FCC-ee Lepton Collider

Frank Zimmermann

FCC Physics, Detector and Accelerator Workshop

Istanbul Aydin University, 11 March 2016

many thanks to M. Aiba, R. Assmann, S. Aumon, E. Belli, M. Benedikt, A. Blondel, A. Bogomyagkov, M. Boscolo, O. Brunner, H. Burkhardt, A. Butterworth, Y. Cai, R. Calaga, F. Cerutti, A. Doblhammer, O. Etisken, A. Faus-Golfe, A. Ferrari, K. Furukawa, C. Garion, E. Gianfelice, S. Glukhov, G. Guillermo, B. Haerer, B. Holzer, P. Janot, M. Jimenez, J. Jowett, R. Kersevan. I. Koop, M. Koratzinos, L. Lari, E. Levichev, R. Martin, L. Medina, V. Mertens, M. Migliorati, S. Ogur, K. Ohmi, K. Oide, J. Osborne, Y. Papaphilipou, P. Piminov, R. Rossmanith, G. Rumolo, A. Saa Hernandez, J. Seeman, D. Shatilov, D. Shwartz, S. Sinyatkin, M. Sullivan, M.A. Valdivia, J. Wenninger, U. Wienands,…

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Outline

- e^+e^- collider landscape & lessons learnt
- FCC-ee baseline parameters
- synchrotron radiation
- RF system, cryo & wall-plug power
- FCC-ee optics
- polarization, energy calibration & mono-chromatization

e^+e^- collider landscape
& lessons learnt

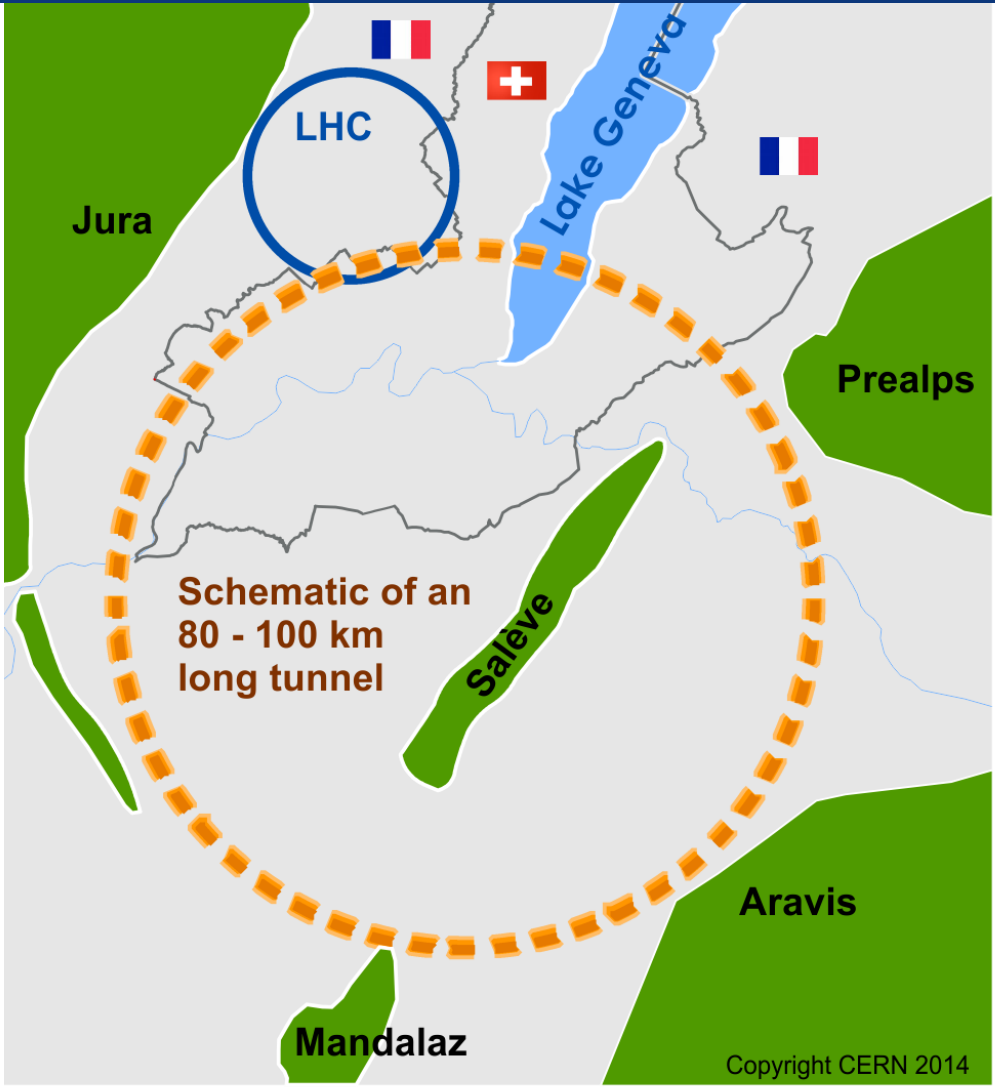
Future Circular Collider Study
GOAL: CDR and cost review for the next ESU (2018)

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

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

~16 T ⇒ 100 TeV *pp* in 100 km

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



CepC/SppC study (CAS-IHEP) 54 km (baseline)

e^+e^- collisions ~2028; *pp* collisions ~2042

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

Yifang Wang

"Chinese Toscana"

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

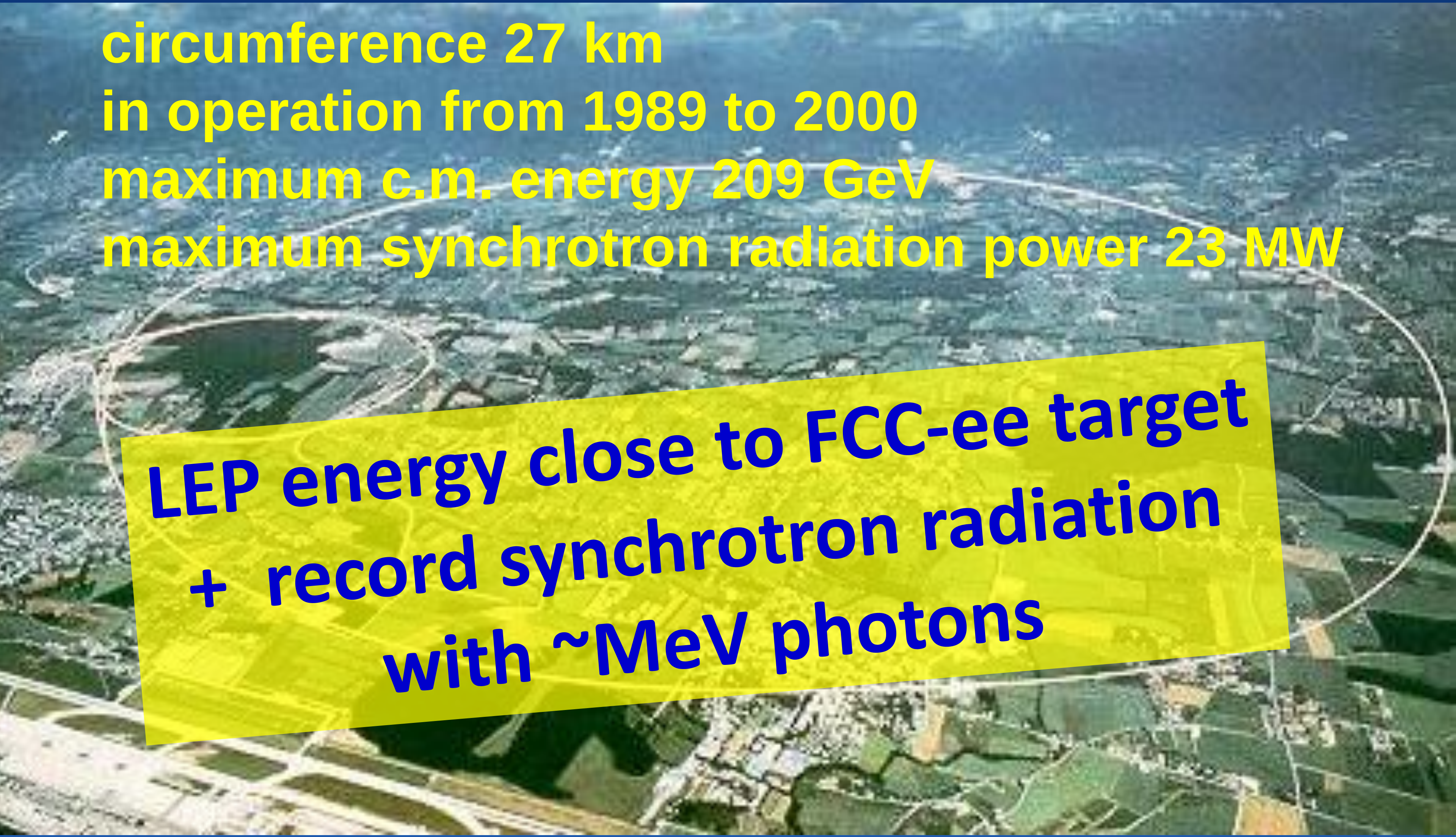
  W (80 GeV) W pair production threshold, high precision M_W

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

  t (175 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

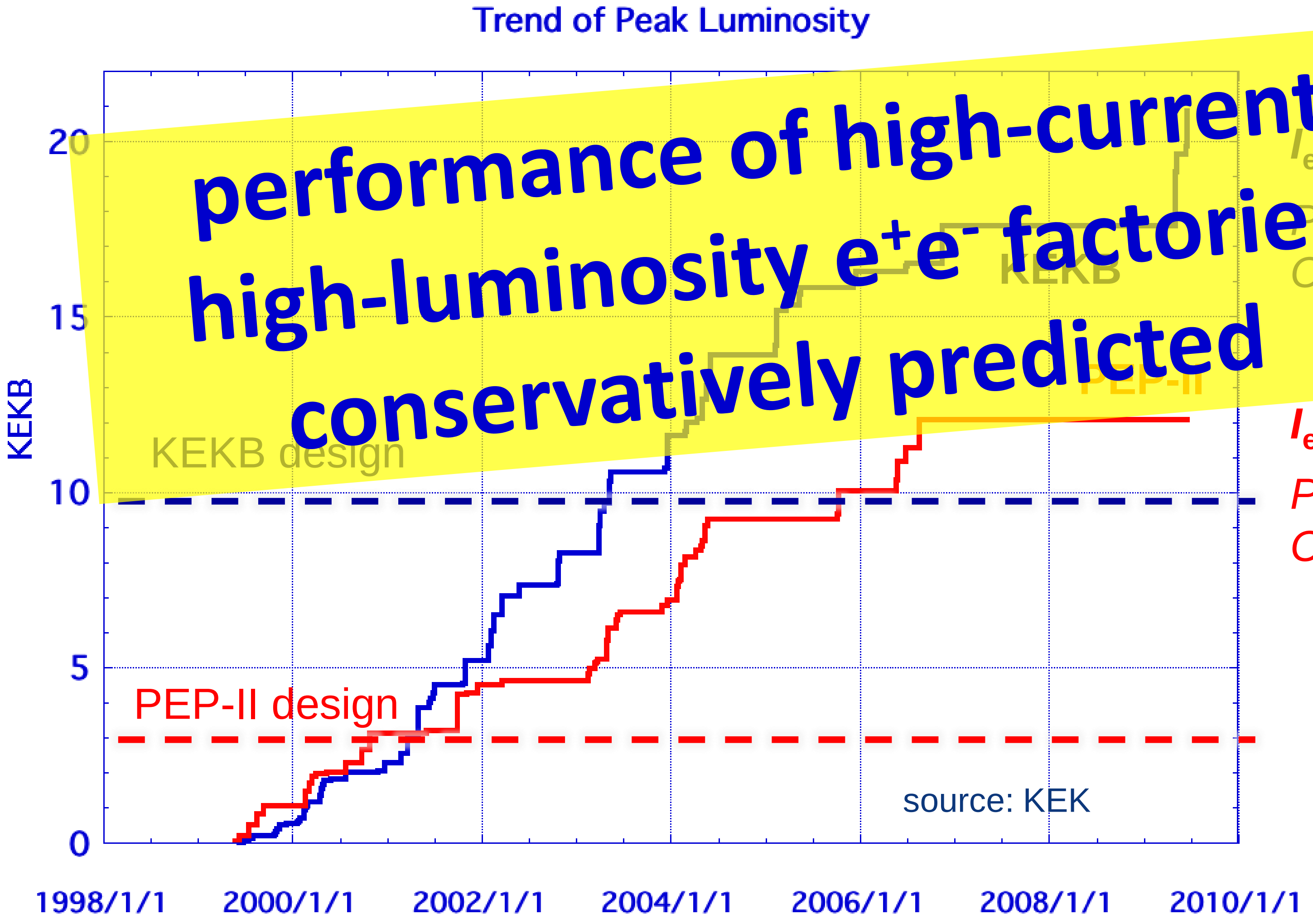
LEP/LEP2: highest energy so far



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

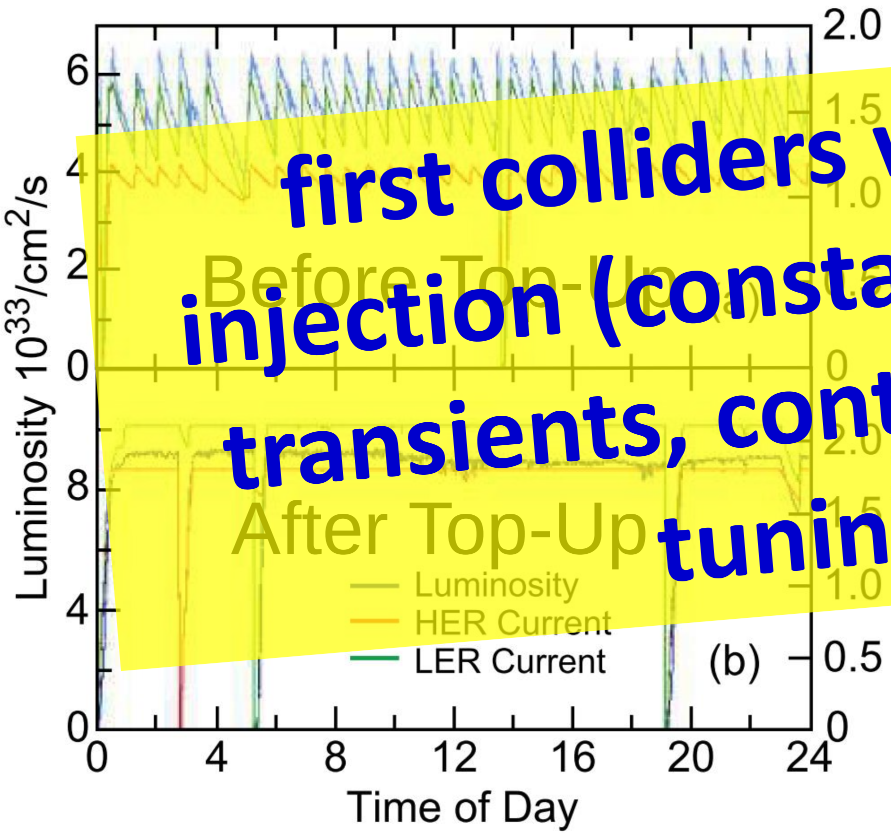
C = 3 km

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

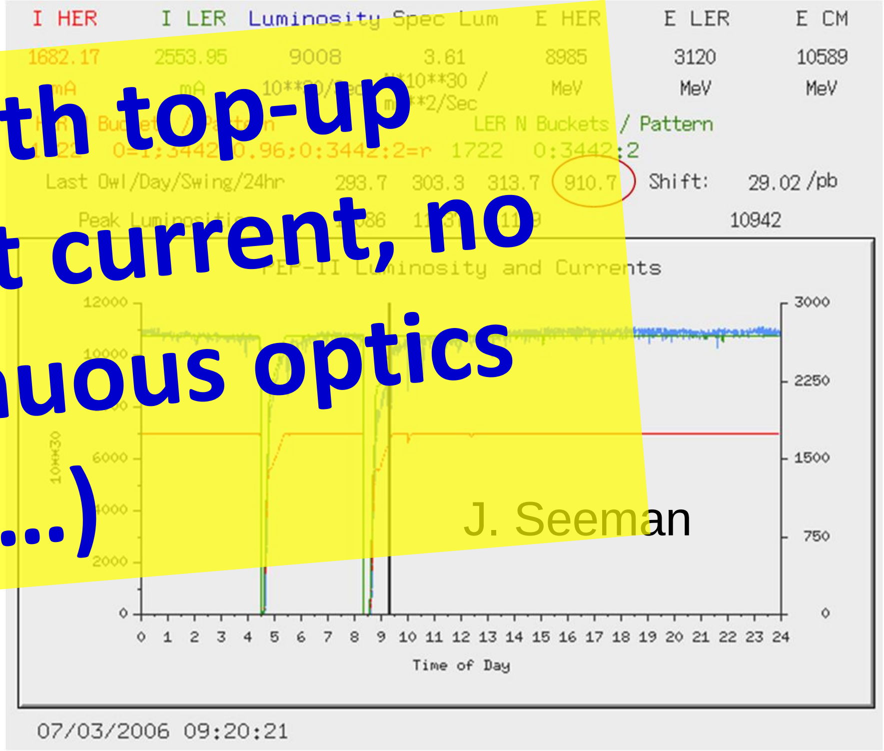
P_{SR} ~ 8 MW

C = 2.2 km

KEKB & PEP-II: top-up injection



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

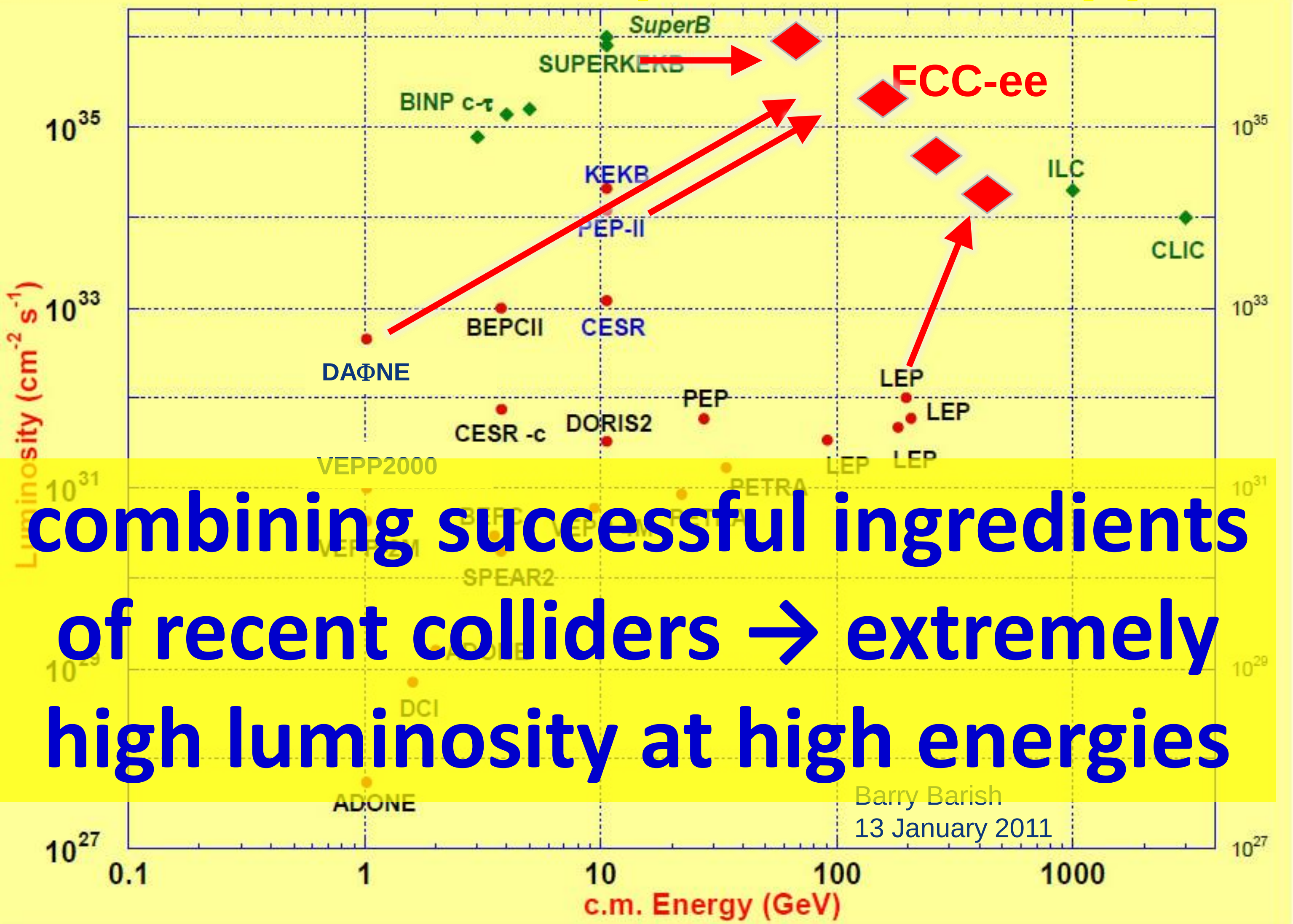


J. Seeman

average luminosity ≈ peak luminosity

similar results from KEKB

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



Barry Barish
13 January 2011

combining successful ingredients of recent colliders → extremely high luminosity at high energies

