Machine Aspects of Future e^+e^- Colliders

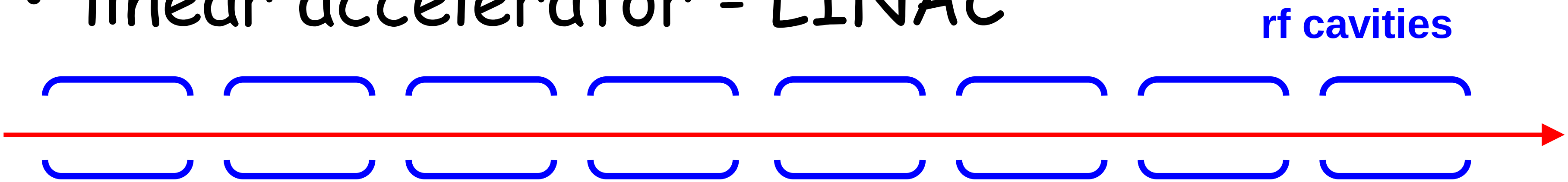
Frank Zimmermann

CERN, Pisa School on Future Colliders

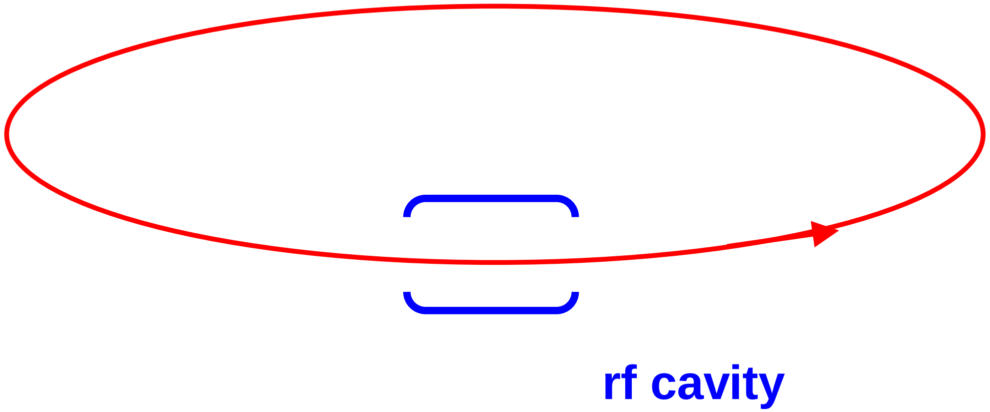
*Work supported by the **European Commission** under the **HORIZON 2020 project ARIES**, grant agreement 730871*

basic types of accelerators

- linear accelerator - LINAC



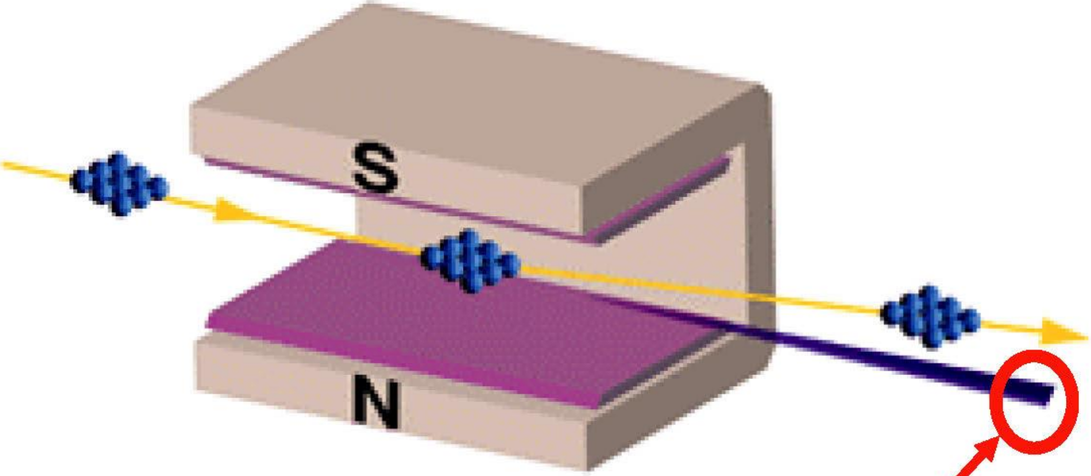
- circular accelerators: synchrotrons, storage rings



particles are accelerated many times by same rf cavity

- hybrid: recirculating linacs

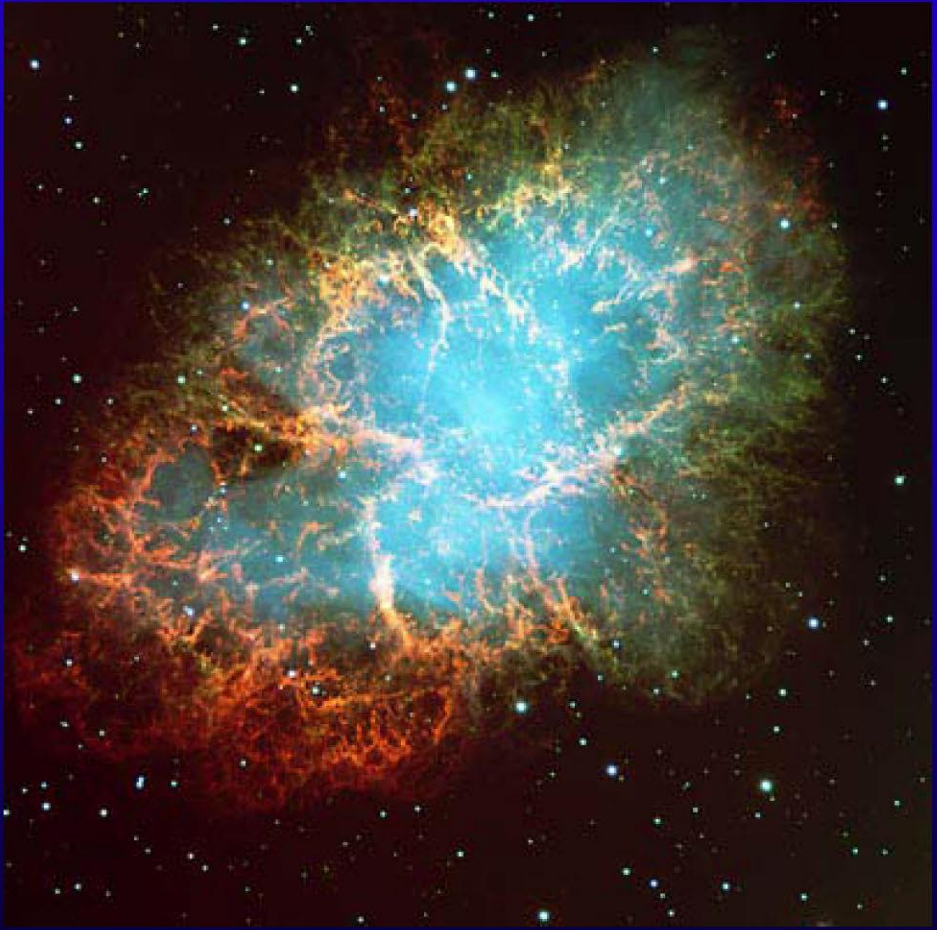
curved orbit of e^- in magnetic field



Accelerated charge → Electromagnetic radiation

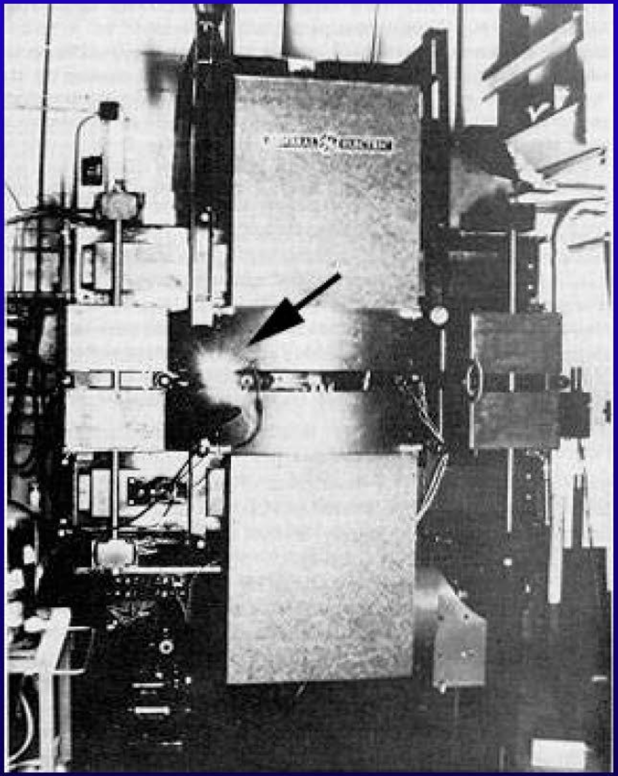
L. Rivkin

Crab Nebula
6000 light years away



First light observed
1054 AD

GE Synchrotron
New York State



First light observed
1947

L. Rivkin

linear collider advantage: little synchrotron radiation at high energy

synchrotron radiation in a storage ring of bending radius ρ_0

energy loss per turn

$$U_0 = \frac{C_\gamma E_0^4}{\rho_0}$$

synchrotron-radiation power for one electron

$$\langle P_\gamma \rangle = \frac{c C_\gamma E_0^4}{2\pi} \left\langle \frac{1}{\rho_0^2} \right\rangle$$

$$C_\gamma = \frac{4\pi r_e}{3(m_e c^2)^3} \approx 8.877 \times 10^{-5}\ \mathrm{m\ GeV^{-3}}$$

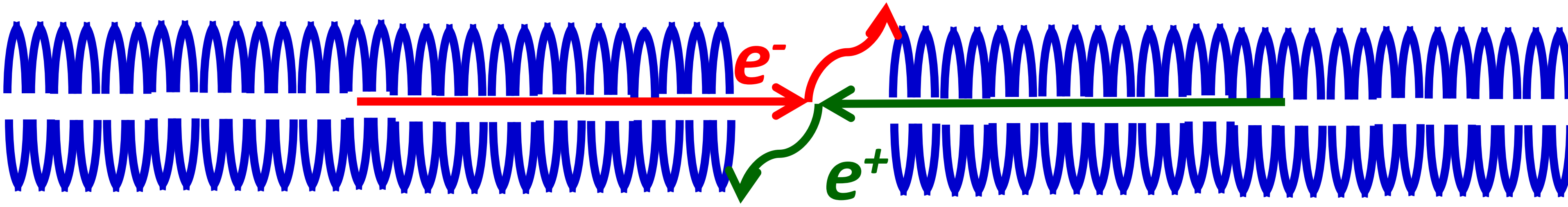
for muons $m_\mu \sim 200\, m_e \rightarrow$ SR $\sim 200^4 \sim 2\times10^9$x less

for protons $m_\pi \sim 2000\, m_e \rightarrow$ SR $\sim 2000^4 \sim 2\times10^{13}$x less

BUT

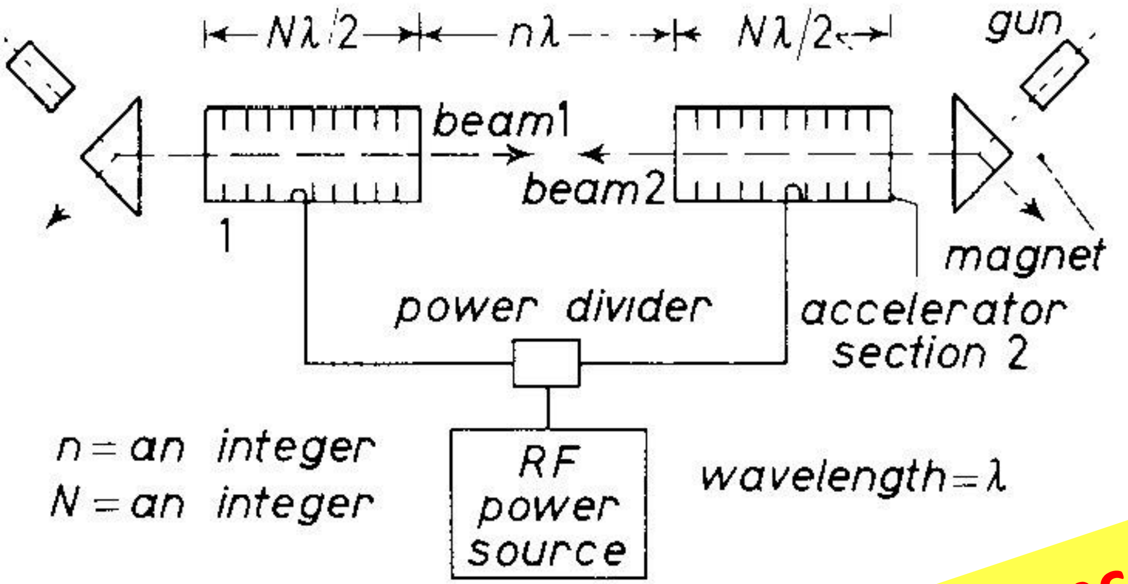
full energy must be provided to beam for every collision

long RF sections w. e.g. 2 x 125 (2 x 1500) GV voltage



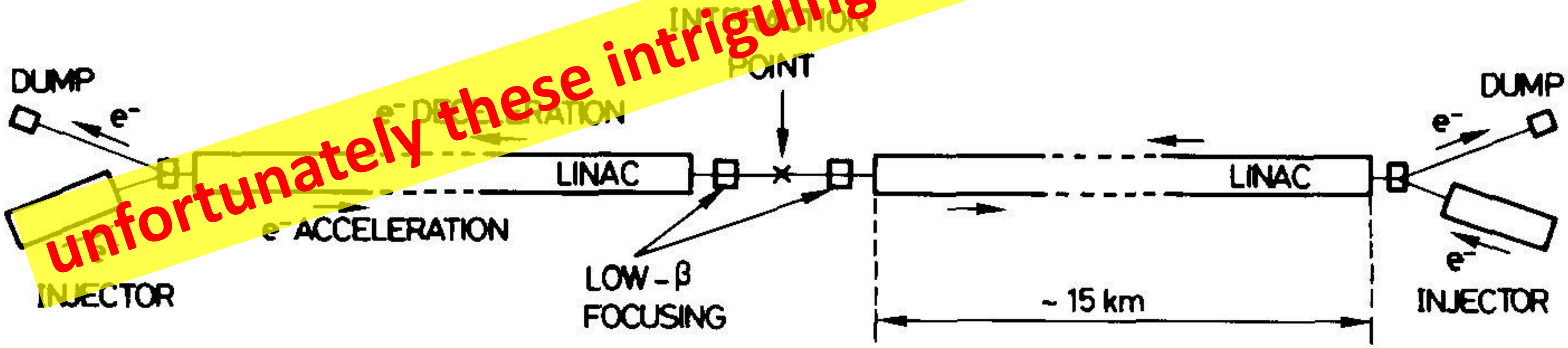
- both beams lost after single collision
- supply energy for each collision, efficiency $\eta \ll 1$

early linear-collider proposals recovered beam energy



Maury Tigner, “*A Possible Apparatus for Clashing-Beam Experiments*”, Nuovo Cimento 37, 1228 (**1965**)

unfortunately these intriguing concepts were not pursued

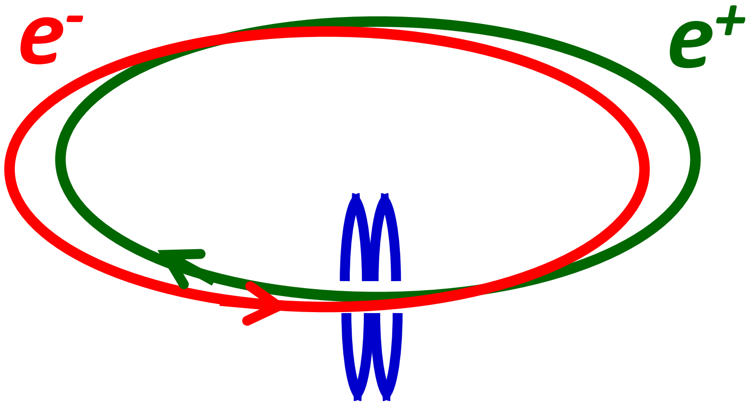


Ugo Amaldi, “*A possible scheme to obtain e-e- and e+e- collisions at energies of hundreds of GeV*”, Physics Letters B61, 313 (**1976**)

circular accelerator/collider concept

“There's just no use trying to build this up. You may get a few million volts. That's limited. What we've got to do is to devise some method of accelerating through a small voltage, repeating it over and over. Multiple acceleration.”

E.O. Lawrence, 1929



- **beams collide many times, e.g. 2x / turn**
- **RF compensates SR loss (~1% E_{beam} / turn)**
- **RF system ~10x or 100x smaller than for LC**

#collisions / (beam energy) ~200x

LEP/LEP2: highest energy so far

circumference 27 km

in operation from 1989 to 2000

1000 pb^{-1} from 1989 to 2000

maximum c.m. energy 209 GeV

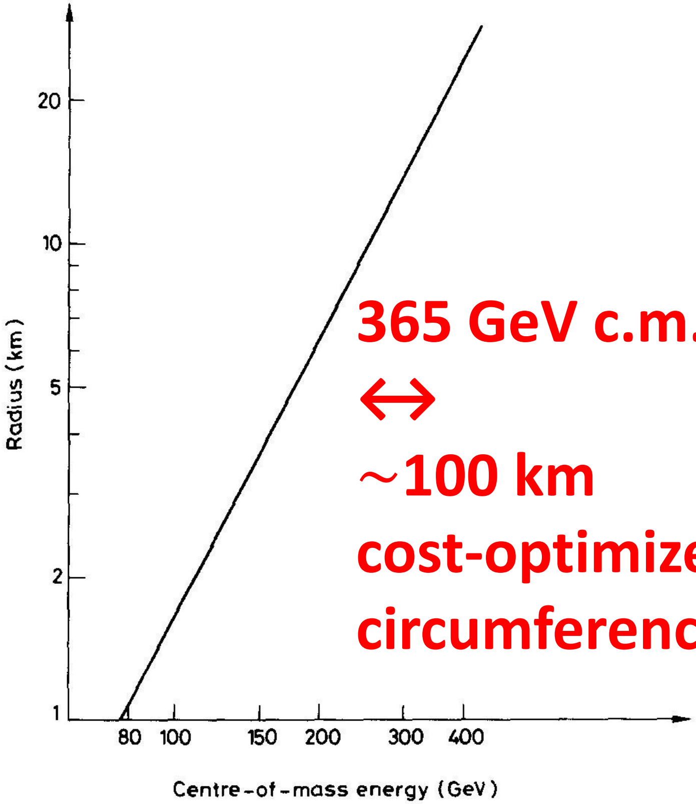
maximum synchrotron radiation power 23 MW

record synchrotron radiation with ~MeV photons

"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."

