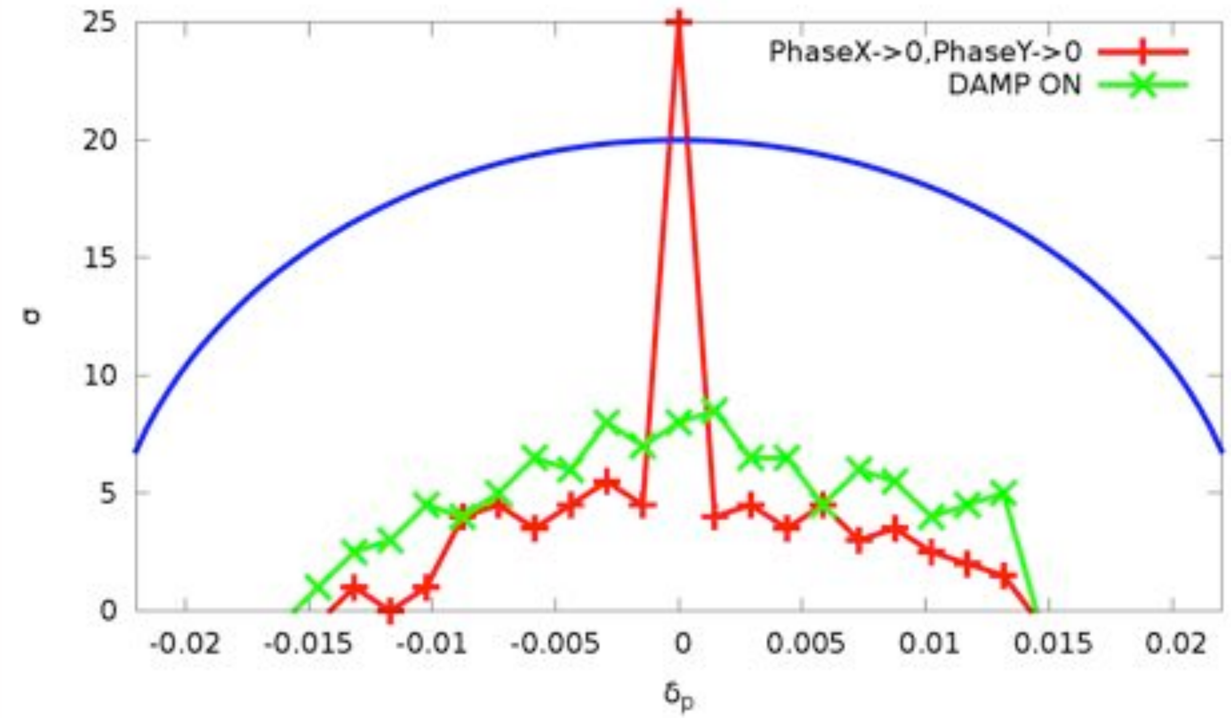
- Dynamic aperture result
  - W/O error of the magnets
  - Synchrotron motion included, **w/o damping**
  - Tracking with around 1 times of damping time
  - Coupling factor κ=0.003 for εy
  - Working point (0.08, 0.22)
- Many cases of sextupole families tried
  - Downhill Simplex algorithm applied
  - Some typical results
  - Further optimization is possible
    - Further optimization with these families
    - More families in IR
    - βy*= 1mm -> 1.36mm
    - Larger dispersion for IR sextupoles



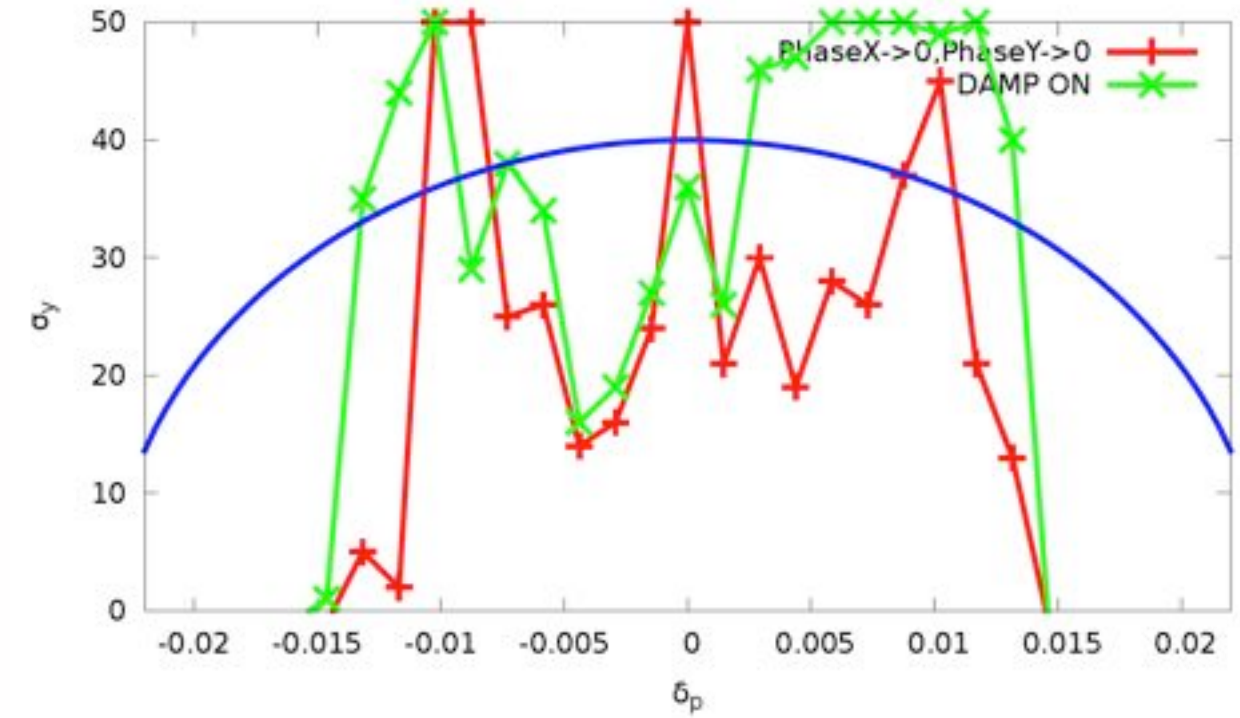


DA Optimization with arc sextupoles (CEPC, PDR)

- 192 sextupole families



X



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MODE:

Multi-Objective optimization by Differential Evolution

The parallel algorithm is referencing to J. Qiang(IPAC'13)

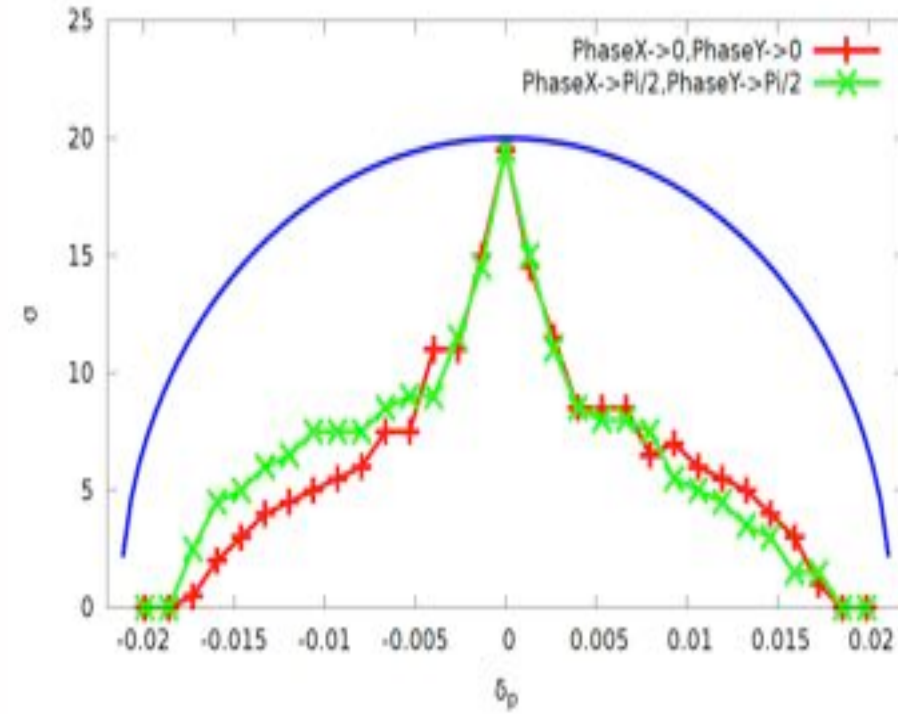
1. Initialize the population of parameter vectors
2. Generate the offspring population using the above differential evolution algorithm
3. Find the non-dominated population, which are treated as the best solutions in DE to generate offspring
4. Sorting all the population, select the best NP solution as the parents
5. Return to step 2, if stopping condition not met

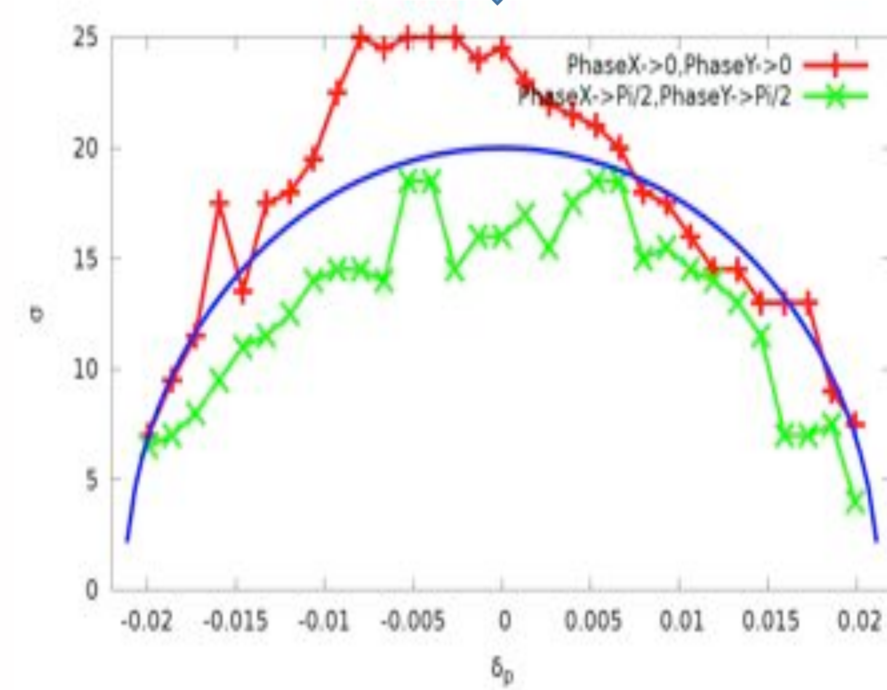
Yuan Zhang

CEPC:
Dynamic Aperture Optimization

single ring, Arc + IR, no pretzel

- DA Objective: $\frac{x^2}{20^2} + \frac{z^2}{16^2} = 1$
  - z for energy deviation in unit of σ_p
  - x for transverse amplitude in unit of σ
- Variables: 240 sextupole familiy in arc
  - Sextupoles interleaved with –*I* map is one pair
- Options:
  - DAPWIDTH=15
  - Turns = 100
  - Synchrotron oscillation on





