A First Look at the TLEP Accelerator

Frank Zimmermann, CERN-BE

on behalf of the *TLEP SG*

TH Seminar, 16 October 2013

thanks to R. Aleksan, R. Assmann, M. Benedikt, A. Blondel, Y. Cai, O. Dominguez, J. Ellis, B. Holzer, P. Janot, M. Koratzinos, H. Maury Cuna, S. Myers, K. Ohmi, K. Oide, J. Osborne, L. Rossi, J. Seeman, V. Telnov, R. Tomas, J. Wenninger, S. White, U. Wienands, K. Yokoya, M. Zanetti, …

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circular colliders & storage rings

since 1960 ~30 ring colliders successfully built & operated

...
CESR
BEPC
LEP
Tevatron
LEP2
HERA
DAFNE
PEP-II
KEKB
BEPC-II
LHC
SuperKEKB (soon)

+ many more e$^{\pm}$ storage-ring light sources (with ever smaller transverse emittance)

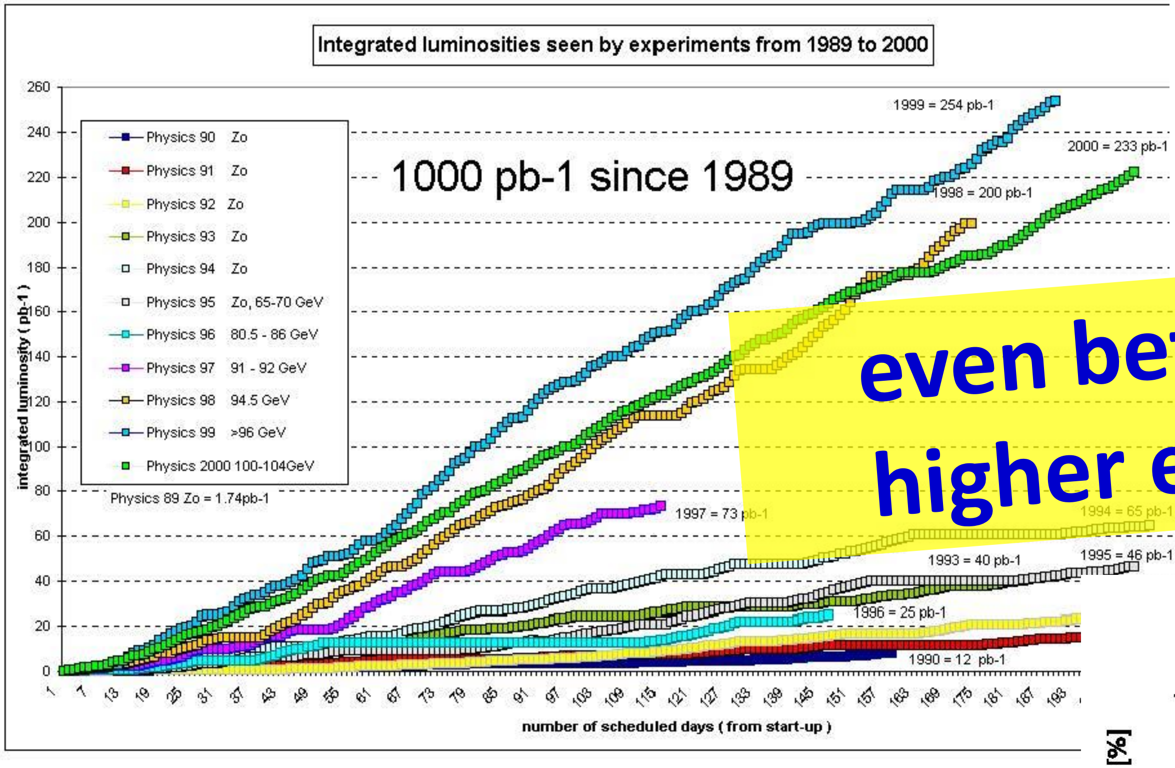
3rd generation light sources

1992	**ESRF**, France (EU)	6 GeV
	ALS, US	1.5-1.9 GeV
1993	**TLS**, Taiwan	1.5 GeV
1994	**ELETTRA**, Italy	2.4 GeV
	PLS, Korea	2 GeV
	MAX II, Sweden	1.5 GeV
1996	**APS**, US	7 GeV
	LNLS, Brazil	1.35 GeV
1997	**Spring-8**, Japan	8 GeV
1998	**BESSY II**, Germany	1.9 GeV
2000	**ANKA**, Germany	2.5 GeV
	SLS, Switzerland	2.4 GeV
2004	**SPEAR3**, US	3 GeV
	CLS, Canada	2.9 GeV
2006	**SOLEIL**, France	2.8 GeV
	DIAMOND, UK	3 GeV
	ASP, Australia	3 GeV
	MAX III, Sweden	700 MeV
	Indus-II, India	2.5 GeV
2008	**SSRF**, China	3.4 GeV
2009	**PETRA-III**, Germany	6 GeV
2011	**ALBA**, Spain	3 GeV

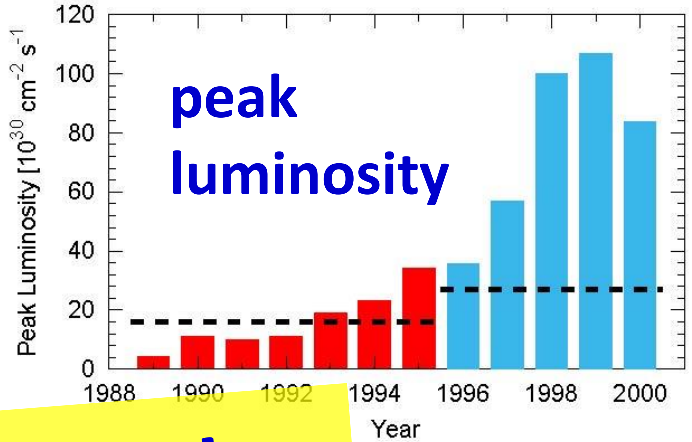
well understood technology & typically exceeding design performance within a few years

LEP achievements

integrated luminosity

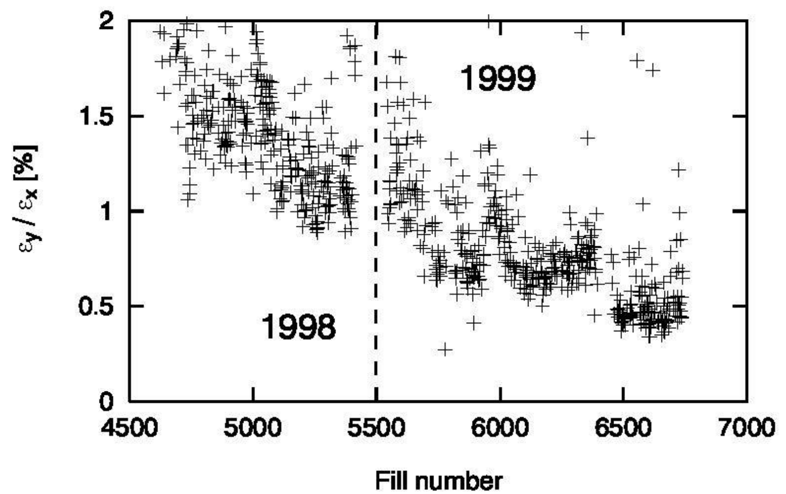


peak luminosity



even better at higher energy

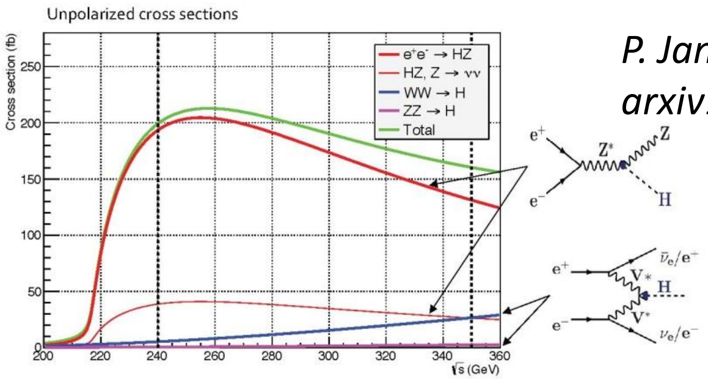
emittance ratio $\varepsilon_x/\varepsilon_y$



R. Assmann
Chamonix XI & APAC'01

TLEP design targets

- c.m. energies: **240 GeV (*ZH*)**



P. Janot et al, arxiv1308.6176

+ 91(*Z*), 160(*WW*), 350($t\bar{t}$), [+ 500 GeV (*ZHH*,*H*$t\bar{t}$)?]

