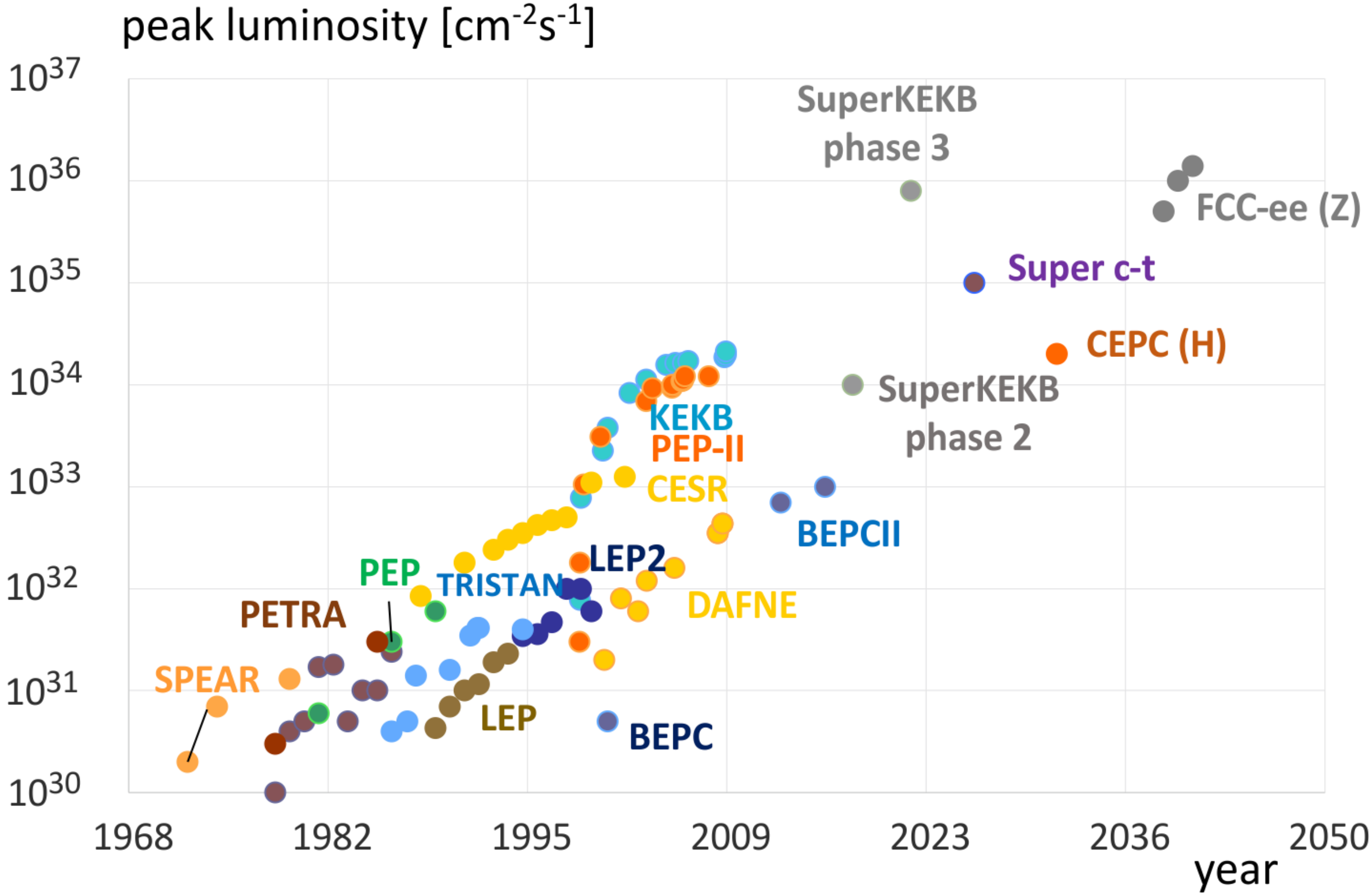
Challenges for Circular e^+e^- Colliders

Frank Zimmermann

eeFACT2018, HKUST, 24 September 2018

circular e^+e^- colliders: 50 year success story



Peak luminosity of circular e^+e^- colliders as a function of year – for past, operating, and proposed facilities including the Future Circular Collider

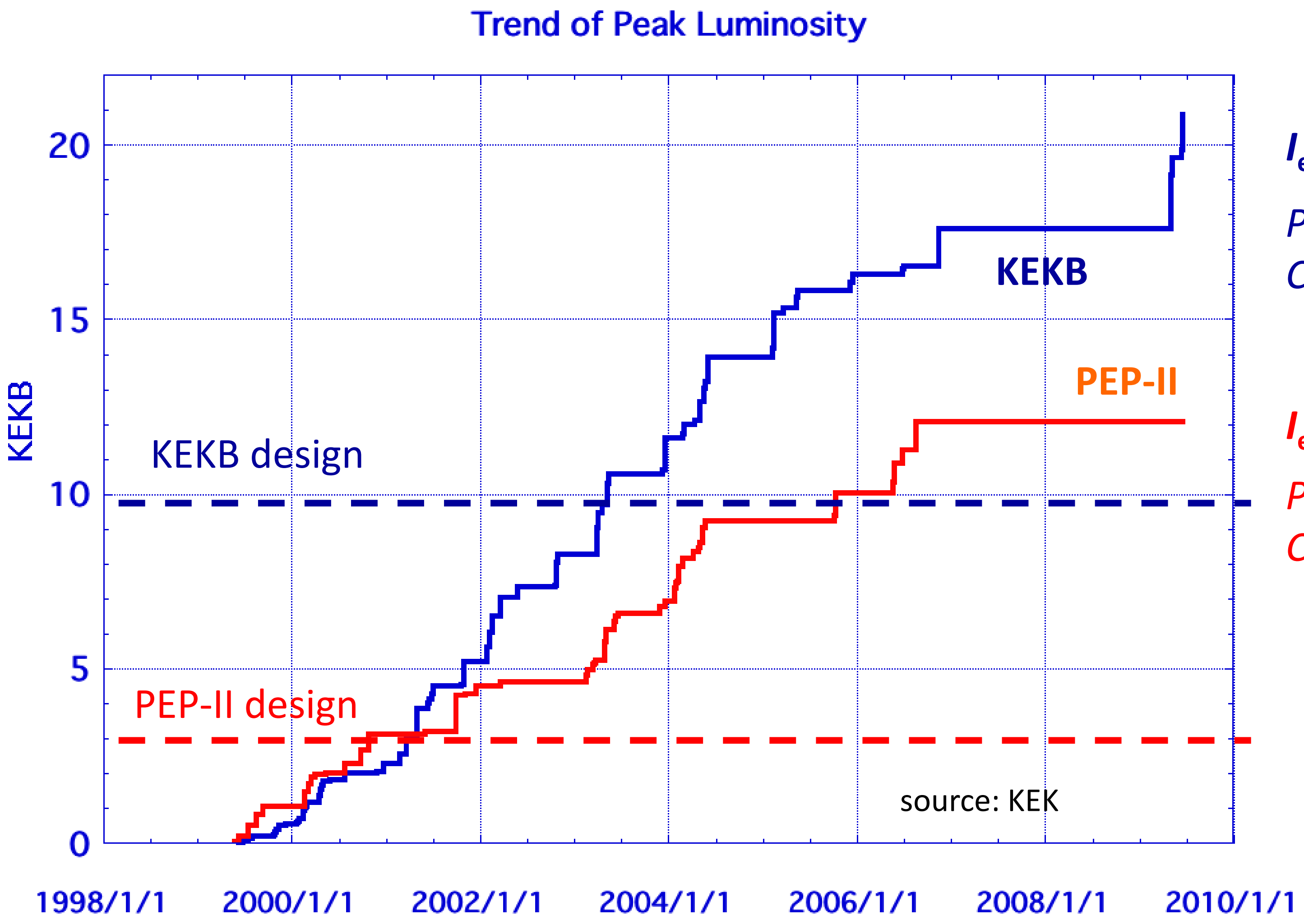
[historical data courtesy Y. Funakoshi]

LEP/LEP-2: the 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
critical photon energy $\sim$1 MeV

B factories: high current, high luminosity

+ top-up injection



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

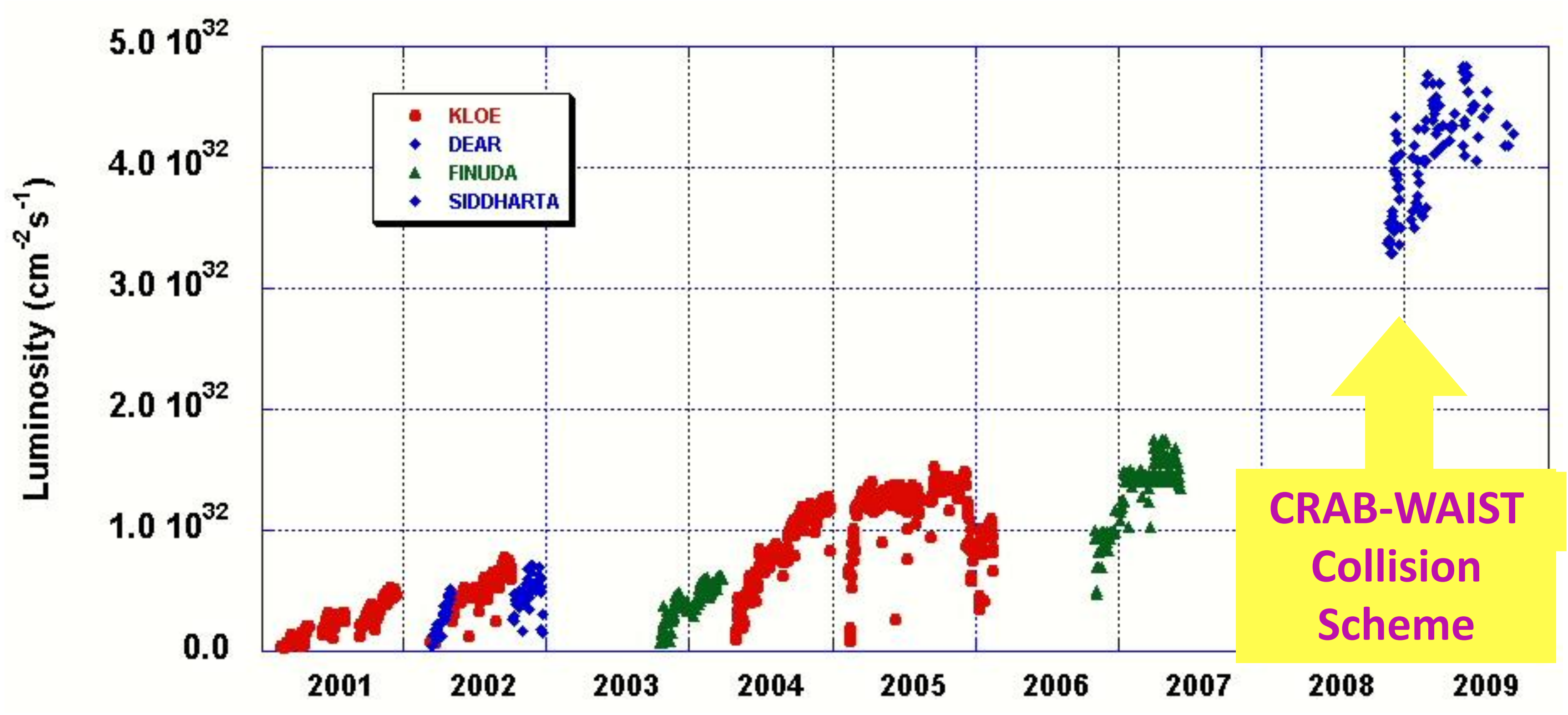
P_{SR} ~ 5 MW
C = 3 km

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

P_{SR} ~ 8 MW
C = 2.2 km

DAΦNE: crab waist collisions

DAΦNE Peak Luminosity



CRAB-WAIST Collision Scheme

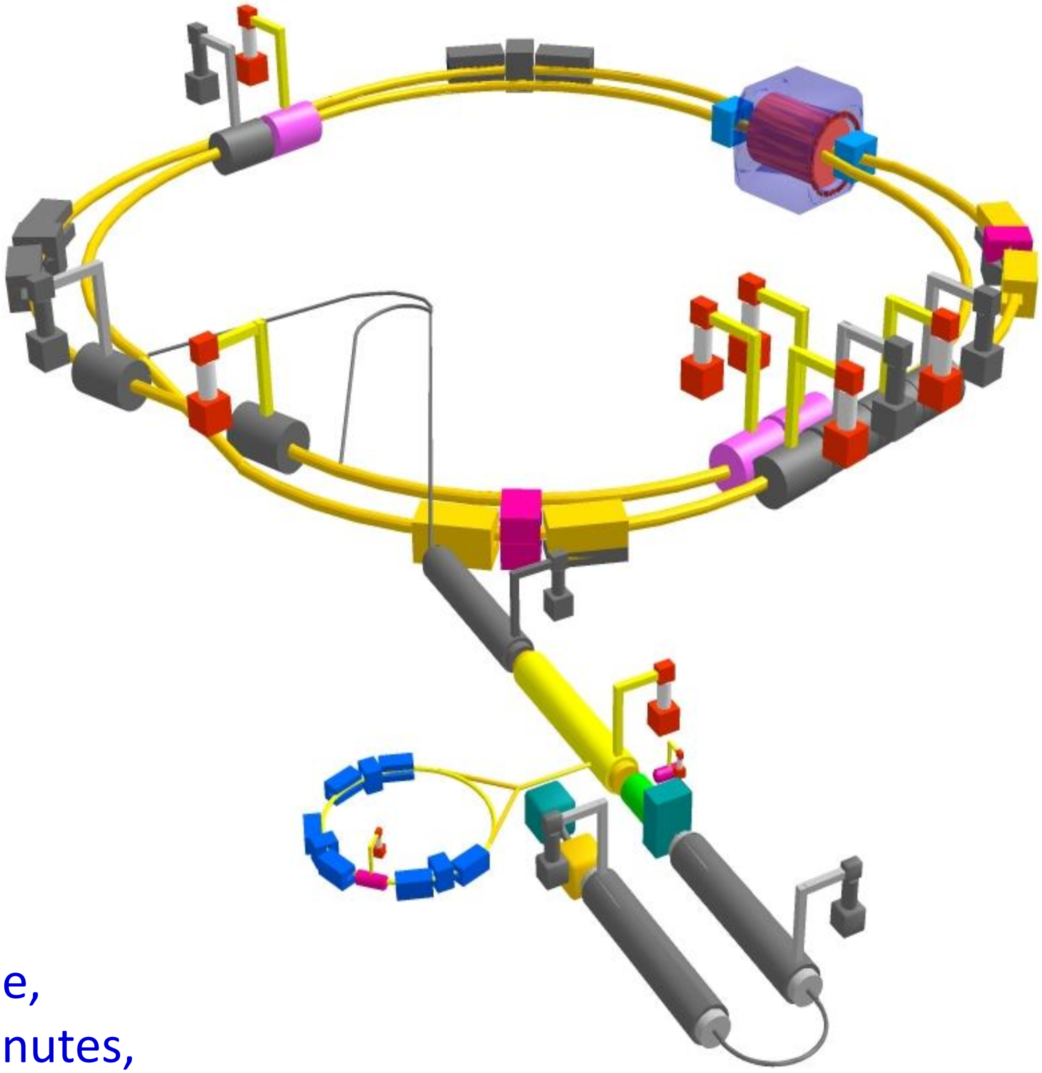
Design Goal

small β_y^*, large beam-beam tune shift

M. Zobov

SuperKEKB: the next BIG step

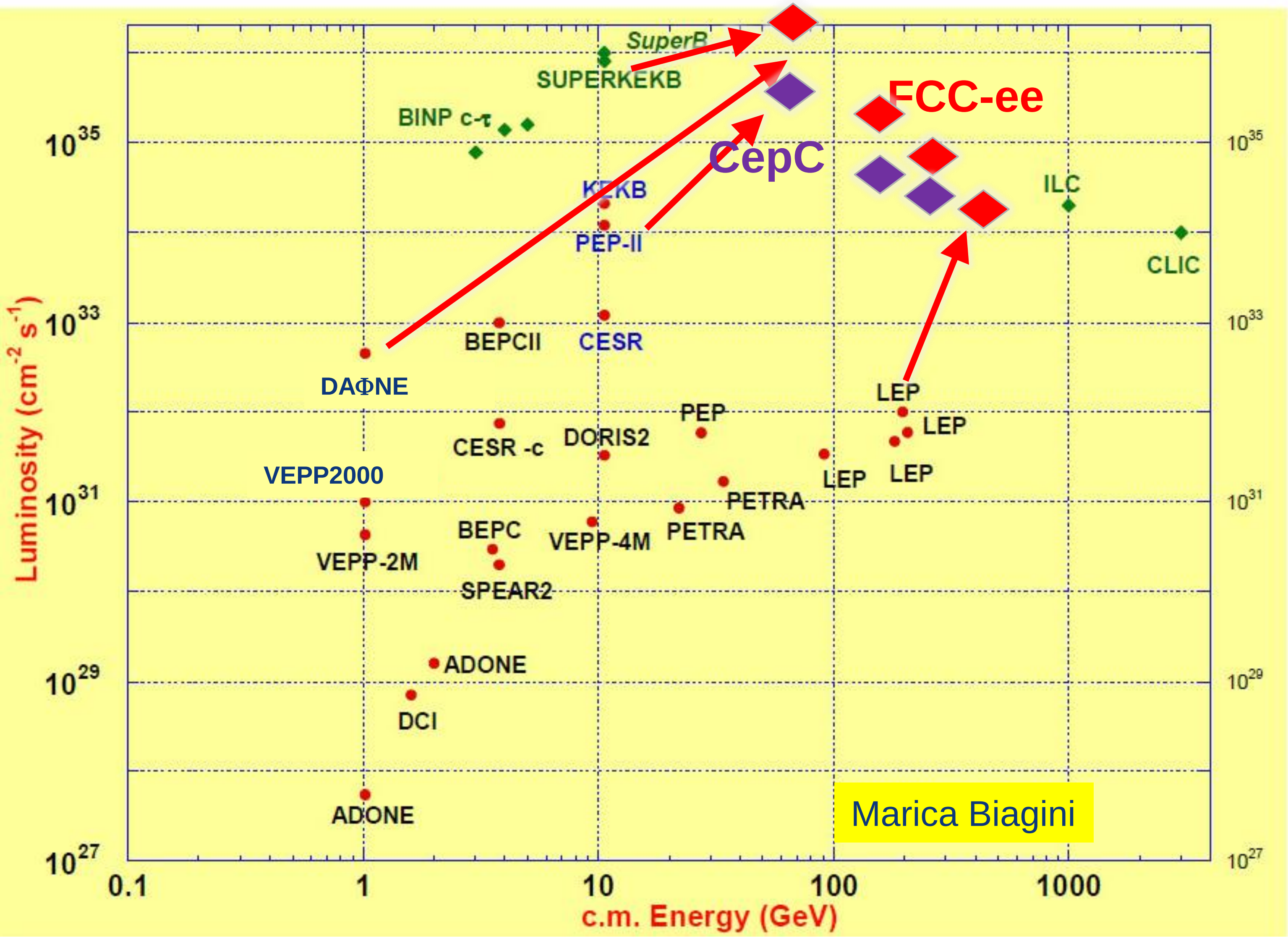
beam
commissioning
started in 2016



nanobeam collision scheme,
design beam lifetime: 5 minutes,
$\beta_y^* \sim 0.3$ mm

