FCC-ee Machine Status

Frank Zimmermann *for the FCC team*

FCC Week 2015, Washington DC, 23 March 2015

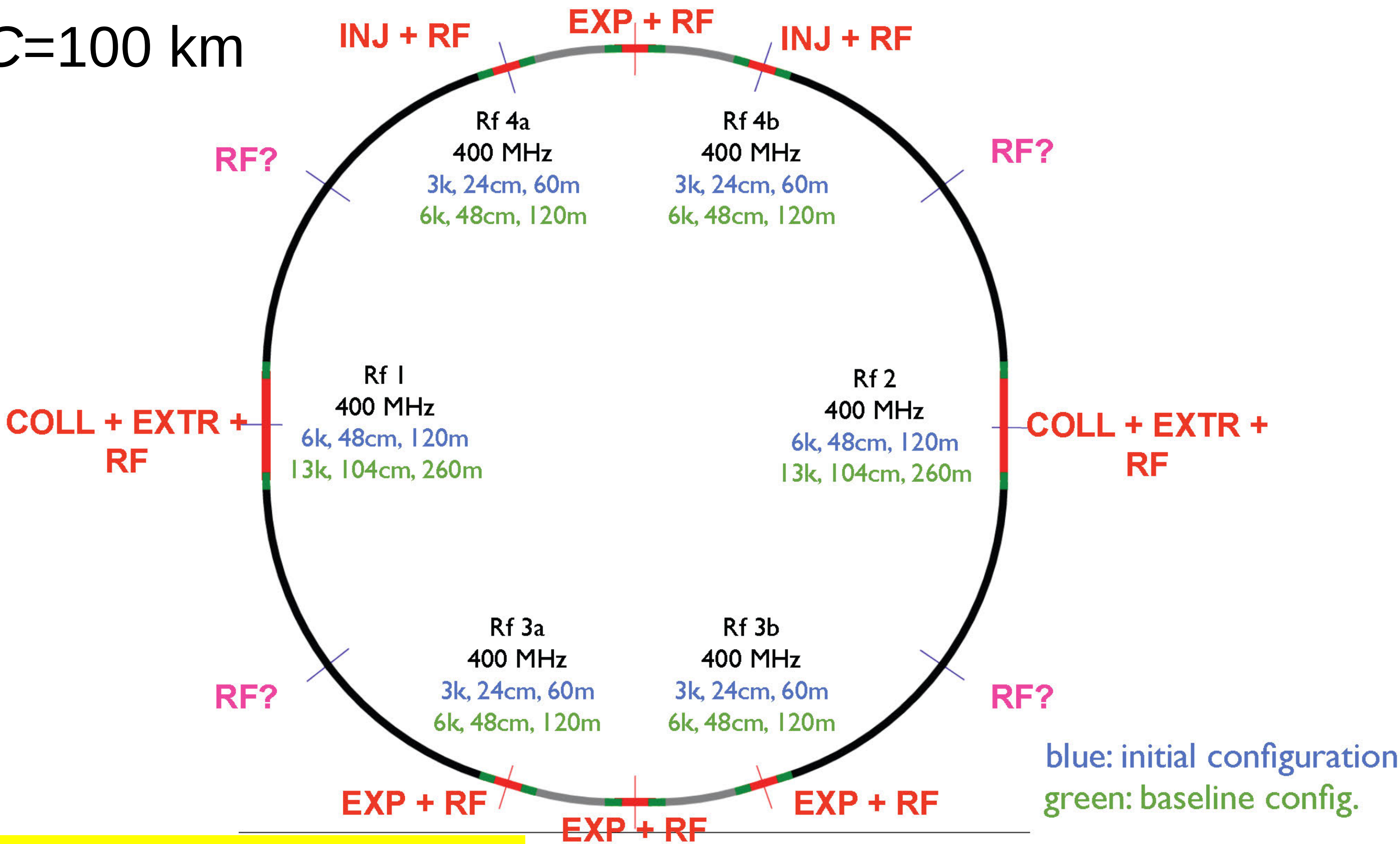
Contributions from Masamitsu Aiba, Ralph Assmann, Mei Bai, Michael Benedikt, Alain Blondel, Anton Bogomyagkov, Manuela Boscolo, Luca Bottura, Olivier Brunner, Helmut Burkhardt, Andy Butterworth, Yunhai Cai, Rama Calga, Francesco Cerutti, Angeles Faus-Golfe, Kazuro Furukawa, Eliana Gianfelice, Bastian Haerer, Bernhard Holzer, Patrick Janot, Erk Jensen, Miguel Jimenez, Roberto Kersevan, Ivan Koop, Mike Koratzinos, Luisella Lari, Philippe Lebrun, Eugene Levichev, Roman Martin, Luis Medina, Mauro Migliorati, Kazuhito Ohmi, Katsunobu Oide, John Osborne, Yannis Papaphilippou, Pavel Piminov, John Seeman, Yurij Senichev, Dmitry Shatilov, Mike Sullivan, Valery Telnov, Rogelio Tomas, Jörg Wenninger, Uli Wienands, Mikhail Zobov, … and many others

physics requirements for *FCC-ee*

- highest possible luminosity
- *beam energy range from 45 GeV to 175 GeV*
- main 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*
- some polarization up to ≥80 GeV for beam energy calibration
- optimized for operation at 120 GeV?! (2nd priority "*Tera-Z*")

FCC-ee preliminary layout

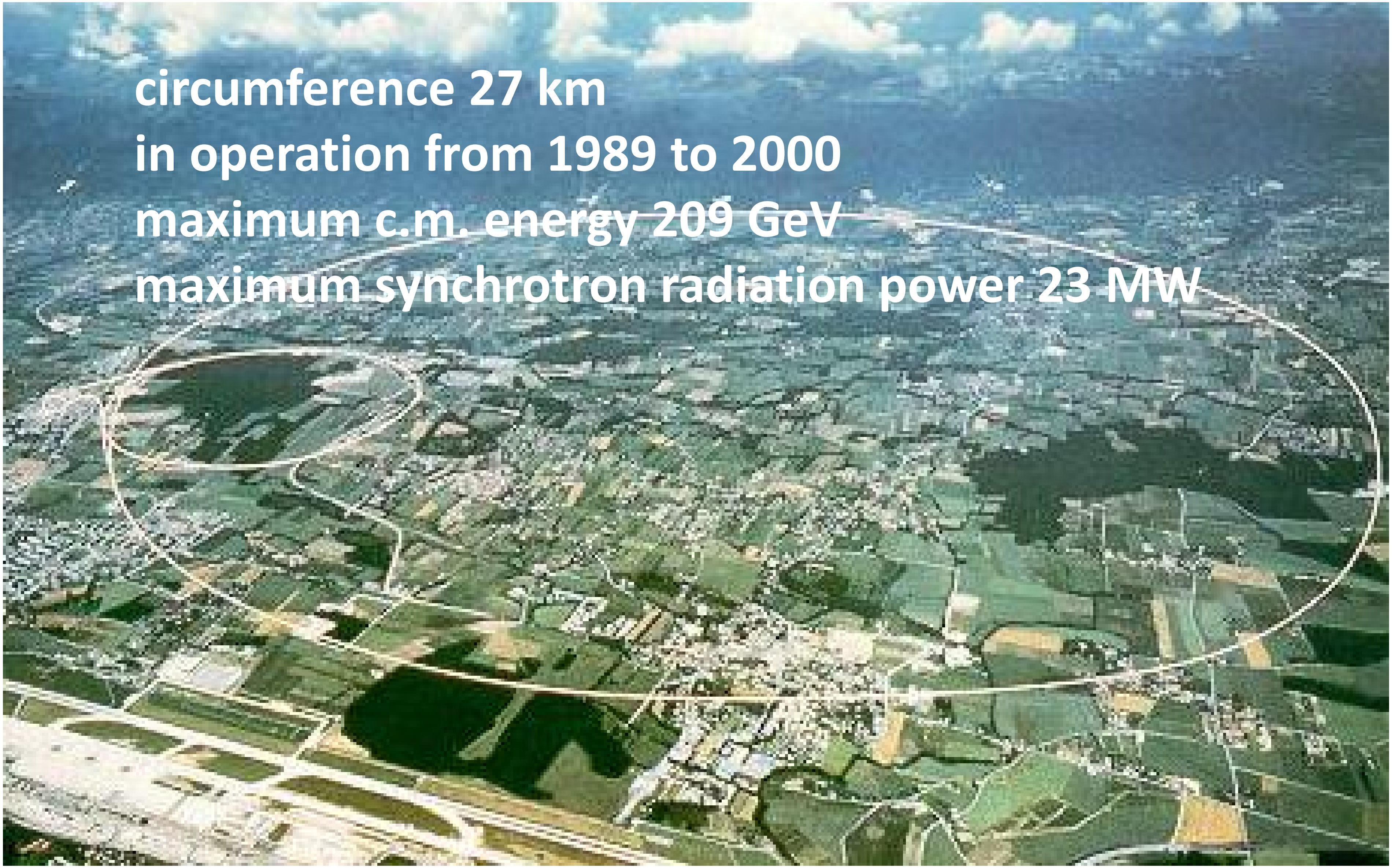
C=100 km



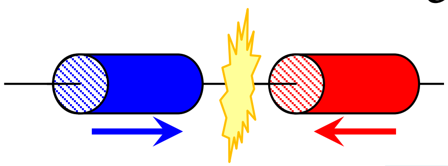
P. Lebrun, J. Osborne,
D. Schulte, U. Wienands

- ✓ consistent with *FCC-hh* layout
- ✓ RF staging scenario defined

LEP – highest energy e^+e^- collider so far

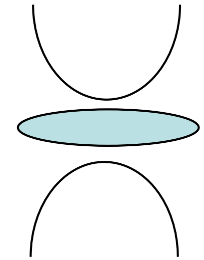


luminosity scaling: larger E & ρ



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

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

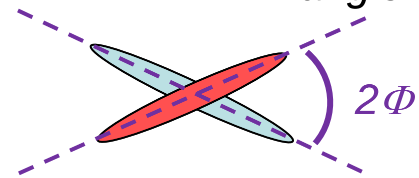


H ≤ 1

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

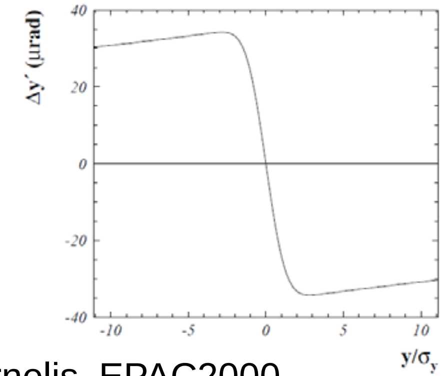
P_{SR} = synch. rad. power

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

J. Wenninger

luminosity scaling: damping

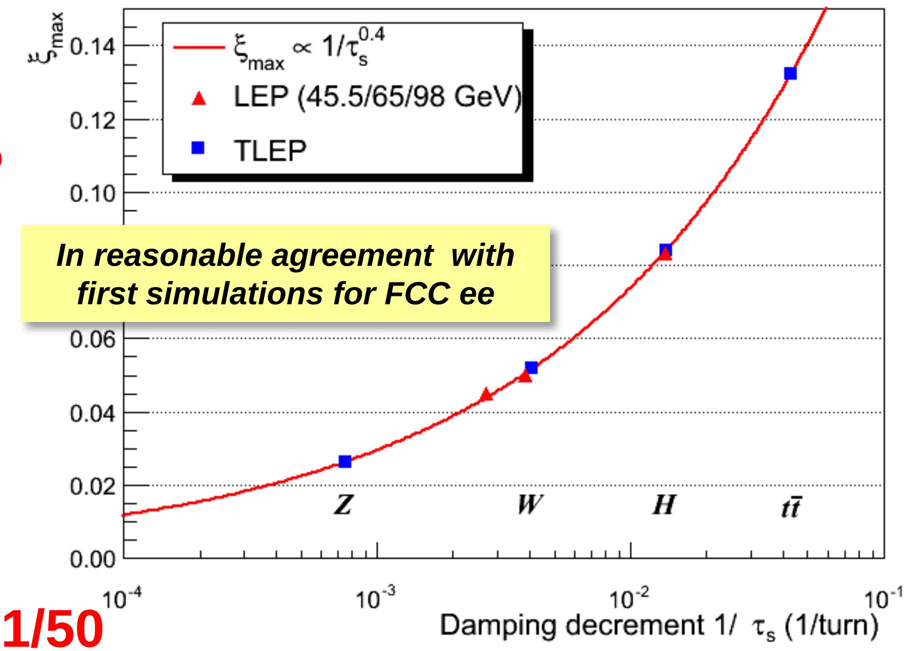
- beam-beam parameter ξ measures strength of field sensed by the particles in a collision
- beam-beam parameter limits are empirically scaled from LEP data (4 IPs)



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

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

R. Assmann & K. Cornelis, EPAC2000



FCC-ee vs LEP

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

x4

x4.5

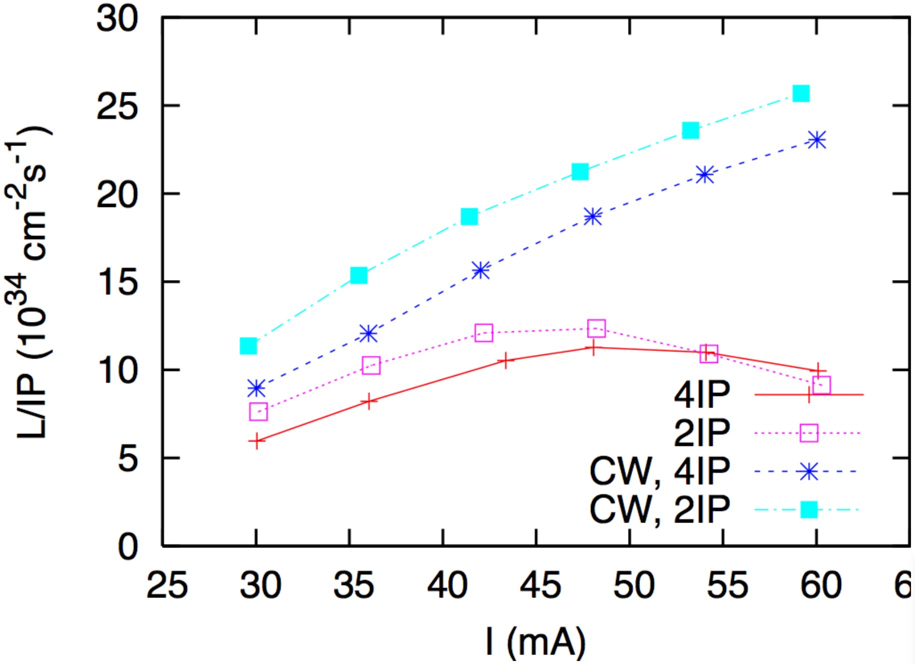
<x2

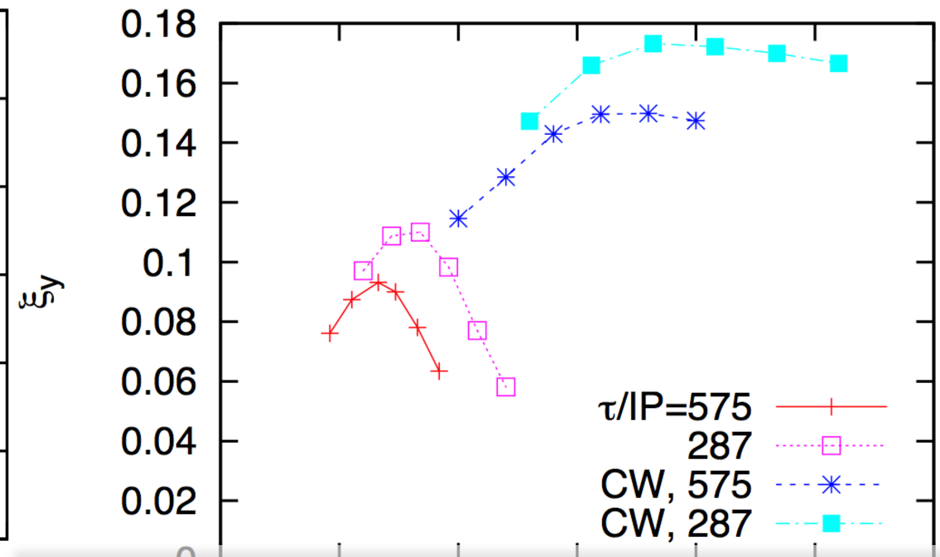
x1/50

→ **extremely high luminosity**

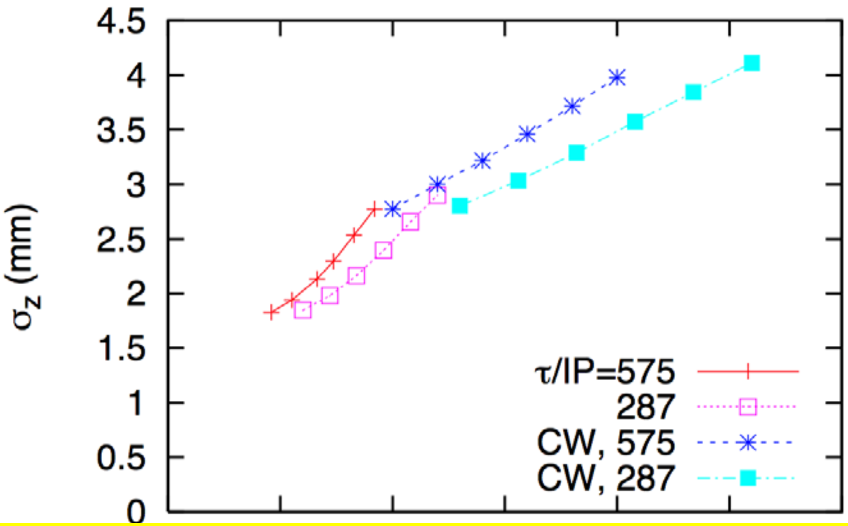
J. Wenninger, R. Assmann, S. White, K. Ohmi, D. Shatilov, et al.

