The Next-Generation Particle Accelerator

"with emphasis on *TLEP* (*FCC-ee*) vs *ILC*"

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CERN, BE Department

IOP April Meeting 2014

ROYAL HOLLOWAY UNIVERSITY OF LONDON

many thanks for Stewart Boogert & Jocelyn Monroe

IOP Institute of Physics

CERN

EuCARD²

XBEAM

FCC hh ee he

http://cern.ch/fcc

TLEP $HZ^0W^-W^+t\bar{t}$

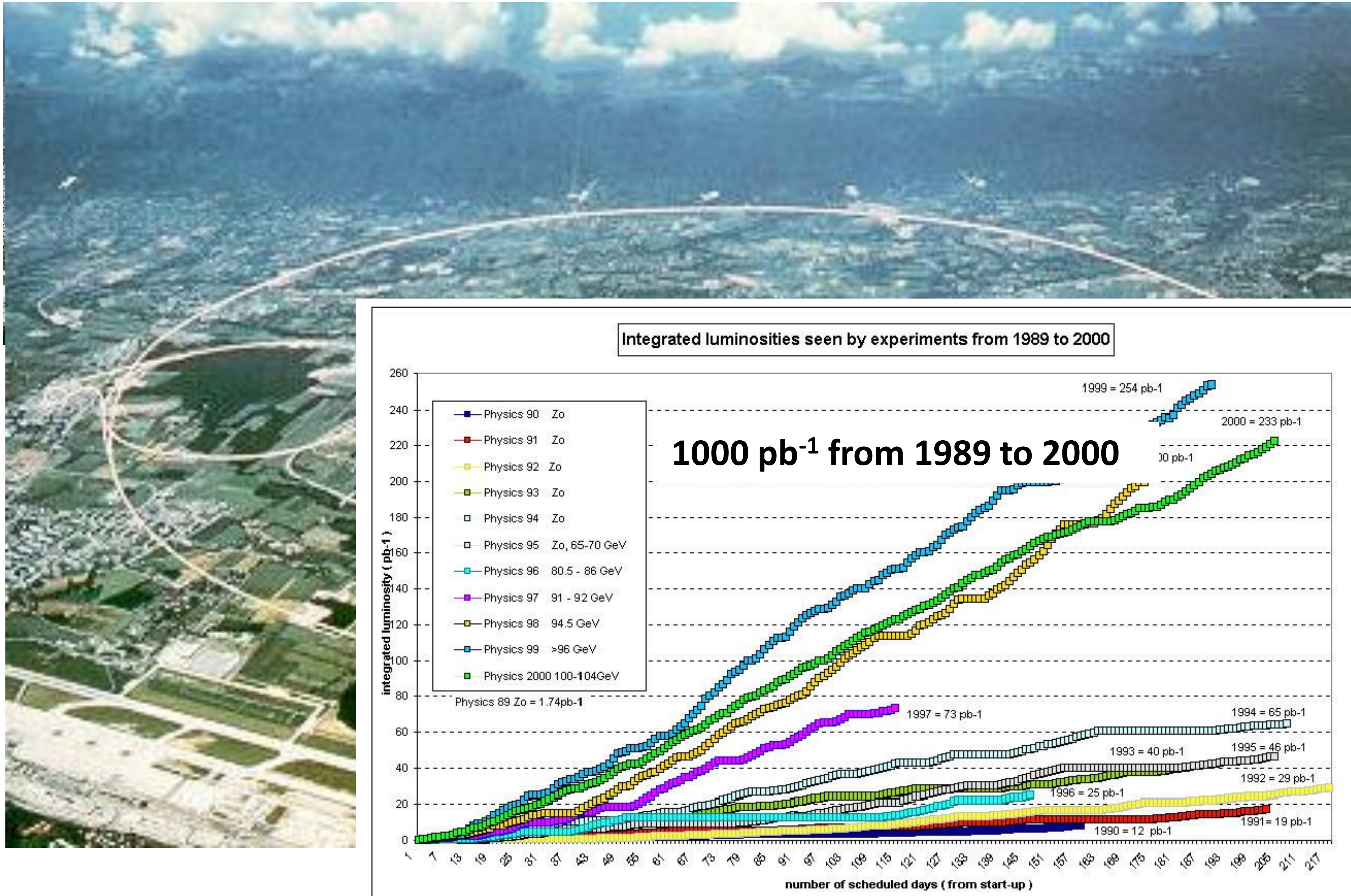
ilc

clic

LHeC

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

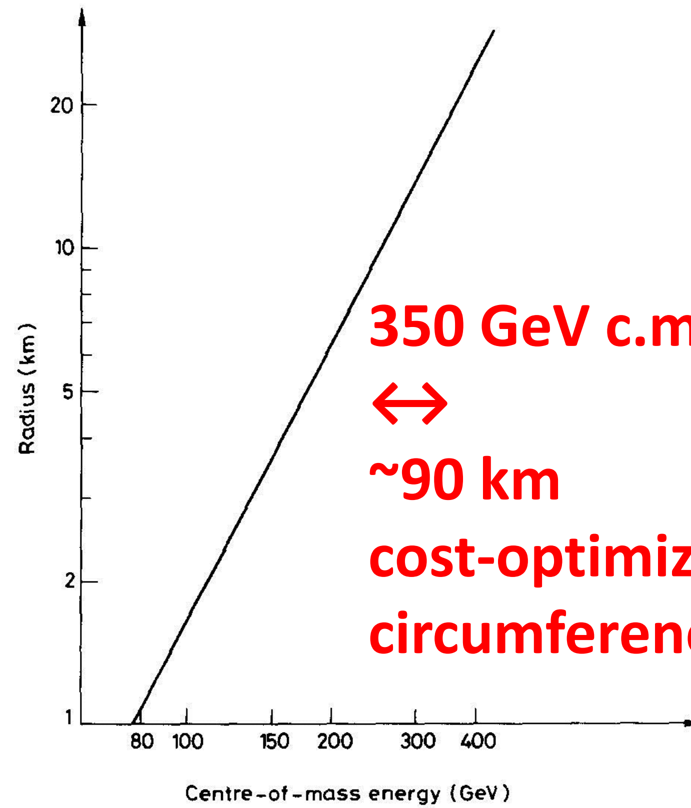
LEP – largest circular e^+e^- collider so far



“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.”

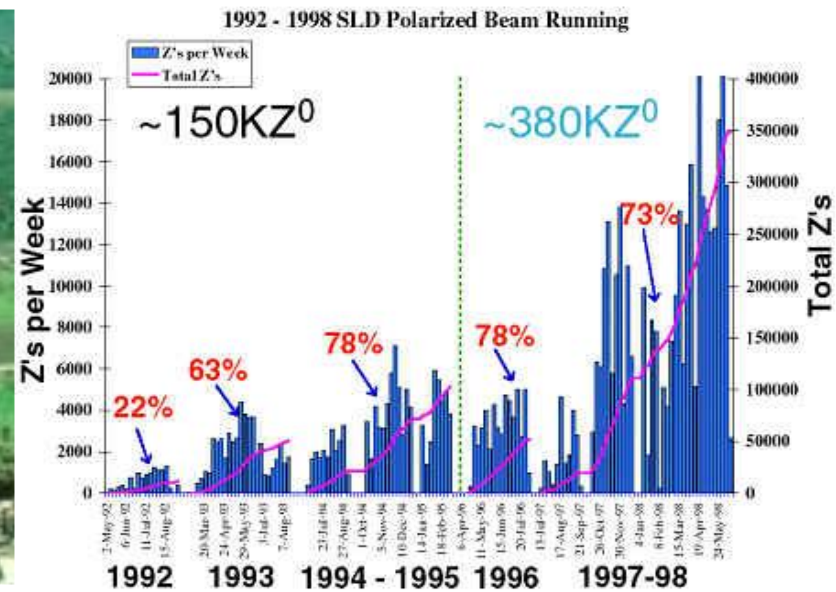
(original LEP proposal, 1976)

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

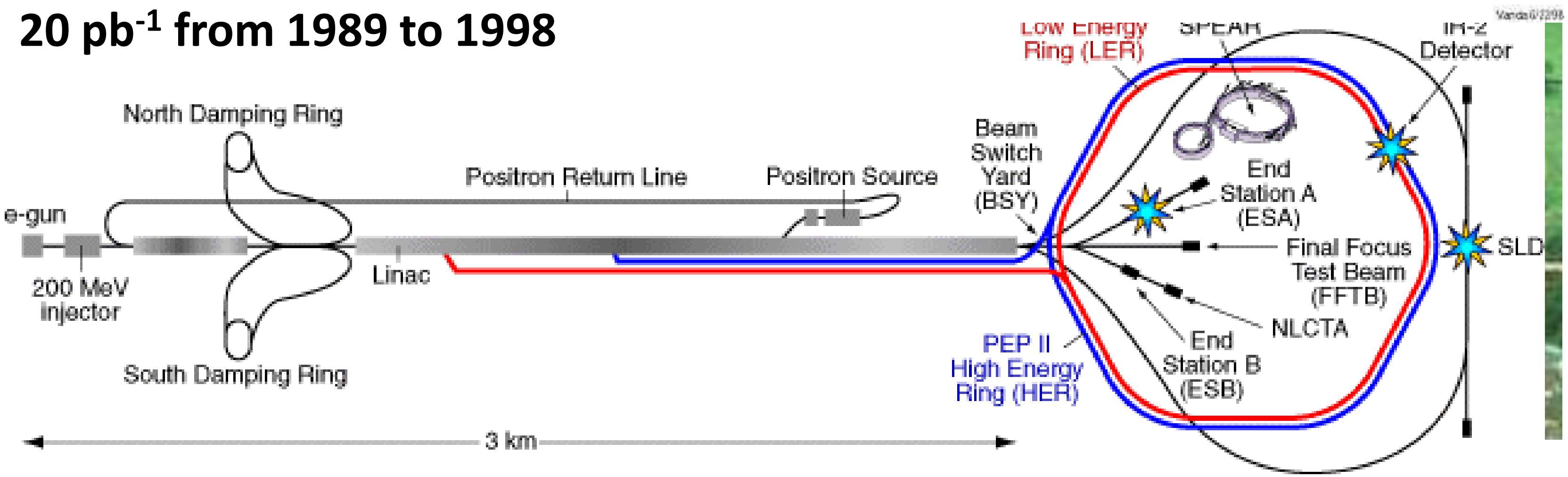


350 GeV c.m. ↔ ~90 km cost-optimized circumference

SLC – the first linear collider

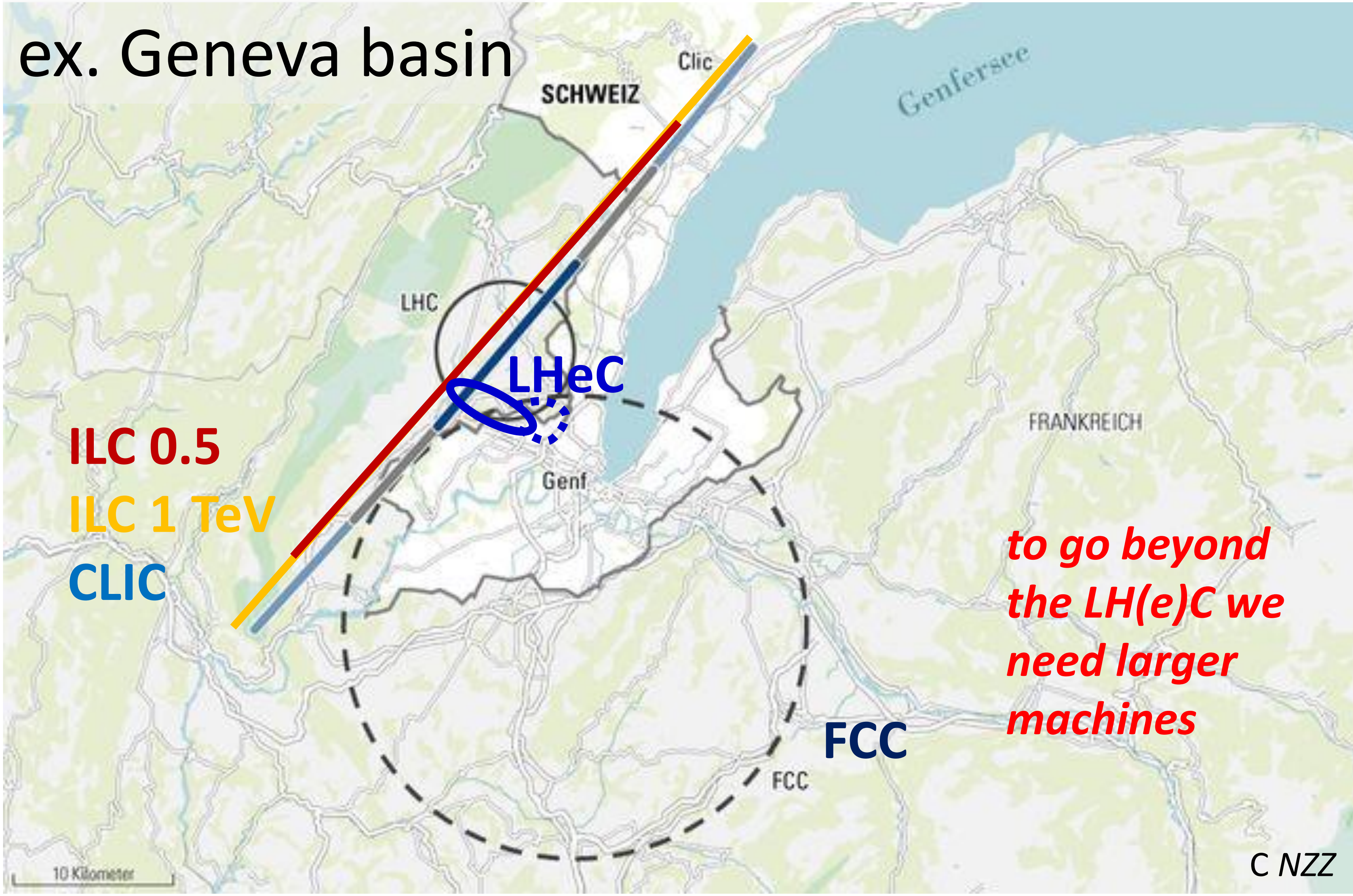


20 pb^{-1} from 1989 to 1998

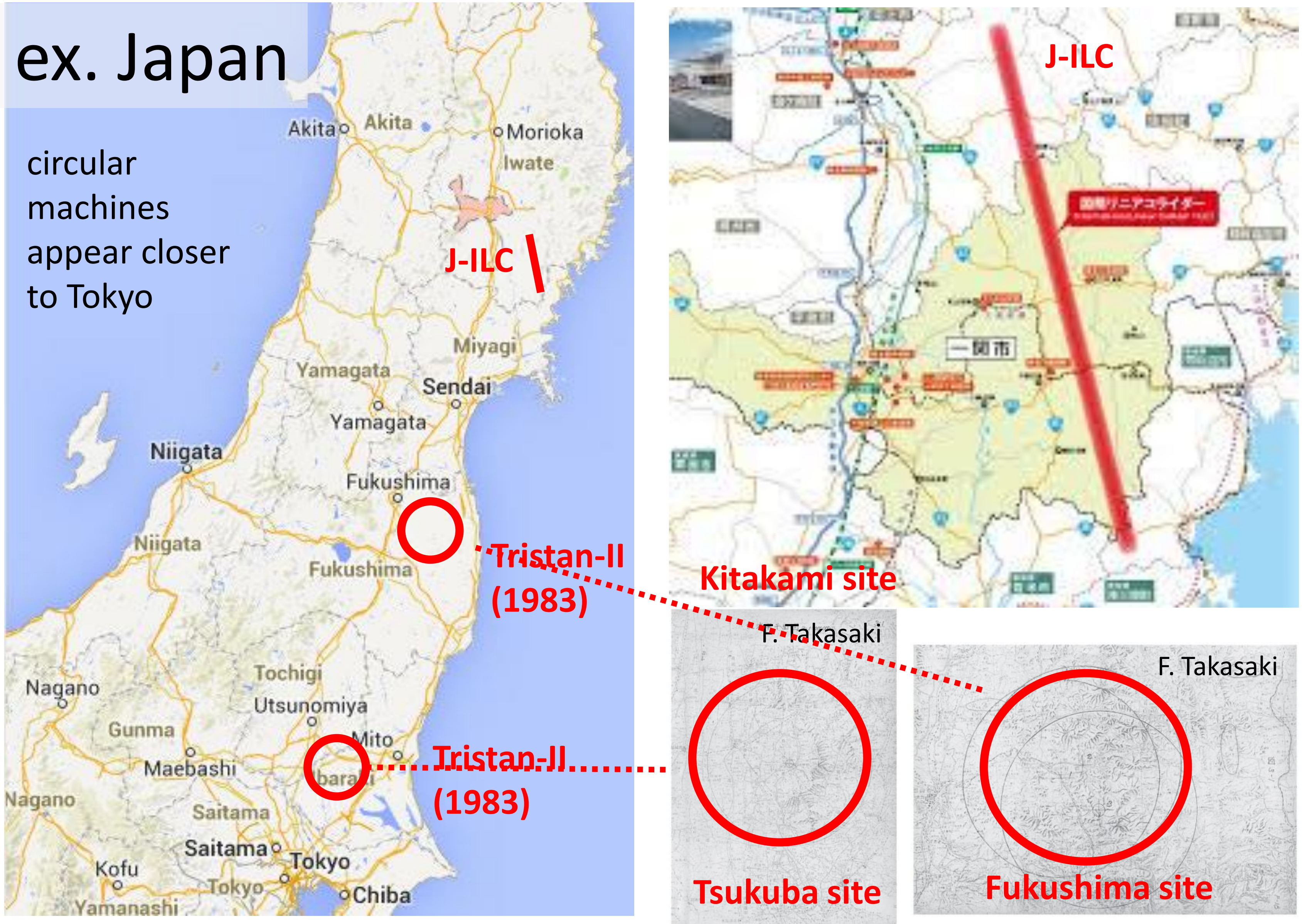


Burton Richter *et al*, “The Stanford Linear Collider”, *11th Int. Conf. on High-Energy Accelerators*, CERN (1980)