- **luminosities: *L*: several 10^{34} cm^{-2}s^{-1}/IP at *ZH*,**

  >> 10^{35} cm^{-2}s^{-1}/IP at the *Z*

- **polarization** up to *WW* for ~100 keV energy calibration
- **extendibility** – reusing tunnel + infrastructure for 100-TeV *pp* collider, 1st step in HEP long-term vision

key constraints: in words …

- **SR power 100 MW** ↔ wall plug power → **beam current**
- limit on **beam-beam tune shift**:
  - extrapolated from LEP2 & KEKB & other colliders
- **#bunches** ↔ **luminosity, e-cloud, parasitic collisions**
- **hor. emittance ε_x: bending radius ρ, optics** (**#magnets**)
- **emittance ratio $\varepsilon_y/\varepsilon_x$**: alignment, tuning, beam-beam
- vertical β^*_y,: **bunch length & optics**
- **beam lifetime**:
  - **radiative Bhabha scattering** (unavoidable)
  - **beamstrahlung** (design optimization)

… and in formulae

$$L = \frac{f_{rev} n_b N_b^2}{4\pi \sigma_x \sigma_y} = (f_{rev} n_b N_b)\left(\frac{N_b}{\varepsilon_x}\right)\frac{1}{4\pi}\frac{1}{\sqrt{\beta_x}}\frac{1}{\sqrt{\beta_y\,\varepsilon_y/\varepsilon_x}}$$

$$(f_{rev} n_b N_b) = \frac{P_{SR}\,\rho}{8.8575 \times 10^{-5}\,\frac{\mathrm{m}}{\mathrm{GeV}^{-3}}\,E^4}$$

SR radiation power limit

$$\frac{N_b}{\varepsilon_x} \approx \frac{\xi_x 2\pi\gamma}{r_e}$$

beam-beam limit

β_x *constrained by beamstrahlung*

$\beta_y(\varepsilon_y/\varepsilon_x)$ *to be reduced as much as possible!*

lifetime limit: rad. Bhabha scattering

beam lifetime $$\frac{1}{\tau_b} = \frac{L}{I_{beam}} \sigma n_{IP} e f_{rev}$$

at beam-beam limit: $$\tau_b = \frac{2 r_e m_e}{n_{IP} \sigma f_{rev}} \frac{\beta_y}{E_b \xi_y}$$

σ for rad. Bhabha:

$$\frac{d\sigma}{dk} = \frac{4\alpha (r_e)^2}{k}\left[\frac{4}{3} - \frac{4}{3}k + k^2\right]\left[\log(4\gamma^2) + \log\frac{1-k}{k} - \frac{1}{2}\right]$$

$$\rightarrow \sigma \approx \int_{k_{\min}}^{1} \frac{d\sigma}{dk} dk \approx 0.32 \text{ barn}$$

H. Burkhardt, R. Kleiss, EPAC1994

help from theorists?

LEP2: $\tau_{\text{beam,LEP2}}$ **~ 6 h** (~30% suppression: σ~0.21 barn)

TLEP **with L~5x10^{34} cm^{-2}s^{-1} at 4 IPs**:

$\tau_{\text{beam,TLEP}}$~21 minutes, unavoidable

lifetime limit: beamstrahlung (BS)

synchrotron radiation in the strong field of opposing beam

Note: Many theoretical beamstrahlung studies in 1980's. Example R. Blankenbecler, S.D. Drell, "A Quantum Treatment of Beamstrahlung," Phys.Rev. D36 (1987) 277

make some $e^{\pm}$ lose large part of their energy

& then be lost→ **limited beam lifetime**

$$\tau_{BS} \approx \frac{20\sqrt{6\pi} r_e}{n_{IP}\alpha^2}\frac{C}{c}\frac{\gamma}{\eta}u^{3/2}e^{u} \quad \text{with} \quad u = \eta\frac{\alpha}{3(r_e)^2}\frac{1}{\gamma}\frac{\sigma_z\sigma_x}{N_b}$$

V. Telnov, PRL 110 (2013) 114801

η: momentum acceptance

σ_x: horizontal beam size at IP

mitigations:

(1) large momentum acceptance η

(2) flat beams [i.e. small ε_y & large β_x^*]

→minimize $\kappa_\varepsilon=\varepsilon_y/\varepsilon_x$, $\beta_y \sim \beta_x(\varepsilon_y/\varepsilon_x)$ & respect $\beta_y \geq \sigma_z$

(3) fast replenishing

from LEP2 to TLEP-H

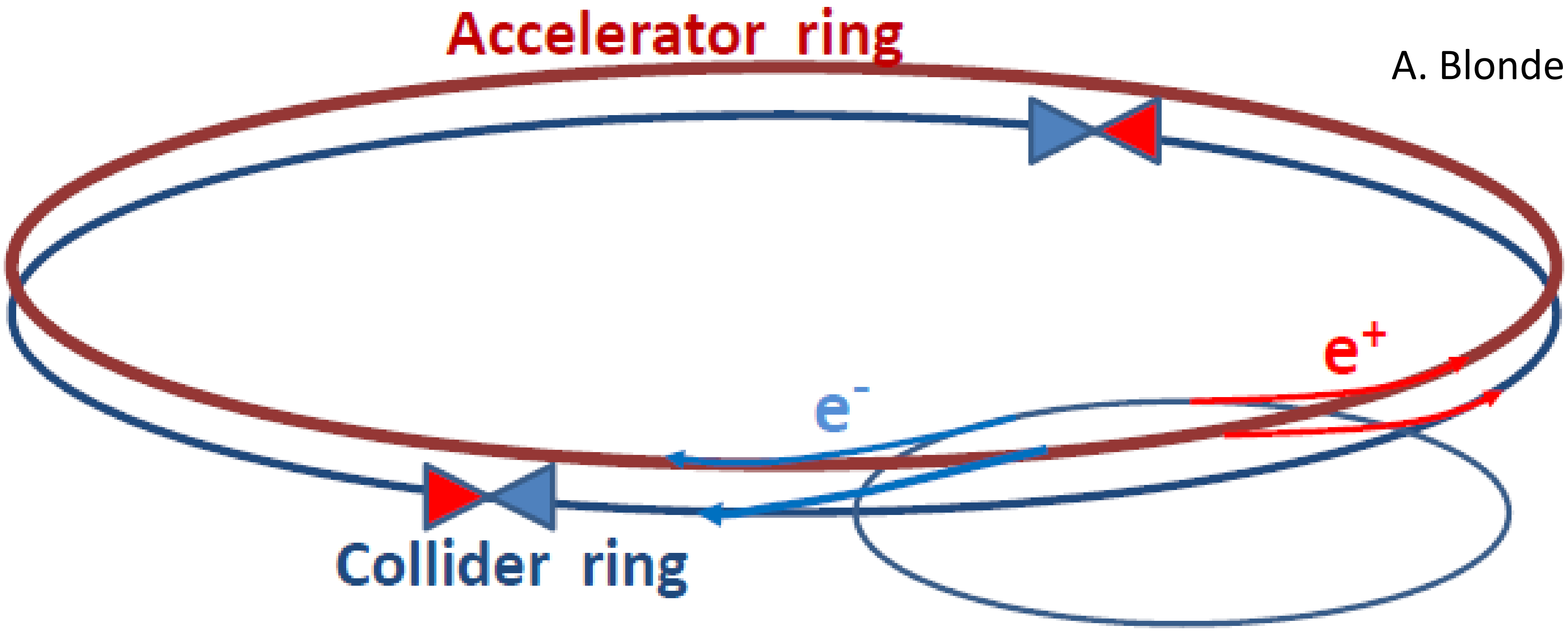
- **larger ring**: higher energy or beam current
- **4-5 x more SR power**: 23 MW → 100 MW
- a **few times smaller emittance** at equal energy (ρ, cell length)
- **β_y^* reduced by factor 50**

  - also requires smaller $\sigma_z \sim \beta_y^*$

    (natural for larger ring)

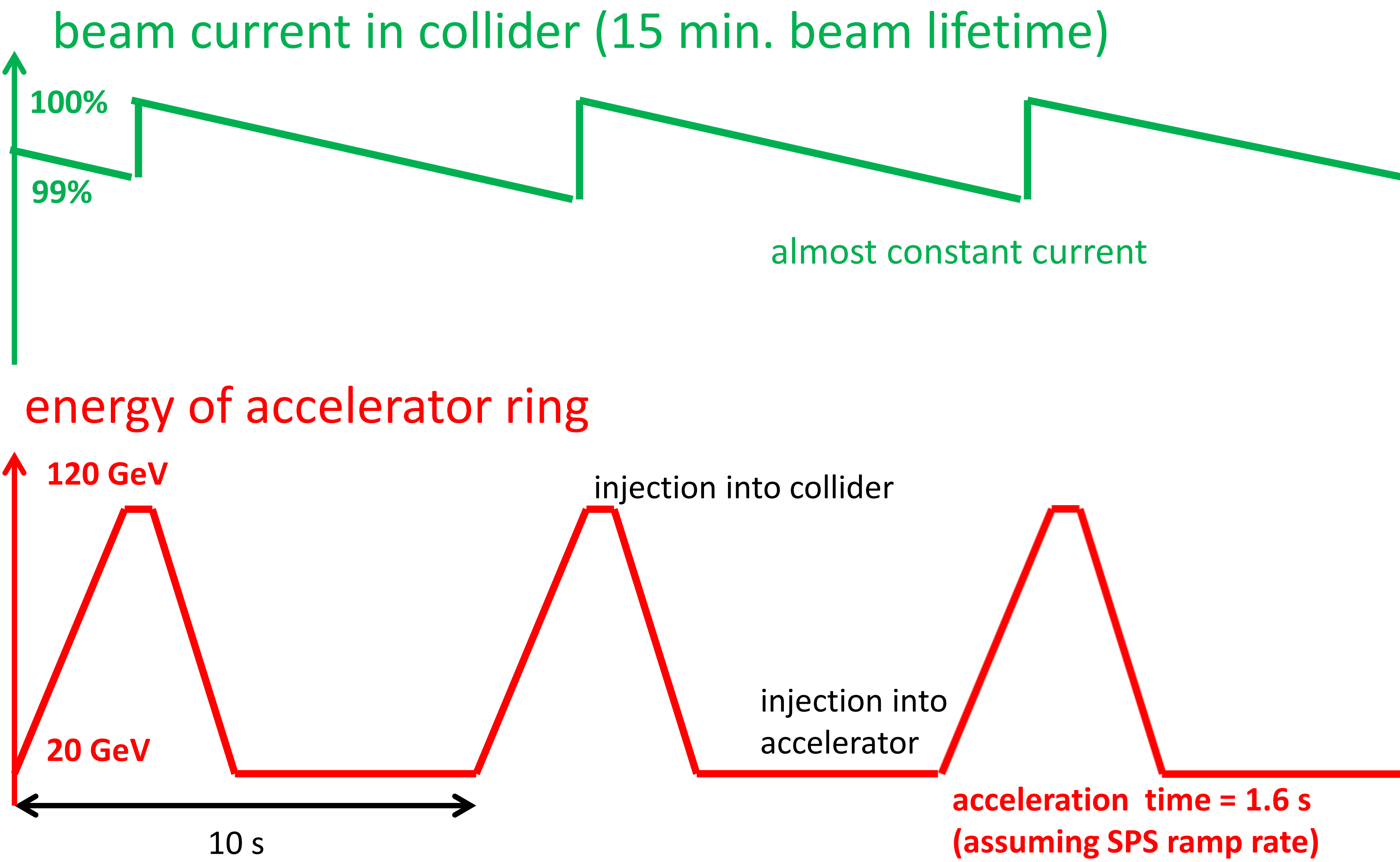
  - **steady-state BS energy spread ≤0.3%**
- **top up injection** to support short lifetime