LEP:
high energy
SR effects

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

DAFNE: crab waist

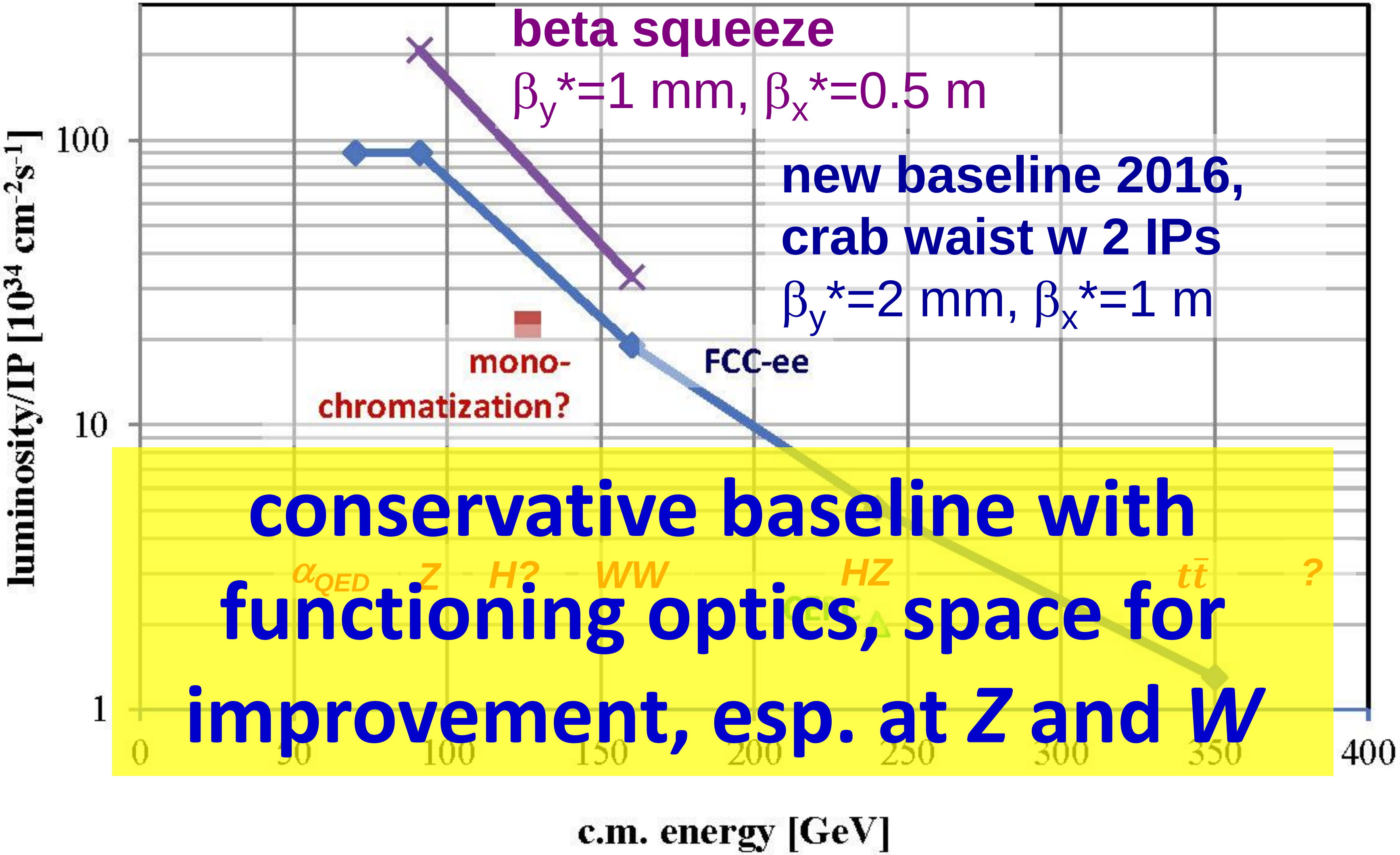
S-KEKB: low β_y^*

KEKB: e^+ source

HERA, LEP, RHIC:
spin gymnastics

FCC-ee baseline parameters

FCC-ee luminosity per IP



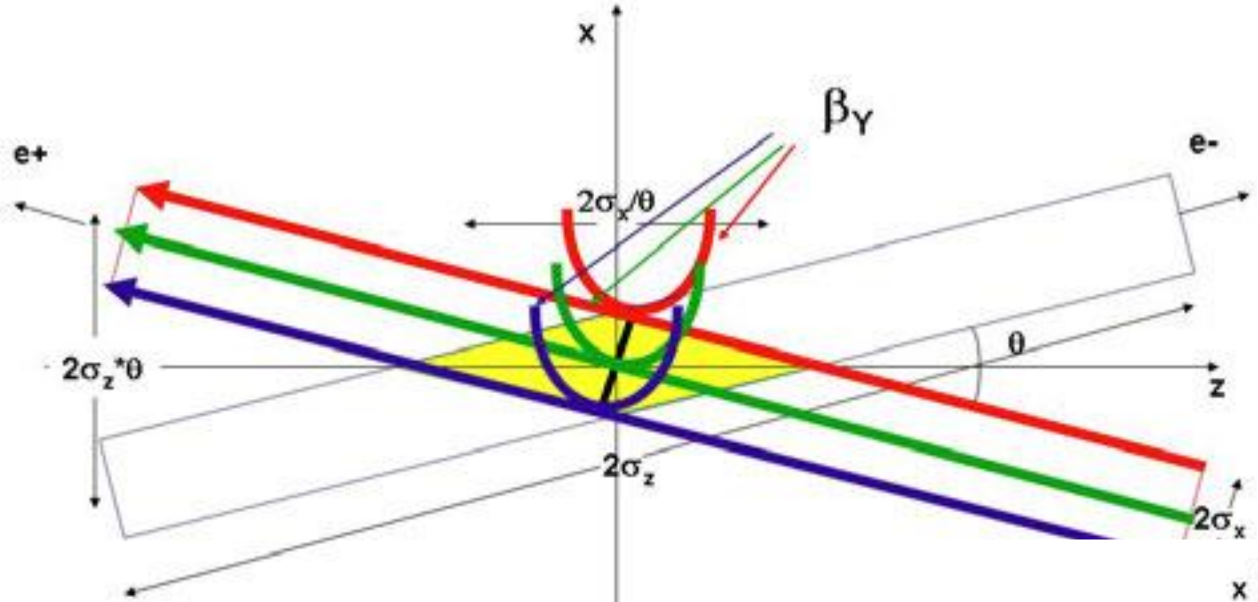
beta squeeze
β_y^*=1 mm, β_x^*=0.5 m

new baseline 2016, crab waist w 2 IPs
β_y^*=2 mm, β_x^*=1 m

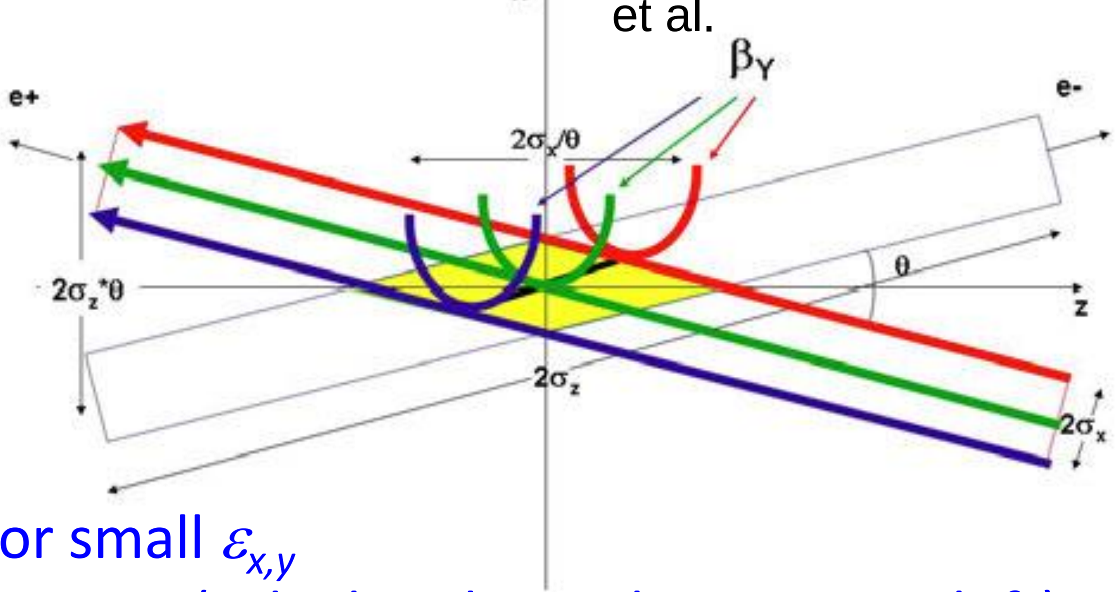
conservative baseline with functioning optics, space for improvement, esp. at *Z* and *W*

crab-waist crossing for flat beams

regular crossing



P. Raimondi,
et al.



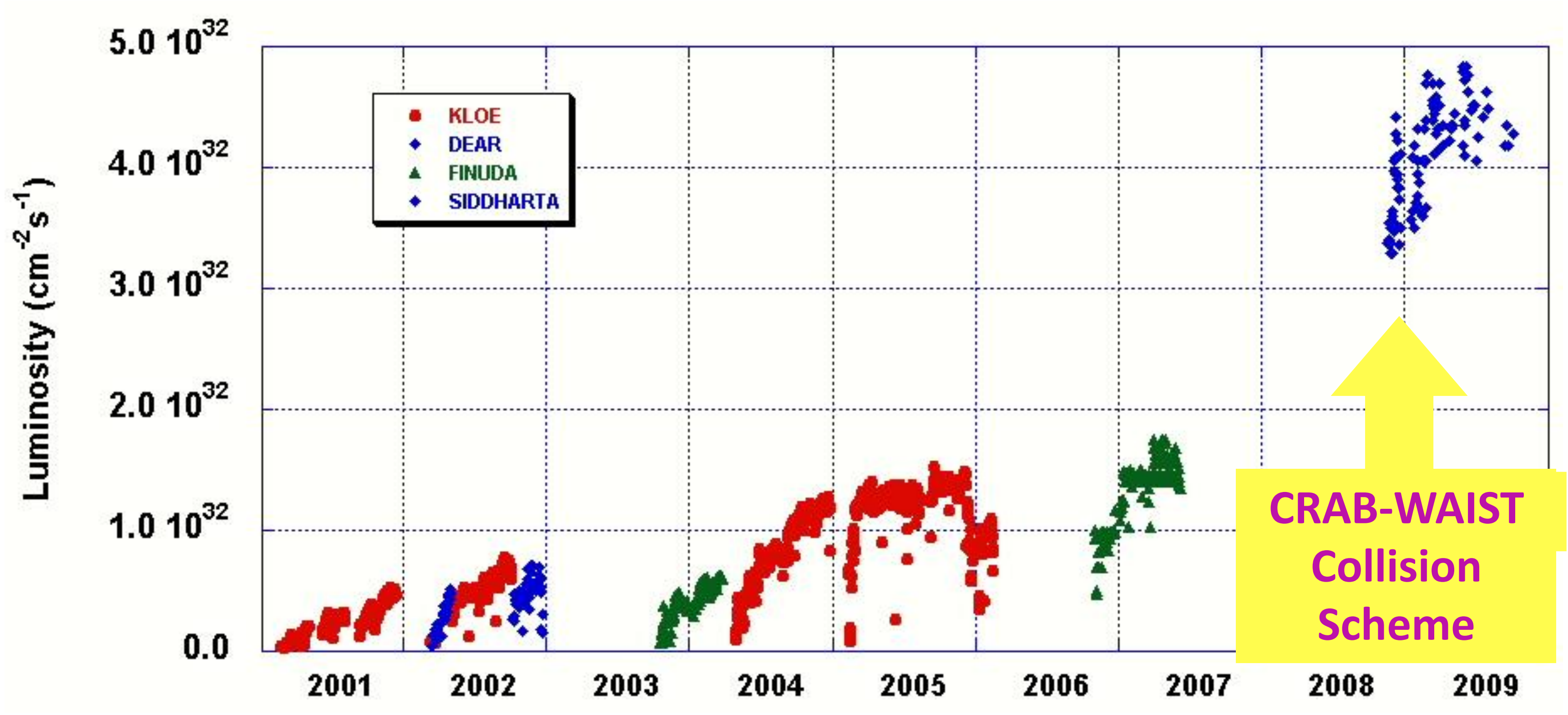
crab waist -

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

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

DAΦNE: "crab waist" collisions

DAΦNE Peak Luminosity



CRAB-WAIST Collision Scheme

Design Goal

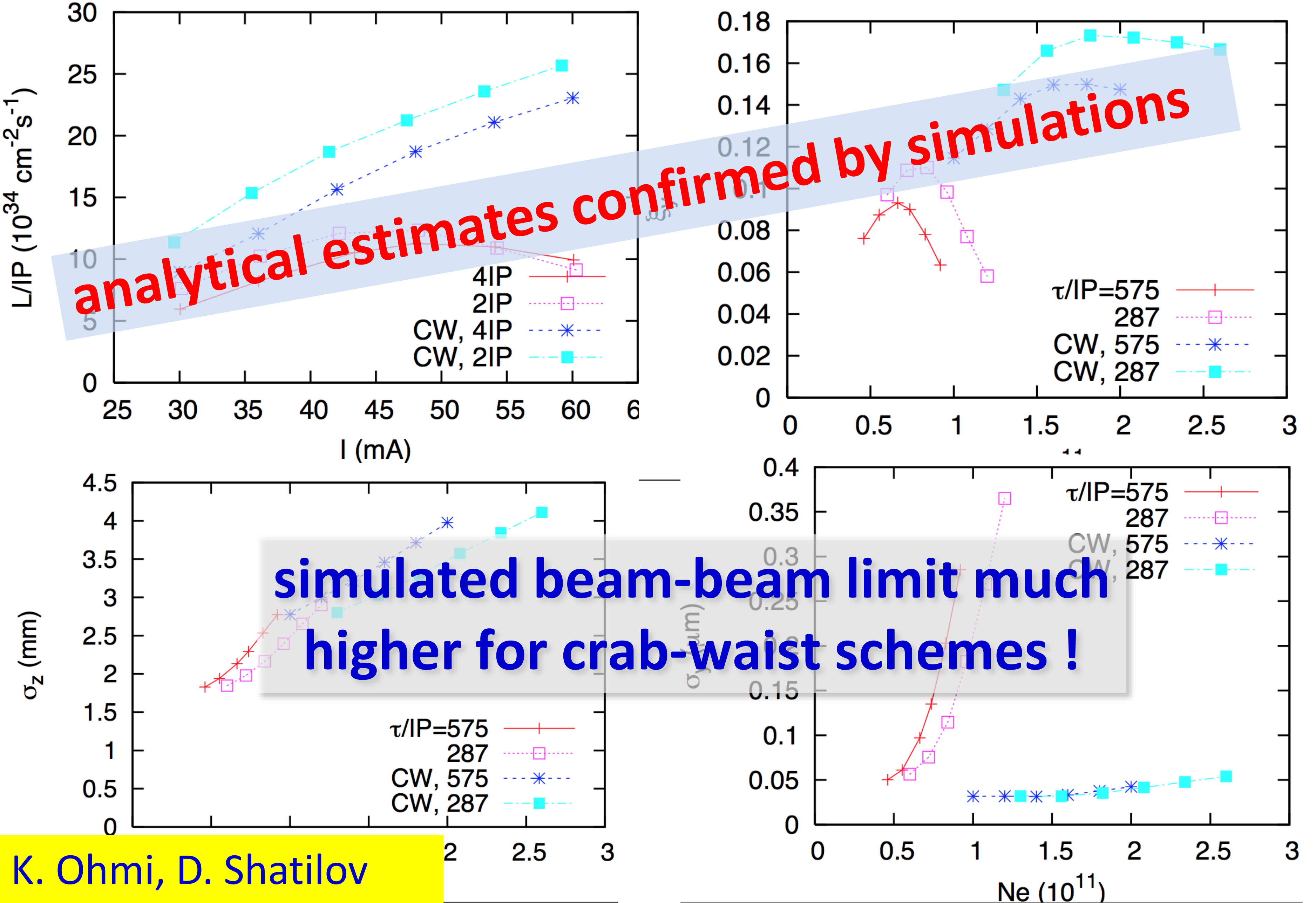
M. Zobov

2016 baseline parameters

parameter	FCC-ee				CEPC	LEP2
energy/beam [GeV]	**45.6**		**120**	**175**	**120**	105
bunches/beam	30.2k	91.5k	770	78	50	4
beam current [mA]	1450		30	6.6	16.6	3
luminosity/IP x 10^{34} cm^{-2}s^{-1}	**207**	**90**	**5.1**	**1.3**	**2.0**	0.0012
energy loss/turn [GeV]	0.03		1.67	7.55	3.1	3.34
synchrotron power [MW]	100				103	22
RF voltage [GV]	0.4	0.2	3.0	10	6.9	3.5
rms bunch length SR+tot [mm]	1.2,6.7	1.6,3.8	2.0,2.4	2.1, 2.5	2.1,2.6	12, 12
rms emittance $\varepsilon_{x,y}$ [nm, pm]	0.09, 1		0.61, 1	1.3, 2.5	6, 18	22, 250
$\beta^*_{x,y}$ [m,mm]	0.5,1.0	1, 2.0	1, 2.0	1, 2.0	0.8,1.2	1.2, 50
longit. damping time [turns]	1320		72	23	39	31
crossing angle [mrad]	30		30	30	0	0
beam lifetime [min]	94	185	67	57	61	434

FCC-ee: 2 separate rings **CEPC: single beam pipe like LEP**

beam-beam simulations



analytical estimates confirmed by simulations

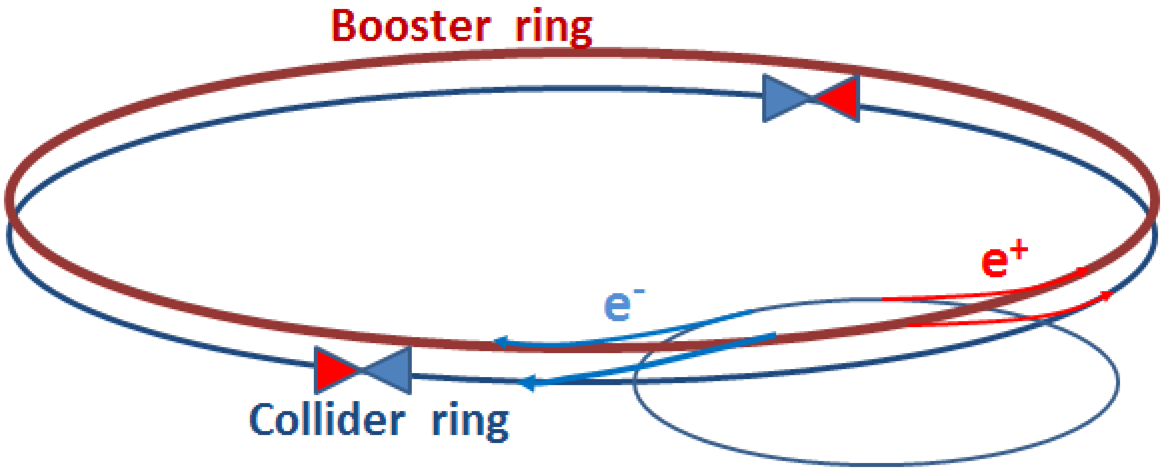
simulated beam-beam limit much higher for crab-waist schemes !