proposed linear & circular colliders

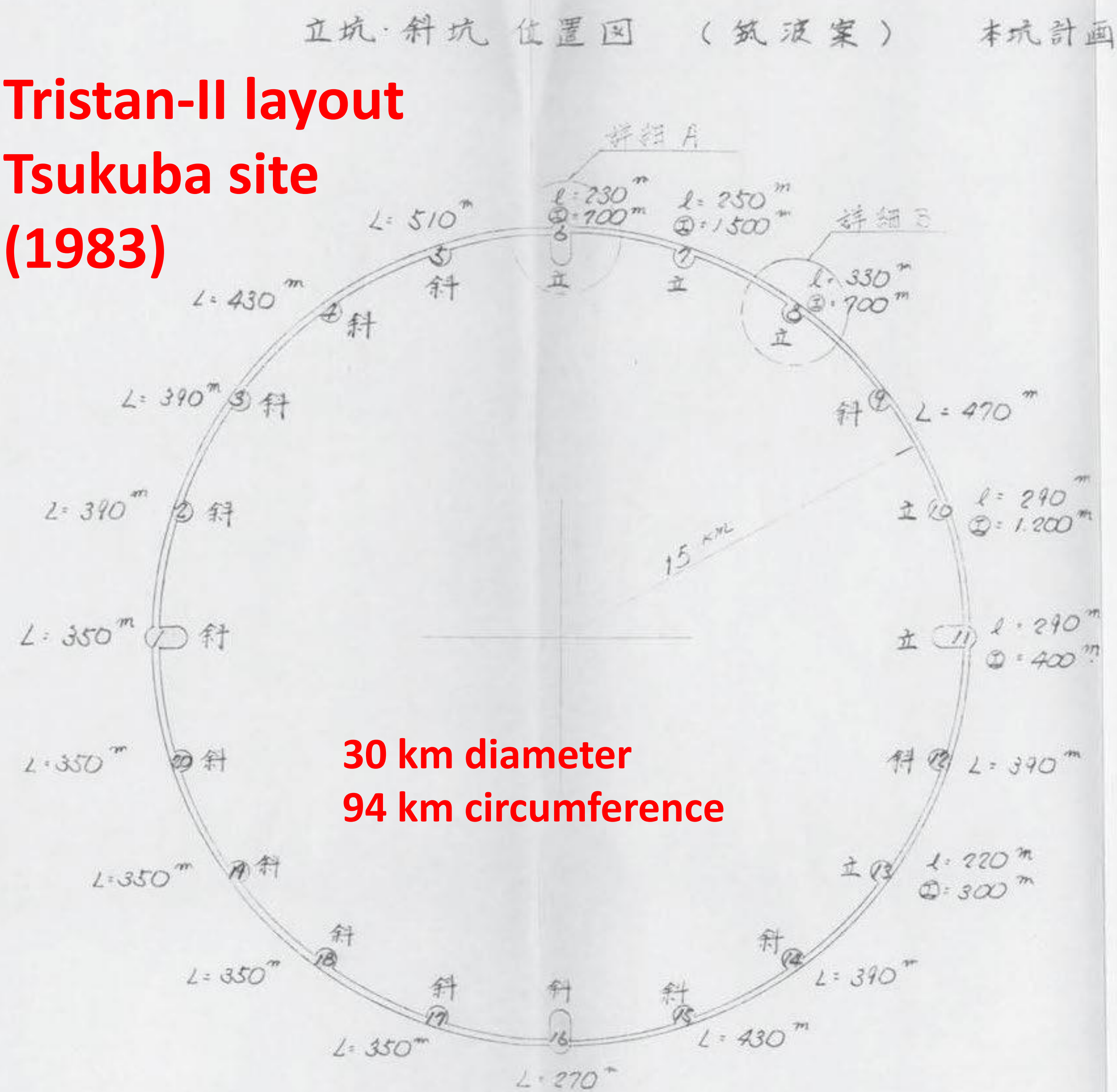


proposed linear & circular colliders



Tristan-II layout
Tsukuba site
(1983)

e⁺e⁻
pp
ep collisions



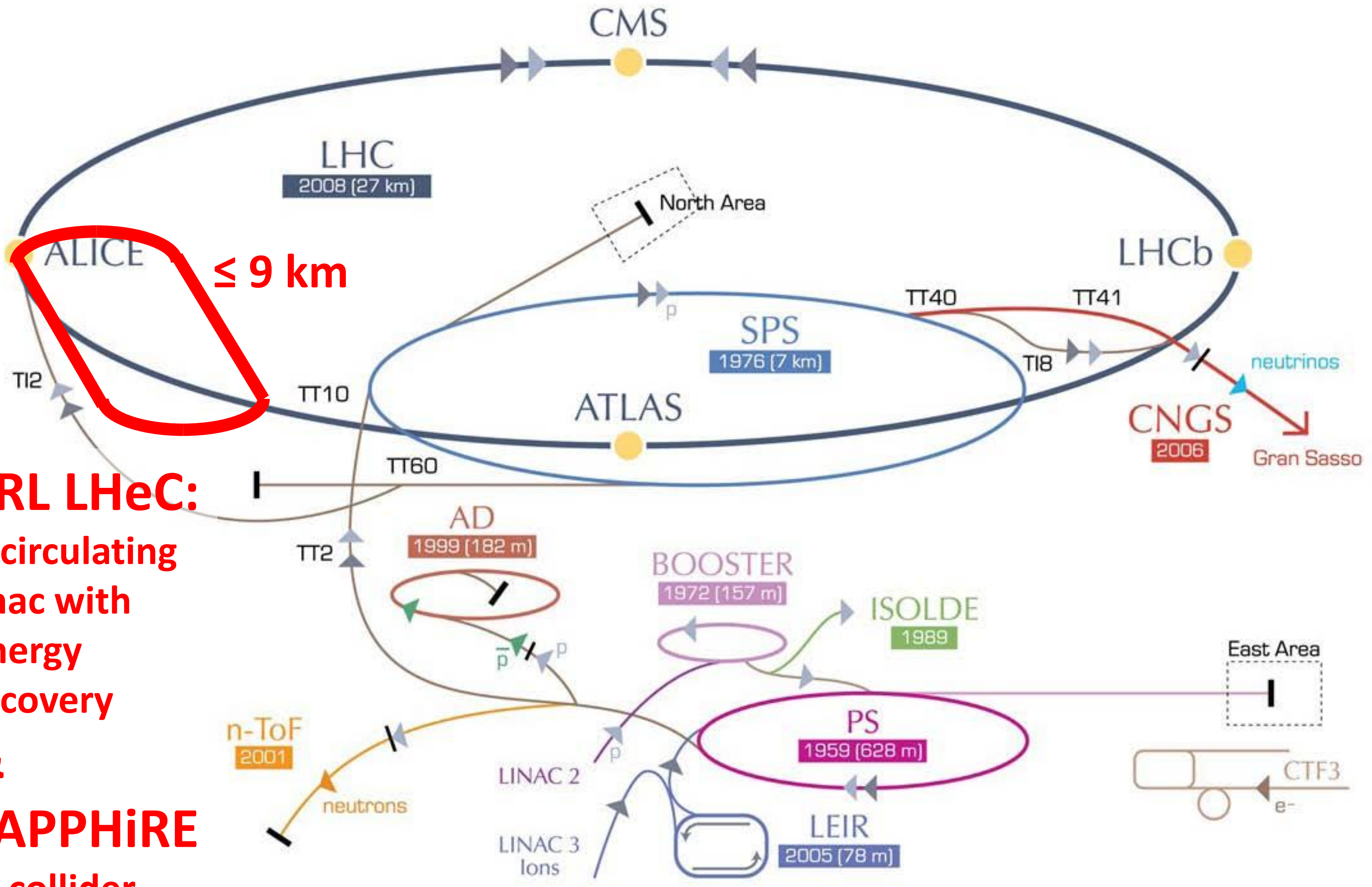
30 km diameter
94 km circumference

F. Takasaki

proposed circular colliders


another proposed circular collider?
ex. Ascot/UK
2.8 km
photo courtesy V. Shiltsev

Large Hadron electron Collider (LHeC)



ERL LHeC:

recirculating linac with energy recovery

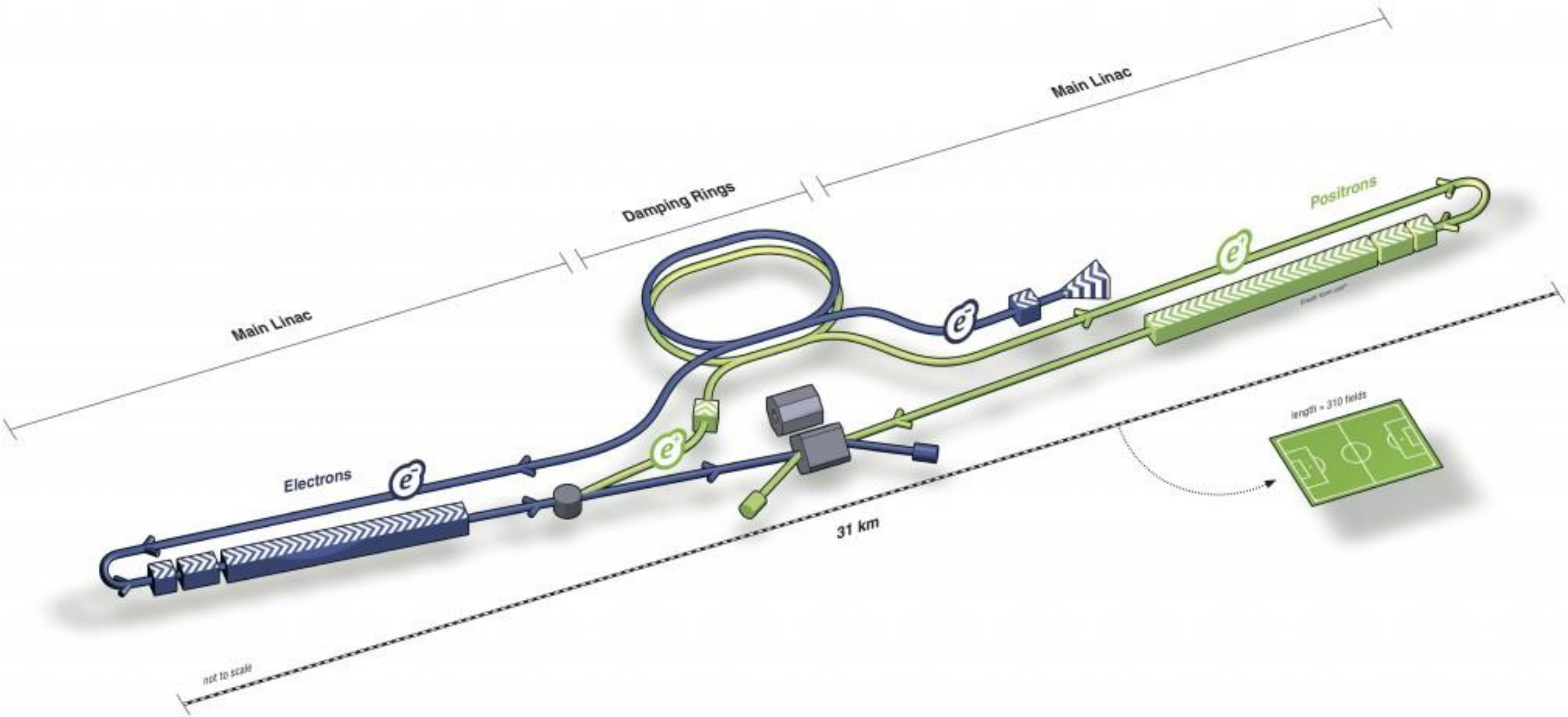
&

SAPPHiRE

$\gamma\gamma$ collider

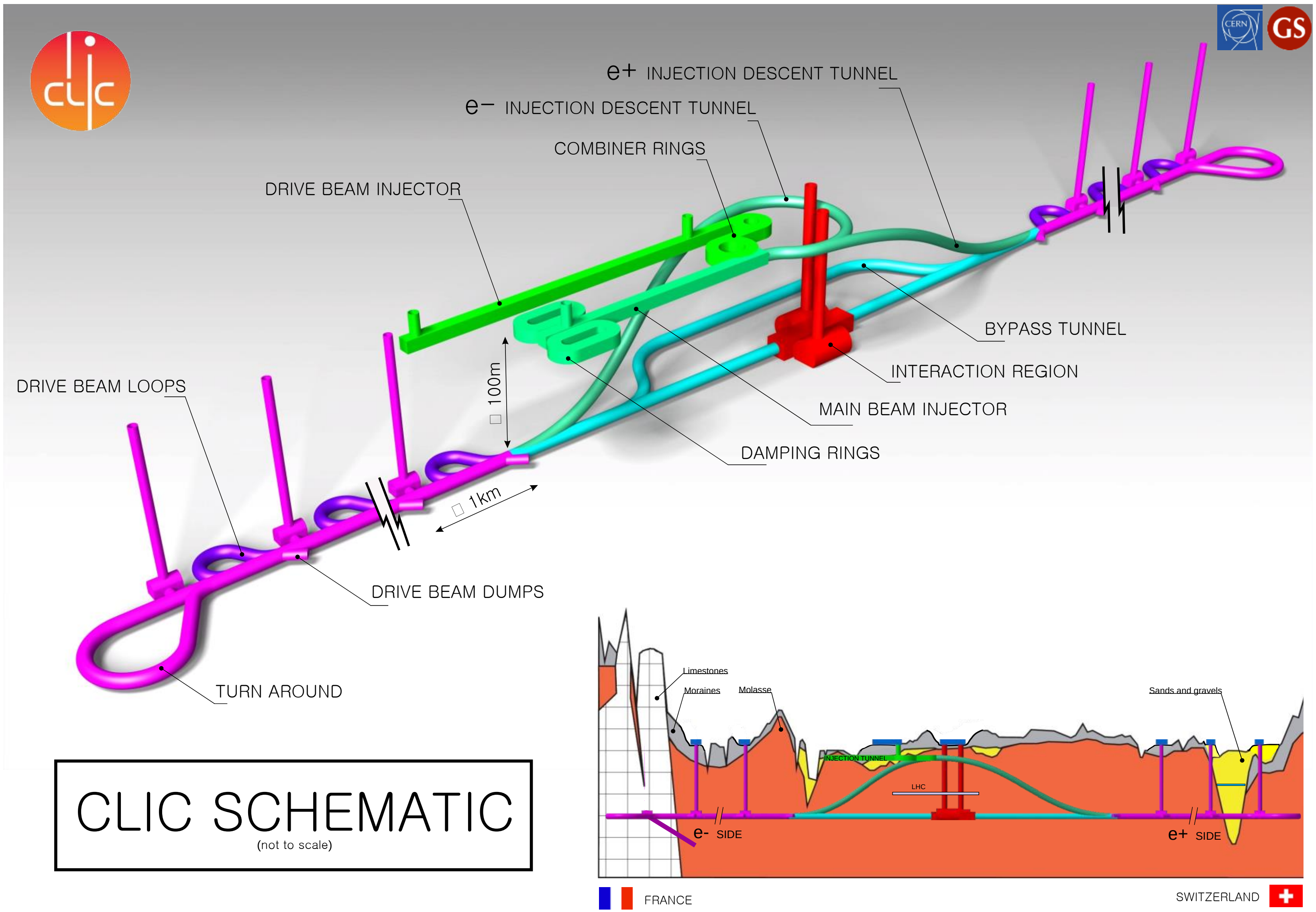
ILC

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



CLIC

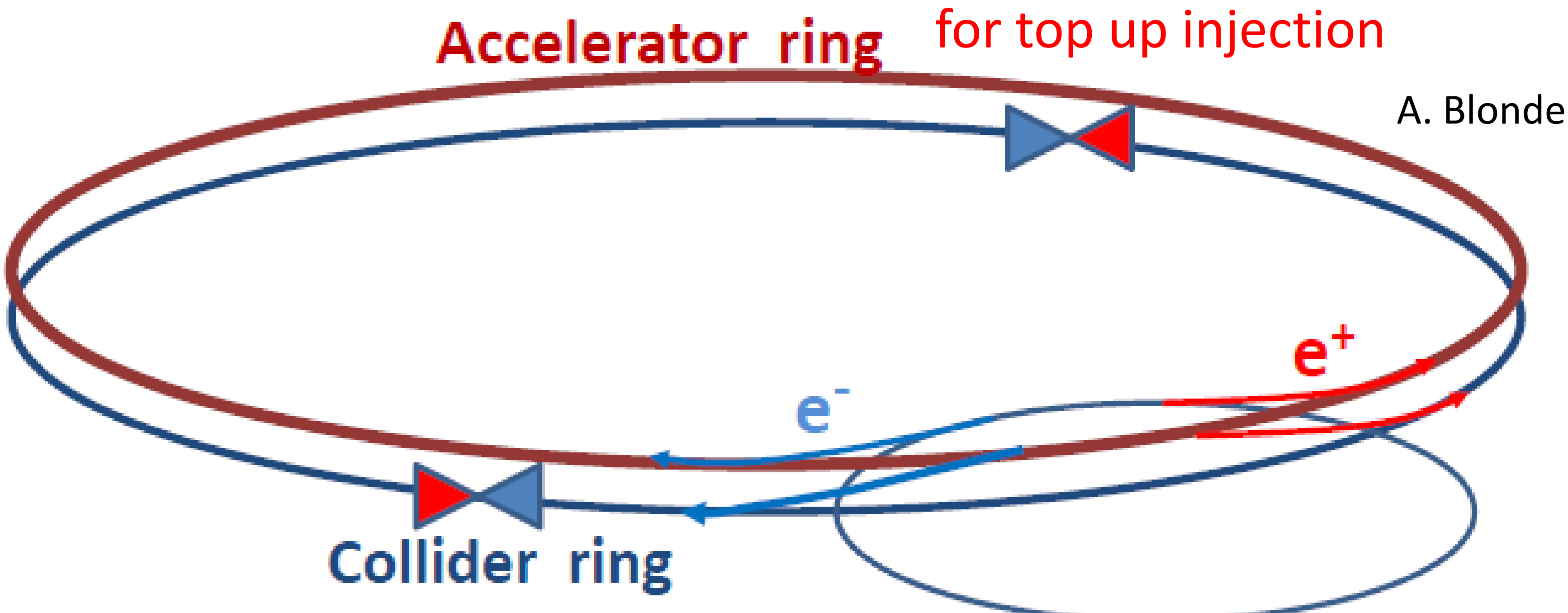
total length (main linac) ~11 (500 GeV) - 48 km (3 TeV)