TLEP: double ring with topping up

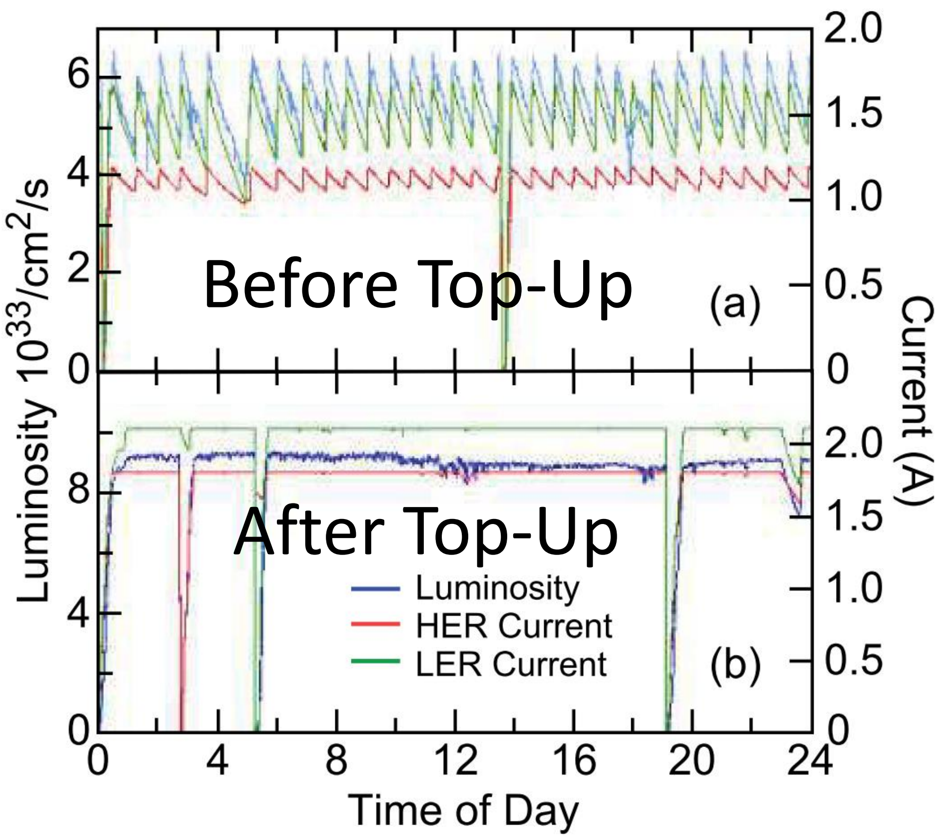


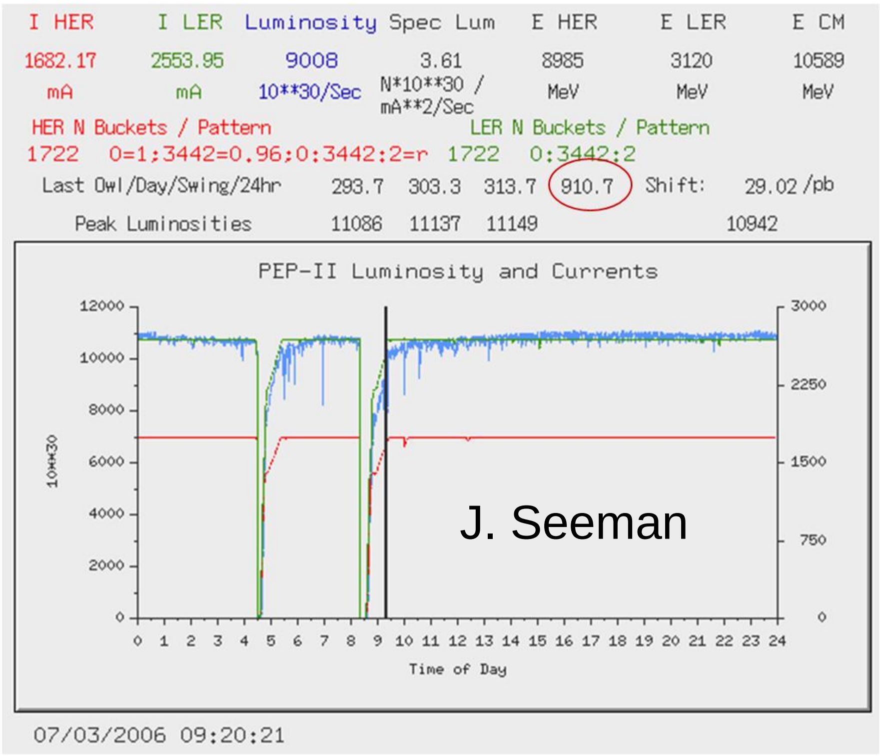
short beam lifetime (~τ_{LEP2}/40) due to high luminosity **supported by top-up injection** (used at KEKB, PEP-II, SLS,…); top-up **also avoids ramping & thermal transients, + eases tuning**

top-up injection: schematic cycle



top-up injection at PEP-II





J. Seeman

average luminosity ≈ peak luminosity

similar results from KEKB

TLEP Main Parameters

energy = 91, 160, 240, 350 & 500 GeV c.m.

circumference ~100 km

total SR power ≤ 100 MW

#IPs = 2 or 4

beam-beam tune shift / IP scaled from LEP

luminosity / IP ~ 5×10^{34} $cm^{-2}s^{-1}$ at the Higgs

~1000 x LEP2

top-up injection

$\beta_y^* = 1$ mm ~ σ_z

parameters	TLEP Z	TLEP W	TLEP H	TLEP t	
$E_{c.m.}$ [GeV]	**91**	**160**	**240**	**350**	
beam current [mA]	**1440**	**154**	**29.8**	**6.7**	
# bunches/beam	7500	3200	167	160	20
$\#e^{\pm}$/bunch [10^{11}]	4.0	1.0	3.7	0.88	7.0
ε_x, ε_y [nm]	29.2, 0.06	3.3,0.017	7.5, 0.015	2, .002	
$\beta^*_{x,y}$ [mm]	500, 1	200, 1	500, 1	1000, 1	
$\sigma^*_{x,y}[\mu$m]	121, 0.25	26, 0.13	61, 0.12	45,.045	126,.13
$\sigma^{tot}_{z,rms}$ [mm] (w BS)	2.93	1.98	2.11	0.77	1.95
E^{SR}_{loss}/turn [GeV]	0.03	0.3	1.7	7.5	
V_{RF},tot [GV]	2	2	6	12	
$\xi_{x,,y}$/IP	0.068	0.086	0.094	0.057	
$\mathcal{L}$ /IP[10^{34}cm^{-2}s^{-1}]	**59**	**16**	**5**	**1.3**	**1.0**
#IPs	**4**	**4**	**4**	**4**	
τ_{beam}[min] (rad.B)	99	38	**24**	**21**	**26**
τ_{beam}[min] (BS,η=2%)	>10^{25}	>10^{6}	**9**	**3.5**	**0.5**

parameters	LEP2	TLEP W	TLEP H	TLEP t	
$E_{c.m.}$ [GeV]	**209**	**160**	**240**	**350**	
beam current [mA]	**4**	**154**	**29.8**	**6.7**	
# bunches/beam	4	3200	167	160	20
$\#e^{\pm}$//bunch [10^{11}]	5.8	1.0	3.7	0.88	7.0
ε_x, ε_y [nm]	48, 0.25	3.3,0.017	7.5, 0.015	2, .002	
$\beta^*_{x,y}$ [mm]	1500, 50	200, 1	500, 1	1000, 1	
$\sigma^*_{x,y}$[μm]	270, 3.5	26, 0.13	61, 0.12	45,.045	126,.13
$\sigma^{tot}_{z,rms}$ [mm] (w BS)	16.1	1.98	2.11	0.77	1.95
E^{SR}_{loss}/turn [GeV]	3.41	0.3	1.7	7.5	
V_{RF},tot [GV]	3.64	2	6	12	
$\xi_{x,,y}$/IP	0.066 (y)	0.086	0.094	0.057	
$\mathcal{L}$ /IP[10^{34}cm^{-2}s^{-1}]	**0.0125**	**16**	**5**	**1.3**	**1.0**
#IPs	**4**	**4**	**4**	**4**	
τ_{beam}[min] (rad.B)	363	38	**24**	**21**	**26**
τ_{beam}[min] (BS,η=2%)	$>10^{35}$	$>10^{6}$	**9**	**3.5**	**0.5**