K. Ohmi, D. Shatilov

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

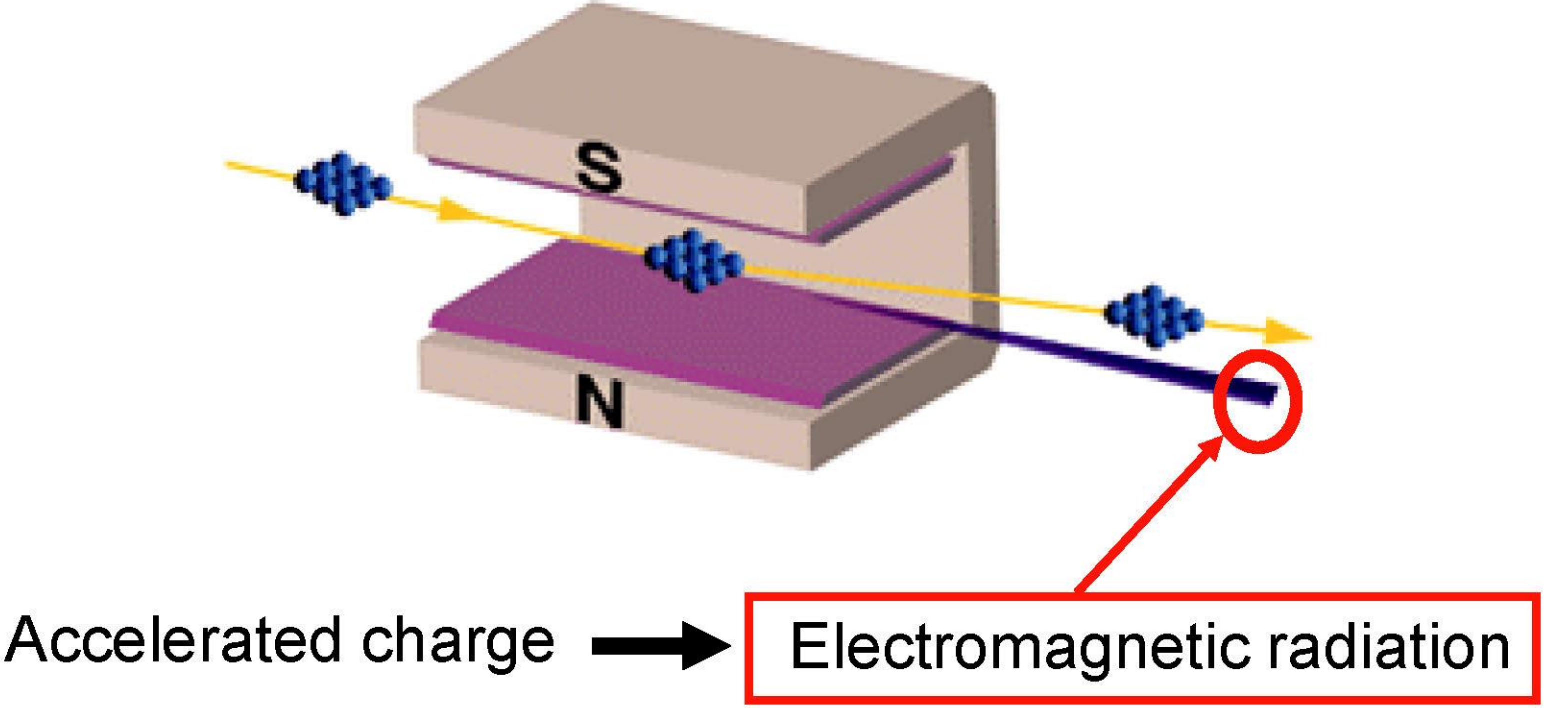
- same size of RF system, but low power (~ MW)
- top up frequency ≈0.1 Hz
- booster injection energy ≈5-20 GeV
- bypass around the experiments



A. Blondel

synchrotron radiation

curved orbit of e^- in magnetic field



Accelerated charge → Electromagnetic radiation

L. Rivkin

arc synchrotron radiation (SR) 1

energy loss per turn

$$U_0 = \frac{e^2}{3\epsilon_0}\frac{\gamma^4}{\varrho}$$

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

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

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

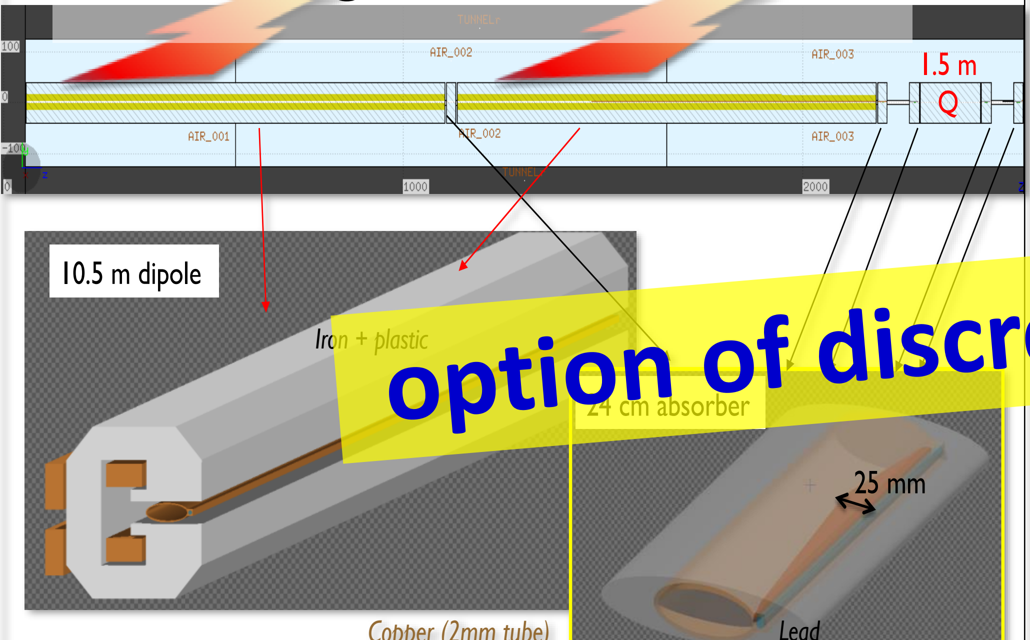
arc SR– heat & shielding

	PEP-II	SPEAR3	FCC-ee Z	FCC-ee H
E [GeV]	9	3	45.5	120
I [A]	3	0.5	1.45	0.03
ρ [m]	165	7.86	11000	11000
linear power [W/cm]	101.8	92.3	7.2	7.2

SR heat per meter much lower than for many operating rings

N. Kurita, U. Wienands, SLAC

shielding SR at 175 GeV

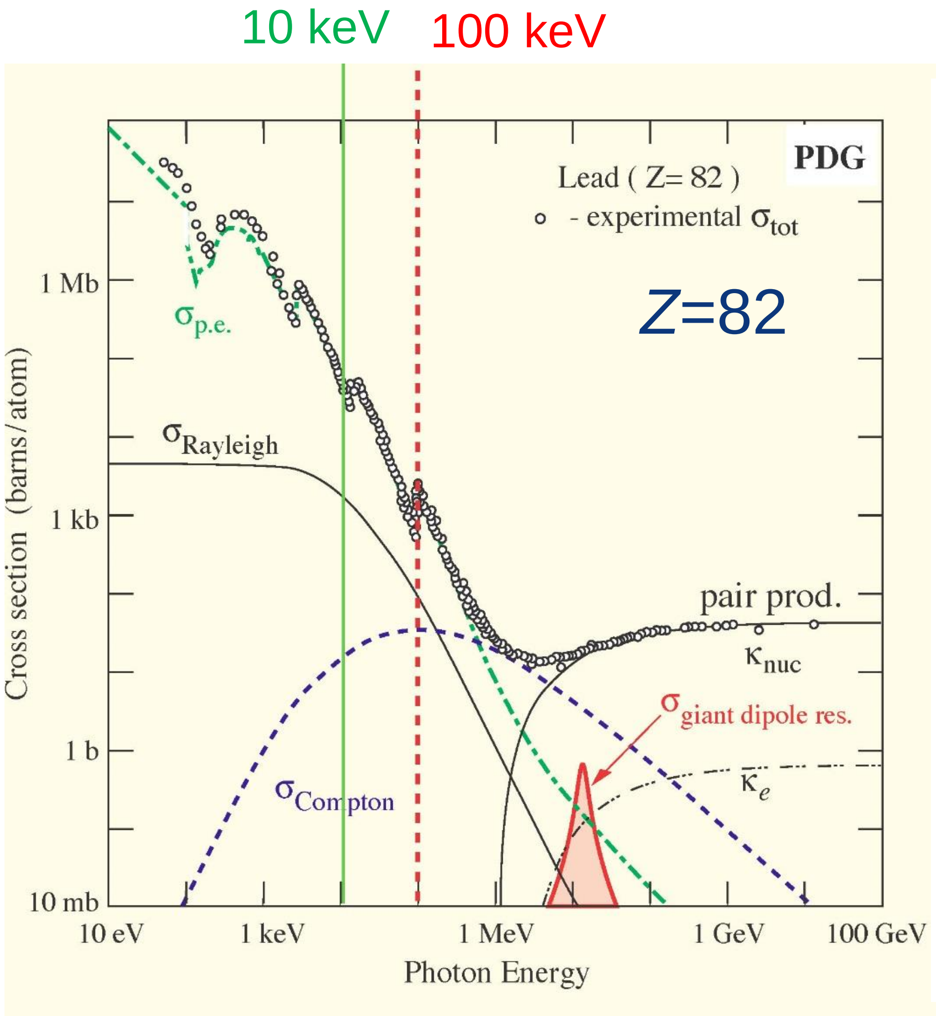


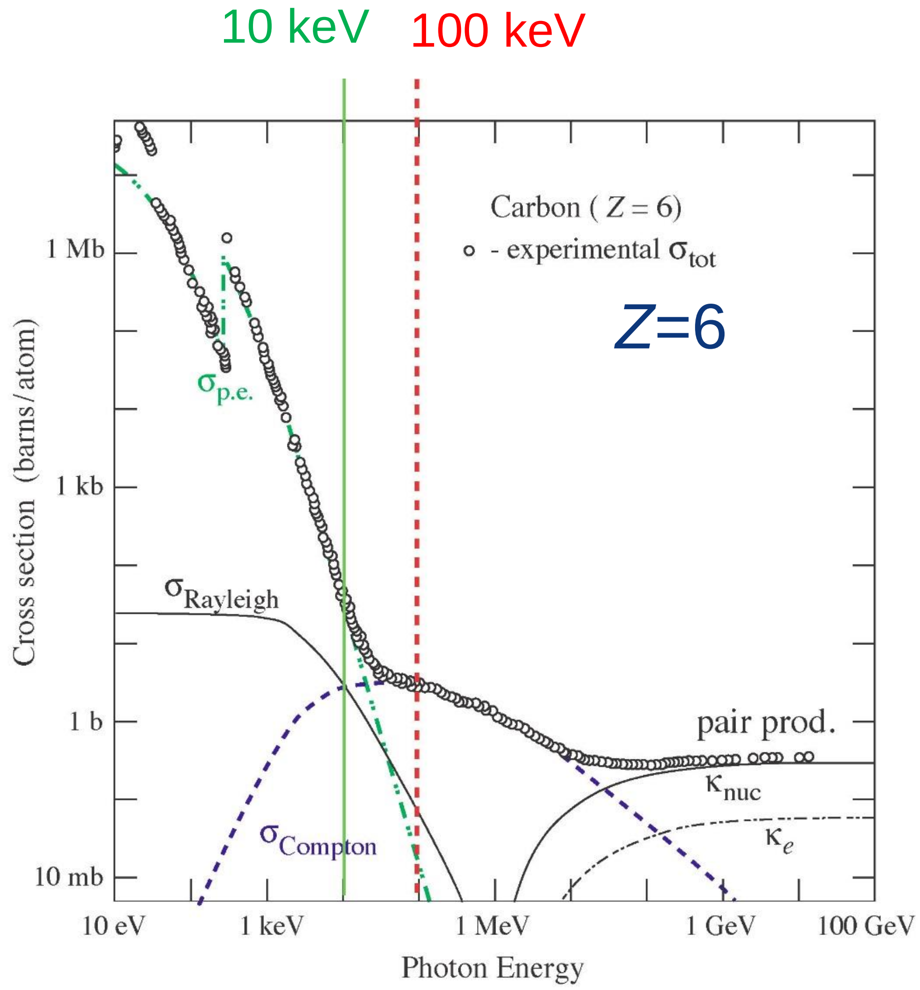
FLUKA geometry layout for half FODO cell, dipole details, preliminary absorber design incl. 5 cm external *Pb* shield