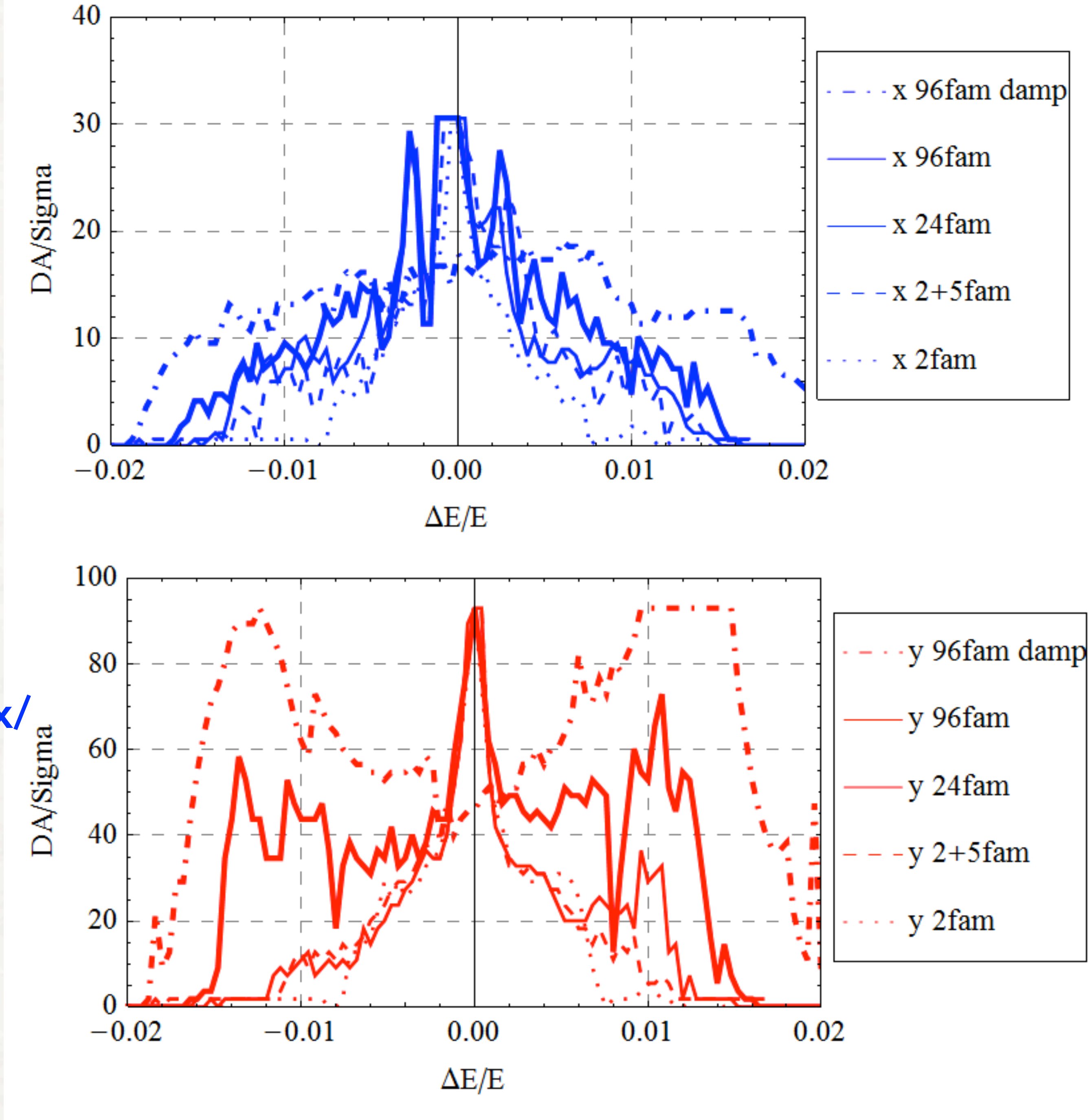
DA almost satisfies the requirements

Yuan Zhang

DA STUDY AND OPTIMIZATION FOR PDR

by Yiwei Wang

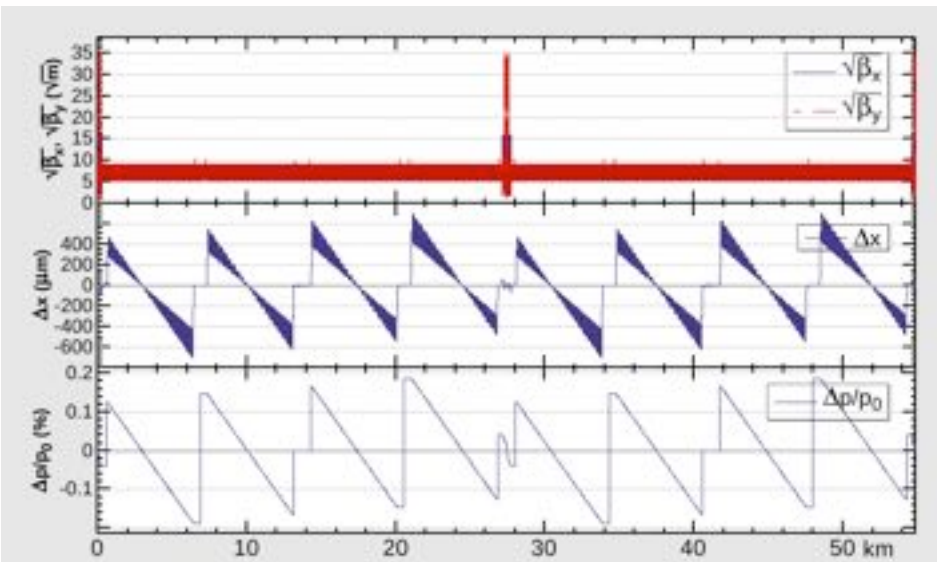
- Dynamic aperture study
  - Bare lattice
  - Synchrotron motion included
  - w/o and w/ **damping**
  - Tracking with around 1 times of damping time
  - Coupling factor κ=0.003 for εy
  - Working point (0.08, 0.22)
  - **Downhill Simplex** algorithm applied up to **96 families** of sexts
  - Achieved DA: 16σx/45σy@0.0% dp/p,**~3σx/5σy @2.0%**
- Further optimization is possible
  - Larger dispersion for IR sextupoles
  - βy*= 1mm -> 1.3mm (new parameters)
  - More families in IR
- Study of effects such as quantum excitation, solenoid field, errors and misalignments are under going



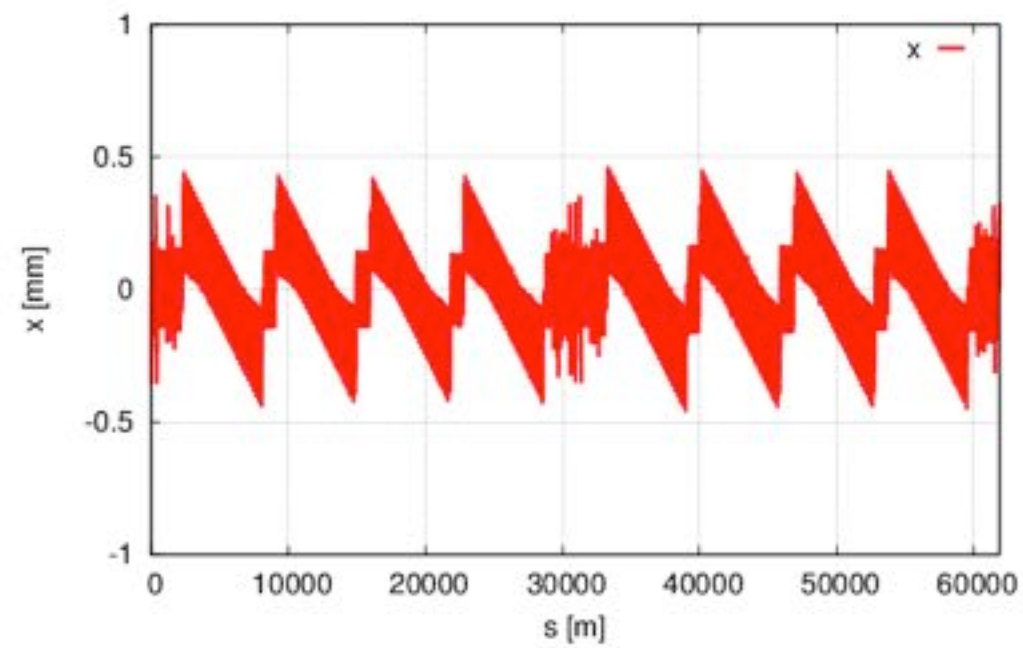
Two important issues on single ring and partial double rings

1) Sawtooth effects induced DA reductions

The potential bottle necks for single ring and partial double rings!

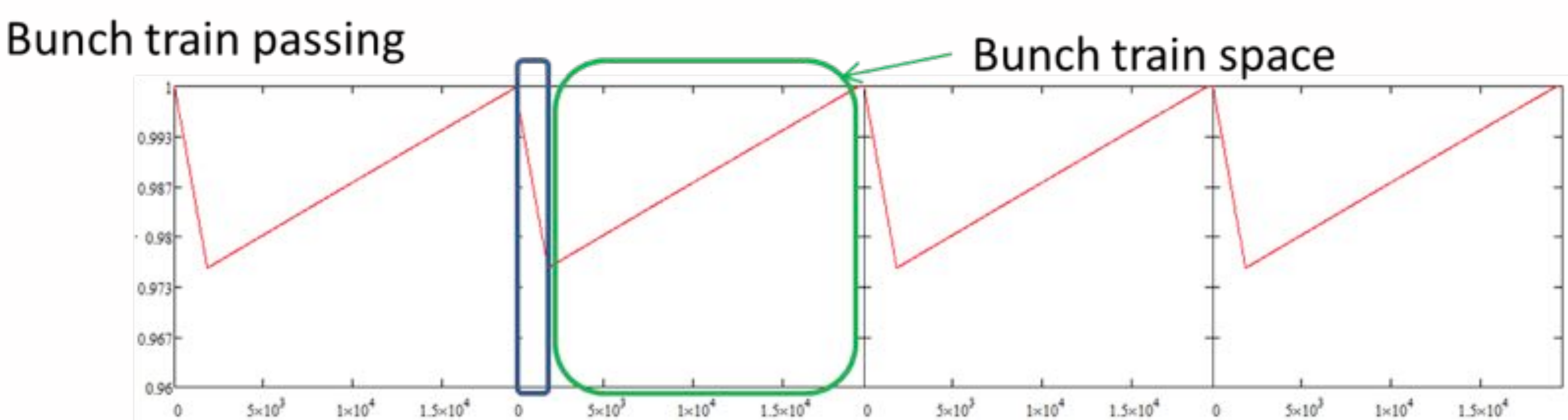


Single ring



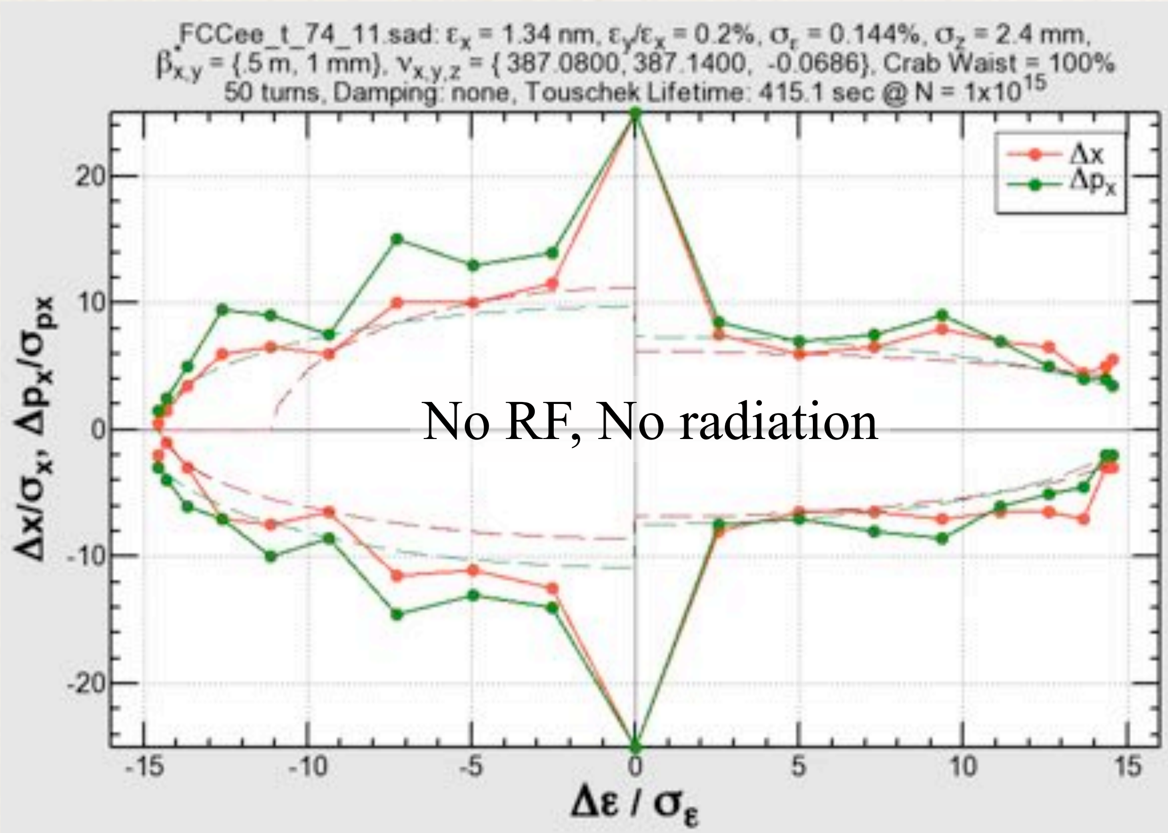
Partial double ring

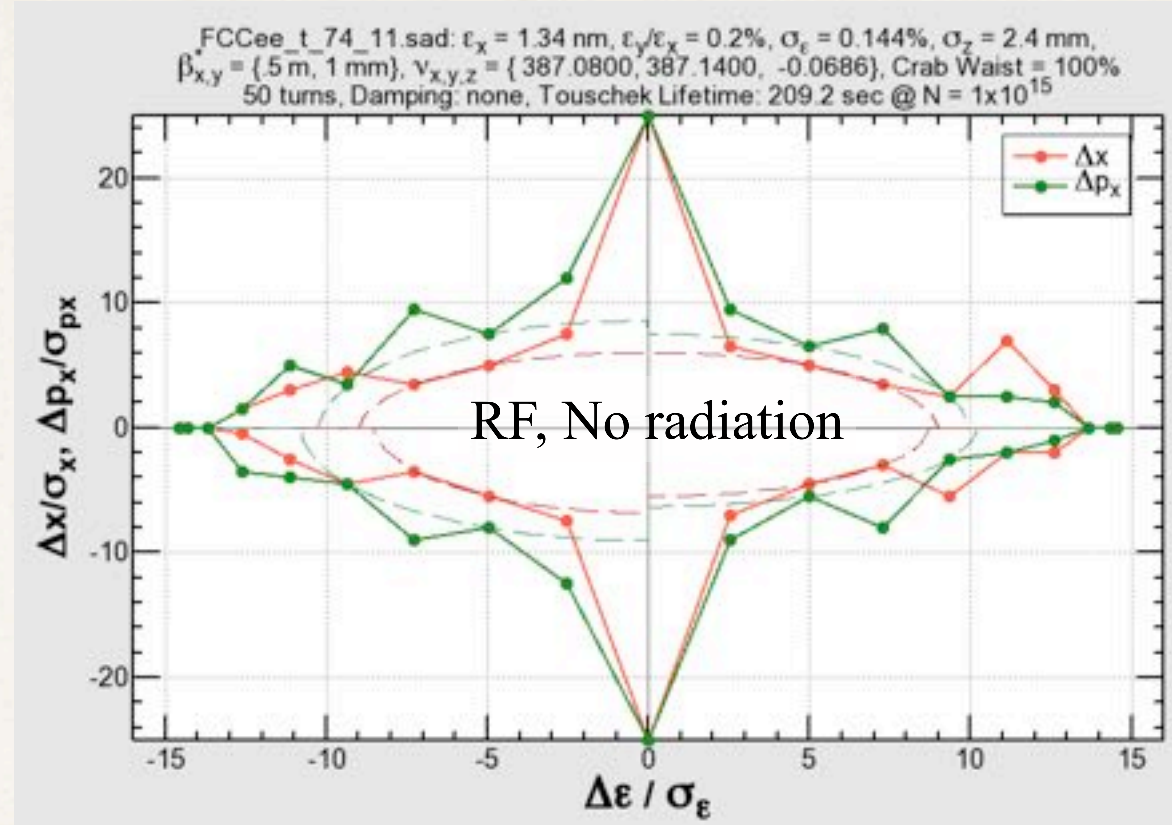
2) Beam loading effects induced DA reduction