com-parison with LEP2

parameters	TLEP W	TLEP H	TLEP t		ZHH&ttH
$E_{c.m.}$ [GeV]	160	240	350		**500**
beam current [mA]	154	29.8	6.7		**1.6**
# bunches/beam	3200	167	160	20	10
$\#e^{\pm}$//bunch $[10^{11}]$	1.0	3.7	0.88	7.0	3.3
ε_x, ε_y [nm]	3.3,0.017	7.5, 0.015	2, .002		4., 0.004
$\beta^*_{x,y}$ [mm]	200, 1	500, 1	1000, 1		1000, 1
$\sigma^*_{x,y}[\mu m]$	26, 0.13	61, 0.12	45,.045	126,.13	63, 0.063
$\sigma^{tot}_{z,rms}$ [mm] (w BS)	1.98	2.11	0.77	1.95	1.81
E^{SR}_{loss}/turn [GeV]	0.3	1.7	7.5		**31.4**
V_{RF},tot [GV]	2	6	12		**35**
$\xi_{x,,y}$/IP	0.086	0.094	0.057		0.075
$\mathcal{L}$ /IP$[10^{34}cm^{-2}s^{-1}]$	16	5	1.3	1.0	**0.5**
#IPs	4	4	4		**4**
τ_{beam}[min] (rad.B)	38	24	21	26	**13**
τ_{beam}[min] (BS,η=2%**)**	$>10^6$	9	3.5	0.5	**~1(η=3%)**

TLEP energy upgrade?

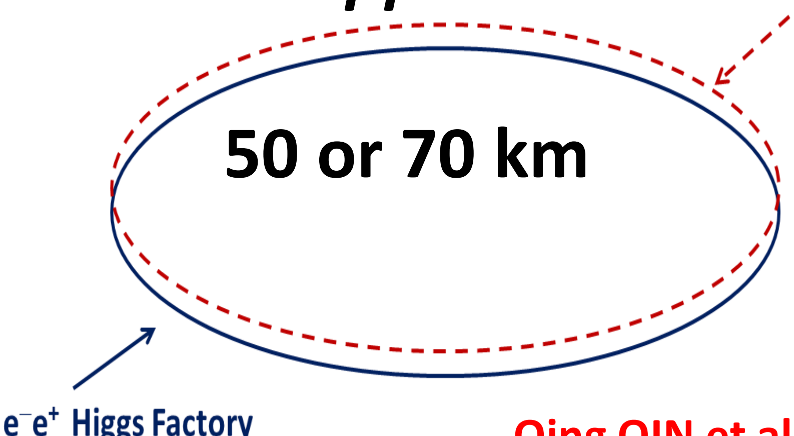
similar proposals around the world

SLAC/LBNL design: 27 km

Y. Cai,
U. Wienands,
A. Chao et al

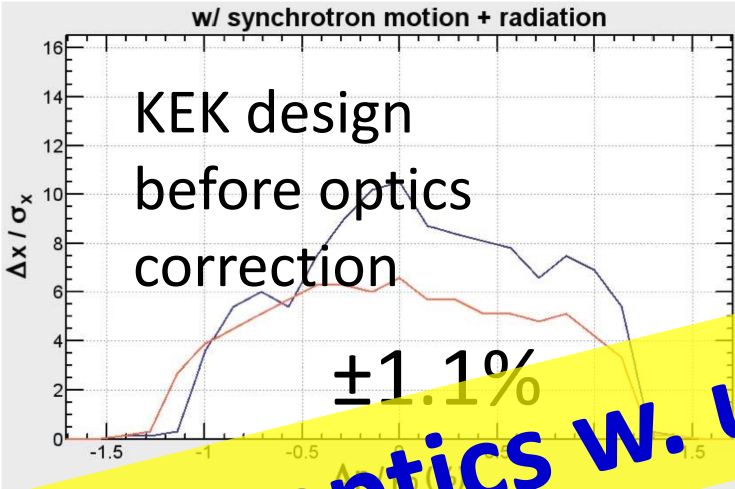
Chinese Higgs Factory *CEPC* + Chinese *pp* Collider

pp collider

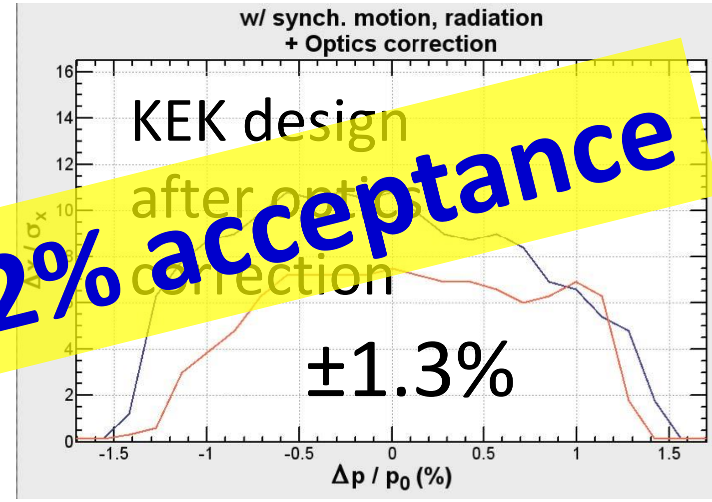


Qing QIN et al

IR optics - momentum acceptance η

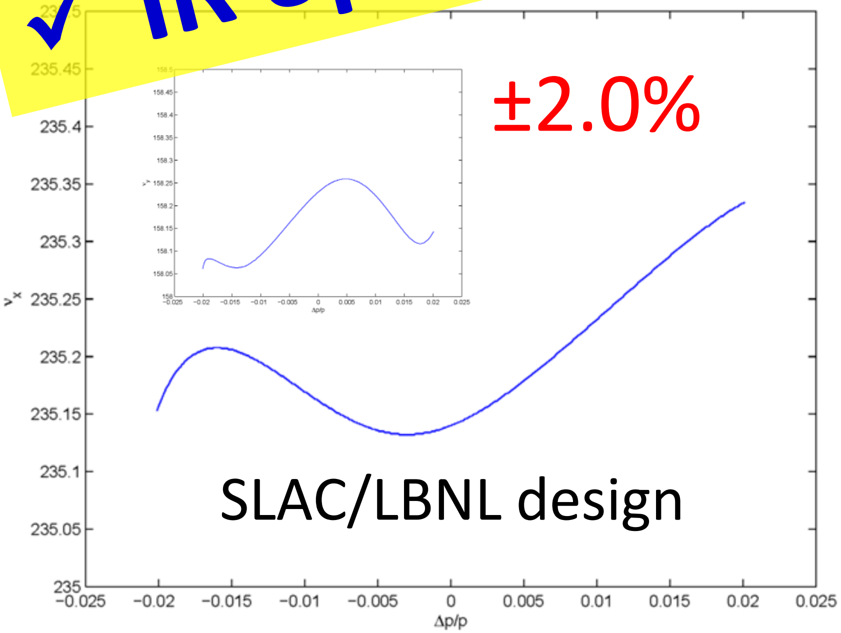


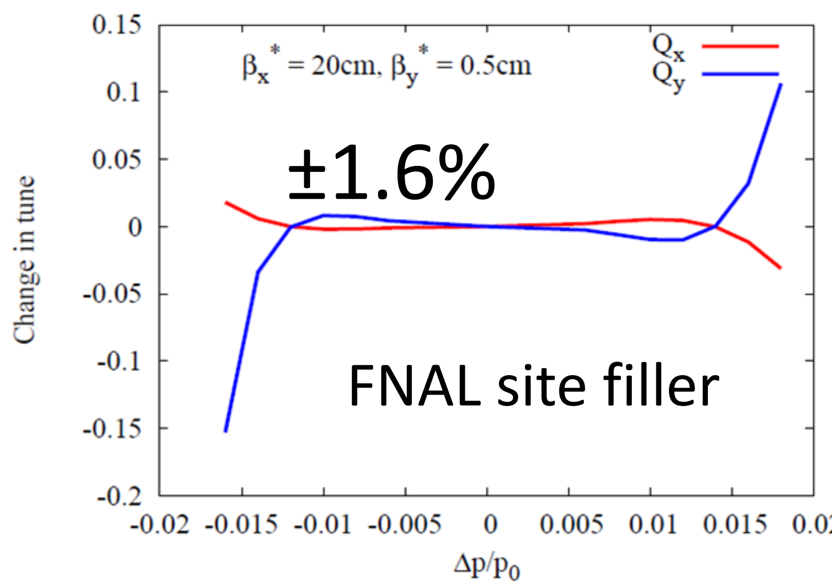
with synchrotron motion & radiation (sawtooth)



