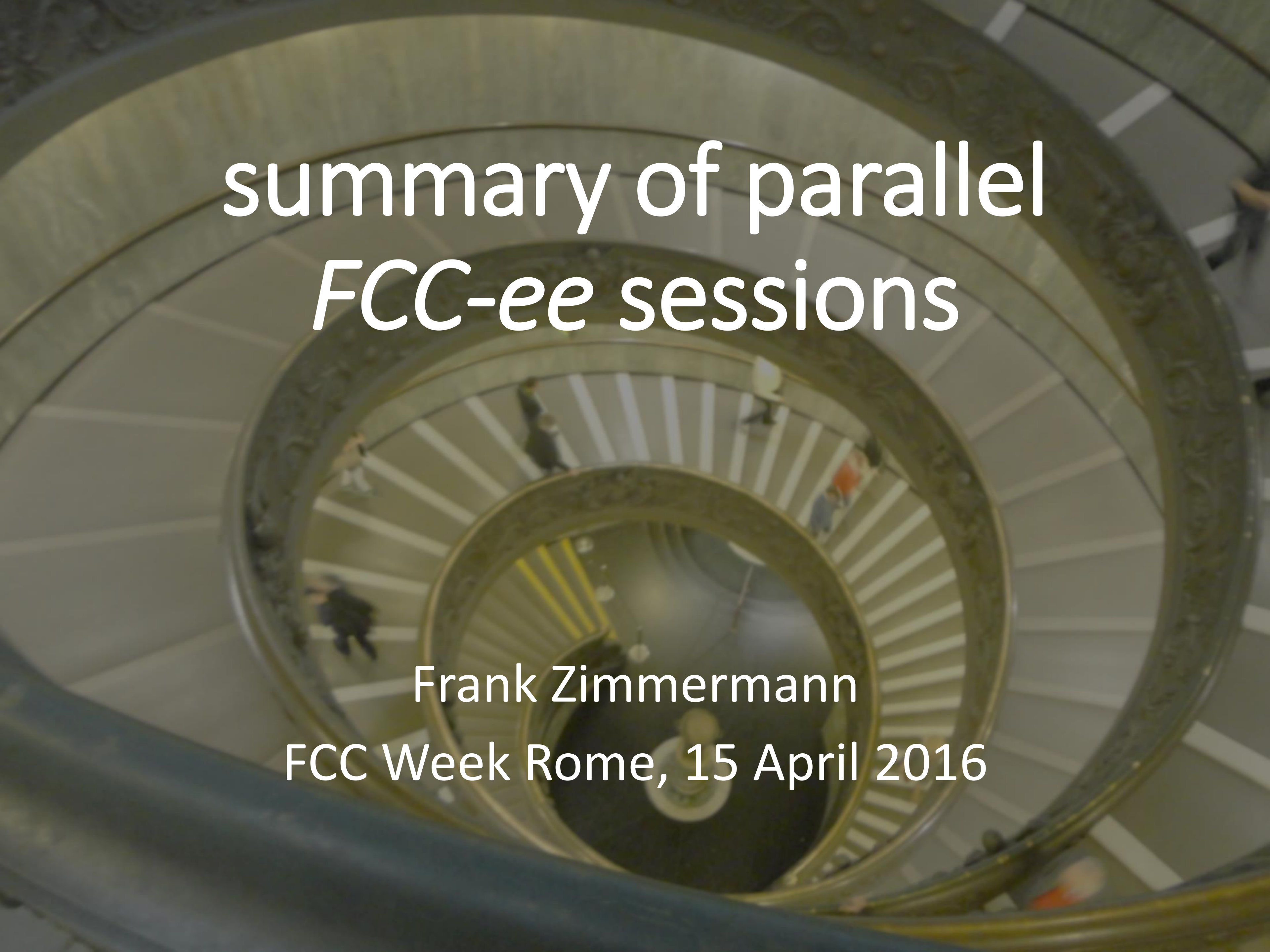


summary of parallel *FCC-ee* sessions

Frank Zimmermann

FCC Week Rome, 15 April 2016

FCC-ee accelerator sessions 1 - 3

FCC-hh machine layout & optics (plenary Monday)	Katsunobu Oide (KEK)
FCC-ee Beam-Beam & Luminosity (session 1, Wednesday)	**Chair Andrew Hutton (JLAB)**
Beam-beam simulations of FCC-ee with Lifetrac	Dmitry Shatilov (BINP)
Beam-beam simulations, e-cloud and ion instabilities	Kazuhito Ohmi (KEK)
Interplay of the beam-beam effect and the lattice nonlinearity	Demin Zhou (KEK)
A new beam-beam effect in collisions with crossing angle	Valery Telnov (BINP)
FCC-ee Single Beam Collective Effects (session 2, Wednesday)	**Chair Evgeny Levichev (BINP)**
Single-beam collective effects in FCC-ee	Mauro Migliorati (Sapienza)
Beam Heating due to Coherent Synchrotron Radiation	Alexander Novokhatski (SLAC)
Collective Effects in Low-Emittance Rings: Projection for FCC	Victor Smalyuk (BNL)
Feedback systems for FCC-ee	Alessandro Drago (INFN-LNF)
FCC-ee Optics (session 3, Wednesday)	**Chair Katsunobu Oide (KEK)**
FCC-ee IR optics solutions	Anton Bogomyagkov (BINP)
Arc optics, global Q' correction and emittance variation	Bastian Harer (KIT Karlsruhe)
CEPC partial double ring scheme and crab-waist parameters	Dou Wang (IHEP)
Update on CEPC pretzel scheme design	Huiping Geng (IHEP)
Lattice for a Higgs factory	Yunhai Cai (SLAC)

FCC-ee accelerator sessions 4 - 6

FCC-ee Energy Calibration and Polarisation (session 4, Thursday)	**Chair Alain Blondel (U Geneva)**
Energy calibration – a look back at LEP	Guy Wilkinson (Oxford)
Self polarization in the collider	Eliana Gianfelice-Wendt (FNAL)
Accelerating and injecting polarized beams	Ivan Koop (BINP)
Polarization study for CEPC	Zhe Duan (IHEP)
FCC-ee Lattice Corrections & Performance (session 5, Thursday)	**Chair Bernhard Holzer (CERN)**
Tolerance studies and coupling correction for FCC-ee	Sandra Aumon (CERN)
Dynamic aperture	Luis Medina (U Guanajuato)
SR-based emittance diagnostics	Toshiyuki Mitsuhashi (KEK)
KEK and SuperKEKB injector experience	Kazuro Furukawa (KEK)
FCC-ee Injector (session 6, Wednesday)	**Chair Andrea Ghigo (INFN-LNF)**
FCC-ee injector complex incl. booster	Yannis Papaphilippou (CERN)
Preliminary injector linac design	Sergey Polozov (MEPhI)
Design of the pre-booster ring optics	Ozgur Etisken (Ankara)
CEPC injector-ring design	Xiaohao Cui (IHEP)
Top-up injection schemes	Masamitsu Aiba (PSI)

FCC-ee accelerator sessions in a nutshell

26 contributions from all around the world

America (5):
BNL (1), FNAL (1), Guanajuato (1), SLAC (2)

Asia (13):
Ankara (1), BINP (4), IHEP(4), KEK (4)

Europe (8):
CERN (2), INFN-LNF (1), KIT (1), MEPhI (1),
Oxford (1), PSI (1), Sapienza (1)

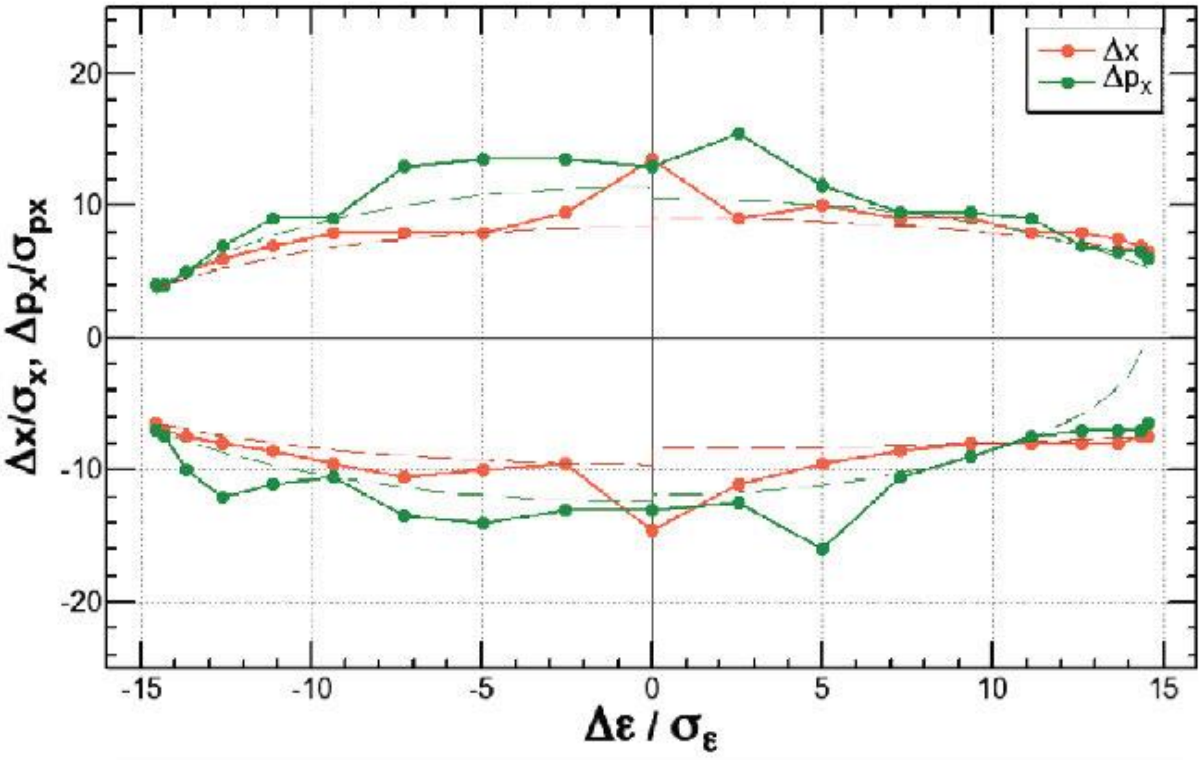
a wealth of information and enormous progress!

dynamic aperture of latest optics

t-tbar (350 GeV) ,$\beta_{x,y}^{*}$=0.5 m, 1 mm (tight betas)

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

Horizontal plane:



