e+e- Circular Colliders
Future – Present – Past

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JUAS I

Session on Colliders

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Energy and Luminosity

High energy physics experiments with particle accelerators demand improved statistics and discovery potential
Solution:
-) Higher energy
-) Higher luminosity

- **Energy:**
- Center-of-mass energy for 2 colliding beams

$$E_{com} = E_1 + E_2$$

- **Luminosity:**
- Collision rate proportional to cross-section and luminosity

$$\frac{\mathrm{d}R}{\mathrm{d}t} = \mathcal{L}\,\sigma$$

- At interaction point colliding beams

Instantenous:

$$\mathcal{L} = \frac{f_{\mathrm{rev}} N_1 N_2}{4\pi\sigma_x\sigma_y} S$$

f_{rev} … revolution frequency
$N_{B1,2}$ … number of particles per beam
$\sigma_{x,y}$ … beam sizes
S … reduction factor

Integrated:

$$\mathcal{L}_{\mathrm{int}} = \int_{t_1}^{t_2} \mathcal{L}\,\mathrm{d}t$$

Typical unit:
$1\ fb^{-1} = 10^{39}\ cm^{-2}$

Future Circular Collider Study

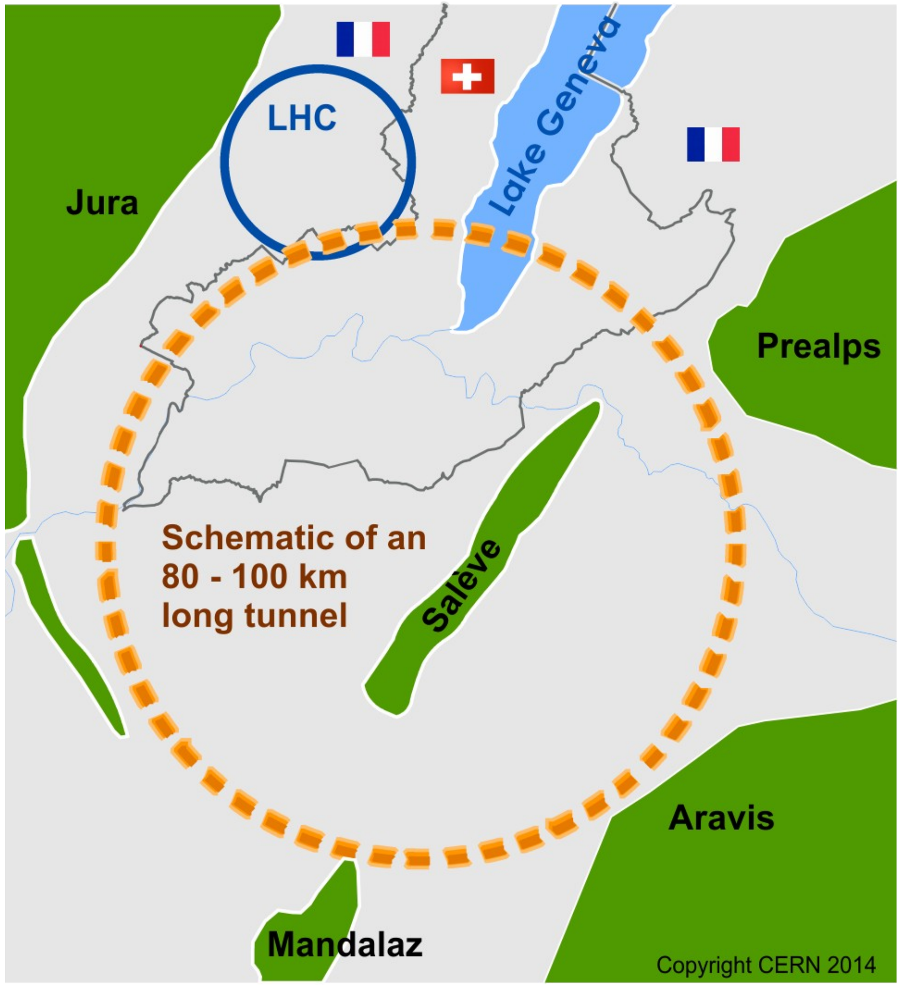
- International collaboration with CERN as host lab
- Launched in 2014

- 80 – 100 km infrastructure in Geneva area

- pp-collider: FCC-hh

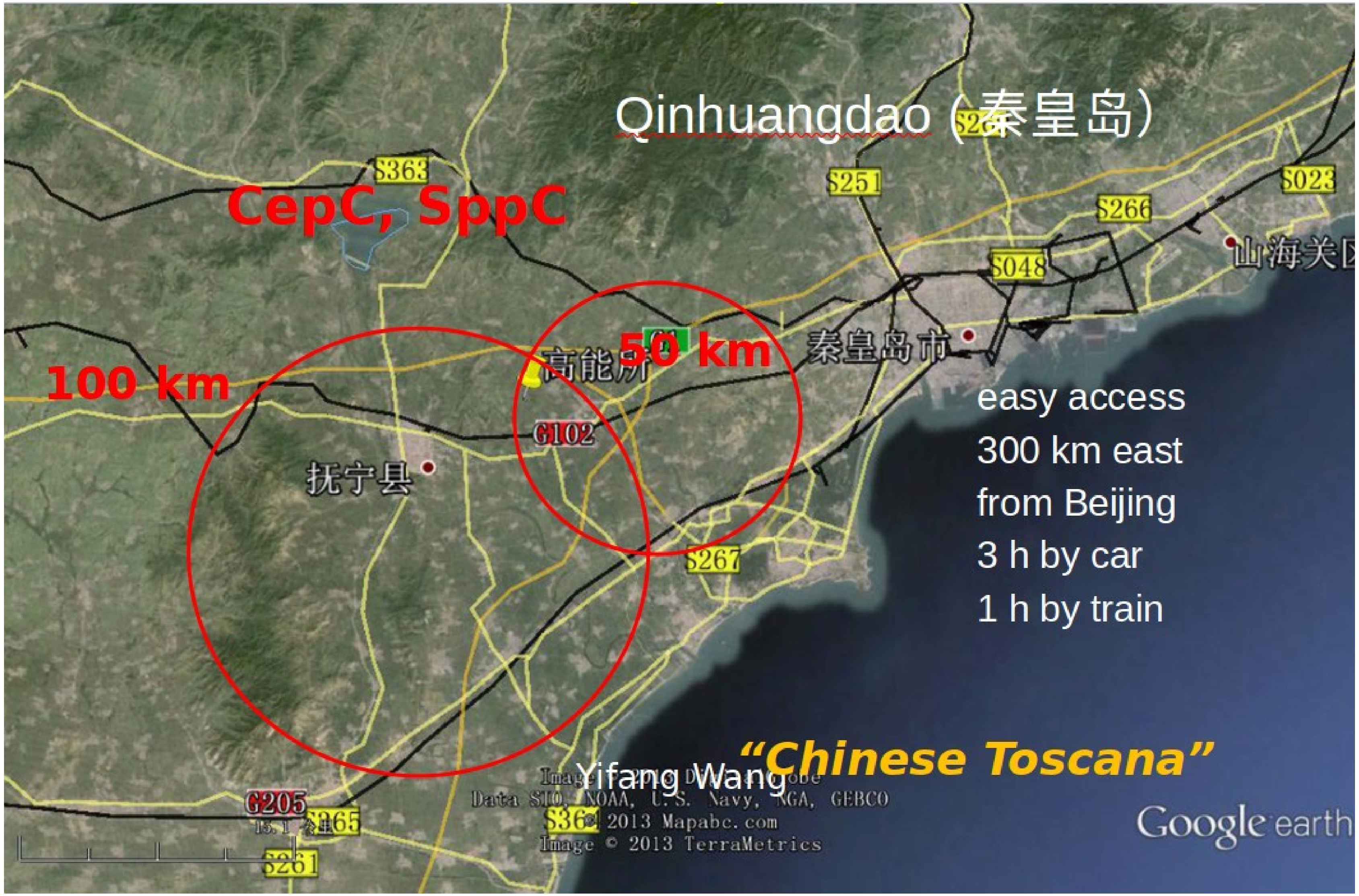
- e+e- collider: FCC-ee
- Could be possible first step before FCC-hh

- e-p collider: FCC-eh



CepC/SppC Study

Yifang Wang



ESPP Update 2020

In 2020 the European strategy upgrade of particle physics (ESPP) expressed the long-term plan for particle colliders

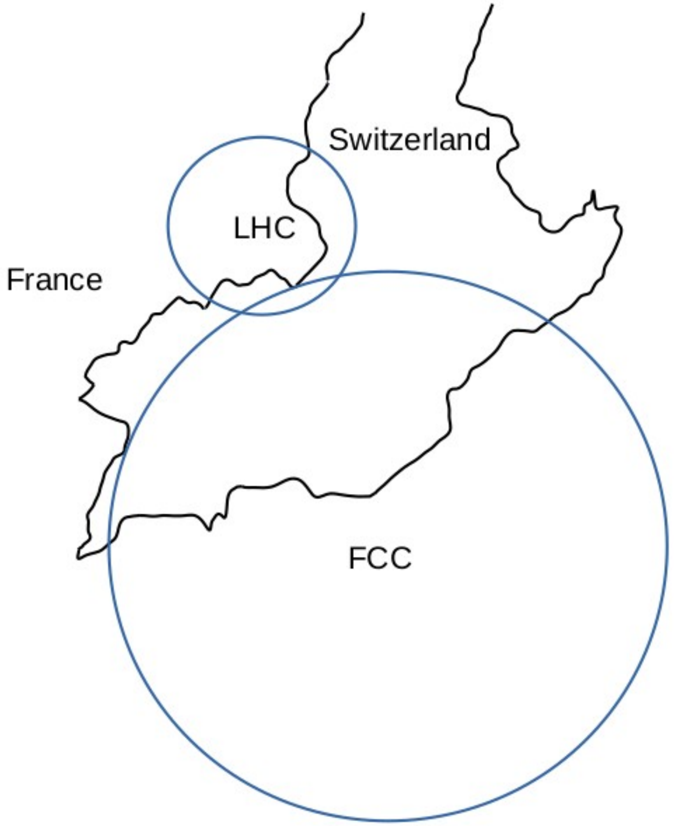
Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a center-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage.