K. Oide

✓ IR optics w. up to η~2% acceptance

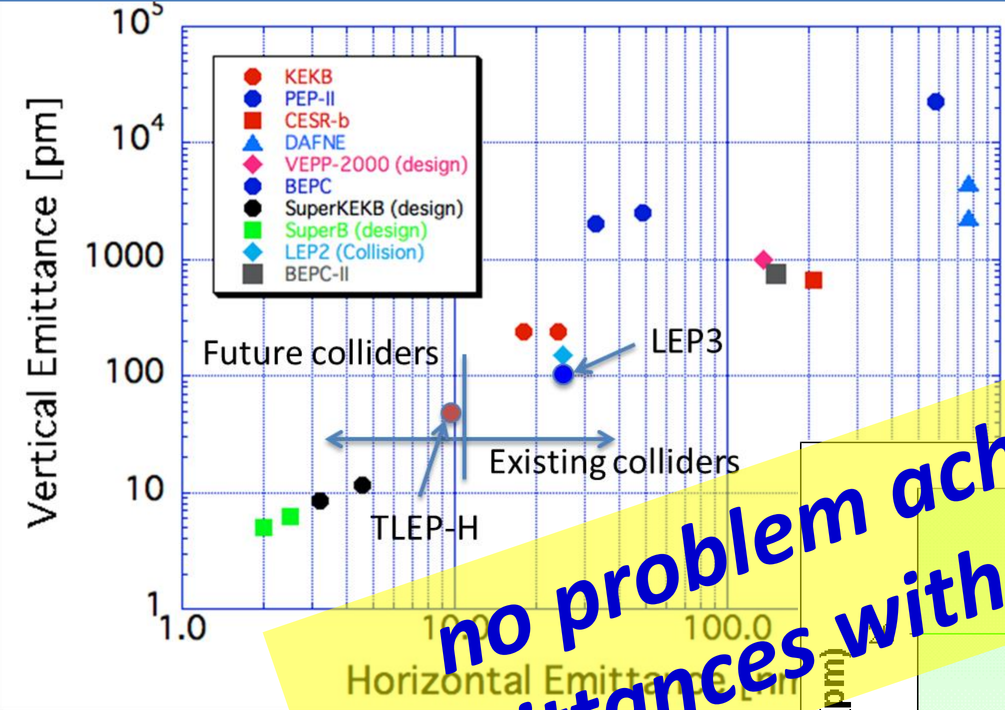




Y. Cai

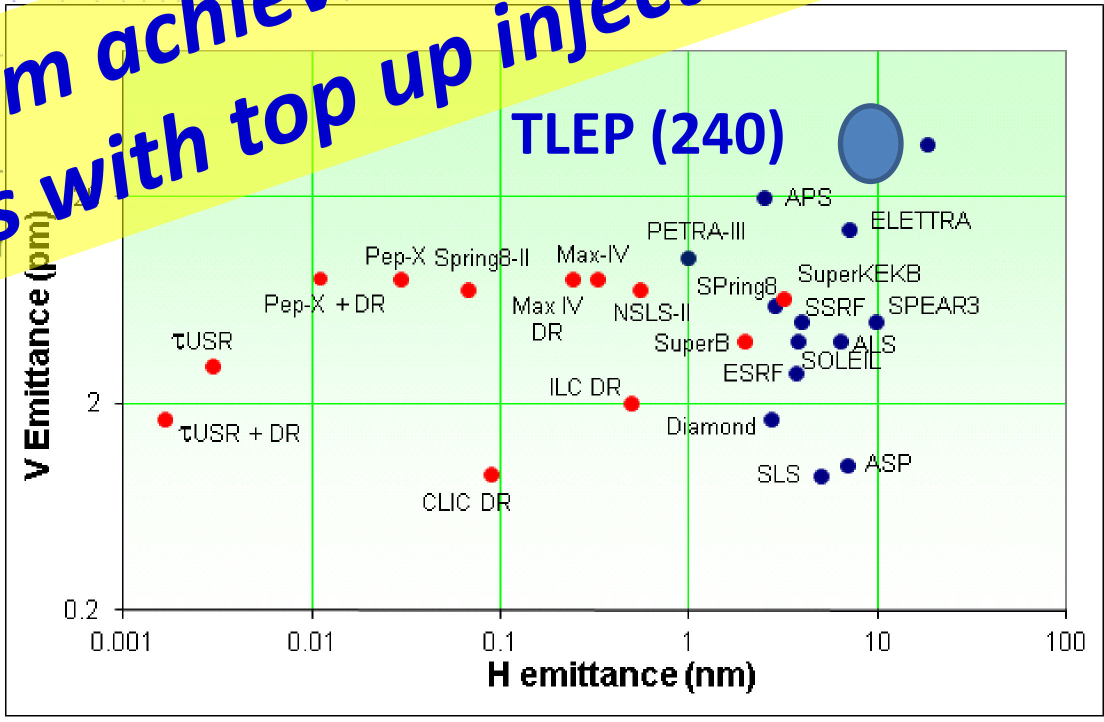
T. Sen, E. Gianfelice-Wendt, Y. Alexahin

