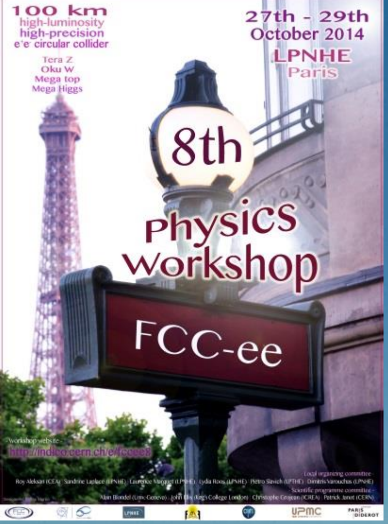


FCC hh ee he

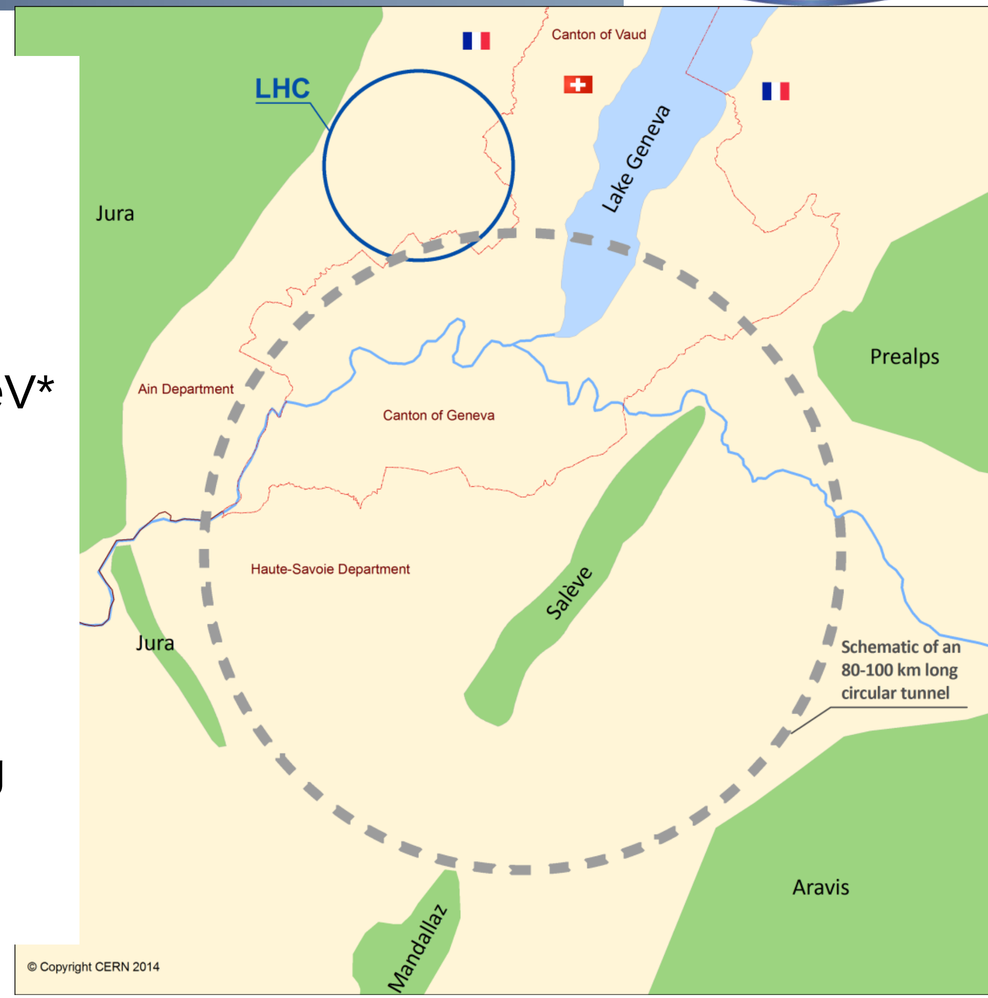
FCC-ee Machine Study

Jörg Wenninger
CERN Beams Department
Operation group - LHC

Acknowledgments to all my FCC-ee colleagues for material and ideas

Future Circular Collider study

- pp collider (FCC-hh) – 50 TeV* – defines infrastructure.
  - B = 16 T ⇒ 100 km
  - B = 20 T ⇒ 80 km
- e^+e^- collider (FCC-ee) – 40-175 GeV* – as intermediate step.
- e-p option.
- Infrastructure in the Geneva area.
- International collaboration is taking shape.
  - *First ICB at CERN in September*



CDR and cost review for the next European Strategy Update in 2018

**beam energy*

Physics goals of FCC-ee

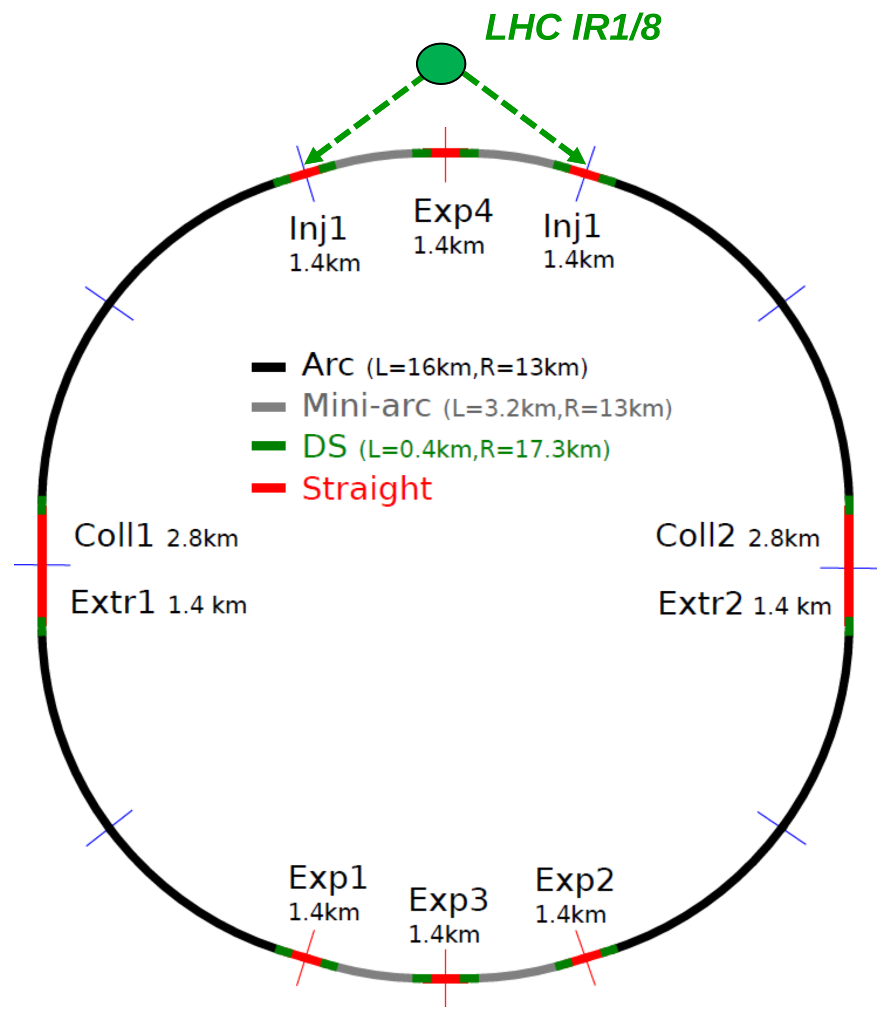
- Provide highest possible luminosity for a wide physics program ranging from the Z pole to the $t\bar{t}$ production threshold.
  - *Beam energy range from 45 GeV to 175 GeV.*
- Main physics programs / energies (+ scans around central values):
  - *Z (45.5 GeV): Z pole, 'TeraZ' and high precision M_Z & Γ_Z,*
  - *W (80 GeV): W pair production threshold,*
  - *H (120 GeV): ZH production threshold ,*
  - *t (175 GeV): $t\bar{t}$ threshold.*

All energies quoted in this presentation refer to BEAM energies

First layout hh – ee

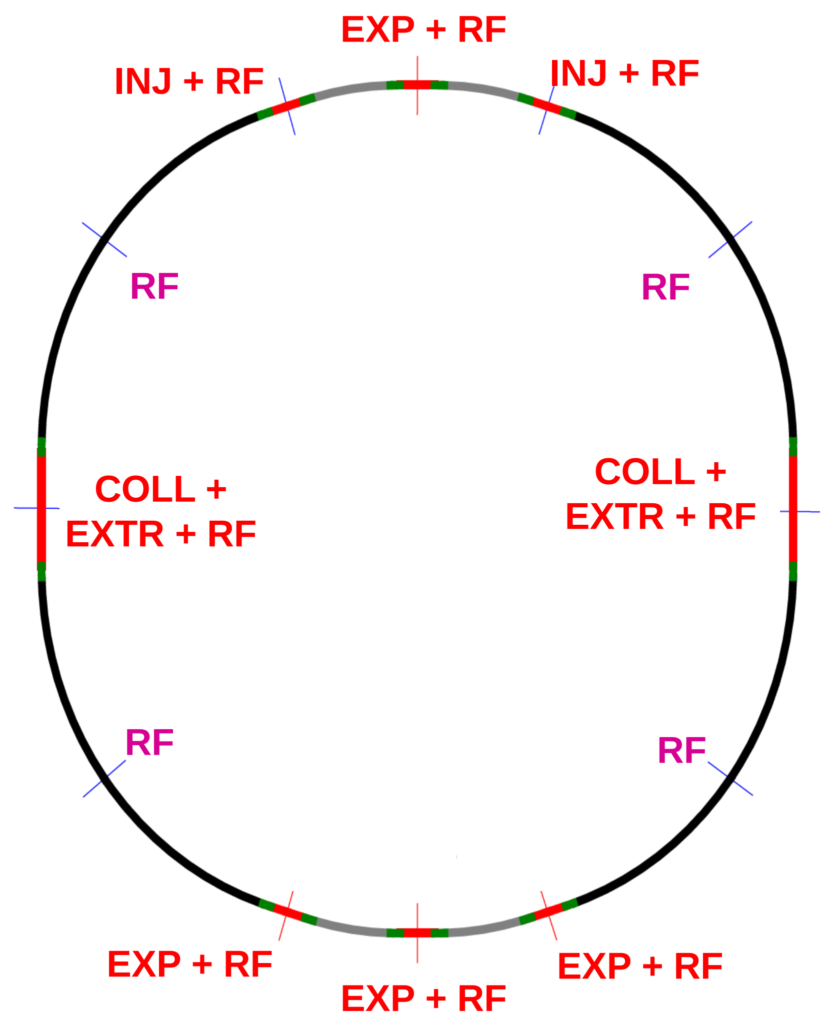
- FCC-hh relies on a modified LHC as a ~3 TeV injector.
  - *Connection to LHC at IR1 (ATLAS) or at IR8 (LHCb).*
  - *Minimize transfer line length → racetrack-like shape.*
- First baseline layout is close to a circular machine with two symmetry planes.