K. Oide et al.

from past successes to new territory



Marica Biagini

LEP:
high energy
SR effects

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

DAFNE: crab waist

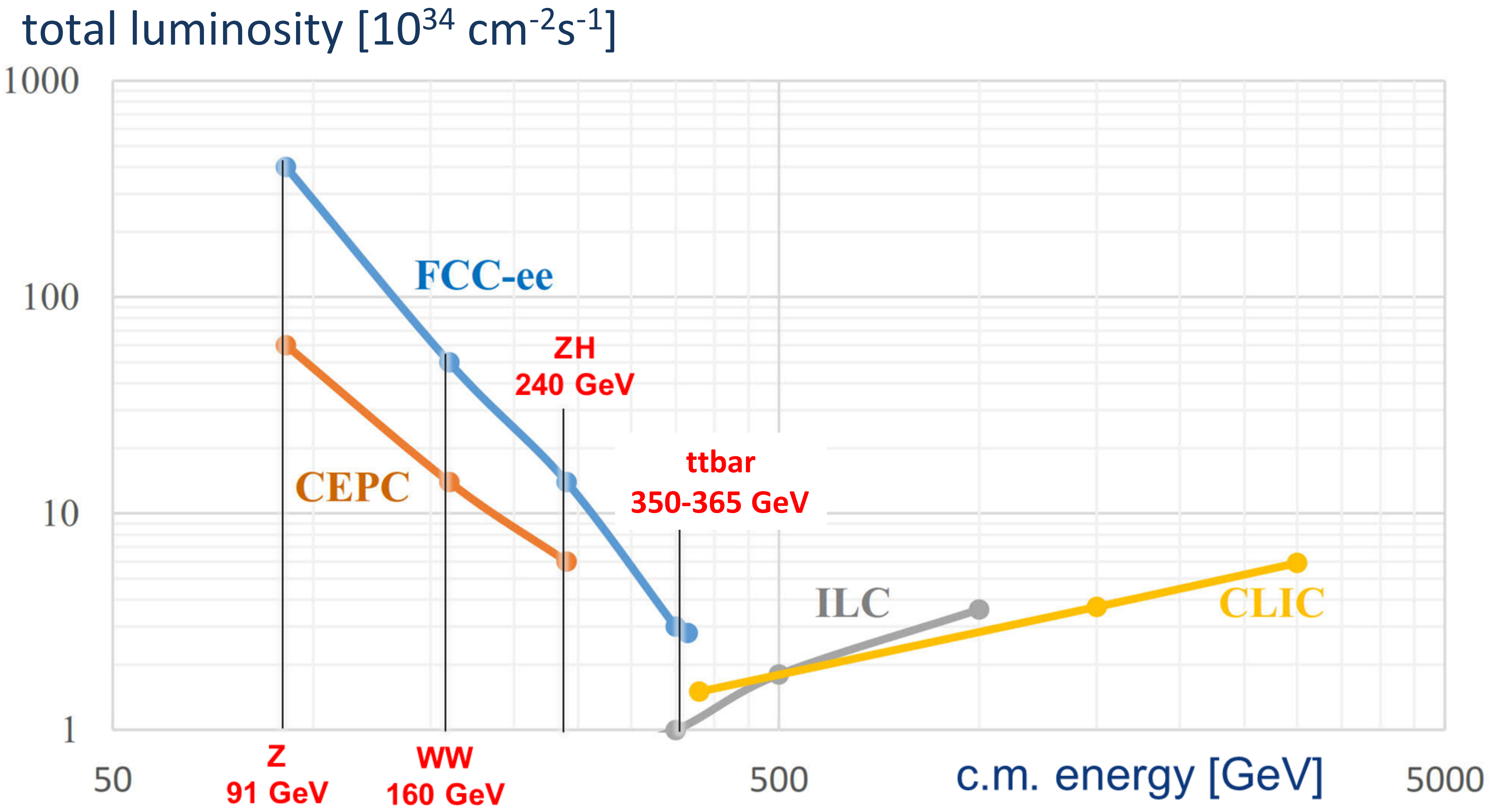
Super B-factories
S-KEKB: low β_y*

KEKB: e^+ source

HERA, LEP, RHIC:
spin
gymnastics

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

tantalizing performance reach till ~400 GeV

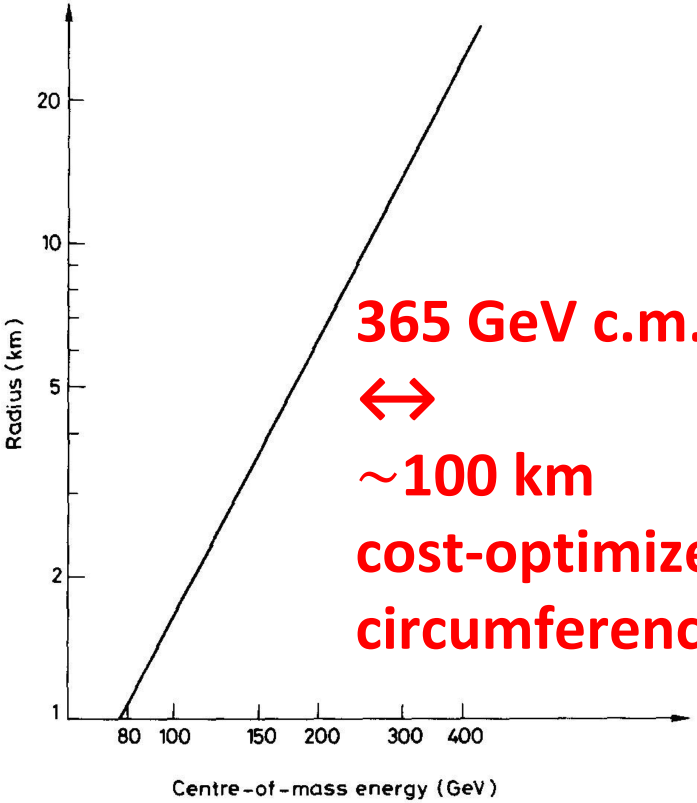


feasibility & optimum circumference

“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.”

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

SR power: supported by staged RF system

“Ampere-class” machine

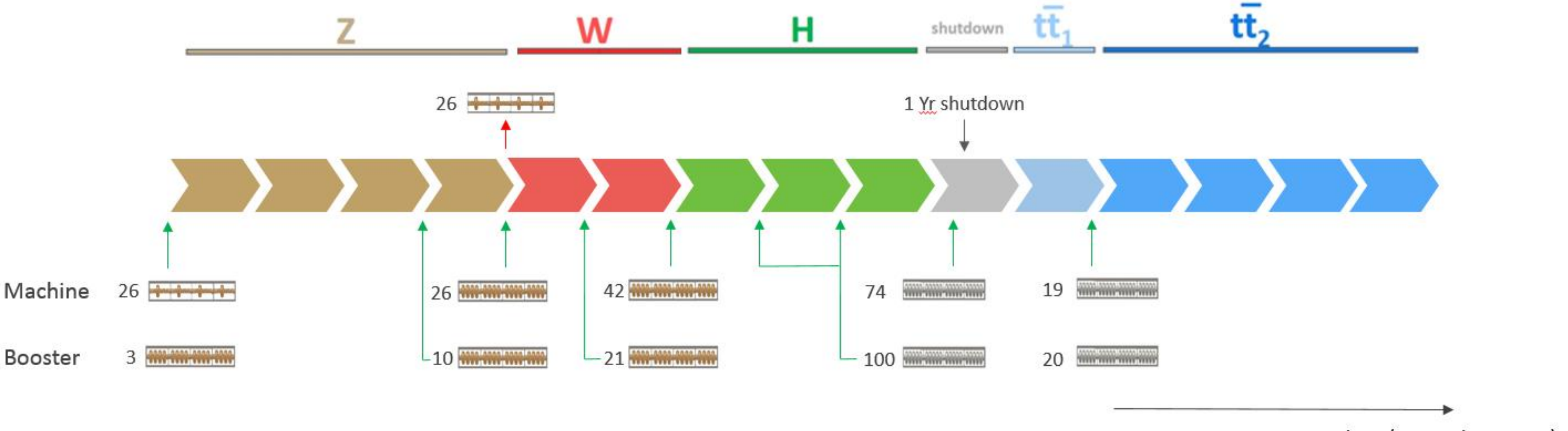
WP	V_{rf} [GV]	#bunches	I_{beam} [mA]
Z	0.1	16640	1390
W	0.44	2000	147
H	2.0	393	29
ttbar	10.9	48	5.4

“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.), Nb/Cu, 4.5 K**
- **higher energy (W, H, t): 400 MHz four-cell cavities (4/cryomodule), Nb/Cu, 4.5 K**
- **ttbar machine complement: 800 MHz five-cell cavities (4/cryom.), bulk Nb, 2 K**
- **installation sequence comparable to LEP (≈ 30 CM/shutdown)**



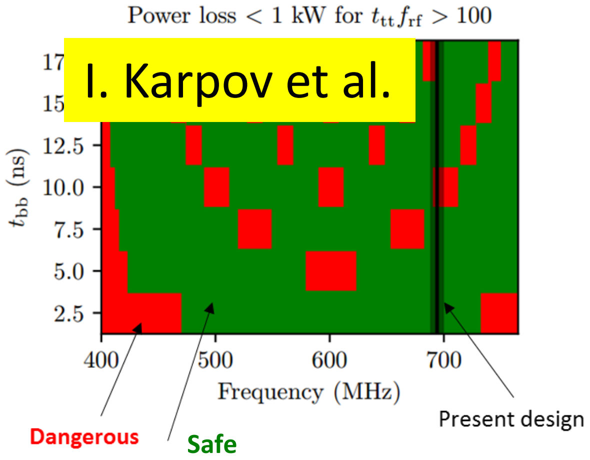
high current, short bunches, large ring: *HOM losses & single-bunch instabilities*

- **shielded, damped**, suitably designed **components**
- HOM energy loss << SR energy loss
- **novel coatings** (thin NEG)

HOM Power Bunch Spacing Loss Factor Current

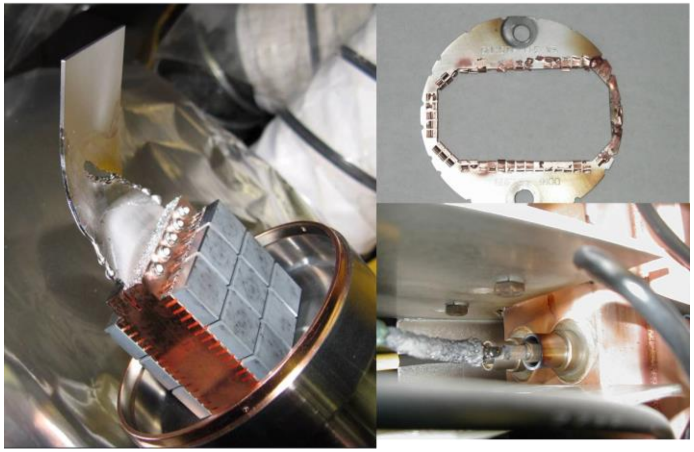
$$P = \tau_b \times k \times I^2$$

some filling schemes should be avoided



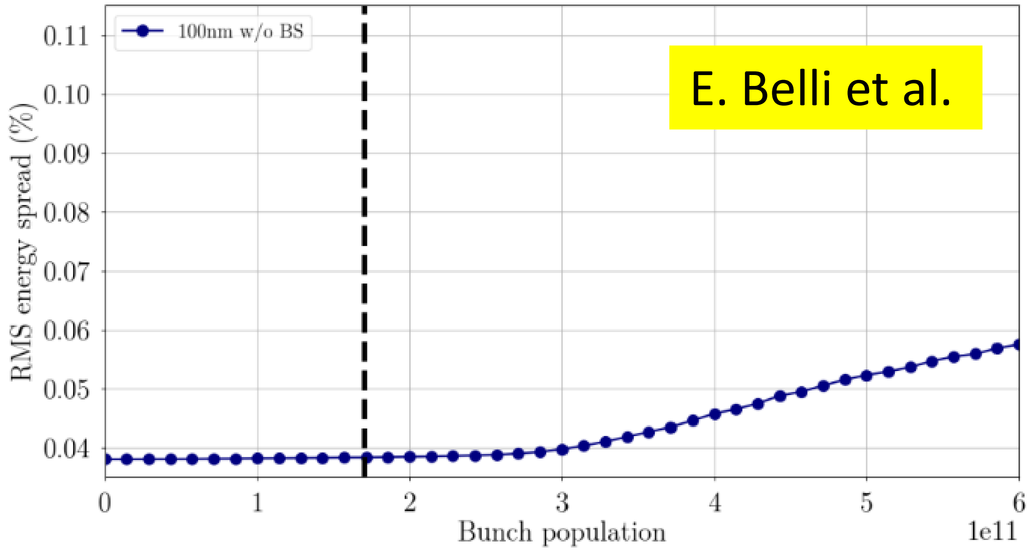
I. Karpov et al.

damaged spoiler, RF shield, BPMs,...



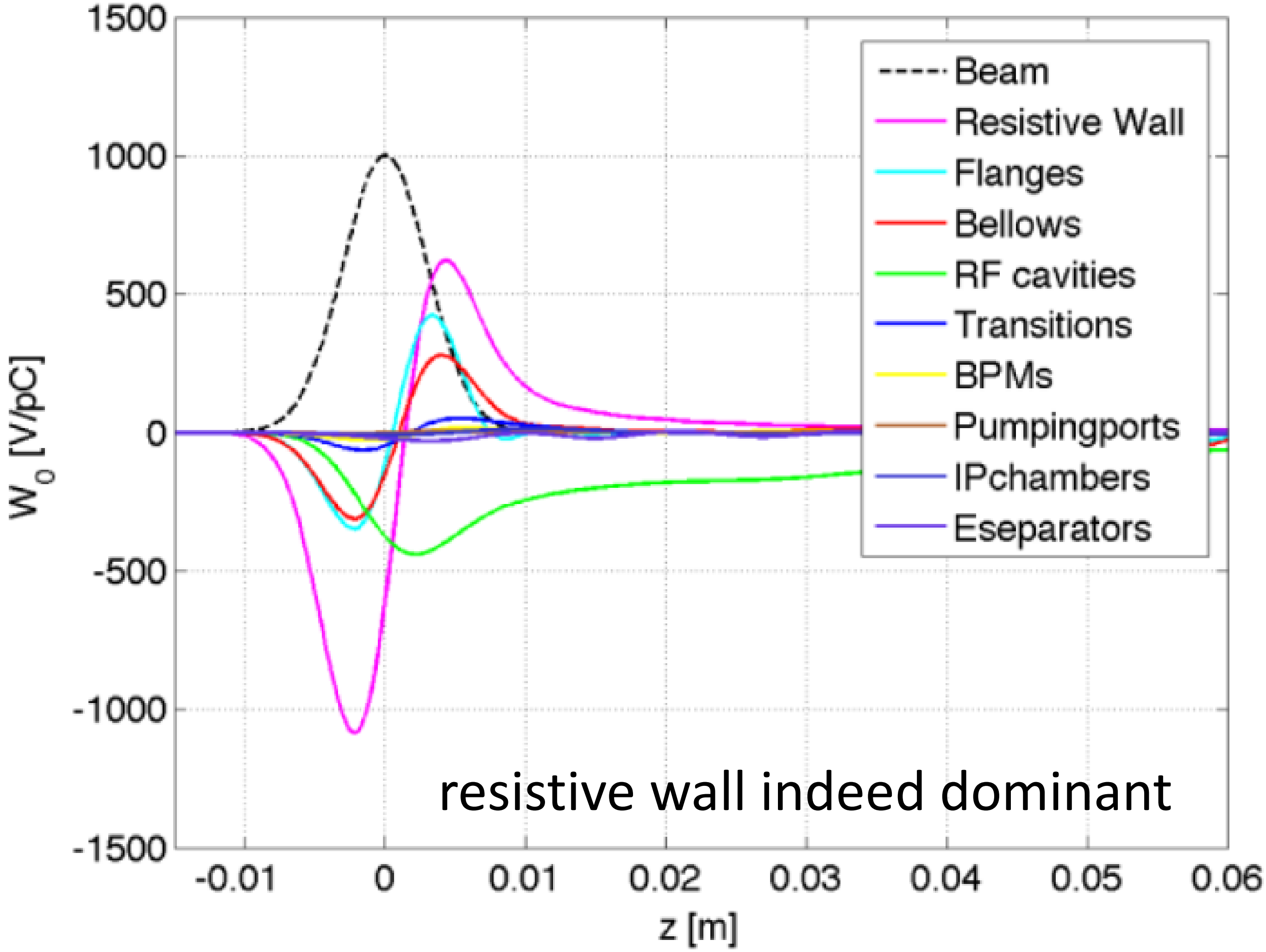
A. Novokhatski

FCC-ee μ-wave threshold with **100 nm NEG**



E. Belli et al.

short-intense bunches: *single-bunch wake*

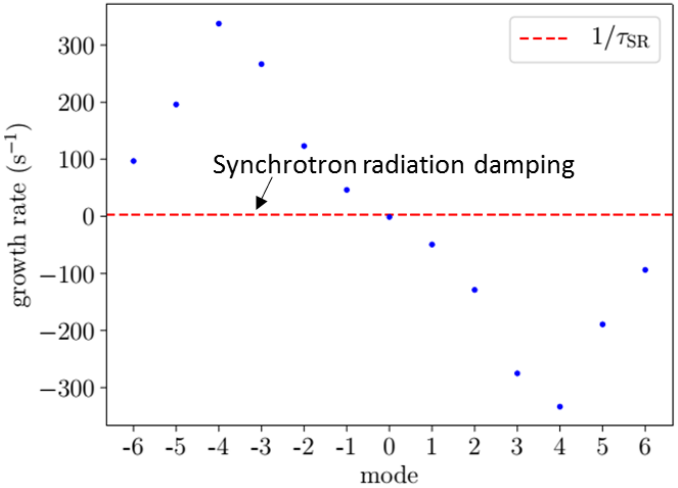


resistive wall indeed dominant

CEPC CDR

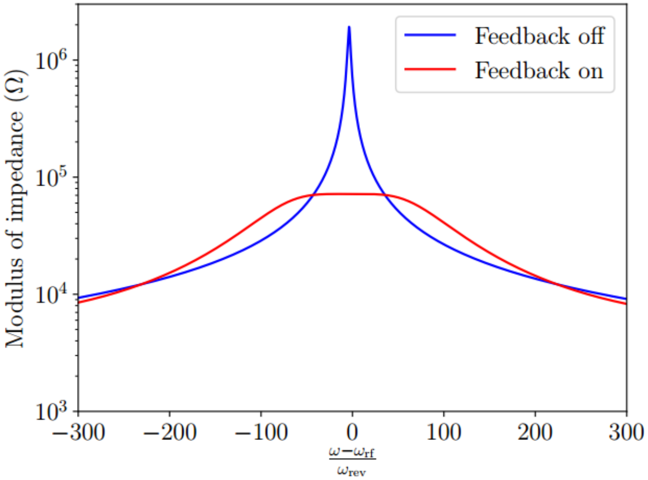
high current, short bunches, large ring: *multi-bunch instabilities*

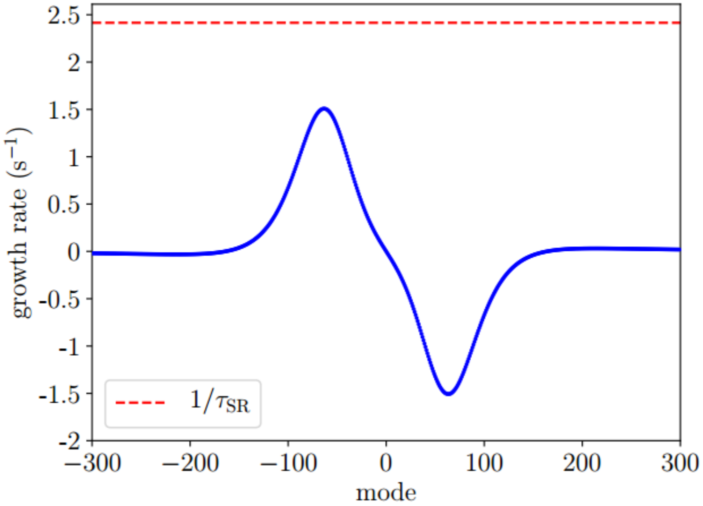
for FCC-ee fundamental mode impedance & optimum detuning (~4 × f_{rev})
most unstable mode: $m = -4$



longitudinal CB growth rates w/o feedback

cavity impedance w/o and with **strong RF feedback**



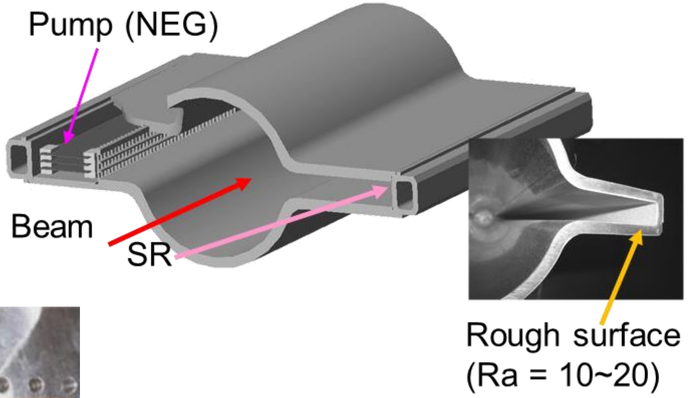


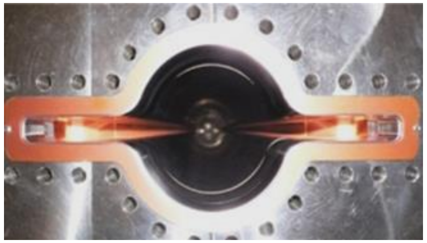
longitudinal CB growth rates with strong RF feedback