Emittances in Circular Colliders & Modern Light Sources



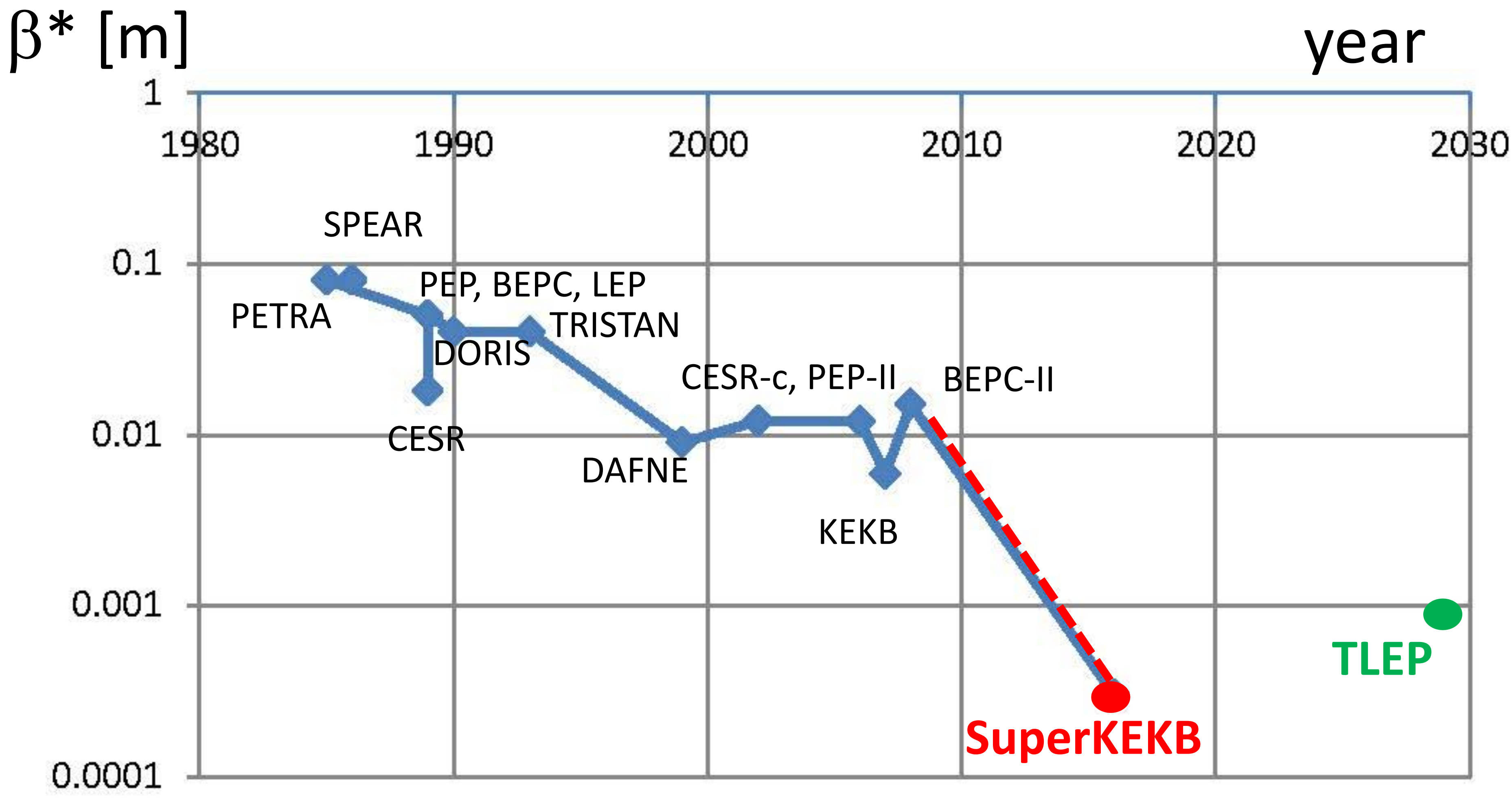
Y. Funakoshi, KEK

no problem achieving target emittances with top up injection



R. Bartolini, DIAMOND

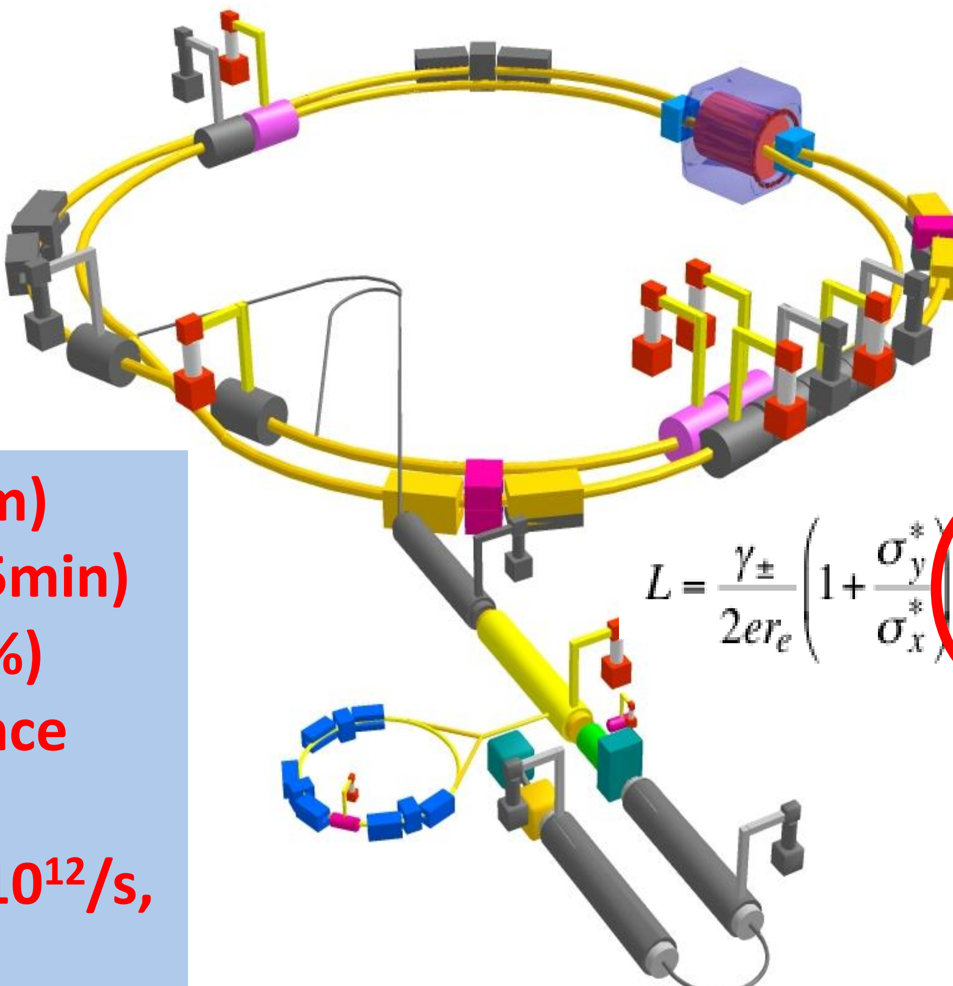
β* history



IP beam size $\sigma^* = \sqrt{\varepsilon\beta^*}$

SuperKEKB – a **TLEP demonstrator**

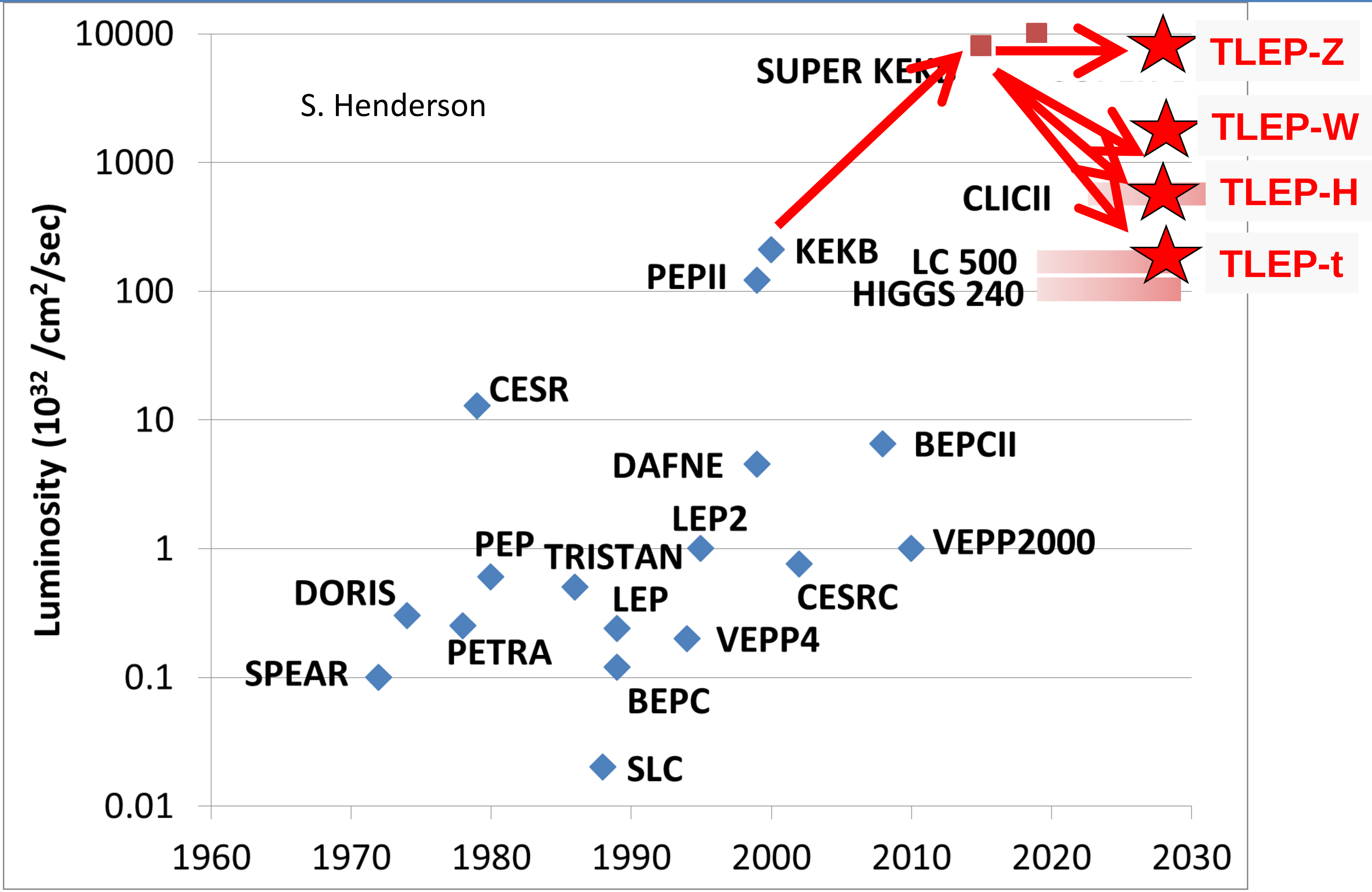
beam commissioning will start in early 2015



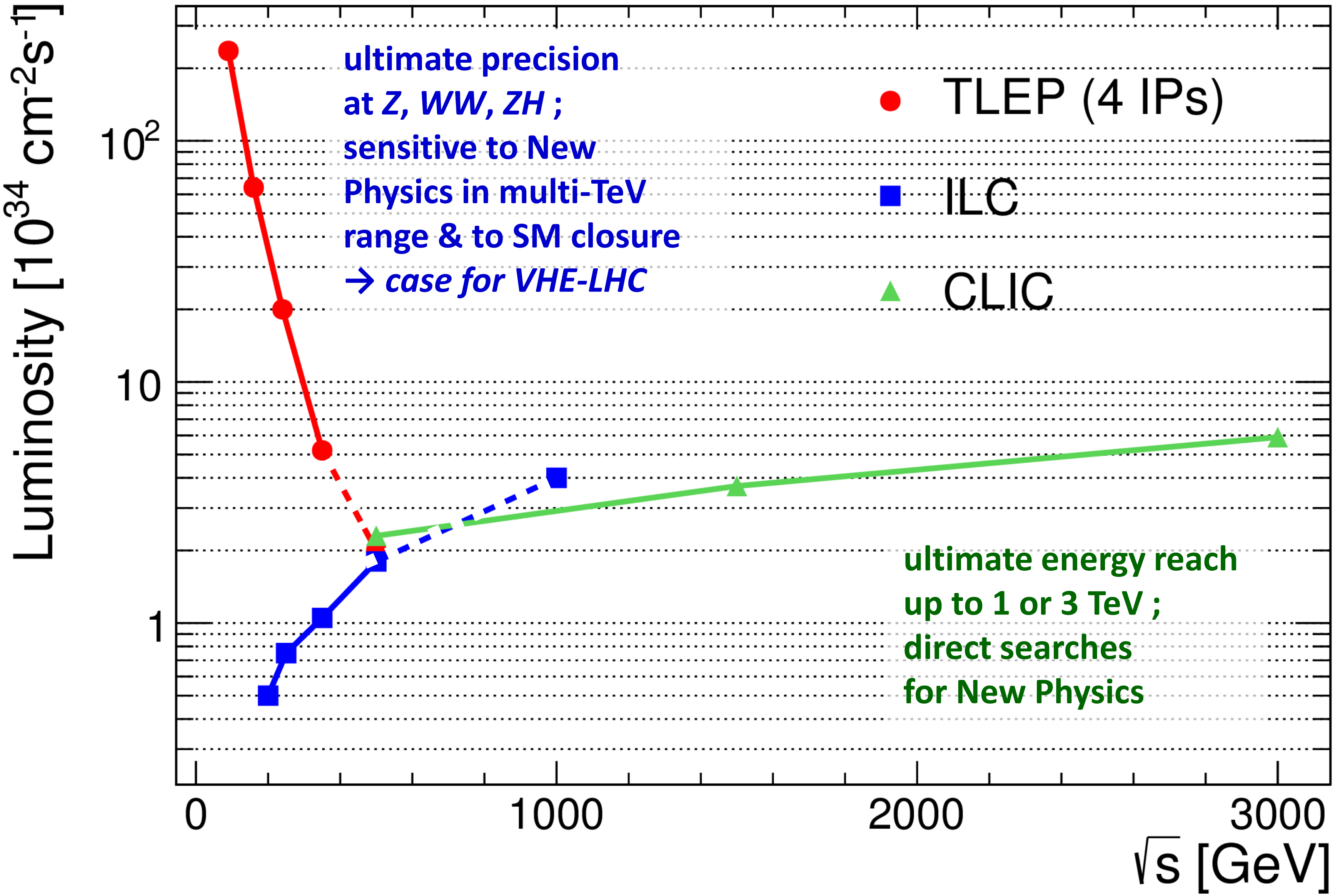
$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_\pm \xi_{\pm y}}{\beta_y^*}\right)\left(\frac{R_L}{R_y}\right)$$

- **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)**

luminosity of e^+e^- colliders



e^+e^- Higgs factories: luminosity



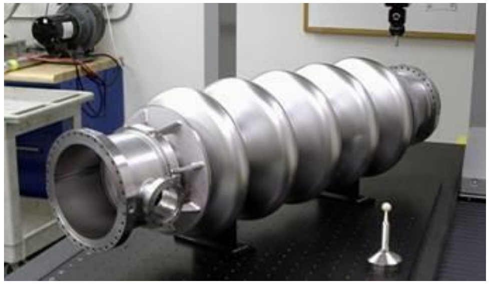
TLEP technical systems

- **SC RF at ~800 MHz**

  as developed for ESS, BNL, CERN SPL
  - need 12 GeV/turn at 350 GeV
    - **~600 m of SC RF cavities @ 20 MV/m**
      - **LEP2 had 600 m at 7 MV/m**
  - high power : ~200 kW / cavity in collider
    - power couplers similar to ESS –
      700-800 MHz preferred

✓ we could build it tomorrow!

