Lectures on the Future Circular Collider – Part 1+2

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Bonn, 1-2 October 2025

Lecture 1 – FCC-ee design concepts

1.0 colliders – revisited

1.1 luminosity – revisited

1.2 synchrotron radiation

1.3 beam-beam effects

1.4 luminosity revised

1.5 FCC concept(s)

1.0 colliders

why high(er) energy?

- quantum mechanics: de Broglie wavelength $\lambda = h/p$
  → examining matter at smaller distance requires higher momentum particles

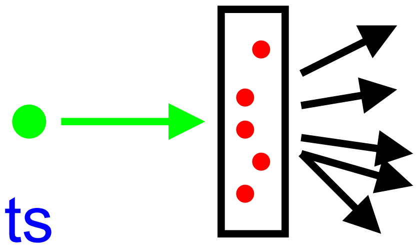
- many of the particles of interest to particle physics are heavy
  → high-energy collisions are needed to create these particles

colliding beams

centre-of-mass energy:

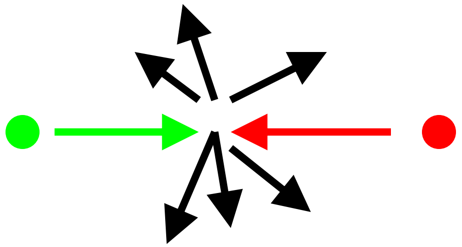
$$E_{c.m.} = \sqrt{2E_{beam}M_{target}c^2}$$

beam hits
a “fixed target”



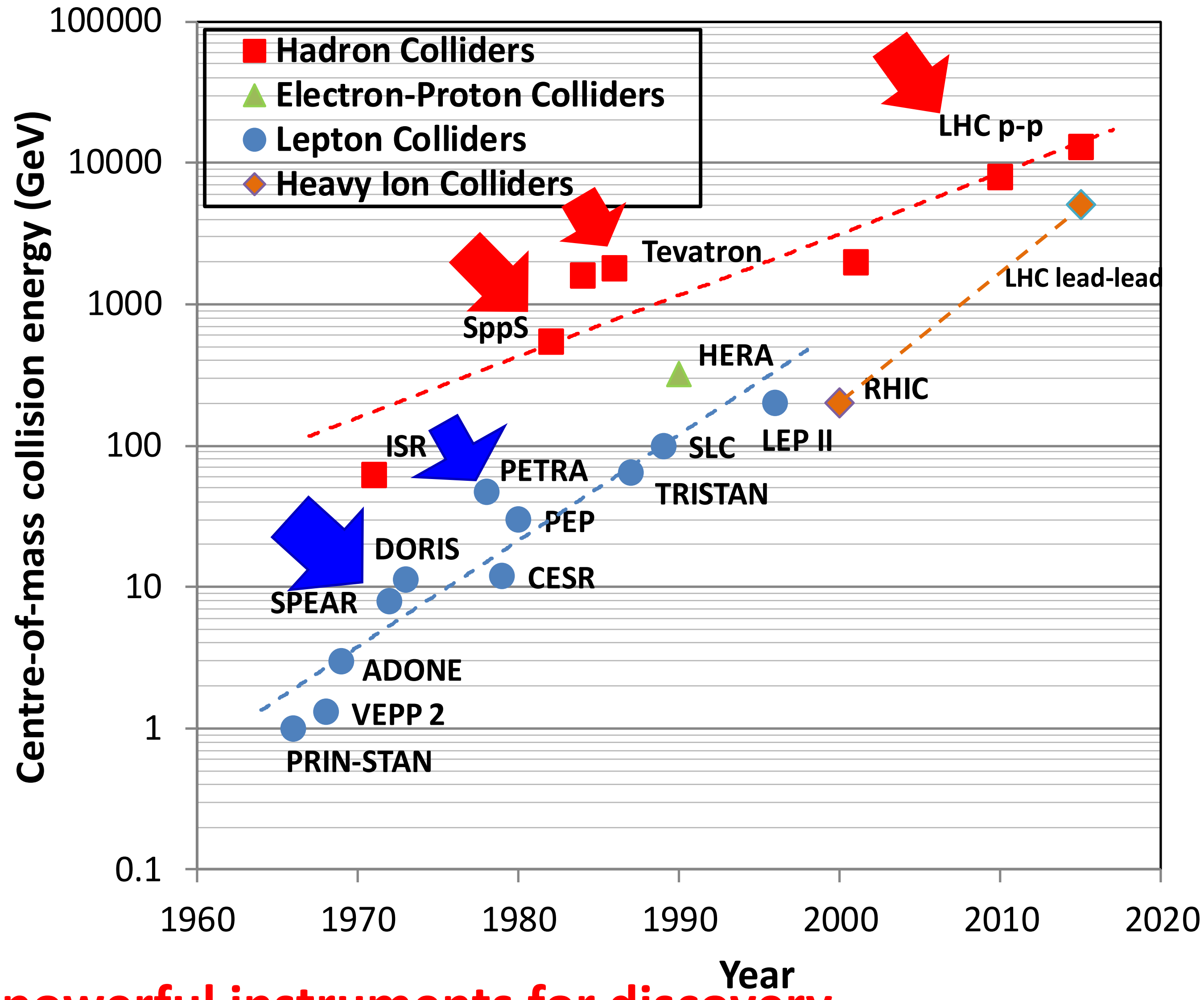
$$E_{c.m.} = 2E_{beam}$$

two beams collide



colliding two beams against each other can provide
much higher centre-of-mass energies than fixed target!

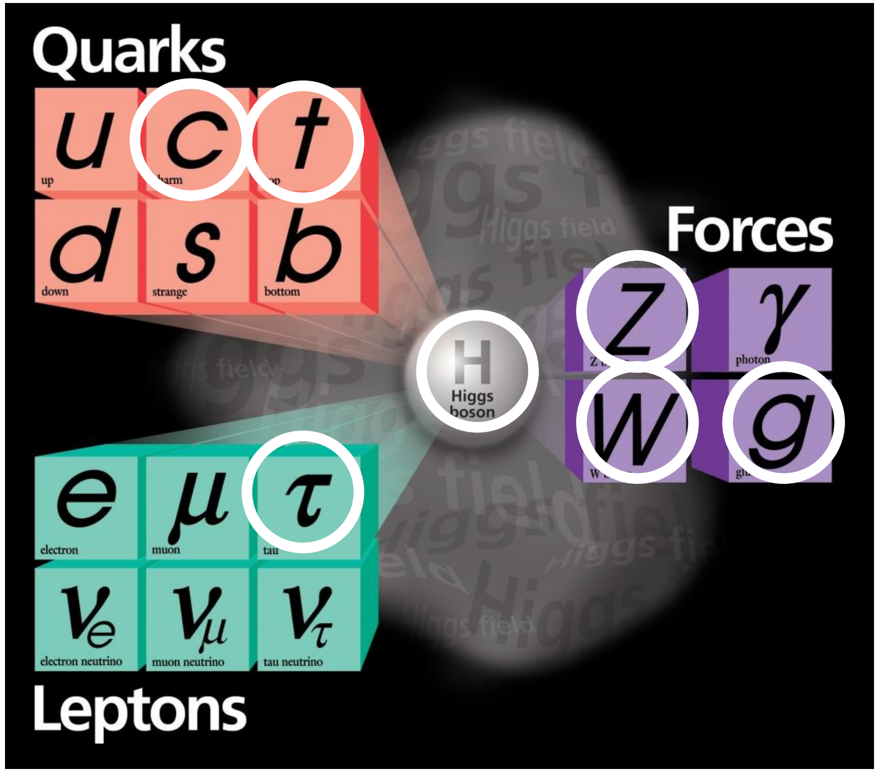
colliders and discoveries



powerful instruments for discovery and precision measurement

A. Ballarino

Standard Model Particles and forces



“An e^+-e^- storage ring in the range of a few hundred GeV in the centre of mass can be built with present technology...” “...the most useful project on the horizon.”

B. Richter, 1976

NIM 136 (1976) 47-60

LEP/LEP2: highest energy so far

circumference 27 km
in operation from 1989 to 2000
maximum c.m. energy 209 GeV
maximum synchrotron radiation power 23 MW

FCC-ee physics requirements

- ***beam energy range from 35 GeV to ≈200 GeV***
- ***highest possible luminosities*** *at all working points*
- physics programs / energies:

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

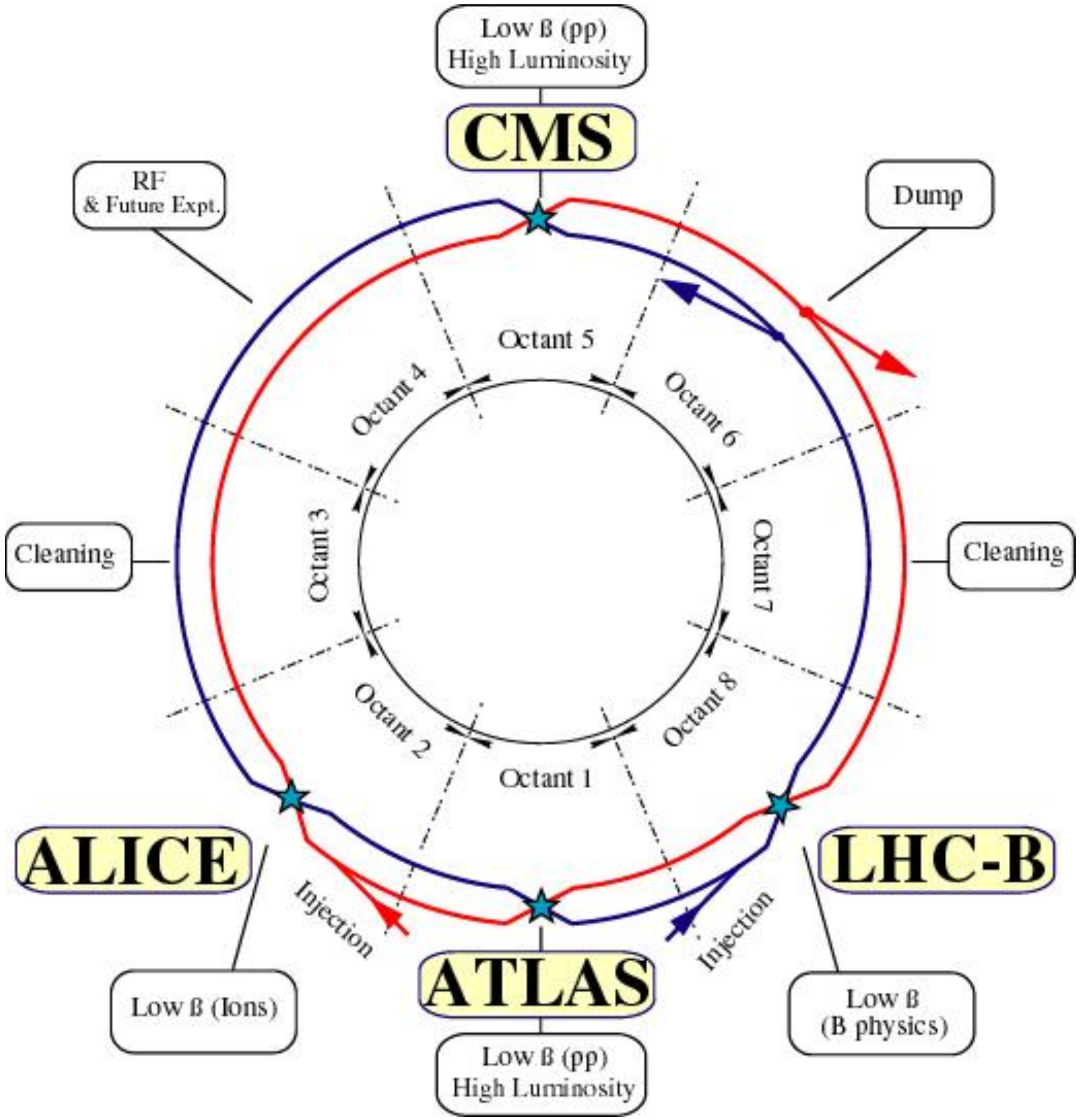
  W (80 GeV) W pair production threshold, high precision M_W

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

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

  more (α_{QED} etc.)
- possibly *H* (63 GeV) direct *s*-channel production w. **monochromatization**
- **some polarization up to ≥80 GeV** for beam energy calibration

present flagship: Large Hadron Collider (LHC)



world's highest energy p-p collider at CERN/Geneva

installed in the LEP tunnel ! – circumference 27 km

running extremely well

4 July, 13 years ago

LHC has already produced
> 30 million Higgs bosons

C. Grojean, SFP2025 Troyes

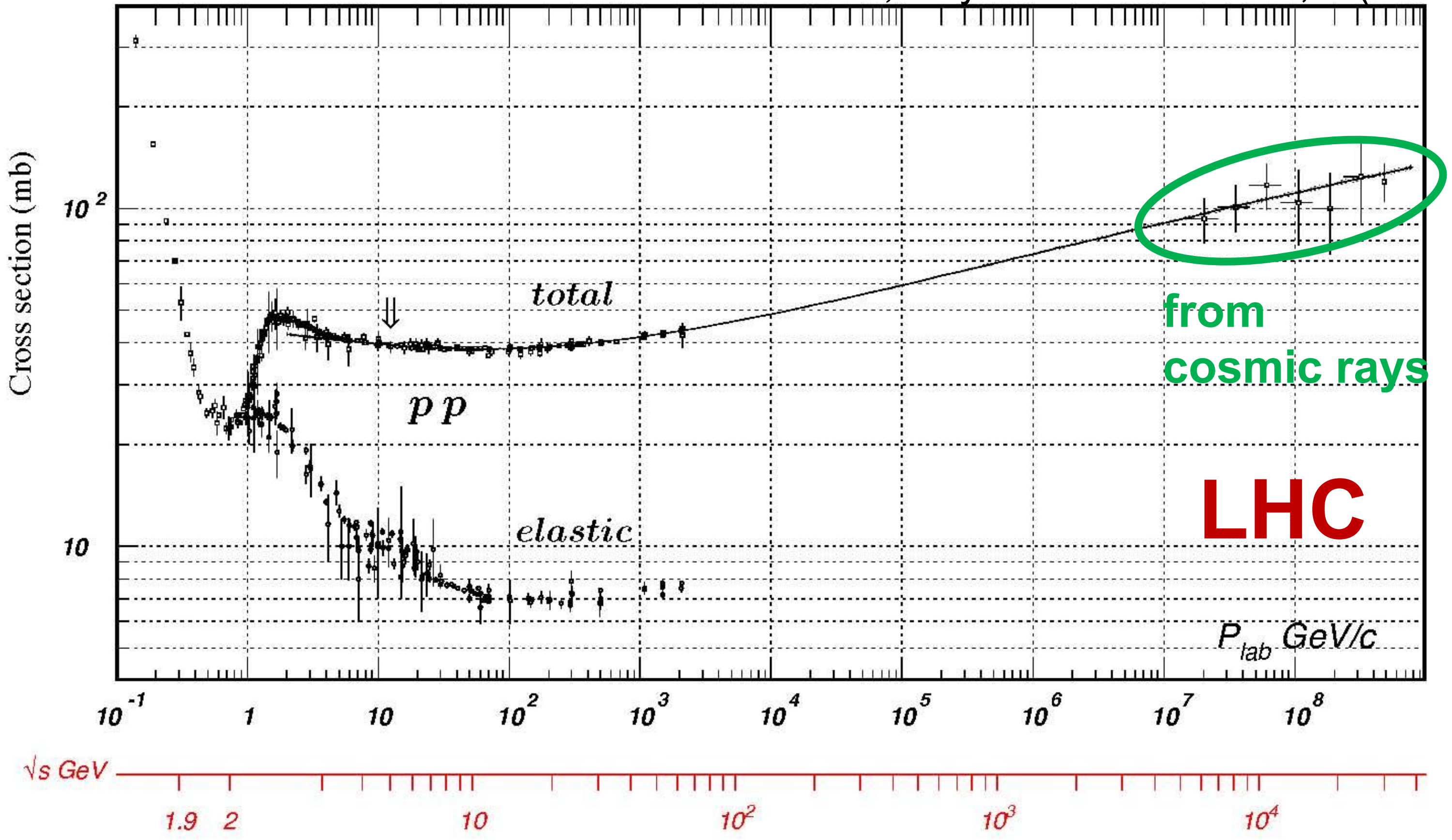
1.1 luminosity

$$R = \sigma L$$

reaction rate · **cross section** · **luminosity**

luminosity

C. Amsler *et al.*, Physics Letters **B667**, 1 (2008)



σ_{tot}~ 100 mbarn ~ 10^{-25} cm^2

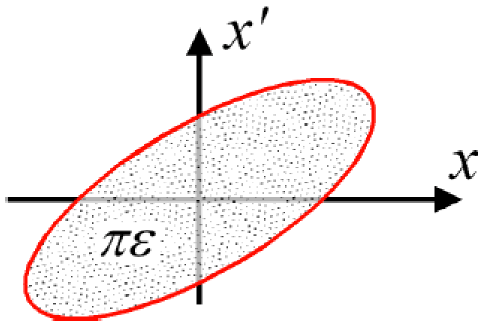
determines proton consumption (beam lifetime)

$\sigma_{Higgs,p\text{-}p}$ ~ 30 pb → with 300 fb^{-1} LHC produces ~ 10 million Higgs

luminosity for collision of flat beams

$$L = \frac{n_b N_b^2 f_{\mathrm{rev}}}{4\pi\sigma_x^*\sigma_y^*}F = \frac{n_b N_b^2 f_{\mathrm{rev}}}{4\pi\varepsilon_x\sqrt{\beta_x^*\beta_y^*\kappa}}F$$

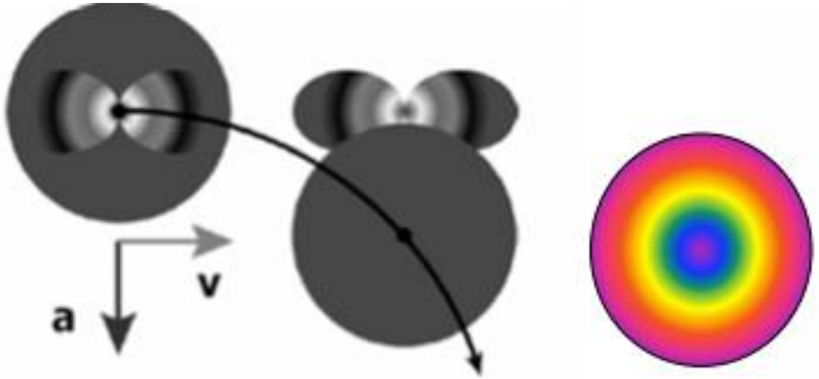
N_b	**number of particles per bunch**
n_b	**number of bunches per beam**
f_{rev}	revolution frequency
$\sigma_{x,y}^*$	**hor./vert. beam size at interaction point**
F	reduction factor due to crossing angle and hourglass effect
ε_x	hor. emittance (from optics)
κ	emittance coupling $\kappa = \varepsilon_y/\varepsilon_x$
β*	**hor./vert, beta function at IP**



$$\sigma^* = \sqrt{\beta^*\varepsilon}$$

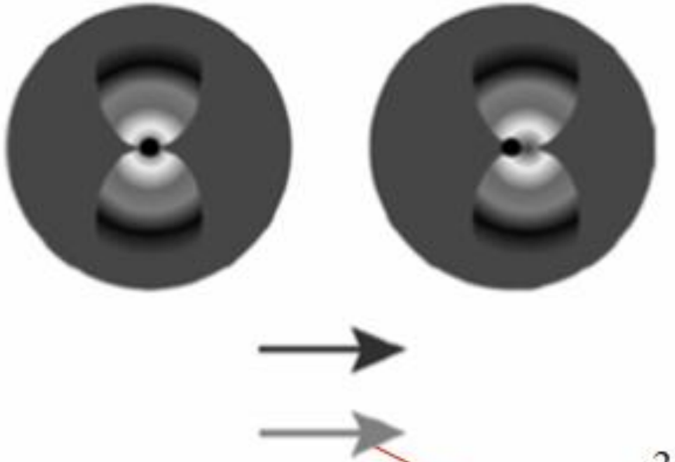
1.2 Synchrotron Radiation (SR)

transverse and longitudinal acceleration



Radiation field quickly separates itself from the Coulomb field

$$P_\perp = \frac{q^2}{6\pi\varepsilon_0 m_0^2 c^3}\gamma^2\left(\frac{d\mathbf{p}_\perp}{dt}\right)^2$$



Radiation field cannot separate itself from the Coulomb field

$$P_\parallel = \frac{q^2}{6\pi\varepsilon_0 m_0^2 c^3}\left(\frac{d\mathbf{p}_\parallel}{dt}\right)^2$$

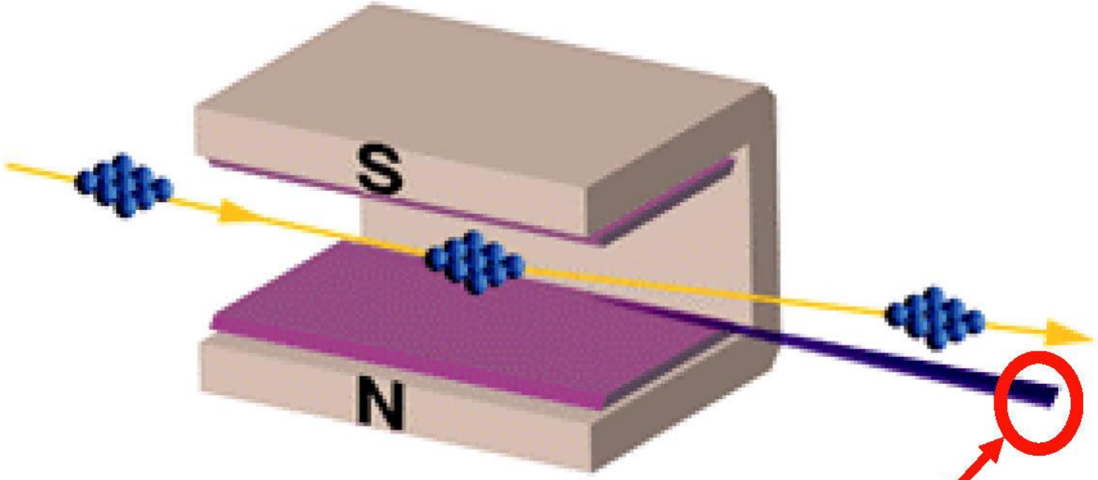
negligible!

$$P_\perp = \frac{c}{6\pi\varepsilon_0} q^2 \frac{(\beta\gamma)^4}{\rho^2} \qquad \rho = curvature\ \ radius$$

W. Barletta, USPAS

excellent news for high-gradient acceleration !

curved orbit of e^- in magnetic field



Accelerated charge → Electromagnetic radiation

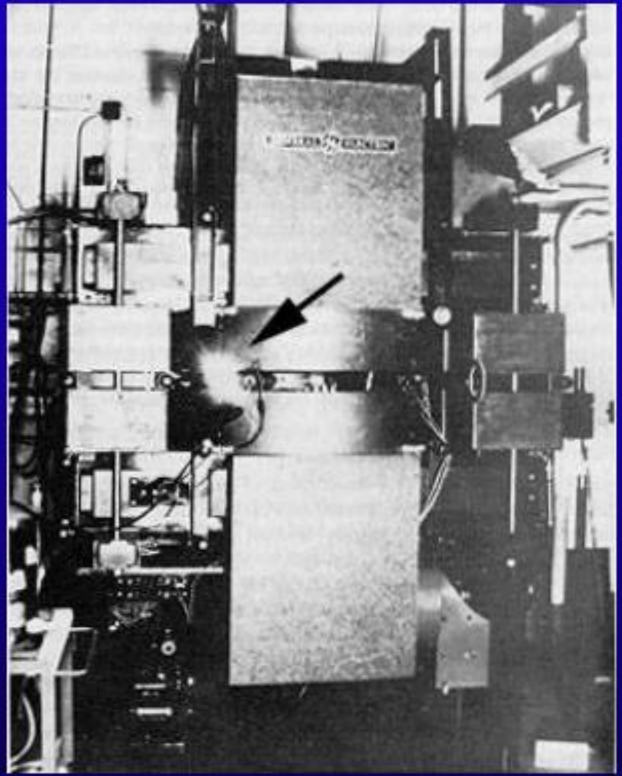
L. Rivkin

L. Rivkin

Crab Nebula
6000 light years away

First light observed
1054 AD

GE Synchrotron
New York State



First light observed
1947

classical theory of electromagnetic radiation

Liénard-Wiechert potentials

$$\varphi(t) = \frac{1}{4\pi\varepsilon_0}\frac{q}{\left[r\left(1-\vec{n}\cdot\vec{\beta}\right)\right]_{ret}}$$

$$\vec{A}(t) = \frac{q}{4\pi\varepsilon_0 c^2}\left[\frac{\vec{v}}{r\left(1-\vec{n}\cdot\vec{\beta}\right)}\right]_{ret}$$

retarded time defined by implicit equation

$$t_{ret} = t - \frac{1}{v}\left|\vec{r} - \vec{r_s}\left(t_{ret}\right)\right|$$

Lorentz gauge

$$\vec{\nabla}\cdot\vec{A} + \frac{1}{c^2}\frac{\partial\varphi}{\partial t} = 0$$

$\longrightarrow$

$$\vec{B} = \vec{\nabla}\times\vec{A}$$

$$\vec{E} = -\vec{\nabla}\varphi - \frac{\partial\vec{A}}{\partial t}$$

energy loss for a particle in a ring

Rate of energy loss (GeV/s) for single particle:

$$P_\gamma = \frac{e^2 c^3}{2\pi} C_\gamma E^2 B^2 = \frac{c C_\gamma}{2\pi} \frac{E^4}{\rho^2}$$

with $C_\gamma = \frac{4\pi}{3} \frac{r_e}{(mc^2)^3} \approx 8.85 \times 10^{-5}\ \mathrm{m\ GeV^{-3}}$

$\rho = \frac{p}{eB}$ bending radius ;

E particle energy ; m particle mass ;

r_e classical particle radius (2.8×10^{-15} m for electrons)

Energy lost in a ring over one turn (GeV):

$$U_0 = \frac{C_\gamma E_0^4}{2\pi} \oint G^2(s)\, ds$$

with $G \equiv 1/\rho$

With a constant guide field $G_0 \equiv 1/\rho_0$ along the curved path of the trajectory and zero elsewhere :

Energy radiated per turn $U_0 = \frac{C_\gamma E_0^4}{\rho_0}$

Average power $\langle P_\gamma \rangle = \frac{U_0}{T_0} = \frac{c C_\gamma}{L} \frac{E_0^4}{\rho_0}$

$T_0 = L/c$ with L circumference

An electron that is not on the ideal orbit radiates at a different rate. But if magnetic field varies linearly with position, **radiated power averaged over a betatron oscillation cycle is the same as that for an electron on the design orbit.** The same is not true for an electron with an energy different from E_0 (next slide).

For ultra-relativistic electrons the radiation is emitted primarily along the direction of motion. Most of the radiation is emitted within the angle $1/\gamma$. The accompanying momentum change is nearly exactly opposite to the direction of motion. **Then only radiation effect is to decrease e$^-$ energy w/o changing its direction of motion**.