R. Calaga et al.

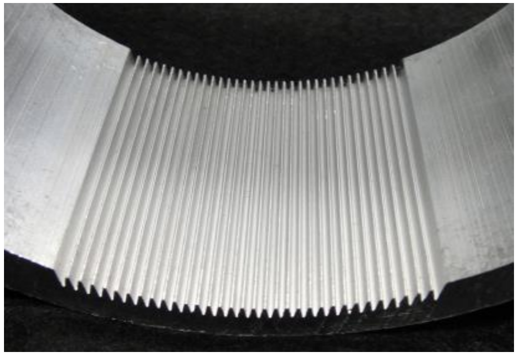
high current: suppress e-cloud everywhere

SuperKEKB countermeasures:
(1) beam pipe with antechamber
(2) low-SEY coatings
(3) grooves
(4) clearing electrode
(5) solenoidal field
(6) beam scrubbing

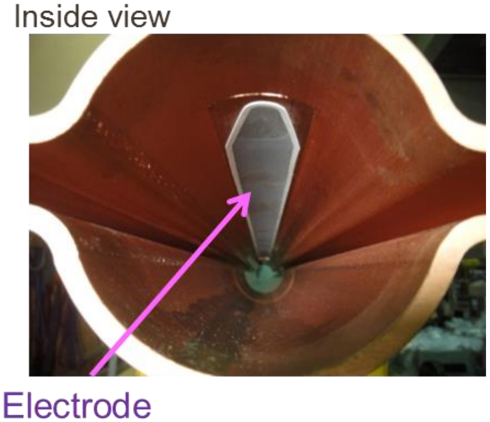




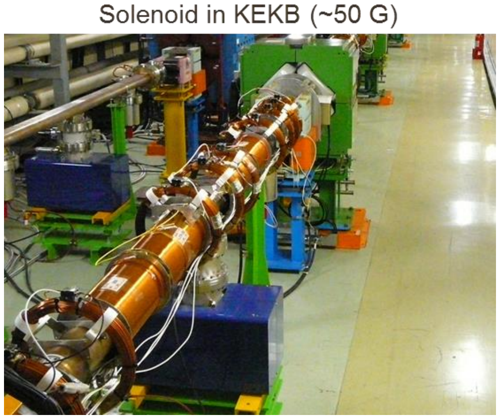
TiN coating for
90% of beam pipes



grooves in bending magnets



clearing electrode in
wiggler chambers

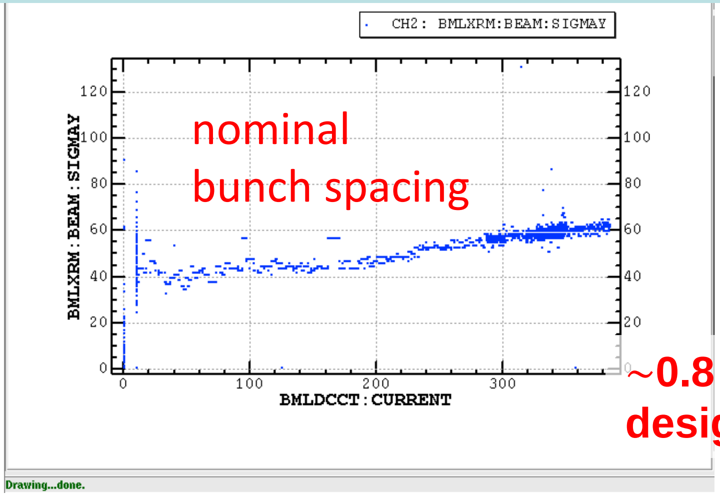


solenoid (50 G) in drift spaces

Y. Suetsugu

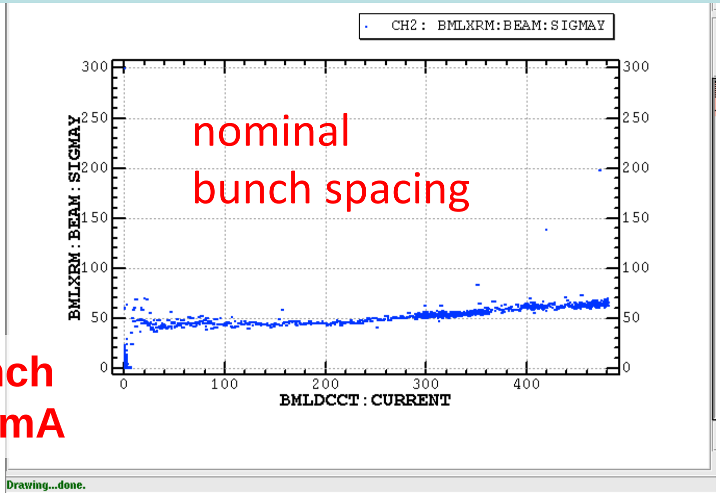
effective e-cloud cure: no beam blow up

4 train/ 120 buckets/ 2 spacing



nominal
bunch spacing

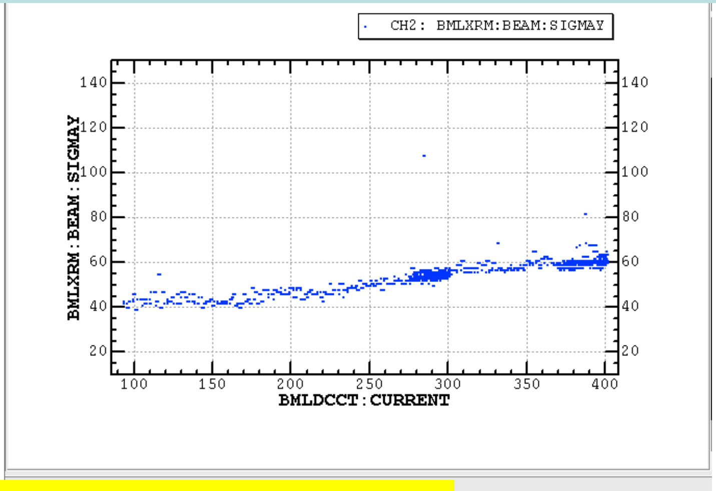
4 train/ 150 buckets/ 2 spacing



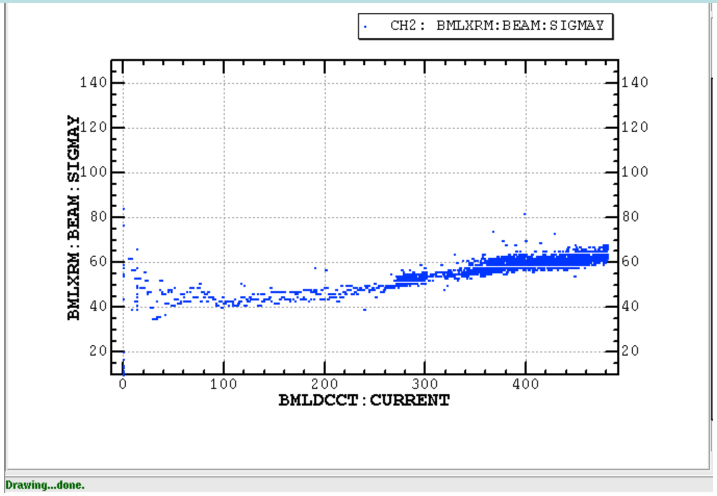
nominal
bunch spacing

~0.8 mA/bunch
design ~1.4 mA

4 train/ 120 buckets/ 3 spacing



4 train/ 120 buckets/ 4 spacing

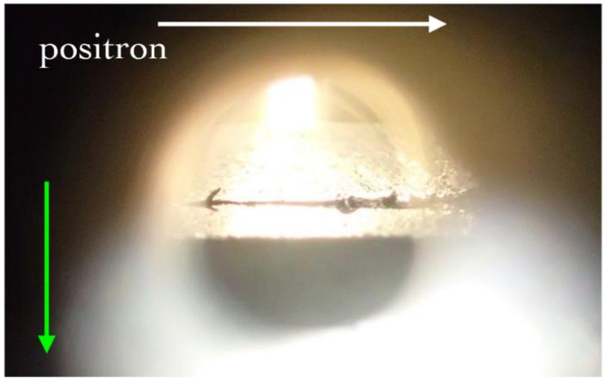


H. Fukuma, Y. Suetsugu

high current: machine protection

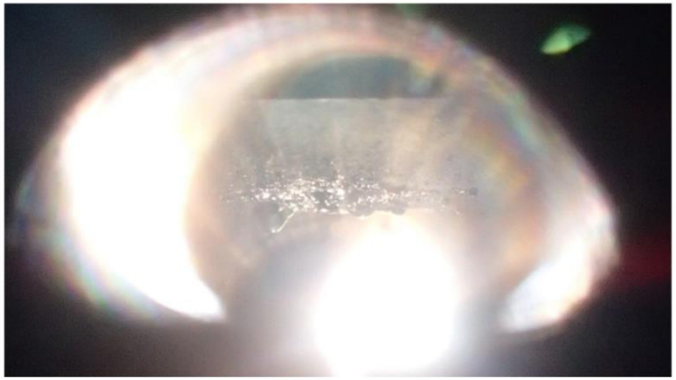
LER

Bottom

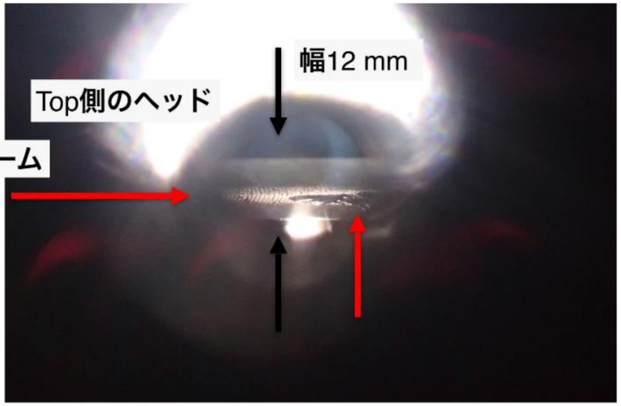


outer of the ring

Top



HER

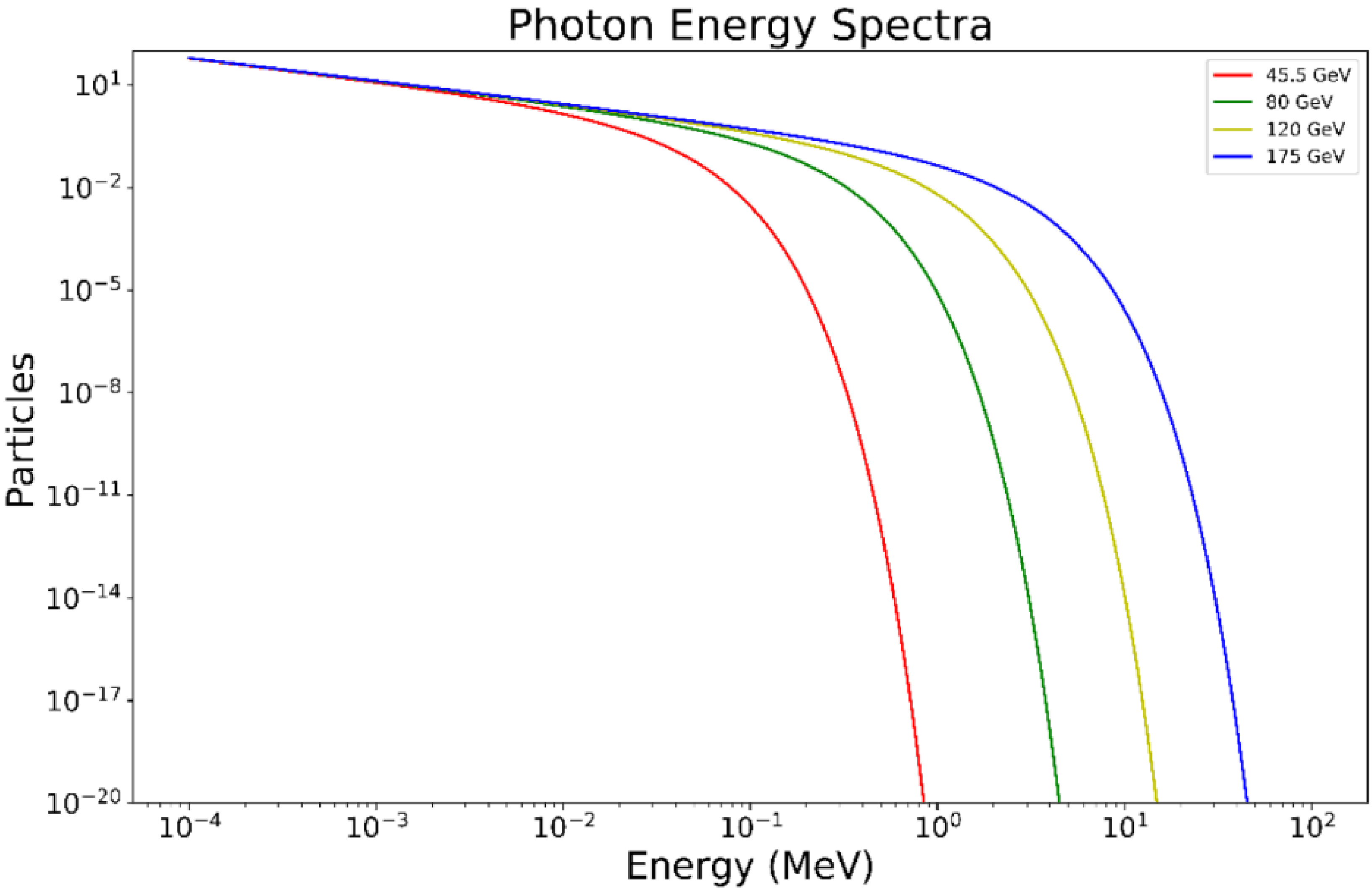


HER　リング外側のビューポートから撮影

damaged collimators, SuperKEKB Phase 2

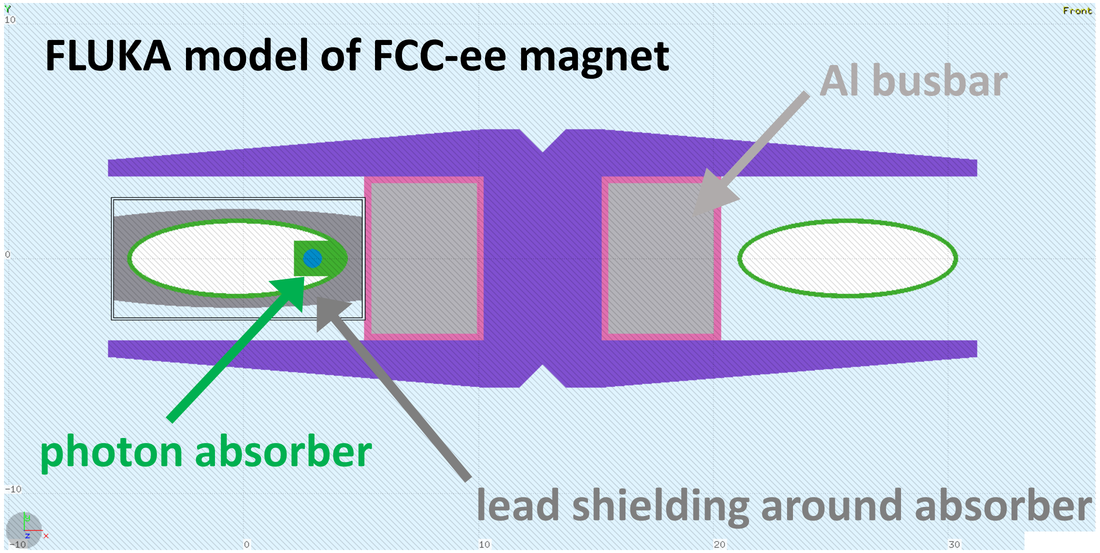
Y. Ohnishi et al.

synchrotron radiation: photon energy spectra



CEPC CDR

synchrotron radiation: discrete local shielding



FLUKA model of FCC-ee magnet

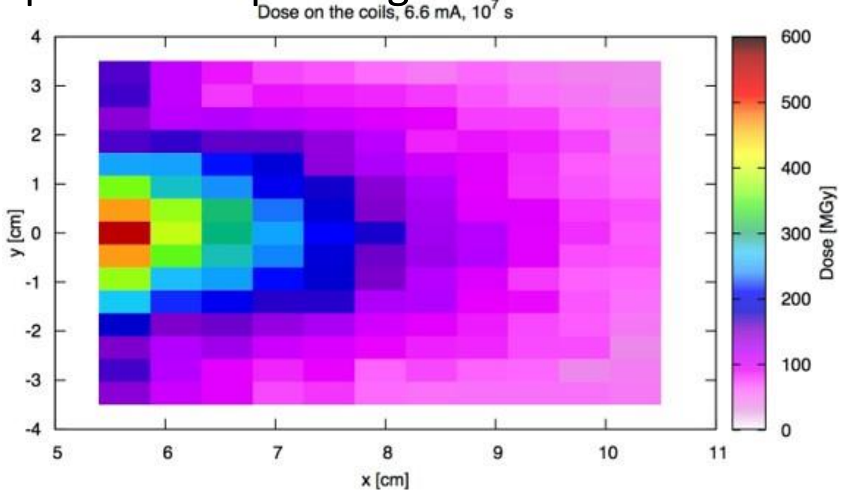
Al busbar

photon absorber

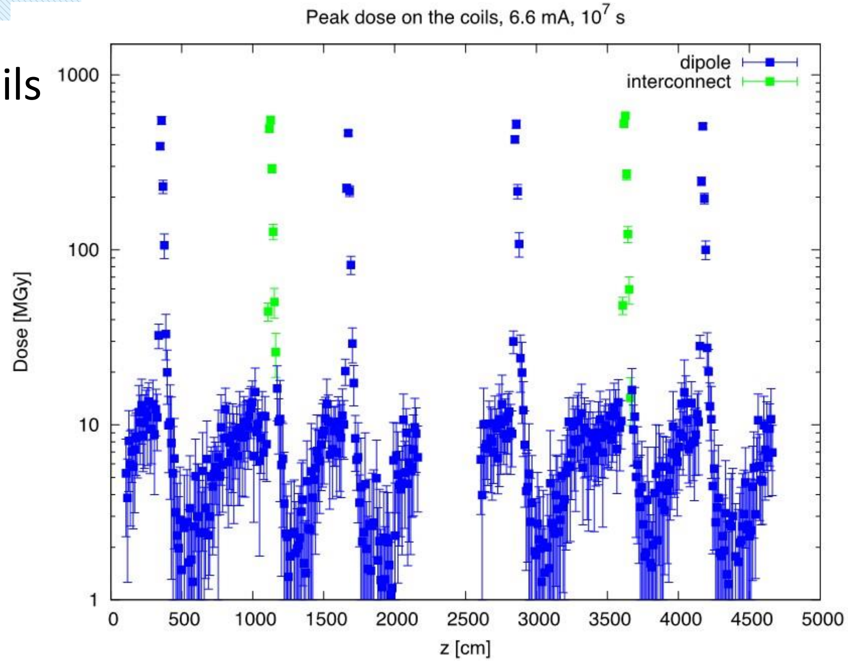
lead shielding around absorber

F. Cerutti, I. Besana

transverse distribution of annual dose in arc dipole coils at the peak corresponding to the absorber location