TLEP / FCC-ee

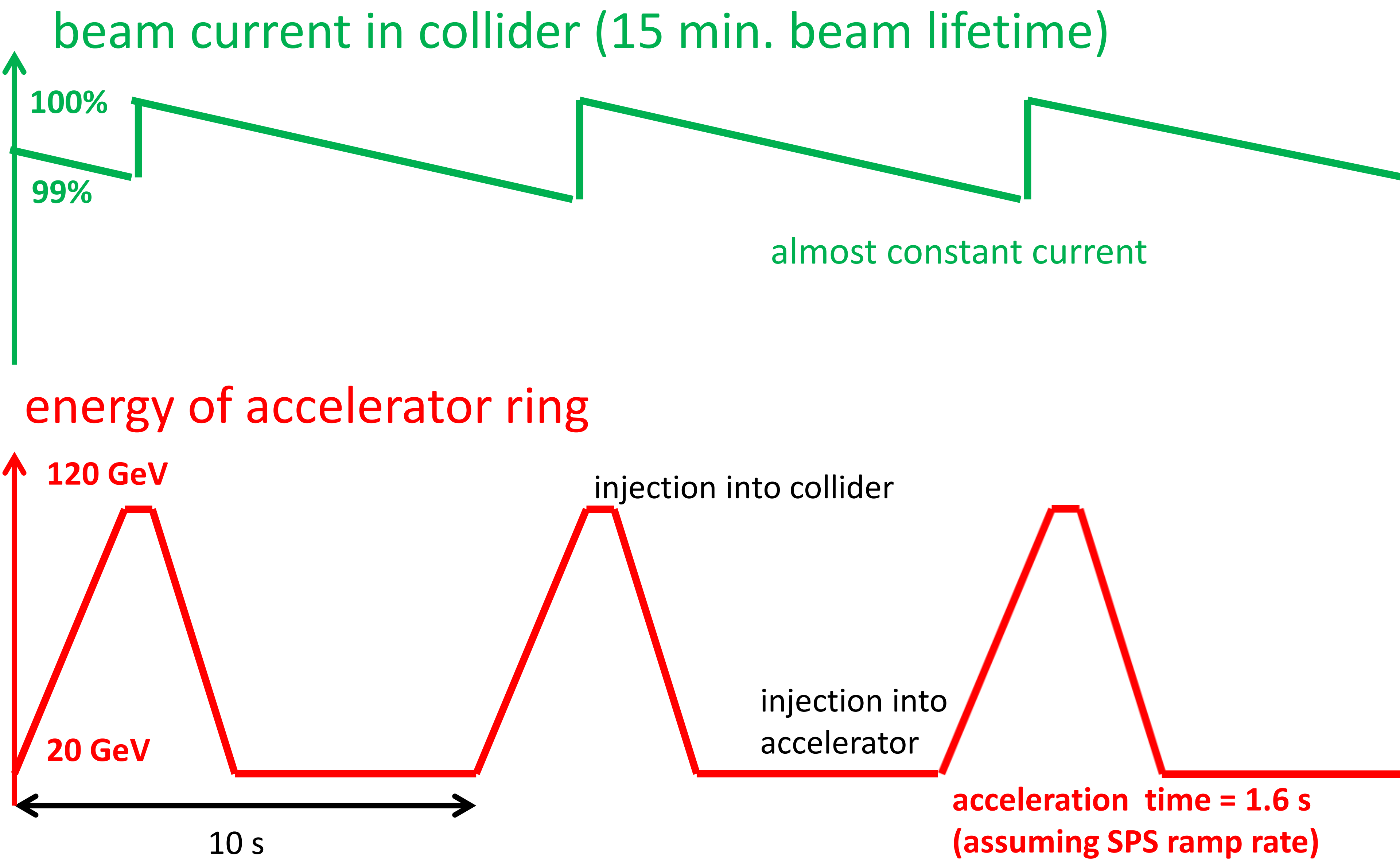
circumference 80-100 km

- maximum e^+e^- cm energy 350-500 GeV
- *pp* collision energy in same tunnel 80-125 TeV

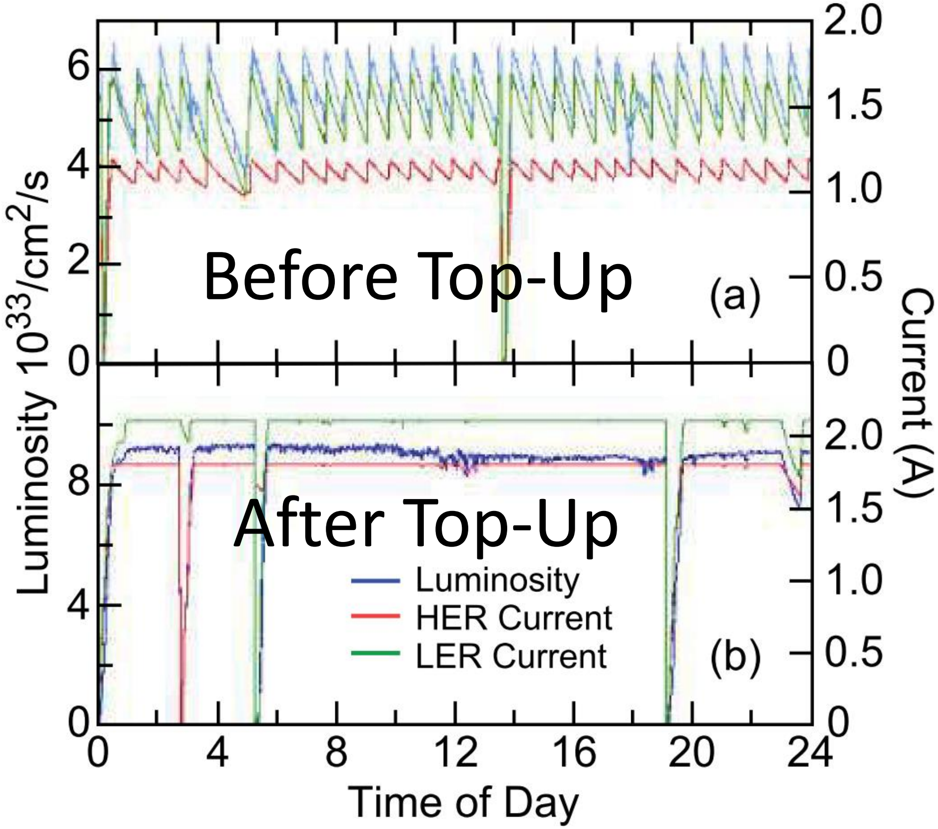


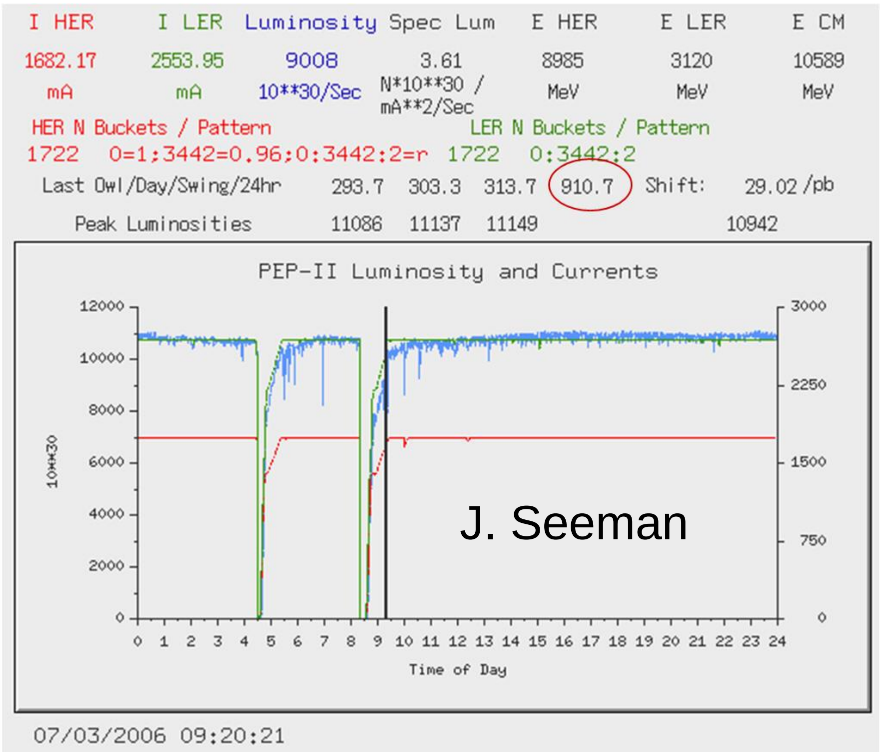
short beam lifetime ($\sim\tau_{LEP2}/40$) due to high luminosity **supported by top-up injection** (used at KEKB, PEP-II, SLS,…); top-up **also avoids ramping & thermal transients, + eases tuning**

top-up injection: schematic cycle



top-up injection at PEP-II



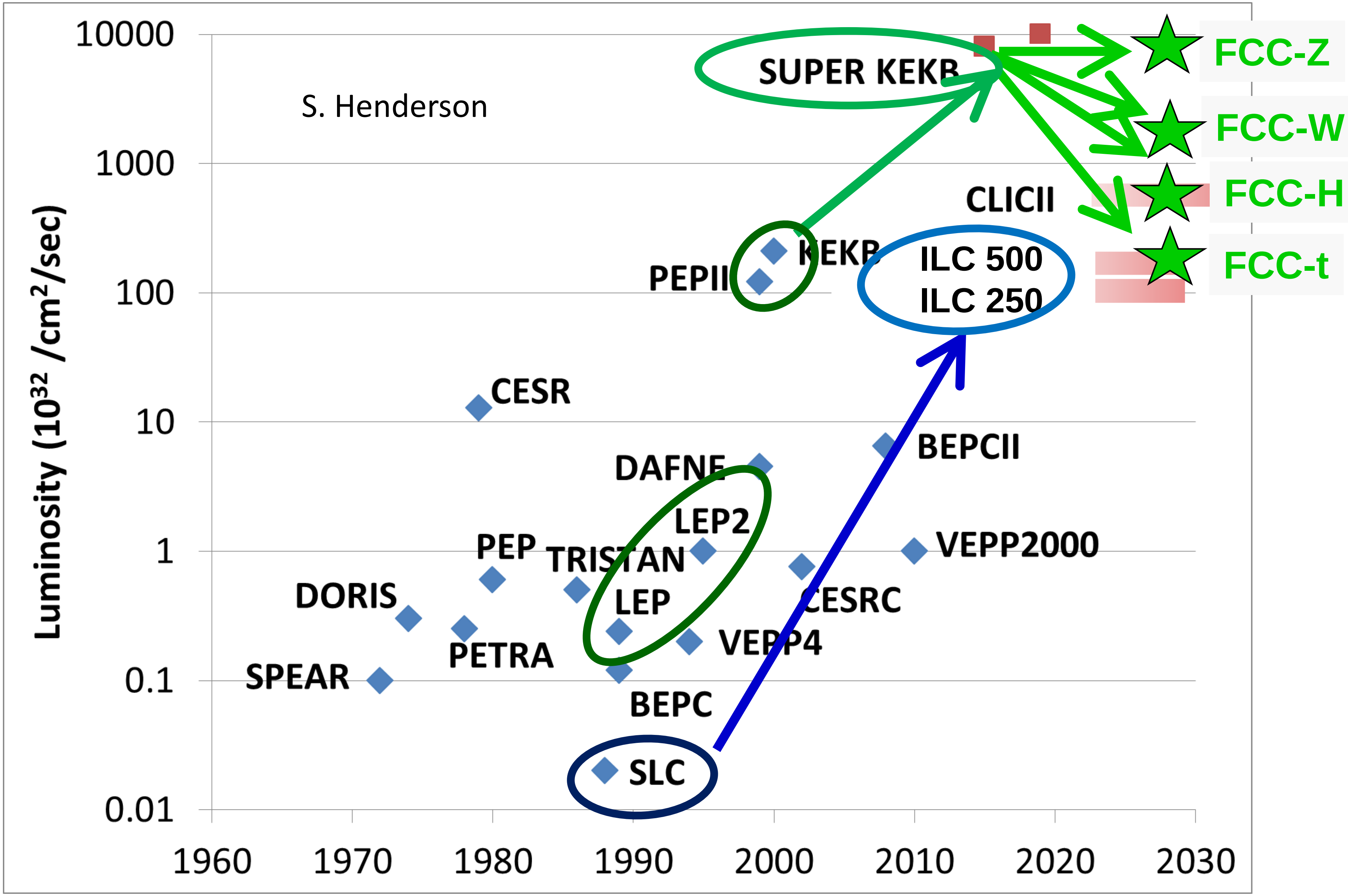


J. Seeman

average luminosity ≈ peak luminosity

similar results from KEKB

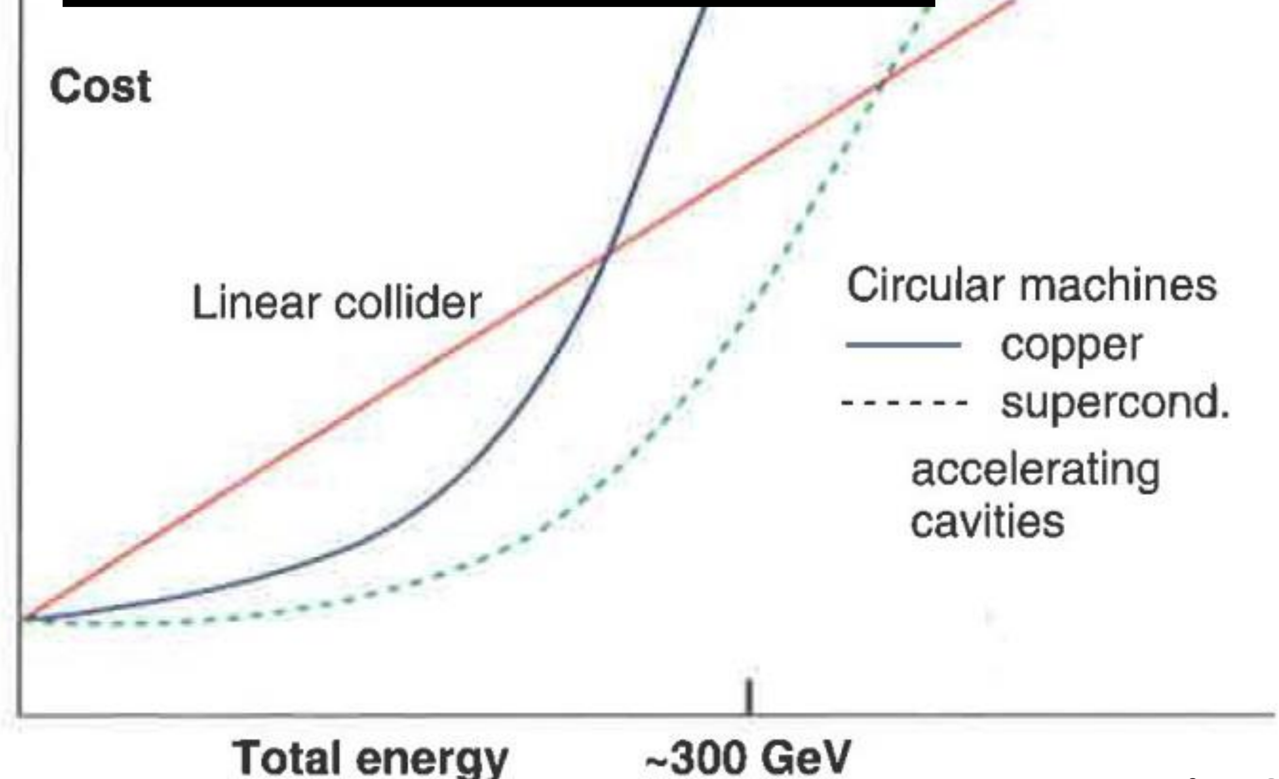
past, future & proposed e^+e^- colliders

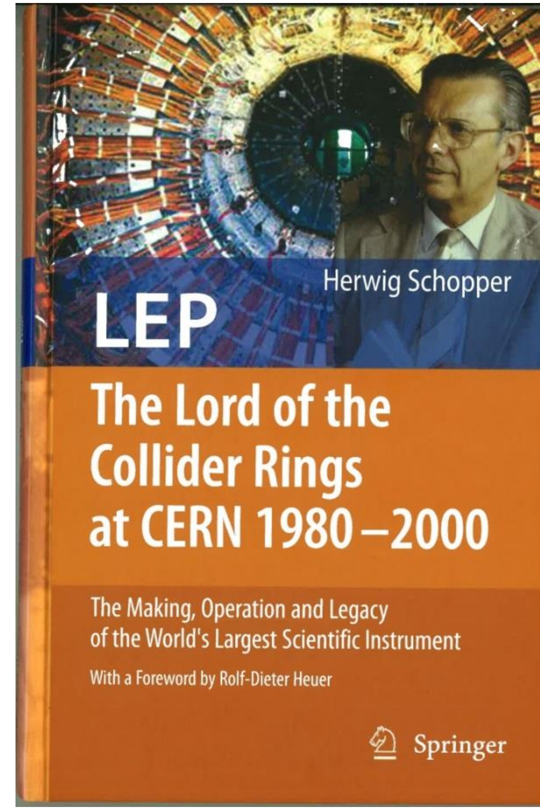


In 1982, when Lady Margaret Thatcher visited CERN, she asked the then CERN Director-General Herwig Schopper *why CERN was building a circular collider rather than a linear one*

argument accepted by the Prime Minister:

<u>cost of construction</u>





up to a cm energy of at least ~350 GeV circular collider with sc RF is cheapest option

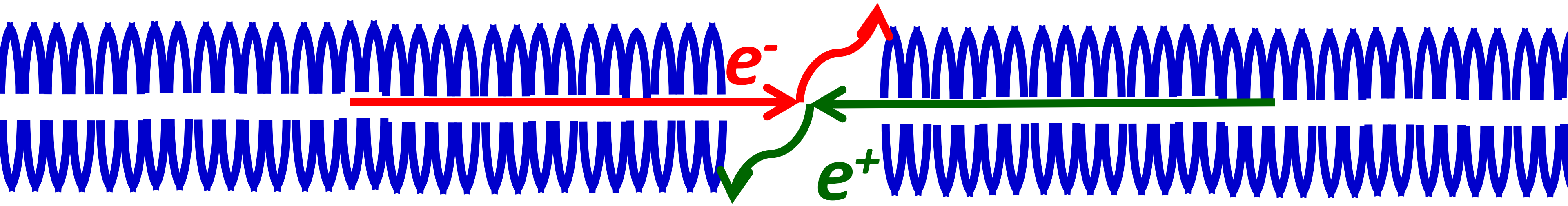
Herwig Schopper, private communication, 2014