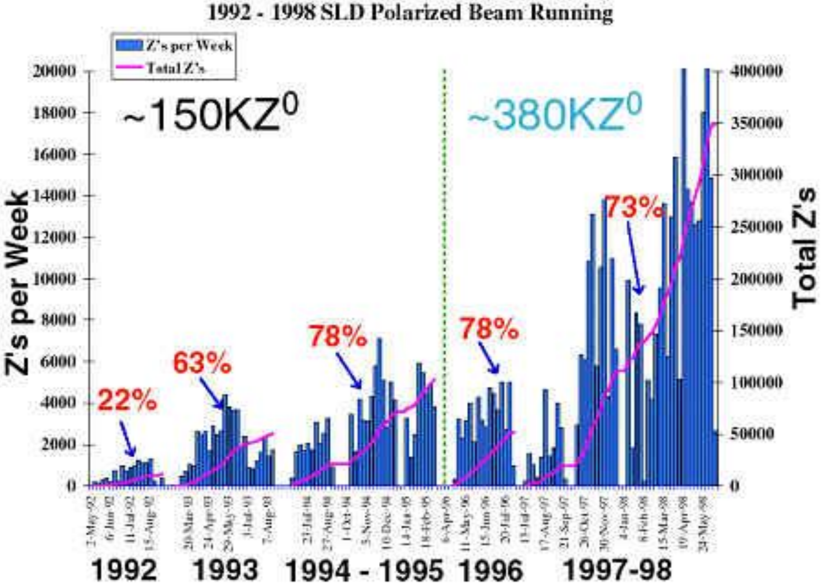
(original LEP proposal, 1976)

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

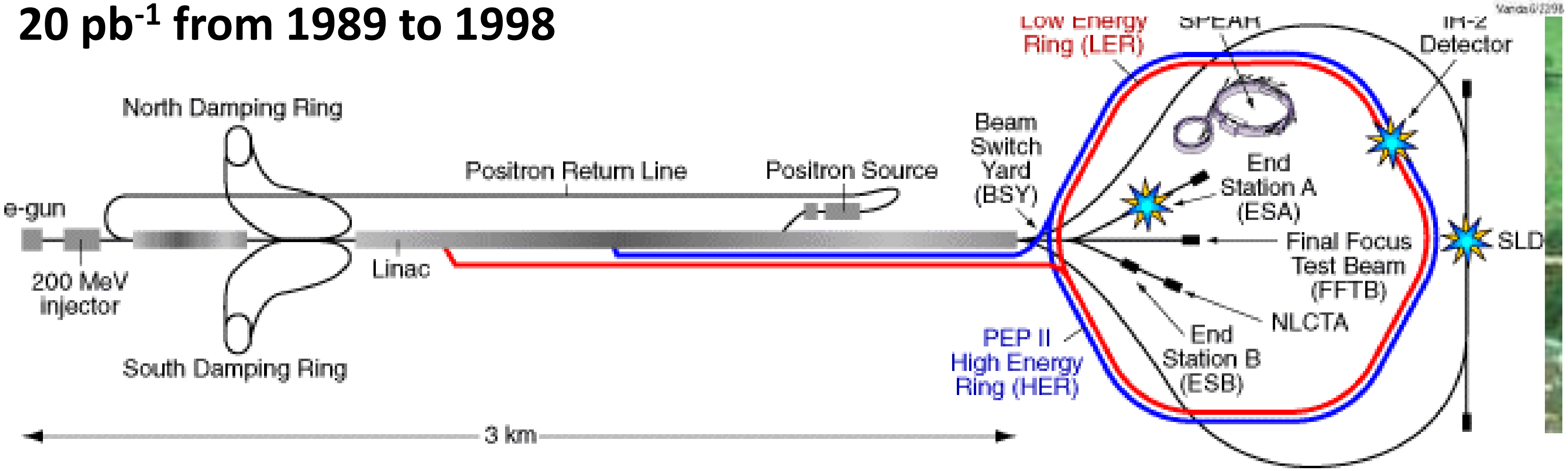


365 GeV c.m.
↔
~100 km
cost-optimized
circumference

SLC: the first & so far only linear collider

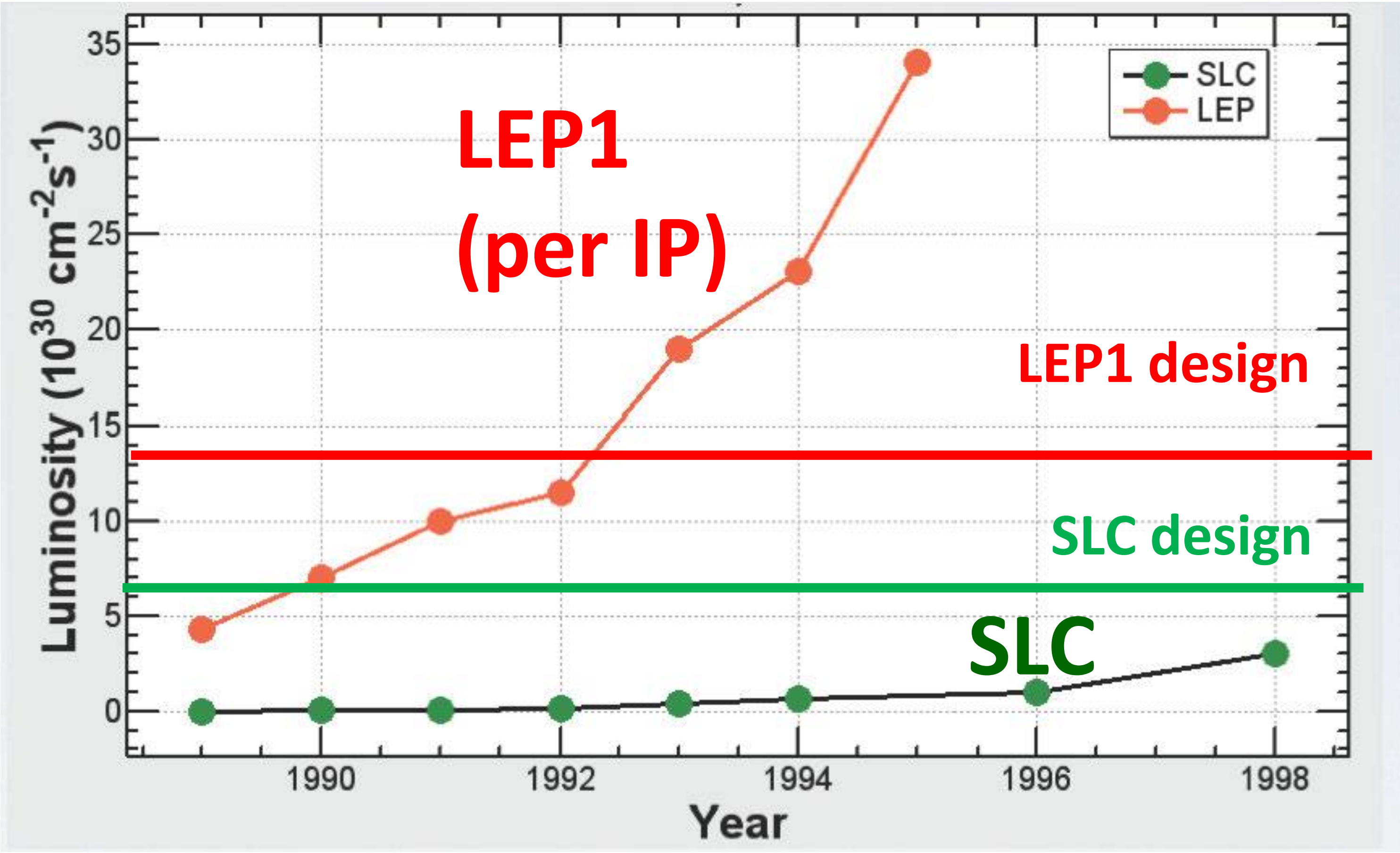


20 pb^{-1} from 1989 to 1998



Burton Richter *et al*, “The Stanford Linear Collider”, *11th Int. Conf. on High-Energy Accelerators*, CERN (1980)

commissioning time & performance of LEP and SLC

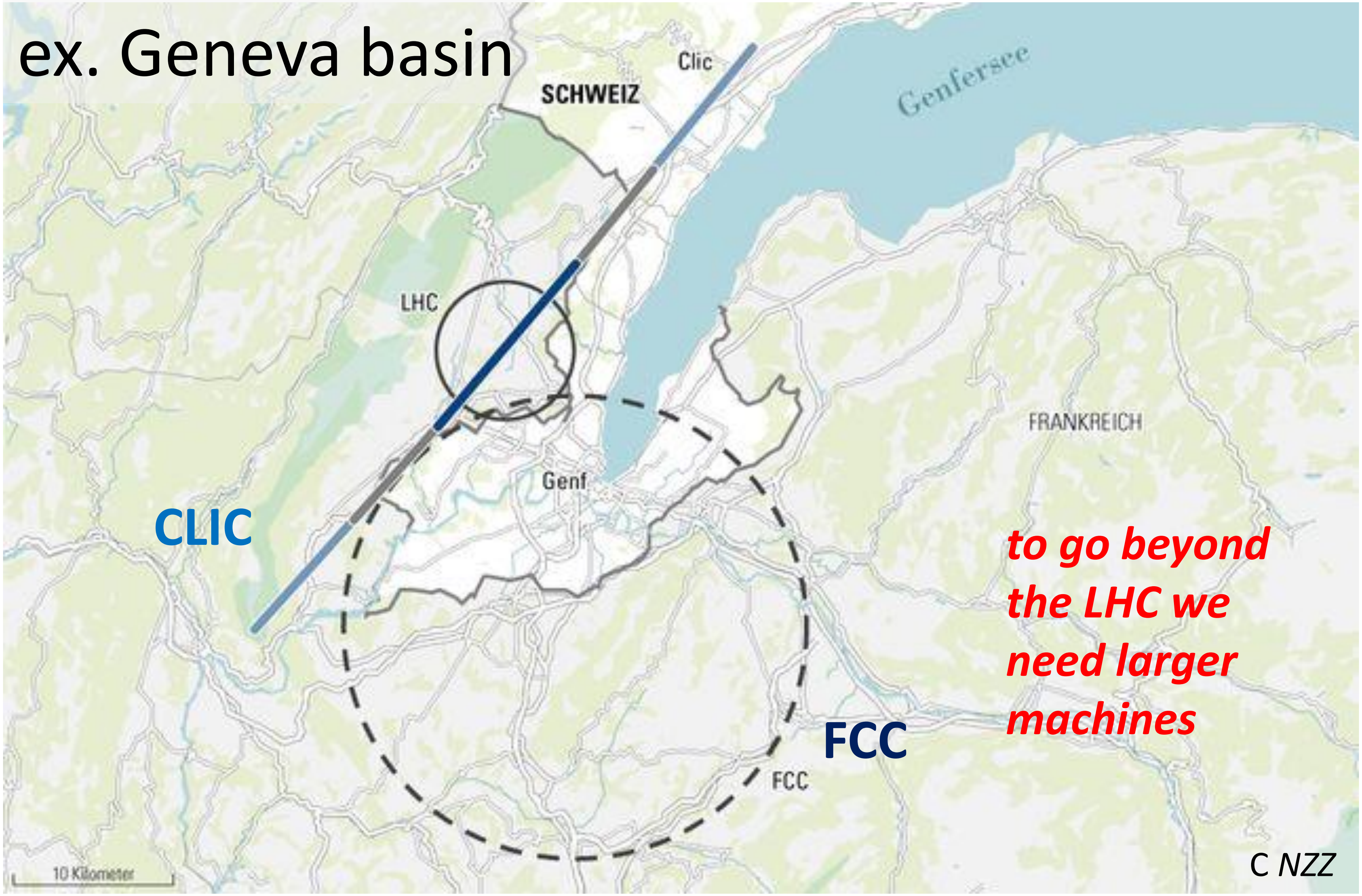


CERN-SL-2002- 009 (OP), SLAC–PUB–8042 [K. Oide, 2013]

SLC

- **½ design value reached after 11 years**

proposed linear & circular colliders



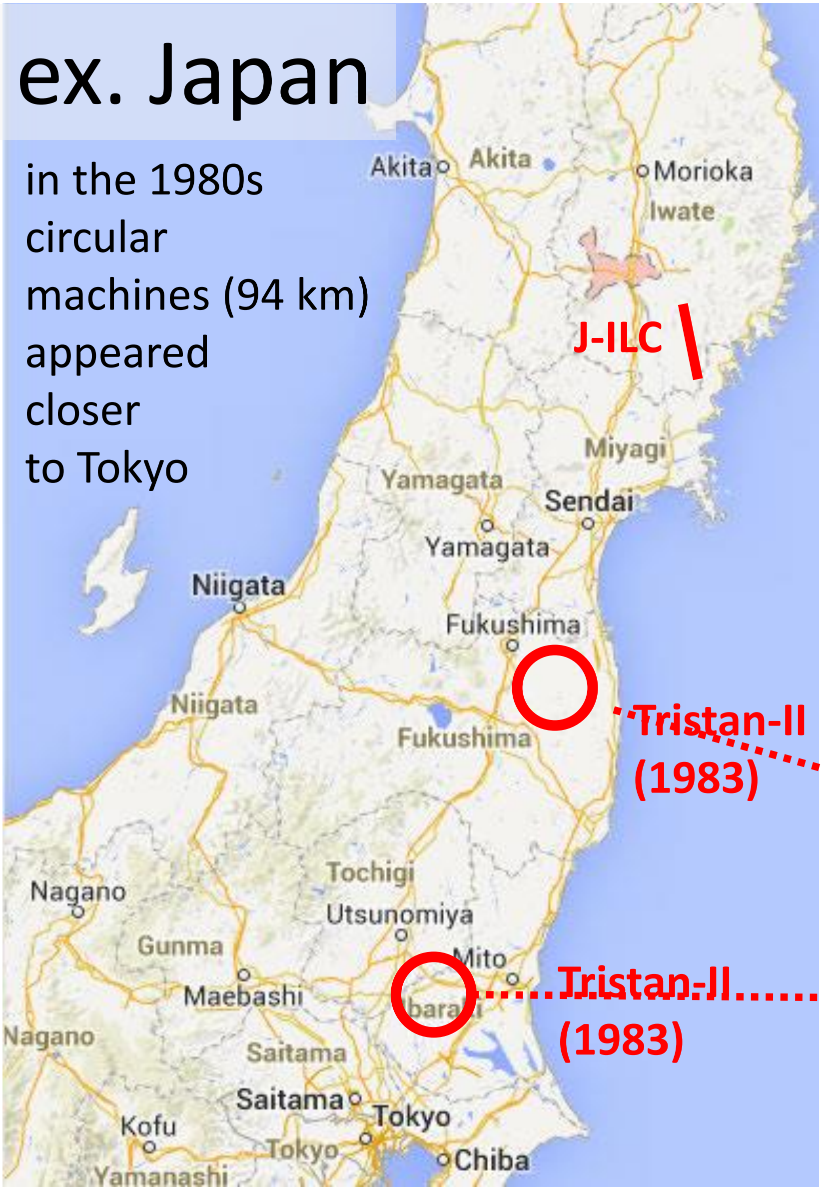
to go beyond the LHC we need larger machines

C *NZZ*

proposed linear & circular colliders

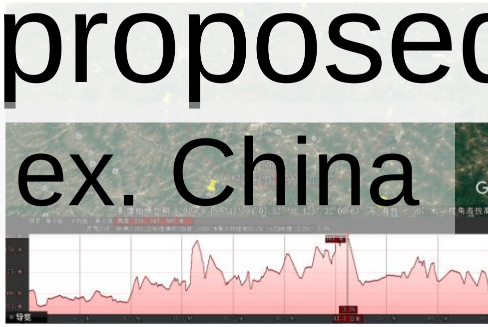
ex. Japan

in the 1980s
circular
machines (94 km)
appeared
closer
to Tokyo



proposed circular colliders

ex. China



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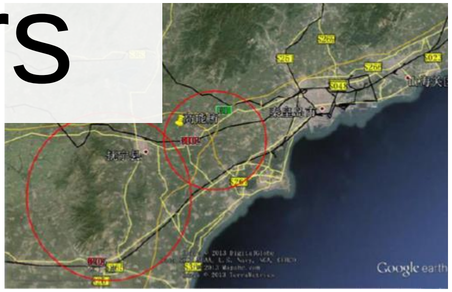
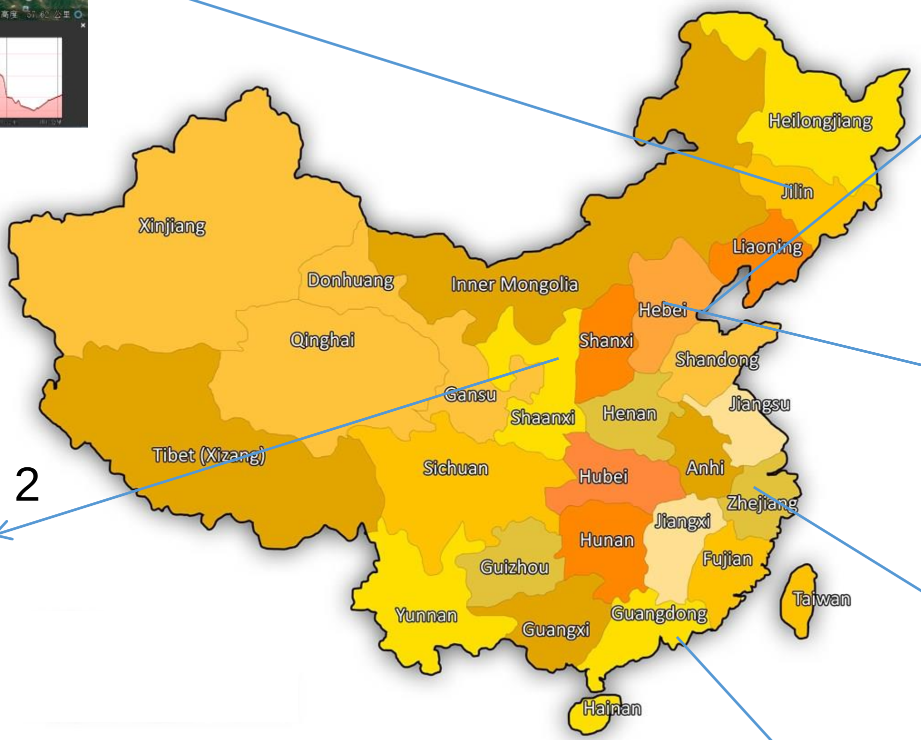


1



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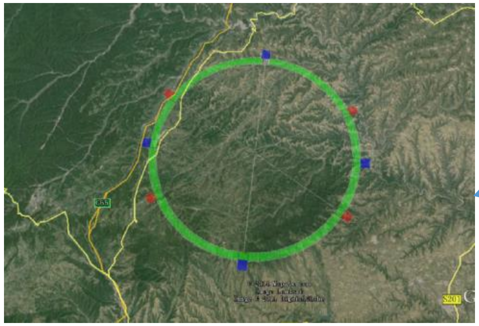

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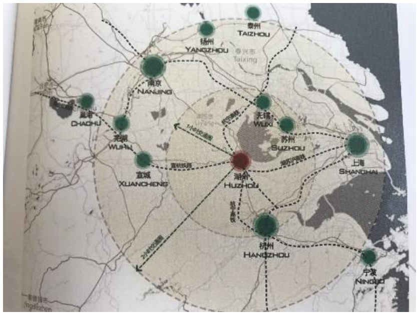


5

3

1) Qinhuangdao, Hebei Province（Completed in 2014）

2) Huangling, Shanxi Province（Completed in 2017)

3) Shenshan, Guangdong Province(Completed in 2016)

4) Baoding (Xiong an), Hebei Province (Started in August 2017)

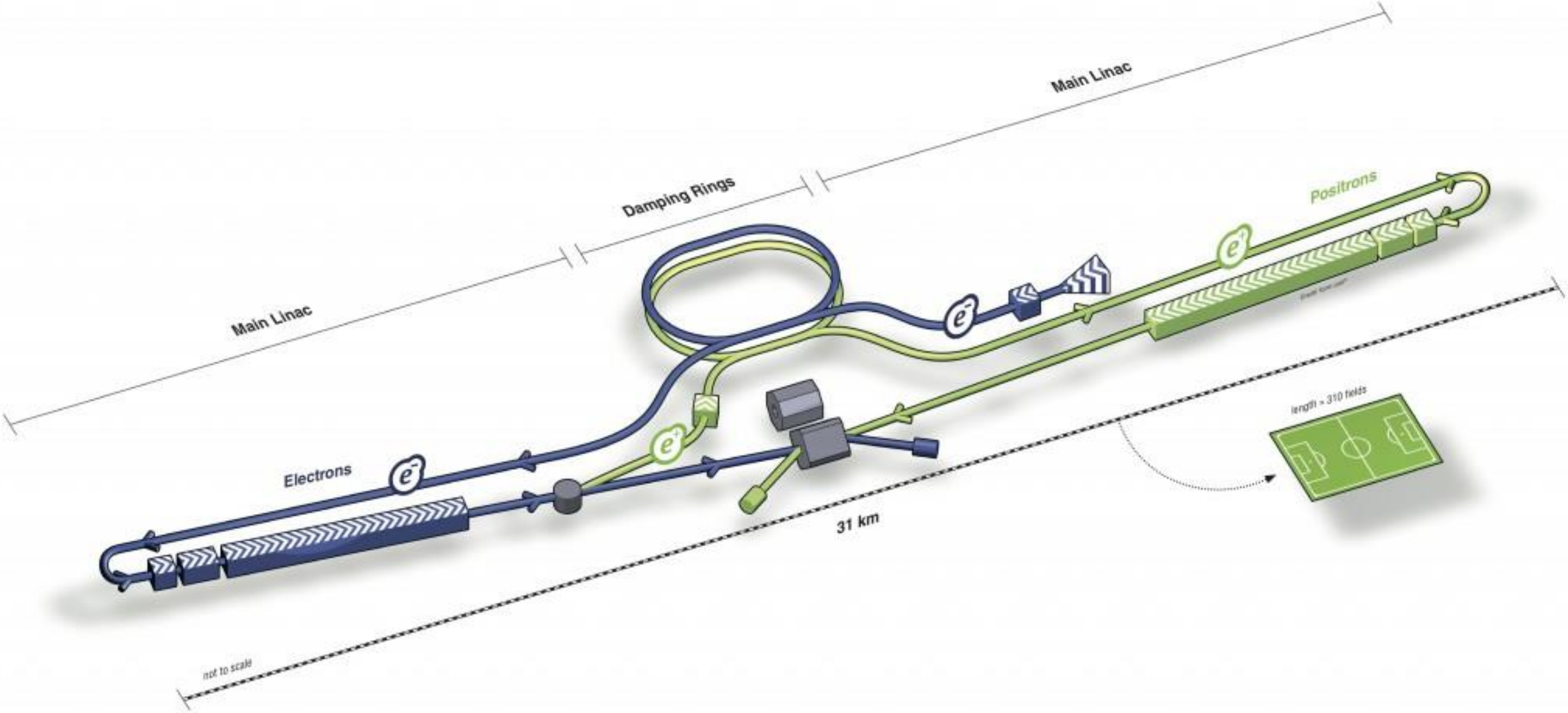
5) Huzhou, Zhejiang Province (Started in March 2018)

6) Chuangchun, Jilin Province (Started in May 2018)