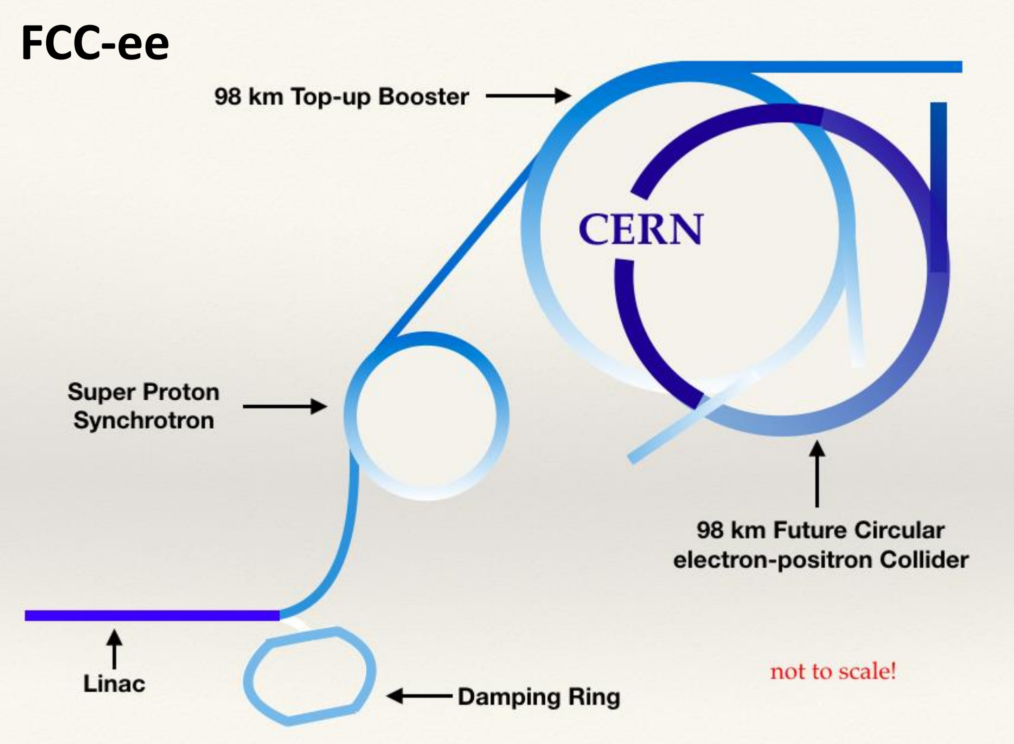


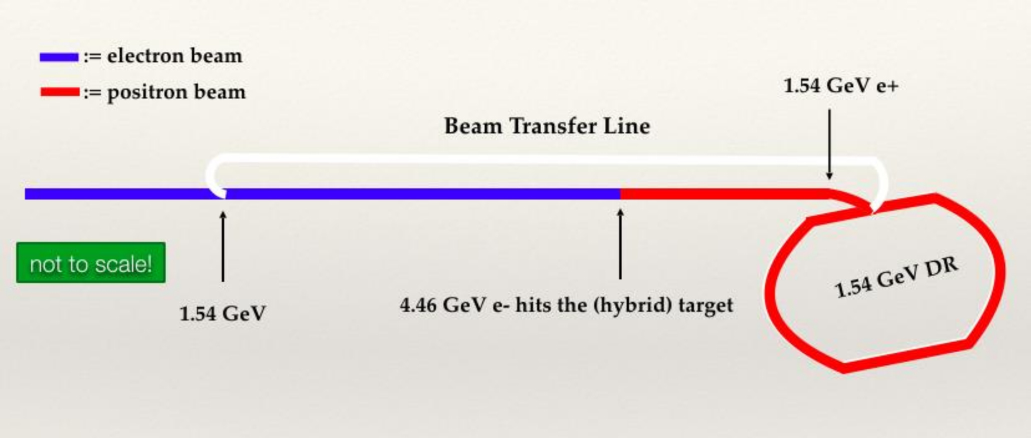
peak annual dose profile in arc dipole coils along a 50 m cell, for 6.6 mA beam current at 175 GeV



injector complex

S. Ogur, K. Oide, Y. Papaphilippou





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

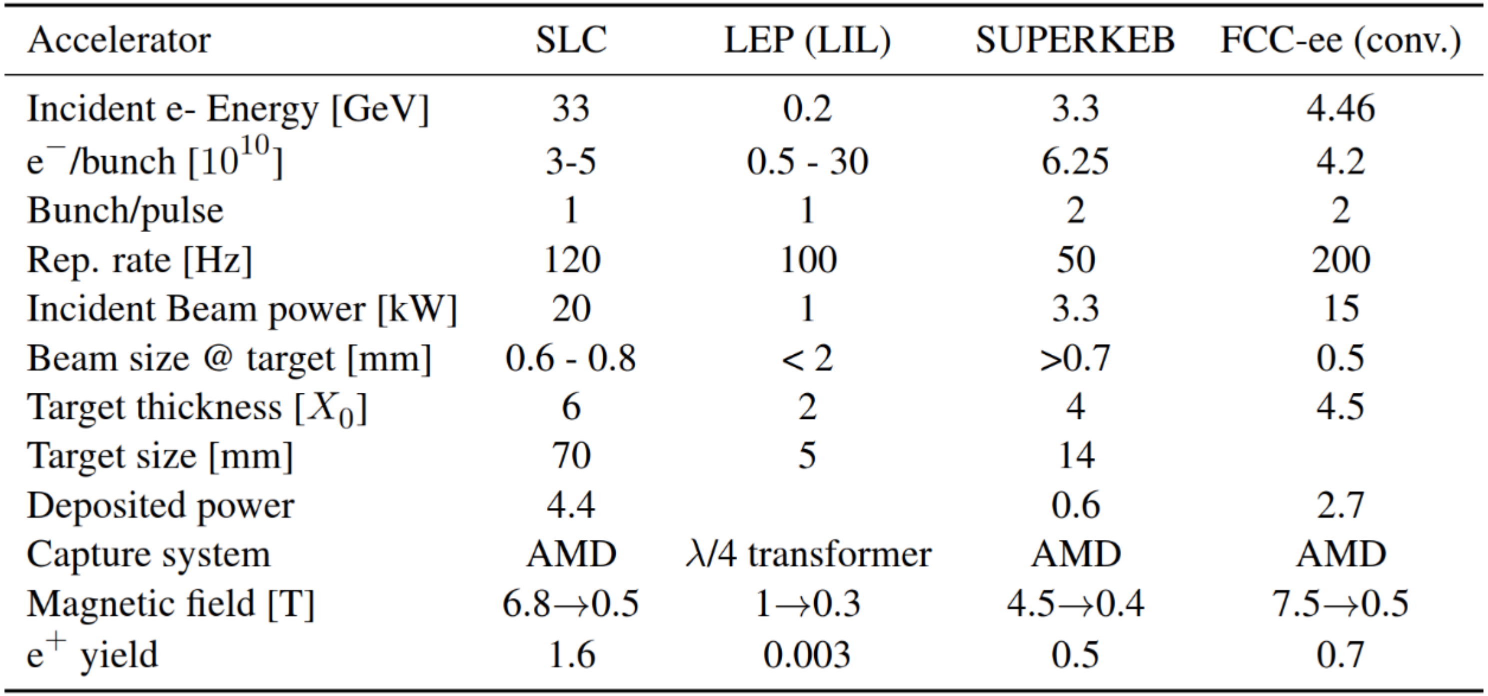
injection to main Booster @ **20 GeV and interleaved** filling of e+/e- (below **20 min** for full filling) and continuous top-up

CEPC: 10 GeV linac, no prebooster

high current, top up injection: e^+ source

	CEPC	**S-KEKB**	**SLC**	**FCC-ee**
e^+ / second	**1×10^{12}**	**2.5×10^{12}**	**6×10^{12}**	**1.1×10^{13}**

parameters of various positron sources

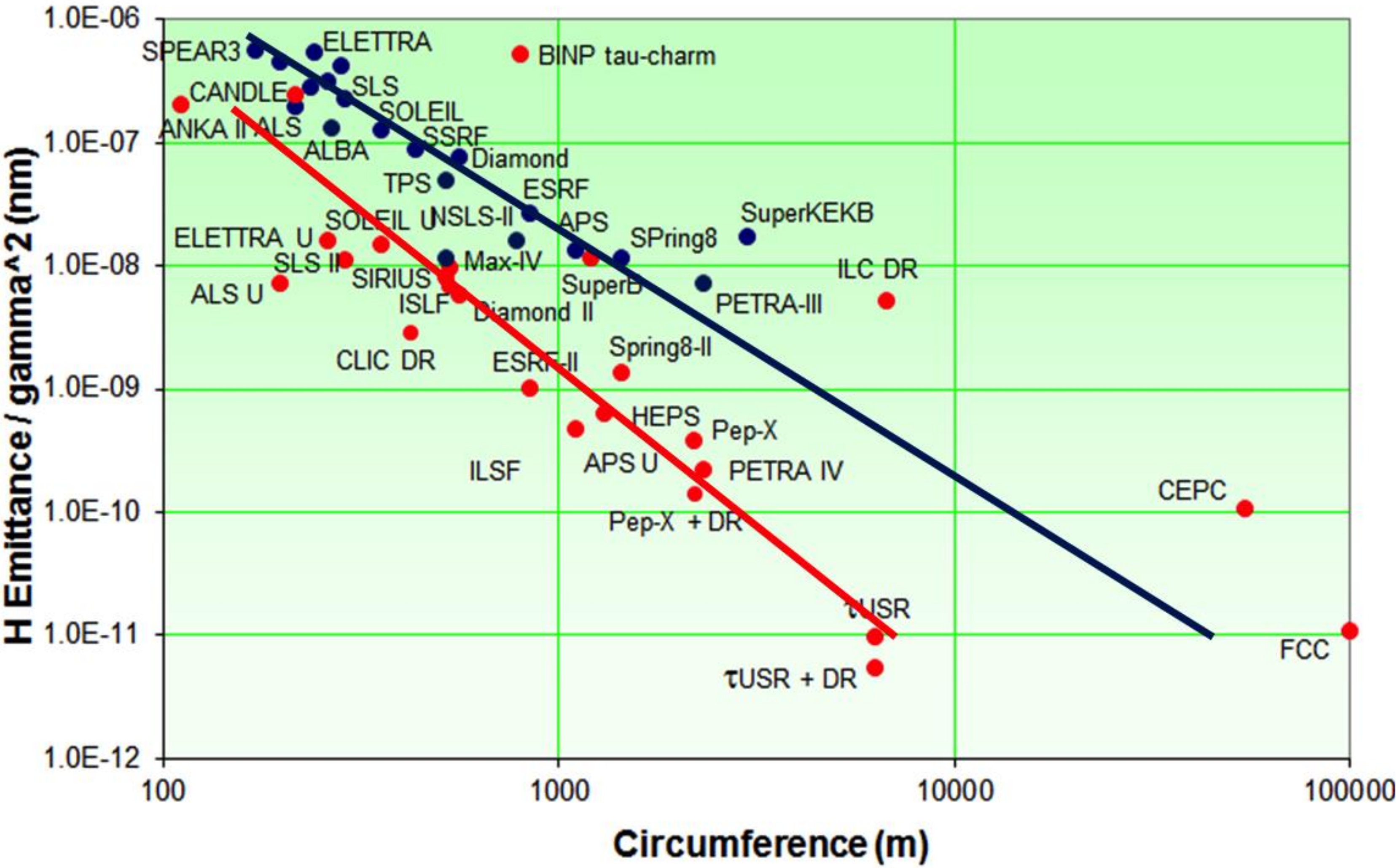


Accelerator	SLC	LEP (LIL)	SUPERKEB	FCC-ee (conv.)
Incident e- Energy [GeV]	33	0.2	3.3	4.46
e^-/bunch $[10^{10}]$	3-5	0.5 - 30	6.25	4.2
Bunch/pulse	1	1	2	2
Rep. rate [Hz]	120	100	50	200
Incident Beam power [kW]	20	1	3.3	15
Beam size @ target [mm]	0.6 - 0.8	< 2	>0.7	0.5
Target thickness $[X_0]$	6	2	4	4.5
Target size [mm]	70	5	14	
Deposited power	4.4		0.6	2.7
Capture system	AMD	$\lambda/4$ transformer	AMD	AMD
Magnetic field [T]	$6.8 \rightarrow 0.5$	$1 \rightarrow 0.3$	$4.5 \rightarrow 0.4$	$7.5 \rightarrow 0.5$
e^+ yield	1.6	0.003	0.5	0.7

I. Chaikovska, R. Chehab, P. Martyshkin, K. Oide, L. Rinolfi, Y. Papaphilippou

horizontal emittance

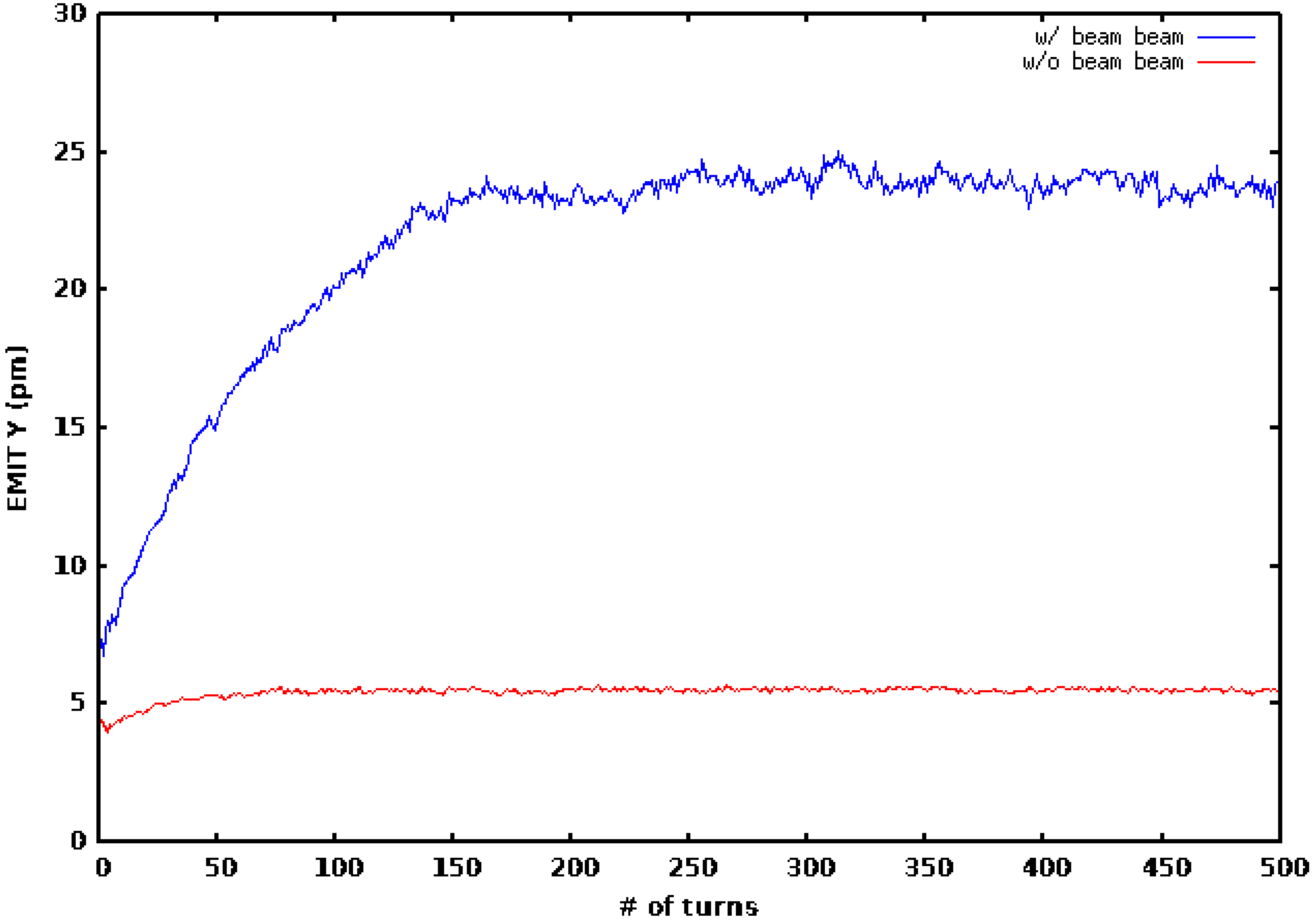
R. Bartolini, 2016



Emittance normalized to beam energy vs. circumference for storage rings in operation (blue dots) and under construction or being planned (red dots). The ongoing generational change is indicated by the transition from the blue line to the red line.