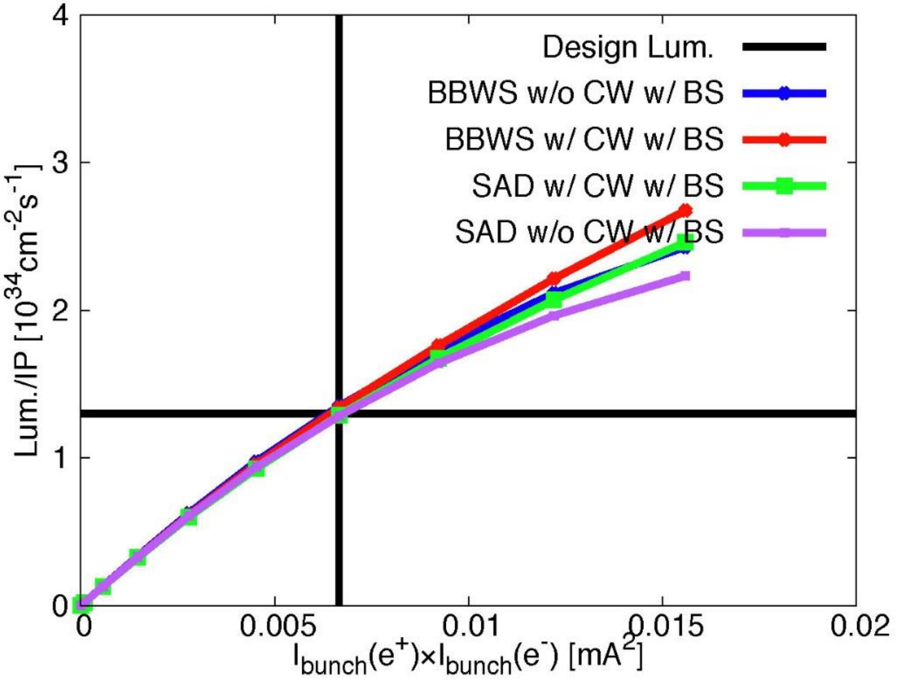
Crab on, 50 turns, $\epsilon_X = 1.34\,\mathrm{nm}\cdot\mathrm{rad}$, $\sigma_E = 0.144\,\%$, $\sigma_Z = 2.4\,\mathrm{mm}$,
$\nu_{X,y,z} = 387.0800, 387.1400, -0.0686$. $U_0 = 7.74\,\mathrm{GeV}$.

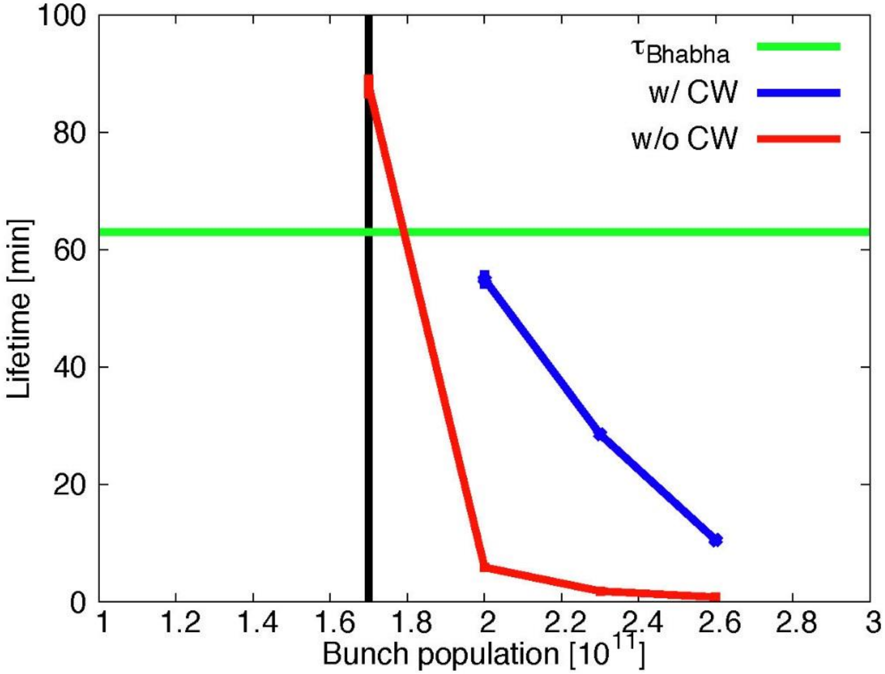
L. Medina, K. Oide

weak-strong beam-beam + full optics lattice

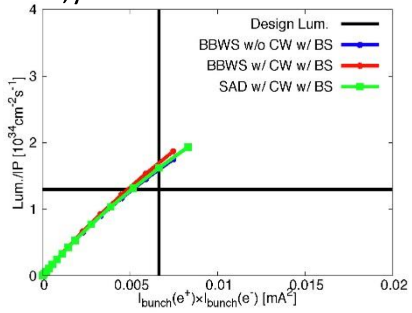
t-tbar (350 GeV)

$\beta_{x,y}{}^{*}$=1 m, 2 mm





$\beta_{x,y}{}^{*}$=0.5 m, 1 mm



simulations confirm design luminosity including full lattice nonlinearities

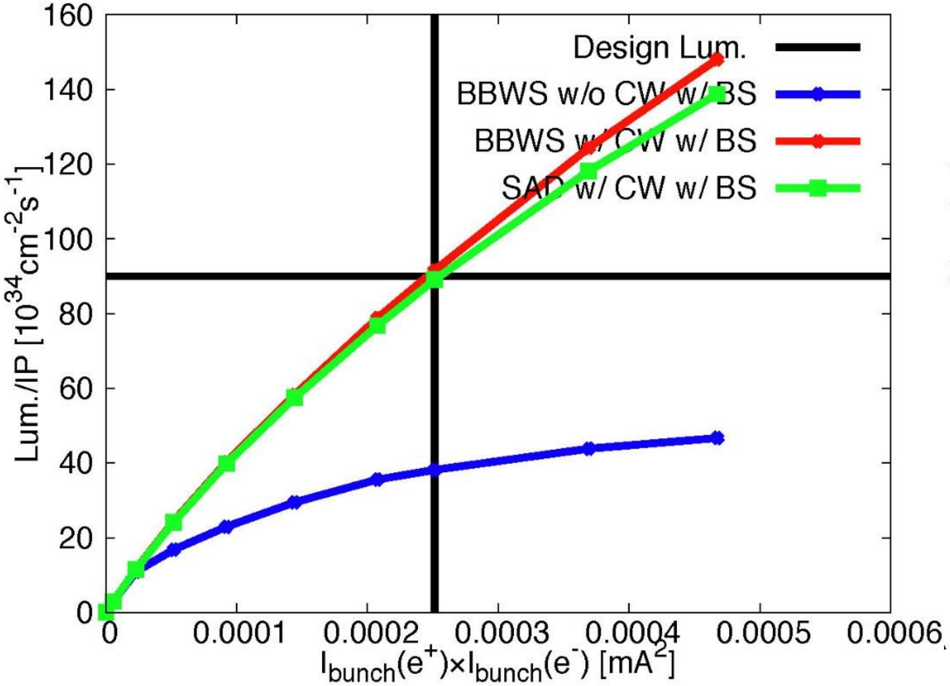
present optics with crab waist: zero particle losses due beamstrahlung at nominal bunch charge

D. Zhou

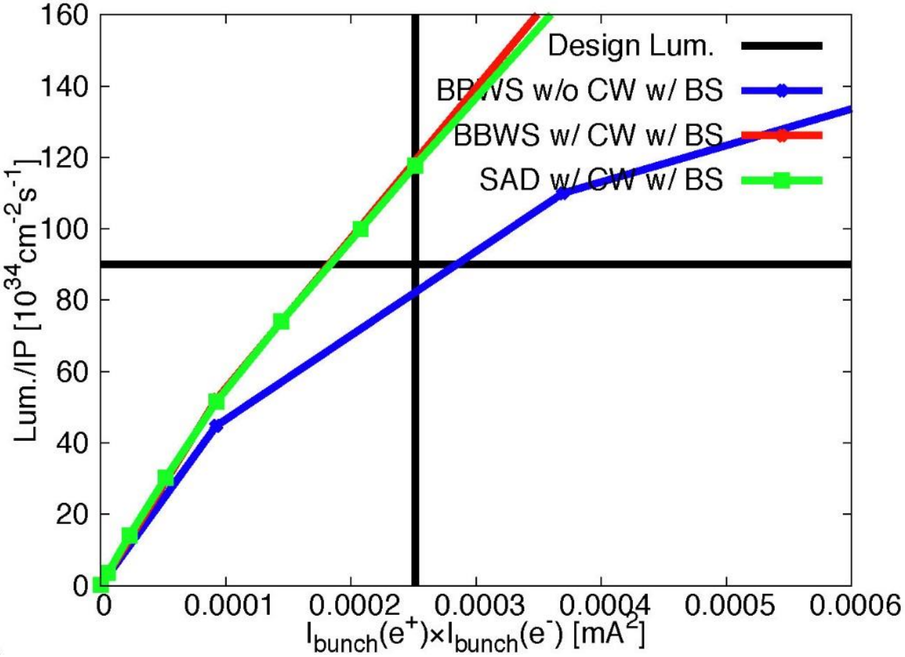
weak-strong beam-beam + full optics lattice

Z (91 GeV)