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

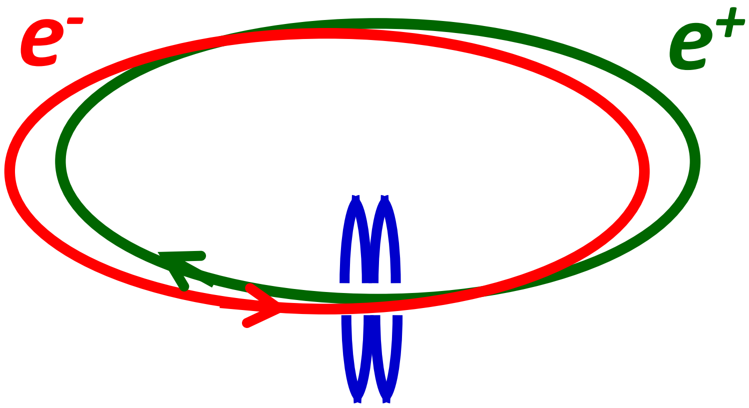
with a foreword by Rolf-Dieter-Heuer

energy provided to beam per collision

ILC: long RF sections w 2 x 125 (2 x 500 GV) voltage



- both beams lost after single collision
- RF must supply full beam energy for each collision

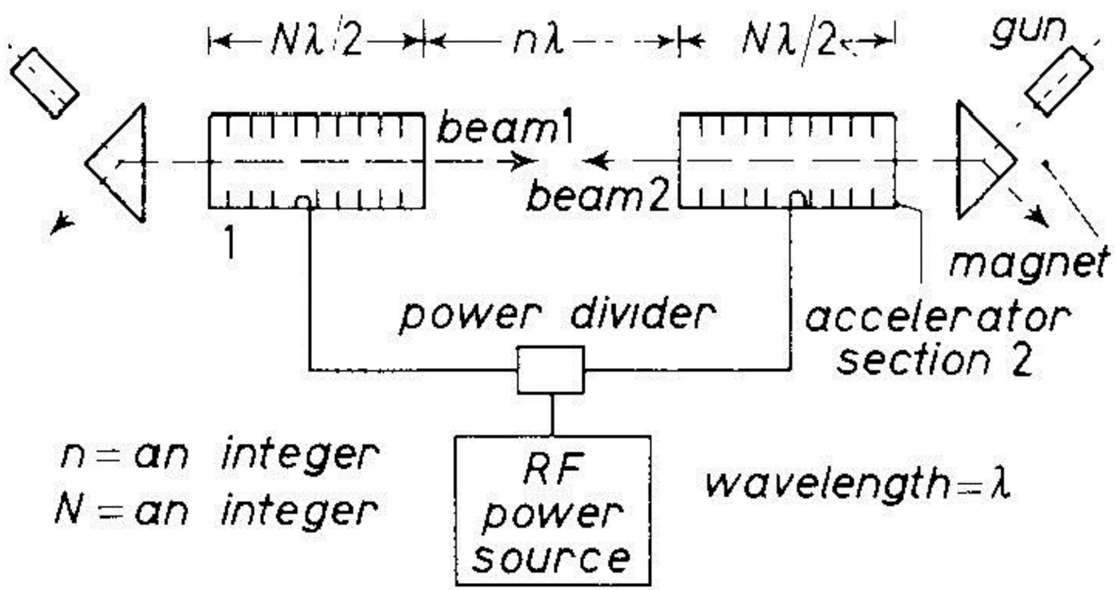


FCC-ee/CepC:

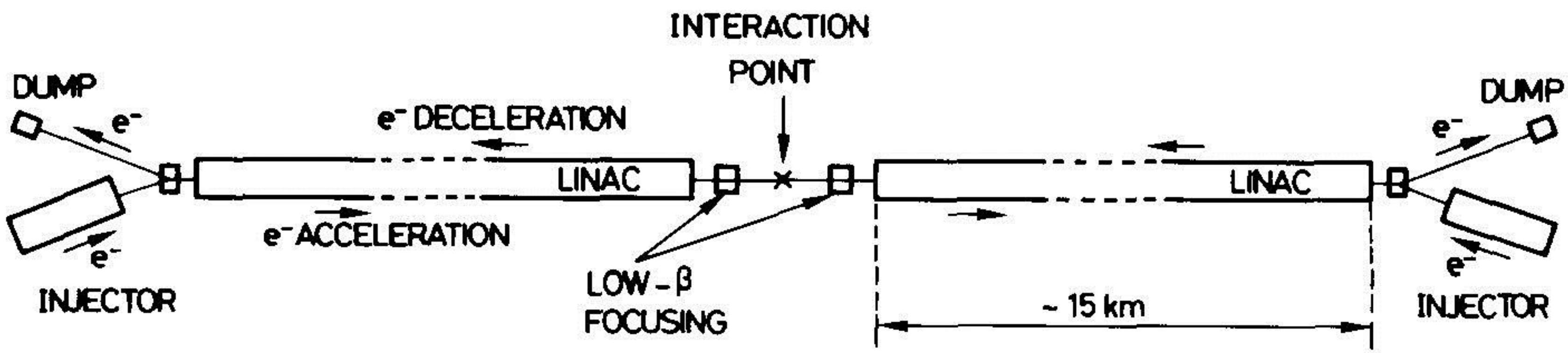
- beams collide many times, e.g. 4x / turn
- RF compensates SR loss (~1% E_{beam} / turn)

difference in #collisions / (beam energy) ~ 300x

early linear-collider proposals recovered beam energy



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



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

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

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

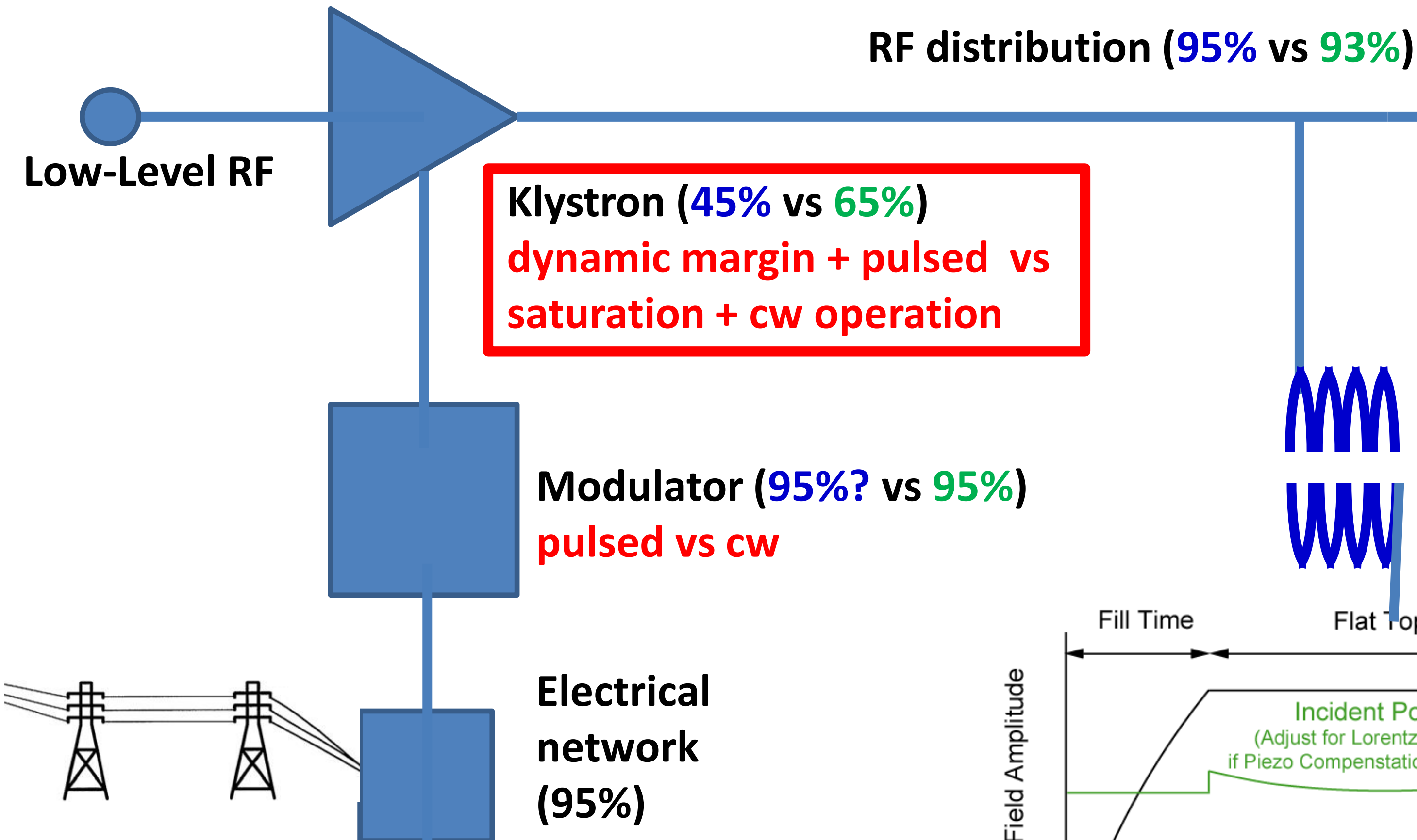
$$P_{cryo} \propto f_{RF} V_{tot} G_{RF} \mathrm{D}/Q_0$$

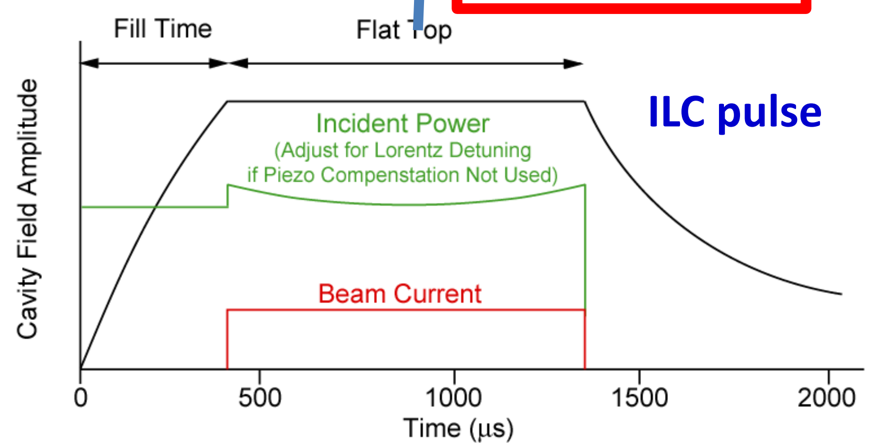
(if SC cavity losses dominated by BCS resistance)

	ILC-H	*FCC-ee-H*
RF voltage V_{tot}	**240 GV**	**6-12 GV**
RF gradient G_{RF}	**31.5 MV/m**	**15-20 MV/m**
effective RF length	**8 km**	**<800 m**
RF frequency f_{RF}	1.3 GHz	400 MHz (?)
Q_0: unloaded cavity Q	10^{10}	$2\text{-}4 \times 10^{10}$ (higher at lower G_{RF})
D: RF duty factor	**0.75% (pulsed)**	**100% (cw)**
total cryo power	**16 MW**	**10-25 MW** (FCC-H & t)

total cryo power similar for both projects

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

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)

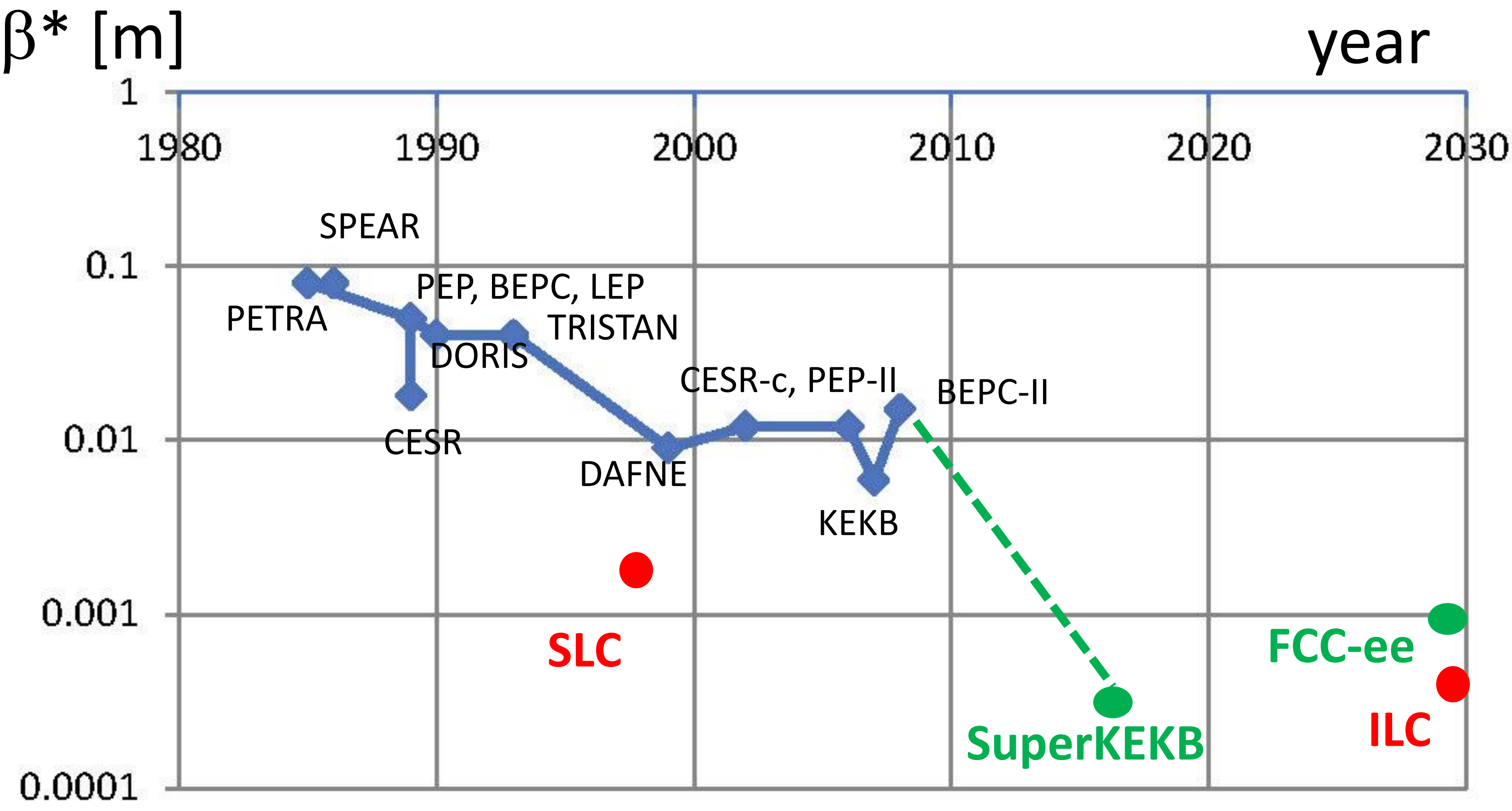
FCC-ee:

1. $\varepsilon \propto E^2\theta_{dip}{}^3$ (synchr. rad.)