  Consider lengths as preliminary !
- Circumference is a rational multiple of LHC: 80, 86.6, **93.3** or 100 km (¼ LHC).
  - *Baseline is the 93.3 km version → average machine radius of 12 km.*
- Beam crossings only at the experiments.
- Machine is planar (no kinks), the two rings are side by side.
  - *Good for vertical emittance, polarization.*



See presentation by P. Lebrun

- At the FCC-ee energies, injection, collimation and dump (extr) systems have reduced space requirements.
  - *Injection, collimation and extraction of both rings may fit in 2-3 of the long straight sections.*
  - ⇒ ***This layout is only indicative.***
  - ⇒ ***The length of the straights may change!***
- The main FCC-ee requirement is an RF system distributed over as many locations as possible.
  - *Minimize: energy offsets, orbit offsets in the sextupoles… ⇔ optics perturbations.*
  - *In this layout roughly one RF station every ~1/5 of the ring. Voltage distribution will be asymmetric (reflect the ring (a)symmetry).*
  - *Simulations must confirm whether additional **RF** stations are required in the middle of the long arcs (175 GeV !).*



RF = length ~ 200 m

93 km option – current baseline

LHC P1/P8 extraction (avoids Jura limestone)

Alignment | **Shaft Tools**

Choose alignment option

93km quasi-circular ▾

Tunnel depth at centre: 295mASL

Gradient Parameters

Azimuth (°):	-15
Slope Angle x-x(%):	.6
Slope Angle y-y(%):	0

CALCULATE

Alignment centre

X: 2499641 Y: 1107637

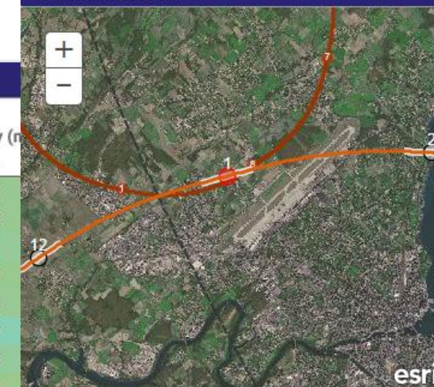
C Intersection	IP 1	IP 2
Angle	-15°	21°
Depth	121m	106m

Alignment Location

Geology Intersected by Shafts | **Shaft Depths**

	Shaft Depth (m)				Geology (m		
Shaft	Actual	Min	Mean	Max	Moraine	Molasse	
1	231	226	230	232	74	157	
2	162	158	168	181	0	162	
3	219	211	220	230	18	201	
4	178	169	177	182	42	136	
5	195	171	196	221	21	175	
6	395	388	405	421	26	369	
7	385	371	379	388	165	220	
8	238	244	251	260	15	101	
9	148	147	151	156	10	138	0
10	290	271	287	304	0	308	0
11	208	206	212	217	90	118	0
12	272	269	275	284	69	203	0
Total	2922	2831	2951	3076	530	2289	12

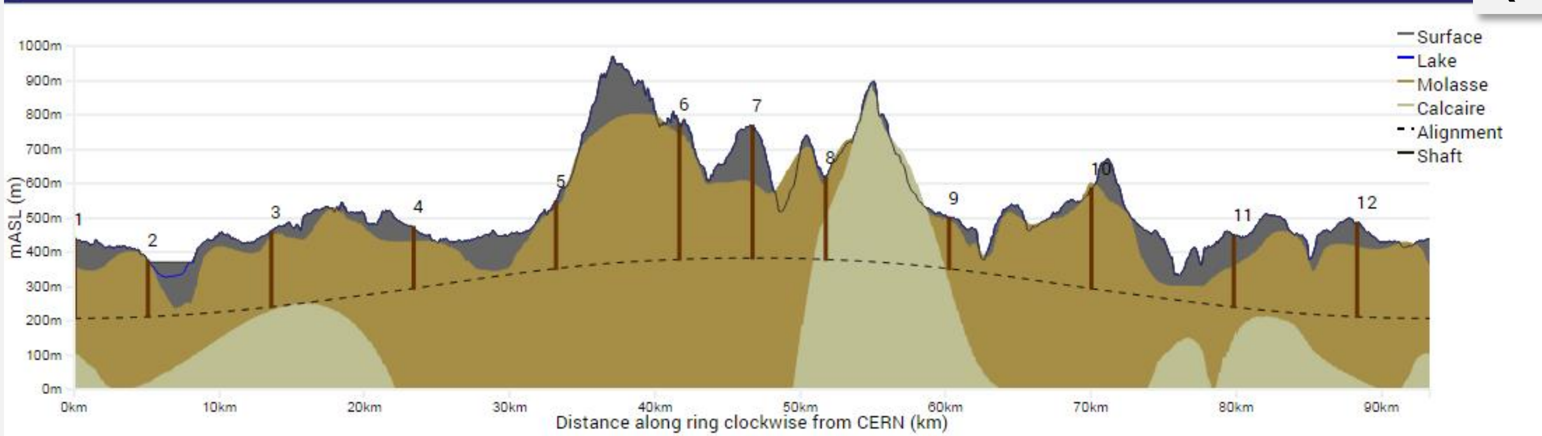
Alignment Location



Deepest shaft close to 400 m

(not optimized)

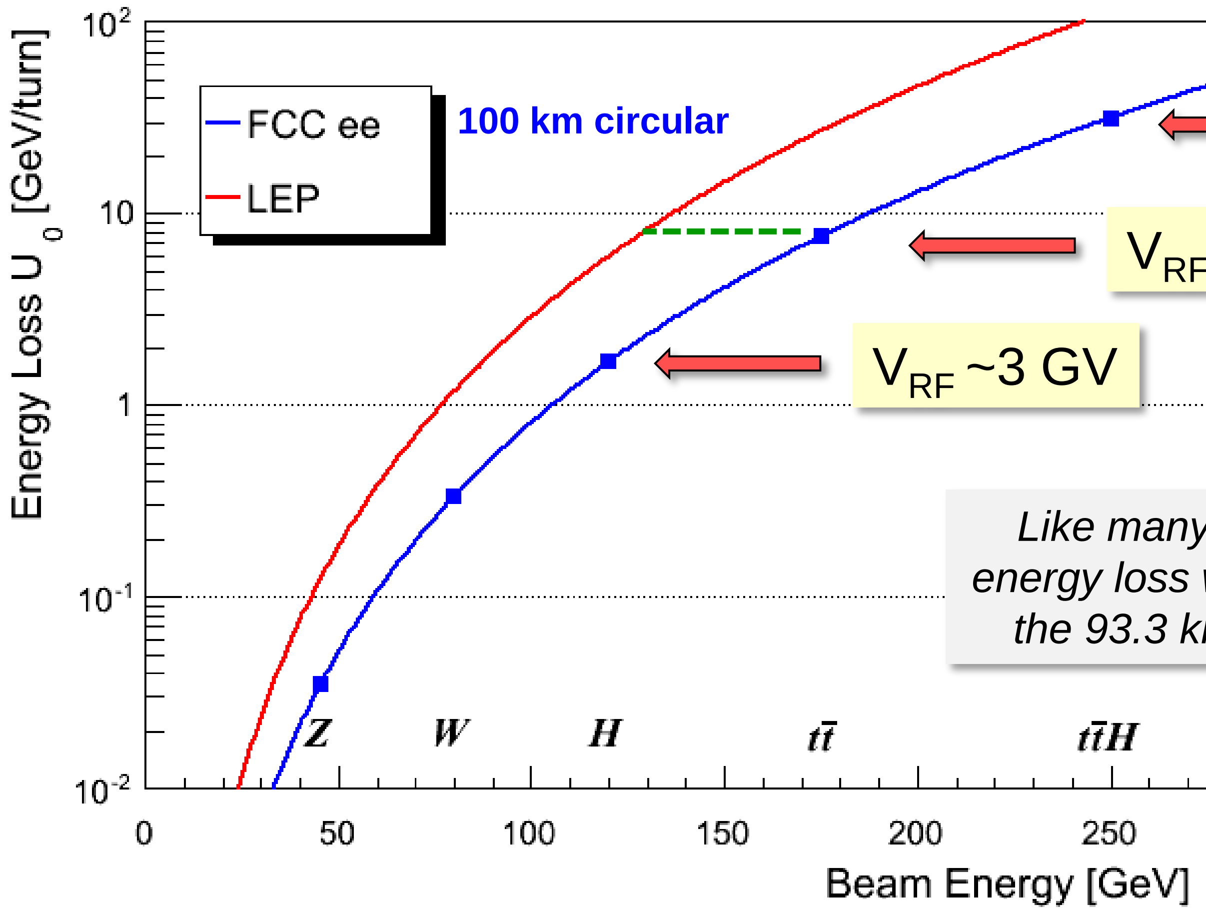
gnment Profile



logy Intersected by Tunnel

- The maximum synchrotron radiation (SR) power P_{SR} is set to **50 MW per beam** – design choice ⇔ power dissipation.
  - ⇒ *defines the maximum beam current at each energy.*

Note that a margin of a few % is required for losses in straight sections.



Like many other numbers the energy loss will change slightly for the 93.3 km racetrack layout !

Main baseline parameters

- Reference set from last February (FCC kick-off) – revision upcoming to remove inconsistency and to match to 93.3 km layout.
  - *For ex: large number of bunches requires 2 rings and large crossing angle – not correctly reflected in parameters.*

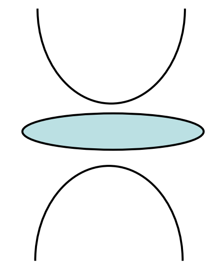
Parameter	Z	W	H	t	LEP2
E (GeV)	45	80	120	175	104
I (mA)	1400	152	30	7	4
No. bunches	16’700	4’490	1’330	98	4
$\beta^*_{x/y}$ (mm)	500 / 1	500 / 1	500 / 1	1000 / 1	1500 / 50
ε_x (nm)	29	3.3	1	2	30-50
ε_y (pm)	60	7	2	2	~250
ξ_y	0.03	0.06	0.09	0.09	0.07
L (10^{34} $cm^{-2}s^{-1}$)	**28**	**12**	**6.0**	**1.8**	**0.012**

- The actual intensities and luminosities will be lowered due to SR losses around the experimental regions (change < 10%).