J. Gao

ILC

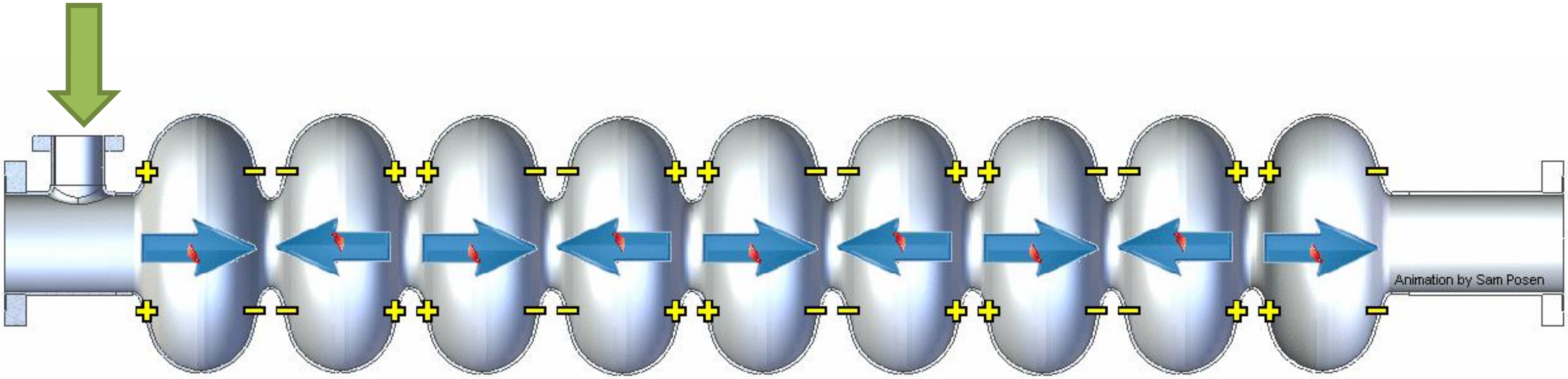
total length (main linac) ∼30 (500 GeV) - 50 km (1 TeV)

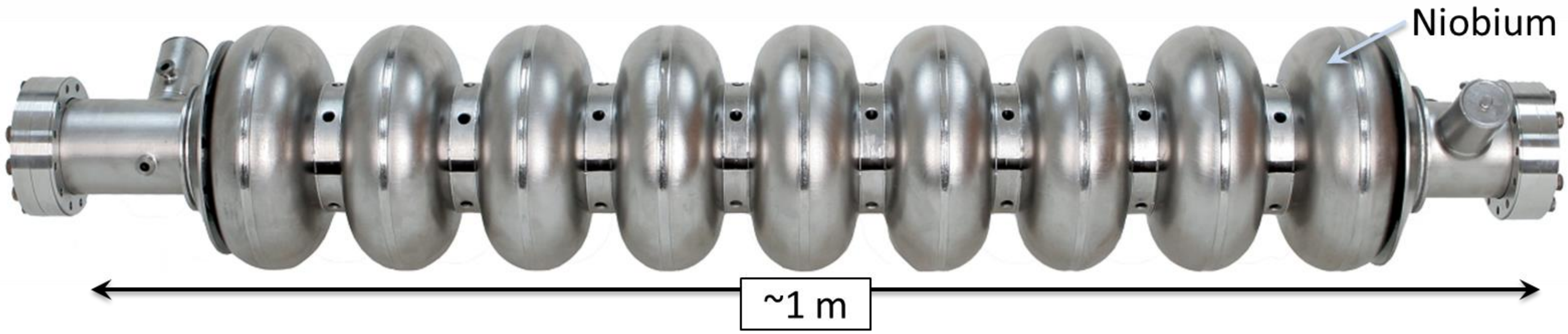


ILC cavity

Input RF power at 1.3 GHz

Slowed down by factor of approximately 4x10^9

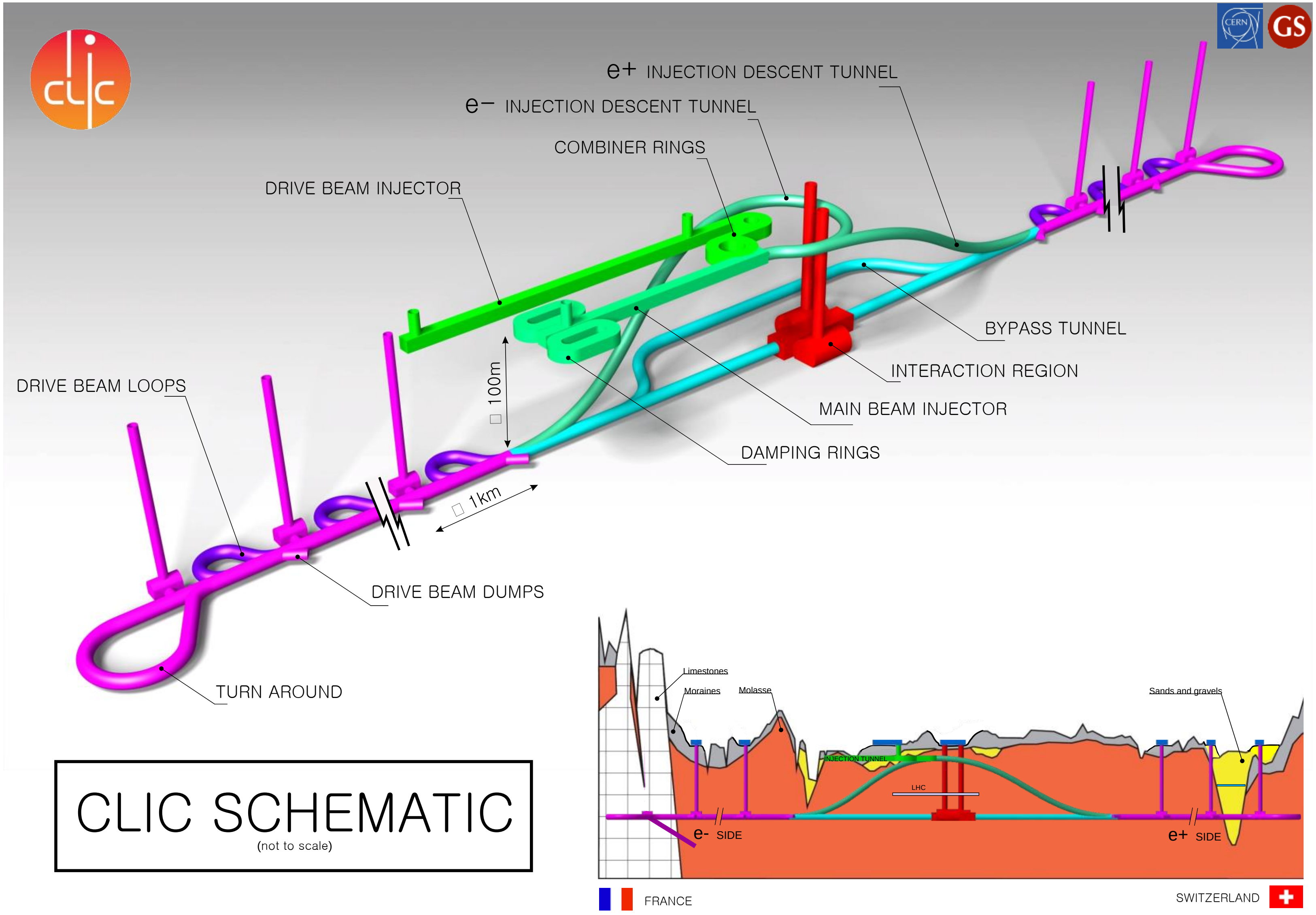




500 GeV ILC: 16,000 9-cell cavities in 31 km linac

CLIC

total length (main linac) ~11 (500 GeV) - 48 km (3 TeV)



FCC-ee

common RF system for ttbar running

double ring e+ e- collider, *C* ~100 km

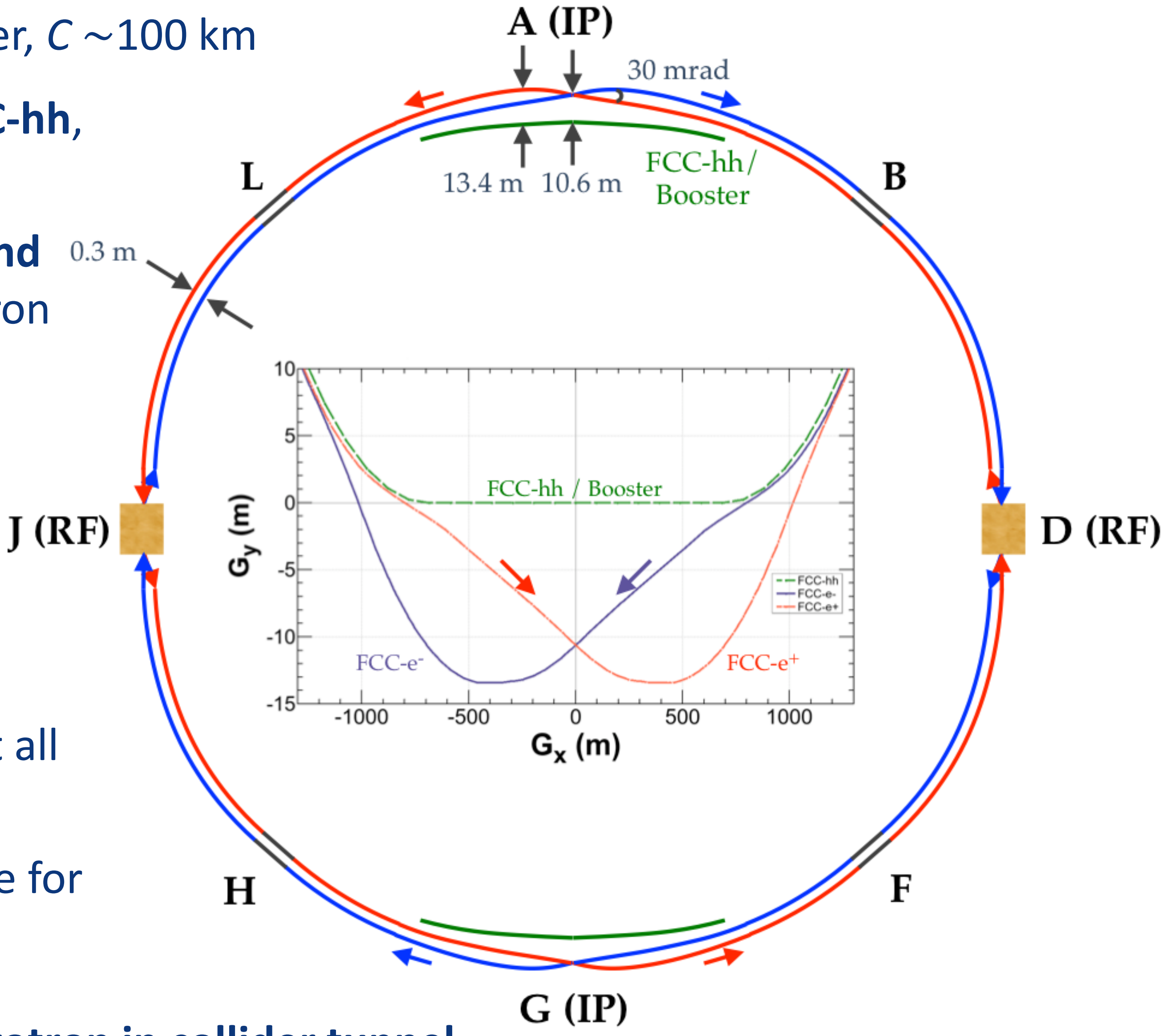
follows footprint of FCC-hh, except around IPs

asymmetric IR layout and optics to limit synchrotron radiation towards the detector

2 IPs, large horizontal crossing angle **30 mrad, crab-waist optics**

synchrotron radiation power 50 MW/beam at all beam energies

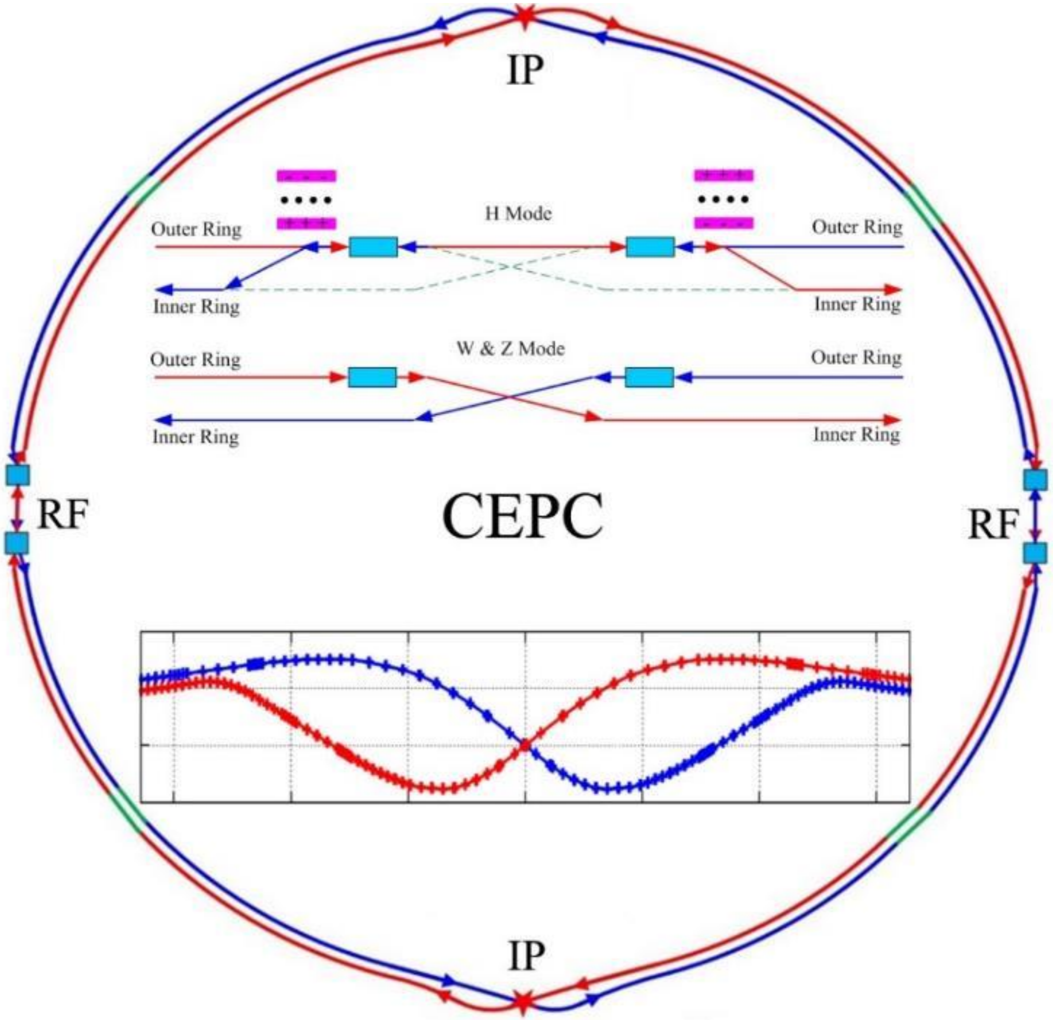
top-up injection scheme for high luminosity



requires **booster synchrotron in collider tunnel**

K. Oide

CEPC



- **Higgs factory as first piority** (“fully partial double ring”, with **common SRF system for e+ and e- beams**)

- **W and Z factories** are incorporated by beam switchyard (W and Z factories are double rings, with **independent SRF system** for e+ and e- beams)

- Higgs factory baseline:
  SR per beam 30 MW

J. Gao

FCC-ee RF staging scenario

"Ampere-class" machine

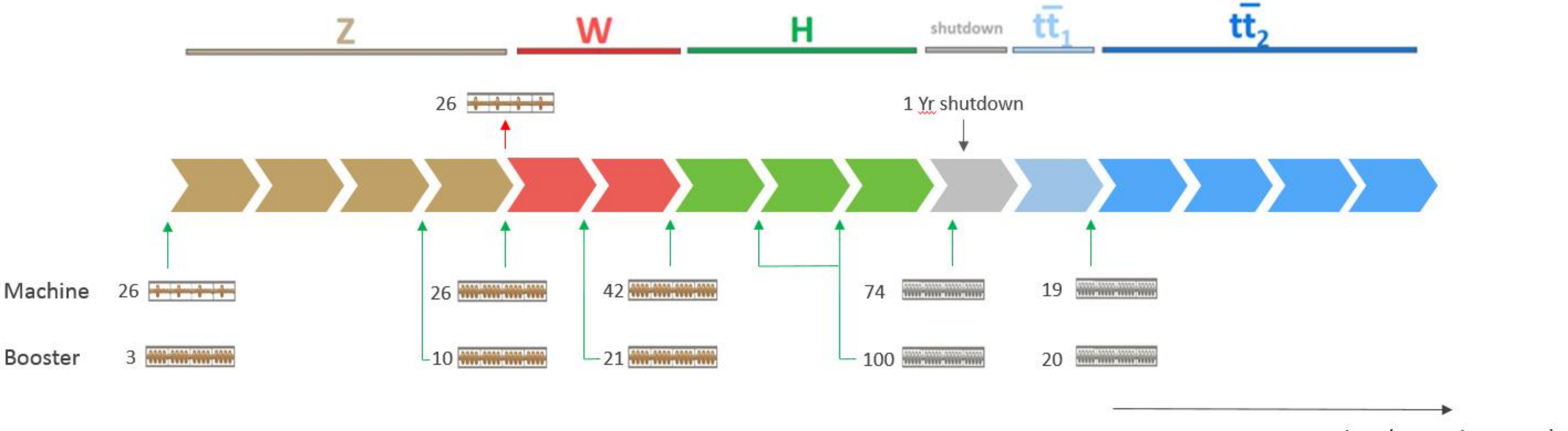
WP	V_{rf} [GV]	#bunches	I_{beam} [mA]
Z	0.1	16640	1390
W	0.44	2000	147
H	2.0	393	29
ttbar	10.9	48	5.4

"high-gradient" machine

O. Brunner

three sets of RF cavities to cover all options for FCC-ee & booster:

- **high intensity (Z, FCC-hh): 400 MHz mono-cell cavities (4/cryom.)**
- **higher energy (W, H, t): 400 MHz four-cell cavities (4/cryomodule)**
- **ttbar machine complement: 800 MHz five-cell cavities (4/cryom.)**
- **installation sequence comparable to LEP (≈ 30 CM/shutdown)**

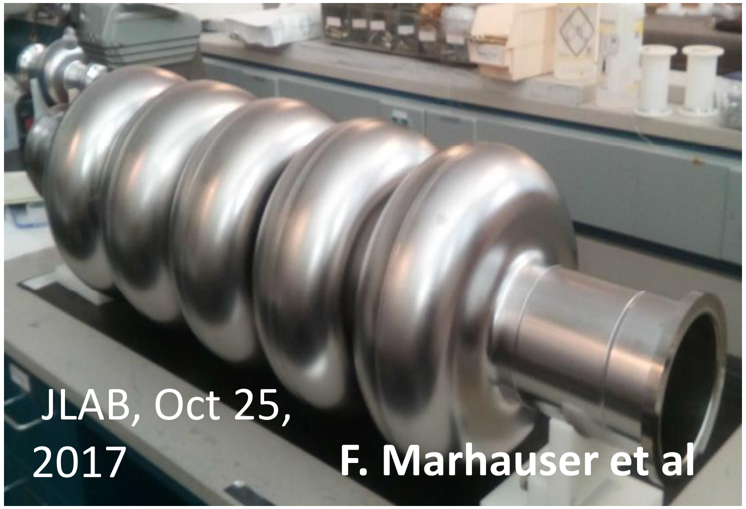


FCC-ee cavities

Z running:
single cell cavities,
400 MHz,
Nb/Cu at 4.5 K,
like LHC cavities

Z-pole FCC-ee: 116 single-cell cavities

ttbar running:
five-cell cavities,
800 MHz,
bulk Nb at 2 K,
in addition to
400 <MHz
four-cell cavities
at 400 MHz