Lepton Future Circular Collider, FCC-ee
Hadron Future Circular Collider, FCC-hh
} **FCC Integrated Project**

Future Circular Colliders

Inspired by LEP-LHC programm

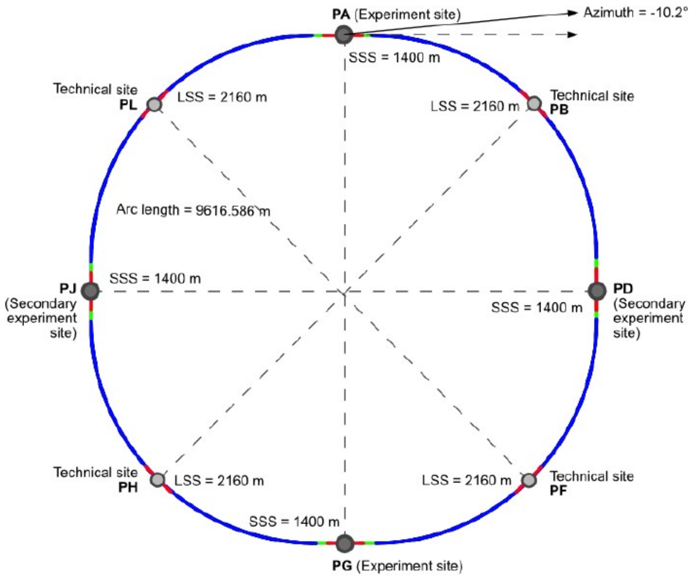
Re-using CERN infrastructure



Compatible lattice designs

FCC-ee

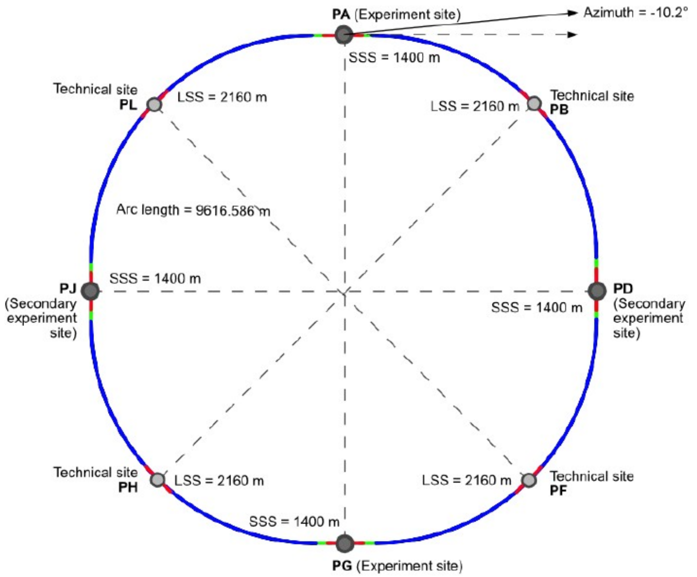
Electron-positron collider



~ 2045 - 2060

FCC-hh

Proton-proton collider

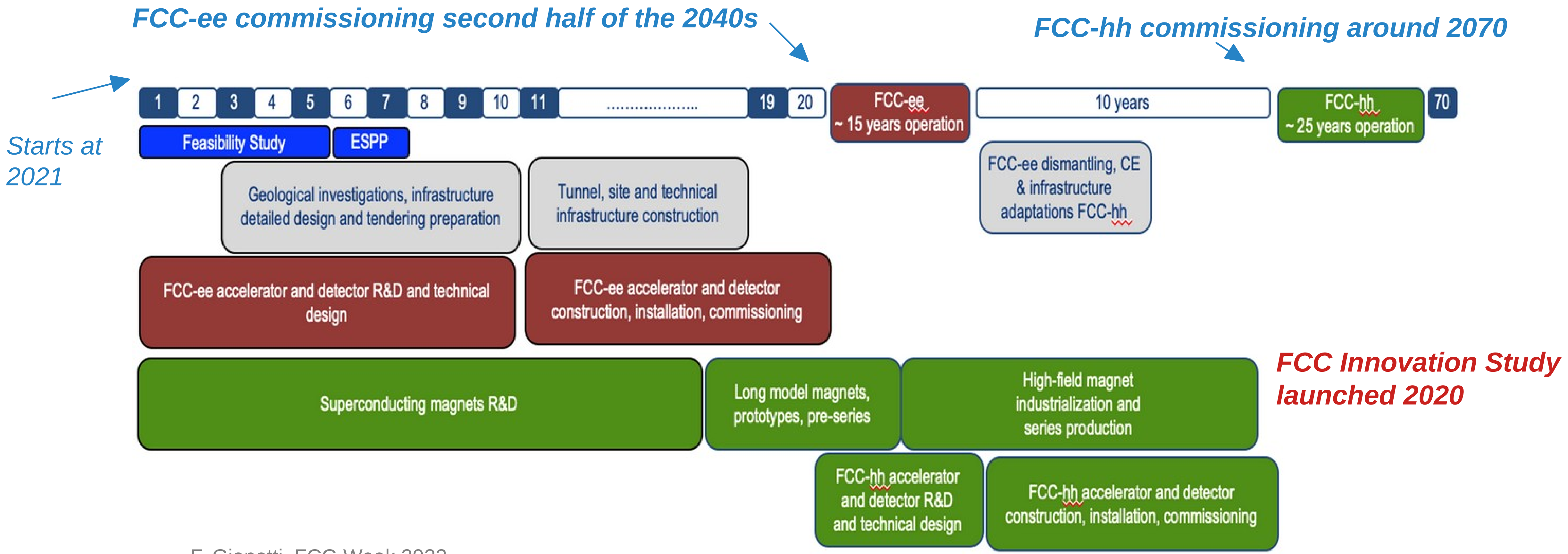


~ 2070 - 2090

Seminar: M. Giovannozzi

FCC Integrated Project

Lepton collider (FCC-ee) followed by hadron collider (FCC-hh)



F. Gianotti, FCC-Week 2022.

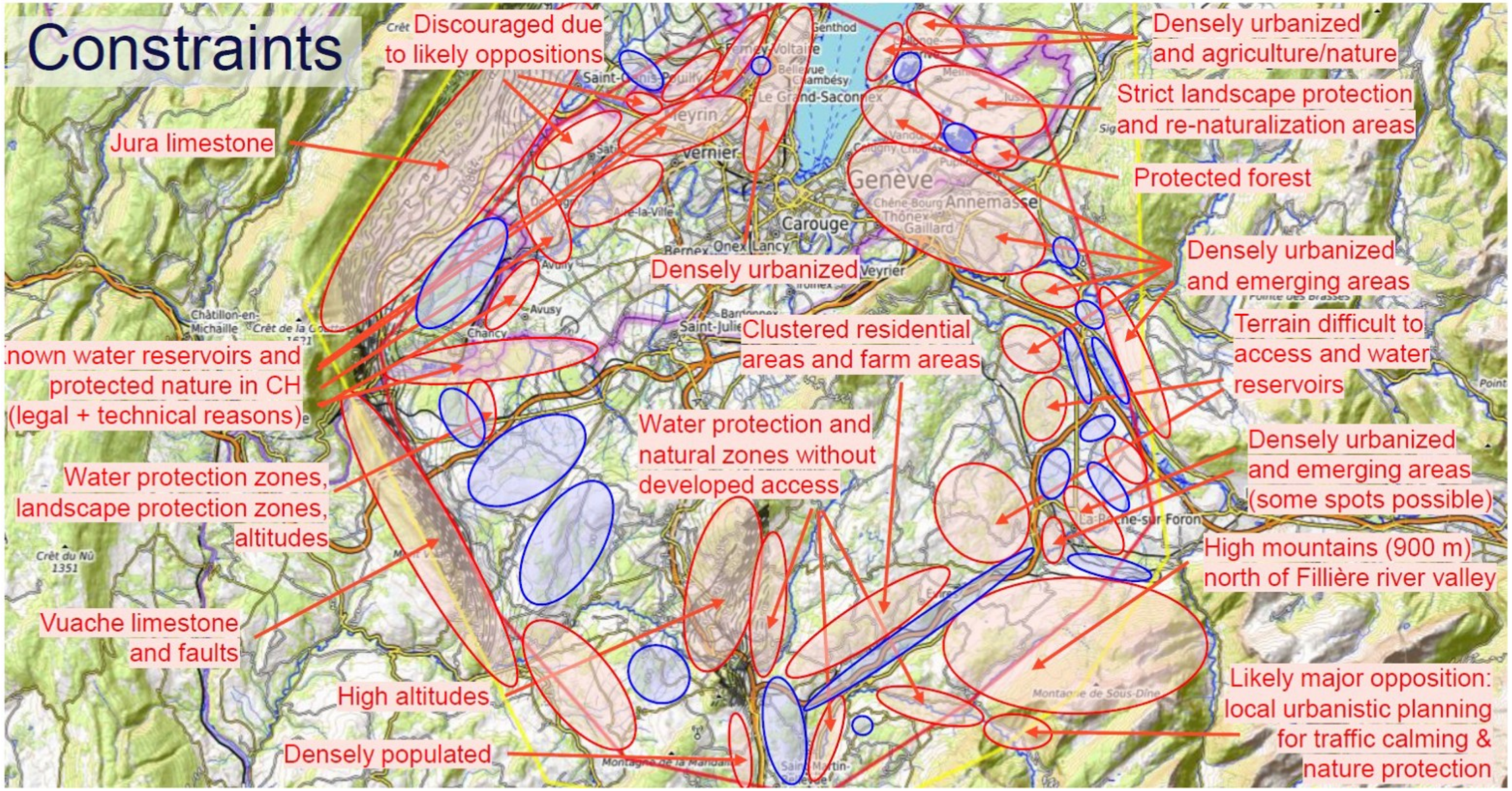
Placement Studies

Constraints:

- 8 or 12 surface sites
- Topography
- Geology
- Infrastructure
- …

Result:

89 km to 91 km best geolical and territorial fits

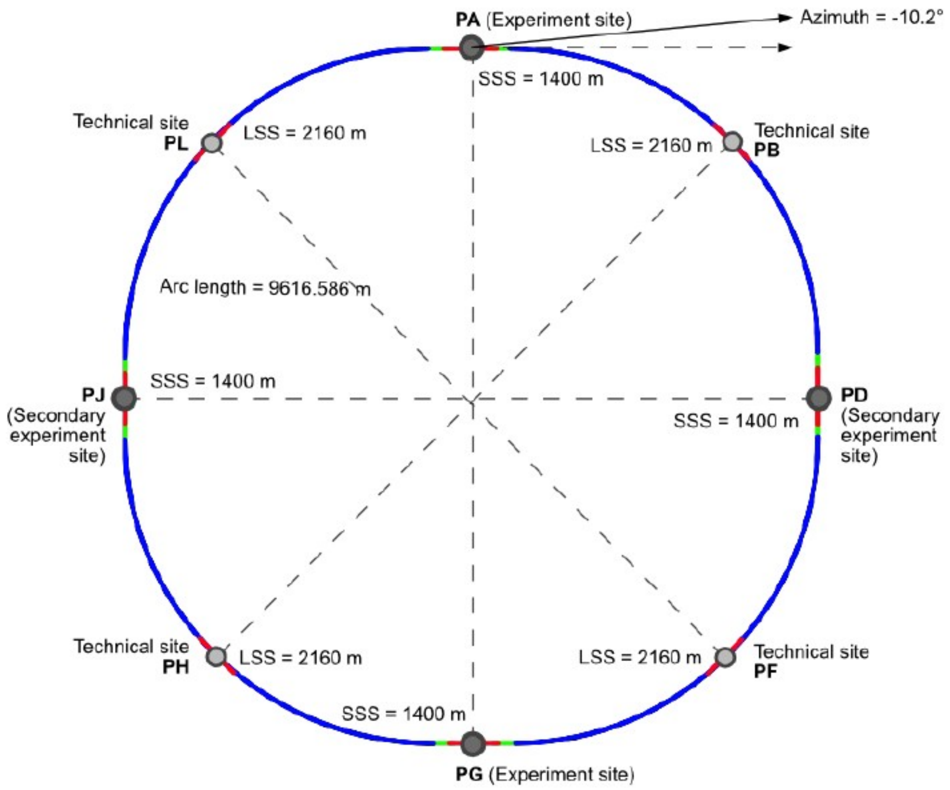


P. Boillon: indico.cern.ch/event/995850

FCC-ee Design

- 8 surface sites, ~90.7 km circumference
- Diverse physics program with beam energies:
  - 45.6 GeV: Z-pole
  - 80 GeV: W-pair production
  - 120 GeV: ZH-production (max H-rate)
  - 182.5 GeV: top-pair threshold
  - (63 GeV requires monochromatization)

What do we need to consider when designing the next e+e- circular collider?