Sands, 1970

is this an issue for high energy accelerators?

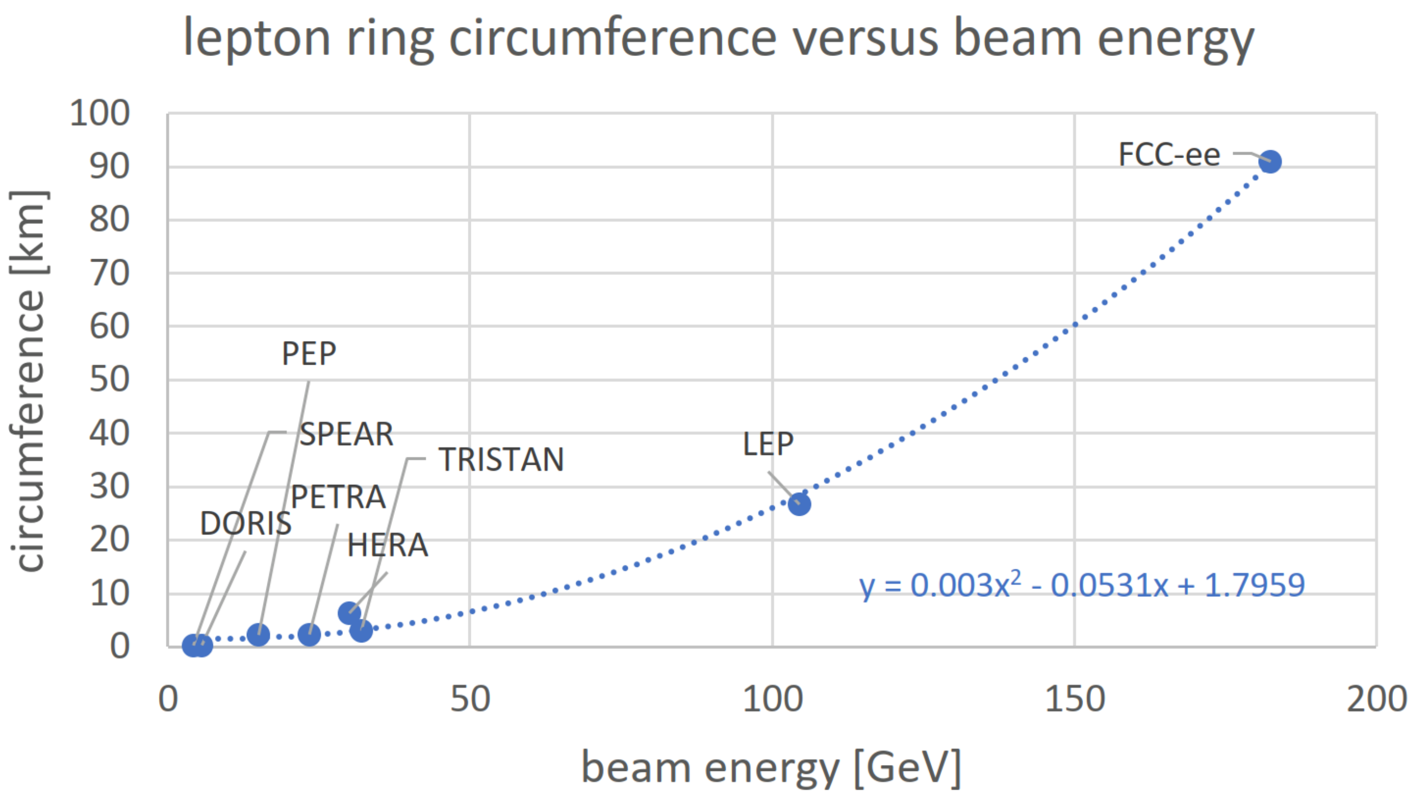
energy loss per particle per turn $U_0 = \frac{C_\gamma E_0^4}{\rho_0}$ → **SR power** $P_{SR} = \frac{I_{beam}}{e} U_0$

$$C_\gamma = \frac{4\pi}{3} \frac{r_e}{(mc^2)^3} \approx 8.85 \times 10^{-5} \text{ m GeV}^{-3}$$

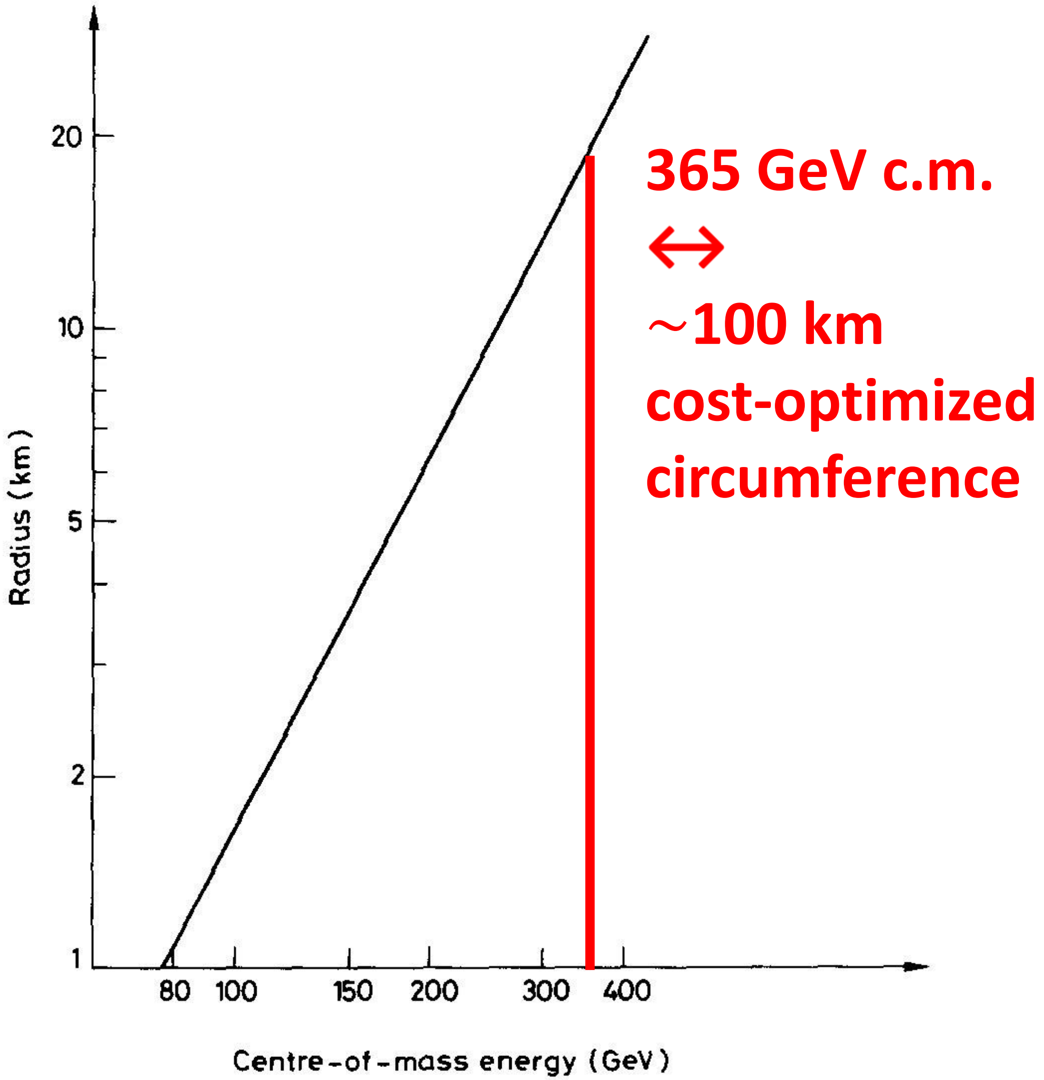
e±: $P_{SR} =$ 23 MW for LEP (former e^+e^- collider in the 27 km LHC tunnel),
100 MW for FCC-ee (new ~90 km ring, imposed as design constraint),

protons: $P_{SR} =$ 0.01 MW for LHC,
up to 5 MW for FCC-hh (new ~90 km ring,~10x collision energy of the LHC)
– this may require >100 MW cryoplant power (FCC-hh CDR, 2018)

SR → size of circular e^+e^- colliders



Data points from S. Myers, "*FCC - Building on the Shoulders of Giants*", Eur. Phys. J. Plus (2021) **136**: 1076



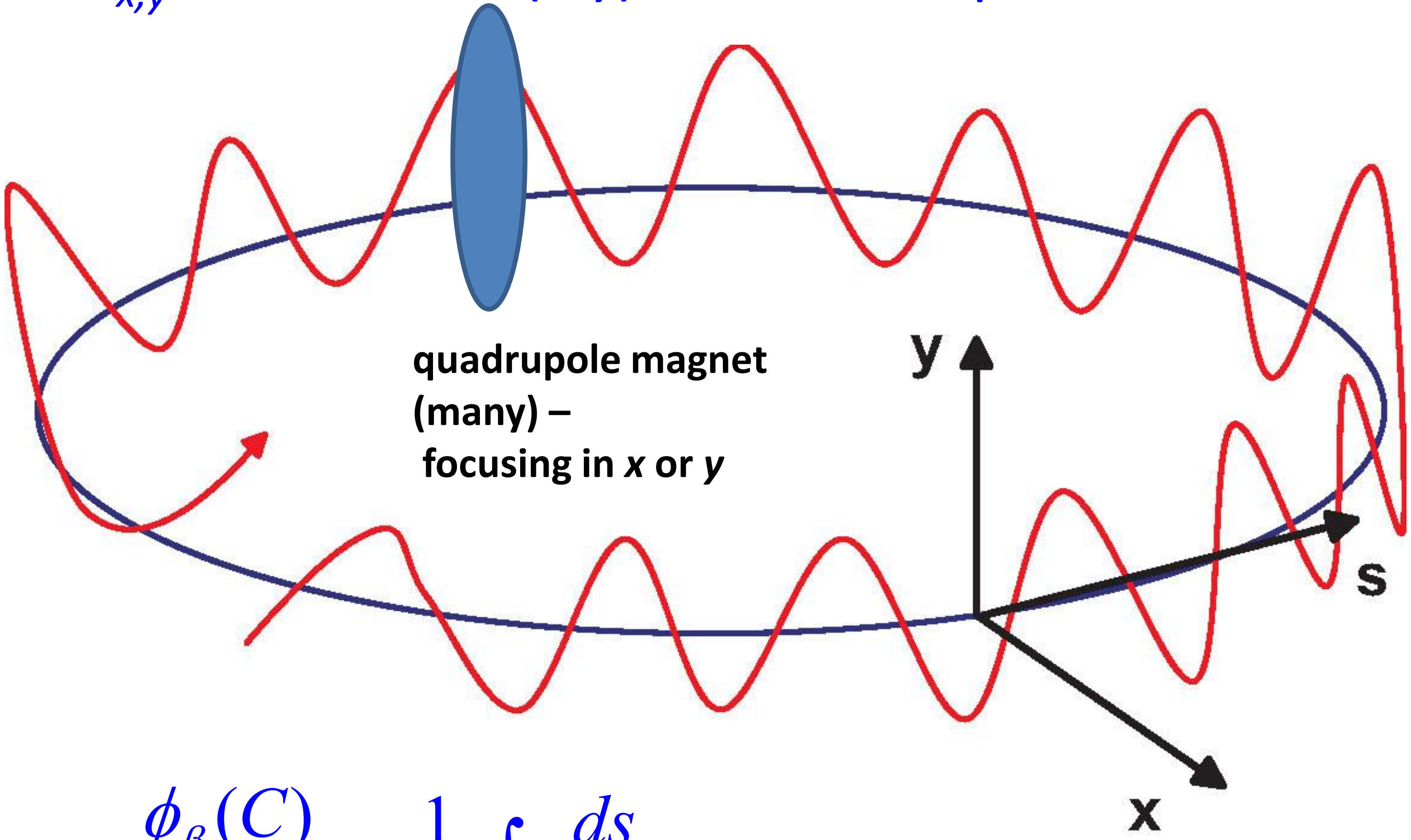
B. Richter, "*Very High Energy Electron-Positron Colliding Beams for the Study of Weak Interactions*", NIM 136 (1976) 47-60

Serendipitously, 90-100 km is exactly the size required for a 100 TeV hadron collider and optimum tunnel size in the Lake Geneva basin !

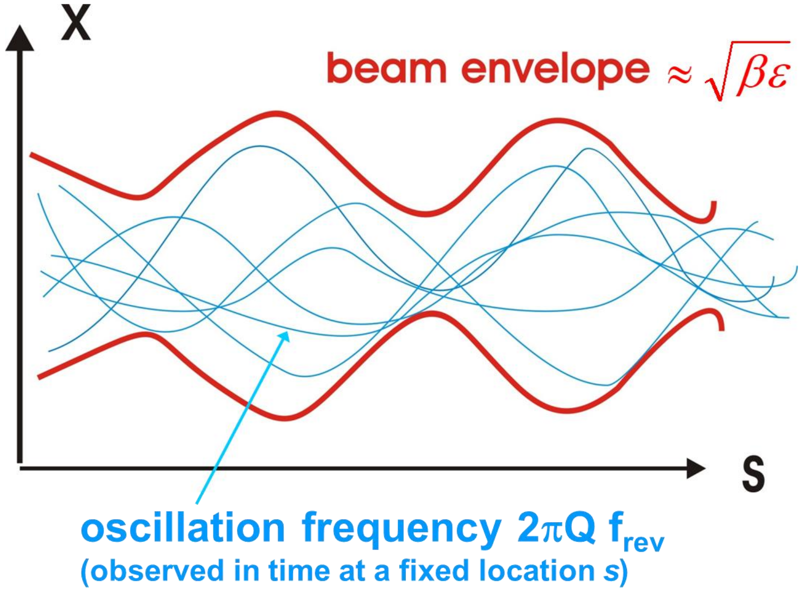
betatron motion

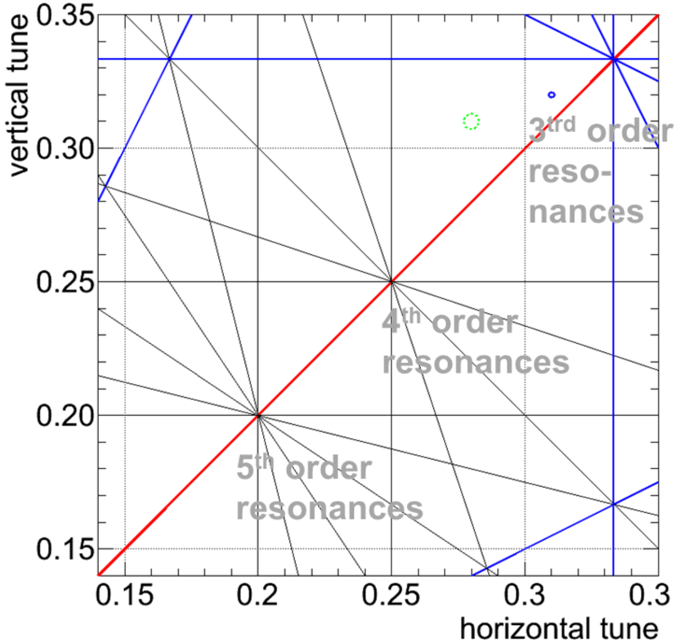
schematic of betatron oscillation around storage ring

tune $Q_{x,y}$= number of (x,y) oscillations per turn



$$Q = \frac{\phi_\beta(C)}{2\pi} = \frac{1}{2\pi}\oint_C \frac{ds}{\beta(s)}$$

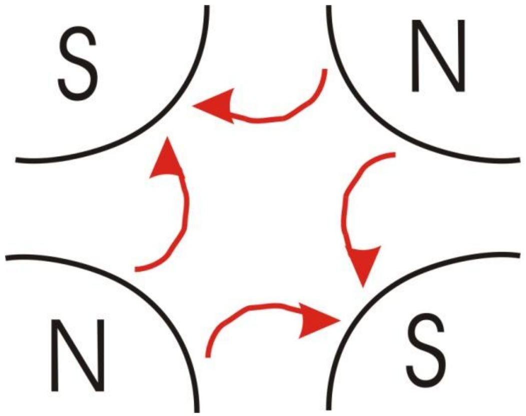




quadrupole strength

$$\frac{d^2x}{ds^2} = -k(s)x$$

$\Delta x' = -Kx$ "kick approximation"



relation between beta function, quadrupole strength, and betatron tune

$\Delta K \rightarrow \Delta Q$ - *perhaps the oldest technique, documented in 1975*

ISR-TH-AH-BZ-amb

$$k = \frac{B_T}{(B\rho)a}$$

B_T: pole-tip field
a: pole-tip radius

$$(B\rho) = p/e = 3.356\ \text{Tm}\ p[\text{GeV}/c]$$

change quadrupole strength by ΔK ;
and detect tune shift

$$K = kl_Q$$

quadrupole length

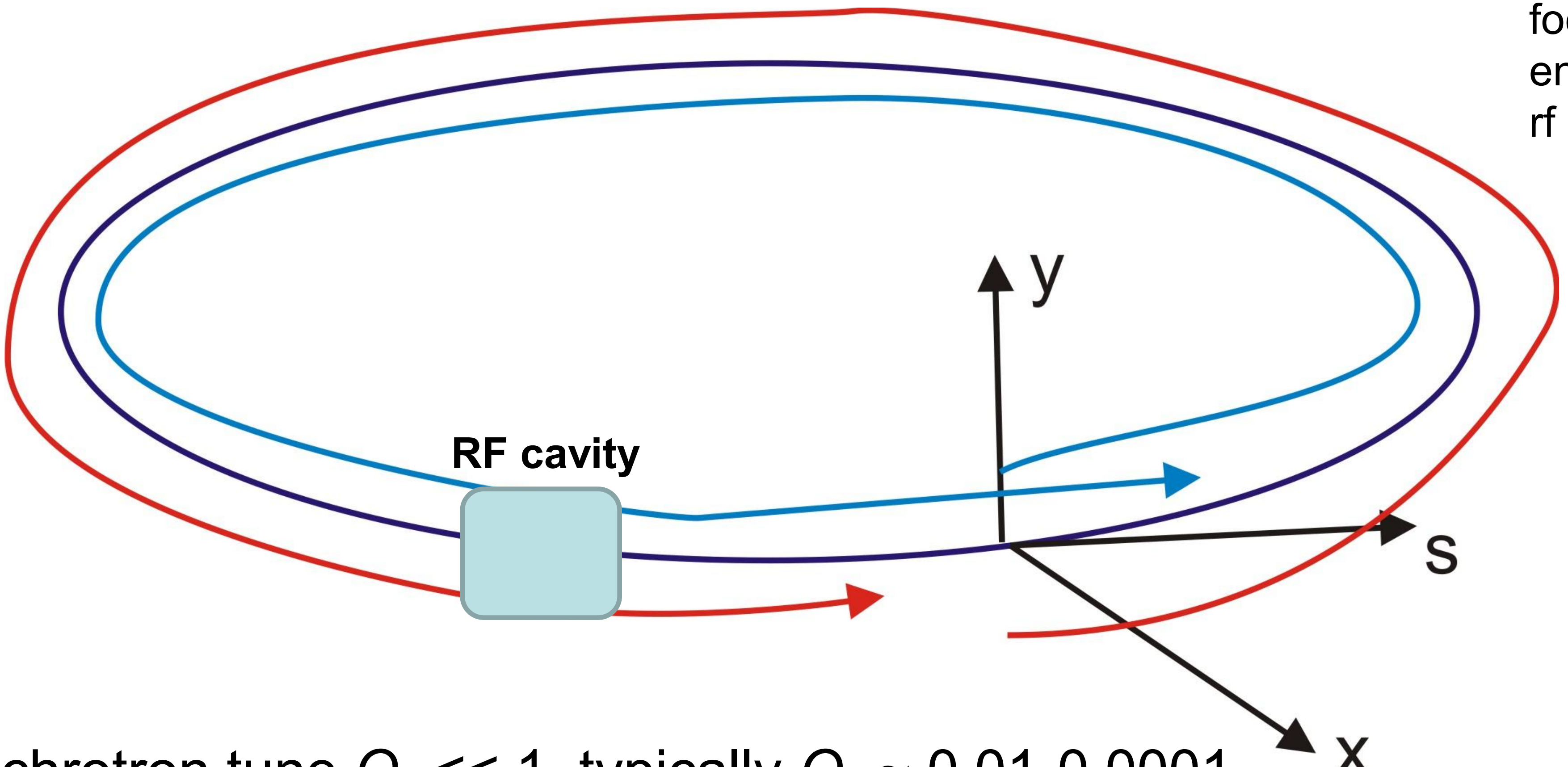
$$\Delta Q \approx \frac{\beta_Q \Delta K}{4\pi}$$

synchrotron motion

schematic of "longitudinal oscillation" around storage ring

tune Q_s = number of synchrotron oscillations per turn

focusing elements:
energy-dependent path length
rf cavities



synchrotron tune $Q_s \ll 1$, typically $Q_s \sim 0.01\text{-}0.0001$
betatron tune $Q_{x,y} > 1$, typically $Q_{x,y} \sim 2 - 70$

radiation damping of synchrotron oscillations

$$\frac{d^2\epsilon}{dt^2} + 2\alpha_\epsilon \frac{d\epsilon}{dt} + \Omega^2\epsilon = 0$$

synchrotron motion with damping

ϵ small energy deviation

synchrotron radiation:

$$U_{\text{rad}} = U_0 + \epsilon D \quad \text{with} \quad D = \left(\frac{dU_{rad}}{dE}\right)_0$$

$$\alpha_\epsilon = \frac{D}{2T_0}$$

general damping decrement

$$\Omega^2 = \frac{\alpha_C e \dot{V}_{\text{rf},0}}{T_0 E_0}$$

angular synchrotron frequency

When energy of an electron deviates from E_0, the energy radiated in one revolution changes because

(1) SR on nominal orbit
(2) traveling through different magnetic field
(3) different path length

U_{rad} from integrating P_γ around one complete off-energy orbit:

$$U_{\text{rad}} = \frac{1}{c}\oint\left(1 + \frac{D_x}{\rho}\frac{\epsilon}{E_0}\right)P_\gamma ds$$

$$\frac{dU_{rad}}{dE} = \frac{1}{c}\oint\left\{2\frac{P_\gamma}{E} + 2\frac{P_\gamma}{B}\frac{D_x}{E_0}\frac{dB}{dx} + \frac{P_\gamma}{E}\frac{D_x}{\rho}\right\}ds$$

(1) (2) (3)

$$\alpha_\epsilon = \frac{U_0}{2T_0E_0}(2 + \mathcal{D})$$

with $\mathcal{D} = \dfrac{\oint D_x G(G^2 + 2K_1)ds}{\oint G^2 ds}$

$$J_\epsilon = 2 + \mathcal{D}$$

partition number

typically $\mathcal{D} \ll 1$ and

$$\alpha_\epsilon \approx \frac{U_0}{T_0E_0} = \frac{\langle P_\gamma\rangle}{E_0}$$

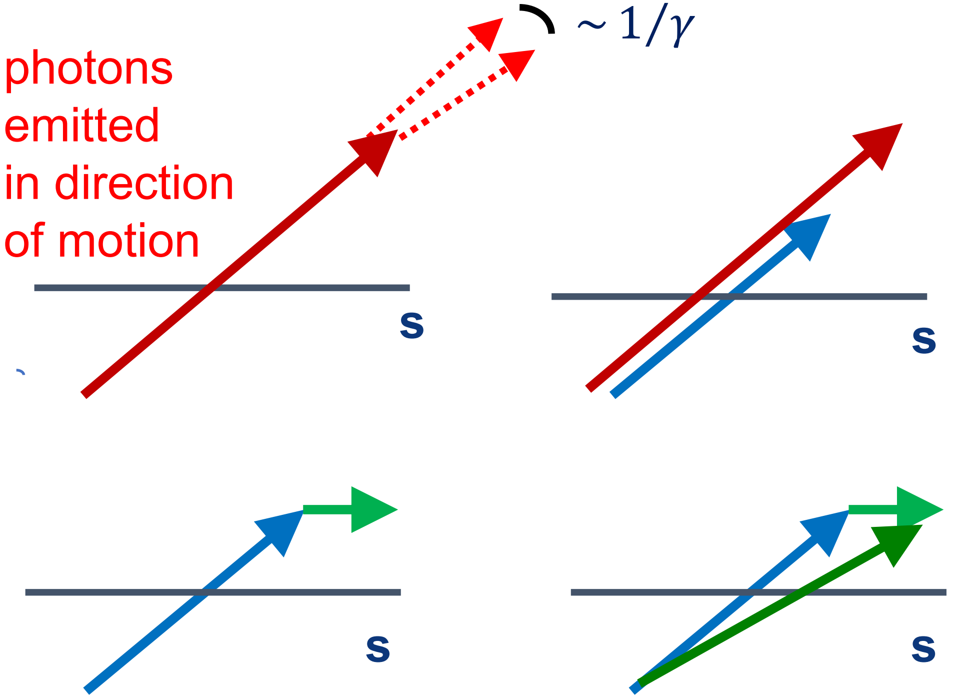
damping time for energy oscillations = the time it takes an electron to radiate away its total energy !

