FCC-ee Higgs and Electroweak Factory

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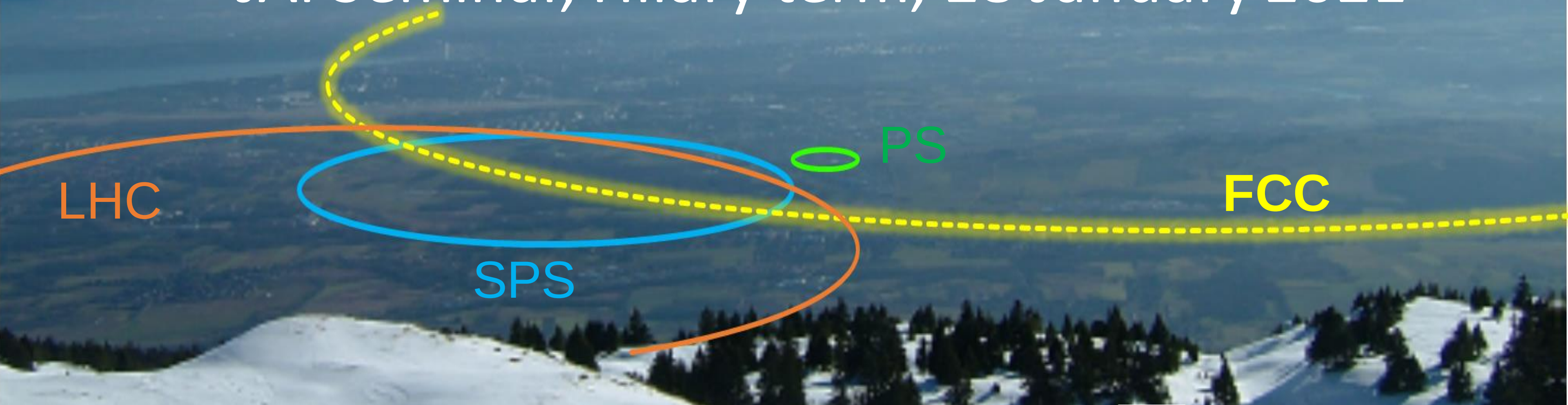
CERN, BE Department

JAI Seminar, Hilary term, 28 January 2021



http://cern.ch/fcc

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photo: J. Wenninger

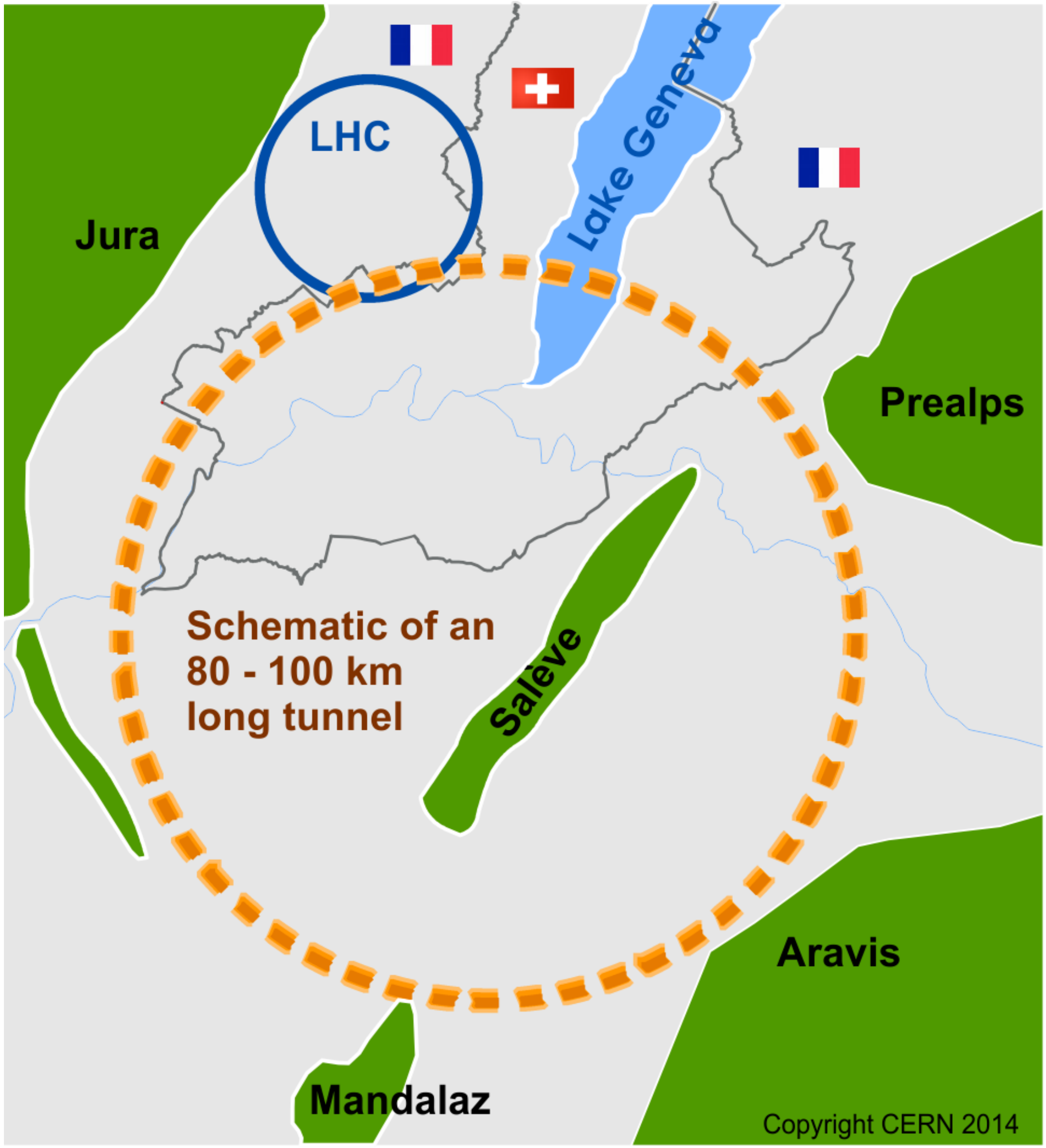
Future Circular Collider Study
launched in 2014

international FCC collaboration (CERN as host lab) to study:

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

~16 T ⇒ 100 TeV *pp* in 100 km

- **80-100 km infrastructure** in Geneva area
- **e^+e^- collider (*FCC-ee*) as a possible first step**
- *p-e* (*FCC-he*) option, HE-LHC …



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CepC/SppC study (CAS-IHEP), 100 km collider, one of the proposed sites

Qinhuangdao (秦皇岛）

CepC, SppC

100 km

50 km

easy access
300 km east
from Beijing
3 h by car
1 h by train

"Chinese Toscana"

Yifang Wang

FCC-ee physics requirements

A. Blondel,
J. Ellis ,
C. Grojean,
P. Janot,
et al.

- ☐ ***beam energy range from 35 GeV to ≈200 GeV***
- ☐ ***highest possible luminosities*** *at all working points*
- ☐ physics programs / energies:

Z (45.5 GeV) Z pole, 'TeraZ' and high precision M_Z *&* Γ_Z

W (80 GeV) W pair production threshold, high precision M_W

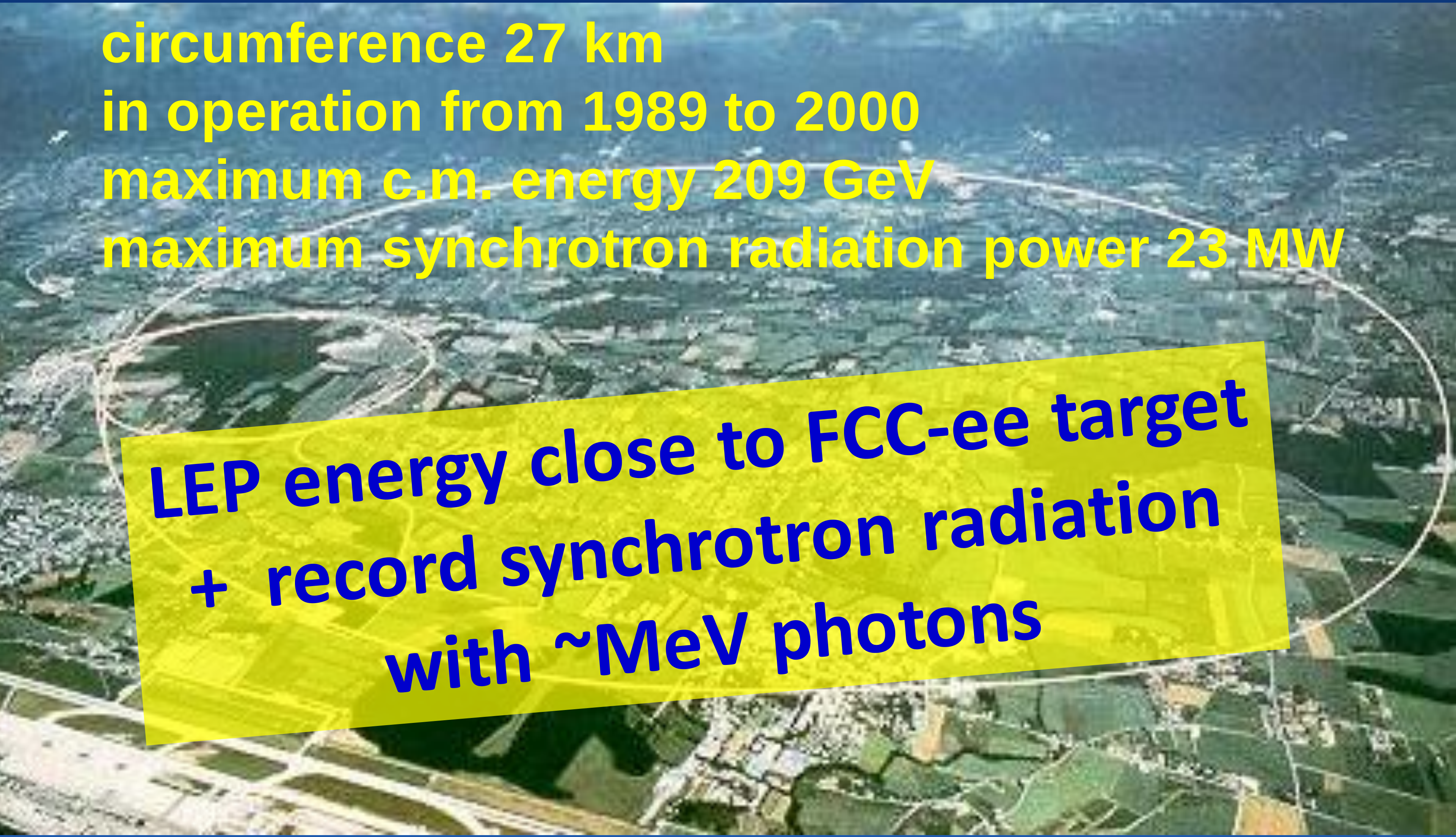
H (120 GeV) ZH production (maximum rate of H's)

t (182.5 GeV): $t\bar{t}$ *threshold, H studies*

more (α_{QED} etc.)

- ☐ possibly *H* (63 GeV) direct *s*-channel production with **monochromatization**
- ☐ **some polarization up to ≥80 GeV** for beam energy calibration
- ☐

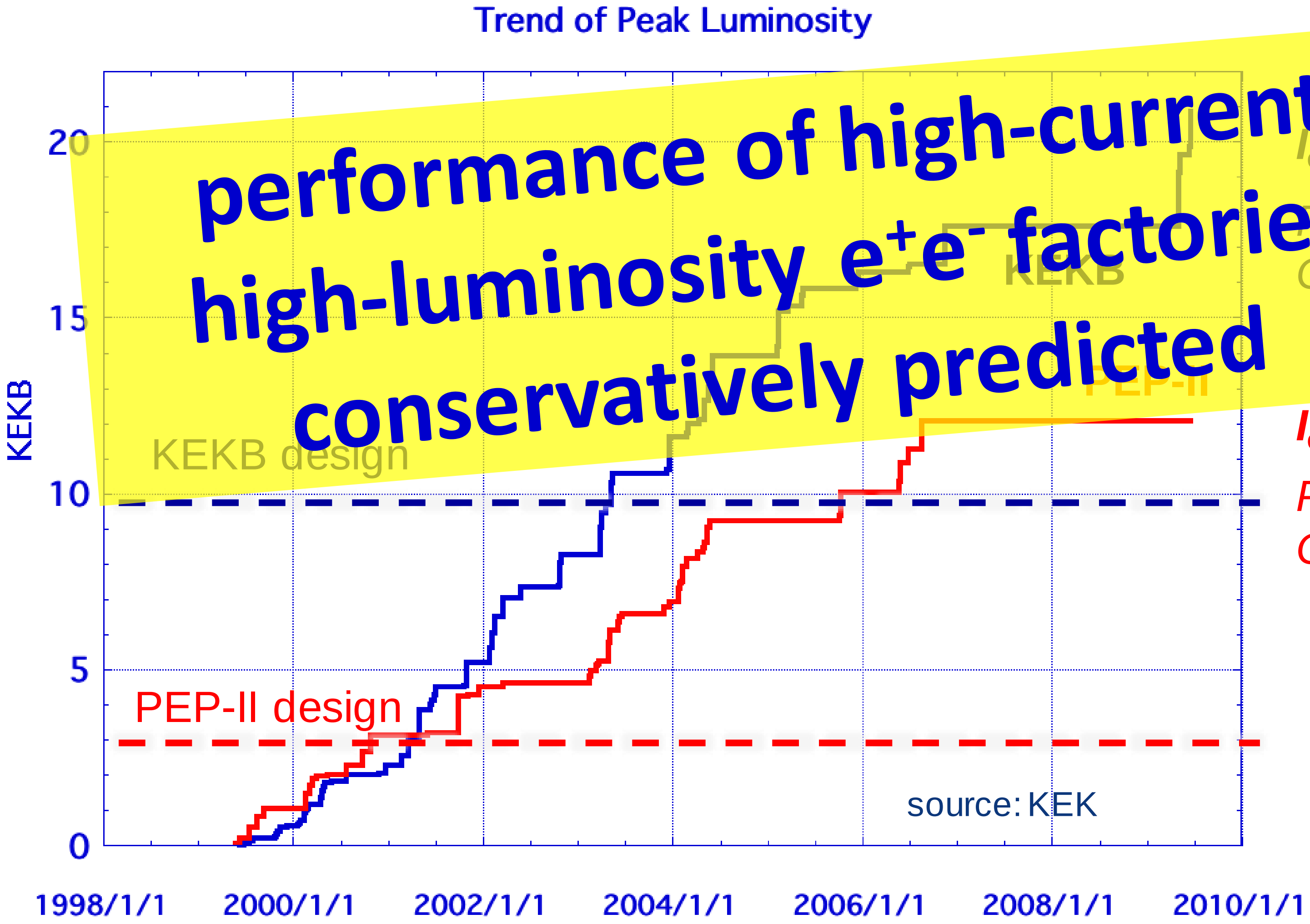
LEP/LEP2: highest energy so far



circumference 27 km
in operation from 1989 to 2000
maximum c.m. energy 209 GeV
maximum synchrotron radiation power 23 MW

LEP energy close to FCC-ee target + record synchrotron radiation with ~MeV photons