option of discrete absorbers

L. Lari, F. Cerutti, A. Ferrari, A. Mereghetti

SR shielding

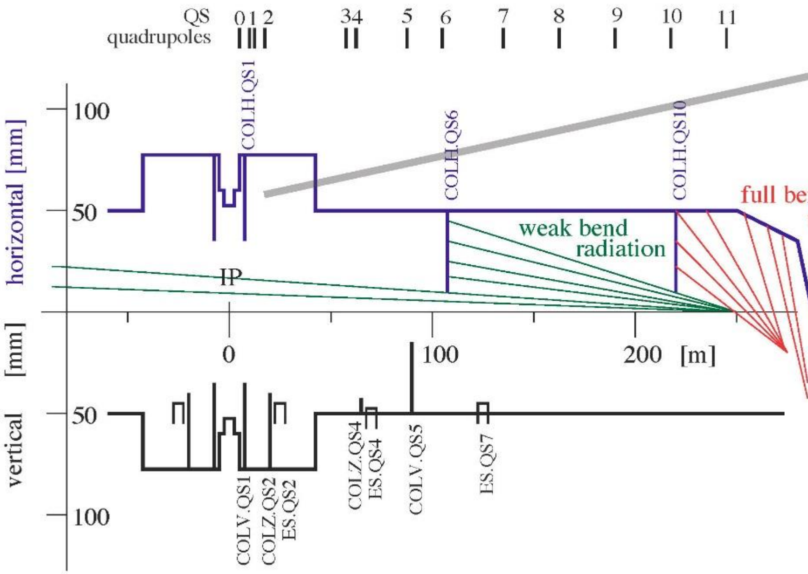




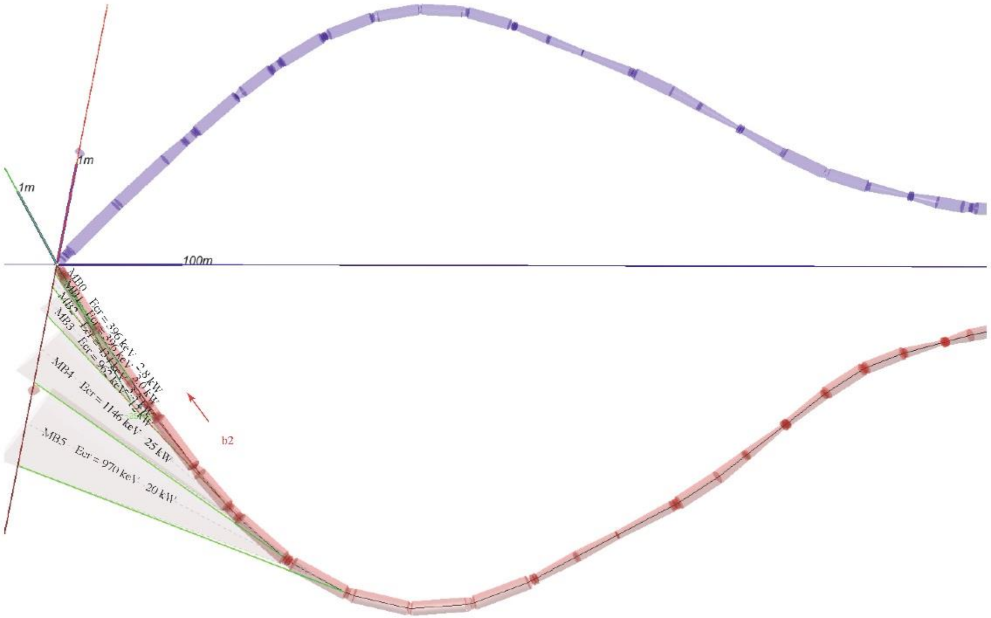
H. Burkhardt

difficult for $E_\gamma \geq 100$ keV, *n* production for $E_\gamma \geq 1$ MeV

synchrotron radiation in the IR



weak bends and
SR masks for LEP



IR SR fans for one
FCC-ee optics

H. Burkhardt, A. Bogomoyagkov

arc synchrotron radiation 2

radiation damping of transverse and longitudinal motion
→beam shrinkage

$$\tau_{||} = \tau_x/2 = (C/c)E/U_0$$

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

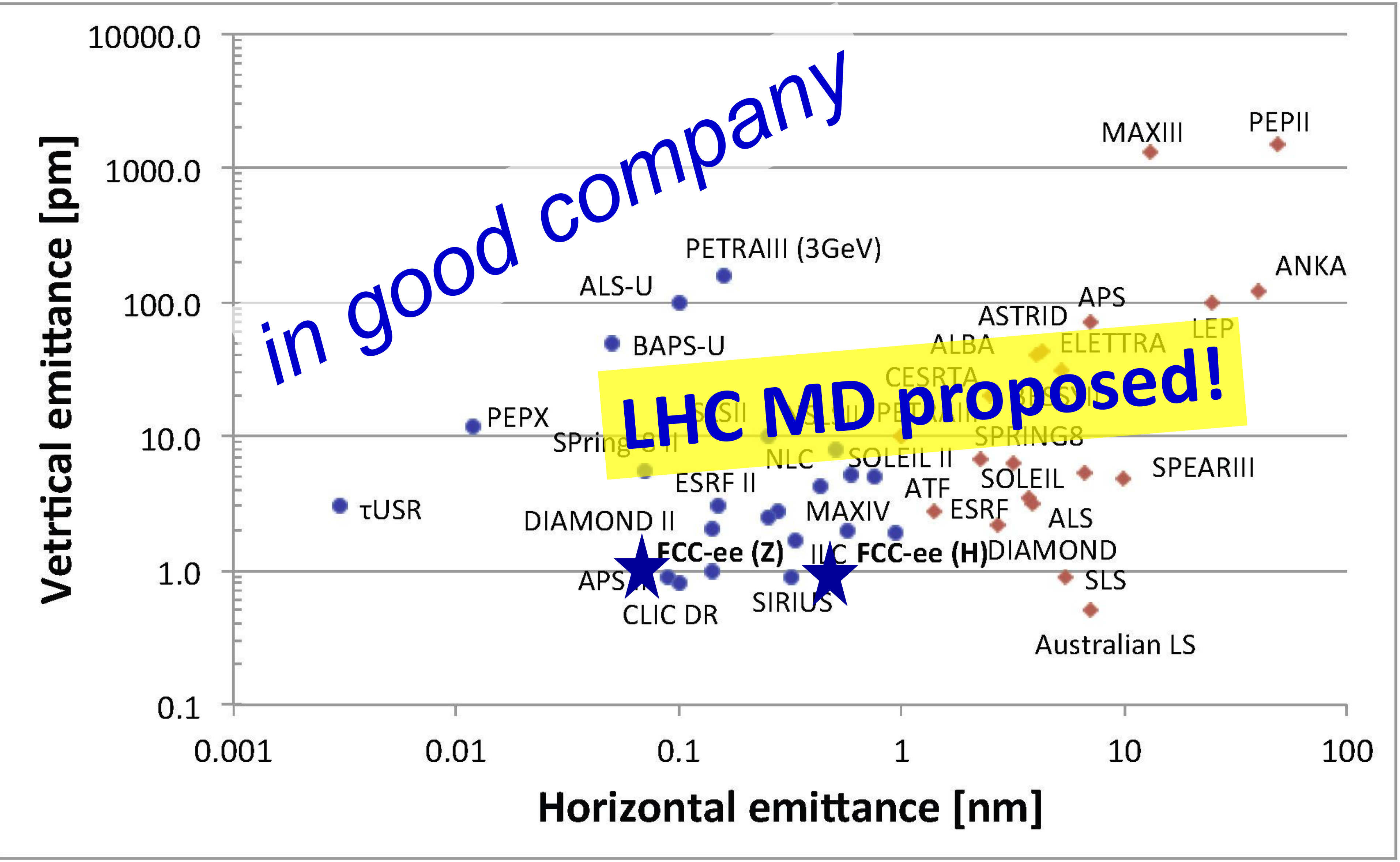
→ cell length

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

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

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

transverse emittances



in good company

LHC MD proposed!

Y. Papaphilippou

beam instabilities

main impedance sources:

100-km vacuum chamber, RF cavities

beam energy higher than LEP, injection synchrotron tune higher, bunch charge lower
→ no TMCI instability, but **μ-wave instability threat**

coupled bunch instabilities driven by cavity modes

e-cloud instability could appear in e^+ ring (antechamber to absorb photoelectrons)

and…

M. Migliorati, N. Mounet, K. Ohmi, G. Rumolo

transverse resistive-wall instability

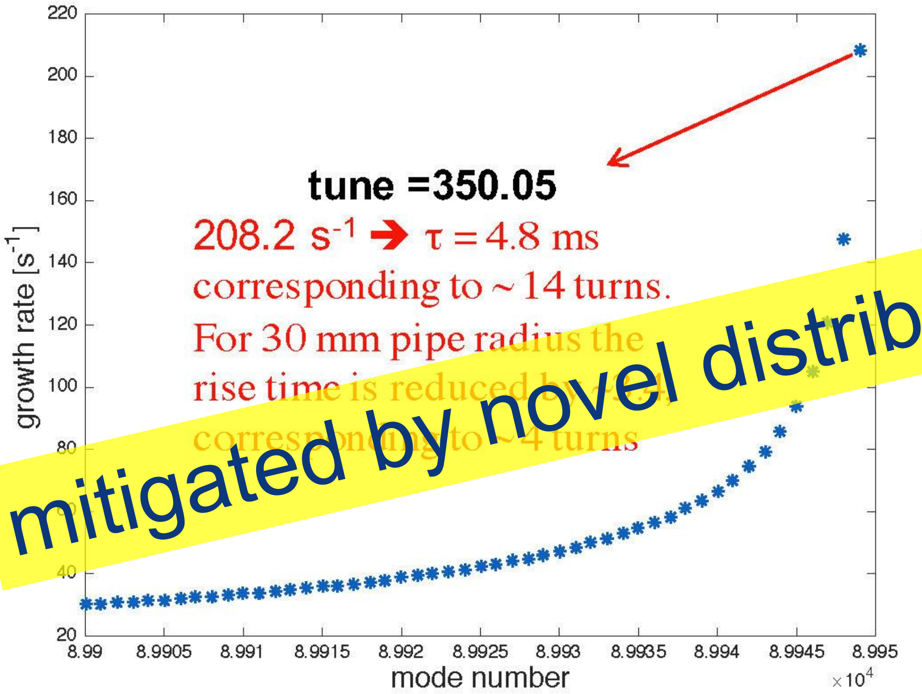
considering *b*=45 mm (pipe radius)

The worst case (lowest energy and highest beam current) is the Z-pole

beam current

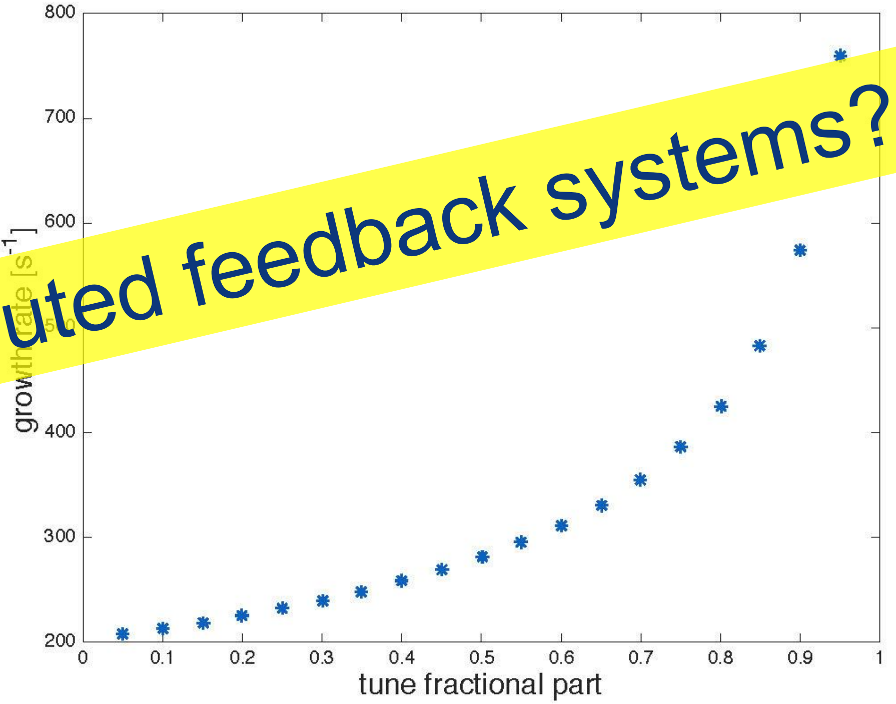
$$\alpha = \frac{c\boxed{N_b I_b}}{4\pi(E/e)Q_\beta}\frac{L}{2\pi b^3}\sqrt{\frac{LZ_0}{\pi|1-\nu_\beta|\sigma_c}}\,G_\perp\left(\frac{\sigma_z}{c}\omega'_q\right)$$

energy



tune =350.05

208.2 s^{-1} ➔ $\tau = 4.8$ ms corresponding to ~ 14 turns. For 30 mm pipe radius the rise time is reduced by ~3.4, corresponding to ~4 turns



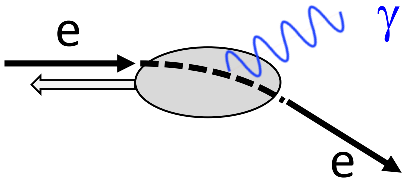
mitigated by novel distributed feedback systems?

M. Migliorati

beamstrahlung – a new limit at 175 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* ***≥1.5% at 175 GeV***
    - LEP: <1% acceptance, SuperKEKB ~ 1.5%

J. Wenninger, et al

RF system

power considerations

continually supplying circulating beam with

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

wall-plug power $P_{wall}=P_{SR}/\eta + P_{cryo}$

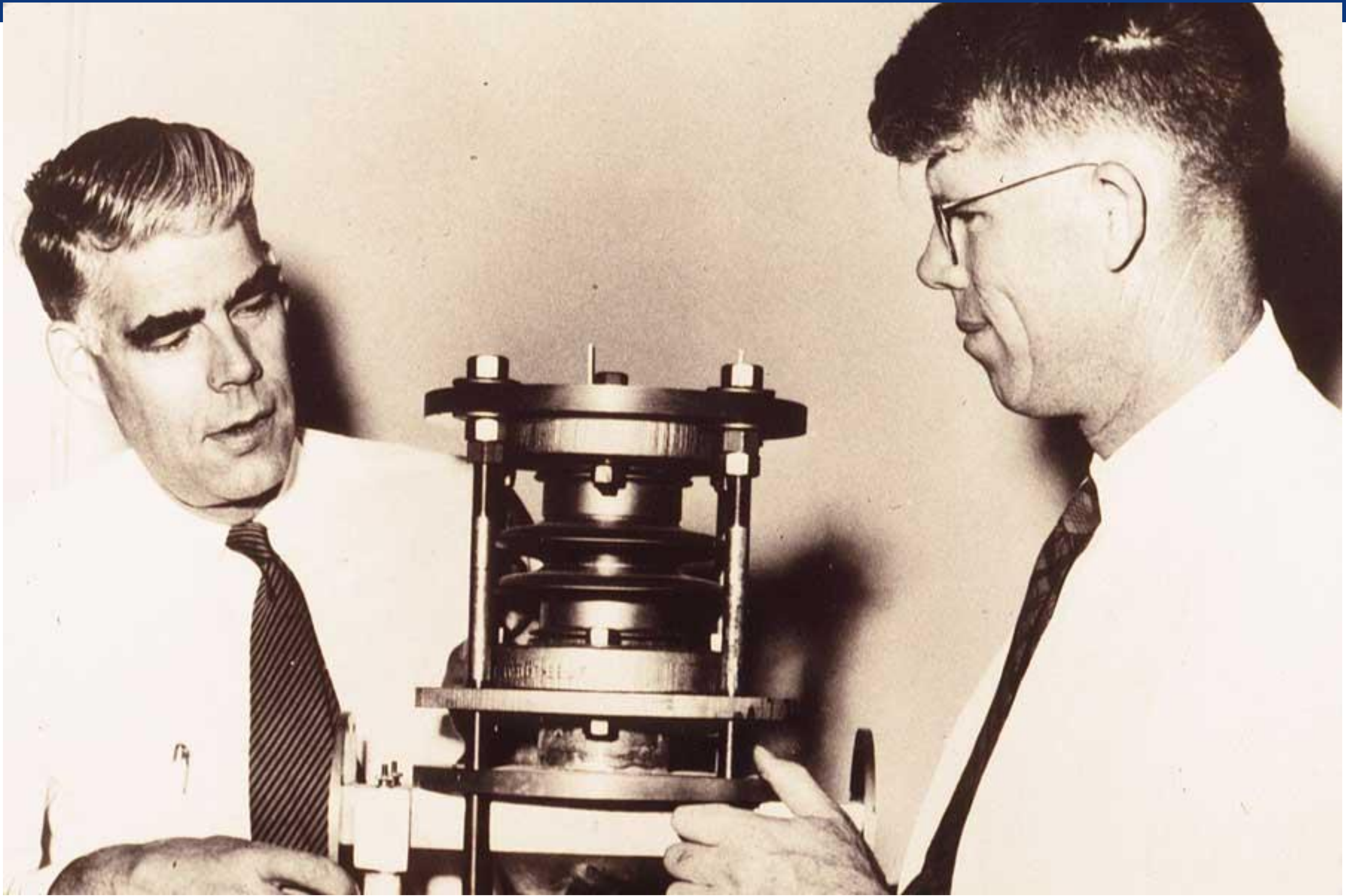
with η=conversion efficiency wall-plug → beam

FCC target: $\eta \geq 50\%$

(achieved at PEP-II and LEP)

note: cw RF systems for storage rings are more efficient than those for pulsed linacs

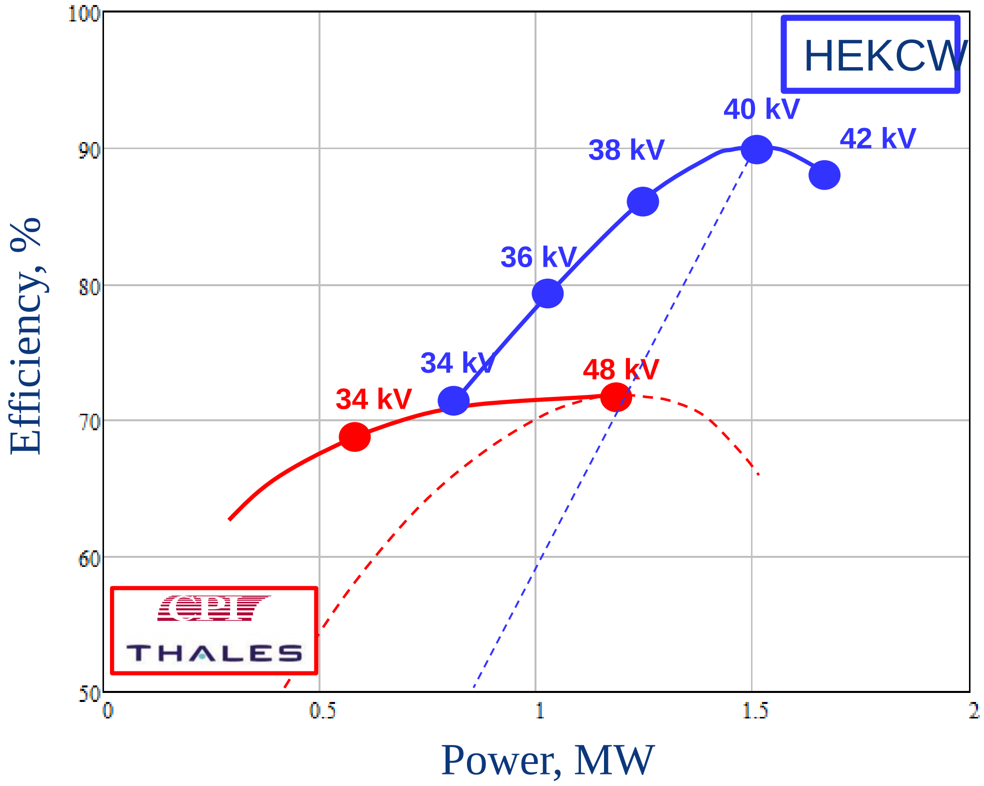
classical rf power source: klystron



Russell & Sigurd Varian invented it at Stanford in 1937

after 80 years a breakthrough in klystron efficiency!

comparing simulated performances of MBIOT and HEKCW MBK



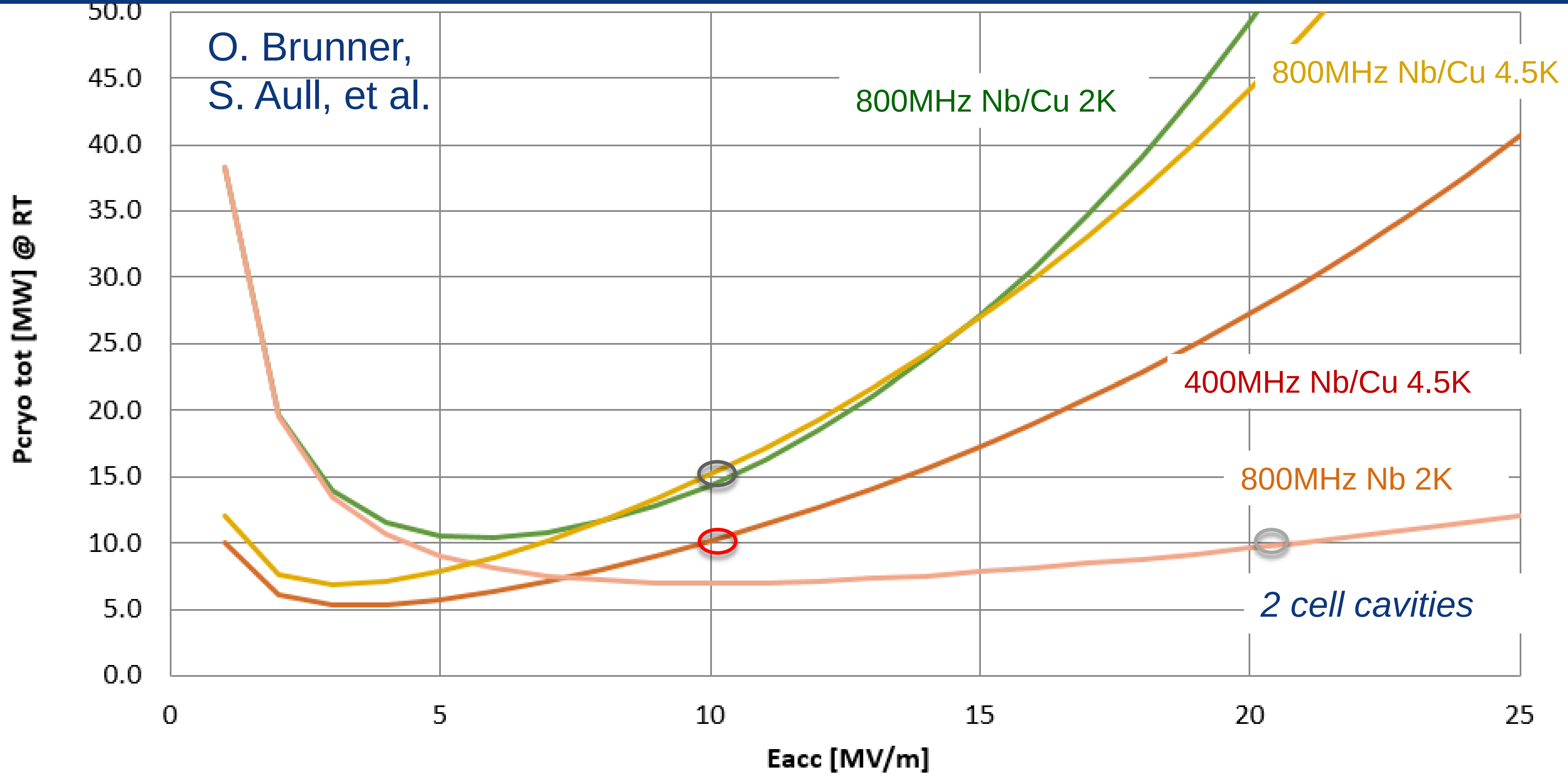
I. Syratchev

demonstration in Russia this month ?!