JLAB, Oct 25,
2017

F. Marhauser et al

ttbar FCC-ee: 396 four-cell 400 MHz + 852 five-cell 800 MHz cavities

Helium inventory

FCC-ee

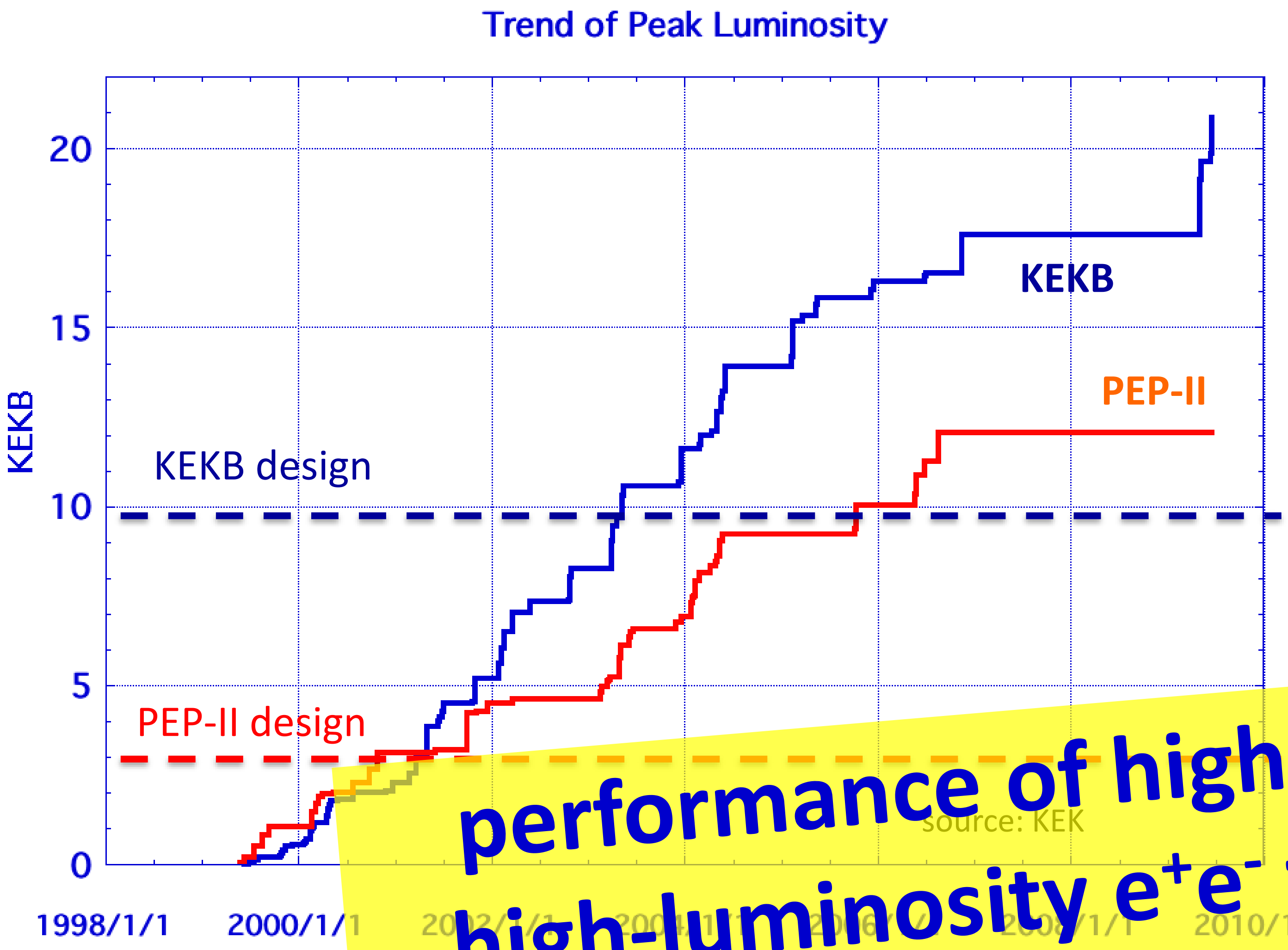
	Z	W	ZH	ttbar
Total [t]	6	7	14	26

ILC

	250 GeV	500 GeV	1 TeV
Total [t]	50	100	200

current world production >30,000 tonne per year

circular KEKB & PEP-II: high current, high *L*


Trend of Peak Luminosity

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

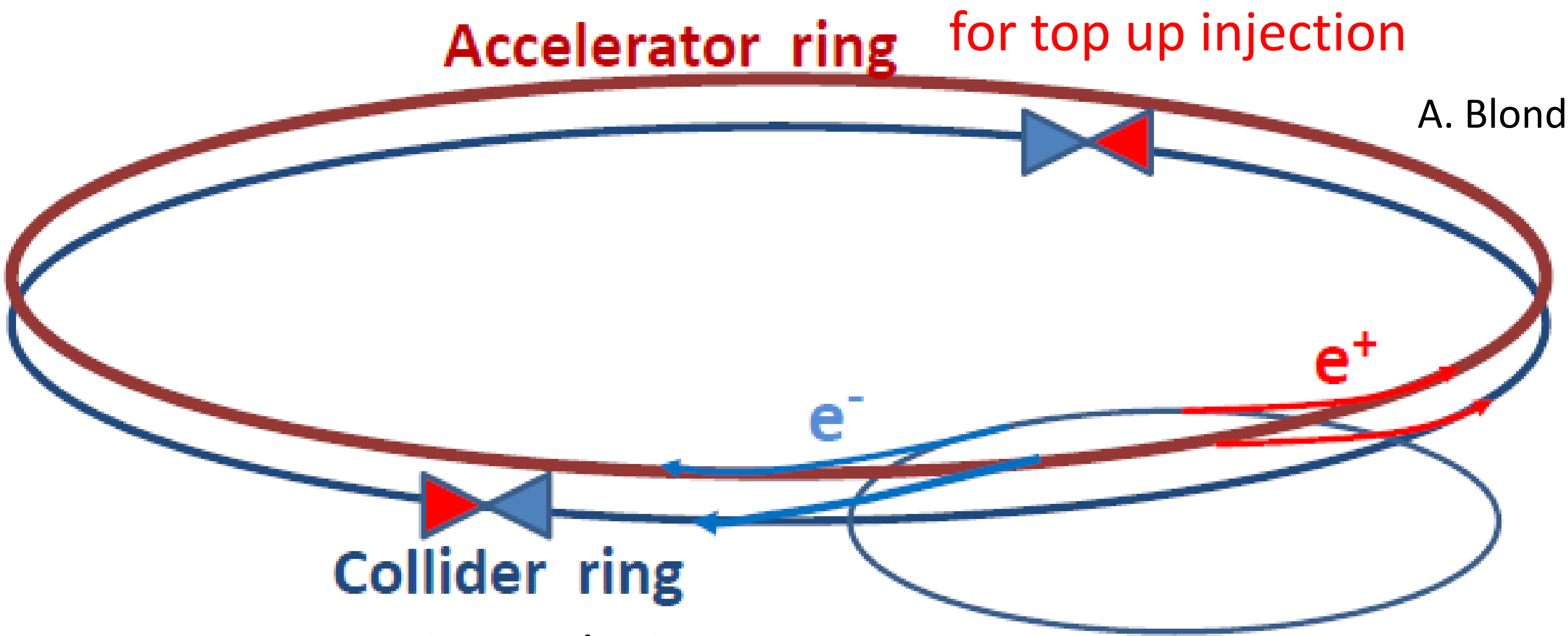
P_{SR} ~ 8 MW
C = 2.2 km

performance of high-current high-luminosity e^+e^- factories conservatively predicted

FCC-ee

circumference ~97 km

- maximum *e*$^+$*e*$^-$ cm energy 365 GeV
- *pp* collision energy in same tunnel 100 TeV



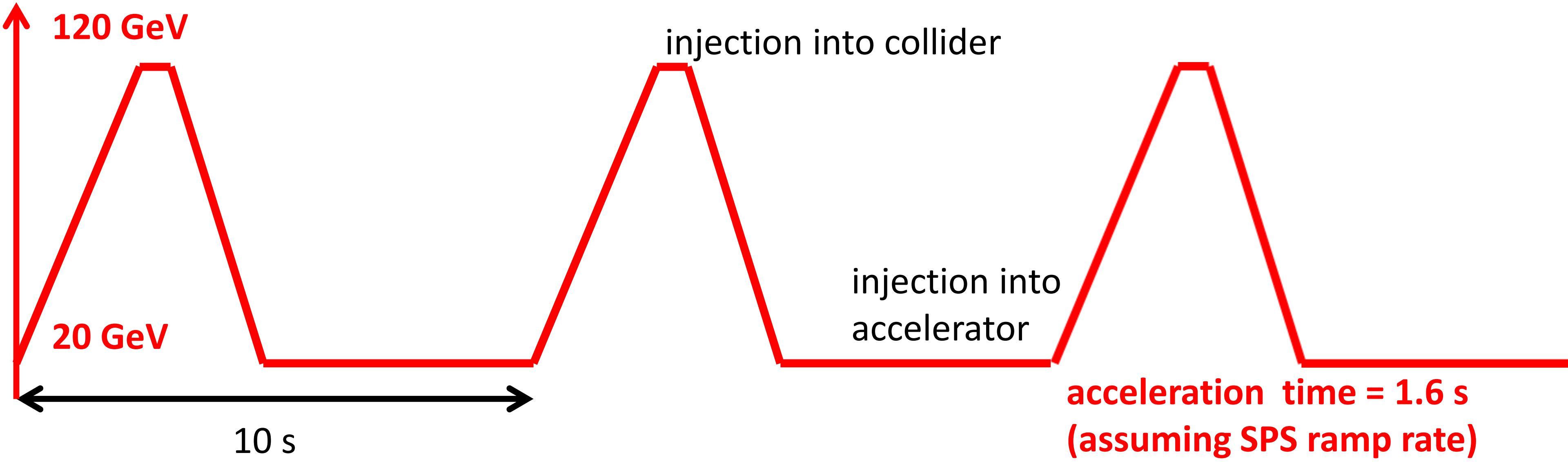
short beam lifetime (~τ_{LEP2}/40) due to high luminosity **supported by top-up injection** (used at KEKB, PEP-II, SLS,…); top-up **also avoids ramping & thermal transients, + eases tuning**

top-up injection: schematic cycle

beam current in collider (15 min. beam lifetime)

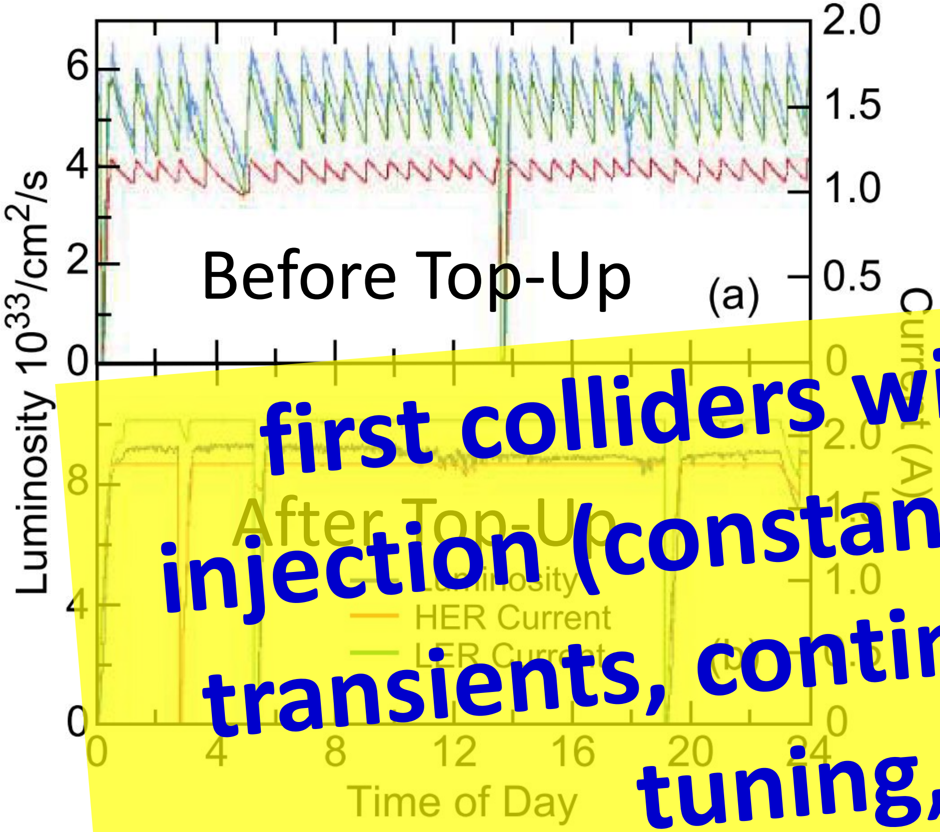
almost constant current

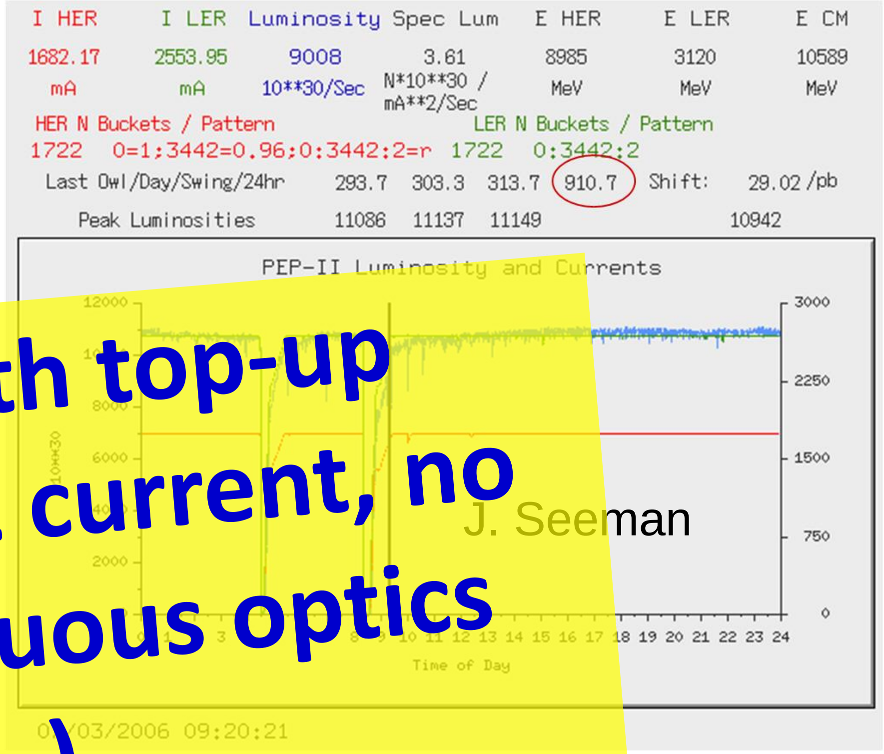
energy of accelerator ring



acceleration time = 1.6 s (assuming SPS ramp rate)

KEKB & PEP-II: top-up injection





I HER	I LER	Luminosity	Spec Lum	E HER	E LER	E CM
1682.17	2553.95	9008	3.61	8985	3120	10589
mA	mA	10**30/Sec	N*10**30 / mA**2/Sec	MeV	MeV	MeV

HER N Buckets / Pattern LER N Buckets / Pattern
1722 0=1;3442=0.96;0:3442:2=r 1722 0:3442:2

Last Owl/Day/Swing/24hr	293.7	303.3	313.7	910.7	Shift: 29.02 /pb
Peak Luminosities	11086	11137	11149		10942

PEP-II Luminosity and Currents

02/03/2006 09:20:21

first colliders with top-up injection (constant current, no transients, continuous optics tuning,…)

J. Seeman

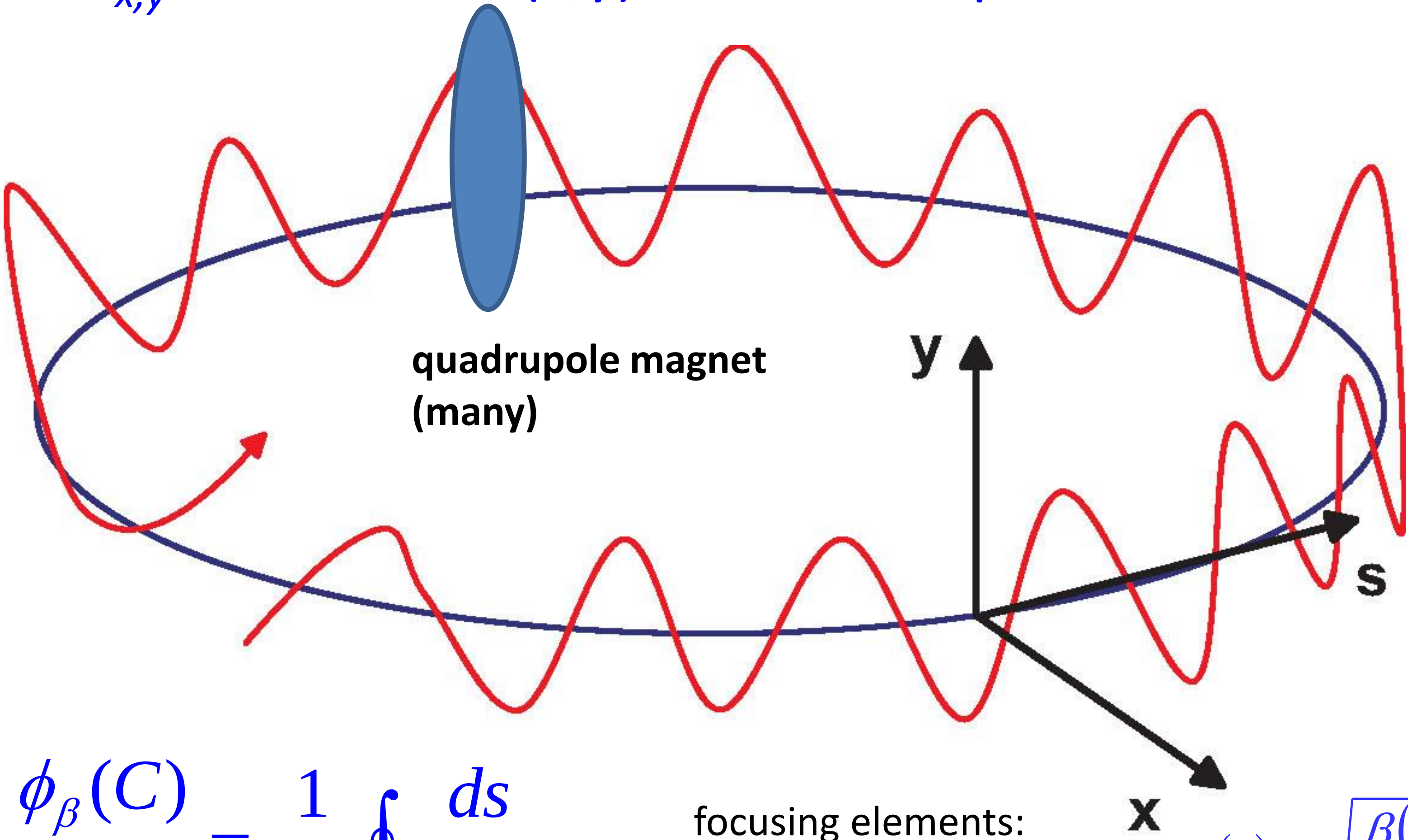
similar results from KEKB

average luminosity ≈ peak luminosity !

betatron oscillation & tune

schematic of betatron oscillation around storage ring

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

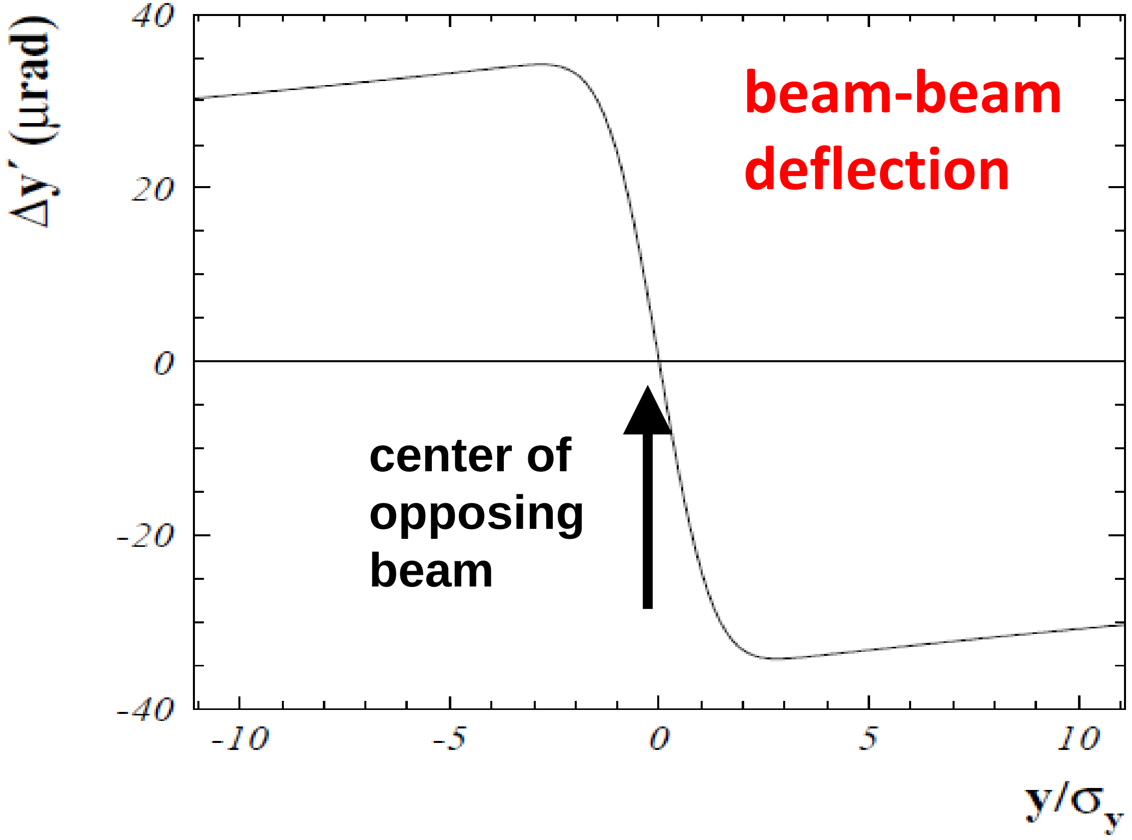


$$Q = \frac{\phi_\beta(C)}{2\pi} = \frac{1}{2\pi}\oint_C \frac{ds}{\beta(s)}$$

focusing elements:
quadrupole magnets

$$\sigma(s) = \sqrt{\frac{\beta(s)\varepsilon_N}{\gamma}}$$

beam-beam tune shift



at small amplitude similar to effect of focusing quadrupole

beam-beam tune shift

$$\Delta Q_{x.y;\max} = \xi_{x,y} = \frac{N r_e \beta^*}{4\pi\gamma\sigma_x\sigma_y} = \frac{N}{\varepsilon_N}\frac{r_0}{4\pi}$$

