FCC-ee accelerator overview

F. Zimmermann

FCC-ee physics workshop (“TLEP7”)

CERN, 21 June 2014

gratefully acknowledging input from
FCC global design study & CepC team

YEARS / ANS CERN

FCC hh ee he

*Work supported by the **European Commission** under Capacities 7th Framework Programme, Grant Agreement 312453*

Future Circular Collider (FCC) study ; goals: CDR and cost review for the next European Strategy Update (2018)

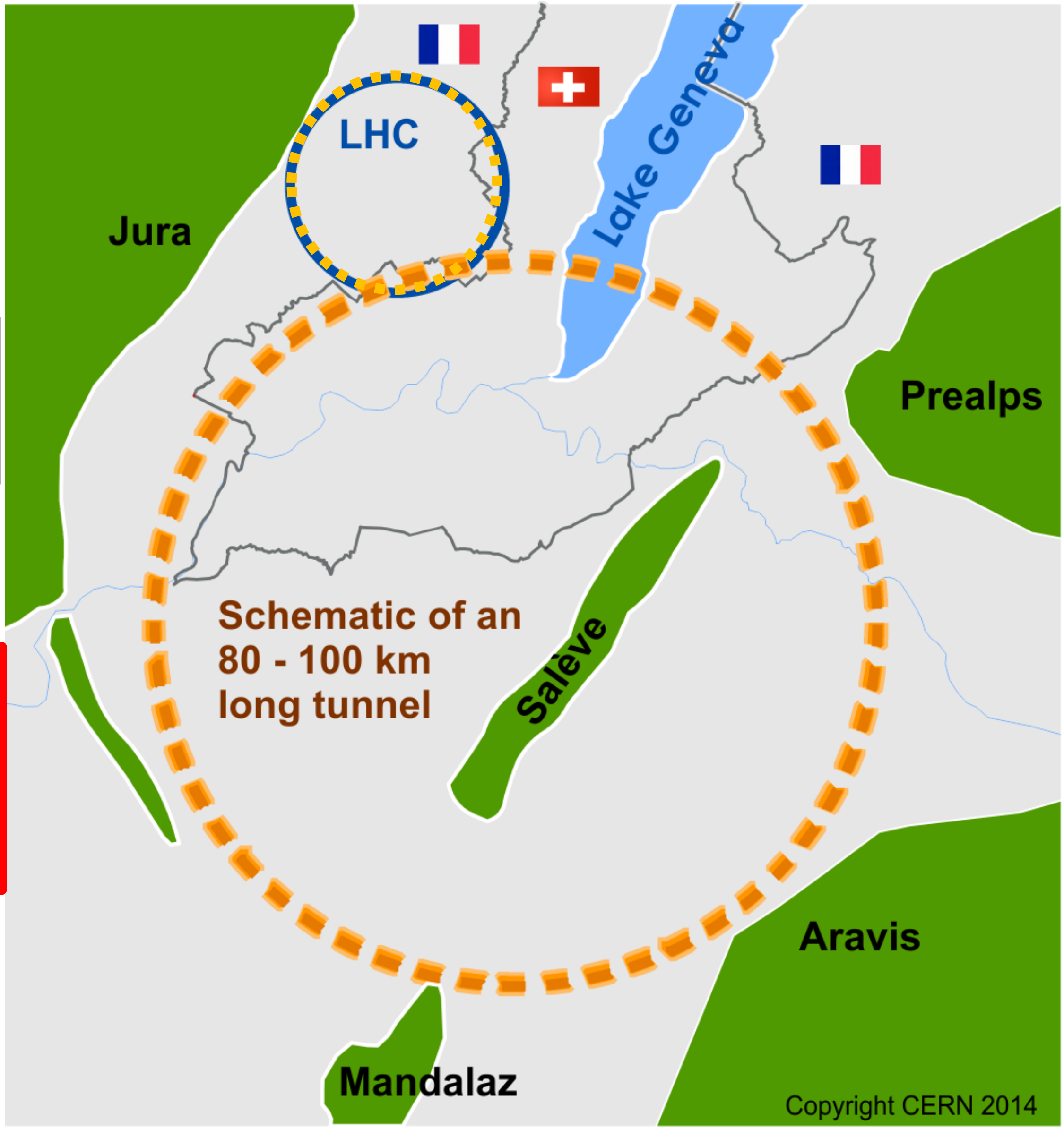
International collaboration :

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

~16 T ⇒ 100 TeV in 100 km
~20 T ⇒ 100 TeV in 80 km

- including ***HE-LHC*** option: 16-20 T in LHC tunnel
- ***e^+e^-* collider (*FCC-ee/TLEP*)** as potential intermediate step
- ***p-e* (*FCC-he*) option**
- **100 km infrastructure** in Geneva area

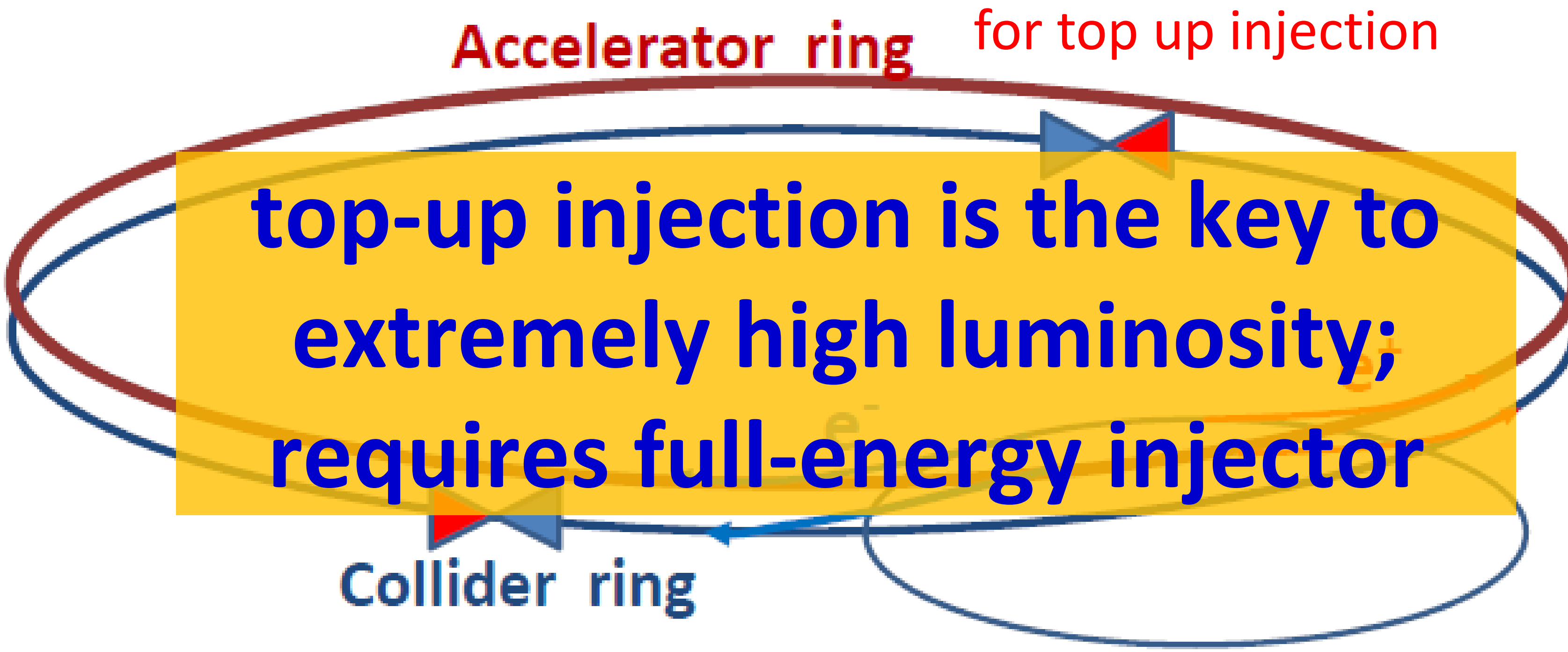
M. Benedikt



FCC-ee: e^+e^- collider up to 350 (500) GeV

circumference ≈100 km

A. Blondel



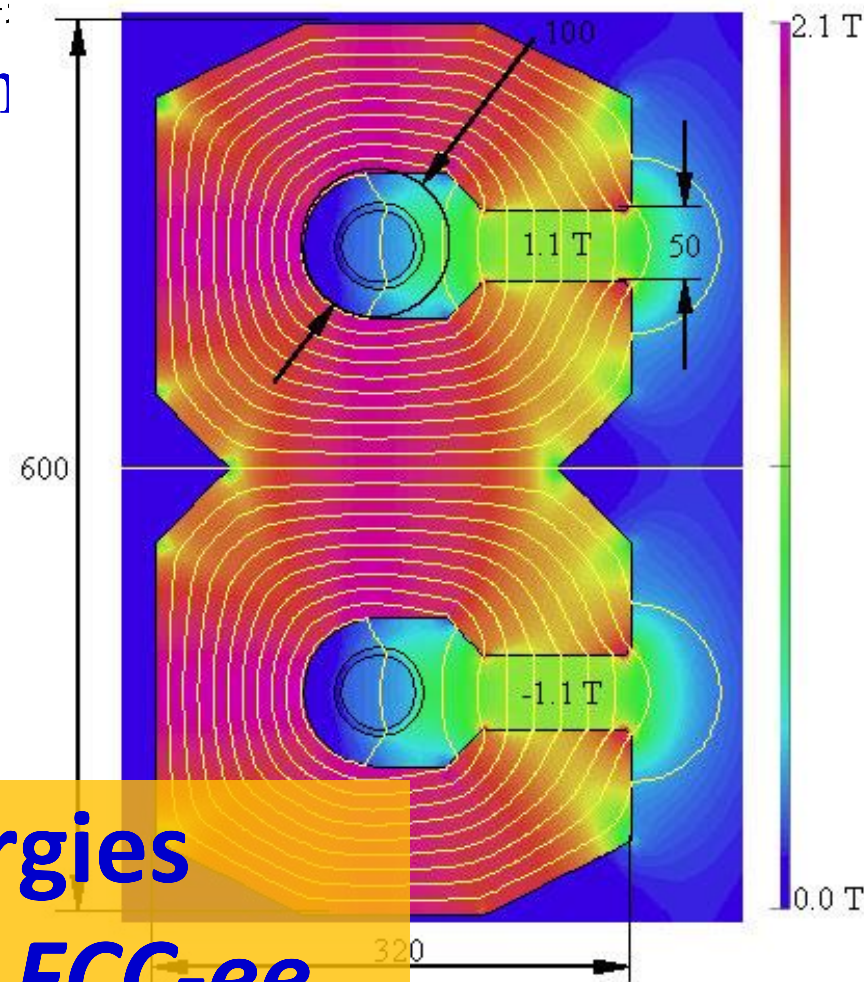
top-up injection is the key to extremely high luminosity; requires full-energy injector

short beam lifetime (~τ_{LEP2}/40) due to high luminosity **supported by top-up injection** (used at KEKB, PEP-II, SLS,…); top-up **also avoids ramping & thermal transients, + eases tuning**