J. Gao

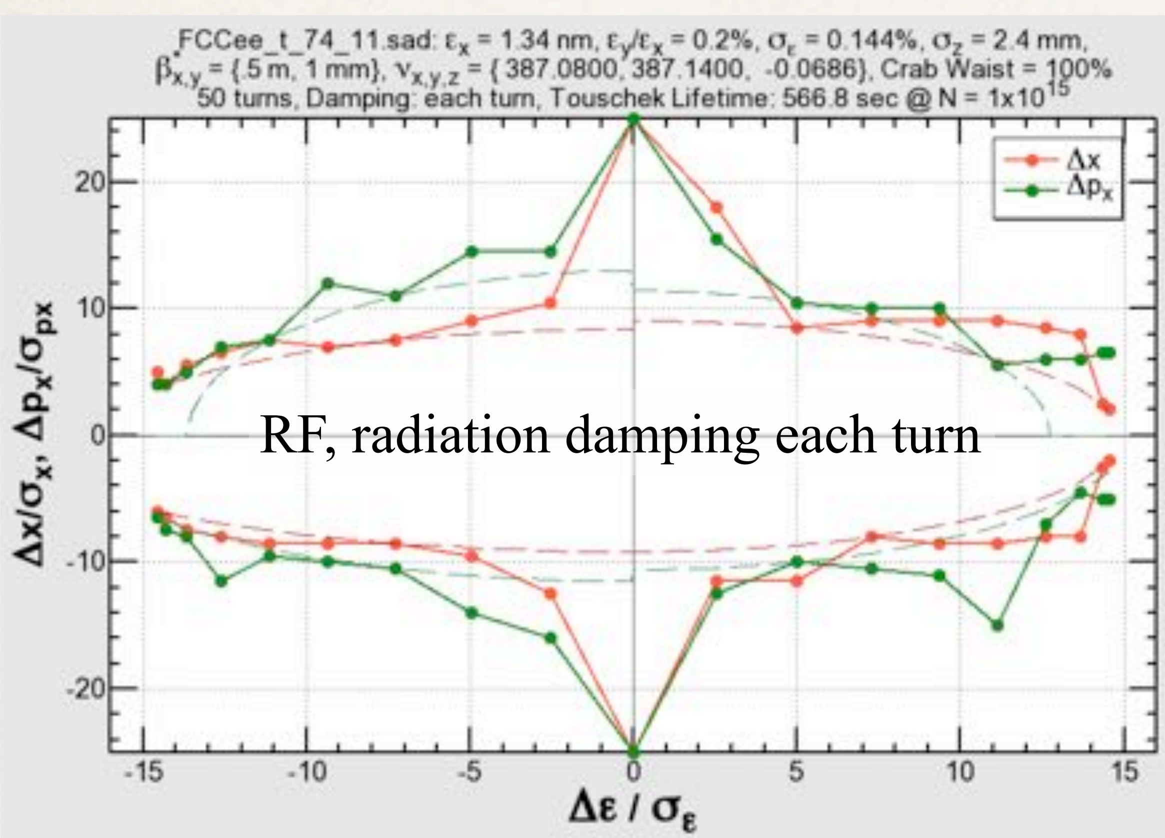
Several effects on the dynamic aperture

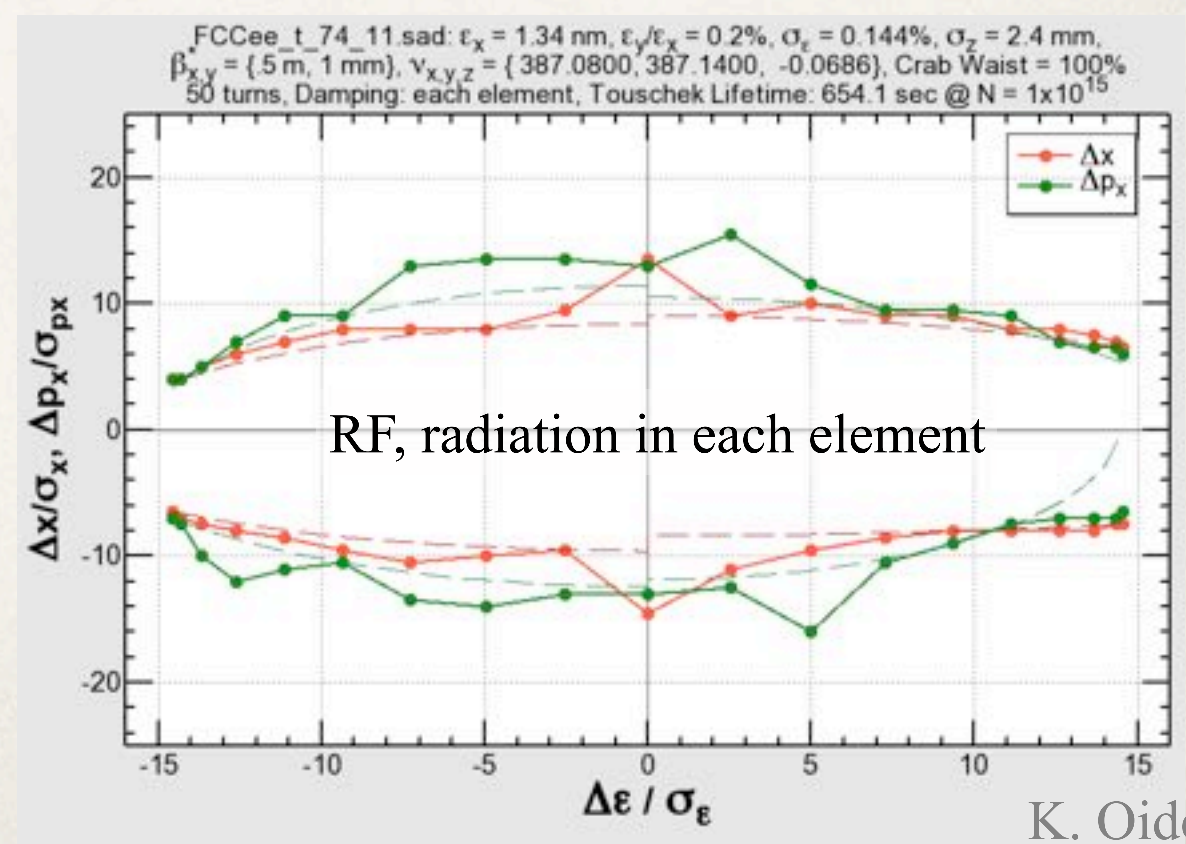




±2%

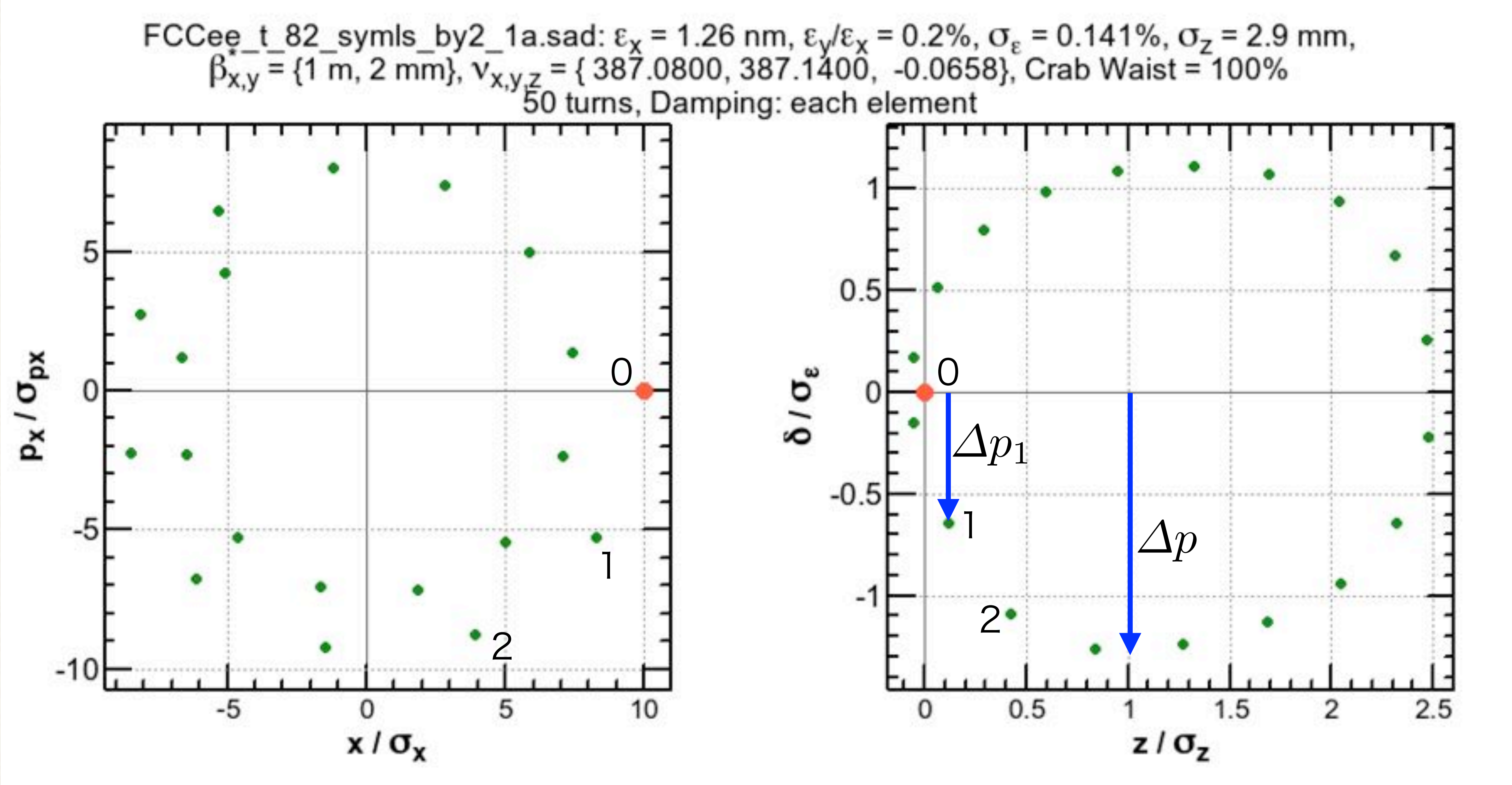
±2%





K. Oide

Synchrotron radiation in quadrupoles



- Horizontal betatron oscillation (left) causes a synchrotron motion (right) due to the energy loss by the synchrotron radiation in arc quadrupoles.

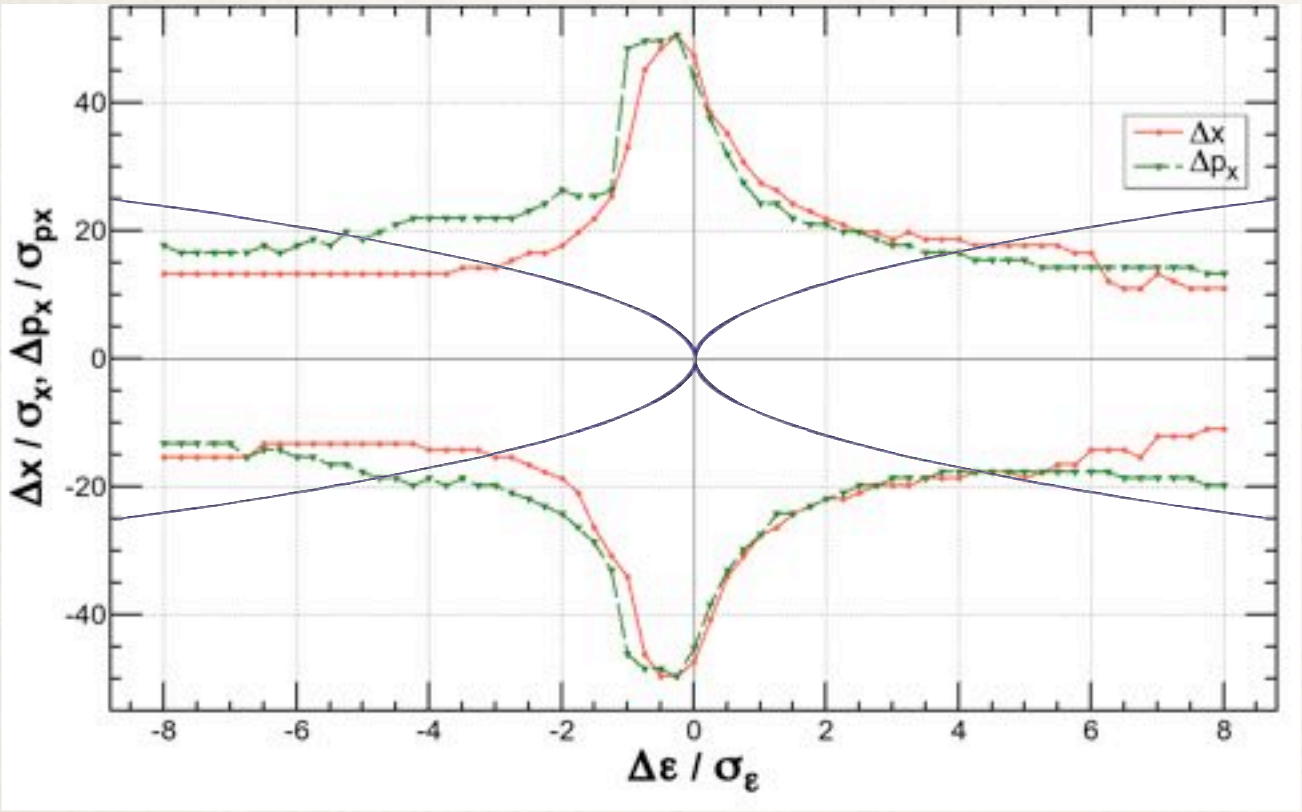
$$\Delta p = \frac{\Delta p_1}{2\pi\nu_s}\exp(-\alpha_z/4\nu_s) = \frac{\alpha_z}{\pi\nu_s J_z} R_{\mathrm{Q}} n^2 \varepsilon_x \exp(-\alpha_z/4\nu_s)\ ,$$