(for head-on collision)

beam-beam tune shift for FCC-ee

tune shift limits empirically scaled from LEP data (also 4 IPs like FCC-ee/TLEP)

$$\xi_y \propto \frac{N}{\varepsilon_x} \leq \xi_y^{\max}(E)$$

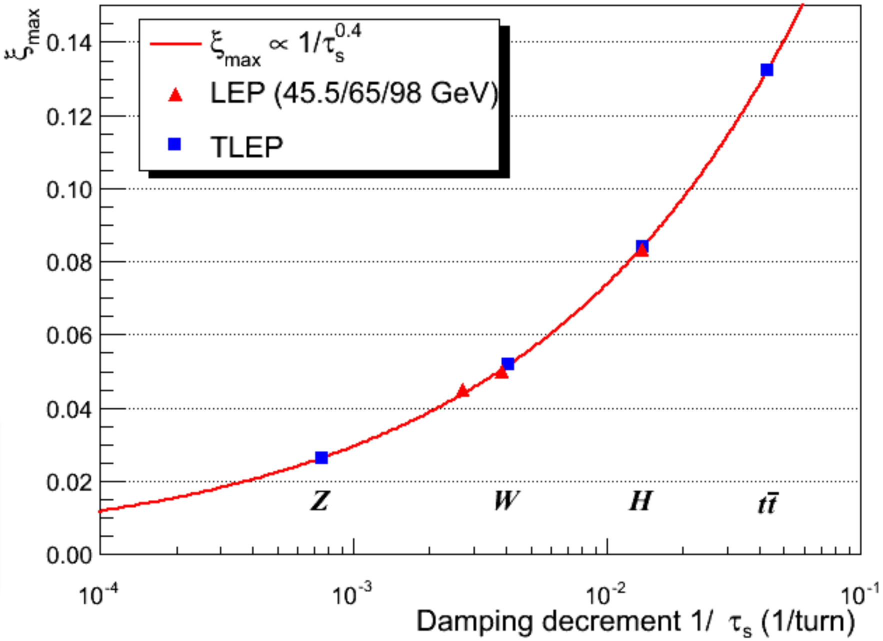
$$\xi_y^{\max}(E) \propto \frac{1}{\tau_s^{0.4}} \propto E^{1.2}$$

R. Assmann & K. Cornelis, EPAC2000

in reasonable agreement with simulations

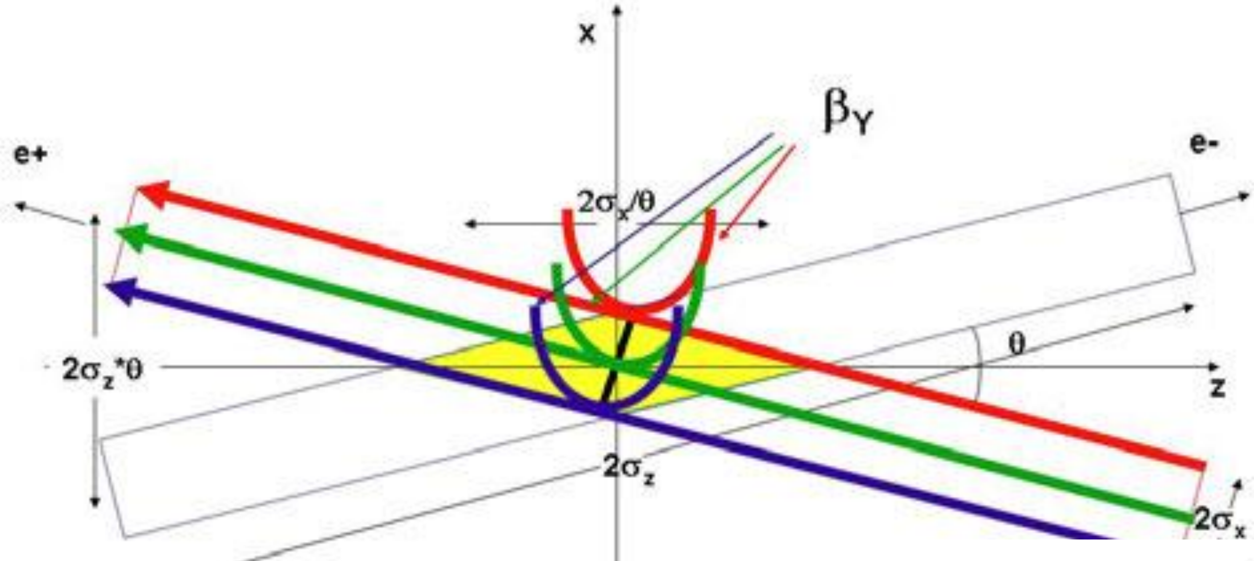
S. White

J. Wenninger

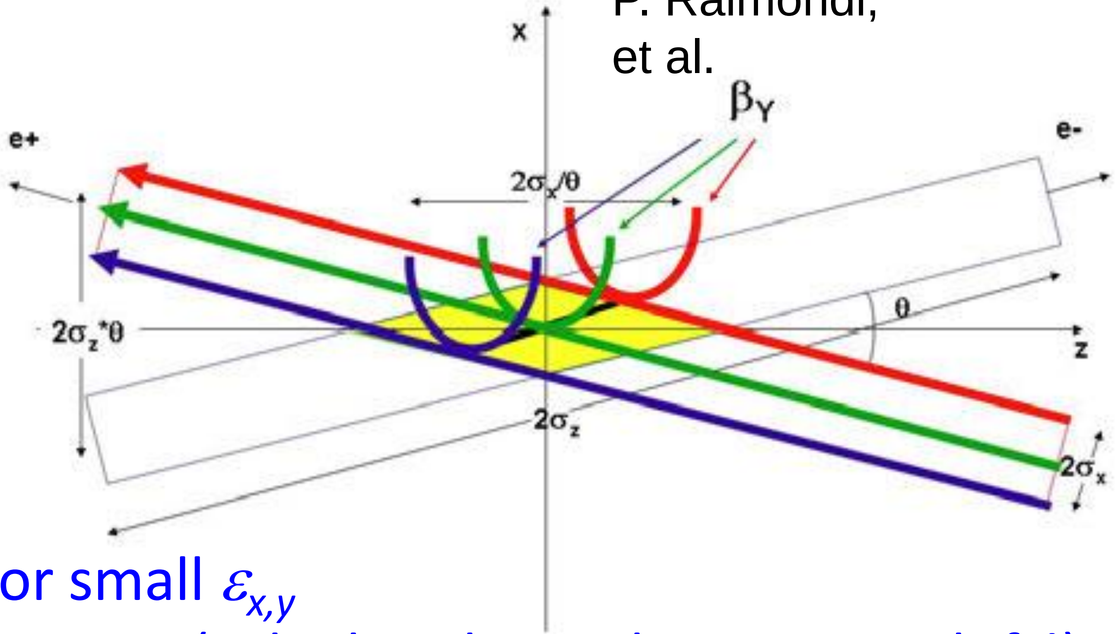


crab-waist crossing for flat beams

regular crossing



P. Raimondi,
et al.



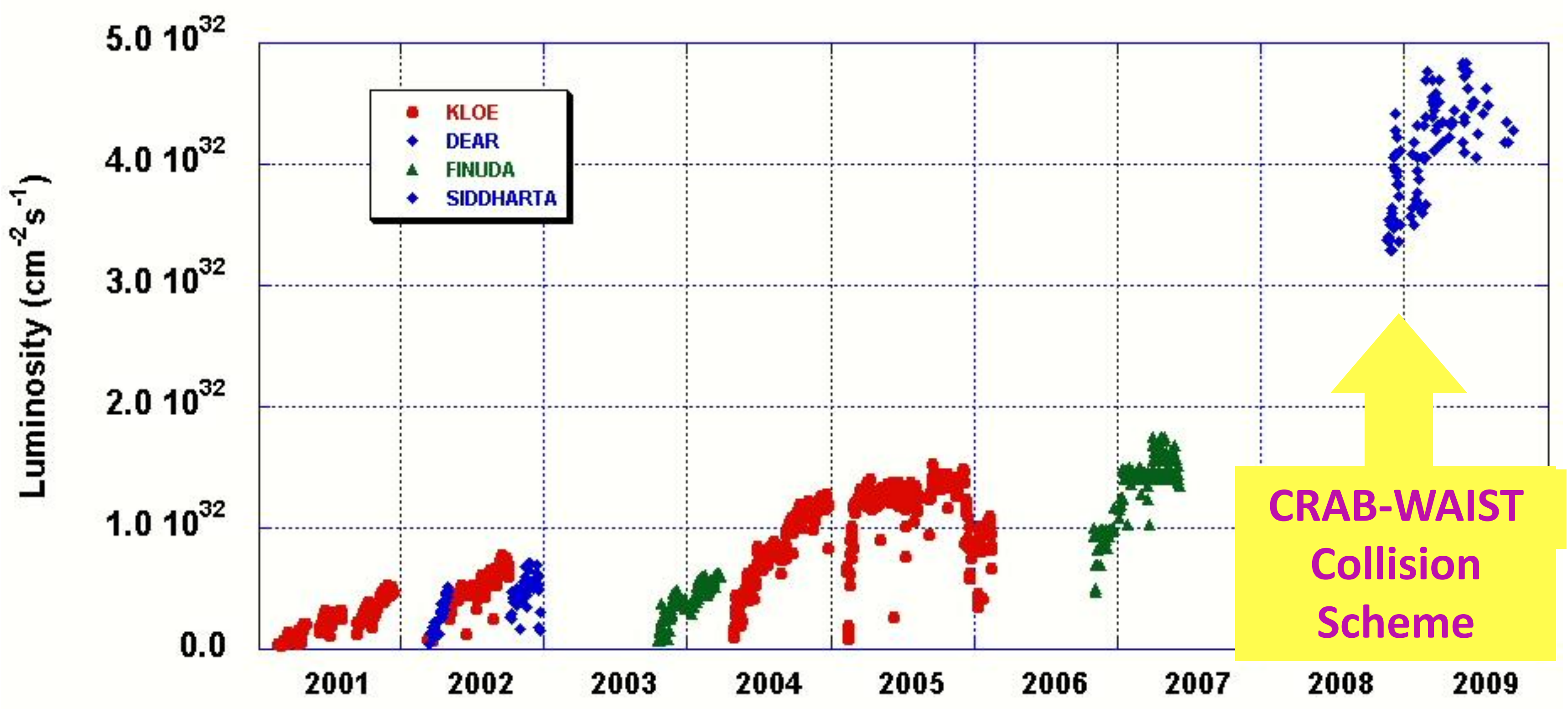
crab waist -

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

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

“crab waist” collisions at DAΦNE

DAΦNE Peak Luminosity



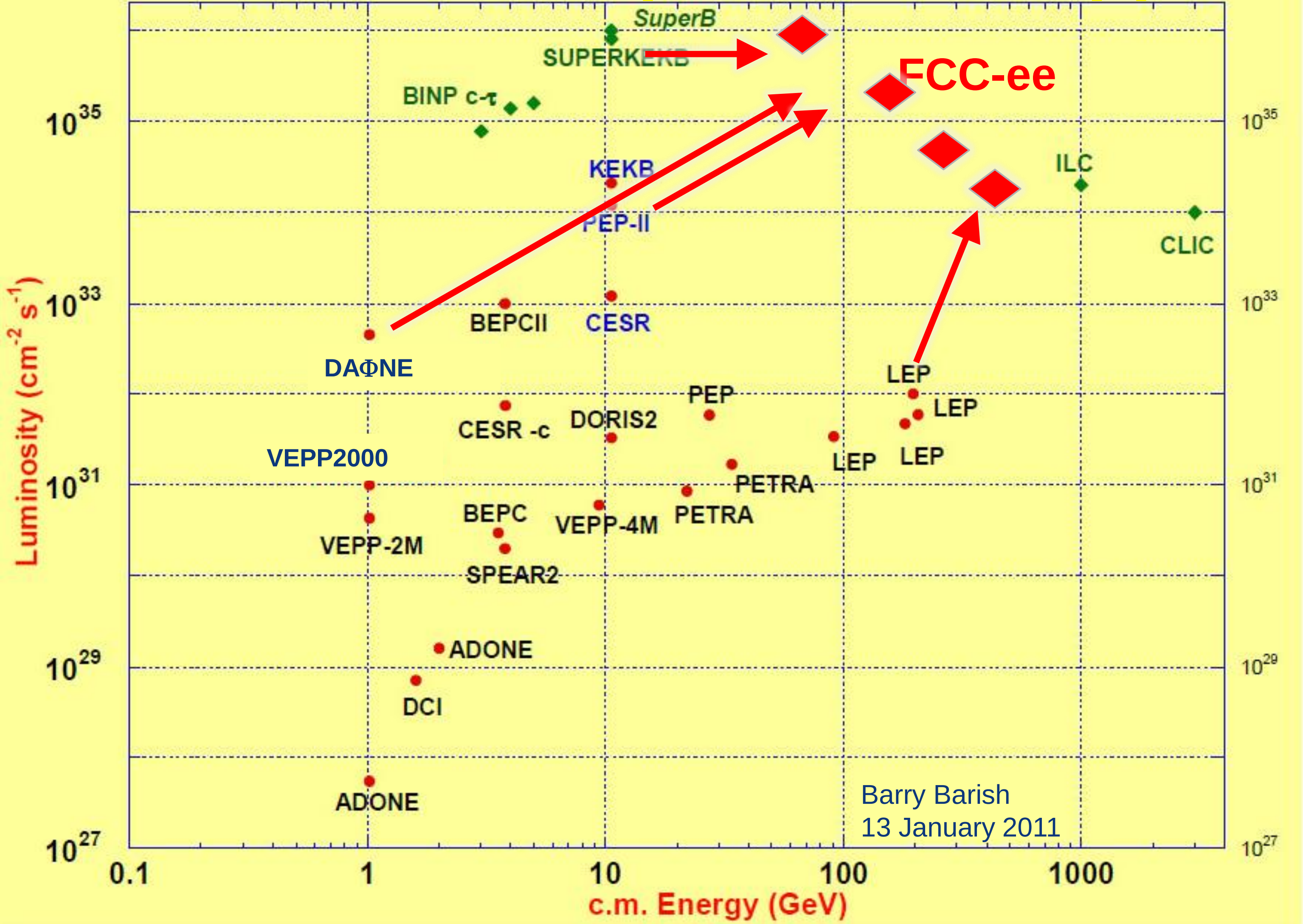
CRAB-WAIST Collision Scheme

Design Goal

M. Zobov

crab waist increases maximum beam-beam tune shift >2x

FCC-ee exploits lessons & recipes from past e^+e^- and *pp* colliders



Barry Barish
13 January 2011

LEP:
high energy
SR effects

B-factories:
KEKB & PEP-II:
high beam
currents
top-up injection

DAFNE: crab waist

Super B-factories
S-KEKB: low β_y^*

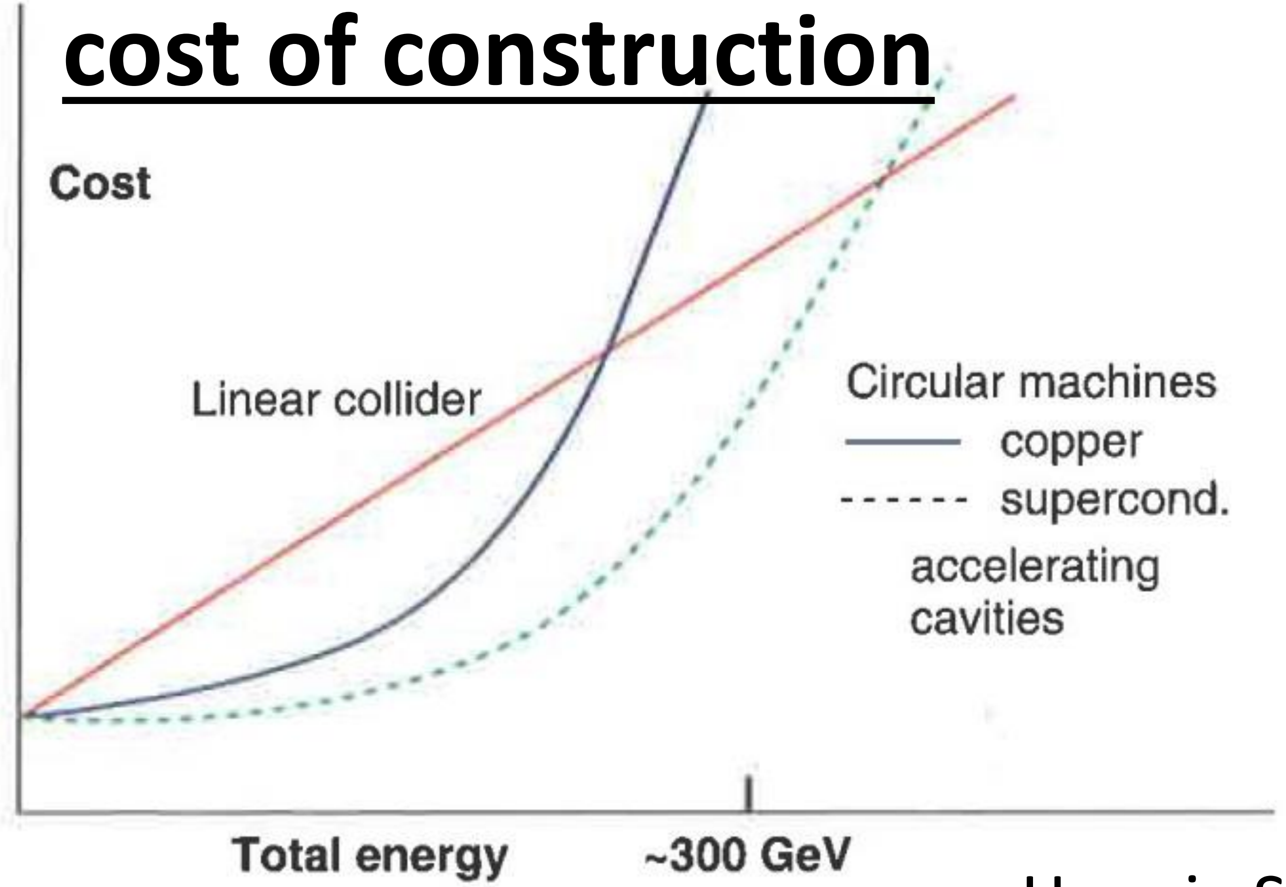
KEKB: e^+ source

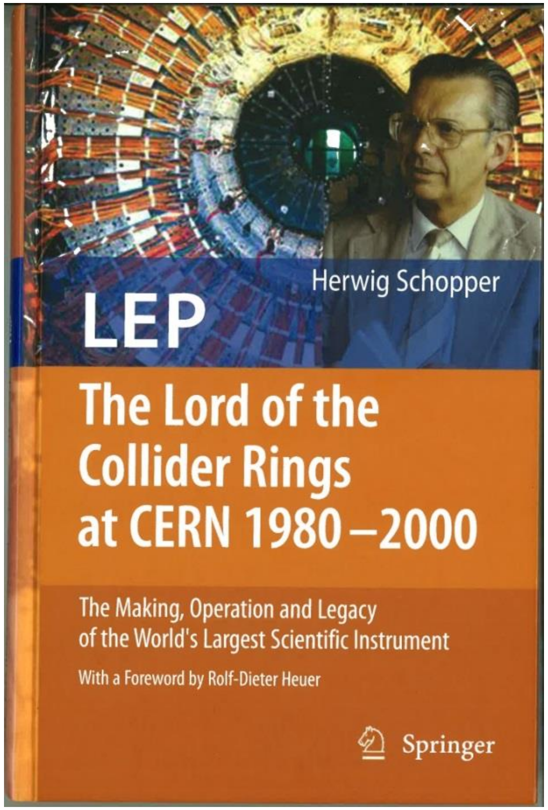
HERA, LEP, RHIC:
spin
gymnastics

combining recent, novel ingredients → extremely high luminosity at high energies

In 1982, when Lady Margaret Thatcher visited CERN, she asked the then CERN Director-General Herwig Schopper *why CERN was building a circular collider rather than a linear one*

argument accepted by the Prime Minister: cost of construction





Herwig Schopper, LEP - The Lord of the Collider Rings at CERN 1980 - 2000, Springer 2009

with a foreword by Rolf-Dieter-Heuer

up to a cm energy of at least ~400 GeV circular collider with sc RF is cheapest option