Luminosity

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

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

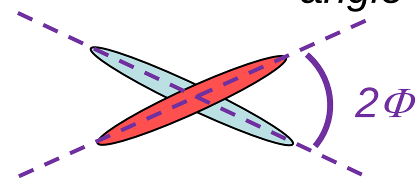


H ≤ 1

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

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

σ = beam size

k = no. bunches

f = rev. frequency

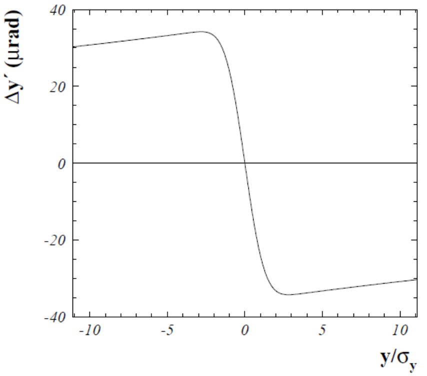
N = bunch population

P_{SR} = synch. rad. power

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

Beam-beam parameter

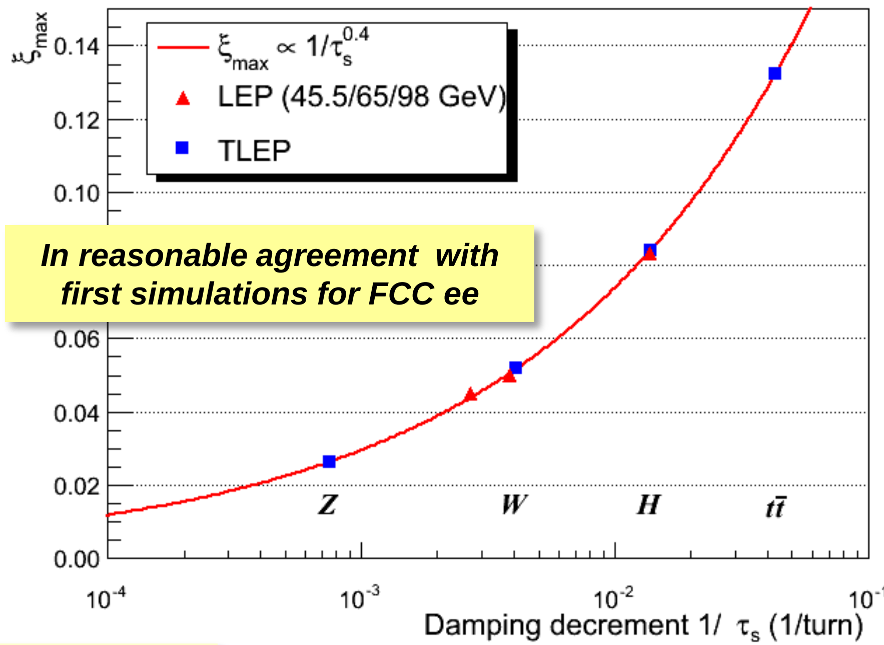
- The beam-beam parameter ξ measures the strength of the field sensed by the particles due to the counter-rotating bunch.
- Beam-beam parameter limits are empirically scaled from LEP data (also 4 IPs).



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

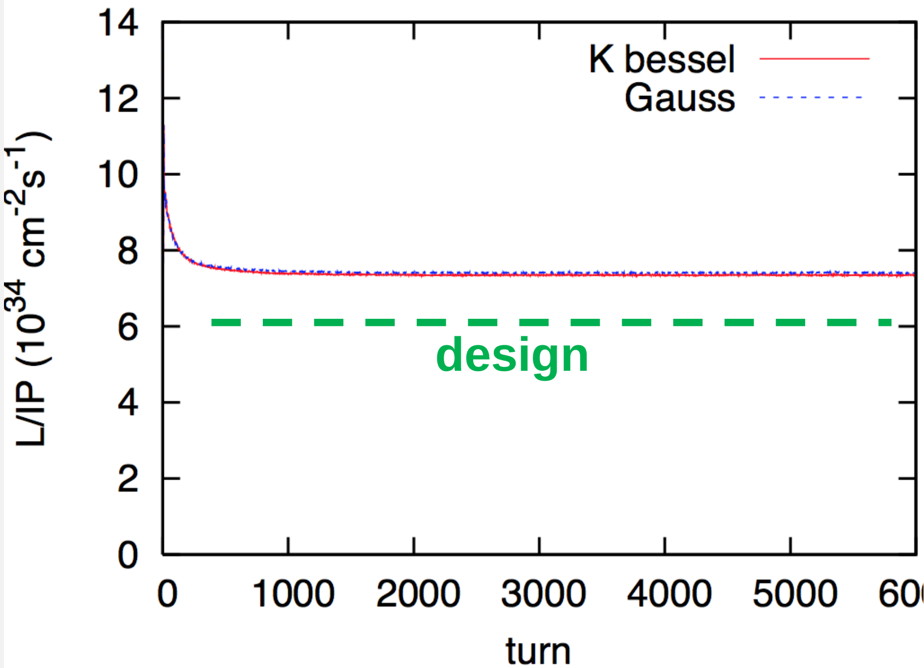
$$\xi_y^{max}(E) \propto \frac{1}{\tau_s^{0.4}} \propto E^{1.2}$$

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



ξ_y and L may be raised significantly (x 4) with Crab-Waist schemes !

Beam-beam simulations



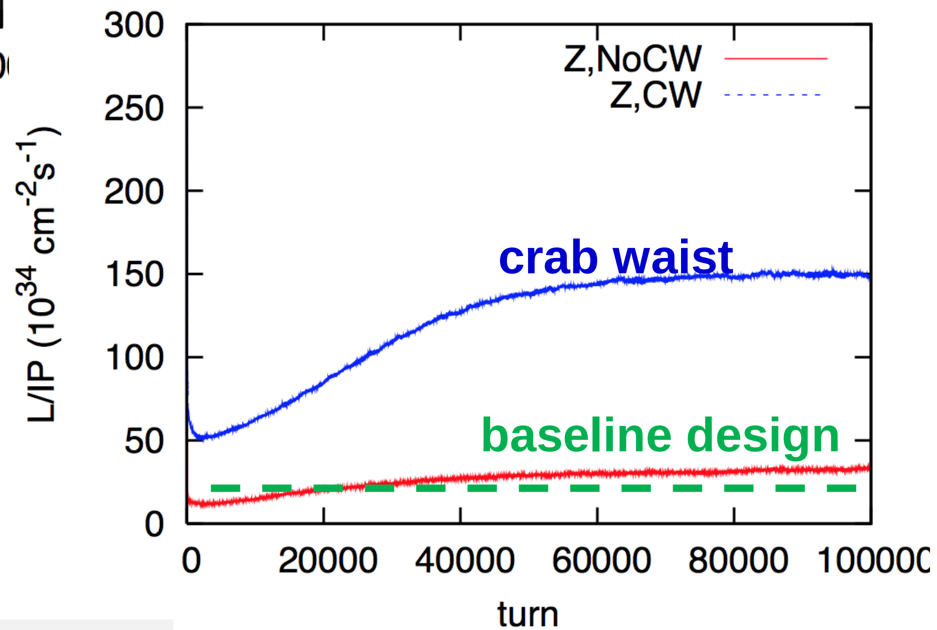
BBSS strong-strong simulation with beamstrahlung

FCC-ee at 120 GeV:

L≈7.5x10^{34} cm^{-2}s^{-1} per IP

FCC-ee in crab-waist mode at the Z pole (45.5 GeV):

L≈1.5x10^{36} cm^{-2}s^{-1} per IP



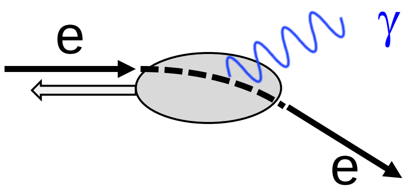
Tracking confirms assumptions!

K. Ohmi, A. Bogomyagkov, E. Levichev, P. Piminov

Beamstrahlung

- Hard photon emission at the IPs, '*Beamstrahlung*', can become a lifetime / performance limit for large bunch populations (N), small hor. beam size (σ_x) and short bunches (σ_s) .

$$\tau_{bs} \propto \frac{\rho^{3/2}\sqrt{\eta}}{\sigma_s}\exp(A\eta\rho) \qquad \frac{1}{\rho} \approx \frac{N r_e}{\gamma \sigma_x \sigma_s}$$



ρ : mean bending radius at the IP (in the field of the opposing bunch)

