

# 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, 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

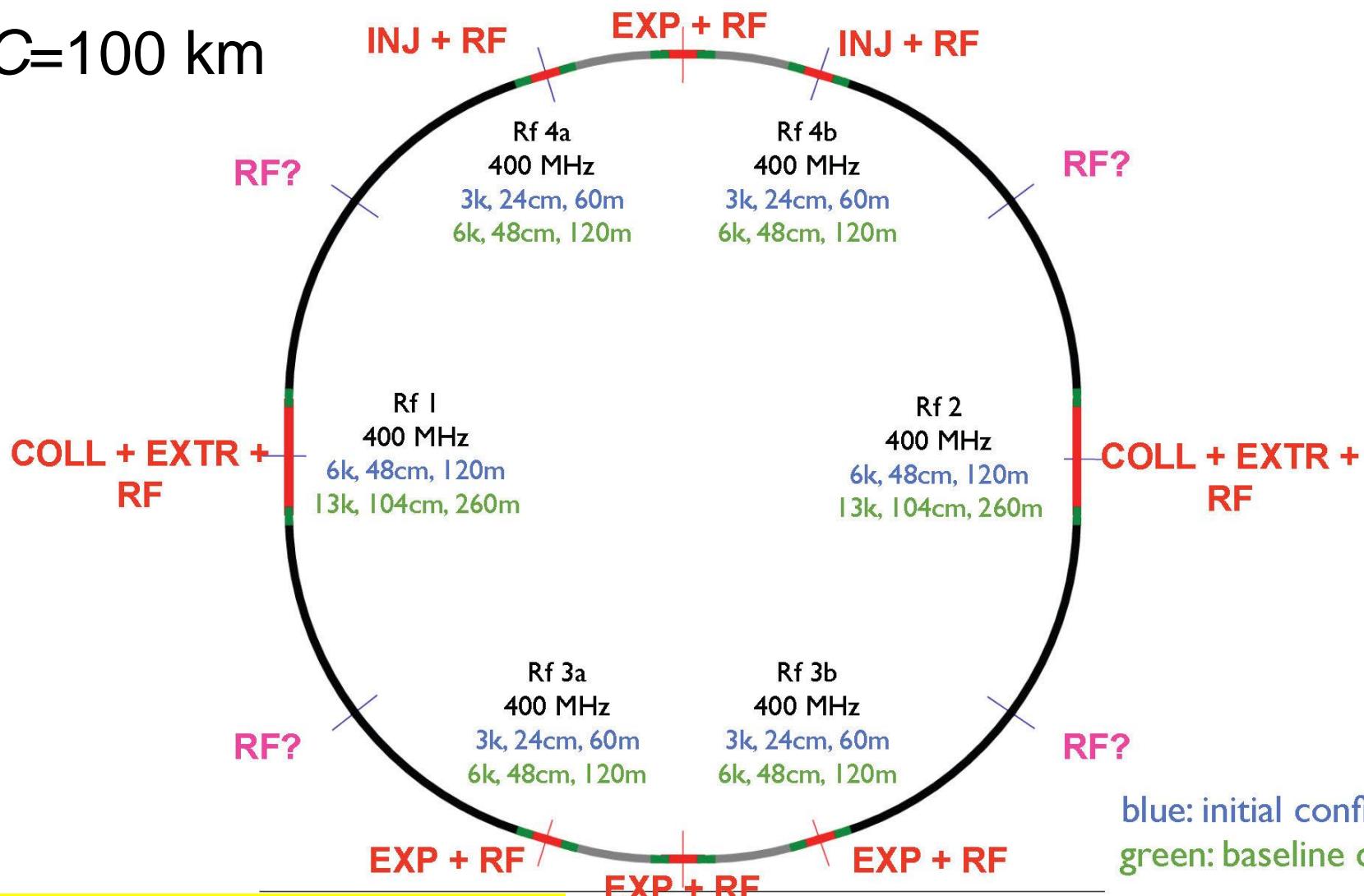


# physics requirements for FCC-ee

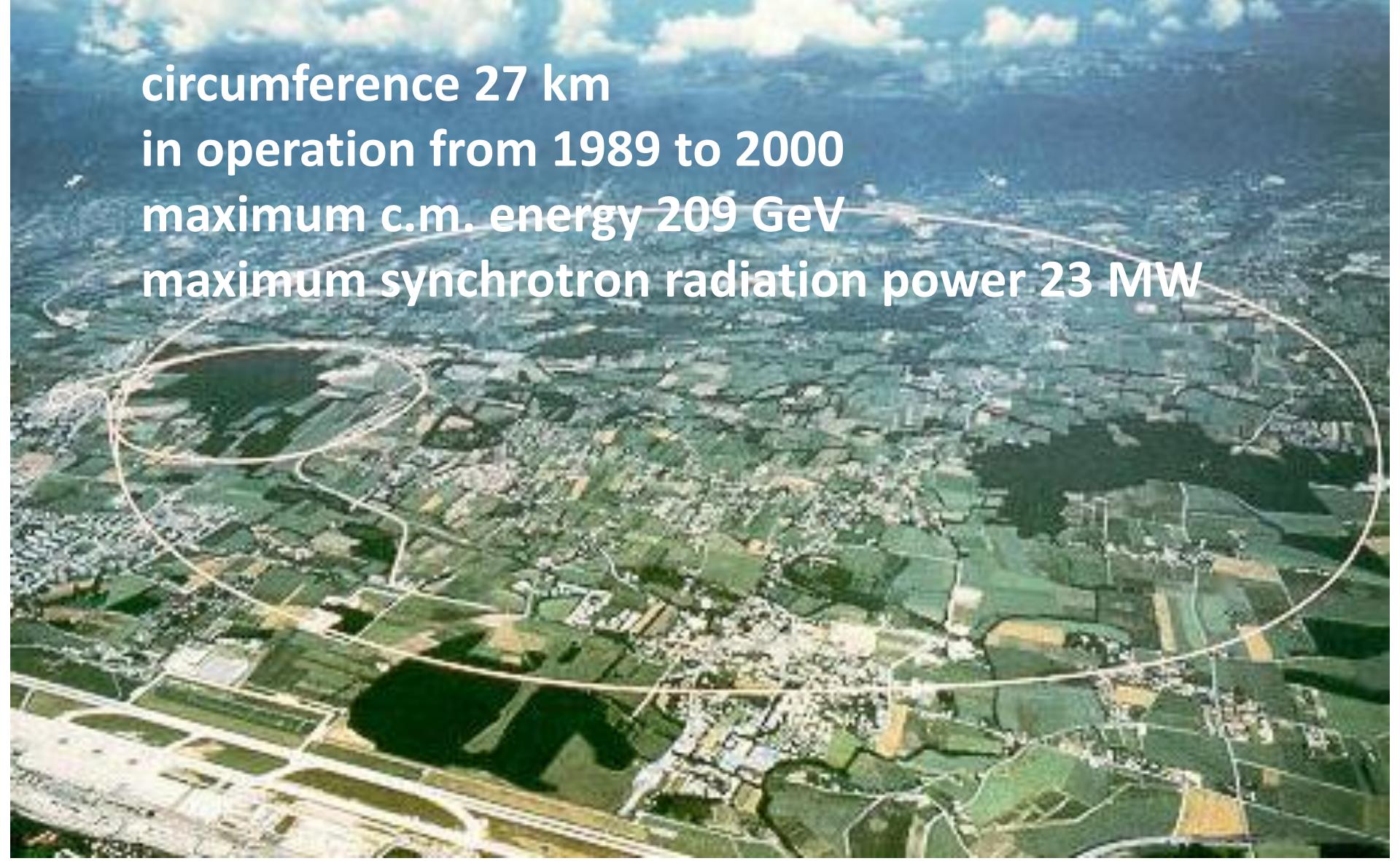


- highest possible luminosity
- *beam energy range from 45 GeV to 175 GeV*
- main physics programs / energies:
  - *Z (45.5 GeV): Z pole, ‘TeraZ’ and high precision  $M_Z$  &  $\Gamma_Z$ ,*
  - *W (80 GeV): W pair production threshold, high precision  $M_W$*
  - *H (120 GeV): ZH production (maximum rate of H’s),*
  - *t (175 GeV): tt} threshold*
- some polarization up to  $\geq 80$  GeV for beam energy calibration
- optimized for operation at 120 GeV?! (2<sup>nd</sup> priority “Tera-Z”)

$C=100$  km

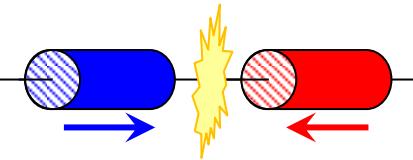


# LEP – highest energy $e^+e^-$ collider so far

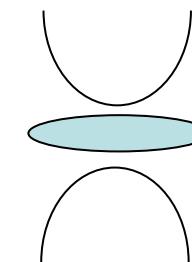
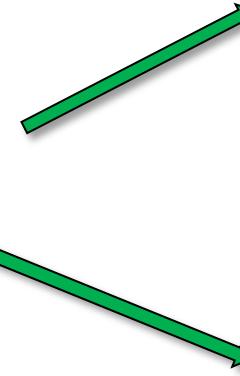


circumference 27 km  
in operation from 1989 to 2000  
maximum c.m. energy 209 GeV  
maximum synchrotron radiation power 23 MW

$$efkN = \text{beam current} \propto \frac{1}{E^4}$$



$$L = \frac{fkN^2}{4\pi\sigma_x\sigma_y} FH$$

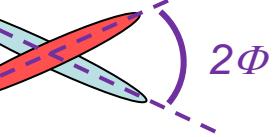


$H \leq 1$

Hour-glass

$F \leq 1$

Crossing angle



$\sigma$  = beam size

$k$  = no. bunches

$f$  = rev. frequency

$N$  = bunch population

$P_{SR}$  = synch. rad. power

$\beta^*$  = betatron fct at IP

(beam envelope)

$$\xi_y \propto \frac{\beta_y^* N}{E\sigma_x\sigma_y} \leq \xi_y^{\max}(E) \quad \text{Beam-beam parameter}$$

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

# luminosity scaling: damping

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

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

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

FCC-ee  
vs LEP

$\rightarrow$

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

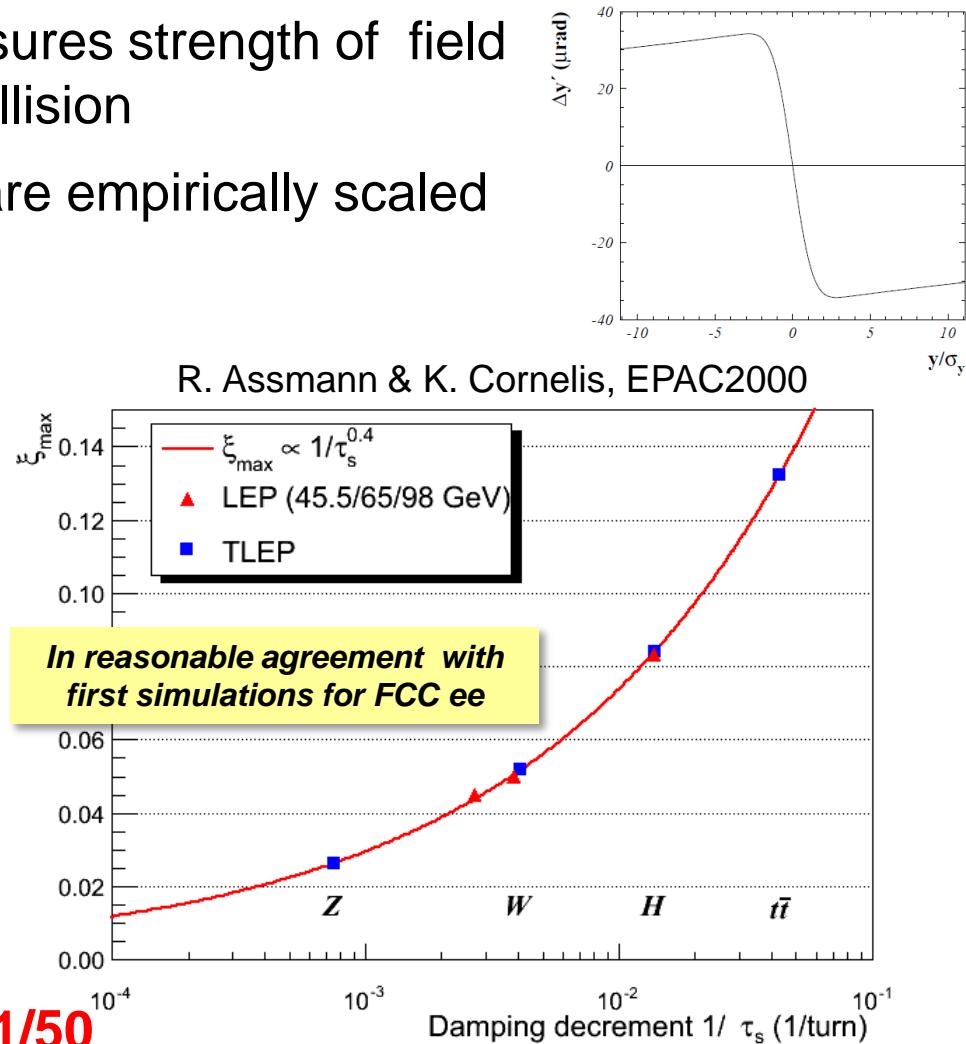
x4.5

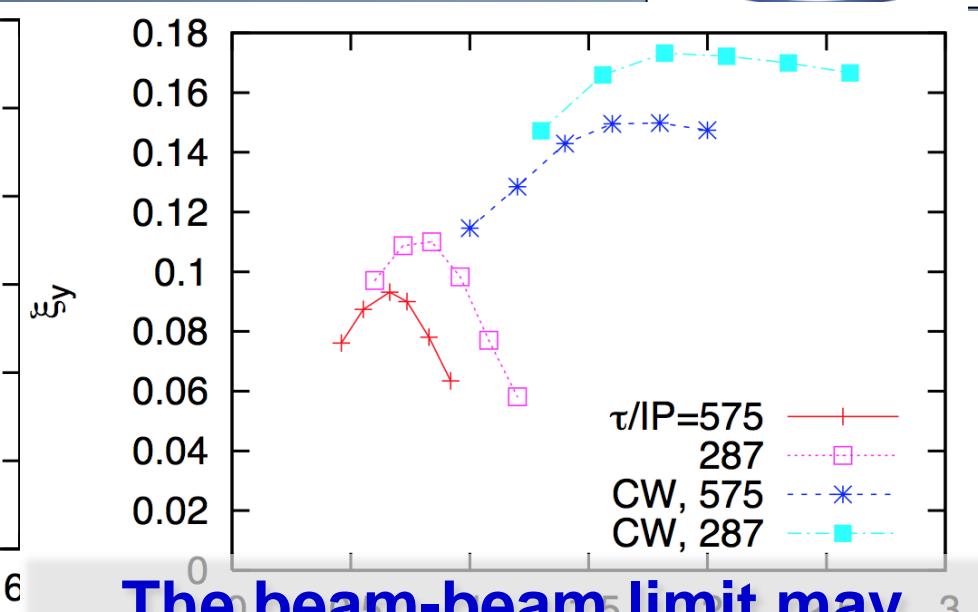
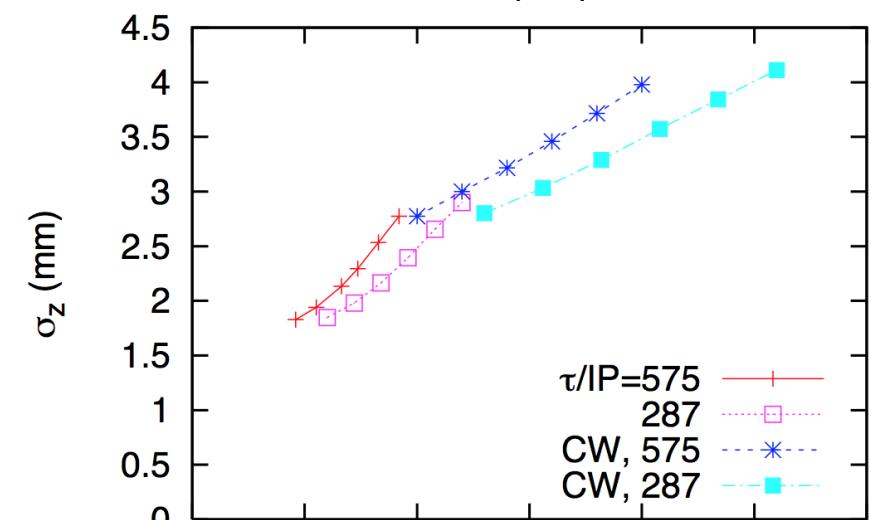
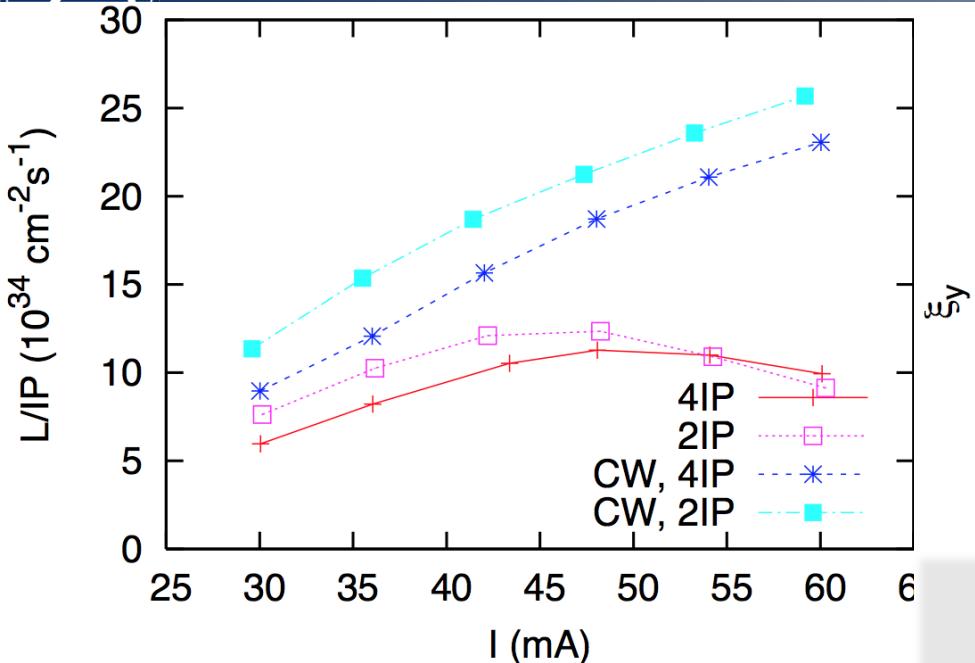
x4