$\beta_{x,y}^{*}$=1 m, 2 mm



$\beta_{x,y}^{*}$=0.5 m, 1 mm



simulations confirm design luminosity including full lattice nonlinearities, crab waist essential here

beam-beam and full lattice nonlinearities permit lower β* at all energies

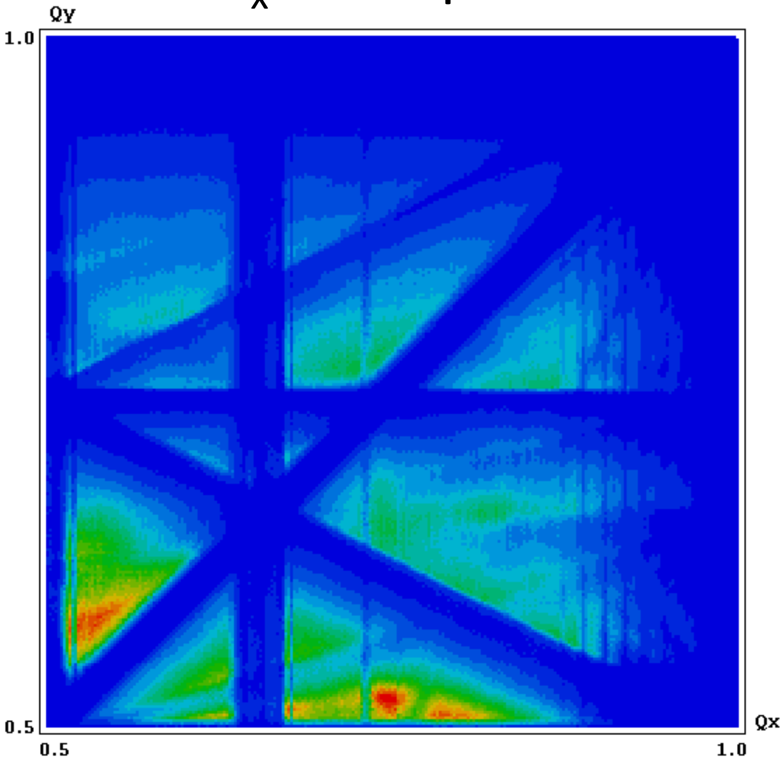
D. Zhou

quasi-strong-strong beam-beam simulations

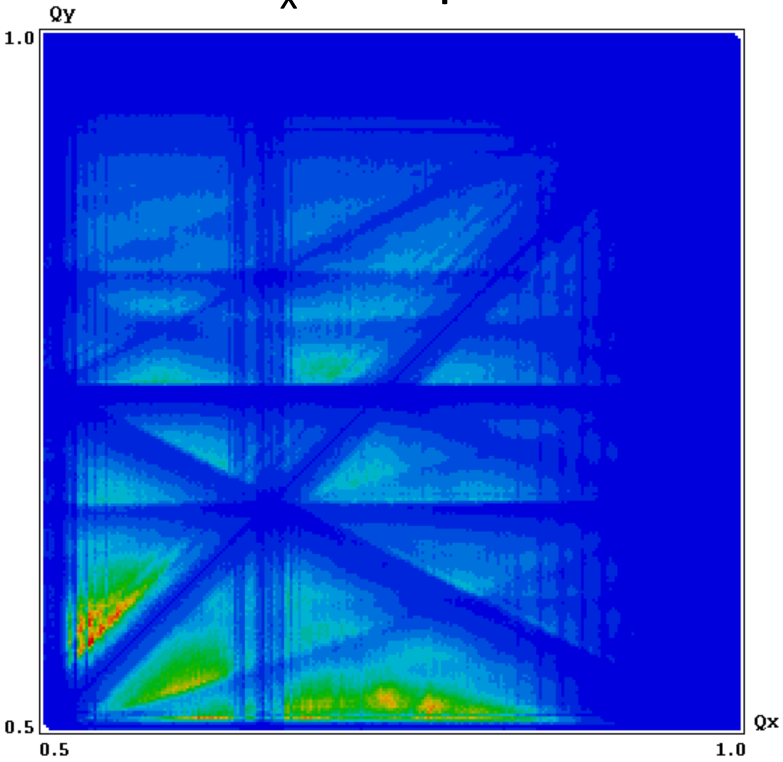
175 GeV: Lifetrac simulations validate baseline beta-functions of 1 m / 2 mm

45.6 GeV: clear preference for alternative baseline: lower β_x (50 cm) and β_y (1 mm), together with larger ε_x (0.2 nm) → narrower tune footprint and **higher threshold of flip-flop instability**

D. Shatilov



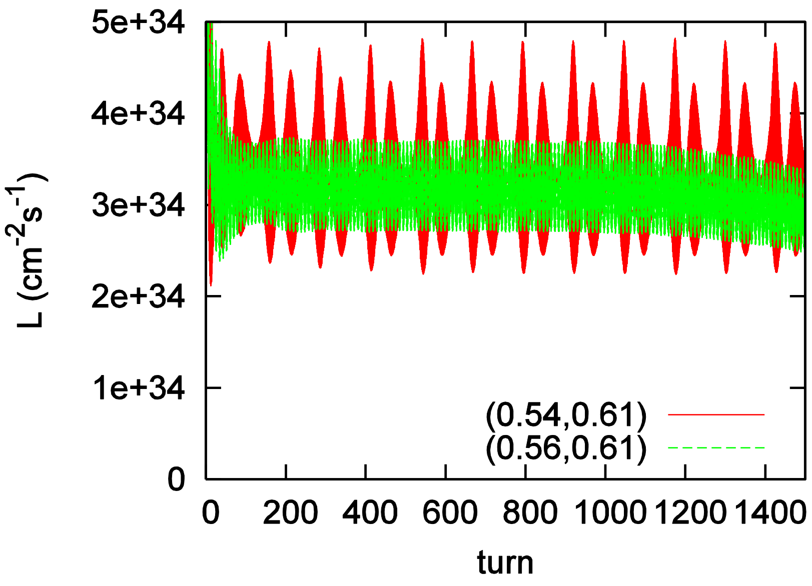
ε_x = 200 pm

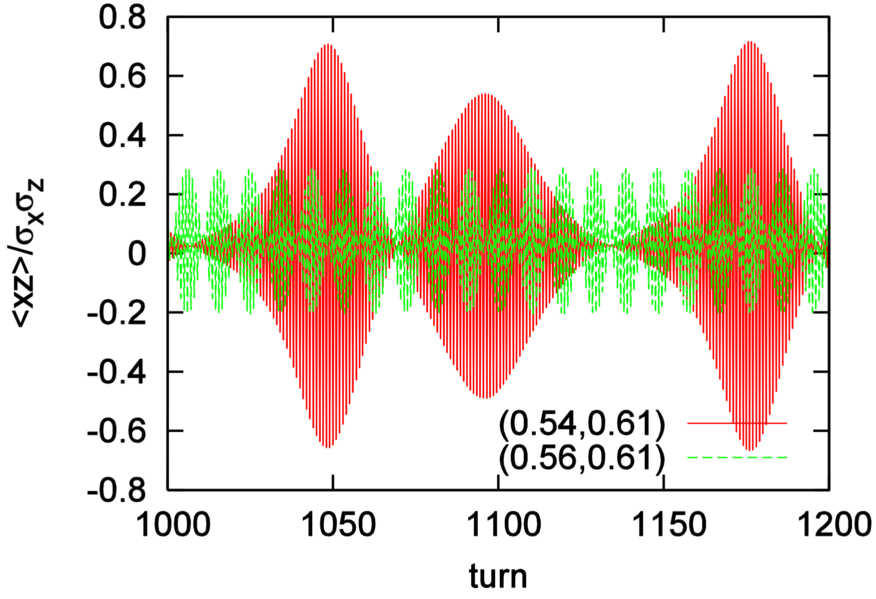


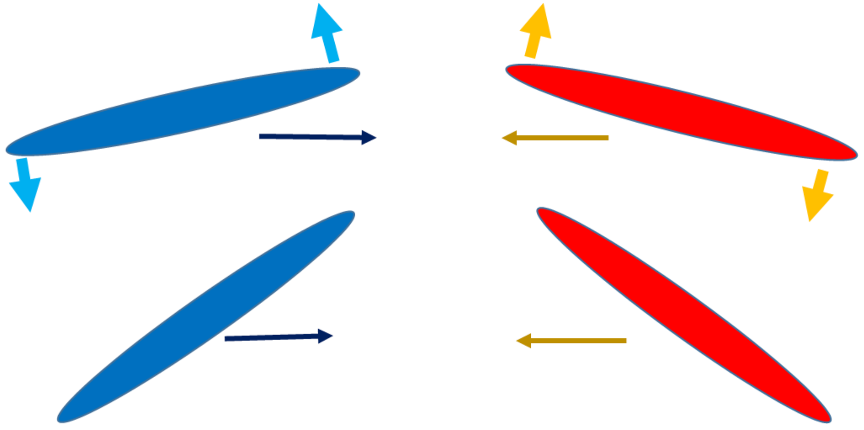
ε_x = 83 pm

strong-strong beam-beam simulations

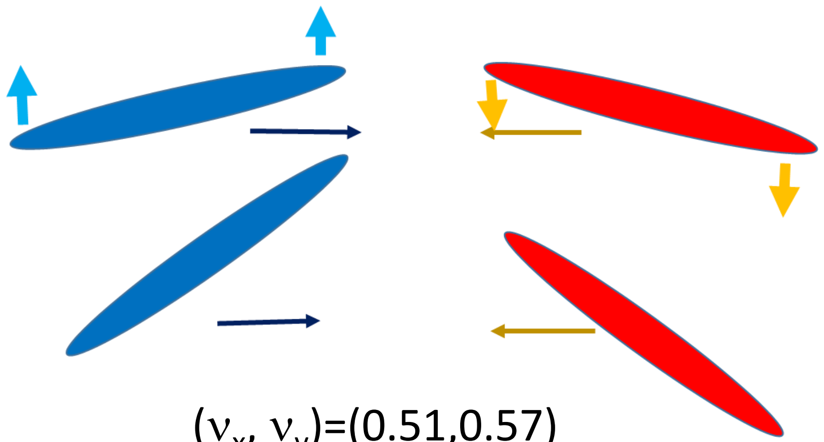
fluctuations in **luminosity** and beam size due to fluctuation of **<xz> correlation**







(ν_x, ν_y)=(0.54,0.61)

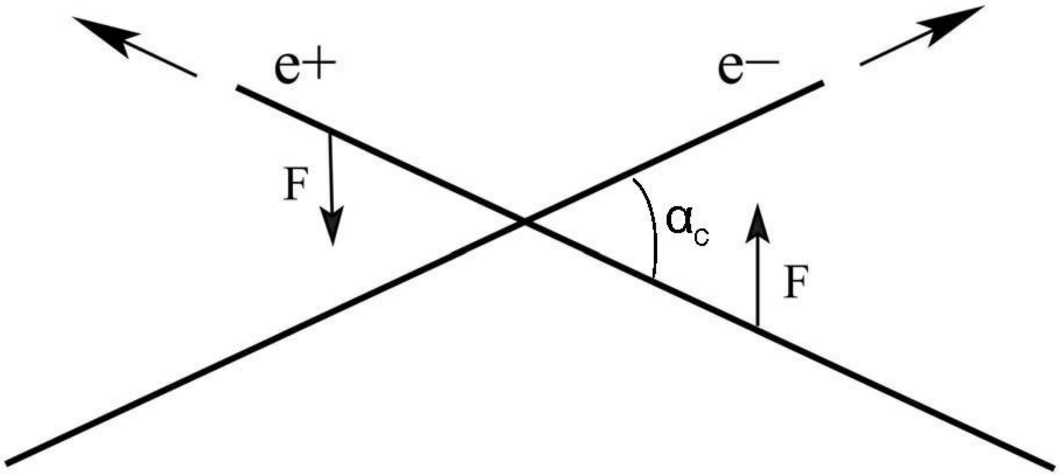


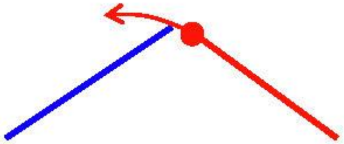
(ν_x, ν_y)=(0.51,0.57)