Sands, 1970

radiation damping of betatron oscillations (sketch)

synchrotron radiation in magnetic field

photons emitted in direction of motion



both transverse and longitudinal momentum of emitting electron reduced

longitudinal acceleration in radiofrequency cavities

only longitudinal momentum is restored by RF cavities

→ net damping

effect of horizontal dispersion

$$\alpha_y = \frac{U_0}{2T_0E_0}$$

$J_y = 1$

$$\alpha_x = \frac{U_0}{2T_0E_0}(1-\mathcal{D})$$

$J_x = 1 - \mathcal{D}$

Note: Robinson sum rule

$$\alpha_x + \alpha_y + \alpha_\epsilon = 4\frac{U_0}{2T_0E_0}$$

$$\alpha_x + \alpha_y + \alpha_\epsilon = 4$$

Robinson, 1956-58

theorem for arbitrary dissipative force:

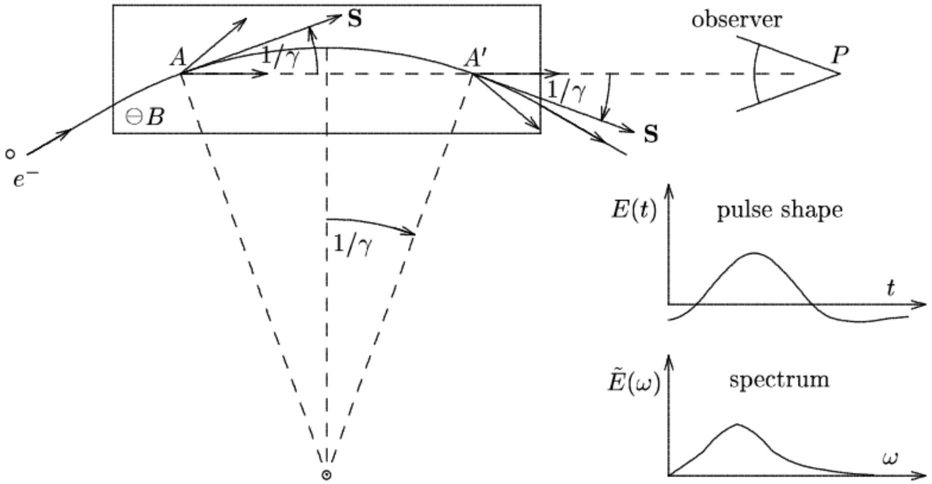
$$\alpha_x + \alpha_y + \alpha_\epsilon = \frac{1}{2}\frac{W}{pc}\left[2 + \frac{\partial \ln W}{\partial \ln p}\right]$$

W: rate of energy loss
p: particle momentum

Pestrikov

SR spectrum

typical frequency of the spectrum emitted in long magnets



arc dipole magnets in electron storage rings

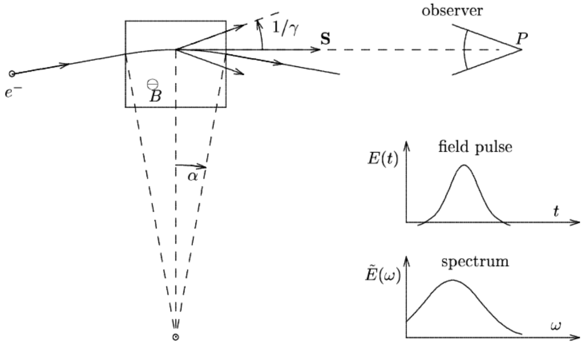
length of the light pulse seen by an observer

$$\Delta t = t_e - t_\gamma = \frac{2\rho}{\beta\gamma c} - \frac{2\rho\sin(1/\gamma)}{c} \approx \frac{4}{3}\frac{\rho}{c\gamma^3}$$

typical frequency

$$\omega_{typ} \sim \frac{2\pi}{\Delta t} \sim \frac{3\pi}{2}\frac{c\gamma^3}{\rho}$$

typical frequency of the spectrum emitted in a short magnet



Hofmann, CAS 1996

length of the light pulse seen by an observer

$$\Delta t_{sm} = \frac{L}{\beta c} - \frac{L}{c} \approx \frac{L}{2c\gamma^2}$$

typical frequency

$$\omega_{sm} \sim \frac{2\pi}{\Delta t_{sm}} \sim \frac{4\pi c\gamma^2}{L}$$

this could be important for future hadron colliders

Zimmermann, IPAC2022

SR spectrum & photon emission

$$P_\gamma = \int_0^\infty \wp(\omega) d\omega$$

power spectrum

$$\wp(\omega) = \frac{P_\gamma}{\omega_c} S\left(\frac{\omega}{\omega_c}\right)$$

$$\omega_c = \frac{3}{2}\frac{c\gamma^3}{\rho}$$

critical frequency
(half of the power each is emitted at lower or higher frequencies)

$$S(\xi) = \frac{9\sqrt{3}}{8\pi}\xi \int_\xi^\infty K_{5/3}(\bar{\xi}) d\bar{\xi}$$

$$\int_0^\infty S(\xi) d\xi = 1$$

first obtained by Schwinger

radiation is emitted in the form of quanta (photons) of energy

$$u = \hbar\omega$$

$$u\, n(u) du = \wp(u/\hbar) d\, u/\hbar$$

$$n(u) = \frac{P_\gamma}{u_c^2} F\left(\frac{u}{u_c}\right)$$

quantum distribution function

$$u_c = \hbar\omega_c = \frac{3\hbar c\gamma^3}{2\rho}$$

critical photon energy

$$\langle u \rangle = \frac{8}{15\sqrt{3}} u_c$$

$$\langle u^2 \rangle = \frac{11}{27} u_c^2$$

photon emission rate

$$\mathcal{N} = \frac{15\sqrt{3}}{8}\frac{P_\gamma}{u_c}$$

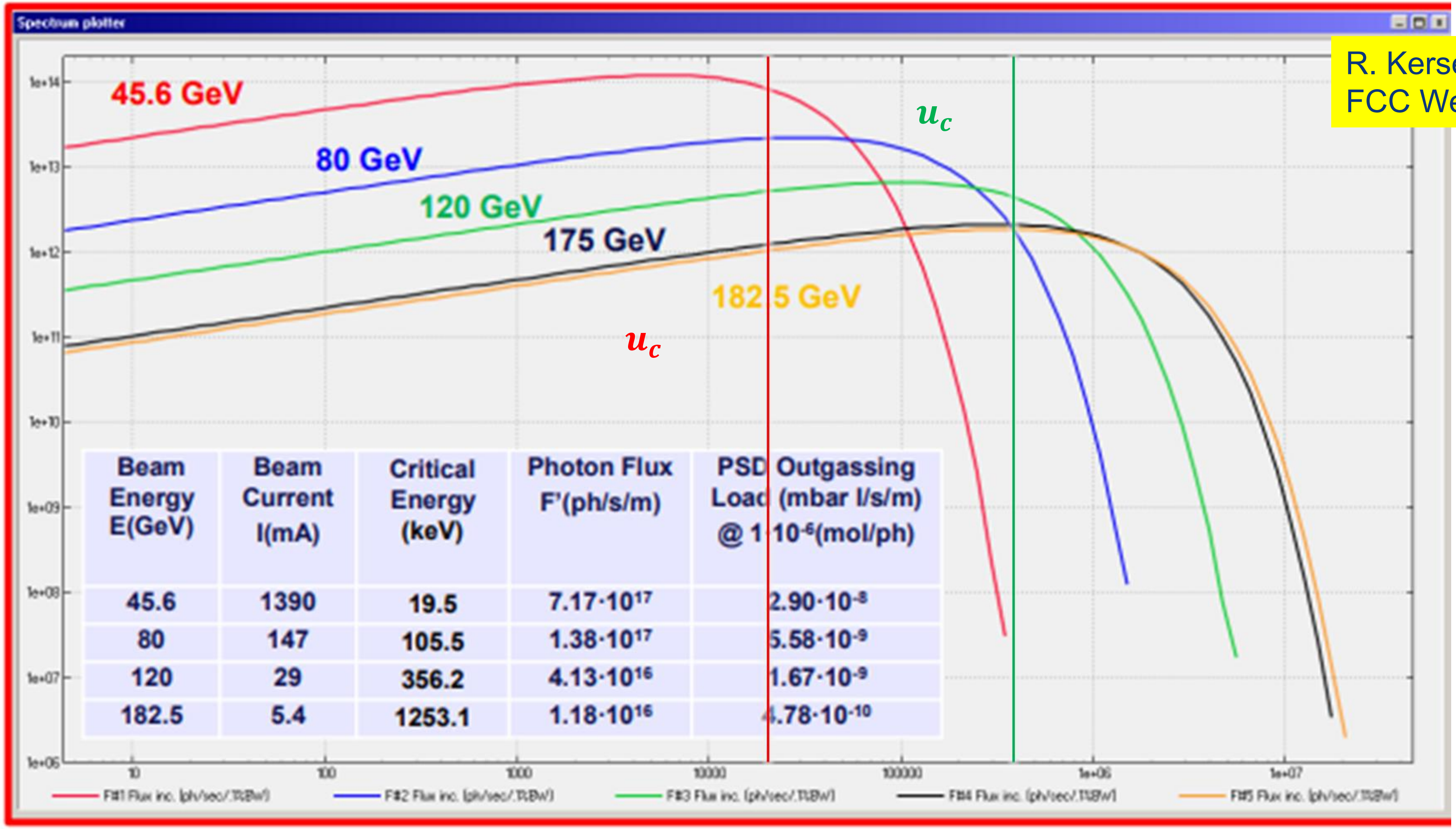
mean number of quanta per radian deflection:

$5/(2\sqrt{3})\alpha\gamma$ with $\alpha \approx 1/137$ fine-structure constant

Sands, 1970

example SR spectra for FCC-ee

R. Kersevan,
FCC Week 2021



Beam Energy E(GeV)	Beam Current I(mA)	Critical Energy (keV)	Photon Flux F'(ph/s/m)	PSD Outgassing Load (mbar l/s/m) @ 1·10⁻⁶(mol/ph)
45.6	1390	19.5	$7.17 \cdot 10^{17}$	$2.90 \cdot 10^{-8}$
80	147	105.5	$1.38 \cdot 10^{17}$	$5.58 \cdot 10^{-9}$
120	29	356.2	$4.13 \cdot 10^{16}$	$1.67 \cdot 10^{-9}$
182.5	5.4	1253.1	$1.18 \cdot 10^{16}$	$4.78 \cdot 10^{-10}$

Units: **Vertical: photons/s/(0.1% bandwidth)/m; Range [10^6 - $2 \cdot 10^{14}$]**
Horizontal eV; Range [4 - $5 \cdot 10^6$]

SR in collision: beamstrahlung

synchrotron radiation in the strong field of the opposing beam ("**beamstrahlung**")

collision of Gaussian bunches:

Chen & Yokoya, 1992 and before

average Upsilon

$$\Upsilon_{av} \approx \frac{5}{6}\frac{N r_e^2 \gamma}{\alpha \sigma_z (\sigma_x + \sigma_y)}$$

where $\Upsilon = \frac{2}{3}\frac{\hbar \omega_c}{E_0} = \gamma \frac{|B| + |E/c|}{B_c}$

linear colliders:
$0.2 \lesssim \Upsilon \lesssim 100$

circular colliders:
$\Upsilon \sim 10^{-4}$

$$n_\gamma \approx \frac{2.16 \alpha r_e N}{\sigma_x + \sigma_y} \frac{1}{\left(1 + \Upsilon_{av}{}^{2/3}\right)^{1/2}}$$

photons emitted per electron

historical design constraint for linear colliders:
$n_\gamma < 1$

$$\delta_E \approx 2.09 \frac{r_e^3 N^2 \gamma}{\sigma_z} \left(\frac{2}{\sigma_x + \sigma_y}\right)^2 \frac{1}{(1 + (1.5\Upsilon_{av})^{2/3})^2}$$

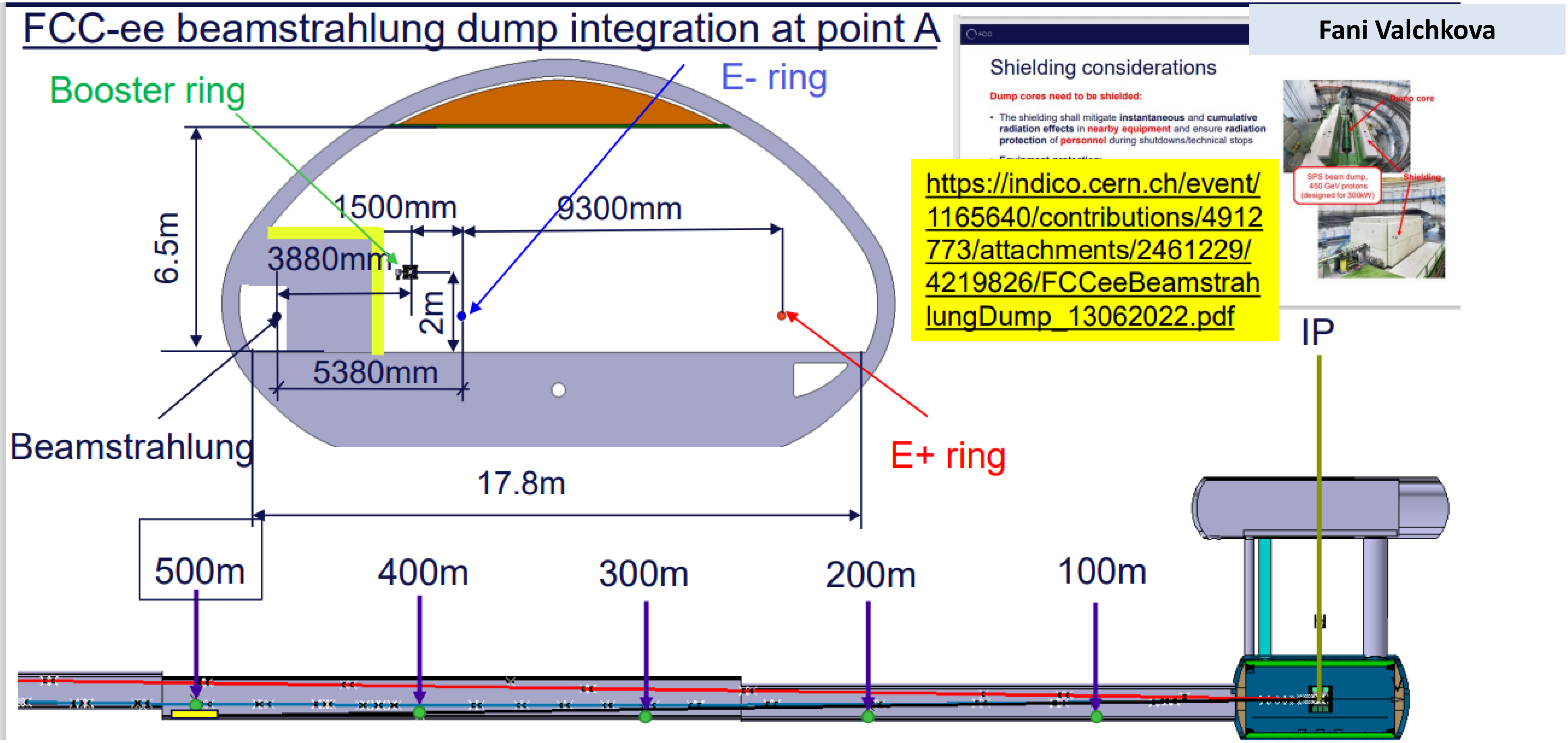
average relative energy loss

how to reduce beamstrahlung: (1) flat beams $\sigma_x \gg \sigma_y$ (!), and/or (2) very short bunches ?

circular colliders	**beamstrahlung** increases equilibrium beam energy spread and/or limits the beam lifetime

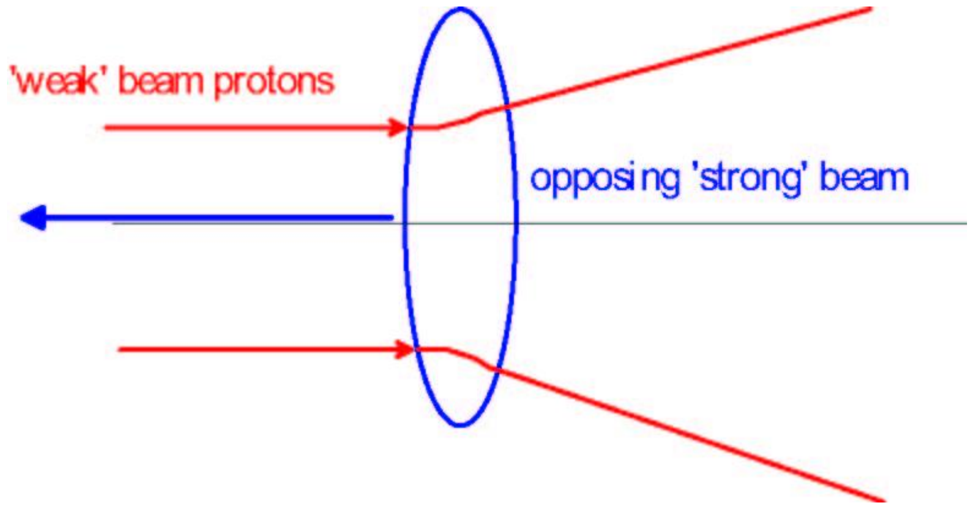
handling of beamstrahlung at FCC-ee

up to 0.5 MW beamstrahlung photon power per beam per IP,
requires dedicated shielded photon beam dumps



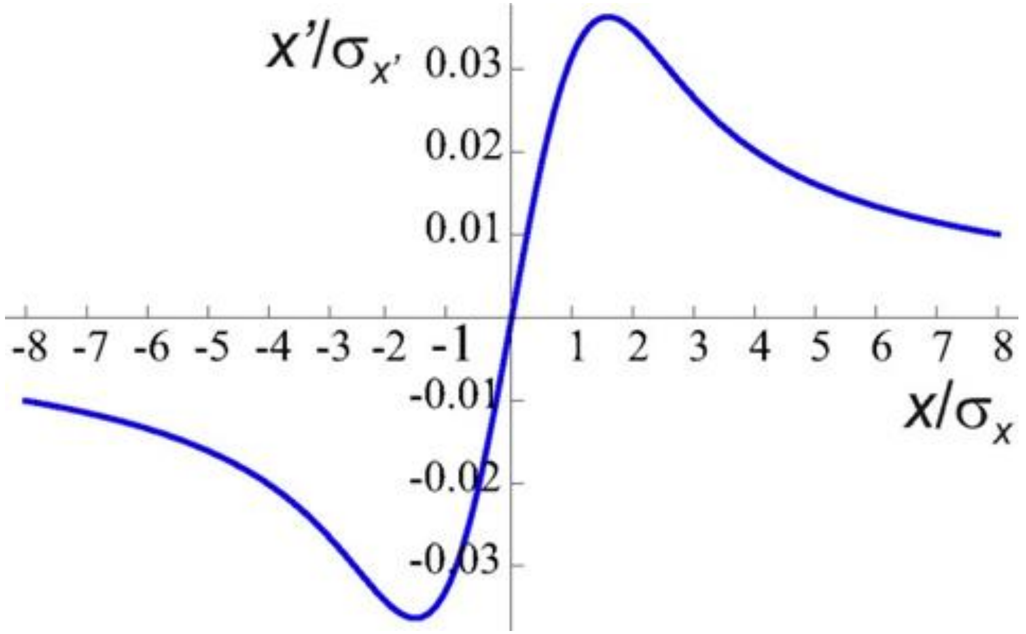
1.3 Beam-beam effects

collider figure of merit: beam-beam tune shift



head-on beam-beam collision in the LHC

(nonlinear) beam-beam force



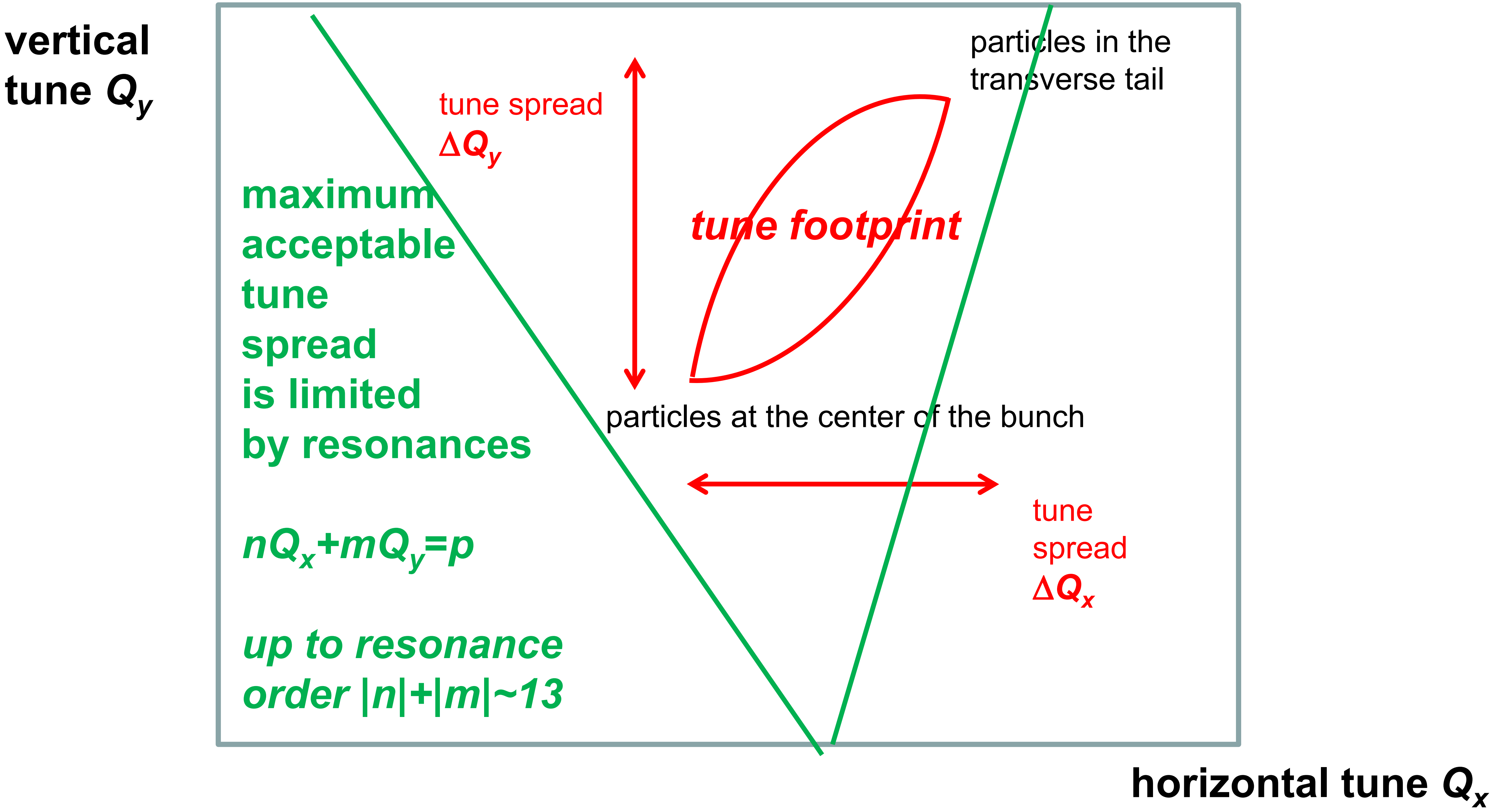
at small amplitude similar to effect of defocusing quadrupo

for pure head-on collision

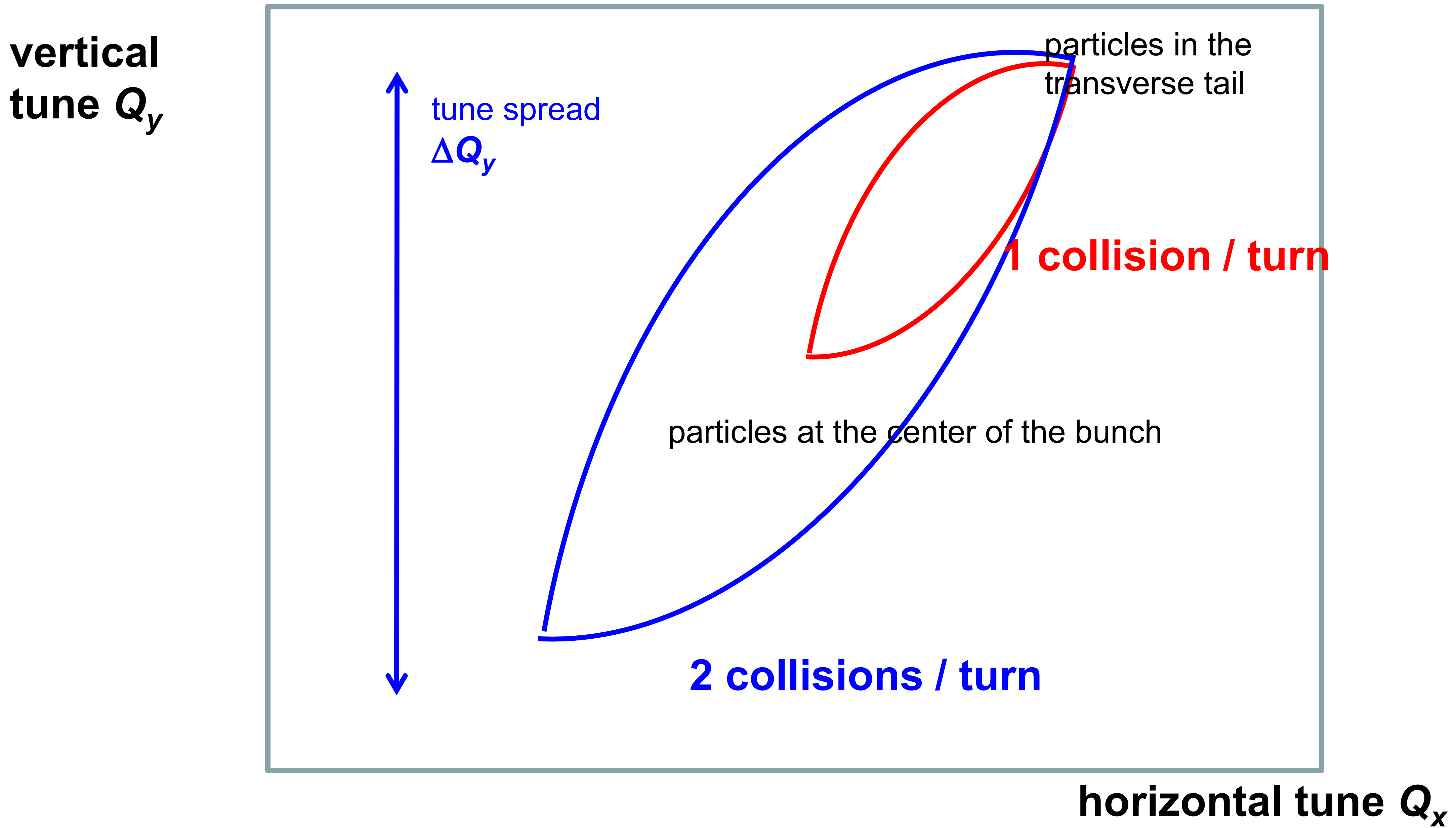
$$\Delta Q_{x.y;\max} = \xi_{x,y} = \frac{2N_b r_0 \beta^*}{4\pi\gamma\left(2\sigma^{*2}\right)} = \frac{N_b}{\varepsilon_N}\frac{r_0}{4\pi}$$

for single collision (nominal LHC ~0.0033)