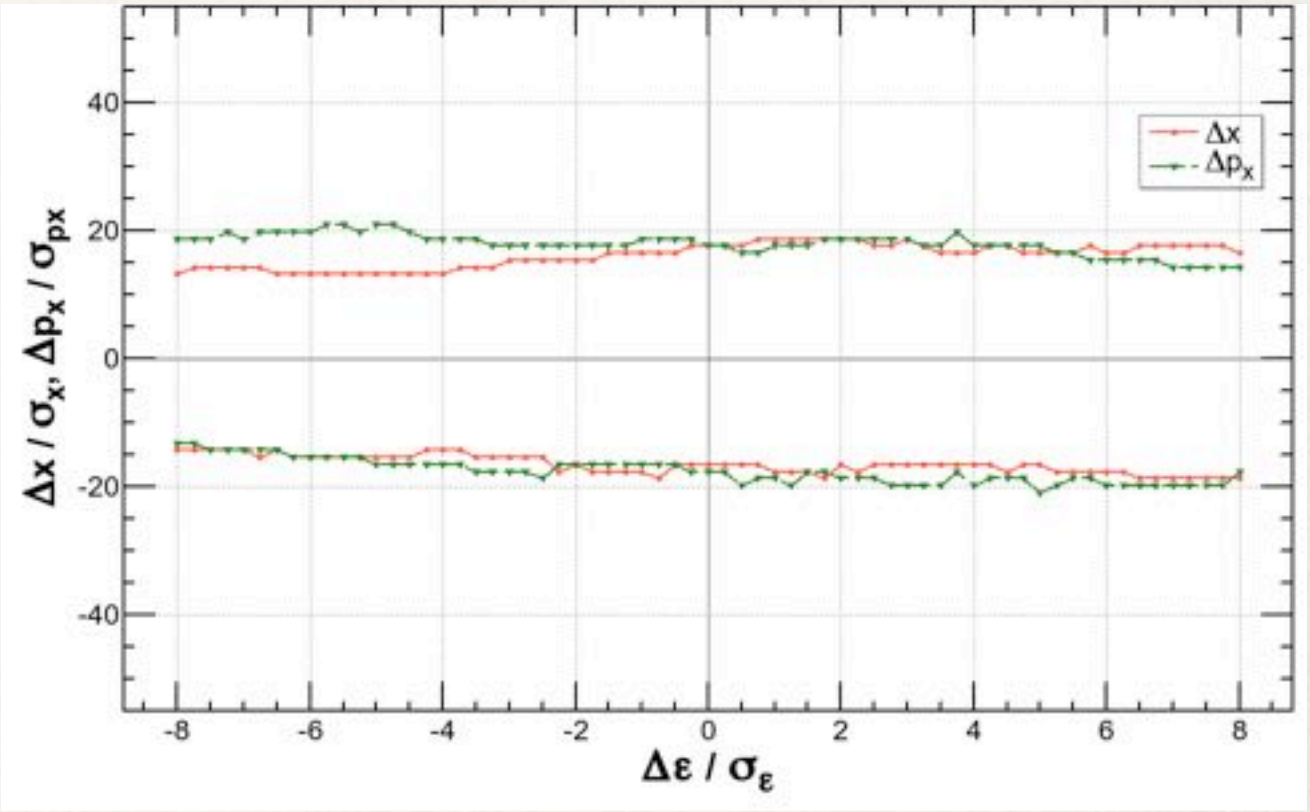
$$R_{\mathrm{Q}} = \frac{2\sqrt{2}}{\theta_c^2}\left(\frac{\sqrt{2}+1}{\ell_{\mathrm{QF}}} + \frac{\sqrt{2}-1}{\ell_{\mathrm{QD}}}\right) \quad (90^\circ\ \text{FODO})$$

- Such particles can not stay on momentum: reduction of the dynamic aperture.

Synchrotron radiation in quadrupoles (cont'd)

E = 175 GeV, $\beta_{x,y}$ = (1 m, 2 mm)

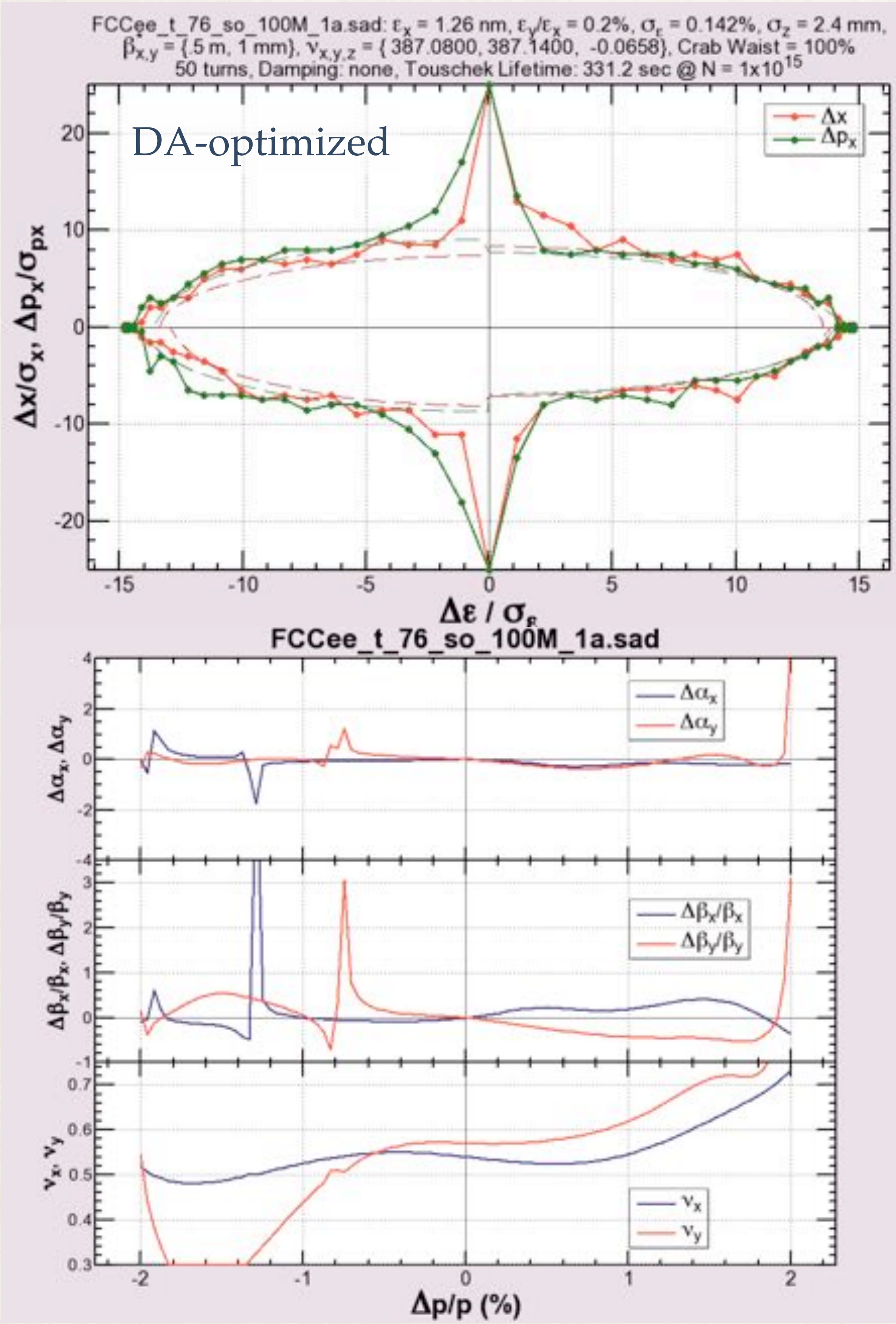


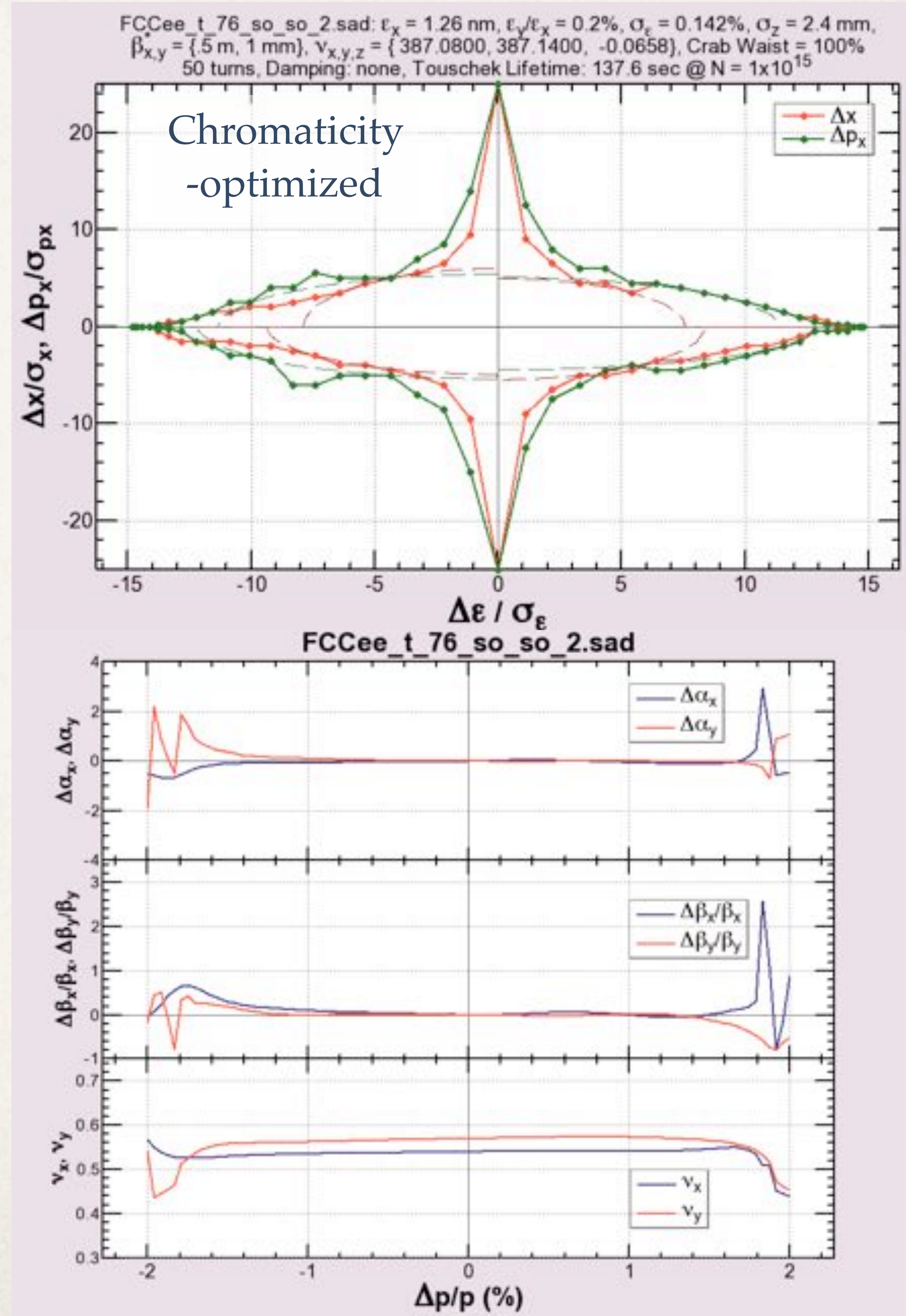


- The dynamic aperture without radiation loss in quadrupoles (left) has a sharp peak at on momentum.
- The peak is destroyed if the radiation in quads is turned on (right).
- The parabolas on the left show the amplitude of the synchrotron motion due to the radiation in the quadrupole. For a given transverse amplitude, if the parabola is beyond the DA, the particle with that amplitude will be lost.