$<\!x2$

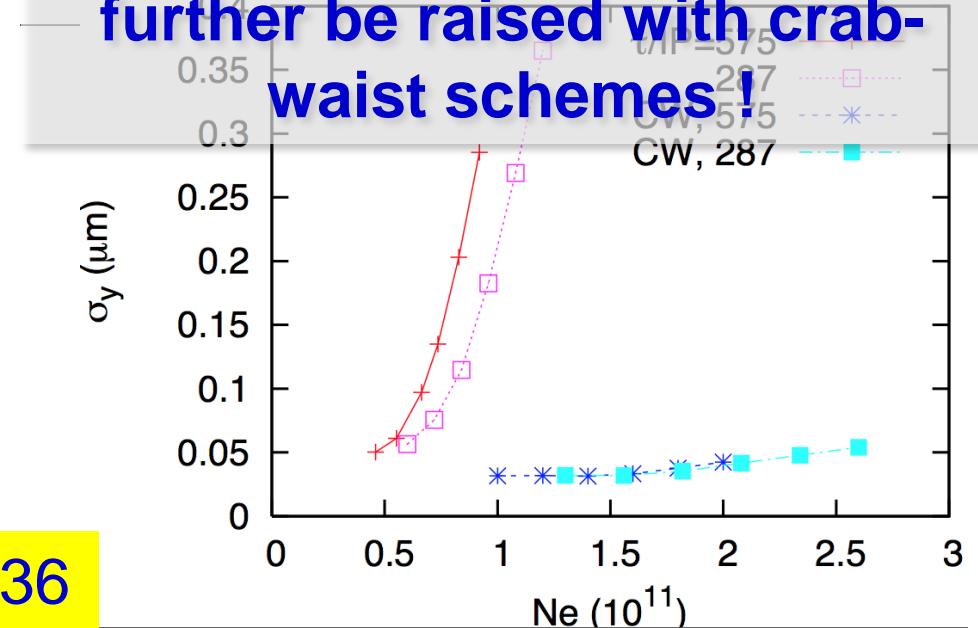
x1/50

→ extremely high luminosity

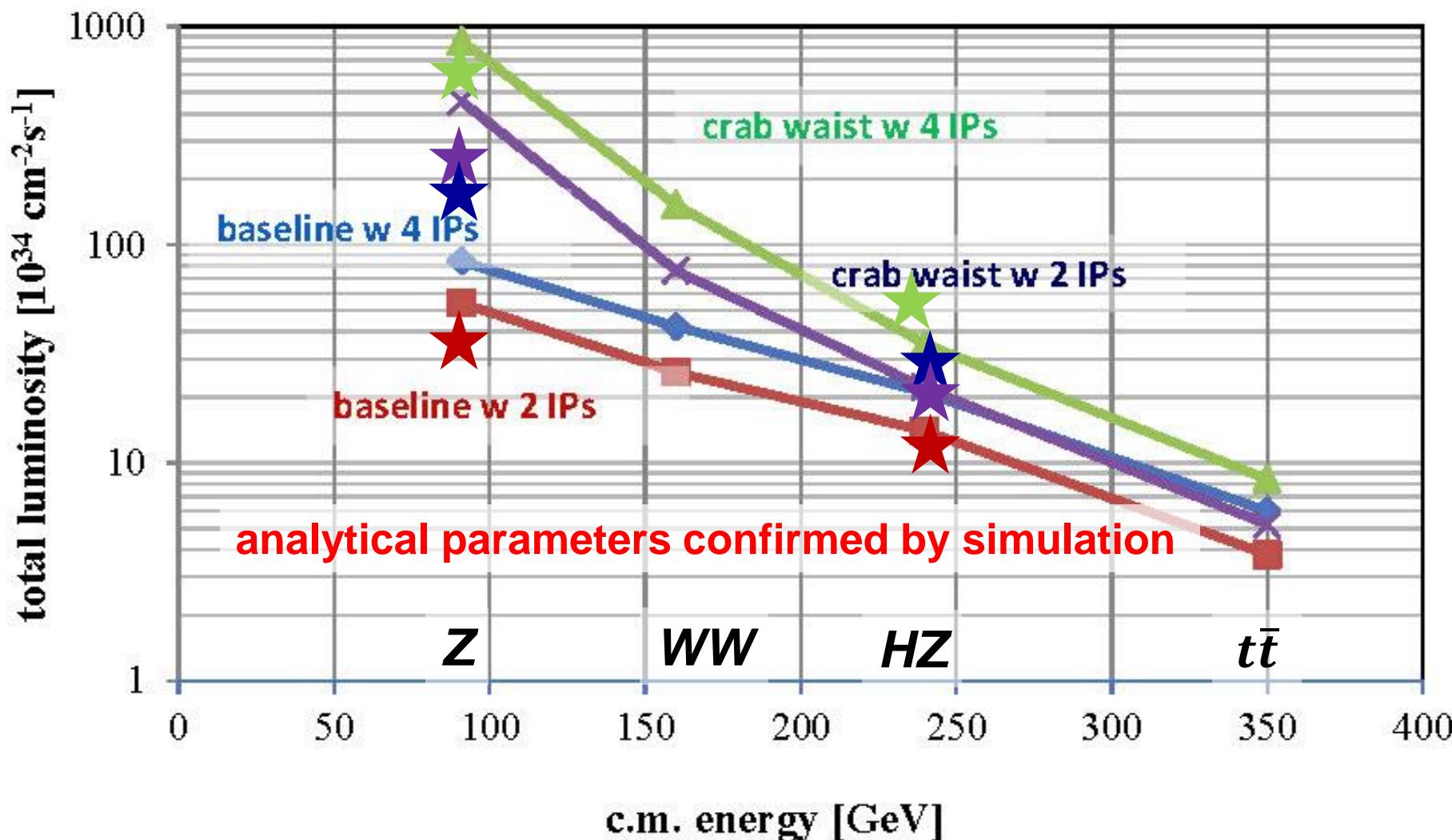




The beam-beam limit may further be raised with crab-waist schemes!



## luminosity vs c.m. energy



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

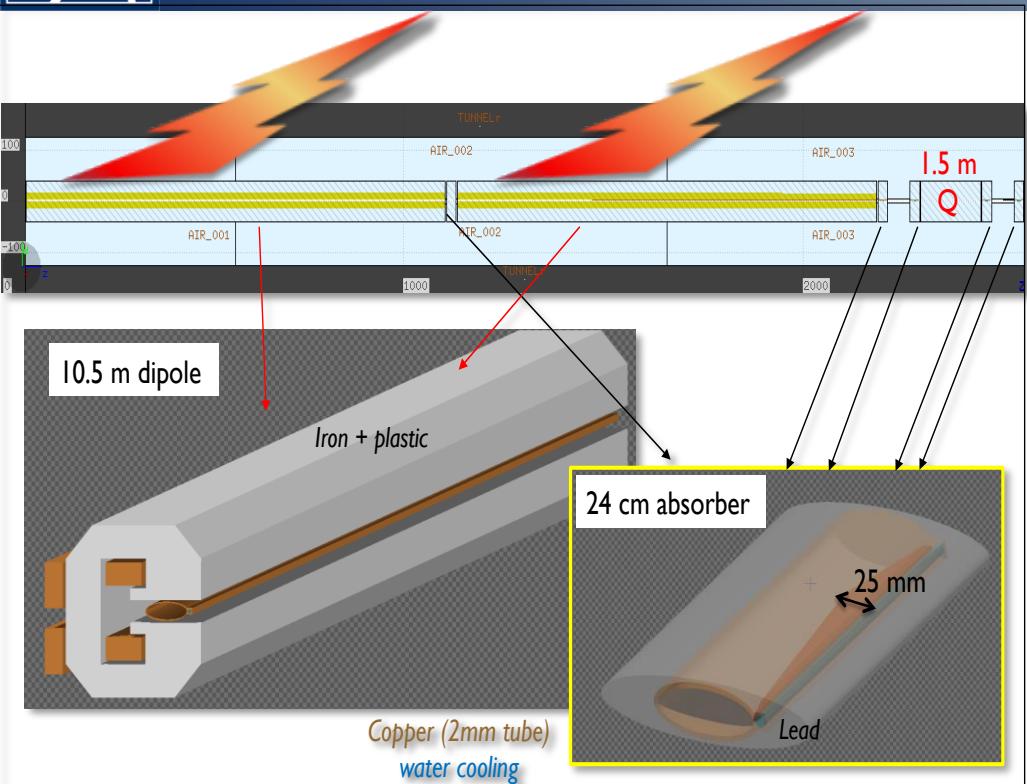


# preliminary FCC-ee parameters

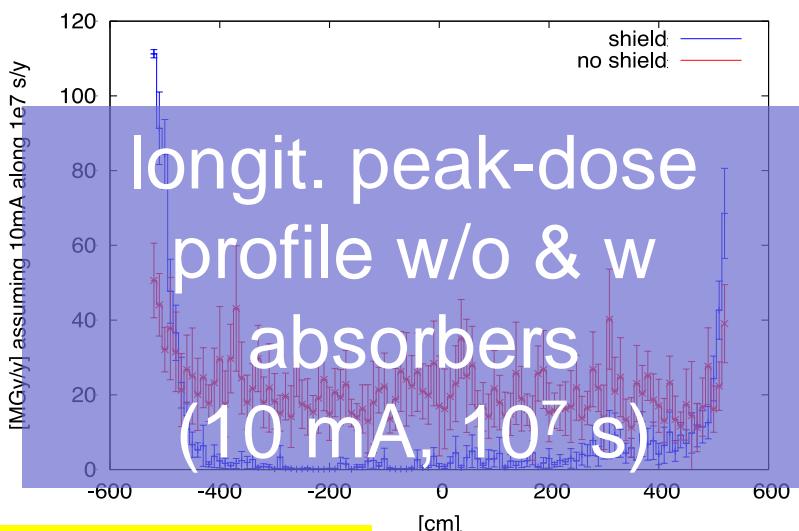
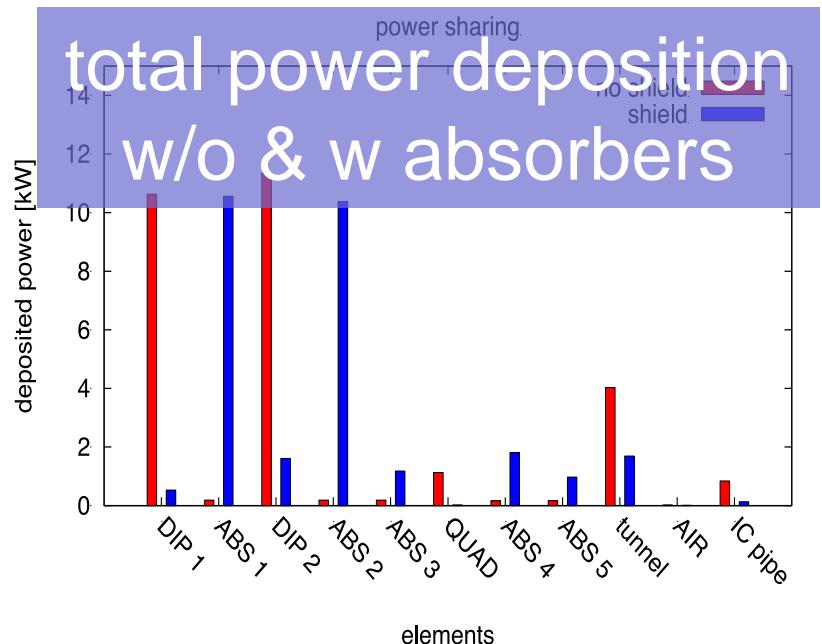
parameter	FCC-ee	LEP2
energy/beam	45 – 175 GeV	105 GeV
bunches/beam	<b>50 – 60000</b>	4
beam current	<b>6.6 – 1450 mA</b>	3 mA
hor. emittance	<b>~2 nm</b>	~22 nm
emittance ratio $\varepsilon_y/\varepsilon_x$	<b>0.1%</b>	1%
vert. IP beta function $\beta_y^*$	<b>1 mm</b>	50 mm
luminosity/IP	<b>1.5-280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





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

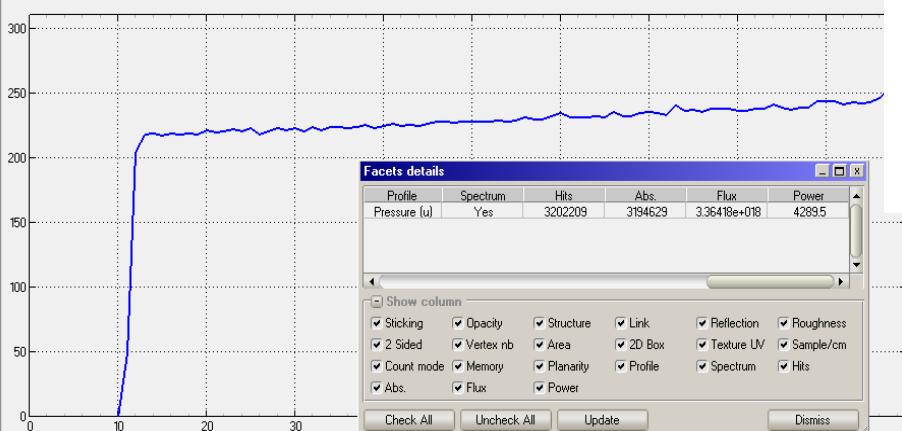


# vacuum chamber w photon stops

Synrad+ 1.3.4 (Mar 4 2015) [FCCeeZCell\_NewLatticeCu\_ABS.syn7z]

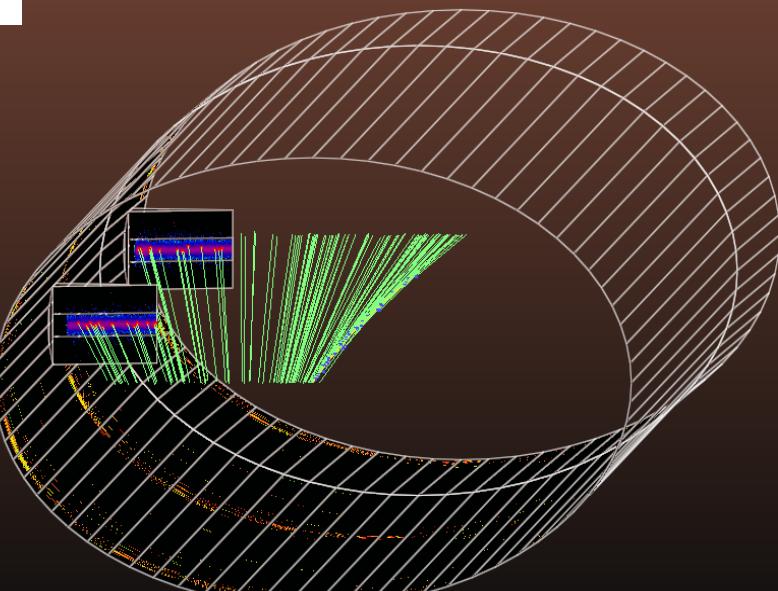
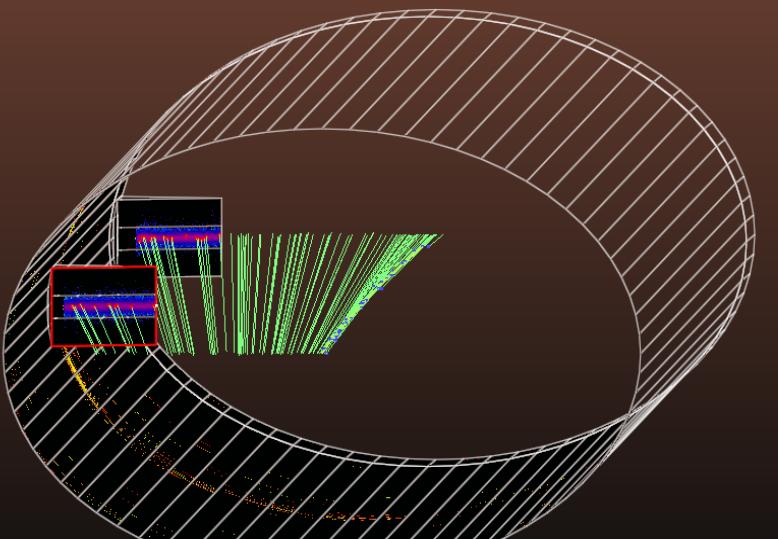
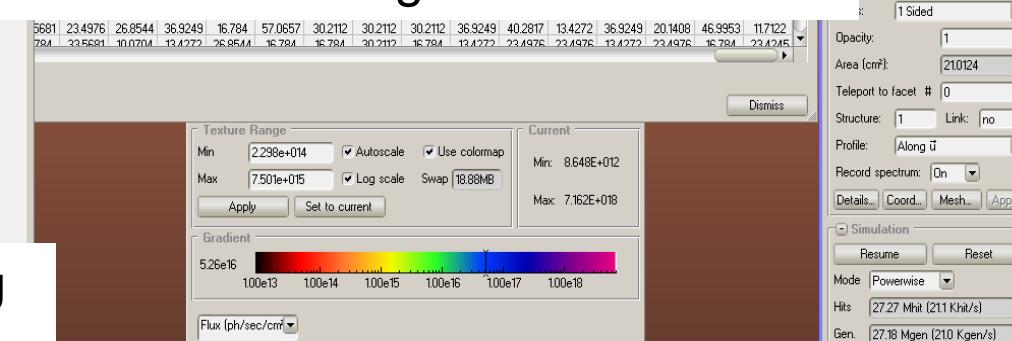
File Regions Selection Tools Facet Vertex View Test