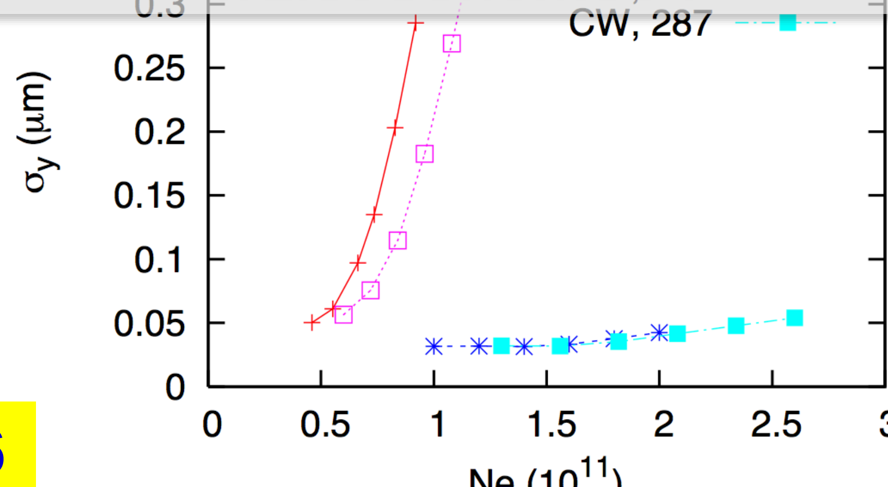
beam-beam simulations





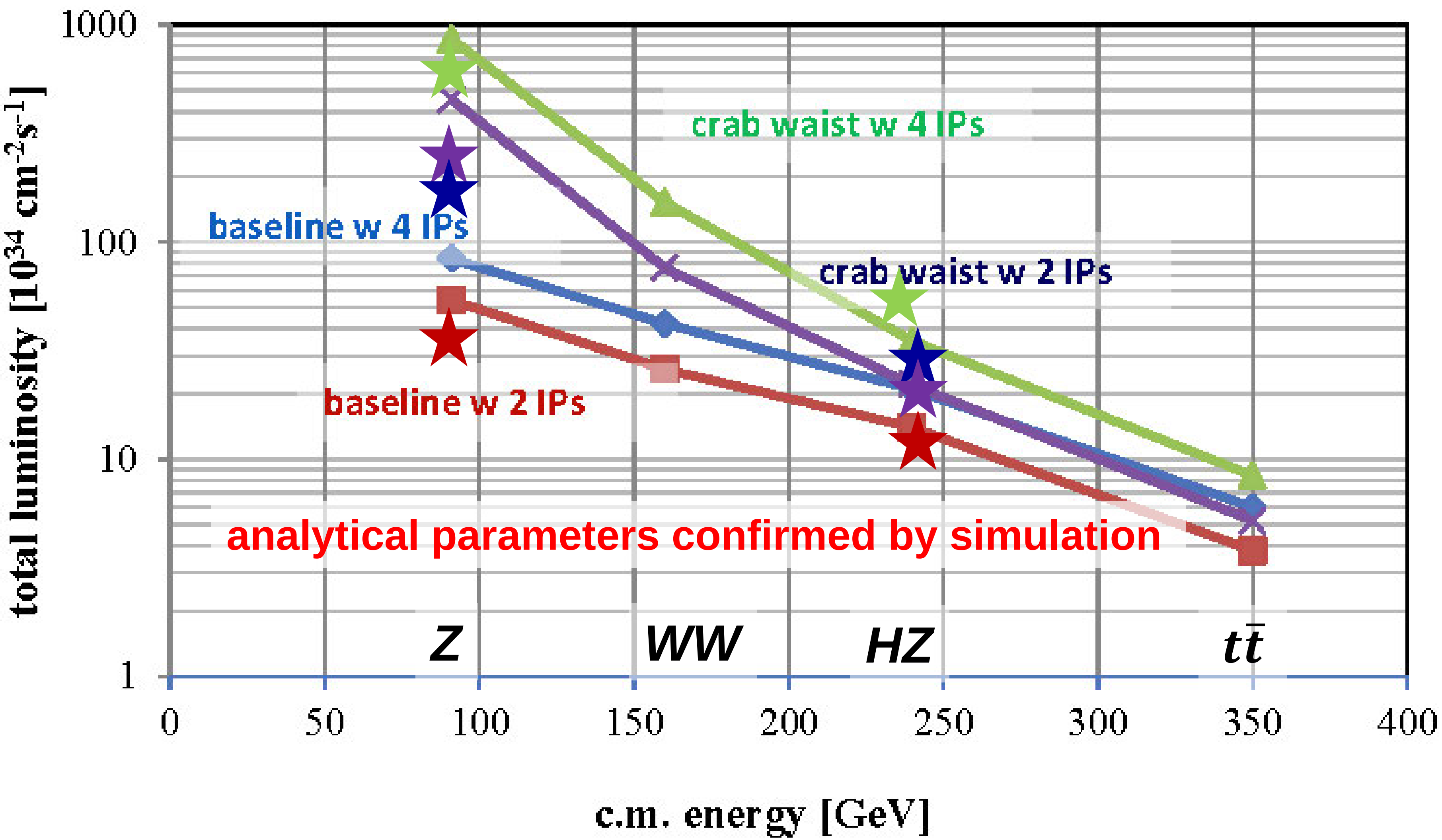
The beam-beam limit may further be raised with crab-waist schemes !





K. Ohmi, D. Shatilov, Wed., 11:36

luminosity vs c.m. energy



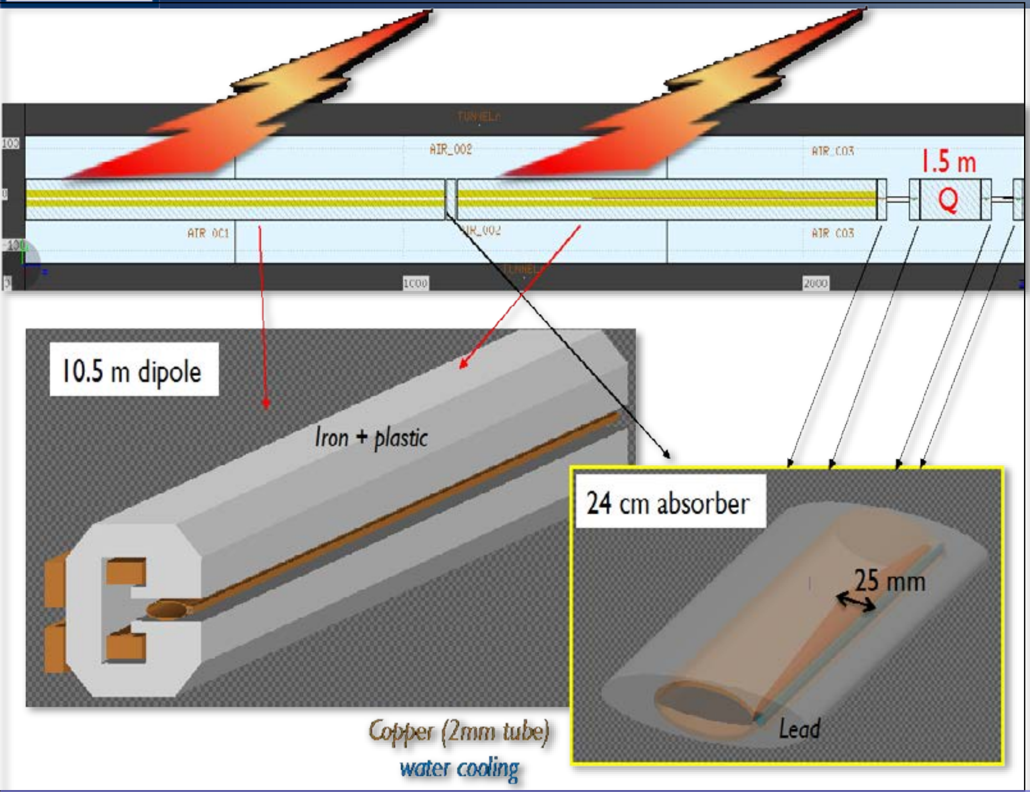
★ beam-beam simulations by K. Ohmi (tunes not optimized)

preliminary FCC-ee parameters

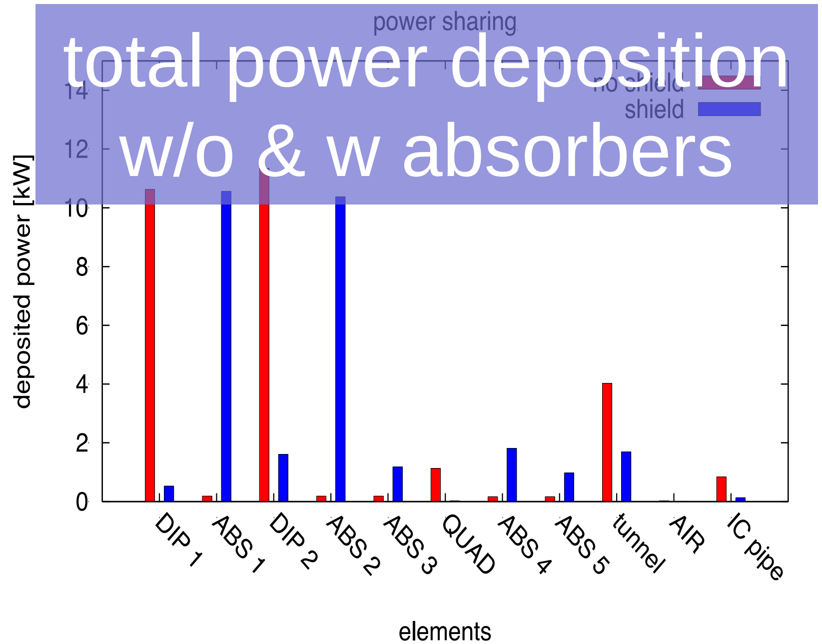
parameter	FCC-ee	LEP2
energy/beam	45 – 175 GeV	105 GeV
bunches/beam	**50 – 60000**	4
beam current	**6.6 – 1450 mA**	3 mA
hor. emittance	**~2 nm**	~22 nm
emittance ratio $\varepsilon_y/\varepsilon_y$	**0.1%**	1%
vert. IP beta function β_y^*	**1 mm**	50 mm
luminosity/IP	**1.5-280** x 10^{34} cm^{-2}s^{-1}	0.0012 x 10^{34} cm^{-2}s^{-1}
energy loss/turn	0.03-7.55 GeV	3.34 GeV
synchrotron radiation power	**100 MW**	23 MW
RF voltage	0.3 – **11 GV**	3.5 GV

- Large number of bunches at Z and WW and H requires **2 rings**.
- High luminosity means short beam lifetime (few mins) and requires continuous injection (**top up**).

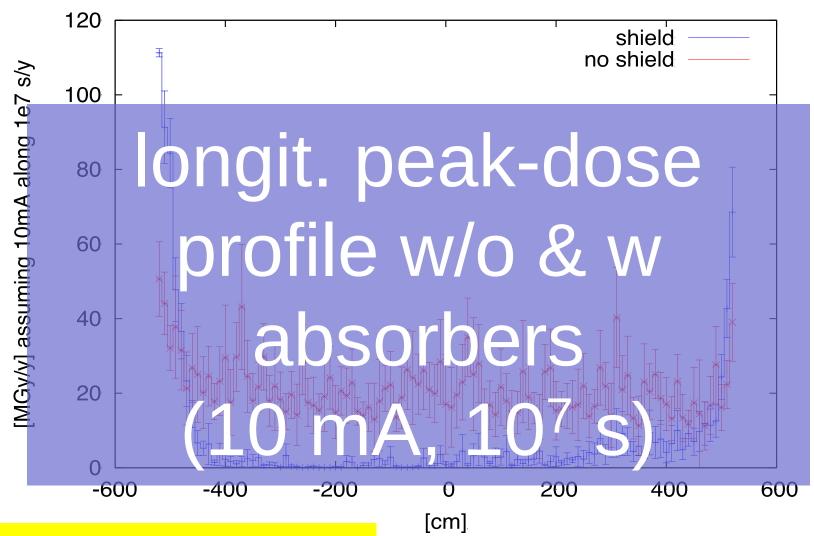
shielding 100 MW SR at 175 GeV



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



total power deposition w/o & w absorbers

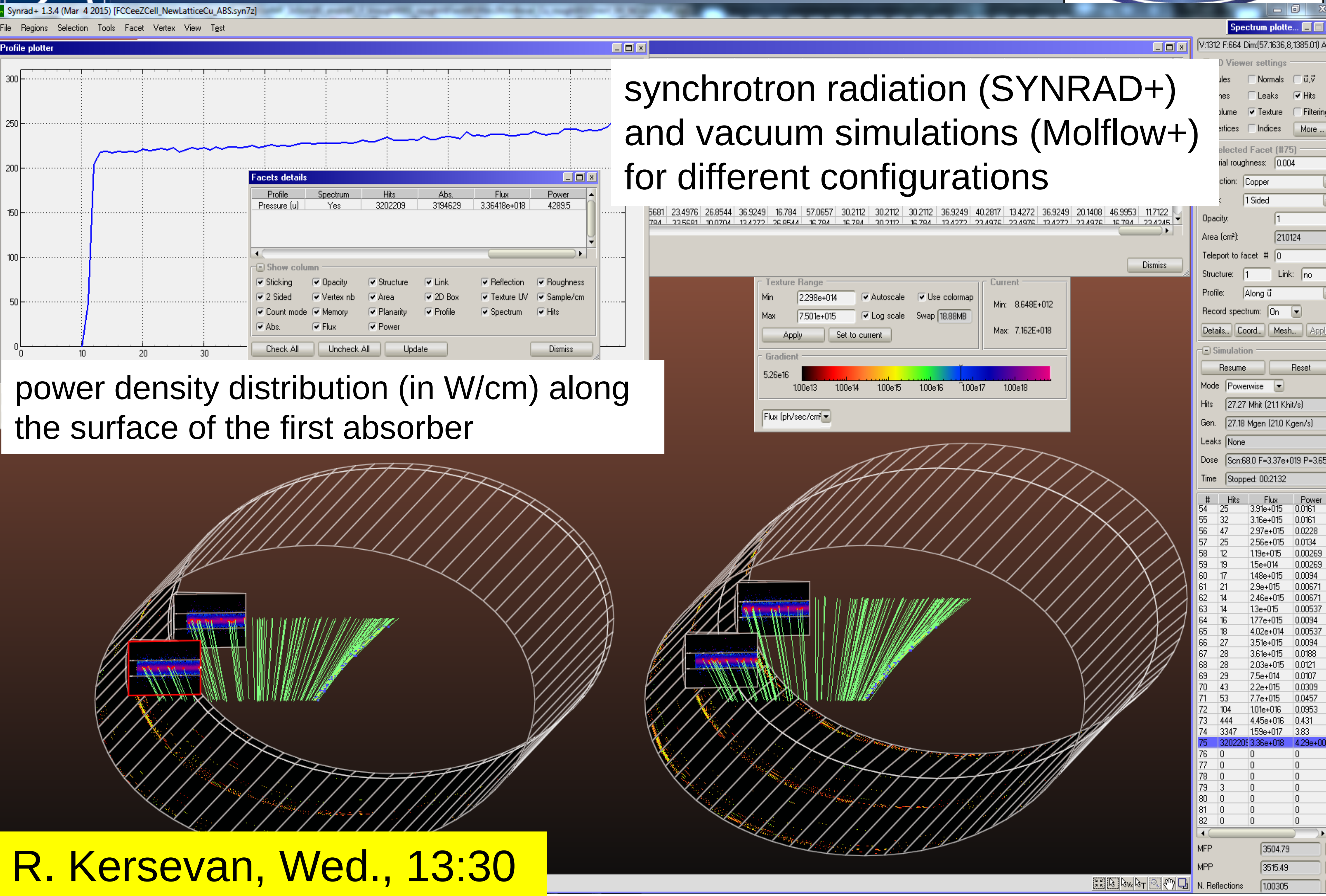


longit. peak-dose profile w/o & w absorbers (10 mA, 10^7 s)

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

vacuum chamber w photon stops

synchrotron radiation (SYNRAD+) and vacuum simulations (Molflow+) for different configurations



power density distribution (in W/cm) along the surface of the first absorber

R. Kersevan, Wed., 13:30

FCC-ee key technology: SRF

range of requirements

Higgs, high RF voltage

- RF power: 50 MW per beam
- 5.5 GV total
- Energy loss: 1.67 GV/turn
- I_{beam} = 30 mA

***Z*, high beam current**

- RF power: 50 MW per beam
- 0.5 - 2.5 GV total
- Energy loss: 0.03 GV/turn
- I_{beam} = 1450 mA

400 MHz offers many benefits (incl. for *FCC-hh*): present baseline!

preliminary design assumptions

about 1200 Nb/Cu cells (300 modules?) operating at 12 MV/m **→ thin film coating**

- SRF performances, cavity technology, cryomodule, low level RF

input power ≈ 40 kW / cell

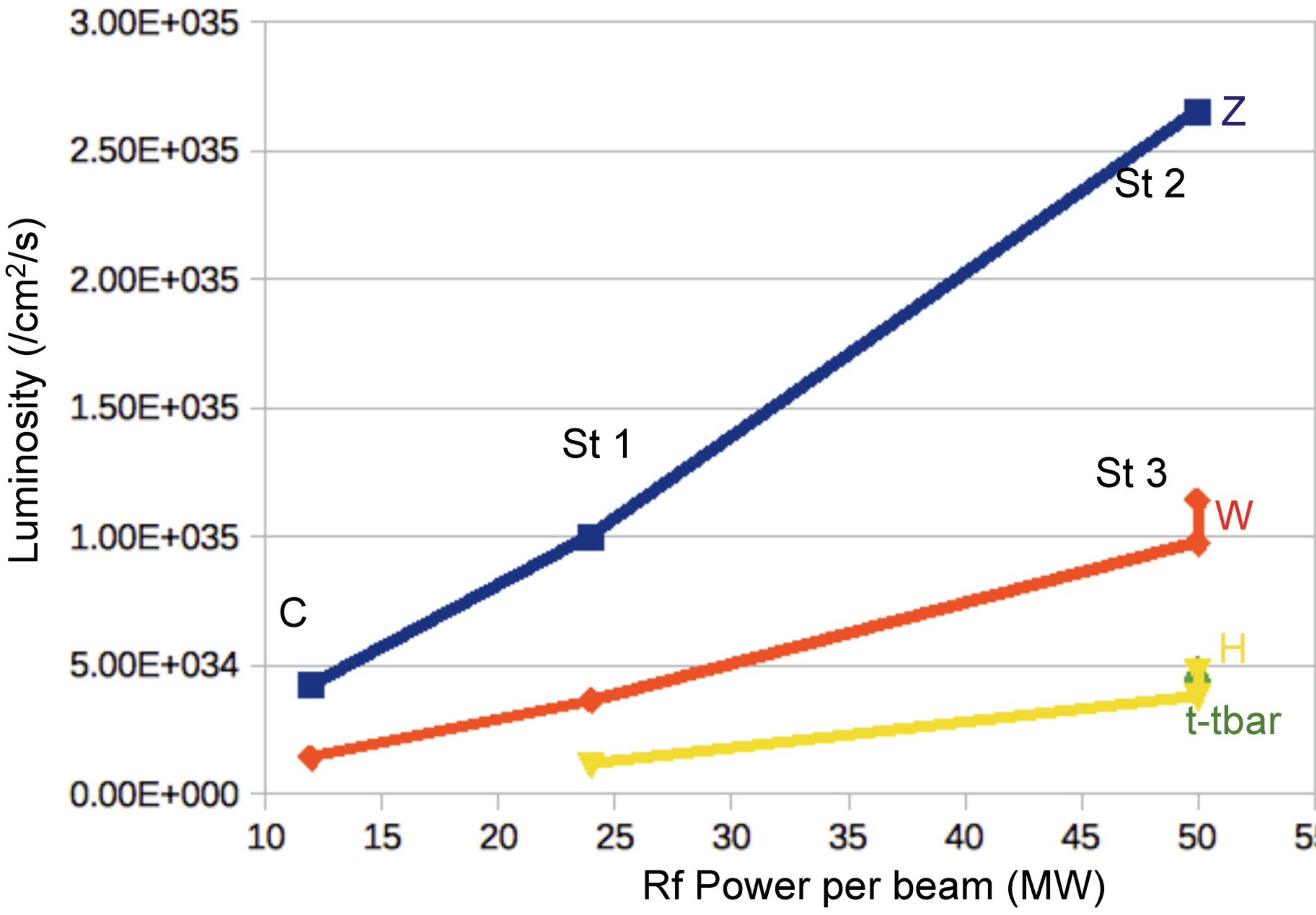
- << state of the art FPC, alternative powering schemes (e.g. SSAs, IOTs)
- variable Q_{ext} range ($1.\ 10^6 - 5.10^6$ considering **2x2 cell cavities**, R/Q = 100)