Herwig Schopper, private communication, 2014

ee luminosity w crab waist and its constraints

synchrotron radiation power / beam:

$$\boxed{P_{SR} = n_b N_b \frac{c C_\gamma E^4}{\rho C}}$$

beam-beam tune shift

$$\boxed{\xi_y = \frac{r_e N_b}{2\pi\gamma} \frac{\beta_y^*}{\sigma_x^* \sigma_y^* \sqrt{1+\phi_{piw}^2}}}$$

constant

maximum acceptable

Piwinski angle

$$\phi_{piw} \equiv \frac{\theta_c \sigma_z}{2\sigma_x^*} > 1$$

$$\xi_x = \frac{r_e N_b}{2\pi\gamma} \frac{\beta_x^*}{\sigma_x^{*2}\left(1+\phi_{piw}^2\right)}$$

luminosity

$$L = \frac{c}{C} \frac{n_b N_b^2}{4\pi \sigma_x^* \sigma_y^* \sqrt{1+\phi_{piw}^2}} \underbrace{F_{hg}\left(\frac{\beta_y^* \sqrt{1+\phi_{piw}^2}}{\sigma_z}\right)}_{\approx 1}$$

luminosity formula for H, Z, W, t factory

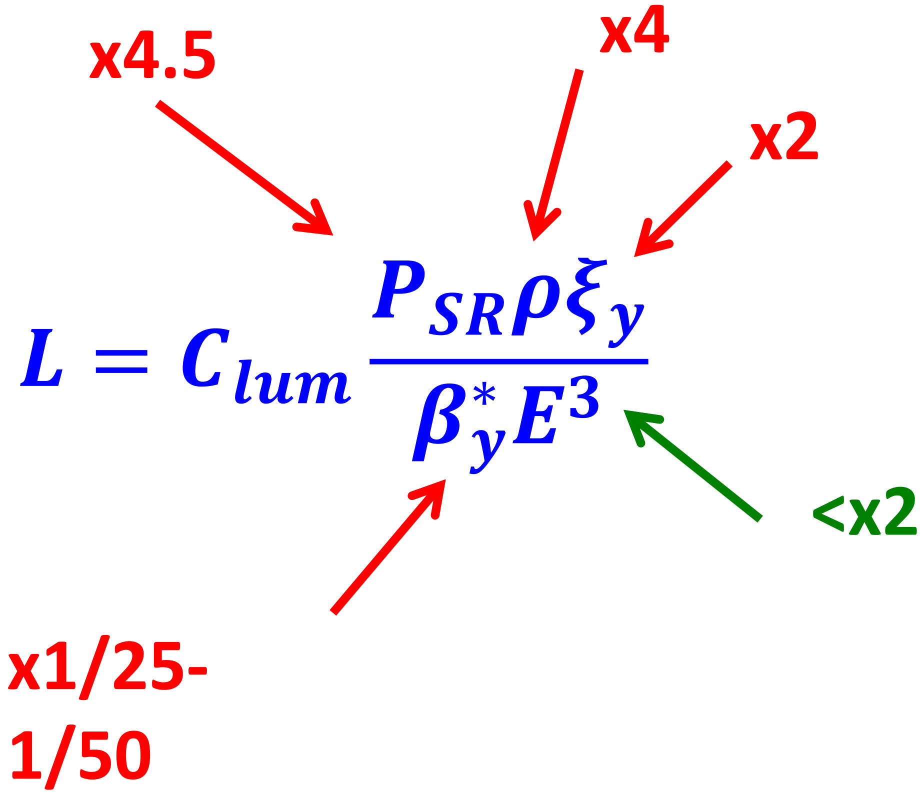
$$\boxed{L = C_{lum} \frac{P_{SR} \rho \xi_y}{\beta_y^* E^3}}$$

with

$$C_{lum} \equiv \frac{3(m_e c^2)^2}{8\pi r_e^2} \approx 4 \times 10^{15} \frac{\mathrm{TeV}^2}{\mathrm{m}^2}$$

ee luminosity scaling

***FCC-ee* vs LEP:**



x4.5

x4

x2

$$L = C_{lum}\frac{P_{SR}\rho\xi_y}{\beta_y^* E^3}$$

<x2

x1/25-1/50

→ extremely high luminosity

IP spot size

$$\sigma^*_{x,y} = \sqrt{\beta^*_{x,y}\varepsilon_{x,y}}$$

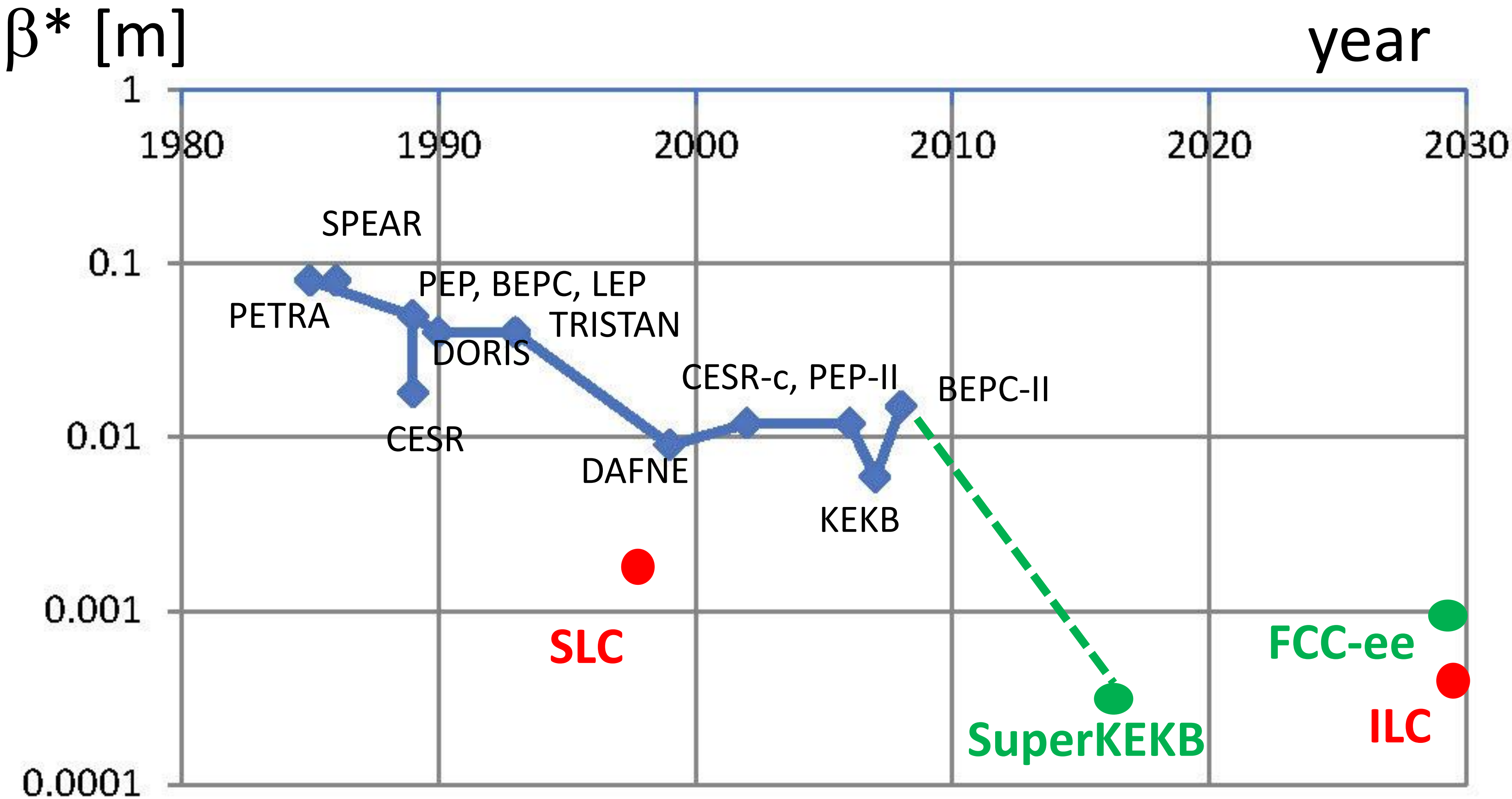
1. **final focus optics**
2. **bunch length**
3. **beamstrahlung**
   (for β_x)

ILC: $\varepsilon \propto 1/E$
(adiabatic damping)

FCC-ee:
1. **$\varepsilon \propto E^2 \theta_{dip}{}^3$ (synchr. rad.)**
2. **beam-beam tune shift**

smaller emittances
needed for linear colliders

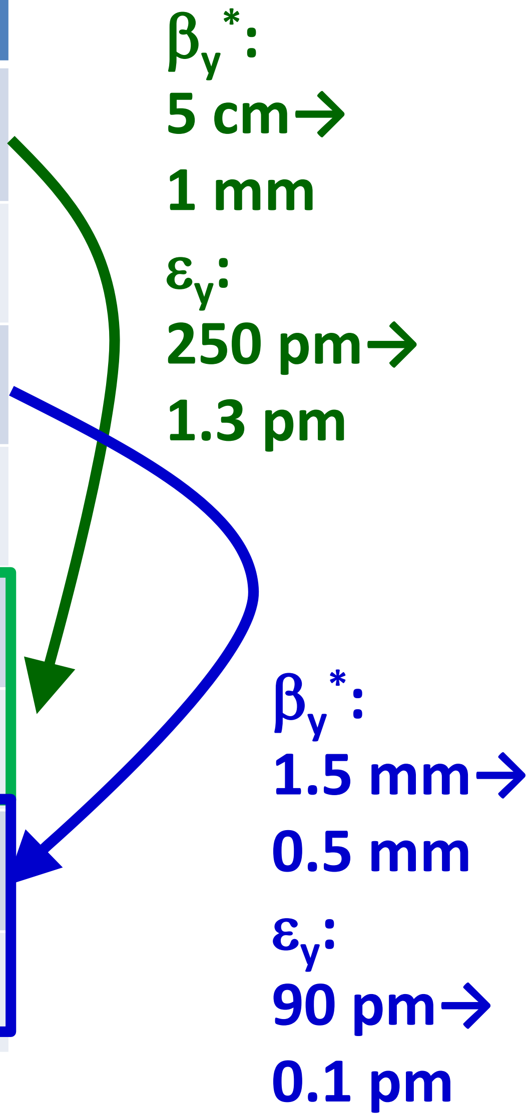
vertical β^* history



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

vertical rms IP spot size

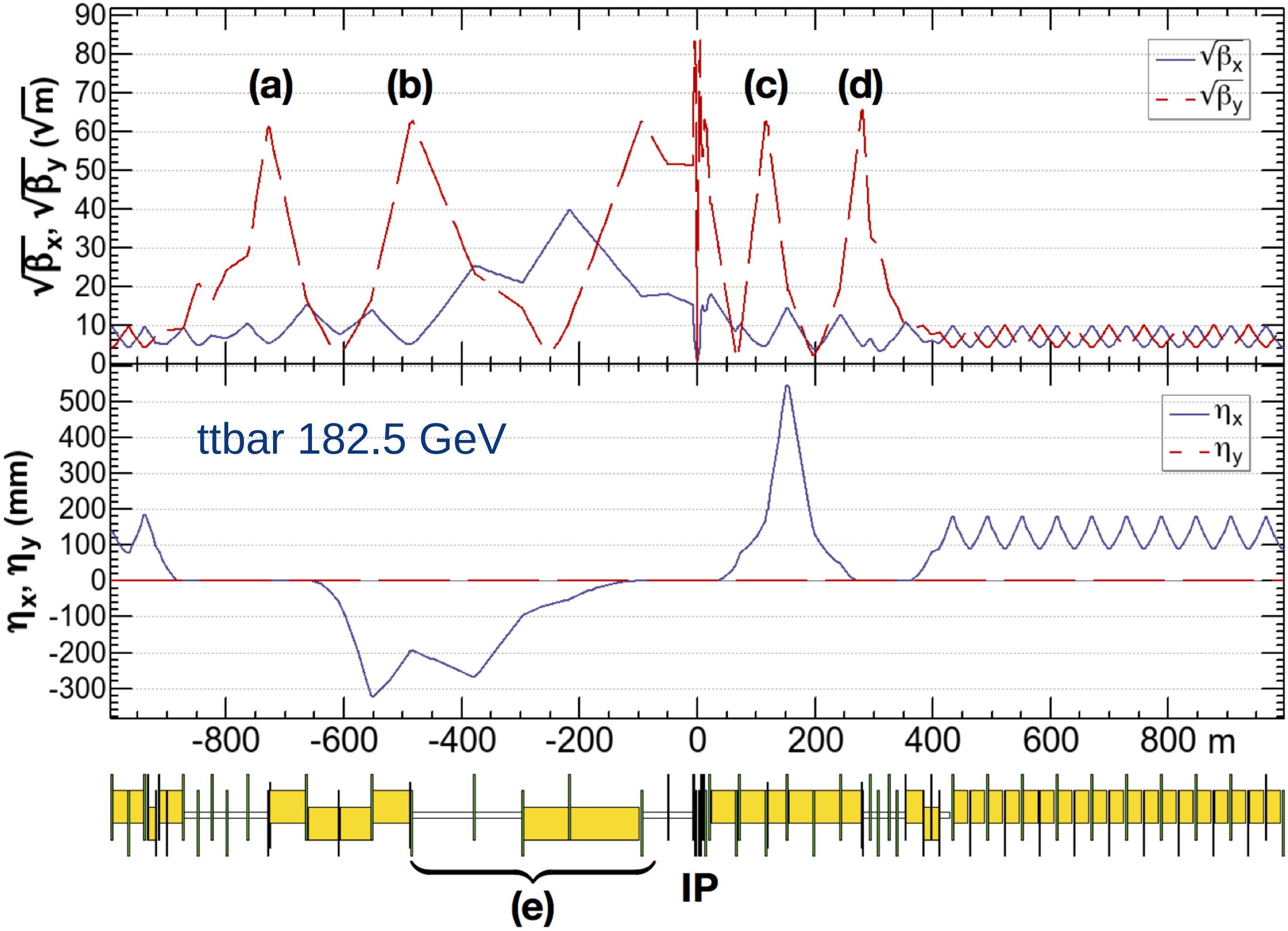
collider / test facility		$\sigma_y{}^*$ [nm]
LEP2	in regular font: achieved	3500
KEKB		940
SLC	in italics: design values	700
ATF2, FFTB		65 (*35*), 77
SuperKEKB		***50***
FCC-ee-H		***40***
ILC		*5 – 8*
CLIC		*1 – 2*



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

$\beta_y{}^*$:
1.5 mm→
0.5 mm
ε_y:
90 pm→
0.1 pm

FCC-ee asymmetric crab waist IR optics



asymmetric IR optics to suppress synchrotron radiation toward the IP, **E$_{critical}$ <100 keV from 450 m from IP (e)**

yellow boxes: dipole magnets

K. Oide

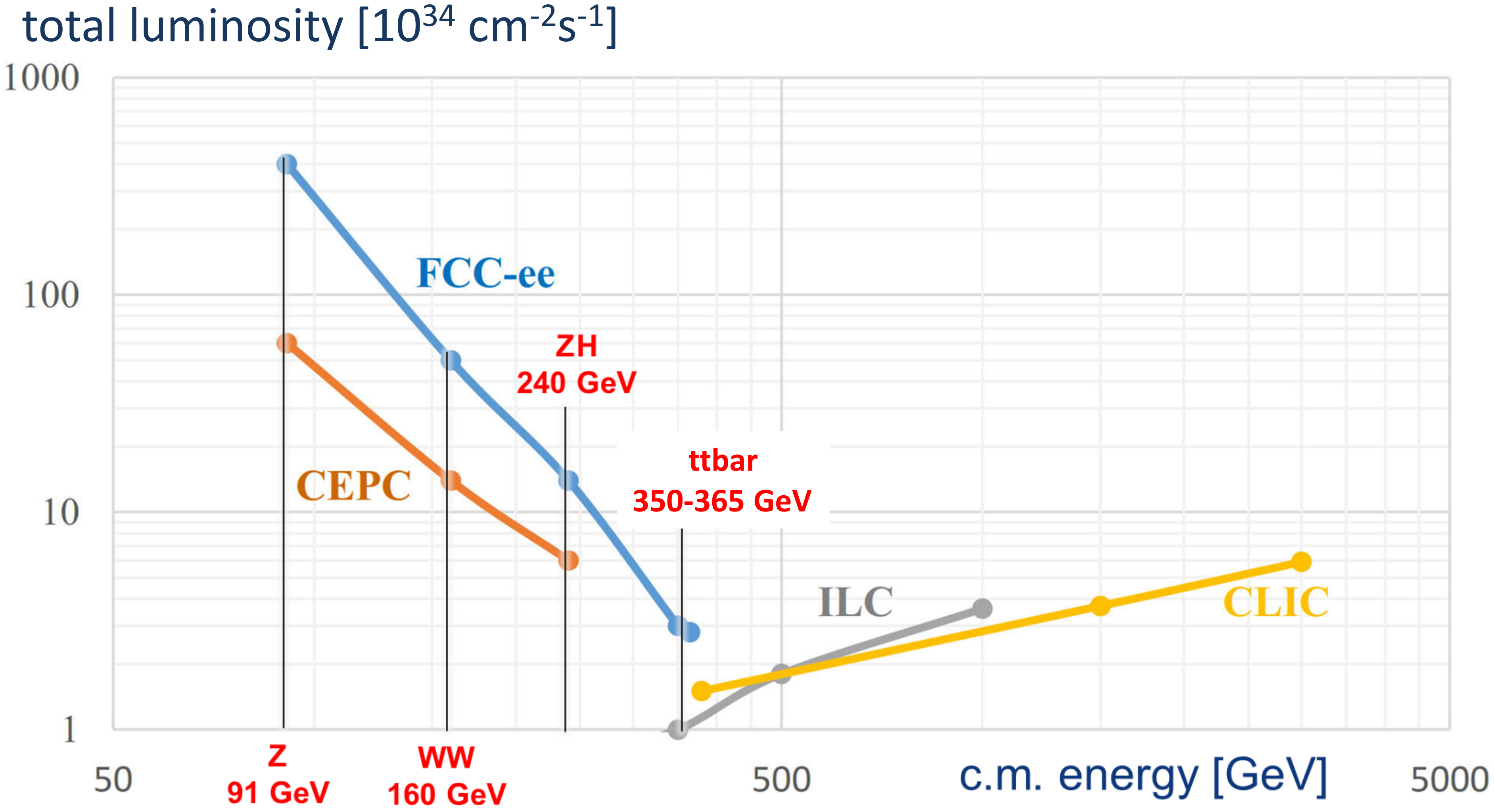
4 sextupoles (a – d) for local vertical chromaticity correction and crab waist, optimized for each working point.