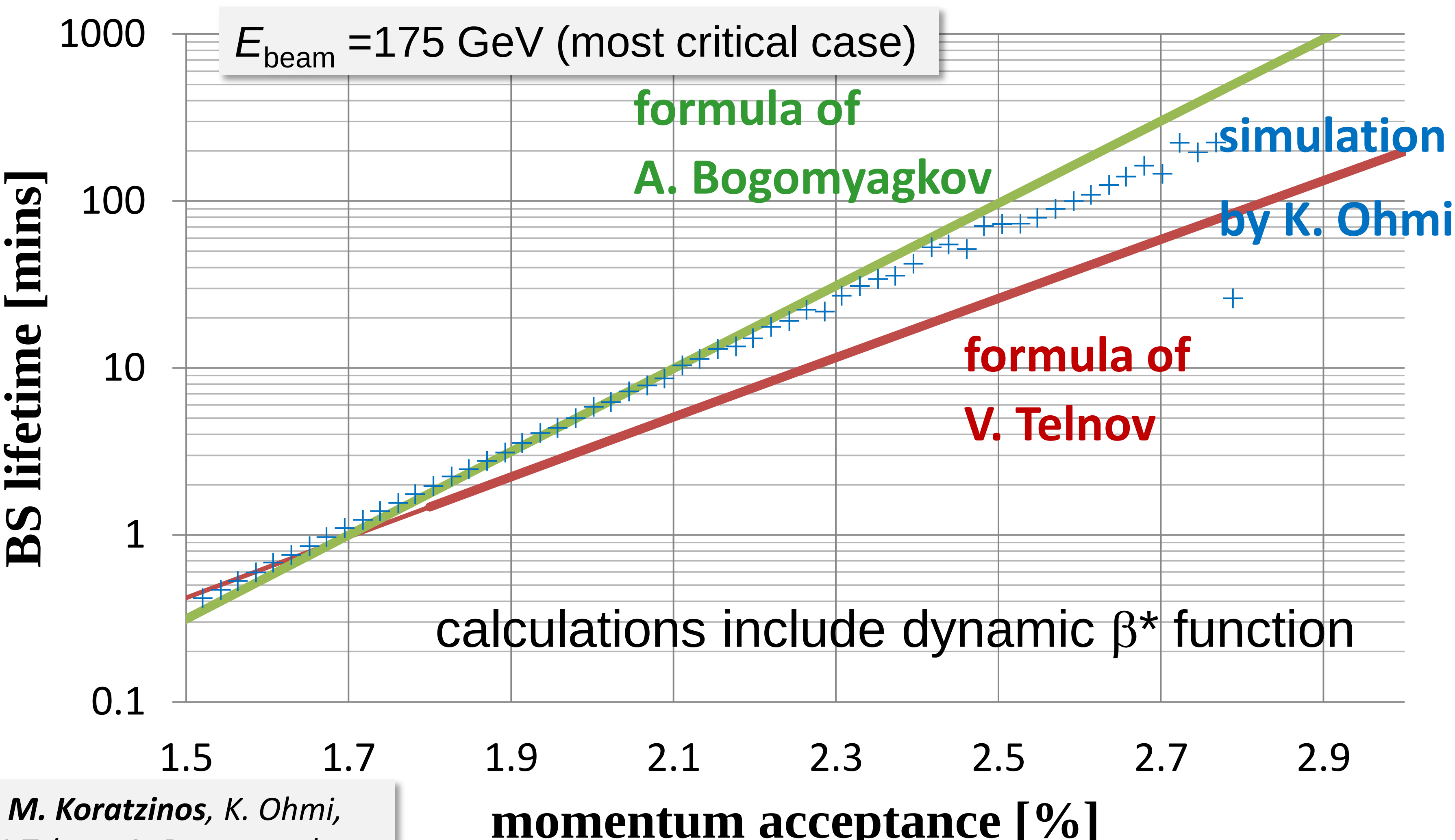
η : ring energy acceptance

Lifetime expression by V. Telnov

- To ensure an acceptable lifetime, $\rho\times\eta$ must be sufficiently large.
  - *Flat beams (large σ_x) !*
  - *Bunch length !*
  - *Large momentum acceptance of the lattice: **1.5 – 2% required**.*
    - LEP had < 1% acceptance, SuperKEKB ~ 1-1.5%.

Beamstrahlung lifetime

Reasonable agreement between tracking and analytical estimates.

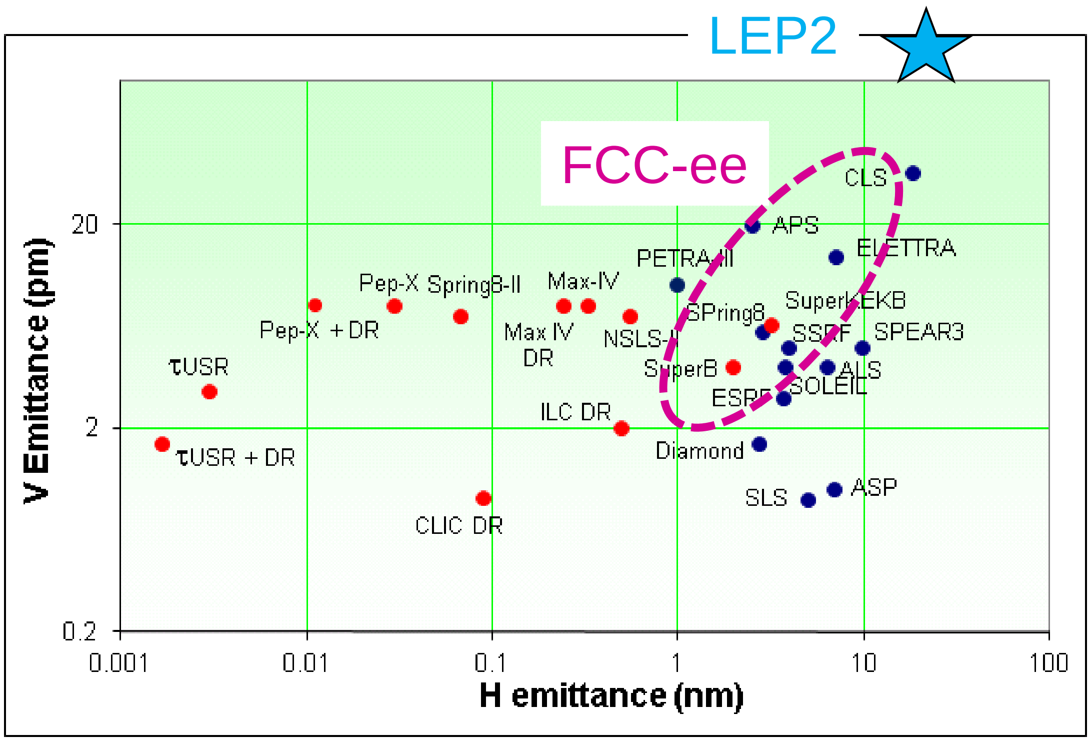


M. Koratzinos, *K. Ohmi,*
V. Telnov, A. Bogomyagkov,
E. Levichev, D. Shatilov

Emittances

- FCC-ee is a very large machine, scaling of achievable emittances (mainly vertical) is not straightforward.
  - Coupling, spurious vertical dispersion.
- Low emittances tend to be more difficult to achieve in colliders as compared to light sources or damping rings – beam-beam !
- FCC-ee parameters:
  - $\varepsilon_y/\varepsilon_x \geq 0.001$,
  - $\varepsilon_y \geq \approx 2$ pm

  with a ring ~50-100 larger than a typical light source.
- Very challenging target for a ring of that size!

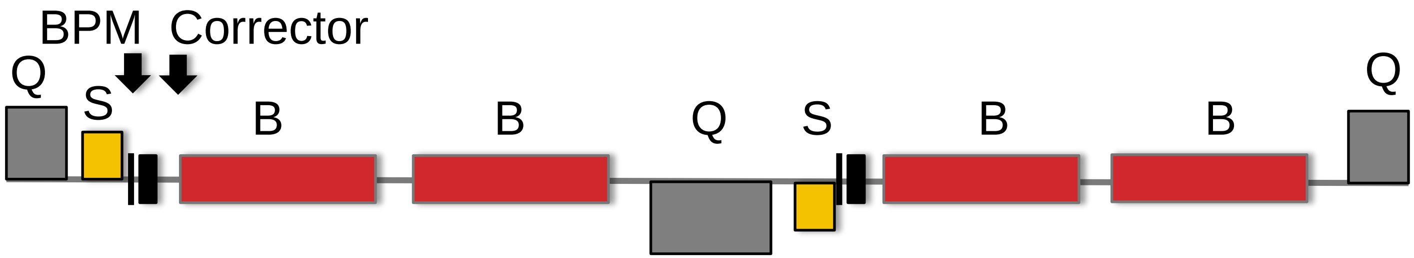


R. Bartolini, DIAMOND

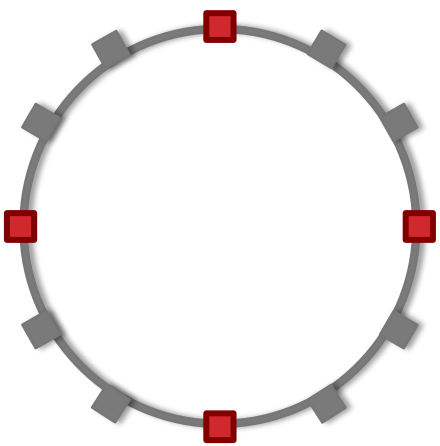
Arc lattice (circular machine)

LATTICE V12B-S

arc cell layout



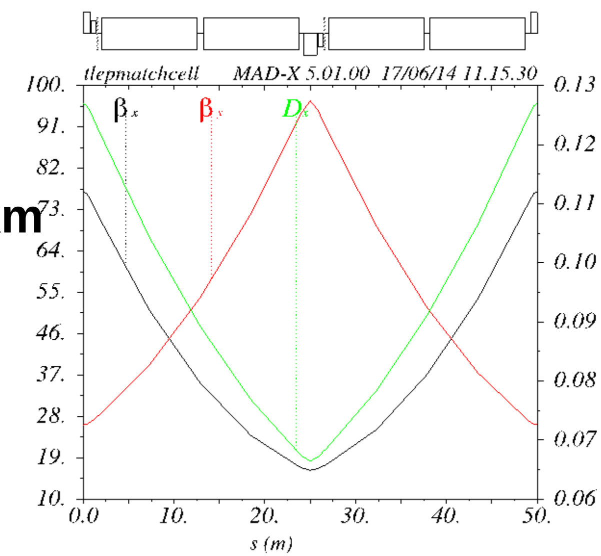
B = bending magnet, Q = quadrupole, S = sextupole

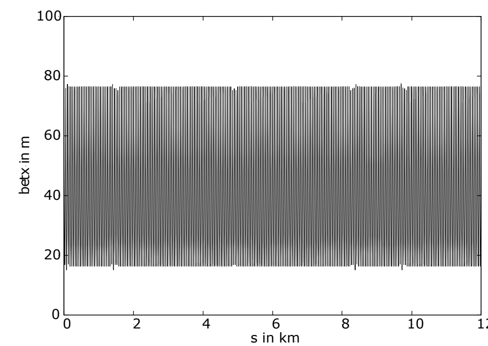


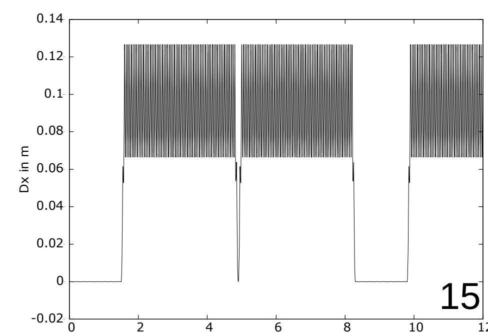
Circumference: 100 km
Arc length: 2 × 3.4 km
Straight section: 1.5 km

B. Harer, B. Holzer

FODO cell optics
cell length 50 m







Lattice options for lower energies

80 GeV

175 GeV and 120 GeV: L_{cell} = 50 m, Ψ = 90°/60°

Half-bend dispersion suppressor

80 GeV: L_{cell} = 50 m, Ψ = 45°/45°

Dispersion suppressor based on quadrupoles

80 GeV: L_{cell} = 100 m, Ψ = 90°/60°

- Arc cells
- Dispersion Suppressor
- Straight matching section (with RF)
- Straight cells (with RF)