2. beam-beam tune shift

smaller emittances needed for linear colliders

vertical β^* history

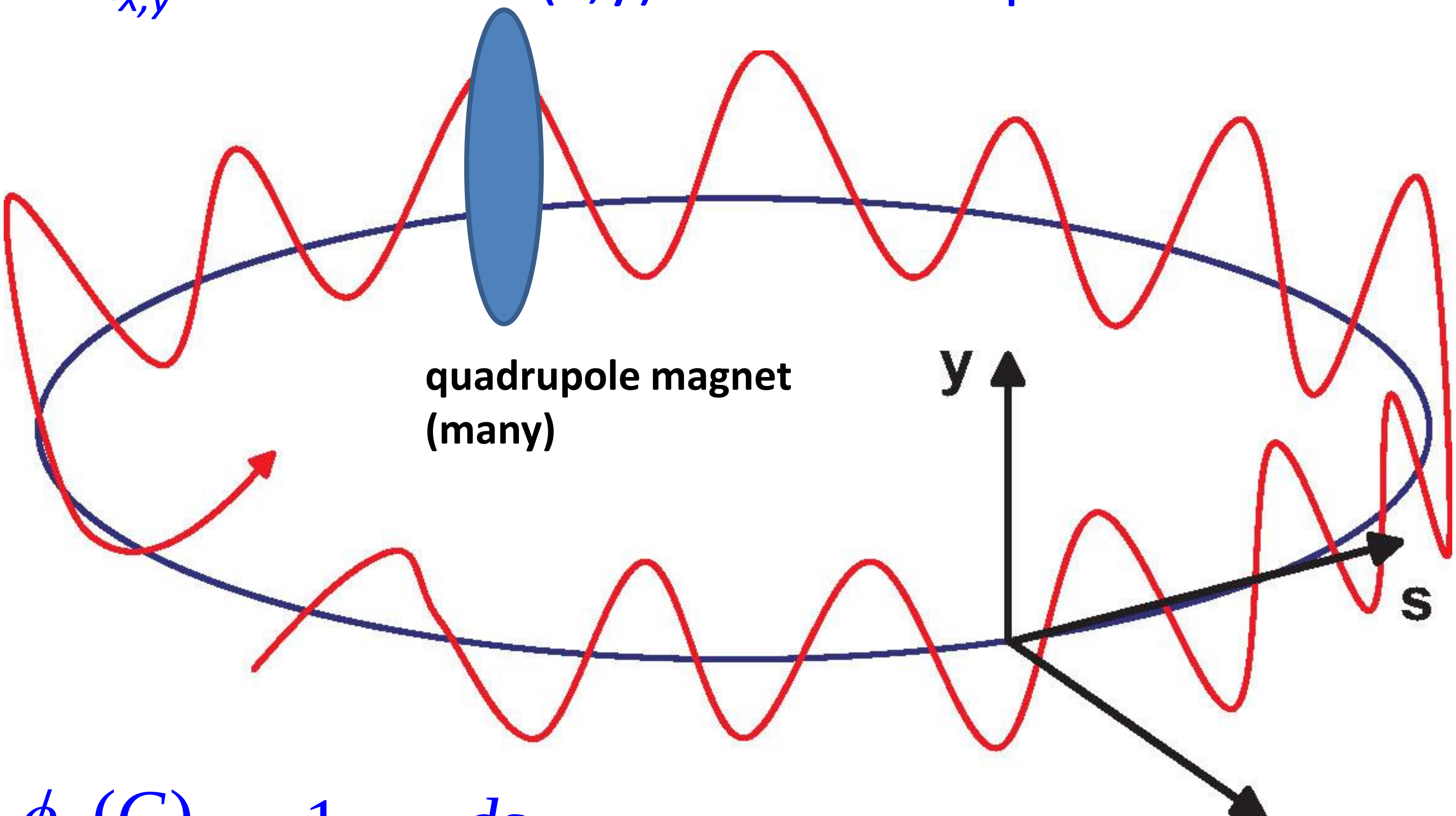


$$\sigma^* = \sqrt{\varepsilon \beta^*}$$

betatron oscillation & tune

schematic of betatron oscillation around storage ring

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

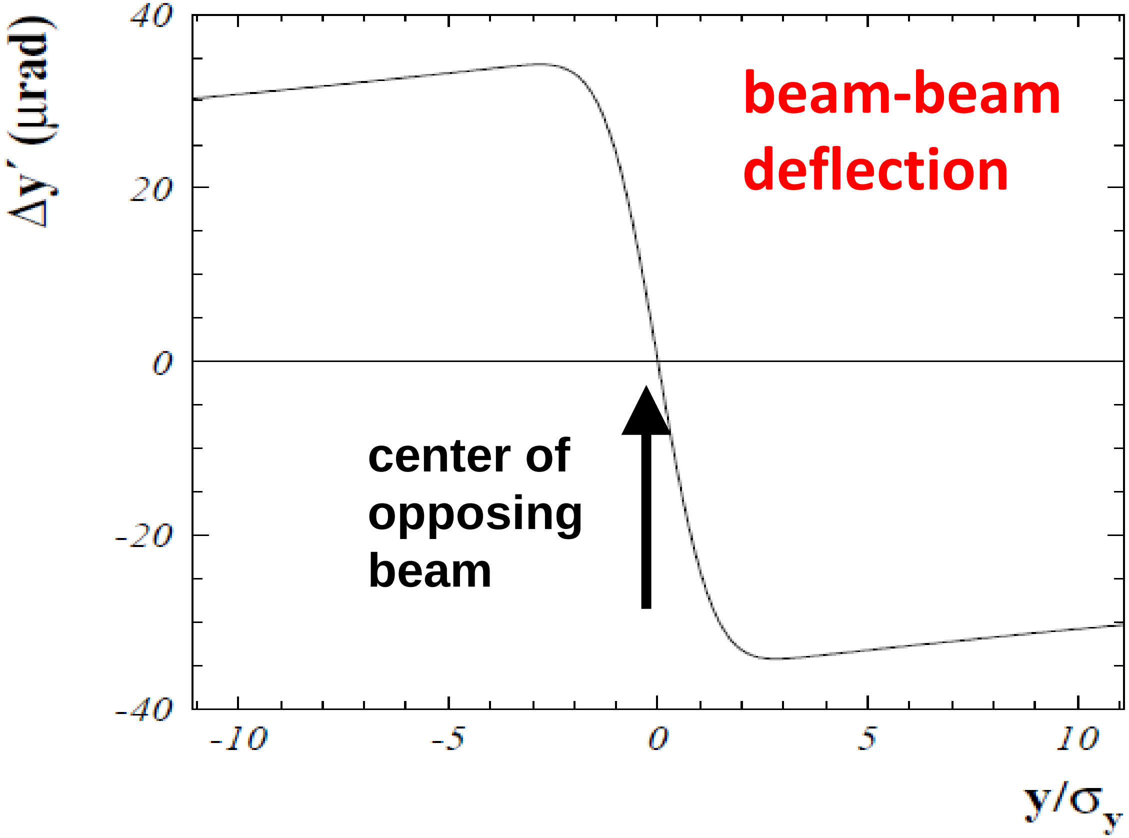


$$Q = \frac{\phi_\beta(C)}{2\pi} = \frac{1}{2\pi}\oint_C \frac{ds}{\beta(s)}$$

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

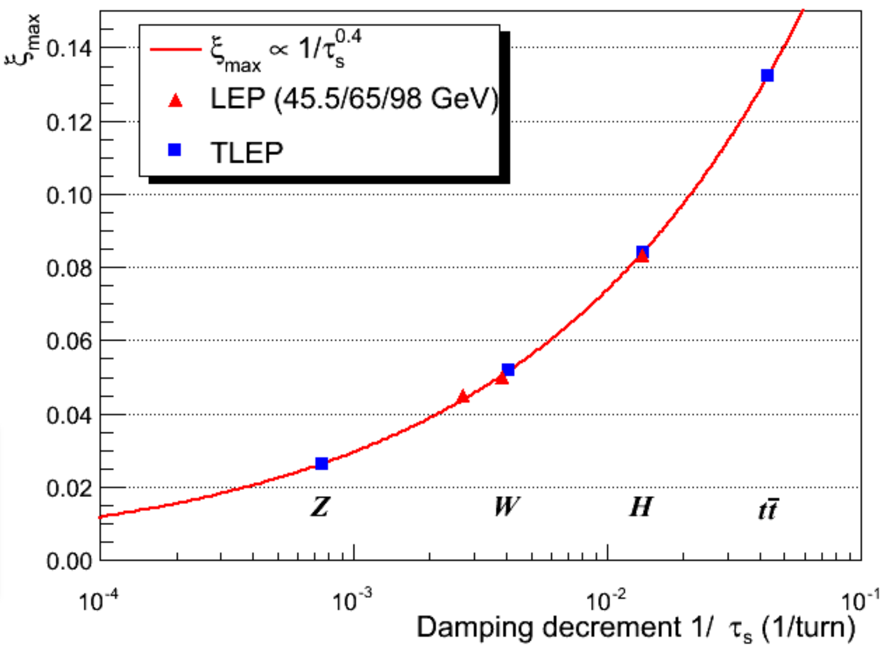
tune shift limits empirically scaled from LEP data (also 4 IPs like FCC-ee/TLEP)

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

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

R. Assmann & K. Cornelis, EPAC2000

J. Wenninger



in reasonable agreement with simulations

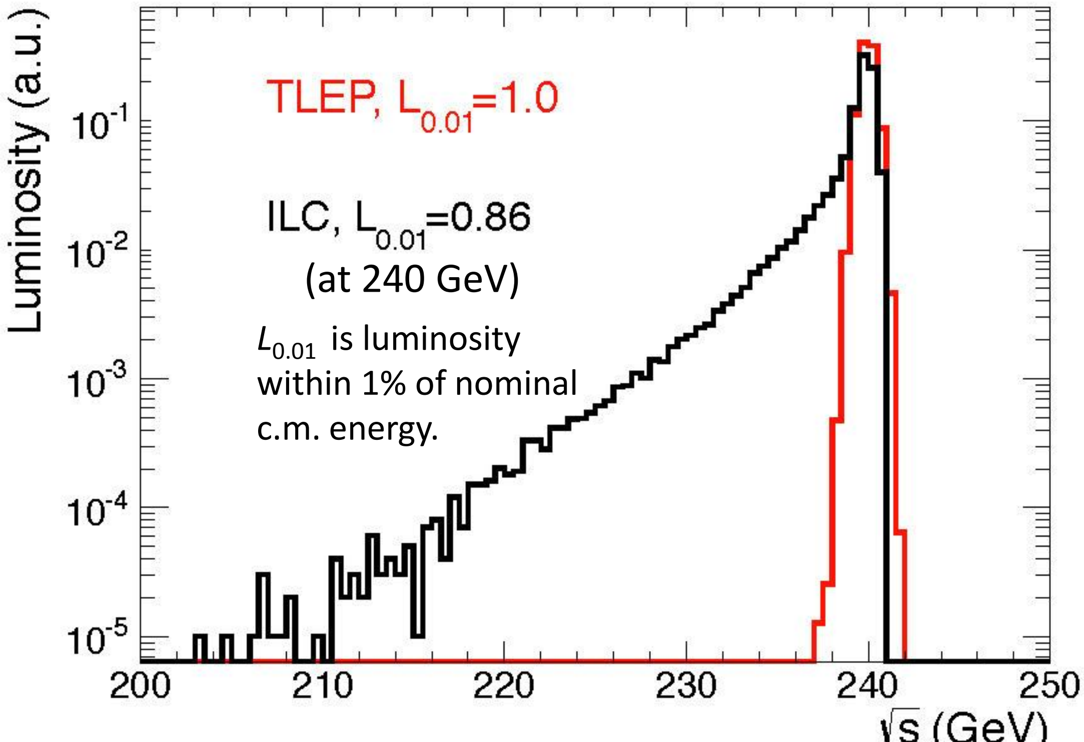
S. White

beamstrahlung (BS)

synchrotron radiation in the strong field of opposing beam

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^-

limit on beam lifetime (circular collider)

V. Telnov, PRL 110 (2013) 114801

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

with $$u = \eta \frac{\alpha}{3(r_e)^2} \frac{1}{\gamma} \frac{\sigma_z \sigma_x}{N}$$

η: momentum acceptance

σ_z: rms bunch length

σ_x: horizontal beam size at IP

collider luminosity

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

FCC-ee:

- higher bunch charge *N* (FCC-ee ~2.5x ILC charge / bunch)
- several IPs (n_{IP}=4)
- 3-4 times higher wall-plug power to beam efficiency η
- ΔE_{beam}/IP ~300 (instead of 1)

→ total factor 2.5x4x300~3000

ILC:

- ~200x smaller IP spot size (smaller emittances and β^{*}'s)

→ for equal wall plug power *FCC-ee-H* has ~15x times more luminosity than *ILC-H*

comparison of key design parameters

Parameter	LEP2	FCC-ee			ILC		
		Z	H	t	H	500	1 TeV
E (GeV)	104	45	120	175	125	250	500
<I (mA)>	**4**	**1400**	**30**	**7**	**0.000021**	**.000021**	**.000027**
$P_{SR/b,tot}$ [MW]	22	100	100	100	5.9	10.5	27.2
P_{AC} [MW]	~200	~260	~270	~300	~129	~163	~300
$\eta_{wall\rightarrow beam}$ [%]	**~30**	**30-40**	**30-40**	**30-40**	**4.6**	**6.4**	**9.1**
$N_{bunch/ring\ (pulse)}$	4	16'700	1'330	98	1312	1312	2450
f_{coll} (kHz)	45	50000	4000	294	6.6	6.6	9.8
$\beta^*_{x/y}$ (mm)	1500/ 50	500 / 1	500 /1	1000/1	13	11	11
ε_x (nm)	30-50	29	1	2	0.04	0.02	0.01
ε_y (pm)	~250	60	2	2	0.14	0.07	0.03
ξ_y (ILC: n_γ)	0.07	0.03	0.09	0.09	(1.12)	(1.72)	(2.12)
n_{IP}	4	4	4	4	1	1	1
$L_{0.01}$/IP	0.012	28	6.0	1.8	0.65	1.05	2.2
$L_{0.01,tot}$ (10^{34} cm^{-2}s^{-1})	0.048	112	**24**	7.2	**0.65**	1.05	2.2

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

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

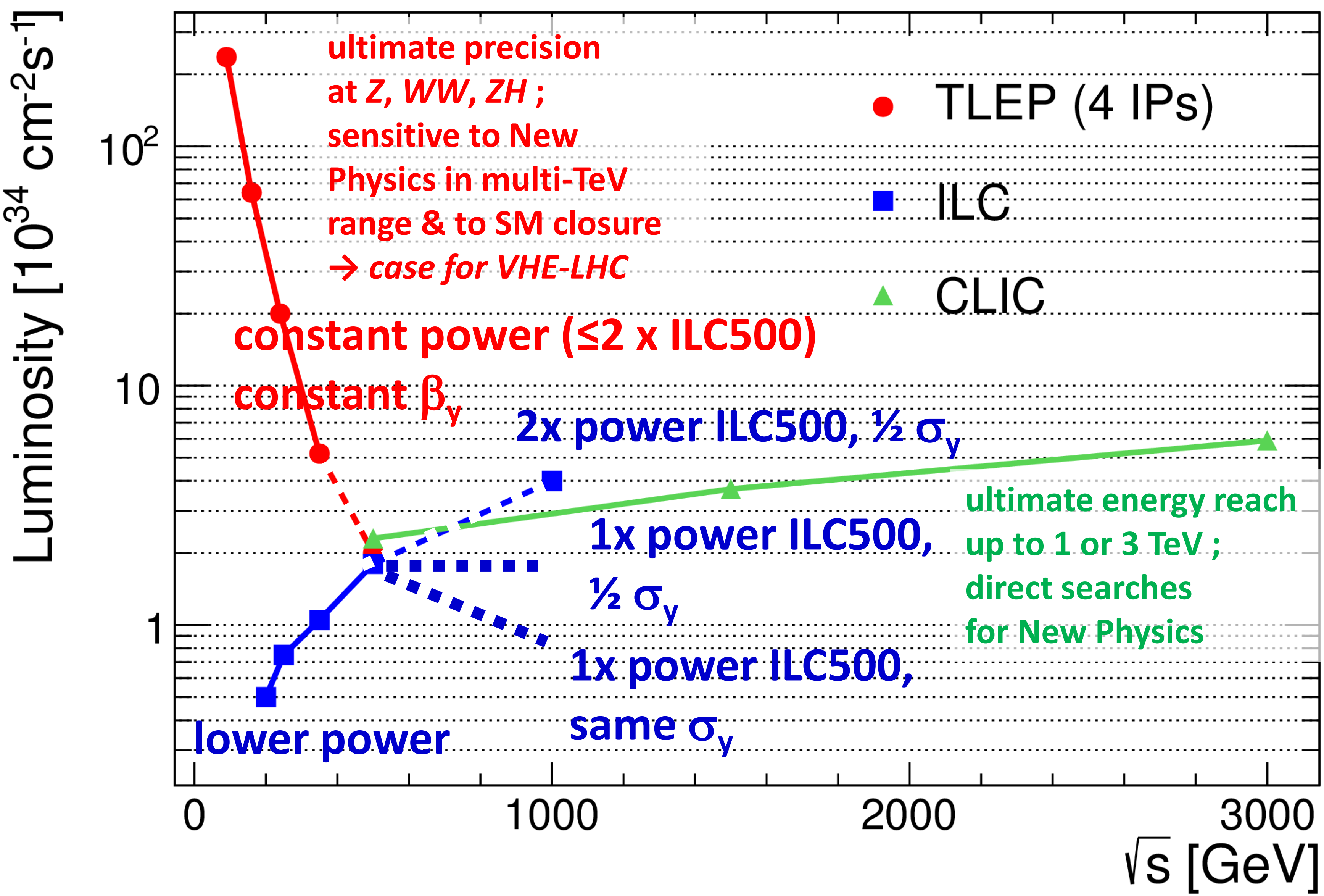
linear collider

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

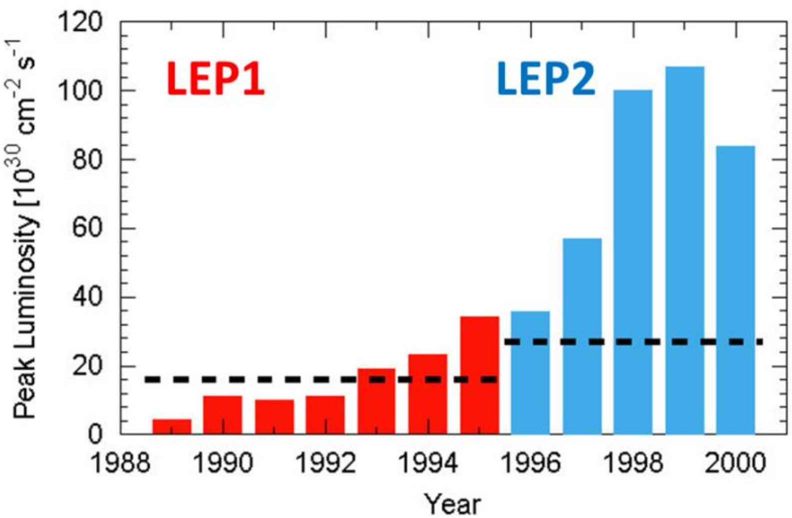
limited by
#BS photons per e±

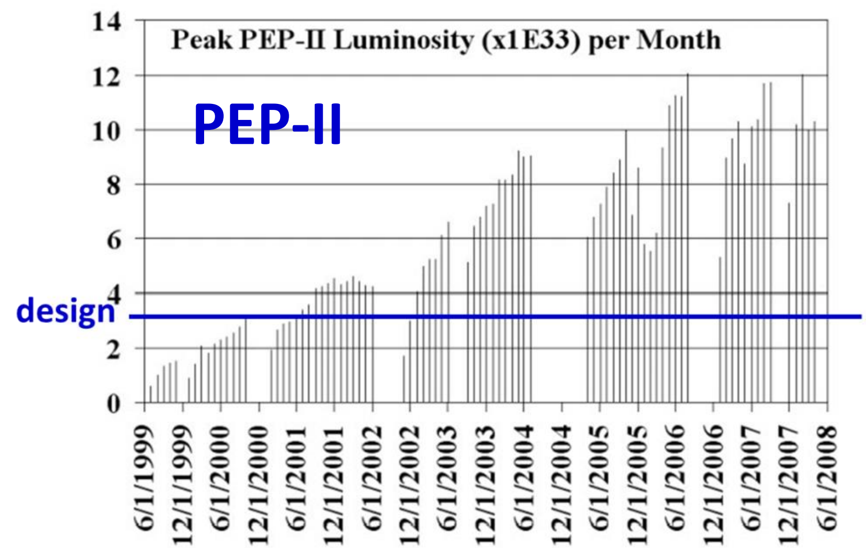
$$N_\gamma \simeq \frac{2\alpha r_e N}{\sigma_x}$$ (luminosity spectrum)