K. Ohmi

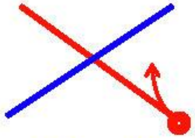
this effect not seen in the past – likely suppressed by lower β^* or larger ε

crabbing effect in crossing angle collision





the head is attracted
only after beam crossing



the tail is attracted
only before the collision

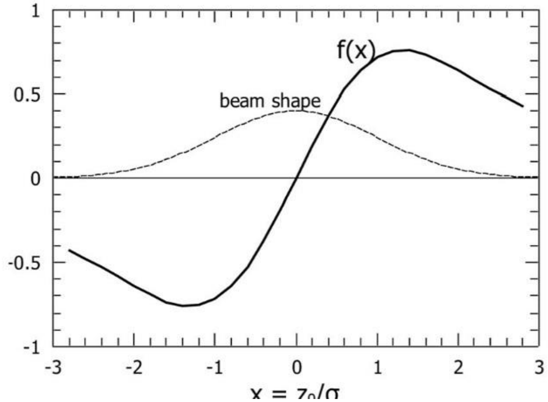
The deflection angle θ_x

$$P_\perp = \int_{-\infty}^{\infty} \frac{4e^2N}{\sqrt{2\pi}\sigma_z c\alpha_c(z+z_0)} e^{-\frac{(2z+z_0)^2}{2\sigma_z^2}} dz$$

$$\theta_x = \frac{P_\perp}{\gamma mc} = \frac{4r_eN}{\gamma\sigma_z\alpha_c} f\left(\frac{z_0}{\sigma_z}\right)$$

$$f(x) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} \frac{e^{-u^2/2}}{x+u} du$$

$$f(x) = x \text{ at } x \ll 1$$

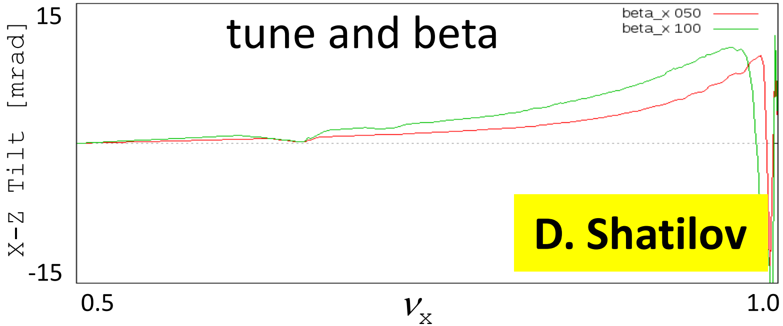


close to ½ integer

$\Delta x = \beta_x^* \theta_x * 0.6$ beating, formula (1)

$\Delta x = \beta_x^* \theta_x * 0.08$ displacement, formula (2)

simulated equilibrium angle depends on tune and beta

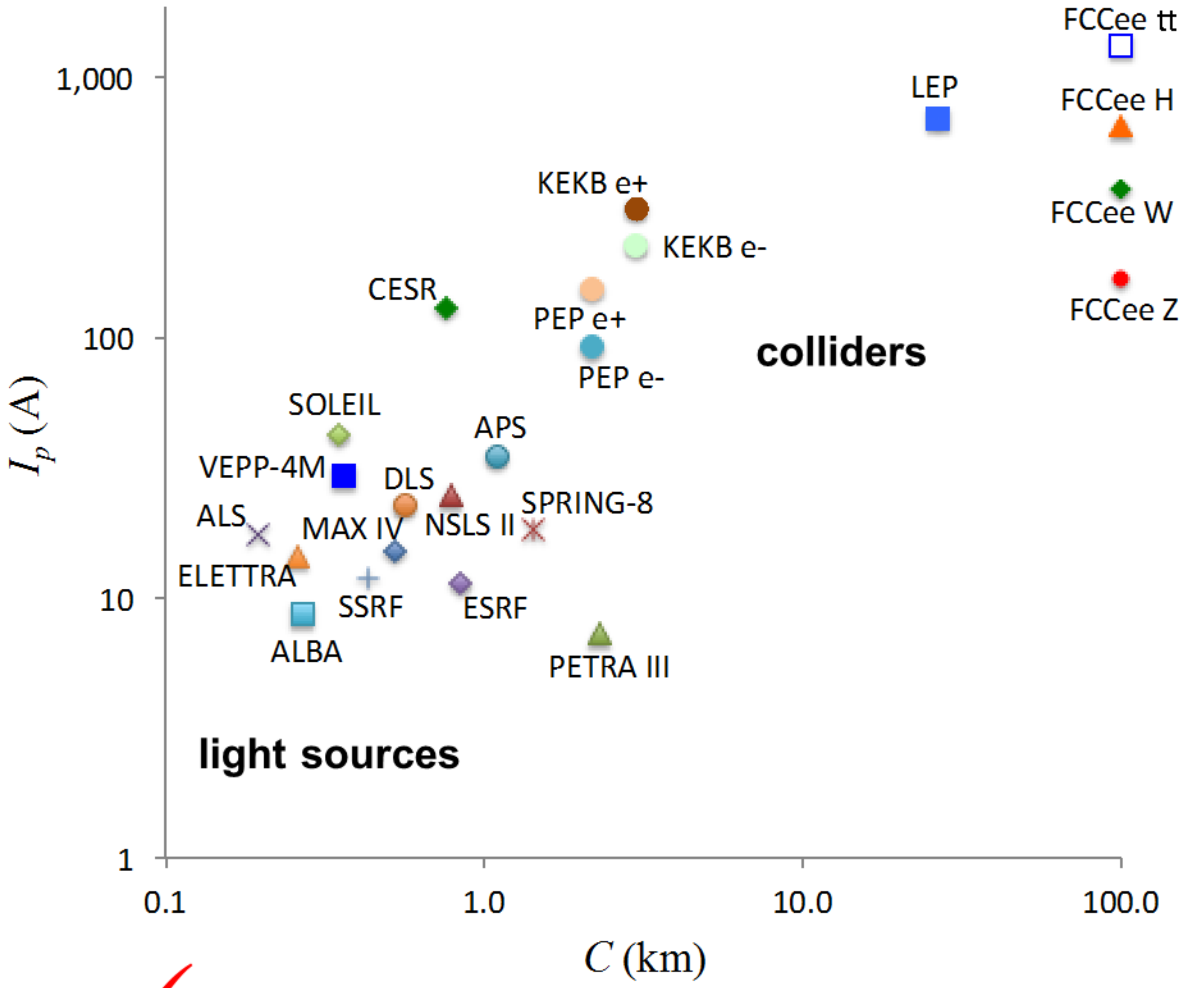


D. Shatilov

V. Telnov

world record peak currents

	σ_t (ps)	I_{aver} (mA)	I_{peak} (A)
MAX IV	40	150	15
NSLS II	12	300	24
PETRA III	44	100	7.2
ALS	25	500	17
APS	20	150	35
DLS	11	300	23
SSRF	14	200	12
SPRING-8	13	100	18
SOLEIL	18	500	42
ESRF	20	200	11
ALBA	16	120	8.5
ELETTRA	18	320	14
LEP	38	3	694
PEP e+	33	3026	153
PEP e-	37	1960	90
KEKB e+	13	1637	310
KEKB e-	13	1188	225
CESR	60	340	129
VEPP-4M	166	20	29
VEPP-2000	133	150	36
FCCee Z	13	1450	166
FCCee W	10	152	372
FCCee H	8	50	539
FCCee tt	8	6.6	1300



✓ Higher bunch charge + shorter bunch

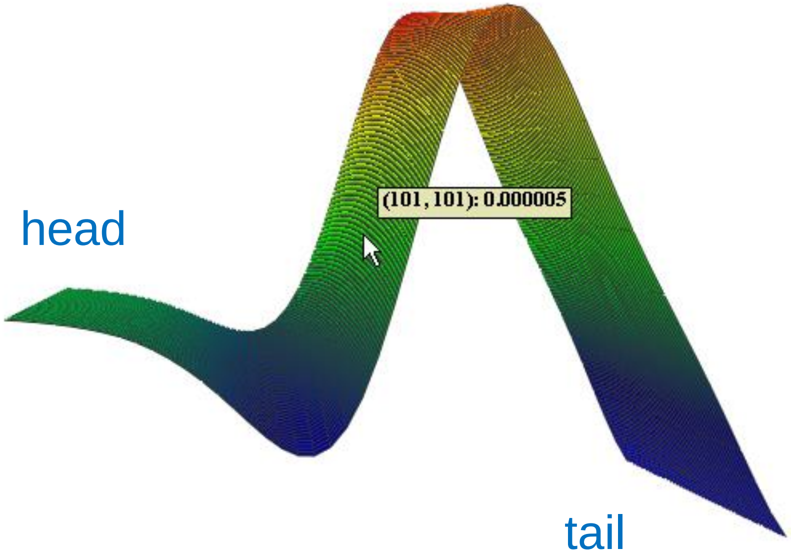
➔ higher peak current $I_{\text{peak}} = \dfrac{q_b}{\sqrt{2\pi}\sigma_t}$

➔ stronger wake fields $V_{\text{wake}} = I_{peak} Z$

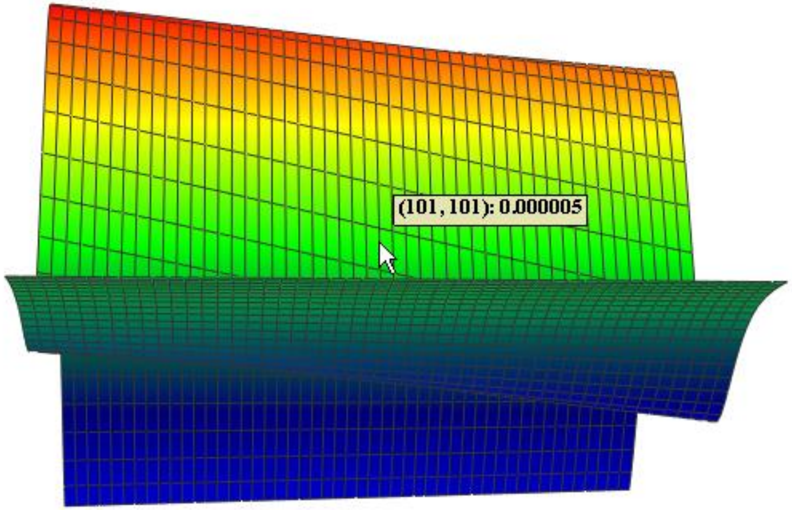
V. Smaluk

coherent synchrotron radiation

additional CSR effects like slice energy spread, centrifugal force and focusing-defocusing in the perpendicular direction and with a possible kink