P_{HOM} ≤ 5 kW/cell at the Z pole **→ efficient RF power sources**

- bunch length, cavity shape, HOM damper design

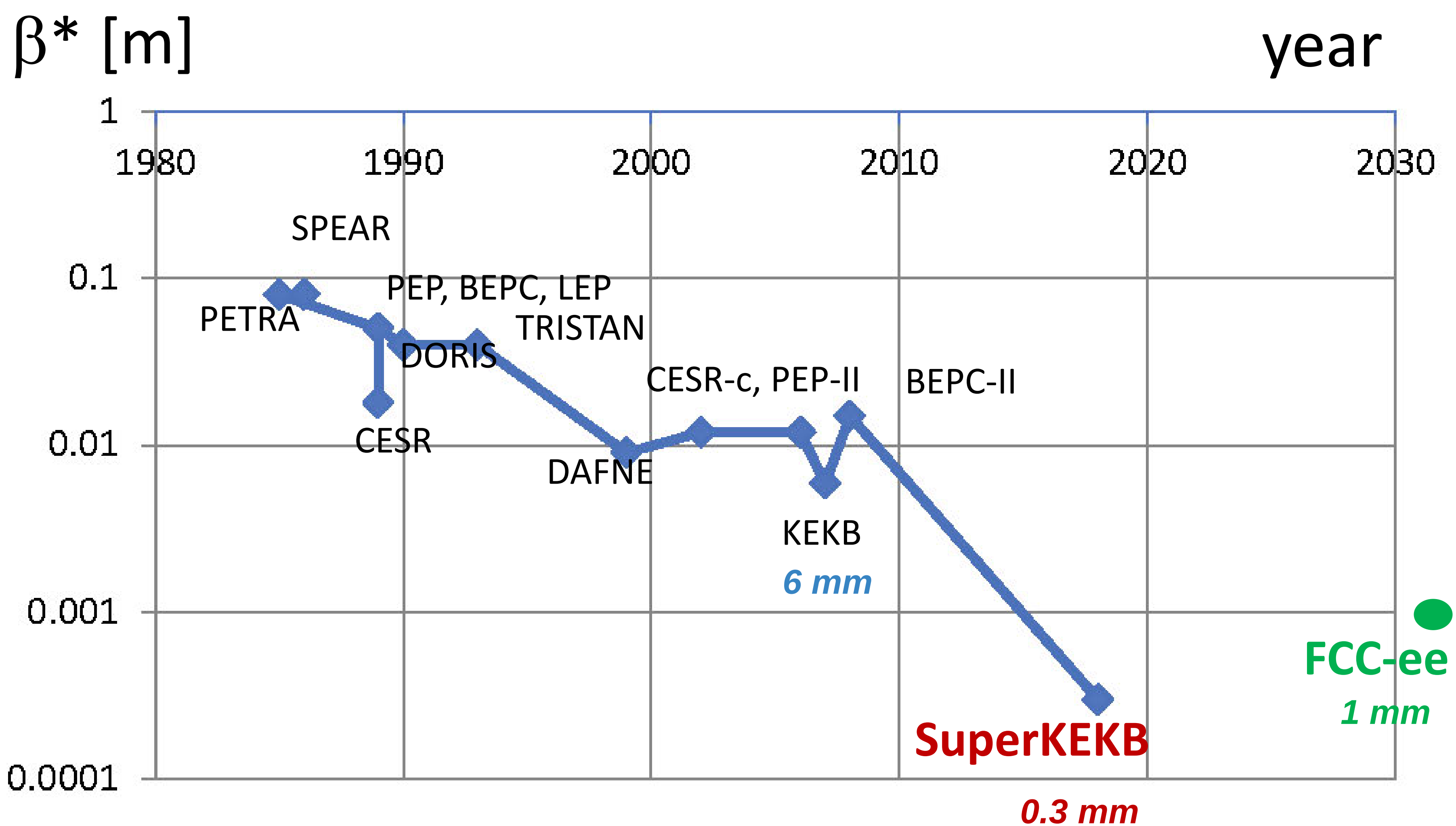
A. Butterworth, O. Brunner, Tue 8:30

RF & physics staging scenario



U. Wienands, Wed. 10:50, Performance & Configurations

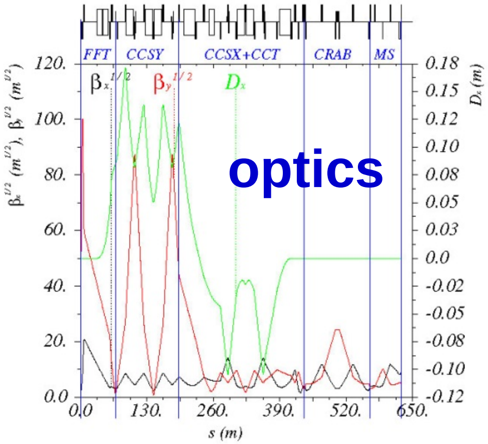
β_y* evolution over 40 years

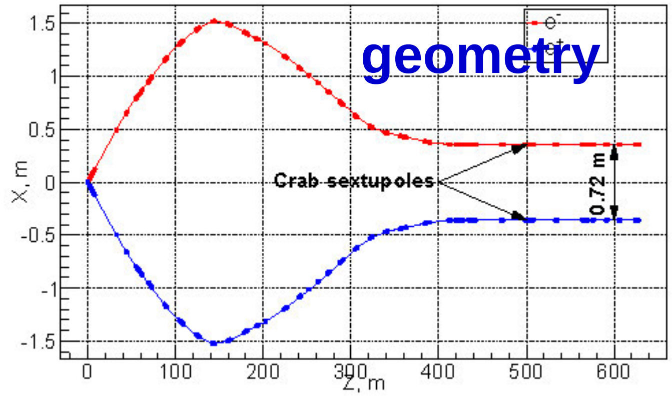


entering a new regime for ring colliders –
SuperKEKB will pave the way towards β*≤1 mm

IR design approaches

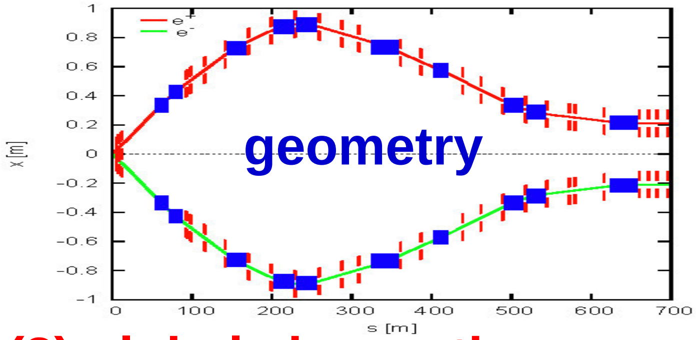
(1) large crossing angle (30 mrad), local chromatic correction, crab waist

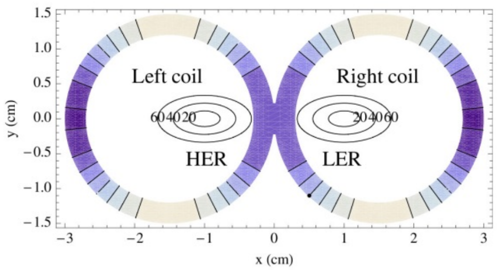




A. Bogomyagkov et al.

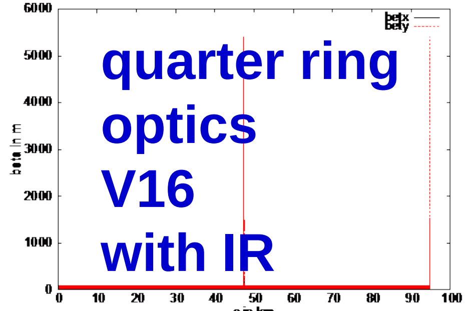
(2) small crossing angle (11 mrad), local chromatic correction, crab cavities

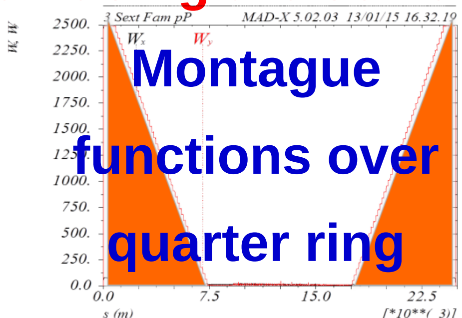




R. Martin, R. Tomas, Wed. 9:00

(3) global chromatic correction using arc sextupole families

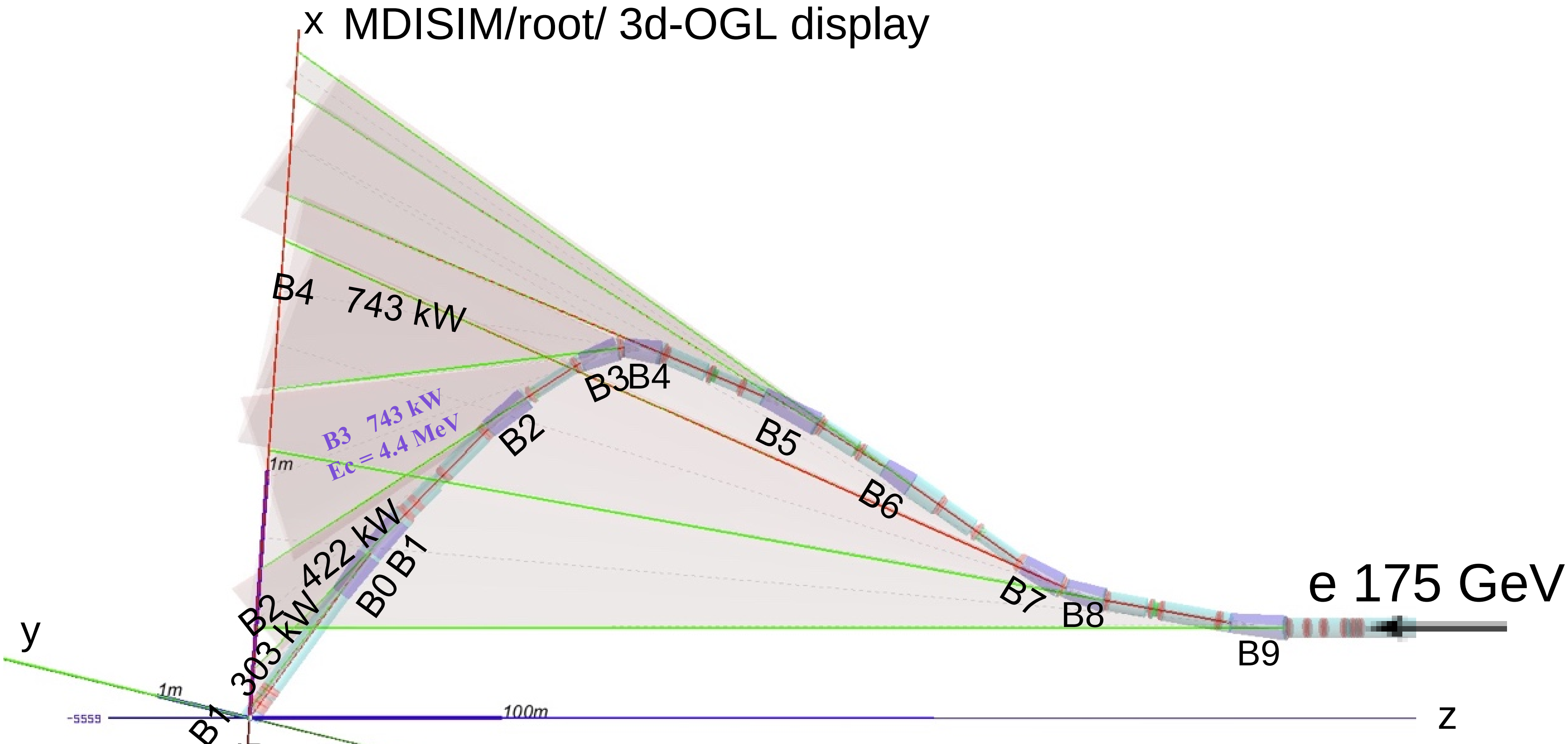




B. Haerer, B. Holzer, Wed. 8:30

IR MDI: synchrotron radiation

SynRad bend cones for TLEP_V14_IR_6-13-2 BINP IR



Synchrotron radiation into IR major challenge :
here **2.2MW**/beam of MeV γ's into detector region

IR MDI: beam losses

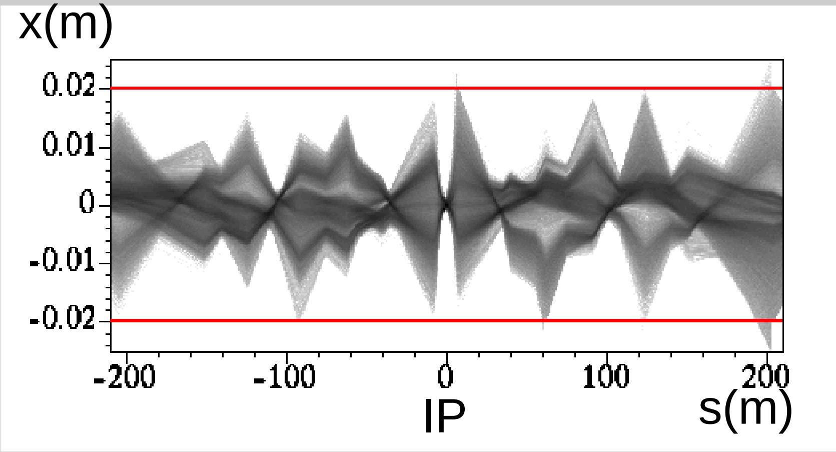
background sources:

(1) single beam effects

- beam-gas interaction: Coulomb scattering & bremsstrahlung
- Touschek scattering

(2) luminosity-related processes

- beamstrahlung
- radiative Bhabha scattering
- 2-photon pair production
  $e^+e^- \to e^+e^-\ e^+e^-$
  $e^+e^- \to e^+e^-\ \mu^+\mu^-$



Ex.: off-energy Touschek scattered particles (TLEP_V14_IR_6-13-2 lattice)

particle tracking:

✓ to simulate IR losses

✓ to simulate collimation around the rings

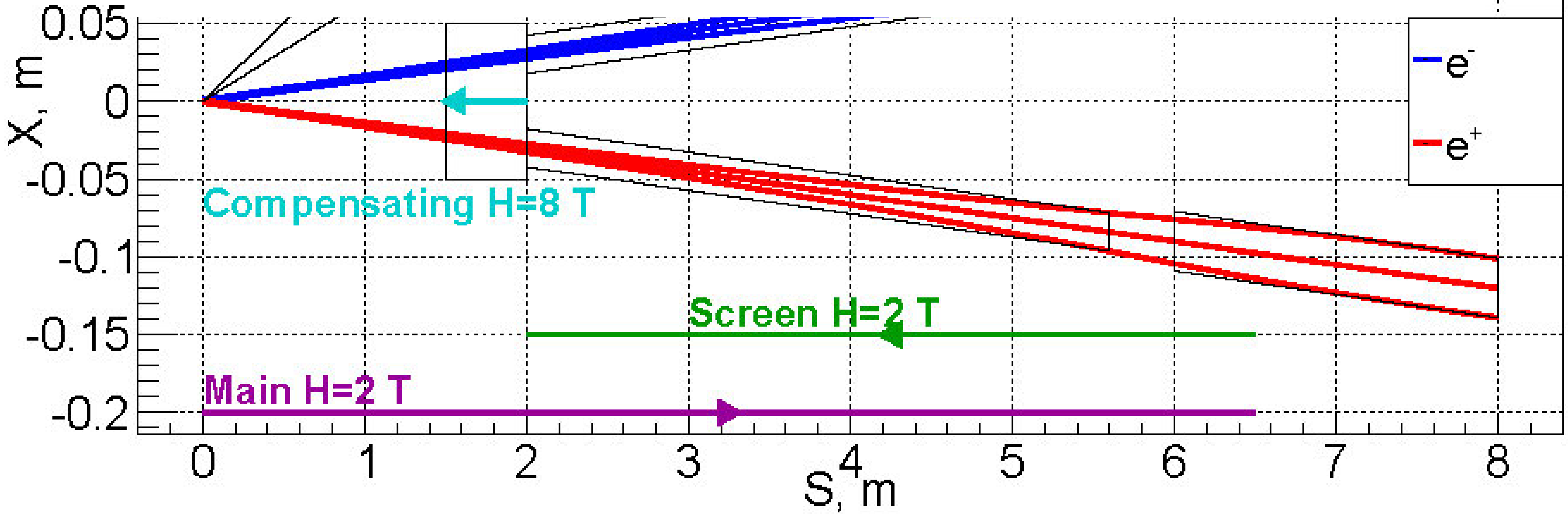
energy acceptance important for most of these effects: check & benchmark

→ **MAD-X / Monte Carlo / Root / Geant4 for full background simulations**

M. Boscolo, Wed. 14:10

detector solenoid compensation

issue of solenoid compensation and the whole IR design will need a strong coordinated effort between experiment and accelerator design

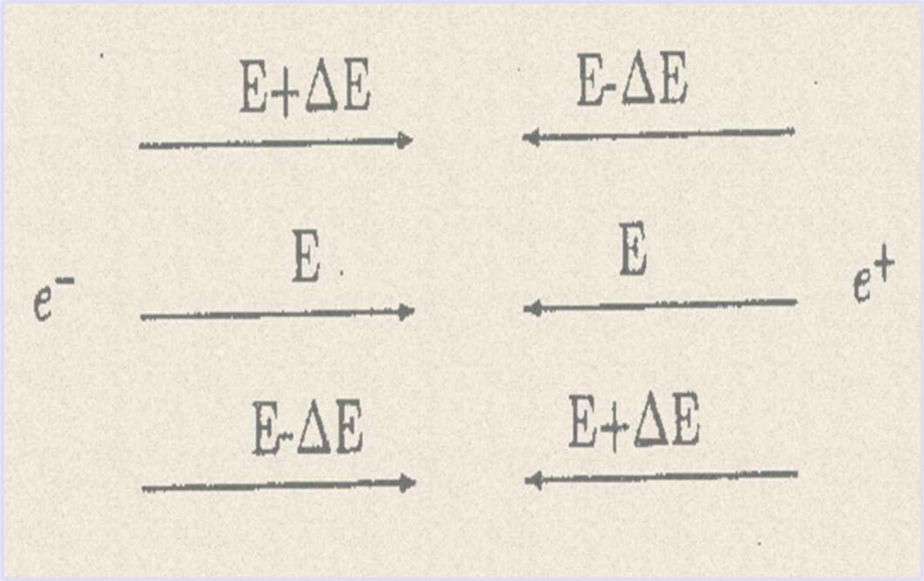


effect of crossing angle and solenoid (fringe) fields on ε_y

A. Bogomyagkov, S. Sinyatkin, V. Telnov, et al.

monochromatization

first proposed by A. Renieri (1975); $D^* \neq 0$;
historical studies for VEPP4, SPEAR, LEP, τ-c factory;
never tested experimentally



effective c.m. energy spread

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

or

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

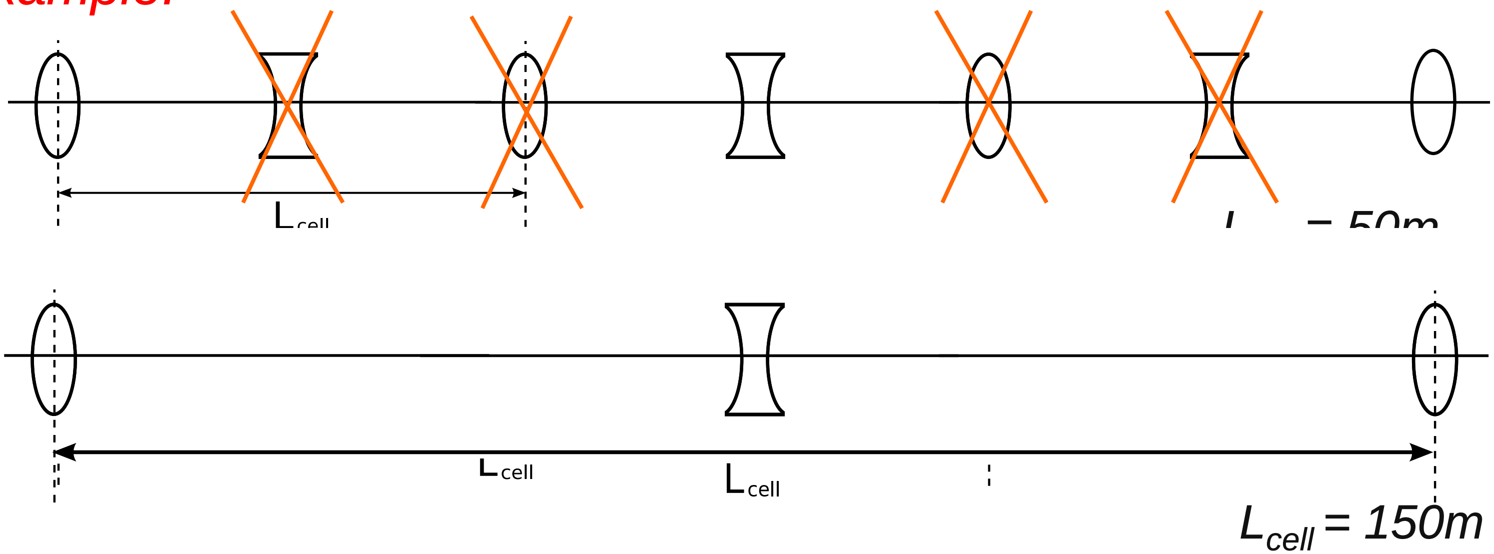
reducing cm energy spread x1/10 w/o loss of luminosity?!
implementation for crab-waist scheme?