beam-beam tune spread

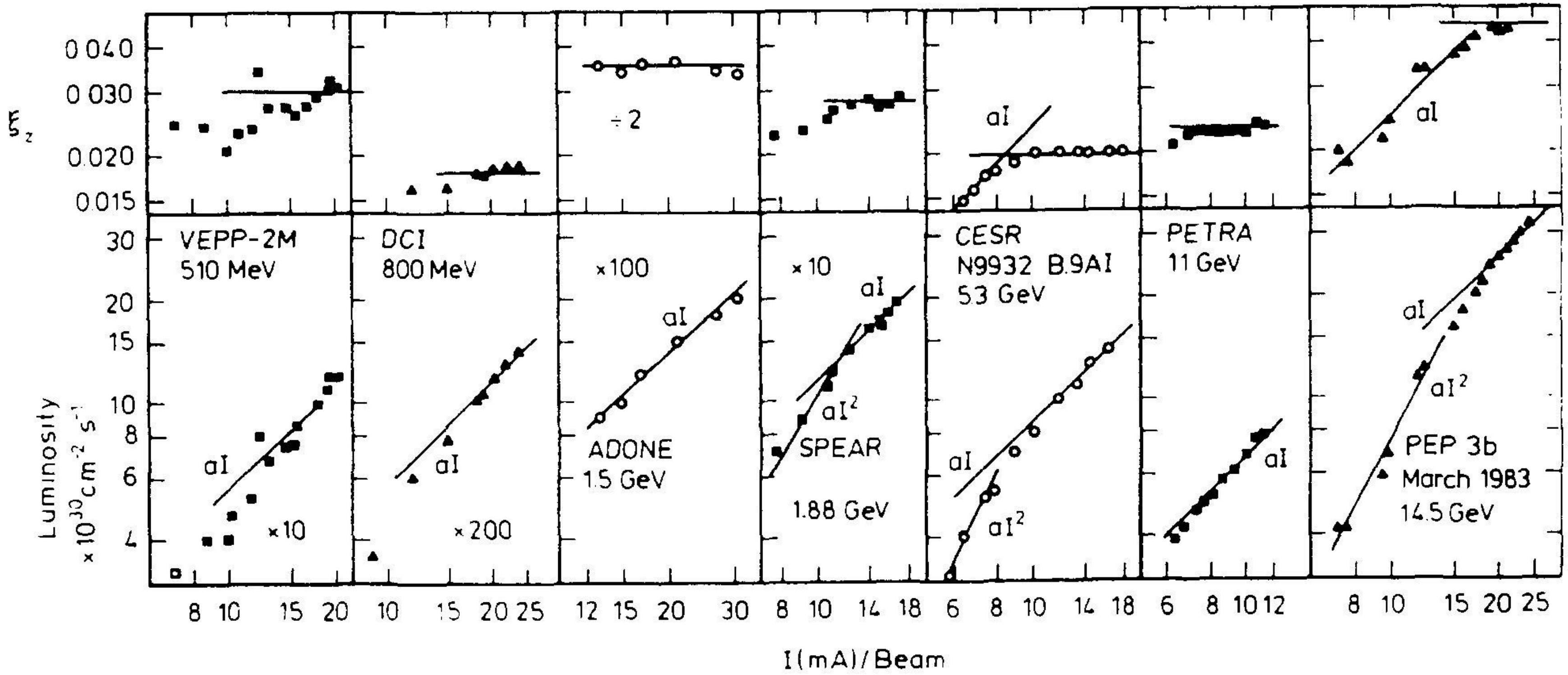


multiple interaction points



beam-beam limit in e^+e^- colliders

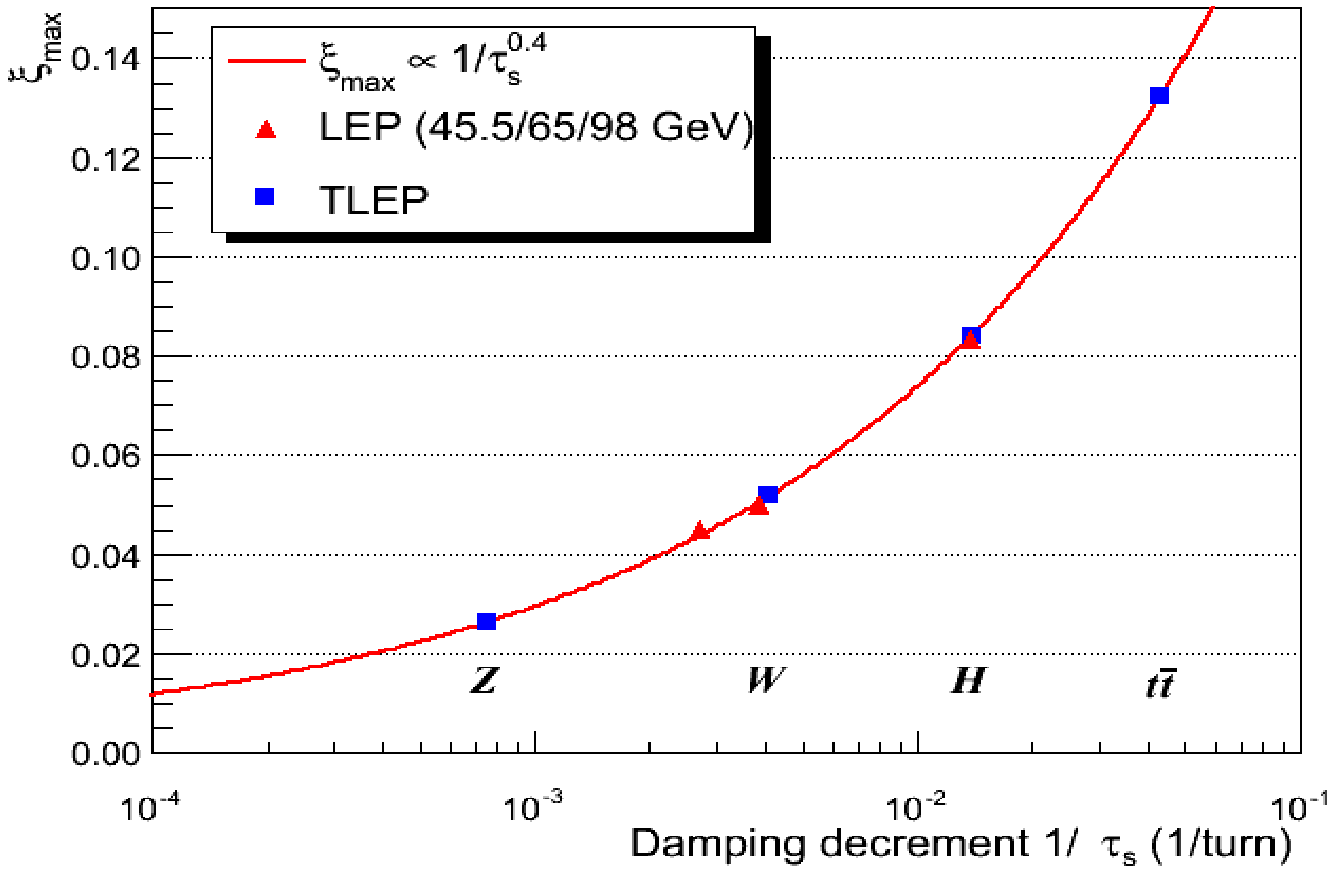
J. Seeman



luminosity and vertical tune-shift parameter versus beam current for various electron-positron colliders; the tune shift saturates at some current value, above which the luminosity grows linearly

beam-beam limit w strong SR damping

R. Assmann



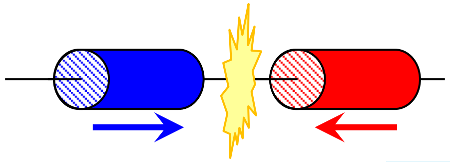
$$\lambda_d = 1/(f_{rev} \cdot \tau \cdot n_{ip}) \qquad \xi_y^\infty \propto (\lambda_d)^{0.4}$$

damping decrement per IP

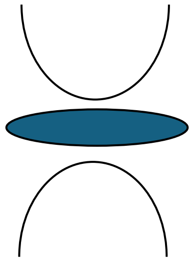
1.4 Luminosity revisited

scaling: larger *E* & ρ

$$e\,f\,k\,N = \text{beam current} \propto \frac{1}{E^4}$$



$$L = \frac{f\,k\,N^2}{4\pi\sigma_x\sigma_y} F\,H$$

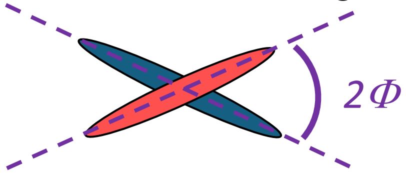


H ≤ 1

Hour-glass

F ≤ 1

Crossing angle



$$\xi_y \propto \frac{\beta_y^* N}{E\sigma_x\sigma_y} \le \xi_y^{max}(E)$$

Beam-beam parameter

$$L \propto \frac{\rho P_{SR}}{E^3} \frac{\xi_y}{\beta_y^*}$$

σ = beam size

k = no. bunches

f = rev. frequency

N = bunch population

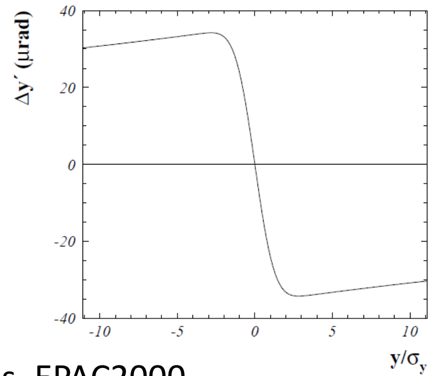
P_{SR} = synch. rad. power

β^* = betatron fct at IP (beam envelope)

J. Wenninger

luminosity scaling: damping

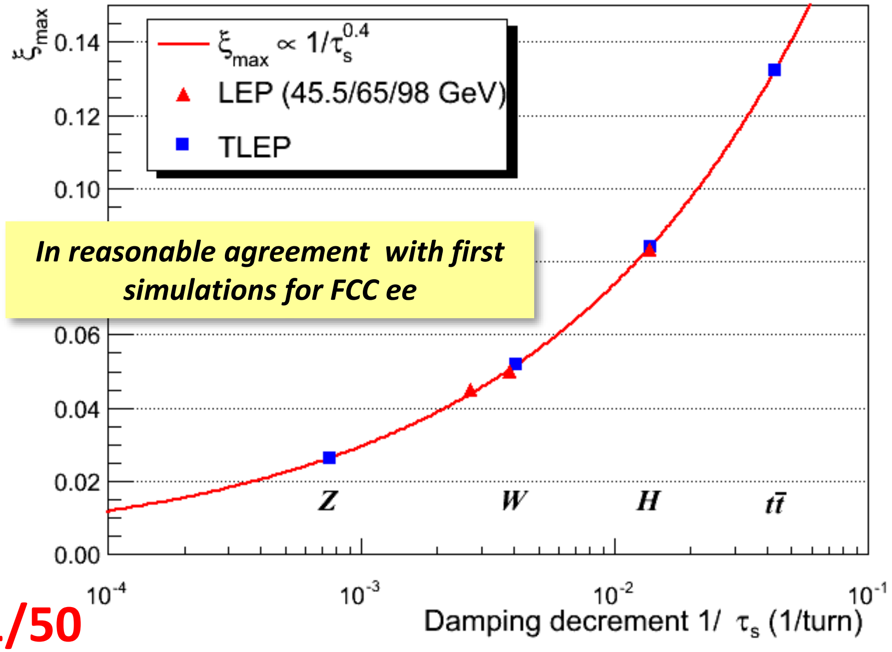
- beam-beam parameter ξ measures strength of field sensed by the particles in a collision
- beam-beam parameter limits can be scaled from LEP data (4 IPs); crab waist allows for higher ξ



$$\xi_y \propto \frac{\beta_y^* N}{E\sigma_x\sigma_y} \le \xi_y^{max}(E)$$

$$\xi_y^{max}(E) \propto \frac{1}{\tau_s^{0.4}} \propto E^{1.2}$$

R. Assmann & K. Cornelis, EPAC2000



In reasonable agreement with first simulations for FCC ee

***FCC-ee* vs LEP**

$$L \propto \frac{\rho P_{SR}}{E^{1.8}} \frac{1}{\beta_y^*}$$

x3.7 (ρP_{SR})

x4.5

<x2 ($E^{1.8}$)

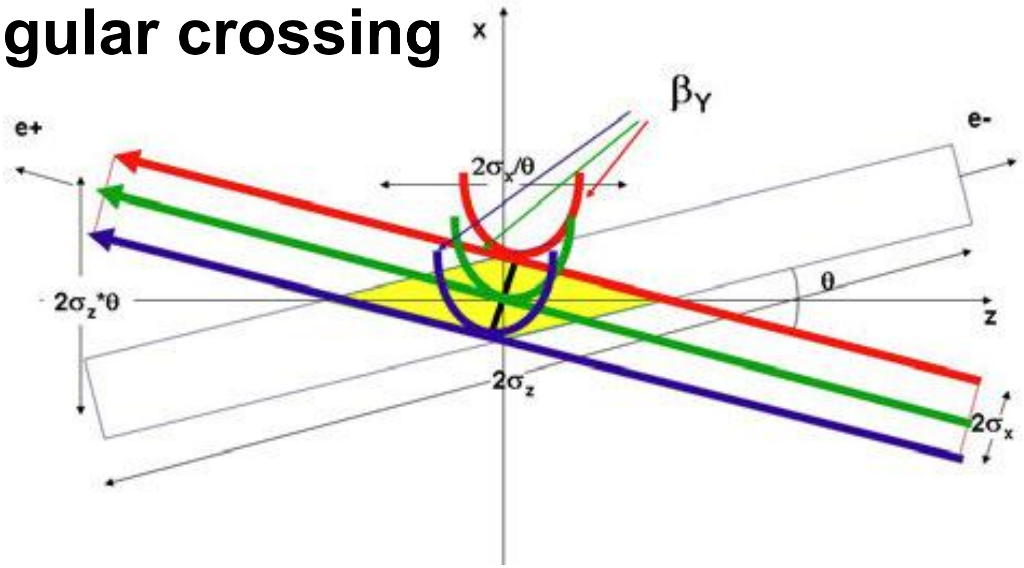
x1/25-1/50 (β_y^*)

→ extremely high luminosity

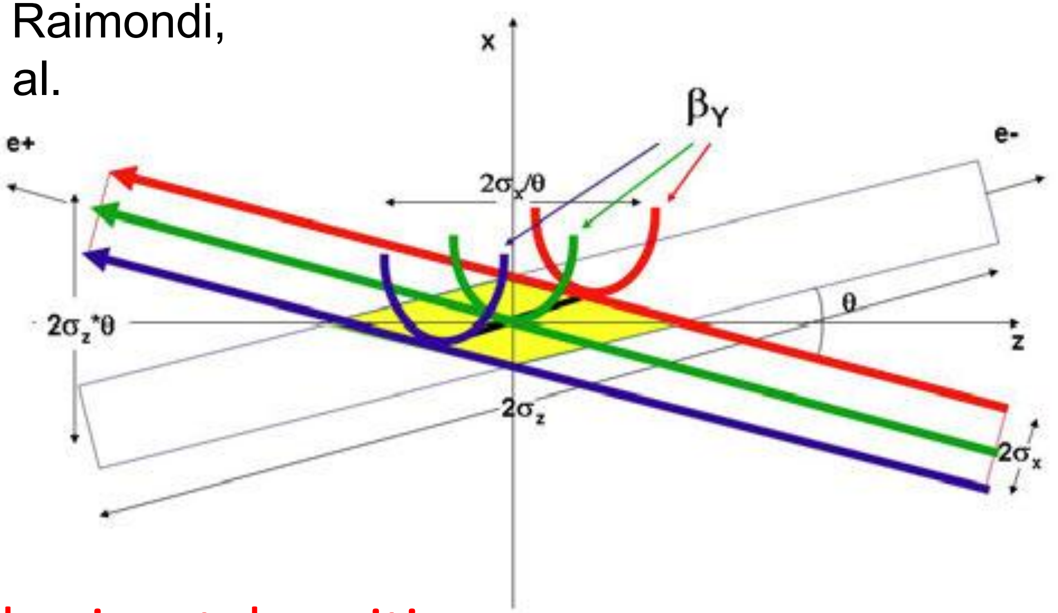
J. Wenninger, R. Assmann, S. White, K. Ohmi, D. Shatilov, et al.

crab-waist crossing for flat beams

regular crossing



P. Raimondi, et al.



crab waist - vertical waist position in *s* varies with horizontal position *x*

- allows for small β_y^* and for small $\varepsilon_{x,y}$
- and avoids betatron resonances (→higher beam-beam tune shift)

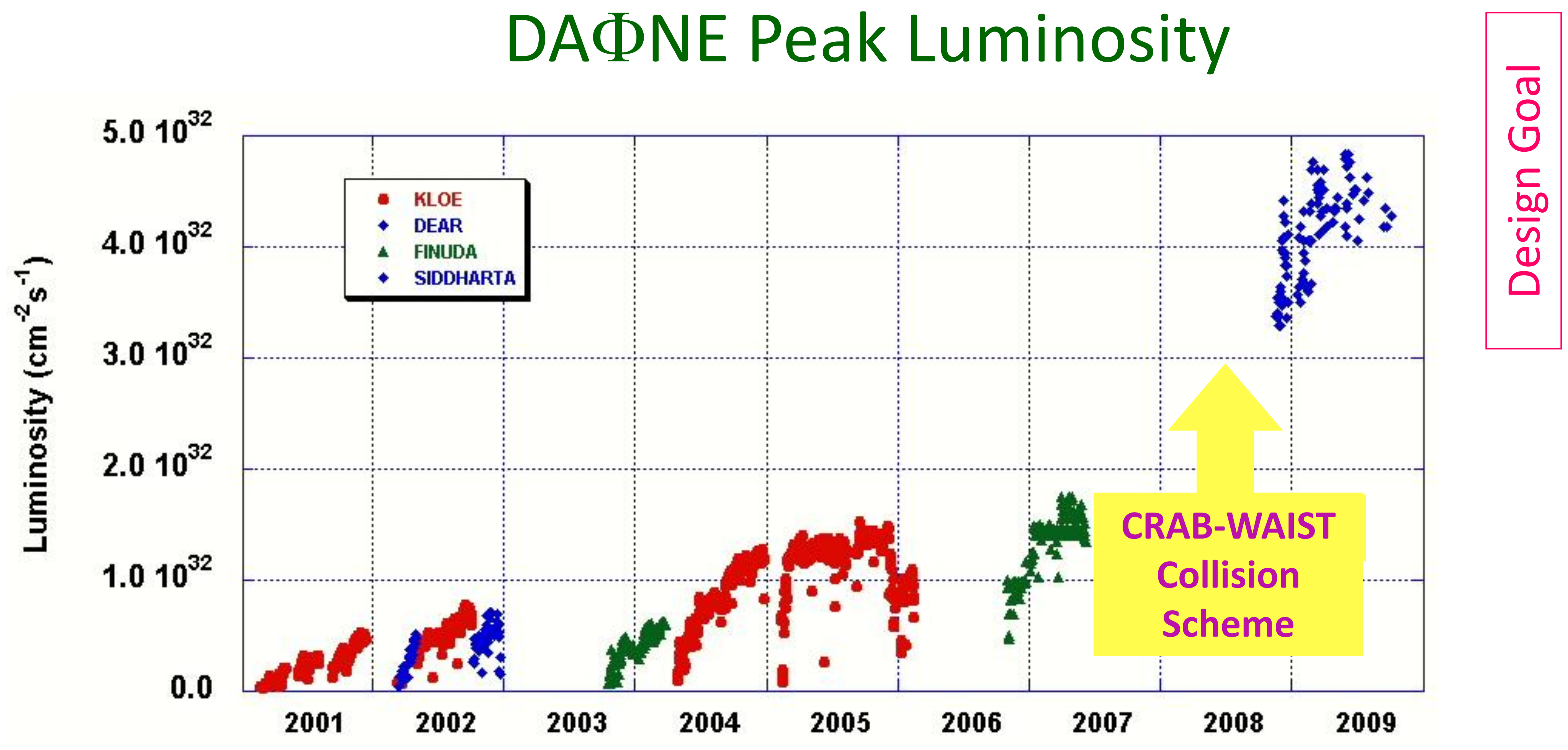
$$\Phi \equiv \frac{\sigma_z \theta}{2\sigma_x^*}$$ “Piwinski angle”

$$L = \frac{N_b f_0}{4\pi\sigma_x\sigma_y}\left[\frac{N^2}{\sqrt{1+\Phi^2}}\right]; \quad \xi_y = \frac{r_e\beta_y}{2\pi\gamma\sigma_x\sigma_y}\left[\frac{N}{\sqrt{1+\Phi^2}}\right]; \quad \xi_x = \frac{r_e\beta_x}{2\pi\gamma\sigma_x^2}\left[\frac{N}{1+\Phi^2}\right]$$

$$\rightarrow \boldsymbol{L = \frac{I_{beam}}{e}\frac{\gamma}{2r_e}\frac{\xi_y}{\beta_y^*}}$$

P. Raimondi, M. Zobov, D. Shatilov

DAΦNE: "crab waist" collisions

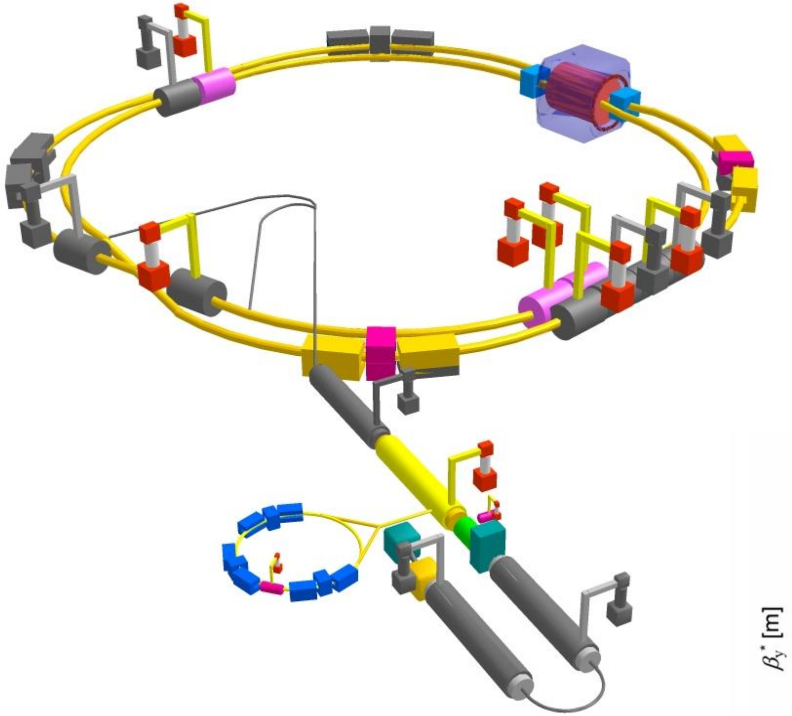


DAΦNE : ~1 GeV e+e- collider in Frascati near Rome

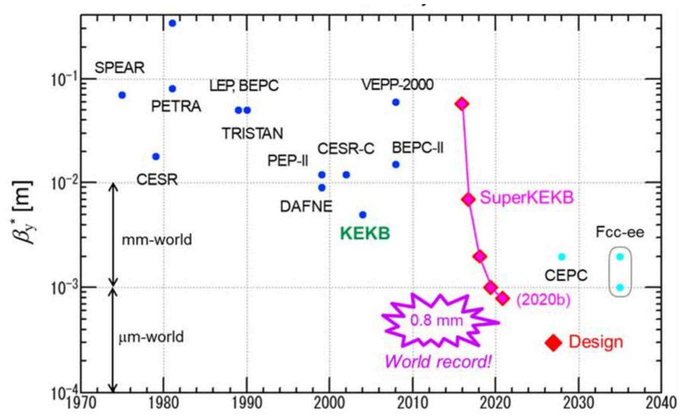
M. Zobov

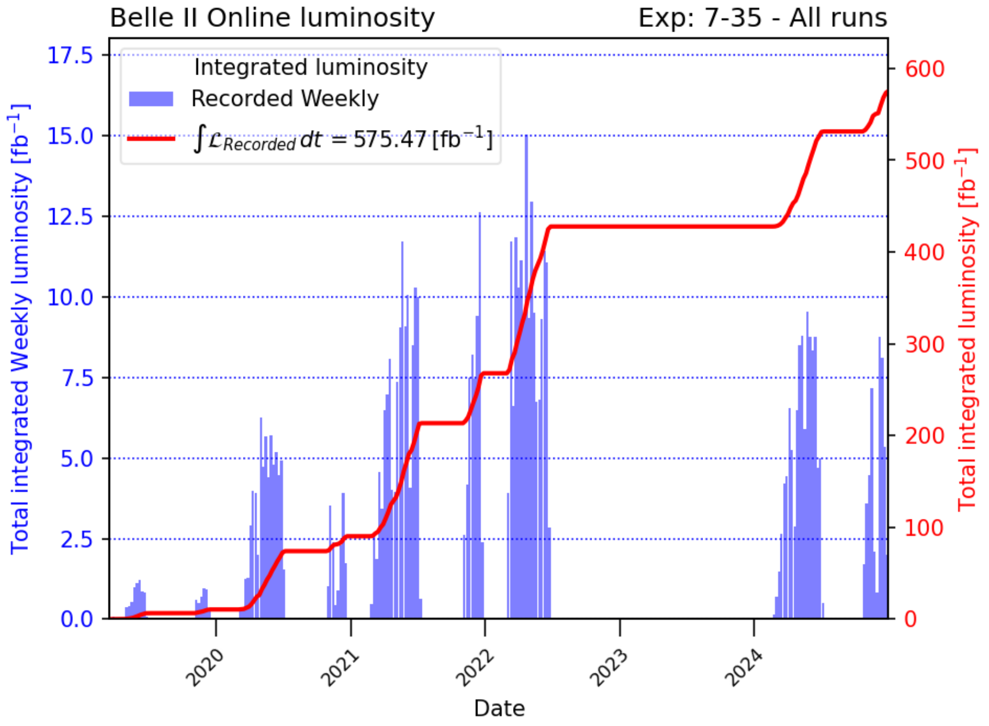
SuperKEKB 4 GeV e^+ vs 7 GeV e^- in Japan

circumference 3 km



world's highest luminosity & lowest β^* e^+e^- collider at KEK/Tsukuba





total integrated luminosity so far ~575 fb^{-1} over ~6 years

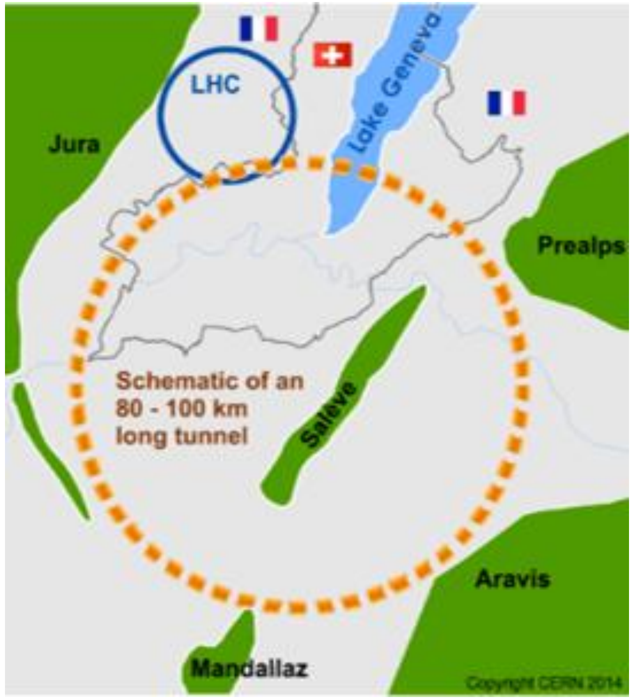
world record luminosity of 4.71×10^{34} $cm^{-2}s^{-1}$, β_y^* = 1.0 mm routinely, also β_y^* = 0.8 mm shown