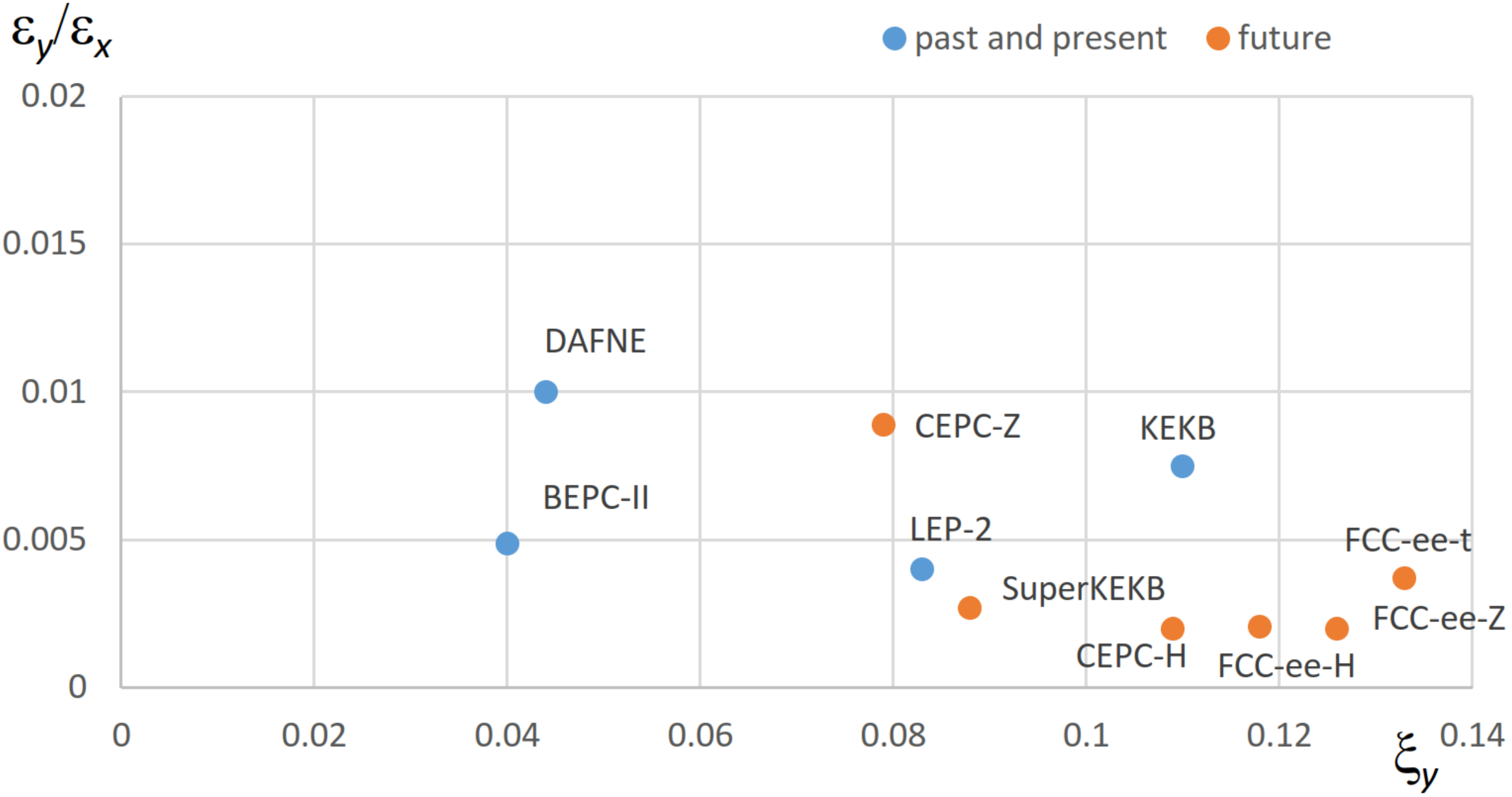
vertical emittance w/o & w collision

example simulation with errors for one random seed



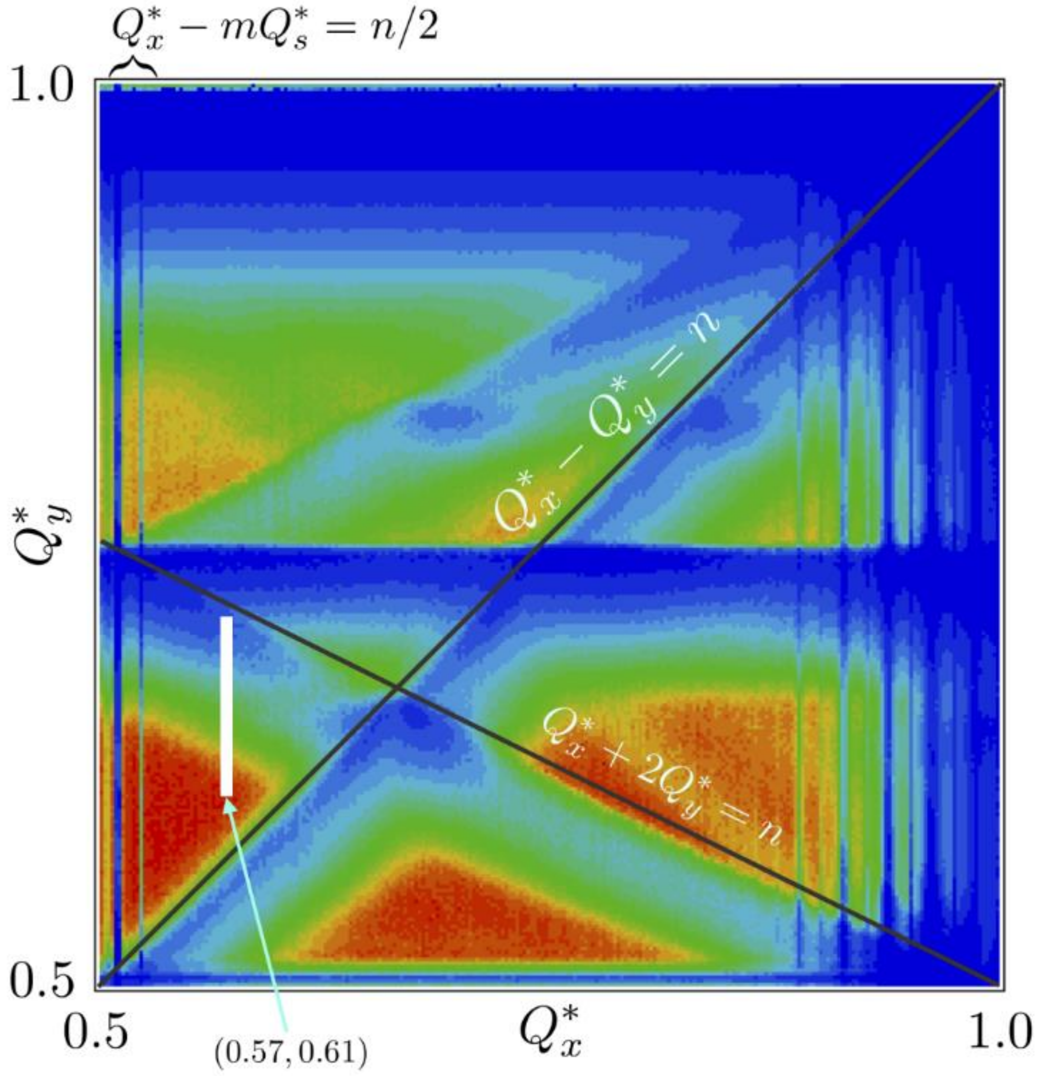
D. El Khechen

vertical emittance in collision



Vertical-to-horizontal emittance radios achieved in various past e^+e^- colliders (blue) along with target values for future machines (orange) as a function of beam-beam parameter (per IP); past values were extracted from [K.A. Olive et al. (Particle Data Group), Chin. Phys. C, 38, 090001 (2014) section 30].

strong-strong beam-beam effects

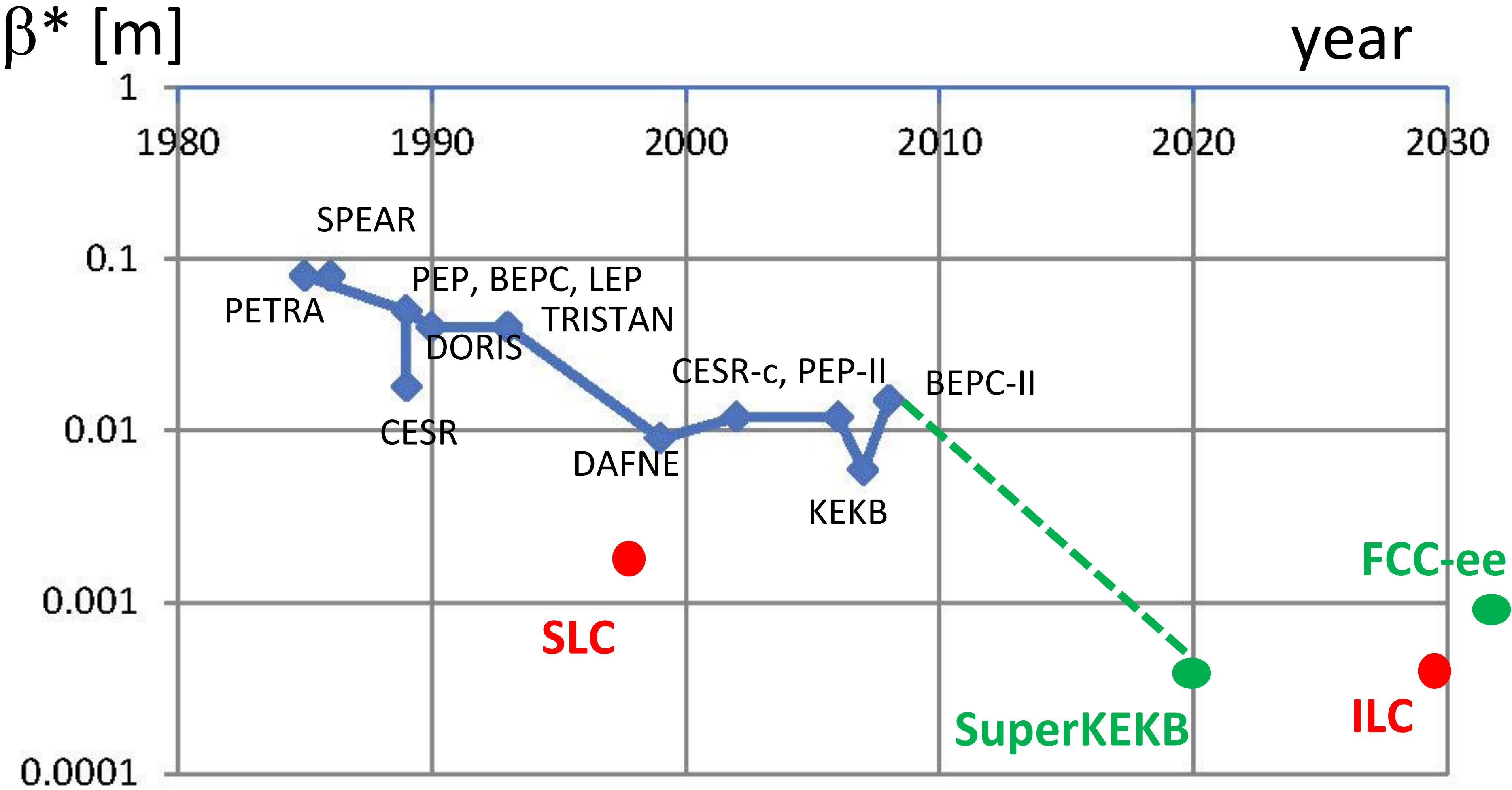


coherent synchro-betatron (*x-z*) instability and **3D flip-flop** with beamstrahlung

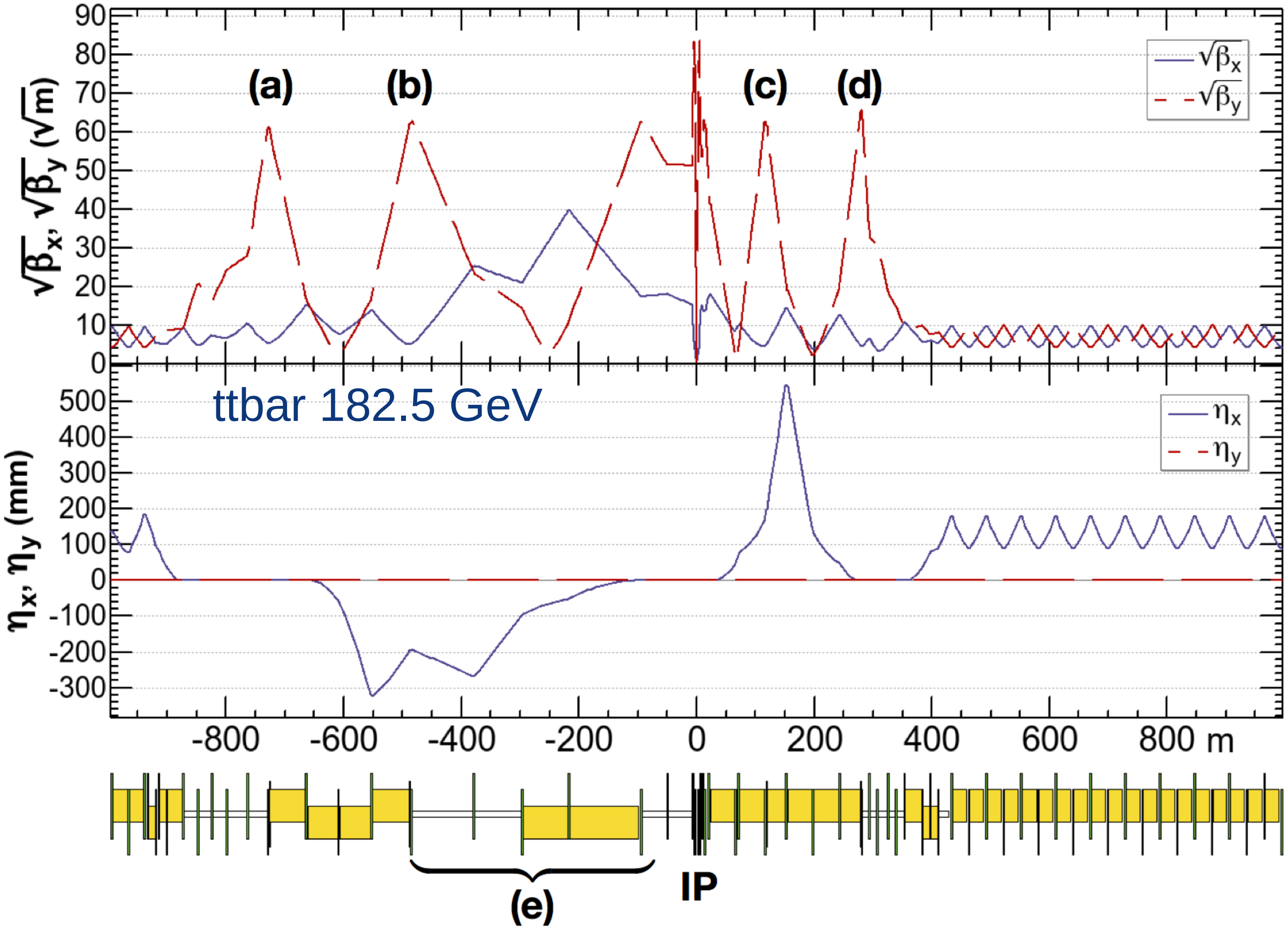
FCC-ee luminosity at the Z as a function of betatron tunes. The colour scale from zero (blue) to 2.3 × 10^{36} $cm^{-2}s^{-1}$ (red). The white narrow rectangle above (0.57, 0.61) shows the footprint due to the beam-beam interaction. A few synchrotron-betatron resonance lines $Q_x^* - mQ_s^* = n/2$ are seen.

D. Shatilov, K. Ohmi et al.

lower β_y^* - crossing the "Talman barrier"