J. Gutleber, FCC-week 2022.

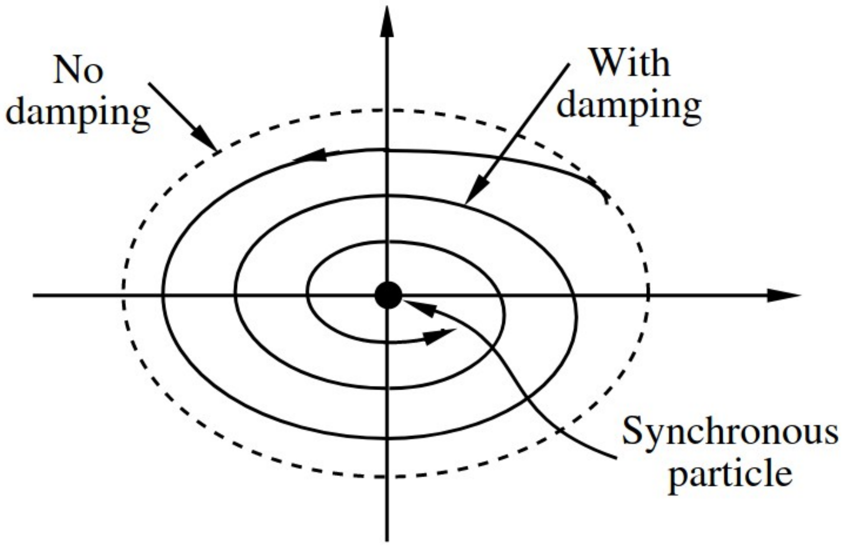
Synchrotron Radiation

- Stronger synchrotron radiation for electrons than for hadrons

→ Synchrotron radiation power 10^{13} greater for electrons than for protons

$$P \propto \frac{E^4}{m_0^4}$$

- Leads to natural damping of emittance



W. Barletta, USPAS lectures on synchrotron radiation, 2009.

- Photons emitted in discrete units
- Disturb particles trajectories in dispersive region
- → Noise = quantum fluctuations
- Leads to emittance increase

Horizontal equilibrium emittance:

$$\epsilon_0 = C_q \gamma_0^2 \frac{I_5}{j_x I_2}$$

Cq… quantum radiation constant
I_2/I_5 … radiation integrals
Jx … partition number

In a flat collider with Dy = 0, vertical emittance dominated by coupling and imperfections!

Polarization

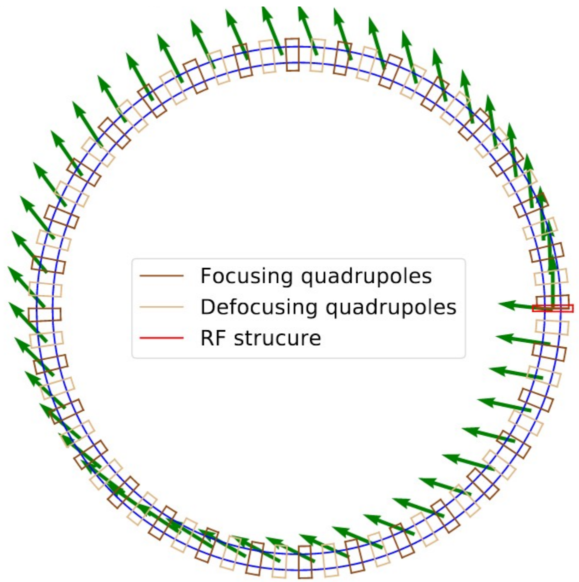
- On average every 10^{10th} emitted photon flips the spin
- Probability for electrons to emit a photon depends slightly on initial spin state
- → Polarization built-up
- → Max. theoretical polarization of 92.4 %
- Spin precesses when particle travels trough the lattice → spin tune

Polarization built-up time about 6 orders of magnitude slower than synchrotron radiation damping

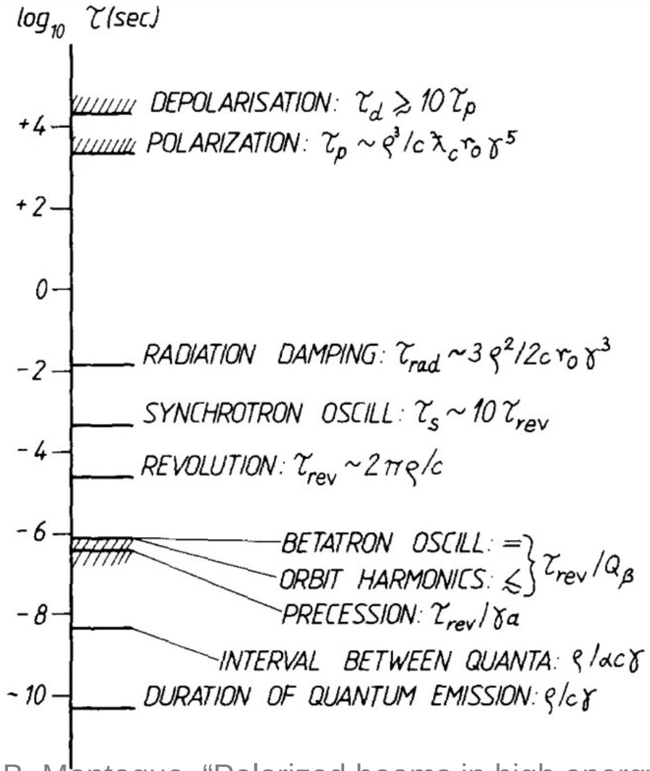
In an ideal storage ring:

E … energy
m … mass
c … speed of light
ν … spin tune
a … anomalous magnetic dipole moment

$$E = mc^2 \left(\frac{\nu}{a} - 1\right)$$



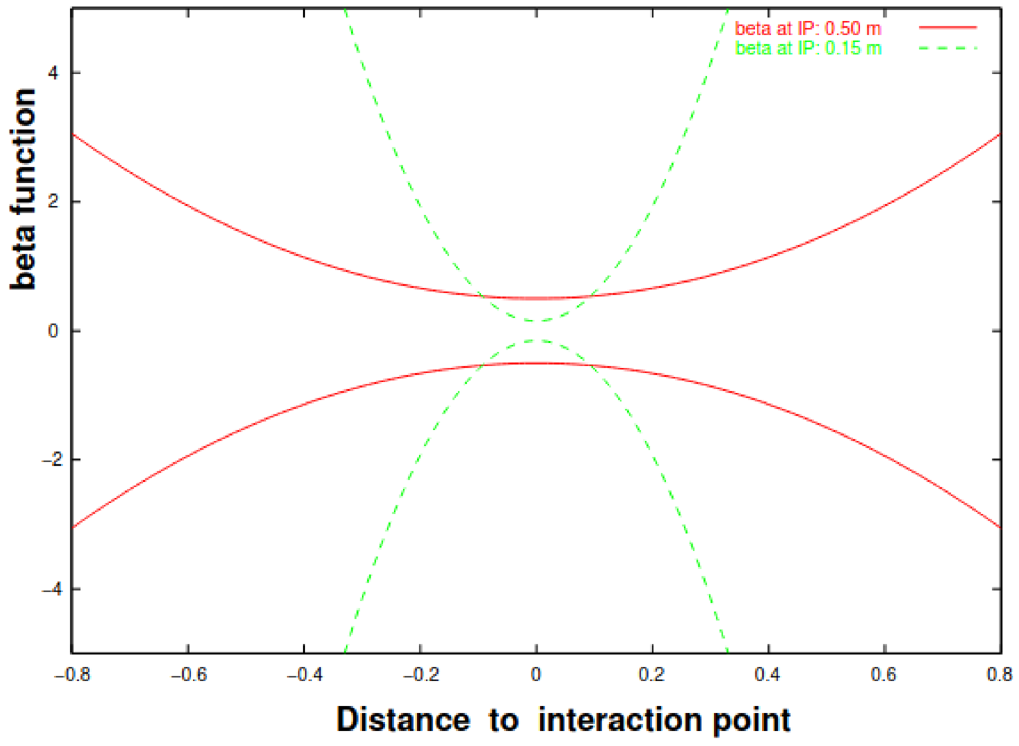
V. Caudan, Master Thesis, 2022.



B. Montague, "Polarized beams in high energy storage rings", 1984.

Hourglass Effect

- Reduction factor from crossing angles, collision offset, dispersion, hourglass effect, ...
- Hourglass effect: β-functions increase parabolically with increasing distance from IP



W. Herr, “Concept of luminosity”, 2006.

$$\beta(s) = \beta^* \left(1 + \left(\frac{s}{\beta^*}\right)^2\right)$$

Luminosity reduction factor from hourglass effect:

$$S \approx \frac{1}{\sqrt{1 + \left(\frac{\theta}{2}\frac{\sigma_s}{\sigma_x}\right)^2}} \qquad \sigma_s \gg \sigma_x, \sigma_y$$

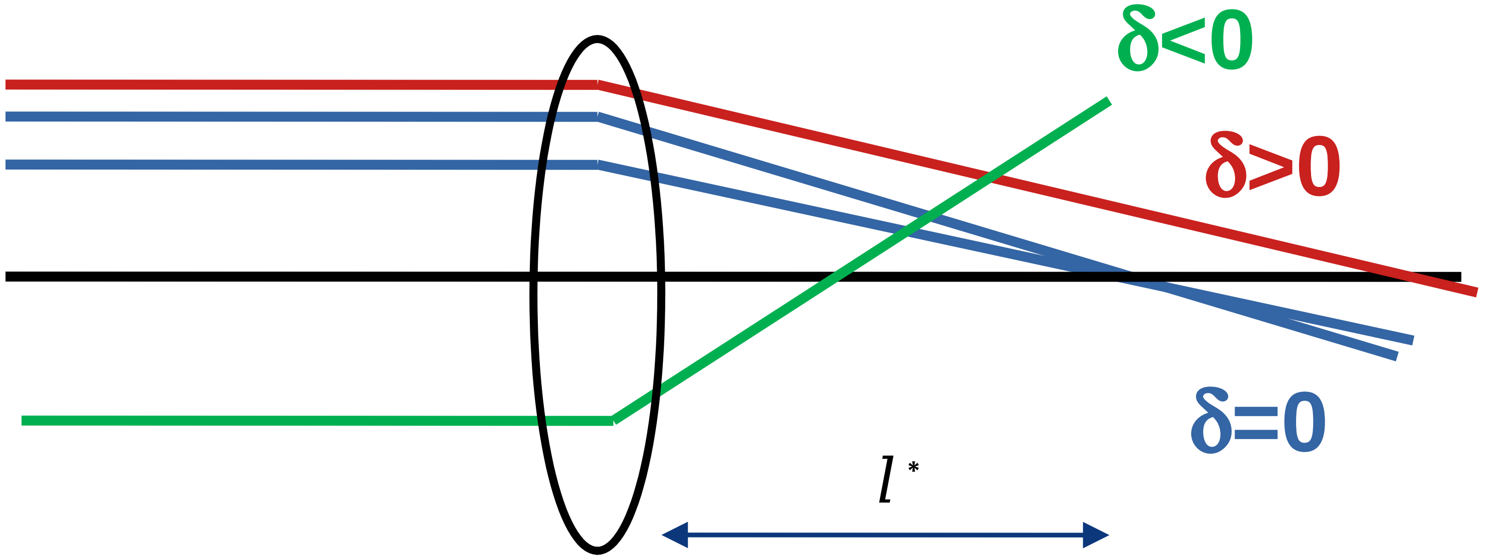
Especially important for smaller β*

Final Focus Chromaticity

- Spot size increase due to (uncorrected) chromaticity generated from final focus (FF)