actual design luminosity vs. energy

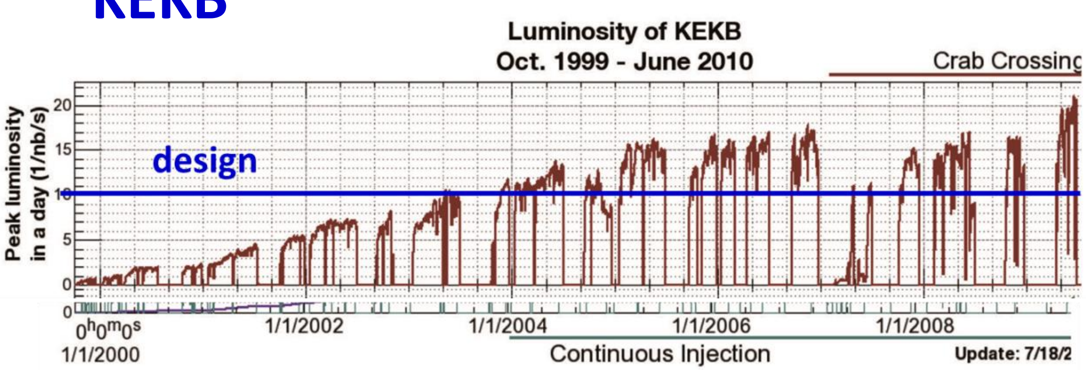


commissioning times & performance of circular e^+e^- colliders

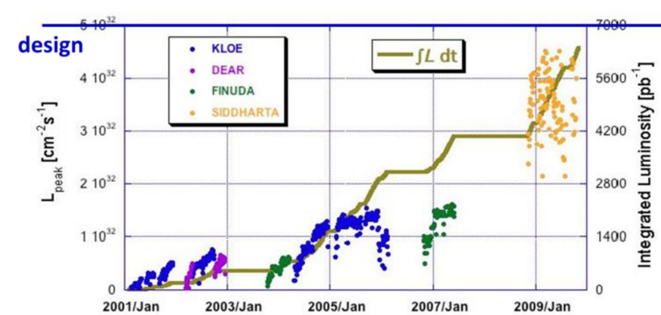




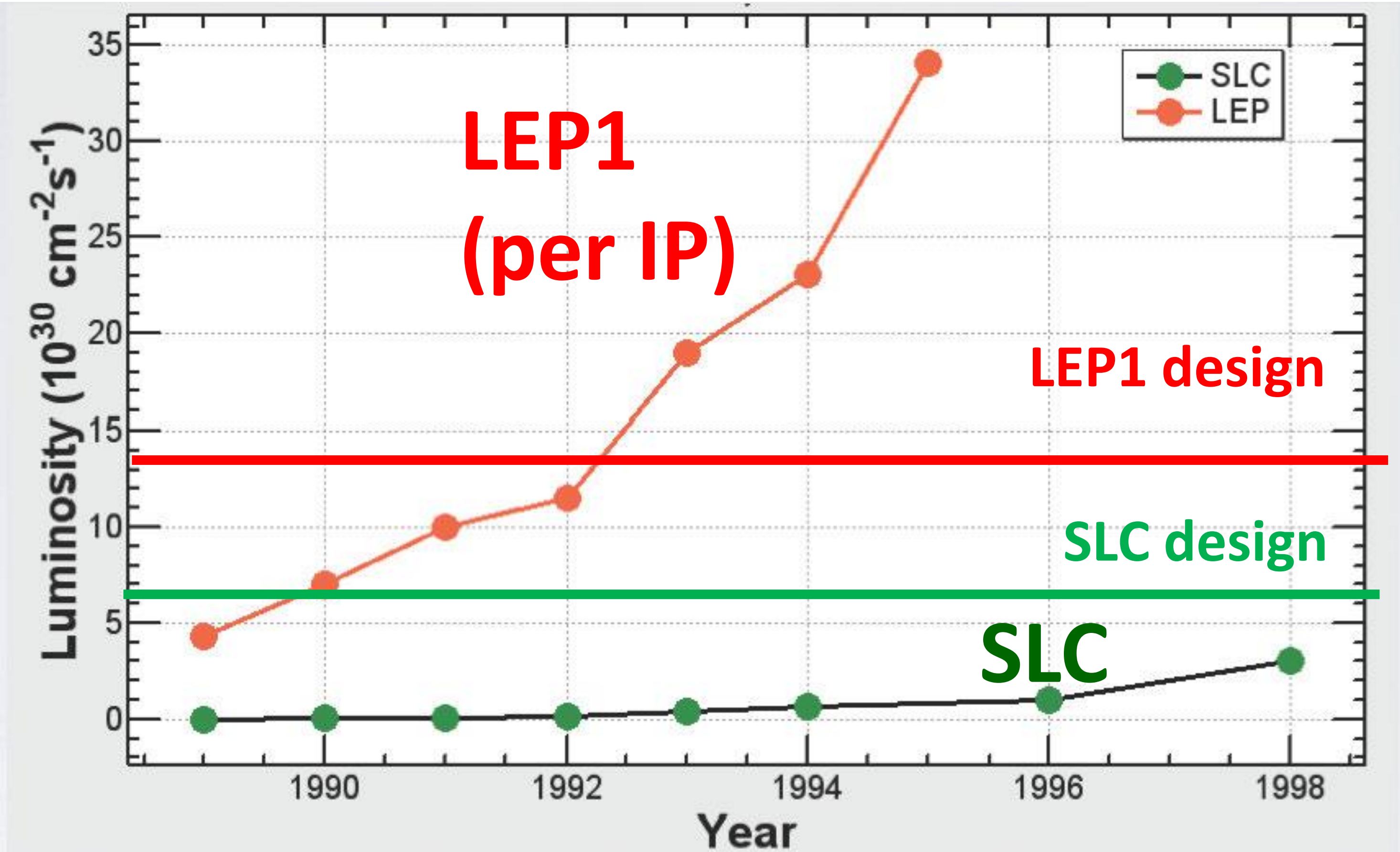
KEKB



DAΦNE



commissioning time & performance of the first linear collider



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

SLC

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

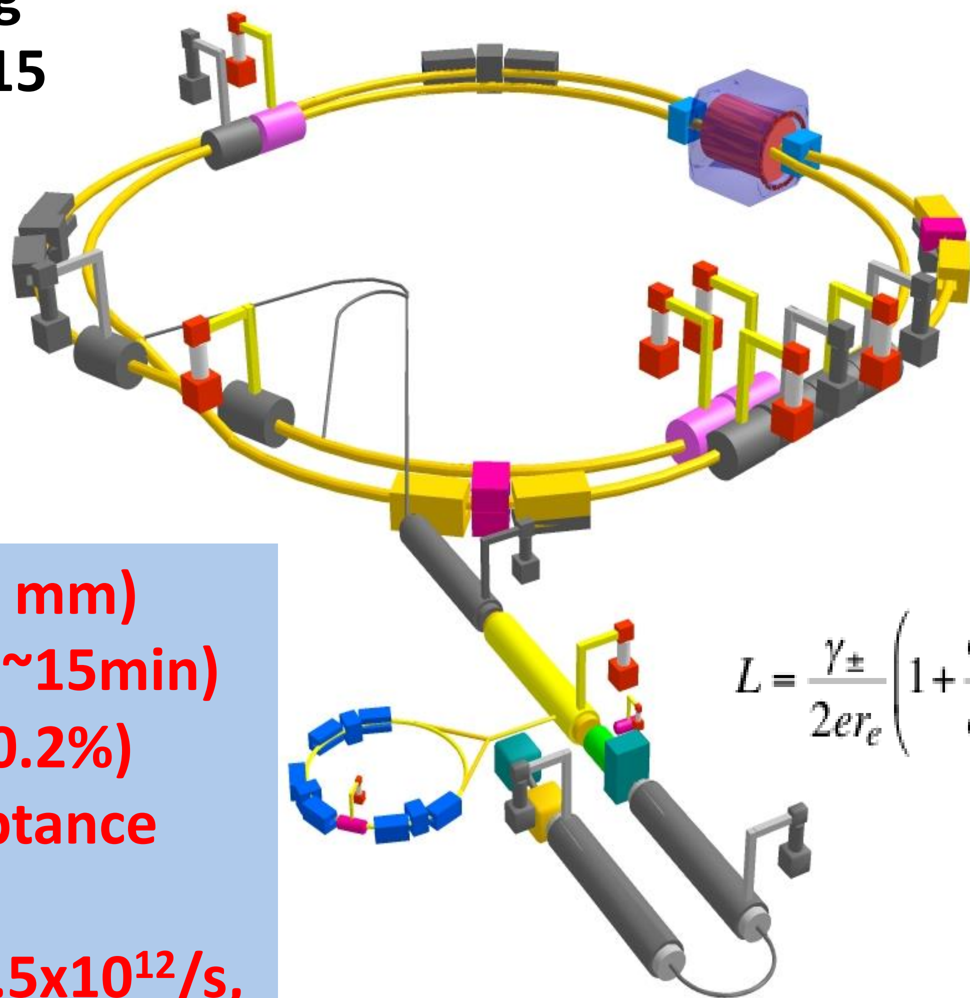
comparing commissioning times & performance

	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*]

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

SuperKEKB – *FCC-ee* demonstrator

beam commissioning will start in early 2015



- **β_y*=300 μm (TLEP: 1 mm)**
- **lifetime 5 min (TLEP: ~15min)**
- **$\varepsilon_y/\varepsilon_x$=0.25% ! (TLEP: 0.2%)**
- **off momentum acceptance (±1.5%, TLEP: ±2%)**
- ***e*$^+$ production rate (2.5x10^{12}/s, TLEP: <1x10^{11}/s)**

$$L = \frac{\gamma_\pm}{2 e r_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_\pm \xi_{\pm y}}{\beta_y^*}\right)\left(\frac{R_L}{R_y}\right)$$

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

x 18

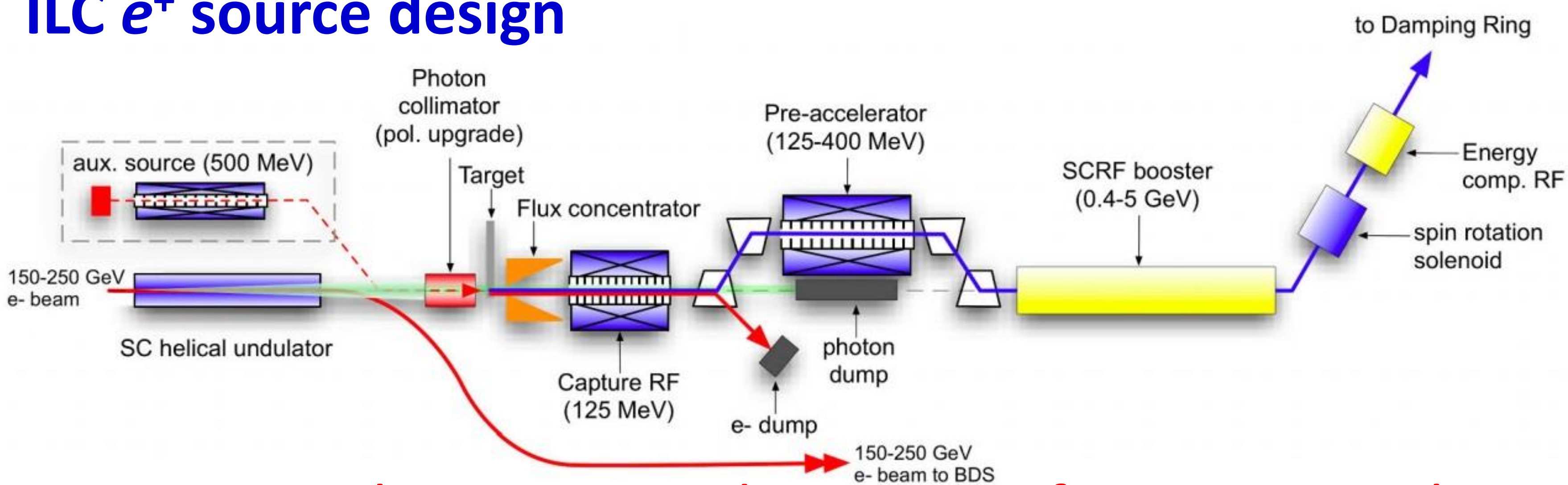
x 33

/ 120

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

factor 20000

ILC e^+ source design



ILC e+ source has no precedent; its performance can be verified only after ILC construction (needs >150 GeV e^- beam)

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

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

linear scenario (example)

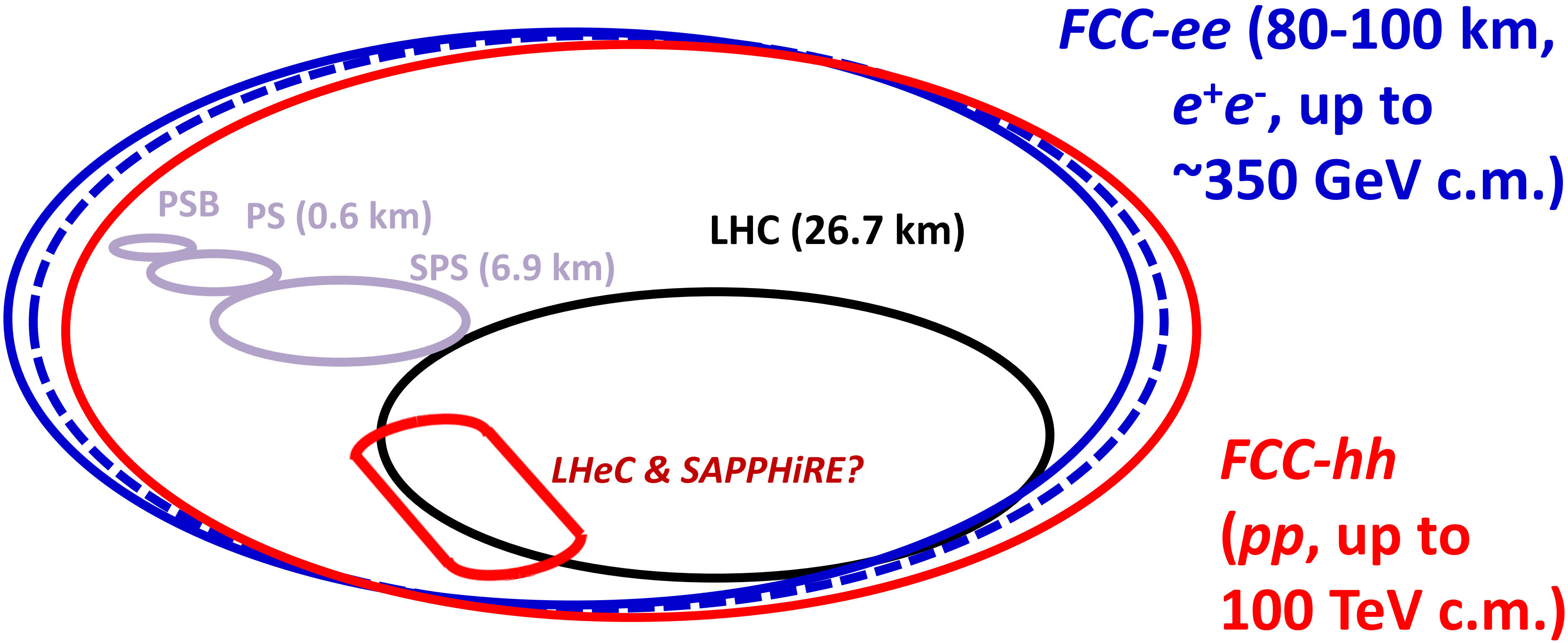
ILC
500 GeV
SC 1.3 GHz
klystrons
31.5 MV/m
31 km

ILC
1 TeV
SC 1.3 GHz
klystrons
36 MV/m?
48 km

CLIC
3 TeV
drive beam
NC 12 GHz
100 MV/m
48 km

≥ 50 years of e^+e^- (e^-e^-, $\gamma\gamma$) collisions up to 3 TeV c.m.

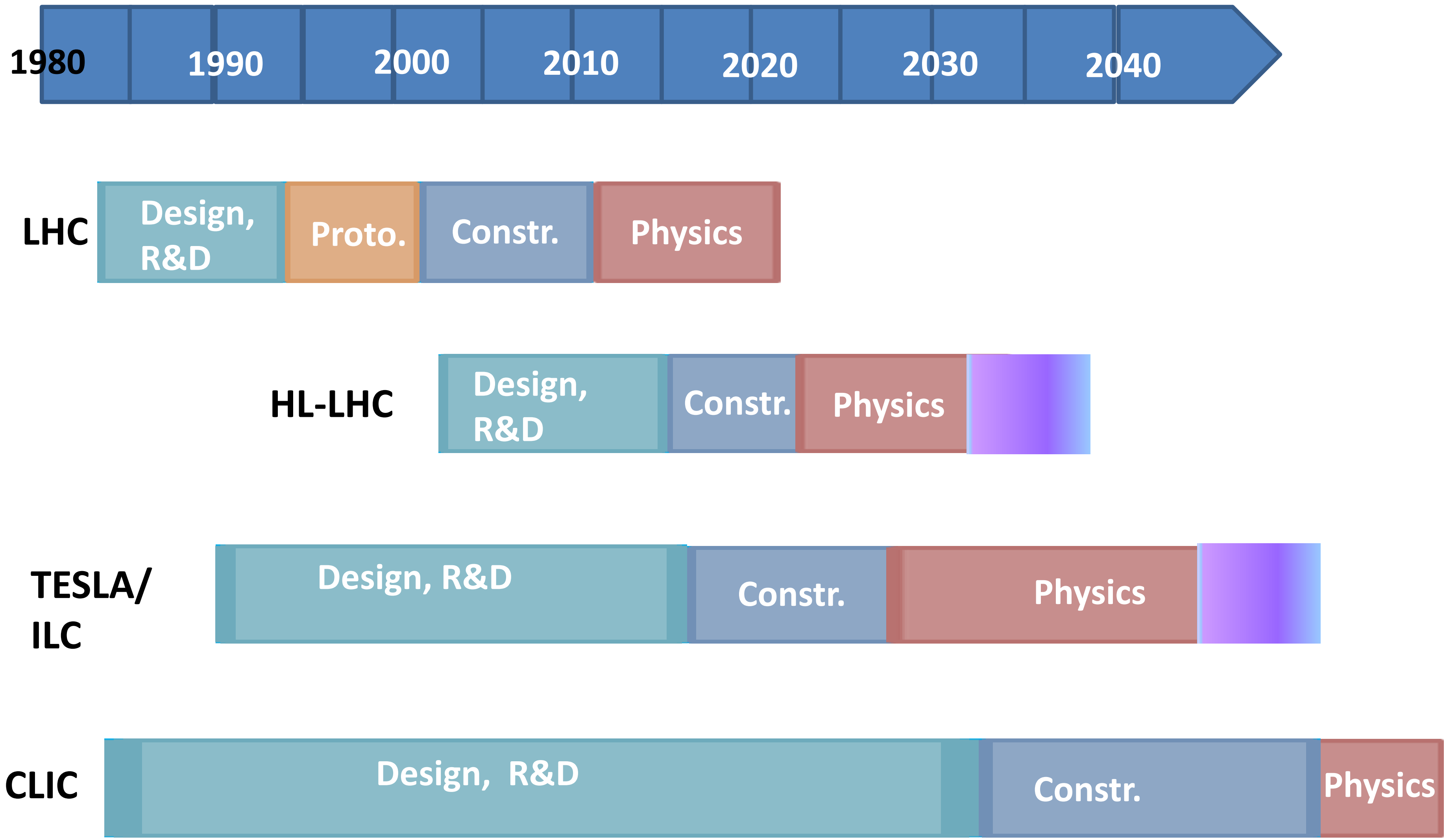
circular scenario (example)