A. Faus-Golfe, Wed. 9:50, FCC-ee lattice and optics

emittance variation

$\varepsilon \propto \gamma^2 L_{cell}{}^3 \rightarrow$ emittance at lower energy controlled via longer arc cells

example:



baseline choices:

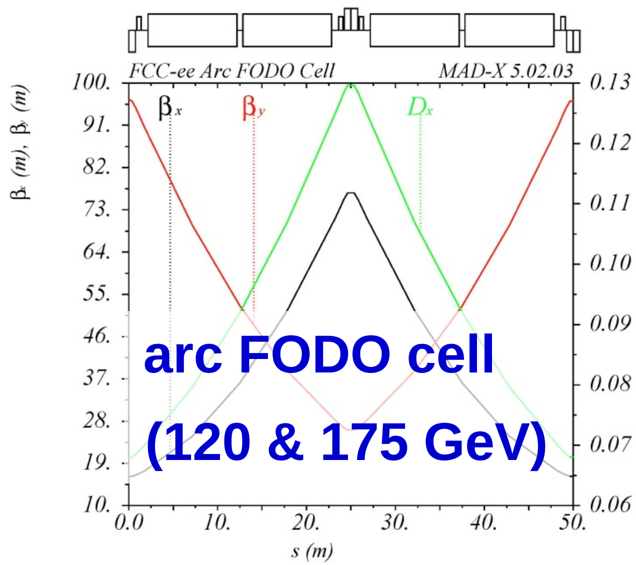
120 & 175 GeV: L_{cell}=50 m

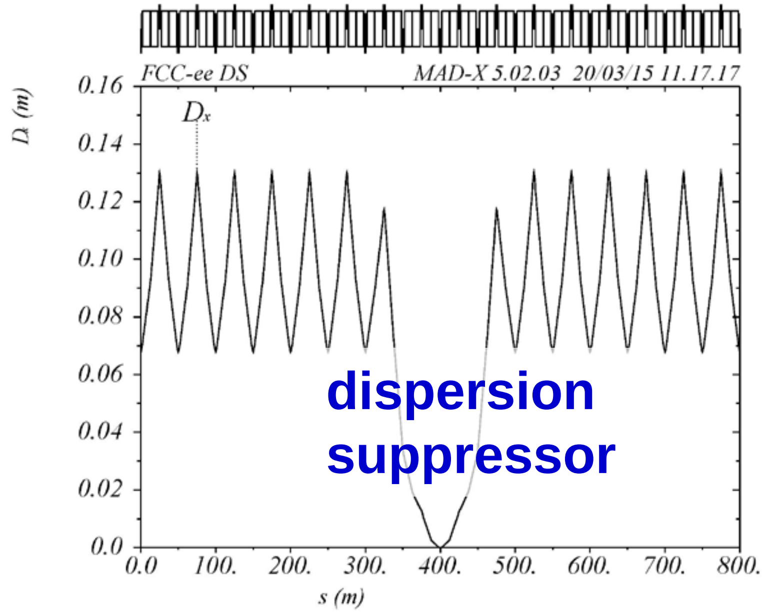
80 GeV: L_{cell}=100 m

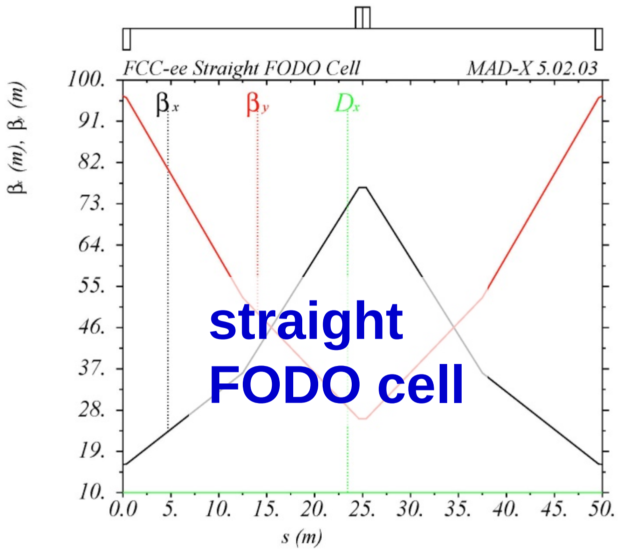
45.5 GeV: L_{cell}=300 m

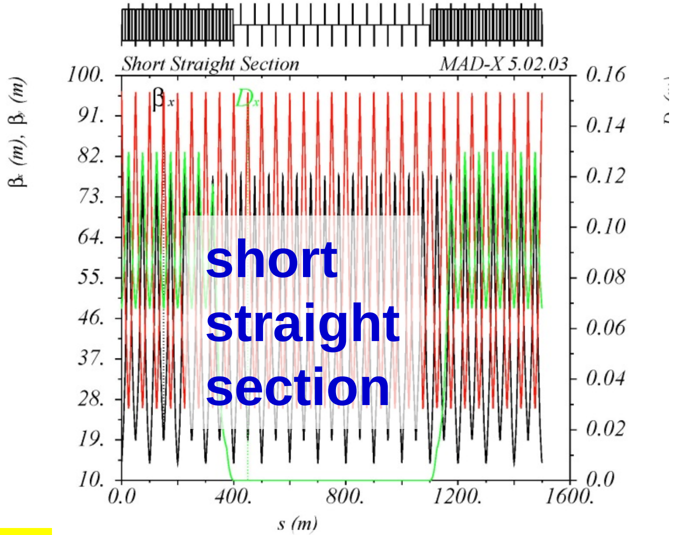
B. Haerer, Wed. 8:30

flexible ring optics







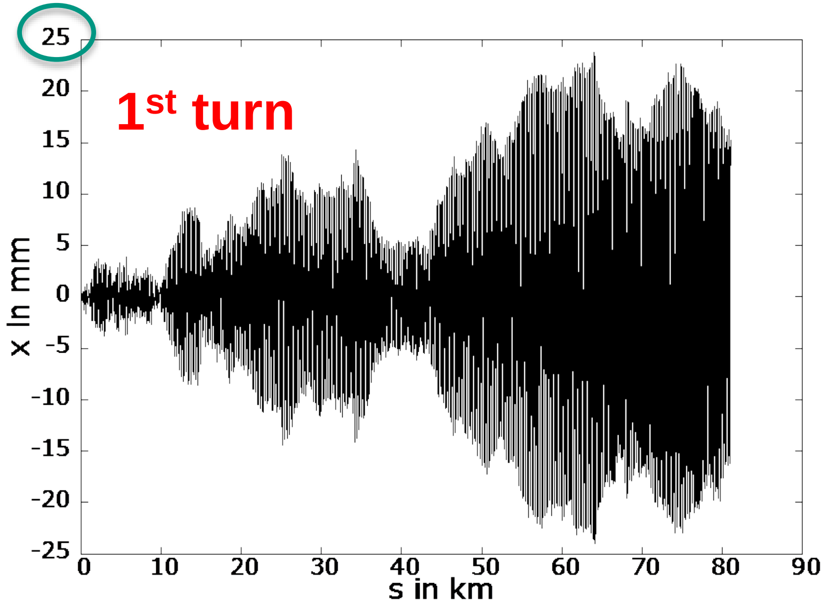


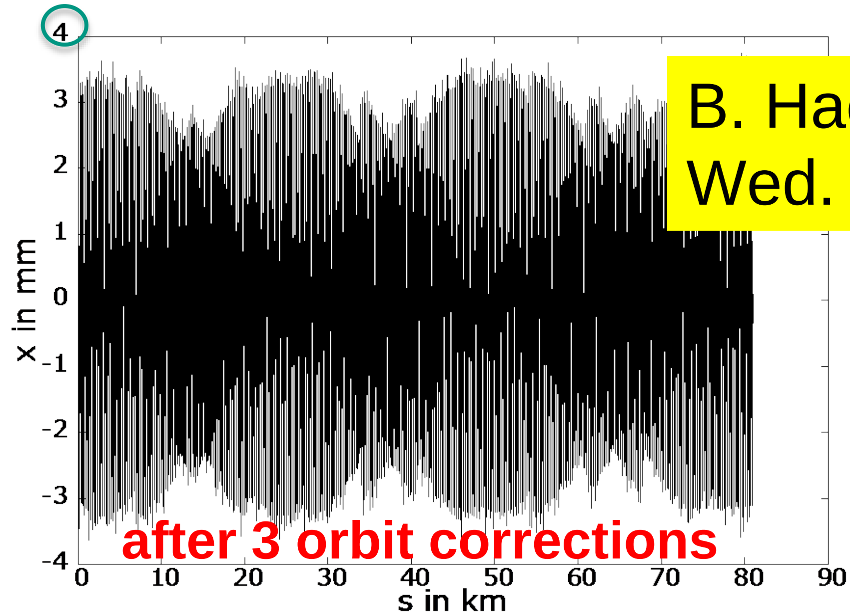
B. Haerer, B. Holzer, Wed 8:30

matched optics for all energies

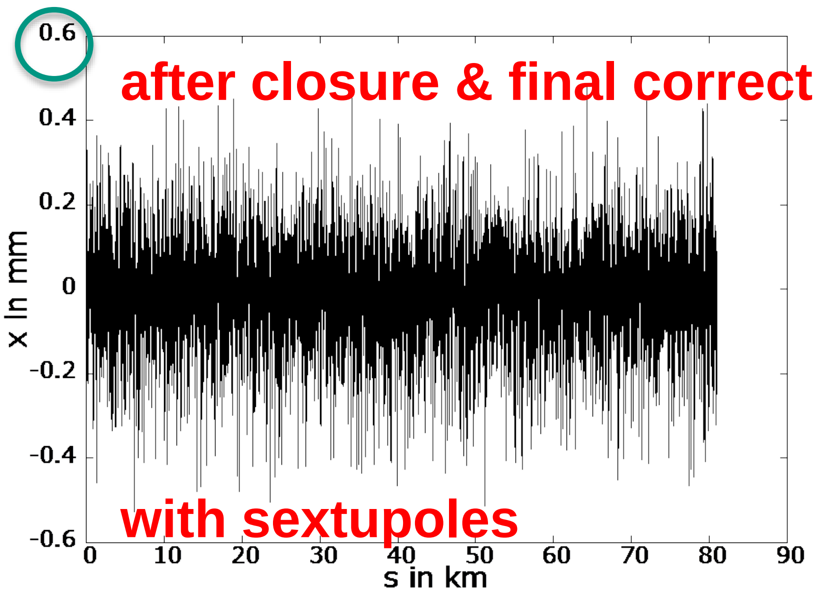
orbit & emittance

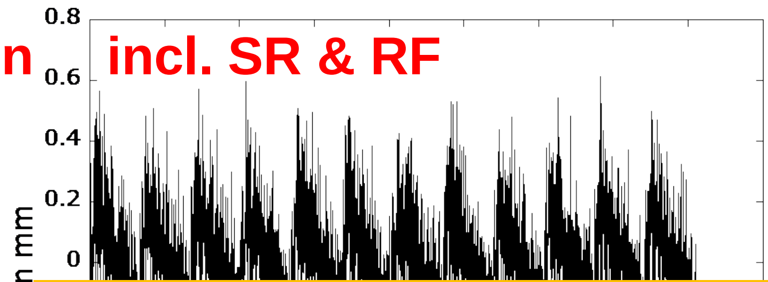
150 μm quad misalignments, no low-beta insertions, MAD-X





B. Haerer,
Wed. 8:30



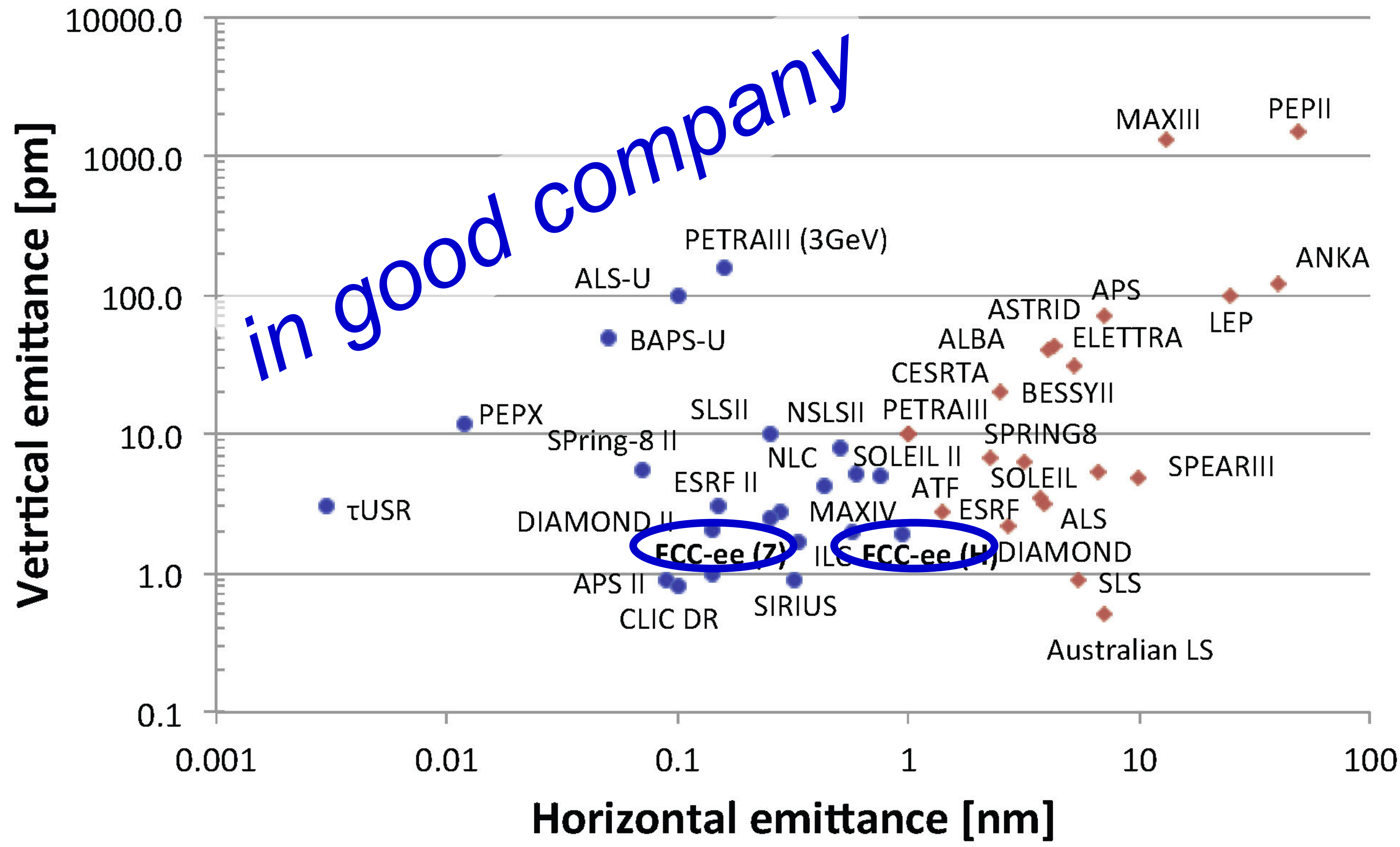


ε_x = 1.23 nm,

ε_y = 1.05 pm ✓

w/o low-β & beam-beam

transverse emittances

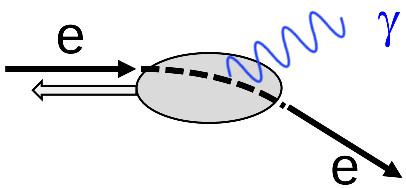


Y. Papaphilippou

beamstrahlung

- 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)*

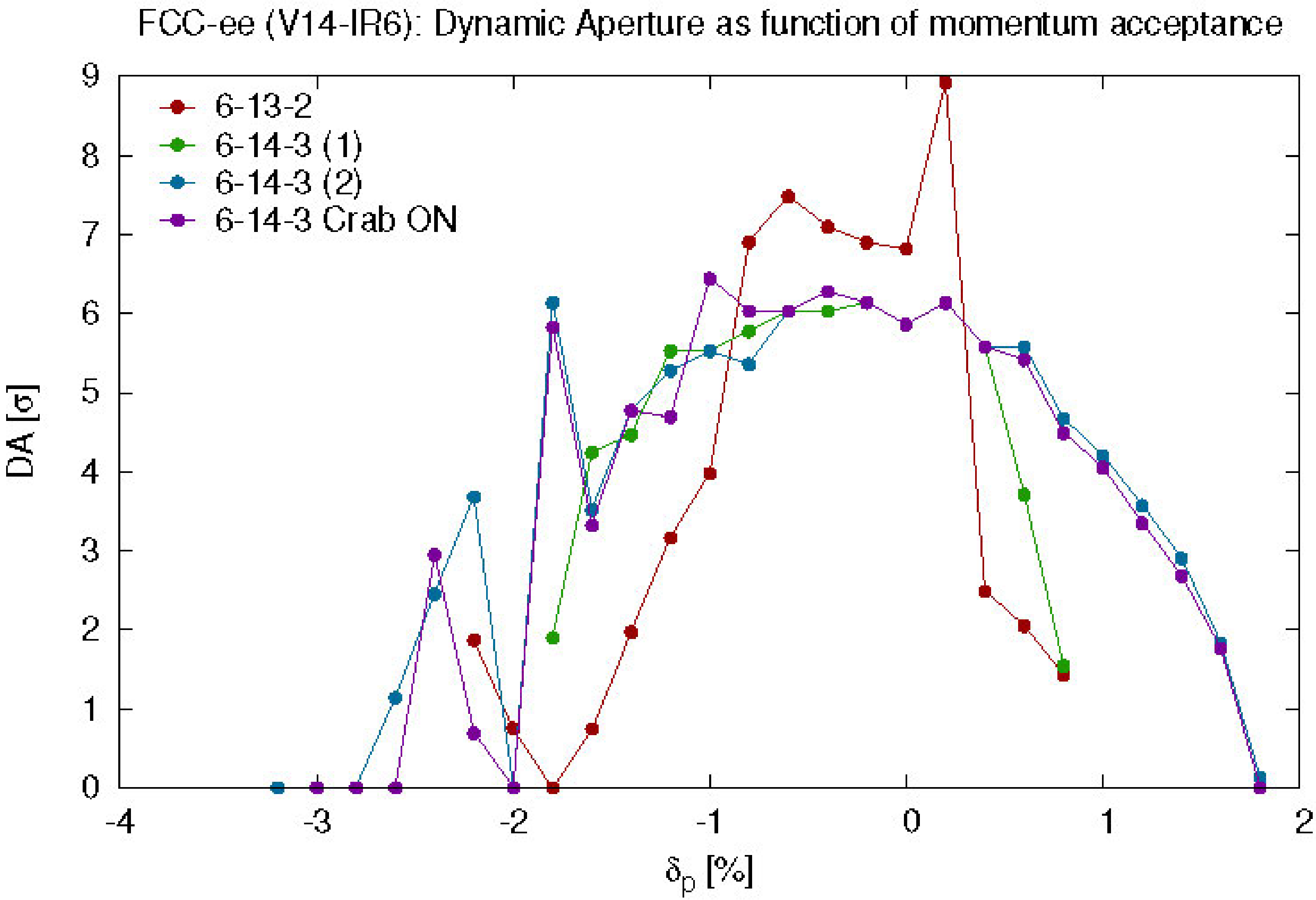
η : ring energy acceptance

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:* ***≥1.5% at 175 GeV***
    - LEP: <1% acceptance, SuperKEKB ~ 1.5%