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



source: KEK

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

I_{e+}=1.6 A, I_{e-}=1.2 A

P_{SR} ~ 5 MW

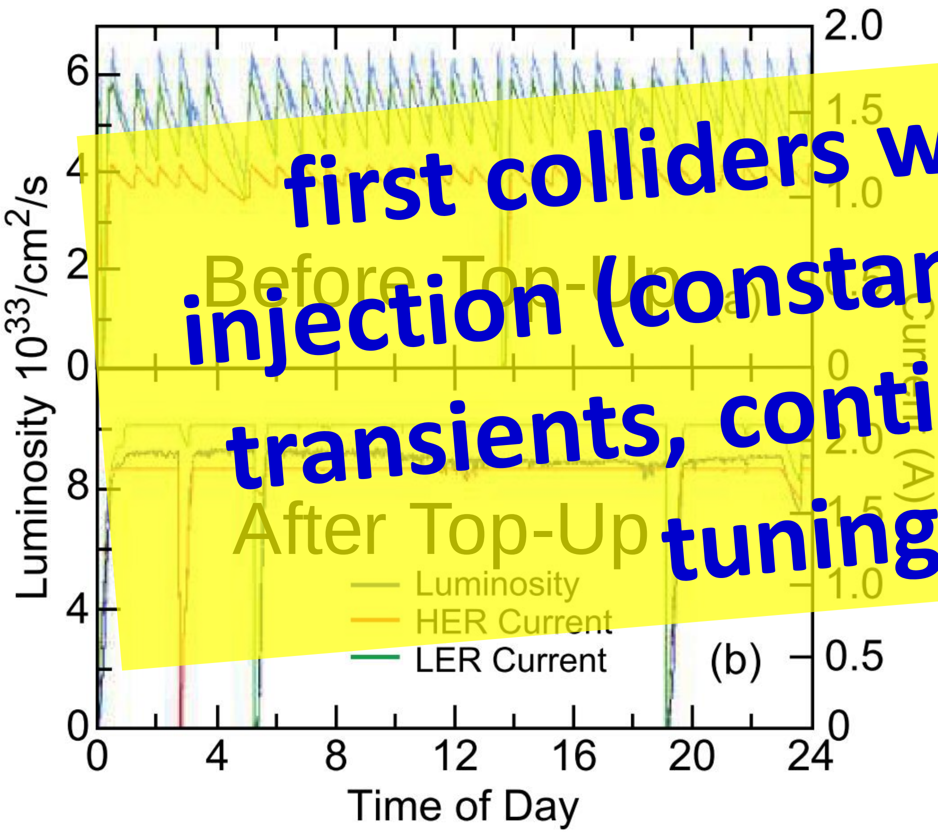
C = 3 km

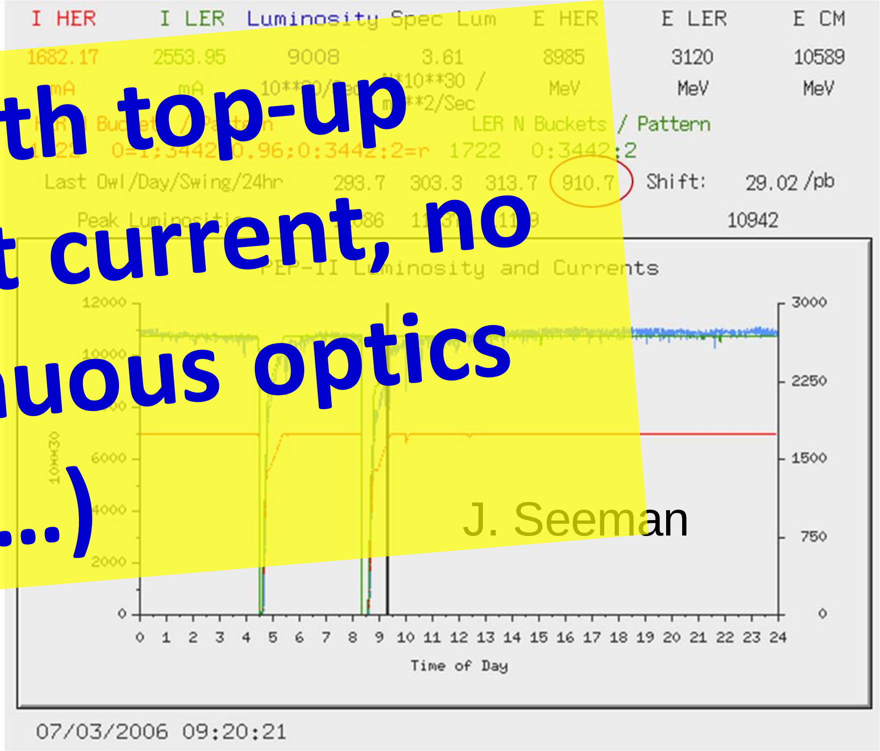
I_{e+}=3.2 A, I_{e-}=2.1 A

P_{SR} ~ 8 MW

C = 2.2 km

KEKB & PEP-II: top-up injection





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

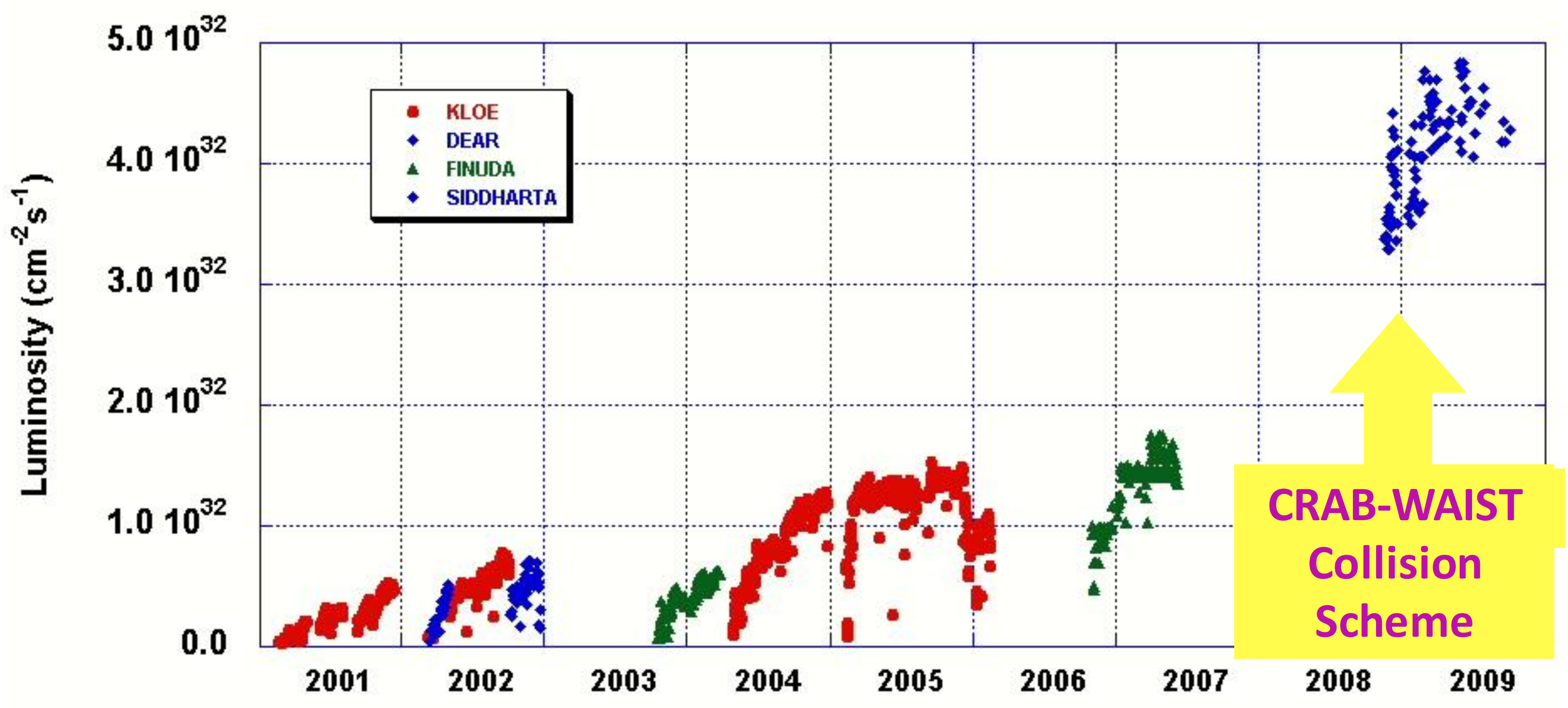
J. Seeman

average luminosity ≈ peak luminosity

similar results from KEKB

DAΦNE: "crab waist" collisions

DAΦNE Peak Luminosity

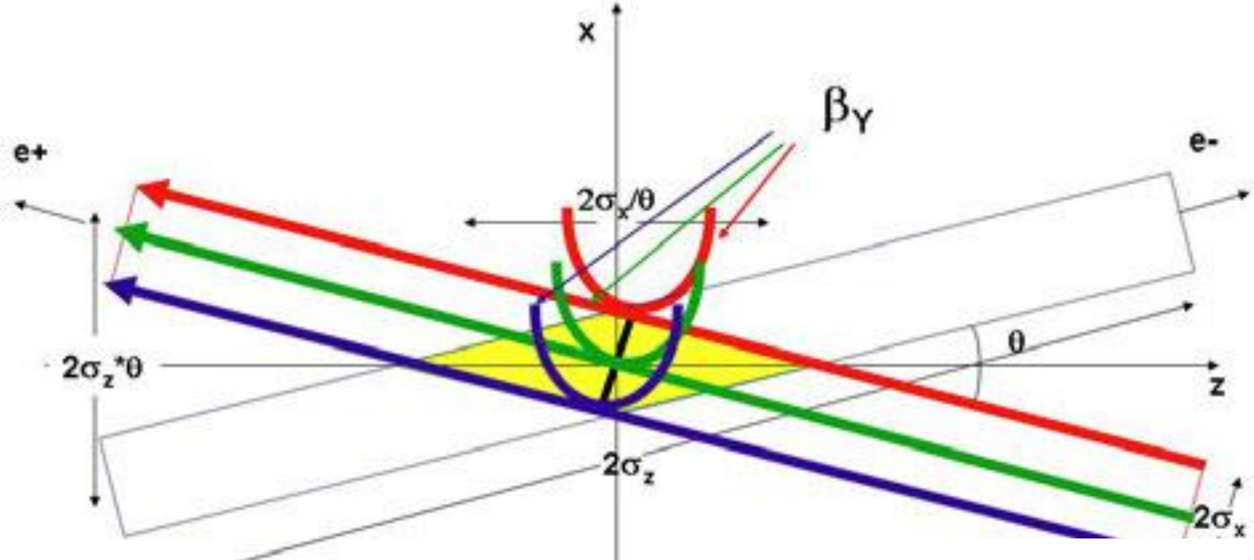


CRAB-WAIST Collision Scheme

Design Goal

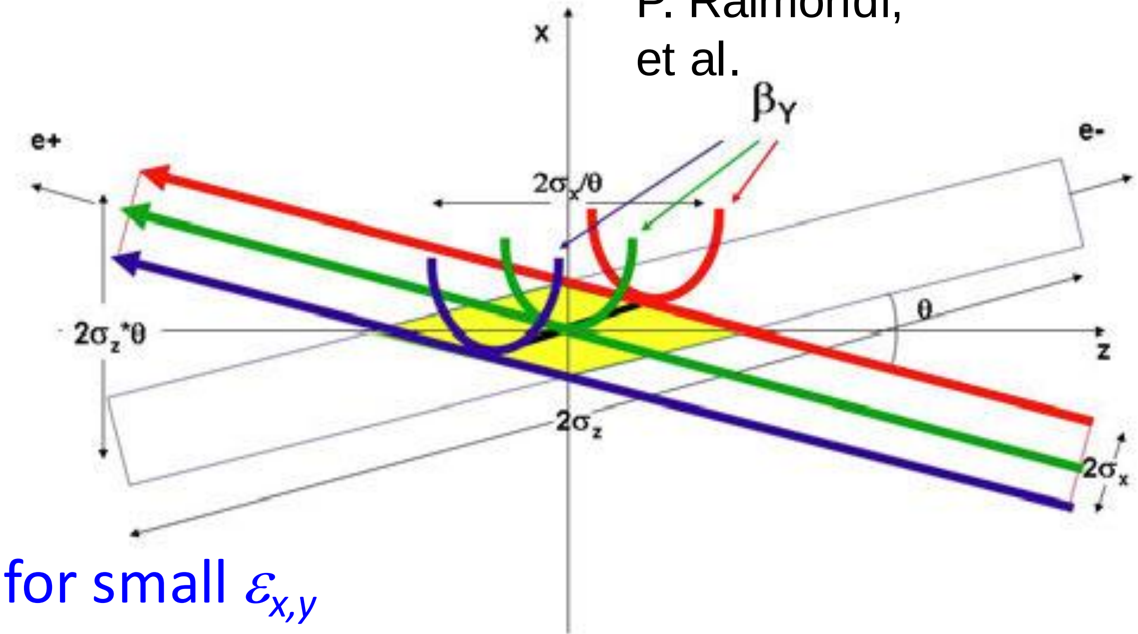
M. Zobov

crab-waist crossing for flat beams



regular crossing

P. Raimondi,
et al.



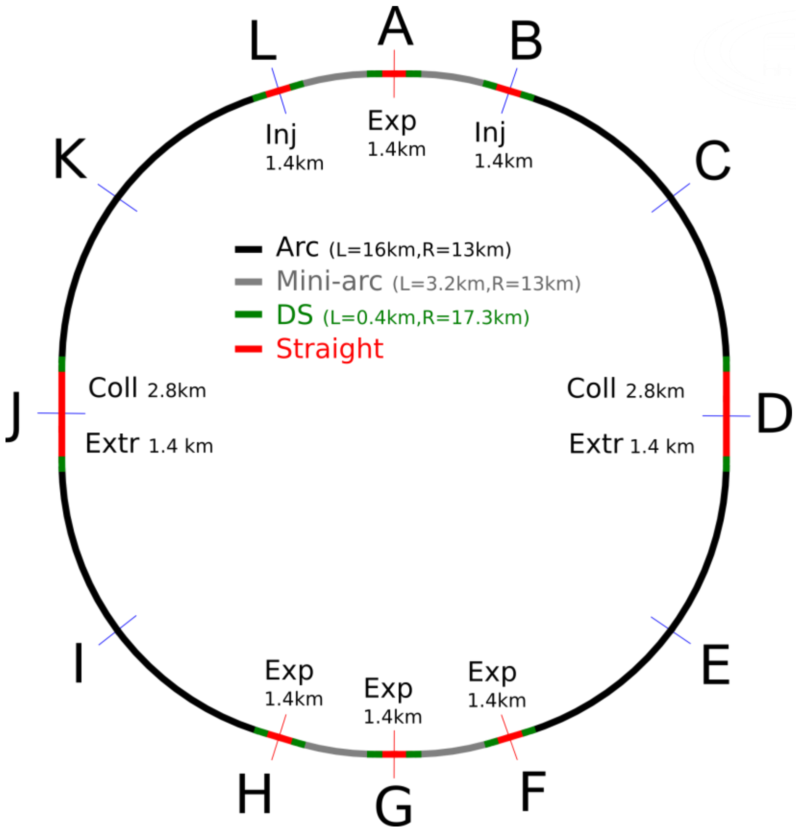
crab waist -

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

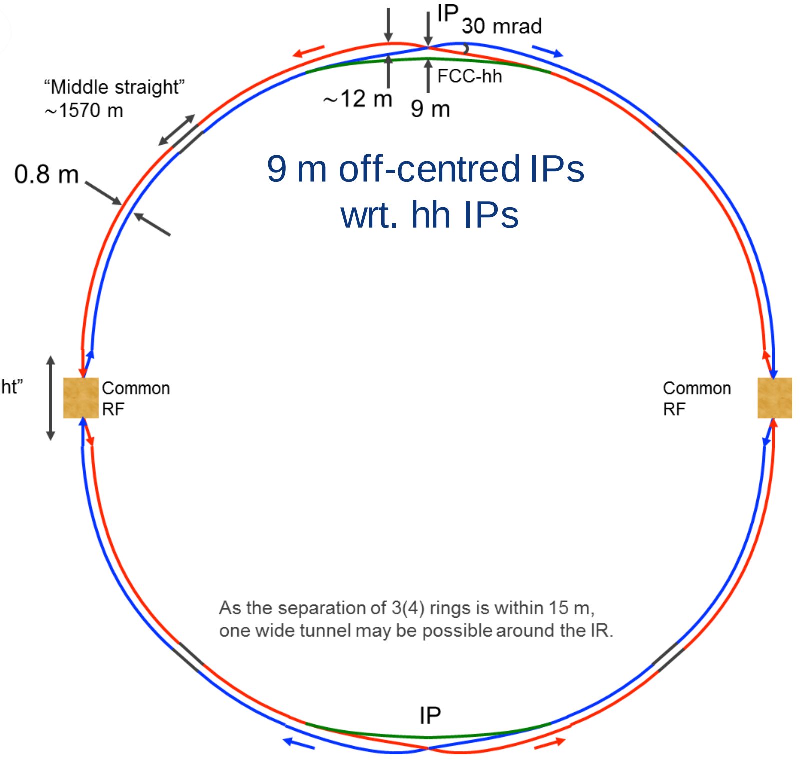
- allows for small $\beta_y{}^*$ and for small $\varepsilon_{x,y}$
- and avoids betatron resonances (→higher beam-beam tune shift)

FCC consistent machine layouts

FCC-hh



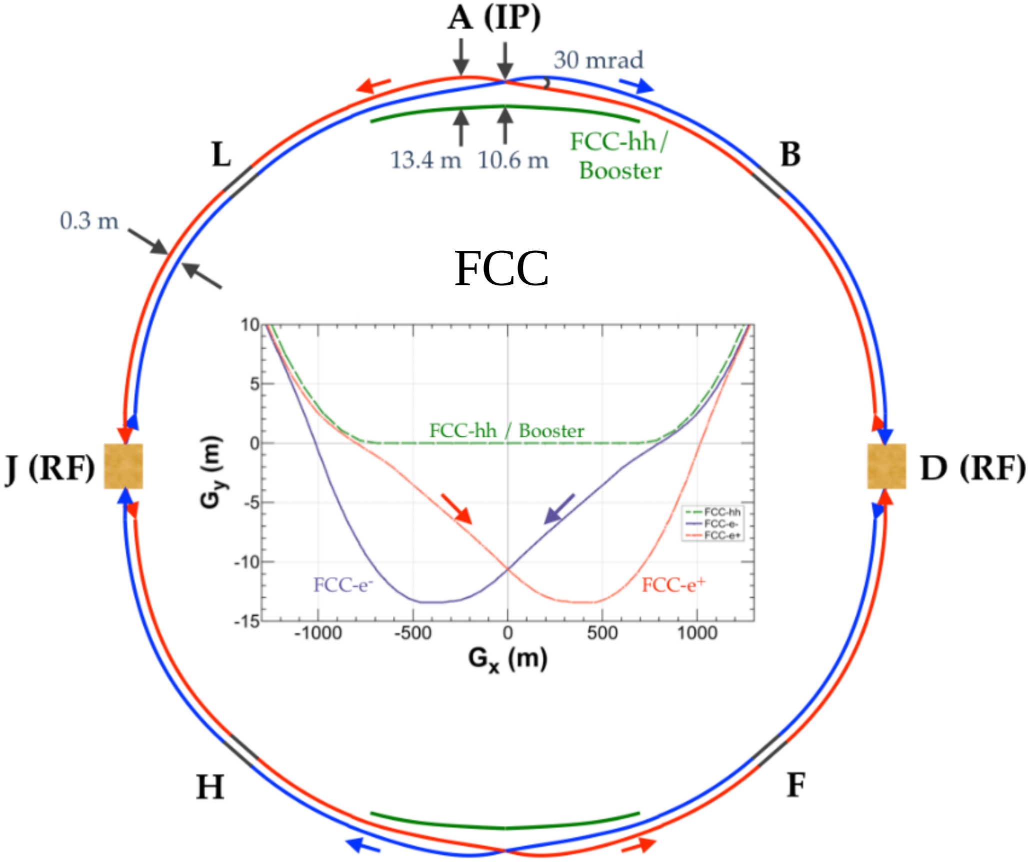
FCC-ee 1, FCC-ee 2, FCC-ee booster (FCC-hh footprint)

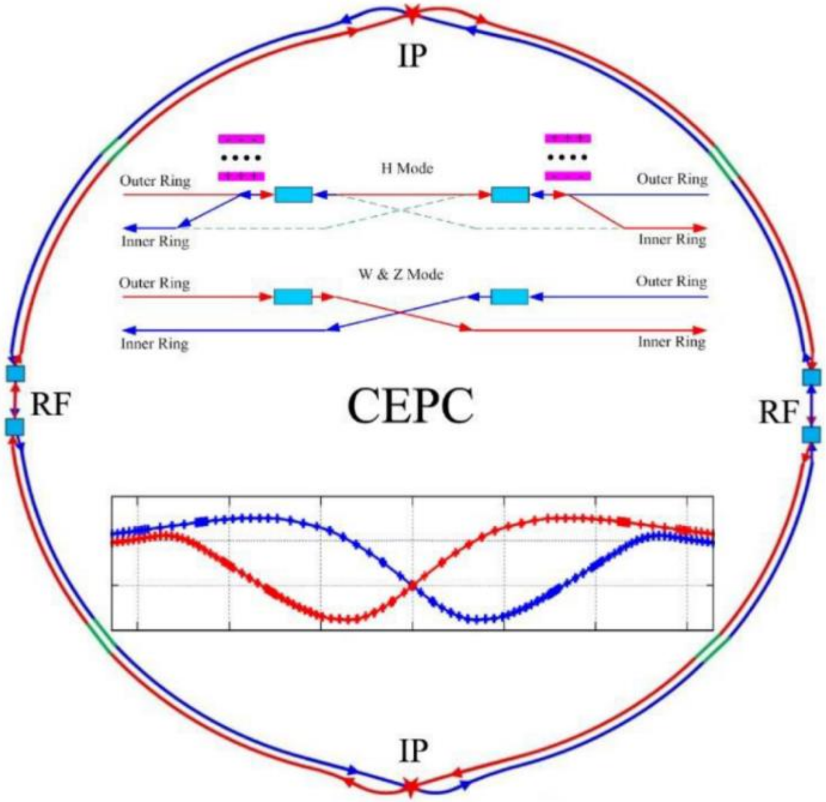


Closed optics solutions for full ring for both machines available

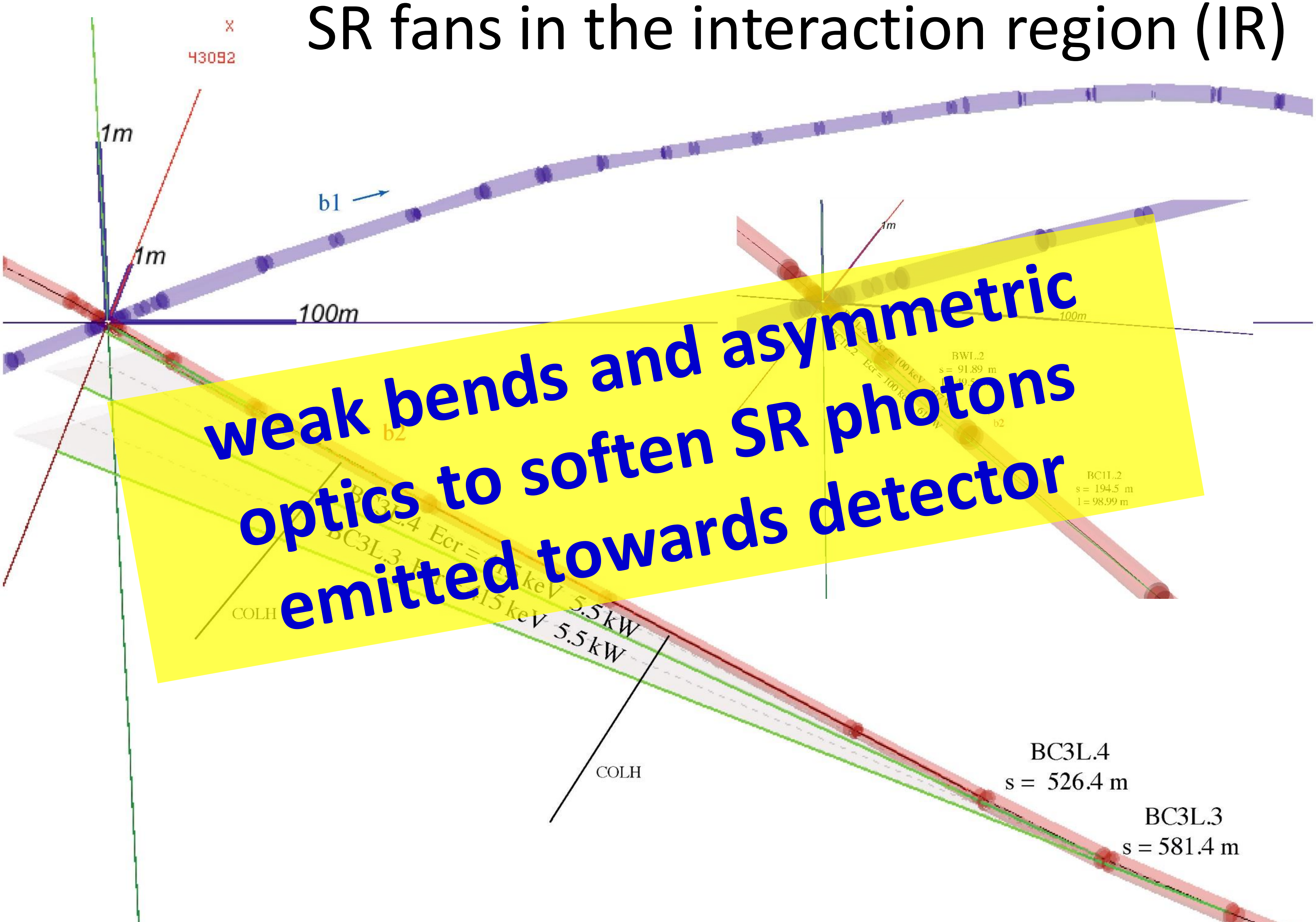
similar solutions for FCC-ee and CEPC

- **Double ring** colliders with full-energy **top-up booster** ring,
- **CEPC evolved** from initial 54 km - single-ring design, practically **to the FCC-ee 100 km design**.
- **2 IPs, 2 RF straights**, tapering of arc magnet strengths to match local energy
- **Asymmetric IR** layout to limit SR of incoming beams towards detectors and generate large crossing angle
- Common use of RF systems for both beams at highest energy working point (ttbar/ZH for FCC-ee/CEPC)





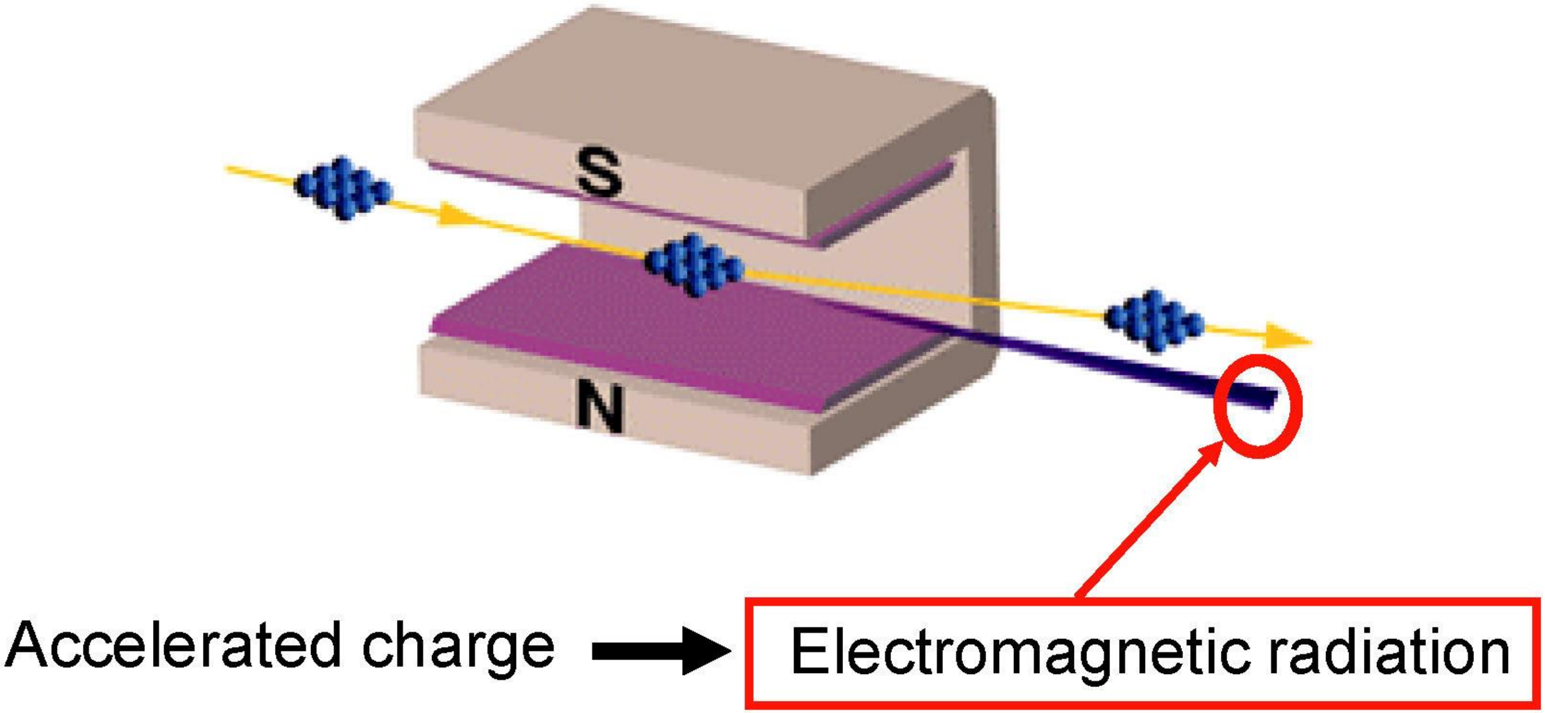
SR fans in the interaction region (IR)



weak bends and asymmetric optics to soften SR photons emitted towards detector

A. Blondel, H. Burkhardt, M. Koratzinos, K. Oide

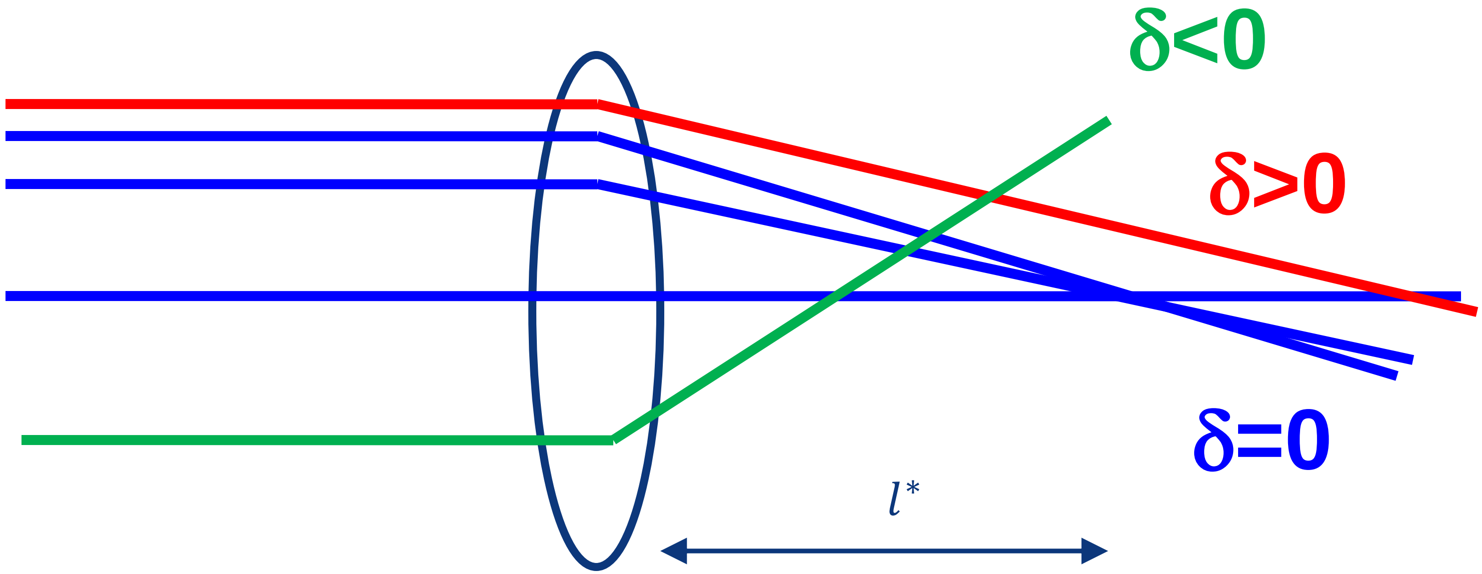
curved orbit of e^- in magnetic field



Accelerated charge → Electromagnetic radiation

L. Rivkin

final focus chromaticity

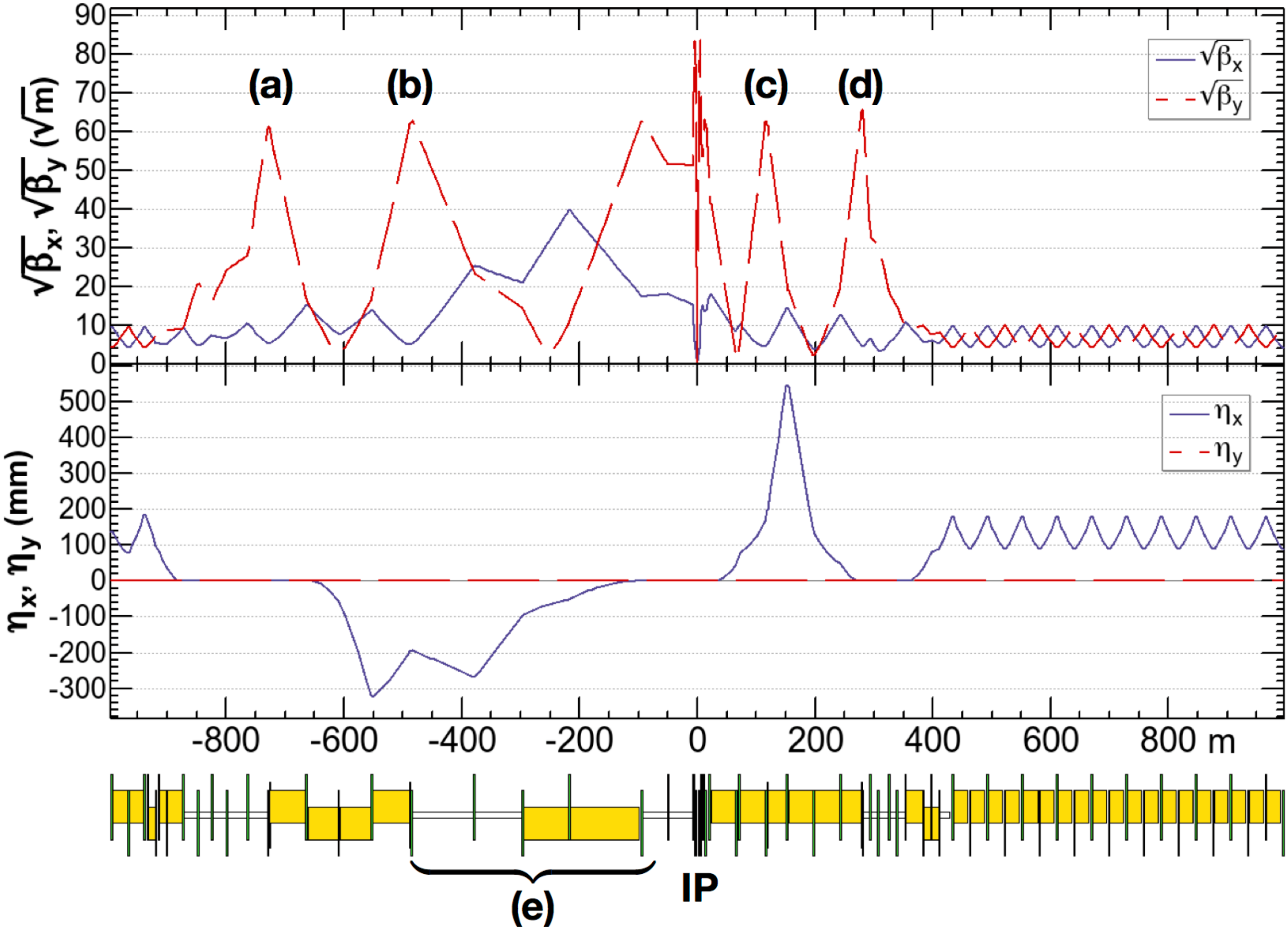


spot size increase due to (uncorrected) chromaticity,

$$\frac{\Delta\sigma_y^*}{\sigma_{y0}^*} = \xi\delta_{rms}$$

$$\sigma_{y0}^* \equiv \sqrt{\beta_y^*\varepsilon_y}, \qquad \xi \approx \frac{l^*}{\beta^*}$$