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

$$\sigma_{y0}^* \equiv \sqrt{\beta_y^*\varepsilon_y},$$



F. Zimmermann, 2023.

ξ … Chromaticity
δ … relative momentum offset
l … distance IP first quadrupole*

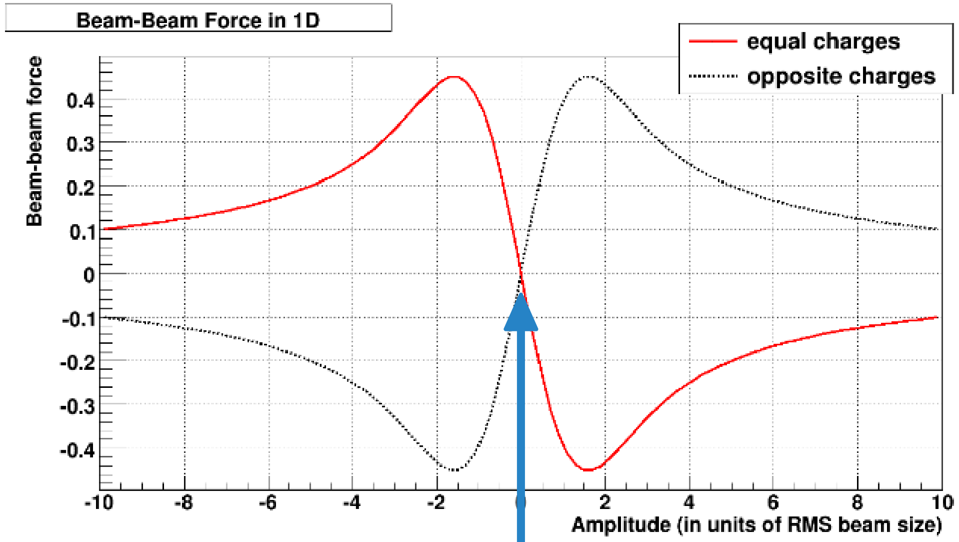
$$\xi \approx \frac{l^*}{\beta^*}$$

Limit on β* to limit generated chromaticity

(Non-Linear) Beam-Beam Force

- Small amplitude similar to effect of focusing (e^+e^-) or defocusing (pp) quadrupole
- For pure head on collisions vertical tune shift of:

$$\Delta Q_{y,\max} = \xi_y = \frac{N r_e \beta_y^*}{2\pi \gamma \sigma_y^* \left(\sigma_x^* + \sigma_y^*\right)}$$



M. Schaumann, Master Thesis, 2011.

Center of opposing bunch

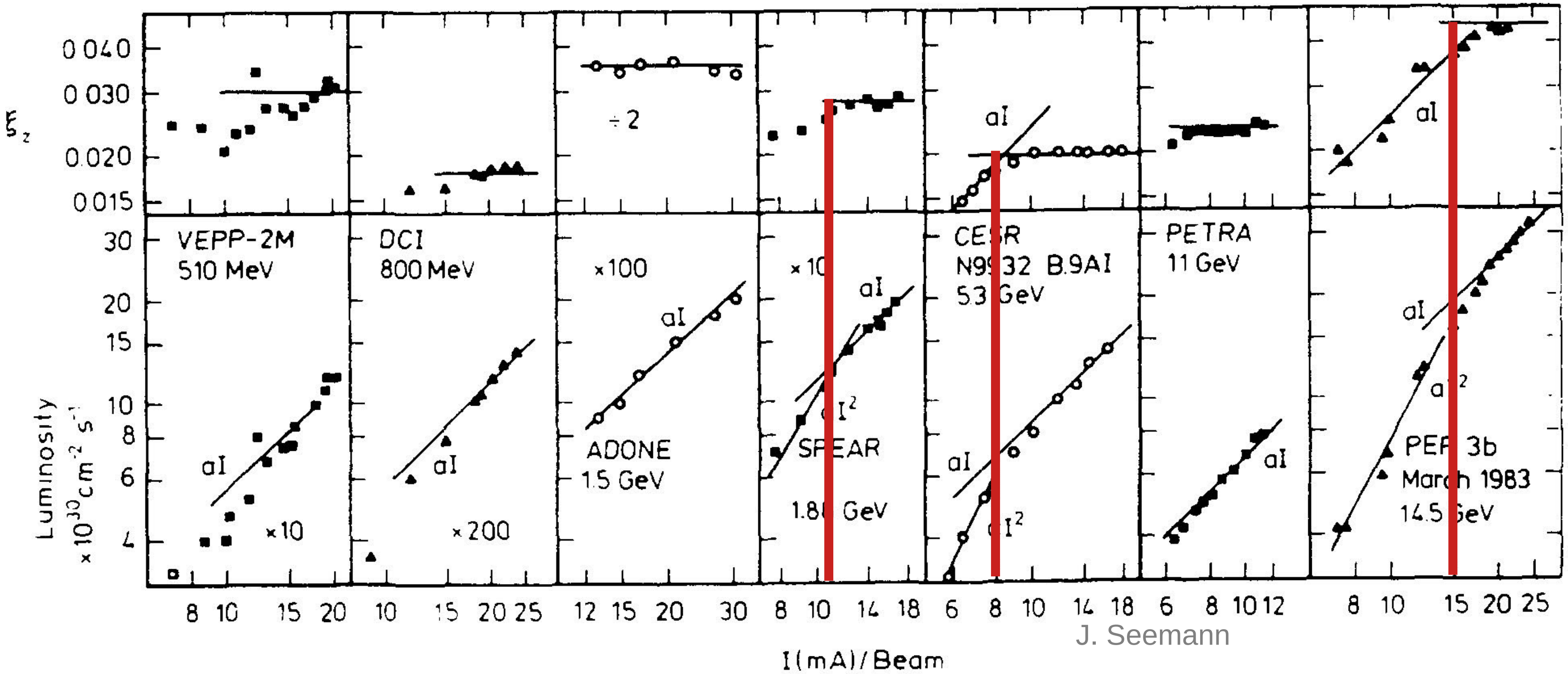
$$L = \frac{N^2 n_b f}{4\pi \sigma_x^* \sigma_y^*} G \approx \frac{1}{e r_e} \left(\frac{1 + \sigma_y^* / \sigma_x^*}{2} \right) \xi_y I_{\text{beam}} \frac{1}{\beta_y^*}$$

Beam-beam tune shift

Total beam current Limited by e.g. synchrotron radiation power

Increases with decreasing vertical β-function!

Beam-Beam Limit



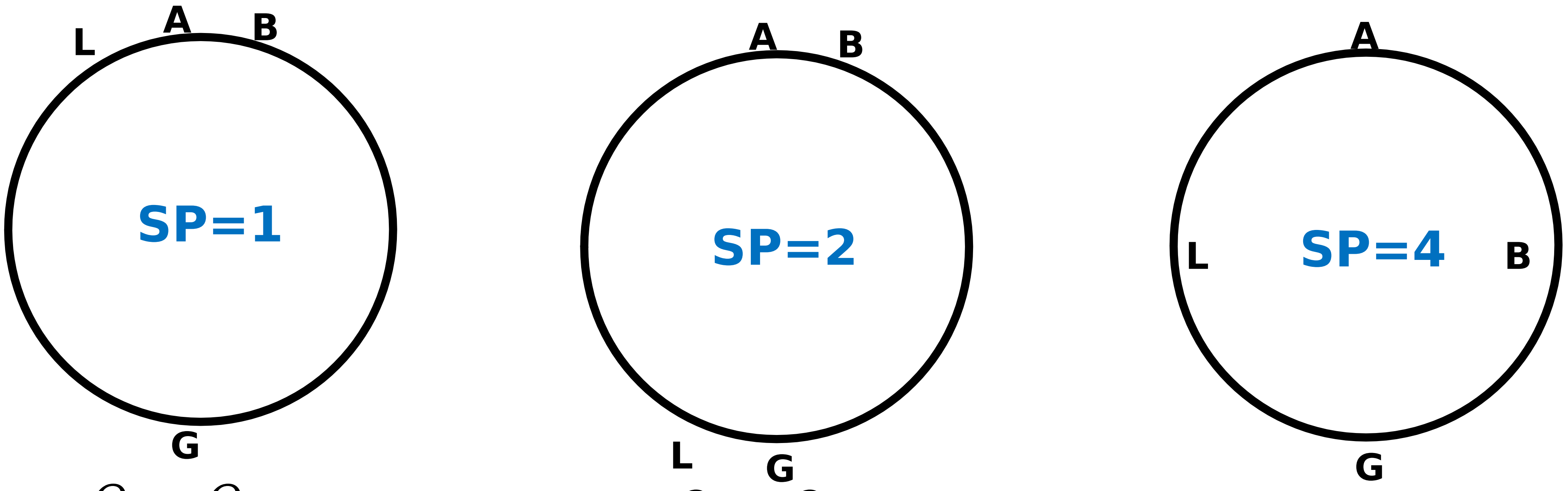
1st beam-beam limit

J. Seemann

- 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**
- At beam currents above the first limit the former CERN LEP collider encountered another, “2nd beam-beam limit” (due to beam blow and tails)

Accommodating Multipole IPs

- Question of superperiodicity, depends on location of IPs (A, B, L, G)
- Resonance condition for lattice errors (DA) and for beam-beam