Less chromaticity ≠ better dynamic aperture

$\beta^*_{x,y}$ = (0.5 m, 1 mm), no radiation damping

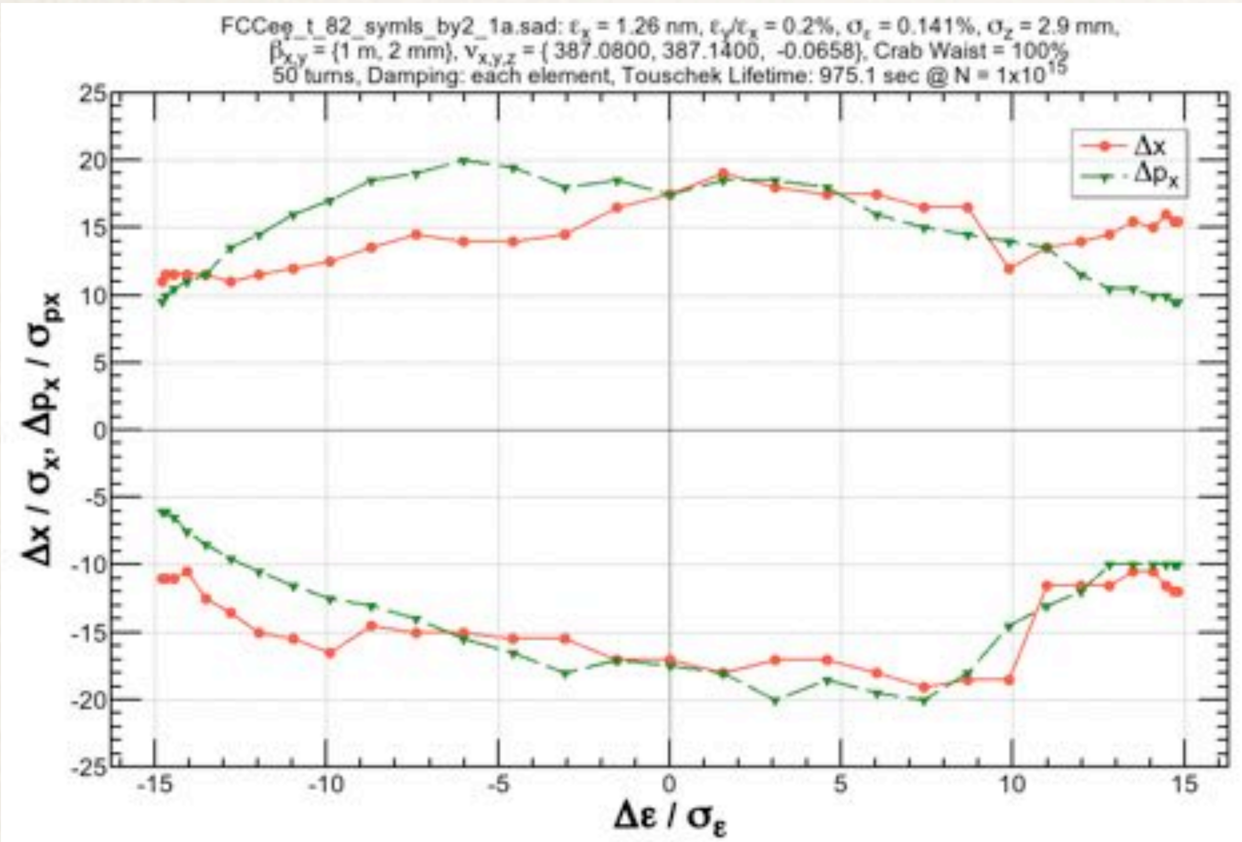




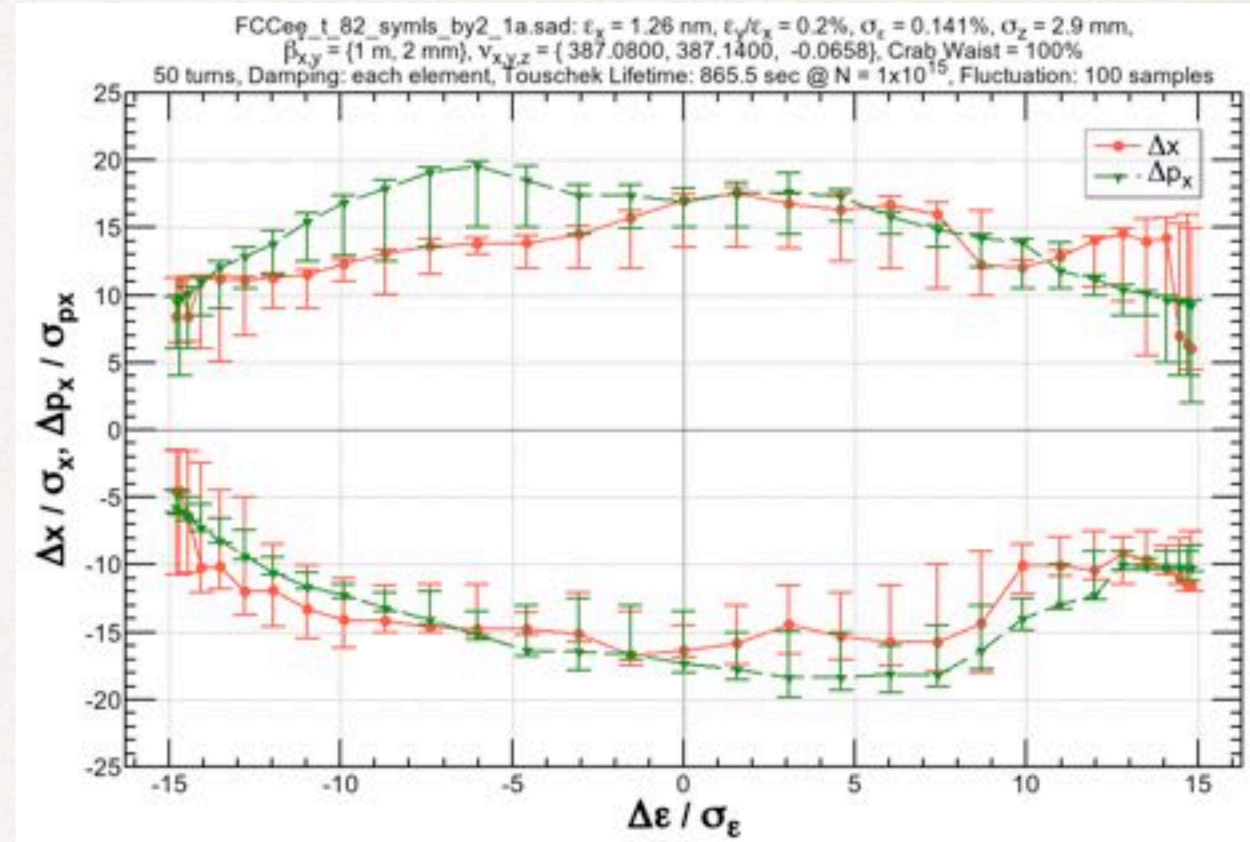
Effect of Radiation Fluctuation

E = 175 GeV, $\beta_{x,y}$ = (1 m, 2 mm)

Radiation damping only | **Radiation damping + fluctuation**



±2%



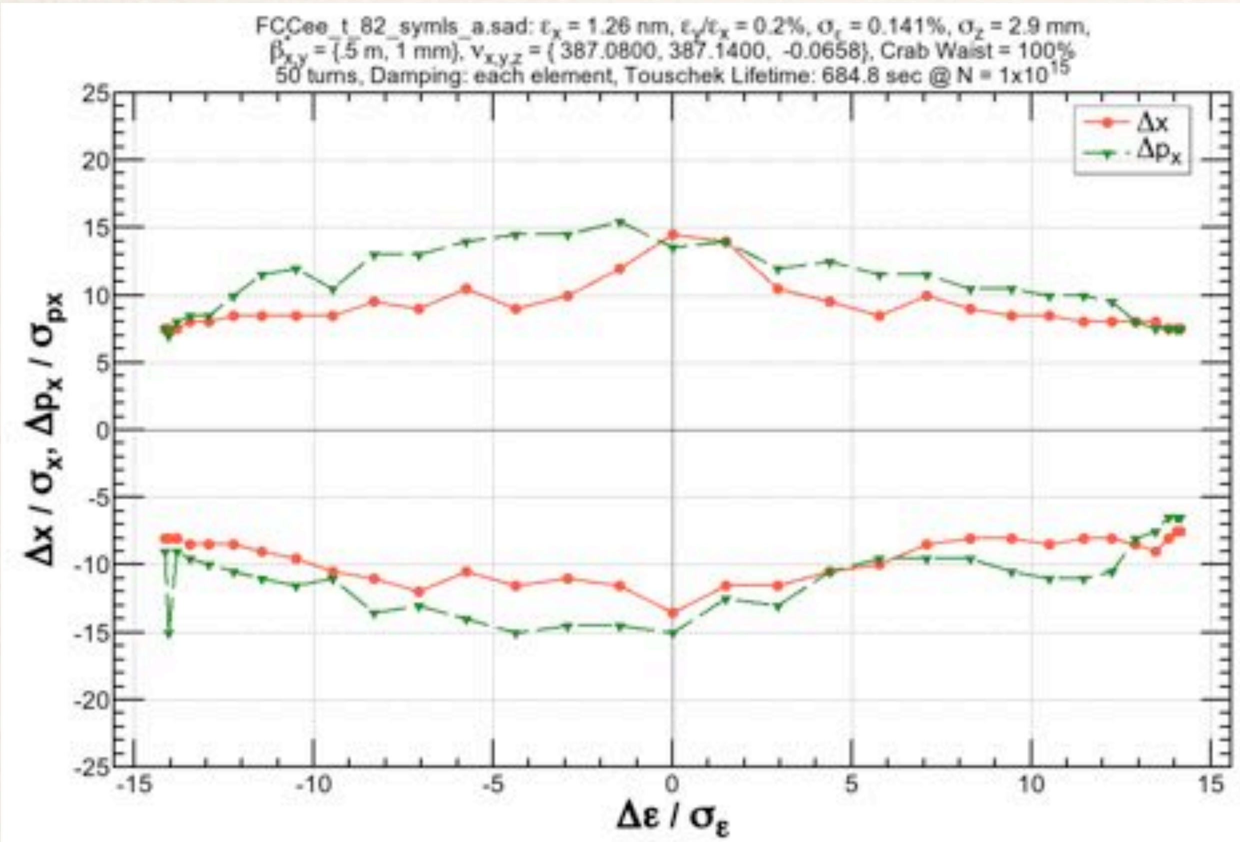
±2%

- (Right figure) 100 samples are taken to evaluate the dynamic aperture with radiation fluctuation.
  - Within the lines: particles survive for 75% of the samples.
  - Error bars correspond to the range of survival between 50% and 100% of the samples.
- It may reasonable that the 50% loss corresponds to the original aperture.
- The thickness between 50% and 100% survival can be attributed to the fractal structure of unstable orbits or resonances in the phase space.

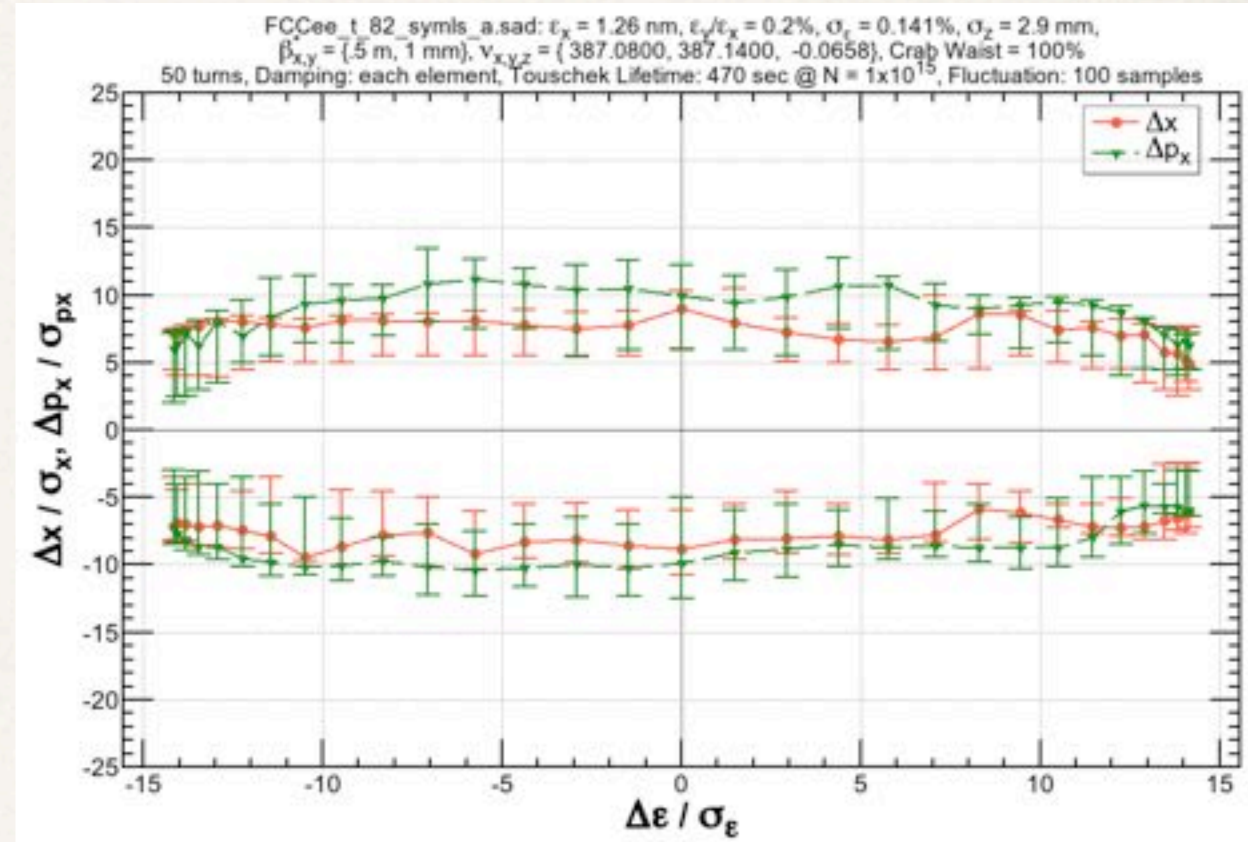
Effect of Radiation Fluctuation (2)

E = 175 GeV, βx,y = (0.5 m, 1 mm)

Radiation damping only | **Radiation damping + fluctuation**



±2%

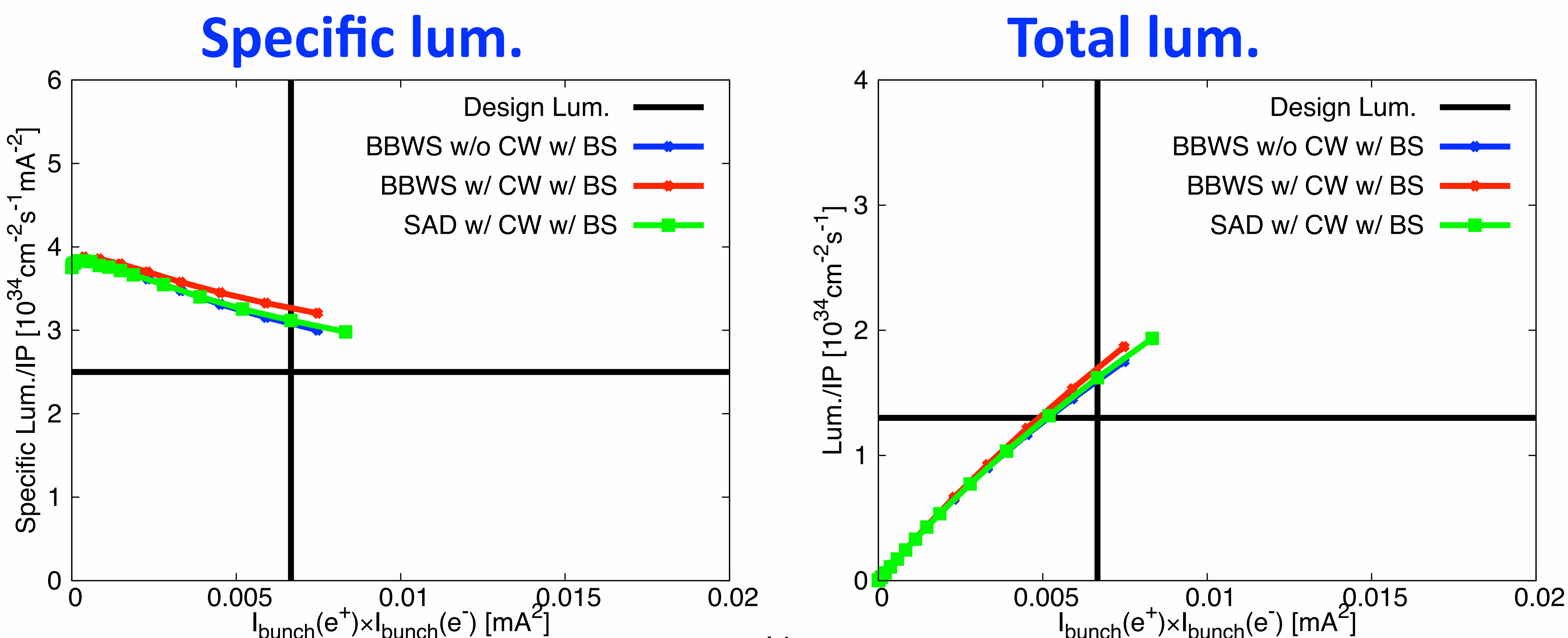


±2%

- (Right figure) 100 samples are taken to evaluate the dynamic aperture with radiation fluctuation.
  - Within the lines: particles survive for 75% of the samples.
  - Error bars correspond to the range of survival between 50% and 100% of the samples.
- The reduction of the 100% survival aperture is more significant than βx,y = (2 m, 2 mm). However, it still maintains ±2% momentum acceptance.