Dotted lines – only changing P drive

Solid lines – changing P drive and Voltage

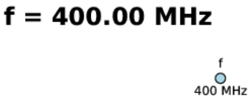
cryo power for FCC-ee "Z" SRF



Static losses dominate @ low fields, dynamic losses @ high fields

4.5k vs 2K operation: 400MHz Nb/Cu @ 10MV/m ≈ 800MHz bulk Nb @ 20MV/m; 800MHz Nb/Cu @ 4.5K ≈ 50% higher

model for RF system optimization with interrelations and limits

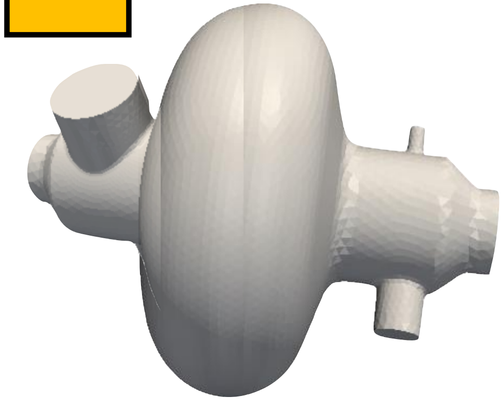


FCC-RF-Working Group
S. Aull, O. Brunner, A. Butterworth,
N. Schwerg, M. Therasse

ex. RF cavities for low and high energy

Z
W
hh

“Z” RF units



400 MHz (1 cell)

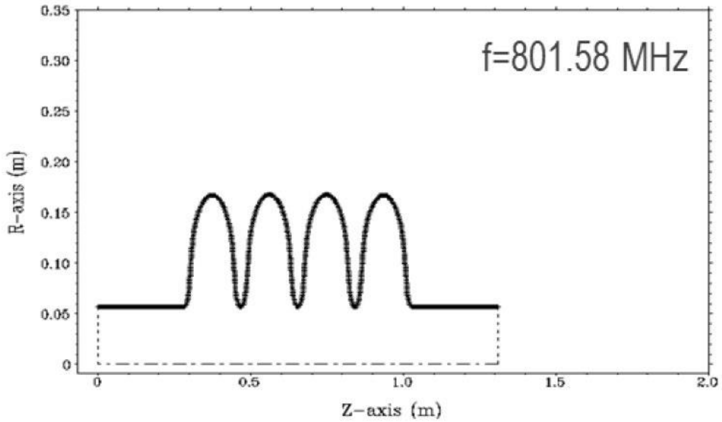
RF Power ≈ 0.5 - 1 MW

HOM Power up to 4 kW

Niobium on Copper @ 4.5 K

H
t
W

“Higgs” RF units



800 MHz (4 cells)

RF Power ≈ 50 - 200 kW

cryo power >> MW

bulk *Nb* at 2 K or new materials (e.g. *Nb_3Sn*) at 4.5 K

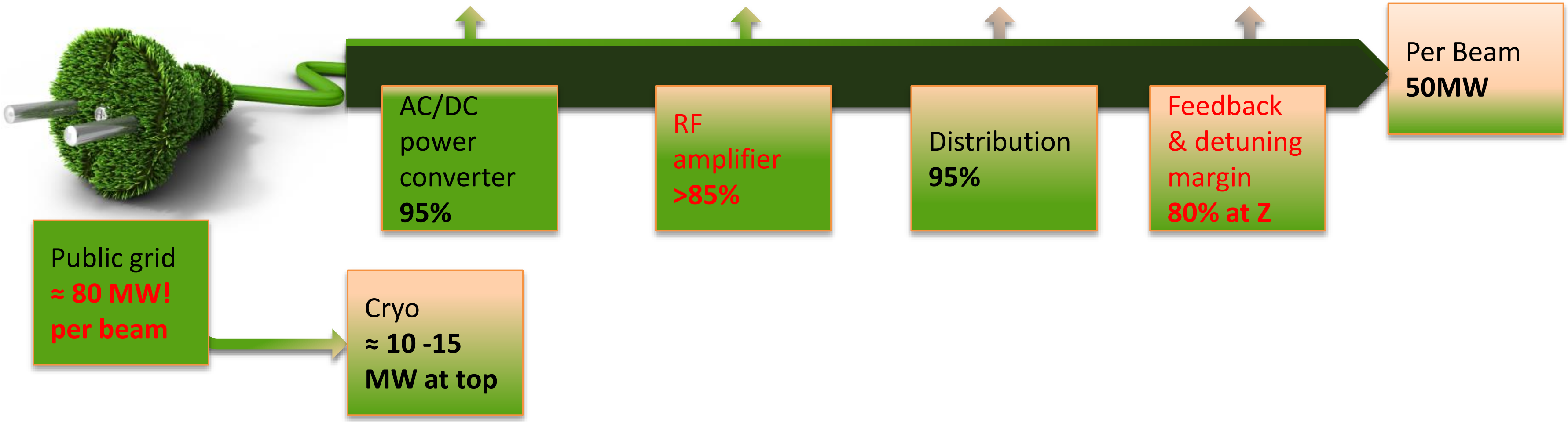
O. Brunner

RF cavities & cryo power (example)

	Z	W	ZH	ttbar
total voltage / beam [GV]	0.2	0.8	3	10
no. cavities / beam	150	150	300	300
RF frequency [MHz]	400		800	
cells / cavity	1		4	
cavity length [m]	0.38	0.38	0.75	0.75
Q_0 [10^9]	4	4	10	8
material & temperature	*Nb/Cu* 4.5K		*Nb* at 2K or Nb_3Sn/Nb at 4.5K	
gradient [MV/m]	3.5	14	13	21
voltage / cavity [MV]	5.3	5.3	10	16
input power / cavity [MW]	0.33		0.17	
HOM loss / cavity [kW]	3.1	0.7	0.80	0.36
total HOM power [MW]	0.93	0.21	0.48	0.22
cryo wall power / cav. [kW]	0.1	2.0	17	50
total cryo power [MW]	<0.5	4.5	<5	<15

S. Gorgi Zadeh, S. Aull

grid power consumption - RF & cryo



Public grid
≈ 80 MW!
per beam

AC/DC power converter **95%**

RF amplifier **>85%**

Distribution **95%**

Feedback & detuning margin **80% at Z**

Per Beam **50MW**

Cryo
≈ 10 -15 MW at top

- The whole system must be optimized – not one efficiency alone
  - RF amplifiers & feedback overheads

- Total ≈ 162 MW + booster ring RF system

O. Brunner

rough estimate of total power [MW]

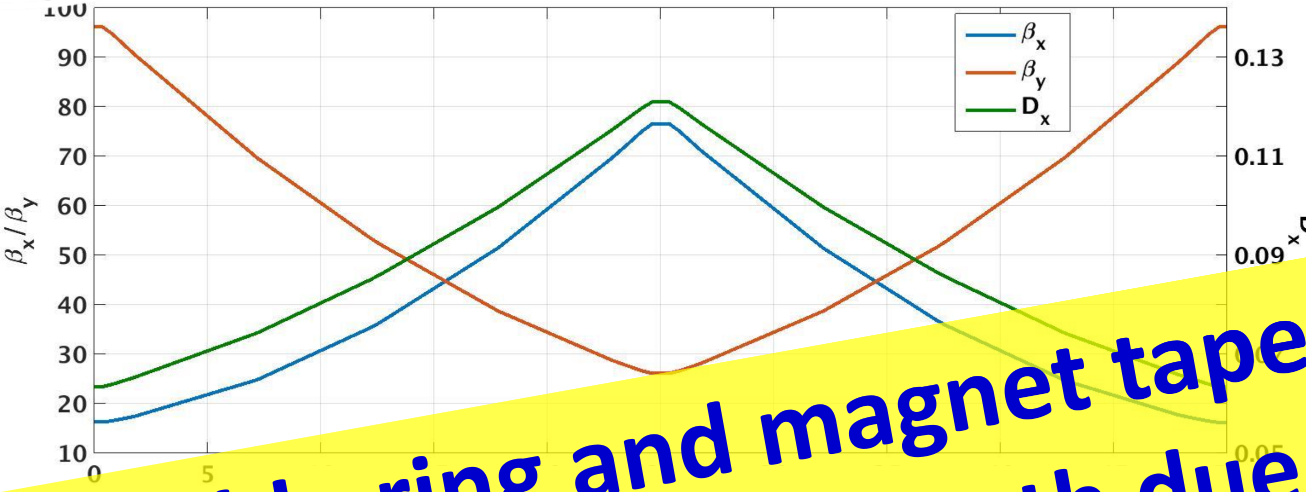
subsystem	Z	W	H	ttbar
collider total RF power	162	162	155	155
collider cryogenics	1	5	5	15
collider magnets	3	10	24	50
booster RF + cryo	4	4	4	4
booster magnets	0	1	2	5
injector complex	10	10	10	10
physics detectors (2)	25	25	25	25
cooling	15	15	15	15
ventilation	30	30	30	30
total	**250**	**262**	**270**	**309**

for comparison, CERN LEP complex in 1998 used 237 MW

Also see: M. Ross, ``Wall-Plug (AC) Power Consumption of a Very High Energy e+/e- Storage Ring Collider,'' 3 August 2013, http://arxiv.or/pdf/1308.0735.pdf ; A. Blondel et al., ``Comments on "Wall-plug (AC) Power Consumption of a Very High Energy e+/e- Storage Ring Collider" by Marc Ross,''12 August 2013, http://arxiv.or/pdf/1308.2629.pdf

FCC-ee optics

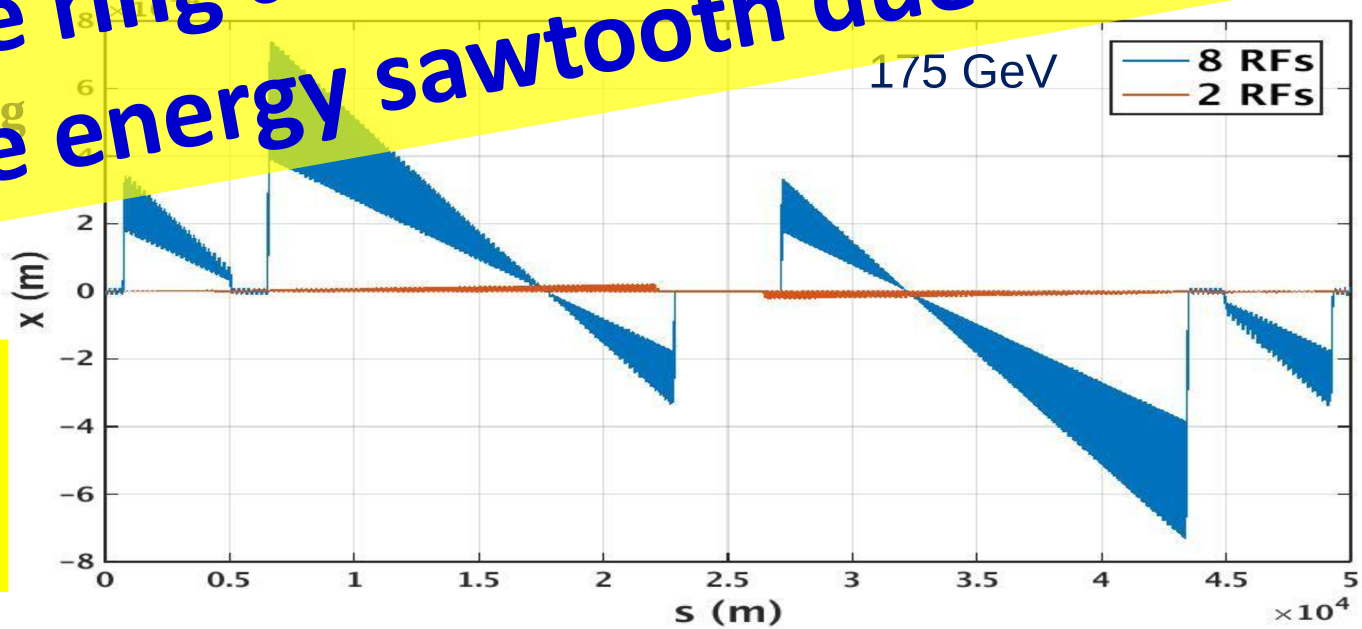
arc optics & sawtooth tapering



arc FODO
cell length
50 m
(LEP 79 m)

double ring and magnet tapering remove energy sawtooth due to SR

Comparison
8 RF w/o tapering
2 RF with
tapered dipoles

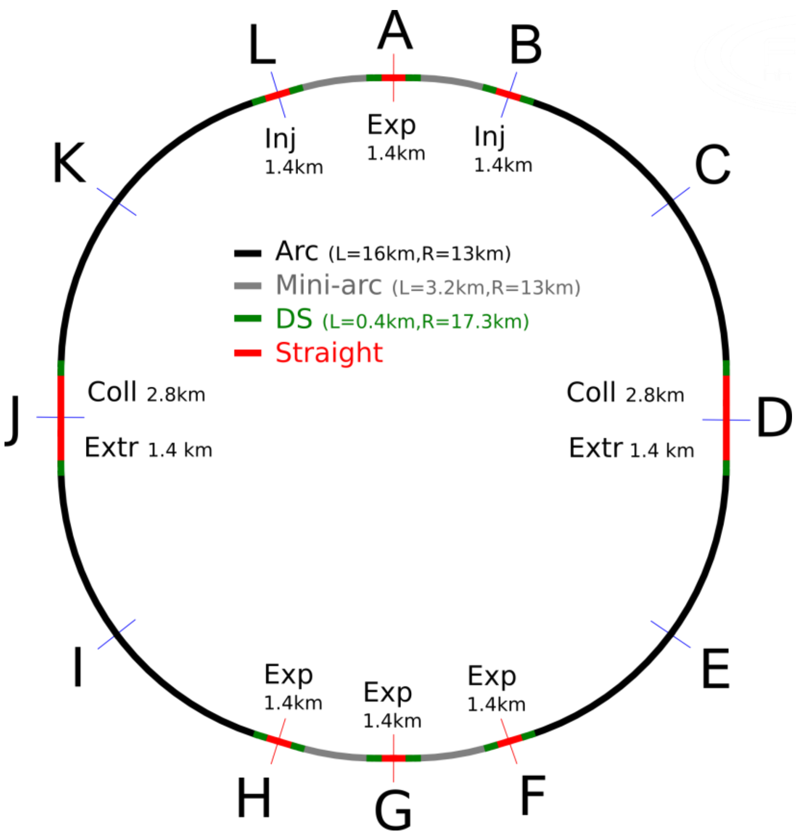


175 GeV

Sandra Aumon,
Bastian Härer,
Andreas Doblhamer,
Bernhard Holzer

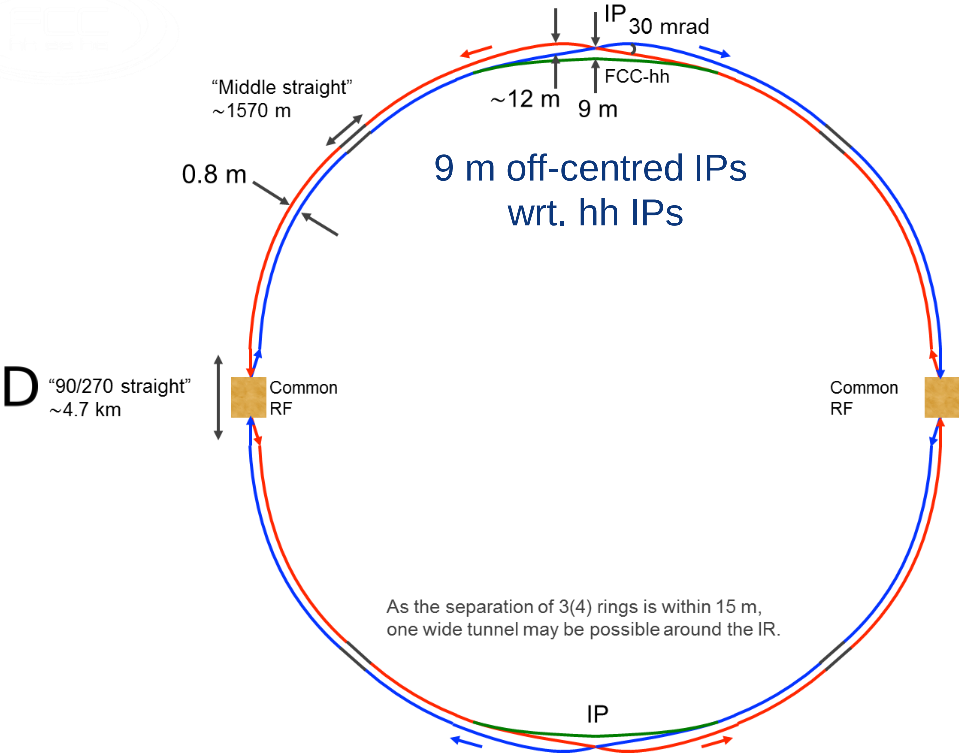
FCC consistent machine layouts

FCC-hh



FCC-ee 1, FCC-ee 2,

FCC-ee booster (FCC-hh footprint)



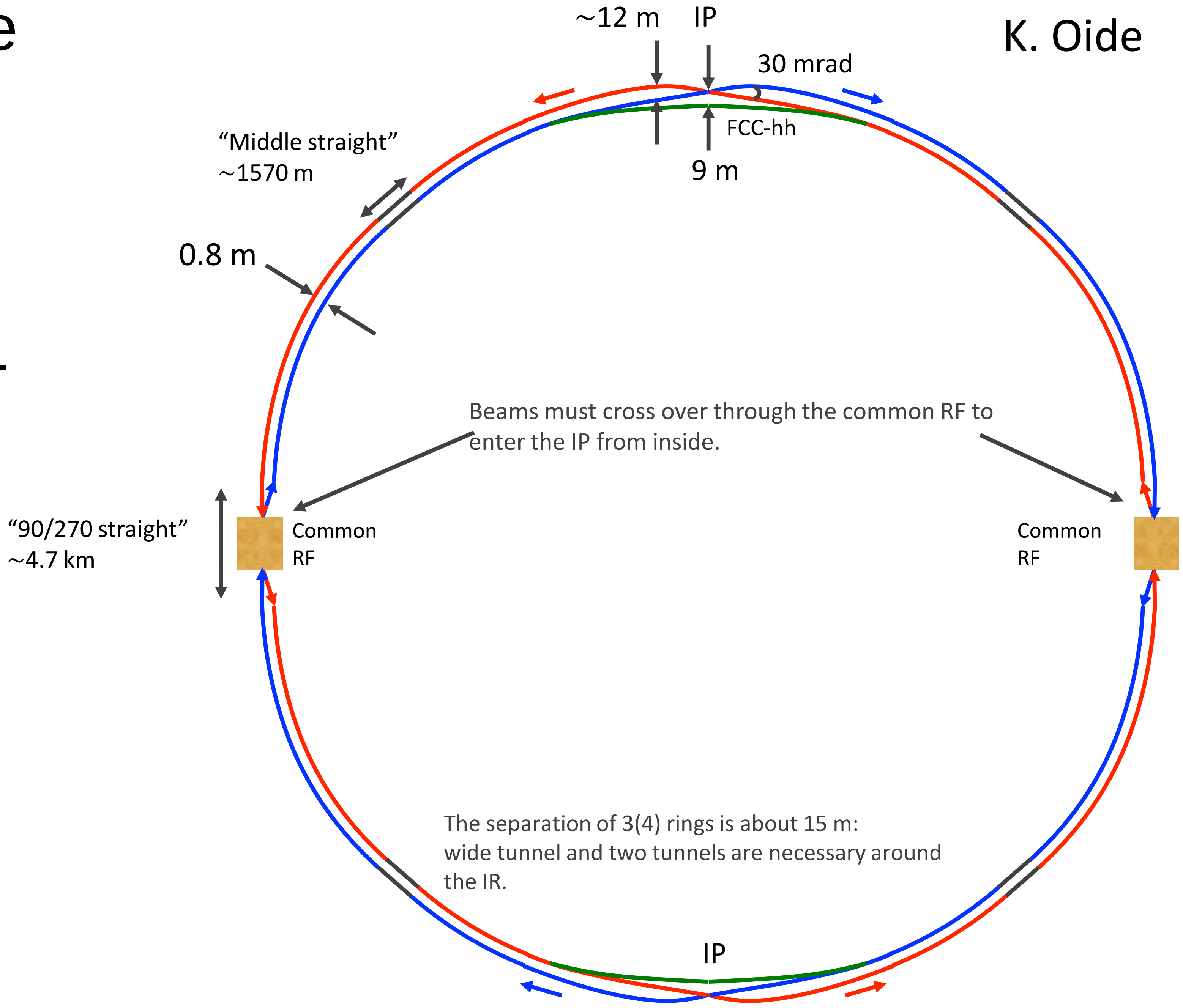
9 m off-centred IPs wrt. hh IPs

As the separation of 3(4) rings is within 15 m, one wide tunnel may be possible around the IR.