45.5 GeV

175 GeV and 120 GeV: L_{cell} = 50 m, Ψ = 90°/60°

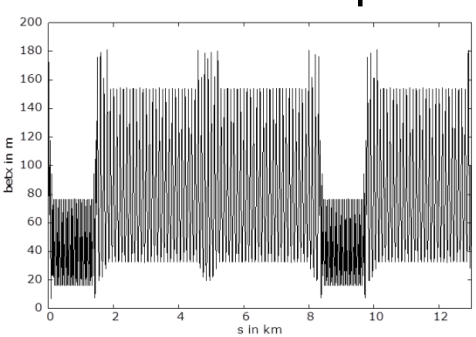
45.5 GeV: L_{cell} = 200 m, Ψ = 60°/60°

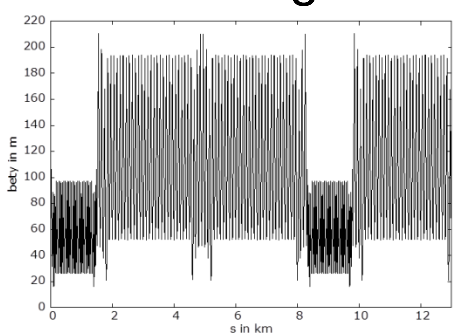
Dispersion suppressor based on quadrupoles

45.5 GeV: L_{cell} = 250 m, Ψ = 72°/72°

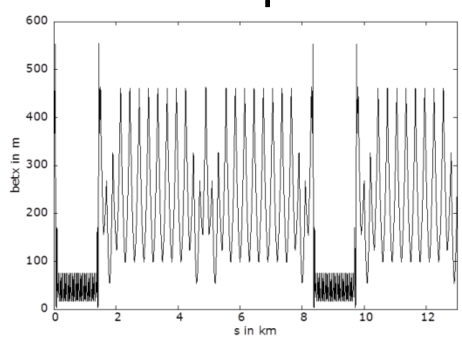
45.5 GeV: L_{cell} = 300 m, Ψ = 90°/60°

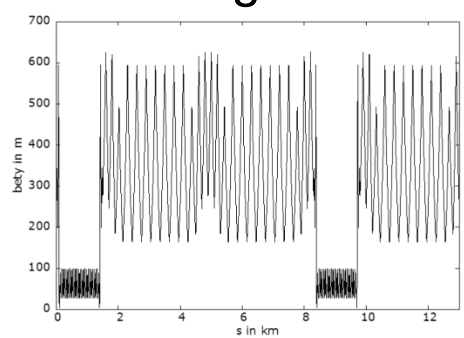
example: 100 m cell length





example: 300 m cell length





In all cases $\varepsilon_x \leq 0.5$ baseline ⇔ cell optimization

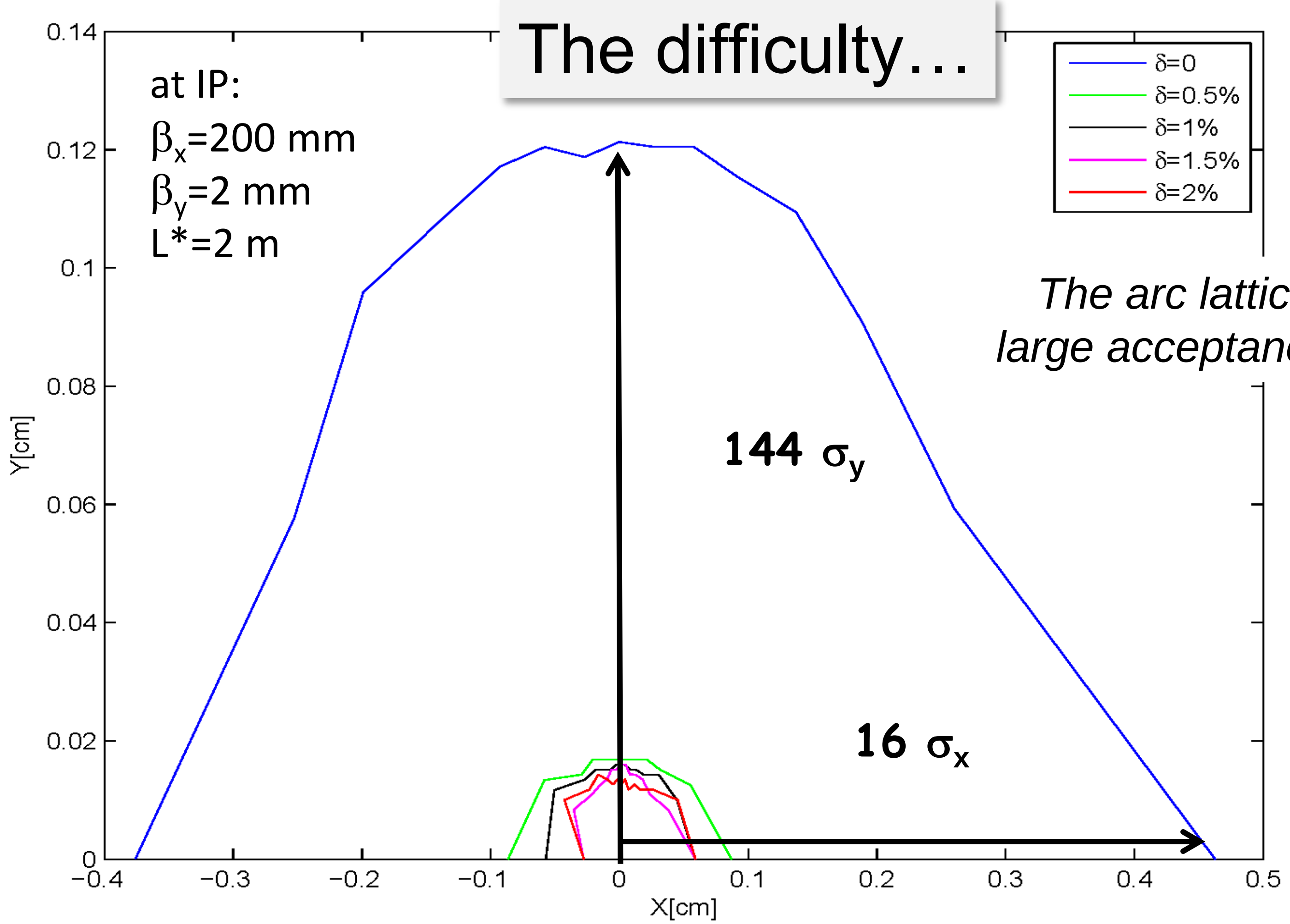
IR parameters

- At the IP the smallest possible β^* must be obtained – see L formula. The target for β^*_y is set to **<u>1 mm</u>**. Such a small β^* requires a local chromaticity correction scheme.
  - *Design taken over from linear collider IR. But with the complexity that the beam does not pass the IR only once.*
  - *Local chromaticity correction must be matched to global correction in the arc sections.*
  - *Very large optical functions → high sensitivity to aberrations.*
  - *Requires bending magnets close to the IP → SR fan !*
- The distance between IP and front-face of the first quadrupole is currently set to **$L^* \geq$ 2 m** (SuperKEKB ~1 m).
  - *Acceptance for experiments, luminosity measurement. To be studied.*

The combination of very small β_y^* and large acceptance is a challenge for the optics and MDI design !

Dynamic Aperture

The difficulty…

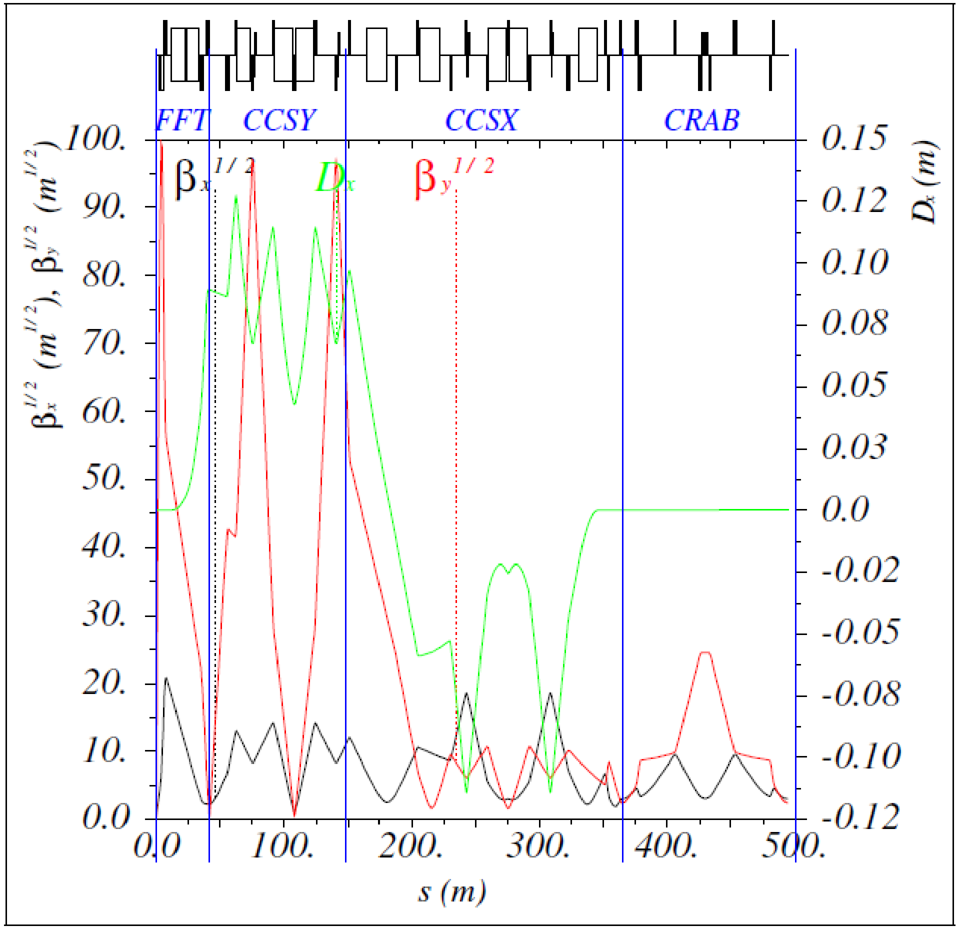


The arc lattice has a large acceptance (> 2%)