J. Wenninger, et al

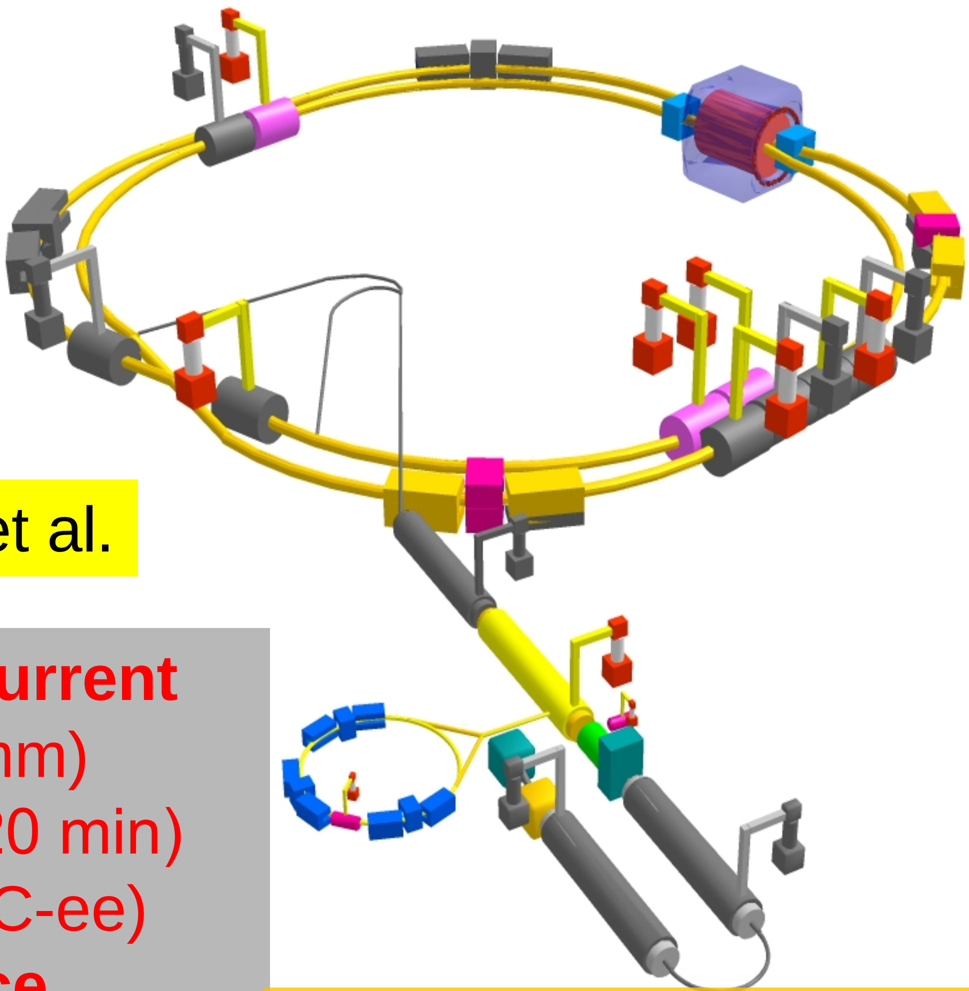
dynamic aperture for optics v16



L. Medina, R. Tomas

SuperKEKB = *FCC-ee* demonstrator

beam commissioning will start in 2015

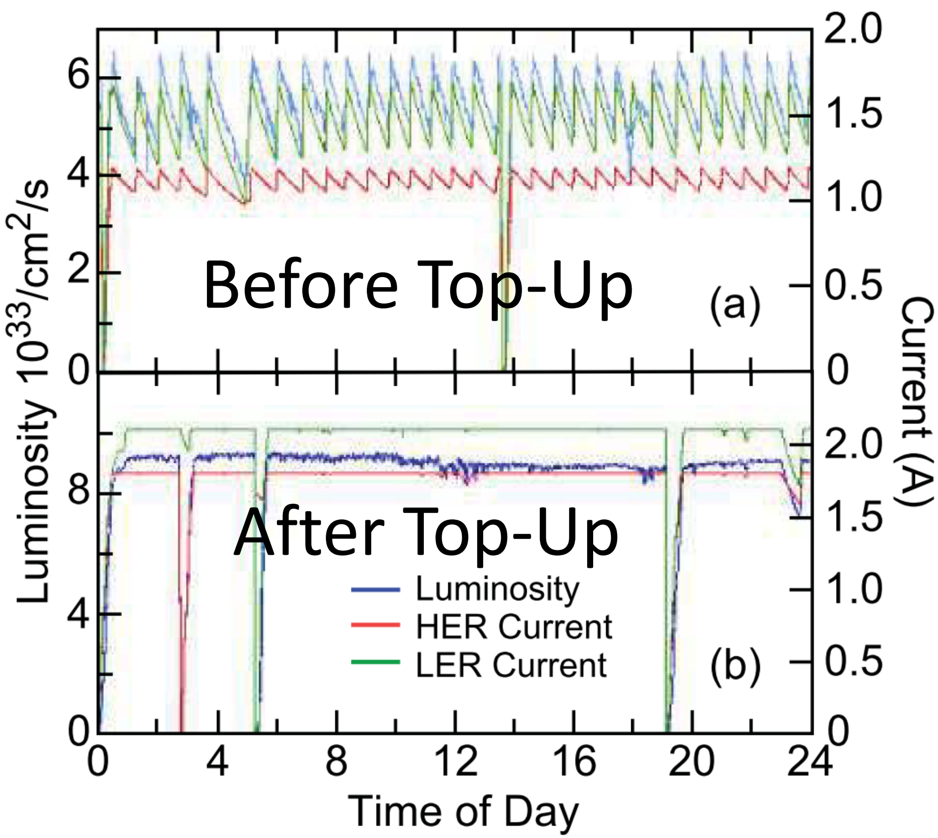


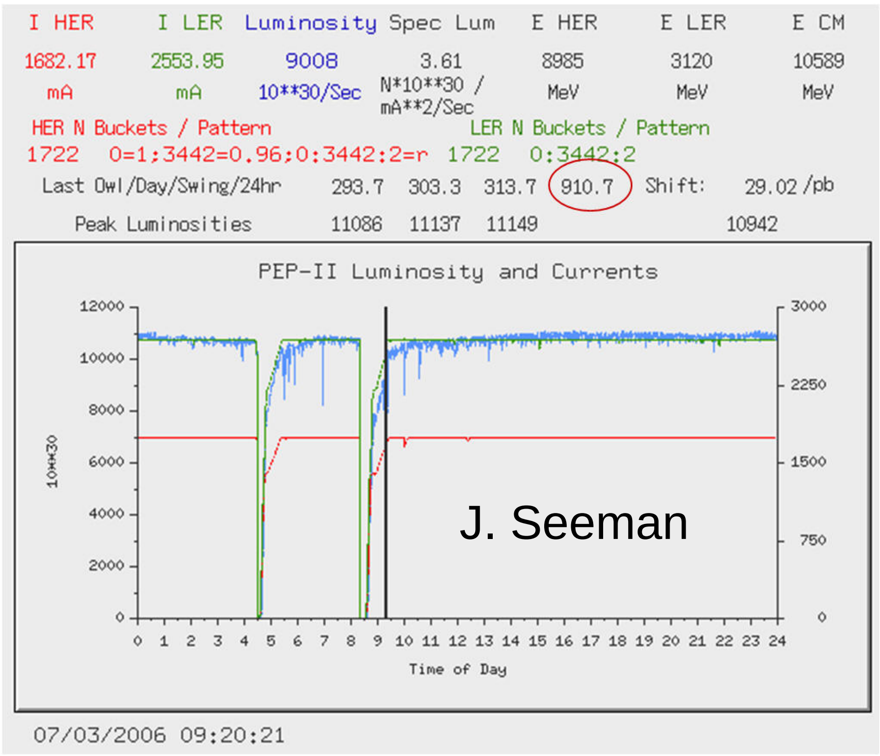
K. Oide et al.

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 concepts

top-up injection at PEP-II





average luminosity ≈ peak luminosity

similar results from KEKB

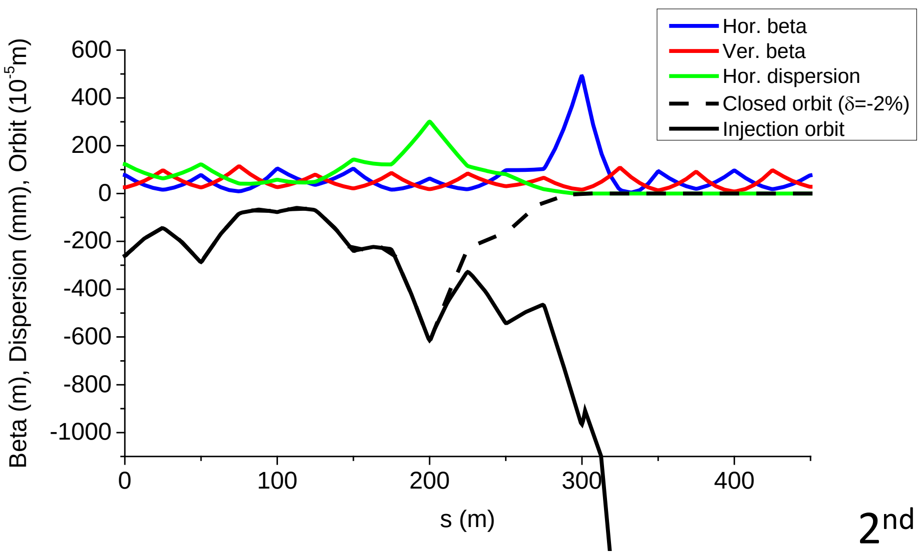
J. Seeman, Wed. 15:50, M. Aiba 16:10

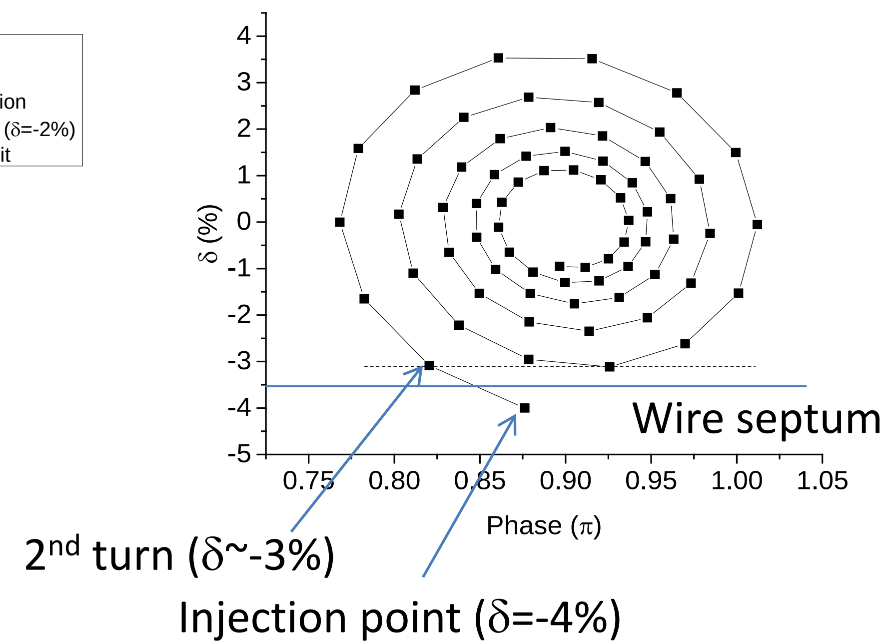
FCC-ee top-up

two new options for top-up:

(1) off-momentum multipole kicker injection

(2) or kicker-less ("dream injection") *

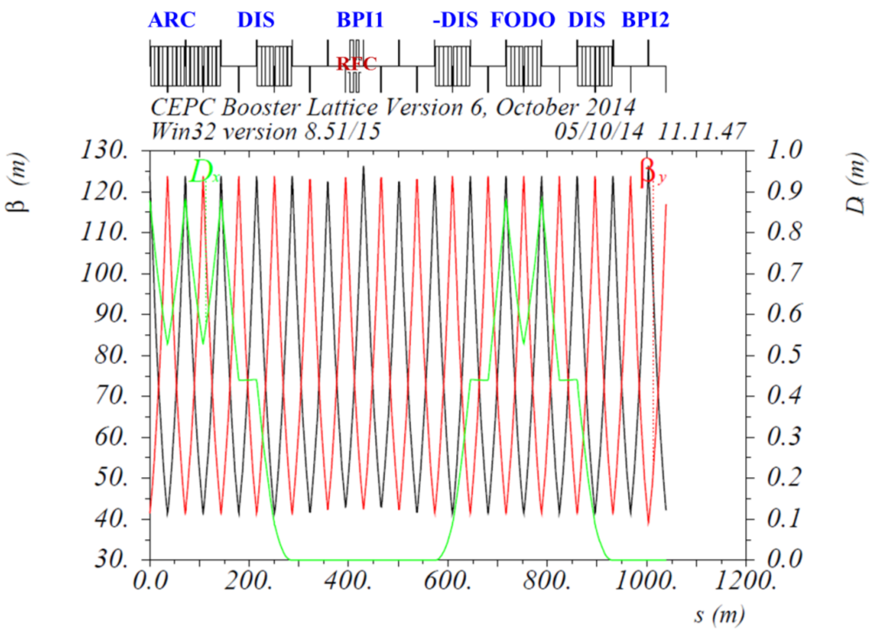




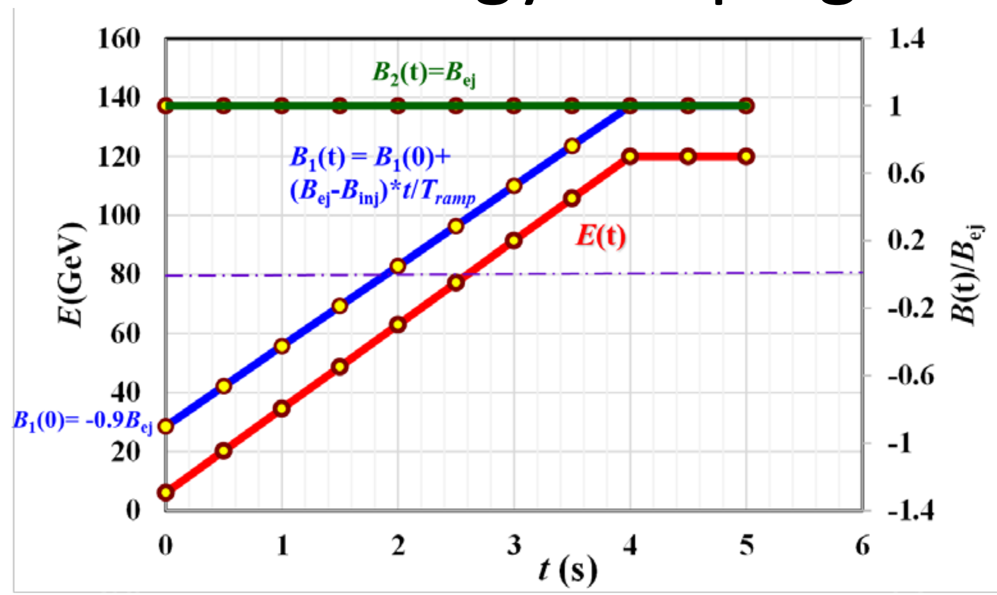
M. Aiba, Wed. 16:10

* earlier proposal by R. Talman

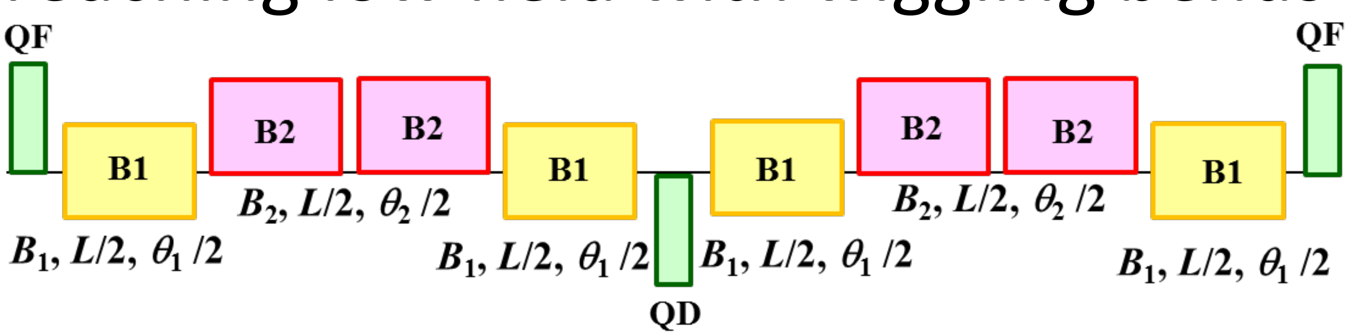
bypass around the experiments



energy ramping



reaching low field with wiggling bends



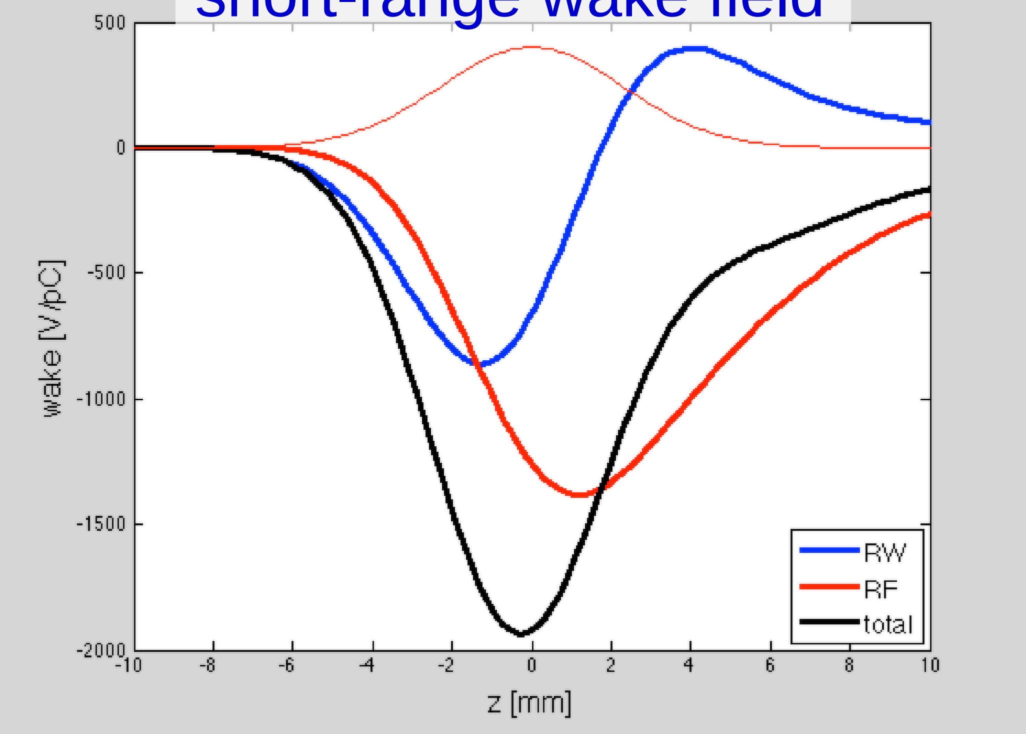
H. Geng, C. Zhang, Wed. 16:30

FCC booster design carried out by FZ Jülich & MEPHI

longitudinal impedance budget

Element	R [kΩ]	L [nH]	k_{loss} [V/pC]	|Z/n| (mΩ)
Resistive wall (Al)	7.5	148	276	1.1*+2.8
RF cavities	26.9	-	1000	3.9*
total	34.3	148	1276	7.8

short-range wake field



microwave threshold

from Keil-Schnell-Boussard criterion

~

7-13 mΩ

M. Migliorati, Wed. 11:10

double ring vs single ring

2 rings (ex. KEKB, PEP-II, LHC, *FCC-ee*):
complete optics control; centered orbit;
no parasitic encounters;
dipole & quad. field can be tailored to beam energy;
possibly shared RF for $t\bar{t}$ running