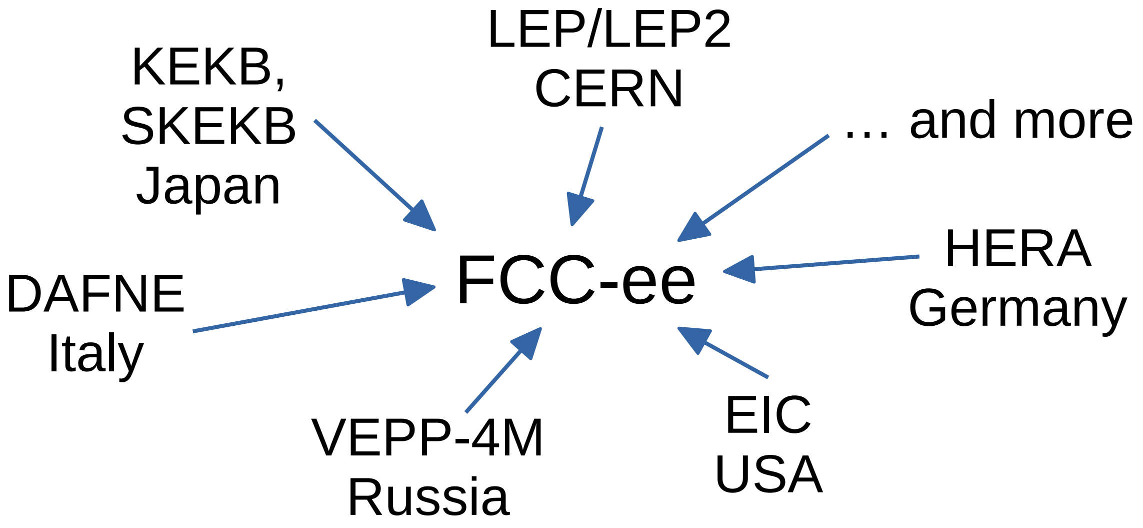


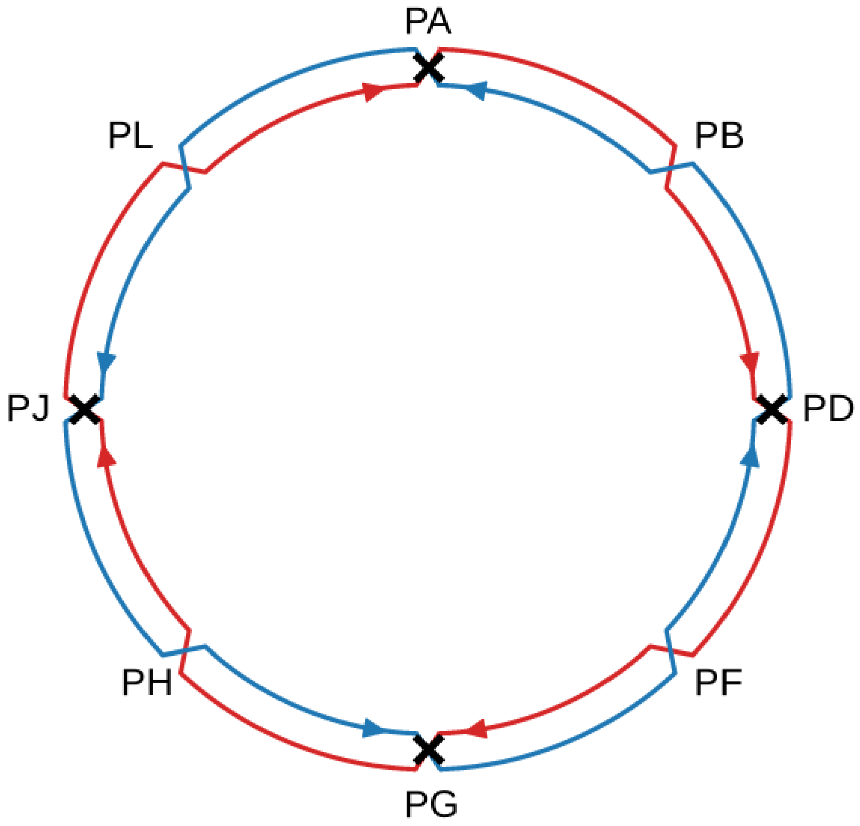
$$mQ_x + nQ_y = p \qquad mQ_x + nQ_y = 2p \qquad mQ_x + nQ_y = 4p$$

If machine is fully superperiodic, e.g. with SP = 4
--> a ¼ turn is equivalent to smaller ring with 1 collision per turn

FCC-ee Design Concepts

- Perfect symmetry and perfect 4-fold superperiodicity
- 8 surface sites, 90.6574 km circumference



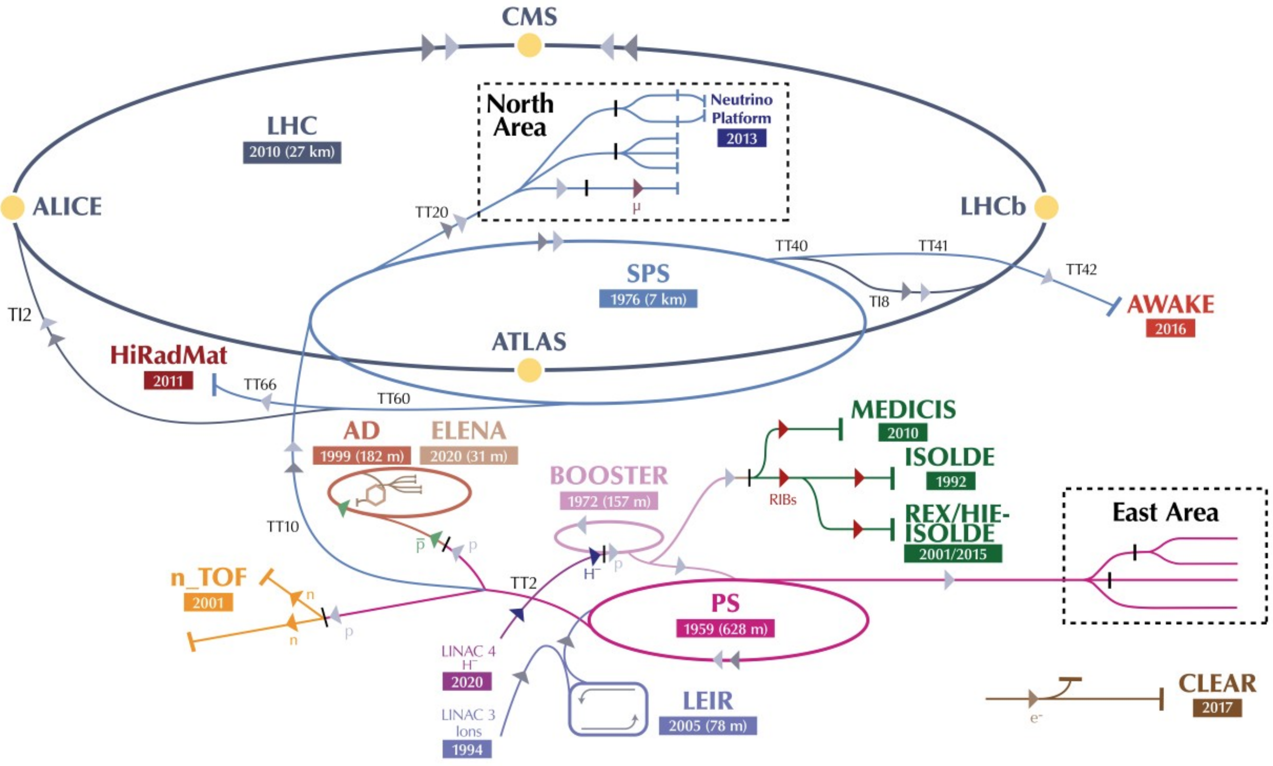


✕ *Interaction Point*

FCC-ee demands successful combination of ingredients of numerous recent colliders and storage rings

LEP/LEP2: Highest Energy so far

- 27 km circumference
- In operation from 1989-2000
- Predecessor of the LHC
- Maximum 209 GeV center-of-mass energy
- Maximum radiation power 23 MW



CERN, 2023.

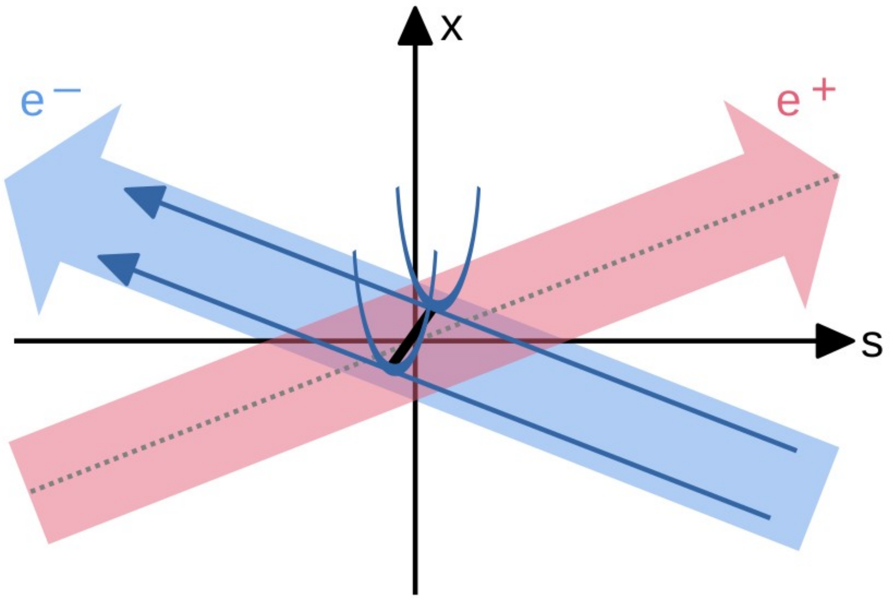
LEP energy close to FCC-ee target plus record synchrotron radiation with MeV photons

Crab-Waist Collision Scheme

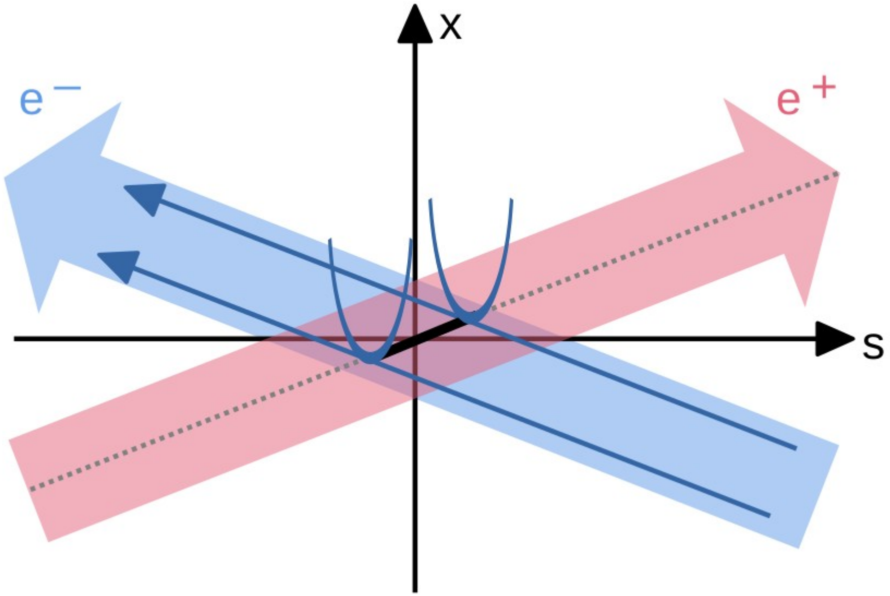
- Original crab-waist scheme used at DAFNE, INFN, Italy — P. Raimondi et al., arXiv:physics/0702033, 2007. M. Zobov et al., arXiv:1608.06150, 2016.
- Virtual crab-waist scheme used in SuperKEKB — Y. Ohnishi et al., Progr. of Theoretical and Experimental Physics, 2013 (3), 2013
- Virtual crab-waist scheme foreseen for FCC-ee — K. Oide et al., Phys. Rev. Accel. Beams 19, p. 111005, 2016.