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)**

ttbar 182.5 GeV

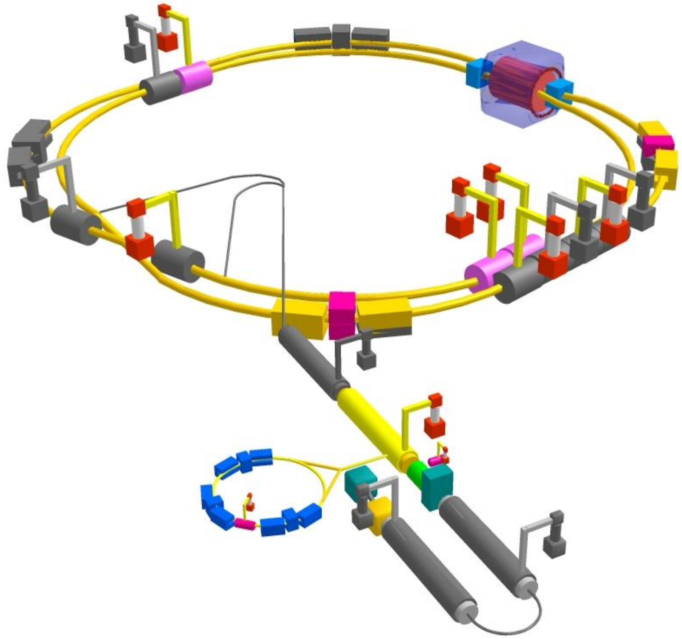
yellow boxes: dipole magnets

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

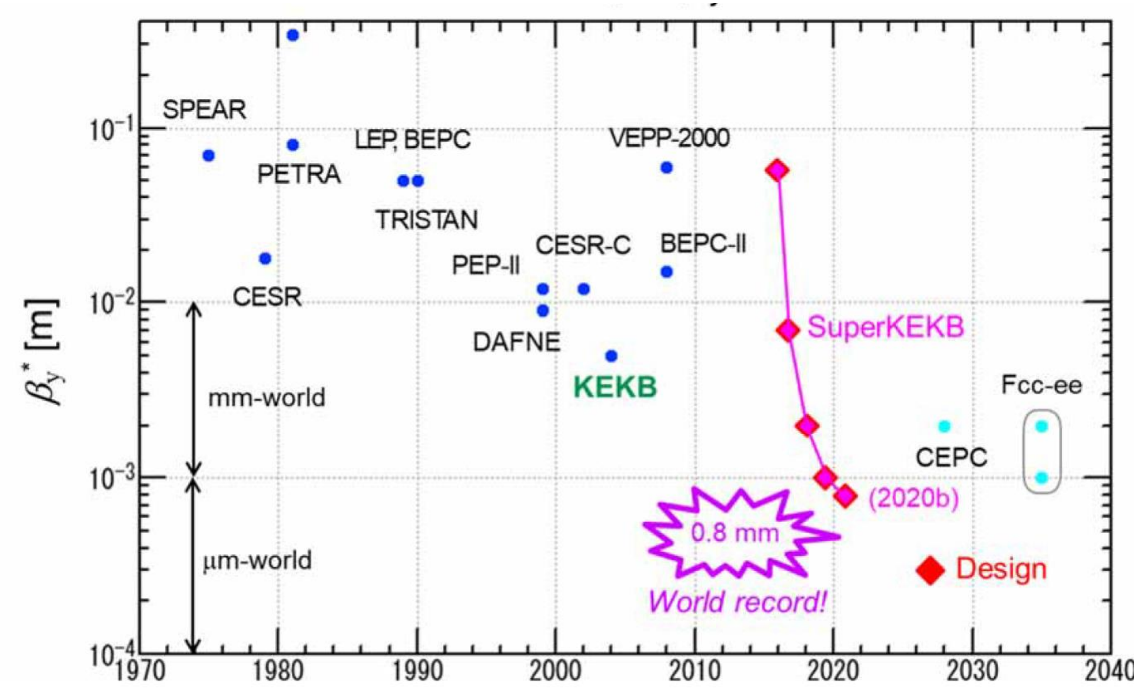
SuperKEKB – pushing luminosity and β^*

Design: **double ring e^+e^- collider as *B*-factory** at 7(e^-) & 4(e^+) GeV; **design luminosity ~8 x 10^{35} cm^{-2}s^{-1}**; β_y^* **~ 0.3 mm; nano-beam – large crossing angle** collision scheme **(crab waist w/o sextupoles)**; **beam lifetime ~5 minutes**; **top-up** injection; ce$^+$ **rate up to ~ 2.5 10^{12} /s ;** **under commissioning**



Y. Funakoshi, Y. Ohnishi, K. Oide

M. Tobiyama, K. Oide



SuperKEKB is demonstrating FCC-ee key concepts

β_y^* = 0.8 mm achieved in both rings in summer 2020 – using the FCC-ee-style "virtual" crab-waist collision scheme

arc synchrotron radiation (SR) 1

energy loss per turn $U_0 = \frac{e^2}{3\epsilon_0}\frac{\gamma^4}{\varrho}$

$$\frac{1}{\rho} = \frac{eB}{p}$$

$$U_0[\text{keV}] = 88.46\frac{E[\text{GeV}]^4}{\rho[\text{m}]}$$

numerical values
for electrons

$\propto E^4/m^4 \propto \gamma^4$

→ RF voltage

synchrotron radiation power

$$P_{SR} = \frac{2U_0 I_b}{e}$$

$\propto E^4/m^4 \propto \gamma^4$

electrons: $P_{SR} = 23$ MW for LEP, 100 MW for FCC-ee
protons: $P_{SR} = 0.01$ MW for LHC, 5 MW for FCC-hh

→ RF power

critical (typical) photon energy

$$E_{\gamma,c} = \frac{3}{2}\hbar c\frac{\gamma^3}{\rho}$$

→ shielding

electrons: $E_{c,\gamma}$ ~ 1 MeV for LEP and FCC-ee;
protons: $E_{c,\gamma}$ ~40 eV LHC, ~4 keV FCC-hh

arc synchrotron radiation 2

radiation damping of transverse and longitudinal motion
→beam shrinkage

$$\tau_{||} = \tau_x/2 = (C/c)E/U_0 \propto \rho^2/\gamma^3$$

electrons: $\tau_{||}\sim$ 3 ms for LEP, 20 ms FCC-ee at 240 GeV cm
protons: $\tau_{||}\sim$13 h for LHC, 0.5 h FCC-hh

equilibrium emittance due to balance of radiation damping and quantum excitation

$$\varepsilon_x = C_q \gamma^2 l_b^3 F/\rho^3$$

l_b: length of half cell

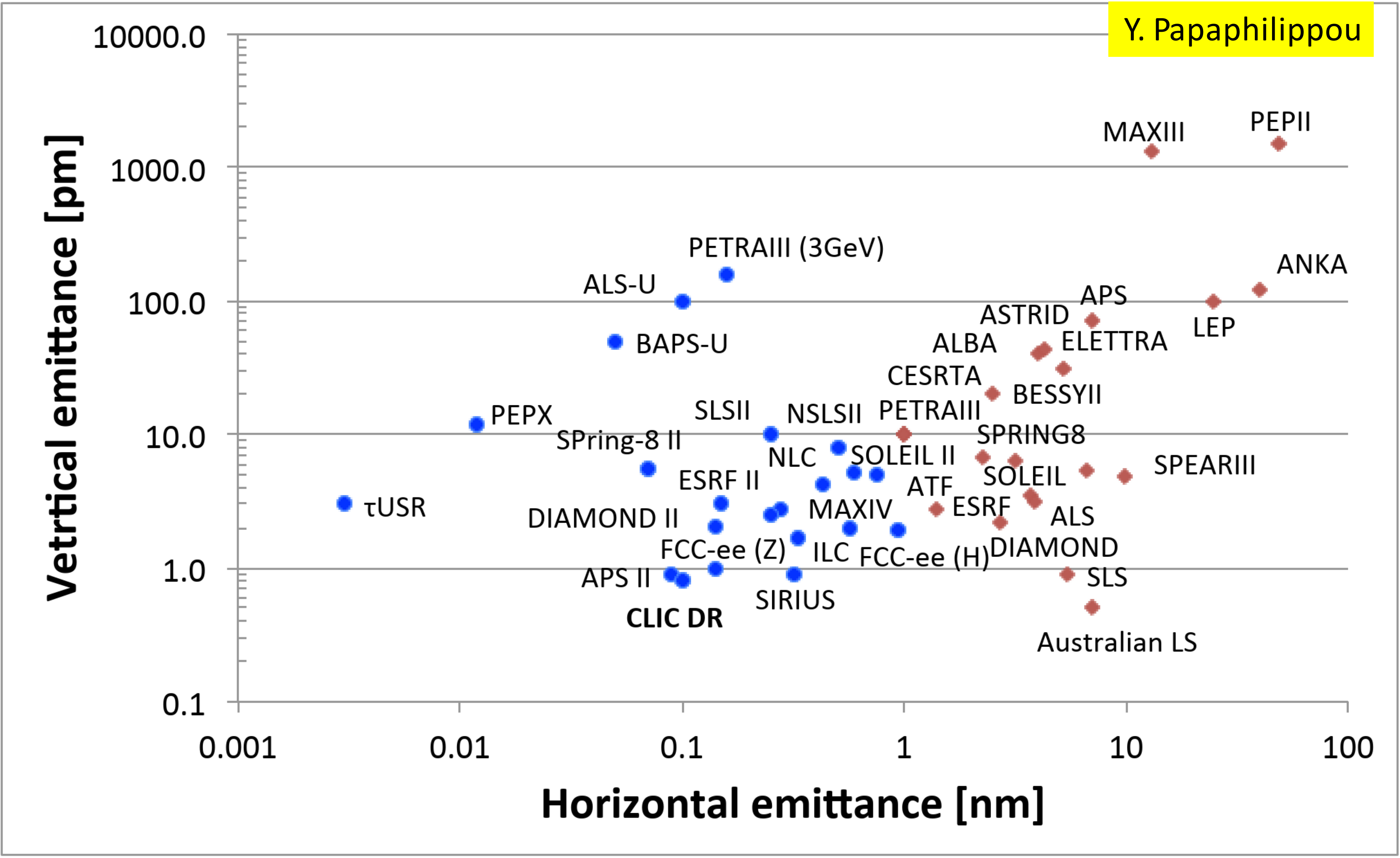
→ cell length

$$C_q = \frac{55}{32\sqrt{3}}\frac{\hbar c}{mc^2} \approx \begin{cases} 4\times 10^{-13}\text{ m for electrons} \\ 2\times 10^{-16}\text{ m for protons}\end{cases}$$

$F \approx 3$ for standard arc optics (90 deg FODO cell)

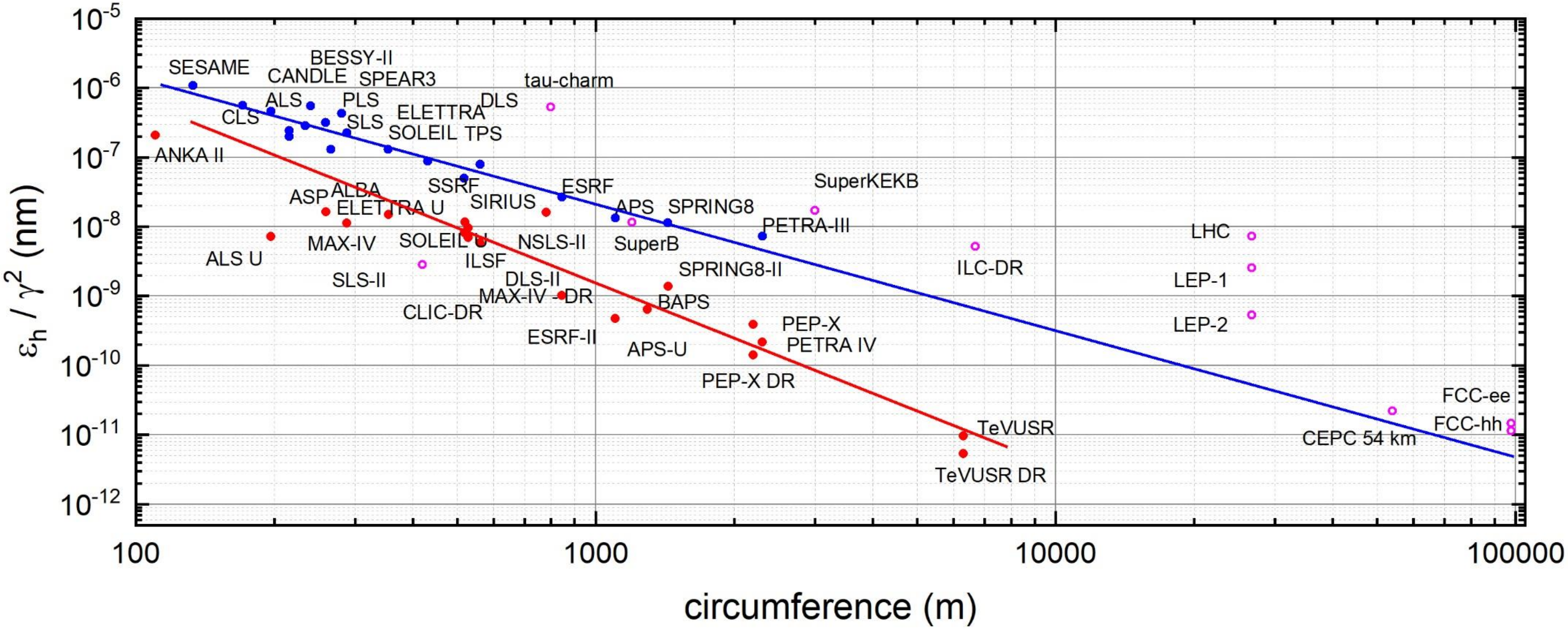
increase of emittance with energy is compensated by large radius (ρ) and short cell length (l_b)

transverse emittances



horizontal emittance (at γ=1)

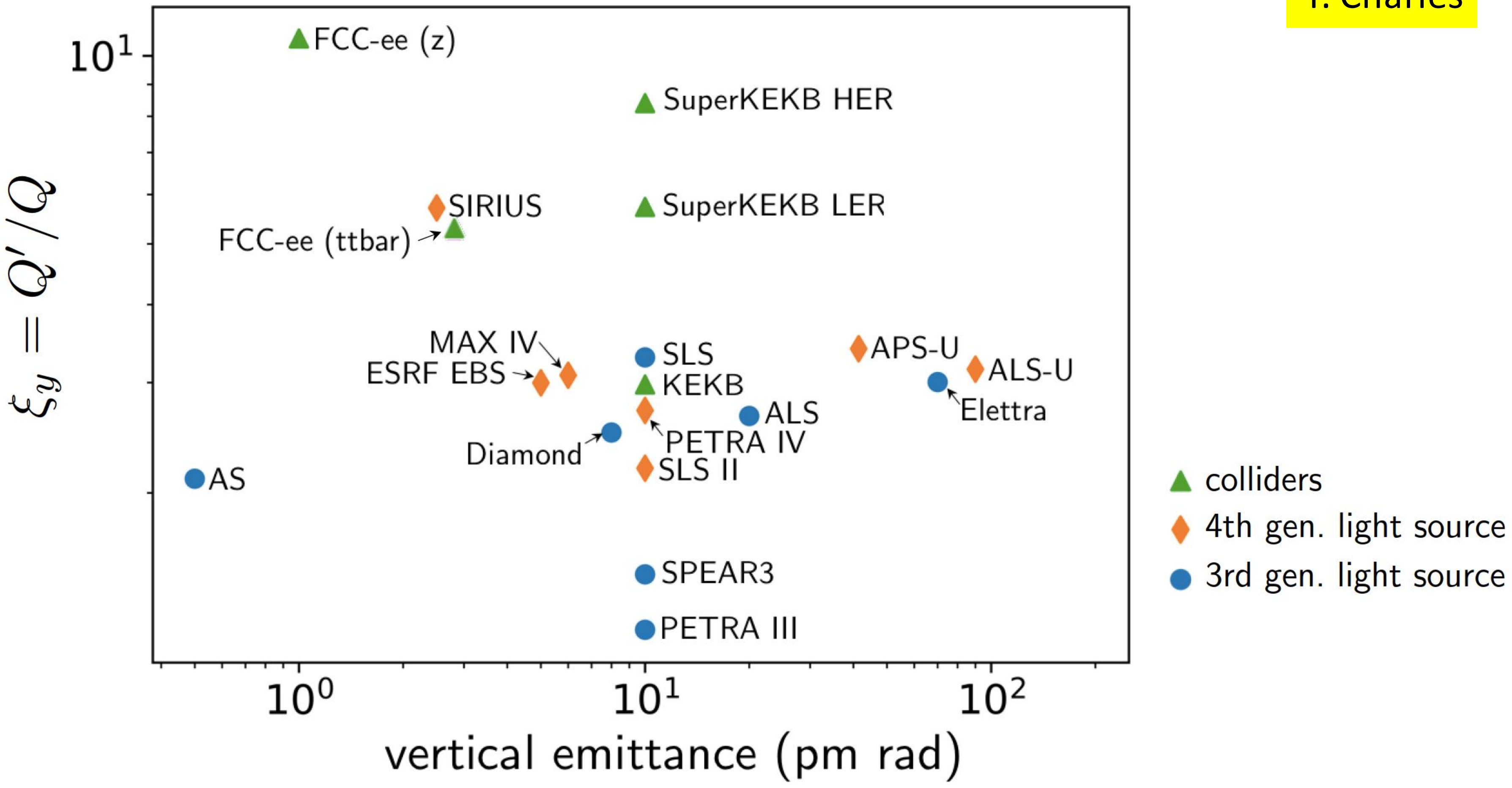
R. Bartolini, S. Casalbuoni



FCC-ee outperforming most of the “ultimate storage ring” light sources

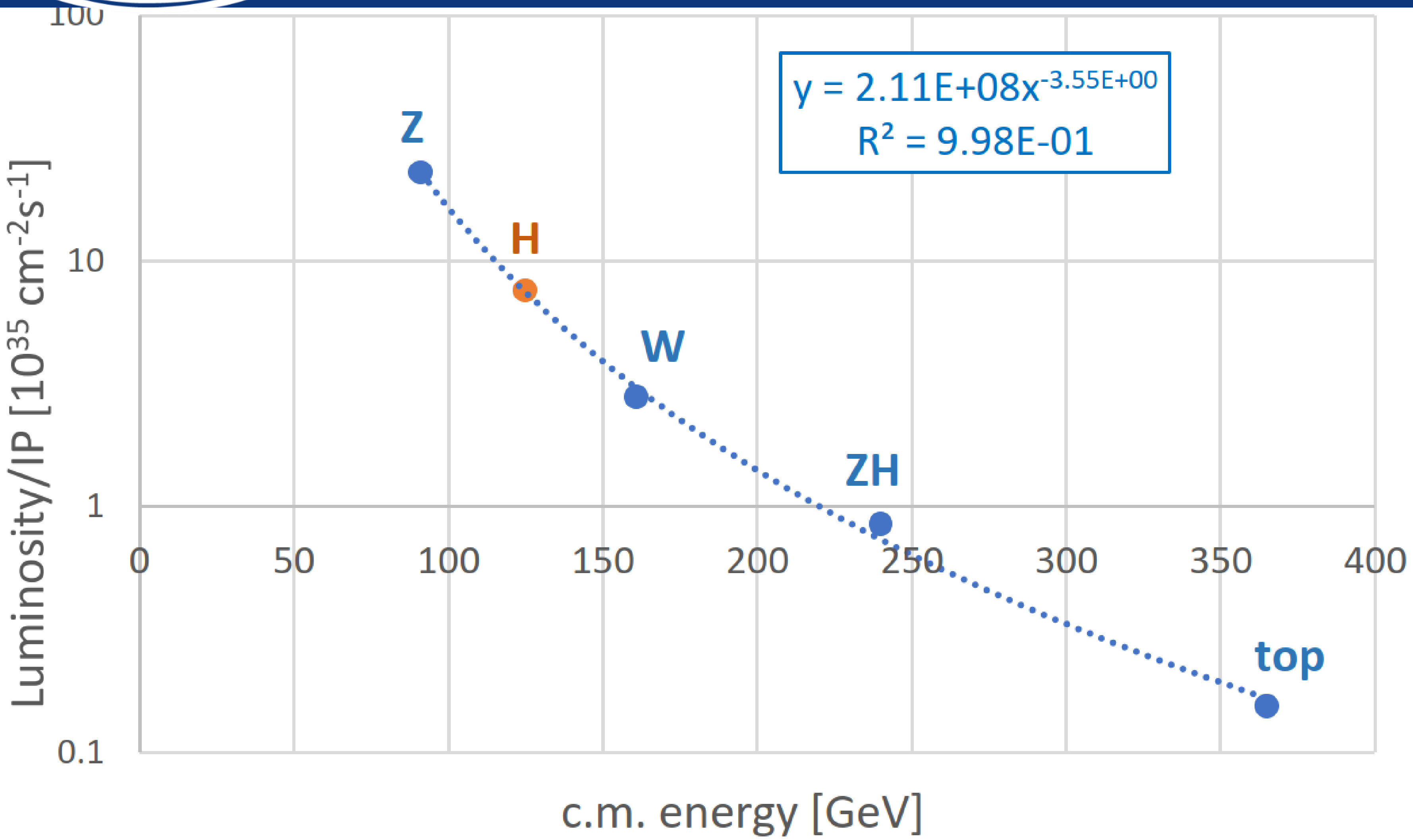
vertical emittance & chromaticity

T. Charles

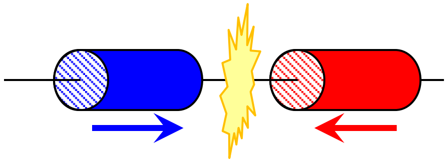


FCC-ee $t\bar{t}$ emittance and chromaticity ξ_y similar to SIRIUS light source

FCC-ee luminosity per IP

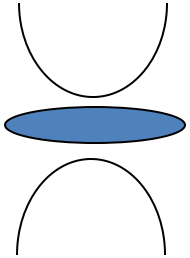


can we understand the luminosity scaling ?



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

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

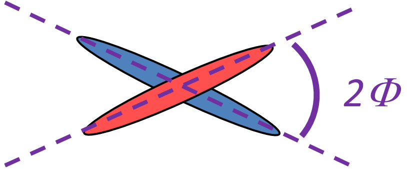


H ≤ 1

Hour-glass

F ≤ 1

Crossing angle



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

Beam-beam parameter

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

ρ: bending radius

$$\beta_y^* \propto \sqrt{E}$$

σ = beam size

k = no. bunches

f = rev. frequency

N = bunch population

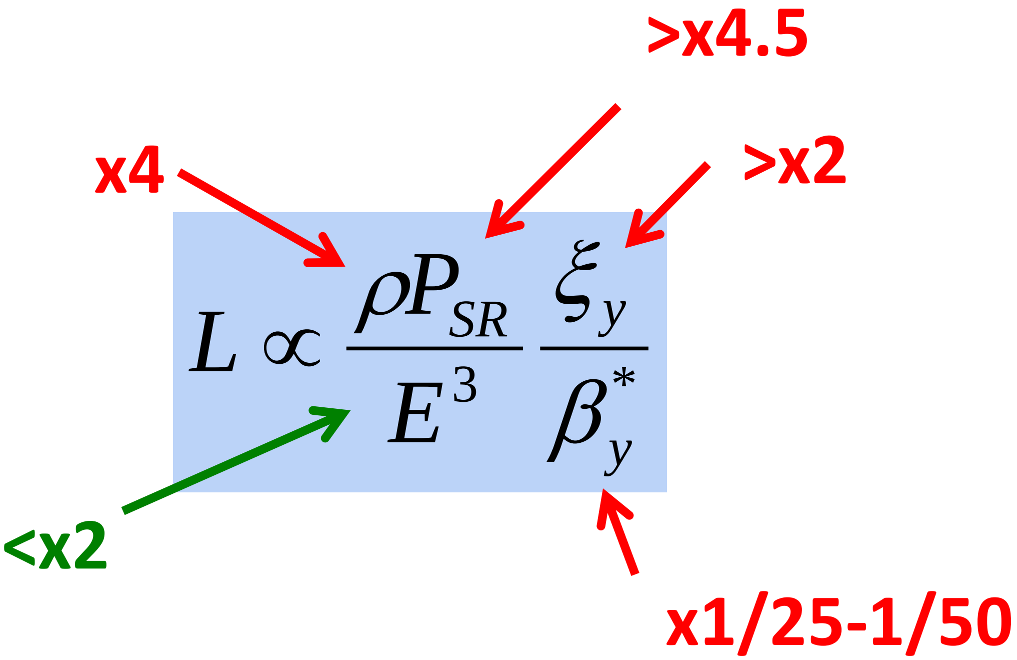
P_{SR} = synch. rad. power

β^* = betatron fct at IP

(beam envelope)

J. Wenninger

luminosity from LEP-2 to FCC-ee



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

>x4.5

x4

>x2

<x2

x1/25-1/50

much bigger factors on the *Z* pole: $10^5\times$ LEP-1 luminosity !

CDR baseline parameters

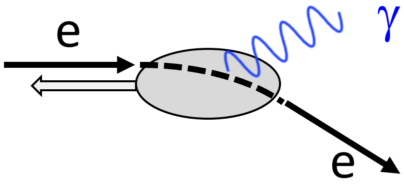
parameter	**FCC-ee**				LEP2
energy/beam [GeV]	**45.6**	**80**	**120**	**182.5**	105
bunches/beam	16640	2000	328	48	4
beam current [mA]	1390	147	29	5.4	3
luminosity/IP x 10^{34} cm^{-2}s^{-1}	**230**	**28**	**8.5**	**1.6**	0.0012
energy loss/turn [GeV]	0.036	0.34	1.72	9.2	3.34
synchrotron power [MW]	100				22
RF voltage [GV]	0.1	0.75	2.0	4.0+6.9	3.5
rms bunch length (SR,+BS) [mm]	3.5, 12	3.0,6.0	3.2, 5.3	2.0, 2.5	12, 12
rms emittance $\varepsilon_{x,y}$ [nm, pm]	0.27, 1	0.84, 1.7	0.63, 1.3	1.5, 2.9	22, 250
longit. damping time [turns]	1273	236	70	20	31
crossing angle [mrad]	30				0
beam lifetime [min]	68	59	**12**	**12**	434

FCC-ee & CEPC: 2 separate rings

beamstrahlung – a new limit at 182 GeV

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

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



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

η : ring energy acceptance

lifetime expression by V. Telnov, modified version by A. Bogomyagkov et al

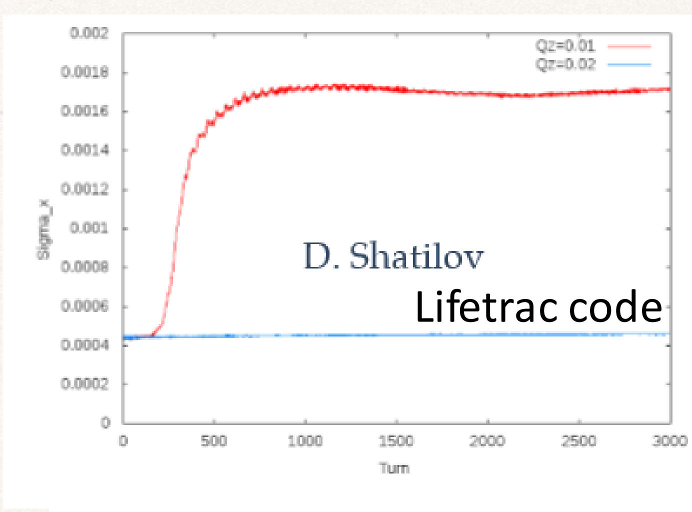
- for acceptable lifetime, ρ×η must be sufficiently large
  - *flat beams (large σ_x) !*
  - *bunch length !*
  - *large momentum acceptance: aiming for* ***≥2% at 182.5 GeV***

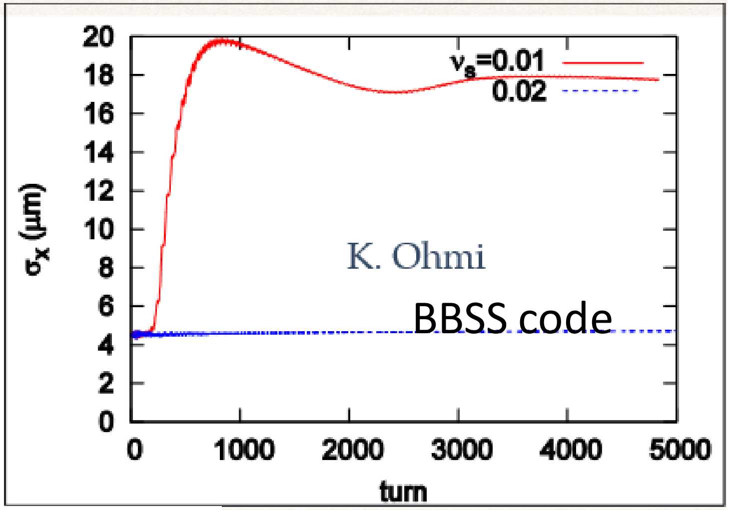
    - LEP: <1% acceptance, SuperKEKB ~ 1.5%

J. Wenninger, et al

coherent x-y beam-beam instability

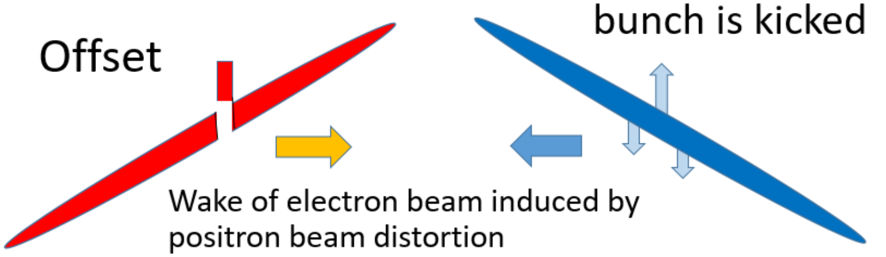
ξ limit, strong coherent instability





Mitigation (Shatilov):

- Decrease β_x^* (and thus ξ_x)
- Increase momentum compaction
- Reduce RF voltage.
- Neat choice of ν_{x}.