2. Simulations: SAD: tt$_{bar}$

- **Luminosity for β_x^*=0.5m, β_y^*=1mm**
  - Lattice ver. FCCee_t_65_26
  - Small gain from CW
  - Small loss(order of a few percents) due to BB+LN
  - Allow lower beam current to achieve the same lum.



FCC-ee talks later:
Emittance tuning: S. Aumon
Tolerance/misalignment: S. Sinyatkin

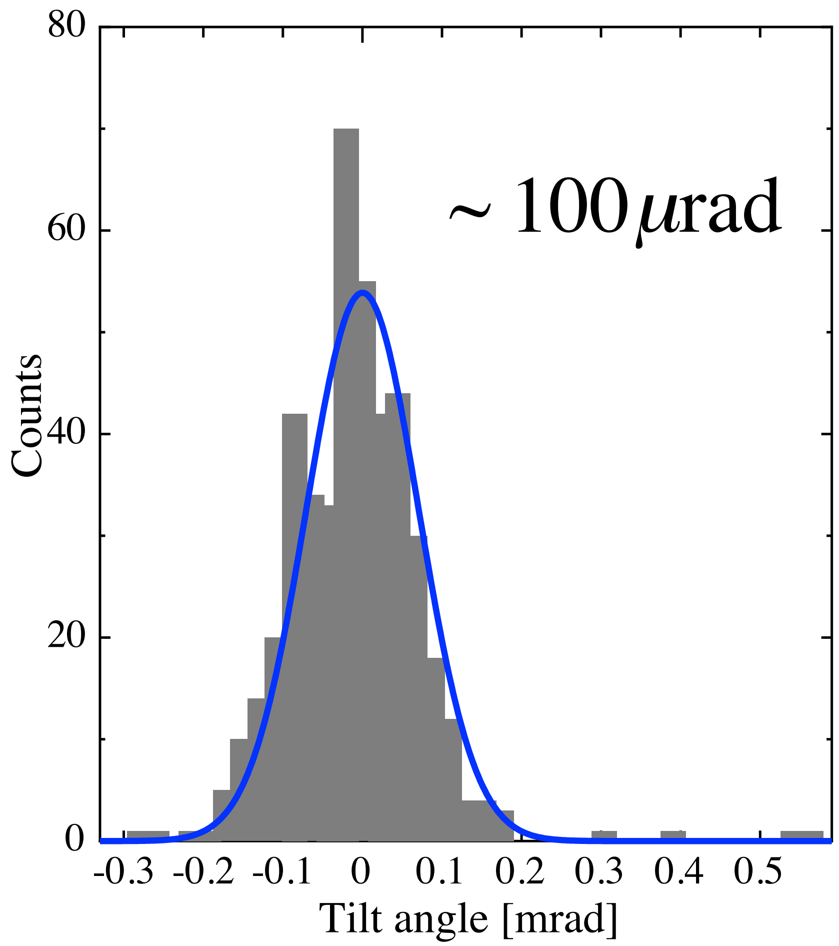
Low Emittance Tuning Simulation

- Assumed machine errors
  - All errors are static in time.
  - Bearing KEKB alignment level in mind.
  - All errors are Gaussian distributed.

	$\sigma_x = \sigma_y$ [μm]	σ_θ [μrad]	$\Delta K/K$
Normal Quad	100	100	2.5×10^{-4}
Sext	100	100	2.5×10^{-4}
Bend	0	100	0
QCS	100	0	0

BPM jitter : 2 μm
BPM tilt : 10 mrad

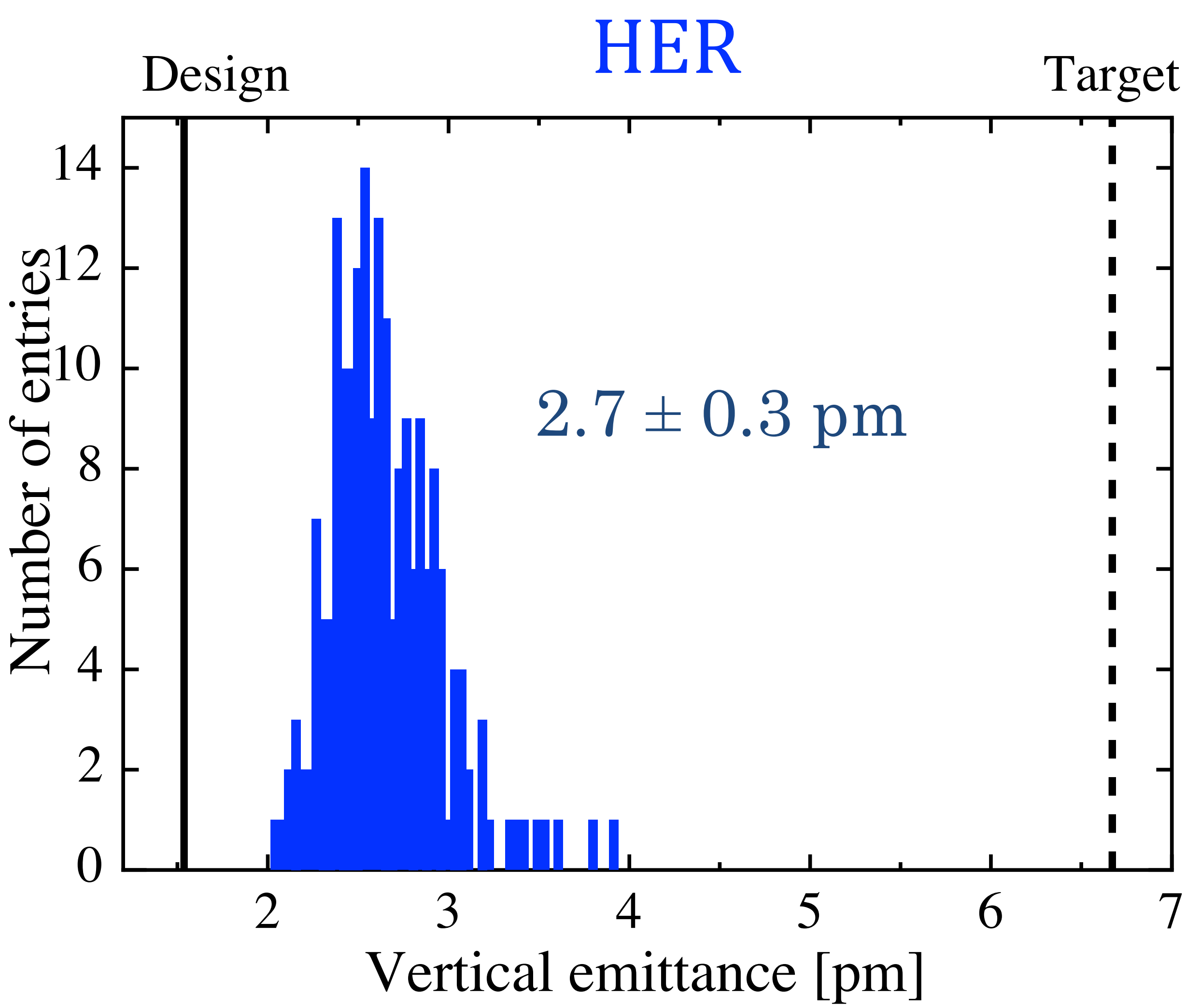
Quadrupole tilt angle measurement at KEKB