1 ring (ex. LEP, CESR, Tevatron, *CepC*):
parasitic collisions → electrostatic separators;
additional sextupoles, octupoles etc. for differential optics control;
uncompensated energy sawtooth;
twice the RF impedance;
head-tail wake-field effects due to off-center orbits

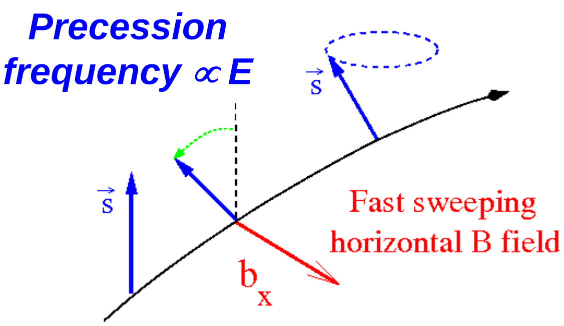
K. Oide, Wed. 10:30

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)*

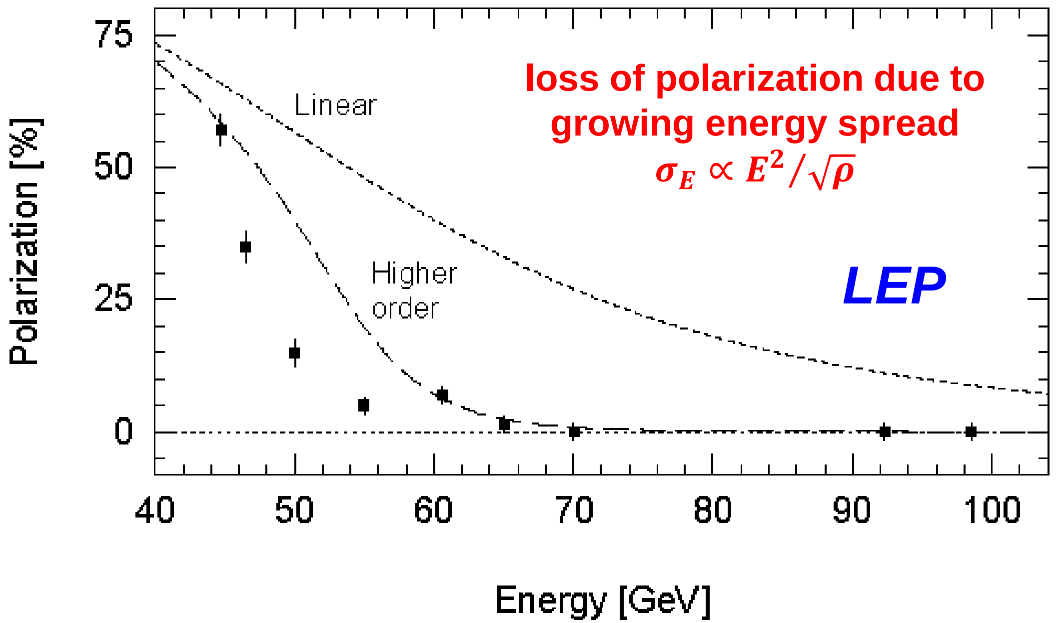
scaling from LEP observations :

polarization expected up to the WW threshold !

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

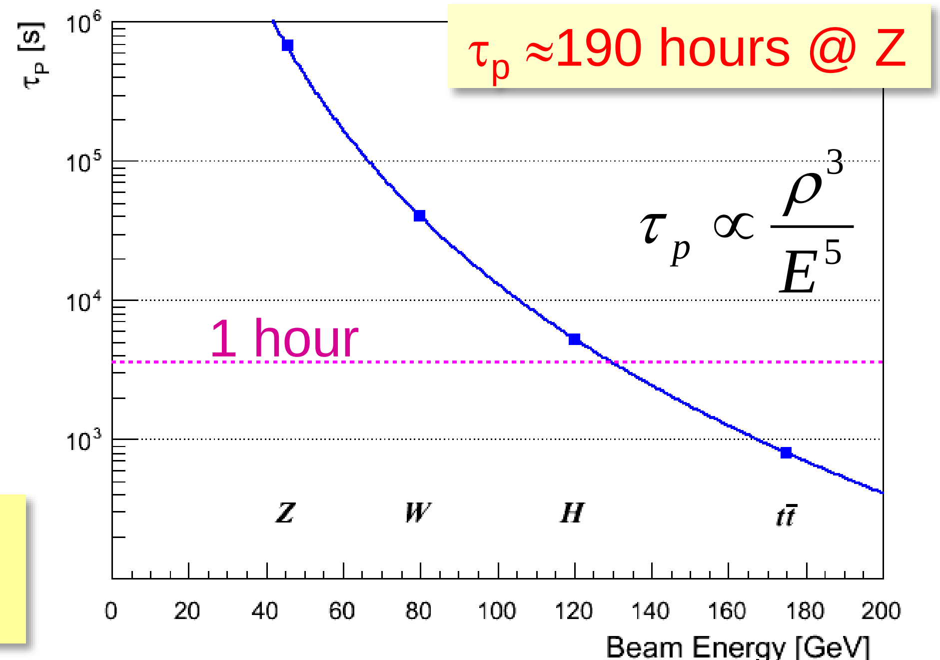
<u>transverse polarization</u> build-up (Sokolov-Ternov) is slow at *FCC-ee* (large bending radius ρ)

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)



<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, J. Jowett, R. Rossmanith, J.Wenninger

E. Gianfelice, Wed. 15:30

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

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

- ✓ use physics measurements
- ✓ other? (laser back scattering / spectrometer?)

M. Koratzinos, Wed. 14:30

conclusions

- real FCC-ee design work has started in all work units
- great progress since FCC kick-off in February 2014
- wide study scope, many interesting questions
- emphasis shifting to optimization and choice between alternatives
- several technologies also need work (SC cavities, RF power sources, magnets, vacuum system,…)
- witnessing a lot of enthusiasm and excitement
- colleagues contributing from around the world (EU, Switzerland, Russia, Japan, Korea, USA, China, …)
- more partners & contributions welcome!

FCC-ee machine session - Wednesday

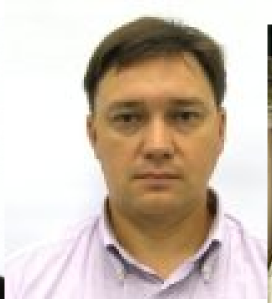
8:30-10:00	**FCC-ee lattice & optics options, chair Katsunobu Oide, KEK**	
8:30-9:00	**Bastian Haerer, CERN & KIT**	**Lattice optimization and emittance tuning**
9:00-9:30	**Roman Martin, CERN & HUB**	**IR designs & dynamic aperture**
9:30-9:50	**Helmut Burkhardt, CERN**	**IR synchrotron radiation + rad.Bhabha lifetime**
9:50-10:00	**Angeles Faus-Golfe, IFIC&CNRS**	**Mono-chromatization**
10:30-12:00	**Performance & configurations, chair Weiren Chou, FNAL & IHEP**	
10:30-10:50	**Katsunobu Oide, KEK**	**1-ring/2-ring issues**
10:52-11:12	**Uli Wienands, SLAC**	**staging scenarios**
11:14-11:34	**Mauro Migliorati, La Sapienza**	**Impedance and collective effects**
11:36-11:56	**Kazuhito Ohmi, KEK**	**beam-beam simulations**
13:30-15:00	**Vacuum, MDI, energy calibration, chair John Seeman, SLAC**	
13:30-13:50	**Roberto Kersevan, CERN**	**Arc vacuum design, SR absorbers & shielding**
13:52-14:12	**Mike Sullivan, SLAC**	**Criteria for IR designs**
14:14-14:34	**Manuela Boscolo, INFN-LNF**	**Losses in IR region**
14:36-14:56	**Mike Koratzinos, U. Geneva**	**Energy calibration options**
15:30-17:00	**Polarization & injectors, chair Uli Wienands, SLAC**	
15:30-15:50	**Eliana Gianfelice, FNAL**	**prospects for FCC-ee polarization**
15:52-16:12	**John Seeman, SLAC**	**Injector options**
16:14-16:34	**Masamitsu Aiba, PSI**	**Top-up injection**
16:36-16:56	**Huiping Geng, IHEP**	**CepC booster design**
17:30-18:10	**Contributed talks (CepC main ring), chair Ralph Assmann, DESY**	
17:30-17:50	**Yiwei Wang, IHEP**	**Status of the CEPC Interaction Region Design**
17:50-18:10	**Huiping Geng, IHEP**	**Lattice design for CEPC main ring**

fantastic opportunity!

acknowledgement

Budker Institute in Novosibirsk (BINP) is making major contributions to FCC-ee study

BINP is leading the work packages on **FCC-ee IR design, beam-beam studies, polarization and energy calibration**

Warm thanks to     …

Anton Bogomyagkov, S.A. Glukhov, Ivan Koop, Eugene Levichev, Nikolay Mezentsev, Nikolai Muchnoi, Sergei Nikitin, Ivan Okunev, Pavel Piminov, Dmitry Shatilov, Sergei Sinyatkin, and Valery Telnov

"The future belongs to those who believe in the beauty of their dreams."

Eleanor Roosevelt

spare slides

FCC-ee / 4 scenarios

- baseline (head-on) with 4 IPs
- baseline (head-on) with 2 IPs
- crab waist with 4 IPs
- crab waist with 2 Ips

baseline parameters for Z pole revised

parameter	FCC-ee baseline (4 IPs)			
	Z	W	H	t
E_{beam} [GeV]	45	80	120	175
current [mA]	1450	152	30	6.6
$P_{SR,tot}$ [MW]	100	100	100	100
no. bunches	16700	4490	1360	98
N_b [10^{11}]	1.8	0.7	0.46	1.4
ε_x [nm]	29	3.3	0.94	2
ε_y [pm]	60	1	2	2
β^*_x [m]	0.5	0.5	0.5	1.0
β^*_y [mm]	3	1	1	1
σ^*_y [nm]	424	84	44	45
σ^*_x [μm]	121	41	22	45

parameter	FCC-ee baseline (4 IPs)			
	Z	W	H	t
RF frequency [MHz]	400	400	400	400
RF voltage [GV]	2.5	4	5.5	11
circumference [km]	100	100	100	100
momentum compaction [10^{-5}]	18	2	0.5	0.5
synchrotron tune	0.458	0.145	0.068	0.070
$\sigma_{z,SR}$ [mm]	3.29	2.02	1.62	2.31
$\sigma_{z,tot}$ [mm] (w beamstr.)	3.80	2.27	1.80	2.45
$\sigma_{\delta,SR}$ [%]	0.052	0.092	0.139	0.202
$\sigma_{\delta,tot}$ [%] (w beamstr.)	0.061	0.104	0.154	0.215
hourglass factor F_{hg}	0.53	0.67	0.73	0.65
beam-beam par. ξ_y/IP (4 IPs)	0.03, 0.05	0.06	0.092	0.091
L/IP [10^{34} cm^{-2}s^{-1}] (4 Ips)	21	10.4	5.3	1.5
τ_{beam} [min] (4 IPs)	403	84	32	25

175-GeV momentum acceptance >±1.3-1.5%

parameter	FCC-ee baseline (2 IPs)			
	Z	W	H	t
E_{beam} [GeV]	45	80	120	175
current [mA]	1450	152	30	6.6
$P_{SR,tot}$ [MW]	100	100	100	100
no. bunches	12846	3453	1046	75
N_b [10^{11}]	2.37	0.91	0.6	1.82
ε_x [nm]	29	3.3	0.94	2
ε_y [pm]	60	1	2	2
β^*_x [m]	0.5	0.5	0.5	1.0
β^*_y [mm]	3	1	1	1
σ^*_y [nm]	424	84	44	45
σ^*_x [μm]	121	41	22	45

parameter	FCC-ee baseline (2 IPs)			
	Z	W	H	t
RF frequency [MHz]	400	400	400	400
RF voltage [GV]	2.5	4	5.5	11
circumference [km]	100	100	100	100
momentum compaction [10^{-5}]	18	2	0.5	0.5
synchrotron tune	0.458	0.145	0.068	0.070
$\sigma_{z,SR}$ [mm]	3.29	2.02	1.62	2.31
$\sigma_{z,tot}$ [mm] (w beamstr.)	3.84	2.29	1.81	2.46
$\sigma_{\delta,SR}$ [%]	0.052	0.092	0.139	0.202
$\sigma_{\delta,tot}$ [%] (w beamstr.)	0.061	0.105	0.155	0.216
hourglass factor F_{hg}	0.53	0.67	0.73	0.65
beam-beam par. ξ_y/IP (2IPs)	0.040,0.070	0.077	0.121	0.118
L/IP [10^{34} cm^{-2}s^{-1}] (2 Ips)	27	13	7.0	1.9
τ_{beam} [min] (2 IPs)	620	130	50	39

175-GeV momentum acceptance >±1.5-1.6%

parameter	FCC-ee crab waist (4 IPs)			
	Z	W	H	t
E_{beam} [GeV]	45	80	120	175
current [mA]	1450	152	30	6.6
$P_{SR,tot}$ [MW]	100	100	100	100
no. bunches	59581	3143	625	68
N_b [10^{11}]	0.5	1.0	1.0	2.0
ε_x [nm]	0.13	0.42	0.94	2
ε_y [pm]	1.0	1.0	1.0	2
β^*_x [m]	0.5	0.5	0.5	0.5
β^*_y [mm]	1	1	1	1
σ^*_y [nm]	32	29	31	45
σ^*_x [μm]	8	14	22	31

parameter	FCC-ee crab waist (4 IPs)			
	Z	W	H	t
RF frequency [MHz]	400	400	400	400
RF voltage [GV]	0.4	1.0	3.6	11
circumference [km]	100	100	100	100
momentum compaction [10^{-5}]	0.5	0.5	0.5	0.5
synchrotron tune	0.030	0.035	0.053	0.070
$\sigma_{z,SR}$ [mm]	0.97	2.08	2.08	2.31
$\sigma_{z,tot}$ [mm] (w beamstr.)	3.24	3.49	2.58	2.80
$\sigma_{\delta,SR}$ [%]	0.037	0.092	0.139	0.202
$\sigma_{\delta,tot}$ [%] (w beamstr.)	0.124	0.155	0.172	0.245
hourglass factor F_{hg}	0.94	0.87	0.81	0.75
beam-beam par. ξ_y/IP (4 IPs)	0.04,0.137	0.04,0.143	.0124,.097	0.03,0.092
L/IP [10^{34} cm^{-2}s^{-1}] (4 Ips)	215	38	8.7	2.1
τ_{beam} [min] (4 IPs)	38	23	20	18

parameter	FCC-ee crab waist (2 IPs)			
	Z	W	H	t
E_{beam} [GeV]	45	80	120	175
current [mA]	1450	152	30	6.6
$P_{SR,tot}$ [MW]	100	100	100	100
no. bunches	45154	2382	474	51
N_b [10^{11}]	0.66	1.3	1.3	2.6
ε_x [nm]	0.13	0.42	0.94	2
ε_y [pm]	1.0	1.0	1.0	2
β^*_x [m]	0.5	0.5	0.5	0.5
β^*_y [mm]	1	1	1	1
σ^*_y [nm]	32	29	31	45
σ^*_x [μm]	8	14	22	31