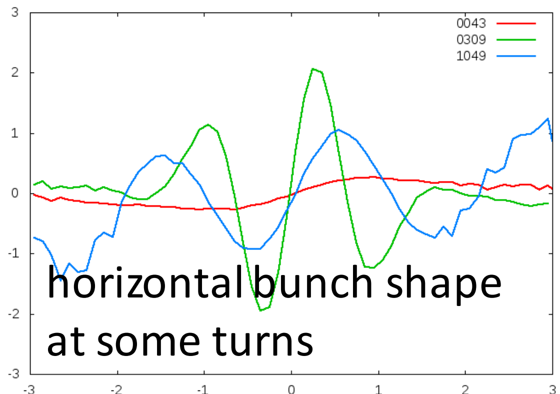


bunch is kicked

Offset

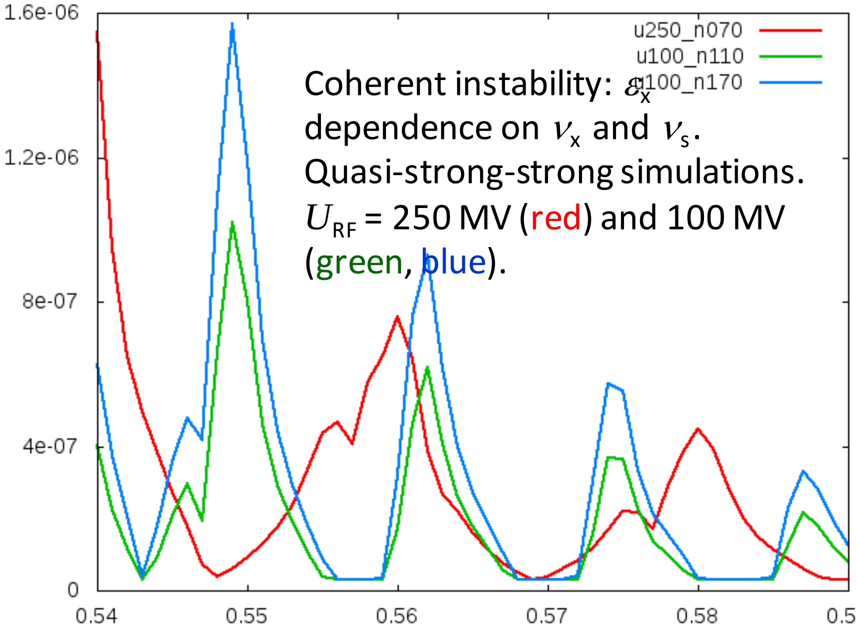
Wake of electron beam induced by positron beam distortion

K. Ohmi



horizontal bunch shape at some turns

D. Shatilov

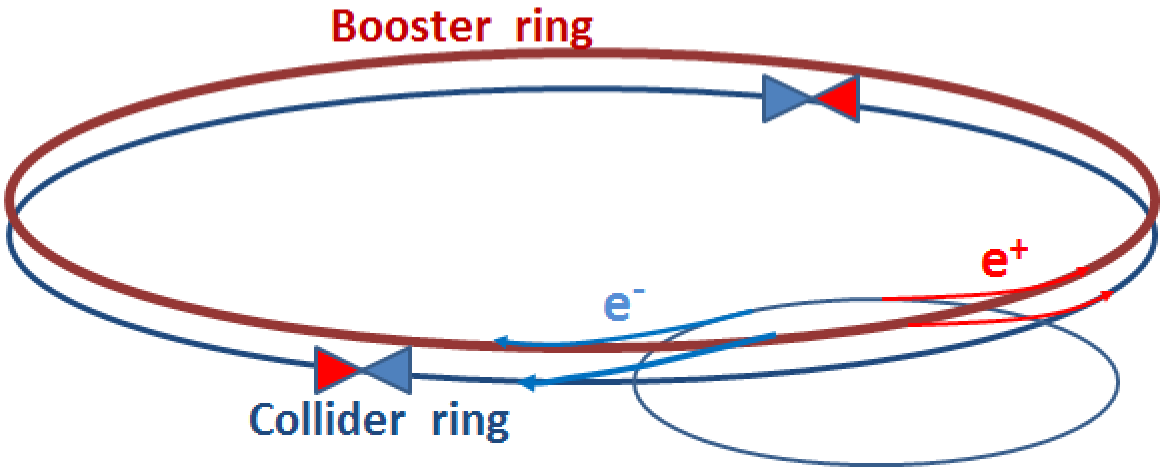


Coherent instability: ε_x dependence on ν_x and ν_s. Quasi-strong-strong simulations. U_{RF} = 250 MV (red) and 100 MV (green, blue).

FCC-ee top-up injection

beside the collider ring(s), a booster of the same size (same tunnel) must provide beams for top-up injection to sustain the extremely high luminosity

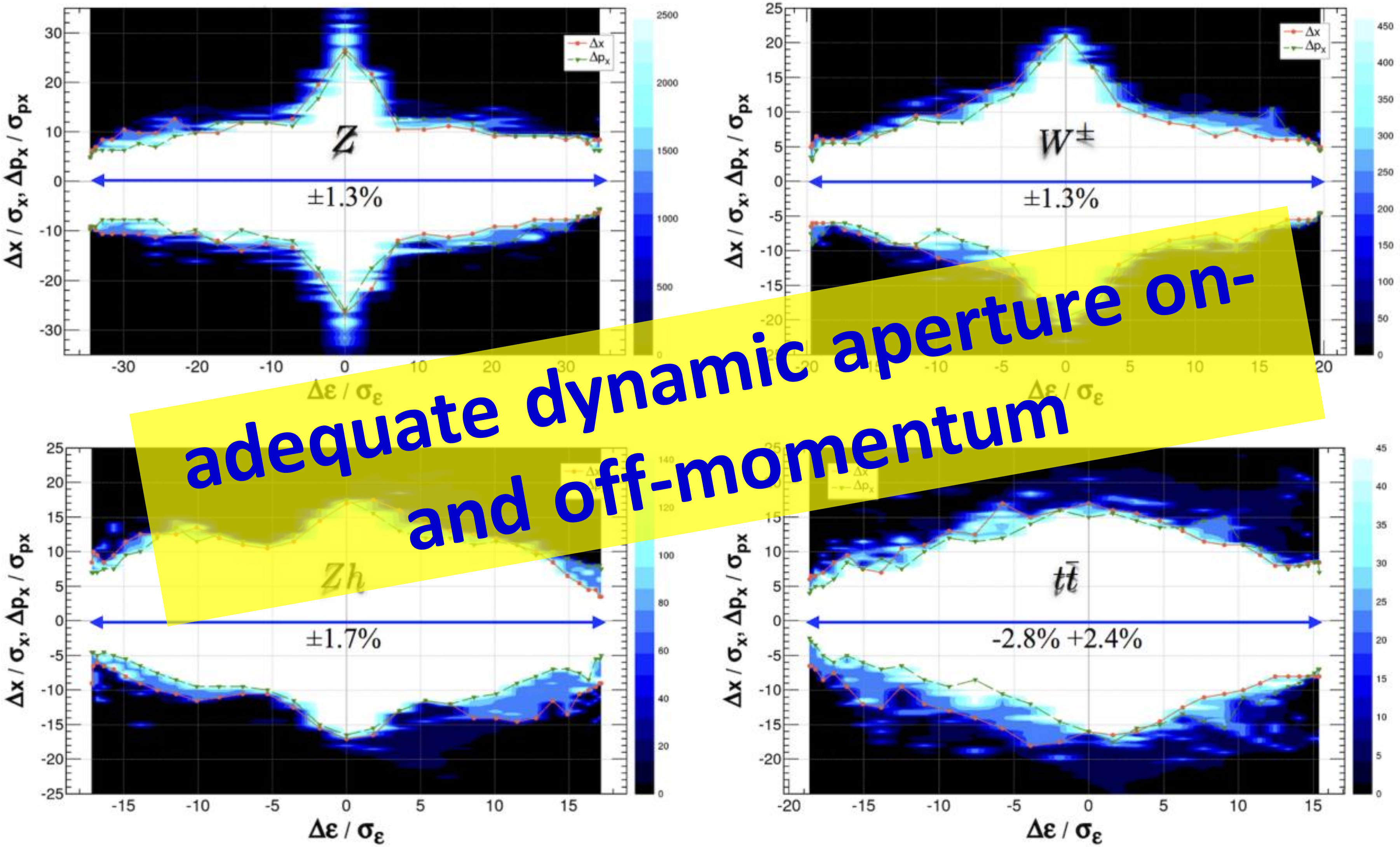
- same size of RF system, but low power (~ MW)
- top up frequency ≈0.1 Hz
- booster injection energy ≈5-20 GeV
- bypass around the experiments



A. Blondel

dynamic aperture

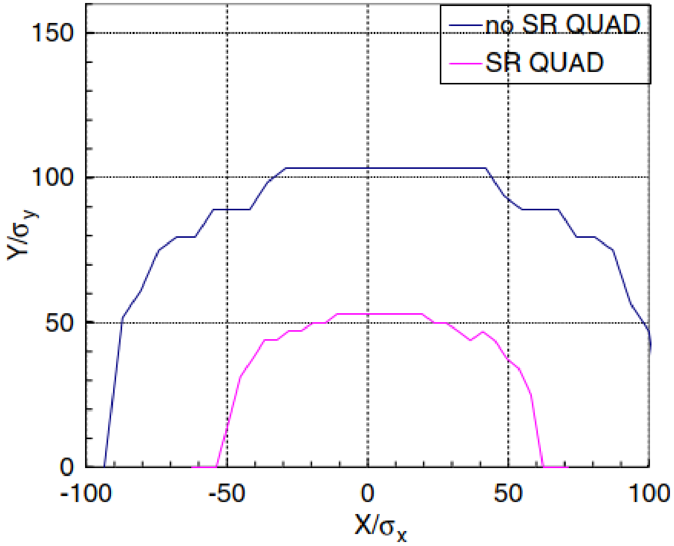
K. Oide



adequate dynamic aperture on- and off-momentum

dynamic aperture limited by synchrotron radiation in quadrupoles !

dynamic aperture with and without deterministic synchrotron radiation in quadrupoles (w/o quantum fluctuations)



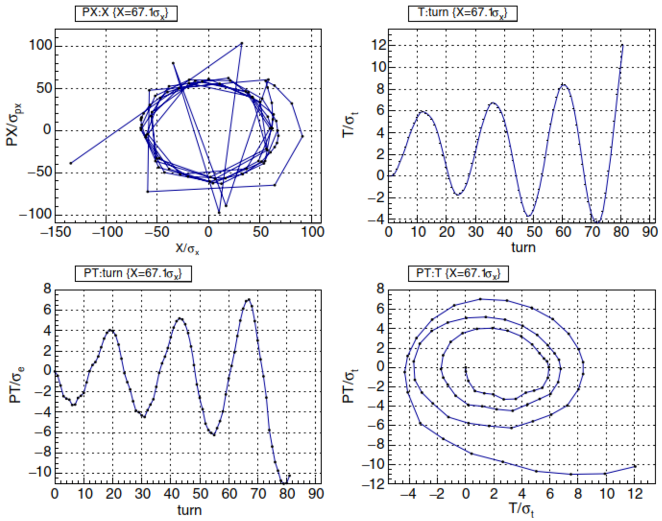
A. Bogomyagkov et al., PRAB 22, 021001 (2019); J. Jowett, Proc. 4th Workshop on LEP Performance, CERN SL/94-06 (DI) (1994)

Horizontal plane:

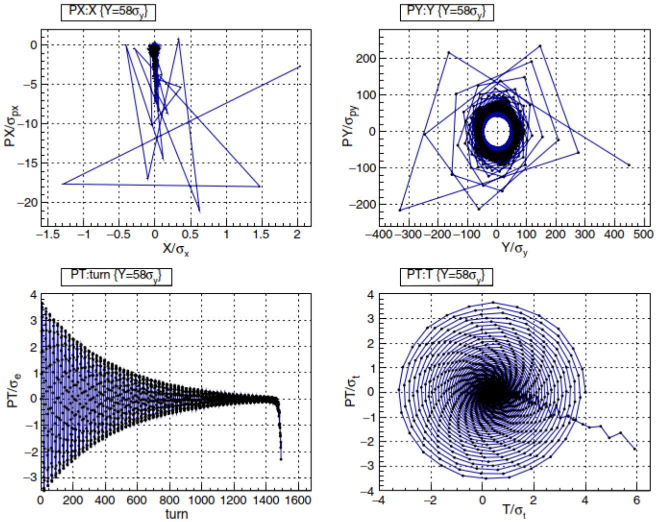
Radiative Beta-Synchrotron Coupling (RBSC) [Jowett, 1994] – additional energy loss due to radiation in quadrupoles shifts synchronous point and develops large synchrotron oscillations.
→ resulting horizontal tune shift onto the integer resonance

Vertical plane:

Radiation from quadrupoles modulates the particle energy at twice the betatron frequency → parametric resonance, independent of tune



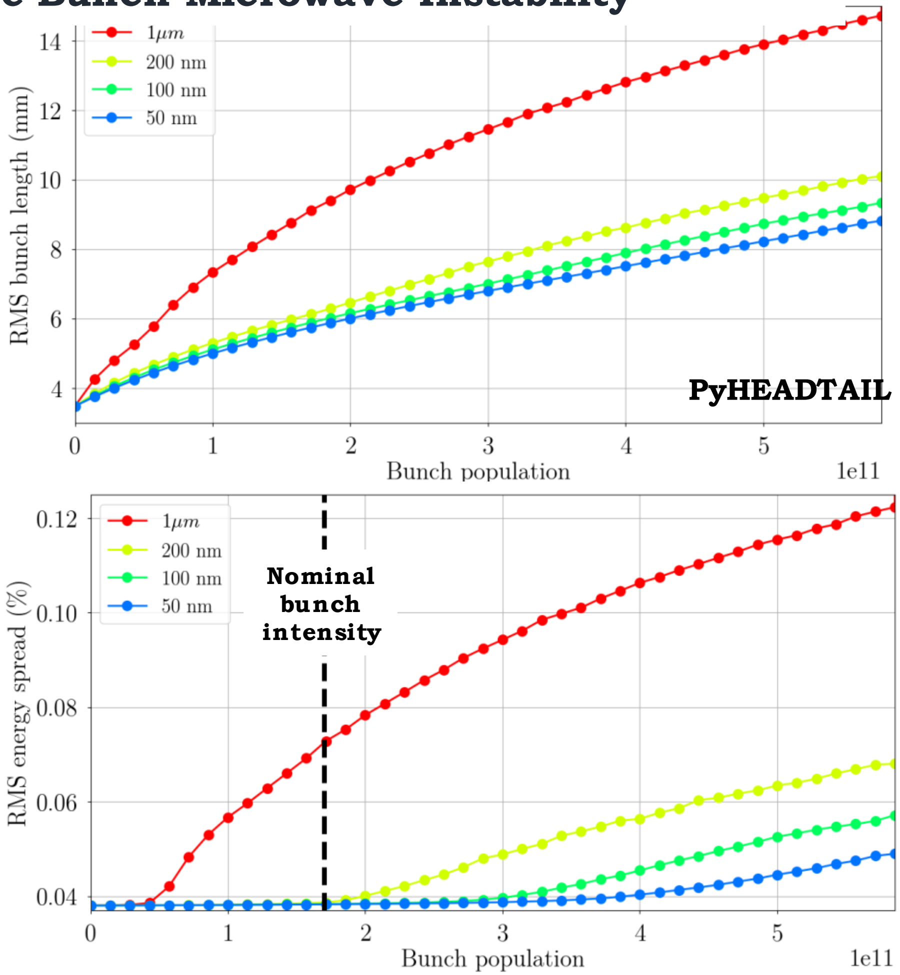
Phase and time trajectories of the first unstable particle with initial conditions $\{x = 67.1\sigma_x, y = 0, p_x = 0, p_y = 0, \sigma = 0, p_\sigma = 0\}$.



Phase and time trajectories of the first unstable particle with initial conditions $\{x = 0, y = 58\sigma_y, p_x = 0, p_y = 0, \sigma = 0, p_\sigma = 0\}$.

resistive wall impedance important for 100 km ring

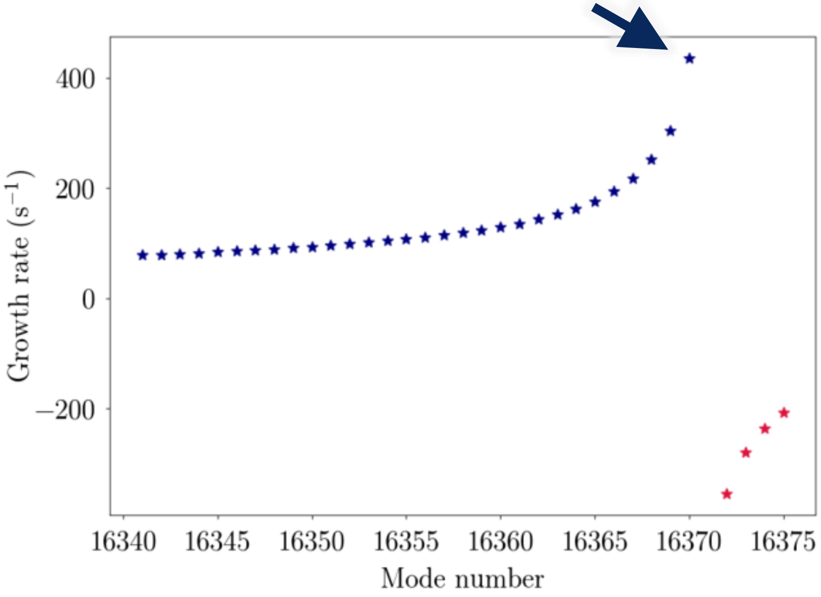
Single-Bunch Microwave Instability



→ **novel ultrathin NEG coating**

Transverse Multibunch Instability

shortest rise time ~7 turns



M. Migliorati, E. Belli, et al., PRAB **21**, 041001 (2018)

luminosity limited by injector

$$L = \frac{f_{\mathrm{rev}}\, n_b N^2}{4\pi \sigma_x^* \sigma_y^*}$$

specific luminosity (*L* per two currents)

$$L_{\mathrm{spec}} = \frac{f_{\mathrm{rev}}}{4\pi e^2 f_{\mathrm{rev}}^2 \sigma_x^* \sigma_y^*}$$

in equilibrium

inj. efficiency

injected beam current

$$e N_{\pm} n_b f_{\mathrm{rev}} = \epsilon_{e\pm} I_{e\pm,\mathrm{inj}} \tau_{\pm}$$

beam lifetime

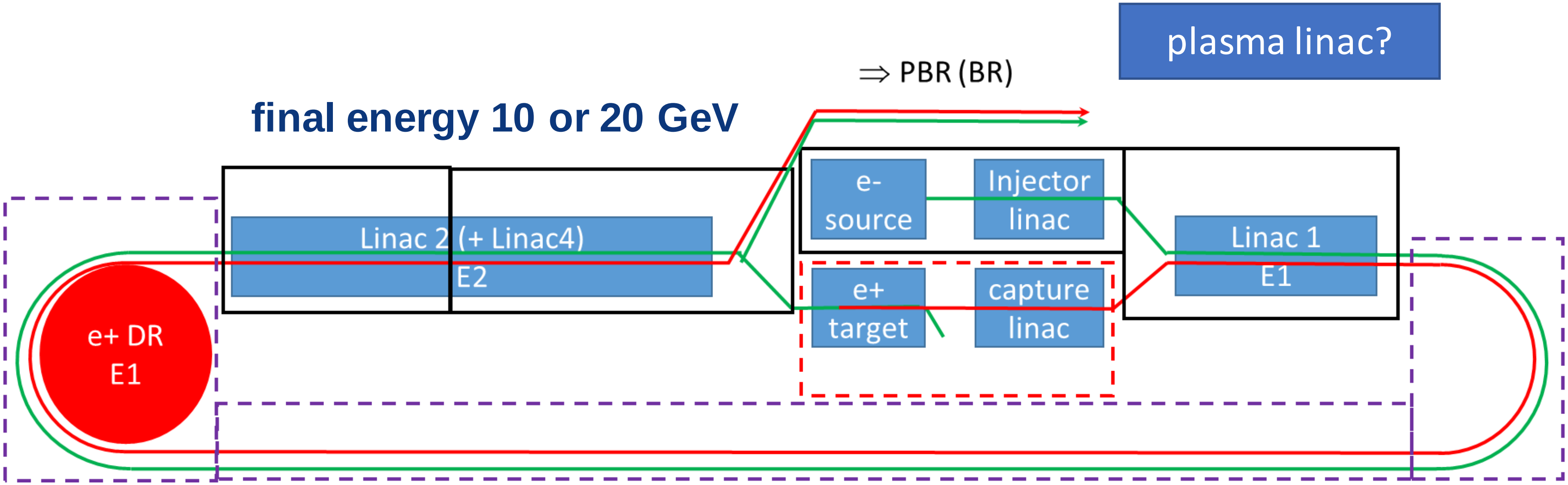
luminosity equation for SuperKEKB

$$L = \epsilon_{e-} I_{e-,\mathrm{inj}} \epsilon_{e+} I_{e+,\mathrm{inj}} \frac{\tau_{e-}\tau_{e+}}{N} \mathrm{L}_{\mathrm{spec}}$$

optimising the pre-injector complex

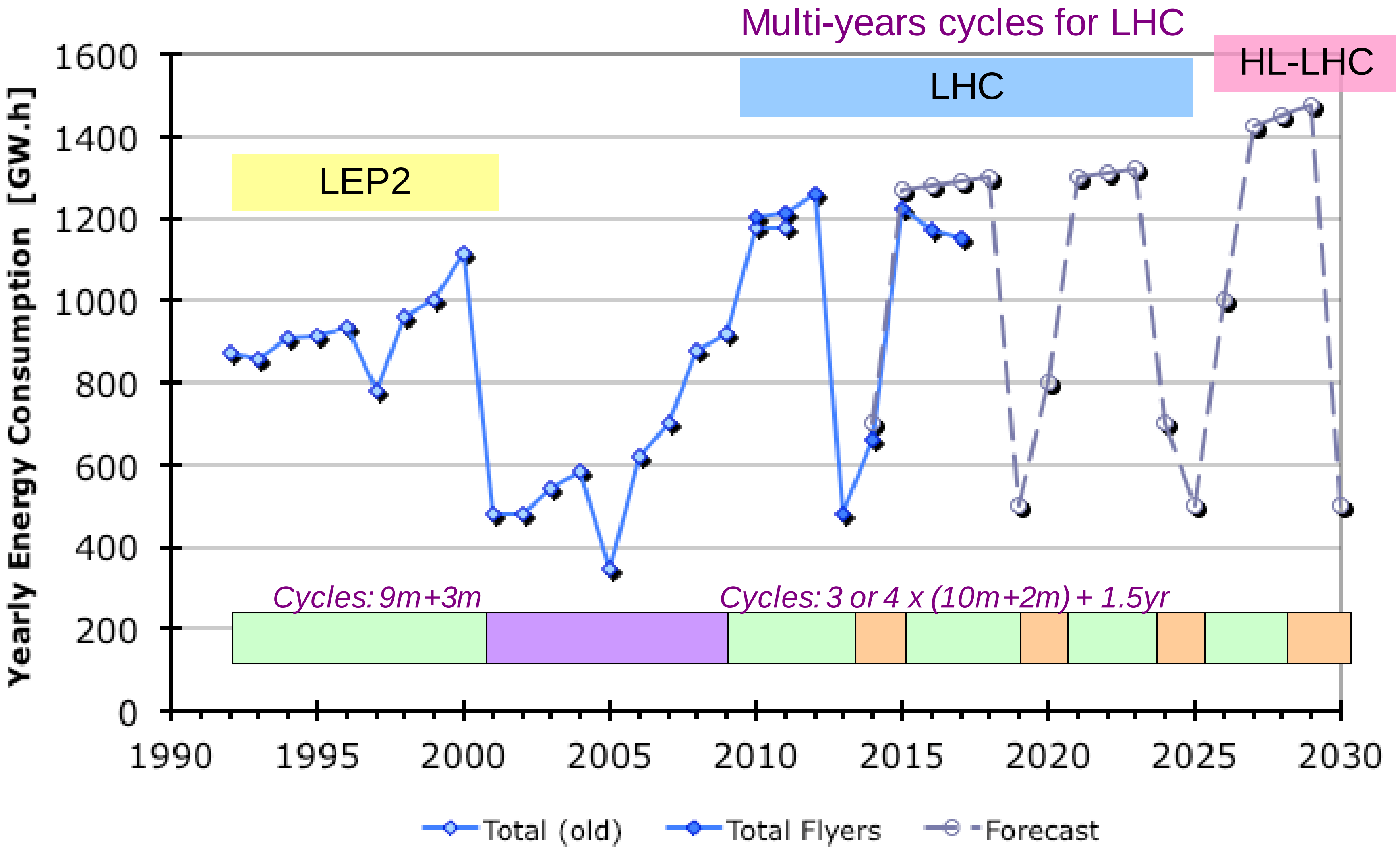
25-162.5 GeV plasma e^+/e^- linac could replace PBR & FEB !