Common arc lattice for all energies, **60 deg for Z, W and 90 deg for ZH, tt** fo maximum stability and luminosity

comparison of key design parameters

Parameter	**LEP2**	**FCC-ee**			**ILC**		
		Z	**H**	**t**	**H**	**500**	**1 TeV**
E (GeV)	104	45.6	120	182.5	125	250	500
<I (mA)>	**4**	**1390**	**29**	**5.4**	**0.021**	**0.021**	**0.021**
$P_{\mathrm{SR/b,tot}}$ [MW]	22	100	100	100	5.9	10.5	27.2
P_{AC} [MW]	~200	~260	~280	~360	~129	~163	~300
$\eta_{\mathrm{wall}\rightarrow\mathrm{beam}}$ [%]	**~30**	**30-40**	**30-40**	**~30**	**4.6**	**6.4**	**9.1**
$N_{\mathrm{bunch/ring\ (pulse)}}$	4	16’640	328	48	1312	1312	2450
f_{coll} (kHz)	45	50000	4000	294	6.6	6.6	9.8
$\beta^*_{x/y}$ (m/mm)	1.5/50	0.15/0.8	0.3/1	1.0/1.6	.013/.41	.011/.48	.011/.48
ε_x (nm)	30-50	0.27	0.63	1.46	0.02	0.02	0.01
ε_y (pm)	~250	1	1.3	2.9	0.14	0.07	0.03
ξ_y (ILC: n_γ)	0.07	0.13	0.12	0.126	(1.91)	(1.72)	(2.12)
n_{IP}	4	2	2	2	1	1	1
$L_{0.01}$/IP	0.012	230	8.5	1.55	0.5	1.05	2.2
$L_{0.01,\mathrm{tot}}$ (10^{34} cm^{-2}s^{-1})	0.048	460	**17**	3.1	**0.5**	1.05	2.2

actual design luminosity vs. energy



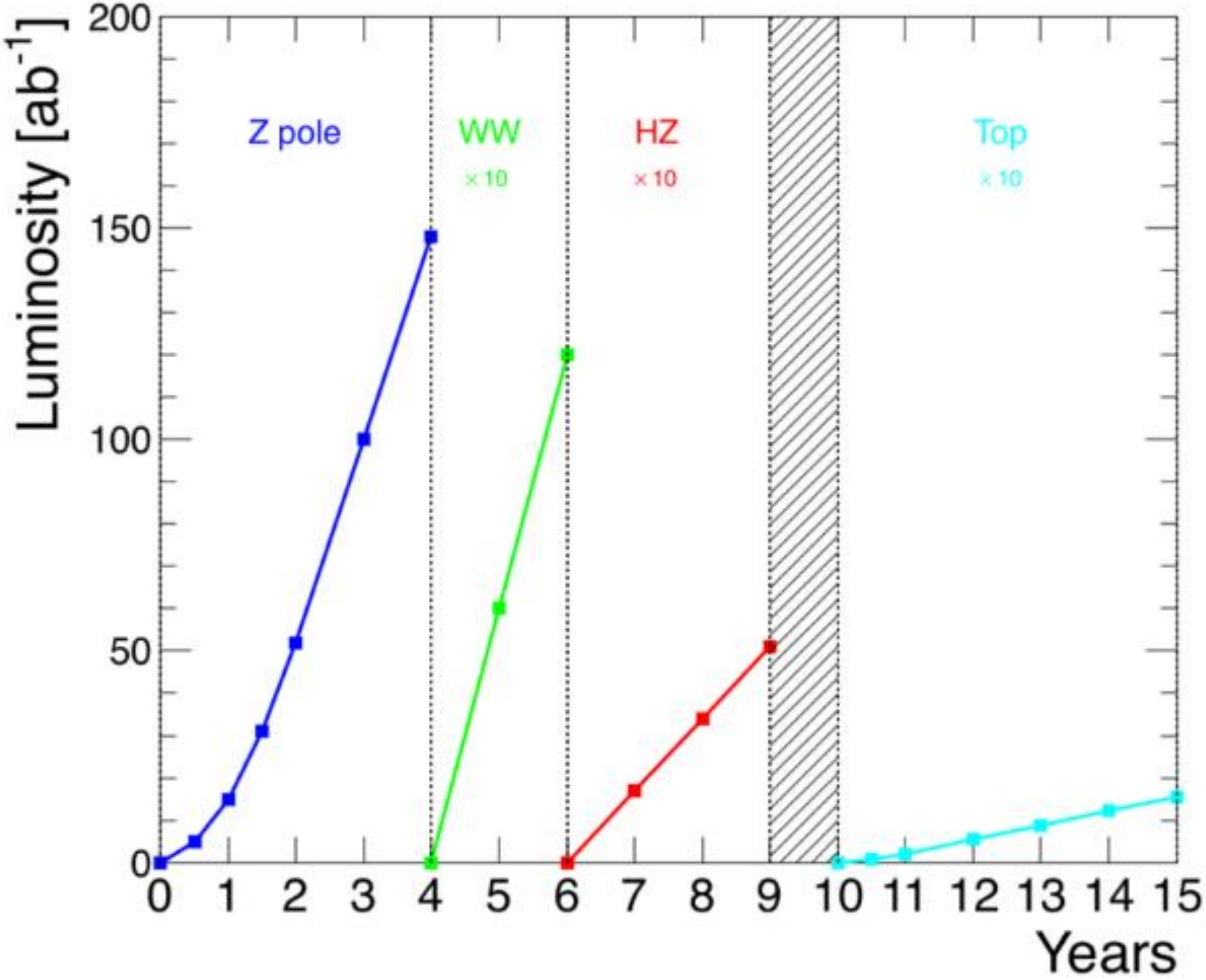
FCC-ee physics operation model

working point	nominal luminosity/IP $[10^{34}\ cm^{-2}s^{-1}]$	total luminosity (2 IPs)/ yr half luminosity in first two years (Z) and first year (ttbar) to account for initial operation	physics goal	run time [years]
***Z* first 2 years**	100	**26 ab^{-1}/year**	**150 ab^{-1}**	**4**
***Z* later**	200	**48 ab^{-1}/year**		
W	25	**6 ab^{-1}/year**	**10 ab^{-1}**	**1 - 2**
H	7.0	**1.7 ab^{-1}/year**	**5 ab^{-1}**	**3**
machine modification for RF installation & rearrangement: 1 year				
top 1st year (350 GeV)	0.8	**0.2 ab^{-1}/year**	**0.2 ab^{-1}**	**1**
top later (365 GeV)	1.4	**0.34 ab^{-1}/year**	**1.5 ab^{-1}**	**4**

total program duration: 14 – 15 years - *including machine modifications*

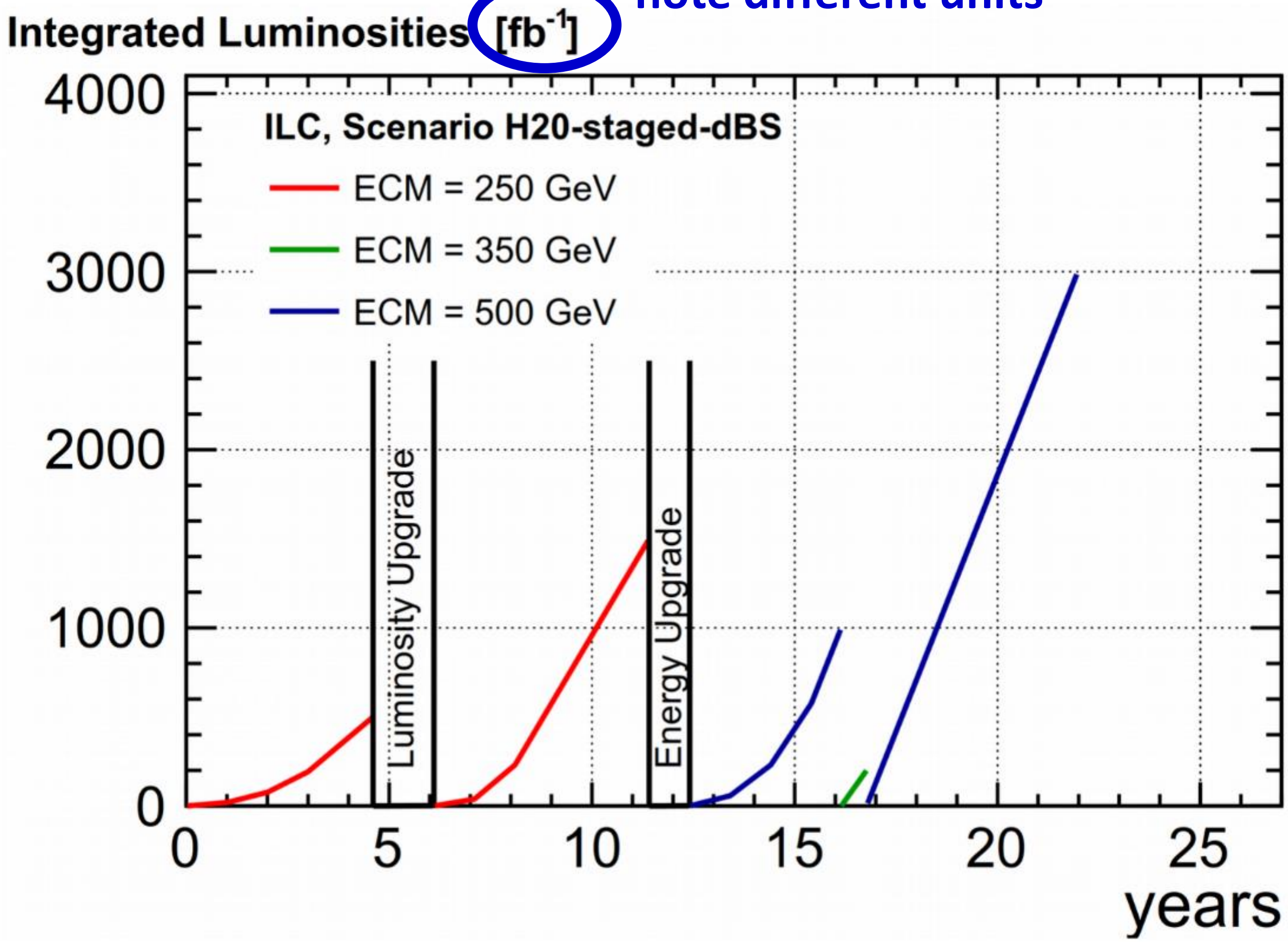
phase 1 (*Z*, *W*, *H*): 8 – 9 years, phase 2 (top): 6 years

FCC-ee luminosity projection



ILC luminosity projection

note different units

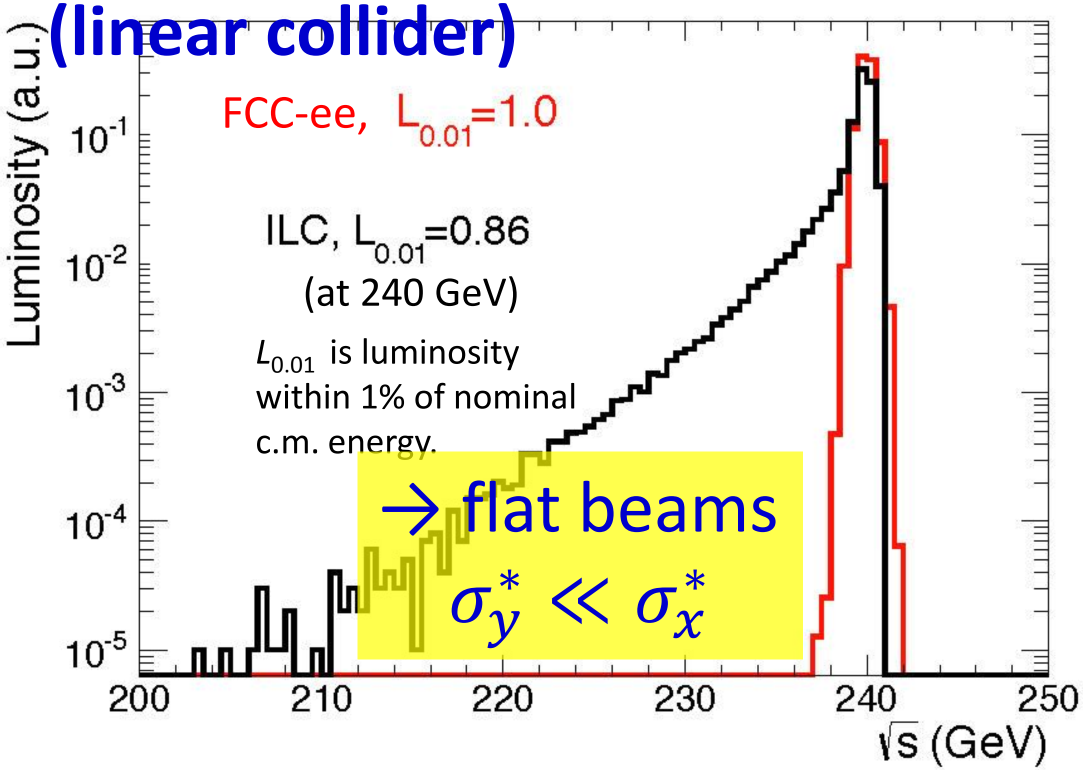


beamstrahlung (BS)

synchrotron radiation in the strong field of opposing beam

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

degraded luminosity spectrum (linear collider)



$L_{0.01}$ is luminosity within 1% of nominal c.m. energy.

→ flat beams $\sigma_y^* \ll \sigma_x^*$

limit on beam lifetime (circular collider)

V. Telnov, PRL 110 (2013) 114801

$$\tau_{BS} \approx \frac{20\sqrt{6\pi} r_e}{n_{IP}\alpha^2}\frac{C}{c}\frac{\gamma}{\Delta}u^{3/2}\boxed{e^u}$$

with $$u = \boxed{\Delta}\frac{\alpha}{3r_e^2}\frac{1}{\gamma}\frac{\boxed{\sigma_z}\boxed{\sigma_x}}{N}$$

Δ: momentum acceptance

σ_z: rms bunch length

σ_x: horizontal beam size at IP

$$\frac{L_{peak}}{L} \simeq \left[\frac{1}{N_\gamma}\left(1-e^{-N_\gamma}\right)\right]^2$$ where $$N_\gamma \simeq \frac{2\alpha r_e N}{\sigma_x}$$ denotes average number of BS photons per e^-

scaling with energy

circular collider

$$L \propto \frac{\eta P_{wall}}{E^3}\frac{\xi_y}{\beta_y} \propto \frac{\eta_{\text{ring}} P_{wall}}{E^{1.8}}\frac{1}{\beta_y}$$

limited by
beam-beam tune shift

$$\xi_y \simeq \frac{\beta_y r_e N}{2\pi\gamma\sigma_x\sigma_y} \qquad \text{if } \xi_{y,\max} \propto \frac{1}{\tau^{0.4}} \propto E^{1.2}$$

linear collider

$$L \propto \frac{\eta_{\text{linac}} P_{wall}}{E}\frac{N_\gamma}{\sigma_y}$$

limited by
#BS photons per e±

$$N_\gamma \simeq \frac{2\alpha r_e N}{\sigma_x}$$ (luminosity spectrum)

superconducting RF needs
cryogenics power

dependent on :

- cavity quality factor (unloaded Q: “Q_0”)
- accelerating gradient G_{RF}
- frequency f_{RF}
- duty factor D

cryo power: *ILC* vs *FCC-ee*

$$P_{cryo} \propto V_{tot} G_{RF} D / Q_0$$ or

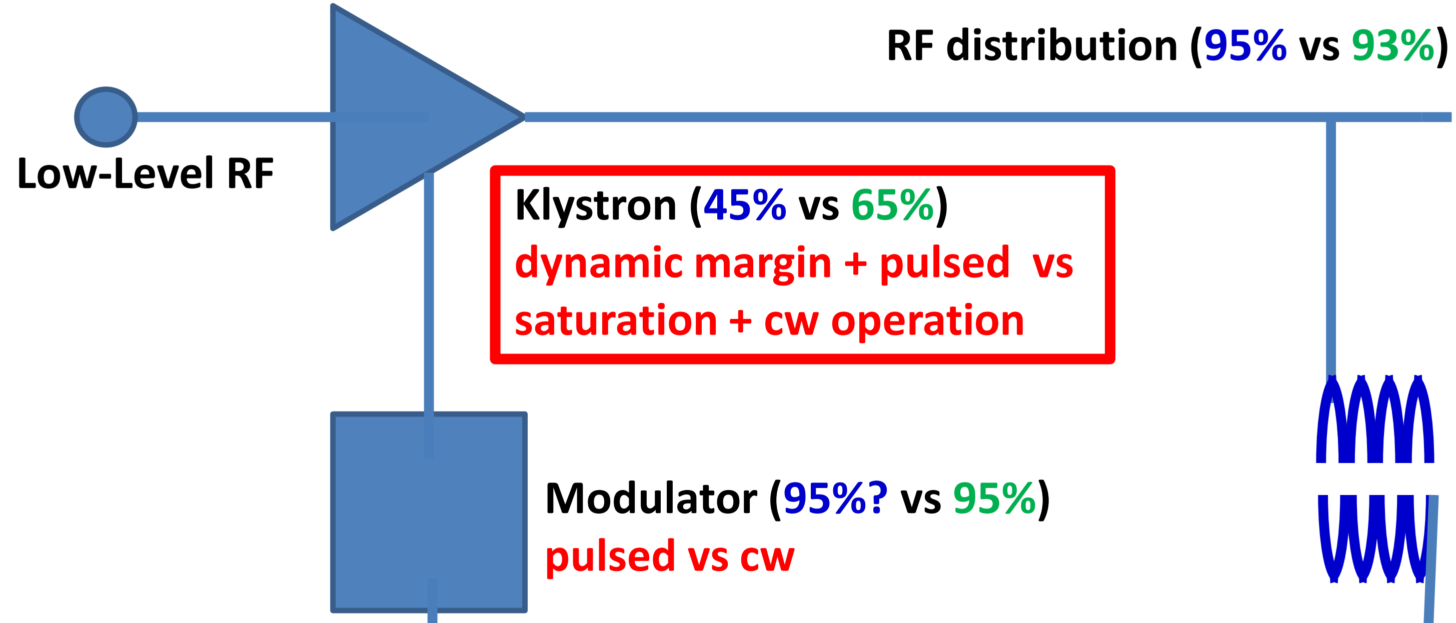
$$P_{cryo} \propto f_{RF} V_{tot} G_{RF} D / Q_0$$

(if SC cavity losses dominated by BCS resistance)

	ILC-H	*FCC-ee-H*
RF voltage V_{tot}	**250 GV**	**2 x 2 GV**
RF gradient G_{RF}	**31.5 MV/m**	**10 MV/m**
effective RF length	**8 km**	**0.4 km**
RF frequency f_{RF}	1.3 GHz	400 MHz
Q_0: unl. cavity Q	$\sim 2 \times 10^{10}$	$> 4 \times 10^{9}$
D: RF duty factor	**0.75% (pulsed)**	**100% (cw)**
total cryo power	**~19 MW**	**17 MW** (incl. booster, & 30% m.)

total cryo power similar for both projects

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



Low-Level RF

RF distribution (95% vs 93%)

Klystron (45% vs 65%)

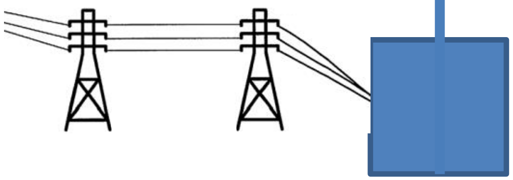
dynamic margin + pulsed vs saturation + cw operation

Modulator (95%? vs 95%)

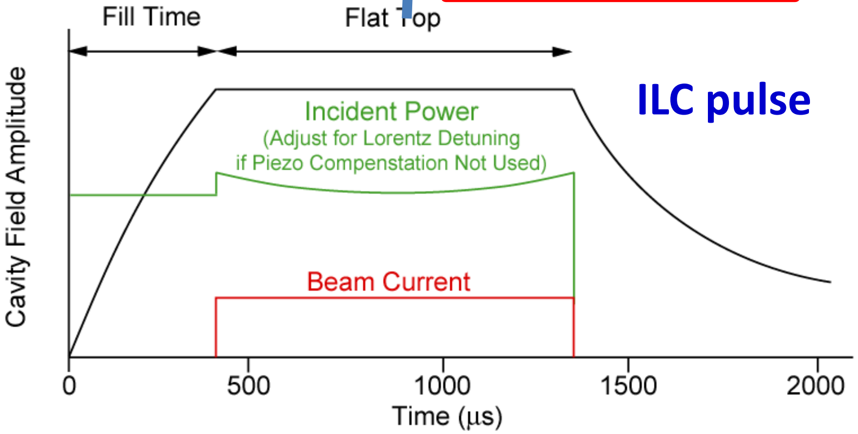
pulsed vs cw

Accelerating cavities (44% vs 100%)

pulsed vs cw



Electrical network (95%)