BNL 5-cell 700 MHz cavity



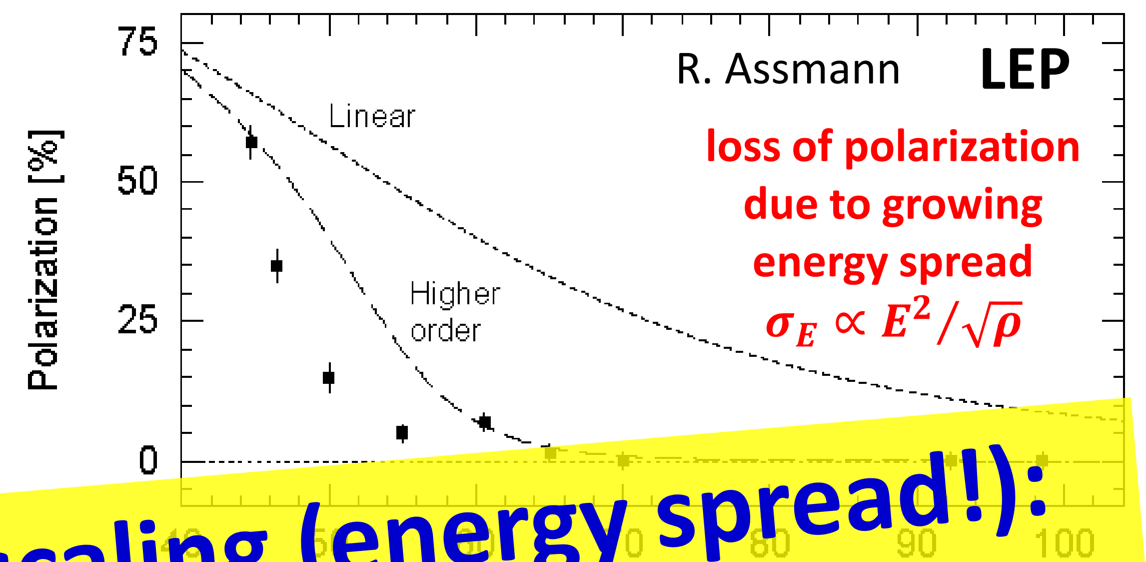
RF Coupler ESS

- **cryogenics system for the RF**
  - like LHC cryo system (~ ½ LHC's)
- **arc magnets**
  - ~500-700 G at top energy, ~50 G at injection
  - similar to LHeC prototype magnets

LHeC dipole w 0.35 mm laminations (BINP)

LHeC dipole with one-turn conductor & air cooled interleaved laminations [1 mm iron, 2 mm plastic] (CERN)

polarization



LEP

observations

+ model predictions

polarization scaling (energy spread!):

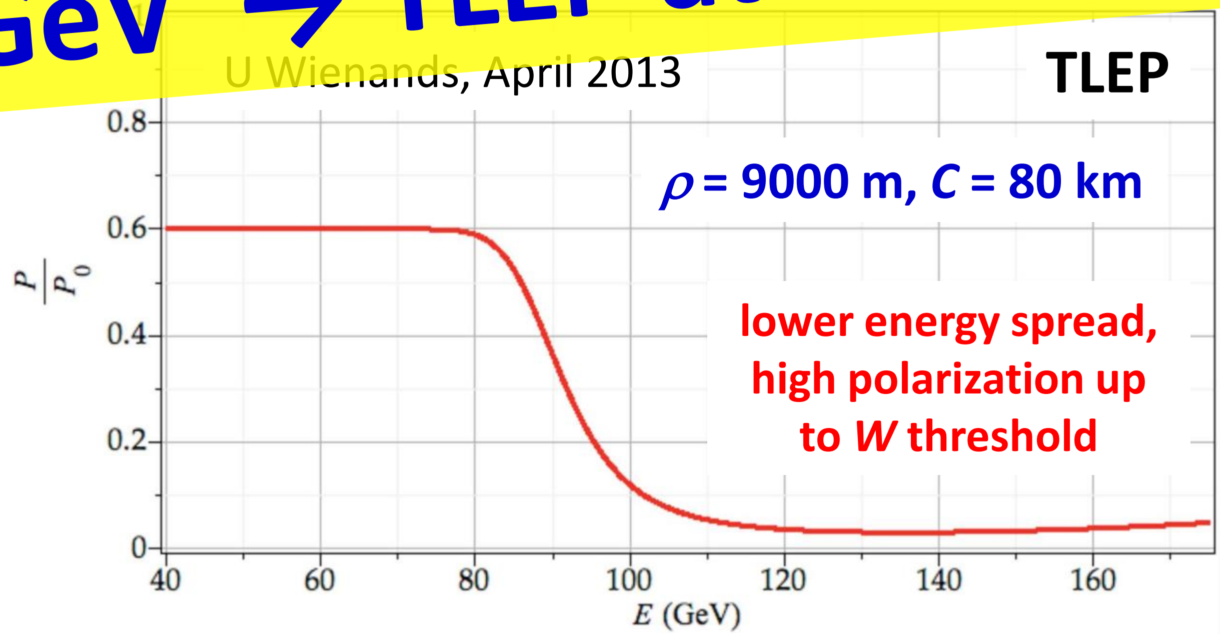
LEP at 61 GeV → TLEP at 81 GeV

TLEP

optimized scenario

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

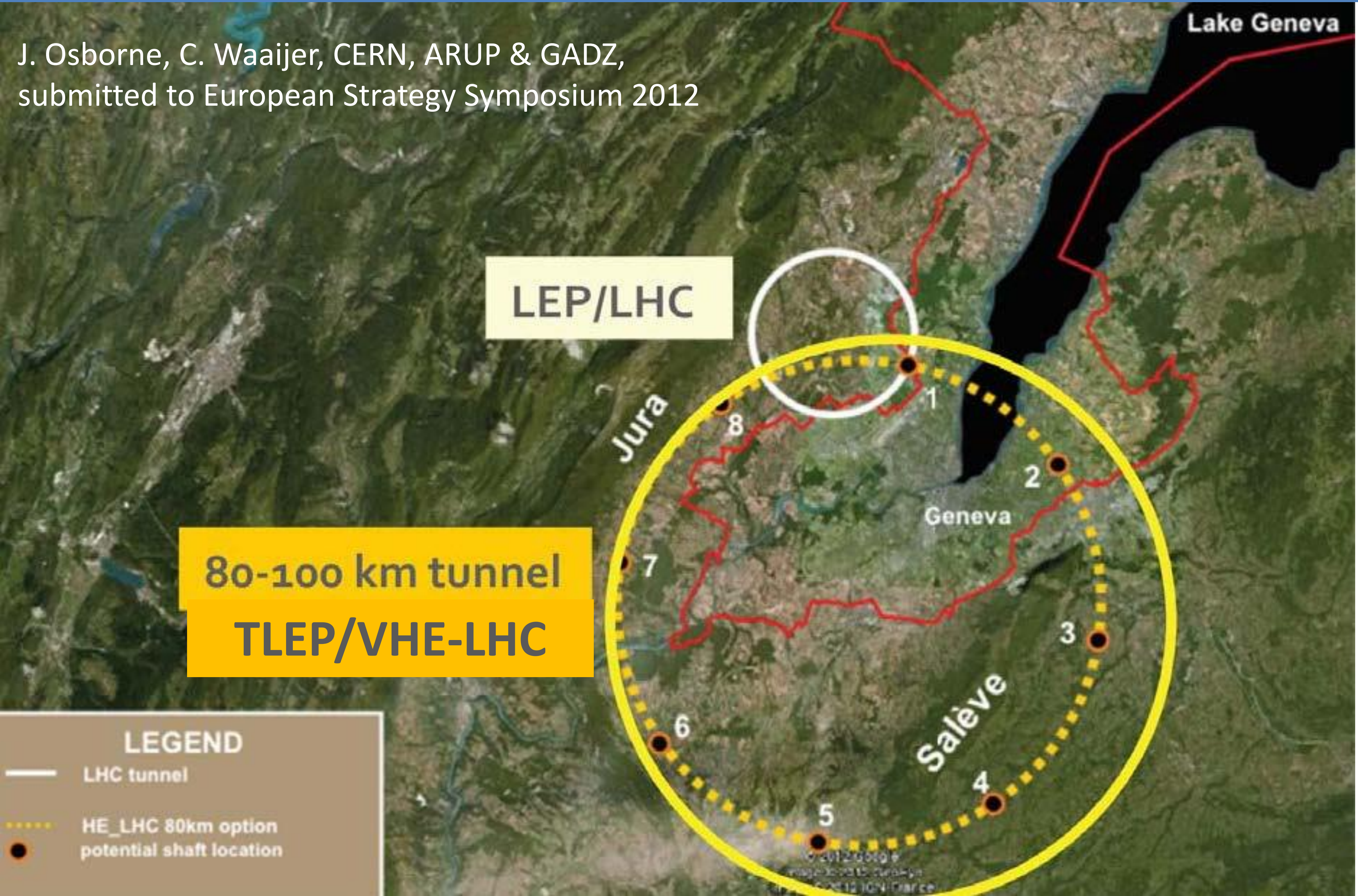
Δm_Z ~0.1 MeV, $\Delta\Gamma_Z$ ~0.1 MeV, Δm_W ~ 0.5 MeV



A. Blondel

80-100 km tunnel in Geneva region

J. Osborne, C. Waaijer, CERN, ARUP & GADZ,
submitted to European Strategy Symposium 2012



is 80-100 km too big?