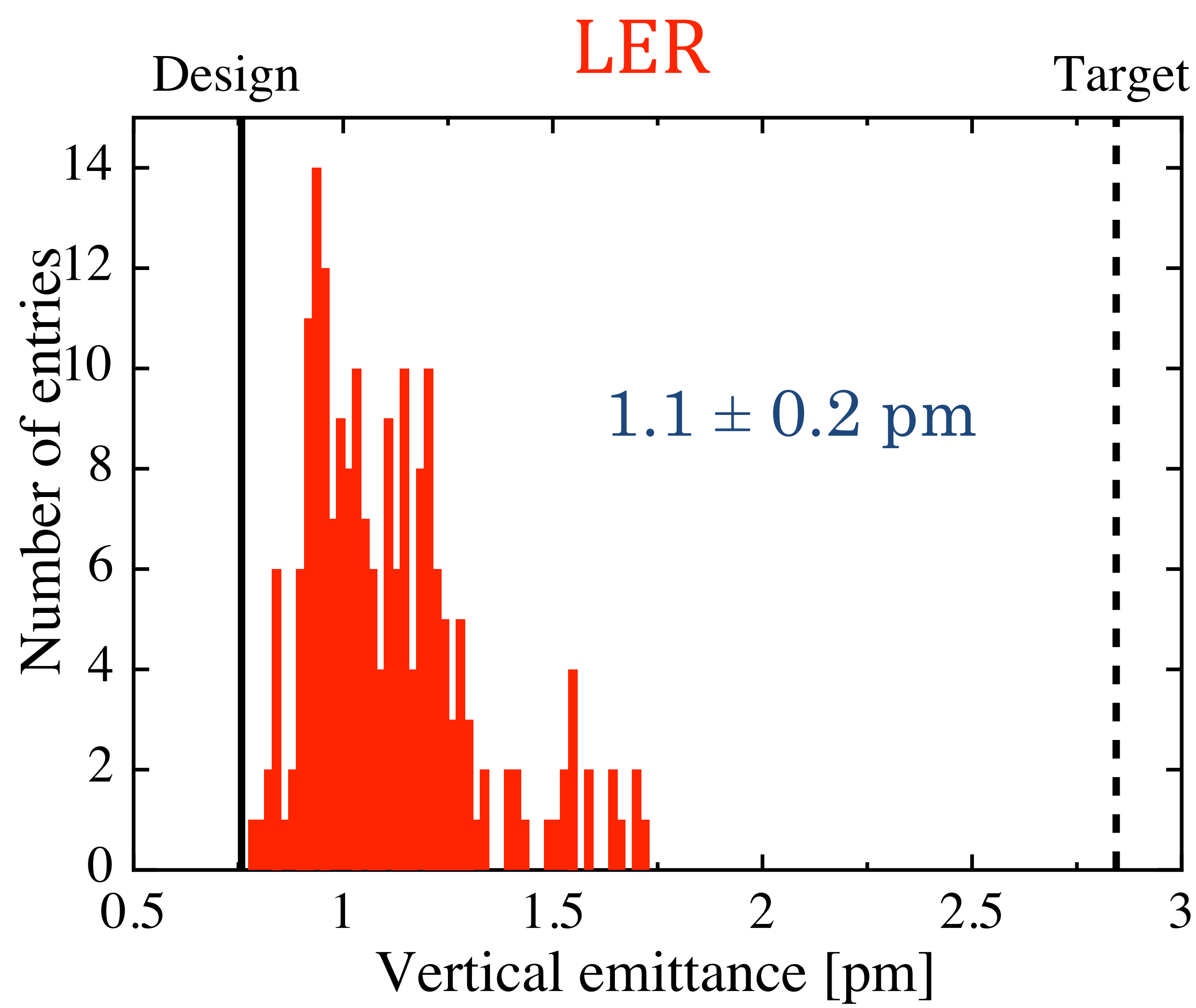


H. Sugimoto

Vertical Emittance

200 samples



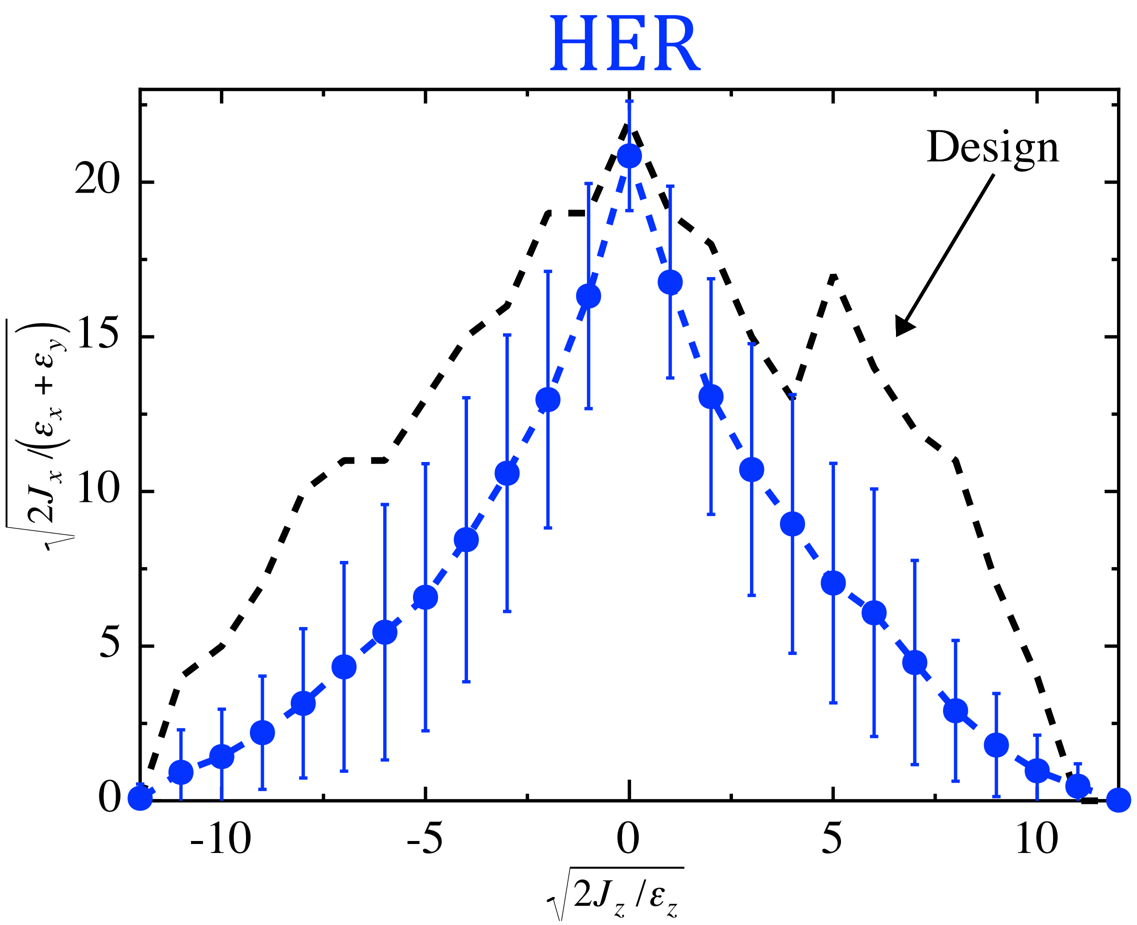


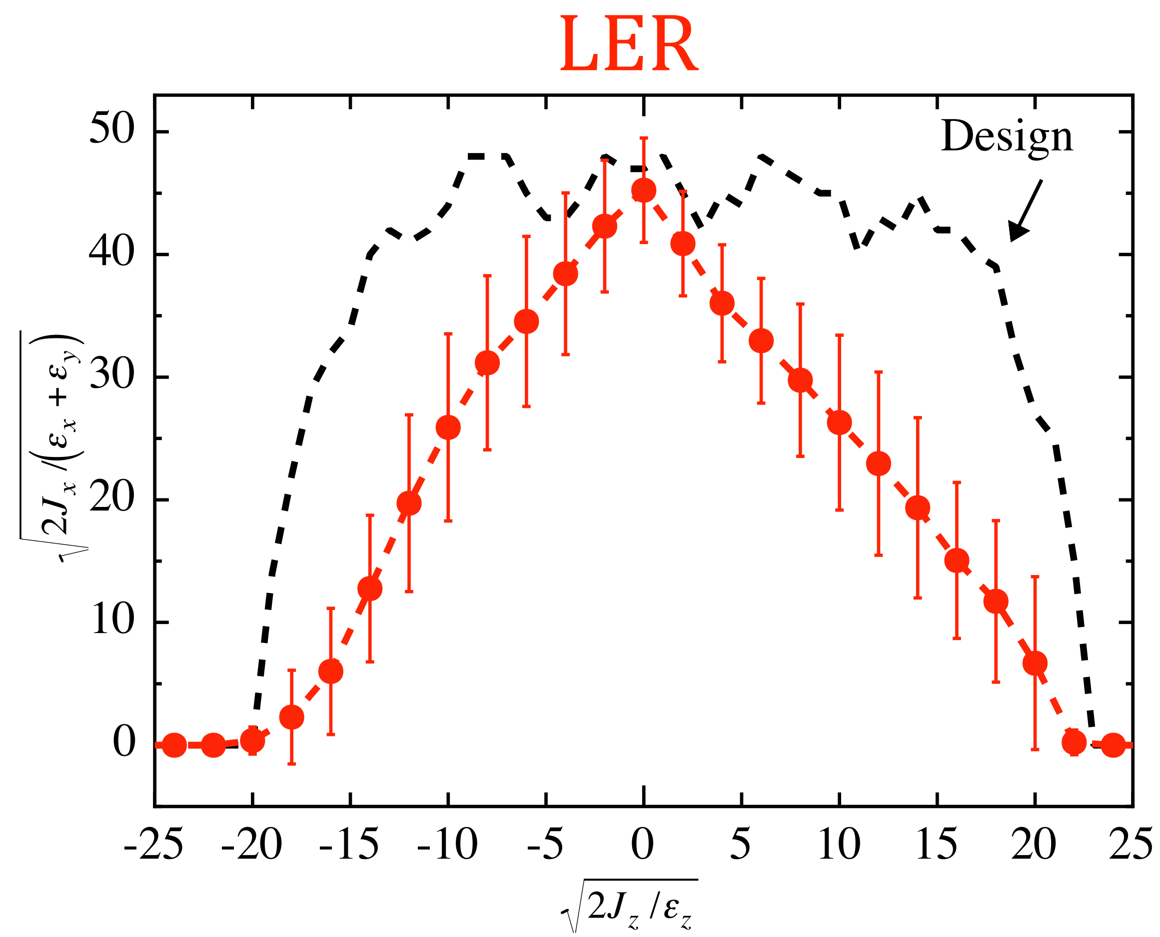
- Vertical emittance is well below the target in both rings.

H. Sugimoto

Dynamic Aperture

200 samples

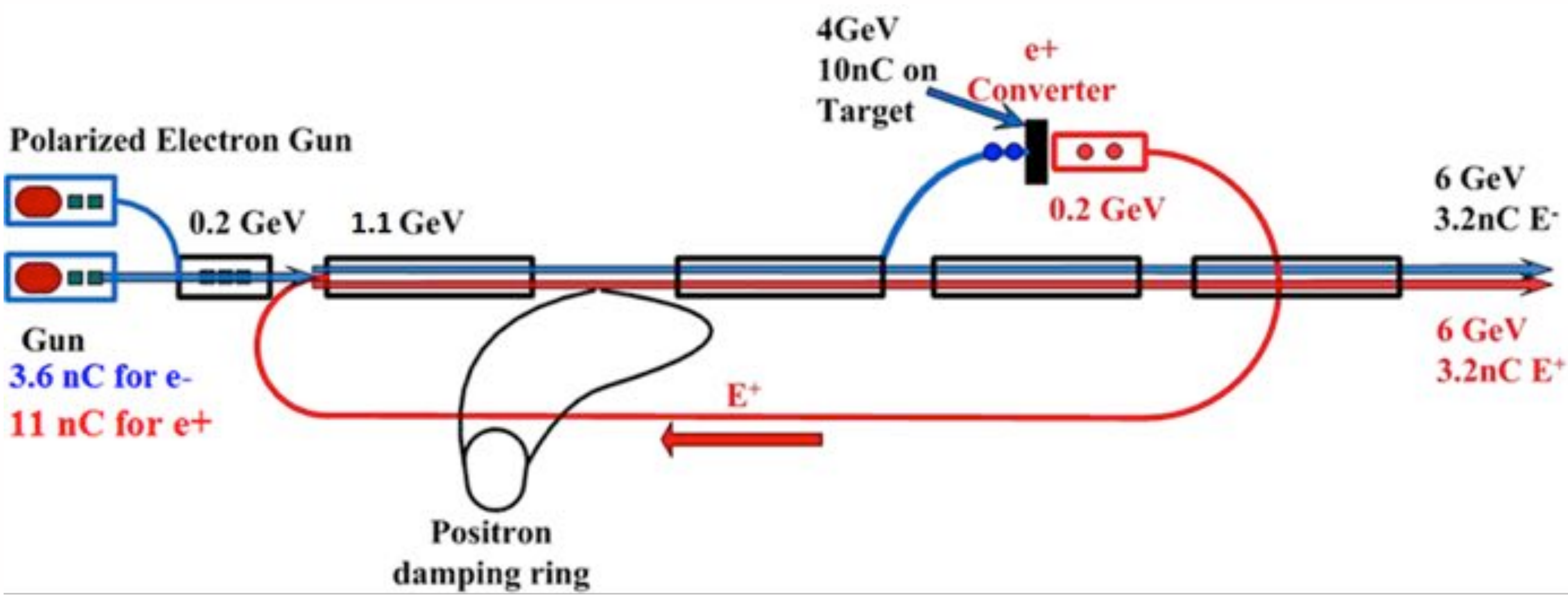




- On-momentum DA is recovered.
- Off-momentum DA is not resumed.
- Need off-momentum optics correction. (under investigation)
  - Reoptimization strategy of sextupole is not trivial because it affects vertical emittance also.

H. Sugimoto

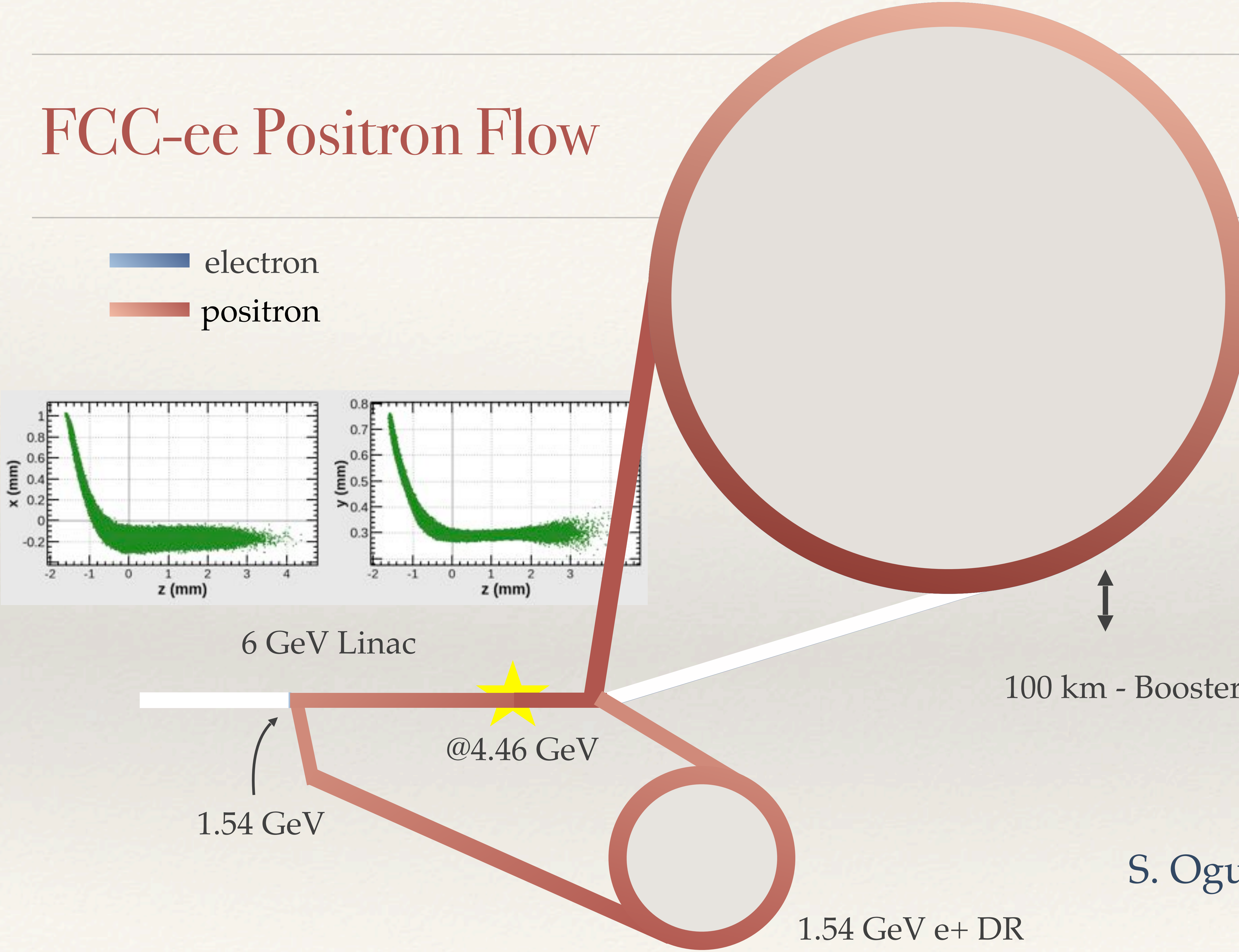
CEPC damping ring requirement



- Energy: 1.1GeV
- Storage time: 20ms
- Injected emittance (normalized): 3500 mm-mrad, injected energy spread ~ 0.25%
- Transverse acceptance > 3*injection beam size
- Extracted energy spread <1×10-3
- No strong requirement for the extracted emittance (<0.5ε_{inj})!

Dou Wang

FCC-ee Positron Flow



S. Ogur

Similarities

	CEPC	FCC-ee
Scheme	Partial Double Ring	Full Double Ring
SR power (2 beam) [MW}	100	
Crossing angle [mrad]	30	
Crab waist	yes, incorpolated with LCCS	
Arc cell	90°/90° FODO	
Sextupoles	non-interleaved -*I* pairs	
Sext. families	up to 240	294
Dynamic aperture optimization method	Munti-Objective Differential Evaluation, etc.	downhill simplex

Differences

	CEPC	FCC-ee
Scheme	Partial Double Ring	Full Double Ring
Circumference [km]	54	100
$\mathcal{L}$ at H [10^{34} $m^{-2}s^{-1}$]	3	5
$\mathcal{L}$ at Z [10^{34} $m^{-2}s^{-1}$]	3.6	200
Sawtooth	uncorrectable. reduced by inserting more RF sects.	completely correctable
SR to IP	< 190 keV @ H	< 100 keV @ tt
Strong-strong beam-beam instability	can be more robust due to smaller β^*_x (= 0.1 m) at Z	luminosity reduction by 50% at Z (β^*_x = 0.5m)
Dynamic aperture	Under development	OK for a perfect machine
Hadron machine	can coexist	removes ee

Summary

- **With the partial double ring (PDR) scheme at CEPC, both machines are obtaining more similarities:**
  - 2 IPs/ring, with 30 mrad crossing angle.
  - Local chromaticity correction with crab waist.
  - 90/90 FODO cells in the arc.
  - Non-interleaved sextupole pairs with -*I* transformation.
  - Optimization of dynamic aperture with hundreds of sextupole families.