FCC-ee/hh: hybrid NC & SC arc magnets

twin-aperture iron-dominated, compact hybrid “transmission line” dipoles - for injector synchrotrons in FCC tunnel

- resistive cable for lepton machine
- superconducting for hadron operation



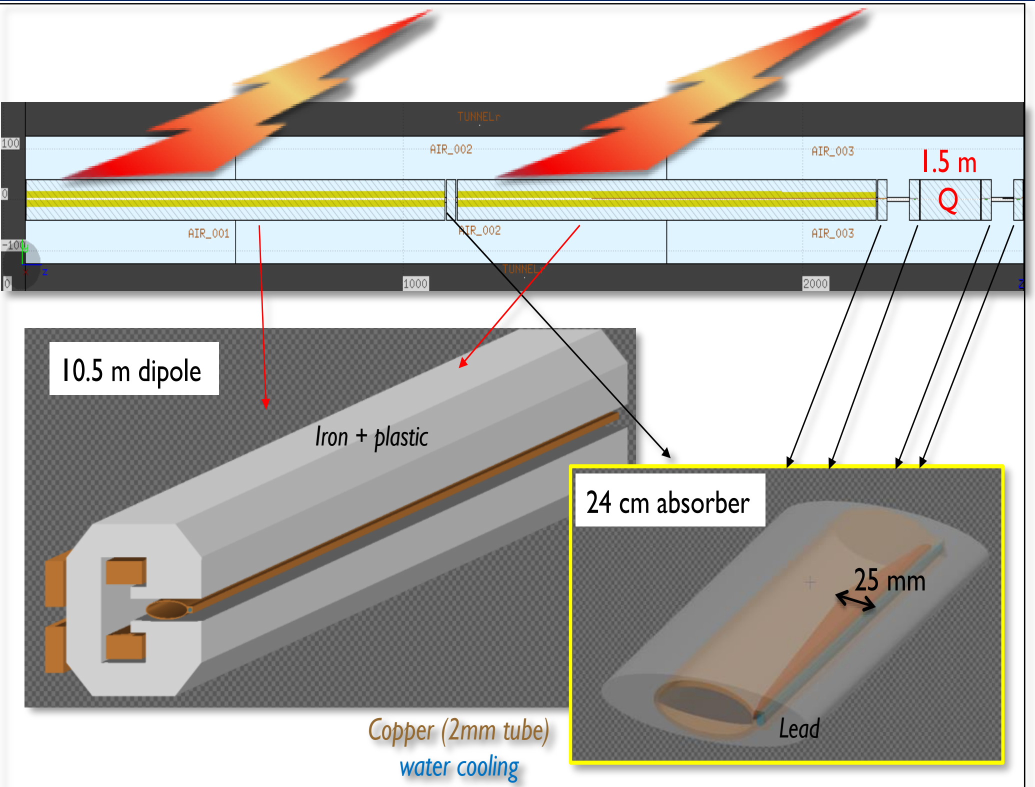
required dynamic range ~100
hadron extraction 1.1 T
lepton injection: 10 mT

one of many synergies between *FCC-hh* and *FCC-ee*

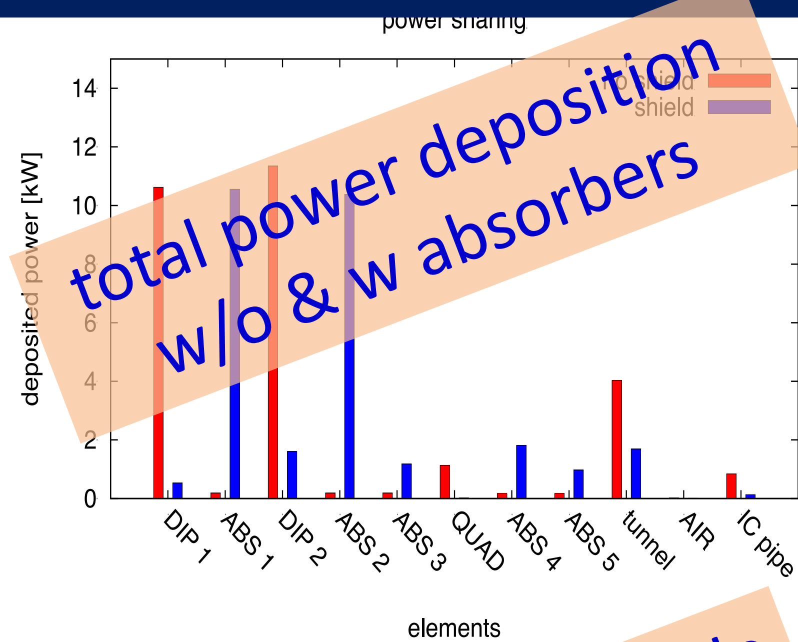
A. Milanese, H. Piekarz, L. Rossi, IPAC2014, TUOCB01

parameter	LEP2	FCC-ee					CepC
		Z	Z (c.w.)	W	H	t	H
E_{beam} [GeV]	104	45	45	80	120	175	120
circumference [km]	26.7	100	100	100	100	100	54
current [mA]	3.0	1450	1431	152	30	6.6	16.6
$P_{SR,tot}$ [MW]	22	100	100	100	100	100	100
no. bunches	4	16700	29791	4490	1360	98	50
N_b [10^{11}]	4.2	1.8	1.0	0.7	0.46	1.4	3.7
ε_x [nm]	22	29	0.14	3.3	0.94	2	6.8
ε_y [pm]	250	60	1	1	2	2	20
β^*_x [m]	1.2	0.5	0.5	0.5	0.5	1.0	0.8
β^*_y [mm]	50	1	1	1	1	1	1.2
σ^*_y [nm]	3500	250	32	130	44	45	160
$\sigma_{z,SR}$ [mm]	11.5	1.64	2.7	1.01	0.81	1.16	2.3
$\sigma_{z,tot}$ [mm] (w beamstr.)	11.5	2.56	5.9	1.49	1.17	1.49	2.7
hourglass factor F_{hg}	0.99	0.64	0.94	0.79	0.80	0.73	0.61
L/IP [10^{34} cm^{-2}s^{-1}]	0.01	28	212	12	6	1.7	1.8
τ_{beam} [min]	300	287	39	72	30	23	40

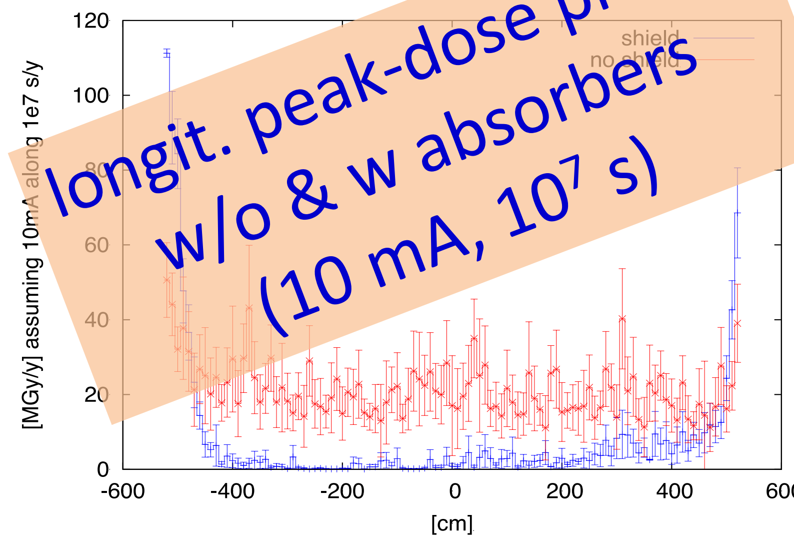
Shielding 100 MW SR at 350 GeV



FLUKA geometry layout for half FODO cell, dipoles details, preliminary absorber design incl. 5 cm external *Pb* shield



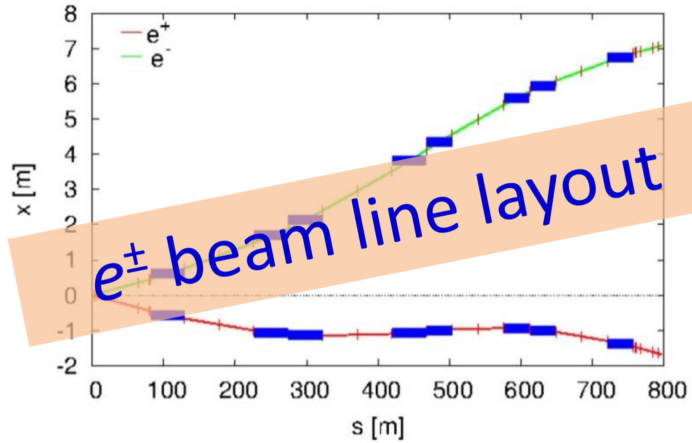
total power deposition w/o & w absorbers