"Of course, it should not be the size of an accelerator, but its costs which must be minimized."

Gustav-Adolf Voss,
builder of PETRA,
† 5. October 2013

FCC study - scope & structure

Future Circular Colliders (FCC) - Conceptual Design Study & Cost Review for next European Strategy Update

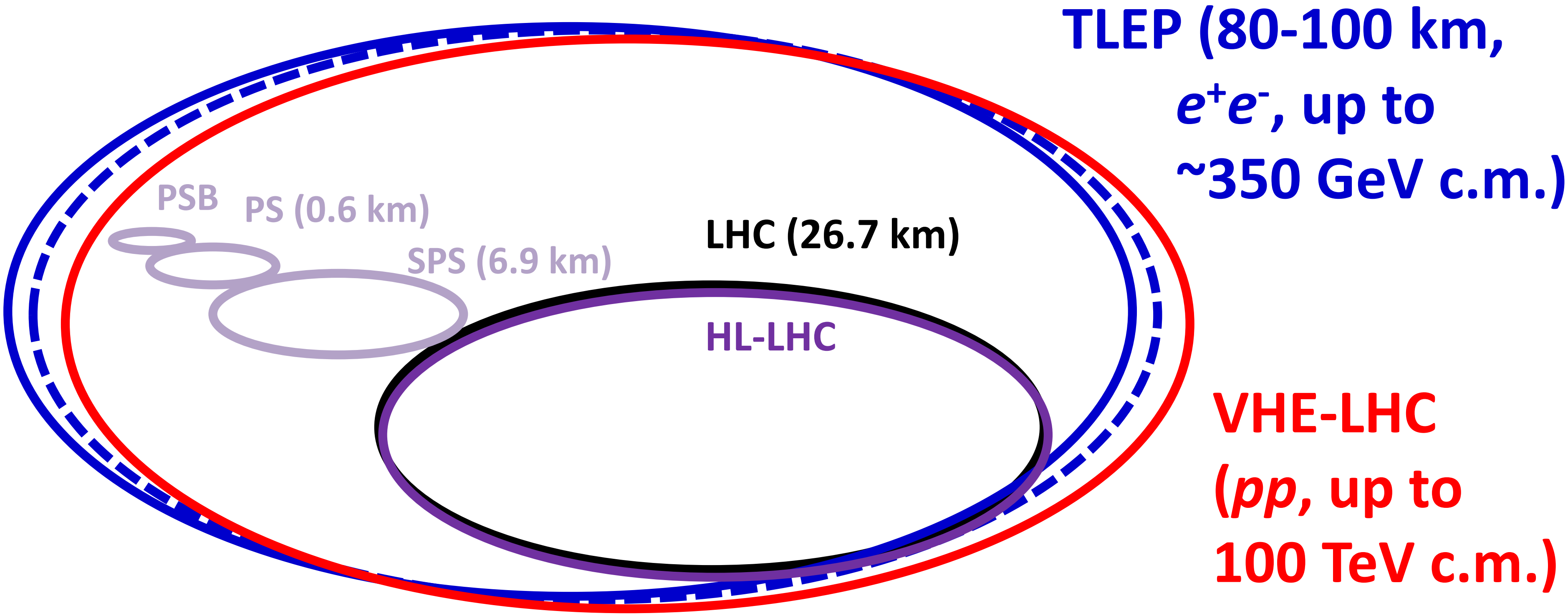
Infrastructure
tunnels, surface buildings, transport (access roads), civil engineering, cooling ventilation, electricity, cryogenics, communication & IT, fabrication and installation processes, maintenance, environmental impact and monitoring,

Hadron injectors	Hadron collider	e+ e- collider
Beam optics and dynamics	Optics and beam dynamics	Optics and beam dynamics
Functional specs	Functional specifications	Functional specifications
Performance specs	Performance specs	Performance specs
Critical technical systems	Critical technical systems	Critical technical systems
Operation concept	Related R+D programs	Related R+D programs
	HE-LHC comparison	Injector (Booster)
	Operation concept	Operation concept
	Detector concept	Detector concept
	Physics requirements	Physics requirements

e- p option: Physics, Integration, additional requirements

two pillars: *pp* & *e*$^+$*e*$^-$; emphasis on *pp* machine, driving infrastructure

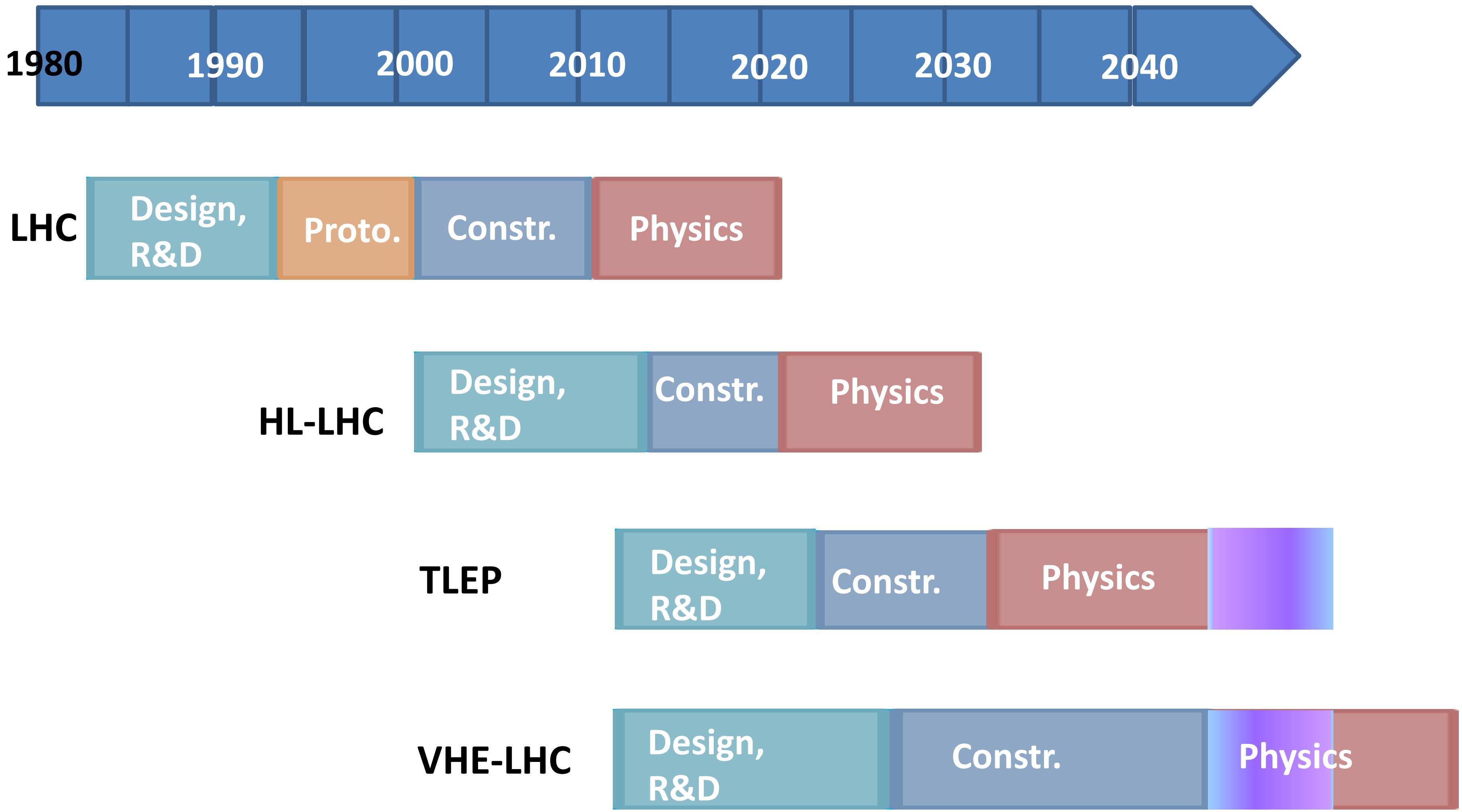
possible long-term strategy



& $e^{\pm}$ **(120 GeV) – *p* (7, 16 & 50 TeV)** collisions (**[(V)HE-]TLHeC**)

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

tentative long-term time line



back up

synchroton-radiation: heat load

	PEPII	SPEAR3	LEP3	TLEP-Z	TLEP-H	TLEP-t
E (GeV)	9	3	120	45.5	120	175
I (A)	3	0.5	0.0072	1.18	0.0243	0.0054
rho (m)	165	7.86	2625	9000	9000	9000
Linear Power (W/cm)	101.8	92.3	30.5	8.8	8.8	8.8

TLEP has >10 times less SR heat load per meter than PEP-II or SPEAR! (though higher photon energy)

N. Kurita, U. Wienands, SLAC

SR heat per meter lower than for many operating rings