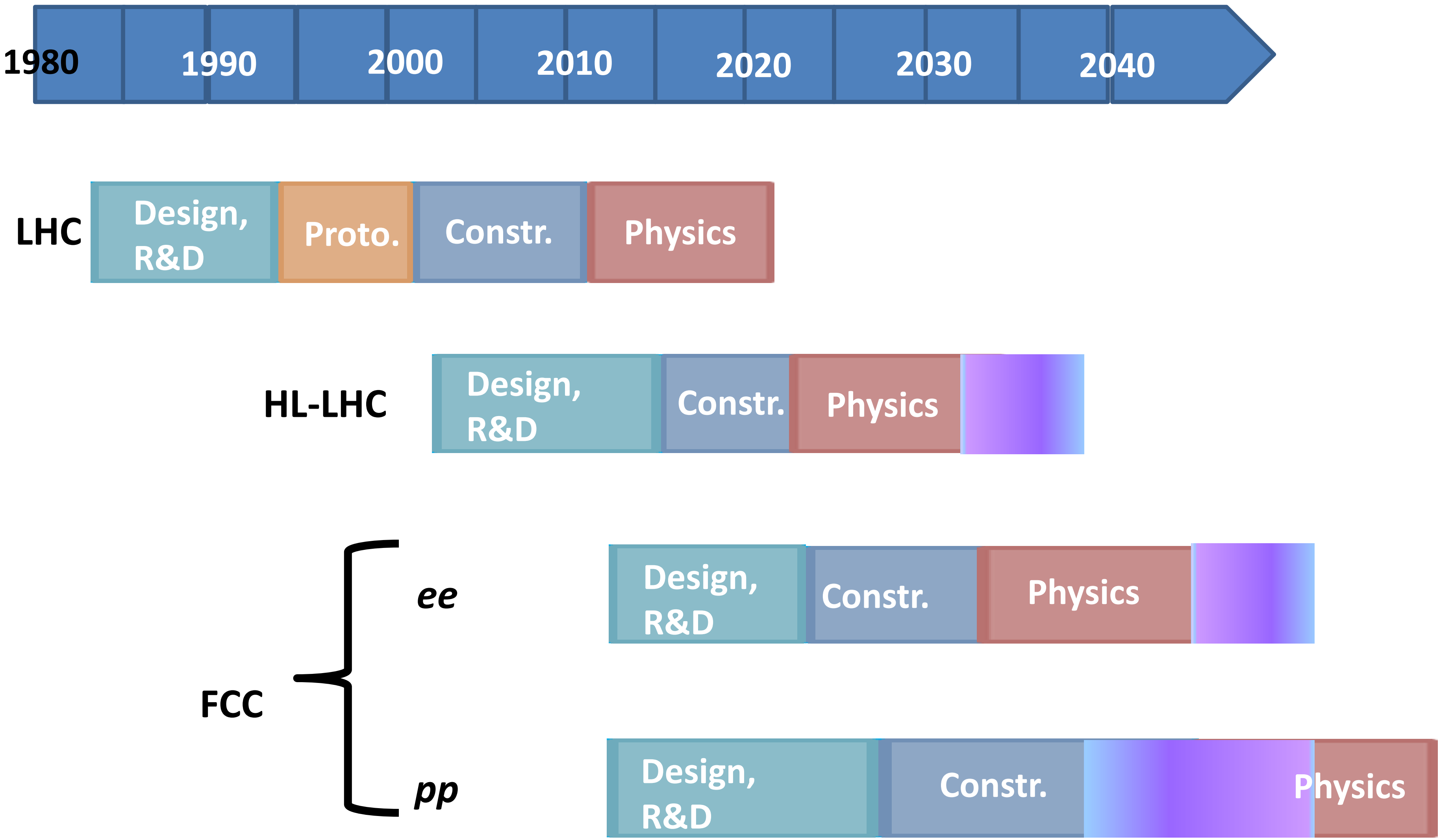
& $e^{\pm}$ **(50-175 GeV) – *p* (50 TeV)** collisions (*FCC-he*)

≥50 years of e^+e^-, *pp*, *ep/A* physics at highest energies

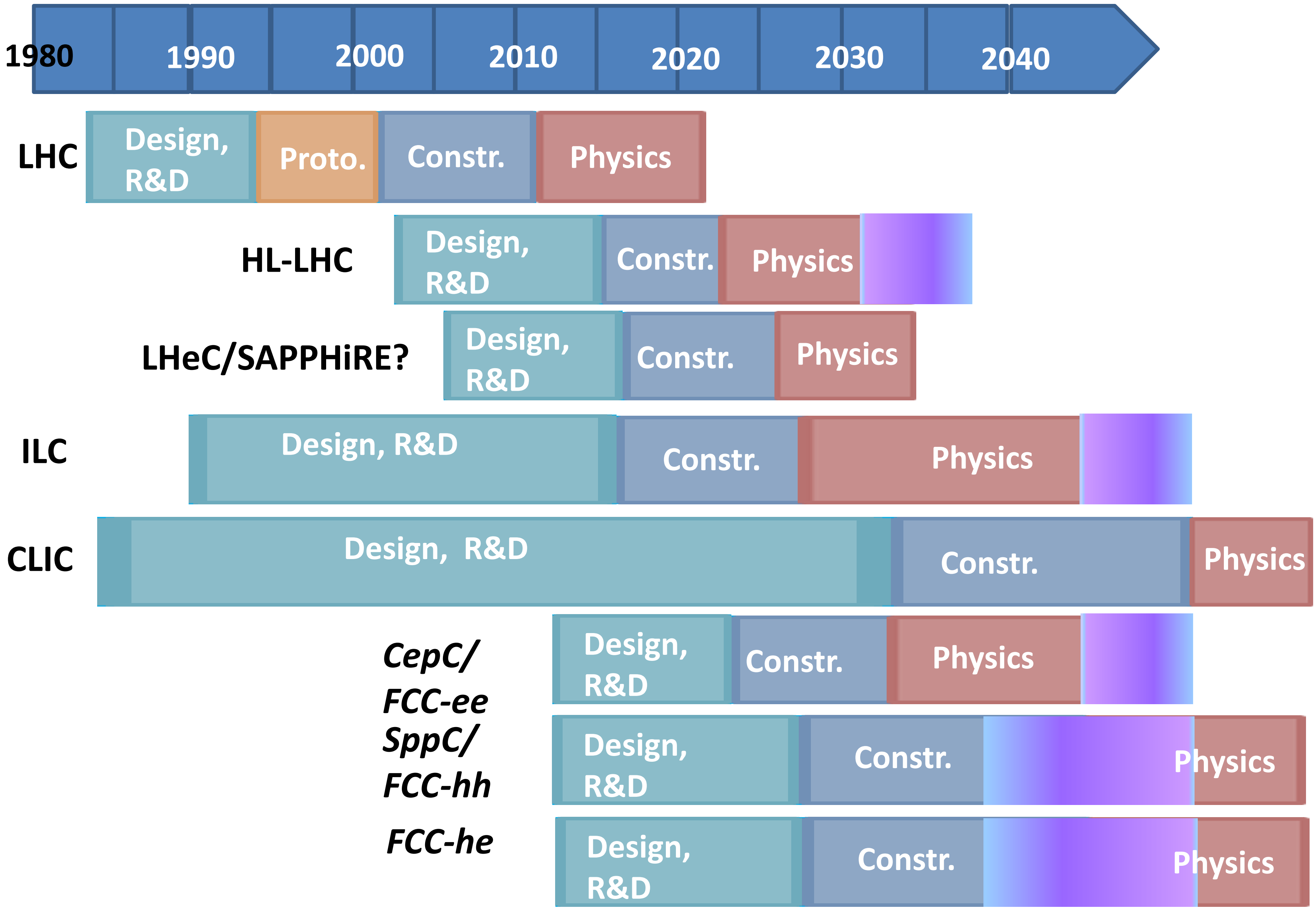
tentative time line - example 1



tentative time line – example 2

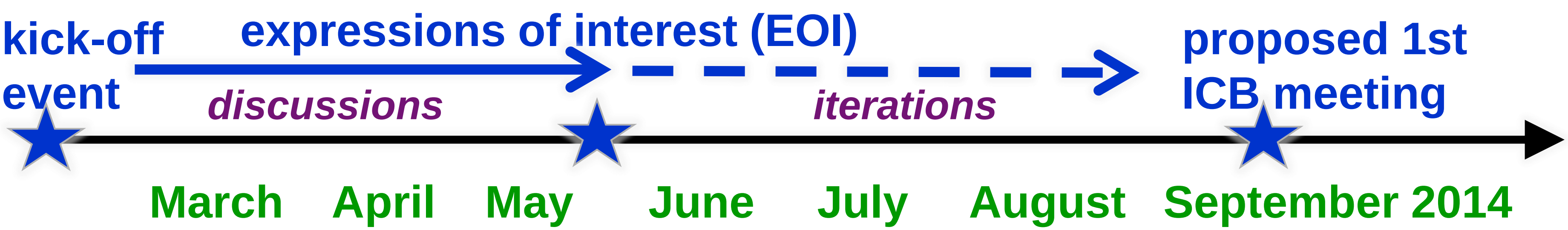


tentative time line – example 3



FCC study FCC long-term goal: **hadron collider**

- **only approach to get to 100 TeV range** in coming decades
- high energy and luminosity at affordable power consumption
- **lead time design & construction > 20 years** (LHC study started 1983!) → **must start now to be ready for 2035/2040**



invitation of non-committing **expressions of interest for contributions** from worldwide institutes **by end May 2014**

5 year time line:

Q2 2014-Q2 2015: Explore options, “weak interaction”, baseline

Q3 2015-Q4 2016: Conceptual study of baseline, “strong interaction”

Q1 2017-Q4 2017: **Cost model**, LHC results, consolidation, re-scoping

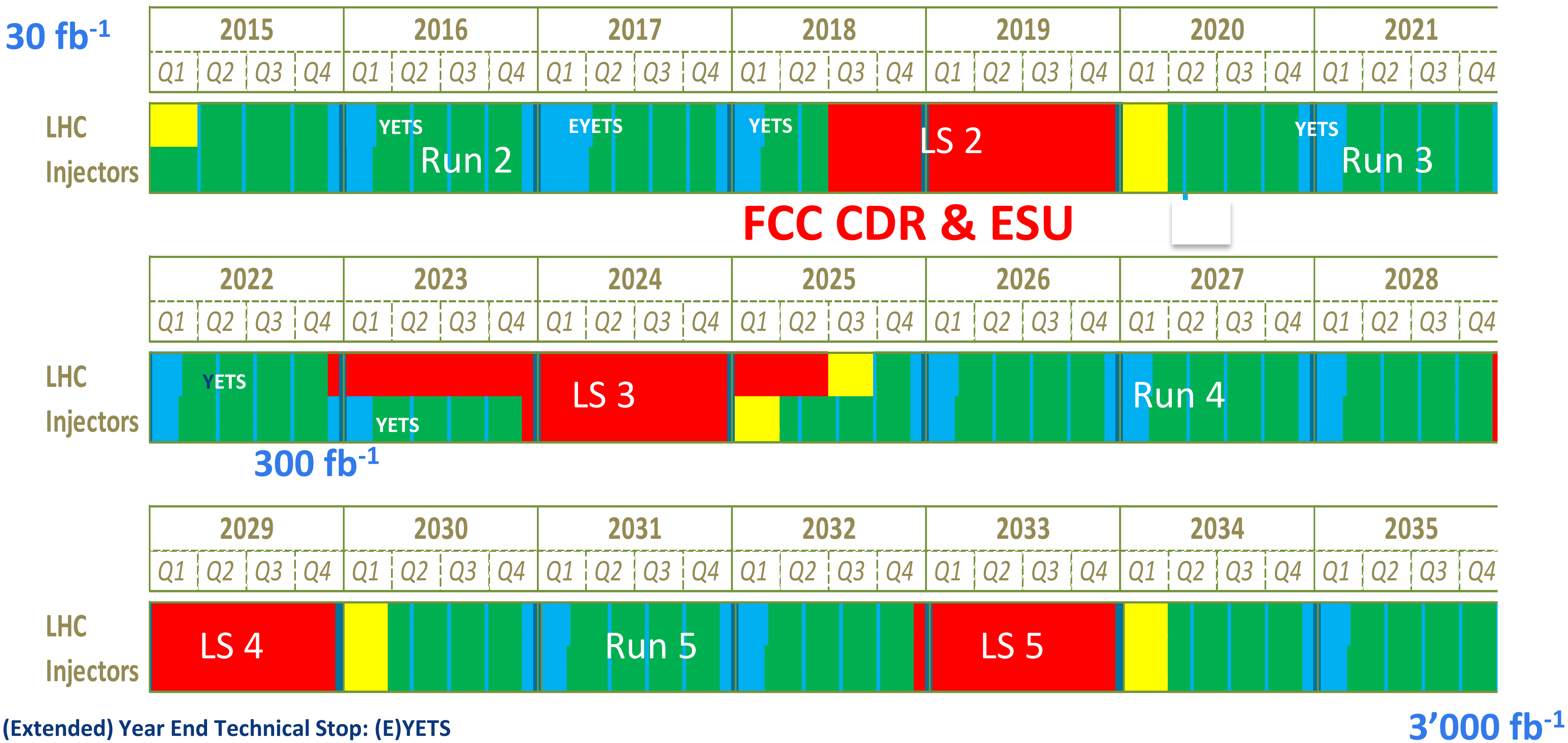
Q3 2018: Release of FCC Conceptual Design Report

M. Benedikt

LHC schedule 2015-2035

LS2 starting in 2018 (July) => 18 months + 3 months BC
LS3 LHC: starting in 2023 => 30 months + 3 months BC
Injectors: in 2024 => 13 months + 3 months BC

- Physics
- Shutdown
- Beam commissioning
- Technical stop



F. Bordry

LHC schedule approved by CERN management and LHC experiments spokespersons and technical coordinators (December 2013)

conclusions

- great history of colliders & collider designs
- linear colliders look more **challenging** technically, also **less efficient** in terms of "RF wall-plug power per collision" (factor ~1000) and "e^+ per luminosity" (factor >10000)
- various scenarios for "Next Accelerator(s)":
  1) **ILC e^+e^- collisions up to 500-1000 GeV TeV** to look for NP, then **CLIC to reach 3 TeV *e^+e^-* (*e^-e^-*, $\gamma\gamma$)**
  2) build **circular e^+e^- collider with higher luminosity to study *Z, W, H* and *t* up to 350 GeV**, then **100 TeV *pp* collider** (+ *AA*&*ep/A* collider) in same tunnel
  3) combinations or all of ***LHeC/SAPPHiRE, ILC+CLIC, CepC/FCC-ee, SppC/FCC-hh*, and FCC-he**
- LHC results in 2015-18 may define the direction(s)

is history repeating itself…?

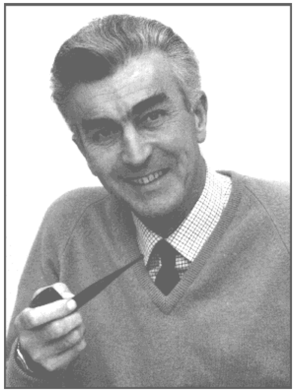
When **Lady Margaret Thatcher** visited CERN in 1982, she also asked the then CERN Director-General **Herwig Schopper** ***how big the next tunnel after LEP would be.***

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

thank you for your attention!

Nima Arkani-Hamed during the inauguration of the Center for Future High Energy Physics (CFHEP) IHEP Beijing, 17 Dec 2013

a few references:

1) The International Linear Collider Technical Design Report - Volumes 1-5, ILC-REPORT-2013-040 (2013)
2) C. Adolphsen, International Linear Collider (ILC) Linac Basics, ILC School 2006
3) A. Blondel and F. Zimmermann, High Luminosity e+e- Collider in the LHC tunnel to study the Higgs Boson, Dec. 2011, http://arxiv.org/abs/1112.2518
4) Future Circular Collider (FCC) study web site http://cern.ch/fcc
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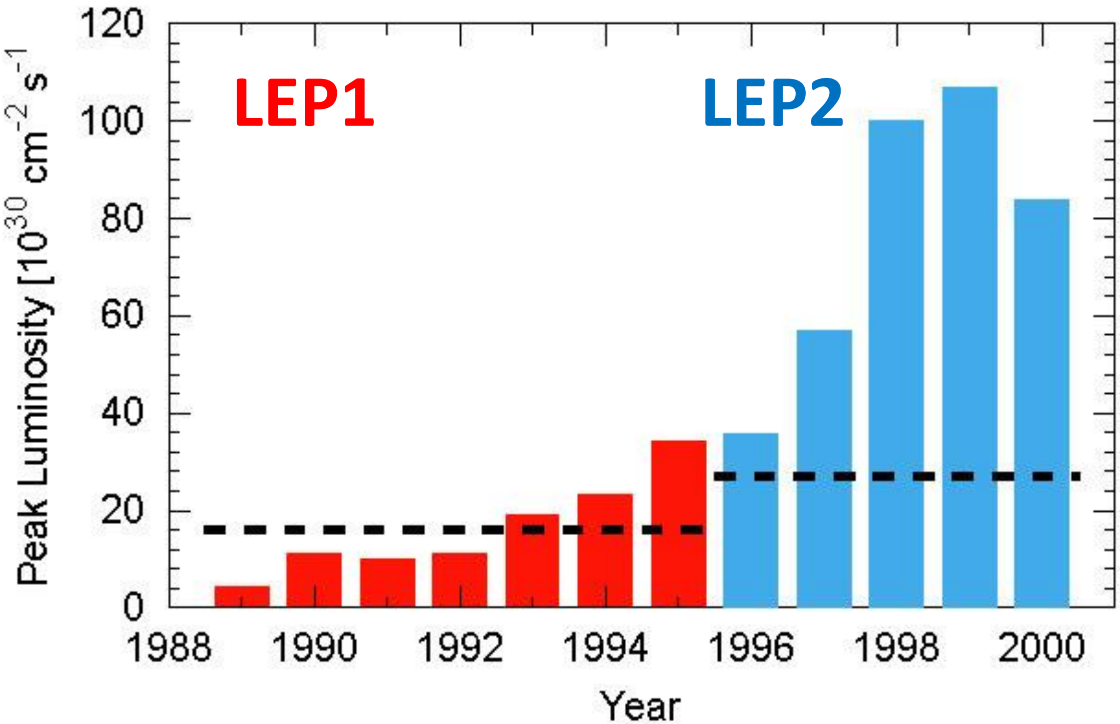
6) A Multi-TeV Linear Collider Based on CLIC Technology - CLIC Conceptual Design Report, CERN-2012-007 (2012)
7) K. Yokoya, e^+e^- Higgs Factory, *Higgs and Beyond*, Sendai 8 June 2013
8) R. Siemann, Progress on Electron-Positron Linear Colliders&Technology,CERN 2002
9) M. Harrison, ILC Status, LCWS 2013
10) K. Oide, Risk of “J-ILC,” Science Council of Japan, July 2013
11) M. Bicer *et al*, First Look at the Physics Case of TLEP, doi: 10.1007/JHEP01(2014)164JHEP 01 (2014) 164
12) M.Harrison, M.Ross, N.Walker, Luminosity Upgrades for ILC, arXiv:1308.3726, 2013
13) A. Blondel *et al*, Comments on "Wall-plug (AC) power consumption of a very high energy e+/e- storage ring collider" by Marc Ross, arXiv:1308.2629, August 2013
14) S. Stapnes, CLIC Accelerator Overview, 2014 CLIC Meeting, 3-7 February 2014
15) J. Abelleira et al, (LHeC CDR), J. Phys. G: Nucl. Part. Phys. 39, 075001 (2012)