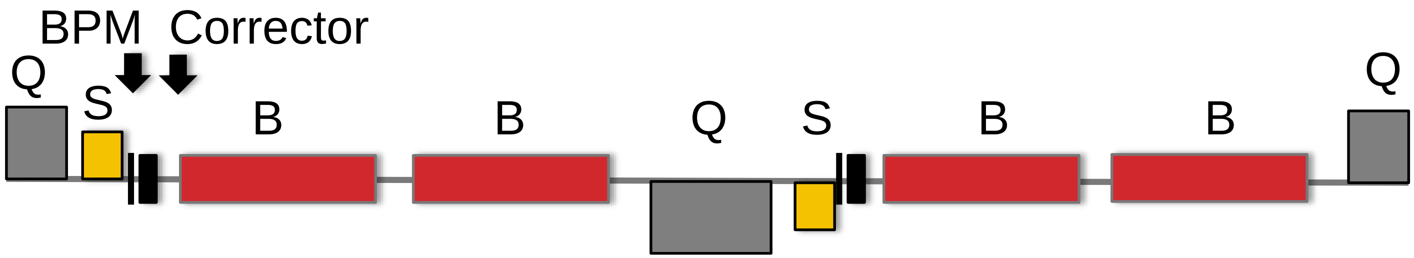
parameter	FCC-ee crab waist (2 IPs)			
	Z	W	H	t
RF frequency [MHz]	400	400	400	400
RF voltage [GV]	0.4	1.0	3.6	11
circumference [km]	100	100	100	100
momentum compaction [10^{-5}]	0.5	0.5	0.5	0.5
synchrotron tune	0.030	0.035	0.053	0.070
$\sigma_{z,SR}$ [mm]	0.97	2.08	2.08	2.31
$\sigma_{z,tot}$ [mm] (w beamstr.)	3.33	3.12	2.61	2.83
$\sigma_{\delta,SR}$ [%]	0.037	0.092	0.139	0.202
$\sigma_{\delta,tot}$ [%] (w beamstr.)	0.127	0.139	0.174	0.248
hourglass factor F_{hg}	0.94	0.87	0.81	0.75
beam-beam par. ξ_y/IP (2 IPs)	0.06,0.21	0.04,0.16	0.03,.124	0.04,0.118
L/IP [10^{34} cm^{-2}s^{-1}] (2 IPs)	277	42	11.0	2.6
τ_{beam} [min] (2 IPs)	60	41	31	28

layout & optics at 120 & 175 GeV

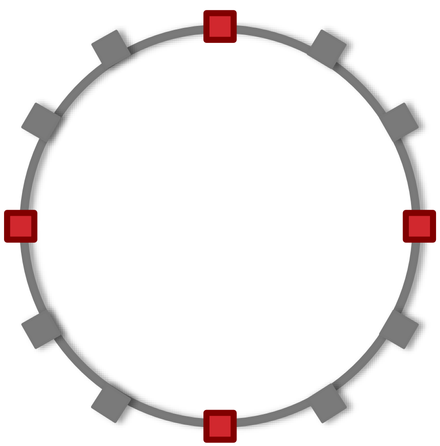
LATTICE V12B-S

arc cell

layout

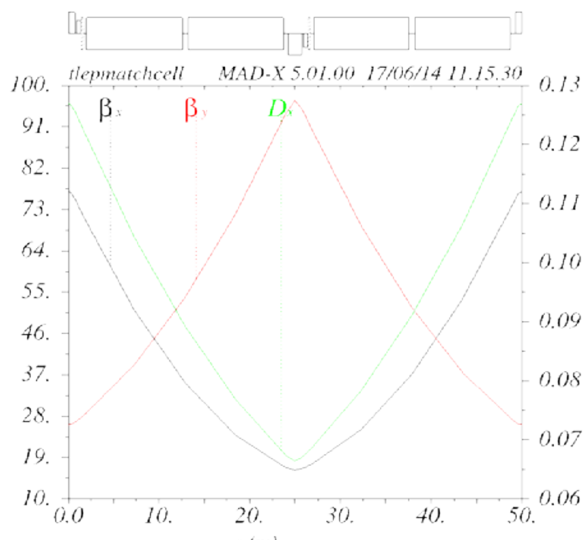


B = bending magnet, Q = quadrupole, S = sextupole

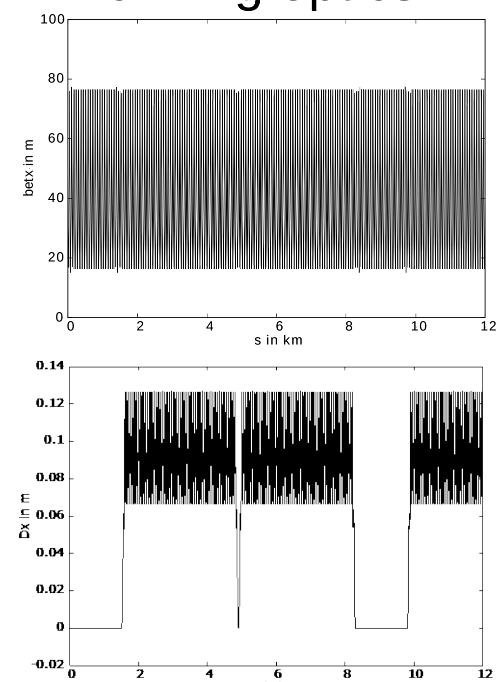


Circumference: 100 km
Arc length: 2 × 3.4 km
Straight section: 1.5 km

FODO cell optics
cell length 50 m



full ring optics



B. Harer, B. Holzer

optics 175 & 120 → 80 & 45.5 GeV

80 GeV

175 GeV and 120 GeV: L_{cell} = 50 m, Ψ = 90°/60°

Half-bend dispersion suppressor

80 GeV: L_{cell} = 50 m, Ψ = 45°/45°

Dispersion suppressor based on quadrupoles

80 GeV: L_{cell} = 100 m, Ψ = 90°/60°

- Arc cells
- Dispersion Suppressor
- Straight matching section (with RF)
- Straight cells (with RF)

45.5 GeV

175 GeV and 120 GeV: L_{cell} = 50 m, Ψ = 90°/60°

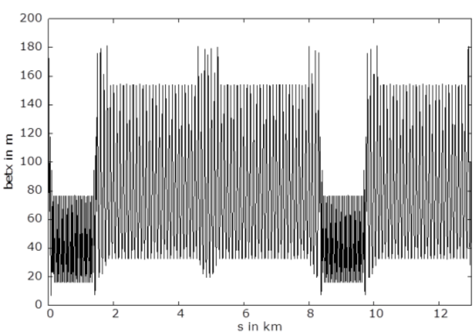
45.5 GeV: L_{cell} = 200 m, Ψ = 60°/60°

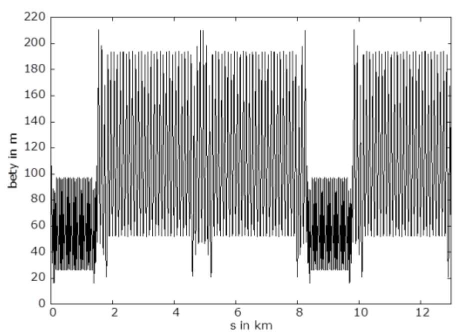
Dispersion suppressor based on quadrupoles

45.5 GeV: L_{cell} = 250 m, Ψ = 72°/72°

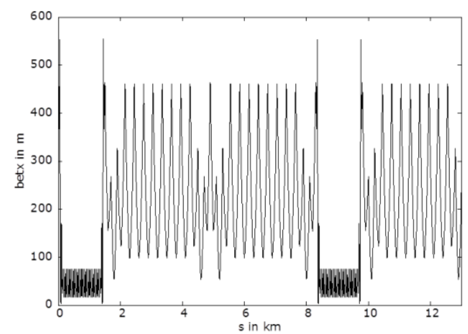
45.5 GeV: L_{cell} = 300 m, Ψ = 90°/60°

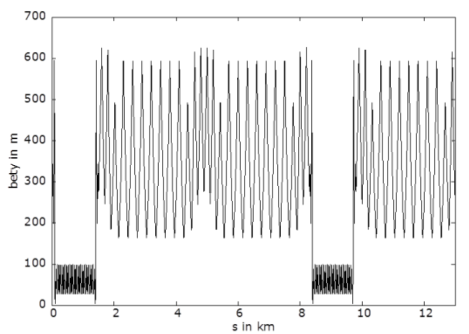
example: 100 m cell length





example: 300 m cell length





B. Harer, B. Holzer

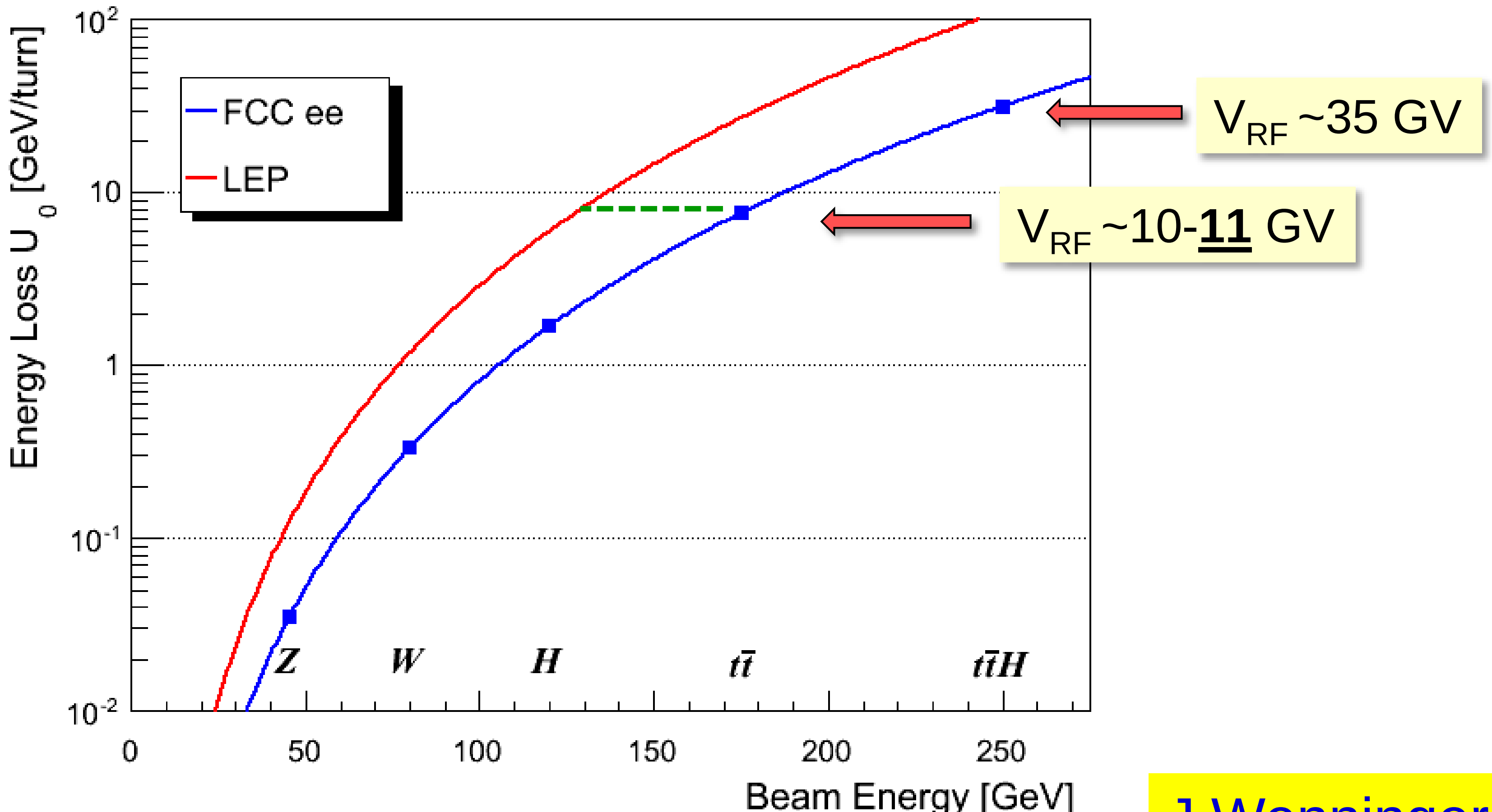
all emittances $\varepsilon_x \leq 0.5$ baseline

Synchrotron radiation power

The maximum synchrotron radiation (SR) power P_{SR} is set to **<u>50 MW per beam</u>** – design choice ⇔ power dissipation.

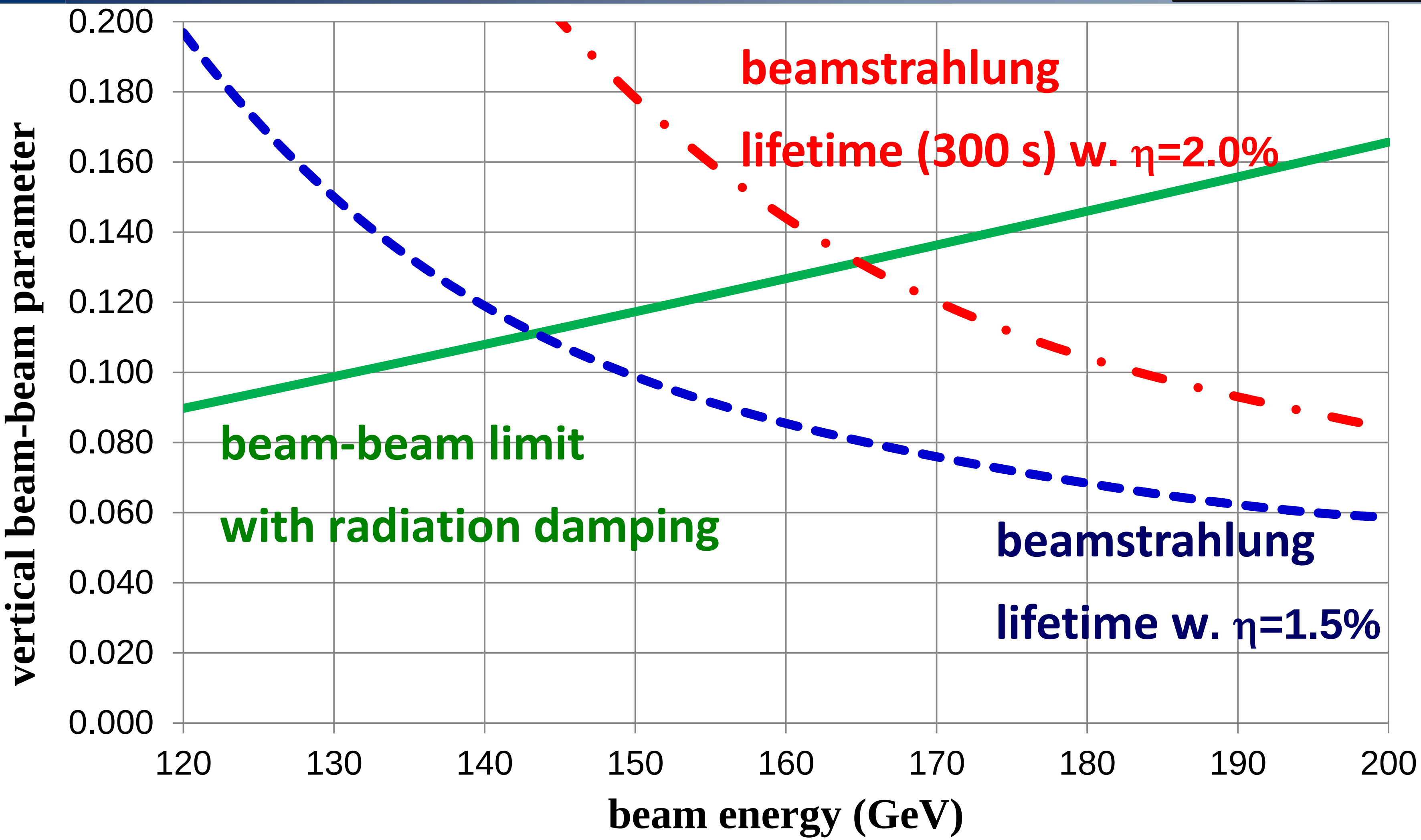
⇒ *defines the maximum beam current at each energy.*

Note that a margin of a few % is required for losses in straight sections.



J.Wenninger

beam-beam limits: 2 regimes

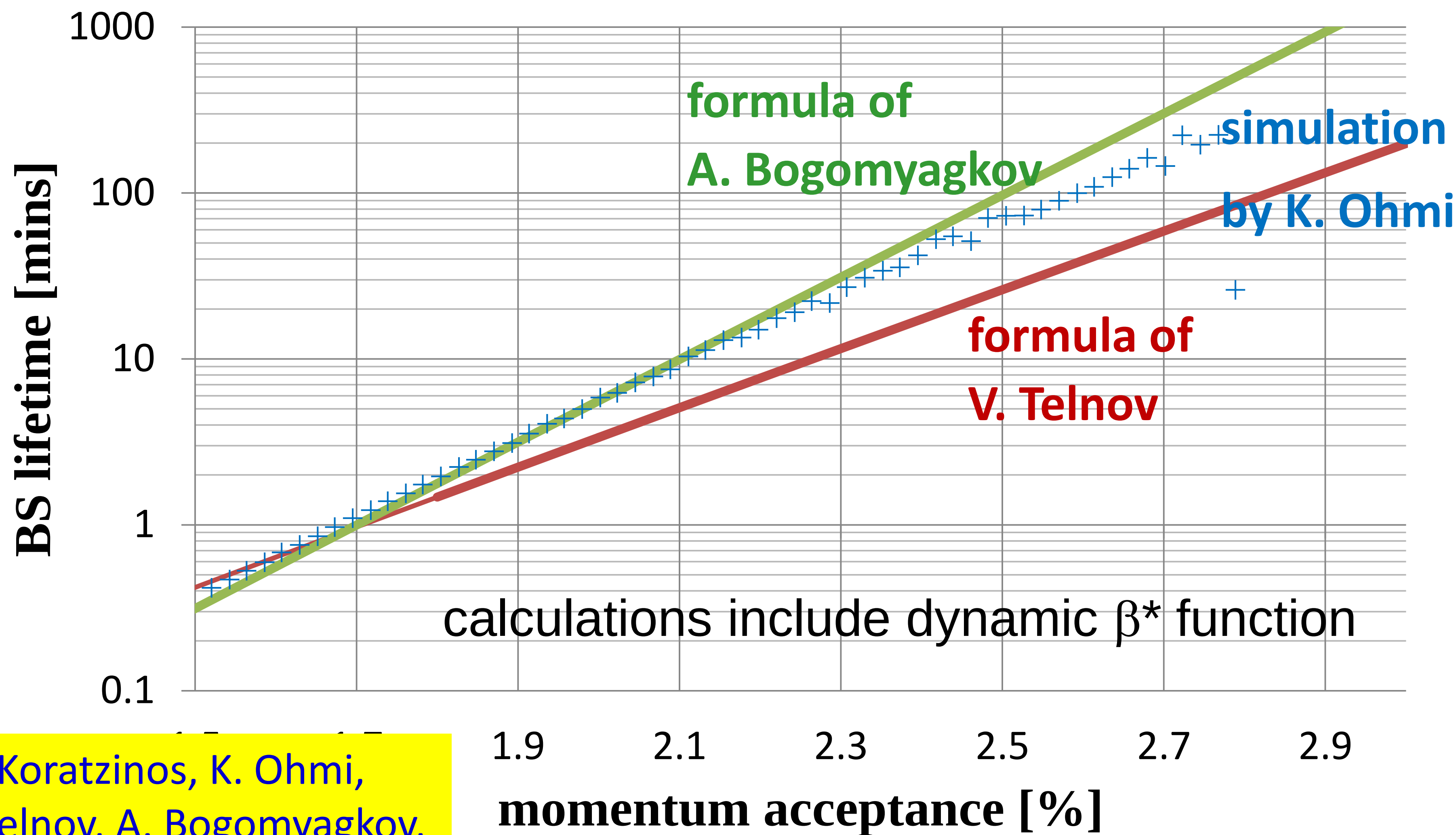


ε_y = 2 pm,
β_y^* = 1 mm

M. Koratzinos, A. Bogomyagkov, E. Levichev, D. Shatilov, K. Yokoya, V. Telnov, K. Oide, …

beamstrahlung lifetime

FCC-ee, E_{beam} =175 GeV (most critical case)



M. Koratzinos, K. Ohmi,
V. Telnov, A. Bogomyagkov,
E. Levichev, D. Shatilov

IR parameters

smallest possible β^* desired; target β^*_y = **1 mm**; so small a value of β^* requires local chromaticity correction

- *design inspired by linear collider IR;*
- *additional complexity that beam does not pass the IR only once → effects of optical aberrations critical*
- *bending magnets close to the IP → SR fan !*