Powering sextupoles rotates the vertical β-function and aligns the minimum on the longitudinal axis on the other beam

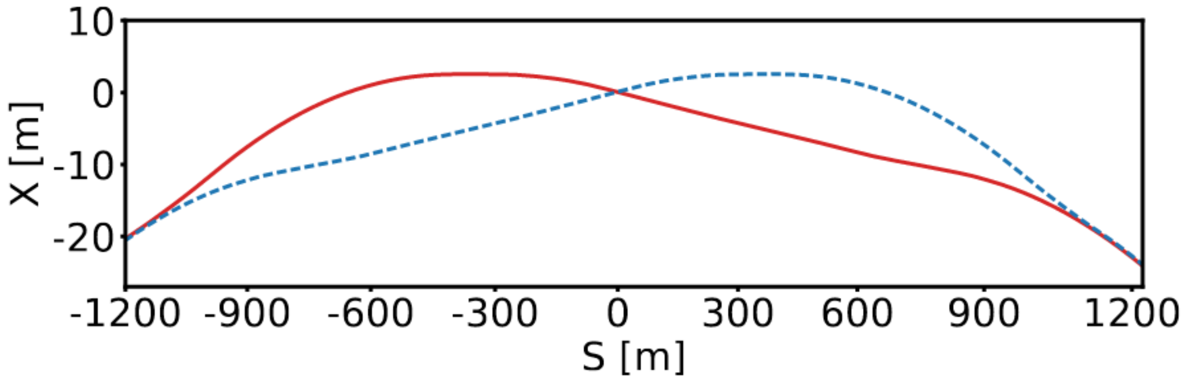
Without crab-waist transformation

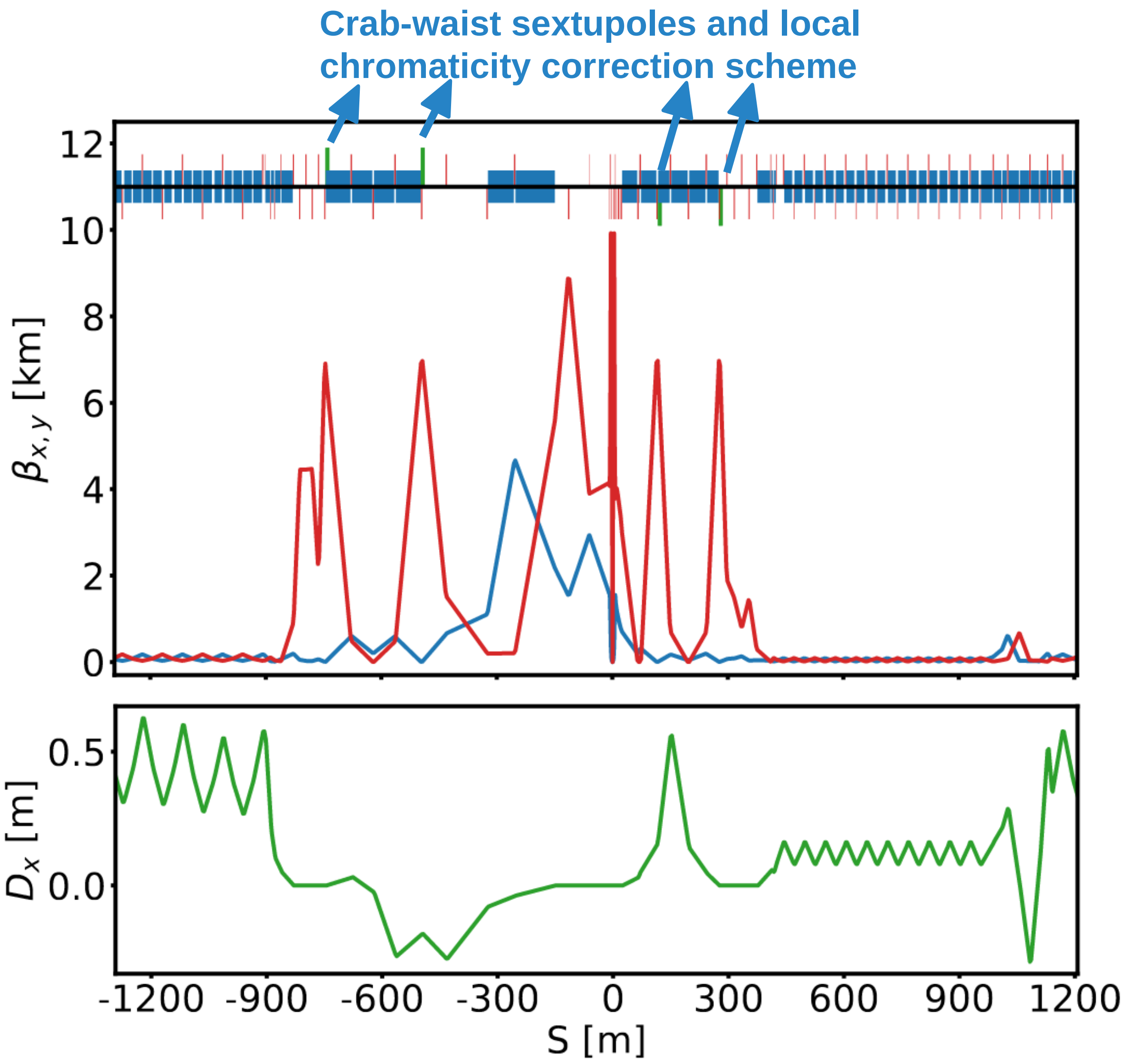


With crab-waist transformation



FCC Final Focus

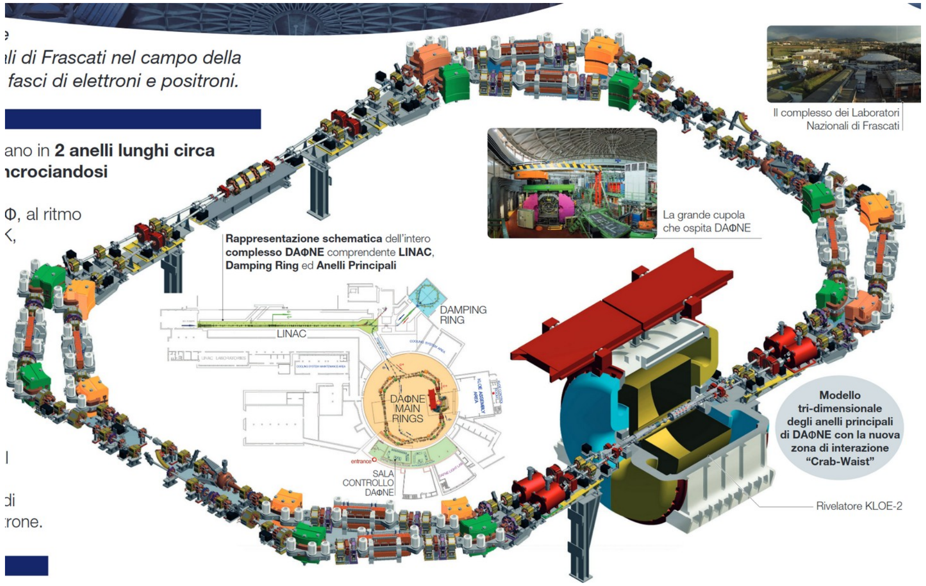




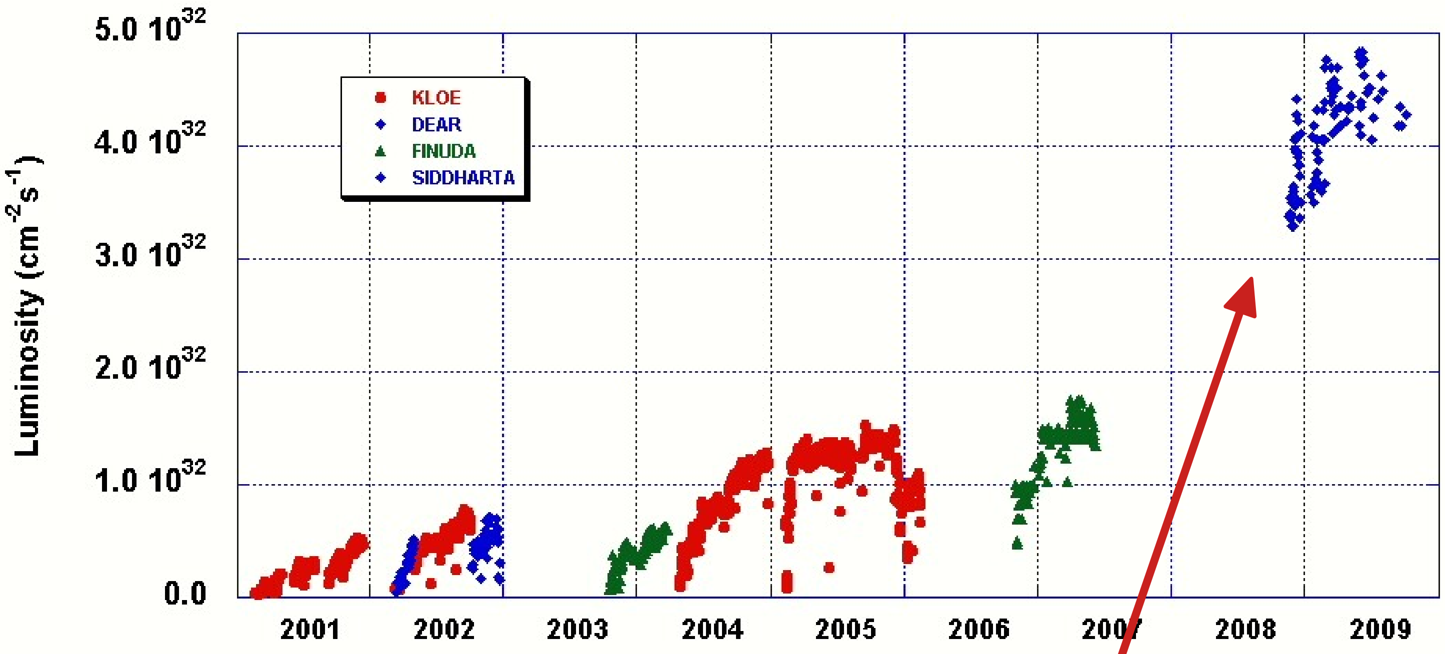
- Assymmetric final focus design to suppress strong synchrotron radiation at the IP
- Critical photon energy < 100 keV
- Crab-waist collision scheme

DAFNE Luminostiy

- 510 MeV beam energy
- 1 experiment
- First collider with crab-waist



DAFNE, 2016.