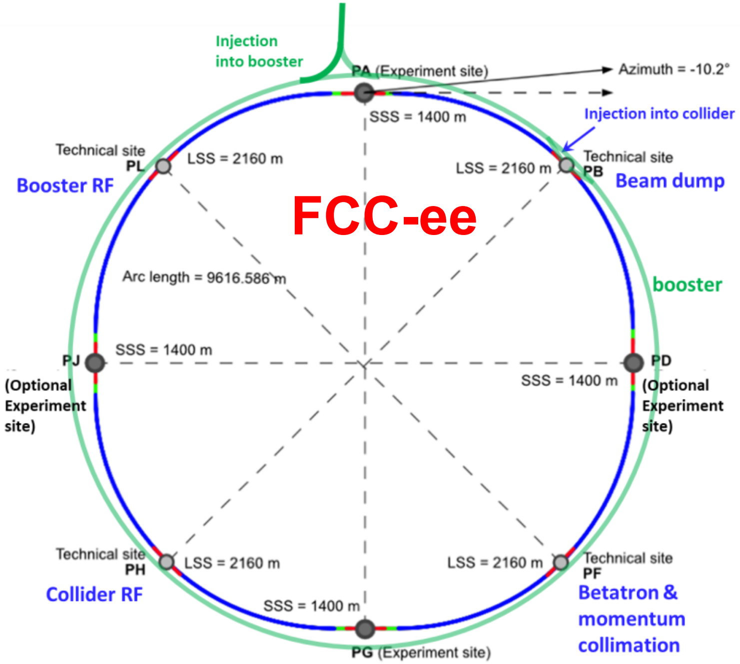
– with "virtual" crab-waist collision scheme originally developed for FCC-ee (K. Oide)

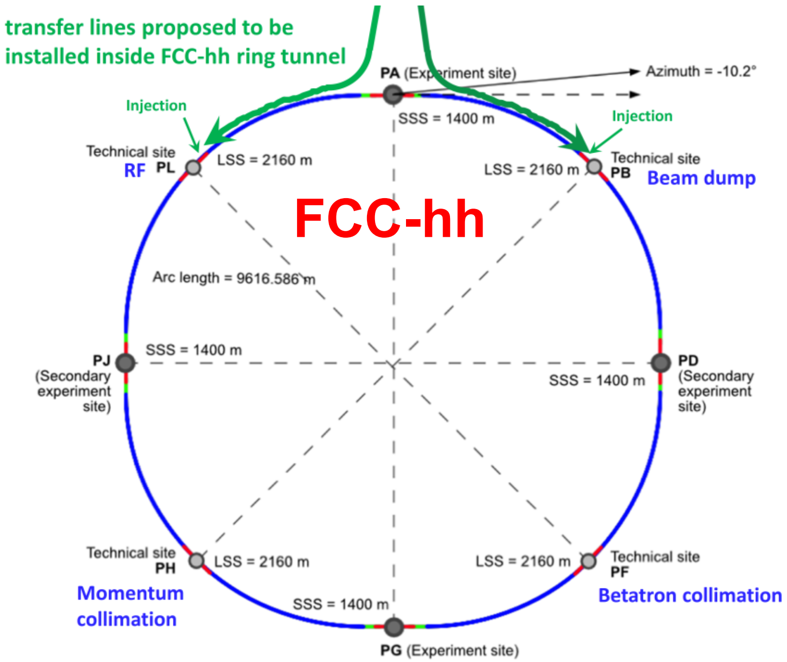
1.5 FCC concepts

FCC integrated program

- inspired by the successful LEP/LHC programs at CERN
- **stage 1: FCC-ee (Z, W, H, $t\bar{t}$) as Higgs factory, electroweak & top factory at highest luminosities**
- **stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, pp & AA collisions; e-h option**
- highly synergetic and complementary programme maximising the physics opportunities
- common civil engineering and technical infrastructures, building on and reusing CERN's existing infrastructure
- FCC integrated project allows the start of a new, major facility at CERN within a few years of the end of HL-LHC







2020 - 2045 | 2045 - 2065 | 2070 -

FCC-ee key design concepts

double ring collider

- many bunches, high current, like LHC and B factories, different from LEP

crab-waist collision scheme

- successfully demonstrated at DAΦNE (Italy) and SuperKEKB (Japan)

top-up injection

- standard at modern light sources, like SLS
- used at recent e^+e^- colliders, PEP-II (USA), KEKB (Japan), BEPCII (China)

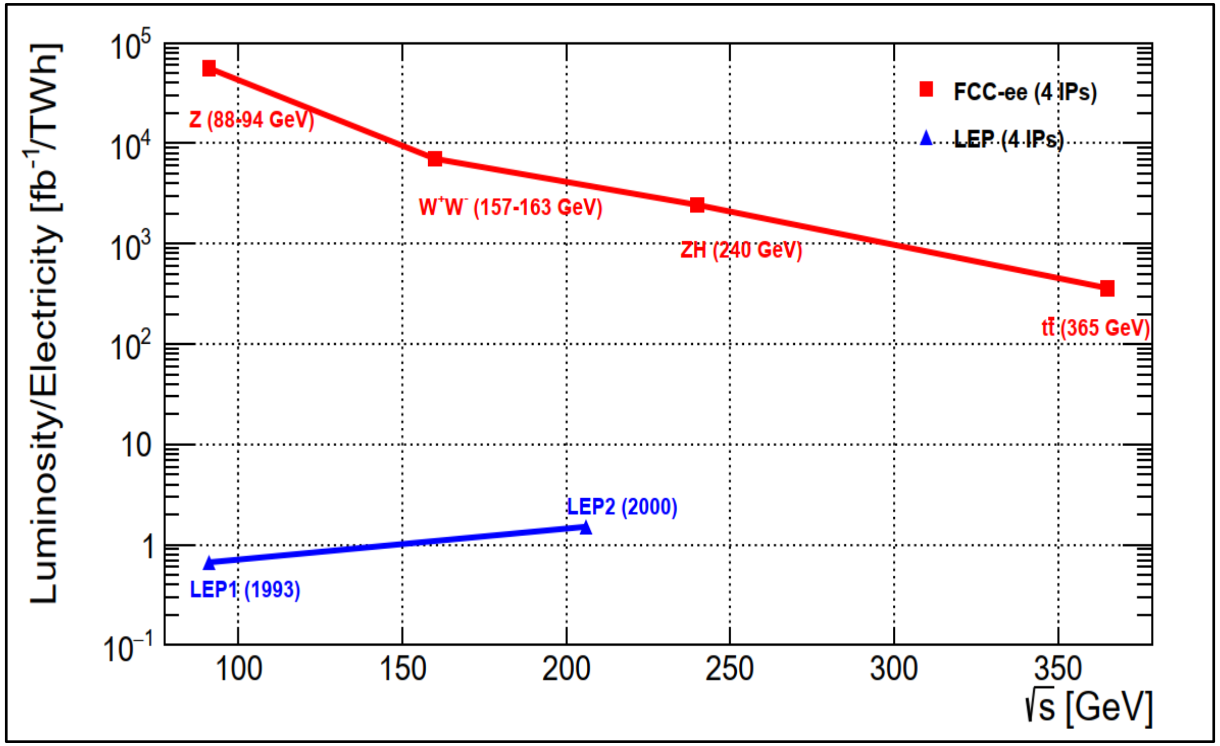
SC radiofrequency system

- Nb/Cu 400 MHz SC cavities pioneered at former CERN LEP
- bulk Nb 800 MHz SC cavities similar to ESS (Sweden), EuXFEL (Germany)
- revolutionary highly efficient RF power sources
- new operation scheme for flexible energy switching & reduced complexity

Combining concepts from past and present lepton colliders yields giant step in efficiency:

→10^4 - 10^5 x luminosity/energy of LEP

→ sustainable physics



FCC-ee design parameters

parameter	Z	WW	H (ZH)	$t\bar{t}$	
Collision energy $\sqrt{s}$ [GeV]	88, 91, 94	157, 163	240	340-350	365
synchrotron radiation/beam [MW]	50	50	50	50	50
beam current [mA]	1294	135	26.8	6.0	5.1
number bunches / beam	11200	1852	300	70	64
total RF voltage 400 / 800 MHz [GV]	0.08 / 0	1.0 / 0	2.1 / 0	2.1 / 7.4	2.1 / 9.2
luminosity / IP [10^{34} $cm^{-2}s^{-1}$]	144	20	7.5	1.8	1.4
luminosity / year [ab^{-1}]	68	9.6	3.6	0.83	0.67
run time (including lumi ramp-up) [years]	4	2	3	1	4
total integrated luminosity [ab^{-1}]	205	19.2	10.8	0.4	2.7
total number of events	6 10^{12} Z	2.4 10^8 WW (incl. WW at higher $\sqrt{s}$)	2.2 10^6 ZH 65k WW $\rightarrow$ H	2 10^6 $t\bar{t}$ + 370k ZH + 92k WW $\rightarrow$ H	

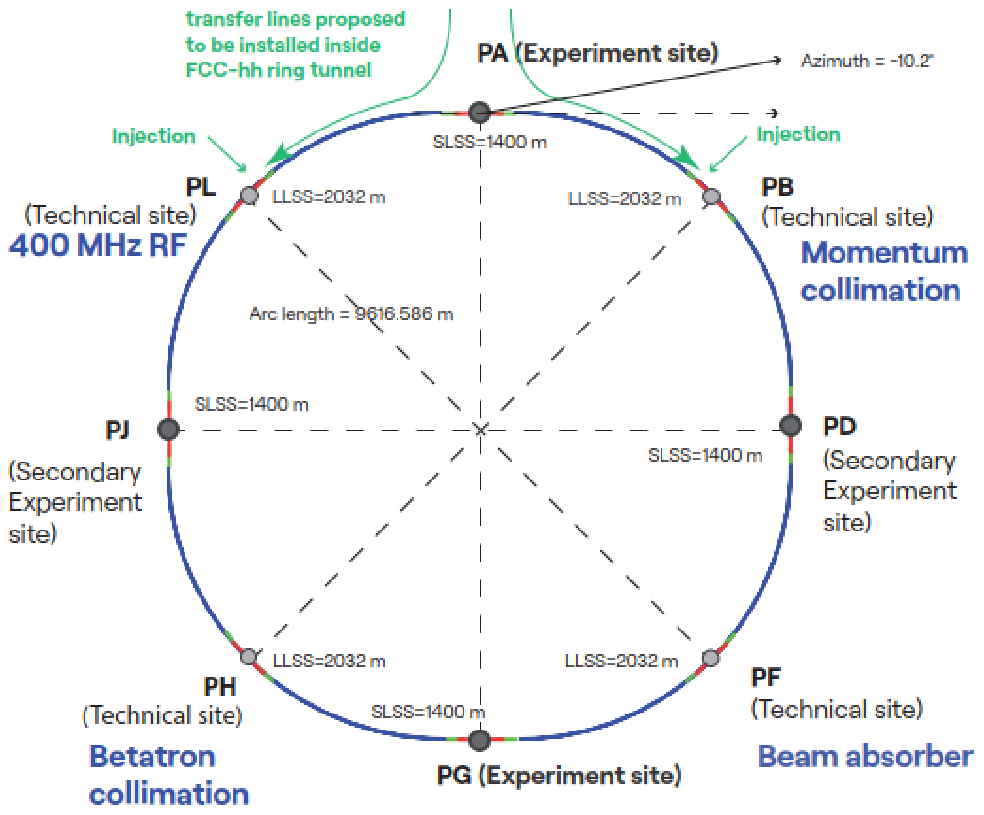
Stage 2: hadron collider FCC-hh

- Parameter optimization to lower electricity consumption (~max. consumption of FCC-ee)
- Magnetic field considered realistic with today's technologies (Nb_3Sn, ~14T; alternative: HTS)

Main parameters 2025

parameter	FCC-hh	HL-LHC
collision energy cms [TeV]	85	14
dipole field [T]	14	8.33
circumference [km]	90.7	26.7
beam current [A]	0.5	1.1
synchr. rad. per ring [kW]	1200	7.3
peak luminos. [10^{34} $cm^{-2}s^{-1}$]	30	5 (lev.)
events/bunch crossing	1000	132
stored energy/beam [GJ]	6.5	0.7
integr. luminosity / IP [fb^{-1}]	20000	3000

FCC-hh functional layout



Lecture 2 – FCC-ee optics

2.1 arc emittance

2.2 final focus

2.3 full ring optics

2.4 errors, DA, MA, BBA, etc.

2.5 beam-beam performance

2.1 arc emittance equilibrium excitation & damping

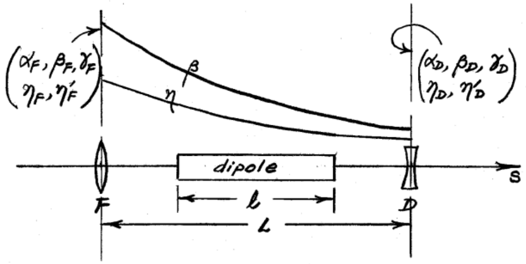
equilibrium energy spread and bunch length:

$$\sigma_\epsilon \approx \sqrt{E_0 u_c}$$

$$\sigma_z \approx \frac{c\alpha_c}{\Omega_s}\frac{\sigma_\epsilon}{E_0}$$

horizontal equilibrium emittance
for bending angle θ per cell:

Teng, TM-1269, 1984



$$\varepsilon_x = \frac{C_q}{1-\mathcal{D}} F_T \gamma^2 \theta^3$$

$$C_q = \frac{55\hbar c}{32\sqrt{3} m_e c^2} \approx 3.84 \times 10^{-13}\ \mathrm{m}$$

$$F_T = \frac{\rho^2}{l^3} \langle \mathcal{H} \rangle_{dipole}$$

$$\langle \mathcal{H} \rangle_{dipole} = \frac{1}{2\pi\rho} \oint (\gamma_x D_x^2 + 2\alpha_x D_x D_x' + \beta_x D_x'^2) ds$$

$F_T \approx 2.5\, L/l$ for 90 deg FODO cell
≈ 0.1 for "useful & realistic" TME cell

vertical equilibrium emittance normally determined by spurious vertical dispersion and betatron coupling – intrinsic limit is set by 1/γ opening angle of the synchrotron radiation:

$$\varepsilon_y \approx C_q\, \beta_{typical}/\rho$$

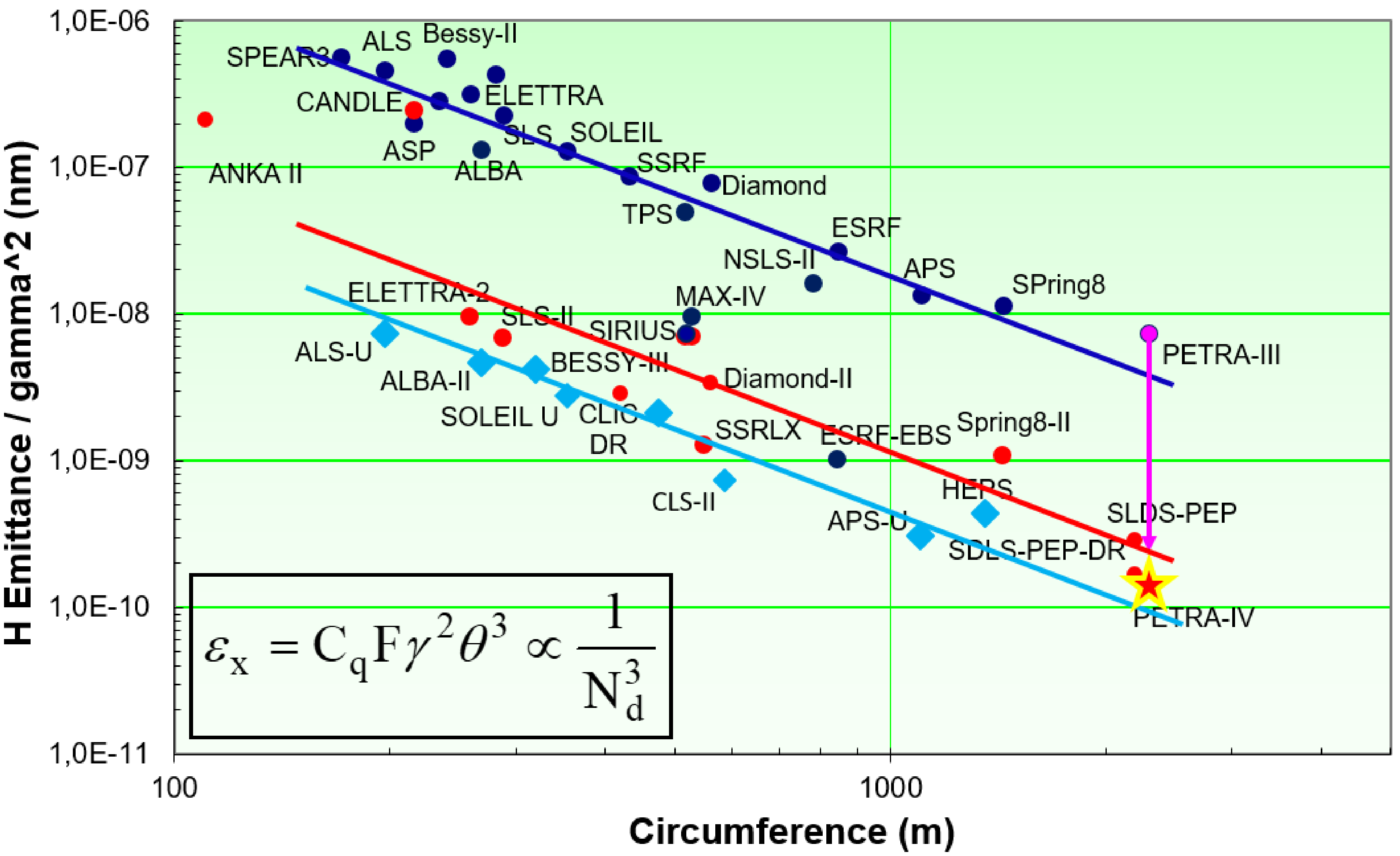
Sands, 1970

$$\varepsilon_y = \frac{13}{55} C_q \frac{\oint \frac{\beta}{\rho^3} ds}{\oint \frac{1}{\rho^2} ds}$$

taking into account correlation between photon emission angle and energy

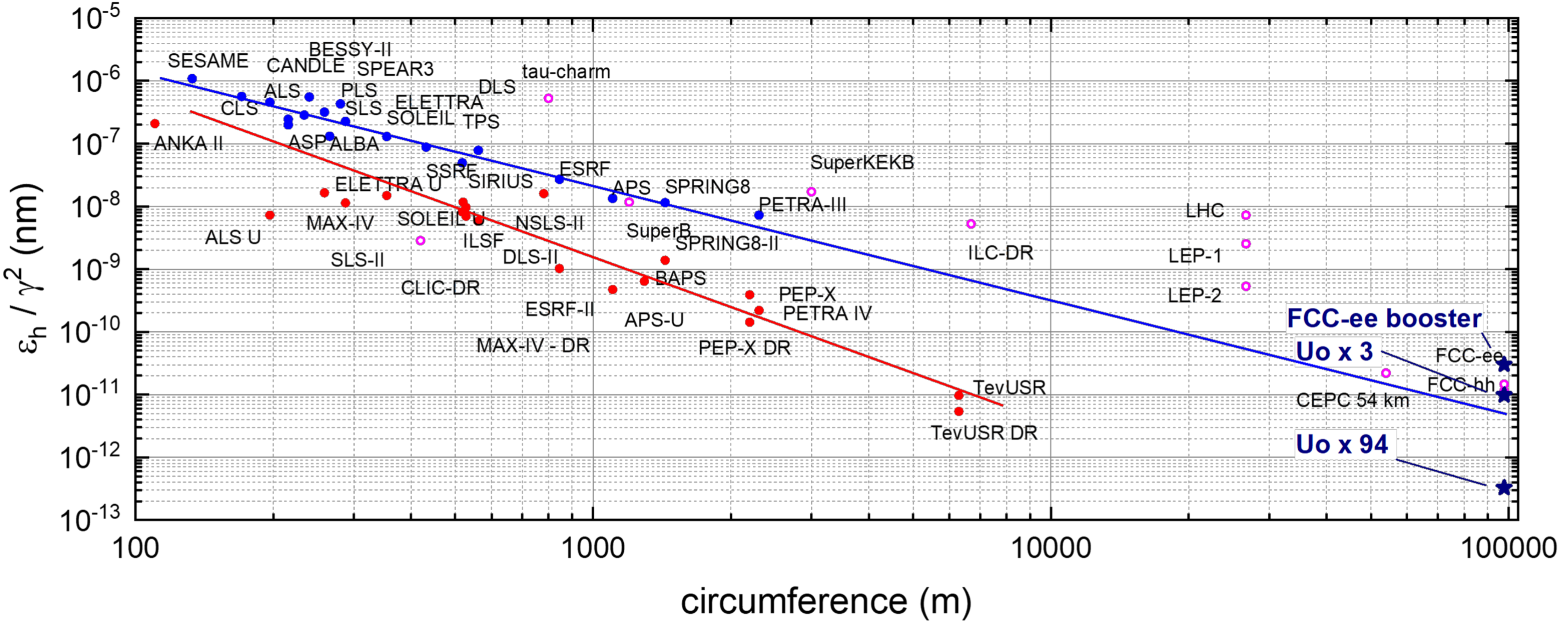
T. Raubenheimer, 1991
K. Hirata, 1993

low-emittance rings – the state of the art



R. Bartolini --
iFAST Annual Meeting,
Trieste, April 2023

low-emittance rings – bring on the FCC-ee !



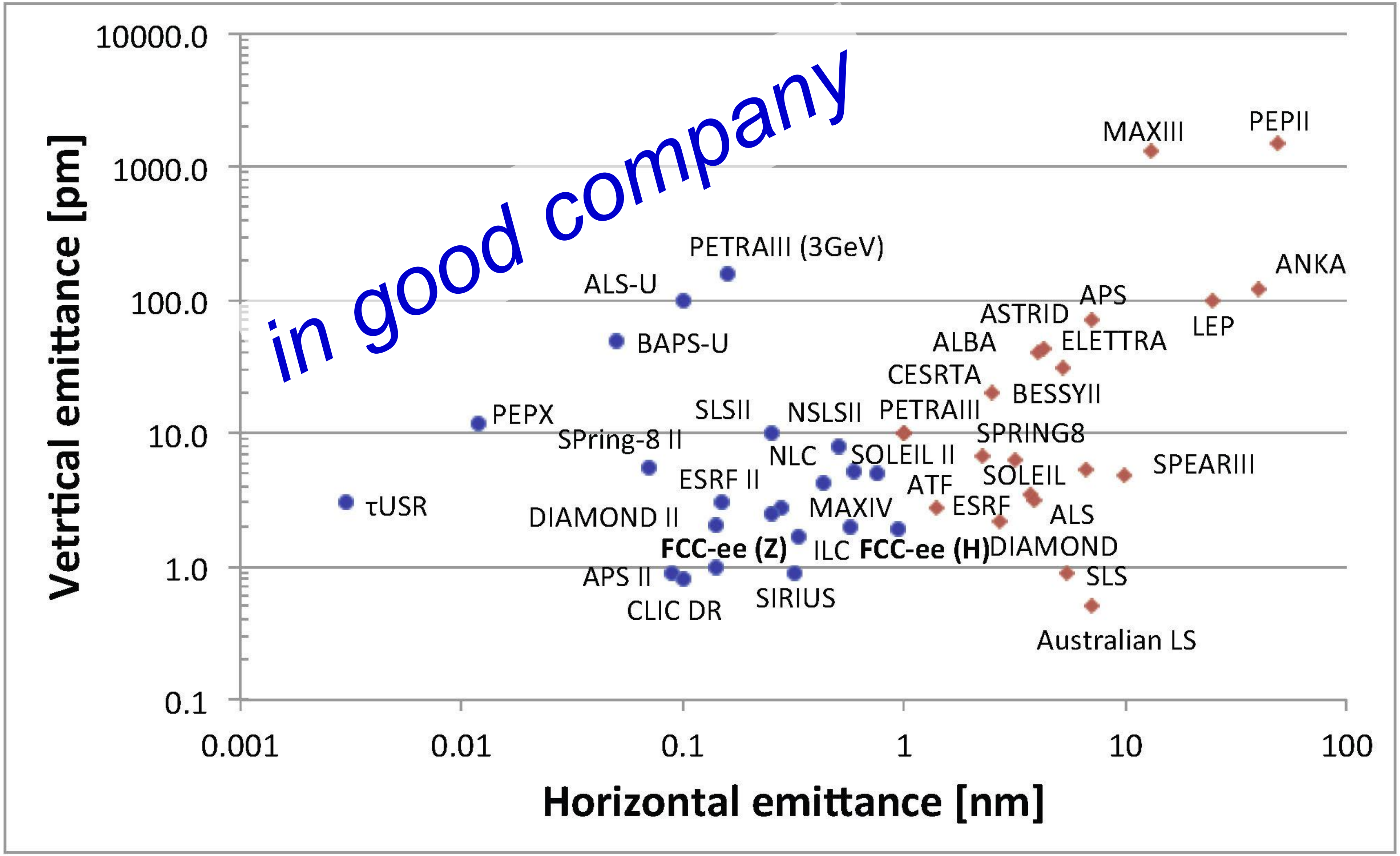
ring equilibrium emittance

$$\varepsilon_x \sim 10^{-12} \left(\frac{l_b}{\rho}\right)^3 \gamma^2 \text{ [m]}$$

	bending radius ρ [km]	beam energy [GeV]	γ	l_b (~1/2 cell length)	ε_x [nm]
LEP2	3.1	104	2.0×10^5	39.5	22
FCC-ee-Z	10	45.6	8.9×10^4	~46	0.7
FCC-ee-H	10	120	2.4×10^5	~20	0.66
FCC-ee-t	10	182.5	3.6×10^5	~20	1.5

we can either use 90 degree FODO optics and half the cell length going to Higgs or higher energy,
or we can change the phase advance per cell

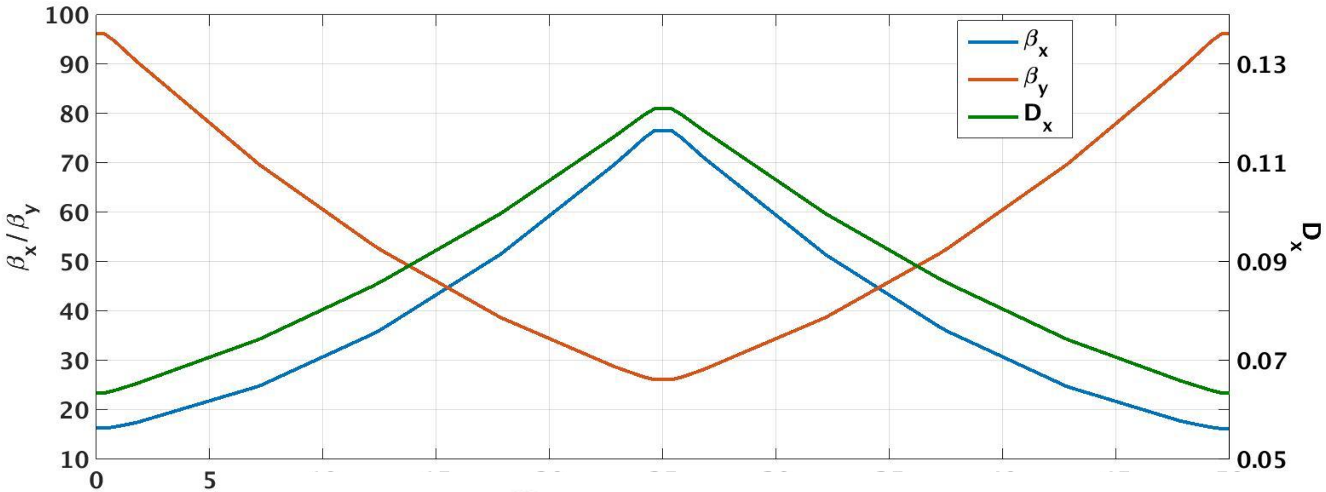
FCC-ee also needs a small vertical emittance ~1 pm