Profile plotter



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

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



MFP 3504.79  
MPP 3515.49  
N. Reflections 100305



# 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
- $I_{beam} = 30 \text{ mA}$

### Z, high beam current

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

**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**

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

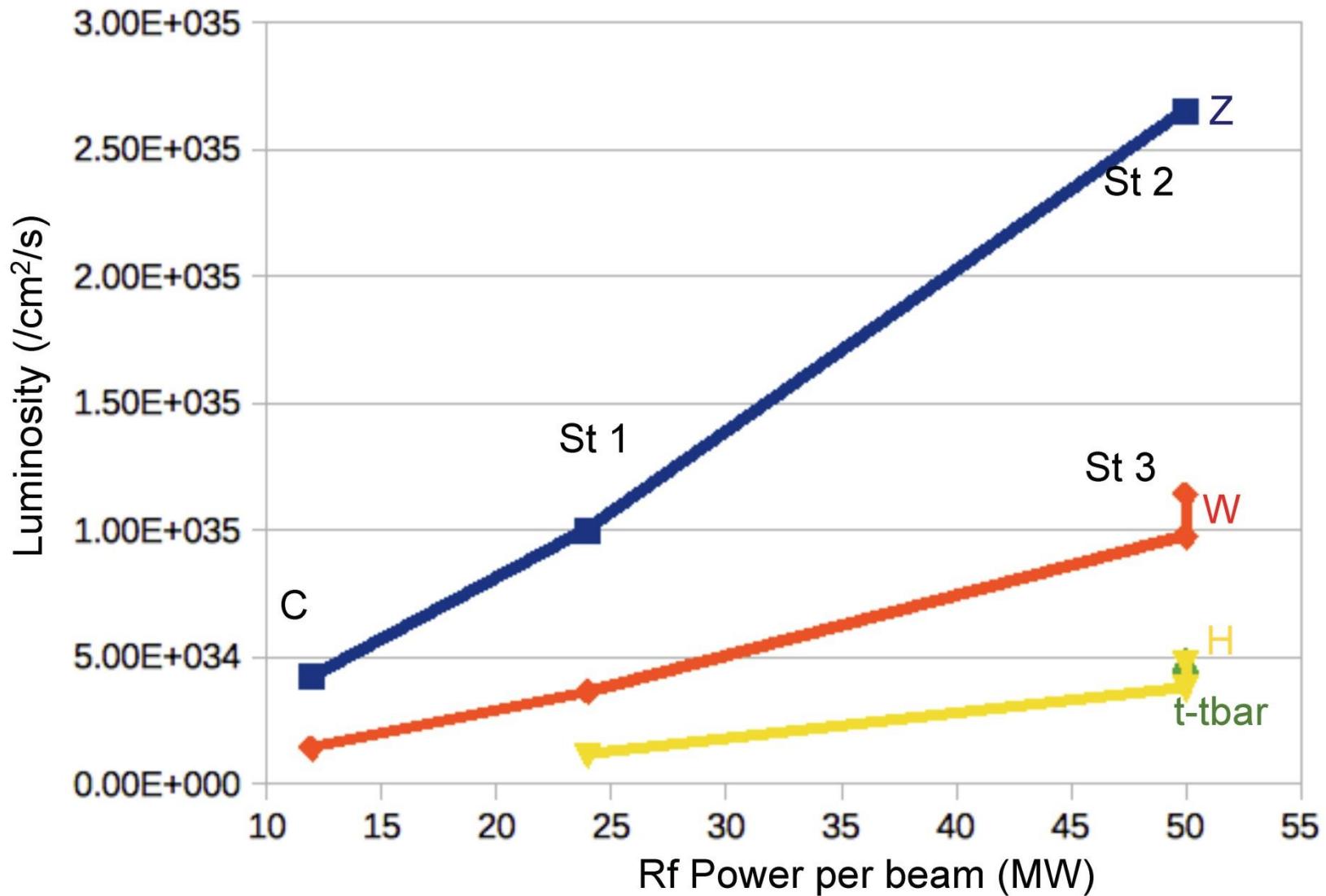
**input power ≈ 40 kW / cell**

- << state of the art FPC, alternative powering schemes (e.g. SSAs, IOTs)
- variable  $Q_{ext}$  range ( $1 \cdot 10^6 - 5 \cdot 10^6$  considering **2x2 cell cavities**,  $R/Q = 100$ )

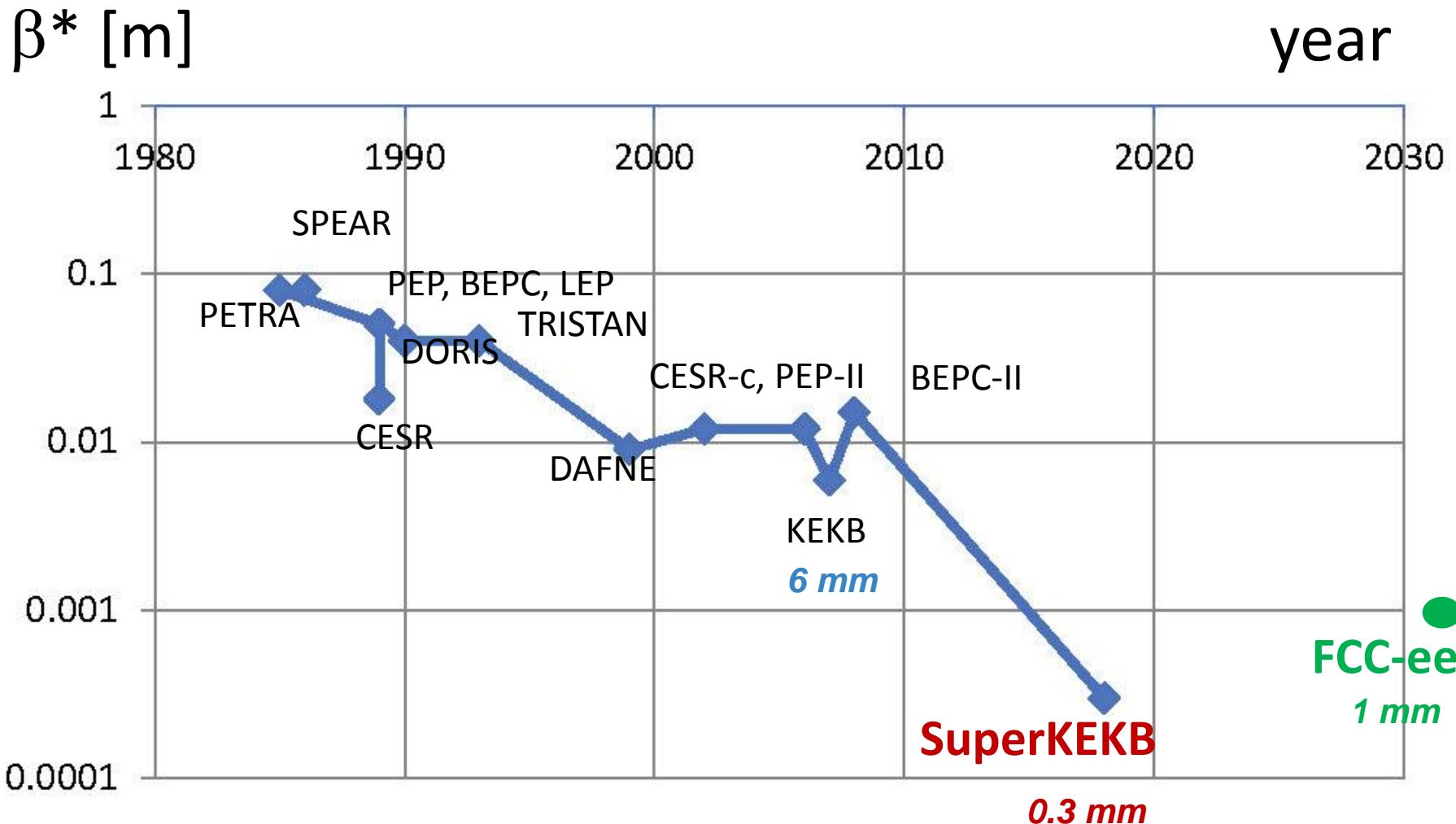
**$P_{HOM} \leq 5 \text{ kW/cell}$  at the Z pole**

→ **efficient RF power sources**

- bunch length, cavity shape, HOM damper design



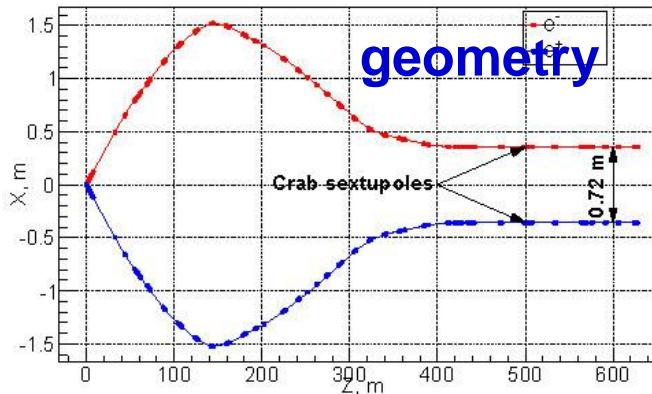
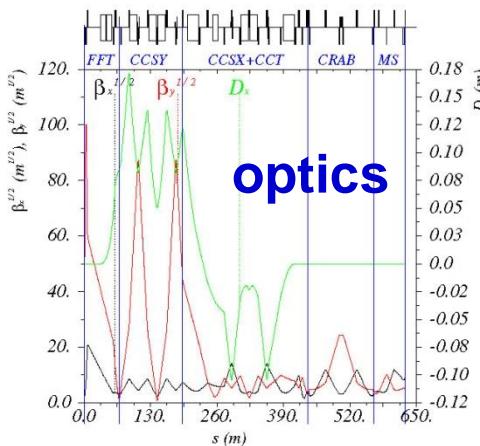
# $\beta_y^*$ evolution over 40 years



entering a new regime for ring colliders –  
SuperKEKB will pave the way towards  $\beta^* \leq 1$  mm

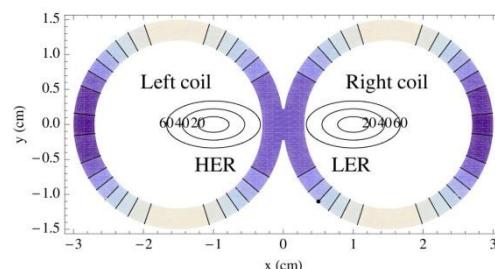
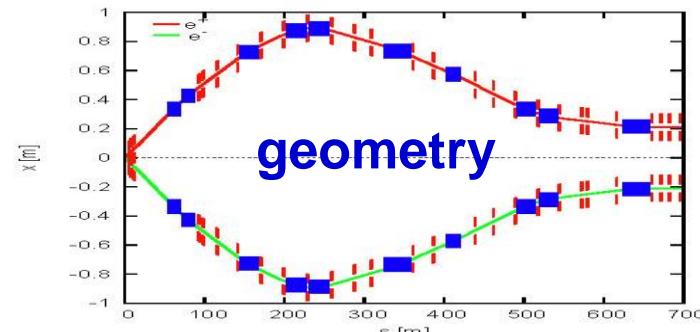
# IR design approaches

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



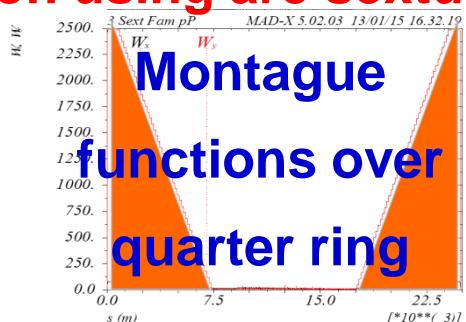
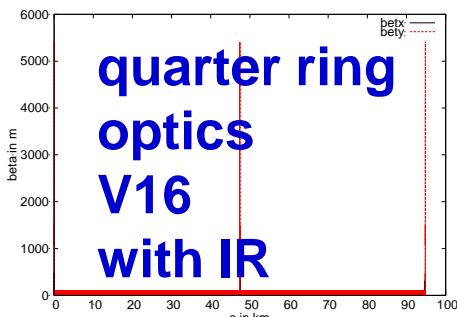
A. Bogomyagkov  
et al.

**(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**

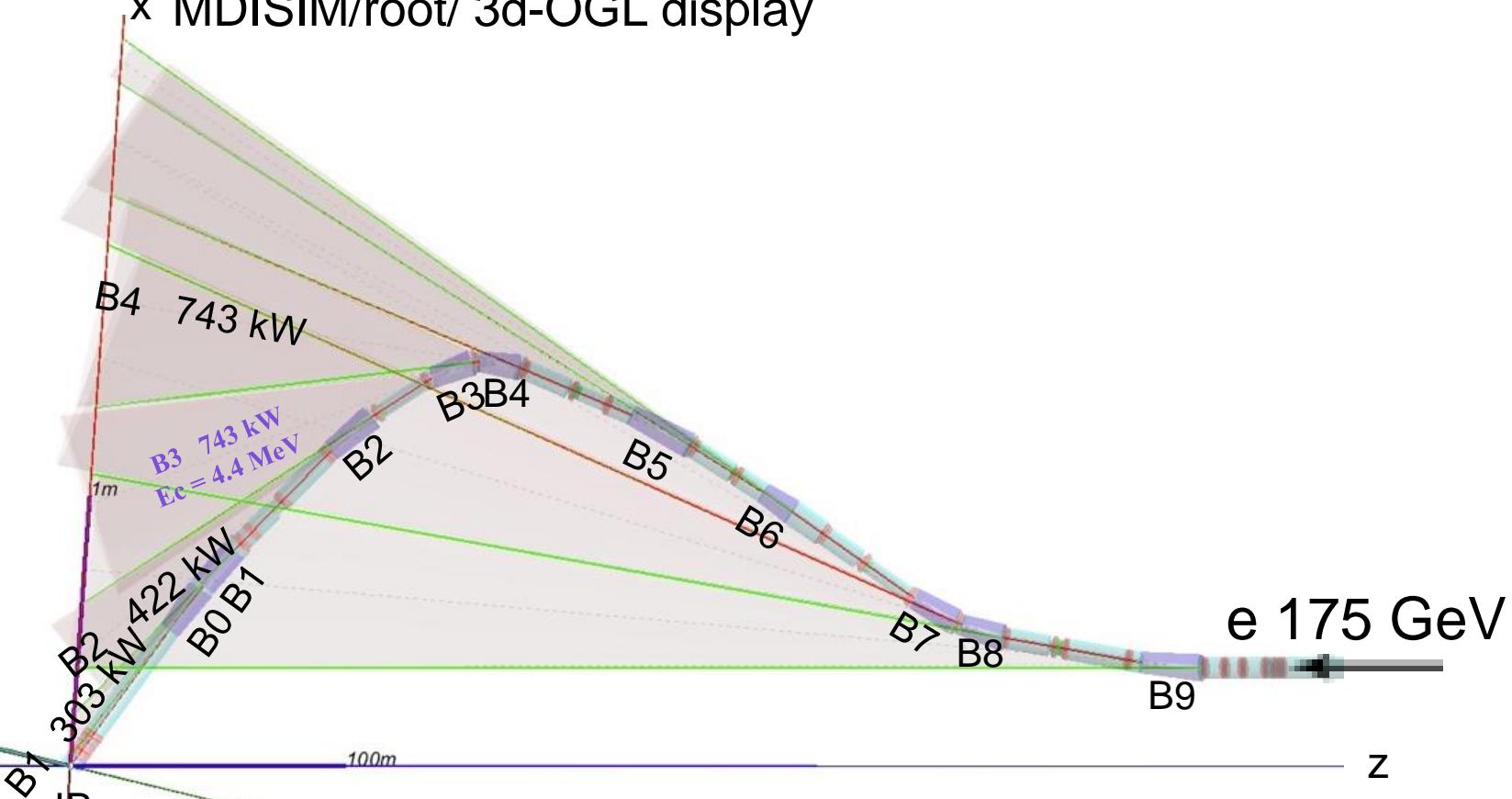


B. Haerer, B. Holzer,  
Wed. 8:30

# IR MDI: synchrotron radiation

SynRad bend cones for TLEP\_V14\_IR\_6-13-2 BINP IR

x MDISIM/root/ 3d-OGL display



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

## background sources:

### (1) single beam effects

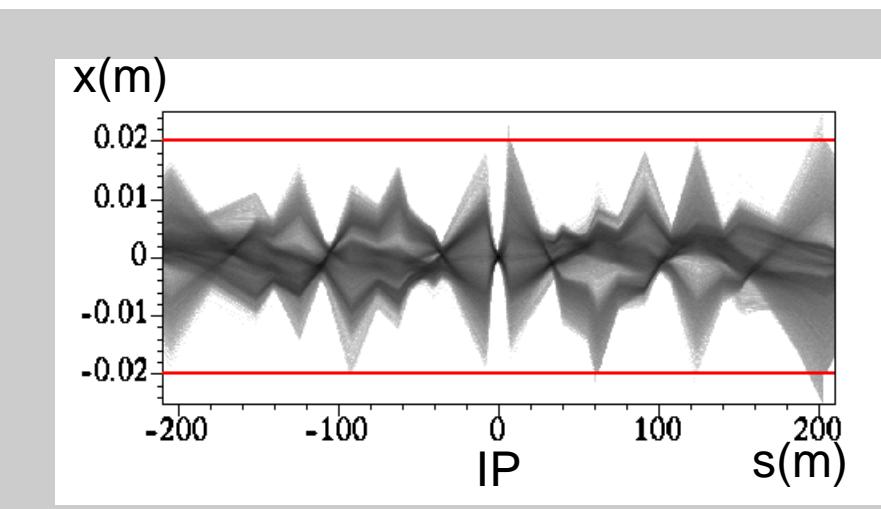
- beam-gas interaction: Coulomb scattering & bremsstrahlung
- Touschek scattering

### (2) luminosity-related processes

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

## particle tracking:

- ✓ to simulate IR losses
- ✓ to simulate collimation around the rings

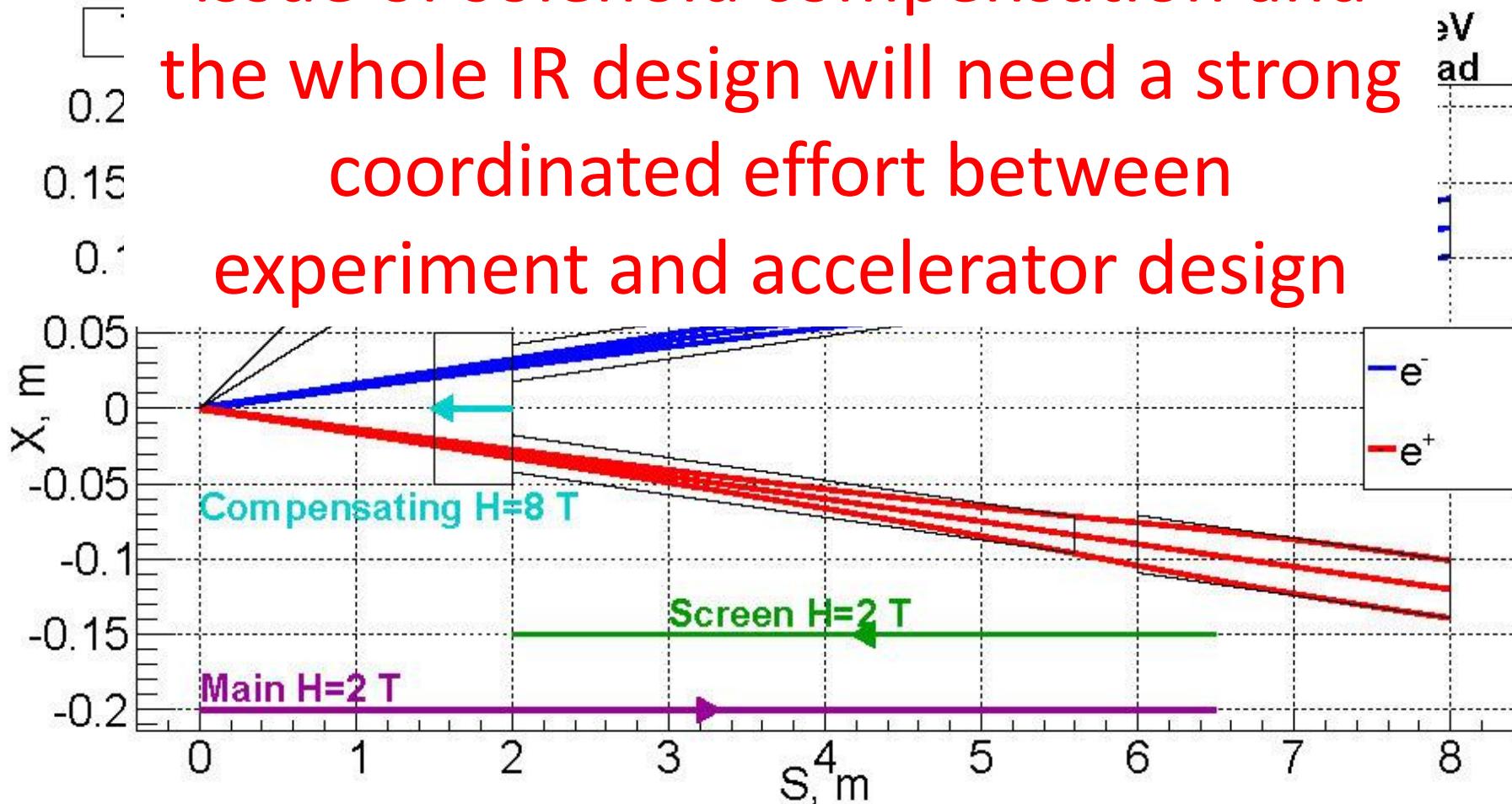


Ex.: off-energy Touschek scattered particles (TLEP\_V14\_IR\_6-13-2 lattice )