Example from Y. Cai (HF2014) for CEPC @ 120 GeV

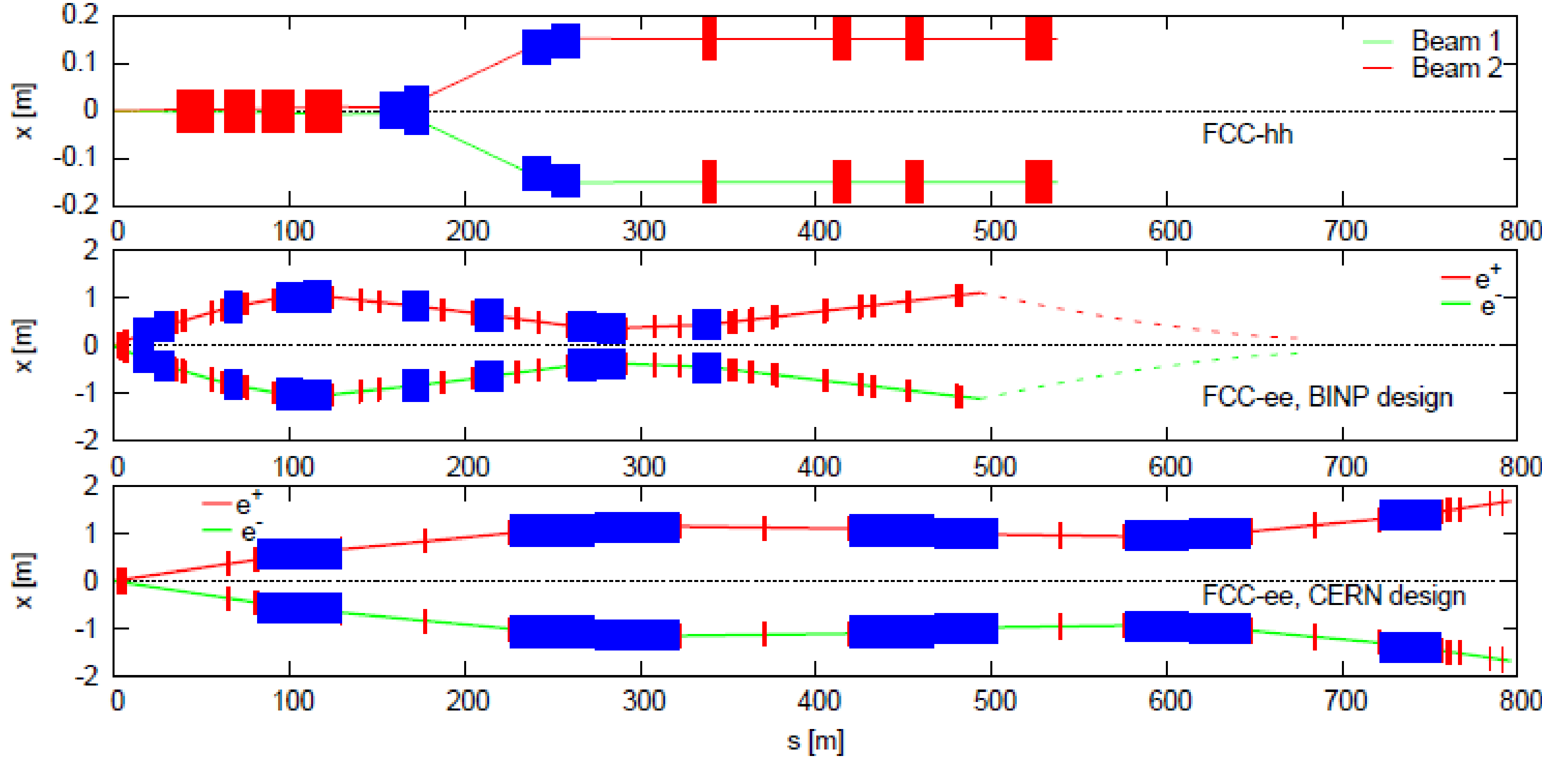
IR optical layout

- Ultra-low β* requires local correction of chromatic effects (copied from Linear Colliders).
  - *Requires dipoles in the 'straight section' → additional SR.*
  - *Lengthens the IR very significantly.*
- Example on this slide was designed by BINP with L* = 2m.
  - *Long sections are needed for the chromatic corrections.*
- The problem of dynamic aperture is coming from high order aberrations that are difficult to compensate.
  - *An when compensated in an ideal machine, how robust it is to machine errors.*



Chromatic correction

IR layouts



Dipoles in blue

Quadrupoles in red

- Tunnel transverse width of both FCC-ee designs ~3-4 m.
- Additional length is required to bend beams back, plus room for RF.
- Synchrotron rad. power per IP: CERN 140 kW, BINP 1400 kW.
  - *Optimum between length and power loss to be identified !*
  - *93 km racetrack IR straights of 1400 m may be too short for ee !*

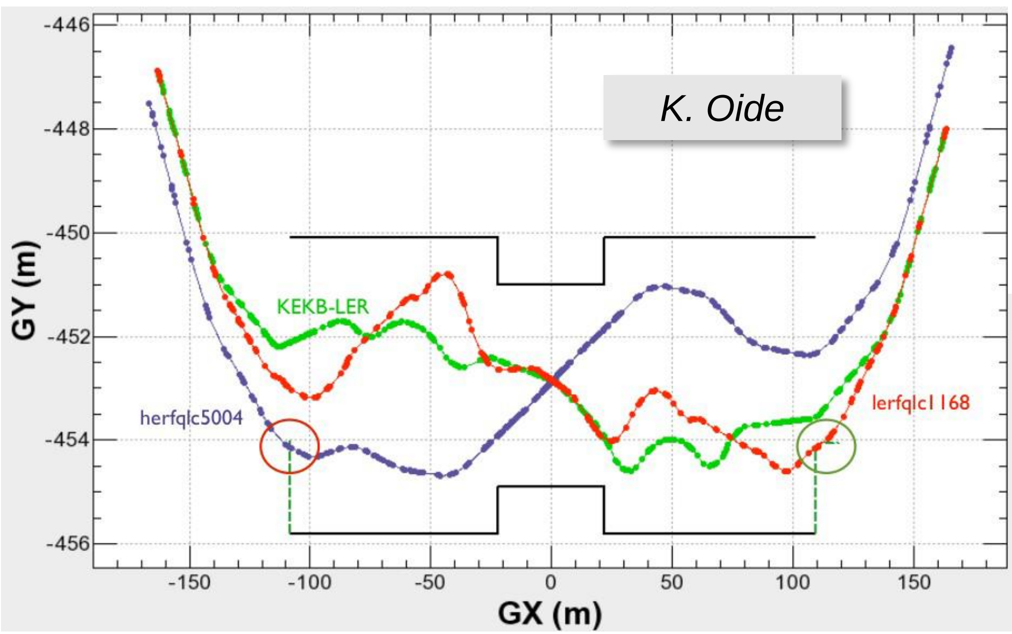
IR challenges and next steps

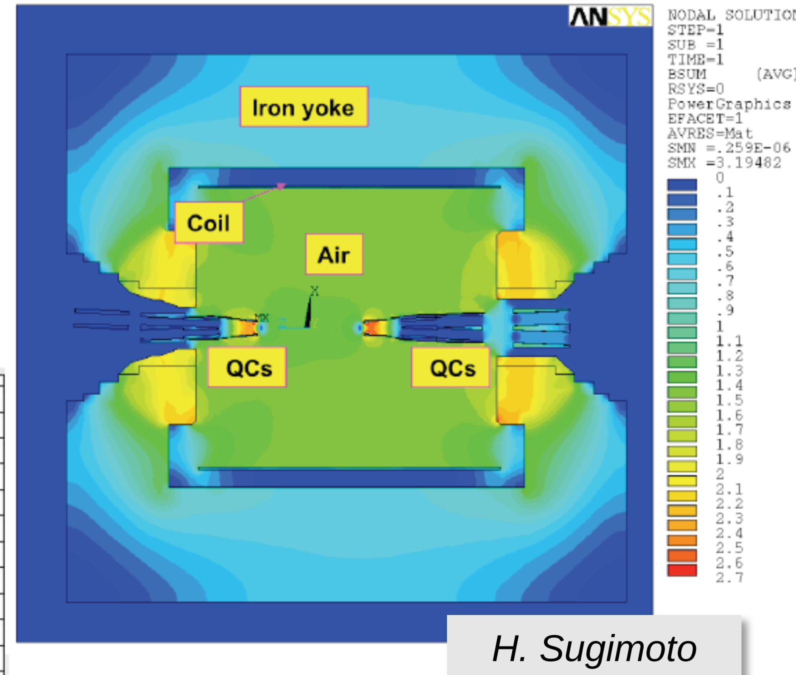
- Find an optics solution with smallest possible β* that satisfies the requirements for momentum aperture of 1.5-2%.
  - *We will soon build a larger β* (~20 mm) optics without local chromatic cor. to study how far one can push a global scheme.*
- Define a viable crossing angle and L* (final focus SC magnet design – 2 apertures, MDI).
- Optimize the bending strength and dipole arrangement to obtain tolerable SR loads on vacuum chambers, SC magnets bores… while preserving performance.
  - *Design masks and local absorbers.*
- MDI integration.
- Study robustness of optics to machine errors (alignment, magnetic fields, fringe fields etc), effect of the experimental solenoids.

Iterate !!!

SuperKEKB IR

- IR layout of SuperKEKB – the only straight thing is the tunnel.
- ‘Wiggling’ of the beam paths ⇔ local chromatic corrections.





- The last focusing quadrupoles are installed deep inside the BELLE detector.
  - *Shielded from the BELLE solenoidal field with anti-solenoids.*

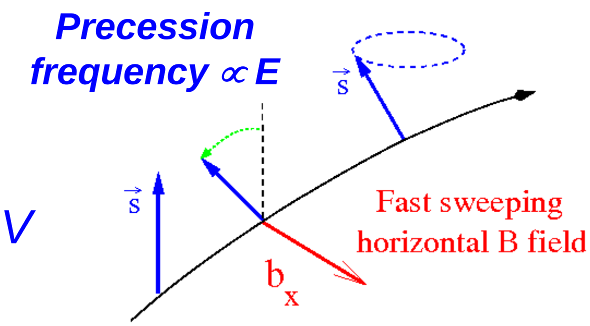
SC RF System

- RF system requirements are characterized by two different regimes.
  - *High gradients for H and $t\bar{t}$ – up to ~11 GV.*
  - *High beam loading with currents of ~1.5 A at the Z pole.*
  - *RF experts are not convinced that one can achieve both goals with the same RF system – part of the study !*
- The RF system must be distributed over the ring to minimize the energy excursions (~4.5% energy loss @ 175 GeV).
  - *Optics errors driven by energy offsets, effect on η.*
- Aiming for SC RF cavities with gradients of ~20 MV/m.
- RF frequency most likely 400 MHz (current baseline 800 MHz).
  - *Crab waist & large crossing angles favor lower frequency → 400 MHz.*
- Conversion efficiency (wall plug to RF power) is critical. Aiming for over 75%!
  - *Key item for the FCC-ee power budget.~65% was achieved for LEP2.*

Polarization

Two main interests for polarization:

- Accurate energy calibration using resonant depolarization ⇒ measurement of M_Z, Γ_Z, M_W
  - *Nice feature of circular machines, δM_Z, $\delta \Gamma_Z$ ~ 0.1 MeV*