Z-direction



Bend direction (Y)

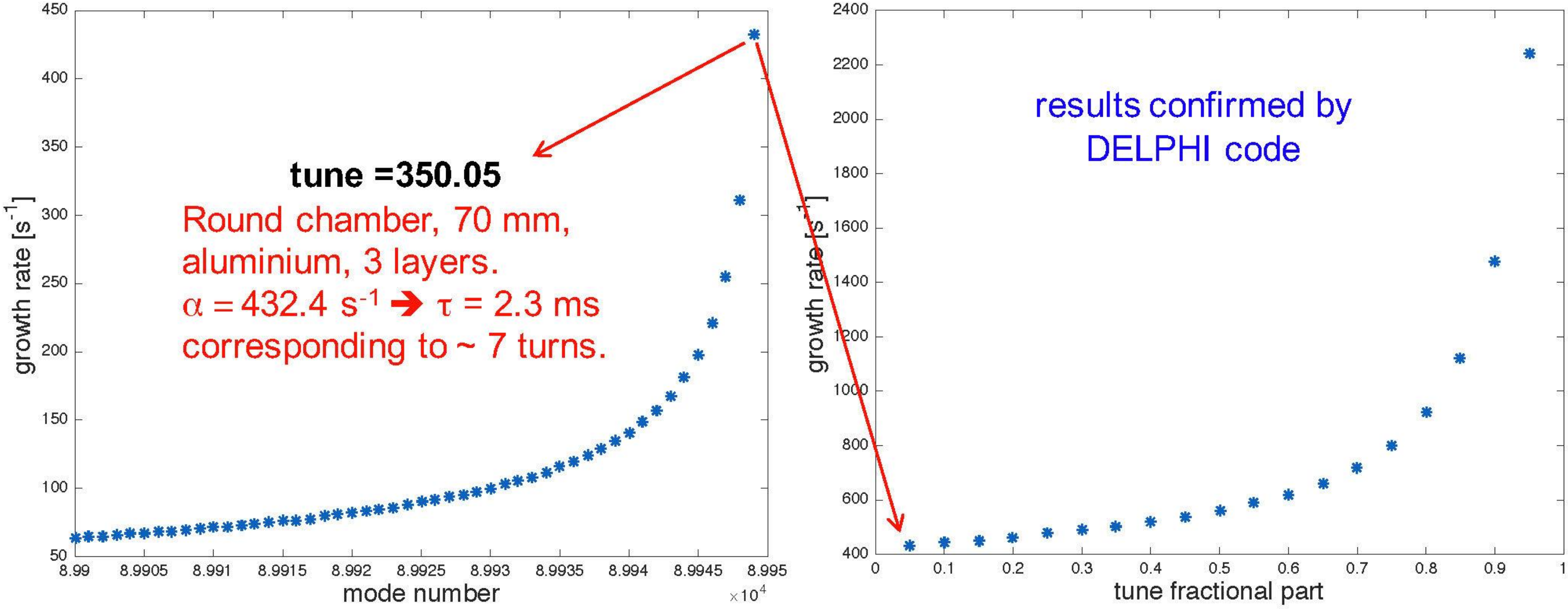
soon first estimates for FCC-ee ?
shielding by beam pipe?

A. Novokhatski

resistive wall instability at the Z pole

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

$$\alpha = \frac{c\,\overset{\text{beam current}}{\boxed{N_b I_b}}}{\underset{\text{energy}}{4\pi(E/e)Q_\beta}}\,\frac{L}{2\pi b^3}\sqrt{\frac{L Z_0}{\pi\left|1-\nu_\beta\right|\sigma_c}}\,G_\perp\left(\frac{\sigma_z}{c}\omega'_q\right)$$



tune =350.05

Round chamber, 70 mm, aluminium, 3 layers.
$\alpha = 432.4\ \text{s}^{-1} \Rightarrow \tau = 2.3$ ms
corresponding to ~ 7 turns.

results confirmed by DELPHI code

M. Migliorati

electron cloud effects for *FCC-ee-Z*

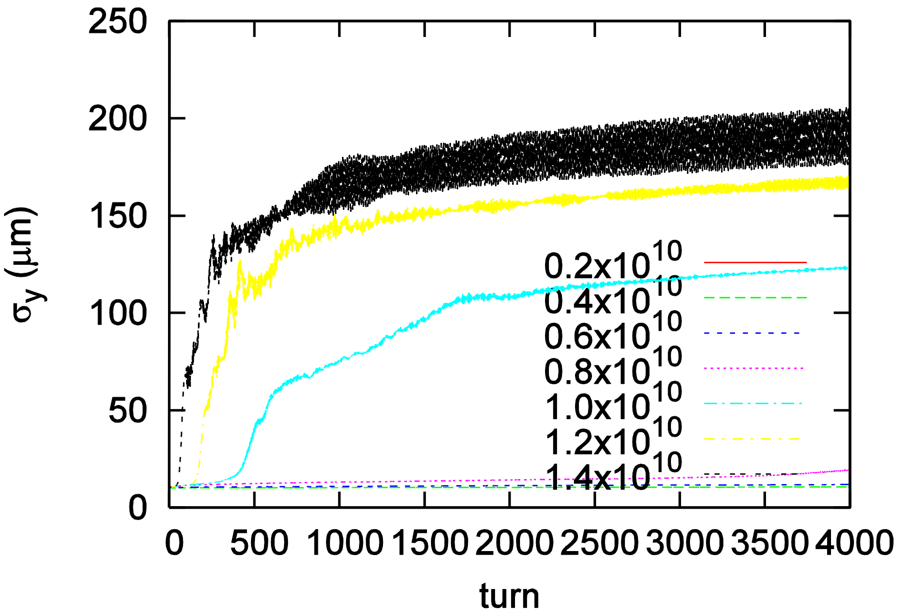
K. Ohmi

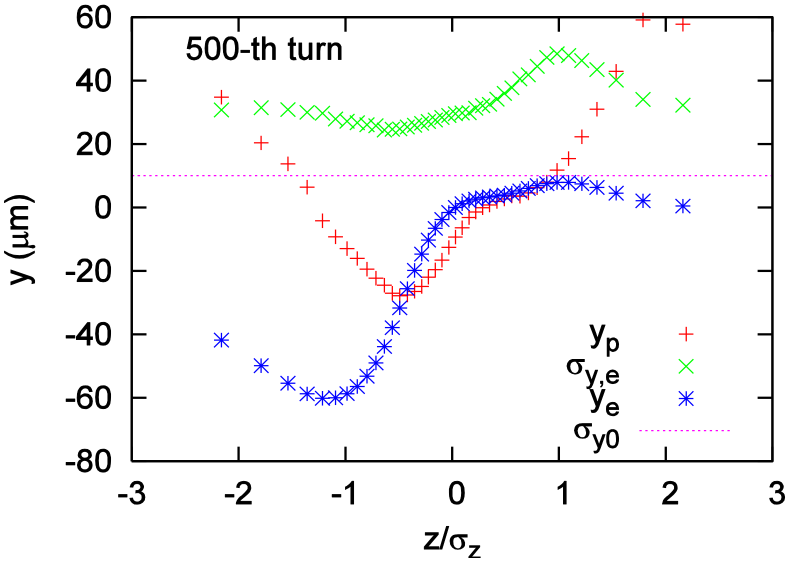
instability threshold density:

$$\rho_{e,th} = \frac{2\gamma\nu_s\omega_e\sigma_z/c}{\sqrt{3}KQr_0\beta L}$$

$\rho_{e,th}=7.8\text{x}10^9$ m^{-3} - very low density

for comparison KEKB $5\text{x}10^{11}$, SuperKEKB $1\text{x}10^{11}$ m^{-3}

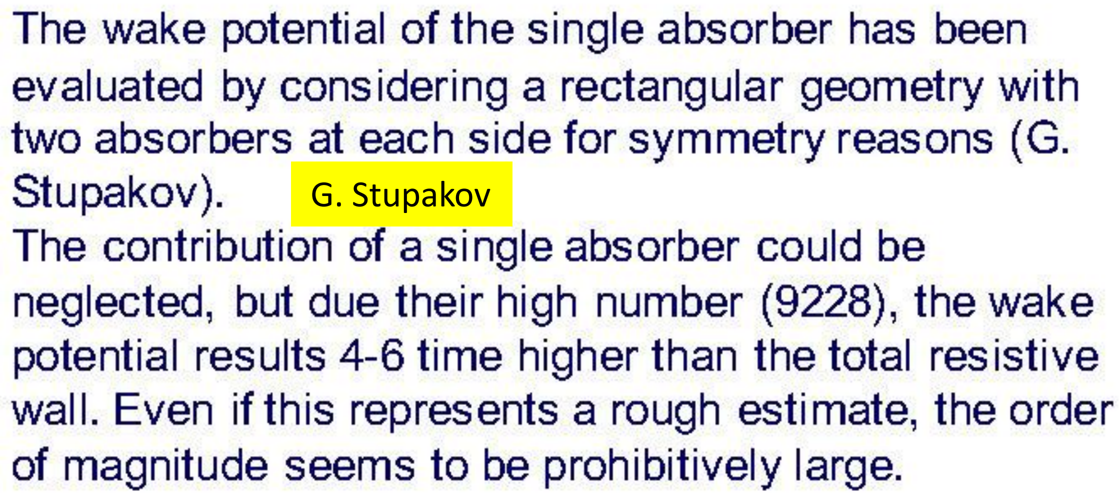




simulated threshold agrees with analytic formula

electron density exceeds $\rho_{e,th}=7.8\text{x}10^9$ m^{-3} even in a bunch passage → antechamber and other cures needed

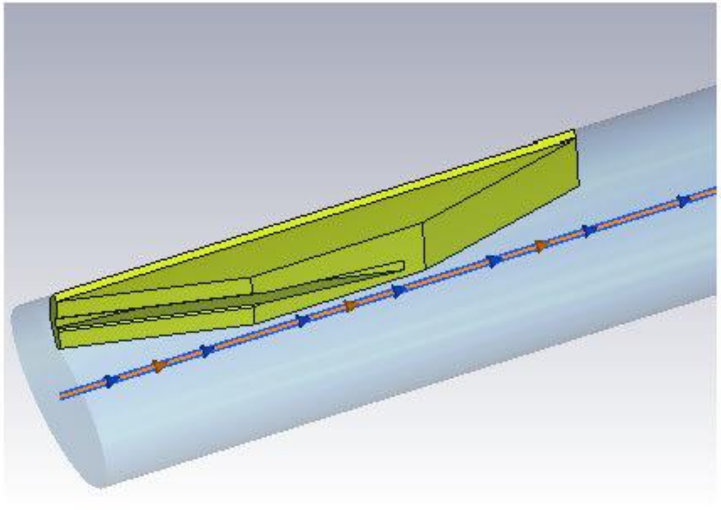
impedance of arc photon absorbers



The wake potential of the single absorber has been evaluated by considering a rectangular geometry with two absorbers at each side for symmetry reasons (G. Stupakov).