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

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

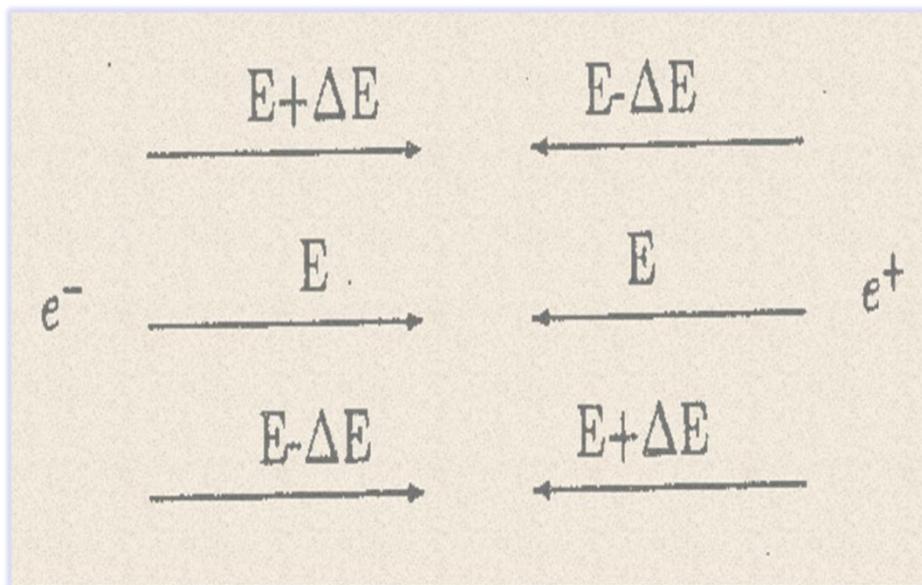
issue of solenoid compensation and  
the whole IR design will need a strong  
coordinated effort between  
experiment and accelerator design



effect of crossing angle and solenoid (fringe) fields on  $\epsilon_y$

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

effective c.m. energy spread



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

or

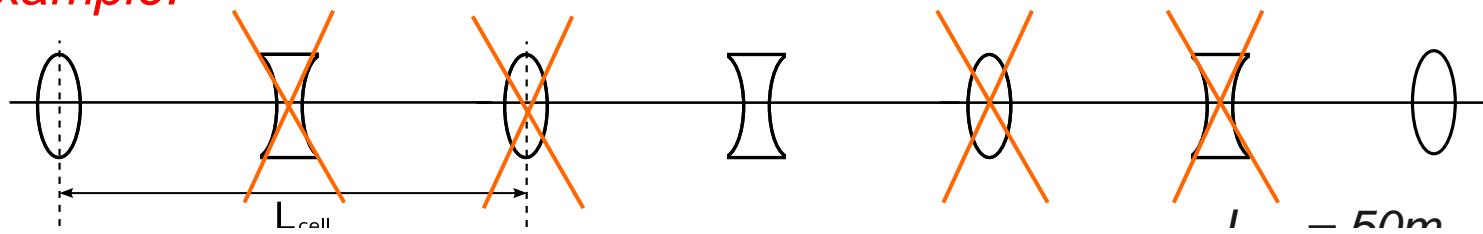
$$\frac{\sigma_W}{W} = \sqrt{\frac{\varepsilon_x}{2\left(\frac{D^*_{x^2}}{\beta^*_{x^2}} + \frac{\varepsilon_x}{\sigma_\epsilon^2}\right)}}$$

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

$$\varepsilon \propto \gamma^2 L_{cell}^3 \rightarrow$$

emittance at lower energy  
controlled via longer arc cells

example:



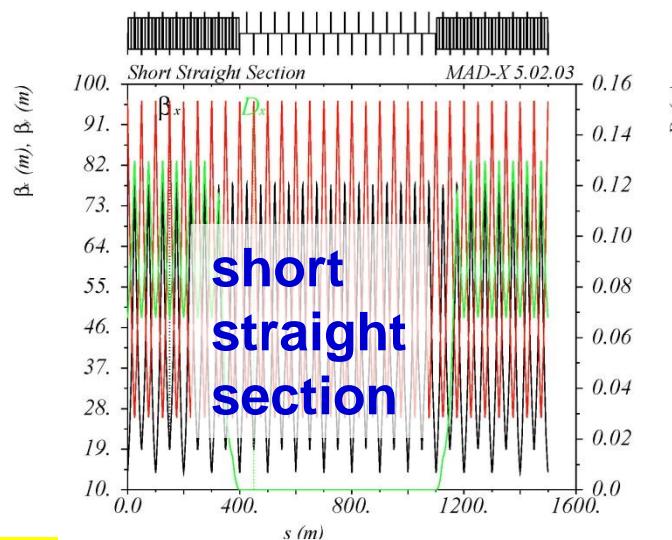
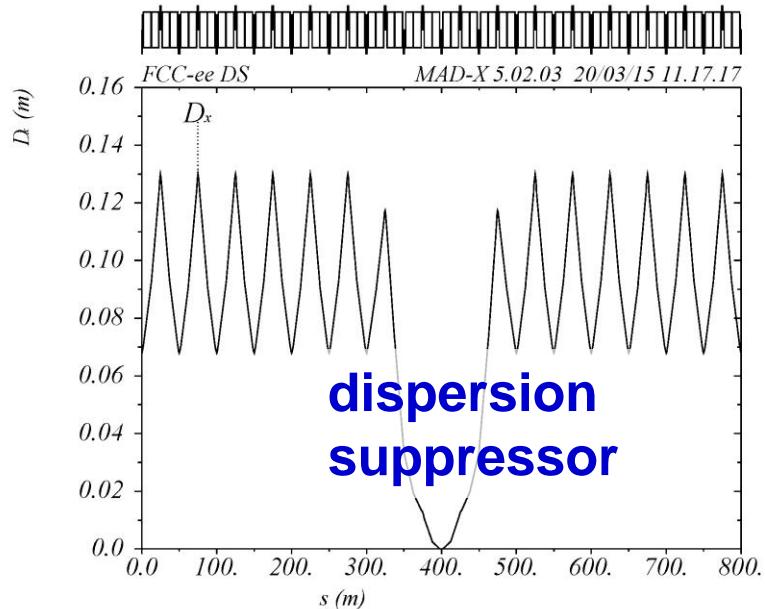
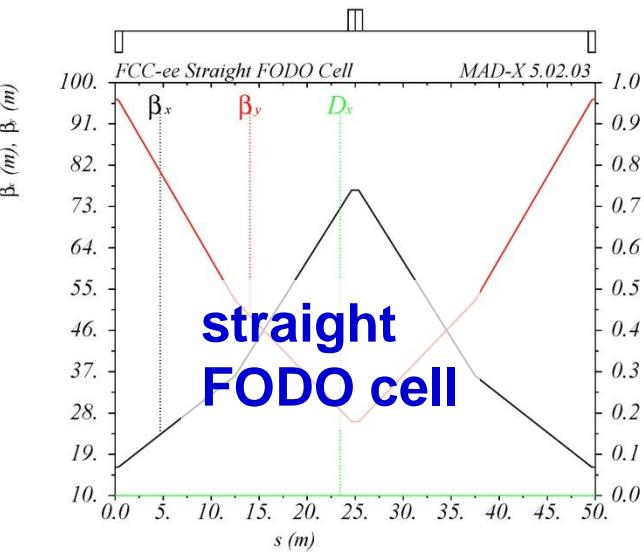
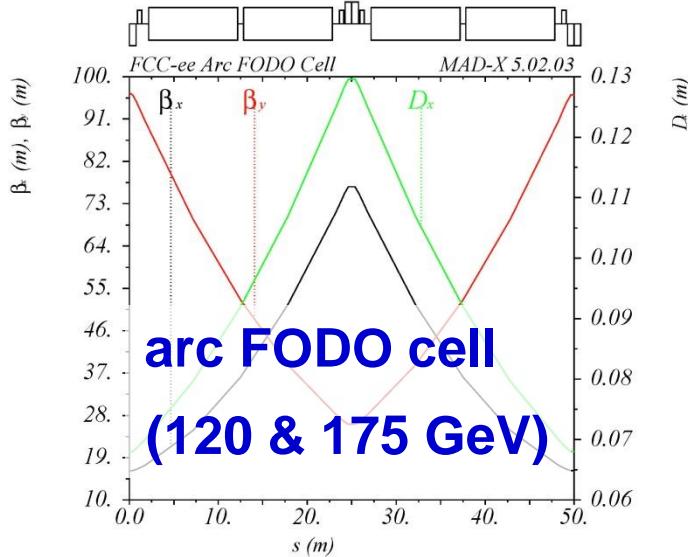
baseline choices:

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

80 GeV:  $L_{cell}=100$  m

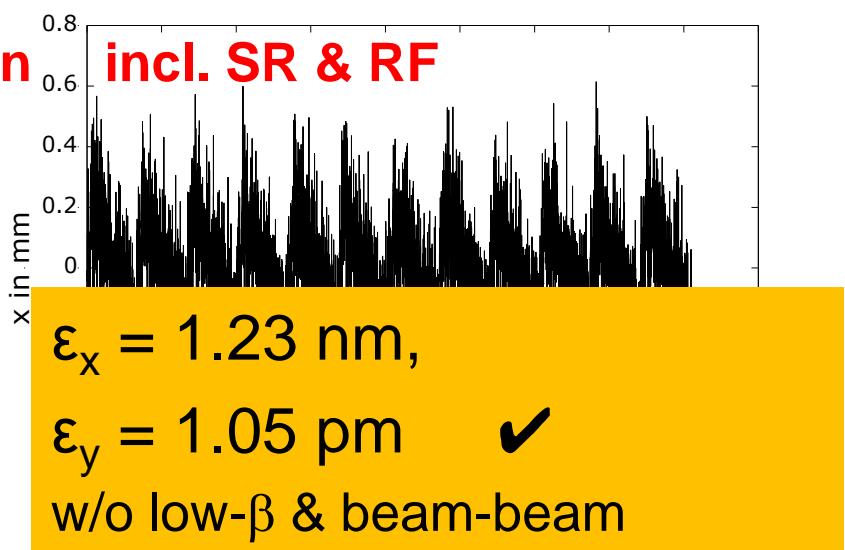
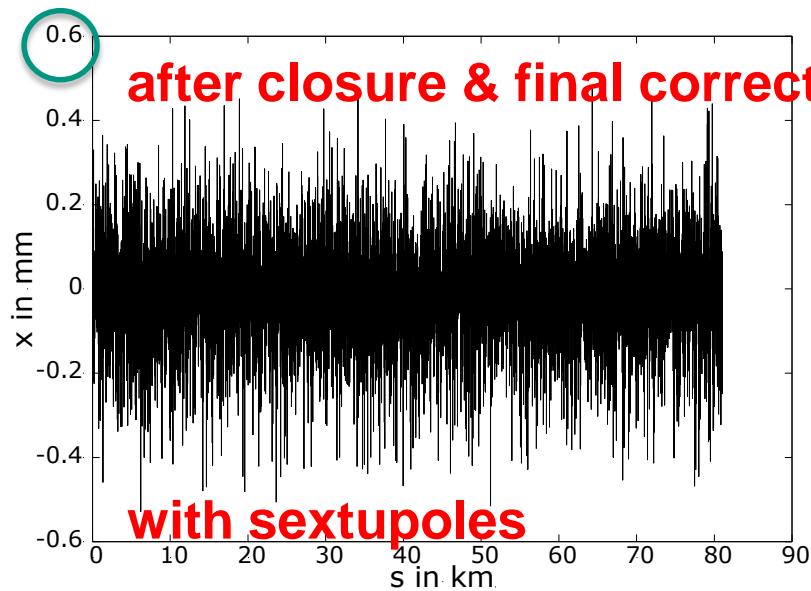
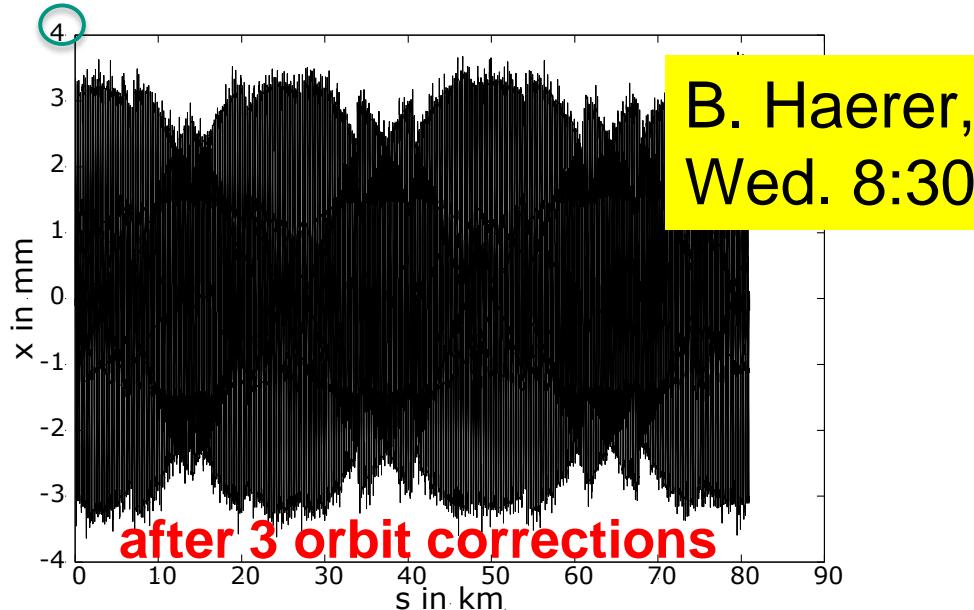
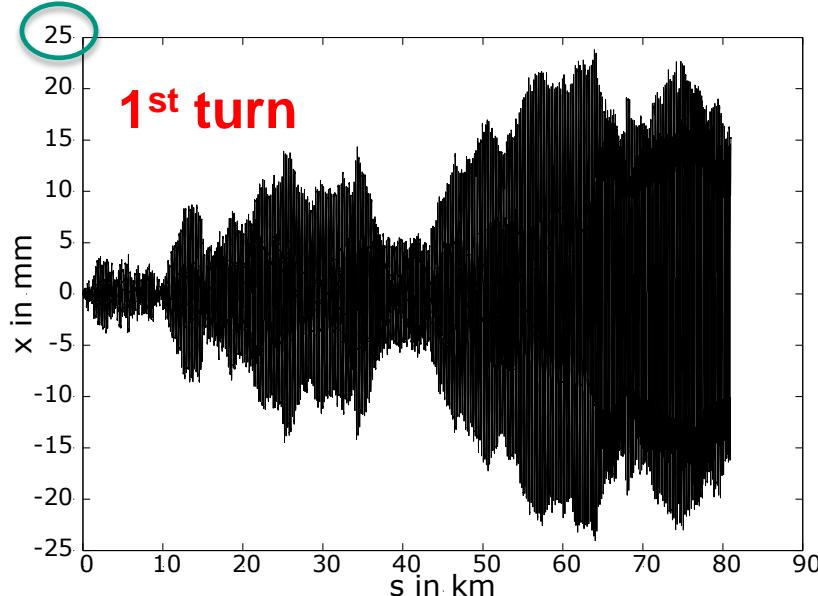
45.5 GeV:  $L_{cell}=300$  m