CEPC, Z. Y. Xu et al., PRAB **23**, 091301 (2020)



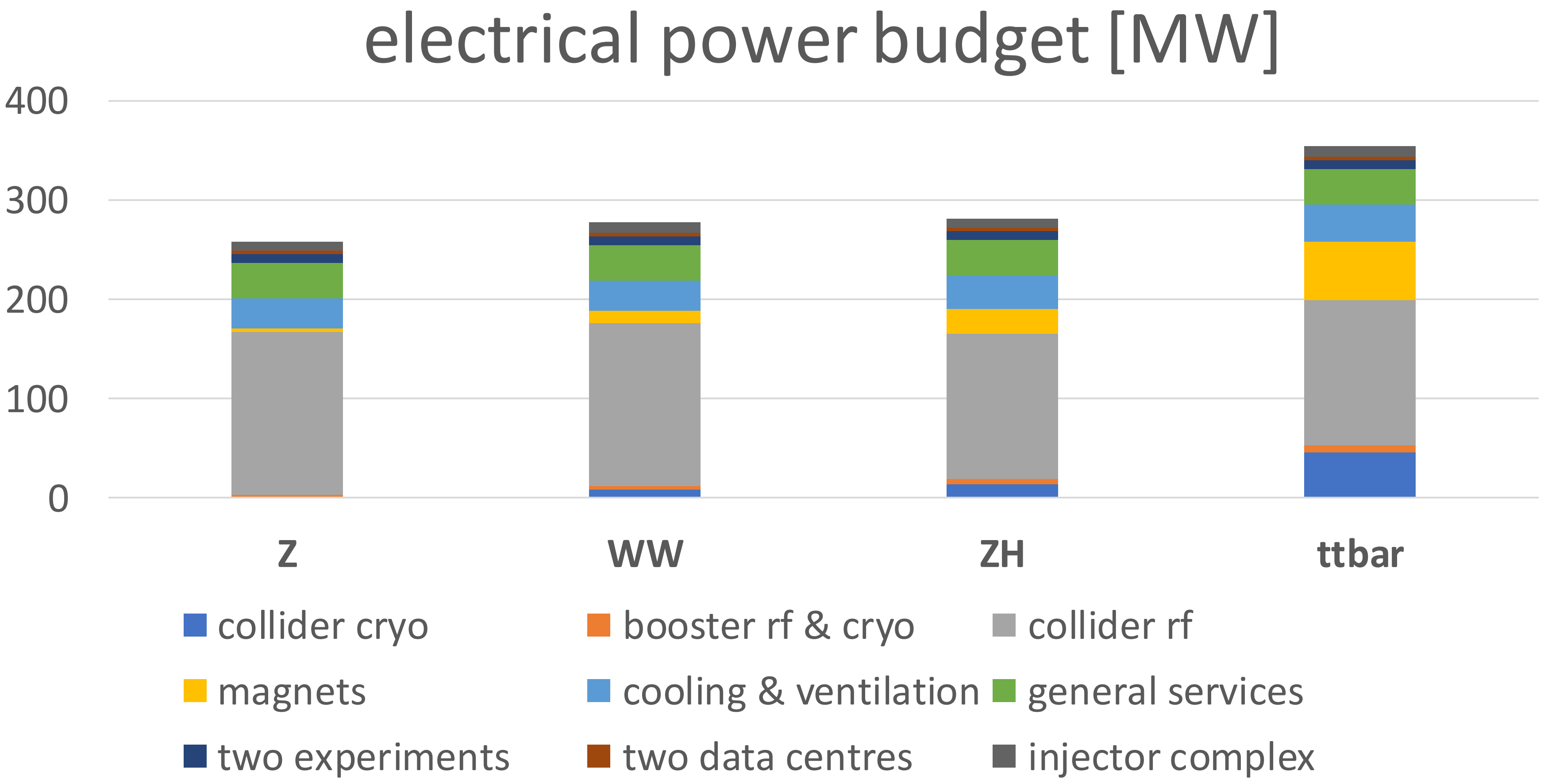
Alexej Grudiev, Paolo Craievich, Katsunobu Oide, Iryna Chaikovska, Catia Milardi, Angeles Faus-Golfe, Hans Braun, Michael Benedikt, Salim Ogur, Ozgur Itasken, Yannis Papaphilippou, et al.

energy consumption – example CERN



V. Mertens

FCC-ee electrical power requirements



RF as main power consumer

continually supplying circulating beam with

P_{SR}=100 MW power (SR losses) requires

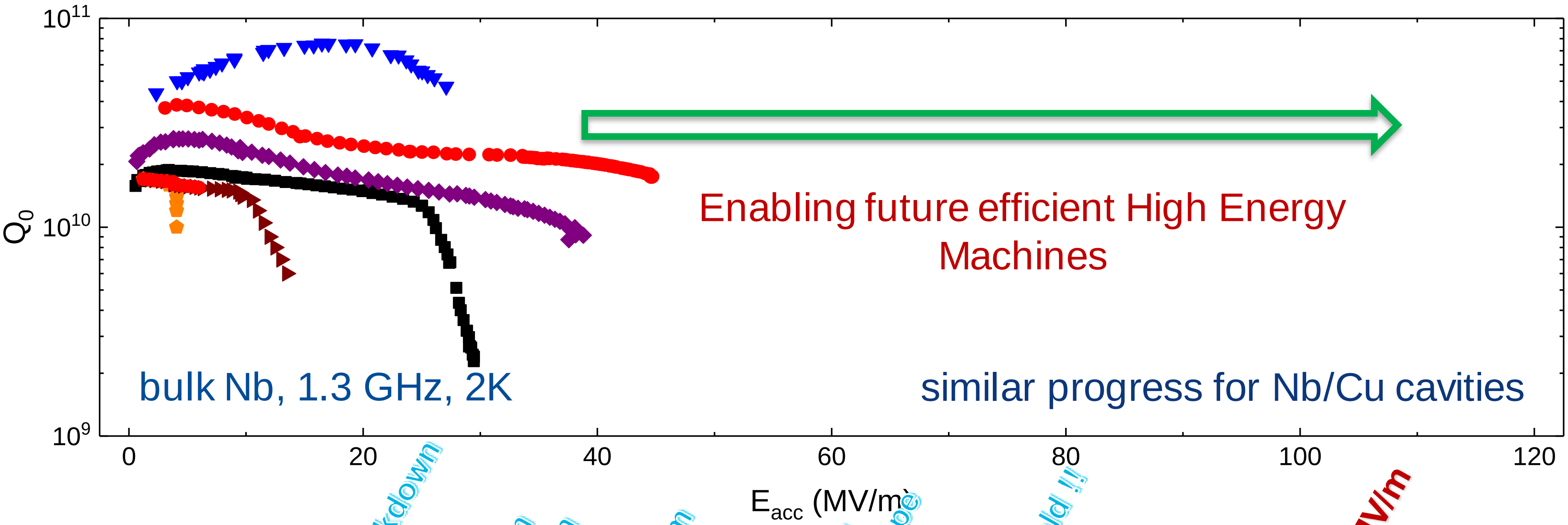
wall-plug power $P_{wall}=P_{SR}/\eta$, note $I_b \propto P_{SR}$

with η=conversion efficiency wall-plug → beam

FCC strategy:

- RF system optimized for each energy
- higher-gradient high-Q SC cavities (negligible wall losses, low cryo power)
- highly efficient RF power sources

SRF cavities over 30 years | high Q_0 & E_{acc} → less cryopower



Enabling future efficient High Energy Machines

bulk Nb, 1.3 GHz, 2K

similar progress for Nb/Cu cavities

3 – 4 MV/m
Multipacting

5 MV/m
Thermal Breakdown

10 – 15 MV/m
Field Emission

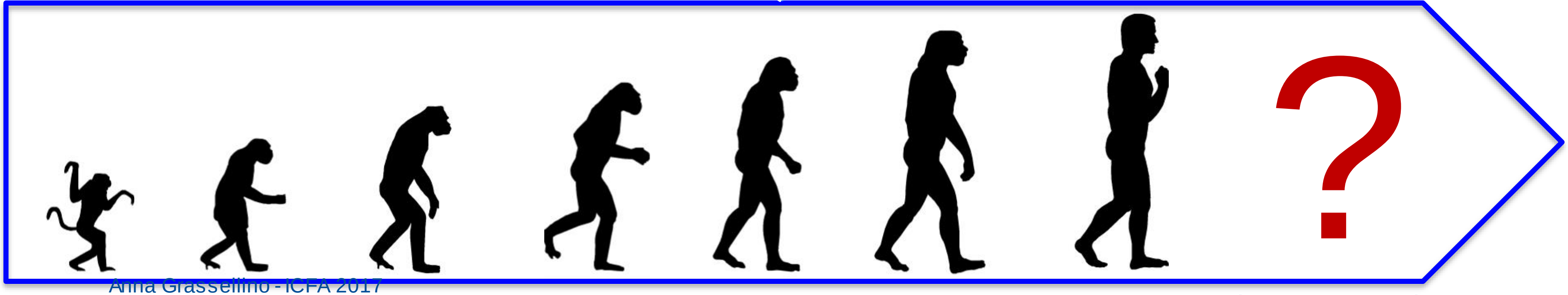
20 - 25 MV/m
High field
Q-SLOPE

35 – 40 MV/m
mid field Q-slope

Q > 5e10
At medium field !!

Q > 2e10
At high field

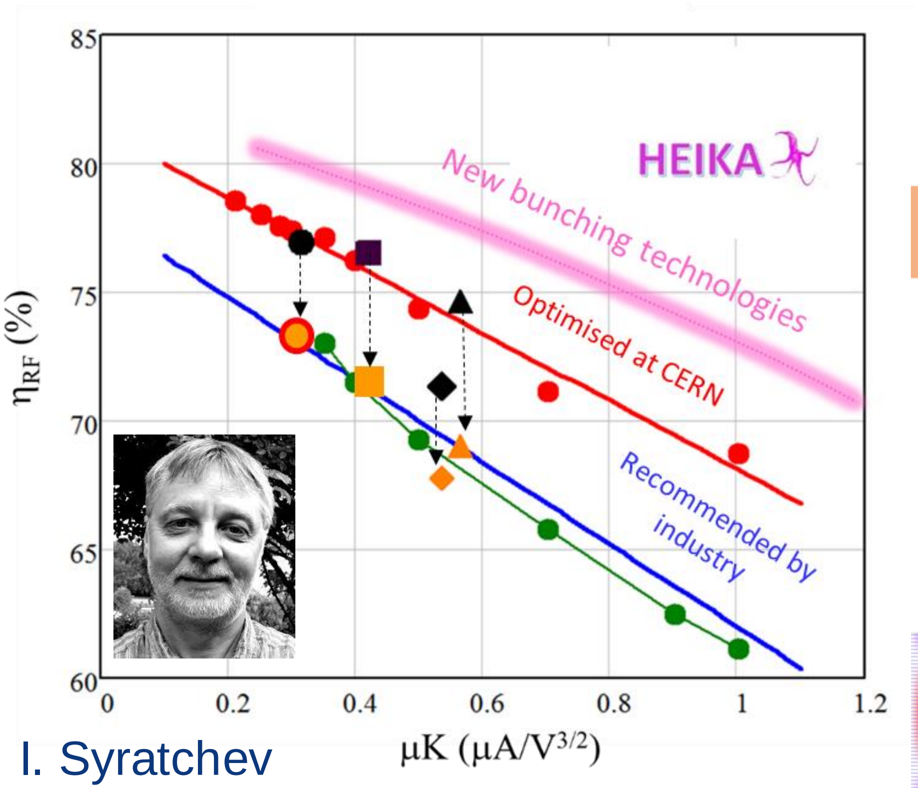
E_{acc} > 100 MV/m
Q > 3e10



Anna Grasselino - ICFA 2017

A. Grasselino, ICFA Seminar, Ottawa 201

after 80 years breakthrough in klystron technology



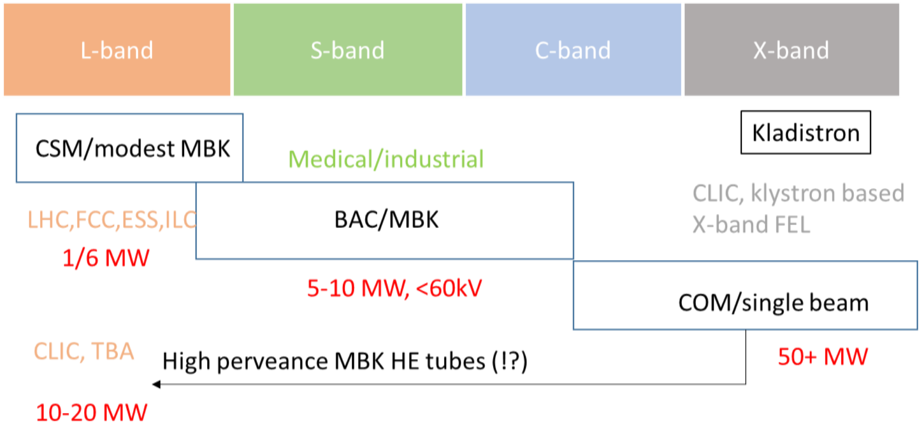
I. Syratchev

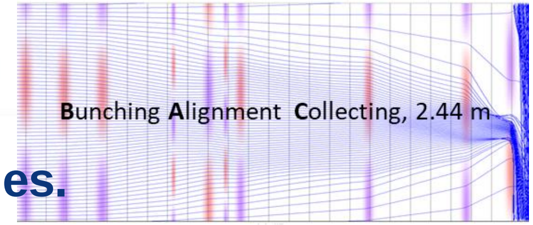
New bunching technologies.

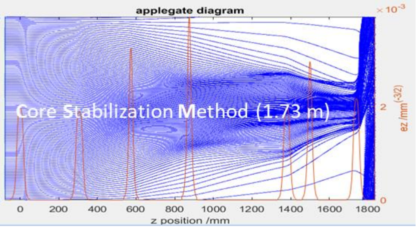
Bunch saturation.

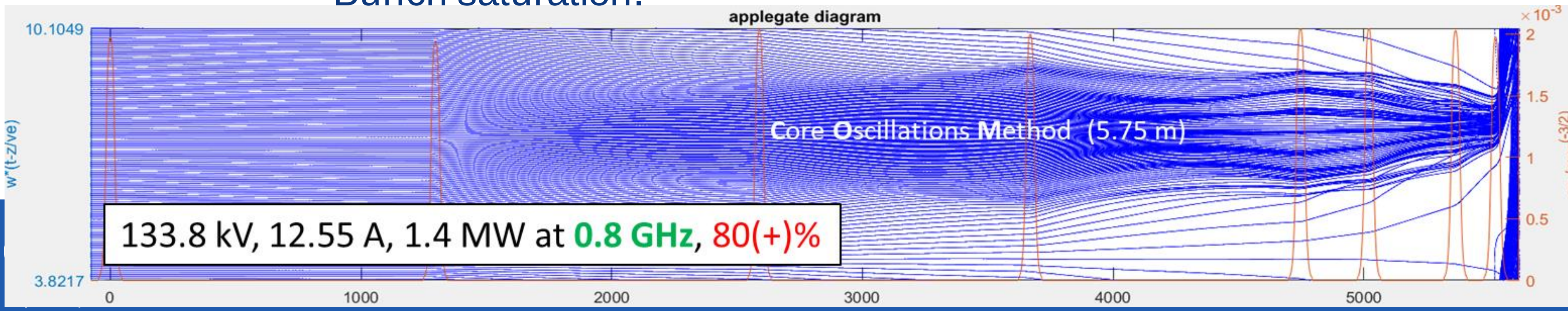
CERN CLIC ess Lancaster University L3 THALES SLAC VDBT HEIKA

The choice of bunching technology may drive the applicable frequency range and multi-beam options (cost/performance):





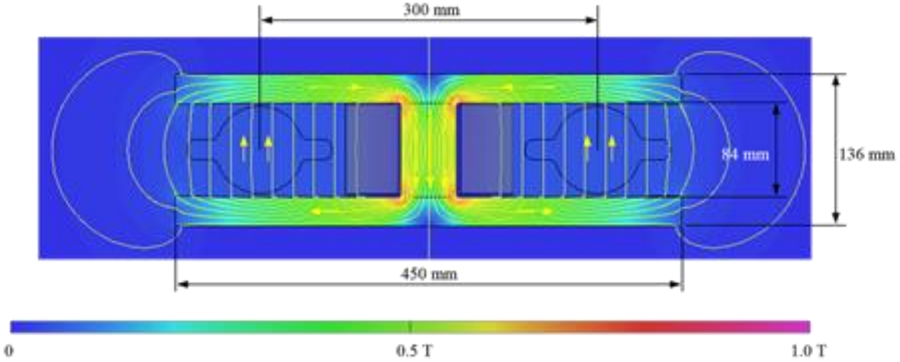


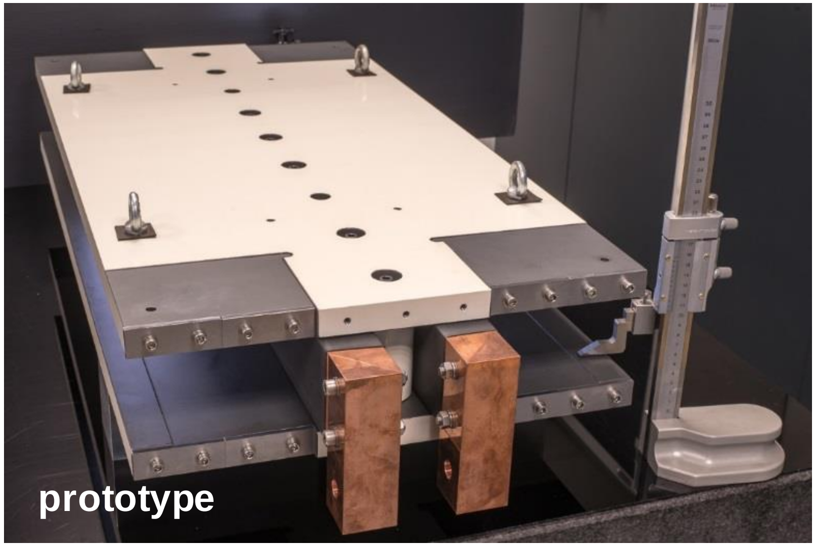


133.8 kV, 12.55 A, 1.4 MW at 0.8 GHz, 80(+)%

low-cost, energy-efficient arc magnets

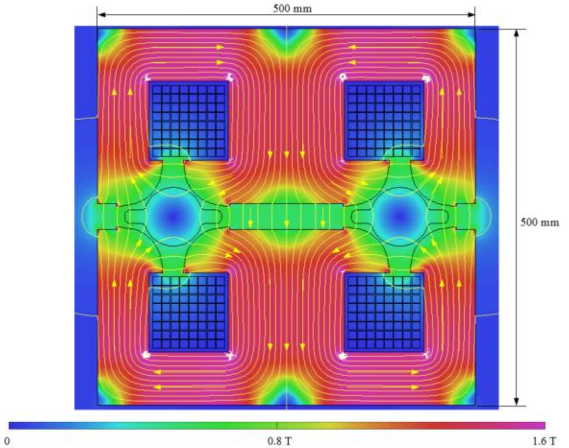
twin-dipole magnet design with 2× power saving 16 MW (at 175 GeV), with Al busbars

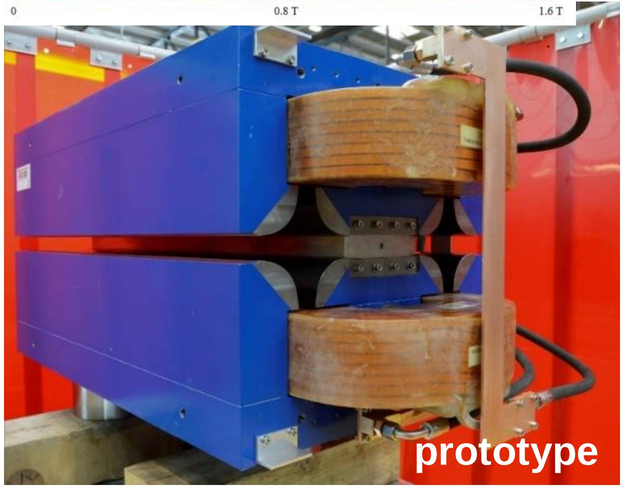




2900 units, 0.057 T, ~22 m

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

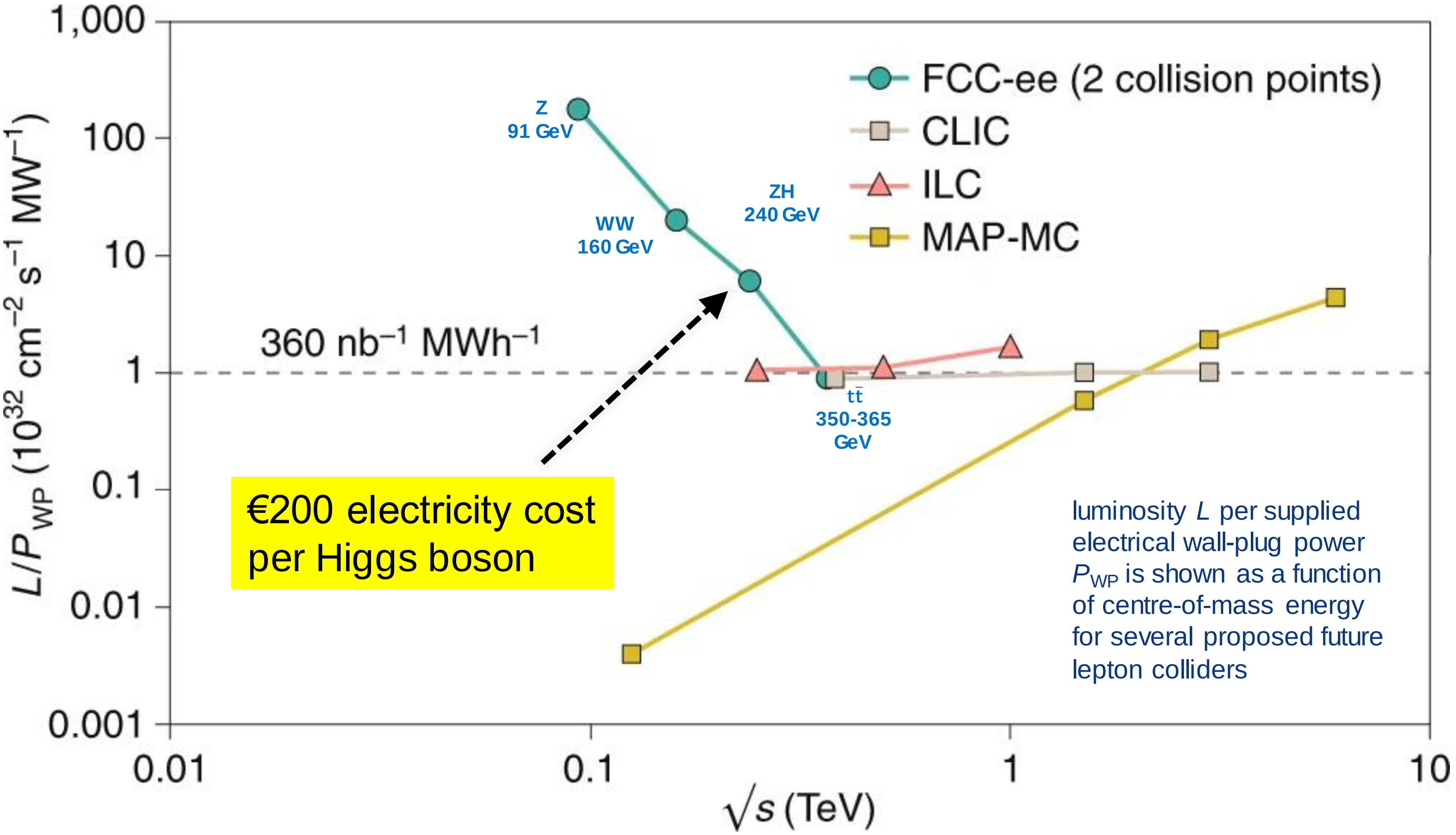




2900 units, 10 T/m, 3.1 m

A. Milanese, *Efficient twin aperture magnets for the future circular e^+/e^- collider,* **Phys. Rev. Accel. Beams 19**, 112401 (2016)

FCC-ee: efficient Higgs/electroweak factory



€200 electricity cost per Higgs boson

luminosity *L* per supplied electrical wall-plug power P_{WP} is shown as a function of centre-of-mass energy for several proposed future lepton colliders

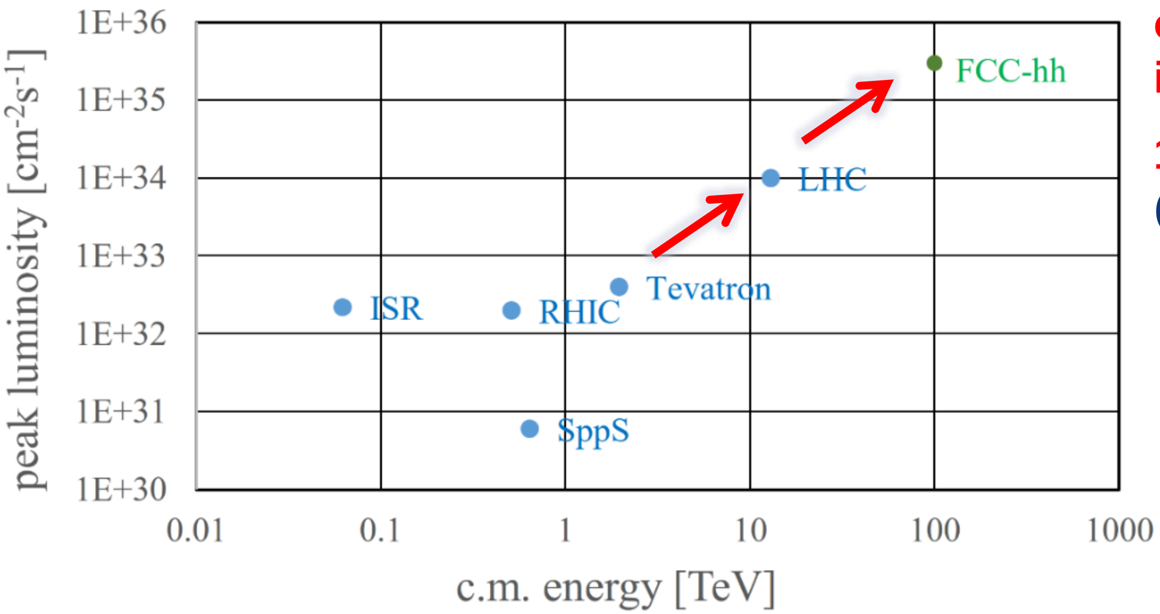
FCC-ee is greenest collider from *Z* to $t\bar{t}$