IR optics design with multiple constraints



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

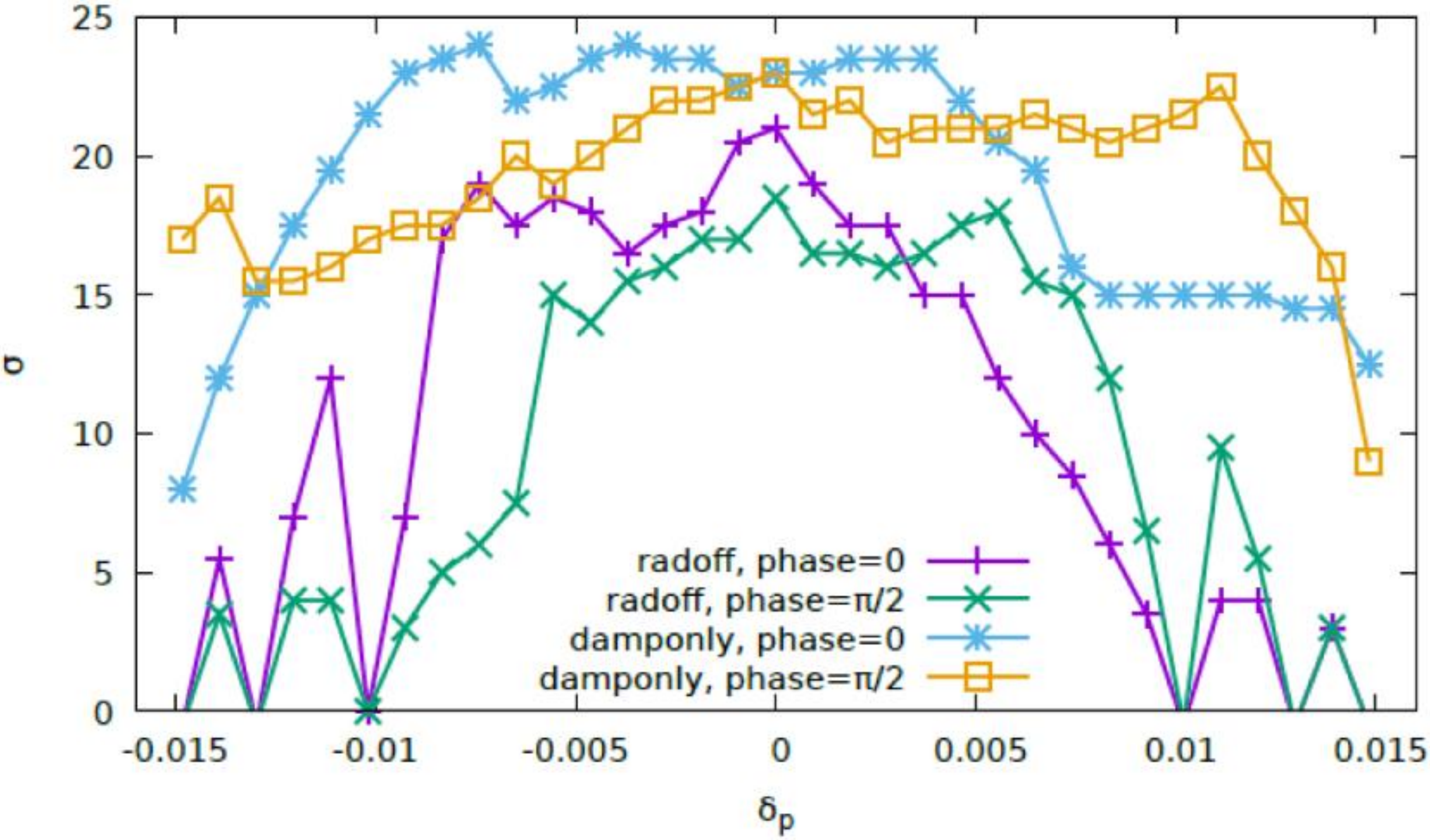
K. Oide

yellow boxes: dipole magnets

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

off-momentum dynamic aperture

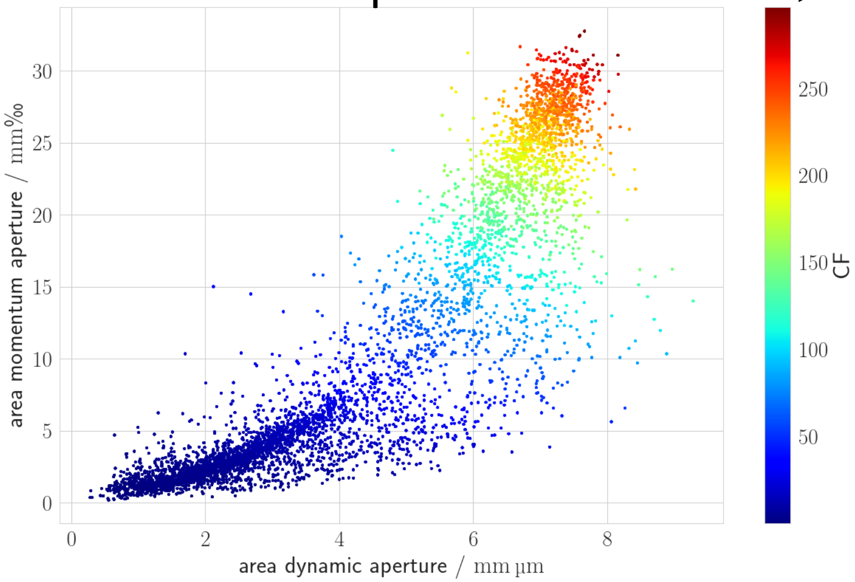


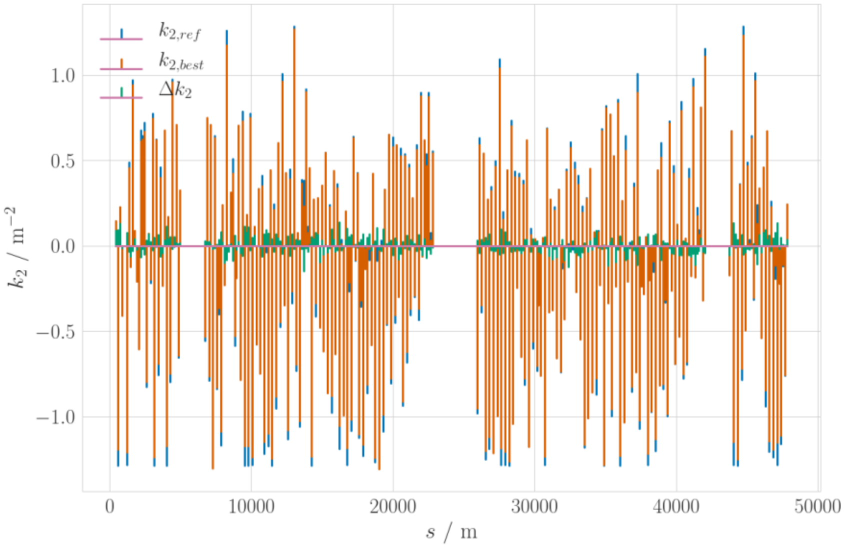
without and with radiation damping

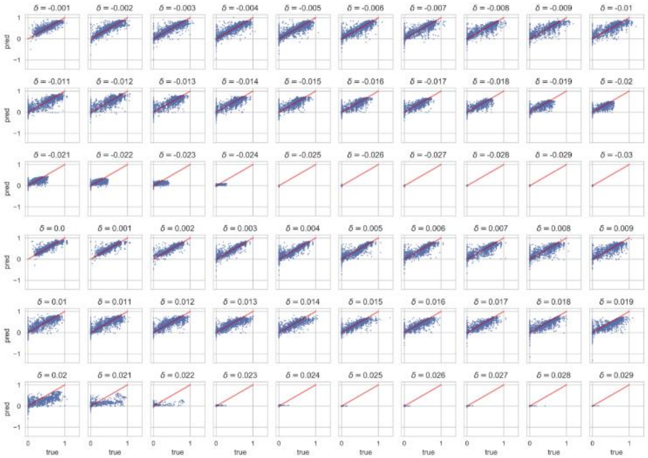
CEPC CDR

optimizing the dynamic aperture

Particle-Swarm Optimization → larger MA/DA & reduced sext. strength



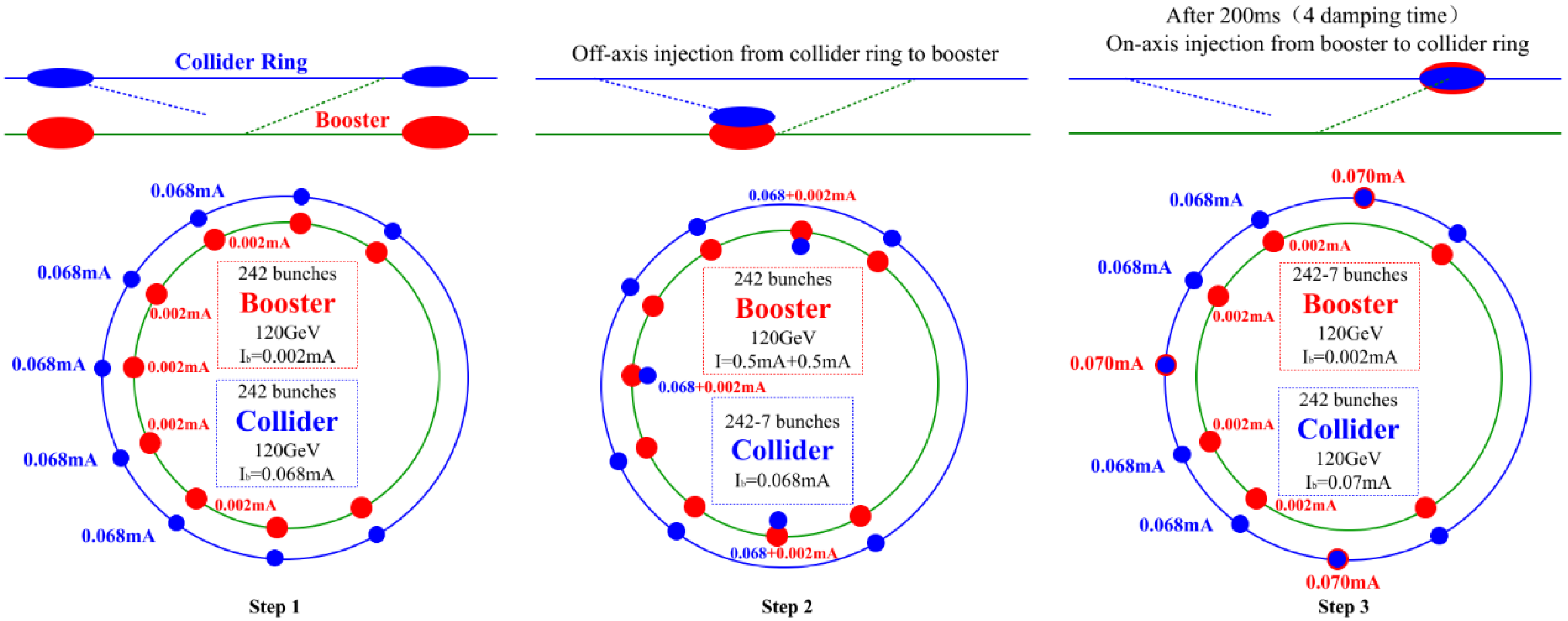




use PSO results to train neural network

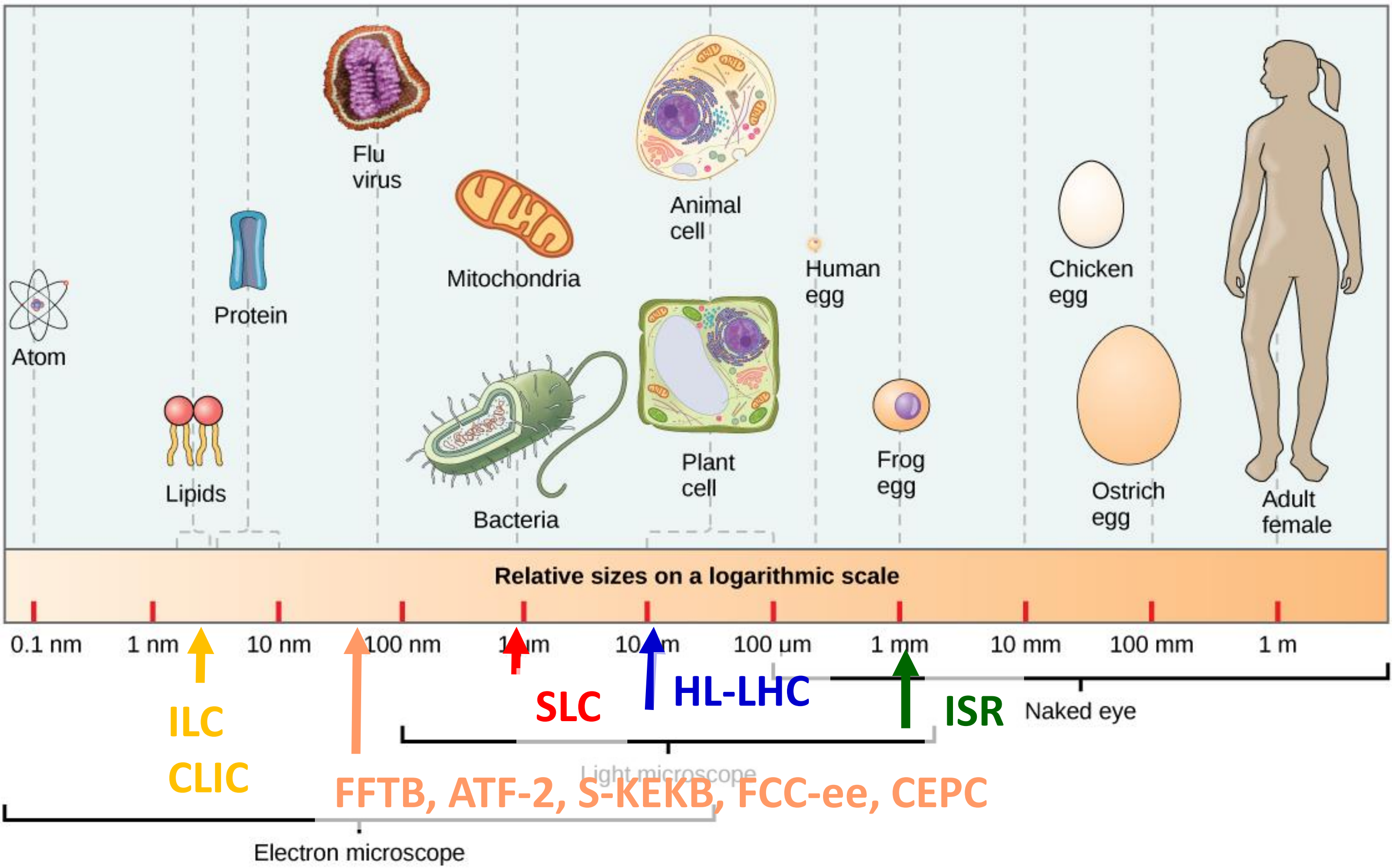
T. Tydecks

“swap-out” injection process



CEPC CDR

spot size challenge



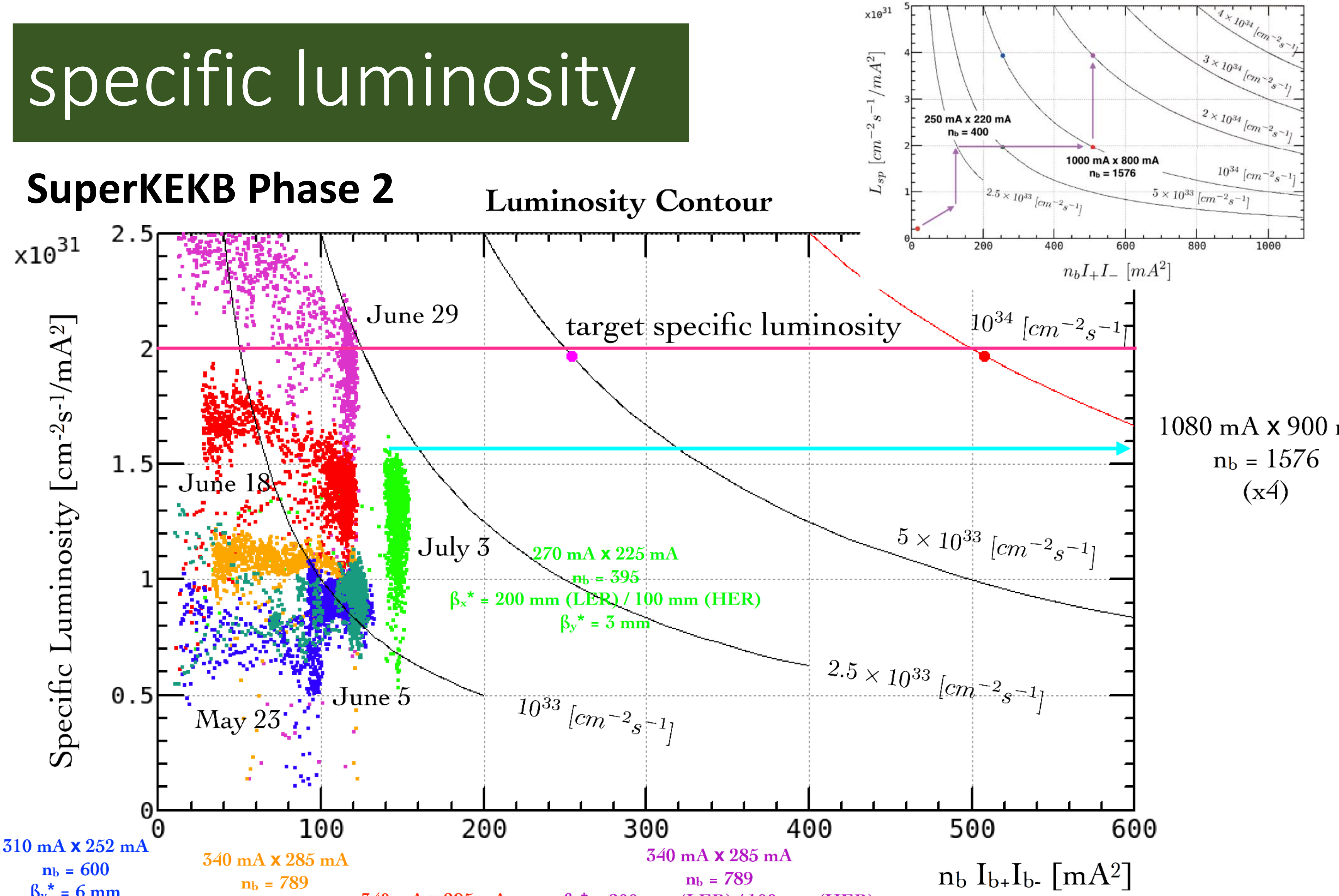
spot sizes

collider / test facility	$\sigma_y{}^*$ [nm]
LEP2	3500
KEKB	940
SLC	700
ATF2, FFTB	55 (*35*), 70 (*50*)
CEPC	***60***
SuperKEKB	***50***
FCC-ee-H	***40***

in regular font: achieved
in italics: design values or expected values

specific luminosity

SuperKEKB Phase 2



310 mA x 252 mA
n_b = 600
β_y^* = 6 mm

340 mA x 285 mA
n_b = 789
β_y^* = 6 mm

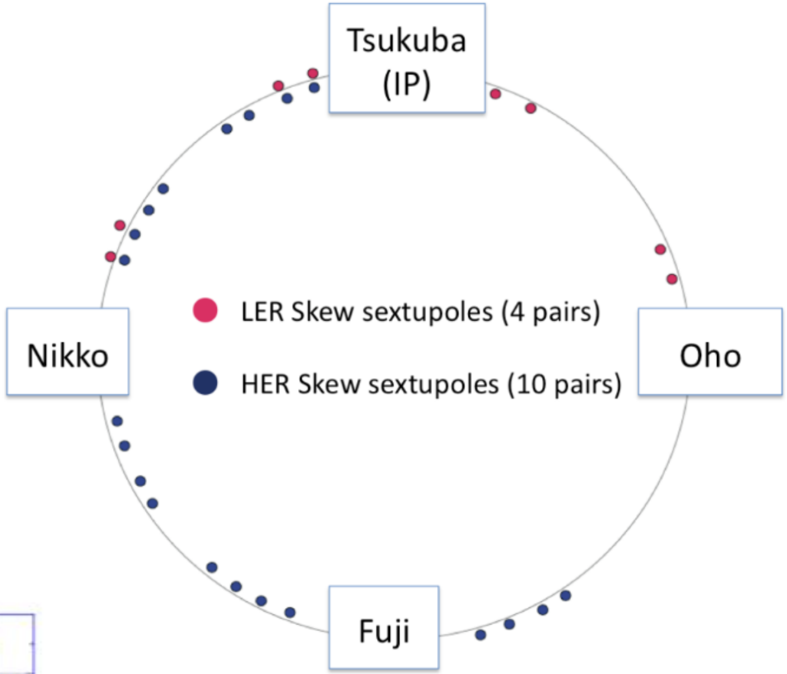
340 mA x 285 mA
n_b = 789
β_y^* = 4 mm

340 mA x 285 mA
n_b = 789
β_x^* = 200 mm (LER) / 100 mm (HER)
β_y^* = 4 mm

340 mA x 285 mA
n_b = 789
β_x^* = 200 mm (LER) / 100 mm (HER)
β_y^* = 3 mm

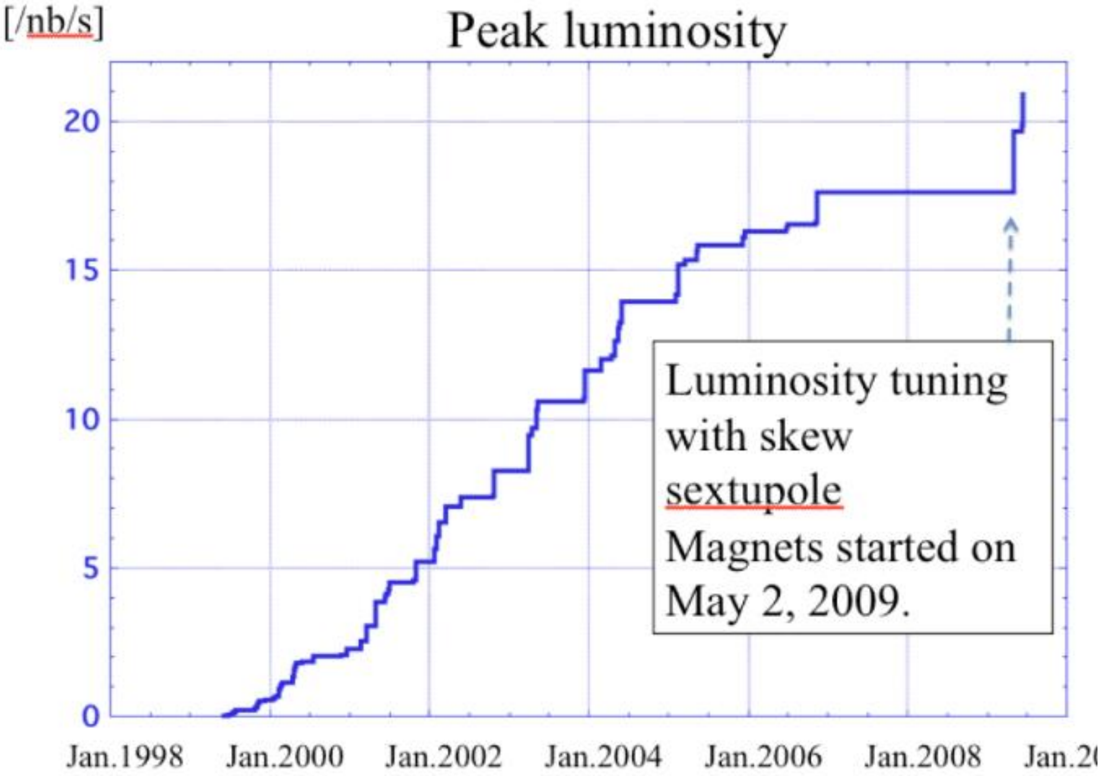
Y. Ohnishi

correcting nonlinear IP aberrations



Location of the 20 and 8 skew sextupole magnetsin the KEKB HER and LER, respectively.

KEKB

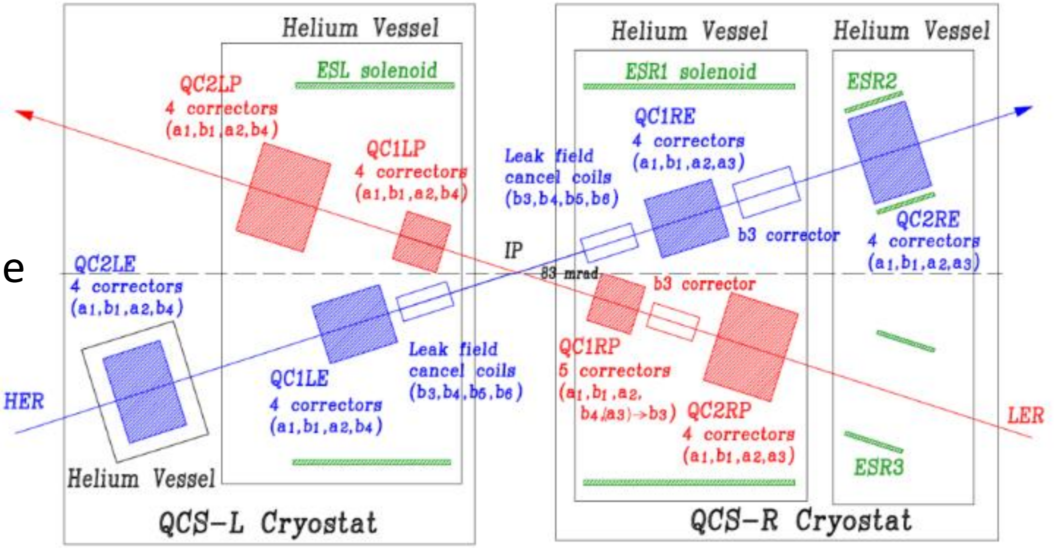


Peak luminosity trend since the KEKB commissioning. The peak luminosity went up significantly by the skew sextupole magnets.