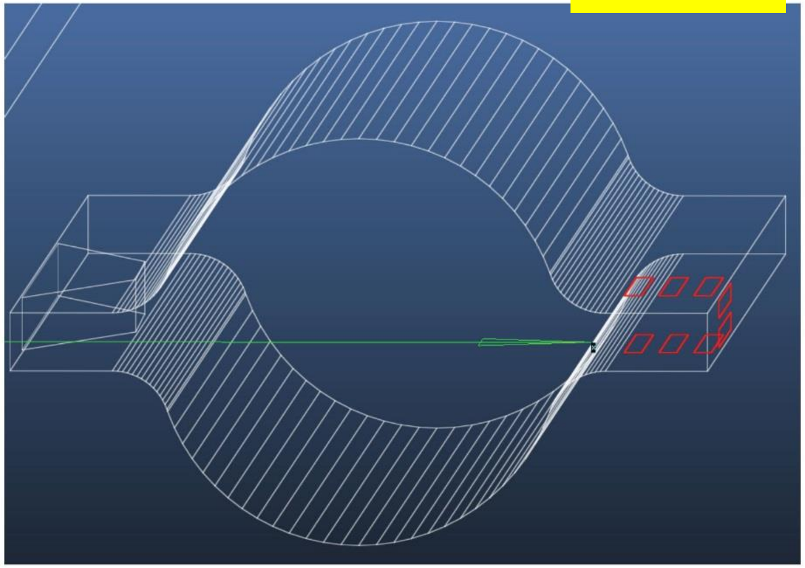
The contribution of a single absorber could be neglected, but due their high number (9228), the wake potential results 4-6 time higher than the total resistive wall. Even if this represents a rough estimate, the order of magnitude seems to be prohibitively large.

G. Stupakov



R. Kersevan

alternative solutions for photon absorbers and pumping slots are under study



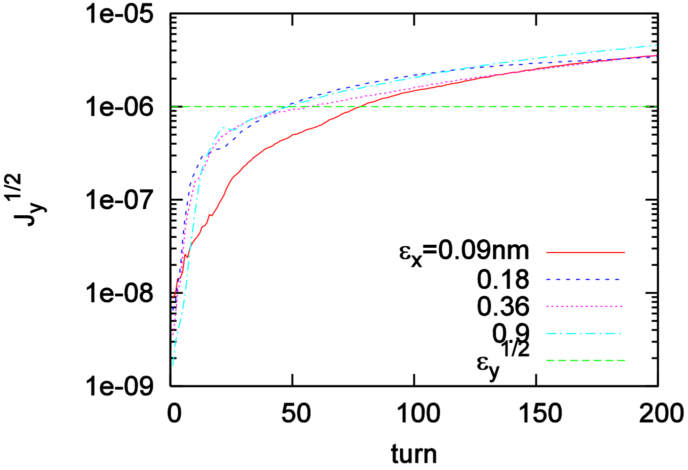
M. Migliorati

ion instability s for *FCC-ee-Z*

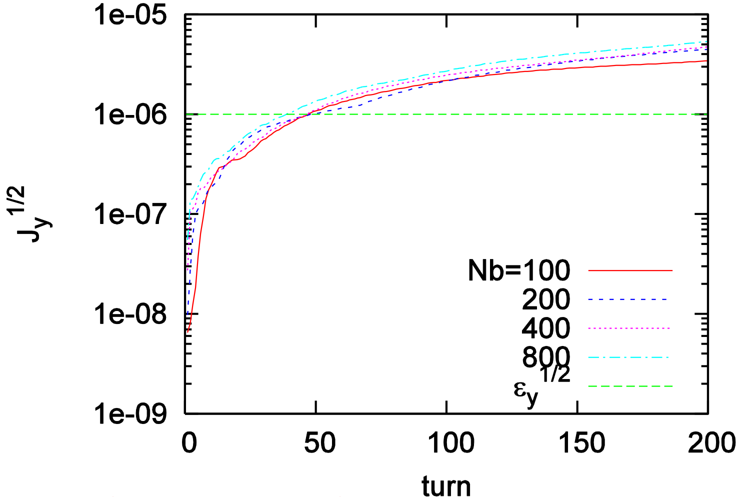
K. Ohmi

simulation results for $P=10^{-8}$ Pa

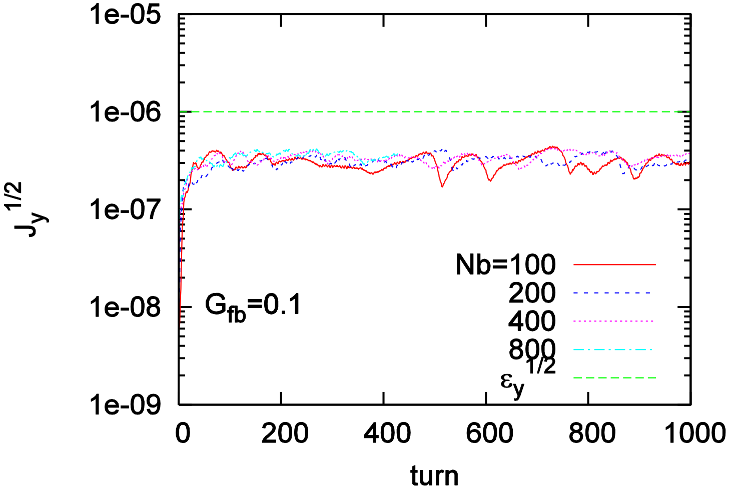
ions are trapped partially for ε_x=0.09nm

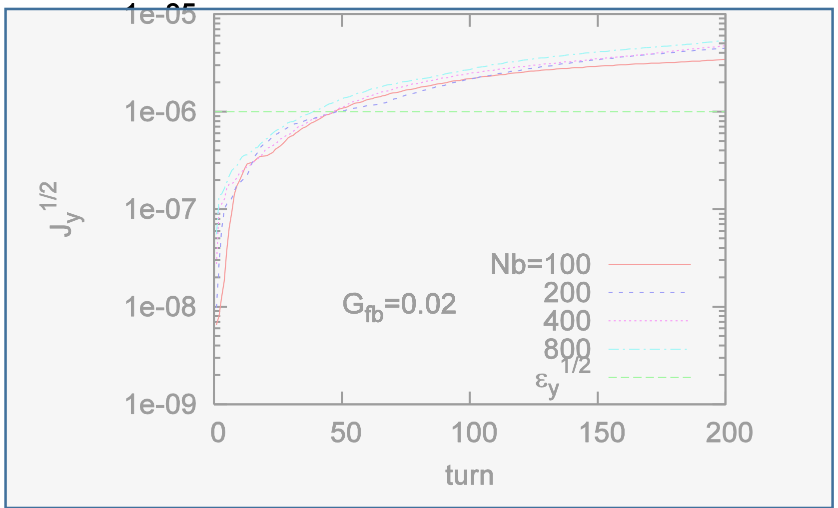


growth does not depend on train length



bunch-by-bunch feedback w G=0.1 (10 turns) damps instability





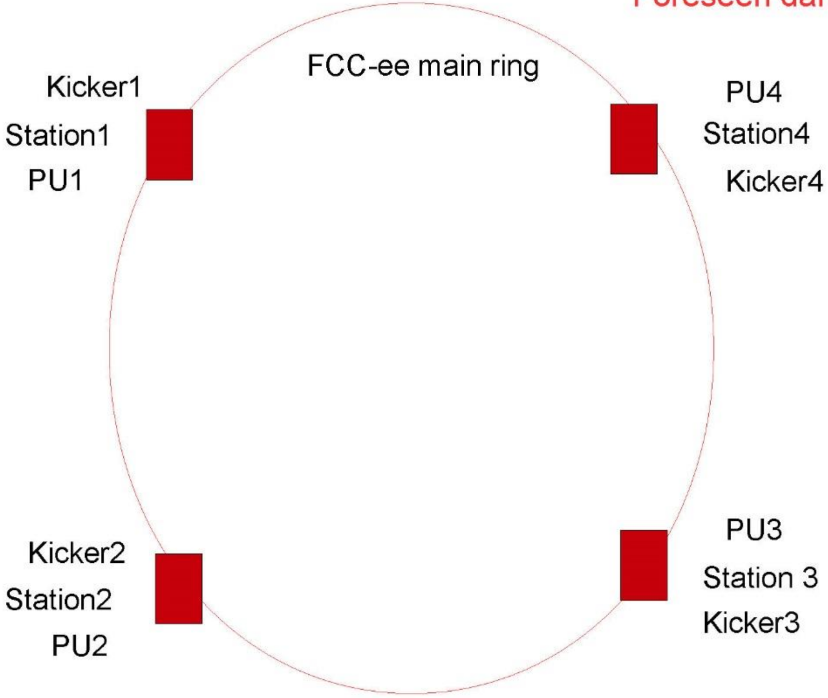
distributed feedback and feedforward

A. Drago

2008: successful DAFNE experiment with two feedback systems cooperating in the same plane (horizontal e+); measured damping rate approximately doubled

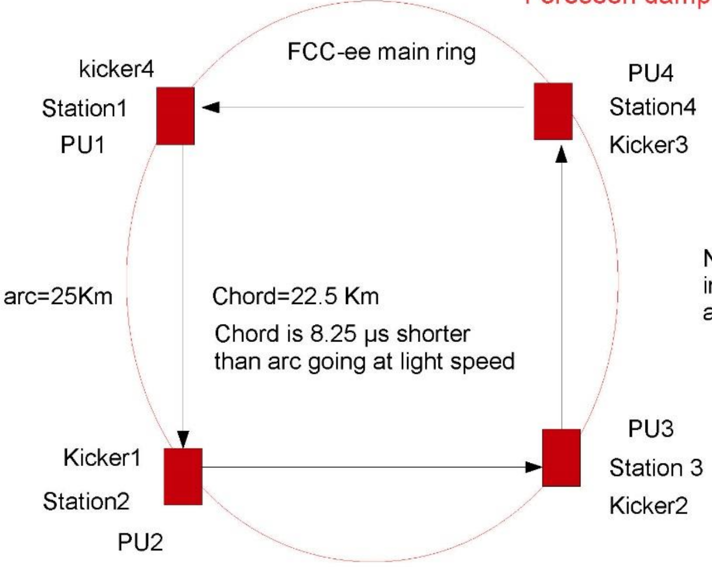
4 Feedback systems (4 stations)