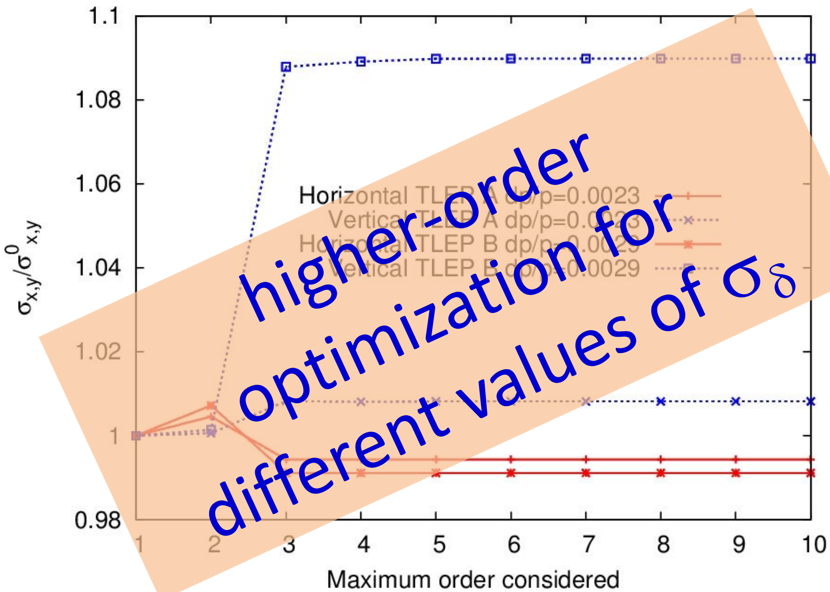
longit. peak-dose profile w/o & w absorbers (10 mA, 10^7 s)

L. Lari et al., IPAC2014, THPRI011

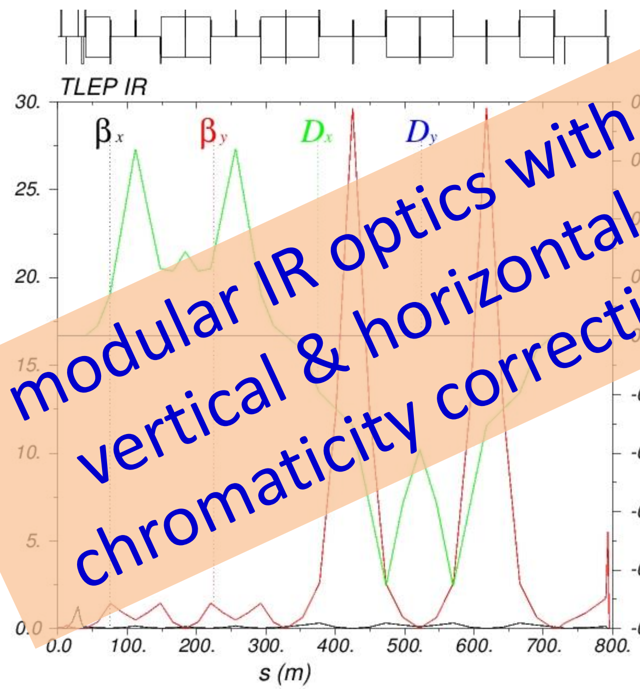
FCC-ee IR design #1



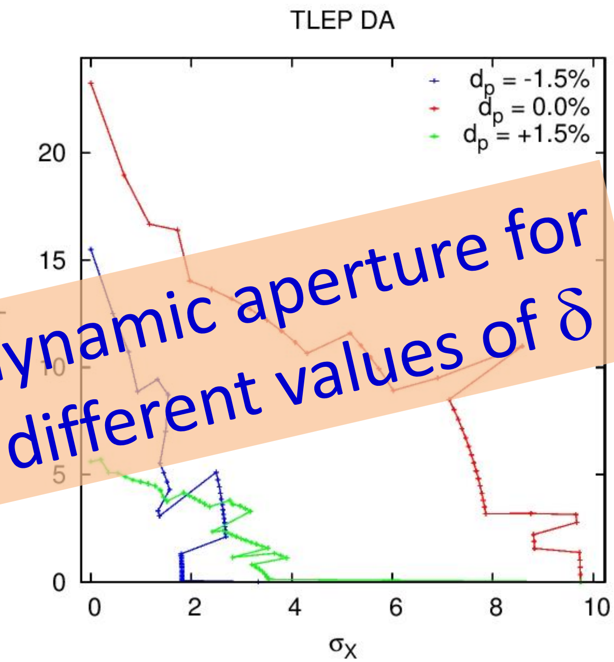
$e^{\pm}$ beam line layout



higher-order optimization for different values of σ_δ



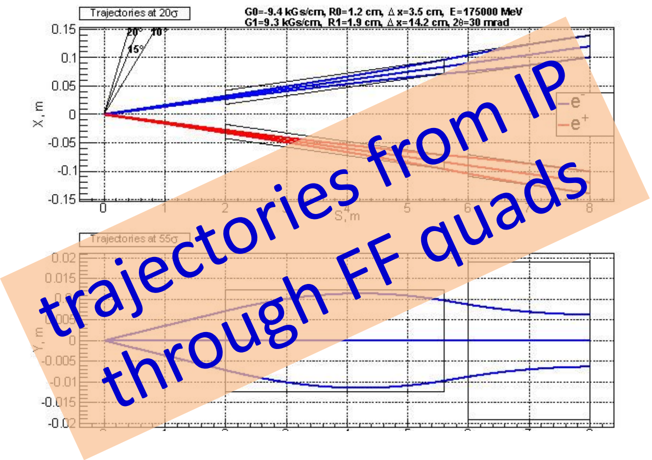
modular IR optics with vertical & horizontal chromaticity correction

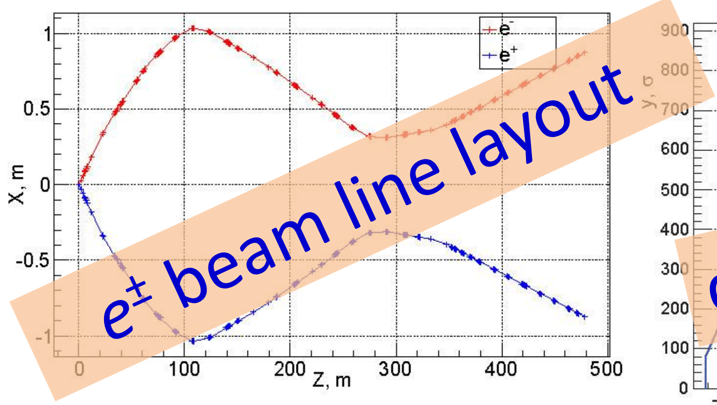


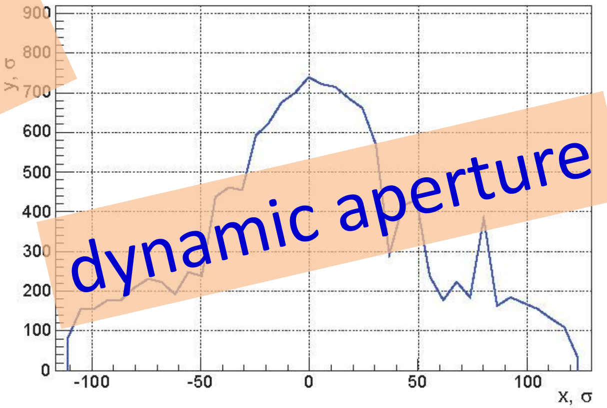
dynamic aperture for different values of δ

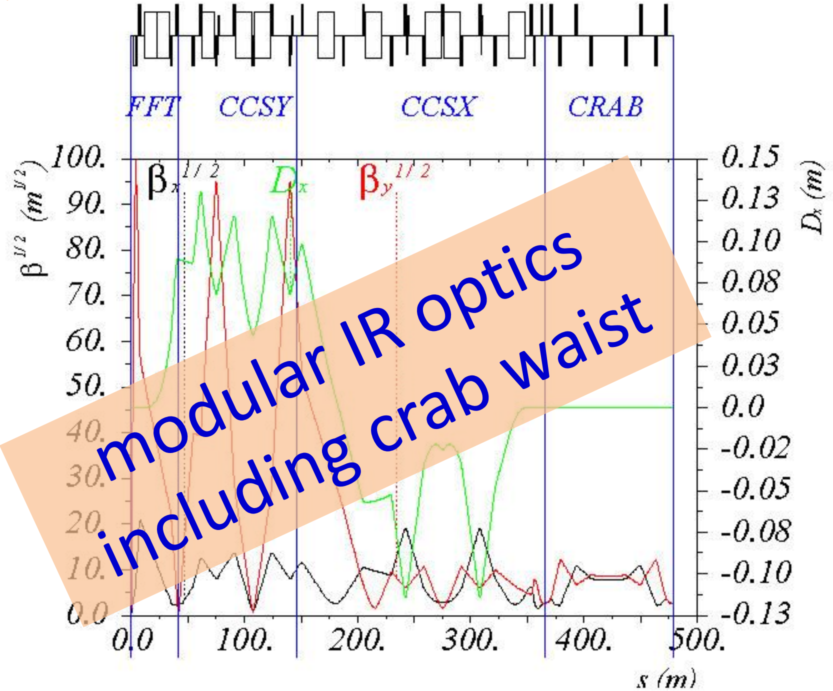
H. Garcia, L. Medina, R. Tomas, IPAC2014, THPRI010