M. Benedikt, A. Blondel, P. Janot, et al., **Nat. Phys. 16**, 402-407 (2020), and **European Strategy** for Particle Physics Preparatory Group, *Physics Briefing Book* (CERN, 2019)

FCC-hh (pp) collider parameters

parameter	FCC-hh		HL-LHC	LHC
collision energy cms [TeV]	100		14	14
dipole field [T]	16		8.33	8.33
circumference [km]	97.75		26.7	26.7
beam current [A]	0.5		1.1	0.58
bunch intensity [10^{11}]	1	1	2.2	1.15
bunch spacing [ns]	25	25	25	25
synchr. rad. power / ring [kW]	2400		7.3	3.6
SR power / length [W/m/ap.]	28.4		0.33	0.17
long. emit. damping time [h]	0.54		12.9	12.9
beta* [m]	1.1	0.3	0.15 (min.)	0.55
normalized emittance [μm]	2.2		2.5	3.75
peak luminosity [10^{34} cm^{-2}s^{-1}]	5	30	5 (lev.)	1
events/bunch crossing	170	1000	132	27
stored energy/beam [GJ]	8.4		0.7	0.36

FCC-hh: performance



order of magnitude performance increase in **energy & luminosity**

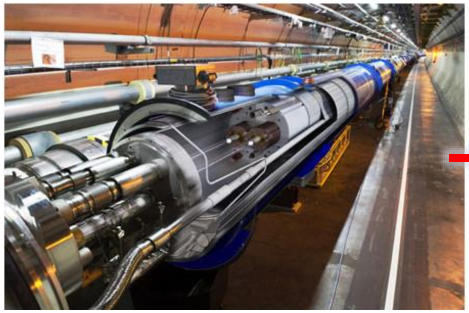
100 TeV cm collision energy (vs 14 TeV for LHC)

20 ab^{-1} per experiment collected over 25 years of operation (vs 3 ab^{-1} for LHC)

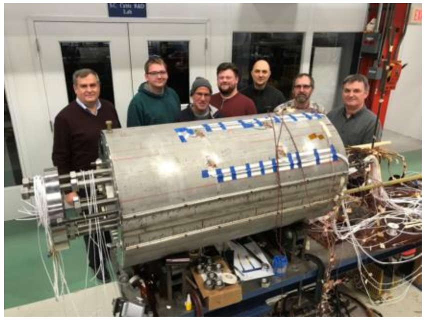
similar performance increase as from Tevatron to LHC

key technology: high-field magnets

from
LHC technology
8.3 T NbTi



via
HL-LHC technology

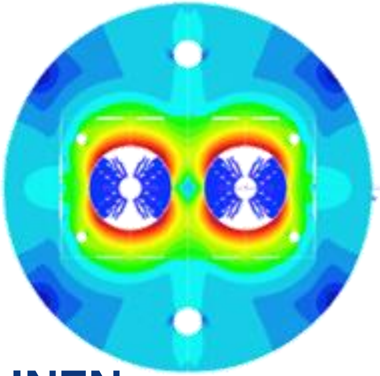


FNAL
demonstrator
14.5 T Nb$_3$Sn

16 T dipole design activities and options

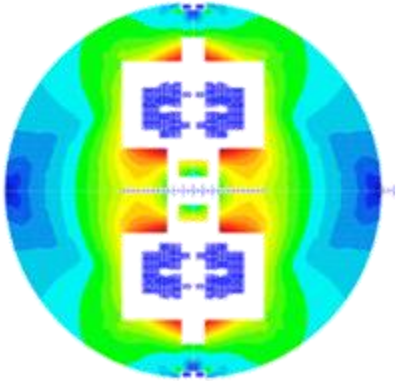
H2020
EuroCirCol
A key to New Physics

Cos-theta



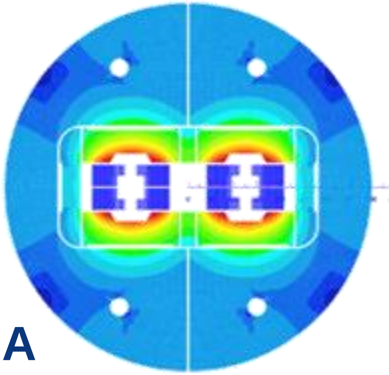
INFN

Common coils



CIEMAT

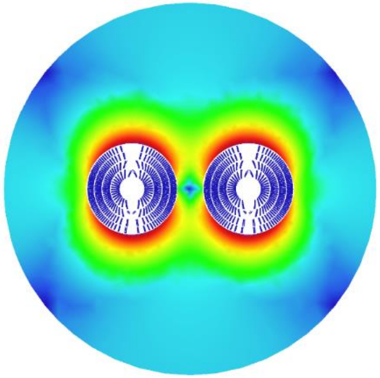
Blocks



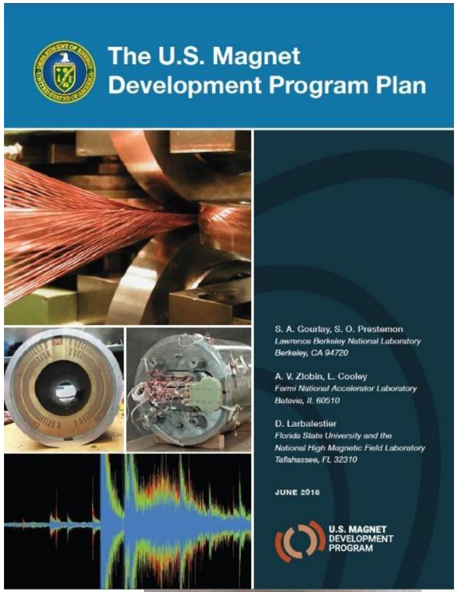
CEA

Swiss contribution

Canted Cos-theta



PSI



The U.S. Magnet Development Program Plan

S. A. Gourlay, S. O. Prestemon
Lawrence Berkeley National Laboratory
Berkeley, CA 94720

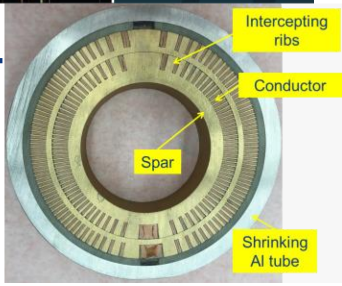
A. V. Zlobin, L. Cooley
Fermi National Accelerator Laboratory
Batavia, IL 60510

D. Larbalestier
Florida State University and the
National High Magnetic Field Laboratory
Tallahassee, FL 32310

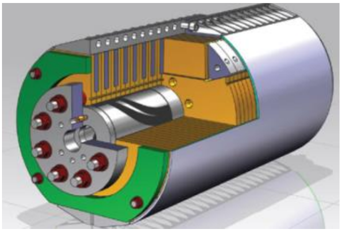
JUNE 2016

U.S. MAGNET DEVELOPMENT PROGRAM

LBNL

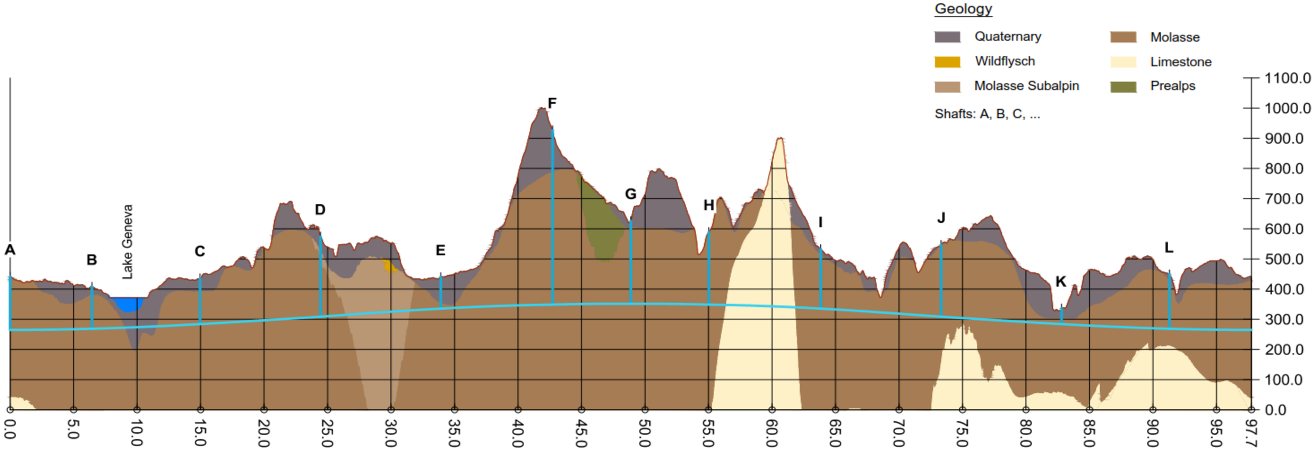


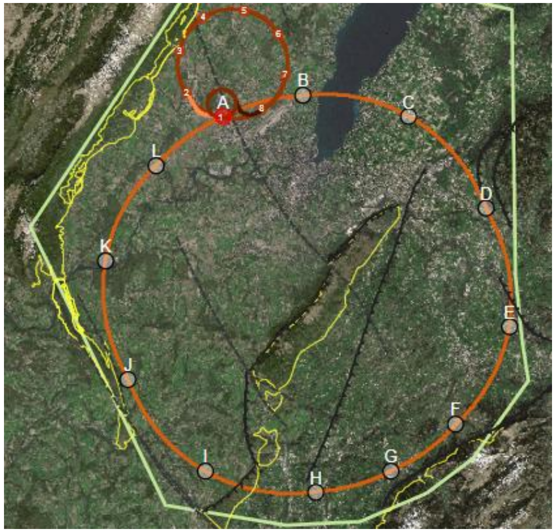
FNAL

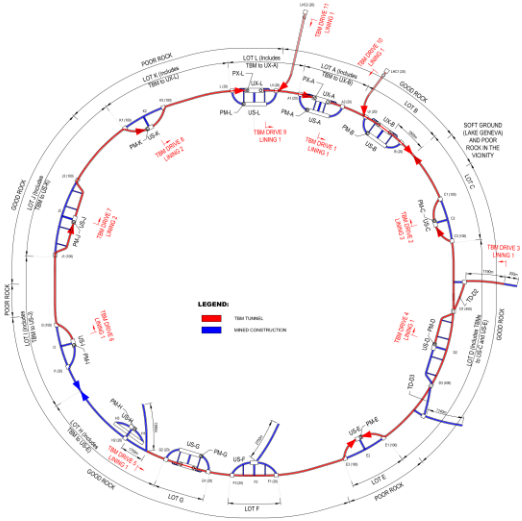


Short model magnets (1.5 m lengths) will be built until ~2025

FCC implementation - footprint baseline



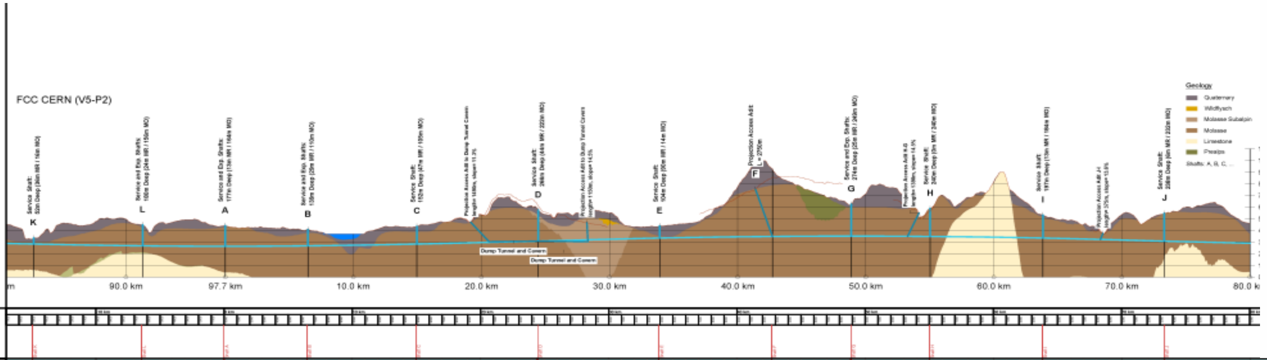


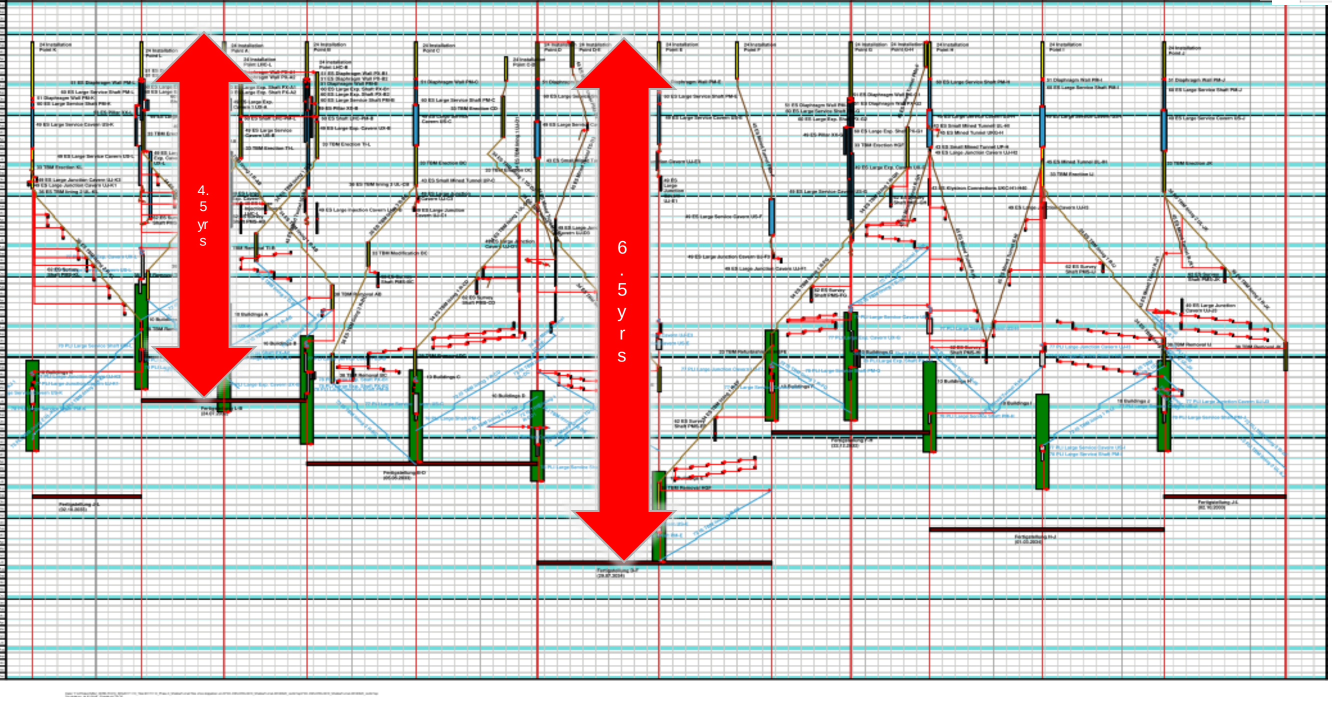


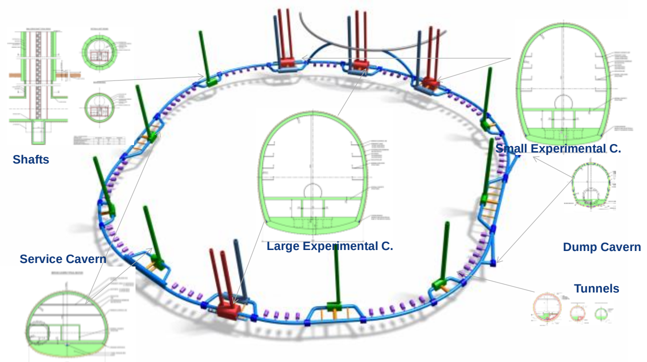
present baseline position based on:

- lowest risk for construction, fastest and cheapest construction
- feasible positions for large span caverns (most challenging structures)
- **90 – 100 km circumference**
- **12 surface sites with few ha area each**

civil engineering studies







total construction duration 7 years

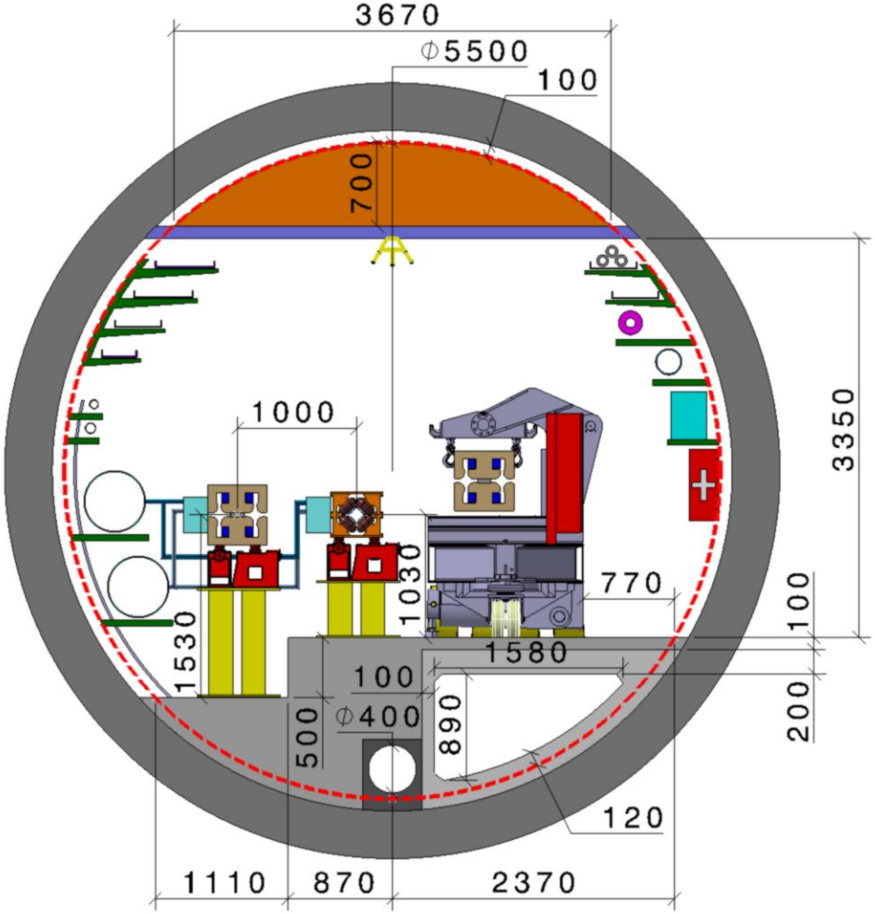
first sectors ready after 4.5 years

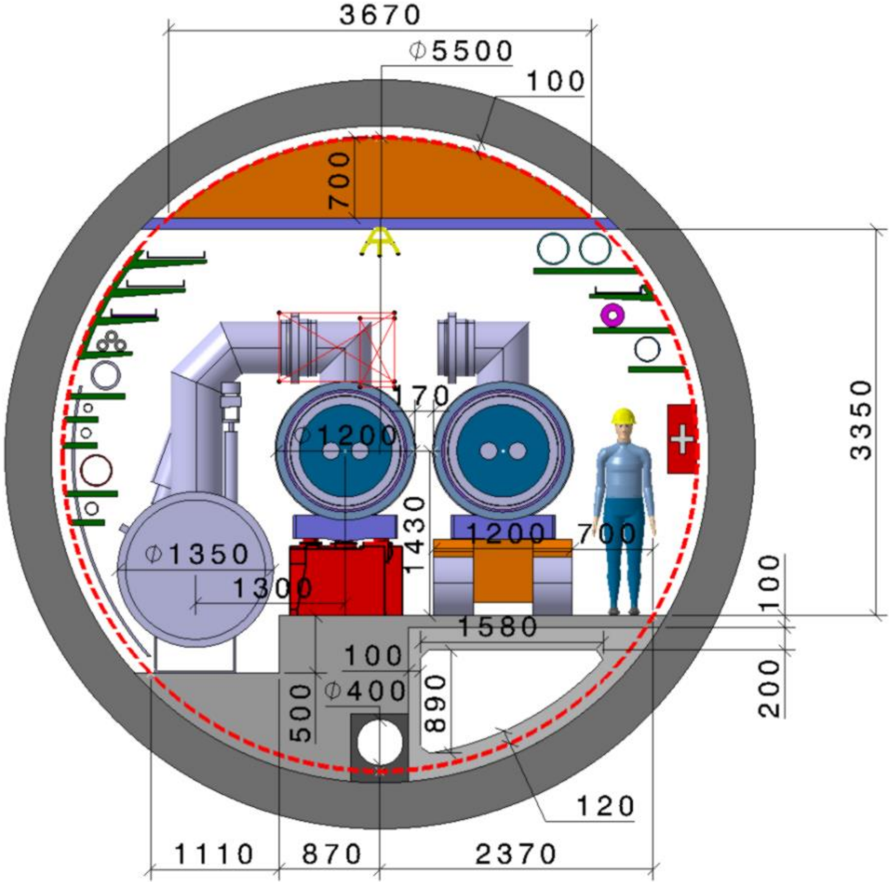
FCC-tunnel integration in the arcs

FCC-ee

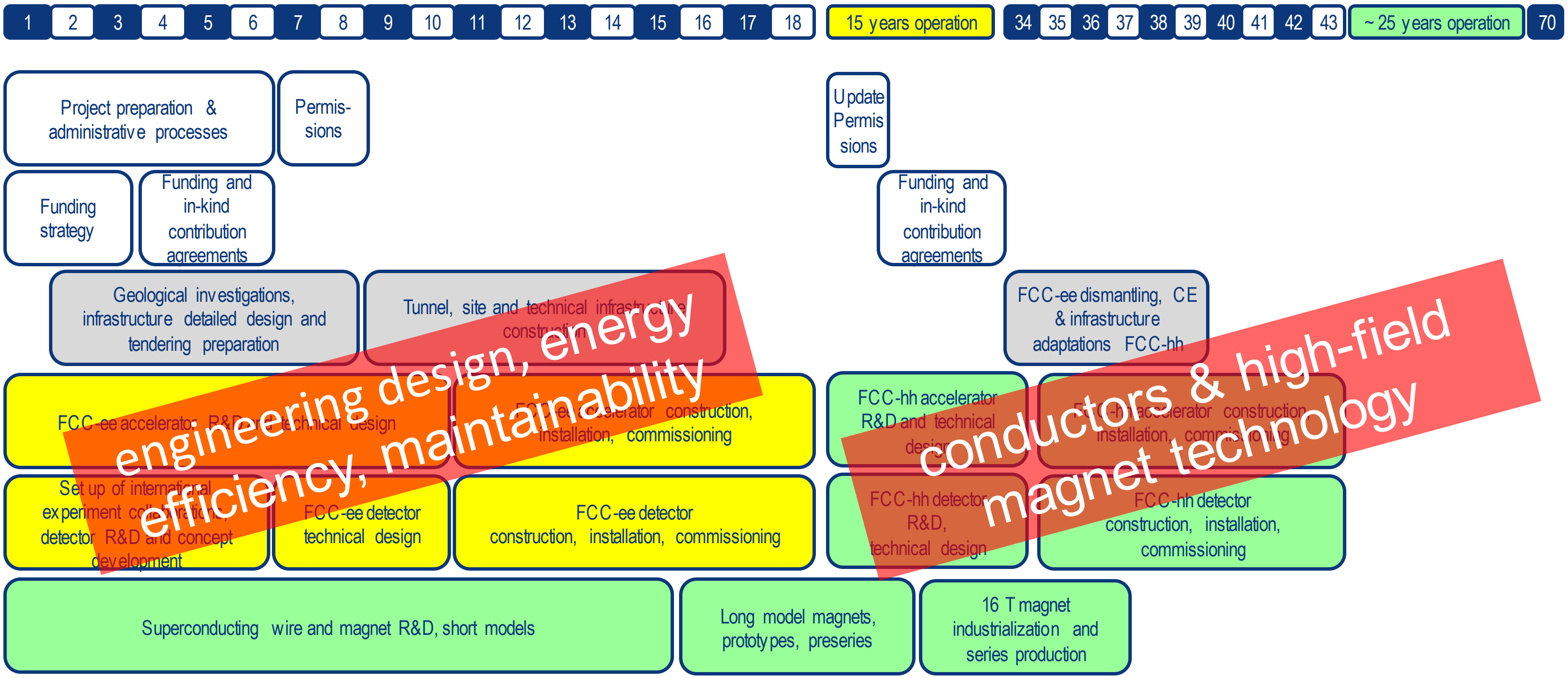
FCC-hh

5.5 m inner diameter





FCC integrated project technical schedule



1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 | 15 years operation | 34 35 36 37 38 39 40 41 42 43 | ~ 25 years operation | 70

Project preparation & administrative processes

Permissions

Funding strategy

Funding and in-kind contribution agreements

Geological investigations, infrastructure detailed design and tendering preparation

Tunnel, site and technical infrastructure construction

FCC-ee accelerator R&D and technical design

FCC-ee accelerator construction, installation, commissioning

Set up of international experiment collaborations, detector R&D and concept development

FCC-ee detector technical design

FCC-ee detector construction, installation, commissioning

Superconducting wire and magnet R&D, short models

Long model magnets, prototypes, preseries

16 T magnet industrialization and series production

Update Permissions

Funding and in-kind contribution agreements

FCC-ee dismantling, CE & infrastructure adaptations FCC-hh

FCC-hh accelerator R&D and technical design

FCC-hh accelerator construction installation, commissioning

FCC-hh detector R&D, technical design

FCC-hh detector construction, installation, commissioning

engineering design, energy efficiency, maintainability

conductors & high-field magnet technology

FCC CDR and Study Documentation

>1350 contributors from
> 350 institutes,
a truly global effort

- **FCC-Conceptual Design Reports (completed in 2018):**
  - **Vol 1 Physics, Vol 2 FCC-ee, Vol 3 FCC-hh, Vol 4 HE-LHC**
  - CDRs published in **European Physical Journal C (Vol 1) and ST (Vol 2 – 4)**

    EPJ C 79, 6 (2019) 474 , EPJ ST 228, 2 (2019) 261-623 , EPJ ST 228, 4 (2019) 755-1107 , EPJ ST 228, 5 (2019) 1109-1382

- **Summary documents provided to EPPSU SG**
  - **FCC-integral, FCC-ee, FCC-hh, HE-LHC**
  - Accessible on http://fcc-cdr.web.cern.ch/

2020 Update of the European Strategy for Particle Physics

Core sentence "order of the further FCC study":

"Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update."