Foreseen damping rate: 2.5 turns



4 Feedforward systems (4 stations)

Foreseen damping rate: 0.625 turns



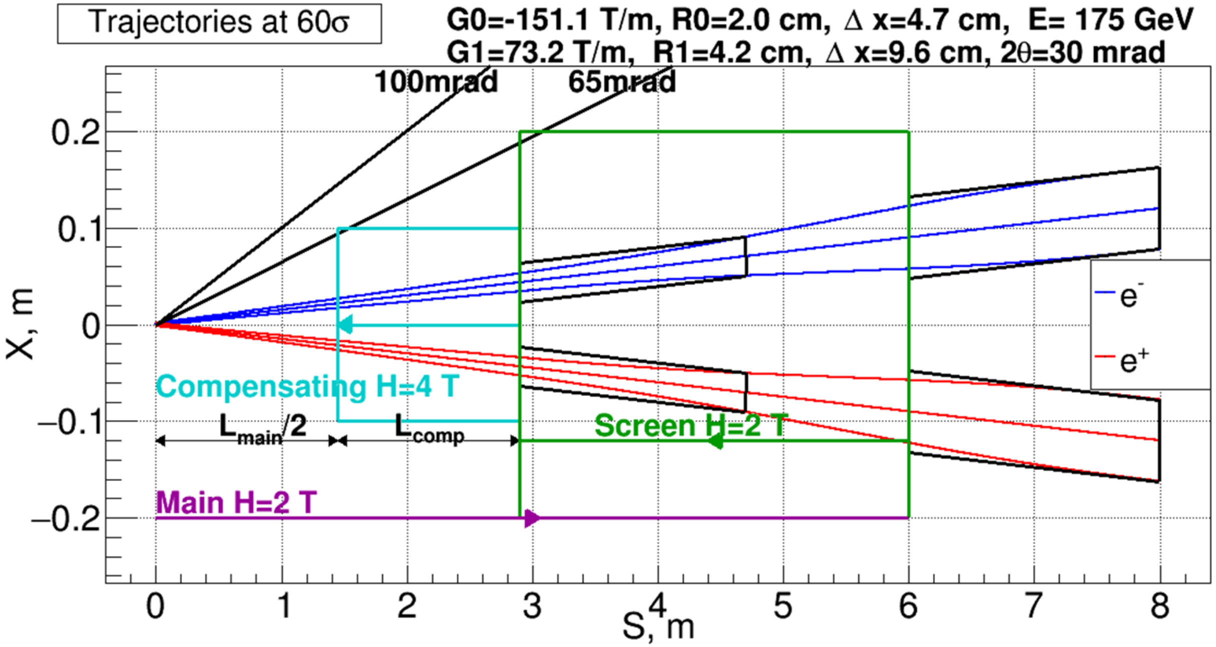
Chord=22.5 Km

Chord is 8.25 μs shorter than arc going at light speed

NOTE: the DPU insertion delay is about 400-600 ns

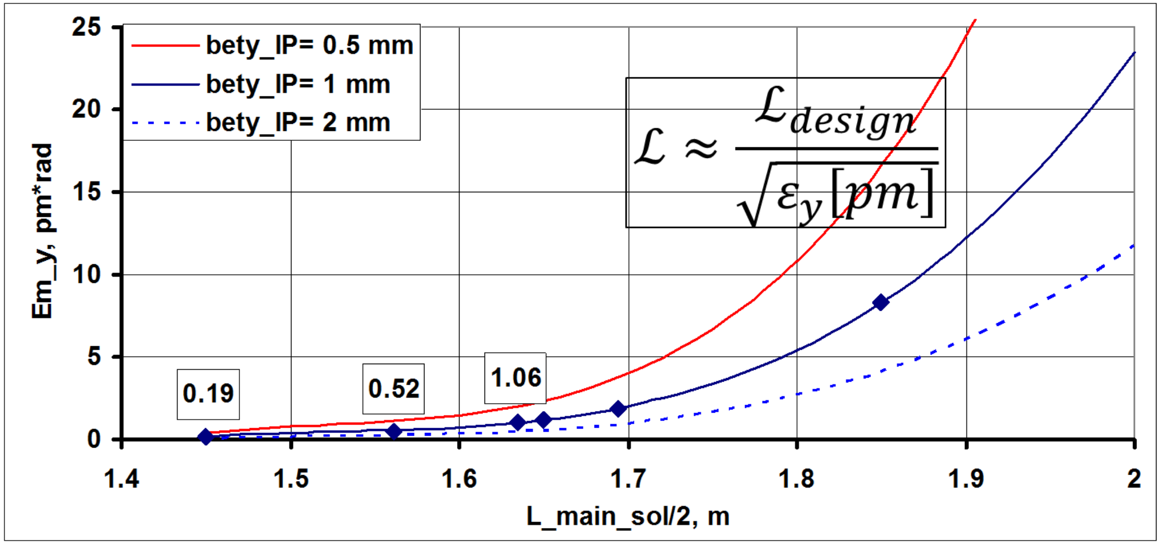
interaction region optics solutions

3 solenoids
+ IR
quadrupoles



Compensating solenoid R = 0.1 m, screening solenoid R = 0.2 m.

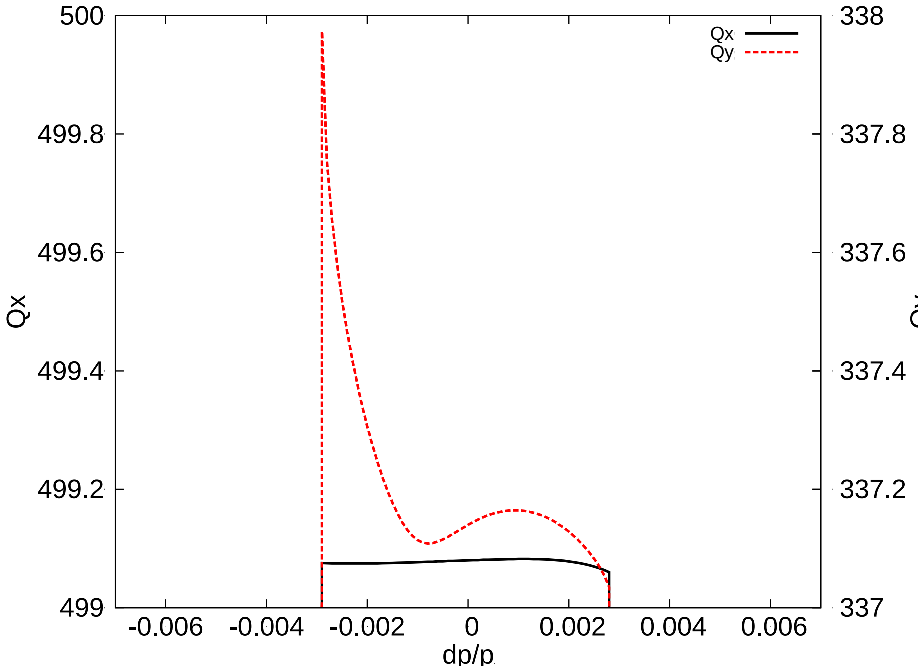
vertical emittance
growth due
to synchrotron
radiation in
in solenoid
fringe fields



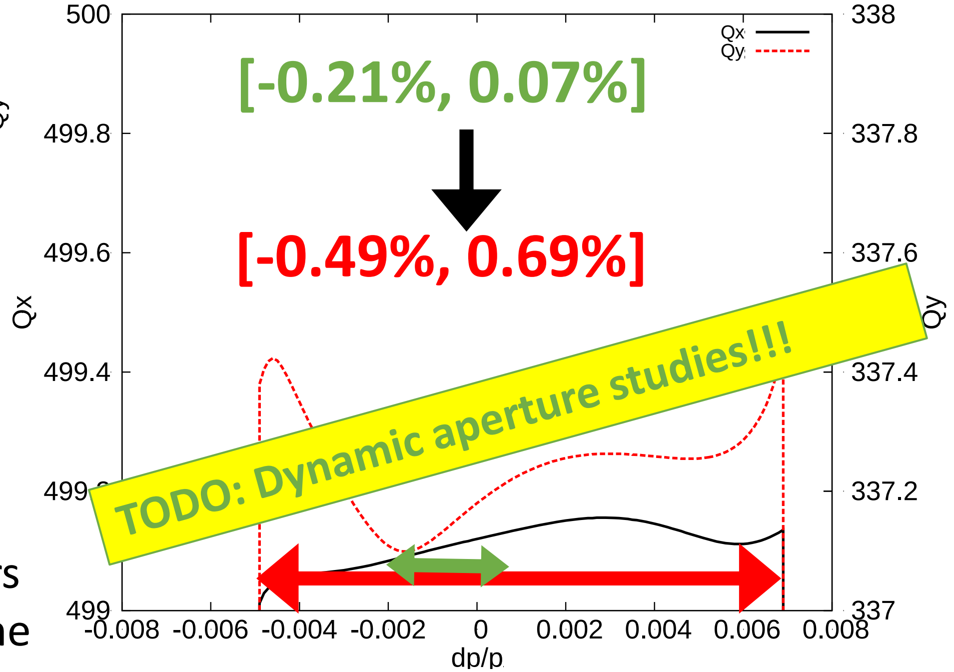
$$\mathcal{L} \approx \frac{\mathcal{L}_{design}}{\sqrt{\varepsilon_y[pm]}}$$

A. Bogomyagkov

sextupole schemes for global Q’ correction



6 sextupole families per arc per plane



[-0.21%, 0.07%]

[-0.49%, 0.69%]

TODO: Dynamic aperture studies!!!