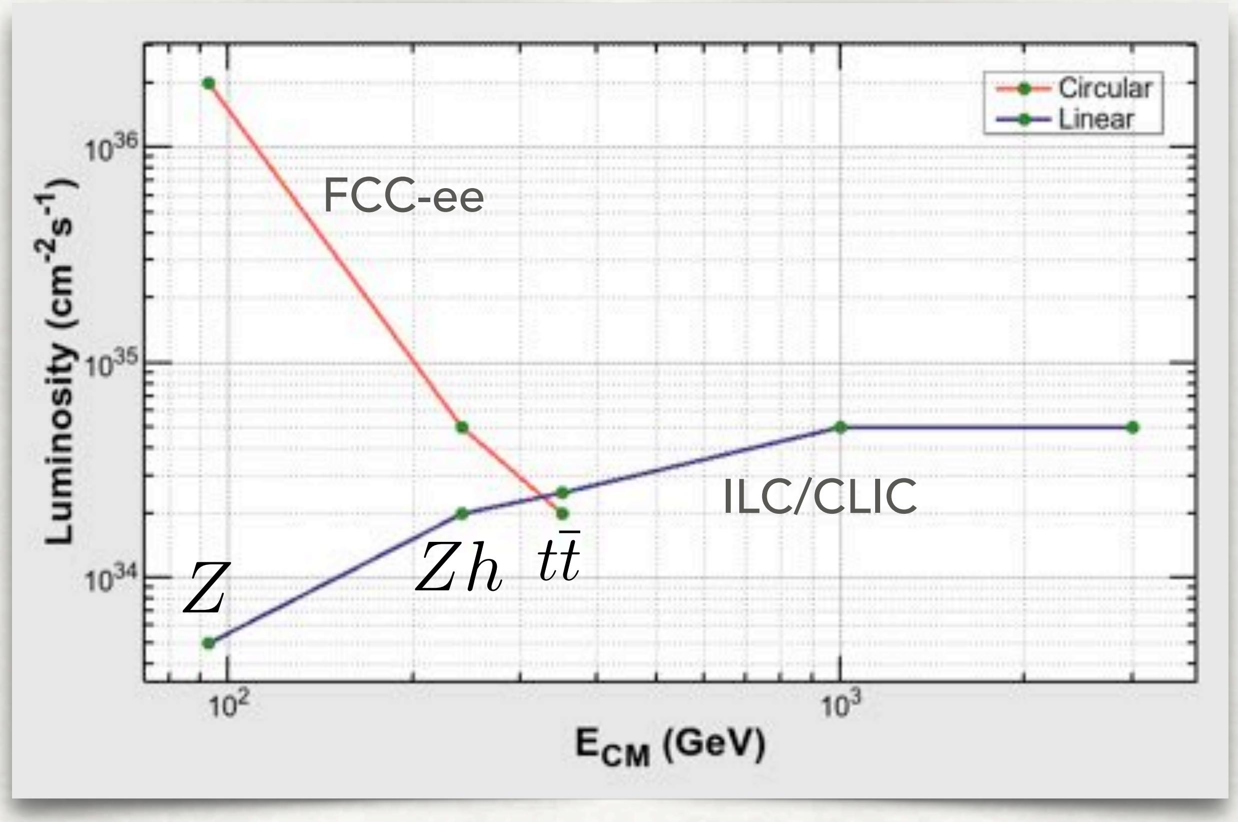
- **Major differences still remain:**
  - The luminosity at Z, CEPC/FCC-ee ≈ 1/50.
  - The level of synchrotron radiation toward the IP (CEPC is x2 higher)
  - Tapering is not possible in PDR.
  - CEPC's β^*_x is 1/5 of FCC-ee's. The strong-strong beam-beam instability may be weaker in CEPC.

POSSIBILITY OF CIRCULAR COLLIDERS (AN OLD IDEA)

21 Dec 2016

K. Oide @ KEK Accelerator Seminar

Luminosity of e+e- Colliders



- Circular collider: luminosity is limited by the synchrotron radiation power:

$$\left.\begin{array}{l} \mathcal{L} \approx \dfrac{1}{2er_e}\left(\dfrac{\gamma I \xi_y}{\beta_y^*}\right) \\[2em] P \propto \dfrac{\gamma^4}{\rho} I \end{array}\right\} \Rightarrow \mathcal{L} \propto \frac{P\rho\xi_y}{\gamma^3\beta_y^*}$$

  - At high energies beamstrahlung sets another limitation.

- Is there any way to overcome this limitation?

An old idea

Volume 61B, number 3 PHYSICS LETTERSq 29 March 1976

U. Amaldi

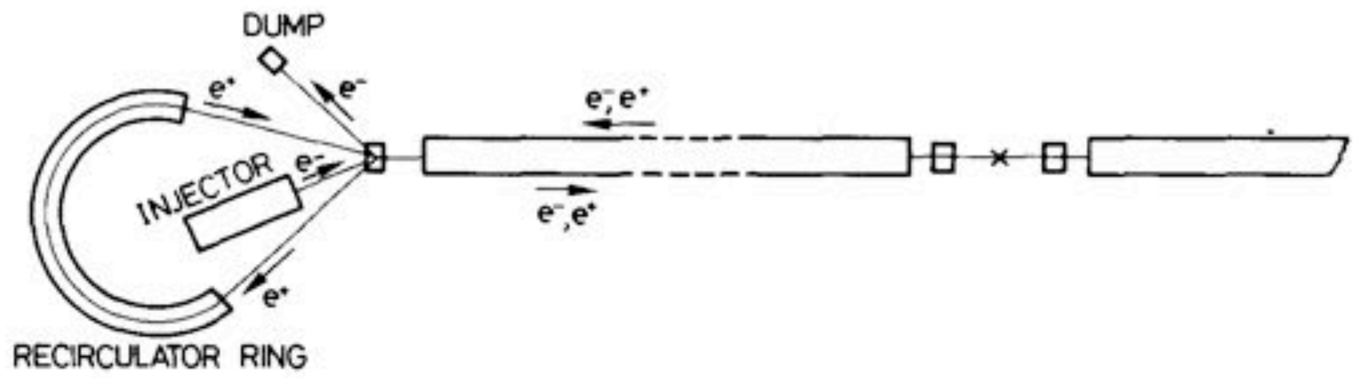
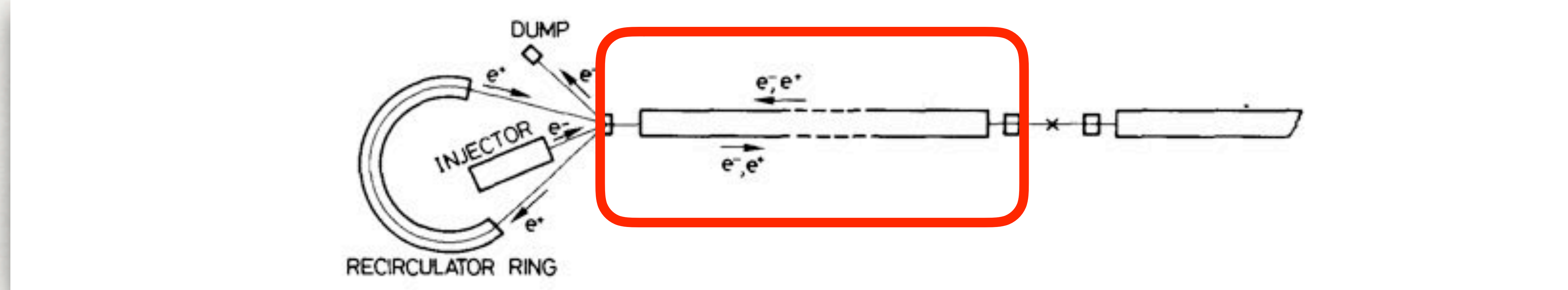


Fig. 2. In this scheme the electron bunches are dumped after a single traversal while, to save positron current, the positrons are recirculated in a low energy ring.

- Linear collider was a ring collider when it was first proposed.
  - The particles and beam energy are totally recovered.
  - The recirculated arc at a low energy works as a part of damping ring.
  - The synchrotron radiation is independent of the collision energy.
- Does this scheme work?

Power dissipation at the energy recovery linac



- The energy recovery linac must use a standing CW, otherwise the synchronization with the counter rotating beam is difficult. Then:

$$P_c = \frac{\omega_{\rm rf} U_{\rm rf}}{Q}$$

$$U_{\rm rf} \approx \frac{\epsilon_0}{2} g^2 \times \pi a^2 L_{\rm acc}$$

$L_{\rm acc}$: total length of acceleration

$g = E_{\rm cm}/L_{\rm acc}$: accelerating gradient

a : effective radius of the field region

- Examples at E_{cm} = 3 TeV:

scheme	f_{rf} (GHz)	Q	a (mm)	g (MV/m)	P_c (GW)	P_{300K} (GW)
X-band	12	10^5	3.5	100	39	39
SRF @ 2K	1.3	4×10^{10}	70	40	0.0017	0.25
P-W	6500	5000	0.3	1000	30800	30800
P-W extreme	6500	5000	0.003	1000	3.08	3.08

- Plasma Wake assumes $g = mc\omega_p$.
- This power dissipation is independent of beam current/luminosity.

Beamstrahlung

- A criteria of beamstrahlung for a circular collider has been given by V. Telnov:

$$\left.\begin{aligned} \frac{N}{\sigma_x^*\sigma_z} &< 0.1\eta\frac{\alpha}{3\gamma r_e^2} \\ \mathcal{L} &\approx \frac{1}{2er_e}\left(\frac{\gamma I\xi_y}{\beta_y^*}\right) \end{aligned}\right\} \Rightarrow \mathcal{L} \approx \frac{I}{2e}\left(\frac{0.1\alpha\eta}{6\pi}\right)^{2/3}\left(\frac{\xi_y}{\gamma r_e^5\varepsilon_y}\right)^{1/3}$$

η : momentum acceptance at the collision energy

α : fine structure constant

- The two notations of the luminosity give:

$$\beta_y^* > \left(\frac{3600\pi^2 r_e^2\gamma^4\xi_y^2\varepsilon_y}{\alpha^2\eta^2}\right)^{1/3} \quad , \text{ or}$$

$$\frac{\mathcal{L}}{I} \propto \frac{\xi_y}{\beta_y^*} < \left(\frac{\alpha^2\eta^2\xi_y}{3600\pi^2 r_e^2\gamma^4\varepsilon_y}\right)^{1/3}$$

- The momentum acceptance at collision:

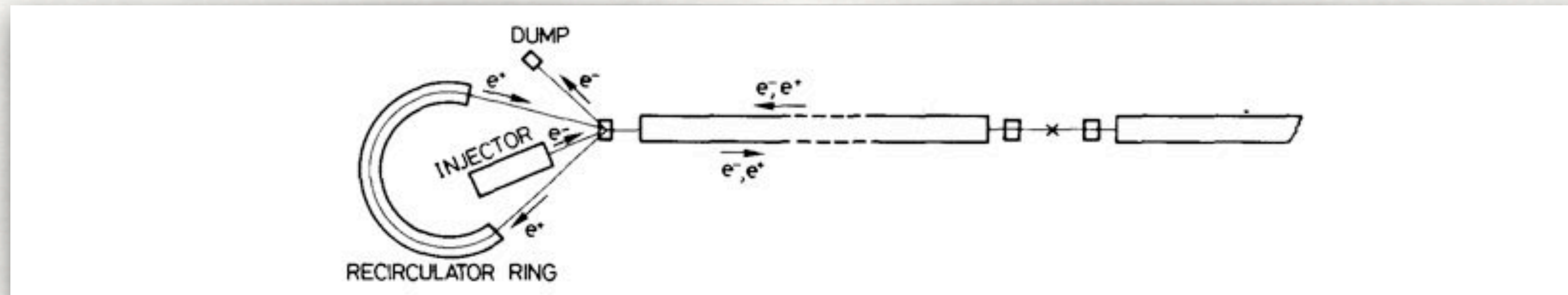
$$\eta = r_{\mathrm{bc}}\eta_0\frac{E_0}{E}$$

r_{bc} : bunch compression ratio

η_0 : energy acceptance of the arc

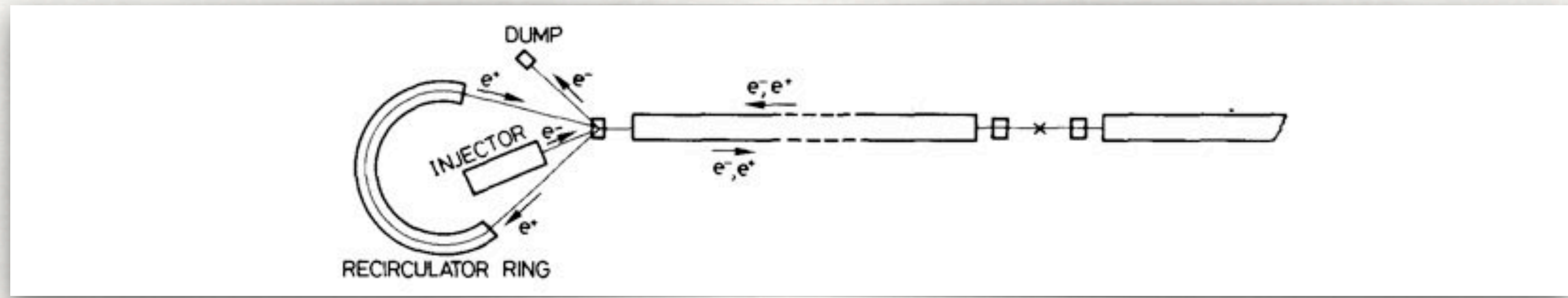
E_0 : arc energy

A possible parameter set for 10^{35} $cm^{-2}s^{-1}$ @ 3 TeV



Beam Energy (TeV)	1.5
Beam current (mA)	14
$\beta^*_{x,y}$ (mm)	460, 4.6
$\varepsilon^*_{x,y}$ (pm) @ 1.5 TeV	1, 0.01
$\sigma^*_{x,y}$ (nm)	680, 6.8
σ_z (mm)	5
Particles / bunch (10^{10})	0.065
$\xi_{x,y}$	0.1, 0.1
Bunch separation (ns)	7.4
Arc energy (GeV)	10
Energy Acceptance @ collision (%)	2
Luminosity (10^{34} $cm^{-2}s^{-1}$)	10

Issues



- The Higher order mode loss in the accelerating structures.
- Efficiency of the energy recovery
- TMCI, microwave, CBI, e-Cloud, etc.
- Dynamic aperture through the long linac
- Bootstrap / stability of the system