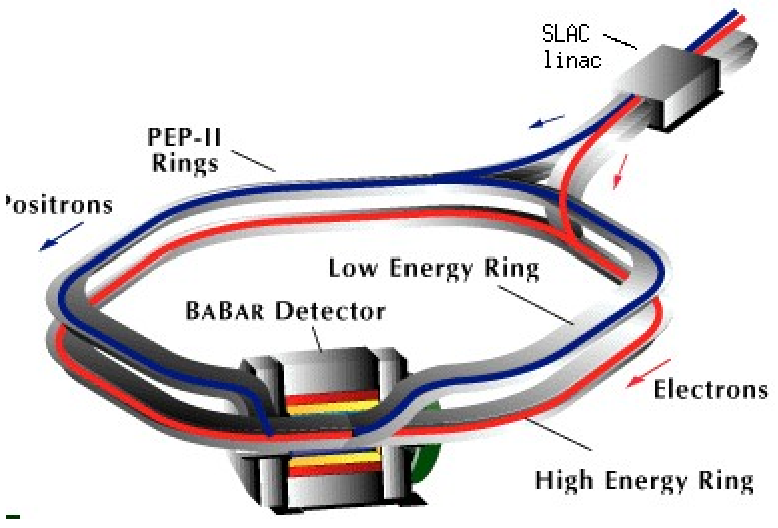


M. Zobov, 2009.

Increase in luminosity thanks to crab-waist collision scheme

KEKB/PEP-II: High Current and L

- Past B-Factories
- PEP-II: 9 GeV / 3 GeV electron /positron ring



Courtesy: SLAC, accessed 2023.

- KEKB: 8 GeV / 3.5 GeV electron /positron ring
- Predecessor of SuperKEKB

I_{e+}=1.6 A, I_{e-}=1.2 A

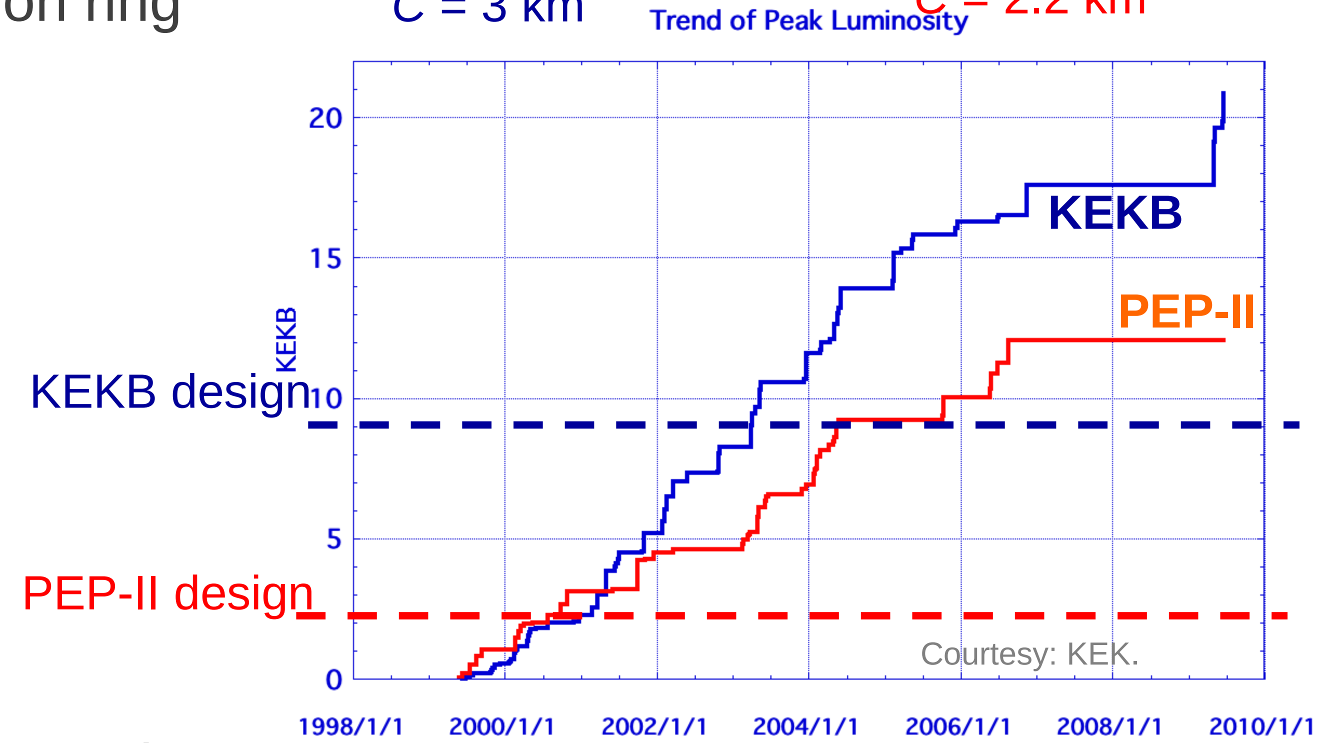
P_{SR} ~ 5 MW

C = 3 km

I_{e+}=3.2 A, I_{e-}=2.1 A

P_{SR} ~ 8 MW

C = 2.2 km

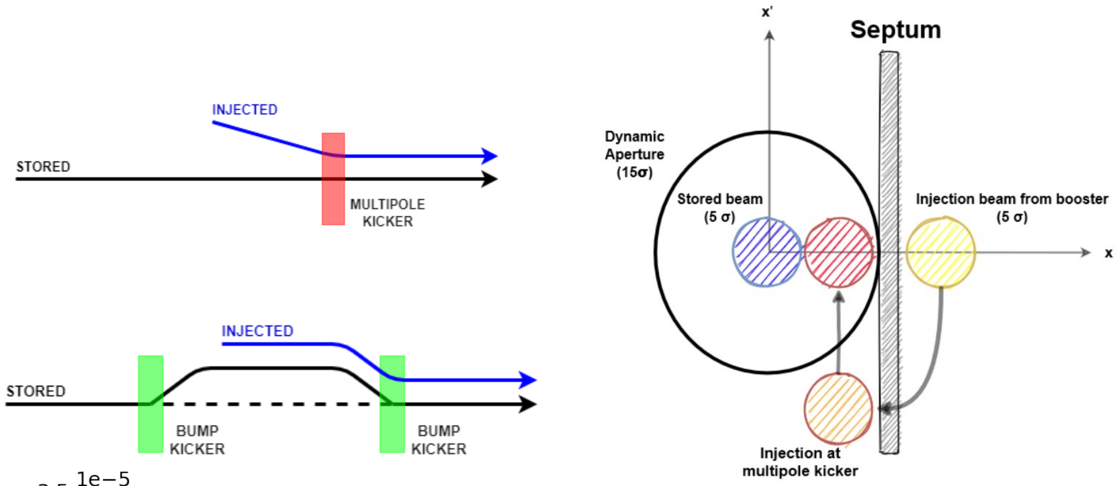


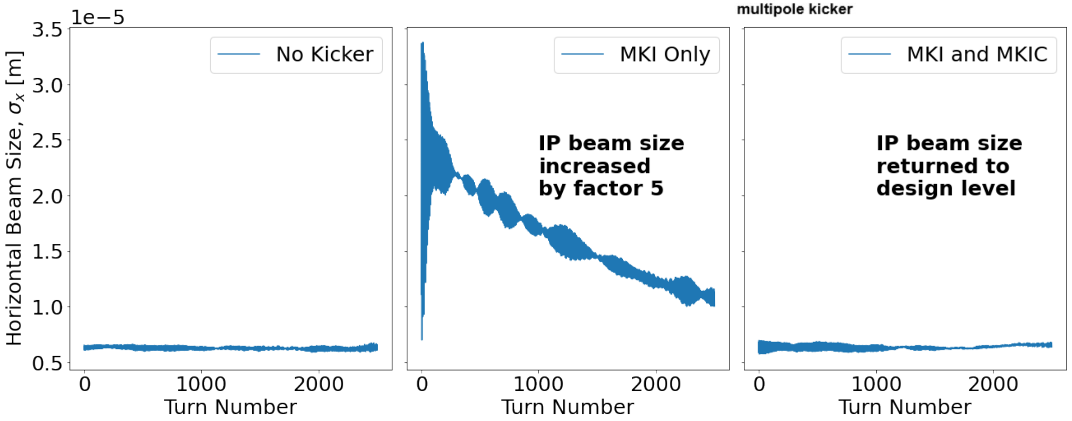
Courtesy: KEK.

Performance of high current high luminosity e+e- factories conservatively predicted

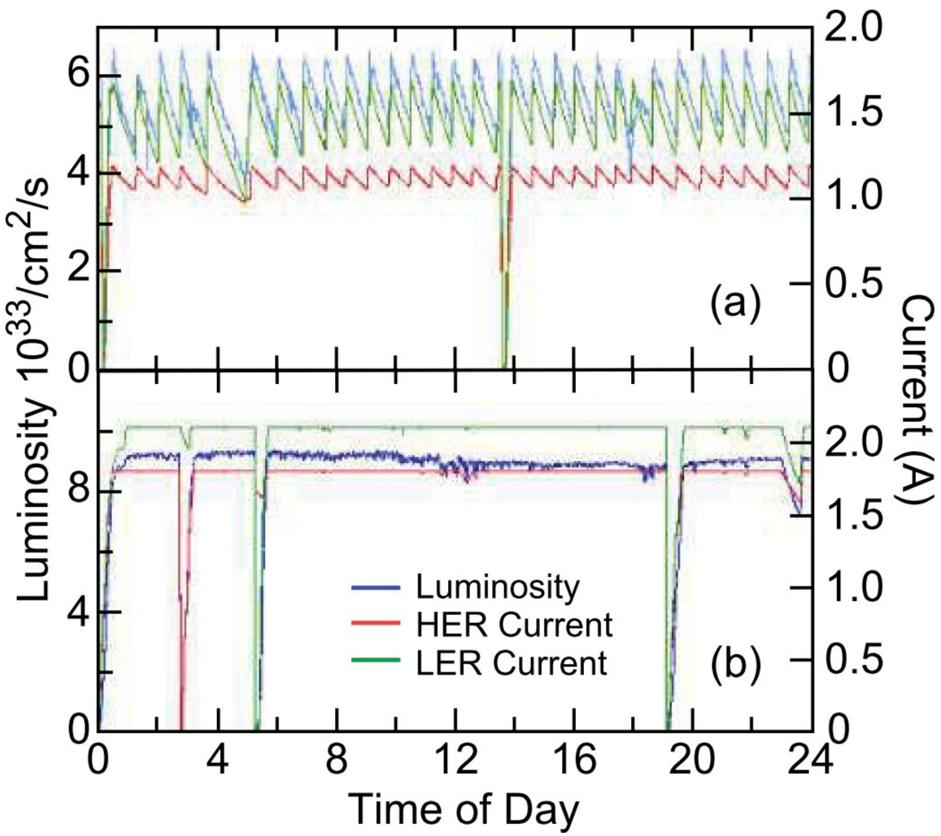
Top-Up Injection

- Continous beam injection at collision energy
- Average luminosity ~ Peak luminosity





Coutesy: P. Hunchak, M. Hofer, R. Ramjiawan.