Y. Papaphilippou

FCC-ee numbers slightly outdated

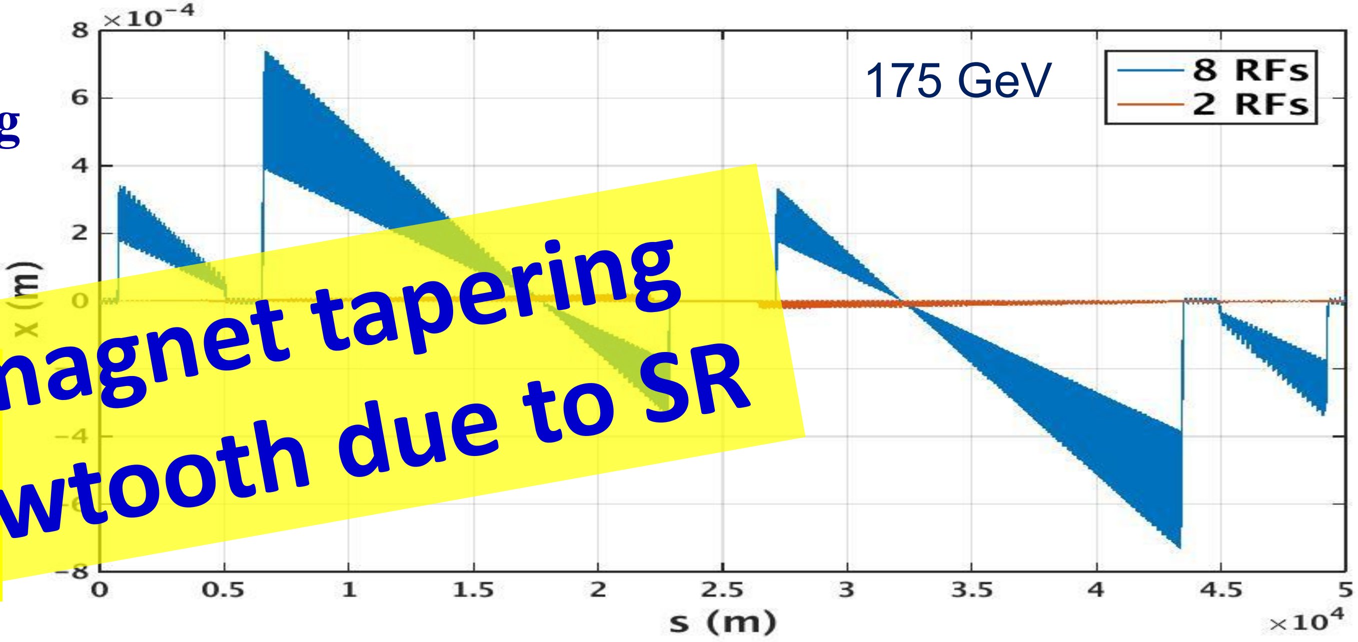
arc optics & sawtooth tapering



arc FODO cell length 50 m

(LEP: 79 m)

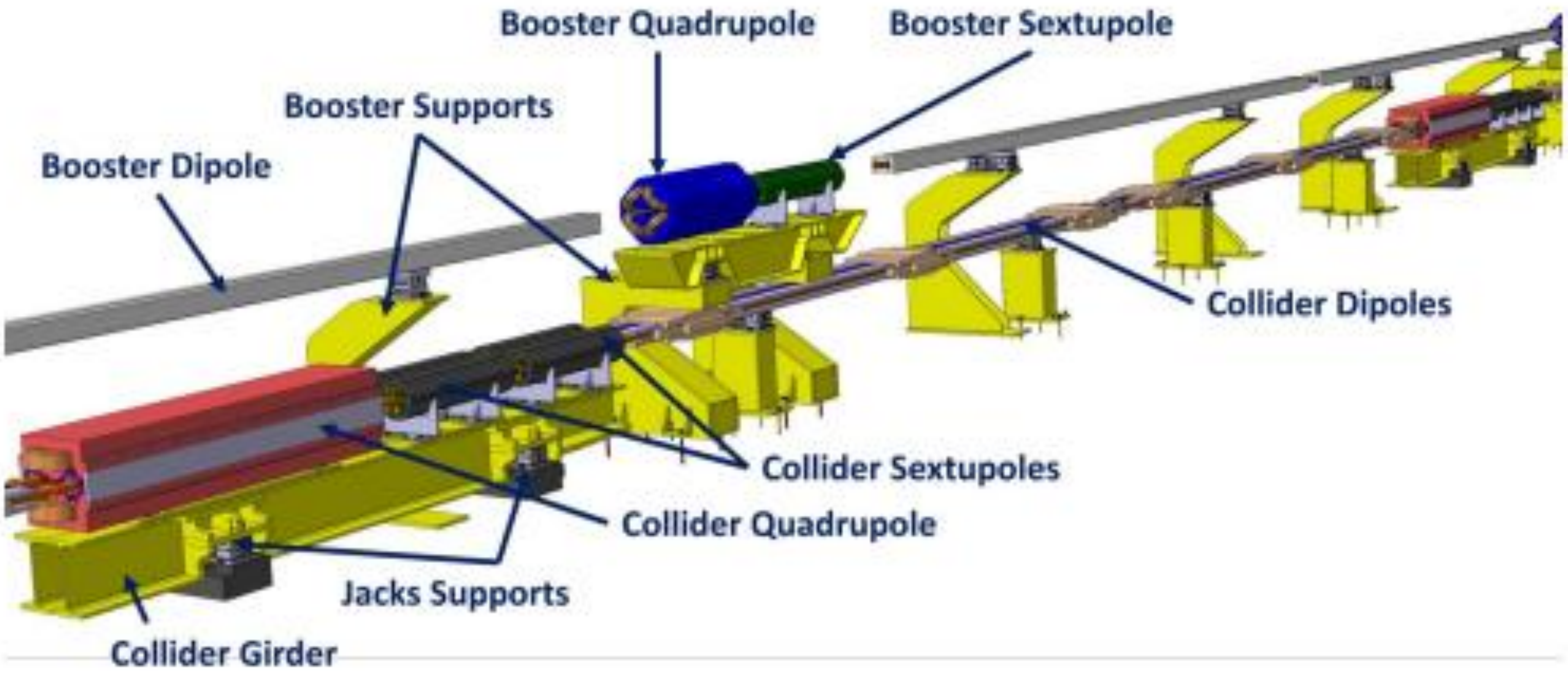
Comparison:
8 RF w/o tapering
2 RF with tapered dipoles



Sandra Aumon, Bastian Harrer, Andreas Doblhammer, Bernhard Holzer

double ring and magnet tapering remove energy sawtooth due to SR

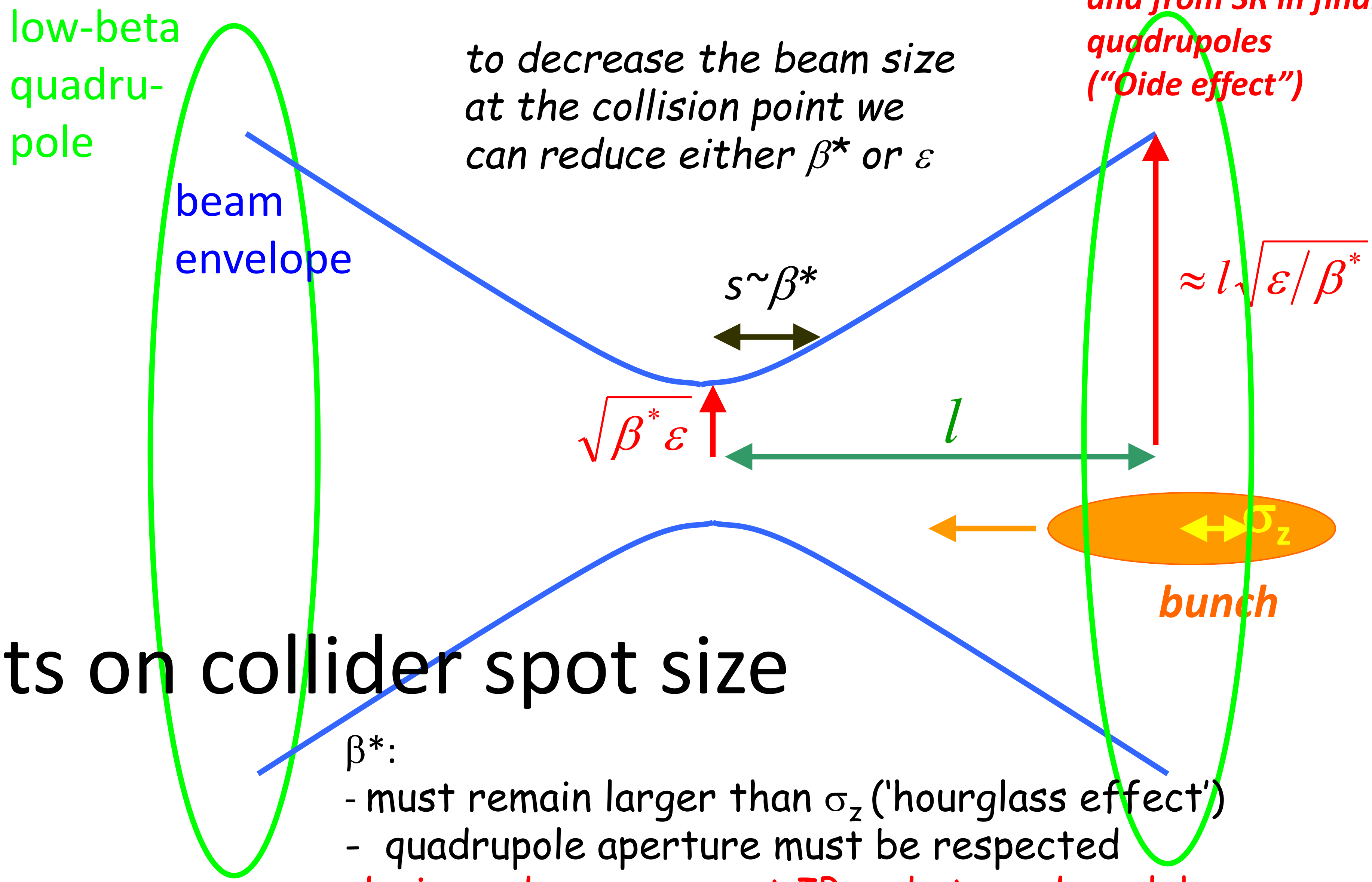
arc half cell



2.2 final focus

other limits from beam-beam effects and from SR in final quadrupoles ("Oide effect")

to decrease the beam size at the collision point we can reduce either β or ε*



limits on collider spot size

β^*:

- must remain larger than σ_z ('hourglass effect')
- quadrupole aperture must be respected

reducing ε decreases σ at IP and at quadrupole!

Machine-Detector Interface

Key topics:

SC IR magnet system &Cryostat design

3D integration

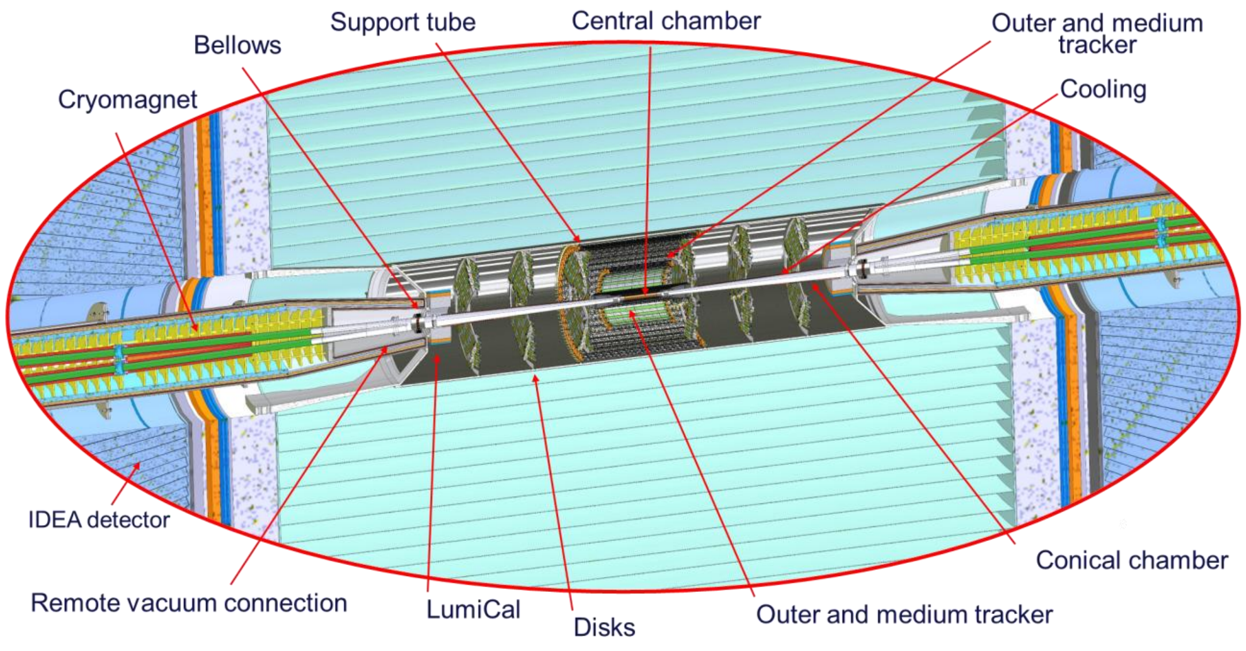
IR mock-up / INFN

Machine		FCCee	CEPC	ILC	SuperKEKB
Crossing-angle	mrad	30	33	14	83
L*	m	2.2	1.9	3.5	0.935
Vertical β_y* at IP	mm	0.7-1.6	0.9-2.7	0.4	0.3
Detector soln field	T	2/3	3	3.5/5	1.5
Detector stay clear	mrad	100	118/141	90	350/436
Two beam ΔX at L*	mm	66	62.7	49	77.6
He temperature	K	1.9	4.2	4.5	4.5

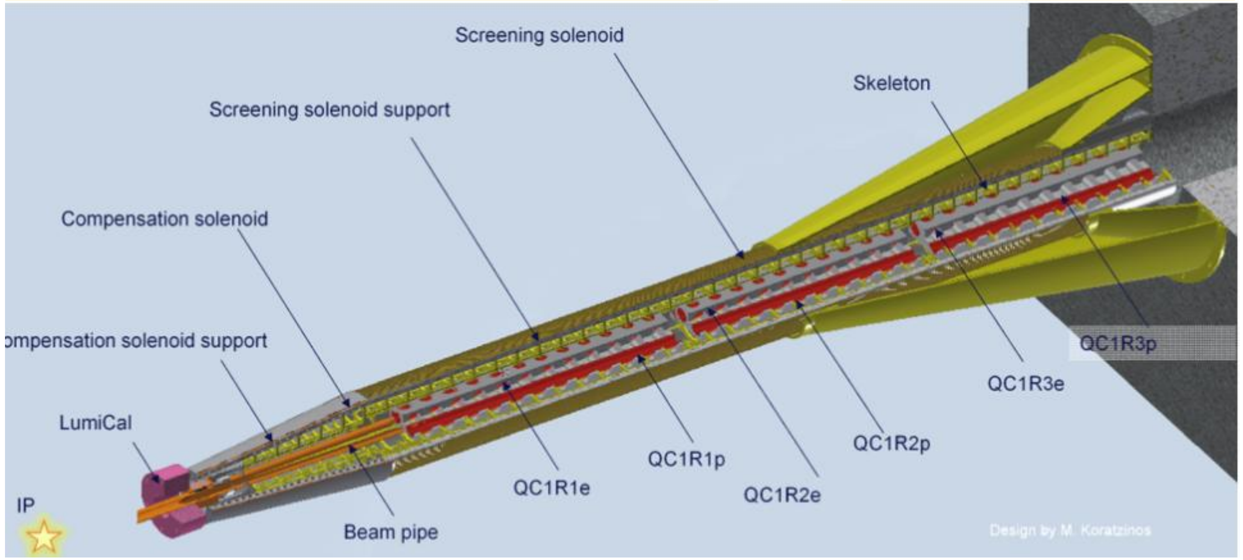
Q1 prototype tested at cold in SM18 (CERN), October '23

M. Koratzinos, PSI

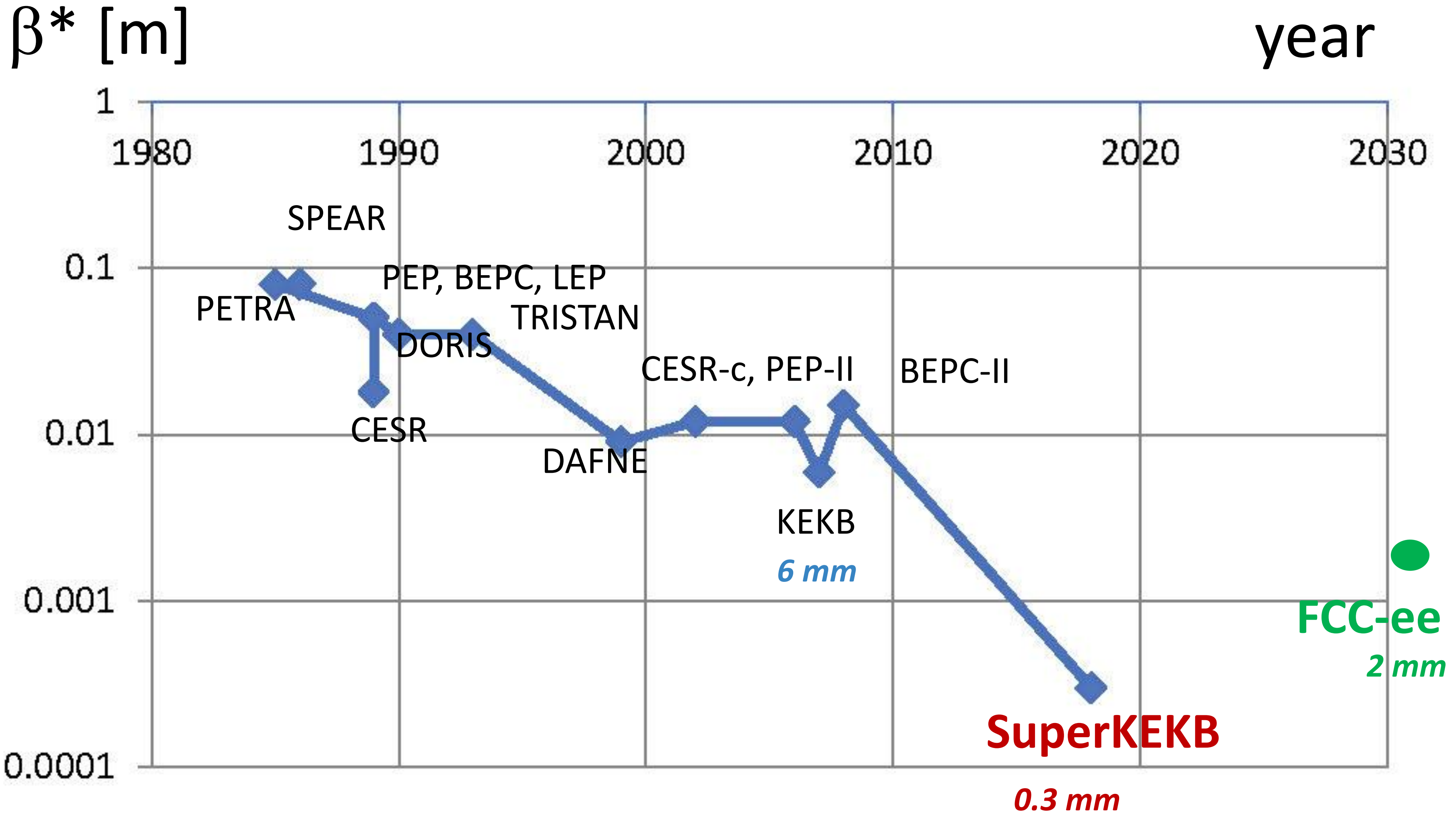
J. Seeman, A. Novokhatski, SLAC
B. Parker, Vikas Teotia, BNL
P. Tavares, CERN



M. Boscolo, F. Palla, INFN

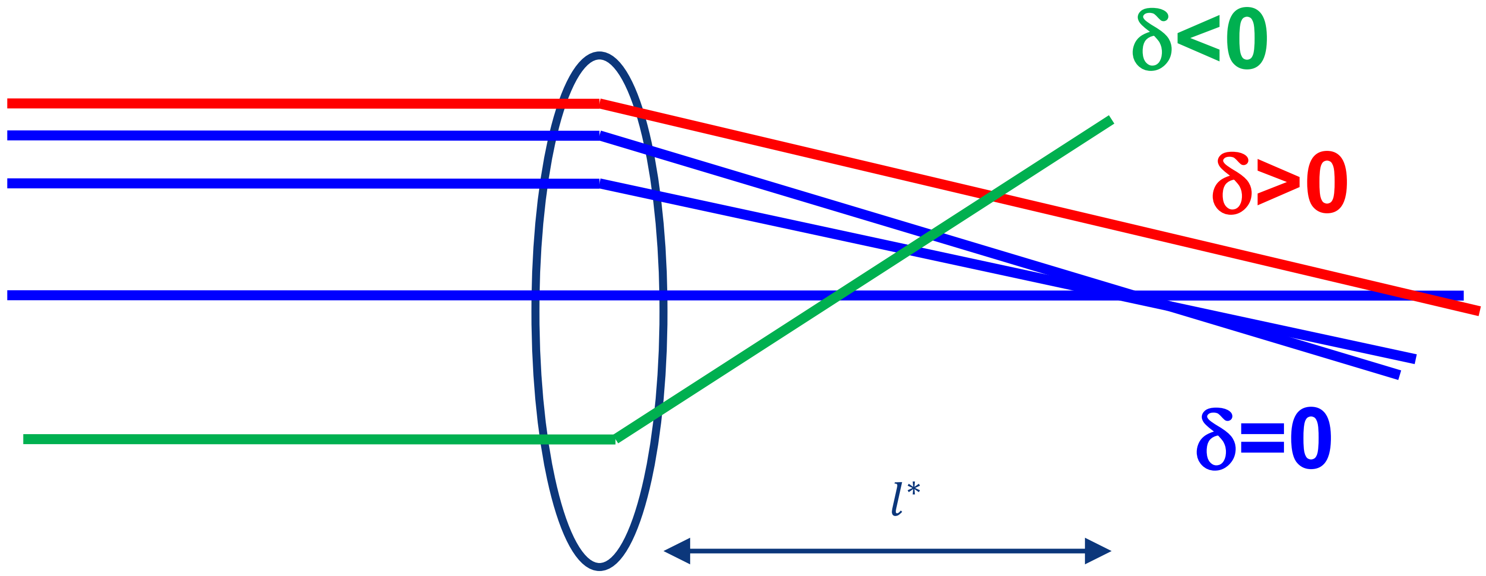


β_y* evolution over 40 years



entering a new regime for ring colliders –
SuperKEKB will pave the way towards $\beta^* \leq 2$ mm

final focus chromaticity



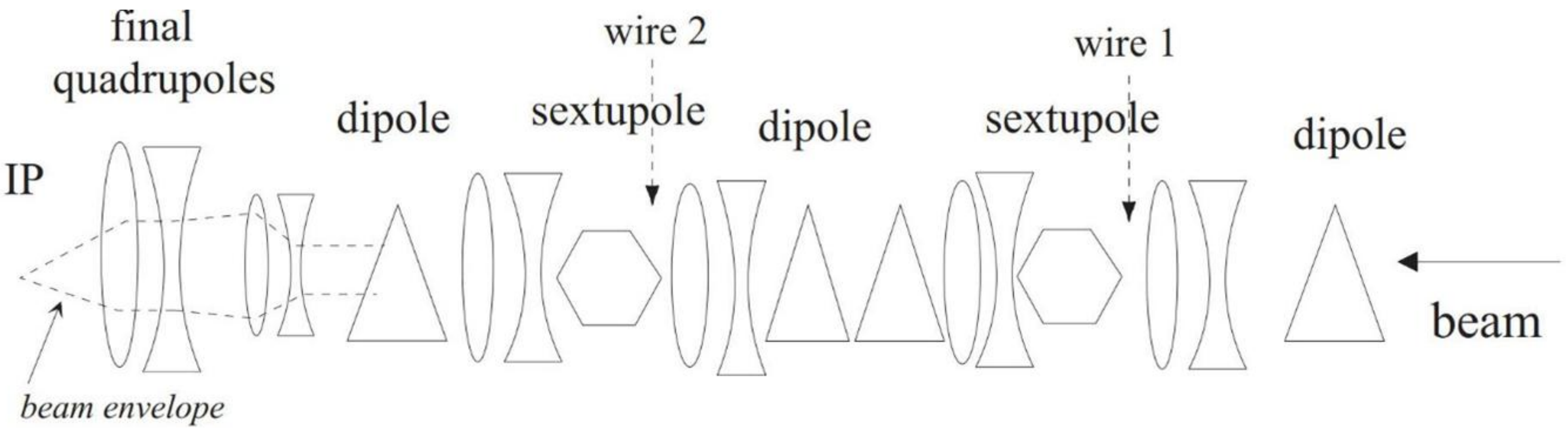
spot size increase due to (uncorrected) chromaticity,

$$\frac{\Delta\sigma_y^*}{\sigma_{y0}^*} = \xi\delta_{rms}$$

$$\sigma_{y0}^* \equiv \sqrt{\beta_y^*\varepsilon_y}, \qquad \xi \approx \frac{l^*}{\beta^*}$$

schematic of a final focus system

sextupole magnets at location with nonzero dispersion
to correct the chromaticity of the final quadrupoles

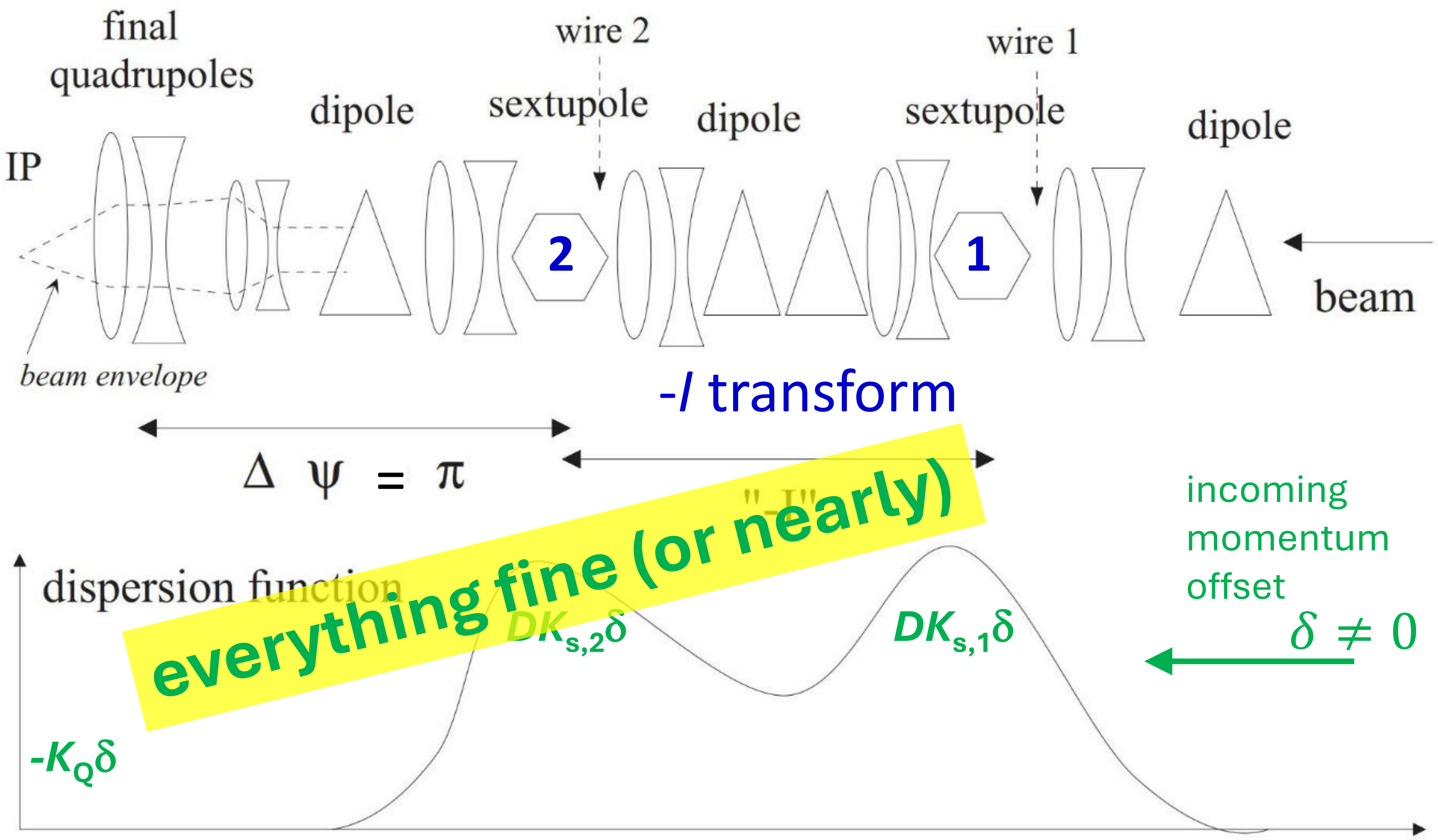


IP

final doublet

dipoles,
quadrupoles,
sextupoles, ...