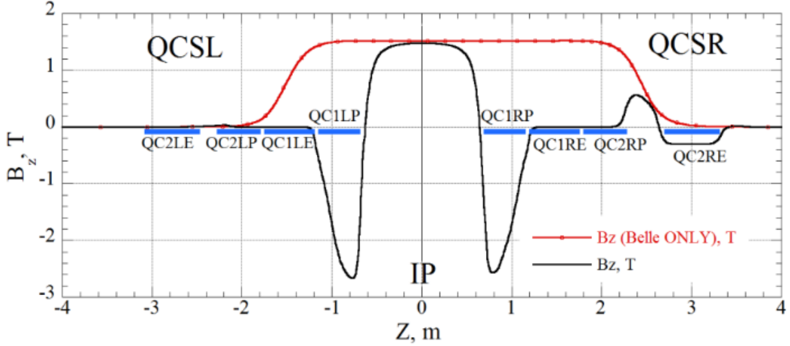
M. Masuzawa et al., IPAC’10

IR magnet configuration

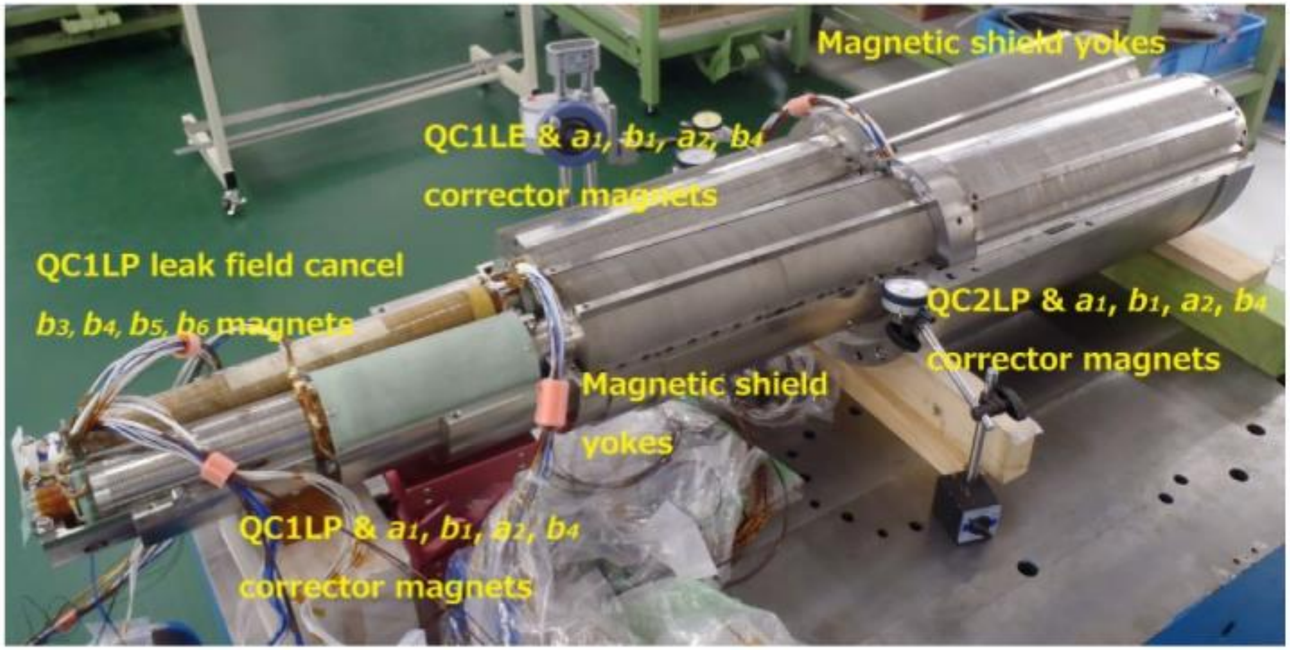
Layout of superconducting magnets in **SuperKEKB IR**



Solenoid field profiles along the beam line



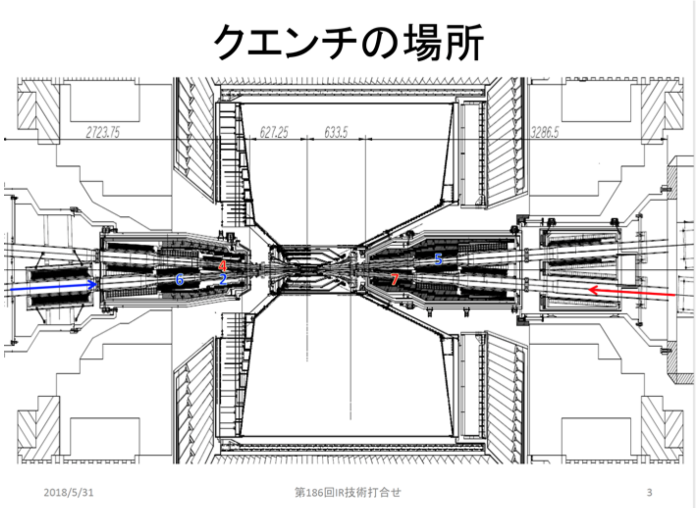
Assembled SC magnets in the front helium vessel of the QCSL cryostat



N. Ohuchi et al.

IR magnet quenches: machine protection (masks and beam abort triggers)

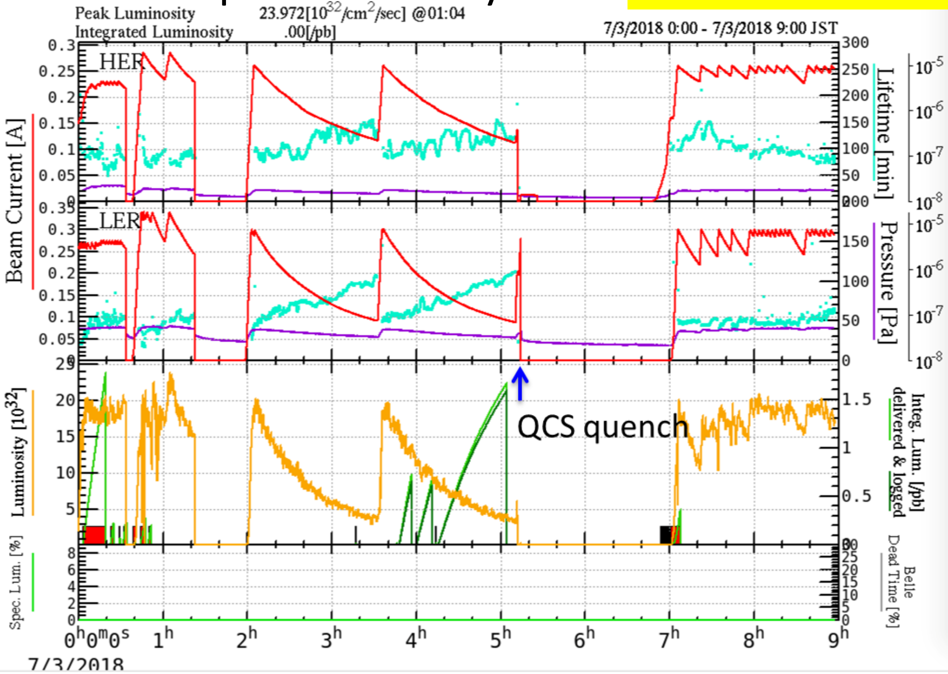
SuperKEKB experienced several QCS quenches (both rings) due to particle losses, ~a few 10^3 e^- (e^+) at 7 (4) GeV lost locally can quench QCS, recovery 2-3 hours


クエンチの場所

2018/5/31 第186回IR技術打合せ 3

example from 3 July

Y. Funakoshi et al.



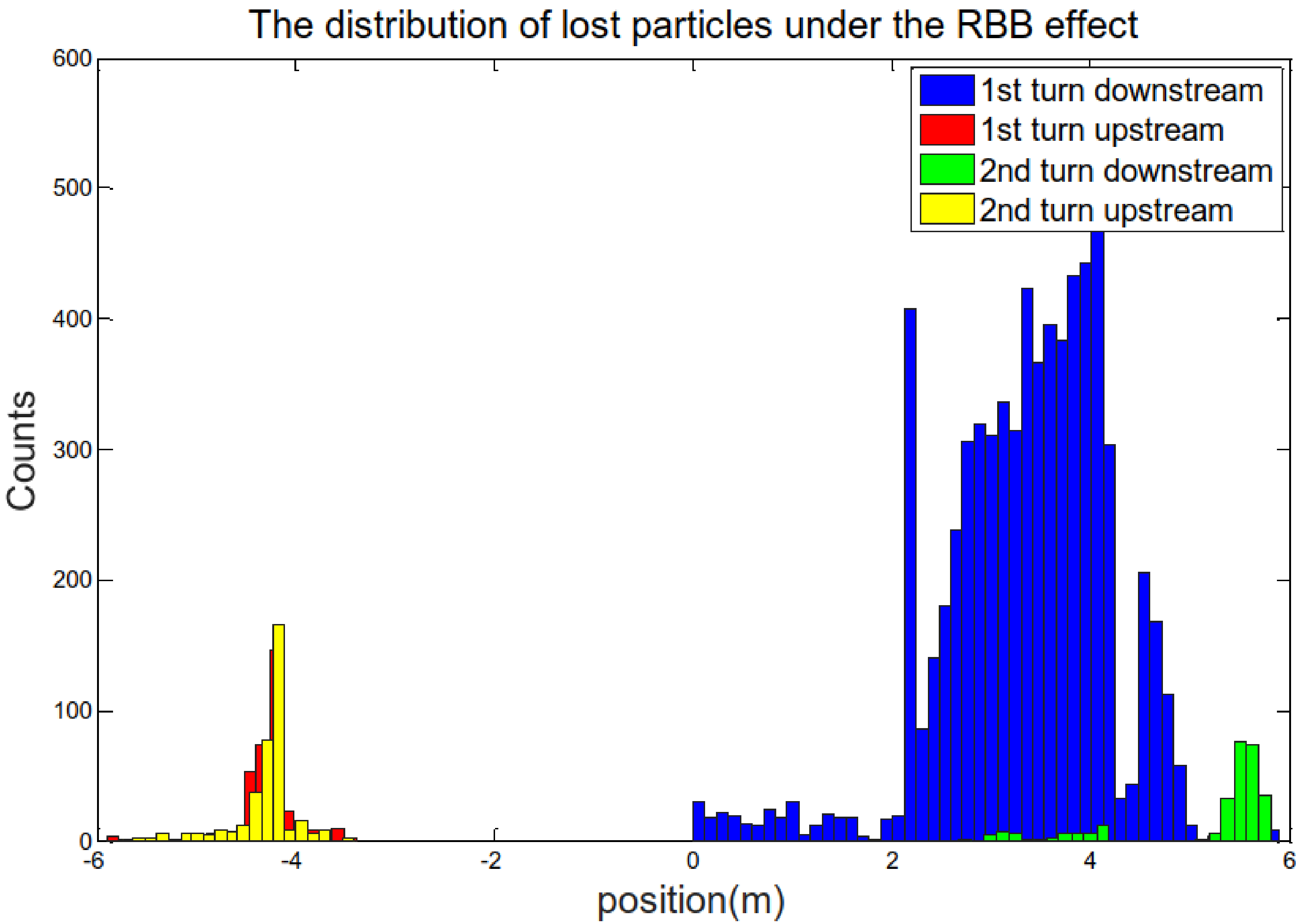
QCS quench

for comparison quench limit for LHC magnet: $2\mathrm{x}10^8$ protons at 450 GeV

B. Dehning et al.

beam energy [TeV]	E_D^{max} [mJ/cm^3] per proton	enthalpy limit H_{strand} [mJ/cm^3]	protons to quench	BLM signal Q_{BLM} [aC/prot]
horizontal, pointlike loss				
0.45	$1.45 \cdot 10^{-7}$	31.29	$2.16 \cdot 10^8$	33.8

particles lost near IP due to radiative Bhabha scattering close to SuperKEKB quench limit?



CEPC CDR

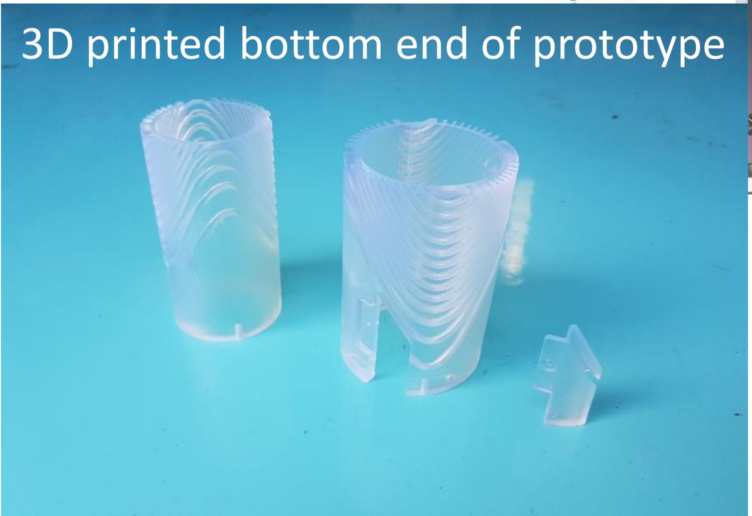
FCC FF CCT quad prototype project

Advantages at a glance:

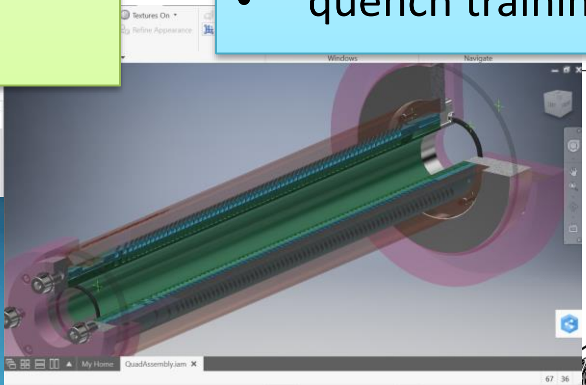
- excellent field quality (<1 unit)
- no need for b3 correctors
- any correctors do not take additional space
- excellent LOCAL field quality at the edges
- excellent crosstalk compensation
- cheap (no pre-stress, simple winding, light construction)

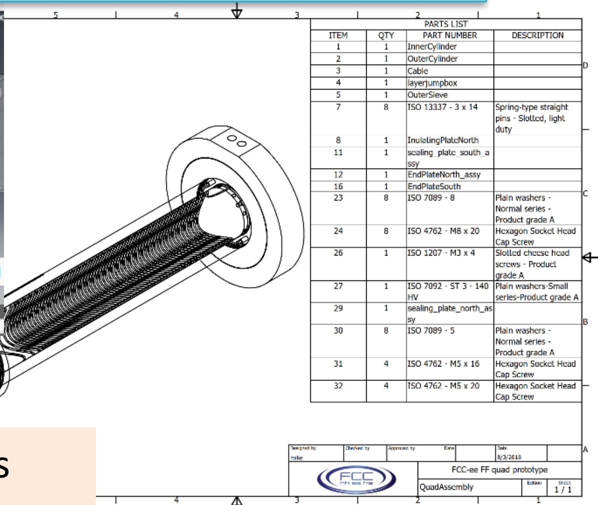
Project milestones:

- magnetic design ✓
- mechanical design ✓
- call for offers for manufacturing ✓
- coil winding
- impregnation
- field measurement (at warm or cold)
- quench training / ultimate current



3D printed bottom end of prototype





PARTS LIST

ITEM	QTY	PART NUMBER	DESCRIPTION
1	1	InnerCylinder	
2	1	OuterCylinder	
3	1	Cable	
4	1	layerjumpbox	
5	1	OuterSleve	
7	8	ISO 13337 - 3 x 14	Spring-type straight pins - Slotted, light duty
8	1	InulatingPlateNorth	
11	1	sealing_plate_south_assy	
12	1	EndPlateNorth_assy	
16	1	EndPlateSouth	
23	8	ISO 7089 - 8	Plain washers - Normal series - Product grade A
24	8	ISO 4762 - M8 x 20	Hexagon Socket Head Cap Screw
26	1	ISO 1207 - M3 x 4	Slotted cheese head screws - Product grade A
27	1	ISO 7092 - ST 3 - 140 HV	Plain washers-Small series-Product grade A
29	1	sealing_plate_north_assy	
30	8	ISO 7089 - 5	Plain washers - Normal series - Product grade A
31	4	ISO 4762 - M5 x 16	Hexagon Socket Head Cap Screw
32	4	ISO 4762 - M5 x 20	Hexagon Socket Head Cap Screw

Designed by	Checked by	Approved by	Date	Date
mike				8/3/2018

FCC-ee FF quad prototype

QuadAssembly

Edition

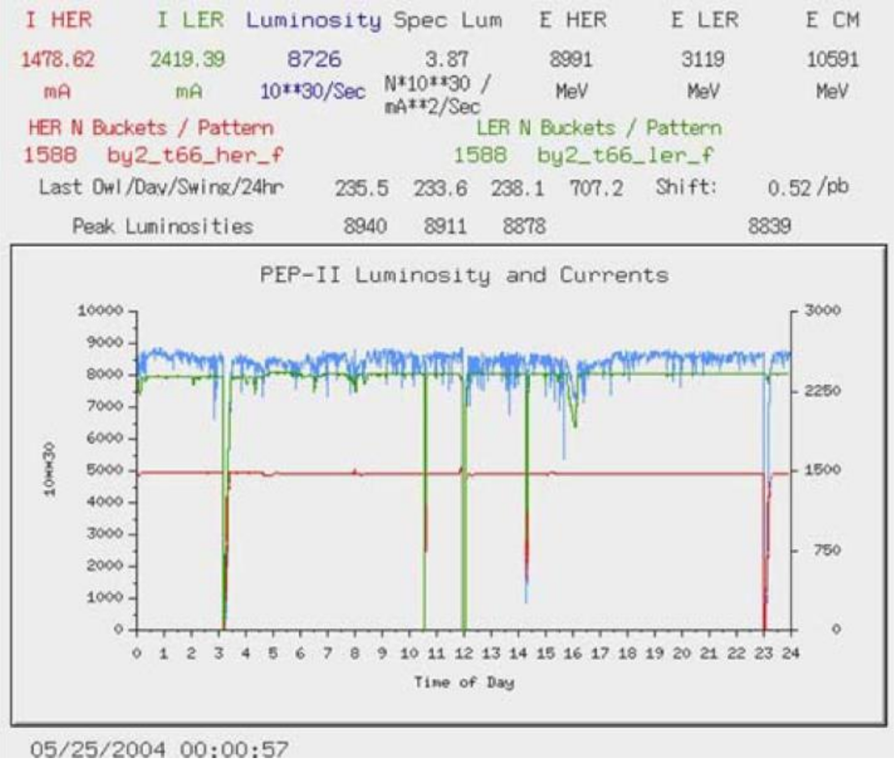
Sheet 1 / 1

suitable for all applications where space is at a premium and field quality is important: FCC-ee, CEPC, SuperKEKb

M. Koratzinos

top-up injection and availability

2004



I HER	I LER	Luminosity	Spec Lum	E HER	E LER	E CM
1478.62 mA	2419.39 mA	8726 10**30/Sec	3.87 N*10**30 / mA**2/Sec	8991 MeV	3119 MeV	10591 MeV

HER N Buckets / Pattern
1588 by2_t66_her_f

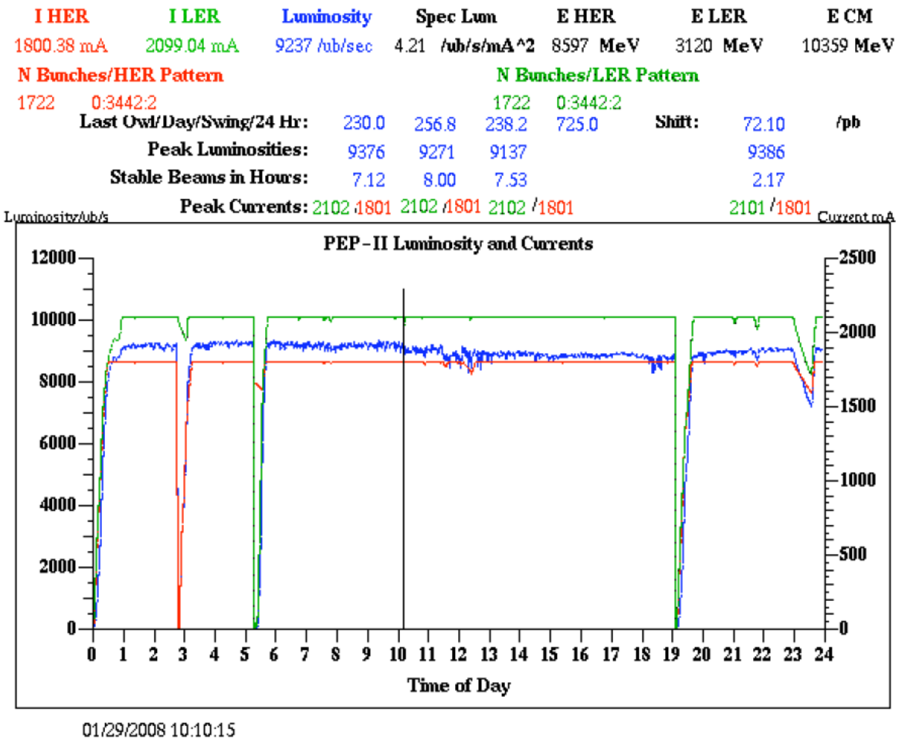
LER N Buckets / Pattern
1588 by2_t66_ler_f

Last Owl/Day/Swing/24hr 235.5 233.6 238.1 707.2 Shift: 0.52 /pb

Peak Luminosities 8940 8911 8878 8839

05/25/2004 00:00:57

2008



I HER	I LER	Luminosity	Spec Lum	E HER	E LER	E CM
1800.38 mA	2099.04 mA	9237 /ub/sec	4.21 /ub/s/mA^2	8597 MeV	3120 MeV	10359 MeV

N Bunches/HER Pattern
1722 0:3442:2

N Bunches/LER Pattern
1722 0:3442:2

Last Owl/Day/Swing/24 Hr: 230.0 256.8 238.2 725.0 Shift: 72.10 /pb

Peak Luminosities: 9376 9271 9137 9386

Stable Beams in Hours: 7.12 8.00 7.53 2.17

Peak Currents: 2102 /1801 2102 /1801 2102 /1801 2101 /1801

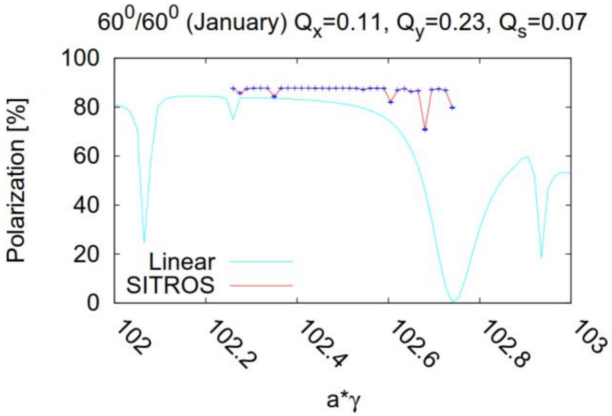
01/29/2008 10:10:15

Example evolutions of PEP-II beam currents and luminosity. Stored beam current of HER (red curve), LER (green curve), and luminosity (blue curve) of PEP-II over 24 h.