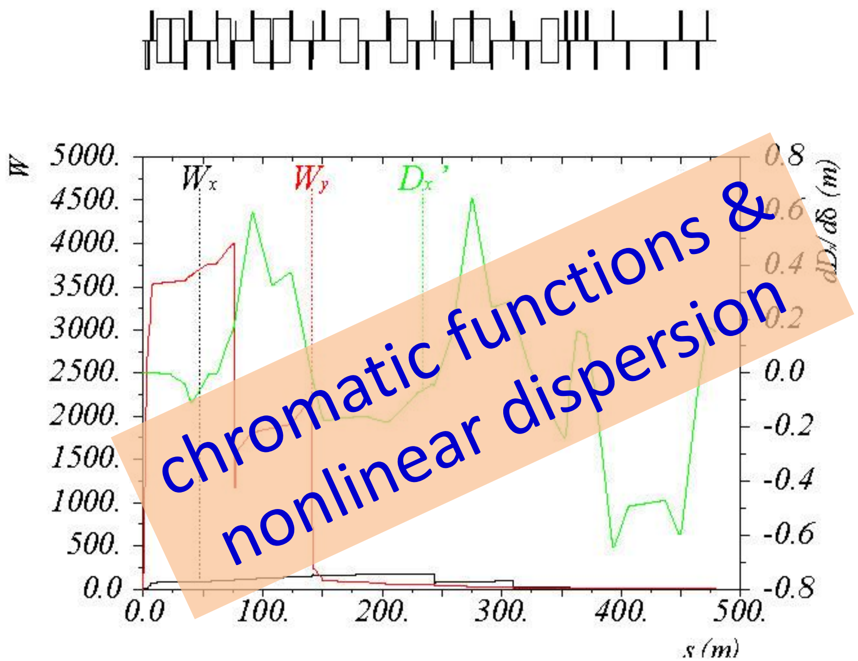
FCC-ee IR design #2









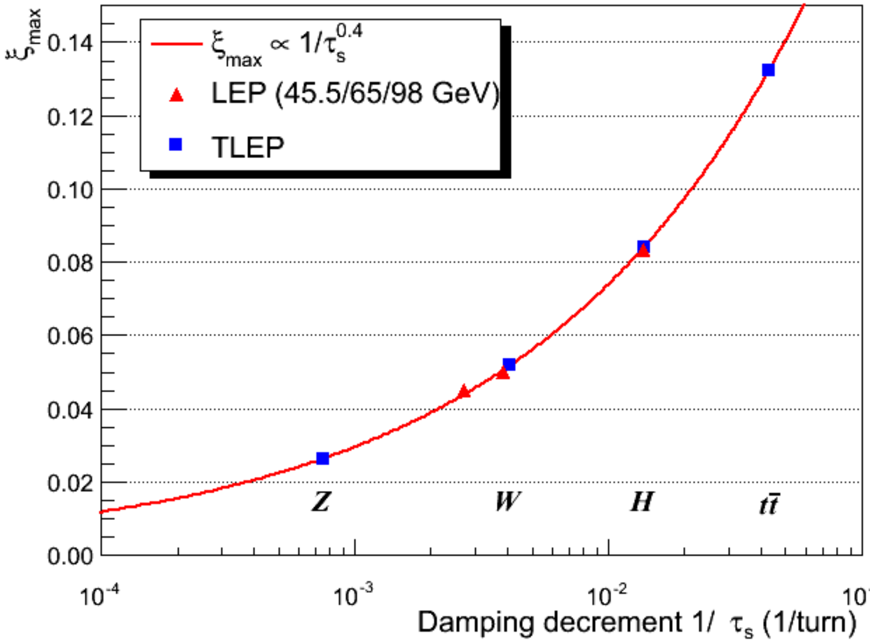


A. Bogomyagkov, E. Levichev, P. Piminov, IPAC2014, THPRI008

beam-beam tune shift & energy scaling

tune shift limits scaled from LEP data, confirmed by FCC simulations (S. White, K. Ohmi, A. Bogomyagkov, D Shatilov,…):

R. Assmann & K. Cornelis, EPAC2000



$$\xi_y \simeq \frac{\beta_y r_e N}{2\pi\gamma\sigma_x\sigma_y} \leq \xi_{y,\max}(E)$$

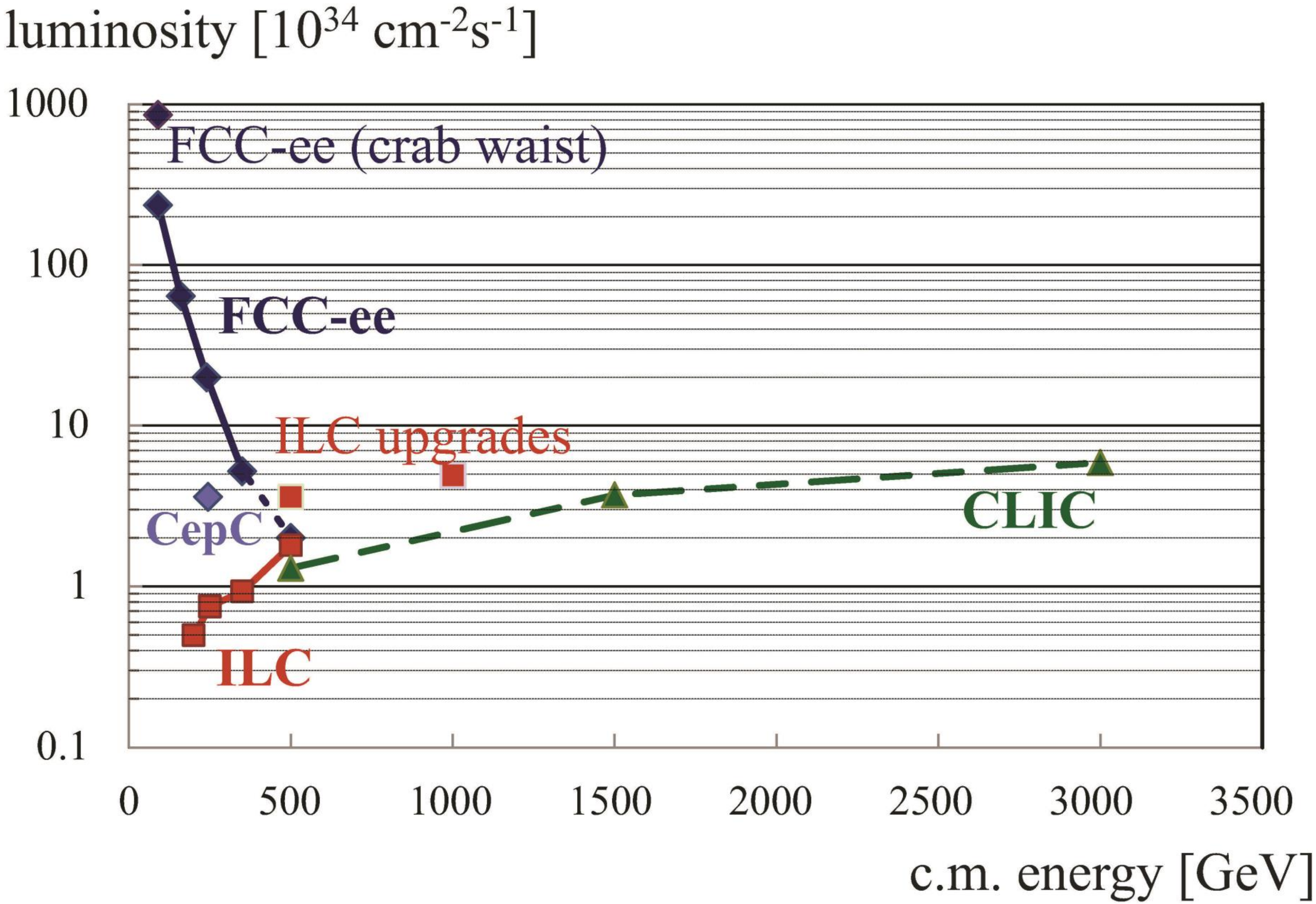
$$\xi_{y,\max}(E) \propto \frac{1}{\tau_s^{0.4}} \propto E^{1.2}$$

→ luminosity scaling with energy:

$$L = n_{IP}\frac{f_{coll}N^2}{4\pi\sigma_x\sigma_y}F_{hg} \propto \frac{\eta P_{SR}}{E^3}\frac{\xi_y}{\beta_y^*} \propto \frac{\eta_{w\to b}P_{wall}}{E^{1.8}}\frac{1}{\beta_y^*}$$

J. Wenninger

e^+e^- luminosity vs energy



beamstrahlung (BS)

synchrotron radiation in the strong field of opposing beam

two effects:

1) increased energy spread & bunch lengthening

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

K. Ohmi & F.Z., IPAC14, THPRI004

with

$$\sigma_{\delta,BS} \approx \delta_{BS}\left(0.333 + \frac{4.583}{n_\gamma}\right)^{\frac{1}{2}} ;\ \delta_{BS} \approx 0.86\frac{r_e{}^3\gamma N_b{}^2}{\sigma_z\sigma_x{}^2};\ n_\gamma \simeq 2.1\frac{\alpha r_e N_b}{\sigma_x}$$

K. Yokoya NIM A251, 1986

2) beam lifetime limitation due to high-energy photons

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

V. Telnov, PRL 110 (2013) 114801

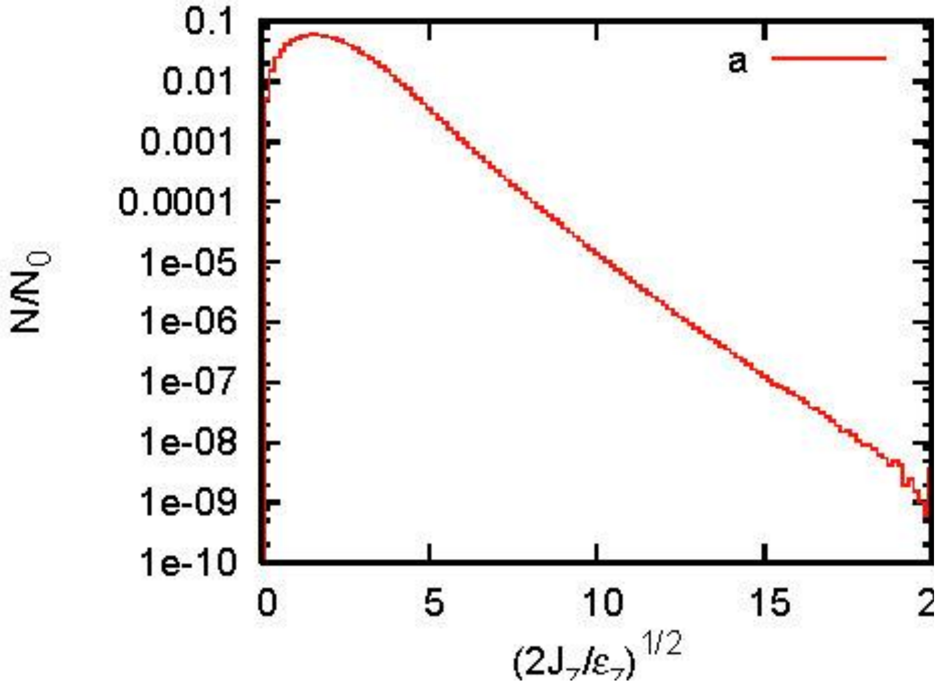
A. Bogomyagkov, E. Levichev, D. Shatilov, PRST-AB 17, 041004 (2014)