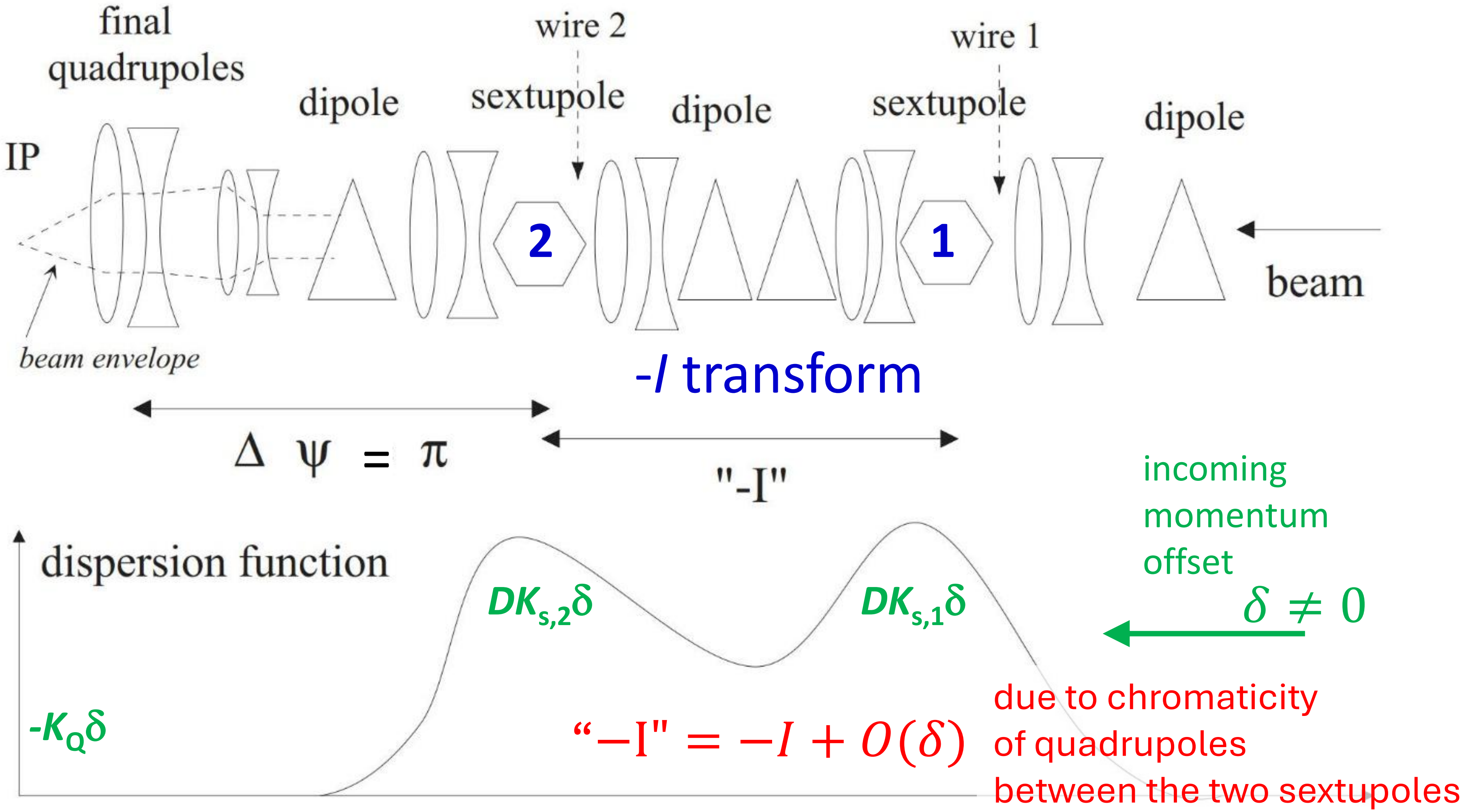
chromatic correction



$$x_2' = -x_\beta' - \frac{1}{2}K_{s,1}(x_\beta^2 + 2x_\beta D_i\delta + D_i^2\delta^2) + \frac{1}{2}K_{s,2}(x_\beta^2 - 2x_\beta D_i\delta + D_i^2\delta^2)$$

$K_{s,1}=K_{s,2}$: $\quad x_2' = -x_\beta' - 2K_s x_\beta D_i\delta.$

one problem: chromatic breakdown of -*I*



$$x_2' = -x_\beta' - \frac{1}{2}K_{s,1}(x_\beta^2 + 2x_\beta D_i\delta + D_i^2\delta^2) + \frac{1}{2}K_{s,2}(x_\beta^2 - 2x_\beta D_i\delta + D_i^2\delta^2)$$

$K_{s,1}=K_{s,2}$: $x_2' = -x_\beta' - 2K_s x_\beta D_i\delta$ $+ c_1\, x\, x'\, \delta + c_2\, x^3\, \delta^2 + \dots$

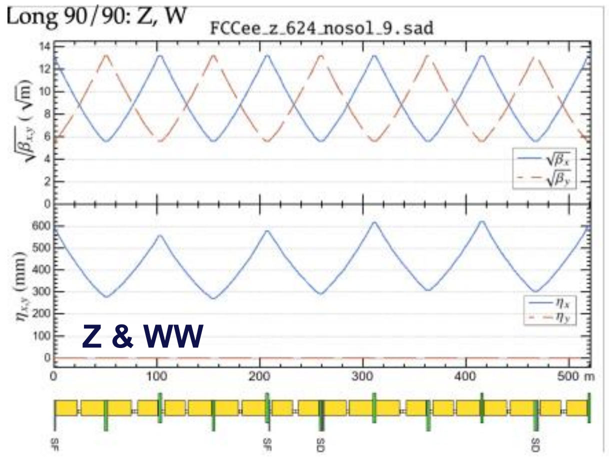
2.3 full ring optics

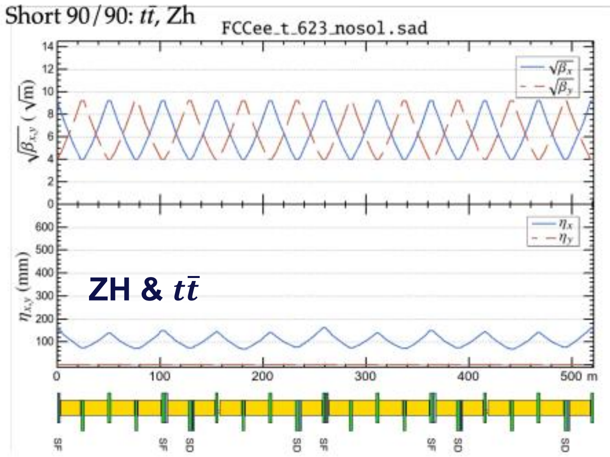
FCC-ee optics baseline GHC alternative LCC

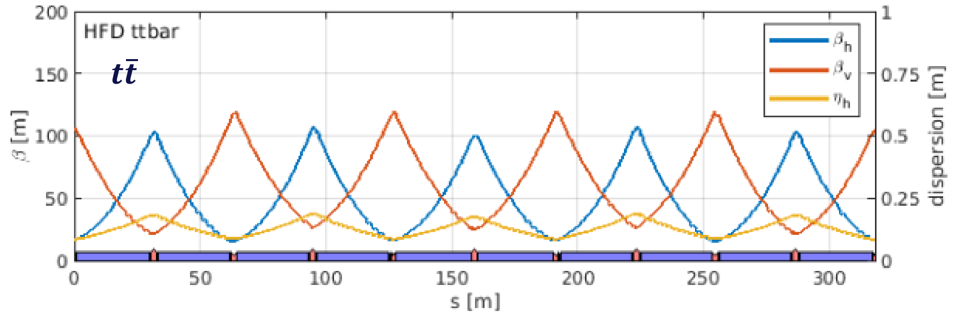
K. Oide et al.

P. Raimondi, S. Liuzzo, et al.

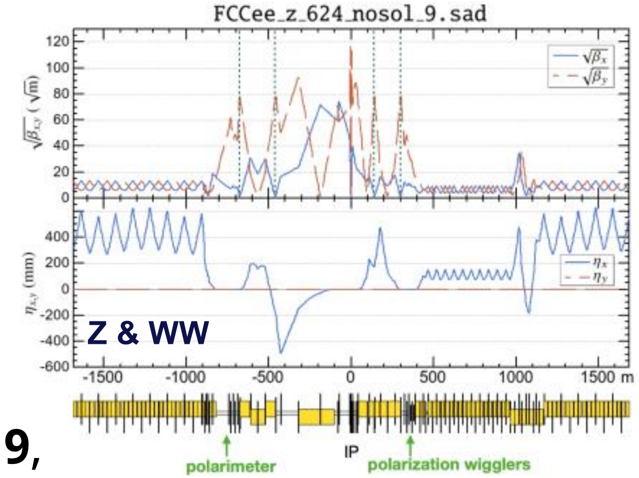
arc

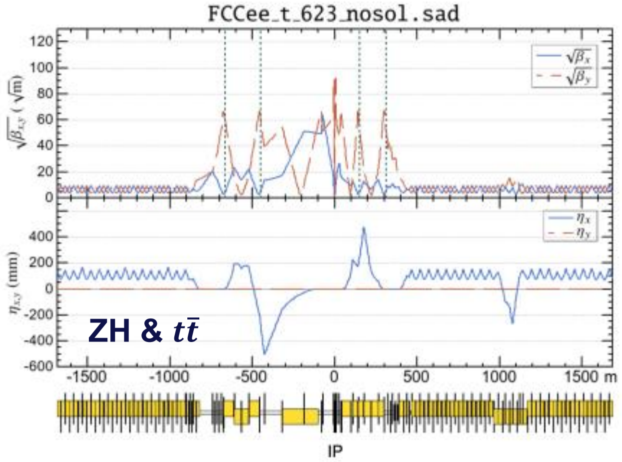


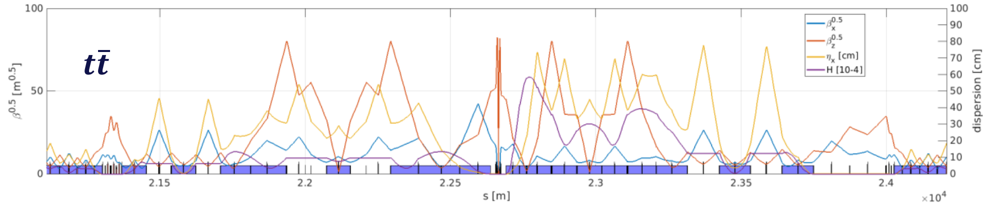




experimental straight







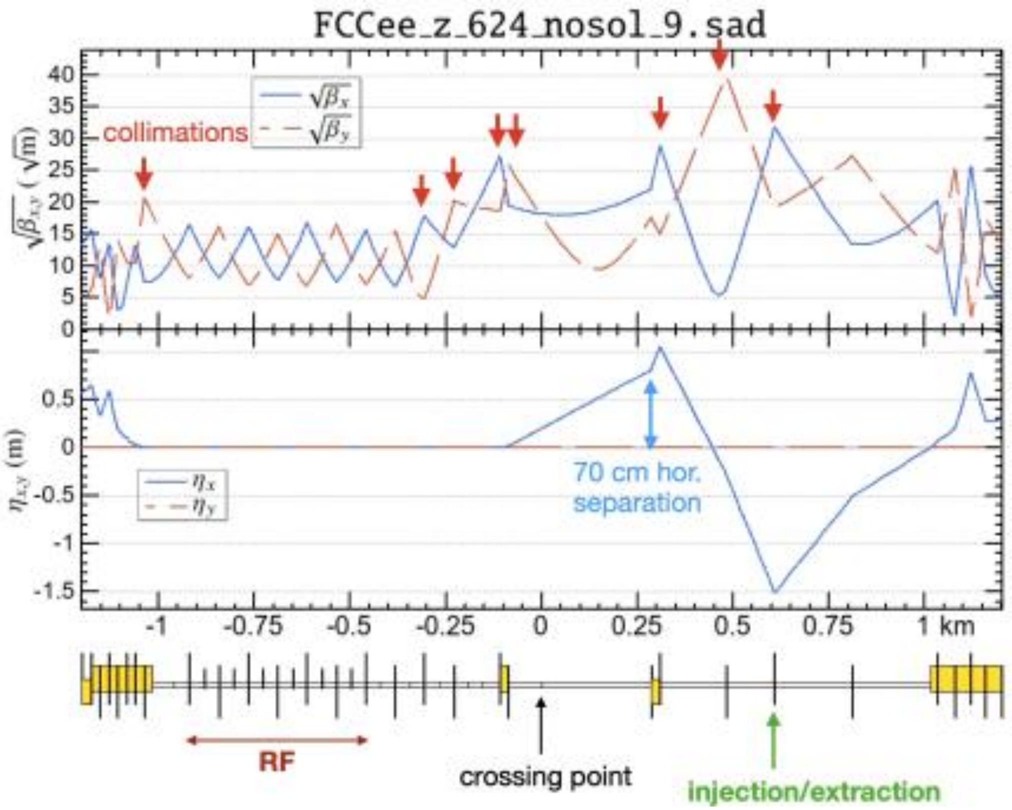
PRAB **19**, 111005 (2016)

→ *March 2026: Decision on Optics*

PRAB **28**, 021002 (2025)

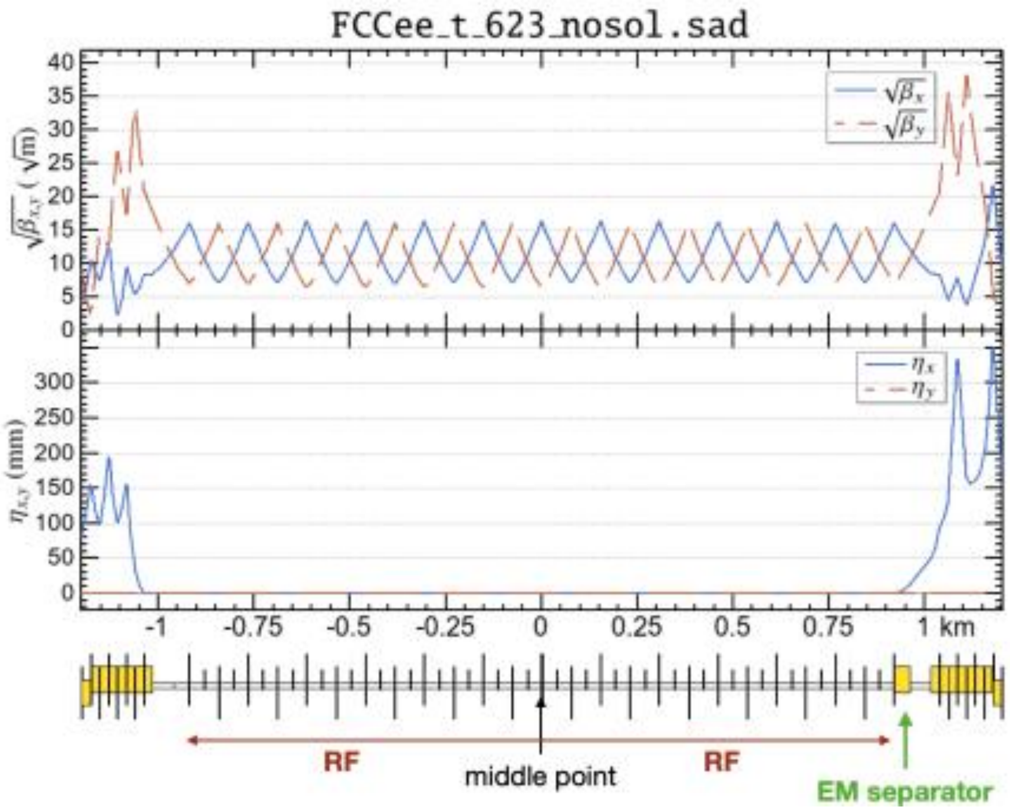
GHC baseline optics: technical straights

Universal optics for all technical insertions in Z/W operation: RF, injection/extraction, & collimation



Maintaining perfect superperiodicity

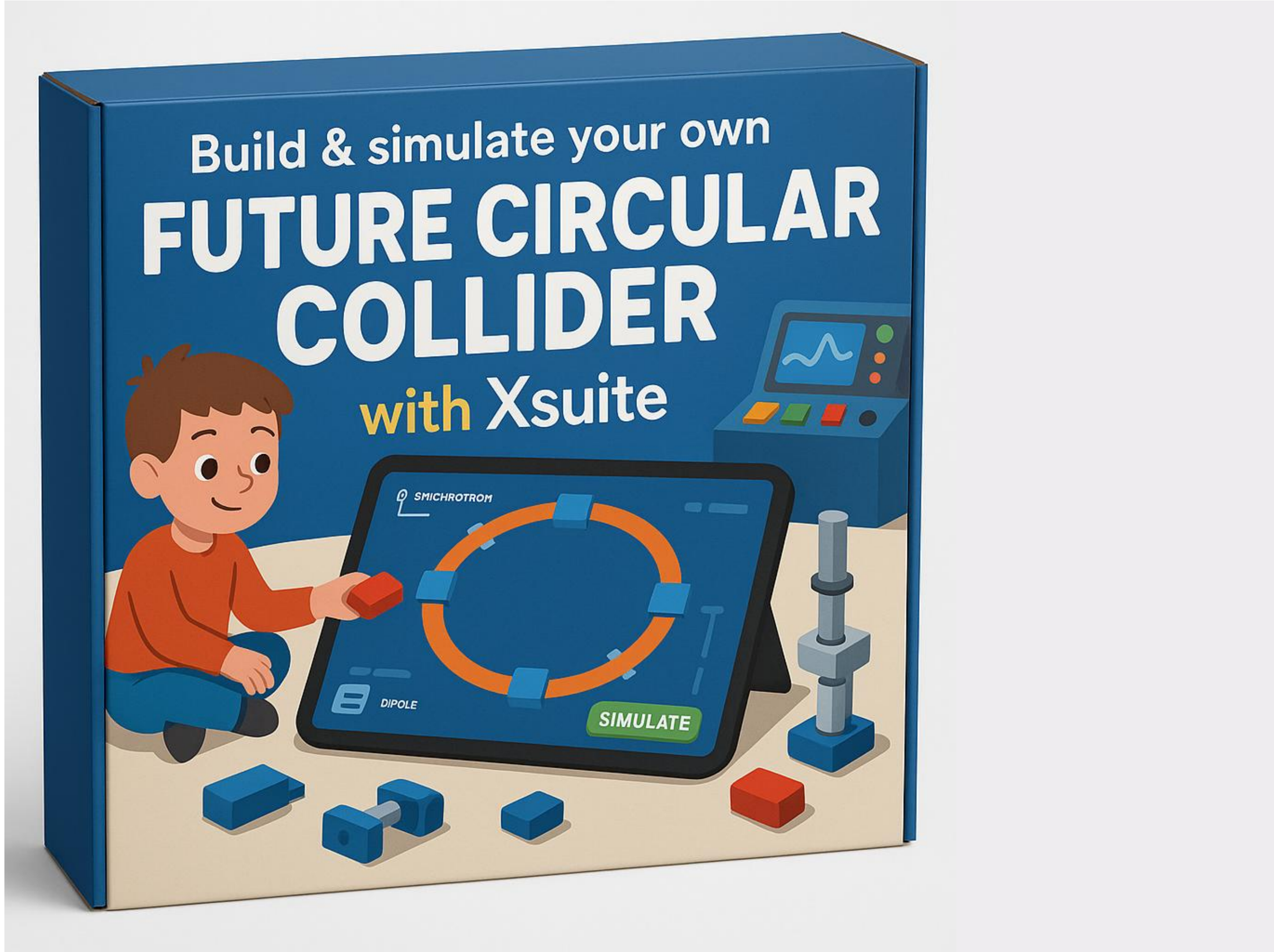
Optics for the common RF section in ZH/ttbar operation



K. Oide

FCC design with Xsuite

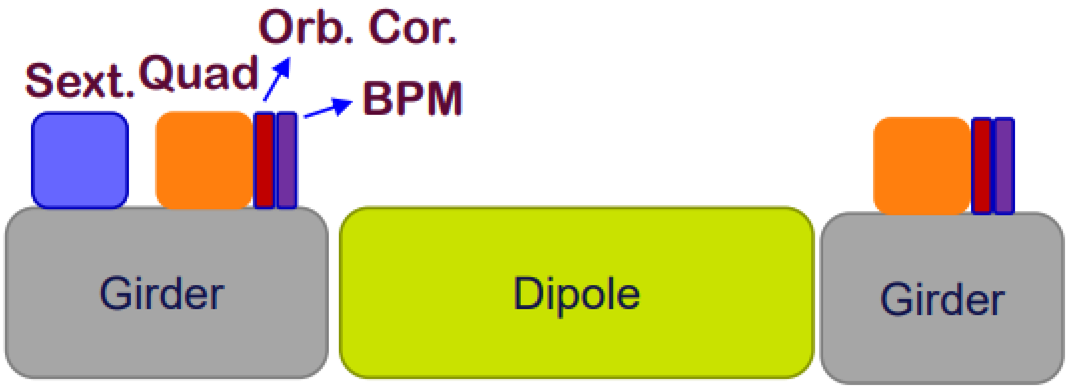
https://xsuite.readthedocs.io/en/latest/



G. Iadarola

tutorials in form of Jupyter notebooks

2.4 errors etc.



Arc alignment and strength tolerances. These values correspond to one sigma Gaussian distribution truncated at 2.5 sigma. Quadrupoles and sextupoles are placed on top of common girders.

Element	$\sigma_{x/y}$ [μm]	$\sigma_{\theta/\psi/\phi}$ [μrad]	$\Delta k/k$ [10^{-4}]
Arc quads & sext.	50	50	2
Dipoles	1000	1000	2
Girders	150	150	-
BPMs-to-quad	100	-	-

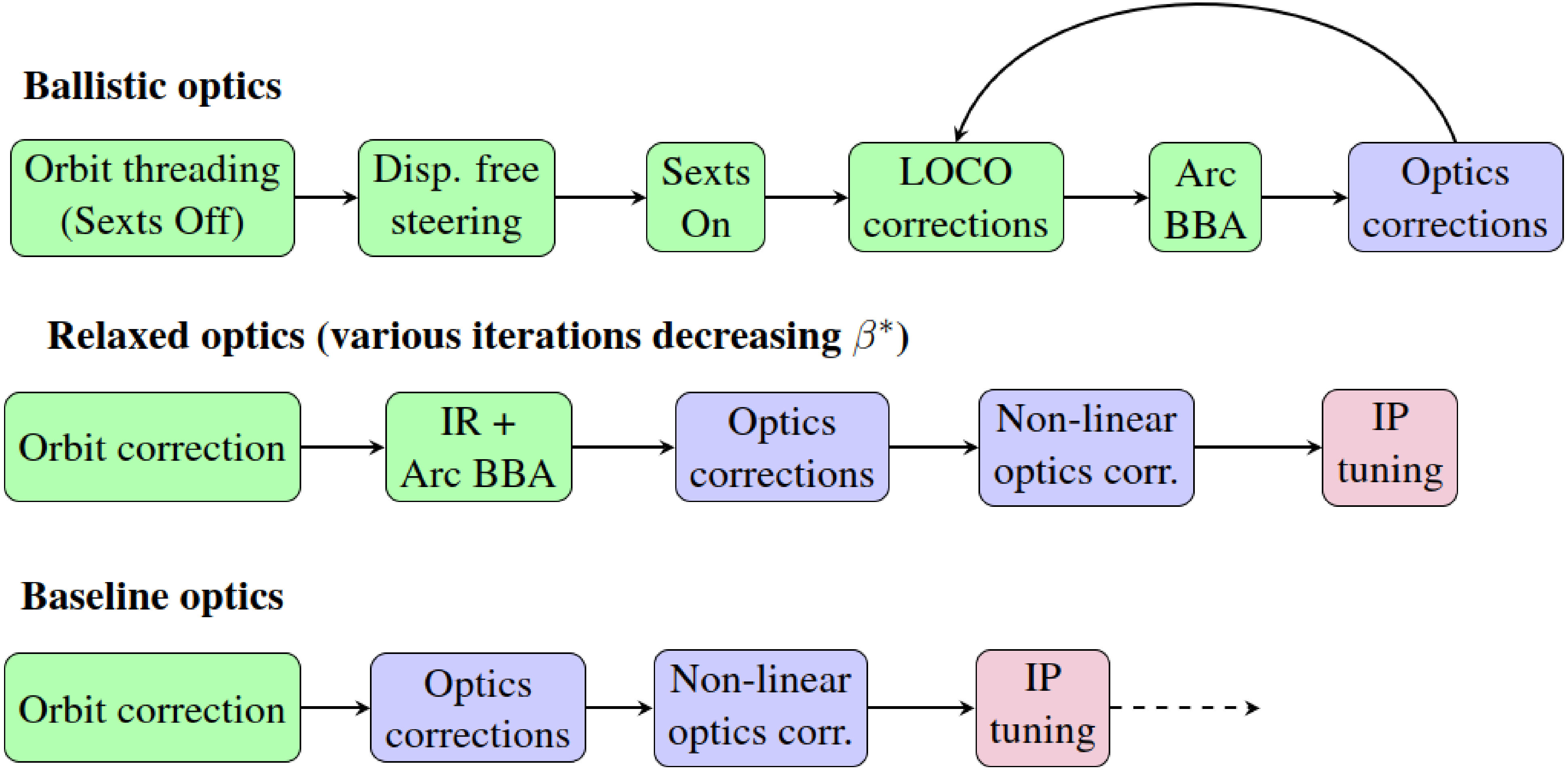
Arc BPM performance specifications.