Closed optics solutions for full ring for both machines available

FCC-ee layouts with space for booster

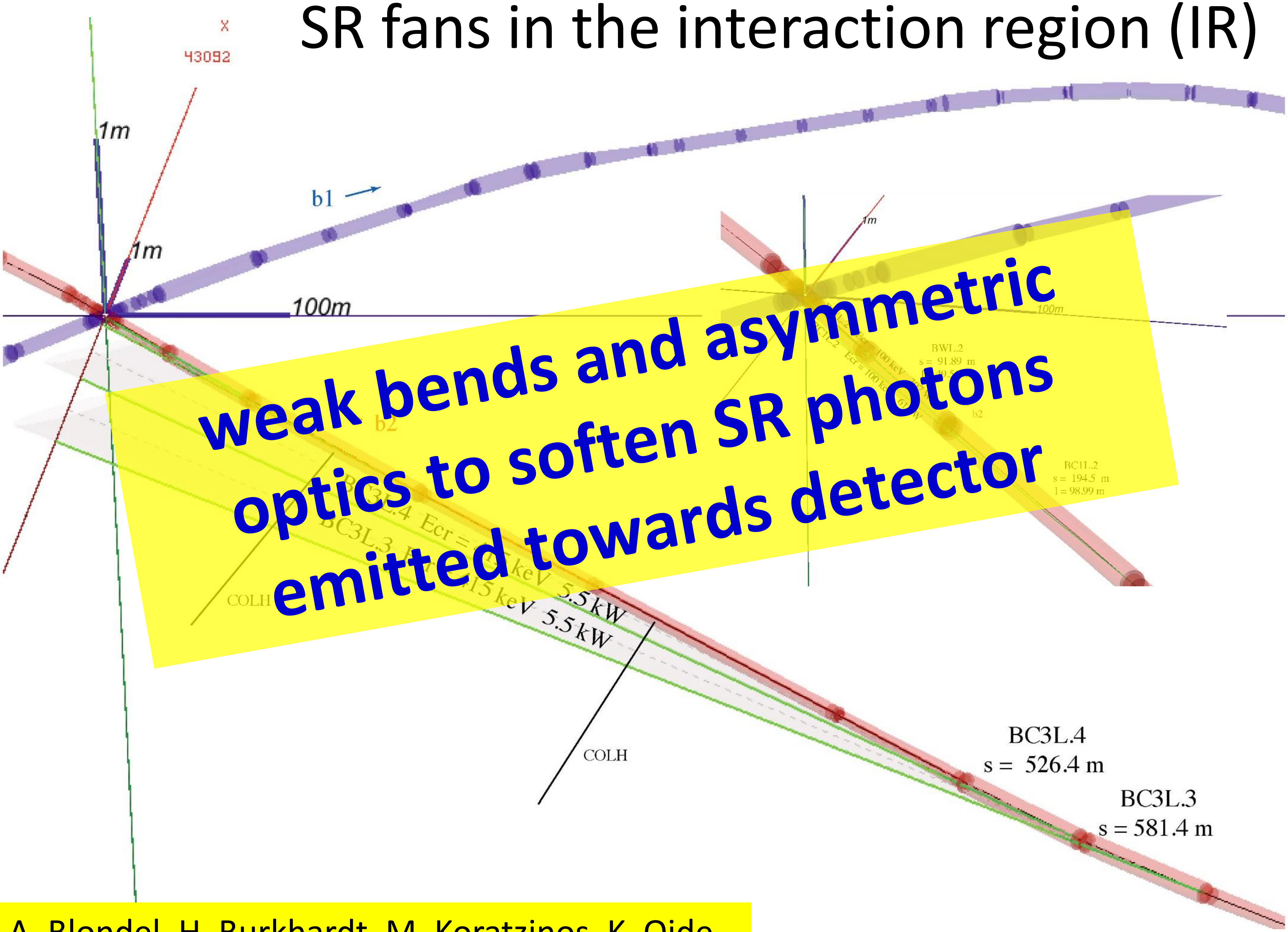
K. Oide



Beams must cross over through the common RF to enter the IP from inside.

The separation of 3(4) rings is about 15 m:
wide tunnel and two tunnels are necessary around the IR.

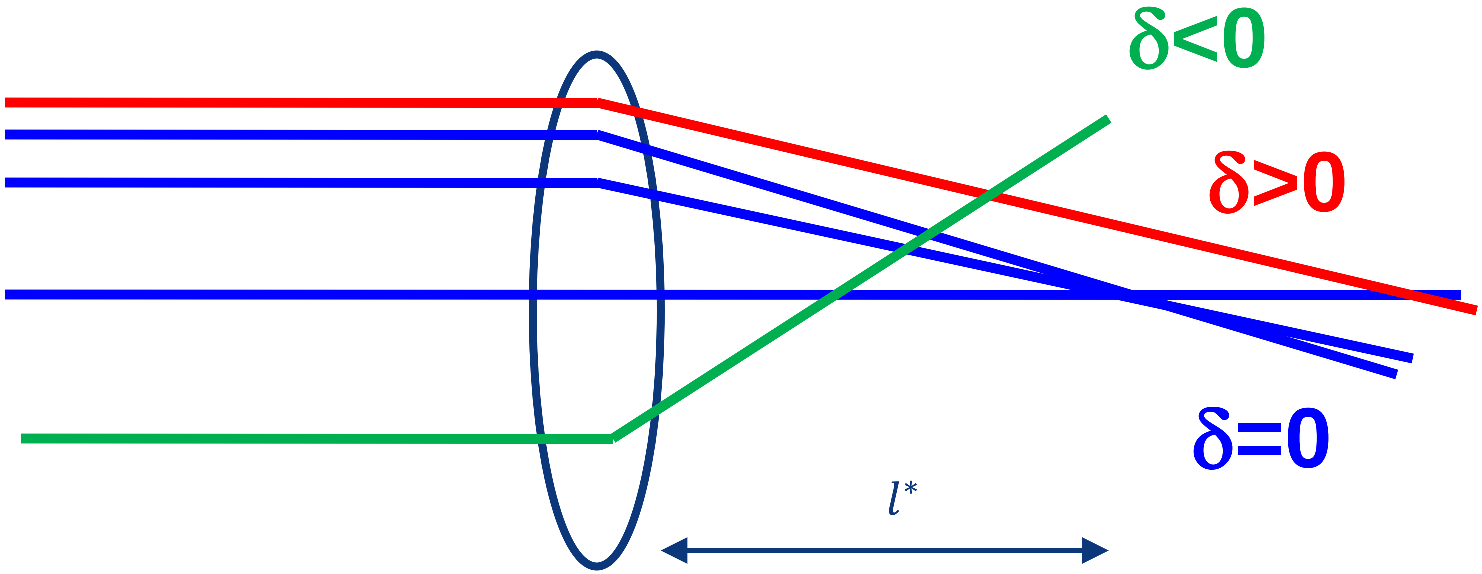
SR fans in the interaction region (IR)



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

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

final focus chromaticity



spot size increase due to (uncorrected) chromaticity,

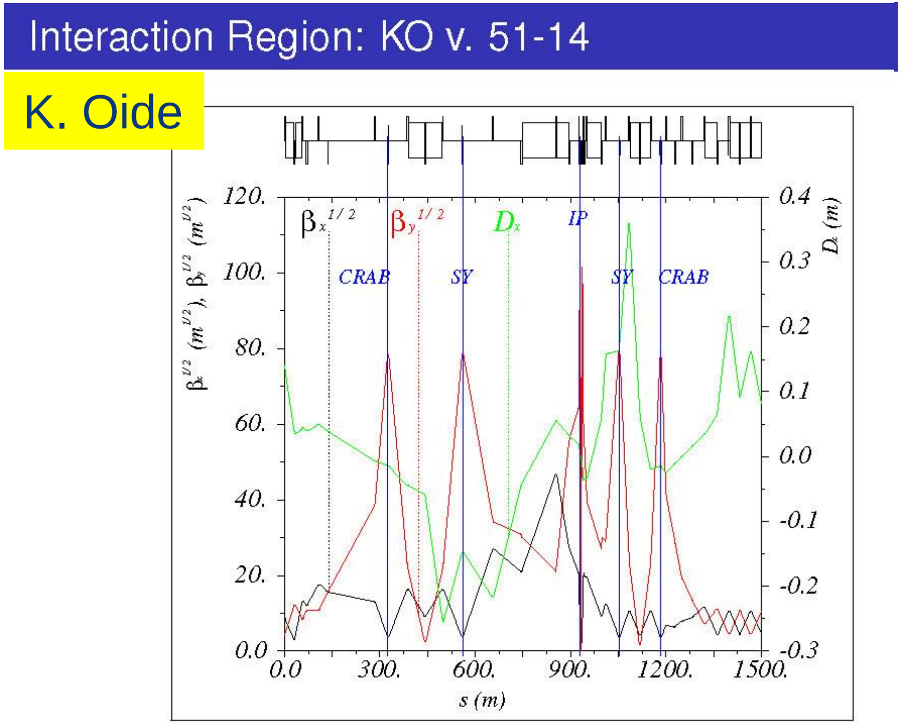
$$\frac{\Delta\sigma_y^*}{\sigma_{y0}^*} = \xi\delta_{rms}$$

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

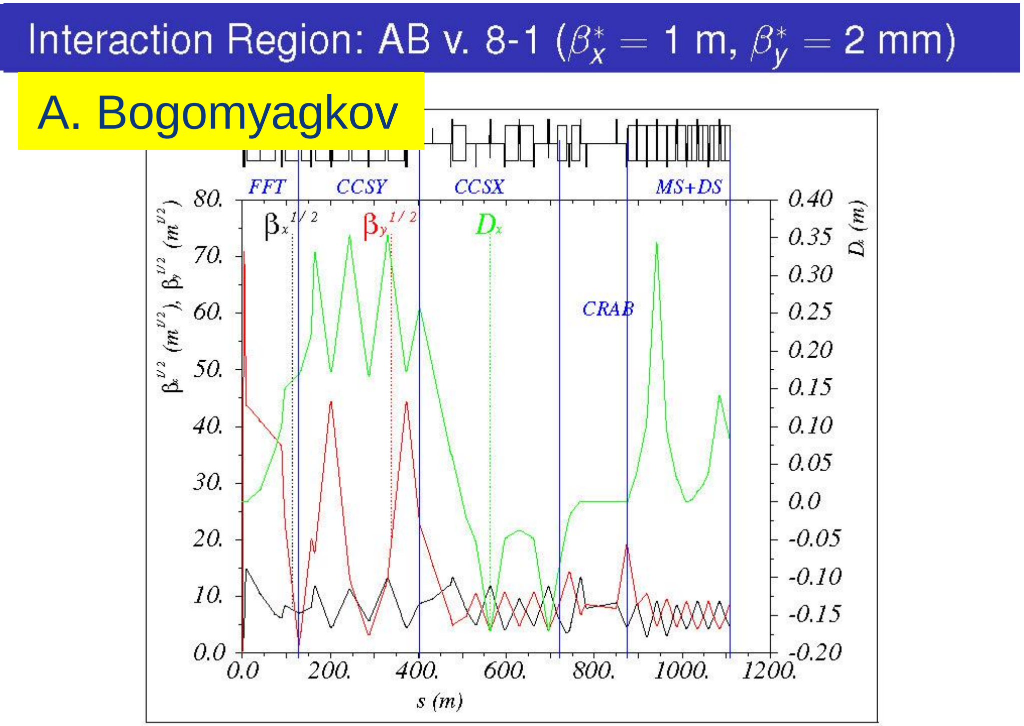
FCC-ee IR optics – two variants

with required momentum acceptance and dynamic aperture

both feature crab waist optics & local chromatic correction

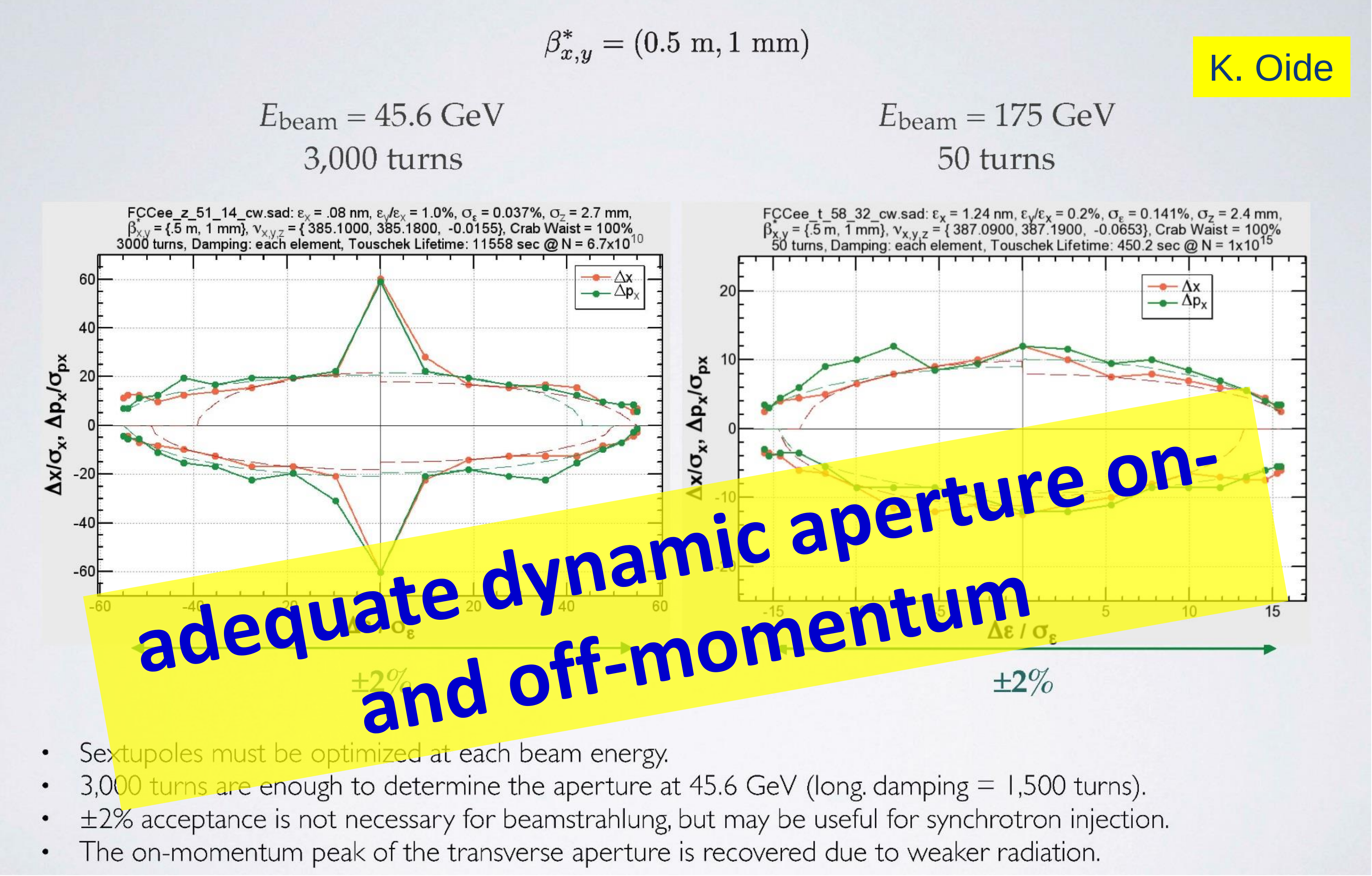


synchroton radiation $E_{\gamma,c} \leq 100$ keV, 2 sextupoles: vert. chromatic correction + “virtual” crab waist



synchrotron radiation $E_{\gamma,c} \leq 400$ keV, 5 sextupoles: hor.+ vert. chromatic correction + crab waist

dynamic aperture



K. Oide

$$\beta^*_{x,y} = (0.5\ \mathrm{m}, 1\ \mathrm{mm})$$

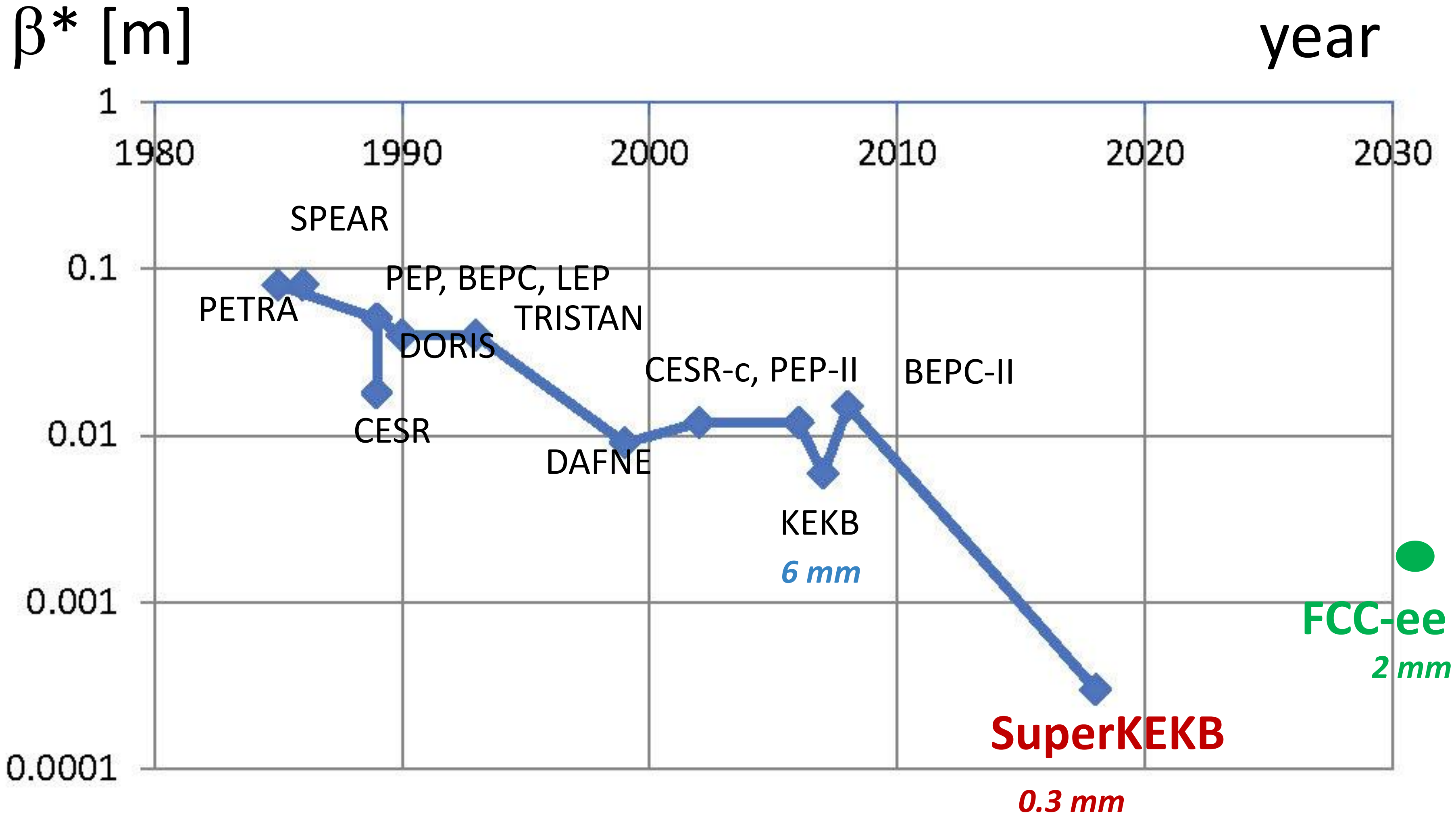
$E_\mathrm{beam} = 45.6$ GeV
3,000 turns

$E_\mathrm{beam} = 175$ GeV
50 turns

adequate dynamic aperture on- and off-momentum

- Sextupoles must be optimized at each beam energy.
- 3,000 turns are enough to determine the aperture at 45.6 GeV (long. damping = 1,500 turns).
- ±2% acceptance is not necessary for beamstrahlung, but may be useful for synchrotron injection.
- The on-momentum peak of the transverse aperture is recovered due to weaker radiation.