FCC feasibility study: main challenges

Financial feasibility

cost of tunnel: ~5.5 BCHF; FCC-ee: ~5-6 BCHF; FCC-hh: ~17 BCHF (if after FCC-ee)

→ cannot be funded only from CERN's (constant) budget + "one-off" contributions from non-Member States → need new mechanisms (global project funding model; EC? private?)

1st priority of feasibility study: find ~ 5 BCHF for the tunnel from outside CERN's budget

Technical and administrative feasibility of tunnel

- ☐ highly-populated area; two countries with different legislative frameworks
- ☐ land expropriation and reclassification
- ☐ high-risk zones
- ☐ environmental aspects

1st priority of feasibility study: no show-stopper for ~100 km tunnel in Geneva region

Technologies of machine and experiments

- ☐ huge challenges, but under control of our scientific community
- ☐ pressing environmental aspects: energy, cooling, gases, etc.

1st priority of feasibility study: magnets; minimise environmental impact; energy efficiency & recovery

Gathering scientific, political, societal and other support

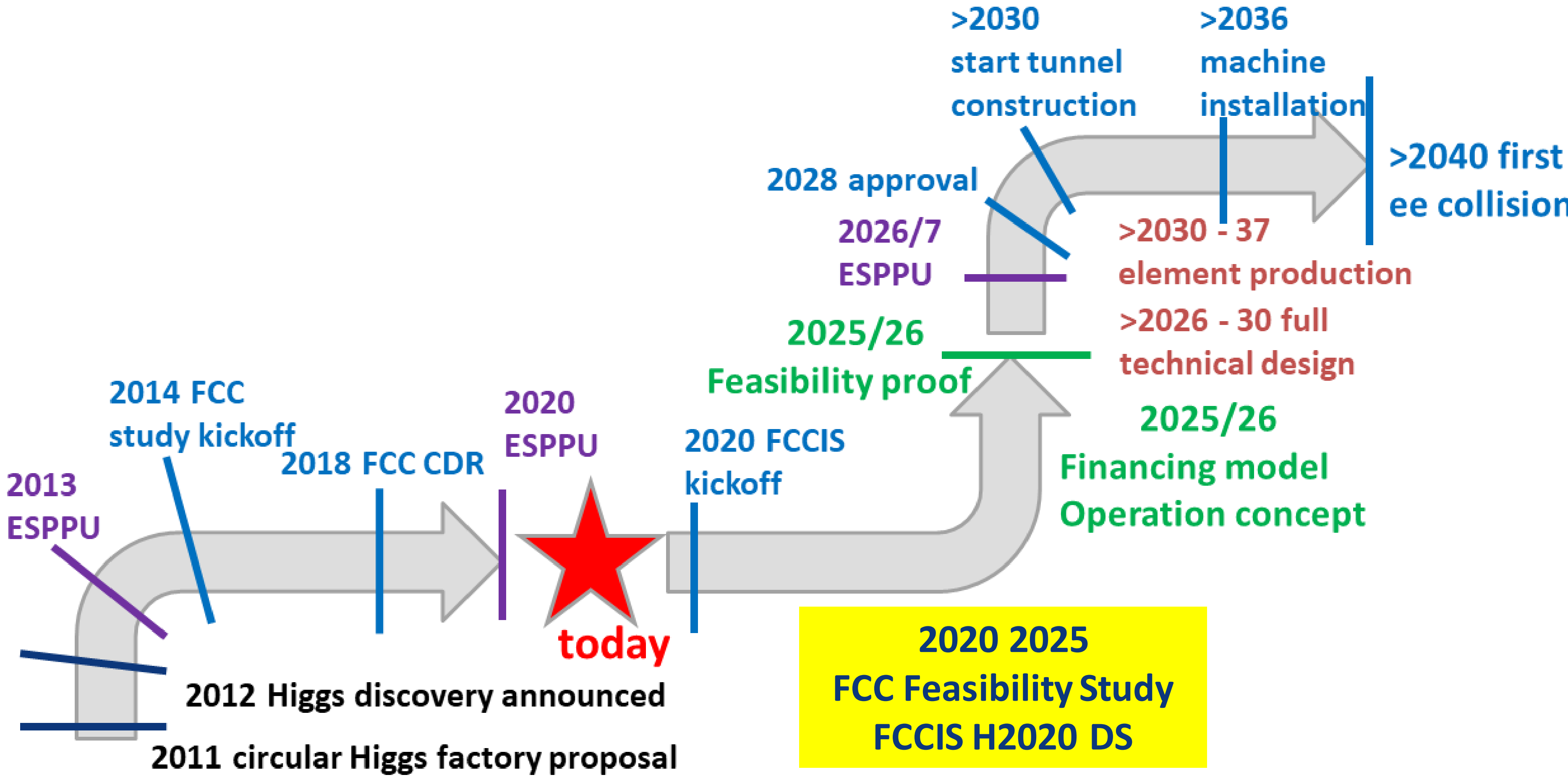
→ requires "political work" and communication campaign for "consensus building" with governments and other authorities, scientists from other fields, industry, general public, etc.

→ **can FCC be a facility also for other disciplines** (nuclear science, photon science, etc.)**?**

→ creative and proactive ideas for technology transfer from FCC to society

Fabiola Gianotti: "CERN vision and goals until next strategy update" FCCIS Kick-Off, 9 Nov. 2020

FCC roadmap towards stage 1



2011 circular Higgs factory proposal

2012 Higgs discovery announced

2013 ESPPU

2014 FCC study kickoff

2018 FCC CDR

2020 ESPPU

today

2020 FCCIS kickoff

2025/26 Feasibility proof

2026/7 ESPPU

2028 approval

>2030 start tunnel construction

>2036 machine installation

>2040 first ee collision

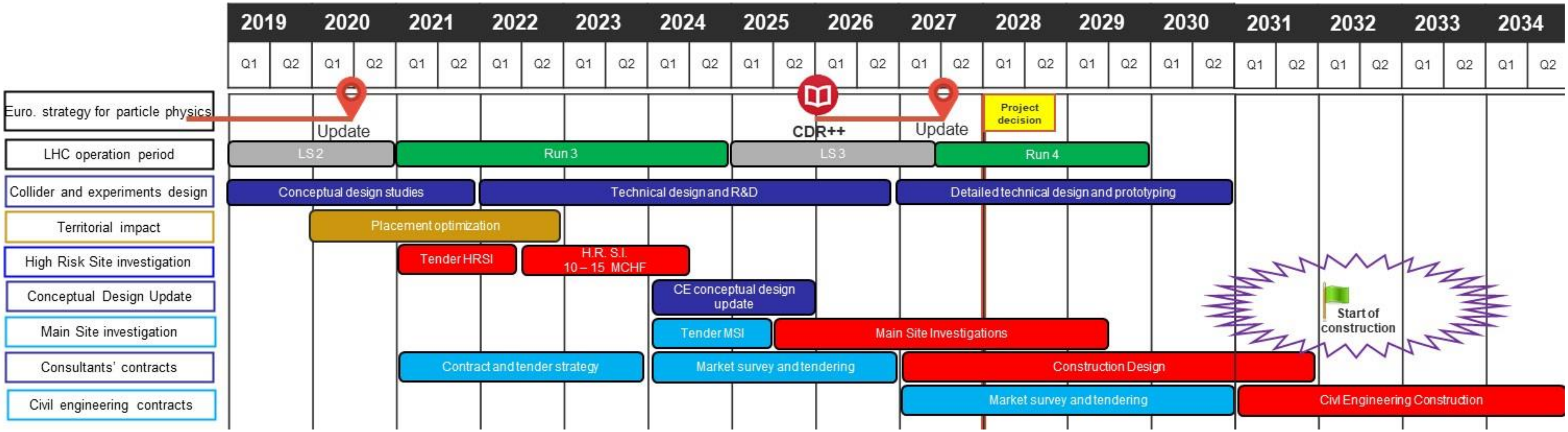
>2030 - 37 element production

>2026 - 30 full technical design

2025/26 Financing model Operation concept

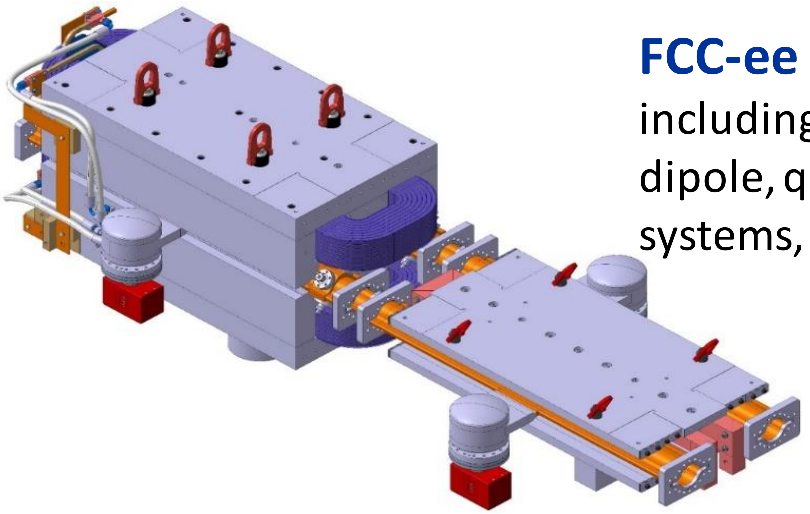
2020 2025
FCC Feasibility Study
FCCIS H2020 DS

CE preparatory activities 2020 - 2030



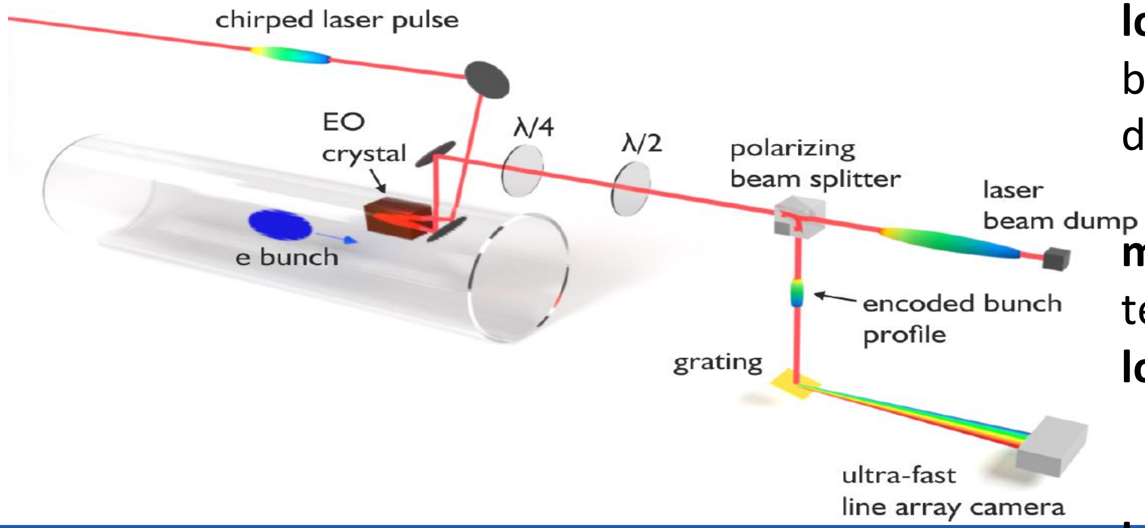
- **technical schedule of main processes leading to start of construction begin 2030ies**
- **for proof of principle feasibility: high risk area site investigations, 2022 – 2024**
- **followed by update of civil engineering conceptual design and CE cost estimate 2025**

FCC key deliverables: prototypes by 2025



FCC-ee complete arc half-cell mock up

including girder, vacuum system with antechamber + pumps, dipole, quadrupole + sext. magnets, BPMs, cooling + alignment systems, technical infrastructure interfaces.



key beam diagnostics elements

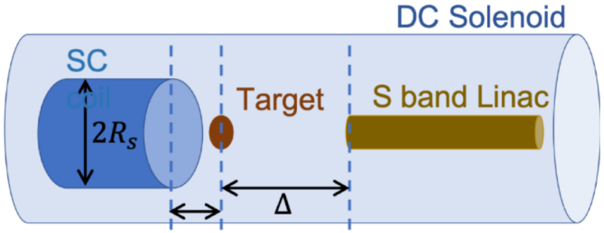
bunch-by-bunch turn-by-turn **longitudinal charge density profiles** based on electro-optical spectral decoding (beam tests at KIT/KARA) ; **ultra-low emittance measurement** (X-ray interferometer tests at SuperKEKB, ALBA) ; **beam-loss monitors** (IJCLab/KEK?) ; **beamstrahlung monitor** (KEK); **polarimeter** ; **luminometer**

FCC key deliverables: prototypes by 2025

400 MHz SRF cryomodule, + prototype multi-cell cavities for FCC ZH operation High-efficiency RF power sources

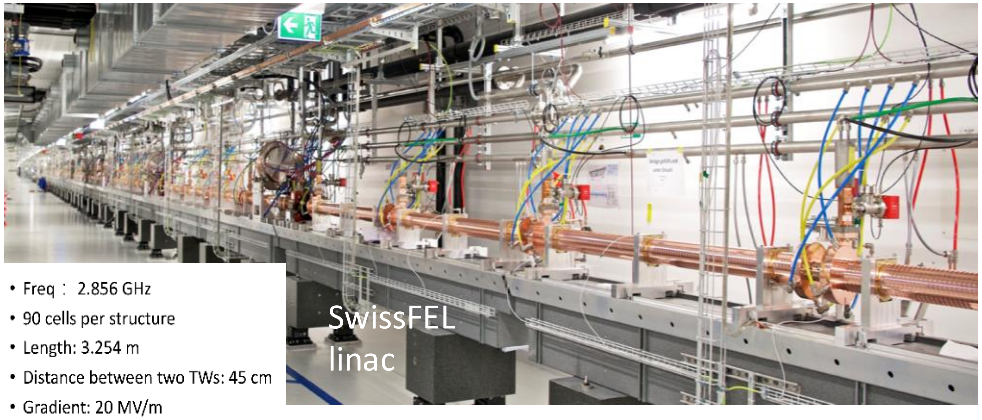
high-yield positron source

target with DC SC solenoid or flux concentrator



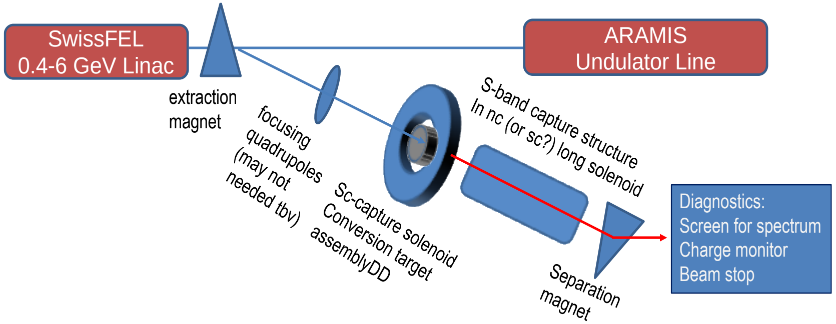
positron capture linac

large aperture S-band linac



- Freq : 2.856 GHz
- 90 cells per structure
- Length: 3.254 m
- Distance between two TWs: 45 cm
- Gradient: 20 MV/m
- Aperture: 30 mm

beam test of e⁺ source & capture linac at SwissFEL – yield measurement

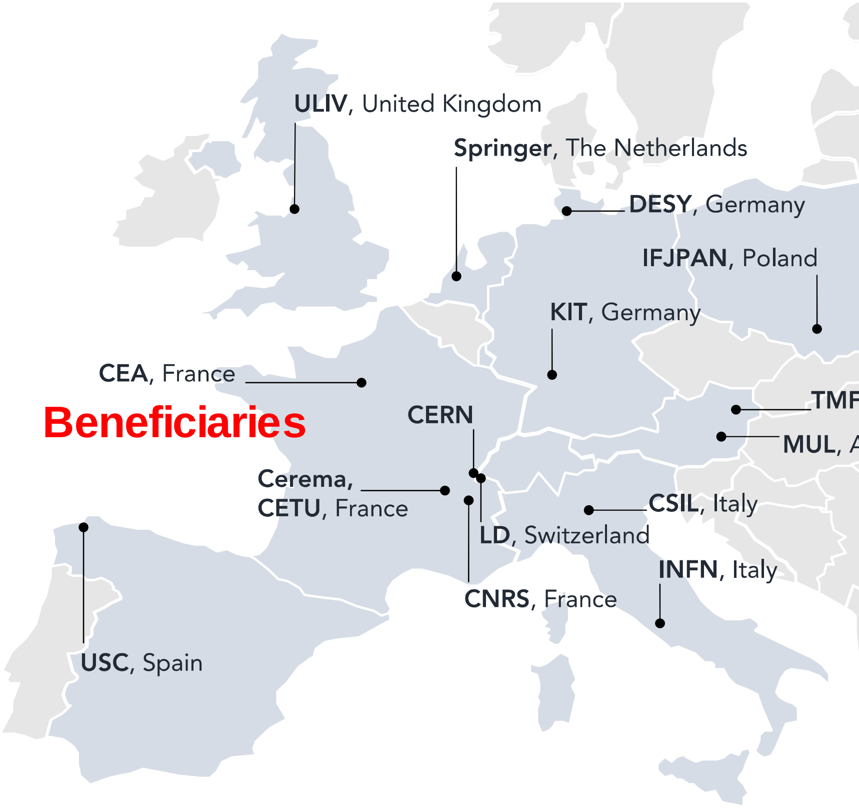


strong support from Switzerland via CHART II program 2019 – 2024 for FCC-ee injector, HFM, beam optics developments, geology and geodesy activities.

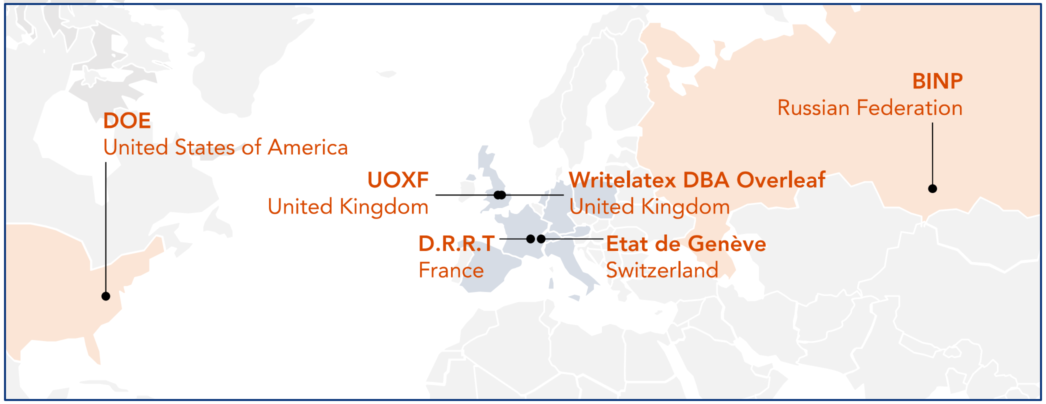
H2020 DS FCC Innovation Study 2020-24

Topic	INFRADEV-01-2019-2020
Grant Agreement	FCCIS 951754
Duration	48 months
From-to	2 Nov 2020 – 1 Nov 2024
Project cost	7 435 865 €
EU contribution	2 999 850 €
Beneficiaries	16
Partners	6

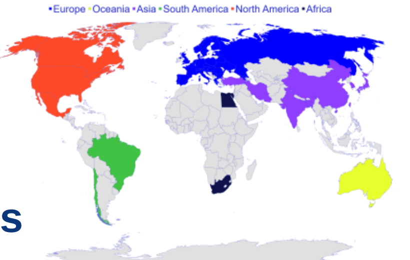
Beneficiaries



Partners



FCCIS kickoff
& physics WS,
Nov'20:
910 participants



Status of Global FCC Collaboration

increasing international collaboration as a prerequisite for success:

links with science, research & development and **high-tech industry** will be essential to further advance and prepare the implementation of FCC

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Institutes

30
Companies

34
Countries

EC
H2020

summary & outlook

circular e^+e^- colliders: glorious history & exciting future

heeding lessons learnt:

SR effects of LEP
high currents of KEKB and PEP-II
top-up of KEKB and PEP-II
crab waist of DAFNE
crab waist & low β_y* of SuperKEKB
***e*$^+$ source** of KEKB
cryo availability of LHC
spin gymnastics of HERA

FCC-ee

individual parameters mostly relaxed compared with those in "demonstrator machines"

"new" effects: beamstrahlung → lifetime limit, *E* spread, *x*-*z* beam-beam instability, synchrotron radiation in quadrupole magnets …

trend & challenge: making future colliders truly green !

- **next steps: concrete local/regional implementation scenario** in collaboration **with host states, machine optimization, physics studies and technology R&D**, performed **via global collaboration** and supported by **EC H2020 Design Study, to prove feasibility by 2025/26**

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

Burt Richter, 1976

NIM 136 (1976) 47-60

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,
PAC1995,
† 5. October 2013

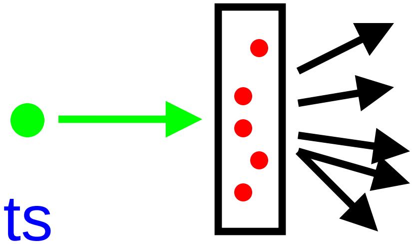
…surely great times ahead!

spare slides

why colliders ? - energy

colliders were invented (1943) and patented (1953) by Rolf Wideröe

centre-of-mass energy:

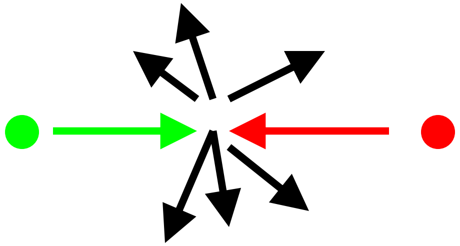


$$E_{\mathrm{c.m.}} = \sqrt{2E_{\mathrm{beam}}M_{\mathrm{target}}c^2}$$

beam hits
a “fixed target”

$$E_{\mathrm{c.m.}} = 2E_{\mathrm{beam}}$$

two equal
beams collide



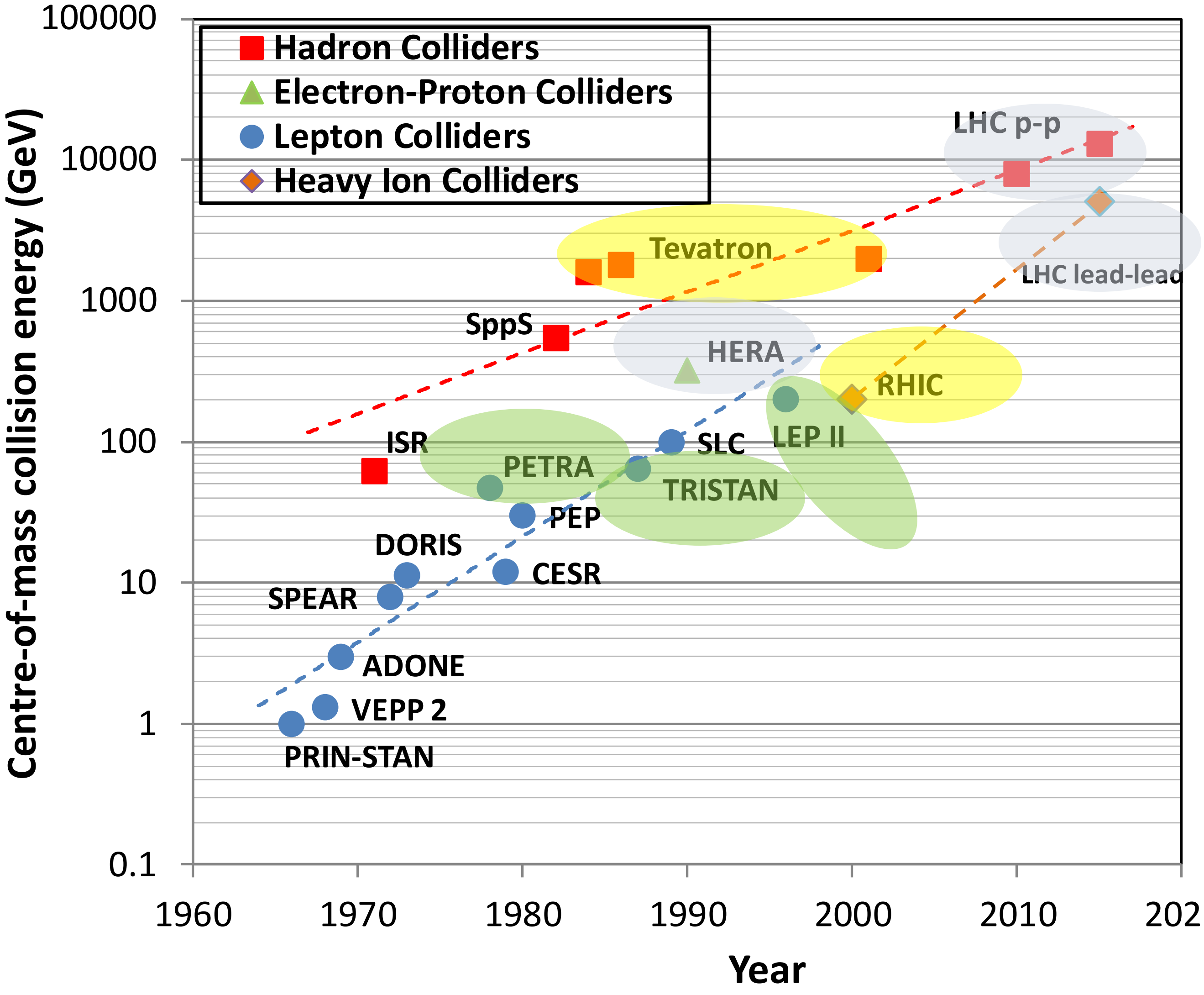
colliding two beams against each other can provide much higher centre-of-mass energies than fixed target!