Coutesy: KEK.

KEKB and PEP-II were first colliders with top-up injection schemes

Beam-lifetime

- Beam-lifetime limits luminosity for colliders with top-up injection

$$N_{\pm} n_b e = I_{\pm} \epsilon_{\pm} \tau_{\pm}$$

maximum injector current just replenishes lost particles → maximum current in collider

$e^{\pm}$ injector beam currents

injection efficiencies

beam lifetimes in collider

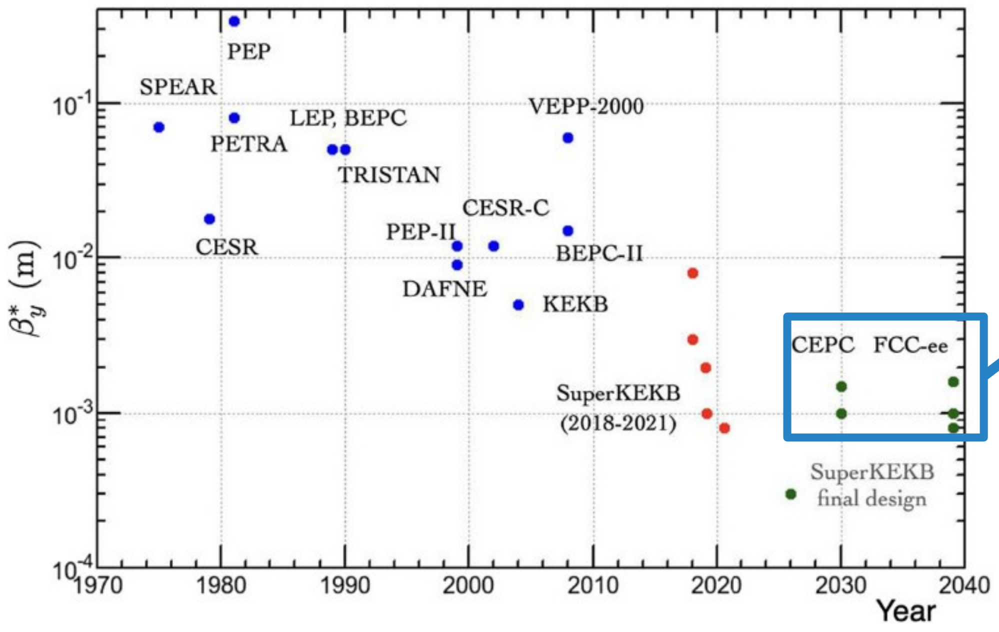
Describes performance of SuperKEKB

$$\mathcal{L} \approx \frac{f}{4\pi e^2 \sigma_x^* \sigma_y^*} \frac{1}{n_b} I_{\pm} \epsilon_{\pm} \tau_{\pm}$$

Coutesy: K. Oide, F. Zimmermann.

SuperKEKB

- Lepton double ring collider and 1 interaction point
- 7 GeV electron ring (HER) and 4 GeV positron ring (LER)
- Record low β_y* of 0.8 mm
- Similar optics, crab-waist scheme, top-up injection

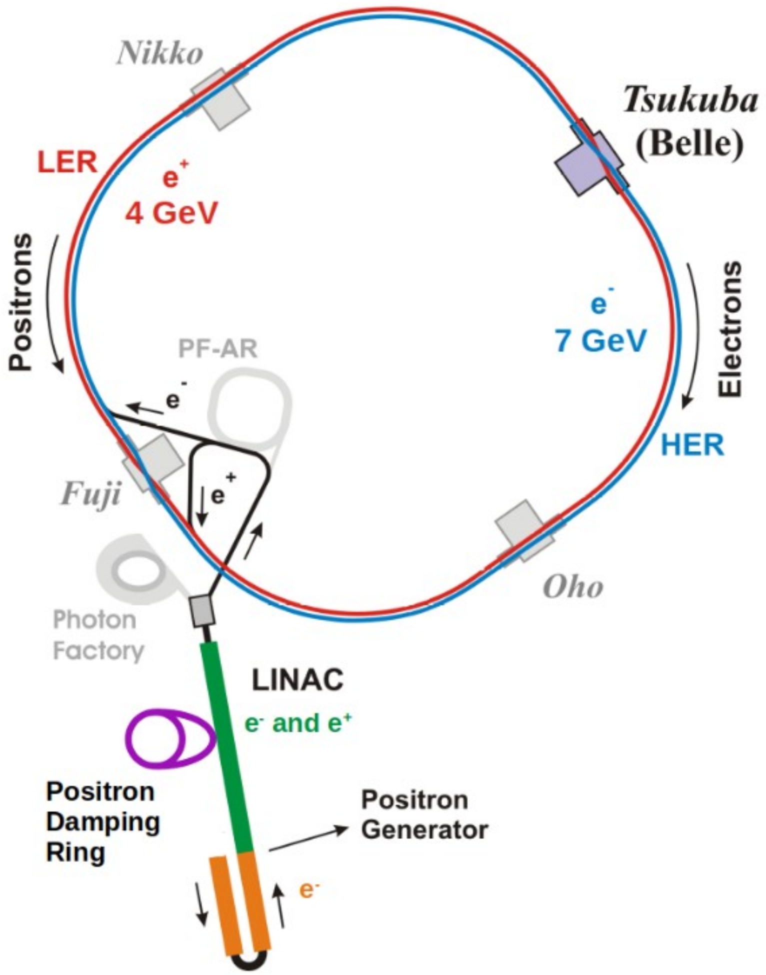


Source: KEK.

SuperKEKB is a small FCC

Optimistic

Lowest βy for FCC-ee already reached in SuperKEKB*
Note: 0.3 mm for final design at SKEKB ~ 0.8 mm at FCC-ee



Source: adapted from Wikipedia.

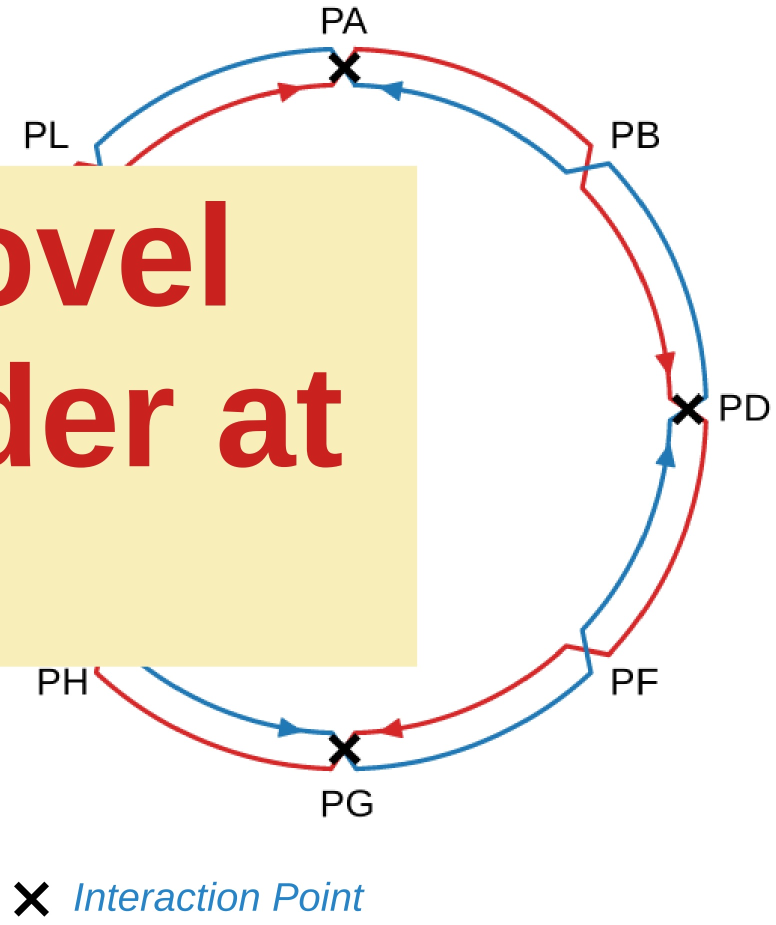
FCC-ee Design Concepts

- Perfect symmetry and perfect 4-fold superperiodicity
- 8 surface sites, 90.6574 km circumference

KEKB
SKEK
Japa

DAFNE
Italy

Let us design a novel e+e- circular collider at CERN now!



FCC-ee demands successful combination of ingredients of numerous recent colliders and storage rings

Questions?

e+ e- Circular Colliders
Future – Present – Past

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FCC-ee Cost and Sustainability

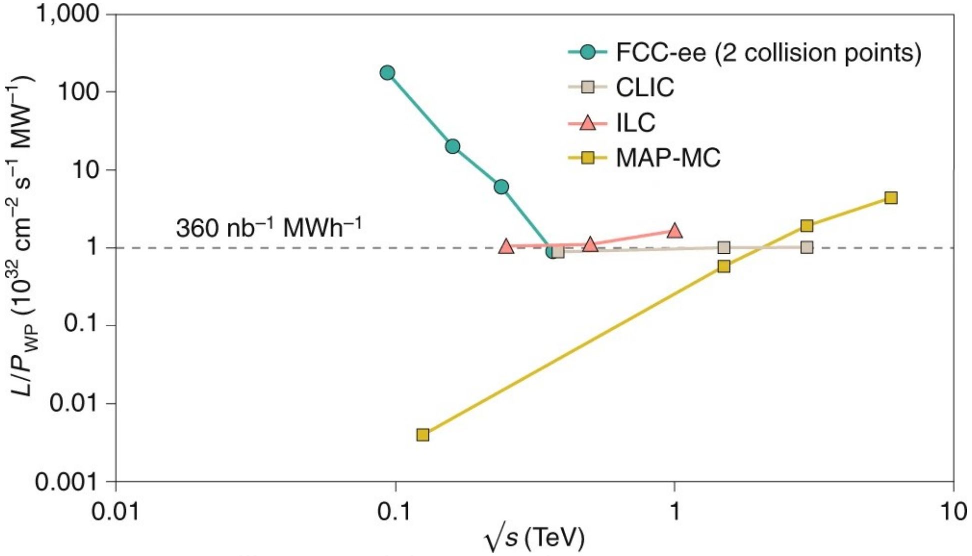
Luminosity vs. capital cost

- For the H running, **with 5 ab^{-1} accumulated over 3 years and 10^6 H produced**, the total investment cost (~10 BCHF) corresponds to ~ **10 kCHF / H**

- For the Z running with **150 ab^{-1} accumulated over 4 years and 5×10^{12} Z produced** (two IPs), the total investment cost corresponds to ~ **10 kCHF / 5×10^6 Z**, almost 2x better still with four IPs
This is the number of Z bosons collected by each experiment during the entire LEP programme !

Capital cost per luminosity dramatically decreased compared with LEP !

Luminosity vs. electrical consumption



M. Benedikt et al., doi:10.1038/s41567-020-0856-2, 2020.

Thanks to twin-aperture magnets, thin-film SRF, efficient RF power sources, top-up injection

Highest lumi/power of all proposals
Electricity cost ~200 CHF per Higgs boson