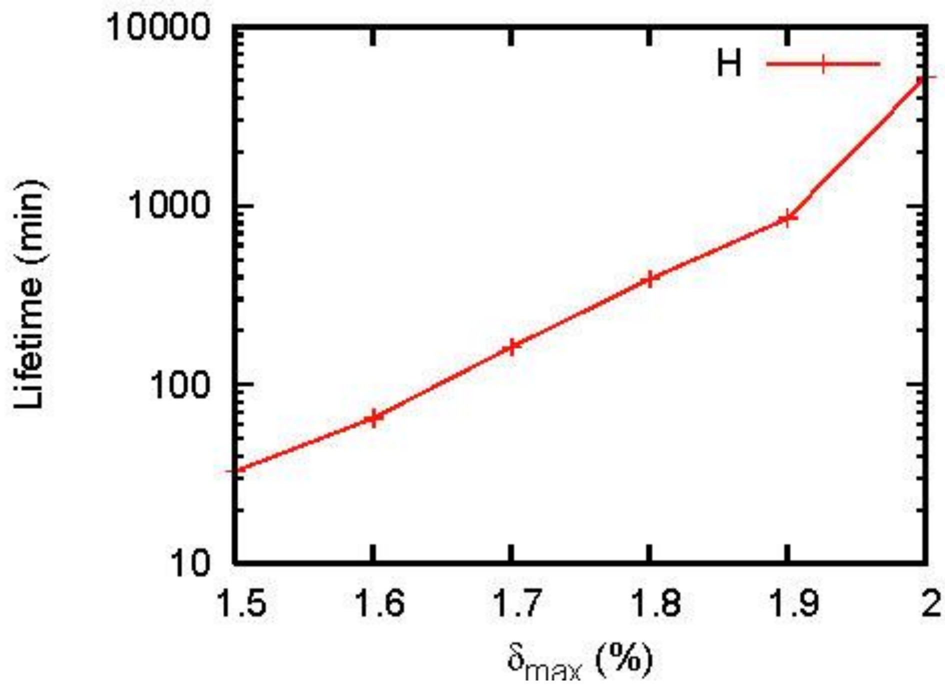
A. Bogomyagkov, E. Levichev, P. Piminov, IPAC2014, THPRI008

beamstrahlung lifetime

example: *FCC-ee H* (240 GeV c.m.) $\tau_{BS} = \frac{\tau_z}{2\xi\rho(\xi)}$ with $\xi \equiv \frac{{\delta_{max}}^2}{2{\sigma_\delta}^2}$

equilibrium distribution w/o aperture limit from simulation → lifetime vs. momentum acceptance



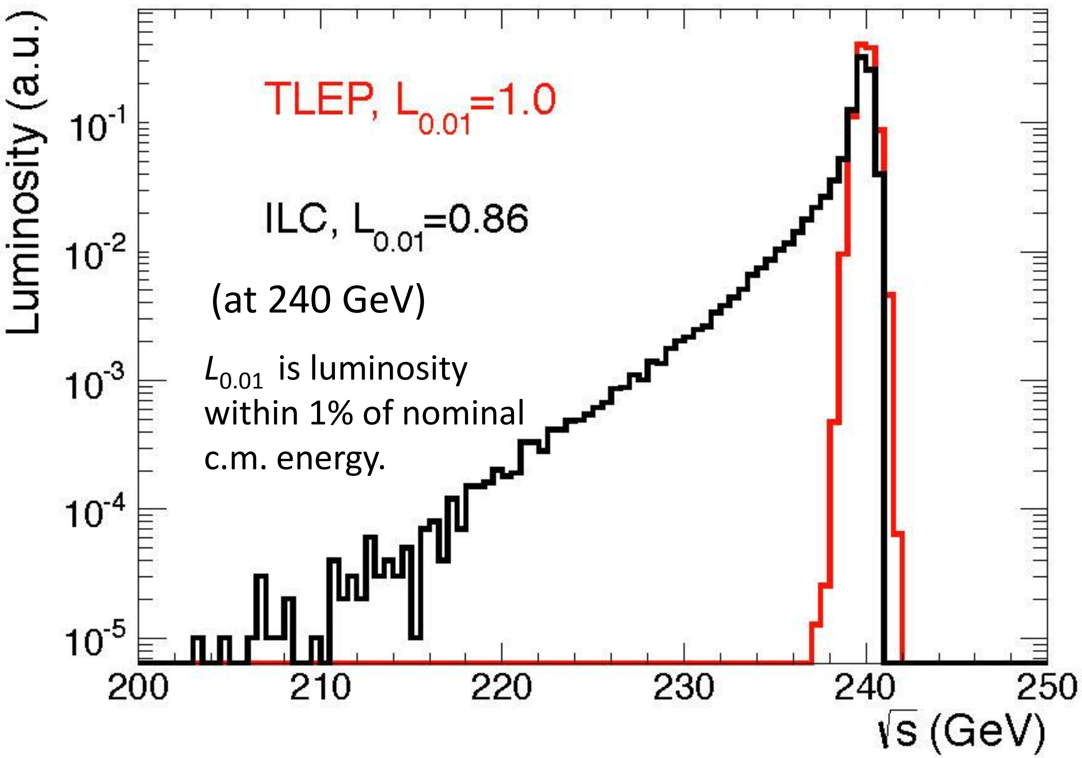


K. Ohmi et al., IPAC2014, THPRI003 & THPRI004

BS effect of luminosity spectrum

some $e^{\pm}$ emit significant part of their energy →

degraded luminosity spectrum



$$\frac{L_{peak}}{L} \simeq \left[\frac{1}{N_\gamma}\left(1 - e^{-N_\gamma}\right)\right]^2$$

where

$$N_\gamma \simeq \frac{2\alpha r_e N}{\sigma_x}$$

denotes average number of BS photons per e^-

The Twin Frontiers of *FCC-ee* Physics

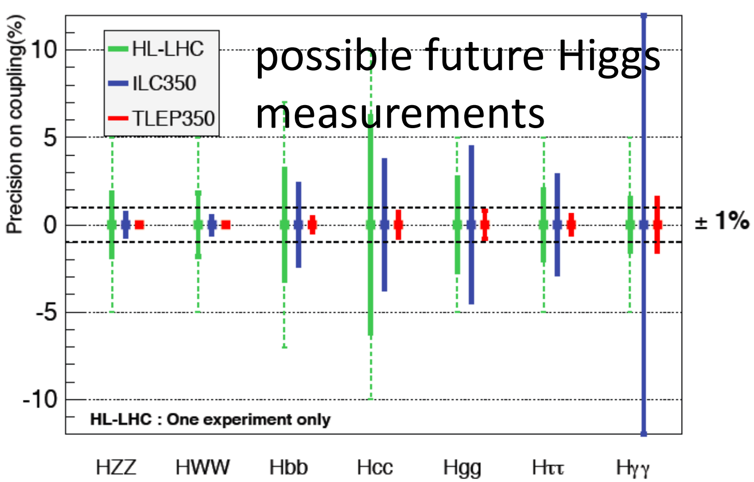
Precision Measurements

- Springboard for sensitivity to new physics
- Theoretical issues:
  - Higher-order QCD
  - Higher-order EW
  - Mixed QCD + EW

Rare Decays

- Direct searches for new physics
- Many opportunities
- Z: 10^{12}
- b, c, τ: 10
- W: 10^{8}
- H: 10^{6}
- t: 10^{6}

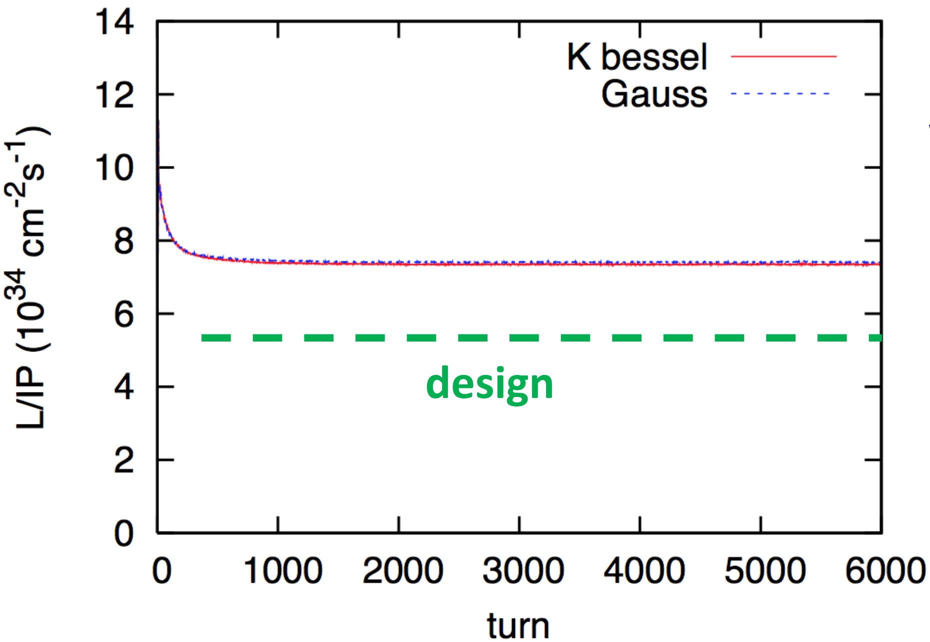
***FCC-ee* promises much higher precision & and many more rare decays than any competitors**