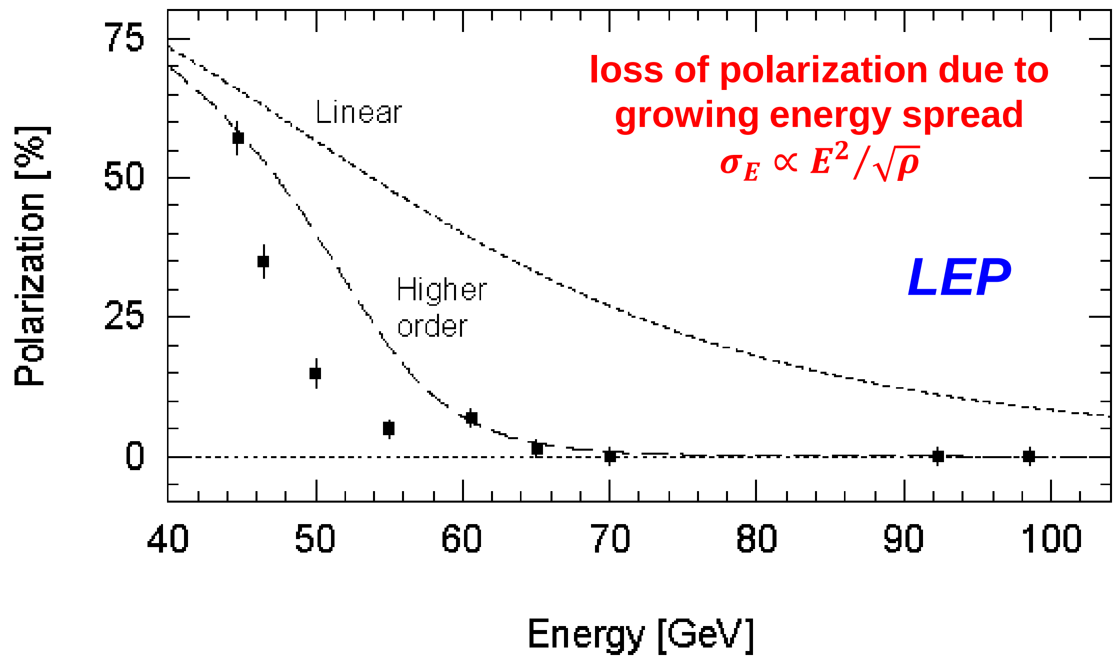
- Physics with longitudinally polarized beams.
  - *Transverse polarization must be rotated in the longitudinal plane using spin rotators (see e.g. HERA).*

Scaling the LEP observations :

polarization expected up to the WW threshold !

Integer spin resonances are spaced by 440 MeV:

energy spread should remain below ~ 60 MeV

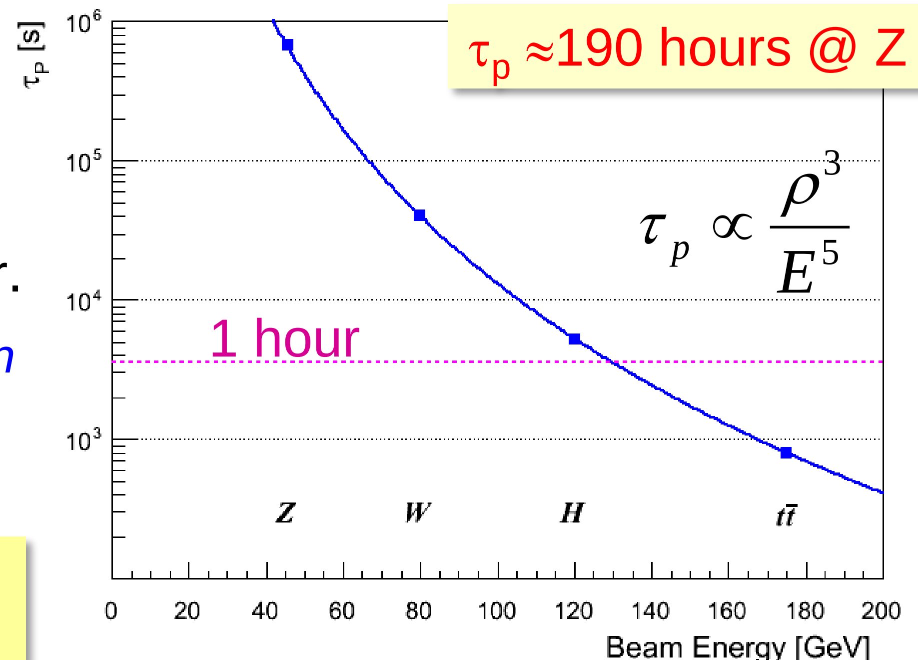


Polarization build up

- Transverse polarization build-up (Sokolov-Ternov) is very slow at FCC-ee (large bending radius ρ).

  Build-up is ~40 times slower than at LEP

- Wigglers may lower τ_p to ~12 h, limited by $\sigma_E \leq 60$ MeV and power.
  - *Due to power loss the wigglers can only be used to pre-polarize some bunches (before main injection).*



$\approx$ OK for energy calibration (few % P sufficient)

- Simulations of polarization with realistic machine errors, solenoids and their compensation should start soon.
  - *The solenoid compensation must be integrated into IR or disp. suppressor – tricky because of the bends and the crossing angle (precession in the H plane) !!*

Energy calibration

- Resonant depolarization has a very high intrinsic accuracy to determine the **AVERAGE** energy (< 0.1 MeV), but some systematic effects must be taken into account.
  - *Example: systematic errors on the spin precession frequency due to vertical misalignments ('rotations due not commute') may not be totally negligible. At LEP this error was at the level of 50-100 KeV.*
- Other ideas for calibration are on the market. But achieving a rel. accuracy of $\sim 10^{-5}$ is not trivial ! Lot's of serious studies to perform.
  - *Beware of local measurements → increased systematic errors!*
- The CM energy is given by the **LOCAL** energy of the beams at IPs. Shifts and uncertainties at the level of O(MeV) are induced by:
  - *Cavity alignment, phase and voltage calibration errors – tough to monitor !*
  - *Residual dispersion when beams do not collide head-on perfectly – important systematic effect for mono-chromators !*

Conclusions

- A baseline racetrack-like layout has now been defined to begin integration and infrastructure studies. Details like straight section lengths will require more studies for both ee and hh.

  FCC-ee parameter set will be adapted to this layout.

- In case you did not know, FCC-ee has loads of challenges, from the layout through the optics to the SC RF system.

  The IR is a key item !

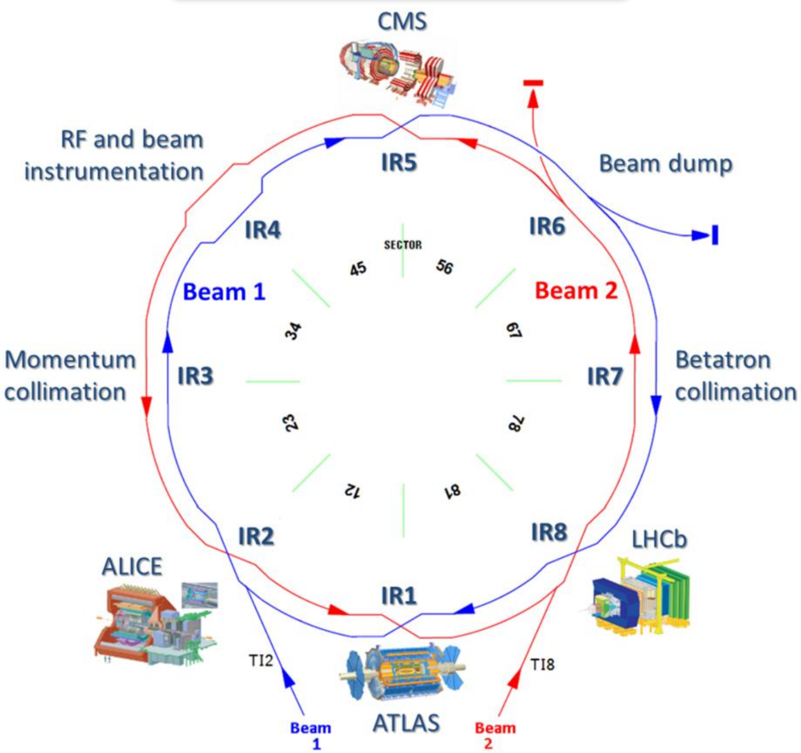
- For the moment FCC-ee is essentially a set of target parameters since we do not have a 'working' machine design…

- …but work on many aspects, in particular the design of the IR, is gaining momentum – in one year from now we will have a clearer idea on the achievable β^* and on the (im-)possible IR layouts !

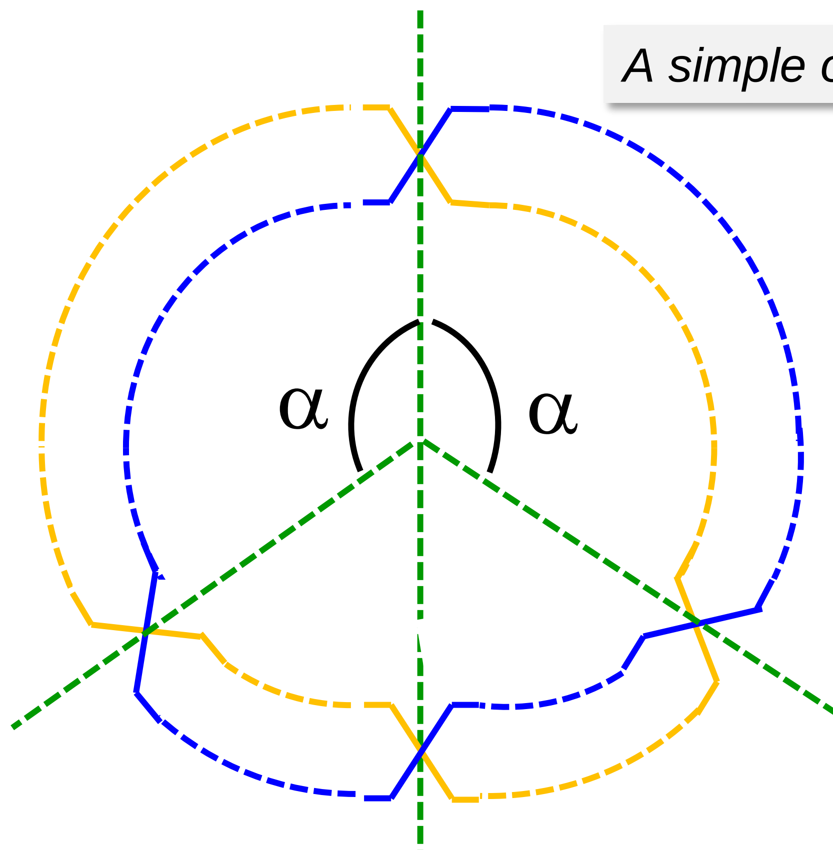
Experiments layout

- ❑ With 2 rings that are side by side there are some constraints on the geometry:
  - ✓ The path length of both beams must be identical (same energy & v/c) → democratic exchange positions between inner an outer ring.
  - ✓ At every crossing the beams exchange roles wrt inside and outside → to close the ring properly the total number of crossings must be an even number.