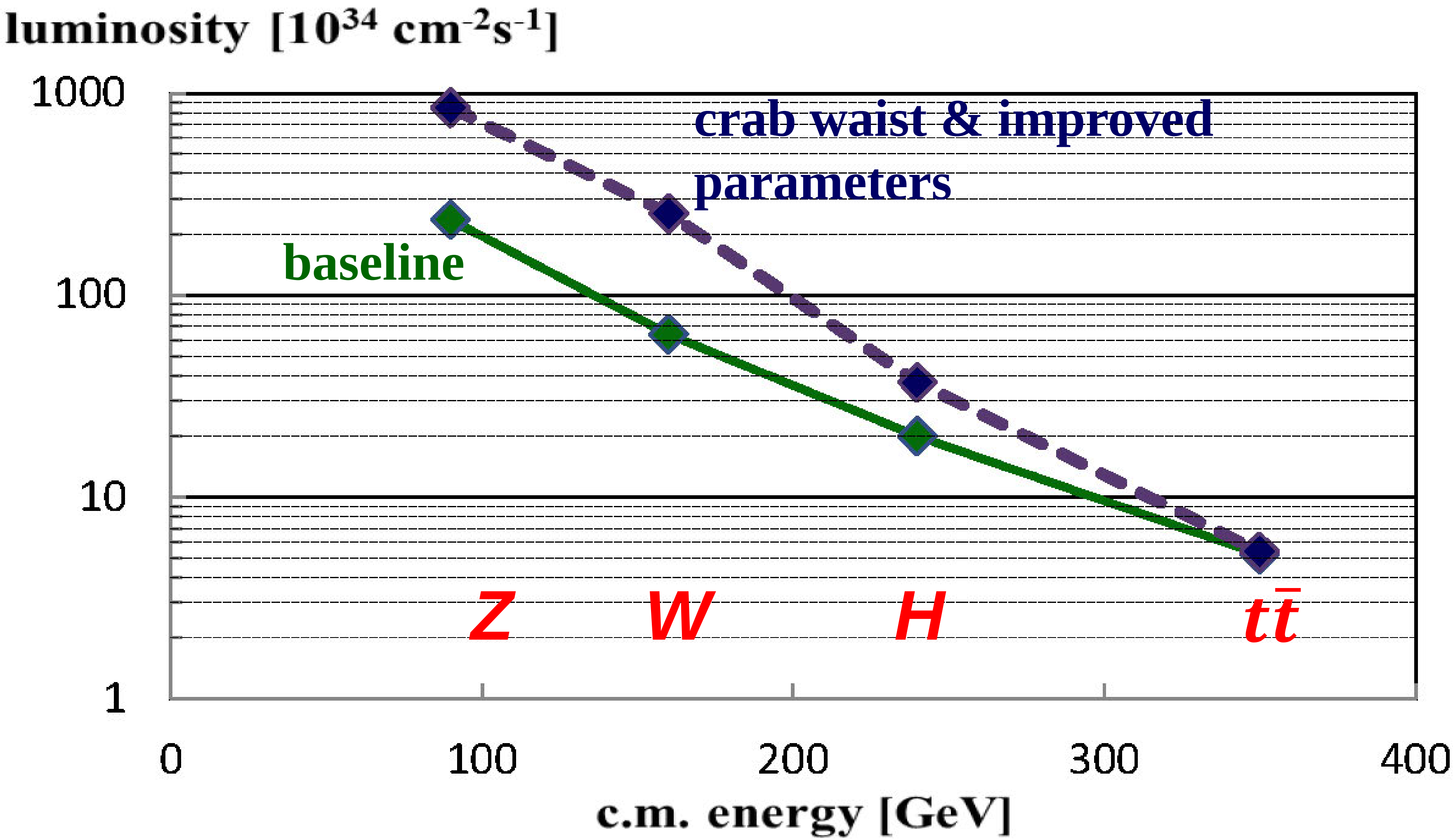
distance between IP and front-face of first quadrupole currently set to **L* ≥ 2 m** (SuperKEKB ~1 m)

- *detector acceptance, luminosity measurement,… .*

combination of very small β_y^* and required large energy acceptance is challenge for optics design !

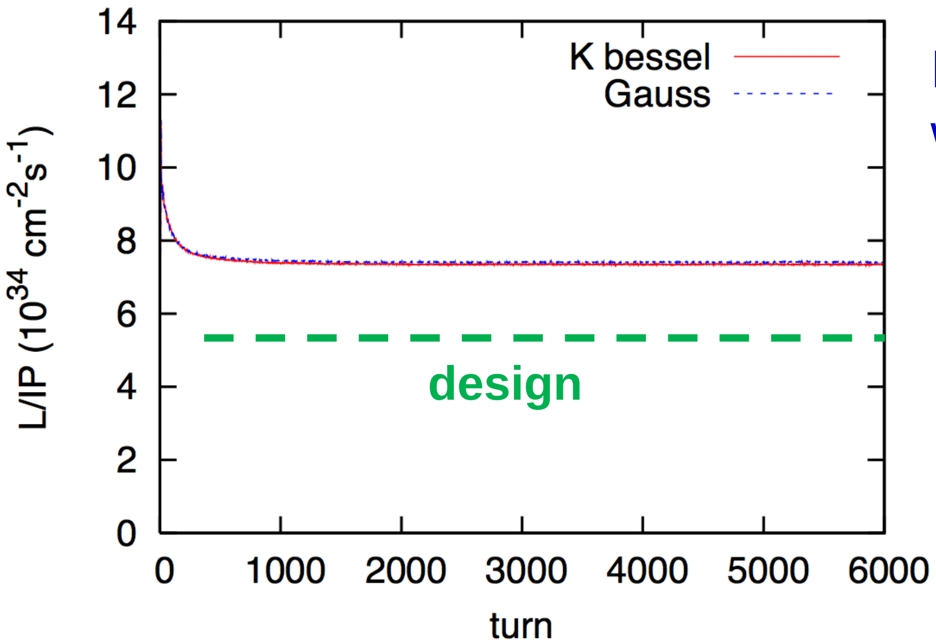
J. Wenninger, R. Tomas,…

FCC-ee luminosity vs energy



A. Bogomyagkov, E. Levichev, D. Shatilov

beam-beam performance checks

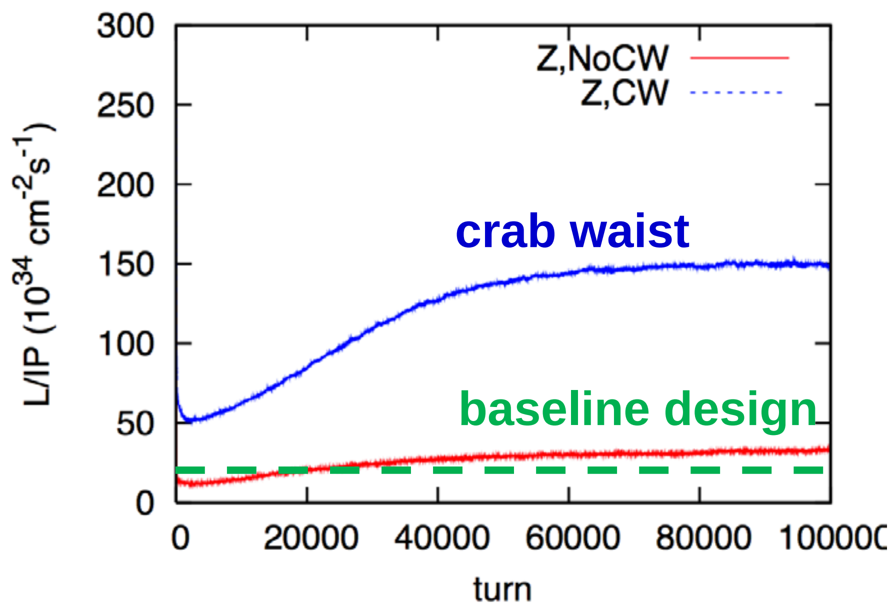


BBSS strong-strong simulation
w beamstrahlung

FCC-ee in Higgs production mode (240 GeV c.m.):
$L \approx 7.5 \times 10^{34}$ cm^{-2}s^{-1} per IP

BBWS weak-strong simulation
w beamstrahlung

FCC-ee in crab-waist mode at the Z pole (91 GeV c.m.):
$L \approx 1.5 \times 10^{36}$ cm^{-2}s^{-1} per IP



K. Ohmi, A. Bogomyagkov, E. Levichev, P. Piminov

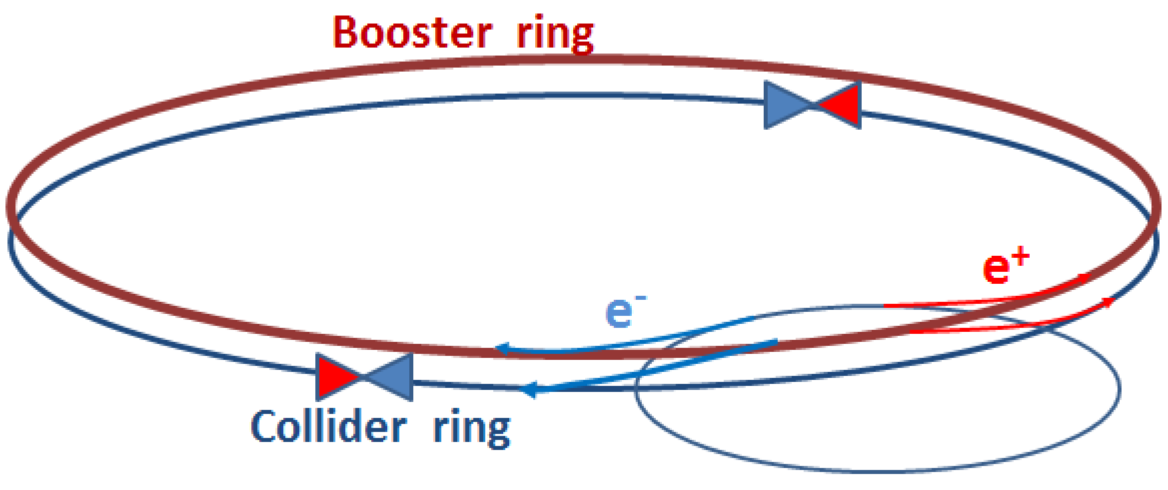
FCC-ee injection

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

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

injector complex for e^+ and e^- beams of 10-20 GeV

- Super-KEKB injector ~ almost suitable



A. Blondel

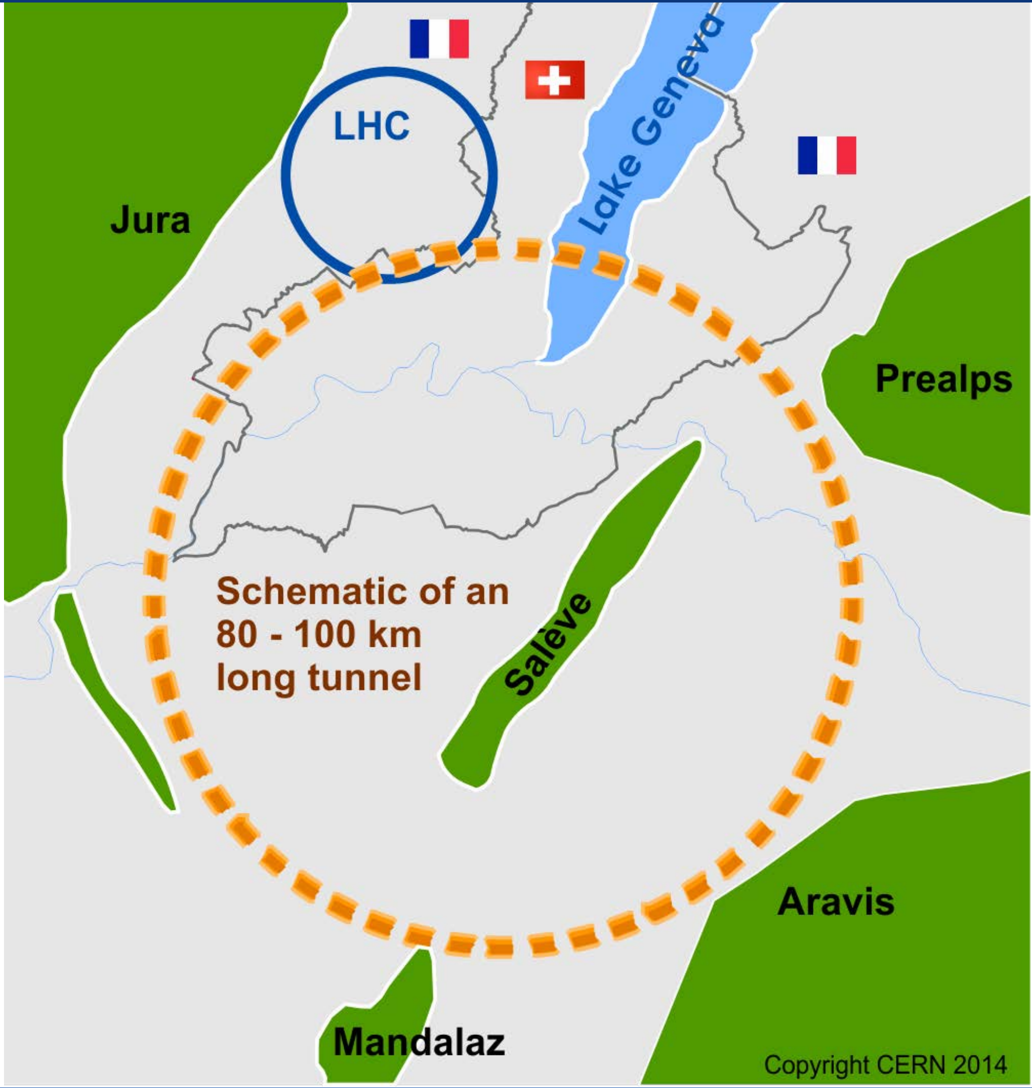
Future Circular Collider Study - SCOPE
CDR and cost review for the next ESU (2018)

Forming an international collaboration to study:

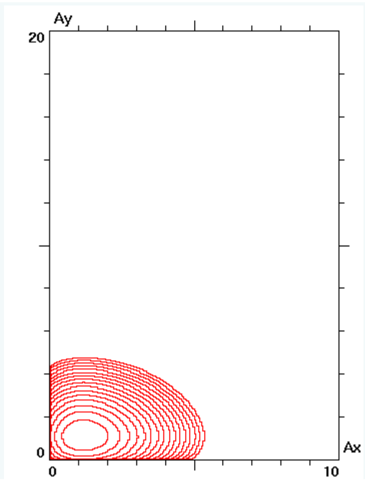
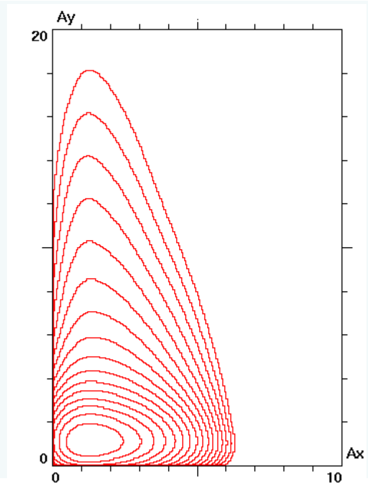
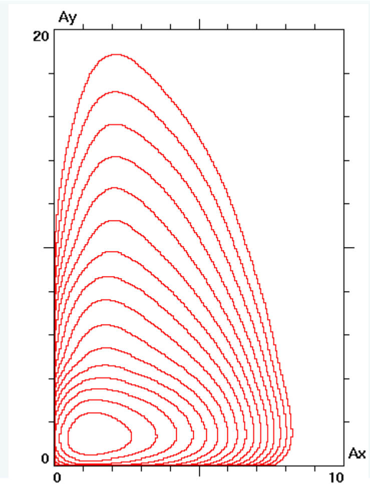
- *pp*-collider (*FCC-hh*) → main emphasis, defining infrastructure requirements

~16 T ⇒ 100 TeV *pp* in 100 km

- 80-100 km infrastructure in Geneva area
- **e^+e^- collider (*FCC-ee*) as potential intermediate step**
- *p-e* (*FCC-he*) option



beam-beam simulations

	Crab Waist	Head-on	Crossing (11 mrad)
RF voltage [GV]	2.3	5.5	5.5
RF frequency [MHz]	400	800	800
Tunes $\nu_x / \nu_y / \nu_s$	0.54 / 0.57 / 0.009	0.54 / 0.61 / 0.0255	0.52 / 0.57 / 0.0255
Bunch length [mm]	2.76 / 6.77	0.98 / 1.47	0.98 / 1.62
Bunch population	3.[illegible]	[illegible]	[illegible]^{10}
Footprint size $\Delta\nu_x / \Delta\nu_y$	0.01[illegible]	[illegible]	[illegible].104
Lifetime bb+bs [min]	17	120	200
Luminosity [cm^{-2}s^{-1}]	$9.8 \cdot 10^{34}$	$7.2 \cdot 10^{34}$	$5.8 \cdot 10^{34}$
Luminosity (β_y = 2 mm)	$8.3 \cdot 10^{34}$	$6.8 \cdot 10^{34}$	$5.0 \cdot 10^{34}$
Density contour plots			

The beam-beam limit may further be raised with Crab-Waist schemes !

D. Shatilov

parameter	LEP2	FCC-ee				
		Z	Z (c.w.)	W	H	t
E_{beam} [GeV]	104	**45**	**45**	**80**	**120**	**175**
circumference [km]	26.7	**100**	**100**	**100**	**100**	**100**
current [mA]	3.0	1450	1431	152	30	6.6
$P_{SR,tot}$ [MW]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
no. bunches	4	16700	29791	4490	1360	98
N_b [10^{11}]	4.2	1.8	1.0	0.7	0.46	1.4
ε_x [nm]	22	29	0.14	3.3	0.94	2
ε_y [pm]	250	60	1	1	2	2
β^*_x [m]	1.2	0.5	0.5	0.5	0.5	1.0
β^*_y [mm]	50	1	1	1	1	1
σ^*_y [nm]	3500	250	32	84	44	45
$\sigma_{z,SR}$ [mm]	11.5	1.64	2.7	1.01	0.81	1.16
$\sigma_{z,tot}$ [mm] (w beamstr.)	11.5	2.56	5.9	1.49	1.17	1.49
hourglass factor F_{hg}	0.99	0.64	0.94	0.79	0.80	0.73
L/IP [10^{34} $cm^{-2}s^{-1}$]	0.01	**28**	**212**	**12**	**6**	**1.7**
τ_{beam} [min]	434	**298**	**39**	**73**	**29**	**21**

the large number of bunches at *Z*, *W* & *H* requires 2 rings

FCC-ee baseline parameters defined in EDMS No. 1346081, FCC-ACC-SPC-0003 (Rev. 2.0)

short lifetimes due to high luminosity → continuous injection (top-up)

parameter	LEP2	FCC-ee				
		Z	Z (c.w.)	W	H	t
E_{beam} [GeV]	104	45	45	80	120	175
beam-beam par. ξ_y/IP	0.06	0.03	0.175	0.06	0.093	0.092
current [mA]	3.0	1450	1431	152	30	6.6
$P_{SR,tot}$ [MW]	22	100	100	100	100	100
no. bunches	4	16700	29791	4490	1360	98
N_b [10^{11}]	4.2	1.8	1.0	0.7	0.46	1.4
ε_x [nm]	22	29	0.14	3.3	0.94	2
ε_y [pm]	250	60	1	1	2	2
β^*_x [m]	1.2	0.5	0.5	0.5	0.5	1.0
β^*_y [mm]	50	1	1	1	1	1
σ^*_y [nm]	3500	250	32	84	44	45
$\sigma_{z,SR}$ [mm]	11.5	1.64	2.7	1.01	0.81	1.16
$\sigma_{z,tot}$ [mm] (w beamstr.)	11.5	2.56	5.9	1.49	1.17	1.49
hourglass factor F_{hg}	0.99	0.64	0.94	0.79	0.80	0.73
L/IP [10^{34} cm^{-2}s^{-1}]	0.01	28	212	12	6	1.7
τ_{beam} [min]	434	298	39	73	29	21

FCC-ee baseline parameters defined in EDMS No. 1346081, FCC-ACC-SPC-0003 (Rev. 2.0)