Appendix:
commissioning & performance history of various colliders and facilities

commissioning time: circular colliders - 1



Peak luminosity for each year of LEP operation. [R. Assmann, APAC2001 Beijing]

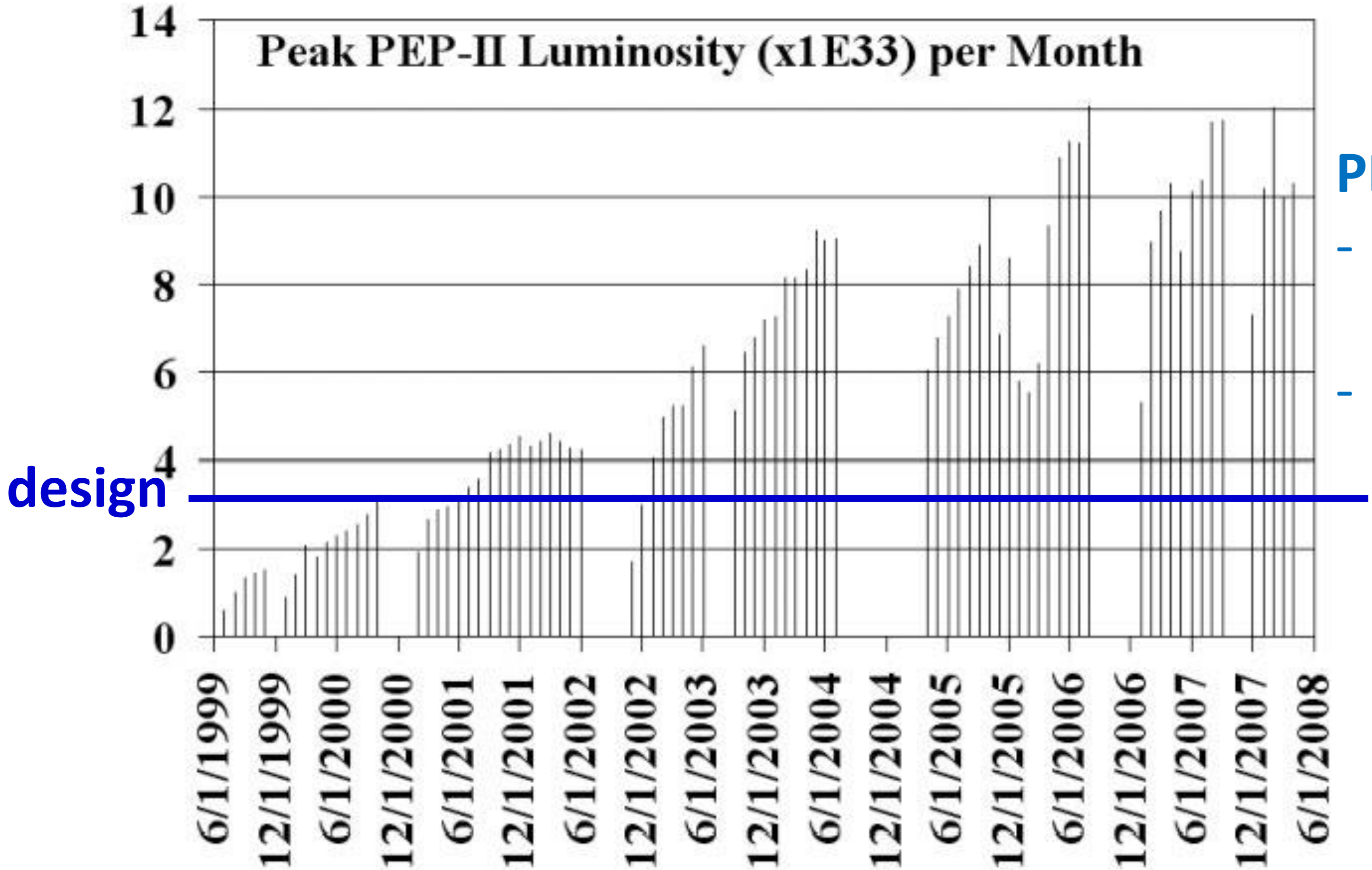
LEP1

- **~60% design in 2nd year**
- **design in 5th year**
- **finally >2x design**

LEP2

- **design exceeded after few months**
- **peak >3x design**

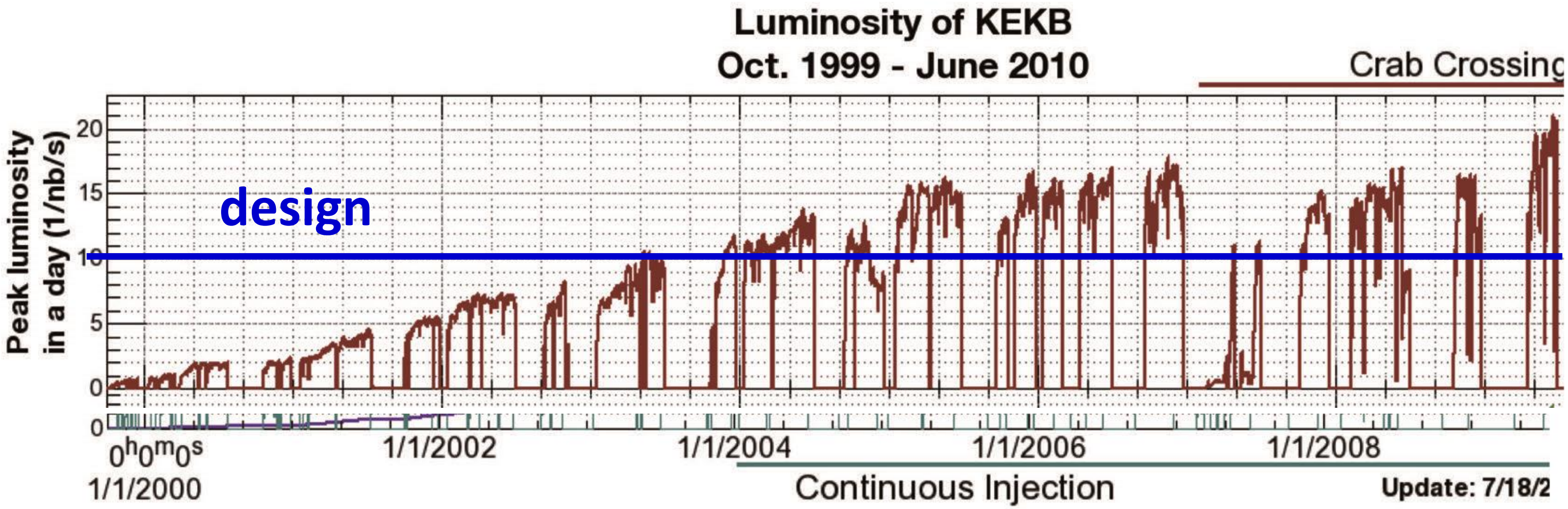
commissioning time: circular colliders - 2



PEP-2
- **design reached after 1.5 years**
- **peak 4x design**

PEP-II peak luminosity in a given month from 1999 to 2008. A peak luminosity of $1.21 \times 10^{34}/cm^2/s$ was achieved. [J. Seeman, EPAC'08 Genoa]

commissioning time: circular colliders - 3

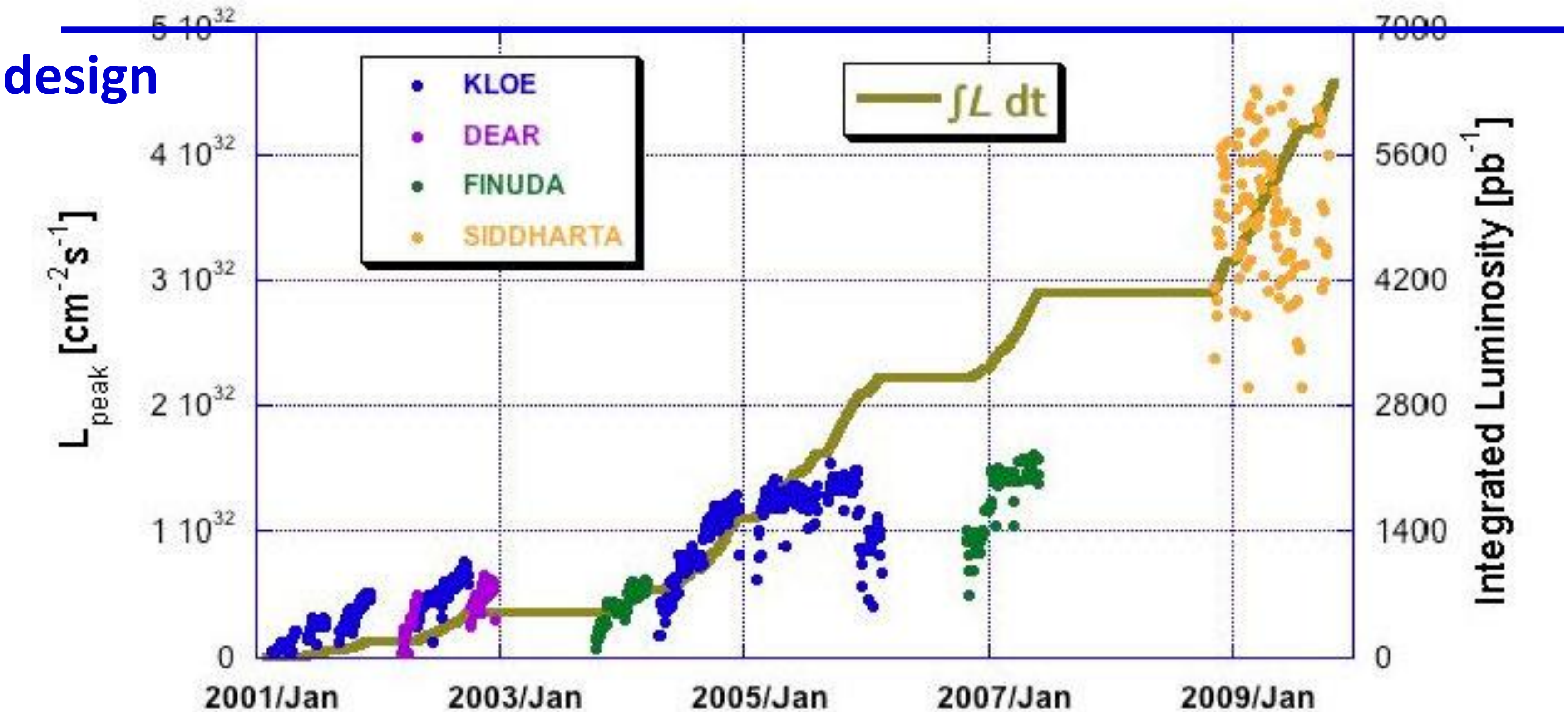


History of the performance of KEKB from October 1999 to June 2010. [Prog. Theor. Exp. Phys. 2013, 03A001]

KEKB

- **design reached after ~3.5 years**
- **peak >2x design**

commissioning time: circular colliders - 4

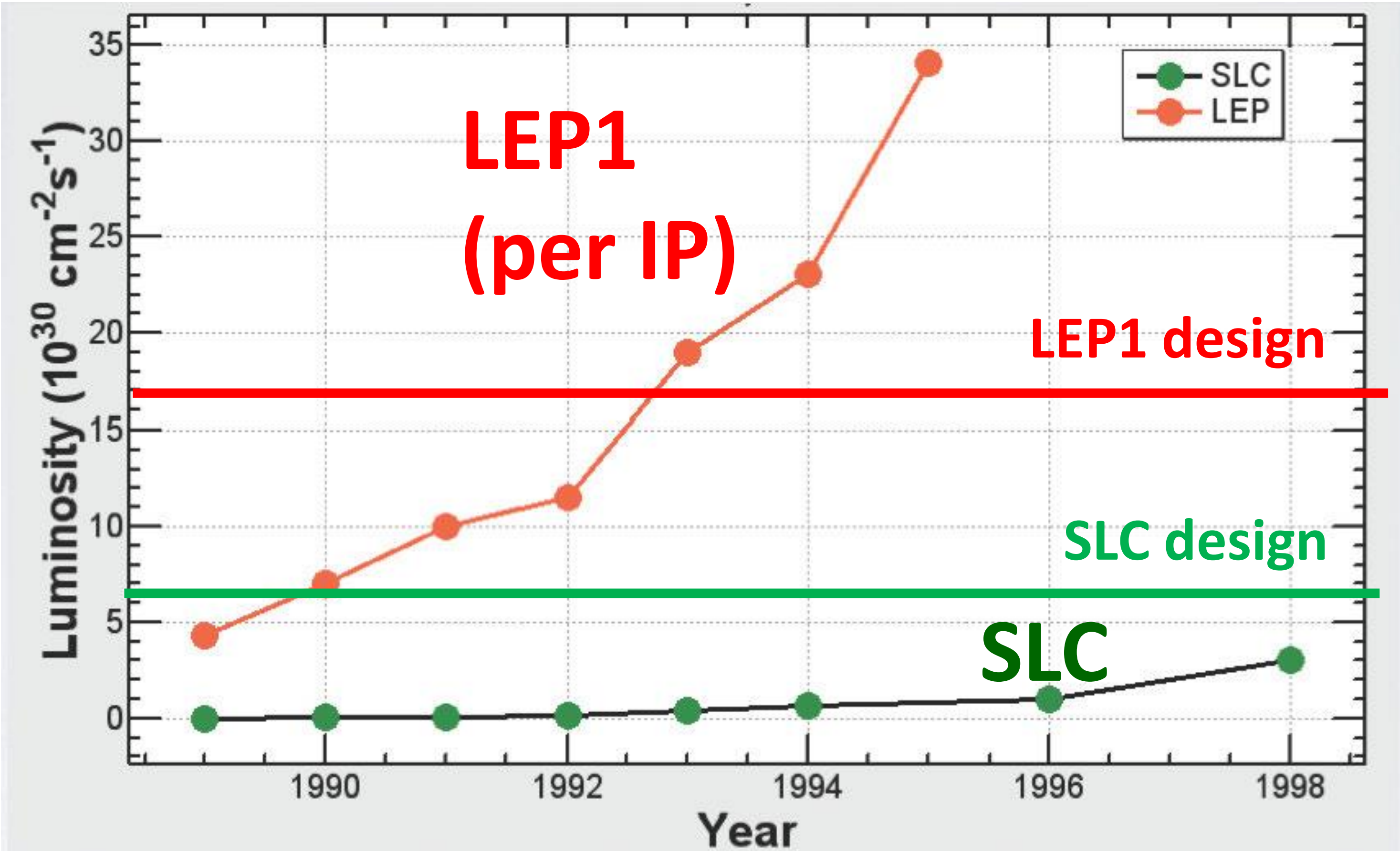


Peak (dots) and integrated (line) luminosity acquired on DAΦNE by the four different experiments (C. Milardi, IPAC'10)

DAFNE

- **design not (yet) reached after >10 years**
- **peak ~90% of design**

commissioning time: linear colliders - 1

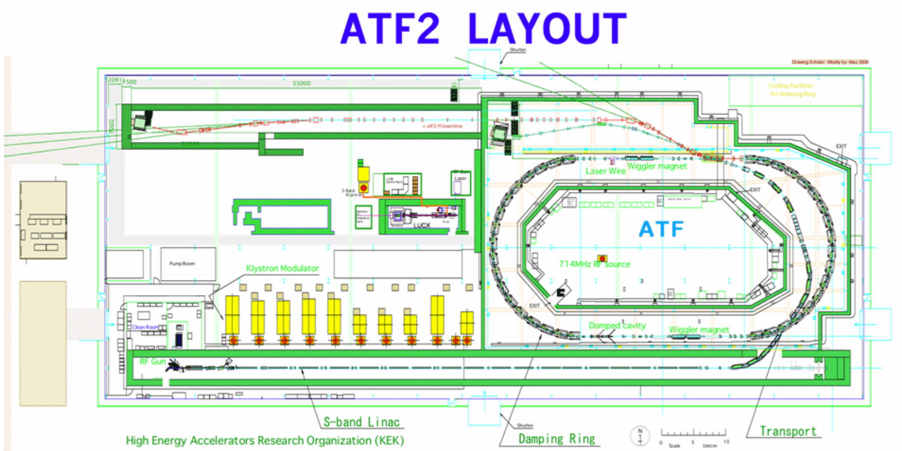


CERN-SL-2002- 009 (OP), SLAC–PUB–8042 [K. Oide, 2013]

SLC

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

commissioning time: linear colliders - 2



ATF2 – goal: demonstrate feasibility of ILC-type final focus

design parameters: σ_y=37 nm (~6x ILC value) at β_x^*=4mm, β_y^*=0.1 mm, N=5x10^9 e/bunch

2009 **2010** **2011** **2012** **2013** **2014**

350 nm **150 nm** **70 nm** **65 nm**

start beam commissioning

originally expected date to reach σ_y=75 nm with nominal β_x^*, β_y^*, N

originally expected date to reach design σ_y=37 nm with nominal β_x^*, β_y^*, N

Big Eastern Japan Earthquake

reached σ_y<75 nm with relaxed β_x^* = 10x design, N ~1/5 design - equivalent to <0.5% of "design luminosity" , thanks to heroic efforts of KEK + international team

(for me) much resembling the SLC experience