M. Bicer et al., "First Look at the Physics Case of TLEP," JHEP 01, 164 (2014)

J. Ellis

simulations confirm tantalizing performance

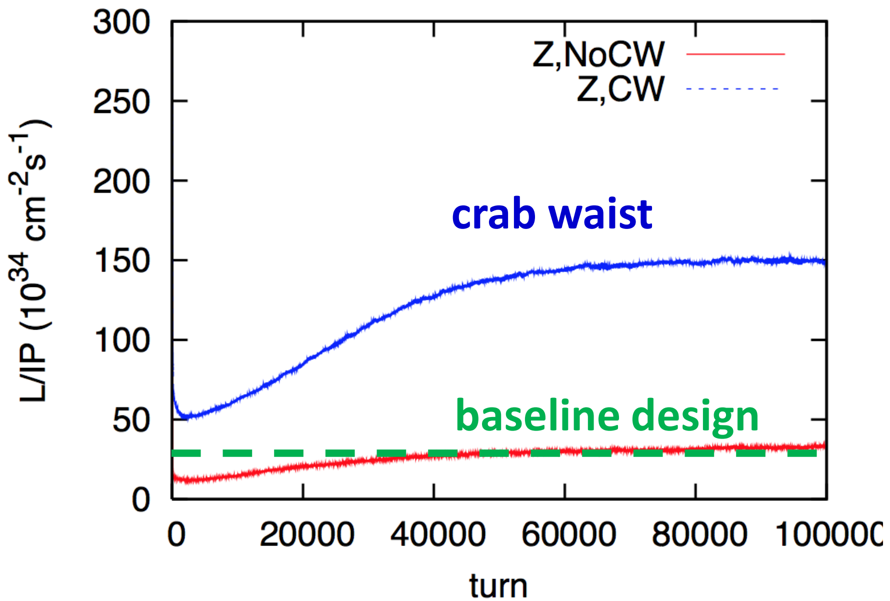


BBSS strong-strong simulation
w beamstrahlung

FCC-ee in Higgs production mode (240 GeV c.m.):
L≈7.5x10^{34} cm^{-2}s^{-1} per IP

BBWS crab-strong simulation
w beamstrahlung

FCC-ee in crab-waist mode at the Z pole (91 GeV c.m.):
L≈1.5x10^{36} cm^{-2}s^{-1} per IP

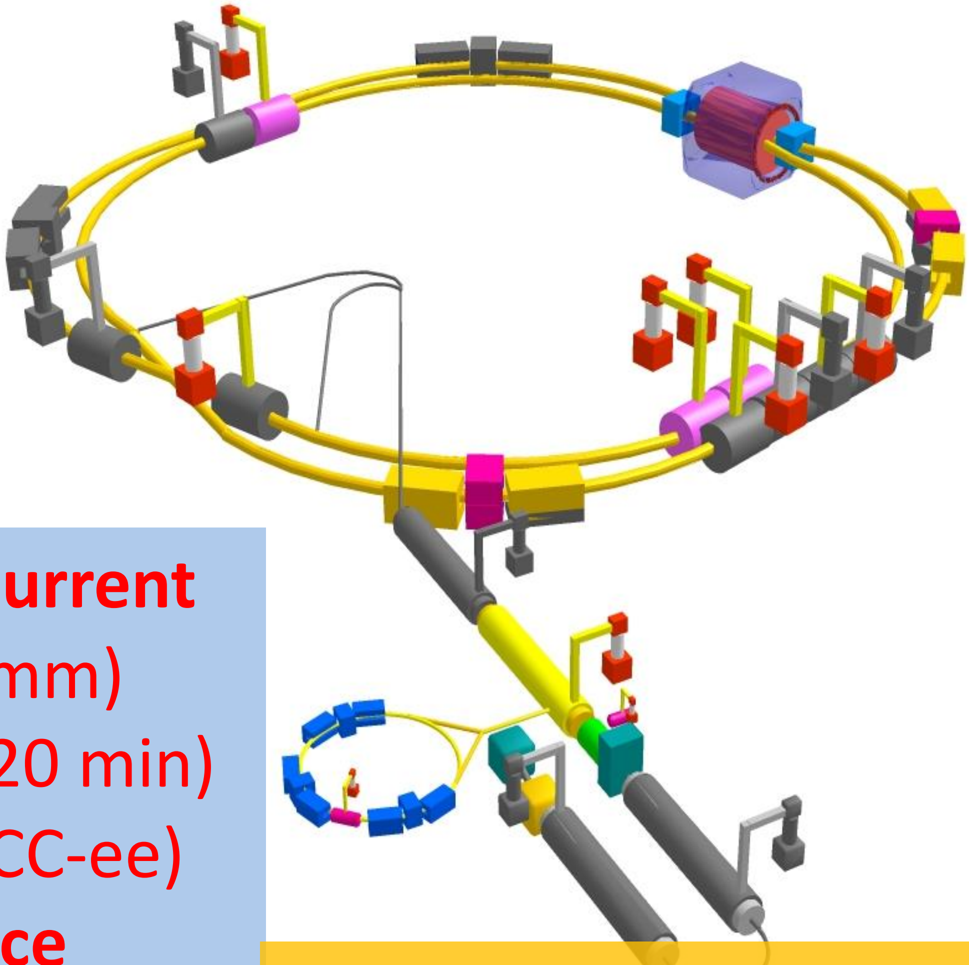


K. Ohmi et al., IPAC2014, THPRI003 & THPRI004

A. Bogomyagkov, E. Levichev, P. Piminov, IPAC2014, THPRI008

SuperKEKB = *FCC-ee* demonstrator

beam commissioning will start in early 2015



top up injection at high current

β_y^* =300 μm (FCC-ee: 1 mm)

lifetime 5 min (FCC-ee: ≥20 min)

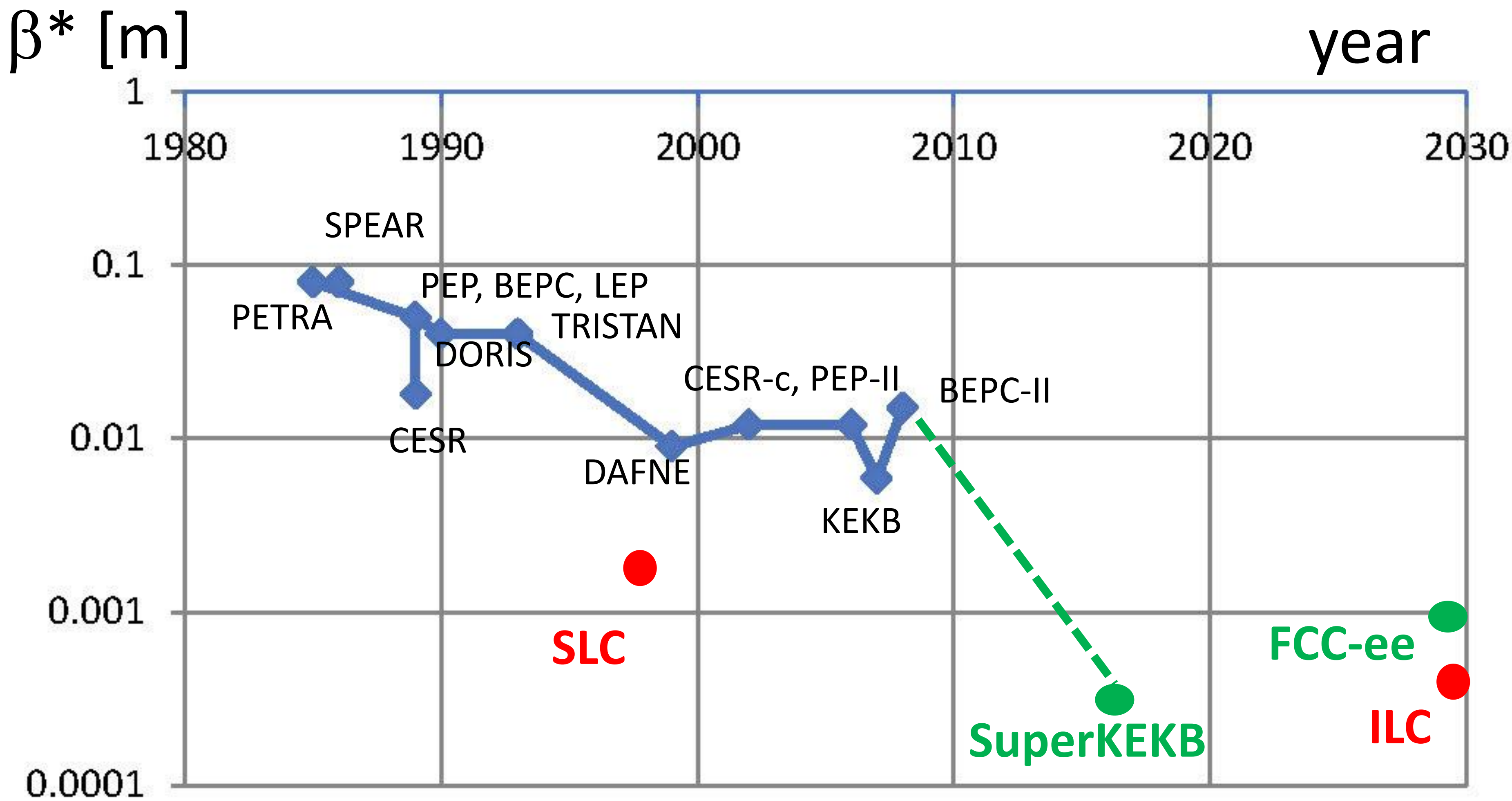
$\varepsilon_y/\varepsilon_x$ =0.25% (similar to FCC-ee)

off momentum acceptance
(±1.5%, similar to FCC-ee)

***e*$^+$ production rate** (2.5x10^{12}/s,
FCC-ee: <1.5x10^{12}/s (*Z* cr.waist)

***SuperKEKB* goes beyond *FCC-ee*, testing all concepts**

vertical β* history



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

vertical rms IP spot size

collider / test facility		$\sigma_y{}^*$ [nm]
LEP2	in regular font: achieved	3500
KEKB		940
SLC	in italics: design values	700
ATF2, FFTB		65 (*35*), 77
SuperKEKB		***50***
FCC-ee-H		***44***
ILC		*5 – 8*
CLIC		*1 – 2*