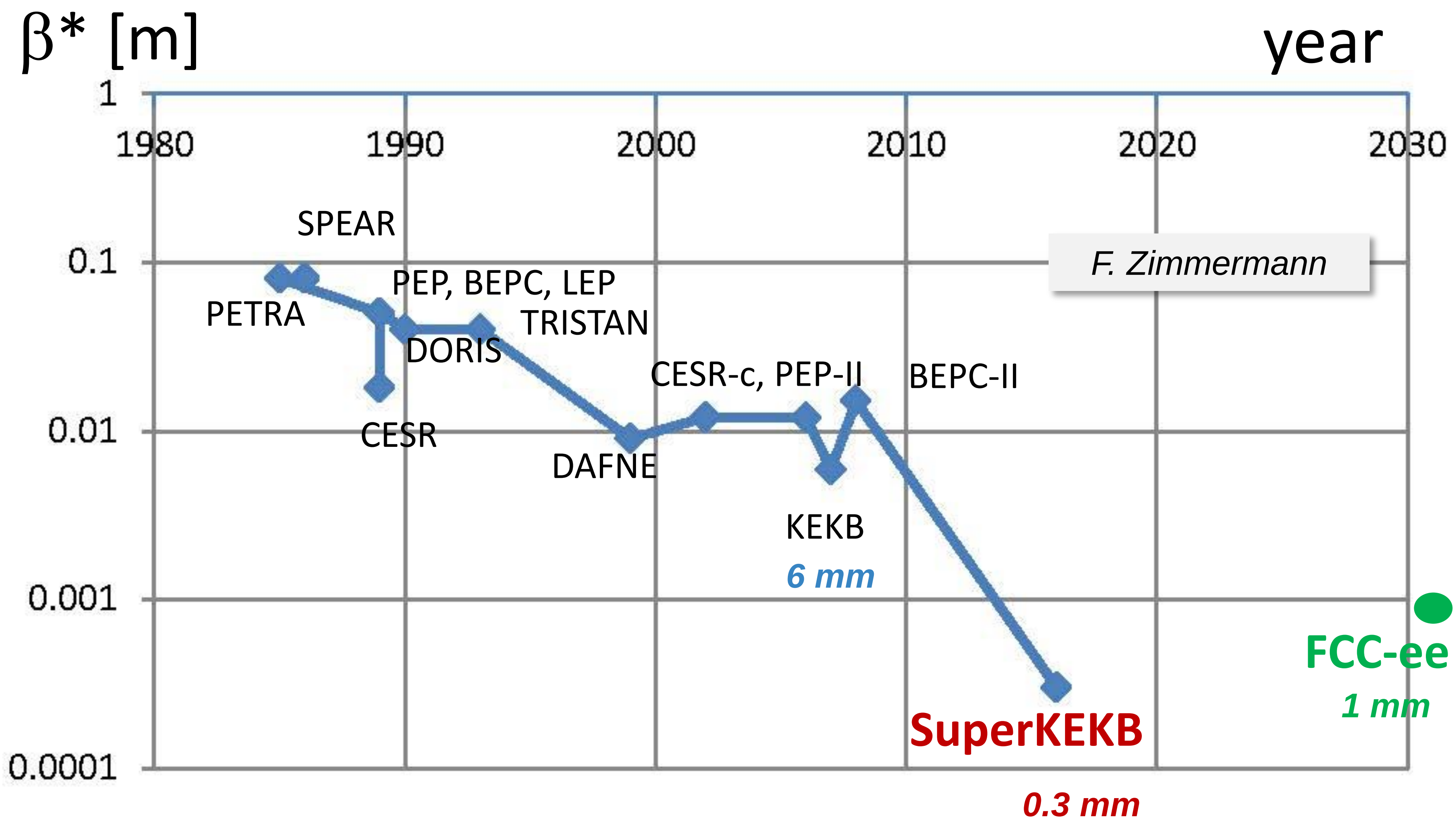
Famous example



A simple option



β* evolution

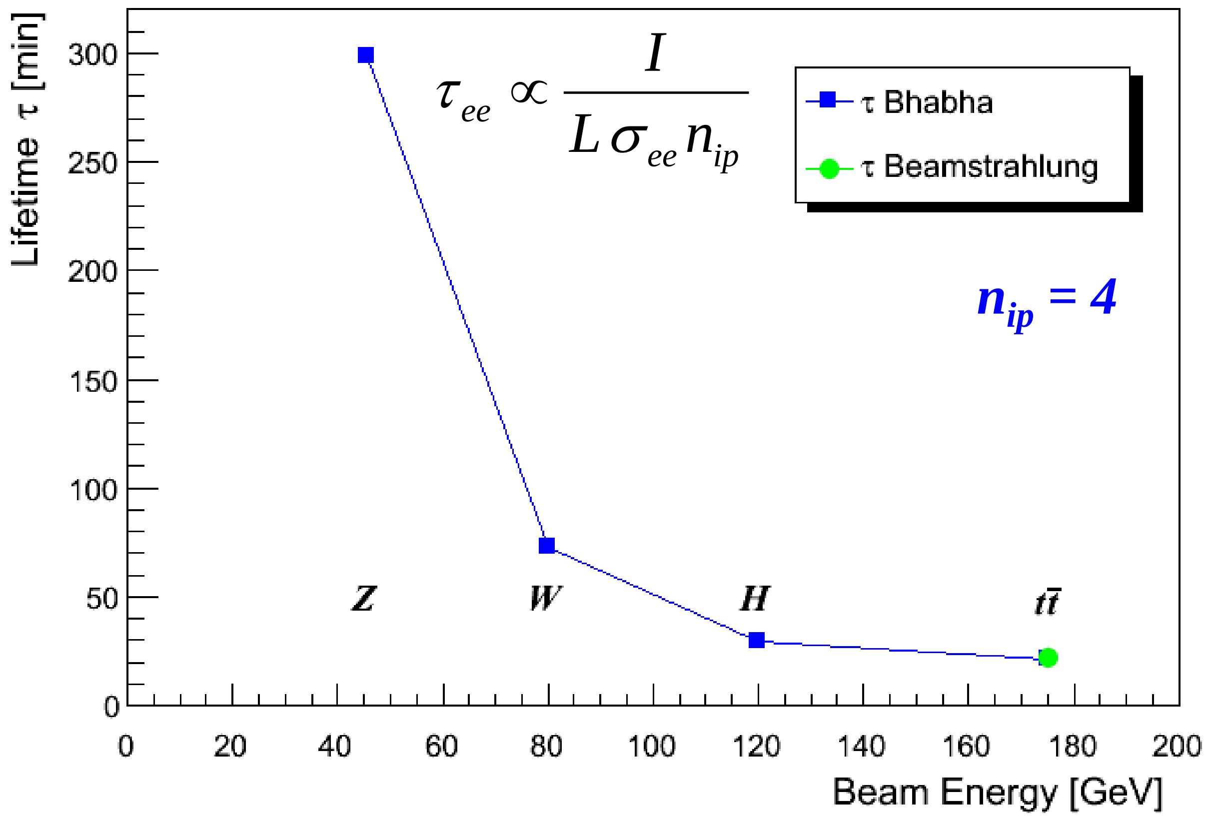


SuperKEKB will be a FCC-ee demonstrator for certain optics aspects !

Luminosity lifetime

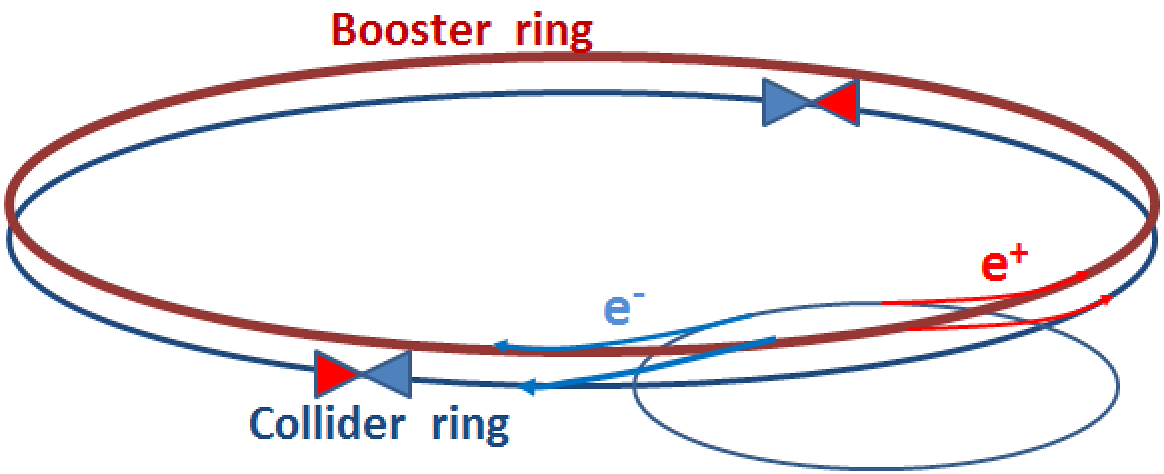
- Lifetime from luminosity depends on radiative Bhabha scattering total cross-section $\sigma_{ee} \approx 0.15$ (b) for η=2% ≈ independent of energy.

  ⇒ Lifetimes down to ~15 minutes. → **Continuous injection (top-up)**



Injection

- Besides the collider ring(s), a booster of the same size (same tunnel) must provide beams for top-up injection.
  - *Same size of RF system, but low power (~ MW).*
  - *Top up frequency ~0.1 Hz.*
  - *Booster injection energy ~20 GeV.*
  - *Bypass around the experiments.*
- Injector complex for e^+ and e^- beams of ~20 GeV.
  - *Super-KEKB injector ~ almost suitable (needs boost of energy).*



Single ring option

- With a single ring electrostatic fields must be used to separate and recombine the beams.
- Such 'Pretzel' schemes were used at many colliders (CESR, LEP, SppS, Tevatron).
  - *The max. number of bunches is much smaller than for 2-ring factories.*
  - *Constraints on arc optics.*
  - *Head-on collisions !*
- The number of bunches would probably be limited to k~50-500.
  - *Luminosity reach for H and $t\bar{t}$ not far from baseline figures, significantly lower luminosity at Z and W.*

Not the baseline option for FCC-ee !

LEP Pretzel scheme