ILC pulse

efficiency (RF): wall plug power to beam power

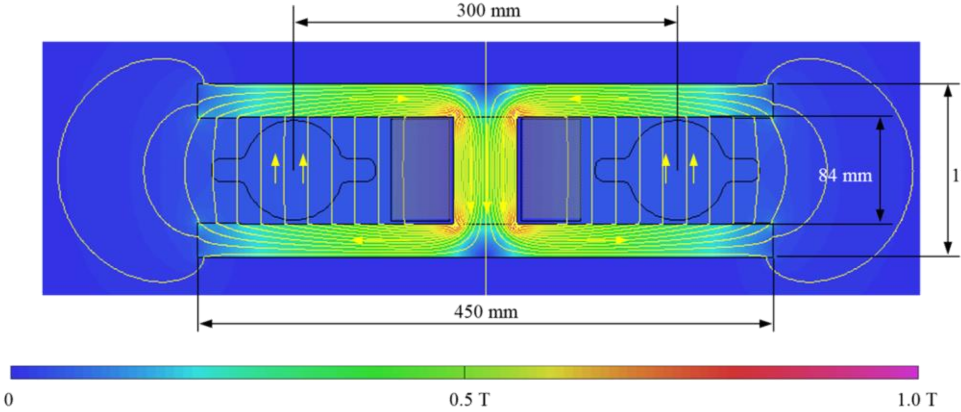
ILC: η~17%

FCC-ee: η~55%

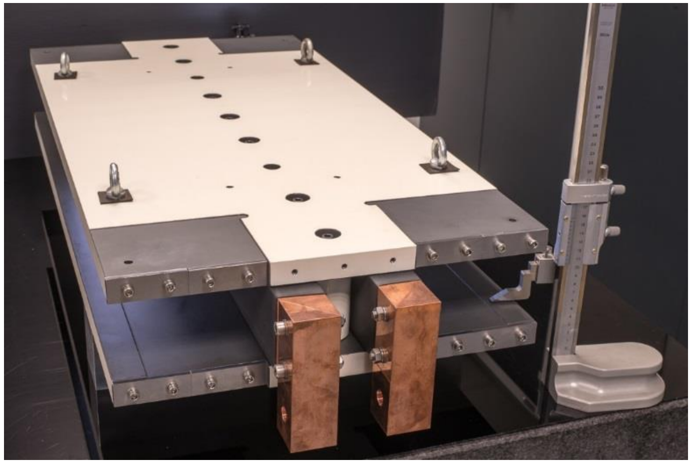
factor ~3 difference in efficiency of converting wall-plug power to beam energy

low-power low-cost design for FCC-ee magnets

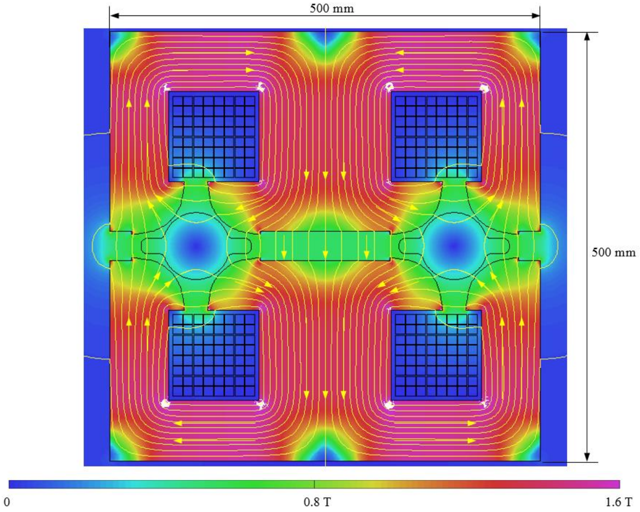
twin-dipole design with 2× power saving 16 MW (at 175 GeV), with Al busbars



first 1 m prototype



twin F/D quad design with 2× power saving; 25 MW (at 175 GeV), with Cu conductor



first 1 m prototype

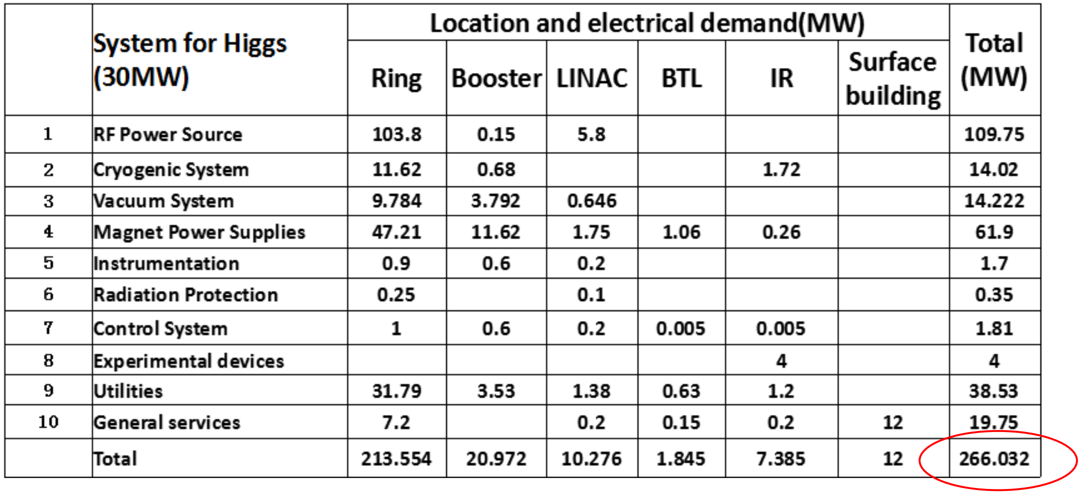
A. Milanese

FCC-ee el. power consumption [MW]

Beam energy (GeV)	45.6 Z	80 W	120 ZH	182.5 ttbar
RF (SR = 100)	163	163	145	145
Collider cryo	1	9	14	46
Collider magnets	4	12	26	60
Booster RF & cryo	3	4	6	8
Booster magnets	0	1	2	5
Pre injector	10	10	10	10
Physics detector	8	8	8	8
Data center	4	4	4	4
Cooling & ventilation	30	31	31	37
General services	36	36	36	36
Total	259	278	282	359

CEPC power & comparing efficiency

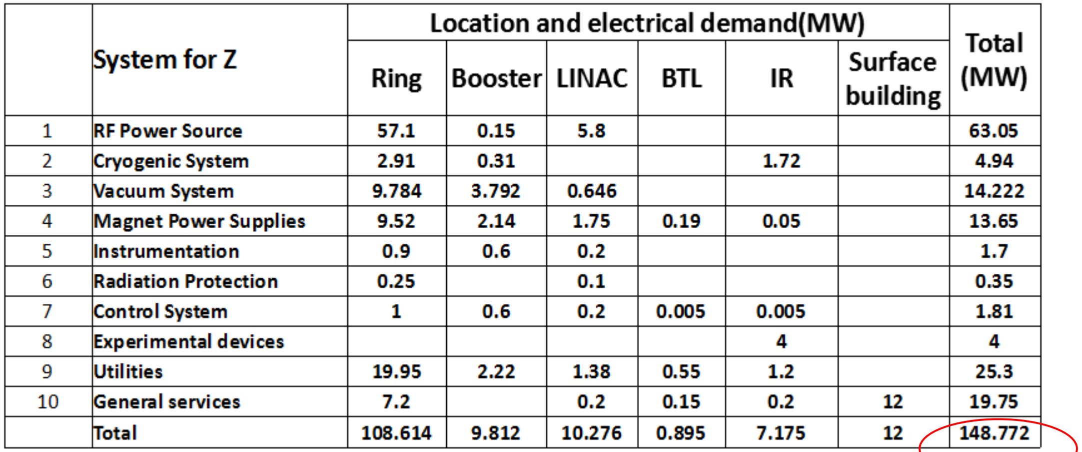
CEPC Power for Higgs and Z



	System for Higgs (30MW)	Location and electrical demand(MW)						Total (MW)
		Ring	Booster	LINAC	BTL	IR	Surface building	
1	RF Power Source	103.8	0.15	5.8				109.75
2	Cryogenic System	11.62	0.68			1.72		14.02
3	Vacuum System	9.784	3.792	0.646				14.222
4	Magnet Power Supplies	47.21	11.62	1.75	1.06	0.26		61.9
5	Instrumentation	0.9	0.6	0.2				1.7
6	Radiation Protection	0.25		0.1				0.35
7	Control System	1	0.6	0.2	0.005	0.005		1.81
8	Experimental devices					4		4
9	Utilities	31.79	3.53	1.38	0.63	1.2		38.53
10	General services	7.2		0.2	0.15	0.2	12	19.75
	Total	213.554	20.972	10.276	1.845	7.385	12	266.032

266MW

2.5x less luminosity than FCC-ee at ~equal power



	System for Z	Location and electrical demand(MW)						Total (MW)
		Ring	Booster	LINAC	BTL	IR	Surface building	
1	RF Power Source	57.1	0.15	5.8				63.05
2	Cryogenic System	2.91	0.31			1.72		4.94
3	Vacuum System	9.784	3.792	0.646				14.222
4	Magnet Power Supplies	9.52	2.14	1.75	0.19	0.05		13.65
5	Instrumentation	0.9	0.6	0.2				1.7
6	Radiation Protection	0.25		0.1				0.35
7	Control System	1	0.6	0.2	0.005	0.005		1.81
8	Experimental devices					4		4
9	Utilities	19.95	2.22	1.38	0.55	1.2		25.3
10	General services	7.2		0.2	0.15	0.2	12	19.75
	Total	108.614	9.812	10.276	0.895	7.175	12	148.772

149MW

8x less luminosity than FCC-ee at ~60% the power

J. Gao

ILC power & comparing efficiency

c.m. energy (GeV)	250 Z factory	500	1000
$L_{0.01,\mathrm{tot}}$ (10^{34} cm^{-2}s^{-1})	0.5	1.05	2.1
P_{wall} (MW)	129	163	$\sim$300

35x less luminosity than FCC-ee-Z at ½ the power

collider luminosity revisited

$$L \approx n_{IP} \frac{f_{coll} N^2}{4\pi\sigma_x\sigma_y} \approx \frac{1}{4\pi} \frac{P_{wall}}{E_{beam}} N\eta \frac{\Delta E_{beam}}{IP} \frac{1}{\sigma_x\sigma_y}$$

FCC-ee:

- higher bunch charge *N* (FCC-ee ~2.5x ILC charge / bunch)
- several IPs (n_{IP}=2 or 4)
- 3-4 times higher wall-plug power to beam efficiency η
- ΔE_{beam}/IP ~200 (instead of 1)

→ total factor 2.5x2(4)x200x3~3000-6000

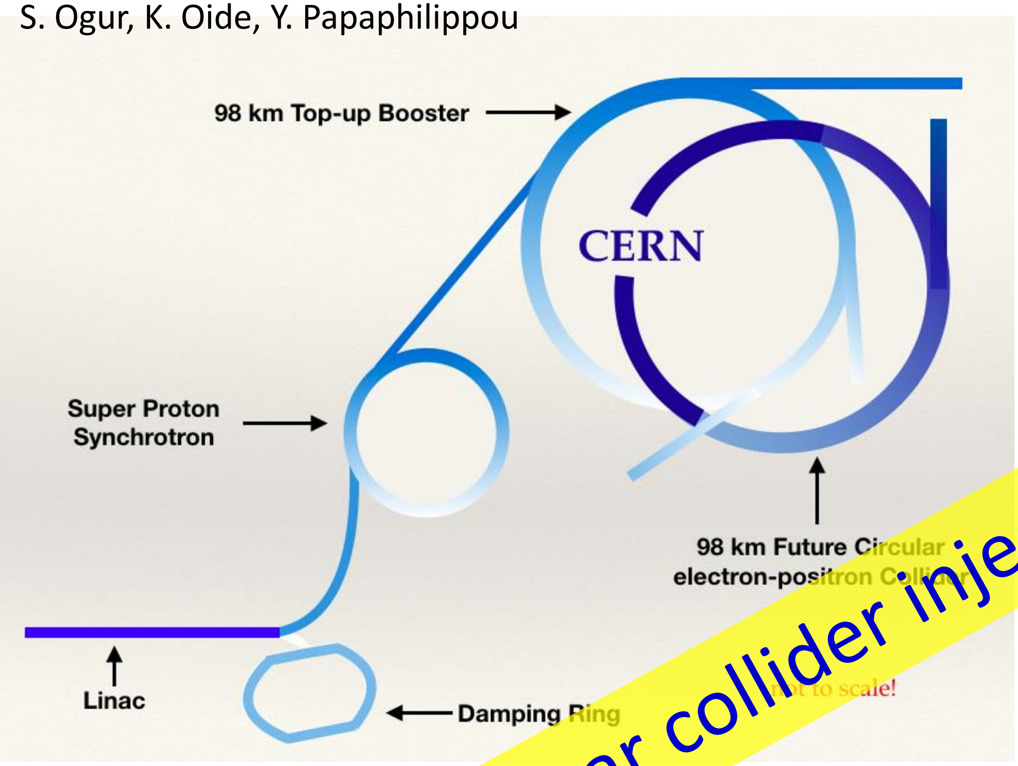
ILC:

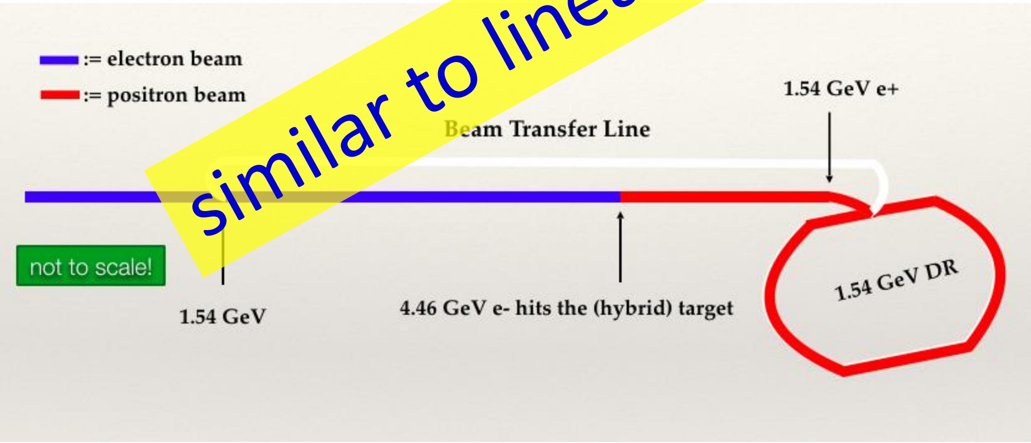
- ~150x smaller IP spot area $\sigma_x\sigma_y$ (smaller emittances & β^*'s)

→ for equal wall plug power *FCC-ee-H* has ~20x times more luminosity than *ILC-H*

FCC-ee injector layout

S. Ogur, K. Oide, Y. Papaphilippou





similar to linear collider injector but simpler

SLC/SuperKEKB-like 6 GeV linac accelerating; **1** or **2** bunches with repetition rate of **100-200 Hz**

same linac used for e+ production @ **4.46 GeV** e+ beam emittances reduced in DR @ **1.54 GeV**

injection @ **6 GeV** into of Pre-Booster Ring (SPS or new ring) and acceleration to 20 GeV

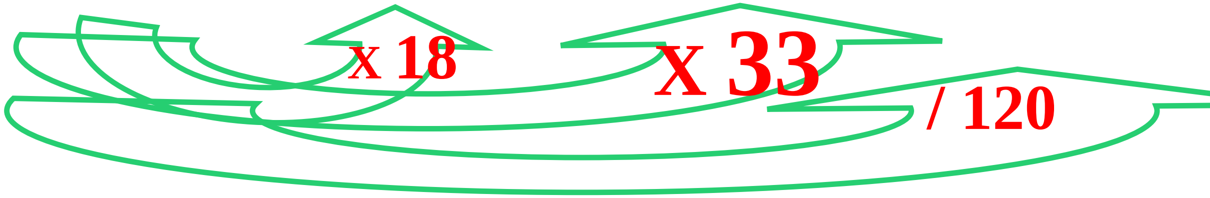
injection to main Booster @ **20 GeV and interleaved** filling of e+/e- (below **20 min** for full filling) and continuous top-up

CEPC: 10 GeV linac, no prebooster

e^+ source – rate requirements

	S-KEKB	SLC	CLIC (3 TeV)	ILC (*H*)	FCC-ee (*H*)
e^+ / second	**2.5×10^{12}**	**6×10^{12}**	**110×10^{12}**	**200×10^{12}**	**0.05×10^{12}**

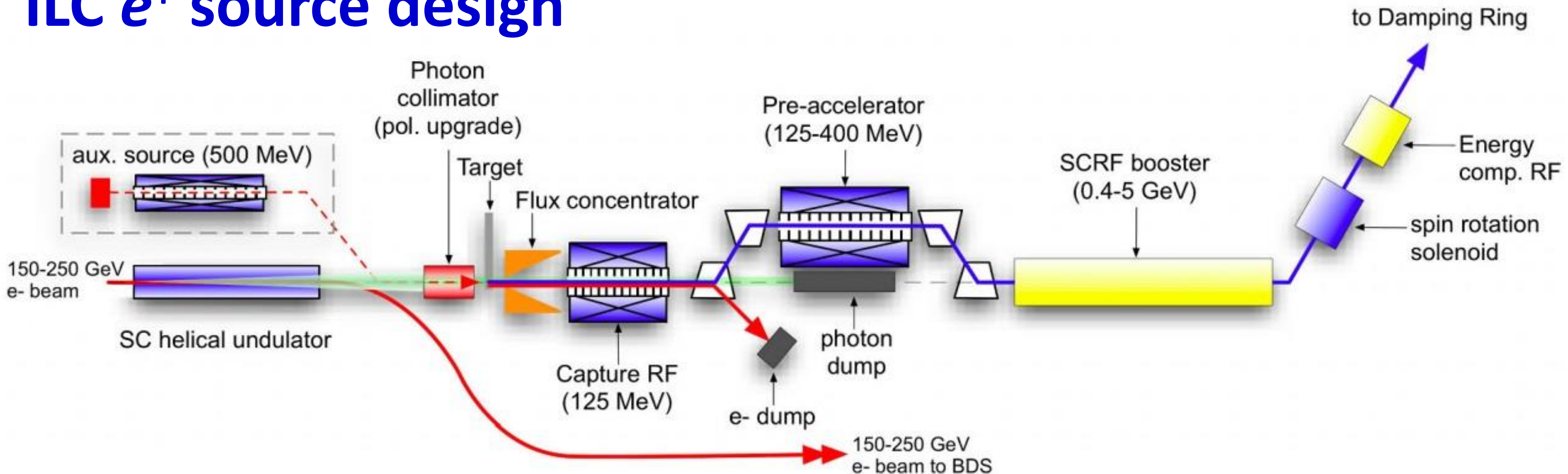
L. Rinolfi



efficiency of e^+ usage: **5×10^{-5} b^{-1}/e^+** **3 b^{-1}/e^+**

factor 60000

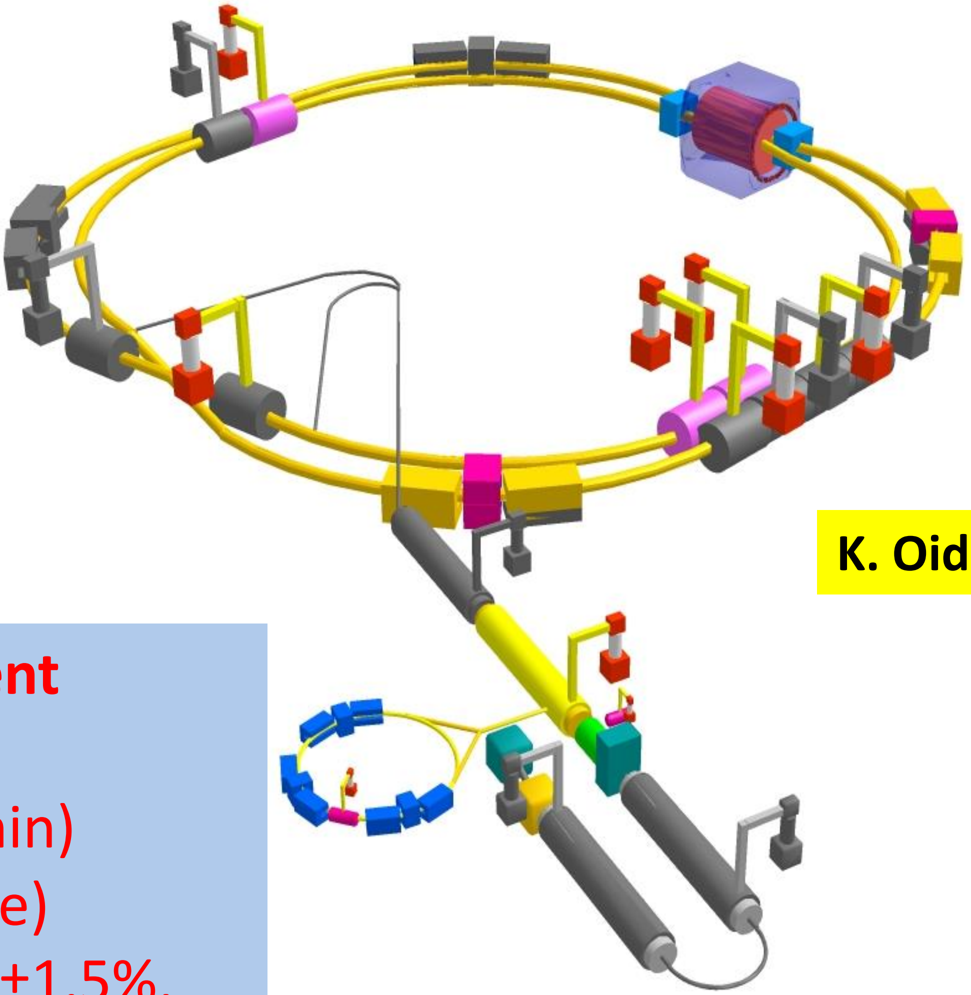
ILC e^+ source design



ILC e+ source has no precedent; its performance can be verified only after ILC construction (needs >100 GeV e^- beam)

SuperKEKB = *FCC-ee* demonstrator

beam commissioning started in 2016



K. Oide et al.

top up injection at high current
β_y^* =300 μm (FCC-ee: 2 mm)
lifetime 5 min (FCC-ee: ≥60 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* crab waist)

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

is history repeating itself…?

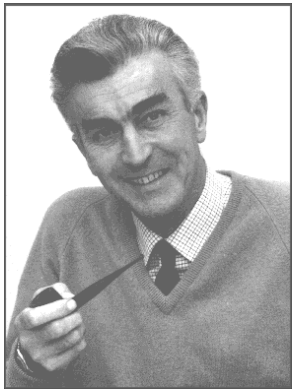
When **Lady Margaret Thatcher** visited CERN in 1982, she also asked the then CERN Director-General **Herwig Schopper** ***how big the next tunnel after LEP would be.***

Margaret Thatcher,
British PM 1979-90

Dr. Schopper‘s answer was ***there would be no bigger tunnel at CERN***.

Herwig Schopper
CERN DG 1981-88
built LEP

Lady Thatcher replied that she had „obtained ***exactly the same answer from* Sir John Adams *when the SPS was built“ 10 years earlier***, and therefore she didn‘t believe him.



John Adams
CERN DG 1960-61 & 1971-75
built PS & SPS

maybe the Prime Minister was right!?

Herwig Schopper, private communication, 2013