$$E_{\mathrm{c.m.}} = 2\sqrt{E_1E_2}$$

for two high-energy beams
of unequal energy

colliders constructed and operated

A. Ballarino



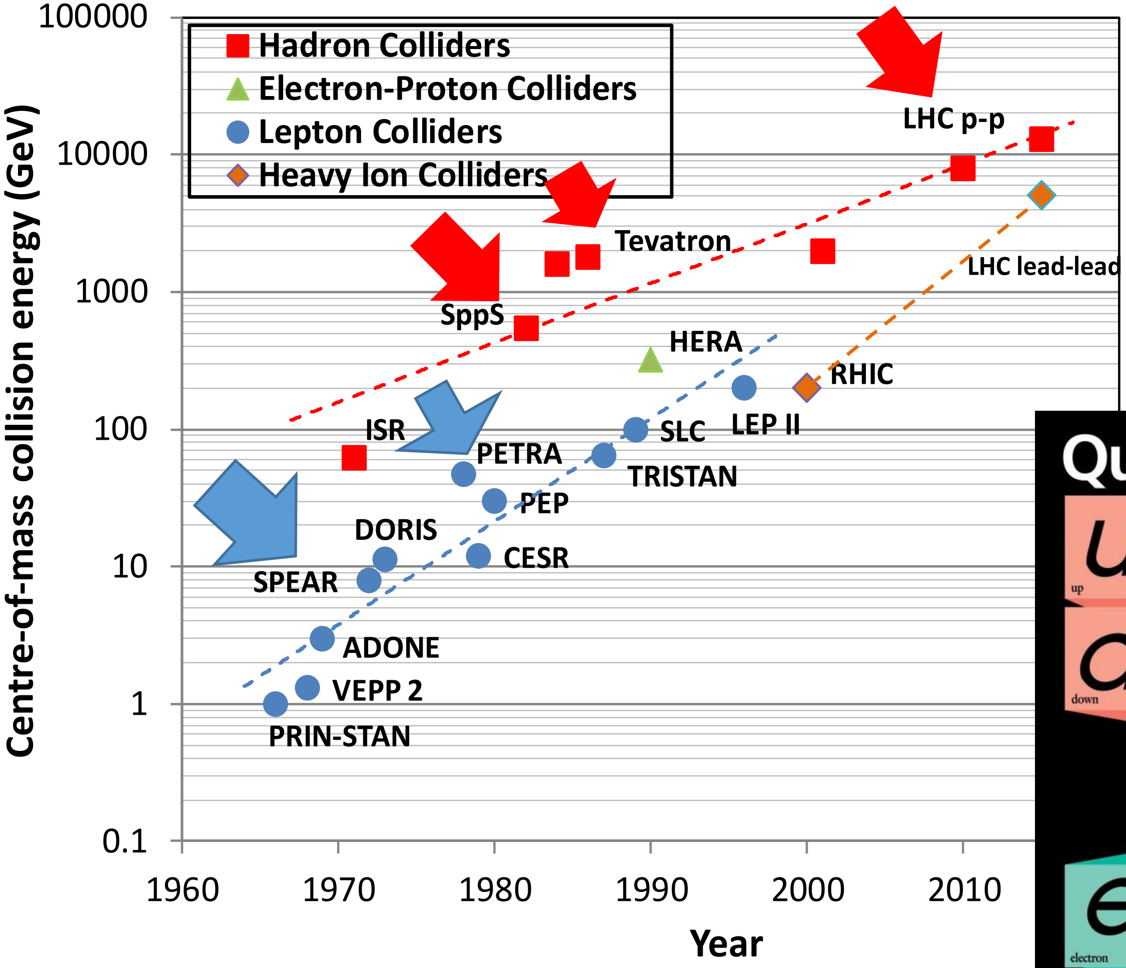
Colliders with superconducting RF system

Colliders with superconducting arc magnet system

Colliders with superconducting magnet & RF

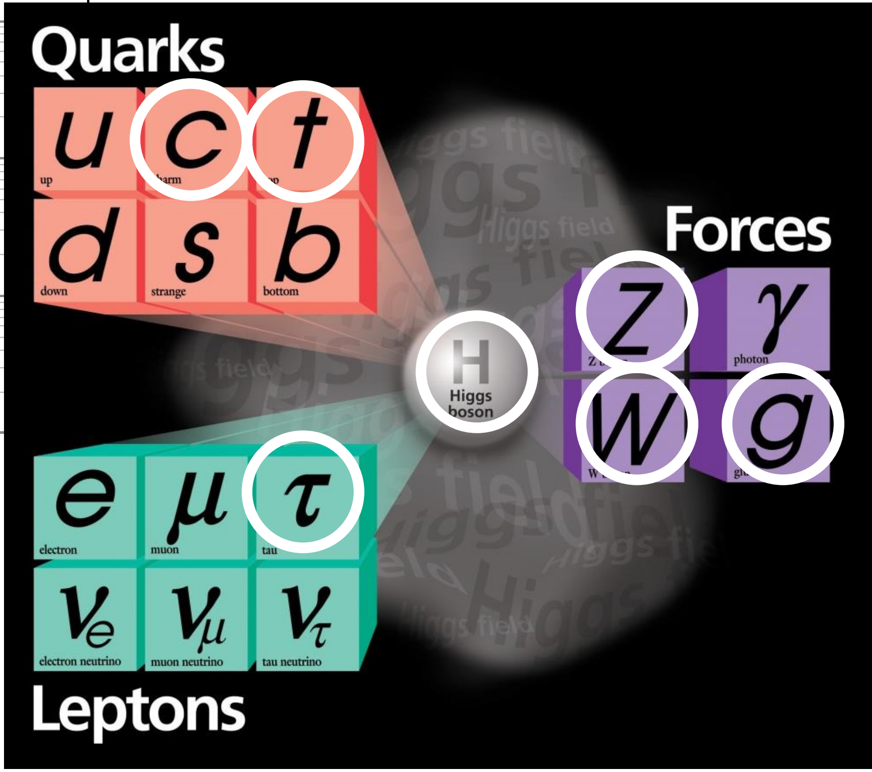
advances by new technologies and new materials

colliders and discoveries



Standard Model
Particles and forces

A. Ballarino

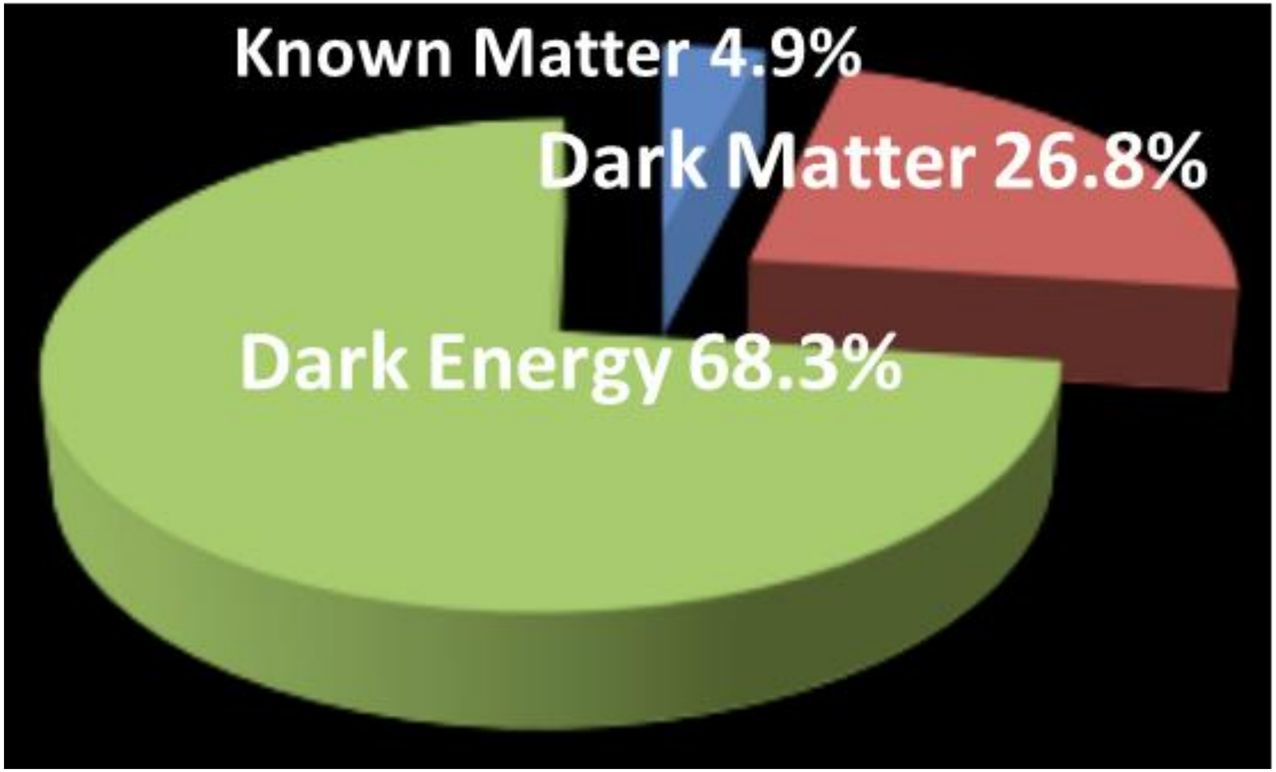


powerful instruments for discovery and precision measurement

still many open questions

Known matter is only 5% of universe!

F. Gianotti



- what is dark matter?
- what is dark energy?
- why more matter than antimatter?
- what about gravity?

collider figure of merit: luminosity

$$R = \sigma L$$

reaction rate

cross section

luminosity

σ tends to decrease as energy^{-2}

bunch population

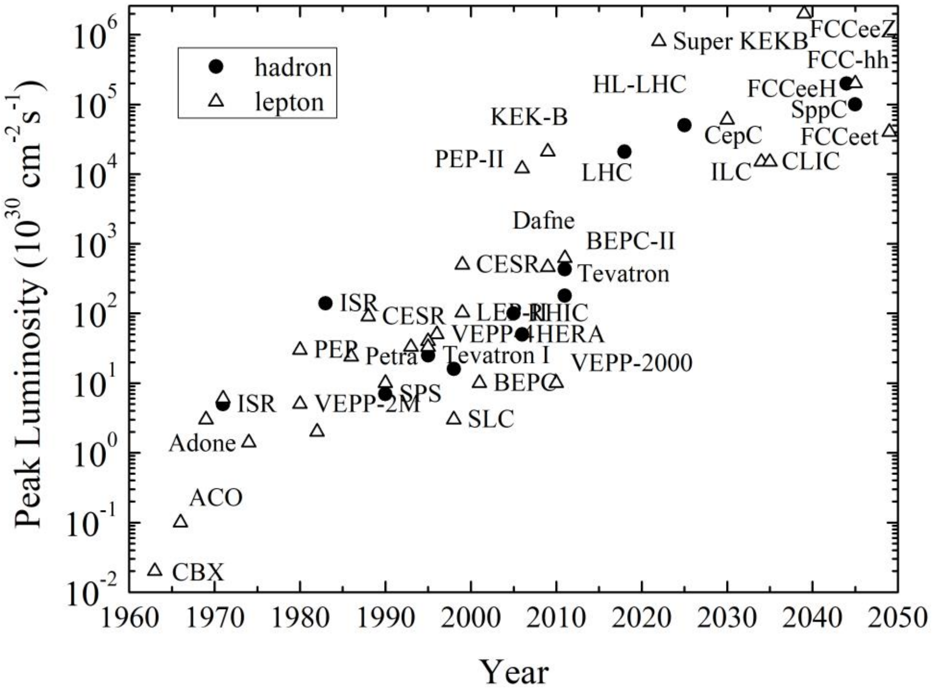
geometric factor (crossing angle, hour glass, pinch, …)

$$L = f_{\text{coll}} \frac{N_b^2}{4\pi \sigma_x^* \sigma_y^*} F$$

bunch collision rate

horizontal & vertical rms beam size at collision point

V. Shiltsev & F.Z., arXiv:2003.09084, submitted to RMP



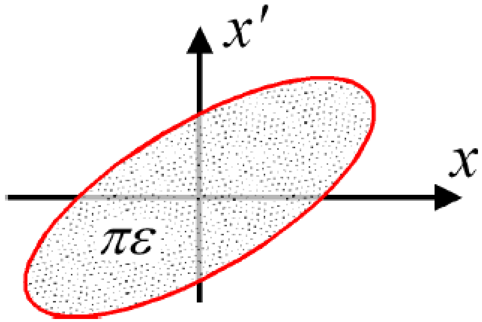
peak luminosity increased by almost 7 orders of magnitude over 60 years

Luminosity

$$L = \frac{N^2 n_b f}{4\pi\sigma_x^*\sigma_y^*} G = \frac{N^2 n_b f}{4\pi\sqrt{\beta_x^*\varepsilon_x\beta_y^*\varepsilon_y}} G$$

various limitations:
beam current (power)
beambeam tune shift
beamstrahlung….

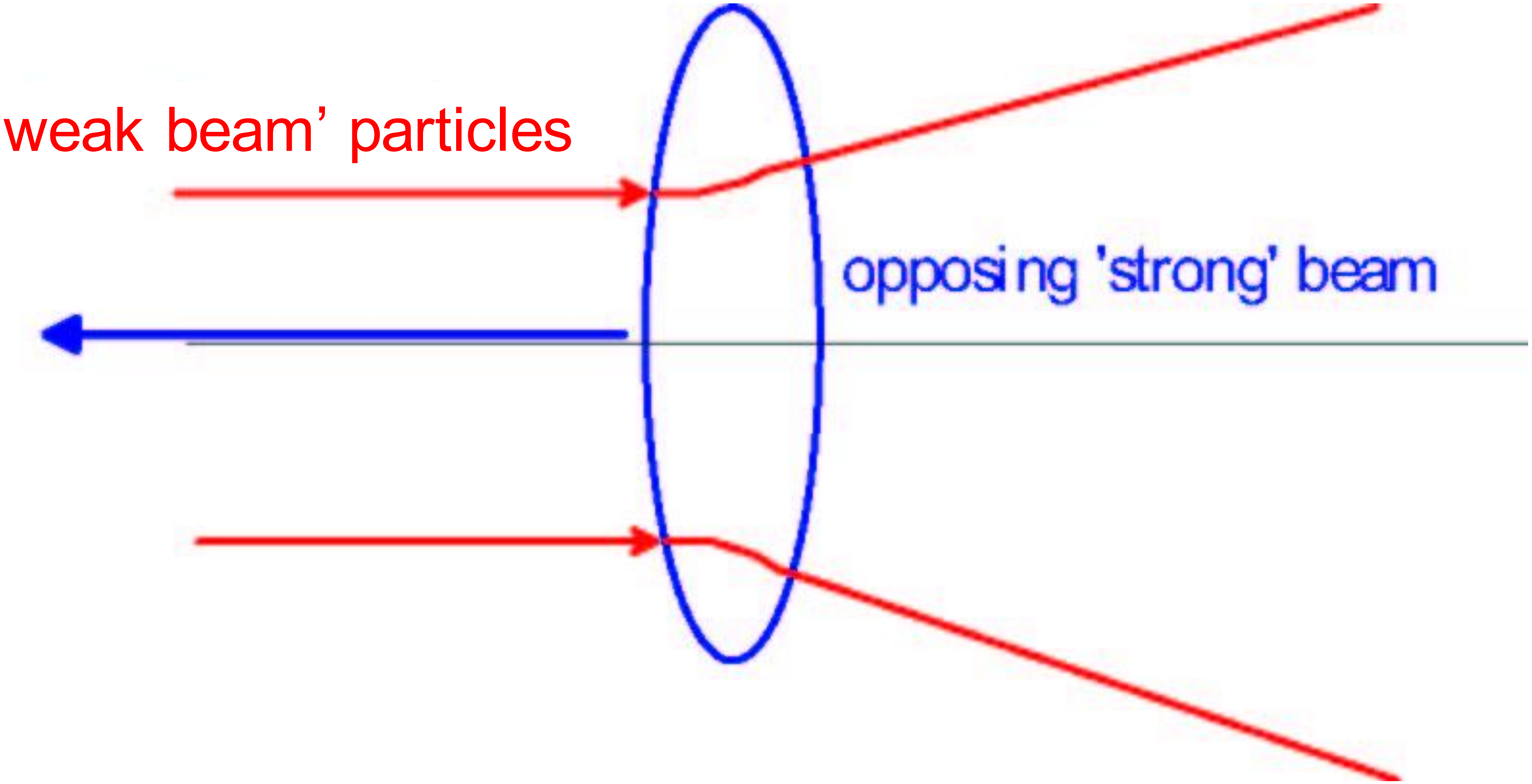
N	**Number of particles per bunch**
n_b	**Number of bunches**
f	Revolution frequency
σ*	**Beam size at interaction point**
G	reduction factor due to crossing angle and “hourglass effect”
ε	Emittance
ε_n	**Normalized emittance**
β*	**Beta function at IP**



$$s^* = \sqrt{b^* e}$$

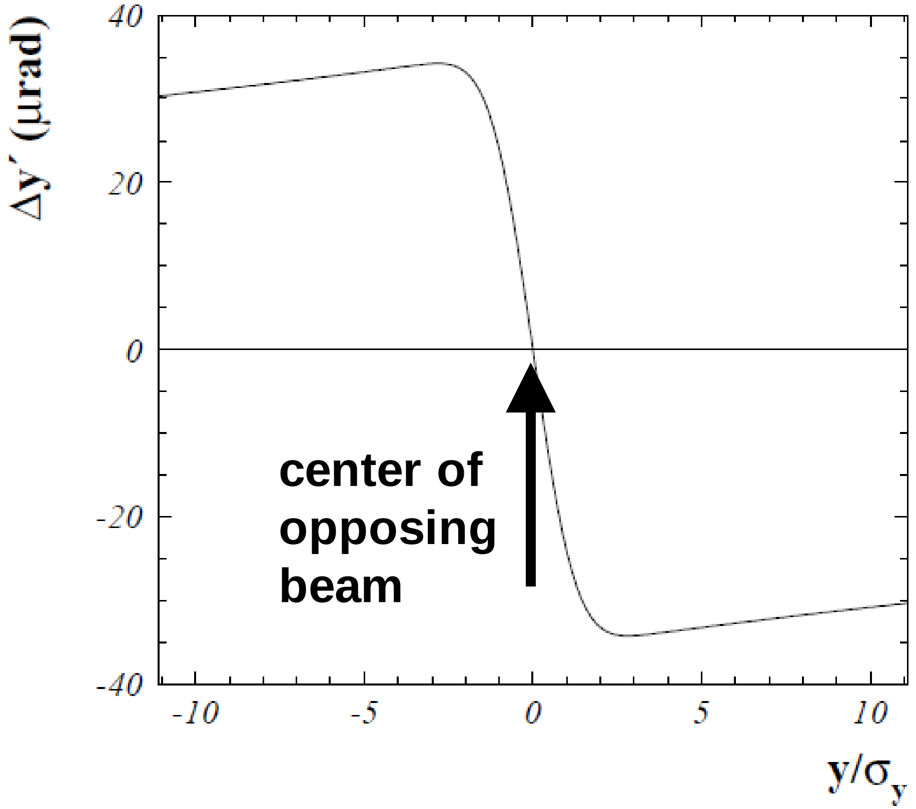
M. Lamont

sketch of beam-beam collision



‘weak beam’ particles

(nonlinear) beam-beam force



at small amplitude similar to effect of defocusing quadrupole

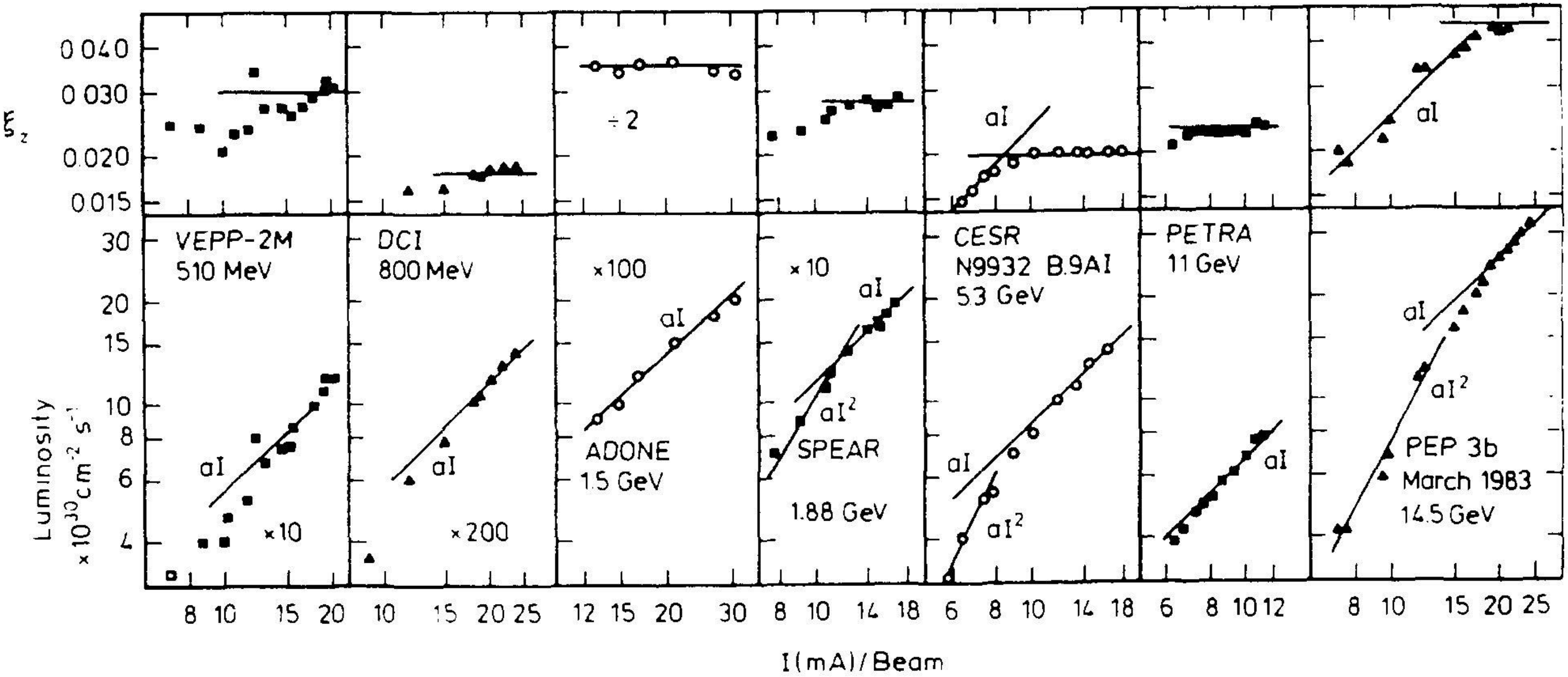
for pure head-on collision

$$\Delta Q_{y,\max} = \xi_y = \frac{N r_e \beta_y^*}{2\pi\gamma\sigma_y^*(\sigma_x^* + \sigma_y^*)}$$

for single collision

beam-beam limit in e^+e^- colliders

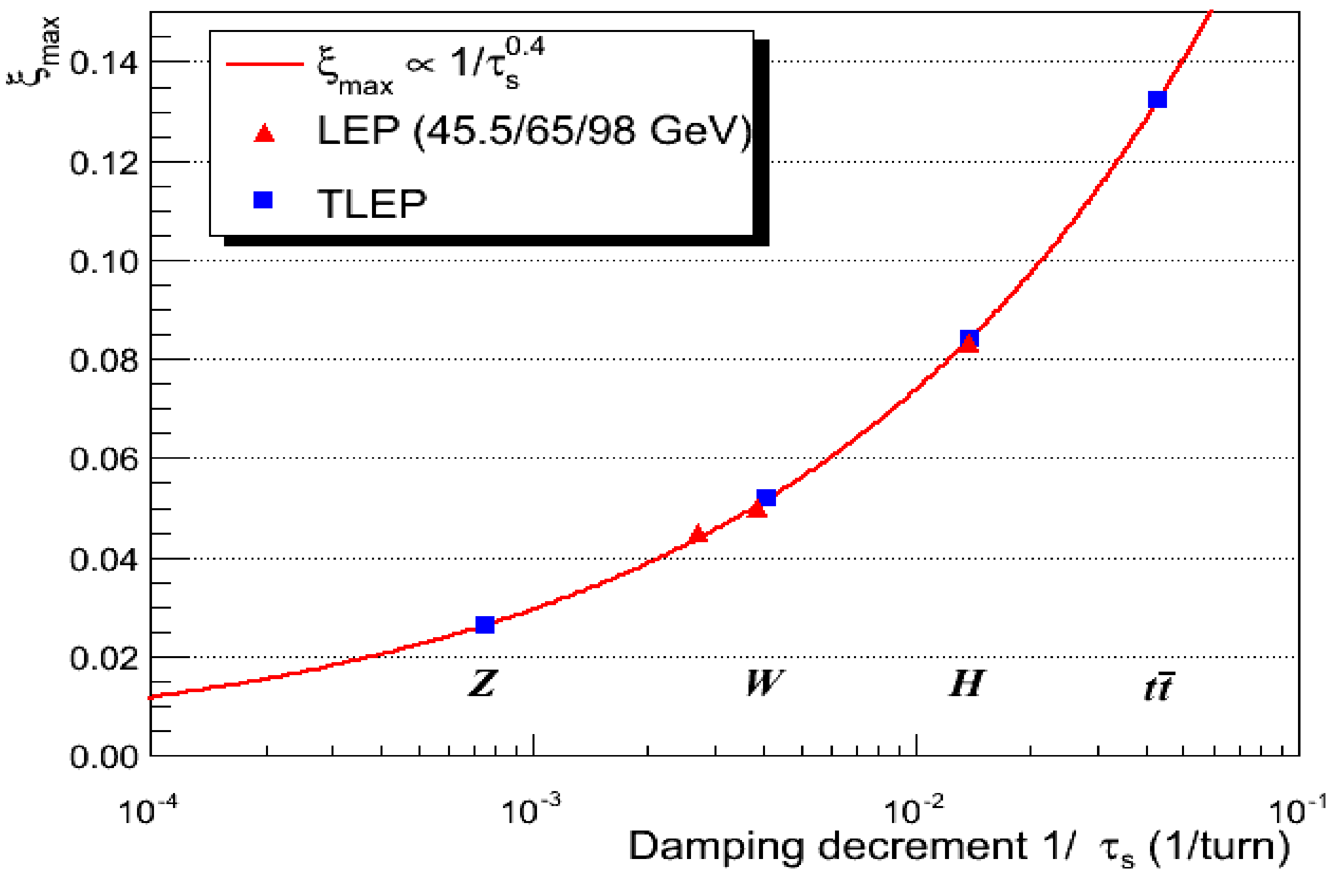
J. Seeman, SLAC-PUB-3825, 1985



luminosity and vertical tune-shift parameter versus beam current for various electron-positron colliders; the tune shift saturates at some current value, above which the luminosity grows linearly

beam-beam limit in e^+e^- colliders with strong radiation damping

R. Assmann



$$\lambda_d = 1/(f_{rev} \cdot \tau \cdot n_{ip})$$

damping decrement per IP

$$\xi_y^\infty \propto (\lambda_d)^{0.4}$$

$$\propto \gamma^{1.2}$$