# flexible ring optics

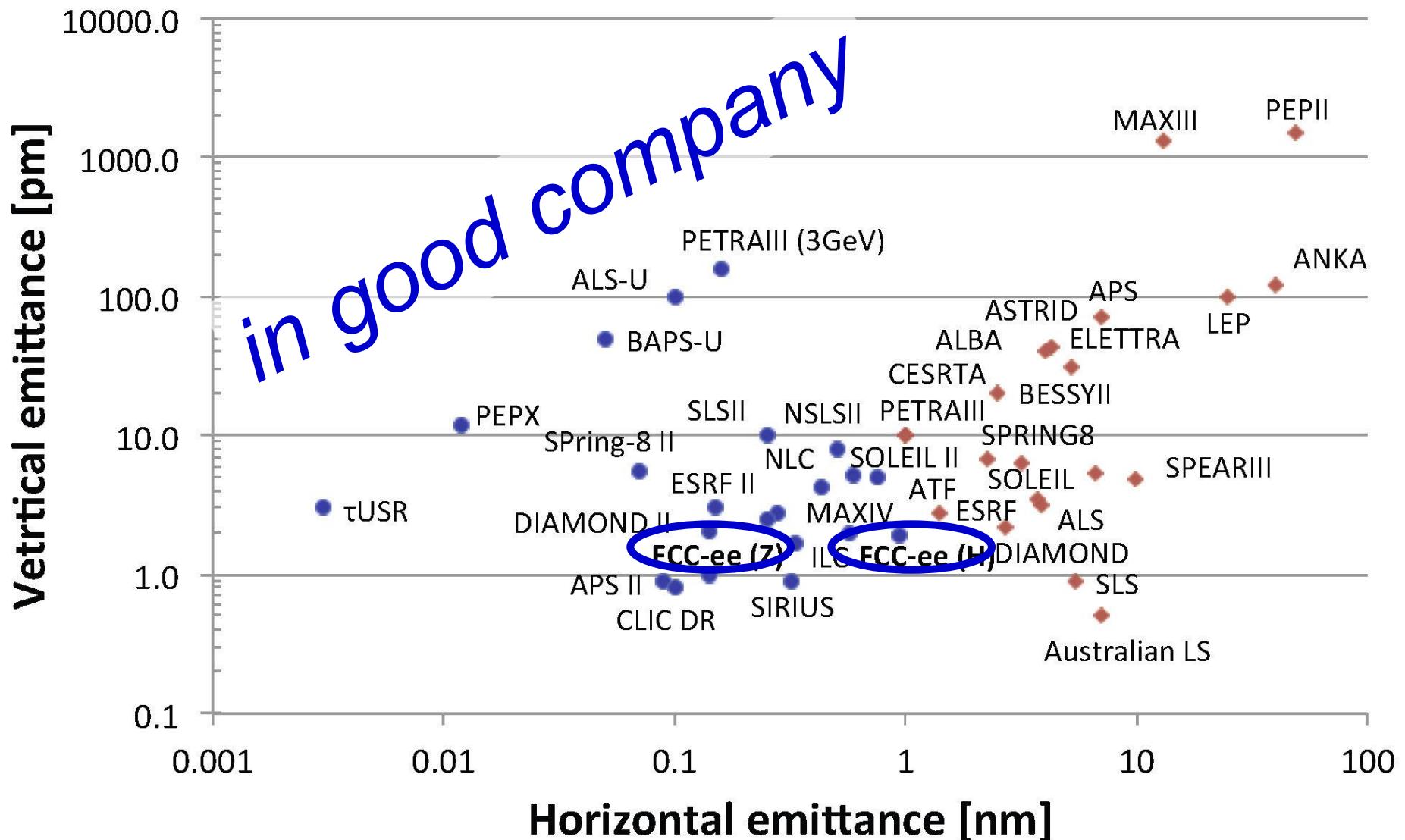


# orbit & emittance

150  $\mu\text{m}$  quad misalignments, no low-beta insertions, MAD-X



## transverse emittances

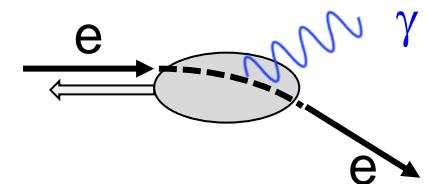


- hard photon emission at the IPs, ‘*Beamstrahlung*’, can become lifetime / performance limit for large bunch populations ( $N$ ), small hor. beam size ( $\sigma_x$ ) & short bunches ( $\sigma_s$ )

$$\tau_{bs} \propto \frac{\rho^{3/2} \sqrt{\eta}}{\sigma_s} \exp(A \eta \rho)$$

$$\frac{1}{\rho} \approx \frac{Nr_e}{\gamma \sigma_x \sigma_s}$$

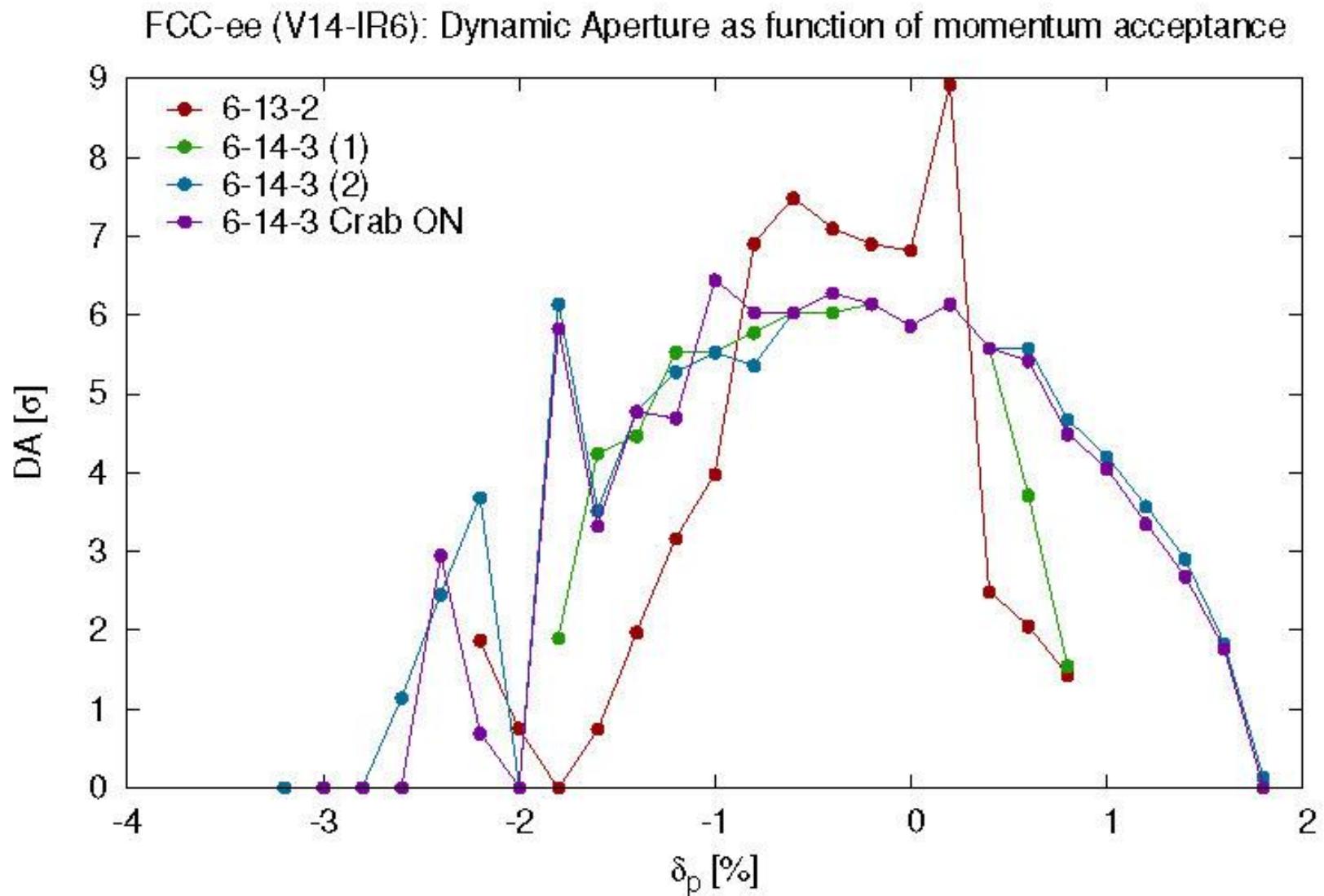
$\eta$  : ring energy acceptance



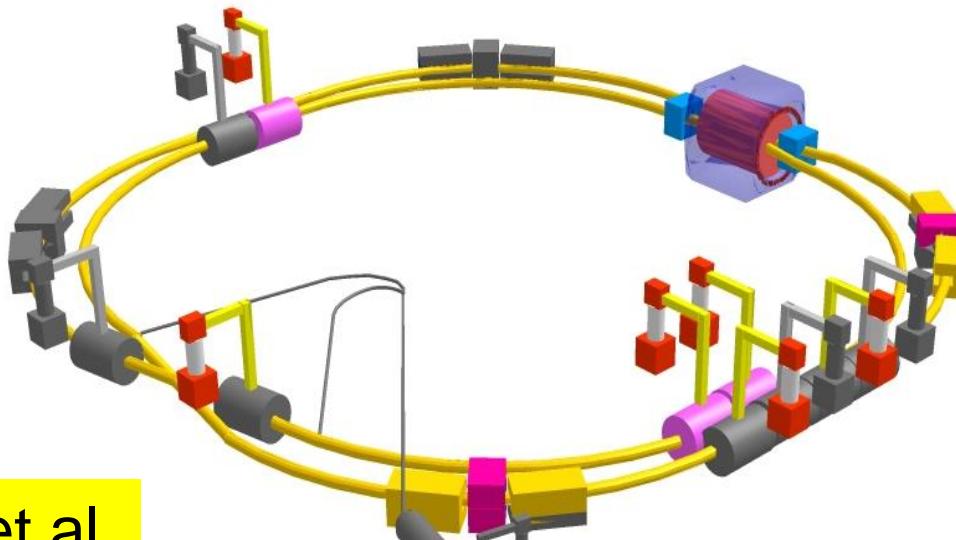
$\rho$  : mean bending radius  
at the IP (in the field of the  
opposing bunch)

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

- for acceptable lifetime,  $\rho \times \eta$  must be sufficiently large
  - flat beams (large  $\sigma_x$ ) !
  - bunch length !
  - large momentum acceptance:  **$\geq 1.5\% \text{ at } 175 \text{ GeV}$** 
    - LEP: <1% acceptance, SuperKEKB  $\sim 1.5\%$



beam  
commissioning will  
start in 2015



K. Oide et al.

**top up injection at high current**

$\beta_y^* = 300 \mu\text{m}$  (FCC-ee: 1 mm)

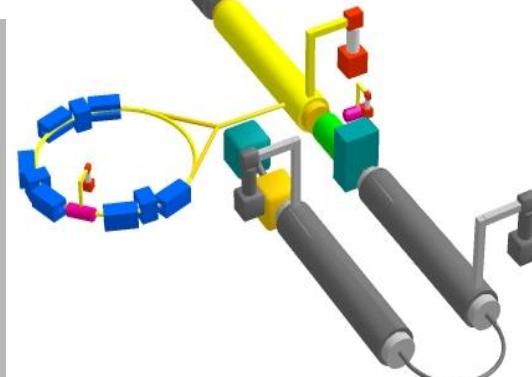
**lifetime** 5 min (FCC-ee:  $\geq 20$  min)

$\varepsilon_y/\varepsilon_x = 0.25\%$  (similar to FCC-ee)

**off momentum acceptance**

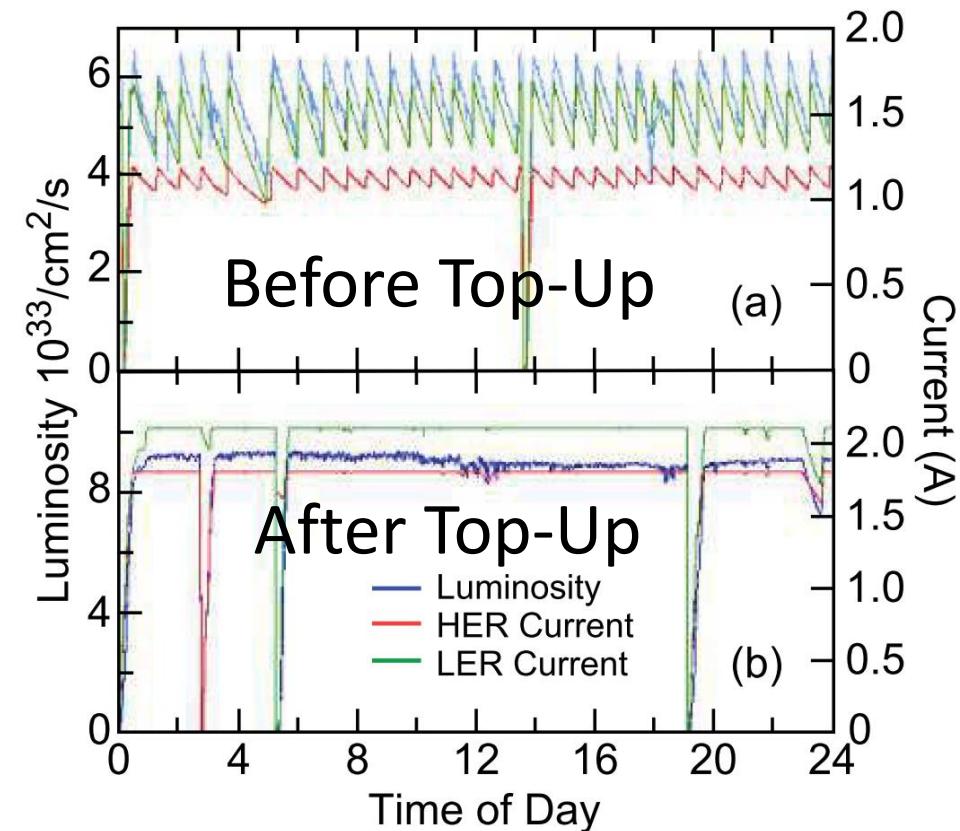
( $\pm 1.5\%$ , similar to FCC-ee)

**e<sup>+</sup> production rate** ( $2.5 \times 10^{12}/\text{s}$ ,  
FCC-ee:  $< 1.5 \times 10^{12}/\text{s}$  ( $Z$  cr.waist))

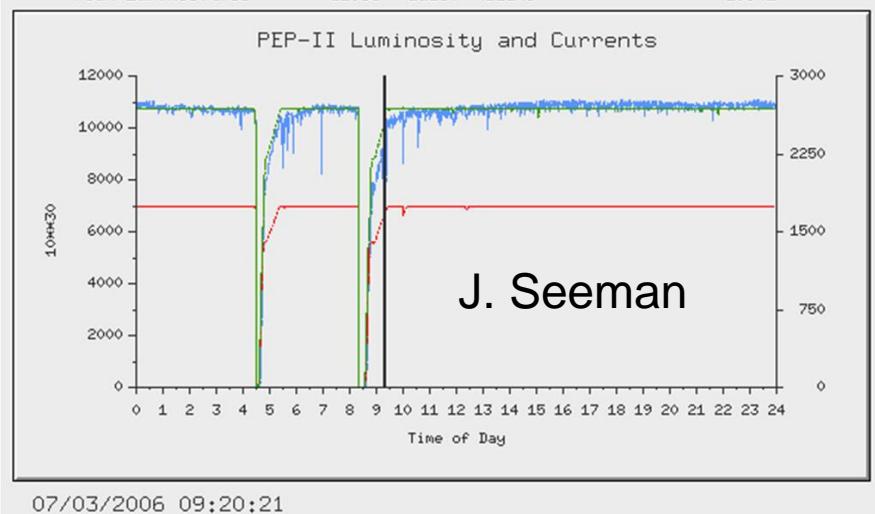


*SuperKEKB goes  
beyond FCC-ee, testing  
all concepts*

# top-up injection at PEP-II



I HER	I LER	Luminosity	Spec Lum	E HER	E LER	E CM
1882.17 mA	2553.95 mA	9008 10**30/Sec	3.61 N*10**30 / mA**2/Sec	8985 MeV	3120 MeV	10589 MeV
HER N Buckets / Pattern 1722 0:1:3442=0.96:0:3442:2=r			LER N Buckets / Pattern 1722 0:3442:2			
Last Owl/Day/Swing/24hr			293.7 303.3 313.7	910.7	Shift:	29.02 /pb
Peak Luminosities			11086 11137 11149			10942

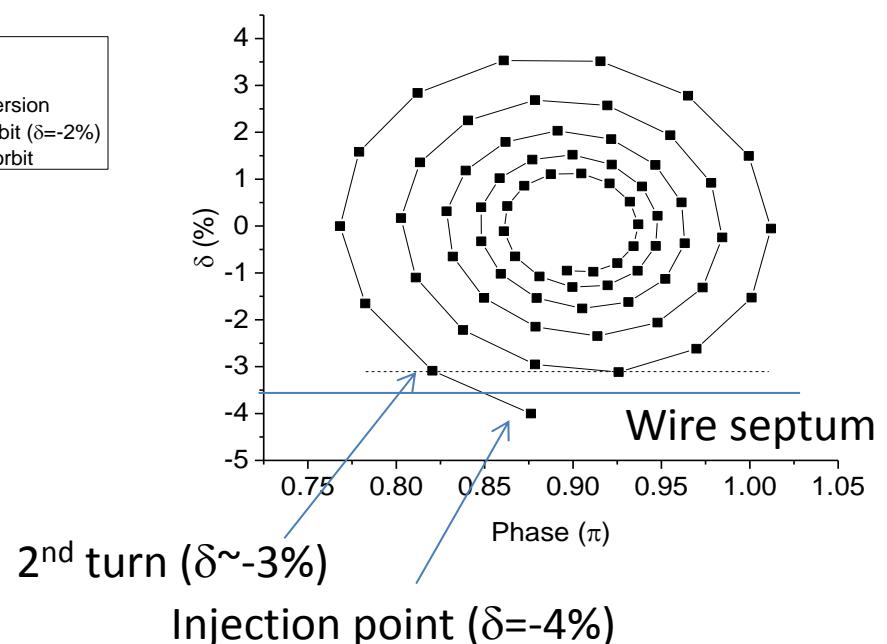
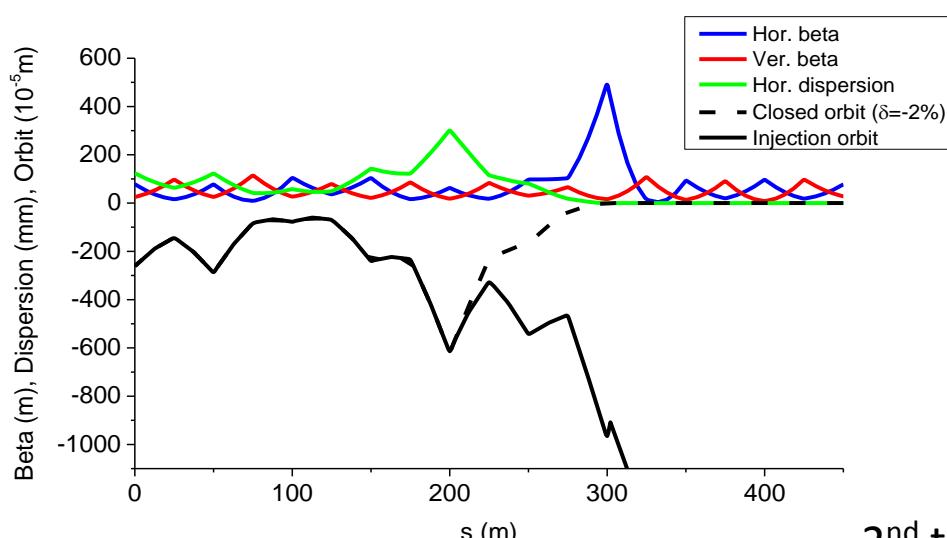


**average luminosity  $\approx$  peak luminosity**

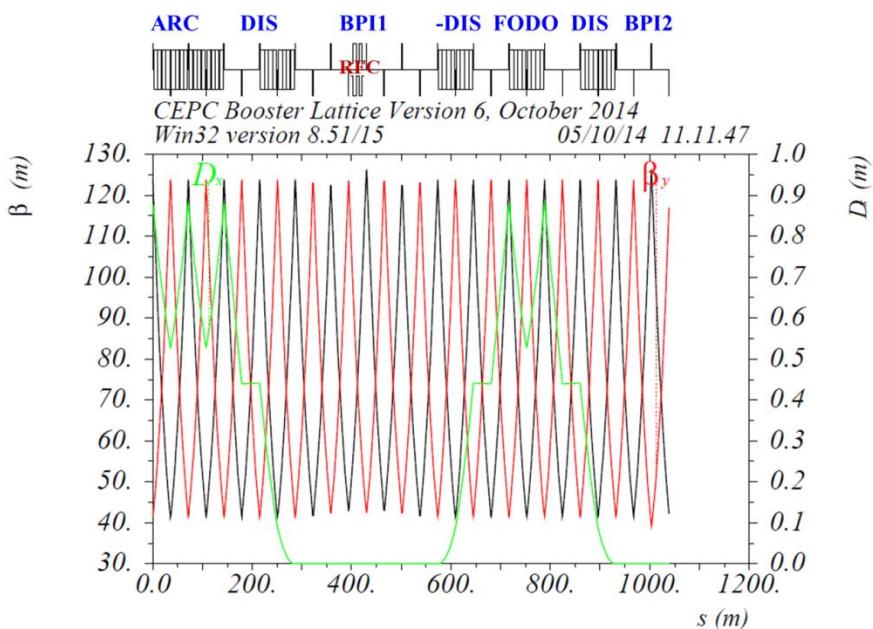
*similar results from KEKB*

two new options for top-up:

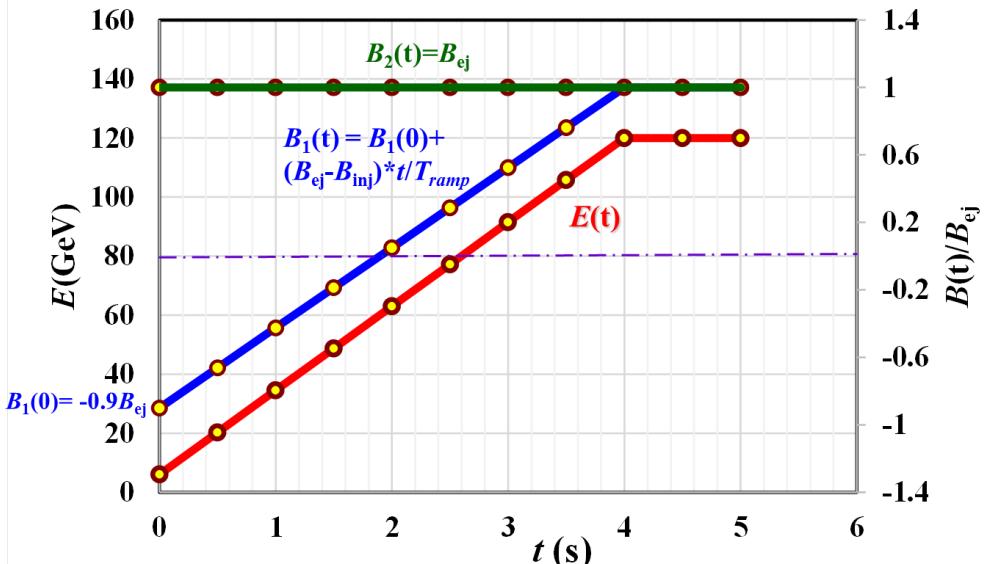
- (1) off-momentum multipole kicker injection
- (2) or kicker-less (“dream injection”) \*



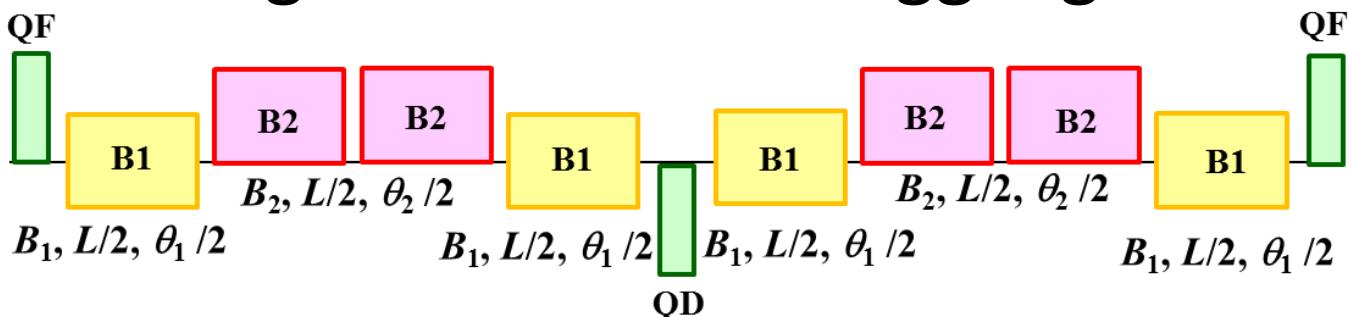
bypass around the experiments



energy ramping

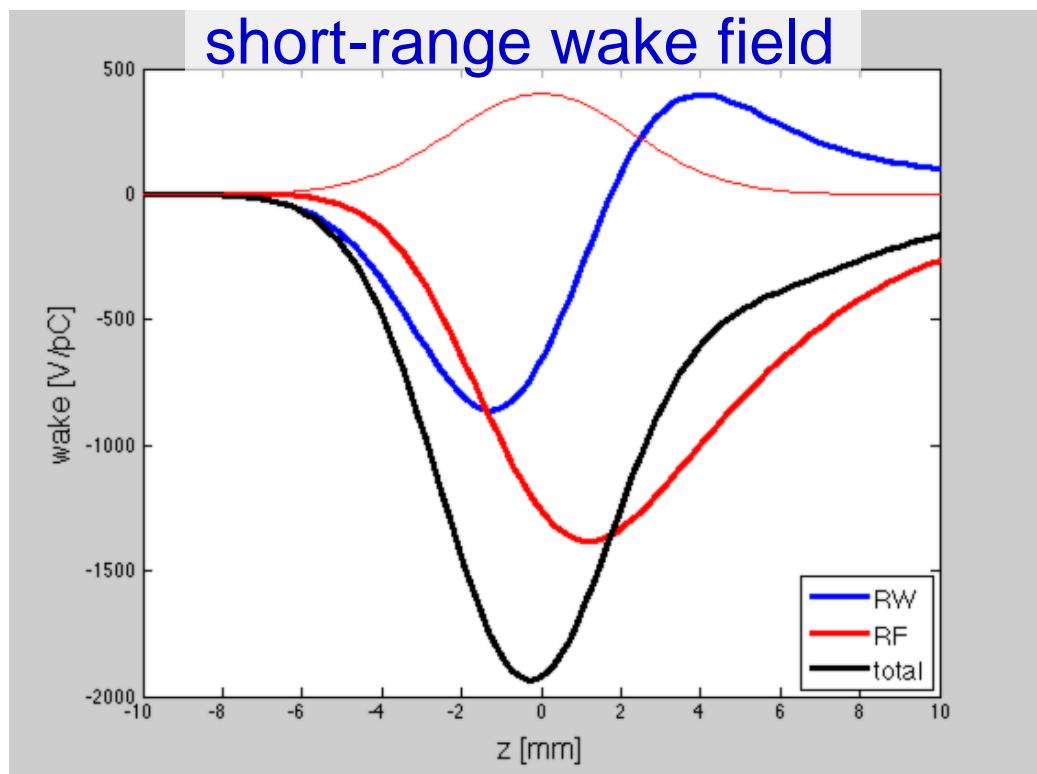


reaching low field with wiggling bends



FCC booster design carried out by FZ Jülich & MEPhI

Element	R [kΩ]	L [nH]	$k_{\text{loss}}$ [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



microwave  
threshold  
from Keil-Schnell-  
Boussard criterion

~

7-13 mΩ



## 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

two primary interests:

**accurate energy calibration** using resonant depolarization  $\Rightarrow$  measurement of  $M_Z$ ,  $\Gamma_Z$ ,  $M_W$

- *appealing feature –  $\delta M_Z$ ,  $\delta \Gamma_Z \sim 0.1$  MeV,  $\delta M_W \sim 0.3$  MeV*

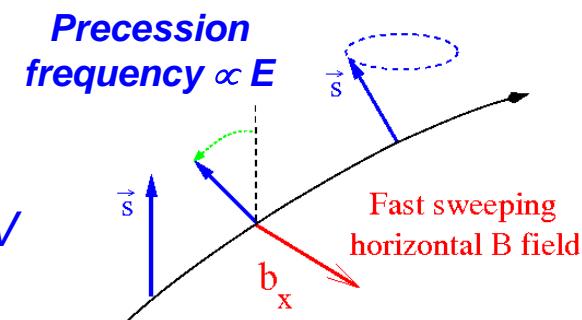
**physics with longitudinally polarized beams**

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

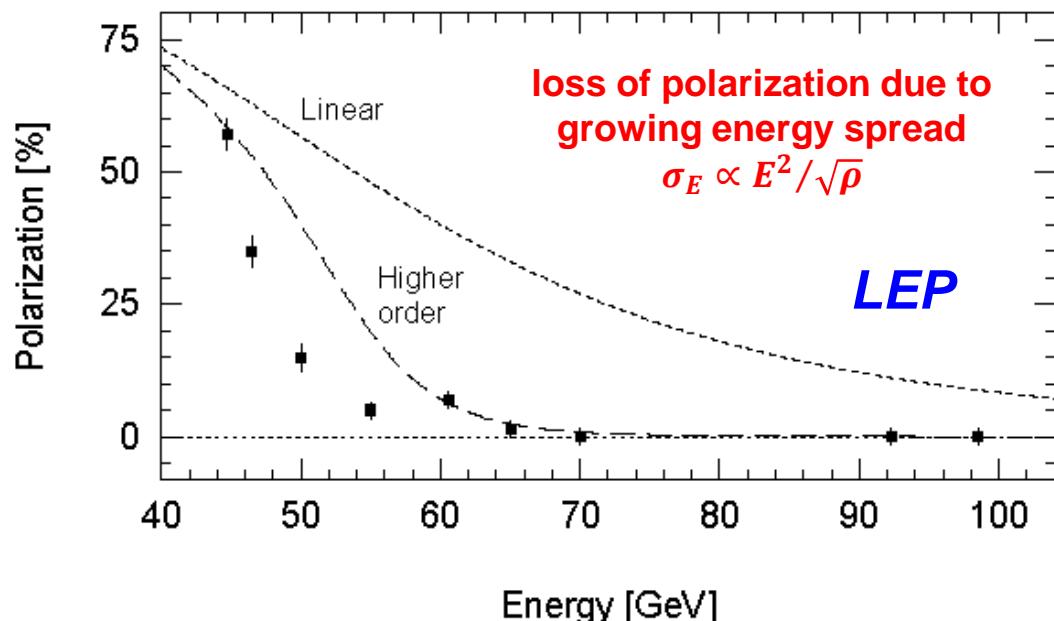
scaling from LEP observations :  
**polarization expected up to the WW threshold !**

integer spin resonances are spaced by 440 MeV:

energy spread should remain below  $\sim 60$  MeV



R. Assmann



# polarization build up

transverse polarization build-up (Sokolov-Ternov) is slow at FCC-ee  
(large bending radius  $\rho$ )

build-up is ~40 times  
slower than at LEP

wigglers may lower  $\tau_p$  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)*

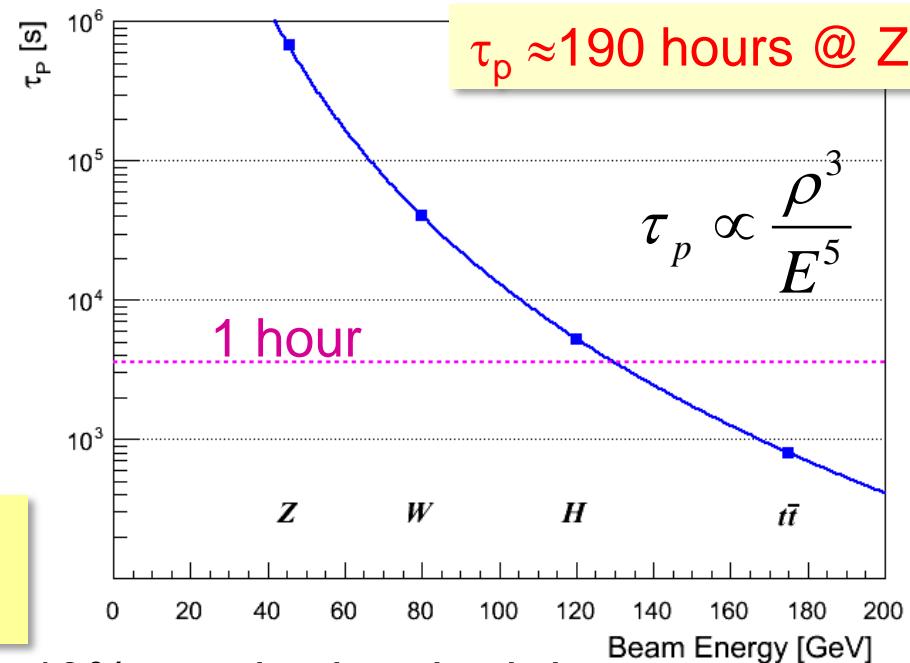
→ ≈ OK for energy calibration  
(few % P sufficient)

longitudinal polarization: levels of  $\geq 40\%$  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





# 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?)



# 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
<b>10:30-12:00 Performance &amp; configurations, chair Weiren Chou, FNAL &amp; IHEP</b>		
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
<b>13:30-15:00 Vacuum, MDI, energy calibration, chair John Seeman, SLAC</b>		
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	Massimiliano Bozzi, INFN-LNF	Losses in IR region
14:36-14:56	Tek Koratzinos, U. Geneva	Energy calibration options
<b>15:30-17:00 Polarization &amp; injectors, chair Uli Wienands, SLAC</b>		
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
<b>17:30-18:10 Contributed talks (CepC main ring), chair Ralph Assmann, DESY</b>		
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, 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
$E_{\text{beam}}$ [GeV]	45	80	120	175
current [mA]	1450	152	30	6.6
$P_{\text{SR,tot}}$ [MW]	100	100	100	100
no. bunches	16700	4490	1360	98
$N_b$ [ $10^{11}$ ]	1.8	0.7	0.46	1.4
$\varepsilon_x$ [nm]	29	3.3	0.94	2
$\varepsilon_y$ [pm]	60	1	2	2
$\beta^*_x$ [m]	0.5	0.5	0.5	1.0
$\beta^*_y$ [mm]	3	1	1	1
$\sigma^*_y$ [nm]	424	84	44	45
$\sigma^*_x$ [ $\mu\text{m}$ ]	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
$\sigma_{z,\text{SR}}$ [mm]	3.29	2.02	1.62	2.31
$\sigma_{z,\text{tot}}$ [mm] (w beamstr.)	3.80	2.27	1.80	2.45
$\sigma_{\delta,\text{SR}}$ [%]	0.052	0.092	0.139	0.202
$\sigma_{\delta,\text{tot}}$ [%] (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. $\xi_y/\text{IP}$ (4 IPs)	0.03, 0.05	0.06	0.092	0.091
$L/\text{IP}$ [ $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ ] (4 Ips)	21	10.4	5.3	1.5
$\tau_{\text{beam}}$ [min] (4 IPs)	403	84	32	25

175-GeV momentum acceptance  $>\pm 1.3\text{-}1.5\%$

parameter	FCC-ee baseline (2 IPs)			
	Z	W	H	t
$E_{\text{beam}}$ [GeV]	45	80	120	175
current [mA]	1450	152	30	6.6
$P_{\text{SR,tot}}$ [MW]	100	100	100	100
no. bunches	12846	3453	1046	75
$N_b$ [ $10^{11}$ ]	2.37	0.91	0.6	1.82
$\varepsilon_x$ [nm]	29	3.3	0.94	2
$\varepsilon_y$ [pm]	60	1	2	2
$\beta^*_x$ [m]	0.5	0.5	0.5	1.0
$\beta^*_y$ [mm]	3	1	1	1
$\sigma^*_y$ [nm]	424	84	44	45
$\sigma^*_x$ [ $\mu\text{m}$ ]	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. $\xi_y/IP$ (2IPs)	0.040,0.070	0.077	0.121	0.118
$L/IP$ [ $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ ] (2 Ips)	27	13	7.0	1.9
$\tau_{beam}$ [min] (2 IPs)	620	130	50	39

175-GeV momentum acceptance  $>\pm 1.5\text{-}1.6\%$

parameter	FCC-ee crab waist (4 IPs)			
	z	w	h	t
$E_{\text{beam}}$ [GeV]	45	80	120	175
current [mA]	1450	152	30	6.6
$P_{\text{SR,tot}}$ [MW]	100	100	100	100
no. bunches	59581	3143	625	68
$N_b$ [ $10^{11}$ ]	0.5	1.0	1.0	2.0
$\varepsilon_x$ [nm]	0.13	0.42	0.94	2
$\varepsilon_y$ [pm]	1.0	1.0	1.0	2
$\beta^*_x$ [m]	0.5	0.5	0.5	0.5
$\beta^*_y$ [mm]	1	1	1	1
$\sigma^*_y$ [nm]	32	29	31	45
$\sigma^*_x$ [ $\mu\text{m}$ ]	8	14	22	31

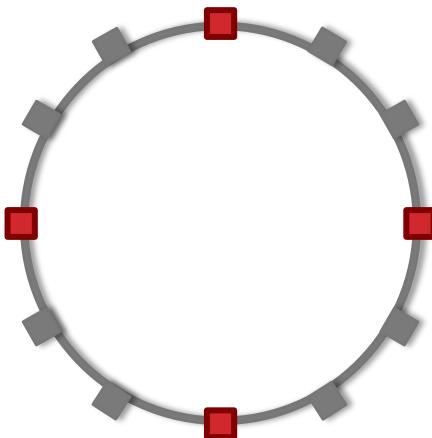
parameter	FCC-ee crab waist (4 IPs)			
	Z	W	H	t
RF frequency [MHz]	400	400	400	400
RF voltage [GV]	0.3	1.0	3.6	11
circumference [km]	100	100	100	100
momentum compaction [ $10^{-5}$ ]	0.5	0.5	0.5	0.5
synchrotron tune	0.030	0.035	0.053	0.070
$\sigma_{z,SR}$ [mm]	0.97	2.08	2.08	2.31
$\sigma_{z,tot}$ [mm] (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. $\xi_y/IP$ (4 IPs)	0.04,0.137	0.04,0.143	.0124,.097	0.03,0.092
$L/IP [10^{34} \text{ cm}^{-2}\text{s}^{-1}]$ (4 Ips)	215	38	8.7	2.1
$\tau_{beam}$ [min] (4 IPs)	38	23	20	18

parameter	FCC-ee crab waist (2 IPs)			
	z	w	h	t
$E_{\text{beam}}$ [GeV]	45	80	120	175
current [mA]	1450	152	30	6.6
$P_{\text{SR,tot}}$ [MW]	100	100	100	100
no. bunches	45154	2382	474	51
$N_b$ [ $10^{11}$ ]	0.66	1.3	1.3	2.6
$\varepsilon_x$ [nm]	0.13	0.42	0.94	2
$\varepsilon_y$ [pm]	1.0	1.0	1.0	2
$\beta^*_x$ [m]	0.5	0.5	0.5	0.5
$\beta^*_y$ [mm]	1	1	1	1
$\sigma^*_y$ [nm]	32	29	31	45
$\sigma^*_x$ [ $\mu\text{m}$ ]	8	14	22	31