β_y^* evolution over 40 years



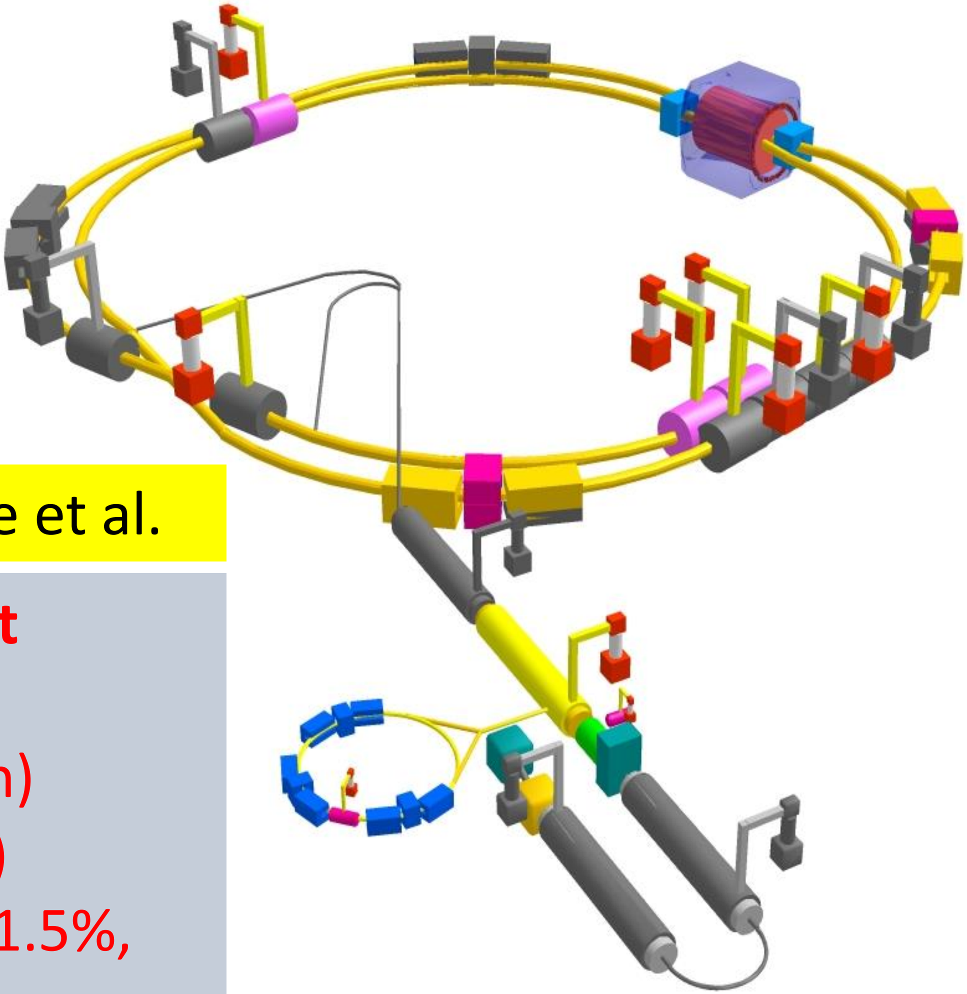
entering a new regime for ring colliders –
SuperKEKB will pave the way towards $\beta^* \leq 2$ mm

SuperKEKB: extremely low β*

I_{e+}=3.6 A, I_{e-}=2.6 A

P_{SR} ~ 13 MW
C = 3 km

beam commissioning starting this year



K. Oide et al.

top up injection at high current
β_y* =300 μm (FCC-ee: 1 mm)
lifetime 5 min (FCC-ee: ≥20 min)
$\varepsilon_y/\varepsilon_x$ =0.25% (similar to FCC-ee)
off momentum acceptance (±1.5%, similar to FCC-ee)
***e*⁺ production rate** (2.5x10^{12}/s, FCC-ee: <1.5x10^{12}/s (*Z* cr.waist)

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

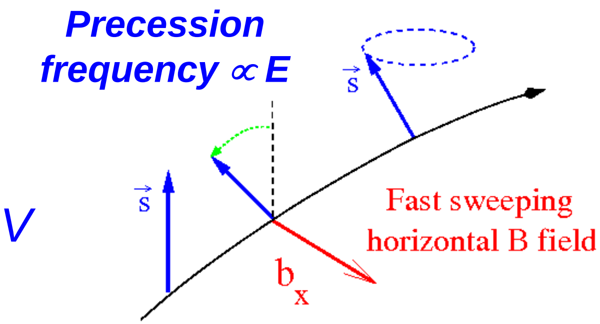
polarization,
energy calibration,
and mono-chromatization

polarization

two primary interests:

accurate energy calibration using resonant depolarization ⇒ measurement of M_Z, Γ_Z, M_W

- *appealing feature – δM_Z, $\delta\Gamma_Z$ ~ 0.1 MeV, δM_W ~ 0.3 MeV*



physics with longitudinally polarized beams

- *transverse polarization must be rotated into the longitudinal plane using spin rotators (see e.g. HERA)*

scaling from LEP observations :

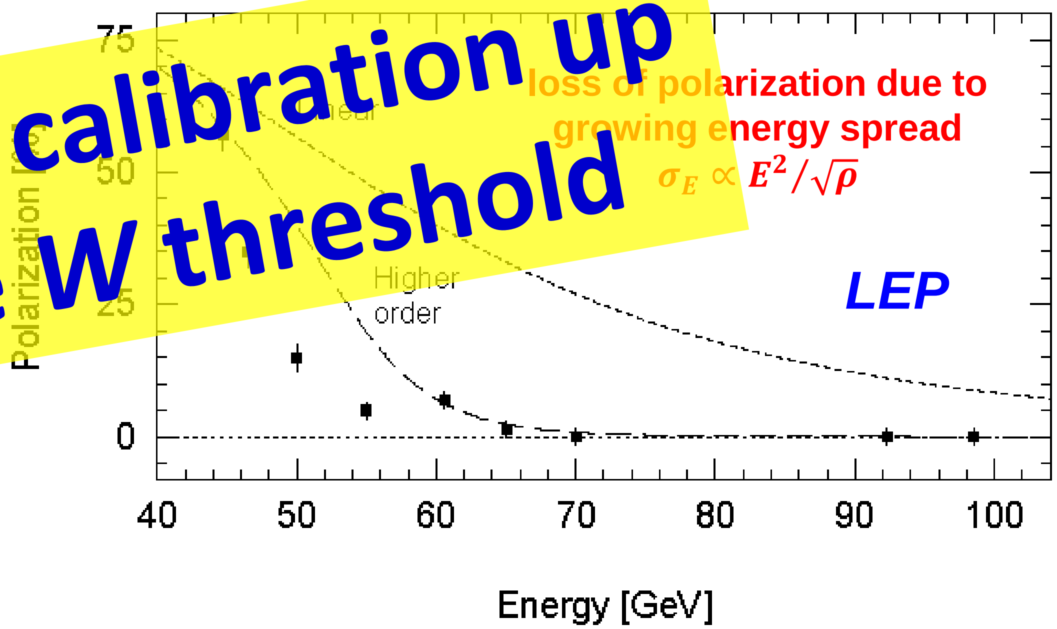
polarization expected up to the WW threshold !

LEP like calibration up to the W threshold

integer spin resonances are spaced by 440 MeV:

energy spread should remain below ~ 60 MeV

R. Assmann



A. Blondel, M. Koratzinos, S. Mane, U. Wienands, J. Wenninger,..

polarization build up

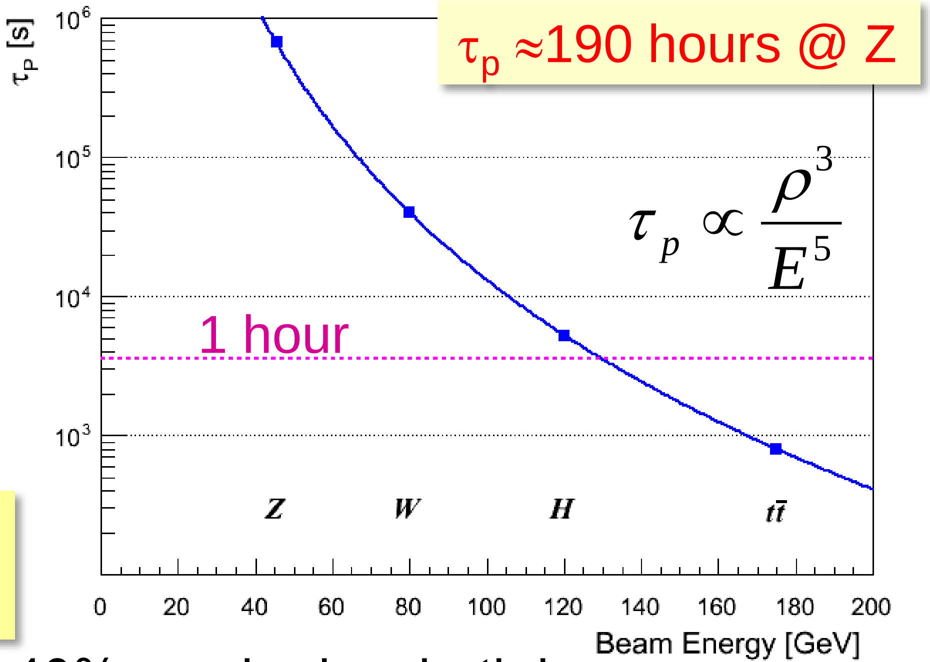
<u>transverse polarization</u> build-up (Sokolov-Ternov) is slow at *FCC-ee* (large bending radius ρ)

build-up is ~40 times slower than at LEP

wigglers may lower τ_p to ~12 h, limited by $\sigma_E \leq$ 60 MeV and power

due to power loss the wigglers can only be used to pre-polarize some bunches (before main injection)

≈ OK for energy calibration (few % P sufficient)



$\tau_p \approx$190 hours @ Z

$$\tau_p \propto \frac{\rho^3}{E^5}$$

<u>longitudinal polarization</u>: levels of ≥ 40% required on both beams; excellent resonant compensation needed

expected to be difficult, requires spin rotators or snakes, most likely only possible at lower intensity and luminosity

SLIM, PETROS, SITF etc. simulations

A. Blondel, U. Wienands,
E. Gianfelice, J. Jowett,
R. Rossmanith, J.Wenninger

energy calibration

at *Z* and *W:* frequent resonant-depolarization measurements with non-colliding bunches

- ✓ much better resolution than at LEP, few tens of keV
- ✓ measurement of energy spread?
- ✓ extrapolation from average to individual IPs
- ✓ OR: injecting polarized beam

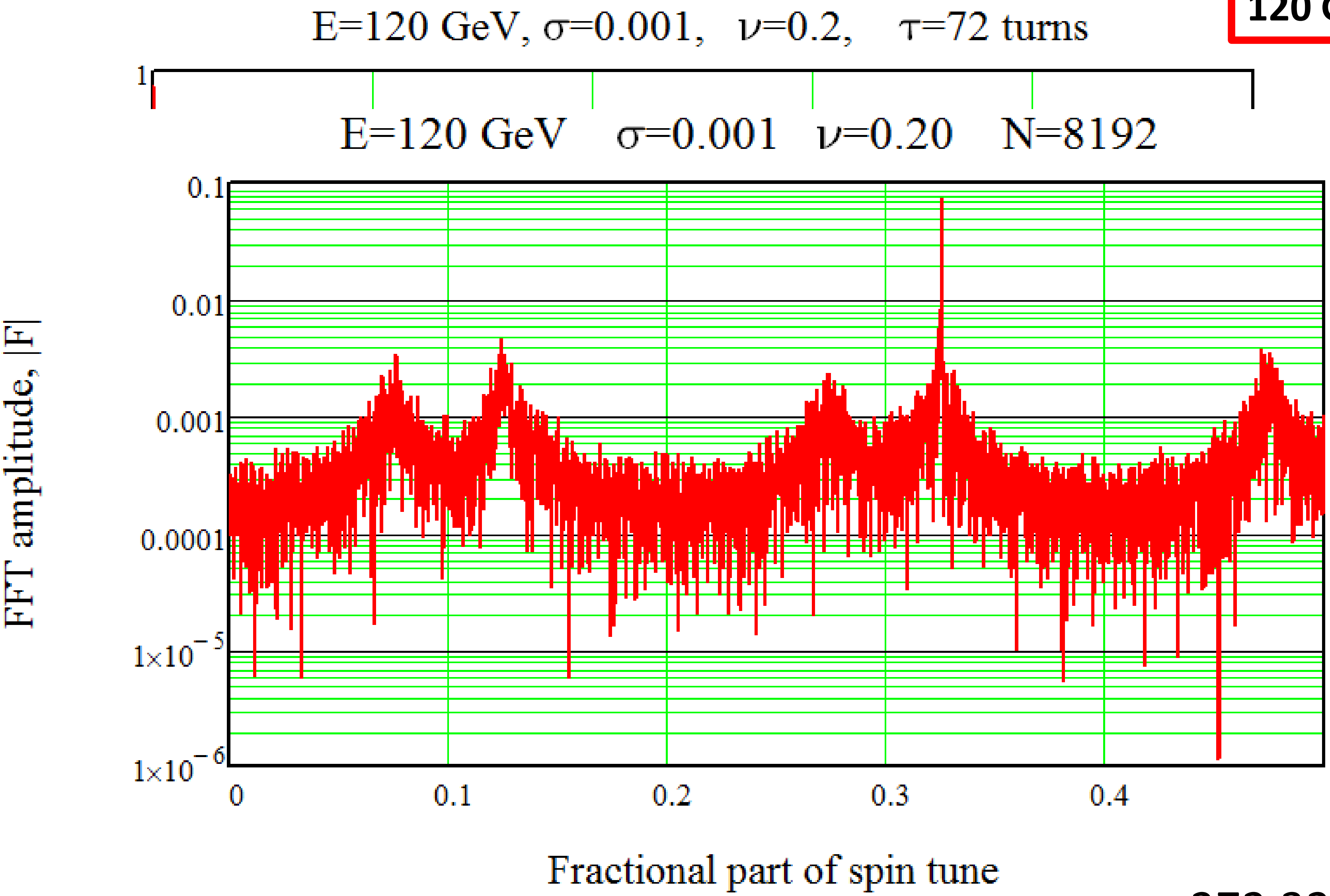
at higher energies, *H* and $t\bar{t}$:

- ✓ use physics measurements
- ✓ other? (laser back scattering / spectrometer?)
- ✓ OR: injecting polarized beam

A. Blondel, I. Koop, M. Koratzinos, N. Muchnoi, et al.

injecting polarized beam & free spin precession

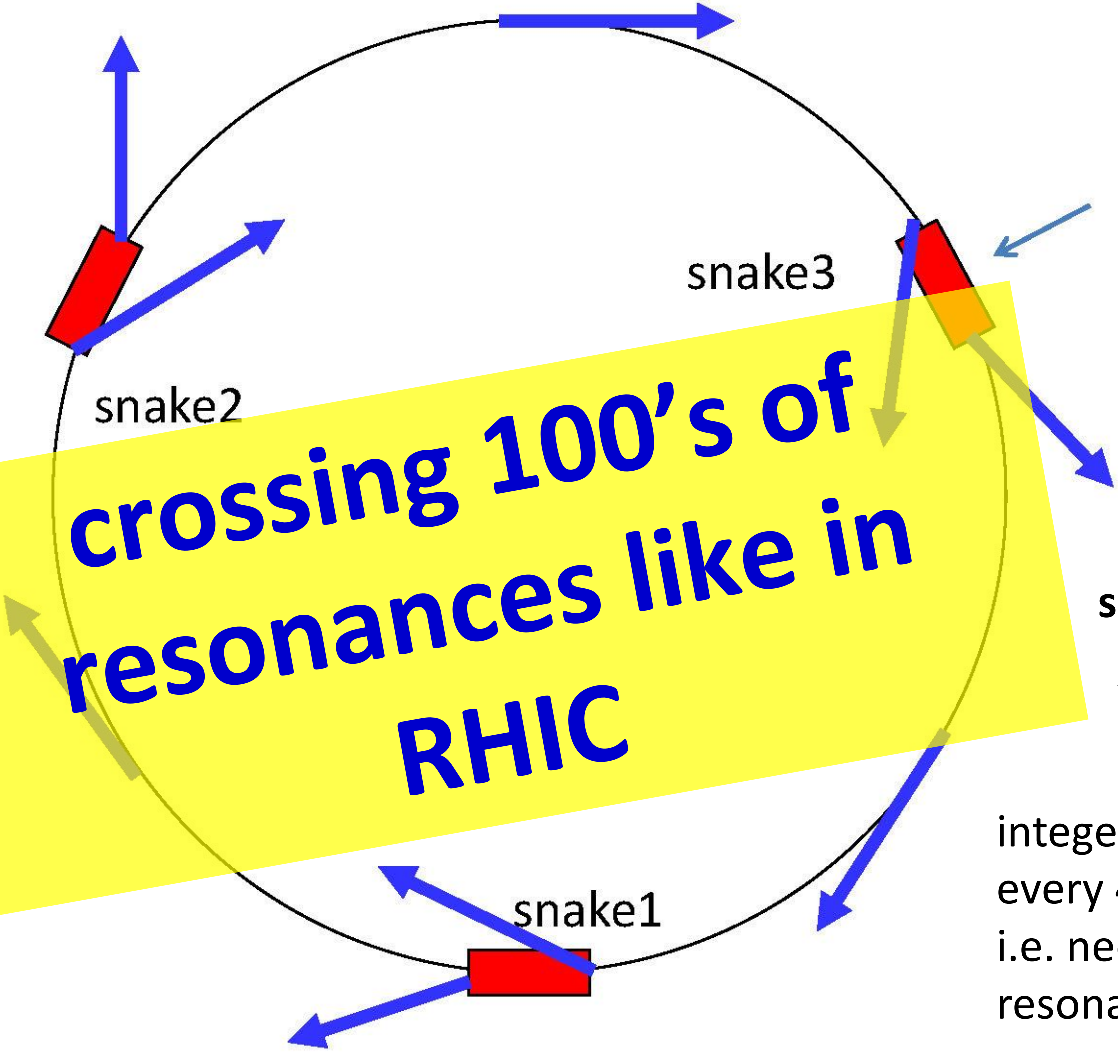
120 GeV



$\nu_0 = 272.325$

I. Koop

preserving polarization in the booster



crossing 100's of resonances like in RHIC

Spin rotation by 180^0 around the longitudinal axis

spin tune

$$\nu_s = \gamma \left(\frac{g-2}{2} \right)$$

integer spin resonances $n\nu_s=p$
every 440 MeV for e^-
i.e. need to cross about 400 resonances till 175 GeV;
every 520 MeV for p
e.g. about 500 resonance crossings for RHIC 250–GeV p's