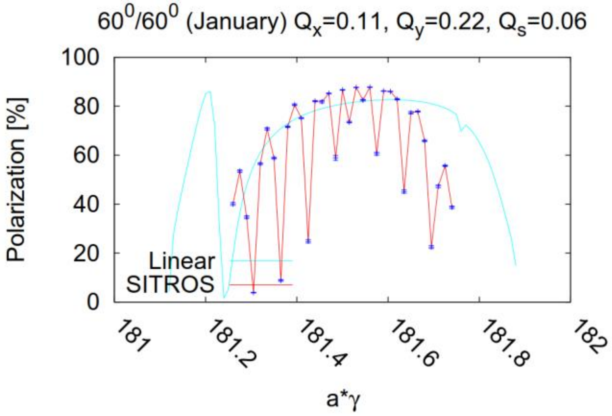
J. Seeman

precise energy calibration using resonant depolarization: pol. wigglers, spin matching etc.

E. Gianfelice Wendt



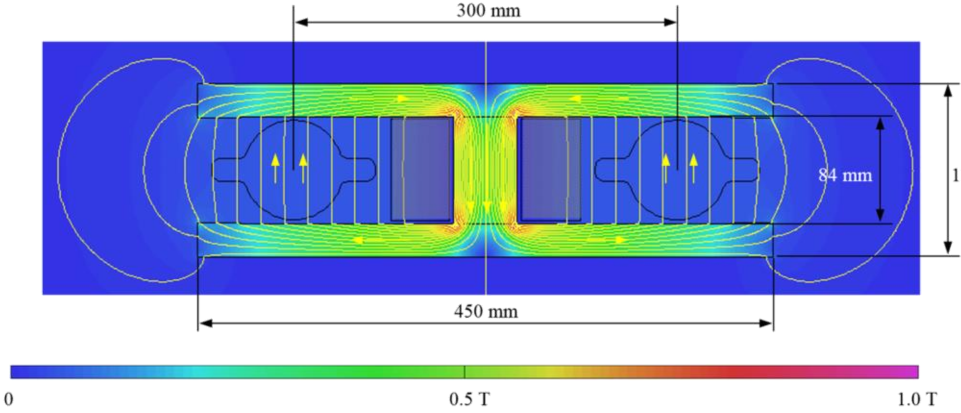
- $\tau_{10\%} \simeq$1.7 h with 8 wigglers and B^+=0.66 T.
- Closed orbit correction only.



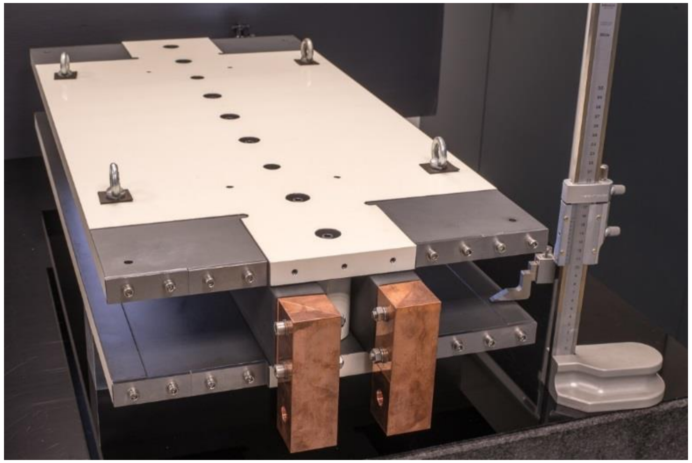
- Closed orbit correction.
- Spin-orbit coupling minimization.
- Coupling correction.
- $\delta\hat{n}_0$ correction.

cost-effective, energy-efficient machine design

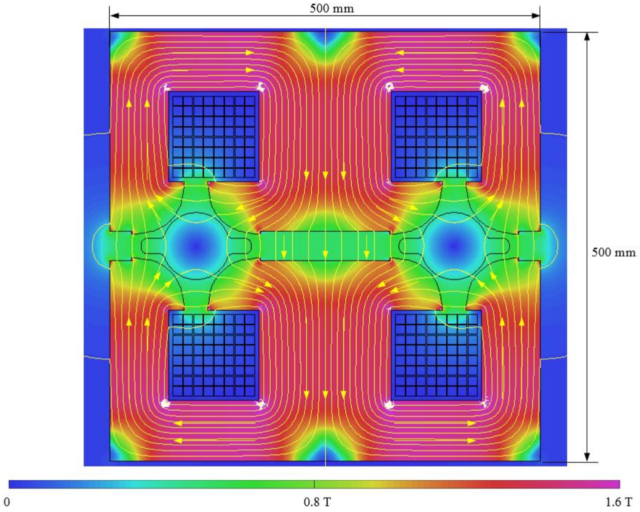
twin-dipole design with 2× power saving 16 MW (at 175 GeV), with Al busbars



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

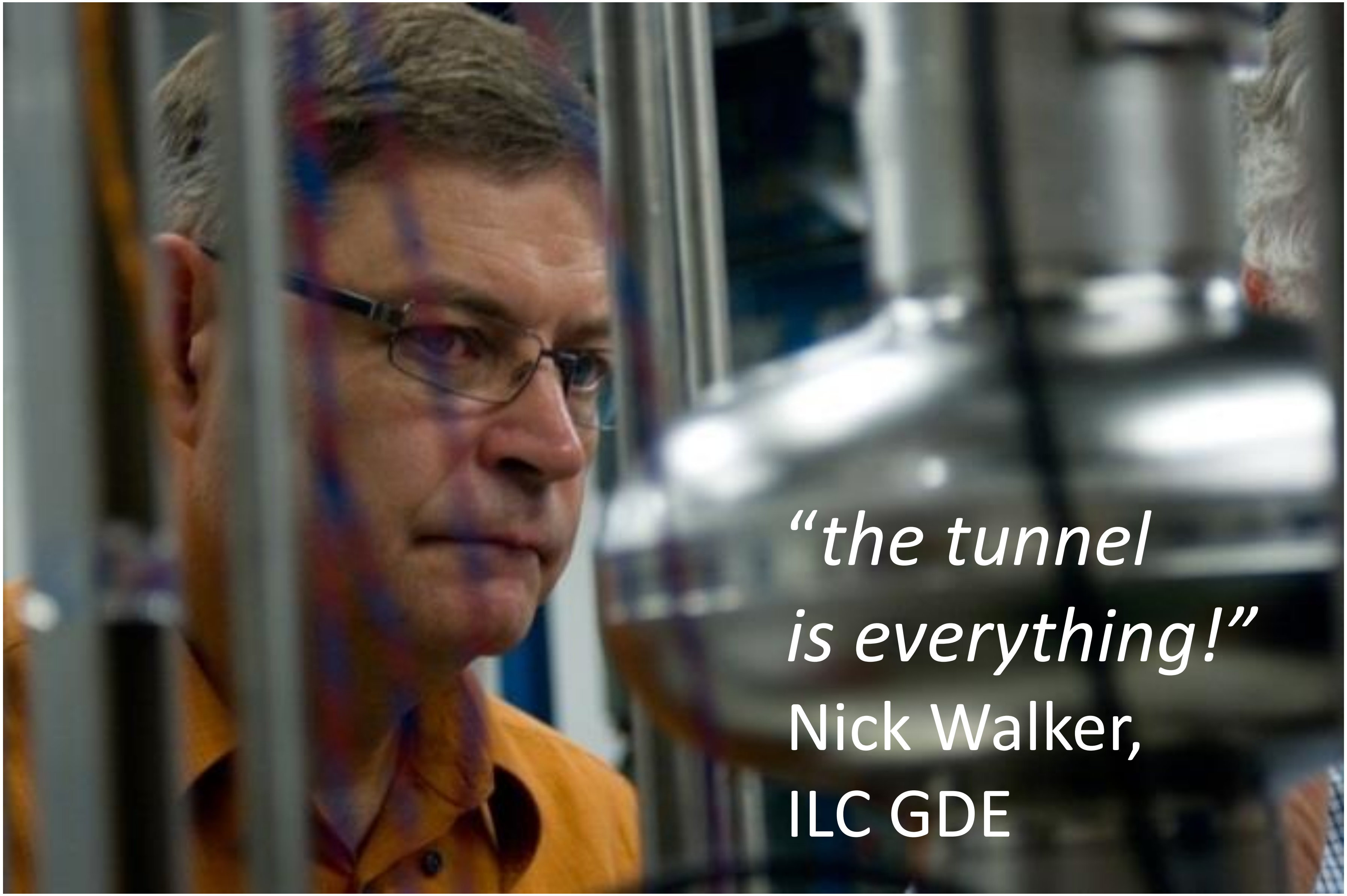
A. Milanese

overall power budgets

D. Bozzini, V. Mertens, F. Zimmermann

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

and the tunnel



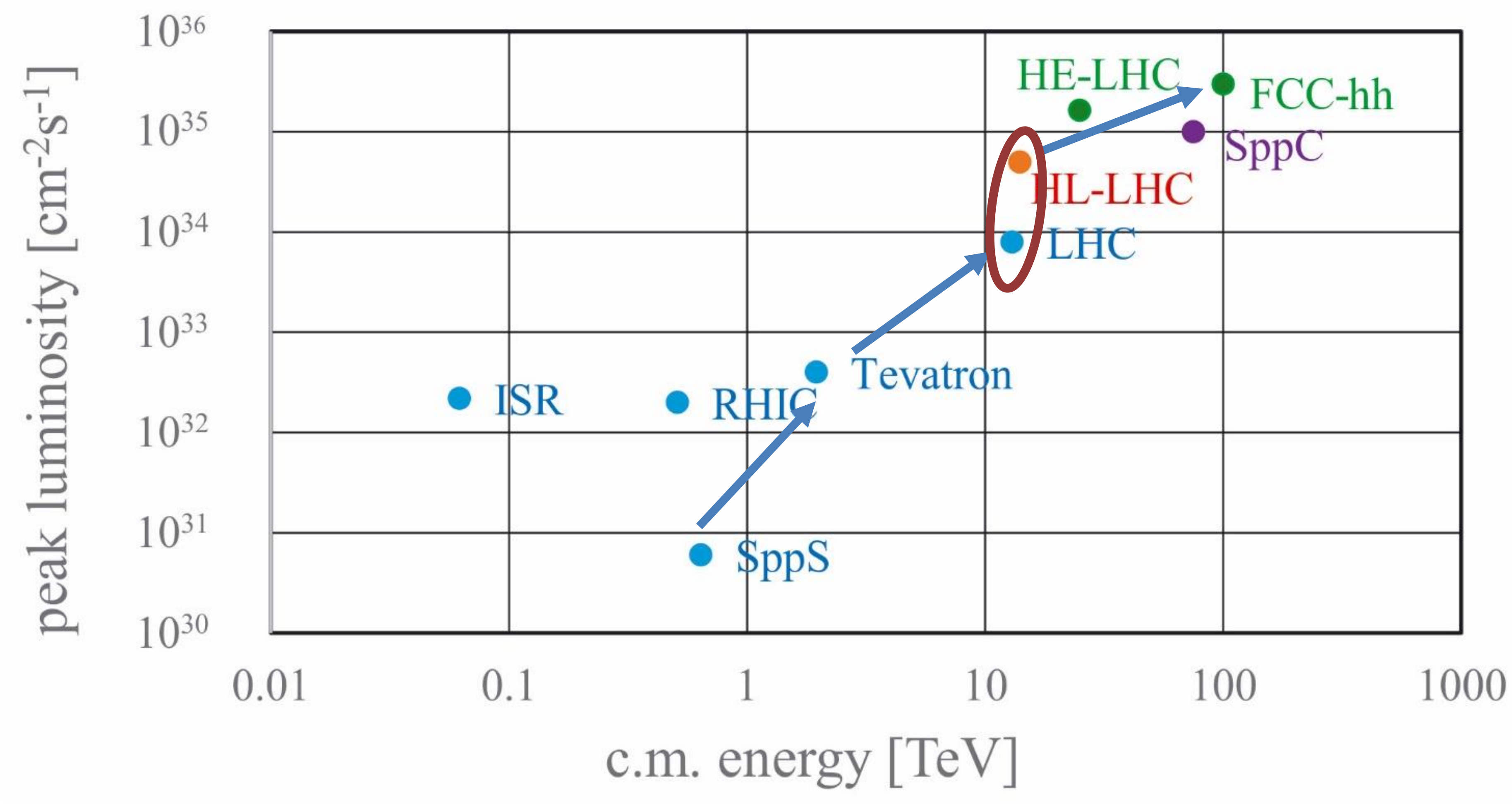
“the tunnel is everything!”
Nick Walker,
ILC GDE

e^+e^- collider: key step to next hadron collider

FCC-ee/CEPC will provide:

- a 100 km tunnel
- infrastructure (general services, cryogenics, cooling + ventilation, RF system, etc.)
- time (15-20 years) to develop and build 1000’s of efficient high-field magnets
- addt’l physics motivations and clear target energy for the subsequent *pp* collider

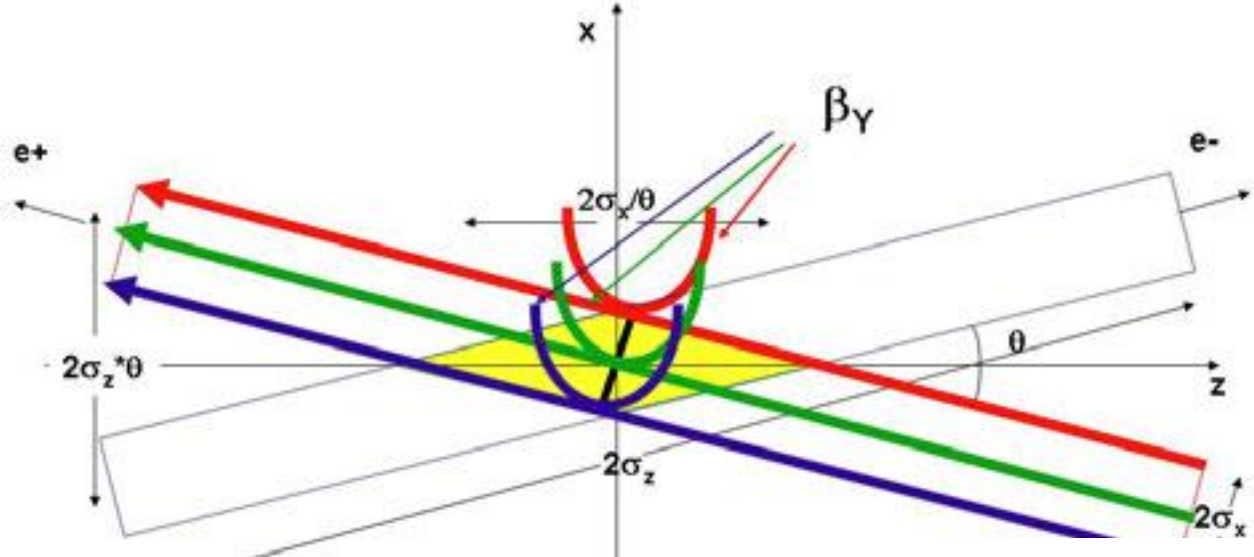
past, present & proposed hadron colliders



… surely great times ahead!

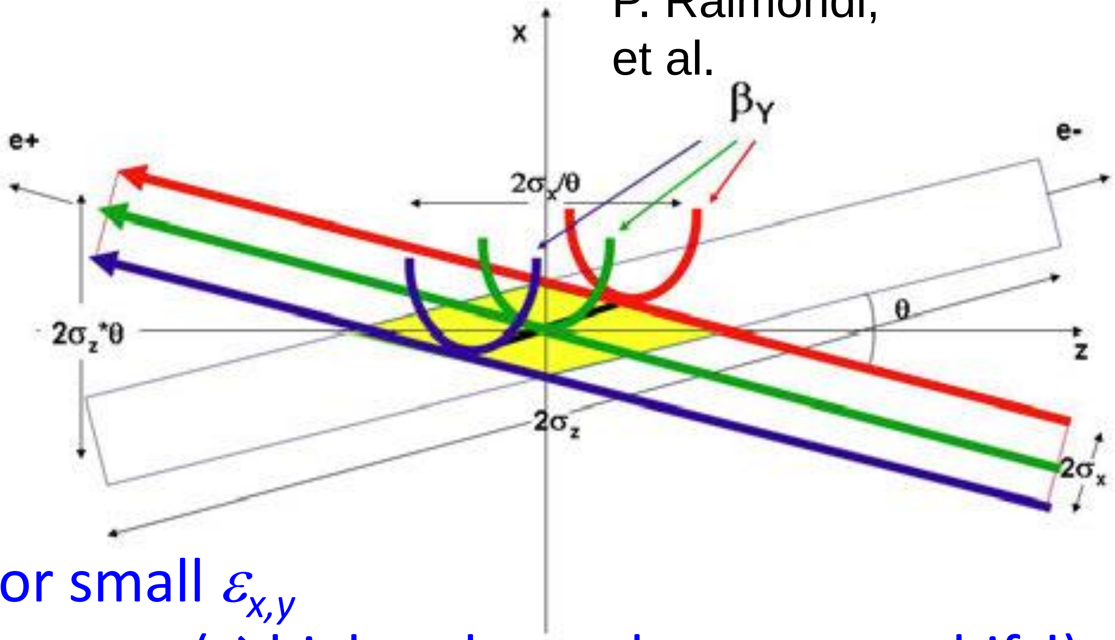
spare slides

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!)