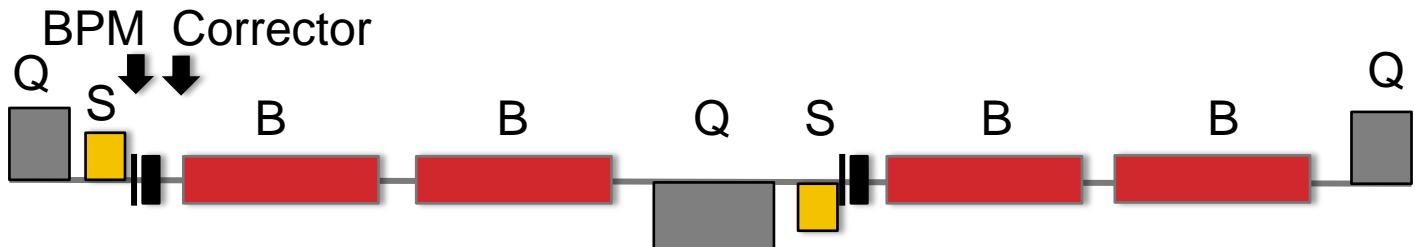
parameter	FCC-ee crab waist (2 IPs)			
	Z	W	H	t
RF frequency [MHz]	400	400	400	400
RF voltage [GV]	0.3	1.0	3.6	11
circumference [km]	100	100	100	100
momentum compaction [ $10^{-5}$ ]	0.5	0.5	0.5	0.5
synchrotron tune	0.030	0.035	0.053	0.070
$\sigma_{z,SR}$ [mm]	0.97	2.08	2.08	2.31
$\sigma_{z,tot}$ [mm] (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. $\xi_y/IP$ (2 IPs)	0.06,0.21	0.04,0.16	0.03,,124	0.04,0.118
$L/IP [10^{34} \text{ cm}^{-2}\text{s}^{-1}]$ (2 IPs)	277	38	11.0	2.6
$\tau_{beam}$ [min] (2 IPs)	60	41	31	28

arc cell

layout

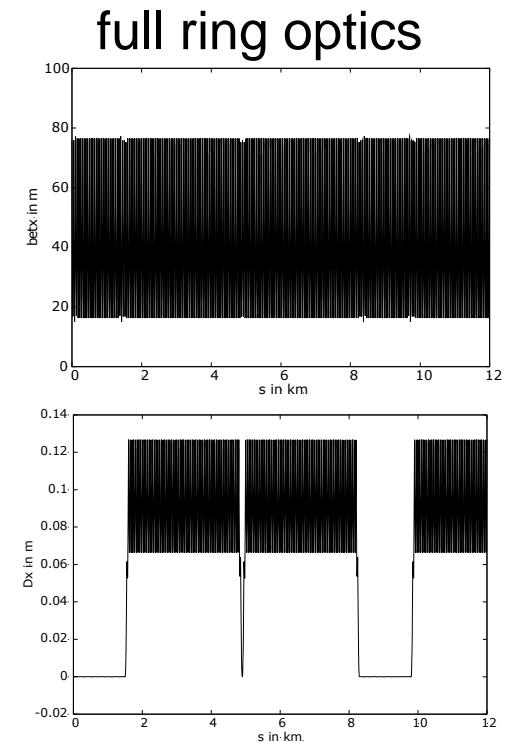
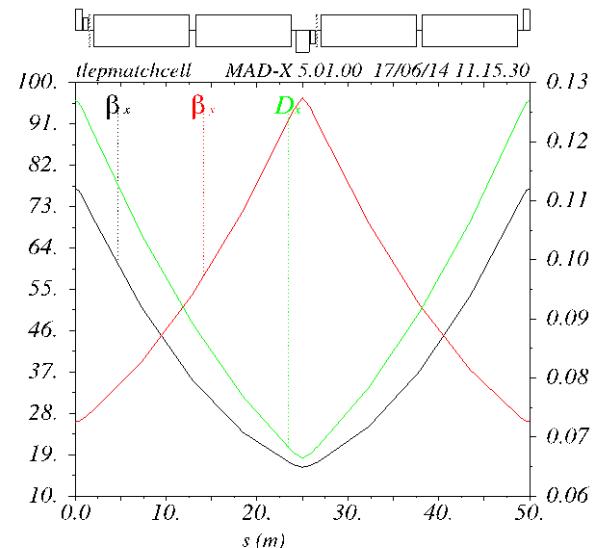


Circumference: 100 km  
 Arc length:  $2 \times 3.4$  km  
 Straight section: 1.5 km



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

FODO cell optics  
 cell length 50 m



## 80 GeV

175 GeV and 120 GeV:  $L_{\text{cell}} = 50 \text{ m}$ ,  $\Psi = 90^\circ/60^\circ$



80 GeV:  $L_{\text{cell}} = 50 \text{ m}$ ,  $\Psi = 45^\circ/45^\circ$



80 GeV:  $L_{\text{cell}} = 100 \text{ m}$ ,  $\Psi = 90^\circ/60^\circ$



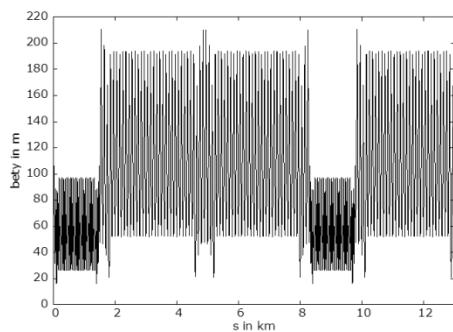
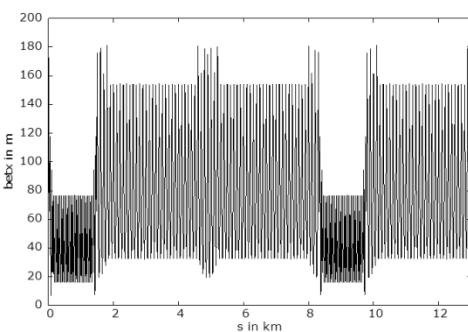
Arc cells

Dispersion Suppressor

Straight matching section (with RF)

Straight cells (with RF)

example: 100 m cell length



## 45.5 GeV

175 GeV and 120 GeV:  $L_{\text{cell}} = 50 \text{ m}$ ,  $\Psi = 90^\circ/60^\circ$



45.5 GeV:  $L_{\text{cell}} = 200 \text{ m}$ ,  $\Psi = 60^\circ/60^\circ$



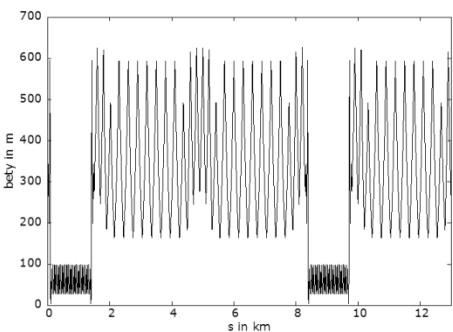
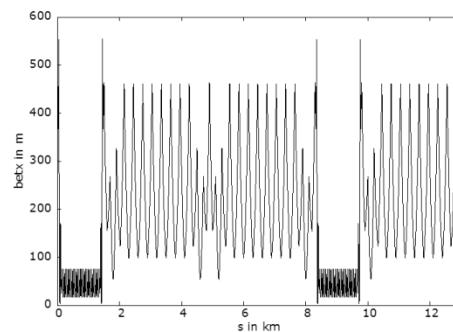
45.5 GeV:  $L_{\text{cell}} = 250 \text{ m}$ ,  $\Psi = 72^\circ/72^\circ$



45.5 GeV:  $L_{\text{cell}} = 300 \text{ m}$ ,  $\Psi = 90^\circ/60^\circ$



example: 300 m cell length

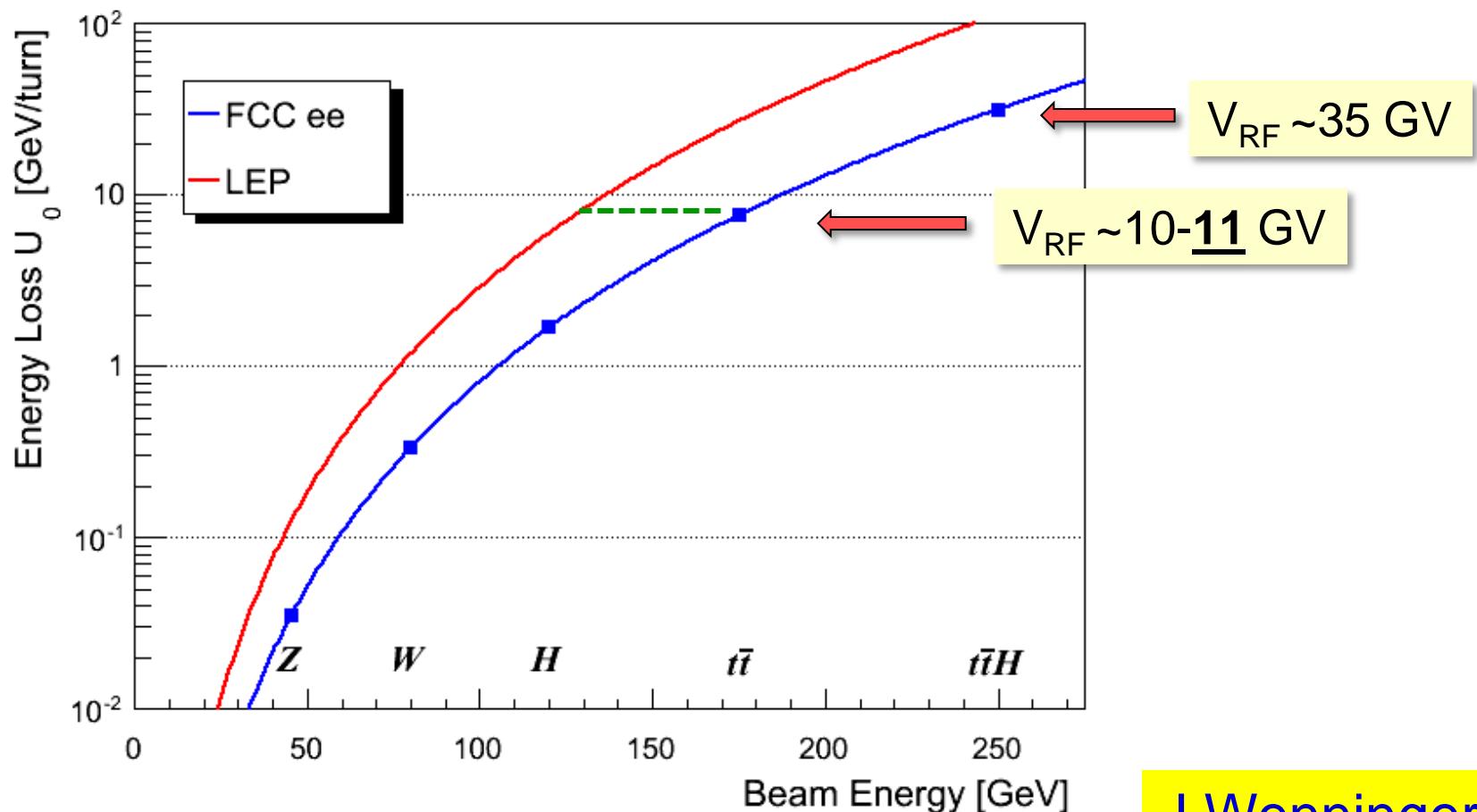


# Synchrotron radiation power

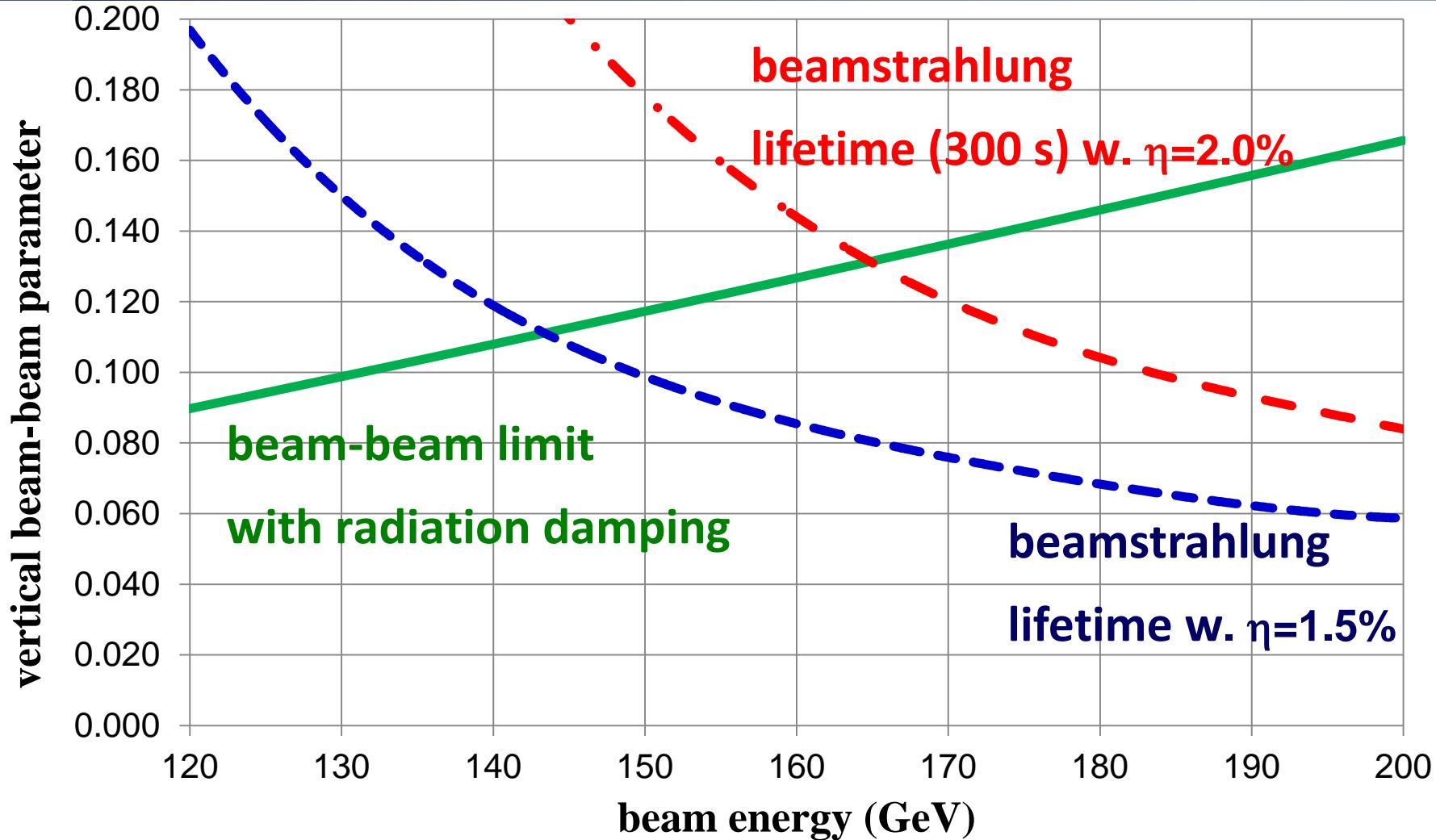
The maximum synchrotron radiation (SR) power  $P_{SR}$  is set to **50 MW per beam** – design choice  $\Leftrightarrow$  power dissipation.

$\Rightarrow$  defines the maximum beam current at each energy.