I. Koop

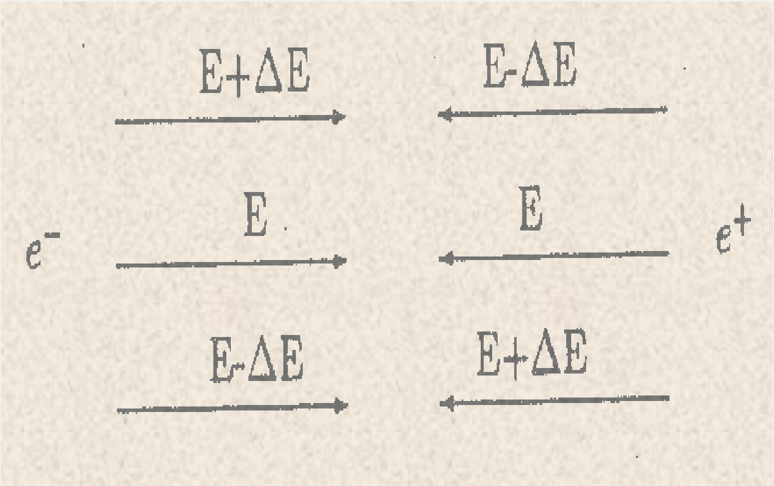
mono-chromatization at 2x63 GeV?

direct *s* channel Higgs production $e^+e^- \rightarrow H$

rms beam energy spread at 63 GeV ~30 MeV
total width of SM Higgs Γ ~ 4 MeV

effective collision energy spread is decreased by introducing opposite-sign IP dispersion

$$\frac{\sigma_W}{W} = \sqrt{\frac{2\varepsilon_x}{\left(\frac{{D^*_x}^2}{\beta^*_x} + \frac{\varepsilon_x}{{\sigma_\epsilon}^2}\right)}}$$



first proposed by A. Renieri (1975); historical studies for VEPP4, SPEAR, LEP, τ-c factory;never tested experimentally

reducing cm energy spread x1/10 w/o loss of luminosity?!
implementation for crab-waist scheme?

summary

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

FCC-ee

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

baseline **luminosity performance predicted w confidence**; further increases possible

optics footprint matched to the hadron collider layout

FCC-ee would bring the **tunnel**, the **infrastructure**, the **time** needed for high-field magnet production, and possibly also an even stronger **physics motivation** (and precise target energy) **for FCC-hh**

“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.”

B. Richter, 1976

NIM 136 (1976) 47-60

…surely great times ahead!

spare slides

chromaticity in selected FF systems

project	status	β_y^* [mm]	l^*[m]	l^*/β_y^*	σ_y^* [nm]
LEP	measured	50	3.7	74	3200
LHC	measured	600	23	38	16000
KEKB	measured	6.0	2.4	400	940
FCC-hh	**design**	**1100**	**46**	**42**	**7000**
S-KEKB	**design**	**0.3**	**1.5**	**5000**	**50**
FCC-ee	**design**	**2.0**	**2.2**	**1100**	**50**
CepC	**design**	**1.2**	**1.5**	**1250**	**150**
SLC	measured	2.0	2.2	1100	500
FFTB	measured	0.167	0.4	2400	70
ATF2	measured	0.1	1.0	10000	~40
ILC	**design**	**0.4**	**3.5**	**8750**	**6**
CLIC	**design**	**0.09**	**3.5**	**39000**	**1**

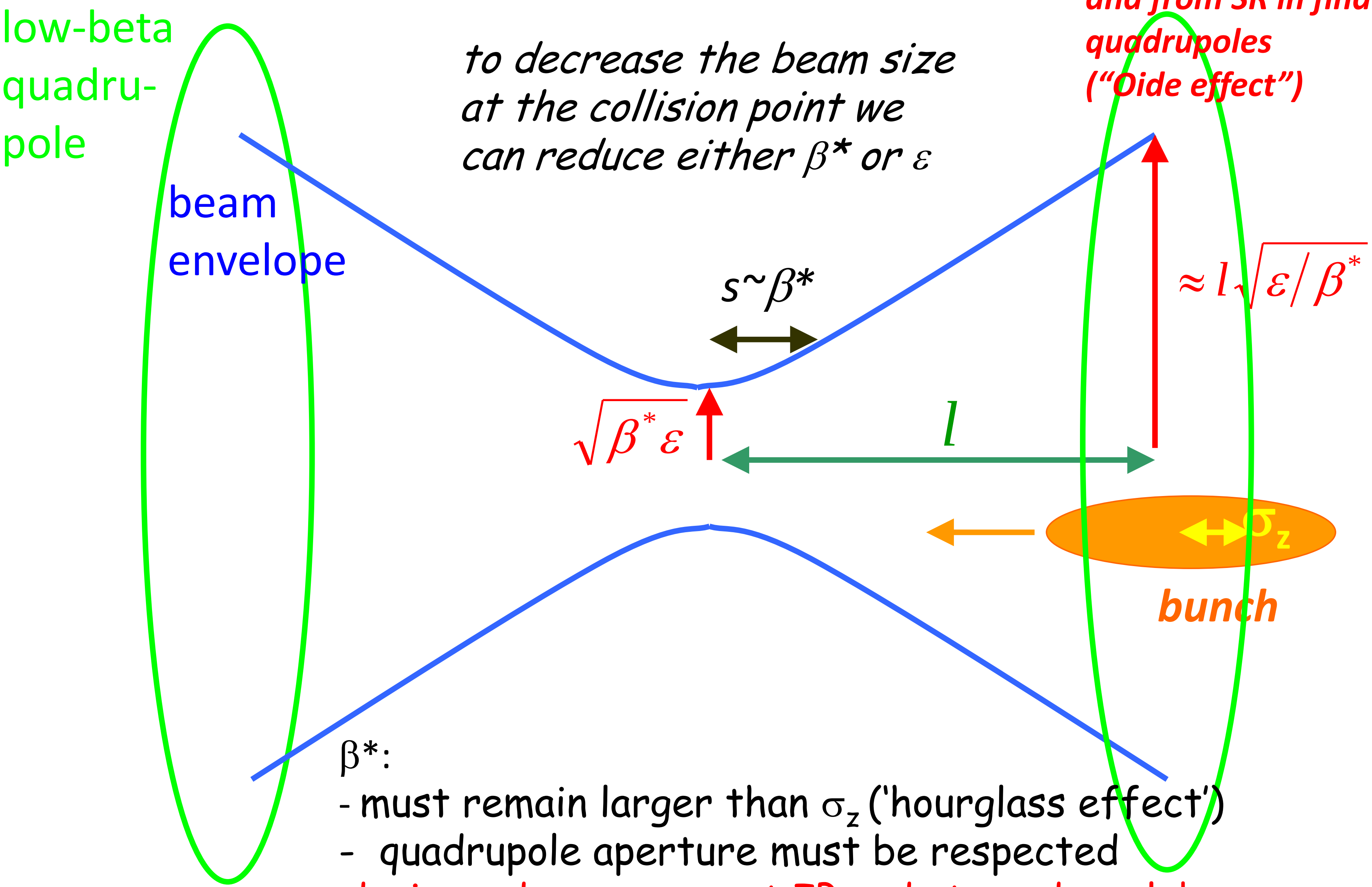
circular

linear

limits on collider spot size

other limits from beam-beam effects and from SR in final quadrupoles ("Oide effect")

to decrease the beam size at the collision point we can reduce either β^* or ε



β^*:

- must remain larger than σ_z ('hourglass effect')
- quadrupole aperture must be respected

reducing ε decreases σ at IP and at quadrupole!

coherent synchrotron radiation (CSR)?

at wave lengths $\lambda > 2\pi\sigma_z \sim 0.012\ \mathrm{m}\ \left(\mathrm{or}\ E_\gamma < 0.1\ \mathrm{meV}\right)$
all e^- in an FCC-ee bunch could radiate coherently

$$P_{SR,coh} \approx N_b P_{SR}$$

at smaller wave lengths still portions of the bunch could radiate coherently ("microbunching instability")

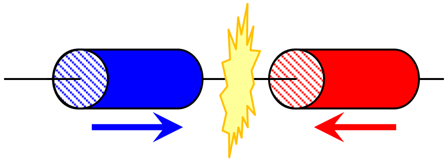
large bending radius and vacuum chamber suppress CSR effects

FCC-ee vacuum chamber (full width *w*, height *h ~6 cm*)

suppresses radiation at* $\lambda > 2\sqrt{\frac{h^2 w}{\rho}} \approx 0.00028\ \mathrm{m}$
$\left(\mathrm{or}\ E_\gamma < 4\ \mathrm{meV}\right)$

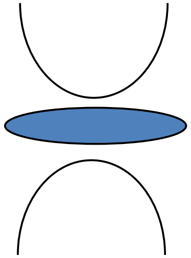
*Y. Derbenev et al., DESY TESLA FEL 95-05, 1995

luminosity scaling: larger *E* & ρ



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

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

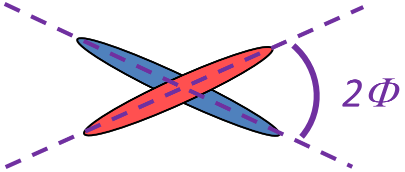


H ≤ 1

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

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

σ = beam size

k = no. bunches

f = rev. frequency

N = bunch population

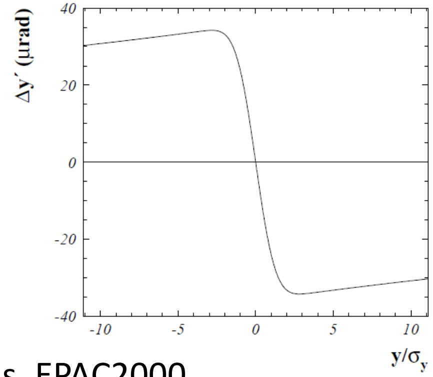
P_{SR} = synch. rad. power

β^* = betatron fct at IP (beam envelope)

J. Wenninger

luminosity scaling: damping

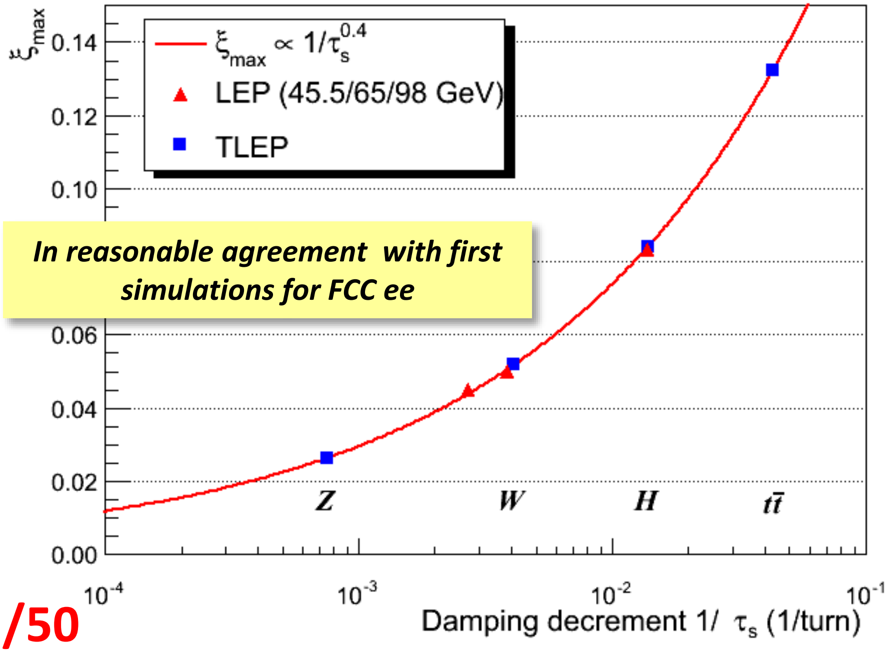
- beam-beam parameter ξ measures strength of field sensed by the particles in a collision
- beam-beam parameter limits are empirically scaled from LEP data (4 IPs)



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

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

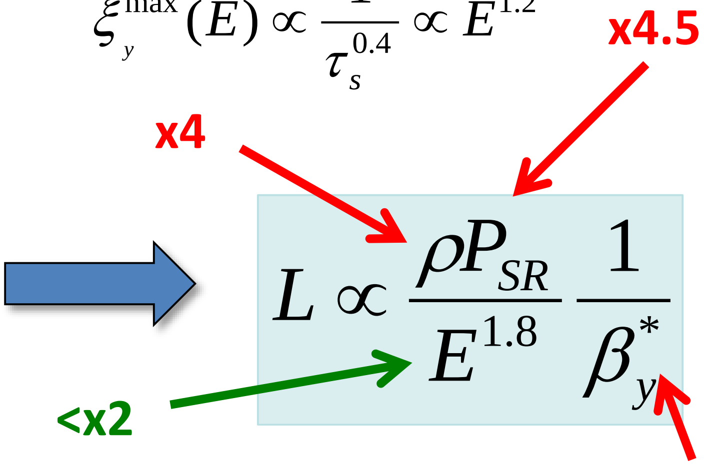
R. Assmann & K. Cornelis, EPAC2000



In reasonable agreement with first simulations for FCC ee

FCC-ee

vs LEP



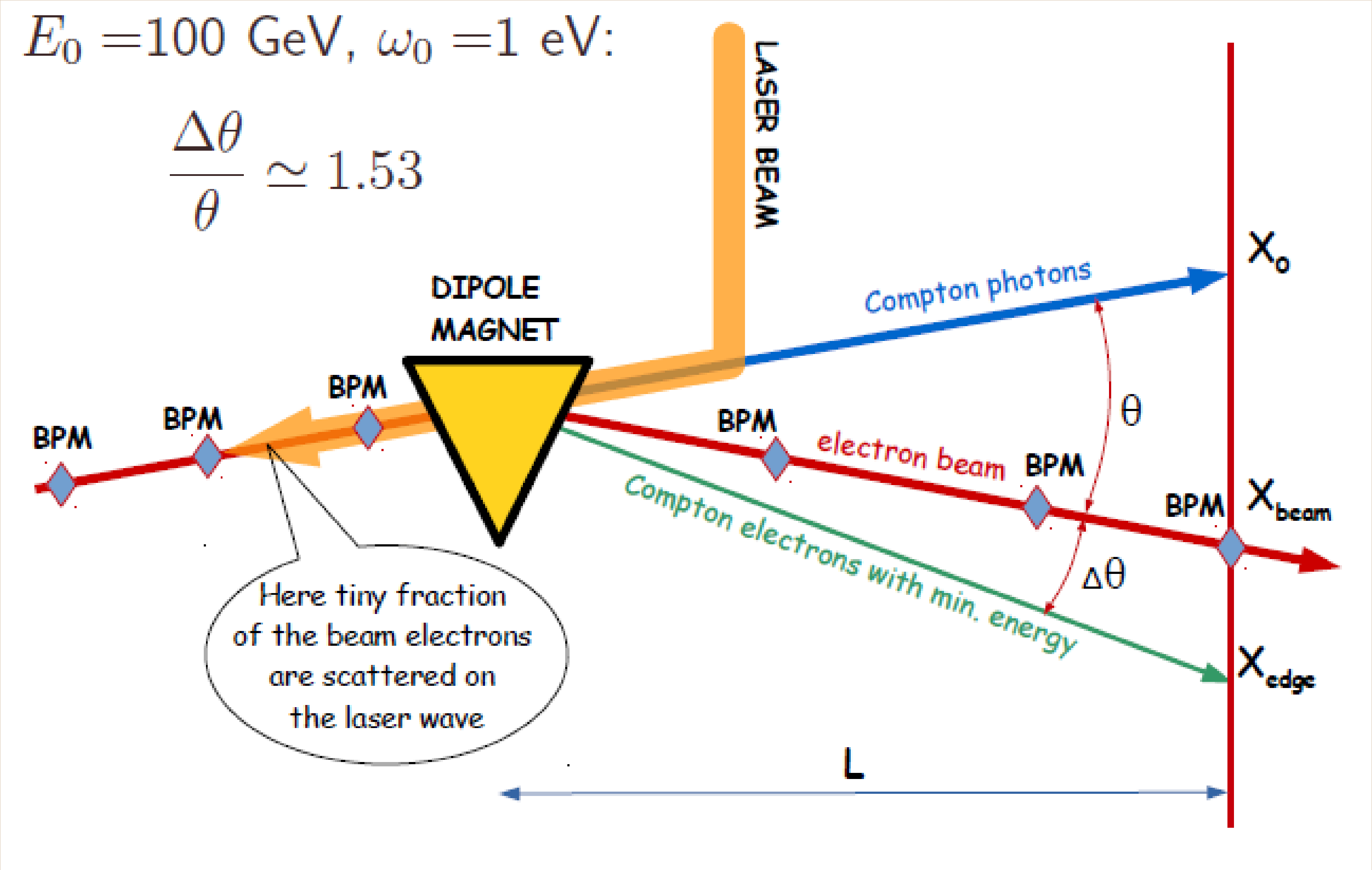
$$L \propto \frac{\rho P_{SR}}{E^{1.8}} \frac{1}{\beta_y^*}$$

x1/25-1/50

→ extremely high luminosity

J. Wenninger, R. Assmann, S. White, K. Ohmi, D. Shatilov, et al.

spectrometer with Compton scattering



$E_0 = 100$ GeV, $\omega_0 = 1$ eV:

$$\frac{\Delta\theta}{\theta} \simeq 1.53$$

Access to the beam energy: $E_0 = \dfrac{\Delta\theta}{\theta} \times \dfrac{m^2}{4\omega_0}$

Nikolai Muchnoi