$\beta_y{}^*$:
5 cm→ 1 mm
ε_y:
250 pm→ 2 pm

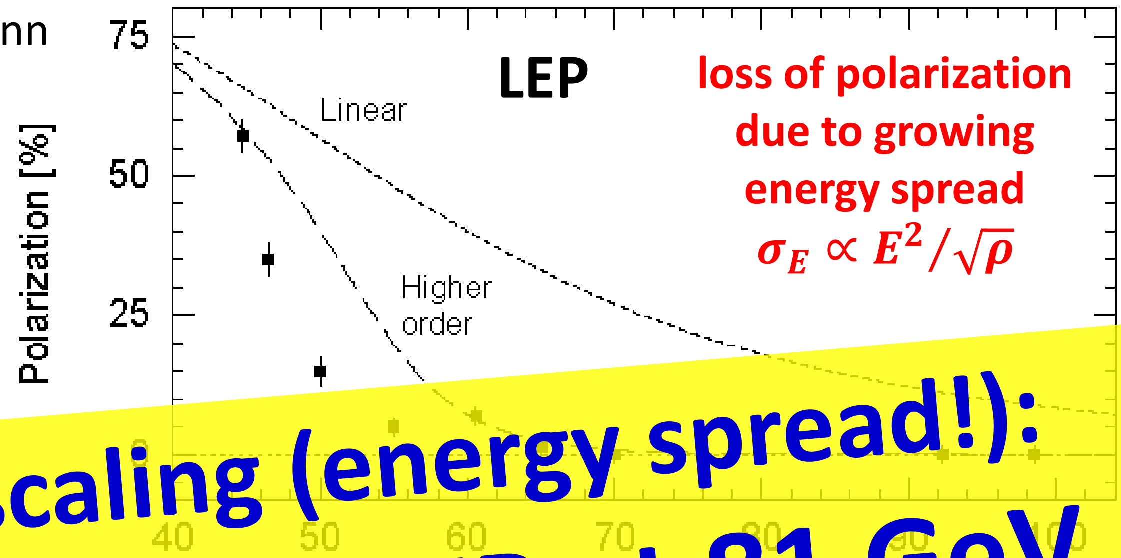
polarization

R. Assmann

LEP

observations

\+ model predictions



loss of polarization due to growing energy spread

$\sigma_E \propto E^2/\sqrt{\rho}$

polarization scaling (energy spread!):

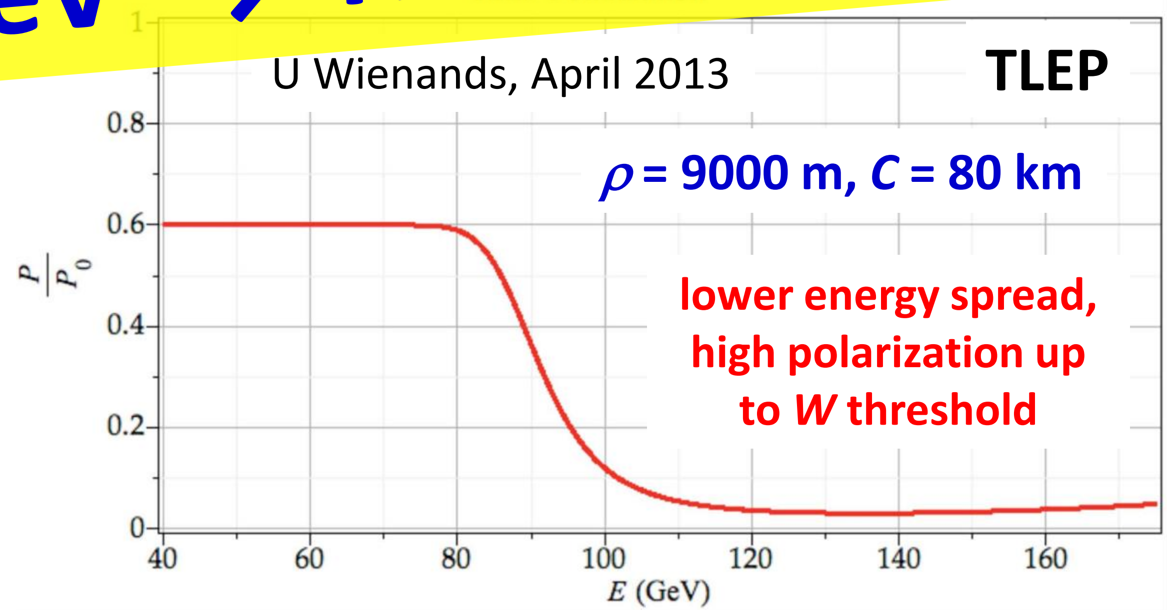
LEP at 61 GeV → TLEP at 81 GeV

TLEP

optimized scenario

➔ 100 keV beam energy calibration by resonant depolarization (using pilot bunches) around *Z* peak and *W* pair threshold:

Δm_Z ~0.1 MeV, $\Delta\Gamma_Z$ ~0.1 MeV, Δm_W ~ 0.5 MeV

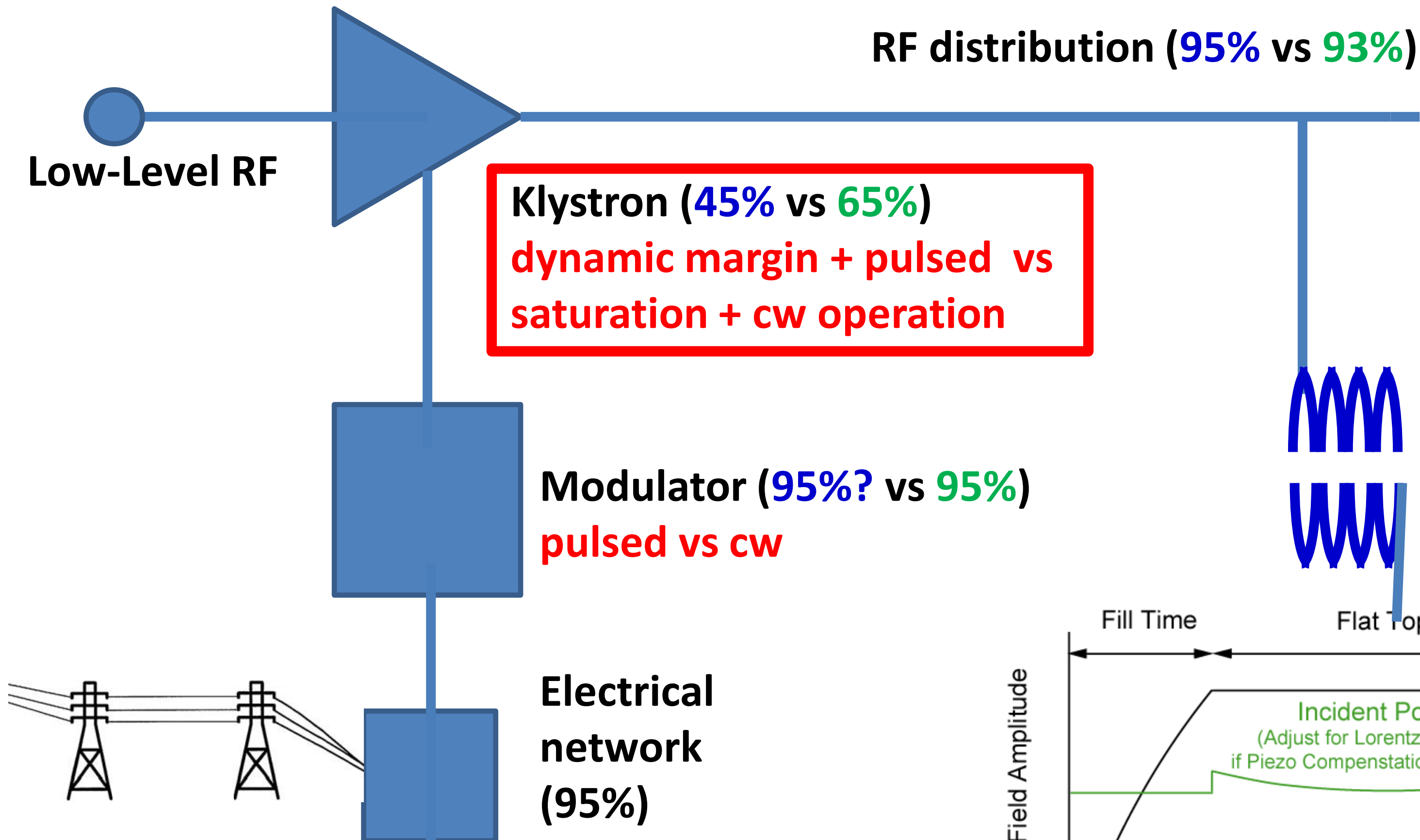


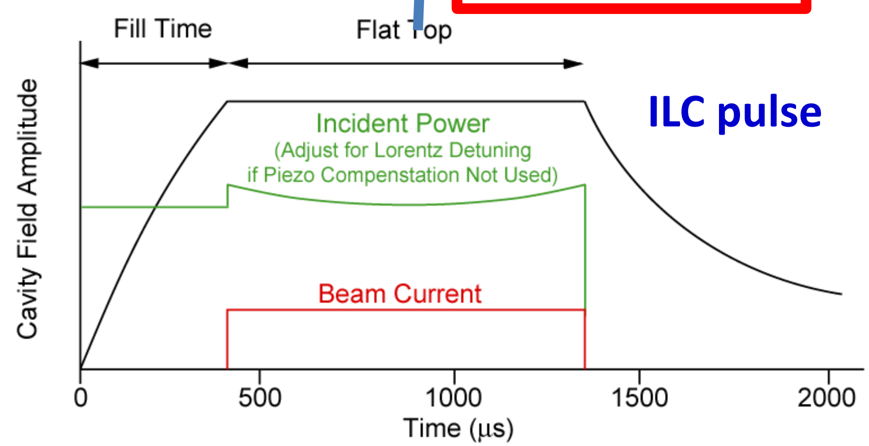
ρ = 9000 m, C = 80 km

lower energy spread, high polarization up to *W* threshold

A. Blondel

RF power efficiencies: *ILC* vs *FCC-ee*





efficiency (RF): wall plug power to beam power

ILC: η~17%

FCC-ee: η~55%

factor ~3 difference in efficiency of converting wall-plug power to beam energy

commissioning time & performance

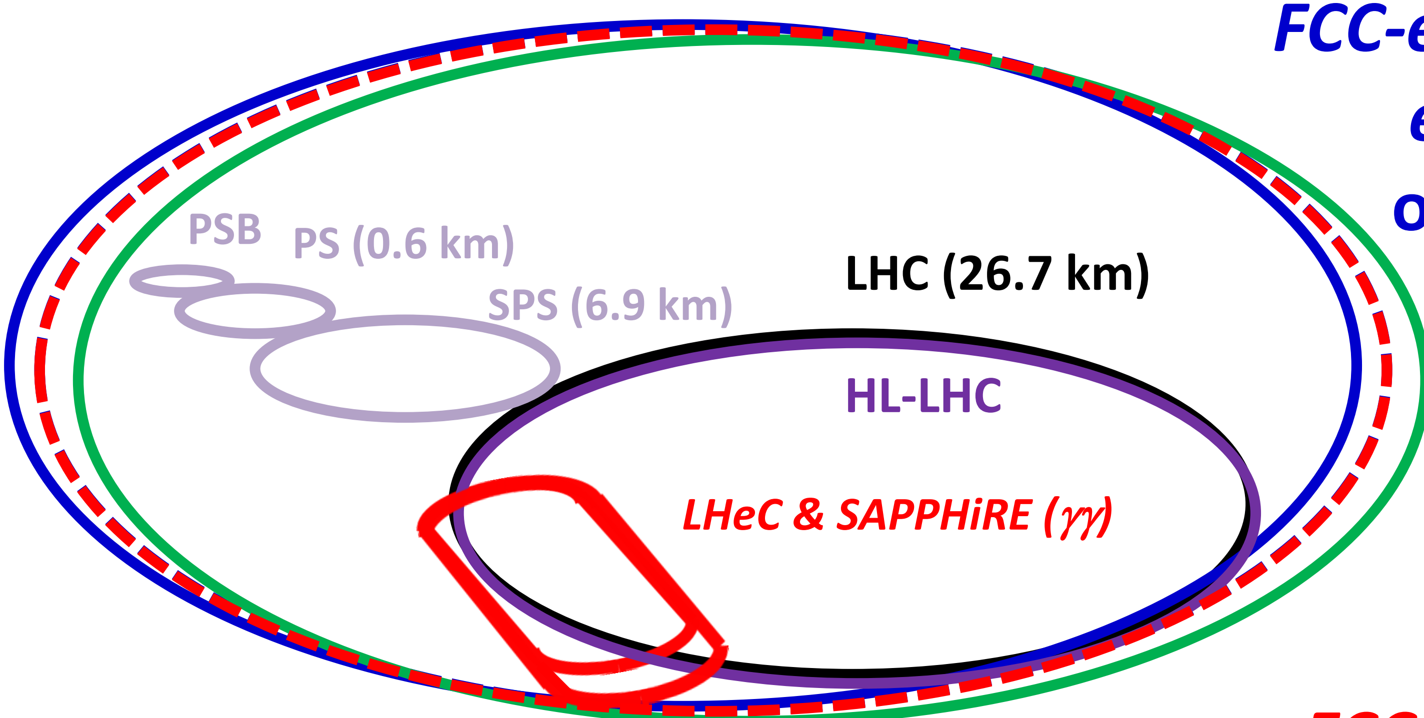
circular & linear facilities	beam energy [GeV]	design luminosity [10^{32} $cm^{-2}s^{-1}$]	peak luminosity /design	time to achieve design [y]
LEP1	45	0.13	2	5
SLC	45	0.06	0.5	- (>10)
LEP2	60-104.5	0.26	3	<0.5
DAFNE	0.5	5.0	0.9	- (>10)
PEP-II	9, 3.1	30	4	1.5
KEKB	8, 3.5	100	2	3.5
ATF-2	1.28	0.000001(eff.)	0.005 (eff.)	- [>4*]
FCC-ee-H	120	6000	?	?

* not counting the year of the earthquake; ATF-2 operating only for fraction of calendar time

a few open questions

- acceptable topology of collider
  vertical kink under the lake?
  - constraints from vertical emittance
    & polarization
- off-momentum dynamic aperture
- RF efficiency
- polarization at energies > 200 GeV
- …

possible evolution of FCC complex



FCC-ee **(80-100 km, e^+e^-, up to 350 or 500 GeV c.m.)**

FCC-hh **(*pp* up to 100 TeV c.m. & *AA*)**

LHeC as FCC-ee injector?

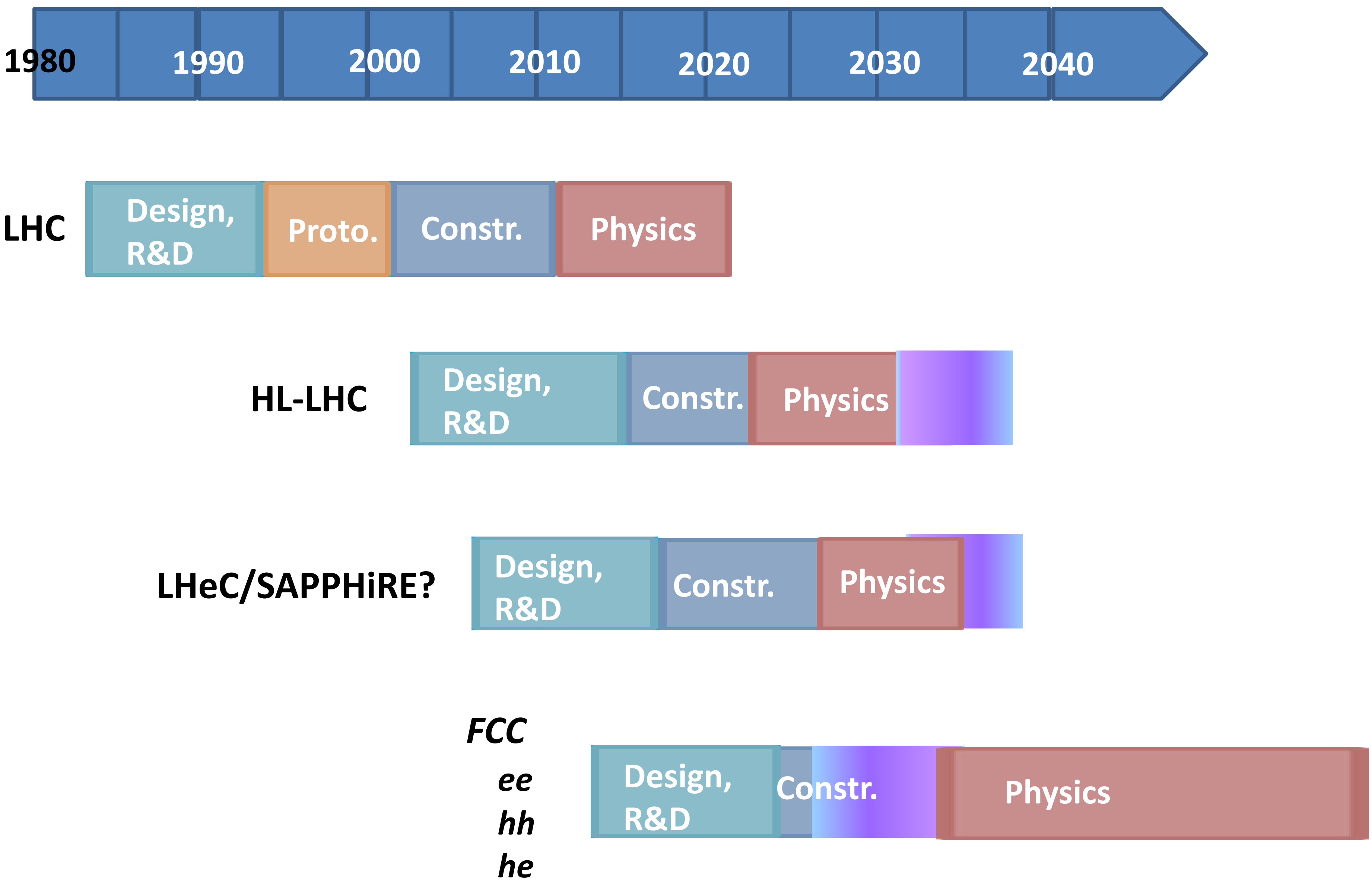
FCC-he **as ring-ring collider ?!**

LHeC-based FCC-he collider?!

FCC-he: $e^{\pm}$ (60-250 GeV) – *p*(50 TeV)/A collisions

≥50 years e^+e^-, *pp*, $e^{\pm}p/A$ physics at highest energies

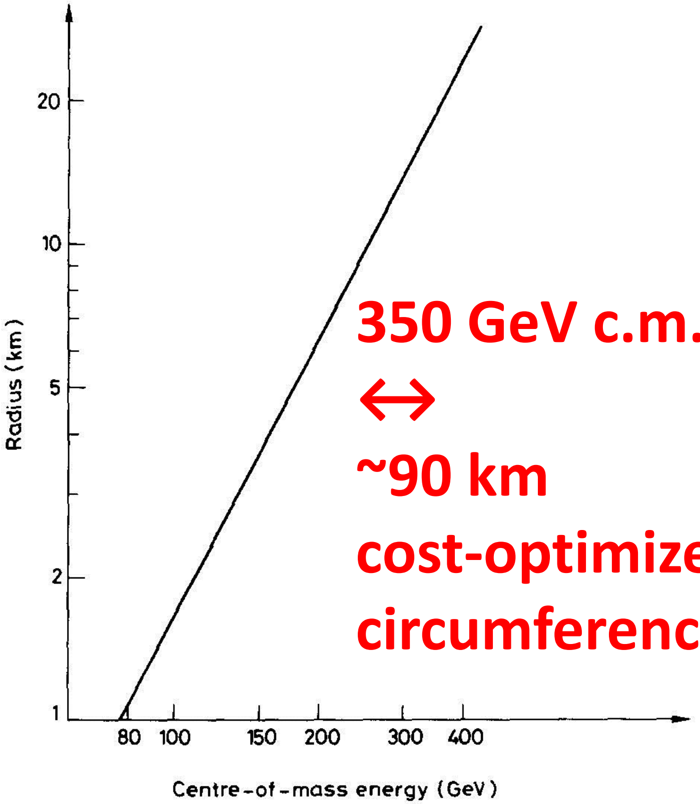
tentative time line



historical foresight

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

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



350 GeV c.m. ↔ ~90 km cost-optimized circumference