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



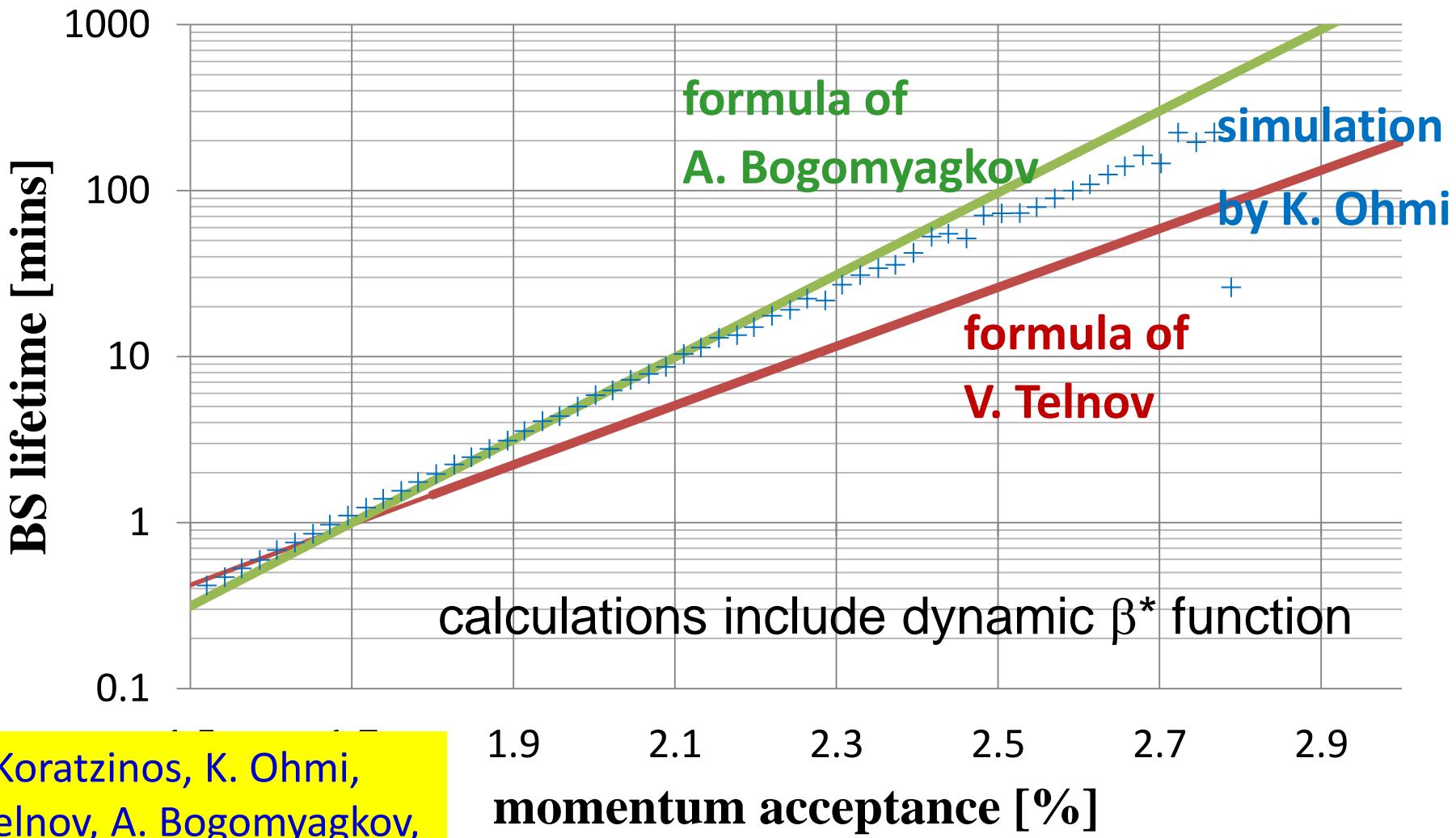
## beam-beam limits: 2 regimes



$$\varepsilon_y = 2 \text{ pm},$$
$$\beta_y^* = 1 \text{ mm}$$

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

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





# IR parameters



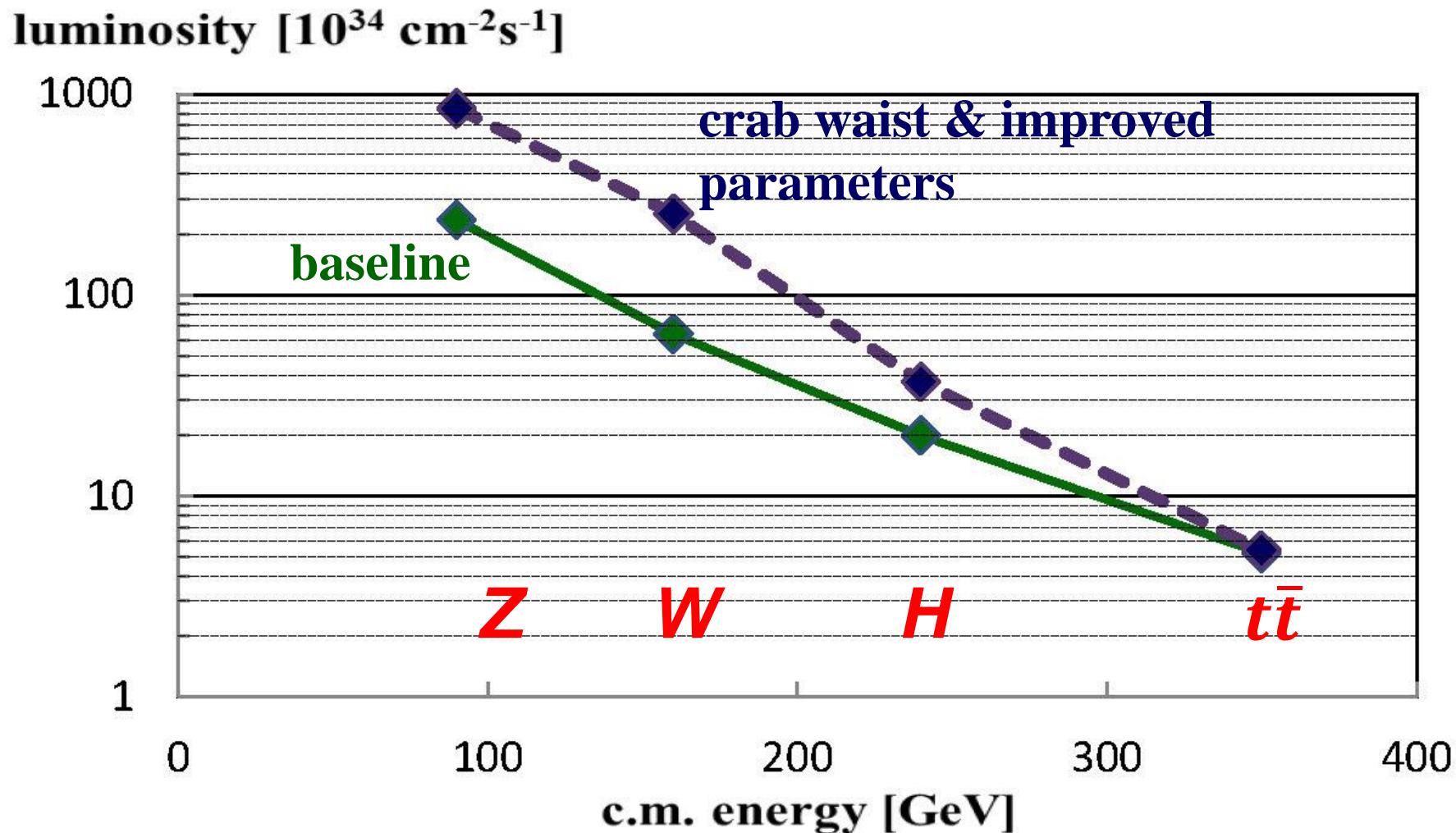
smallest possible  $\beta^*$  desired; target  $\beta_y^* = \underline{1 \text{ mm}}$ ; so small a value of  $\beta^*$  requires local chromaticity correction

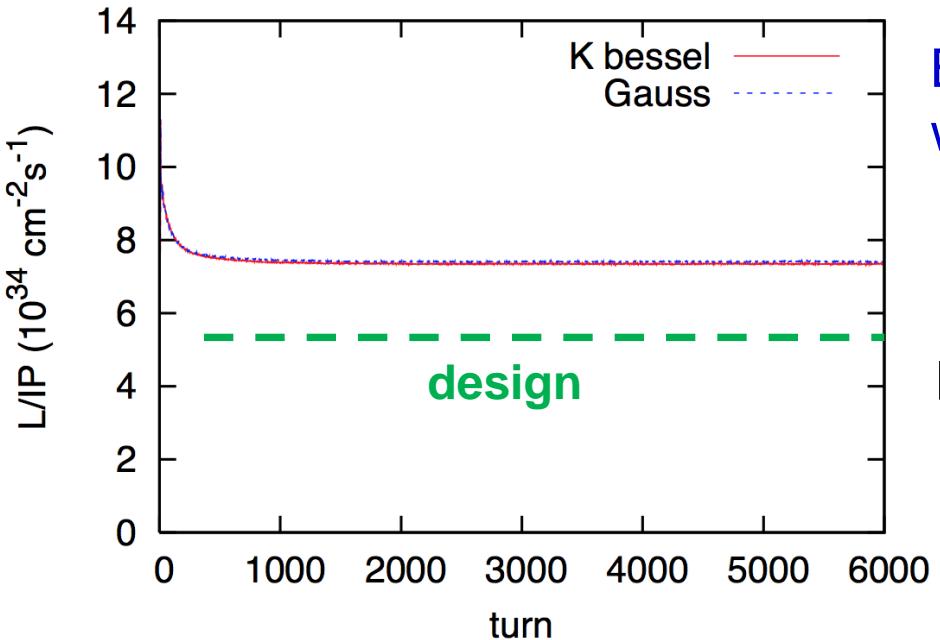
- *design inspired by linear collider IR;*
- *additional complexity that beam does not pass the IR only once → effects of optical aberrations critical*
- *bending magnets close to the IP → SR fan !*

distance between IP and front-face of first quadrupole currently set to  $L^* \geq 2 \text{ m}$  (SuperKEKB  $\sim 1 \text{ m}$ )

- *detector acceptance, luminosity measurement, ...*

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



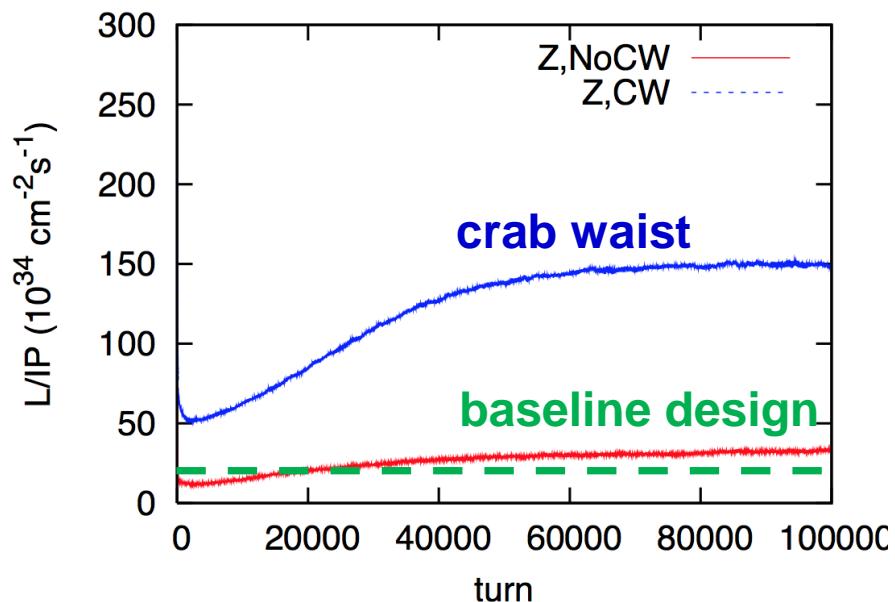


BBSS strong-strong simulation  
w beamstrahlung

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

BBWS weak-strong simulation  
w beamstrahlung

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

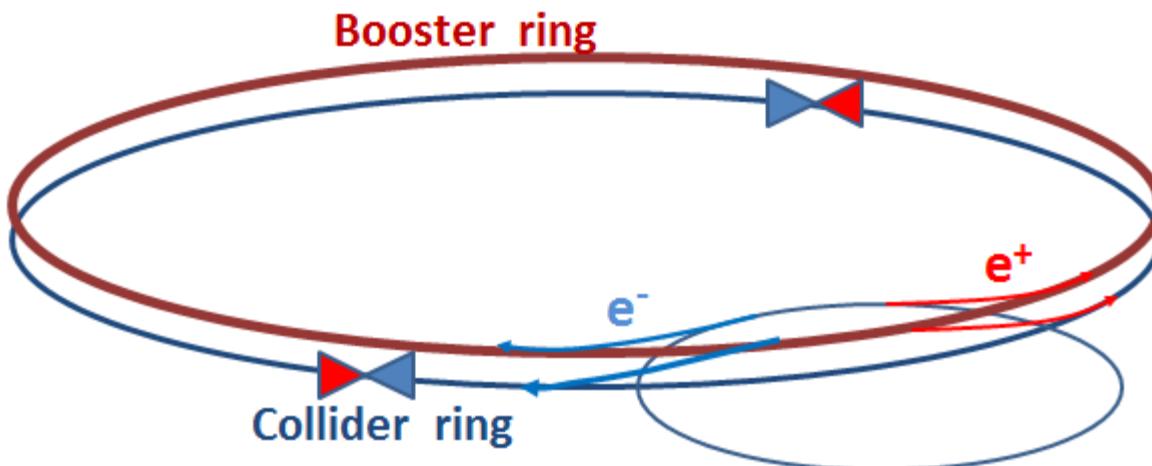


beside the collider ring(s), a booster of the same size (same tunnel) must provide beams for top-up injection

- 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



# Future Circular Collider Study - SCOPE

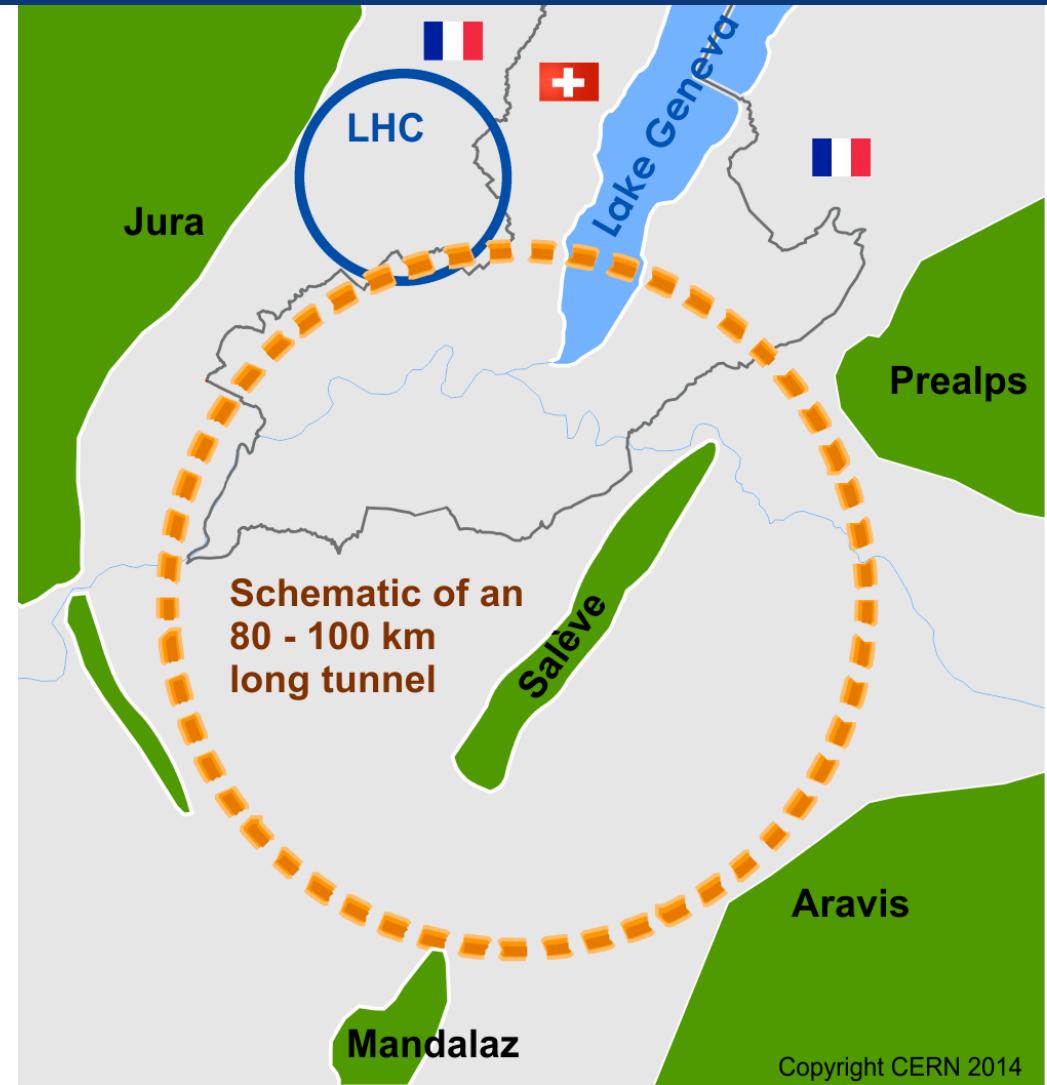
## CDR and cost review for the next ESU (2018)

Forming an international collaboration to study:

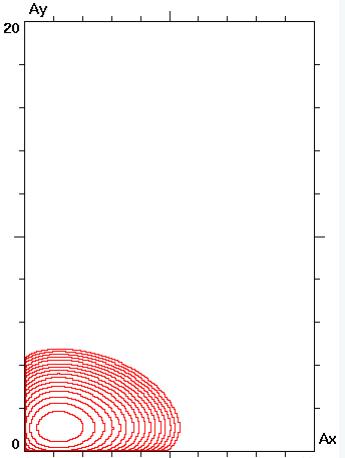
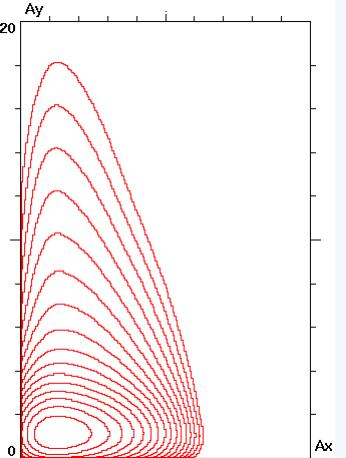
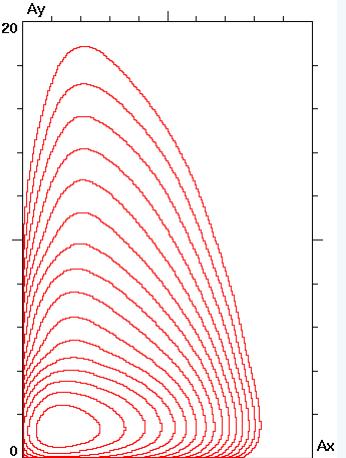
- $pp$ -collider (*FCC-hh*) → main emphasis, defining infrastructure requirements

$\sim 16\text{ T} \Rightarrow 100\text{ TeV } pp \text{ in } 100\text{ km}$

- 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	3.5	<b>The beam-beam limit may further be raised with Crab-Waist schemes !</b>	
Footprint size $\Delta \nu_x / \Delta \nu_y$	0.01		0.104
Lifetime bb+bs [min]	17	120	200
Luminosity [ $\text{cm}^{-2}\text{s}^{-1}$ ]	$9.8 \cdot 10^{34}$	$7.2 \cdot 10^{34}$	$5.8 \cdot 10^{34}$
Luminosity ( $\beta_y = 2 \text{ mm}$ )	$8.3 \cdot 10^{34}$	$6.8 \cdot 10^{34}$	$5.0 \cdot 10^{34}$
Density contour plots			

parameter	LEP2	FCC-ee				
		Z	Z (c.w.)	W	H	t
$E_{\text{beam}}$ [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
$P_{\text{SR,tot}}$ [MW]	the large number of bunches at Z, W & H requires 2 rings					
no. bunches	4	16700	29791	4490	1360	98
$N_b$ [ $10^{11}$ ]	4.2	1.8	1.0	0.7	0.46	1.4
$\varepsilon_x$ [nm]	22	29	0.14	3.3	0.94	2
$\varepsilon_y$ [pm]	250	60	1	2		2
$\beta^*_x$ [m]	12	0.5	0.5	0.5	0.5	1.0
$\beta^*_y$ [mm]	50	1	1	1	1	1
$\sigma^*_y$ [nm]	3500	250	32	84	44	45
$\sigma_{z,\text{SR}}$ [mm]	11.5	1.64	2.7	1.01	0.81	1.16
$\sigma_{z,\text{tot}}$ [mm] (w beamstr.)	11.5	2.56	short lifetimes due to high luminosity → continuous injection (top-up)			
hourglass factor $F_{hg}$	0.99	0.64	73	149	117	140
$L/\text{IP}$ [ $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ ]	0.01	28	212	12	6	1.7
$\tau_{\text{beam}}$ [min]	434	298	39	73	29	21

parameter	LEP2	FCC-ee				
		Z	Z (c.w.)	W	H	t
$E_{\text{beam}}$ [GeV]	104	45	45	80	120	175
beam-beam par. $\xi_y/\text{IP}$	0.06	0.03	0.175	0.06	0.093	0.092
current [mA]	3.0	1450	1431	152	30	6.6
$P_{\text{SR,tot}}$ [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
$\varepsilon_x$ [nm]	22	22	14	3.3	0.94	2
$\varepsilon_y$ [pm]	250	60	1	1	2	2
$\beta^*_x$ [m]	12	0.5	0.5	0.5	0.5	1.0
$\beta^*_y$ [mm]	50	1	1	1	1	1
$\sigma^*_y$ [nm]	3500	250	32	84	44	45
$\sigma_{z,\text{SR}}$ [mm]	11.5	1.64	2.7	1.01	0.81	1.16
$\sigma_{z,\text{tot}}$ [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
$L/\text{IP}$ [ $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ ]	0.01	28	212	12	6	1.7
$\tau_{\text{beam}}$ [min]	434	298	39	73	29	21

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