Closed orbit resolution	0.1 μm
Turn-by-turn (TbT) position resolution	1 μm
Number of turns in TbT mode	50000

Location of arc magnet correctors and BPMs.

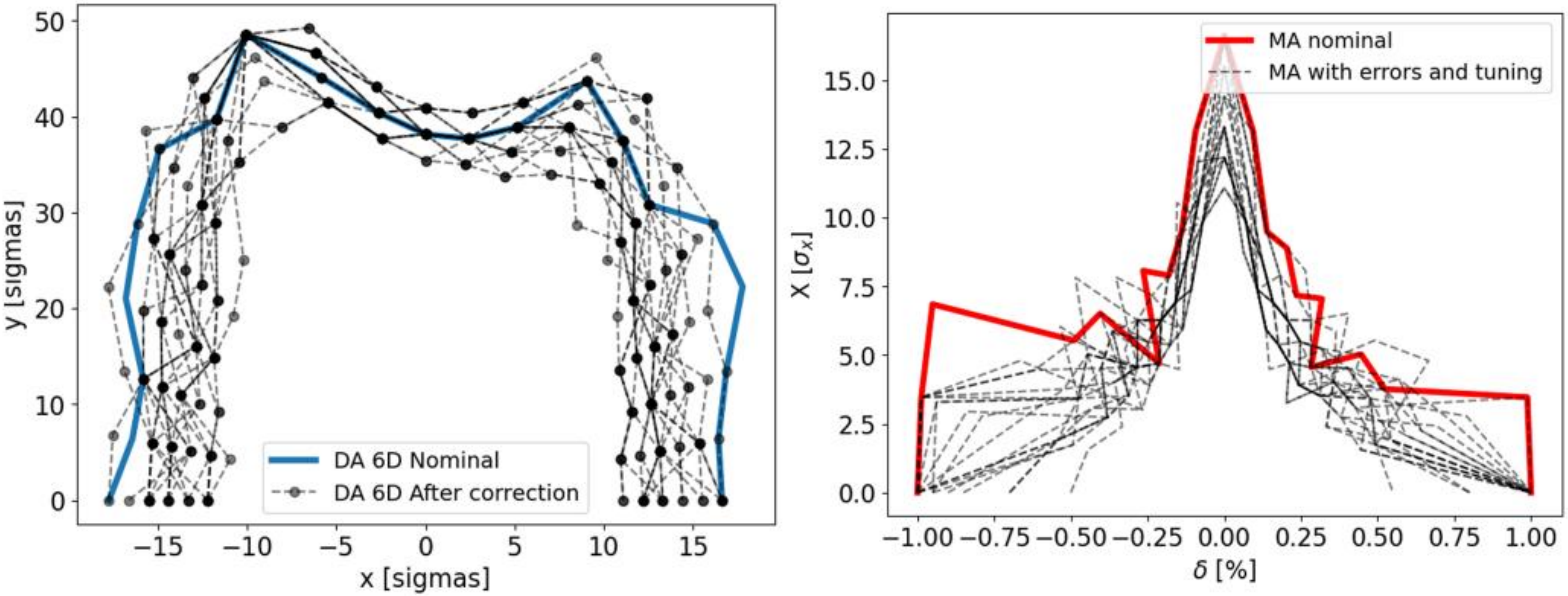
Device	Location
Horizontal orbit corrector	Embedded at the edge of main dipole next to main quadrupole
Vertical orbit corrector	Embedded at the sextupole or stand-alone
Quadrupolar corrector	Trim coil in all main quadrupoles
Skew quadrupole	Embedded at the sextupole
BPM (H & V)	Attached to the main quadrupole

Optics commissioning sequence



Steps during the FCC-ee optics commissioning starting with the most relaxed optics, the ballistic optics.

Simulated performance of baseline optics with errors

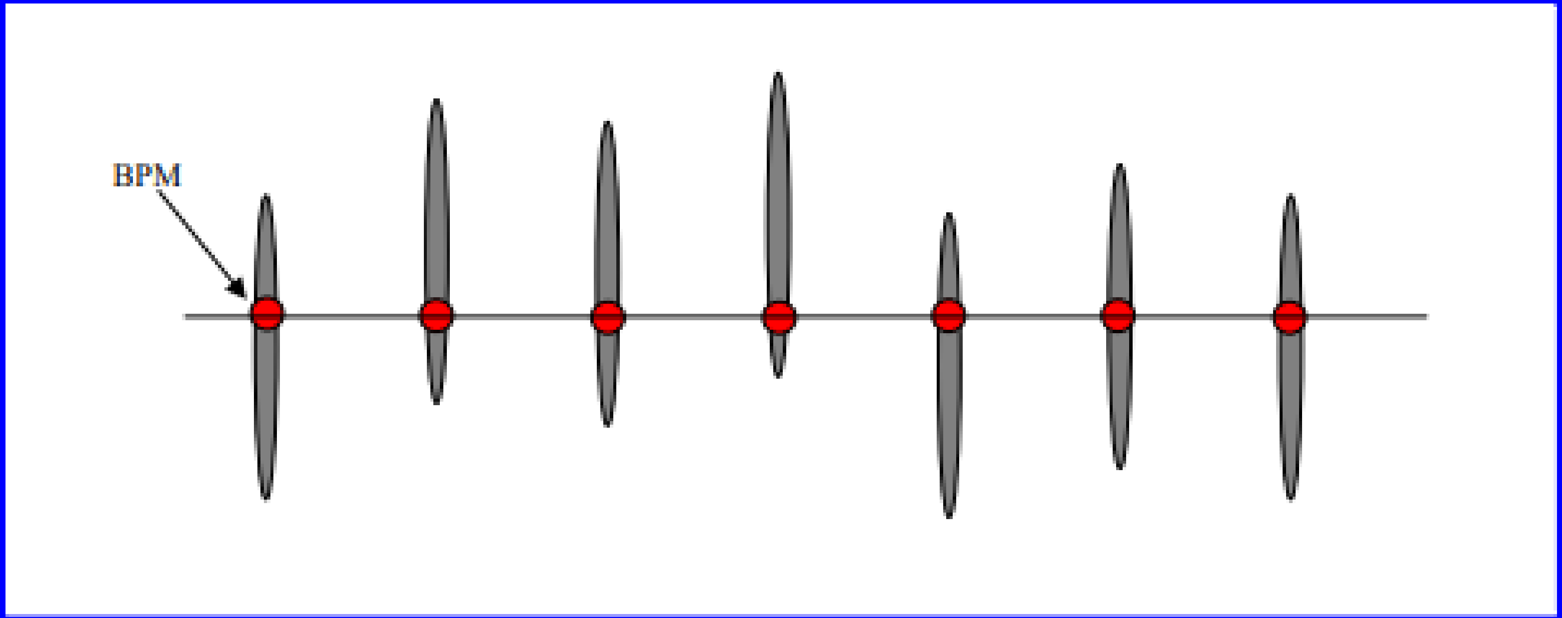


Dynamic Aperture (left) and Momentum Acceptance (right) after linear optics corrections having used the errors described before.

Median rms values of several optics parameters before (after sextupole ramping) and after linear optics correction (nominal lattice). ΔÈ stands for phase advance deviations between nearby BPMs.

Parameter	Before correction (rms)	After correction (rms)
horizontal orbit (μm)	120.2	120.5
vertical orbit (μm)	217.5	217.6
$\Delta\beta_x/\beta_x$ (%)	7.41	0.29
$\Delta\beta_y/\beta_y$ (%)	15.79	2.81
ΔD_x (mm)	57.79	0.28
ΔD_y (mm)	62.24	2.80
ε_h (nm)	0.72	0.71
ε_v (pm)	26.01	0.57
horiz. $\Delta\psi$ $[2\pi]$	1.1×10^{-2}	2.9×10^{-4}
vert. $\Delta\psi$ $[2\pi]$	1.9×10^{-2}	2.3×10^{-3}
Re f_{1001}	4.9×10^{-2}	1.7×10^{-4}
Im f_{1001}	4.4×10^{-2}	5.2×10^{-5}
Re f_{1010}	3.7×10^{-2}	1.3×10^{-4}
Im f_{1010}	3.7×10^{-2}	1.3×10^{-4}

Scenario 1: Quad offsets, but BPMs aligned



Assuming:

- a BPM adjacent to each quad

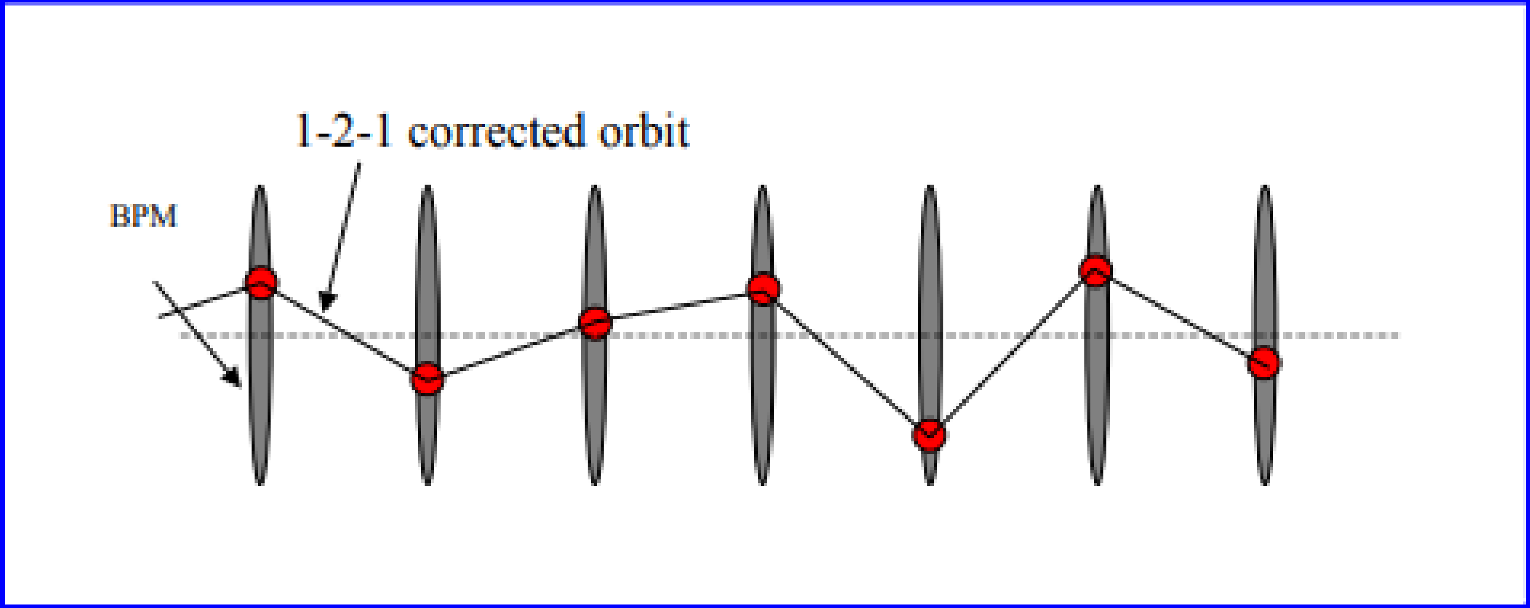
- a 'steerer' at each quad

steerer { quad mover / dipole corrector

simply apply one to one steering to orbit

N. Walker, USPAS 2003, Santa Barbara

Scenario 2: Quads aligned, BPMs offset



one-to-one correction BAD!

Resulting orbit not Dispersion Free ⇒ emittance growth

Need to find a steering algorithm which effectively puts BPMs on (some) reference line

beam-based alignment
followed by dispersion-free steering

real world scenario: some mix of scenarios 1 and 2

N. Walker,
USPAS 2003,
Santa Barbara

Beam-based alignment (BBA)

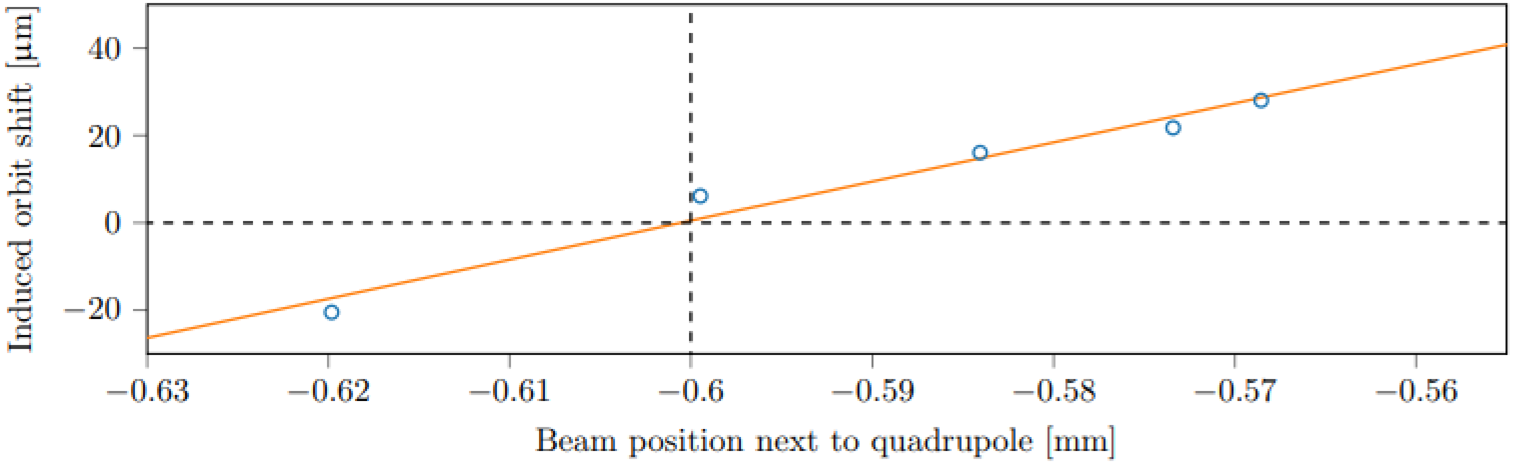
BBA can be performed after the sextupoles have been switched on

sheer size of the FCC → parallel approaches are explored, aimed at achieving approximately 10 to 20 μm effective alignment after BBA

Using Parallel Quadrupole Modulation System (PQMS), a technique which has already successfully been tested at SLAC/SPEAR, is applied to the FCC-ee.

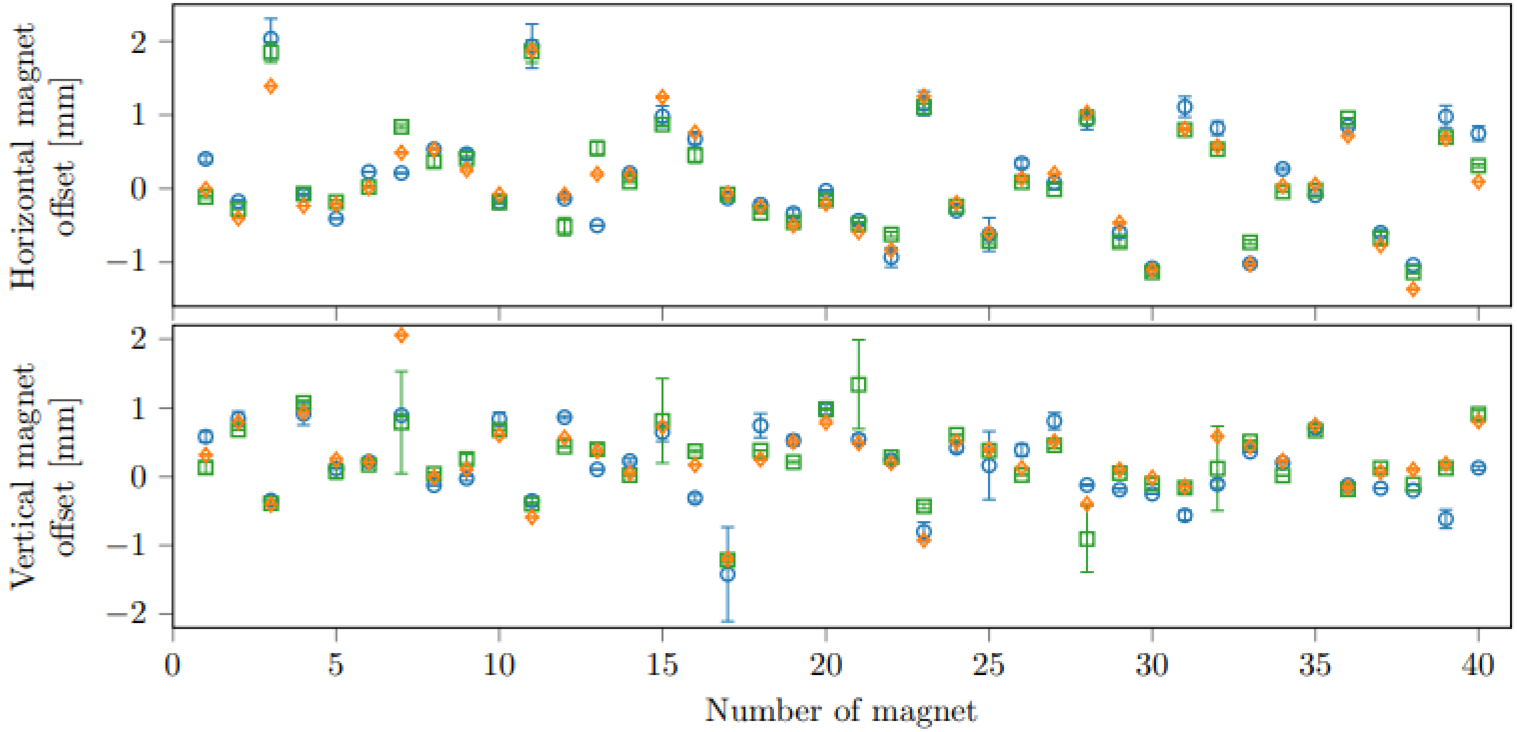
Modulating 10 quadrupoles in parallel with a $\Delta K/K$ of 2%, distributed equally over one arc, and using a calibrated lattice with 1 μm BPM resolution, an accuracy below 20 um for vertical and horizontal arc quadrupole BBA is expected.

BBA tests for FCC-ee at KIT/KARA in Karlsruhe



Dependence of measured induced orbit shift on beam position close to quadrupole.

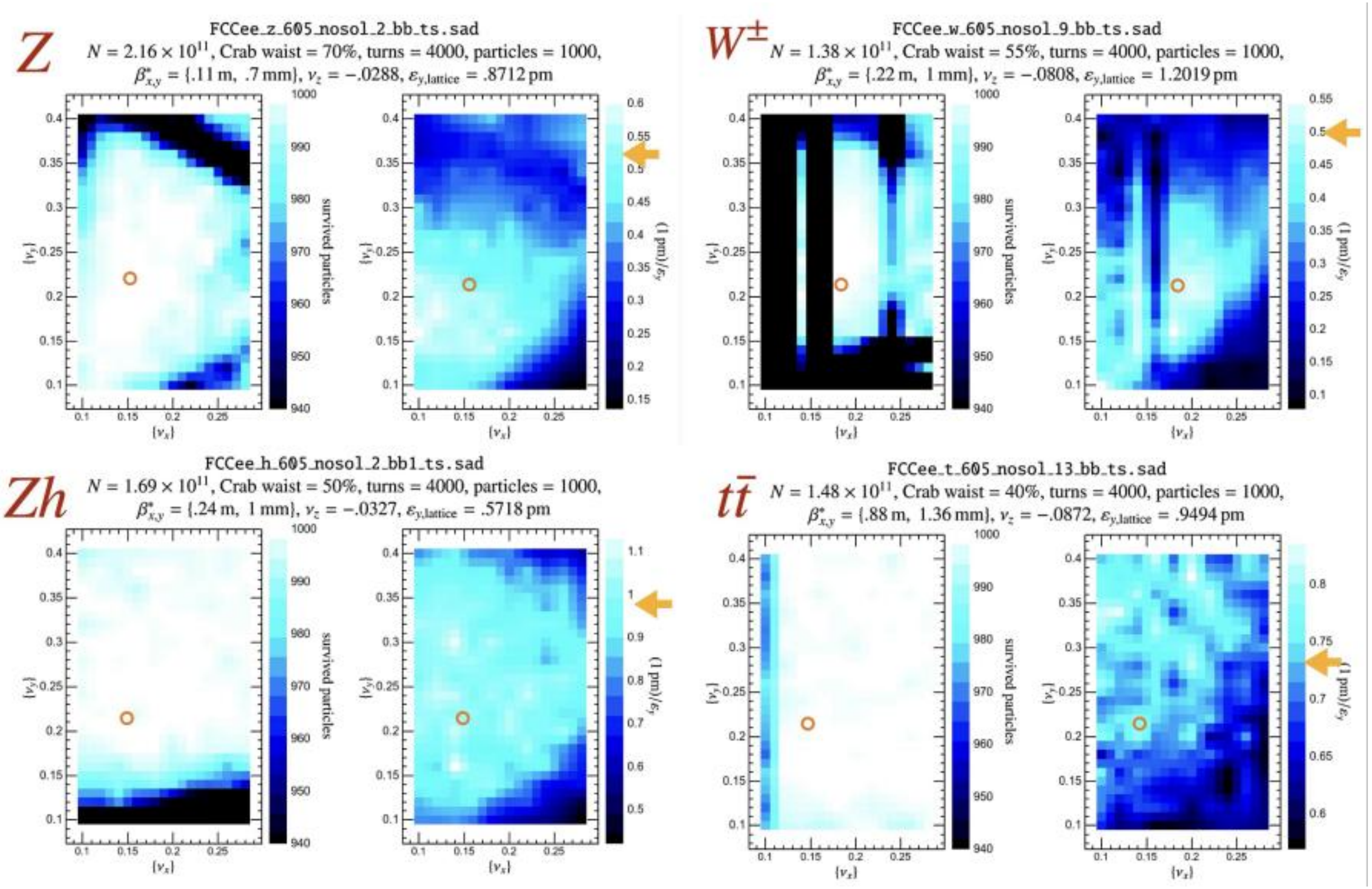
Estimated magnet offsets with respect to closest BPM using linear (blue), rms (orange) and parallel BBA (green).



C. Goffing / KIT & CERN

2.5 beam-beam performance

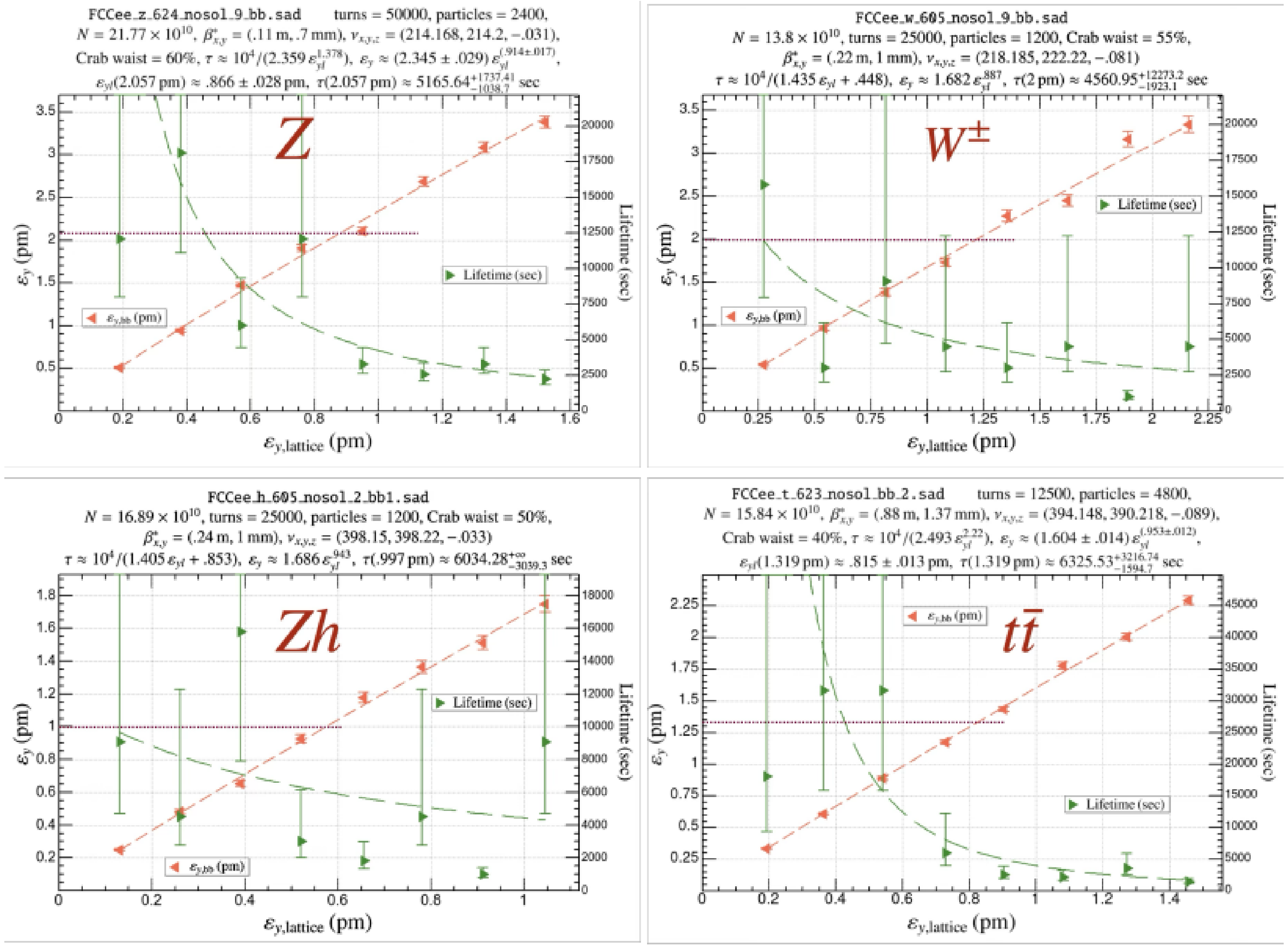
GHC optics



tune scan of the beam-beam effect with the full lattice

K. Oide

vertical bare lattice emittance required with beam-beam



results of beam-beam tracking with lattice and beamstrahlung for each energy

K. Oide

further reading

M. Sands, The Physics of Electron Storage Rings, SLAC Report 121 (1970)

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H. Wiedemann, Synchrotron Radiation, Springer-Verlag Berlin Heidelberg (2003)

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