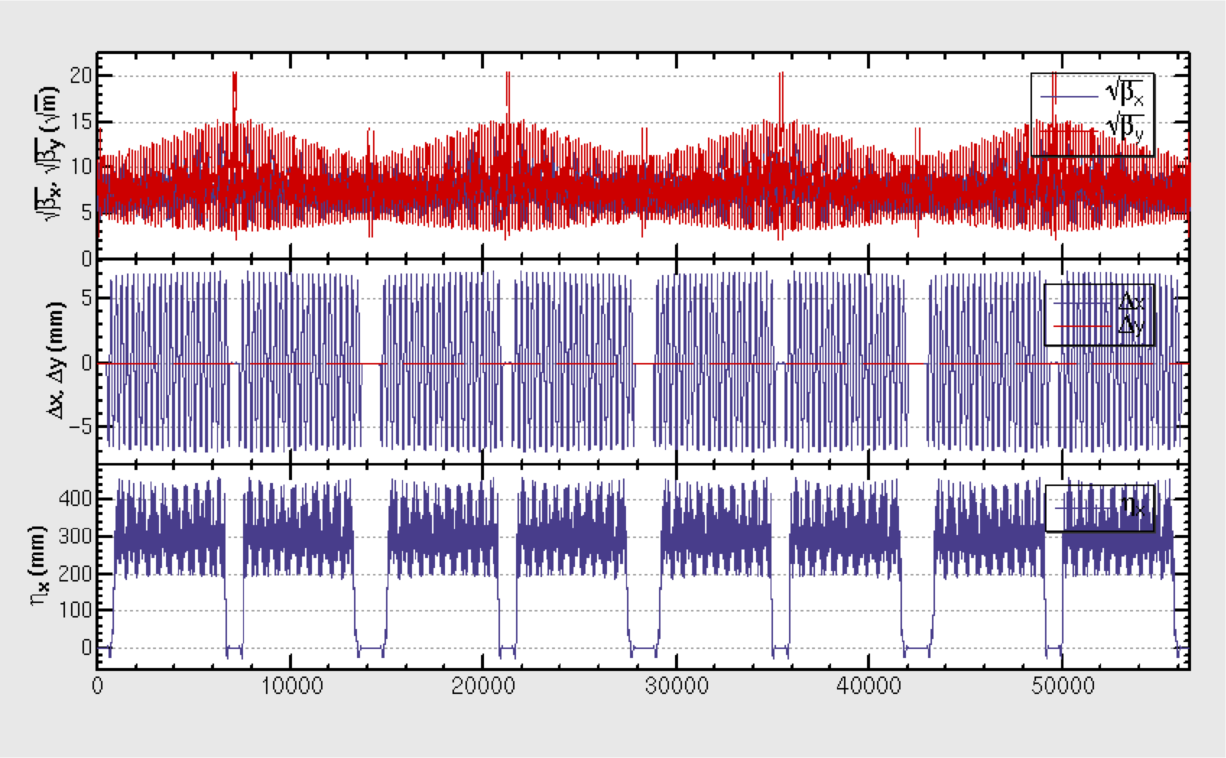
6 sextupole families + 12 free sextupole pairs per arc per plane

Vary individual sextupole pairs to flatten Q(Δp/p)

B. Haerer

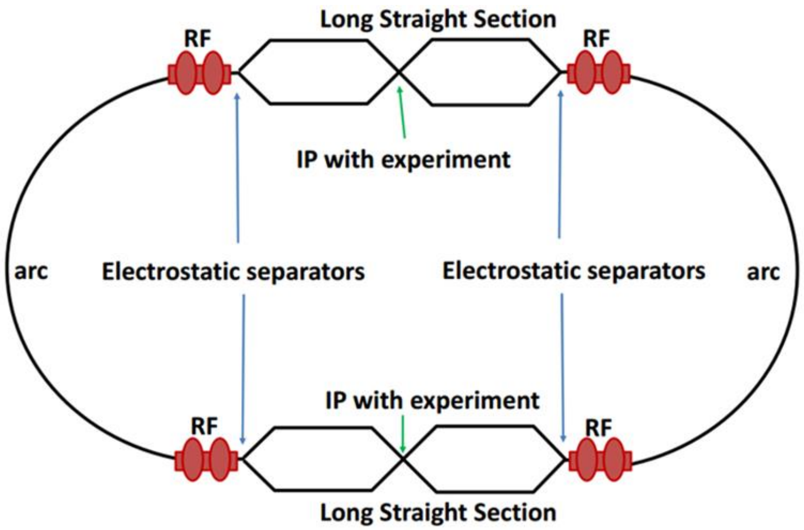
CEPC Pretzel scheme: correcting orbit effects

- Pretzel-induced distortion of beta functions and dispersions can be corrected by making quadrupoles individually adjustable
- Every 12 FODO cells were regrouped as a new period with a phase advance of n2Pi; both quadrupoles and sextupoles are adjustable

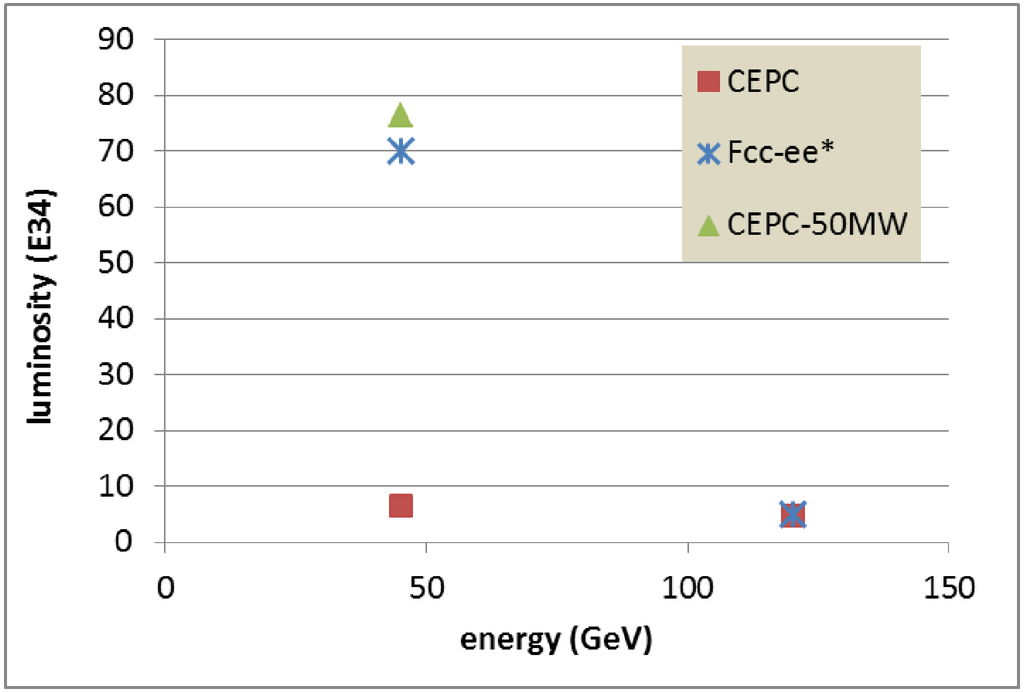


H. Geng

“CEPC partial double ring vs FCC-ee”



partial double ring*



D. Wang

* M. Koratzinos, Proc. IPAC’15

lattice for Higgs factory

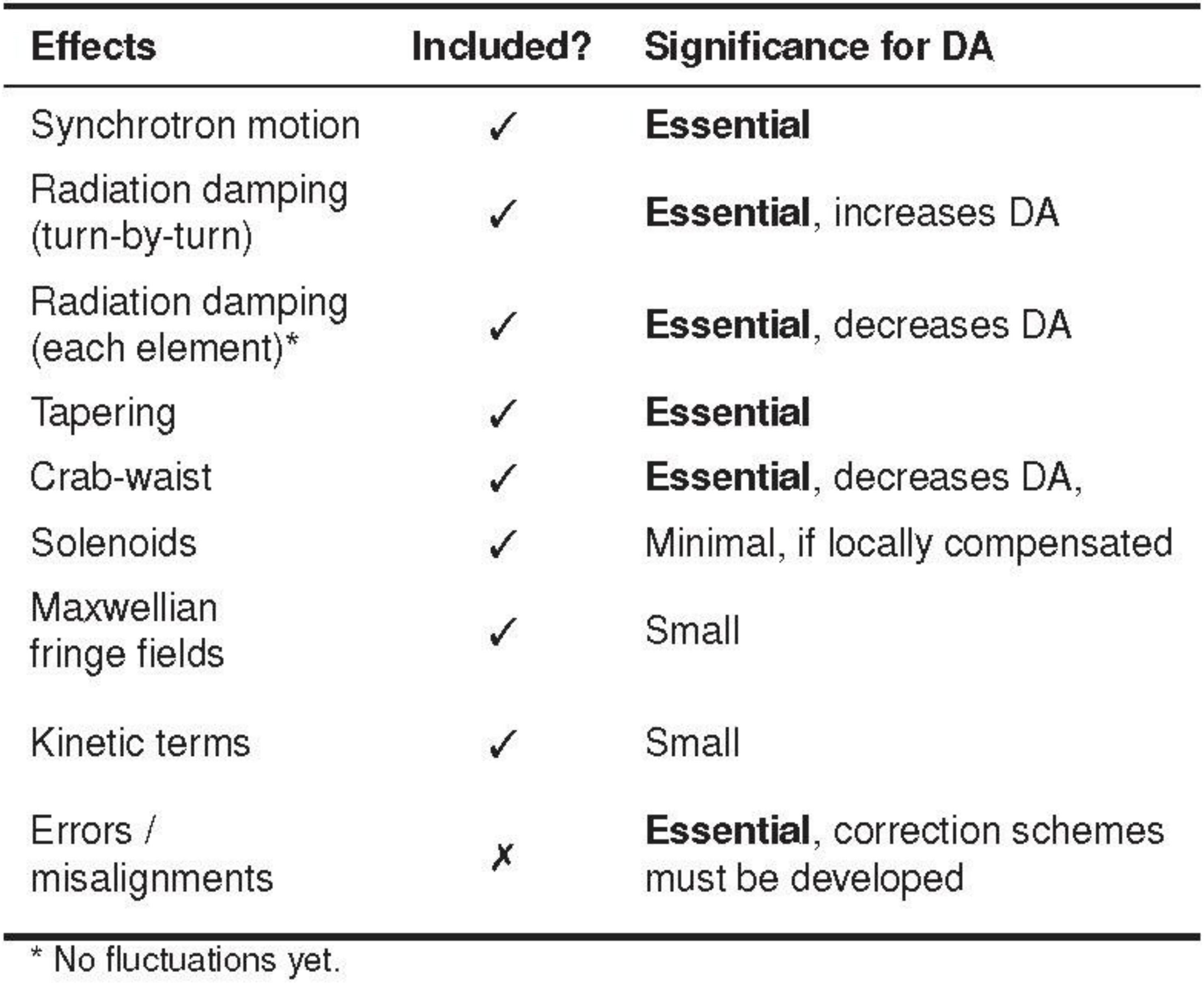
design recipe, dependence on l*, β*,…

systematic approach to chromatic correction

additional sextupoles (octupoles, decapoles,..)

Y. Cai

FCC-ee dynamic aperture

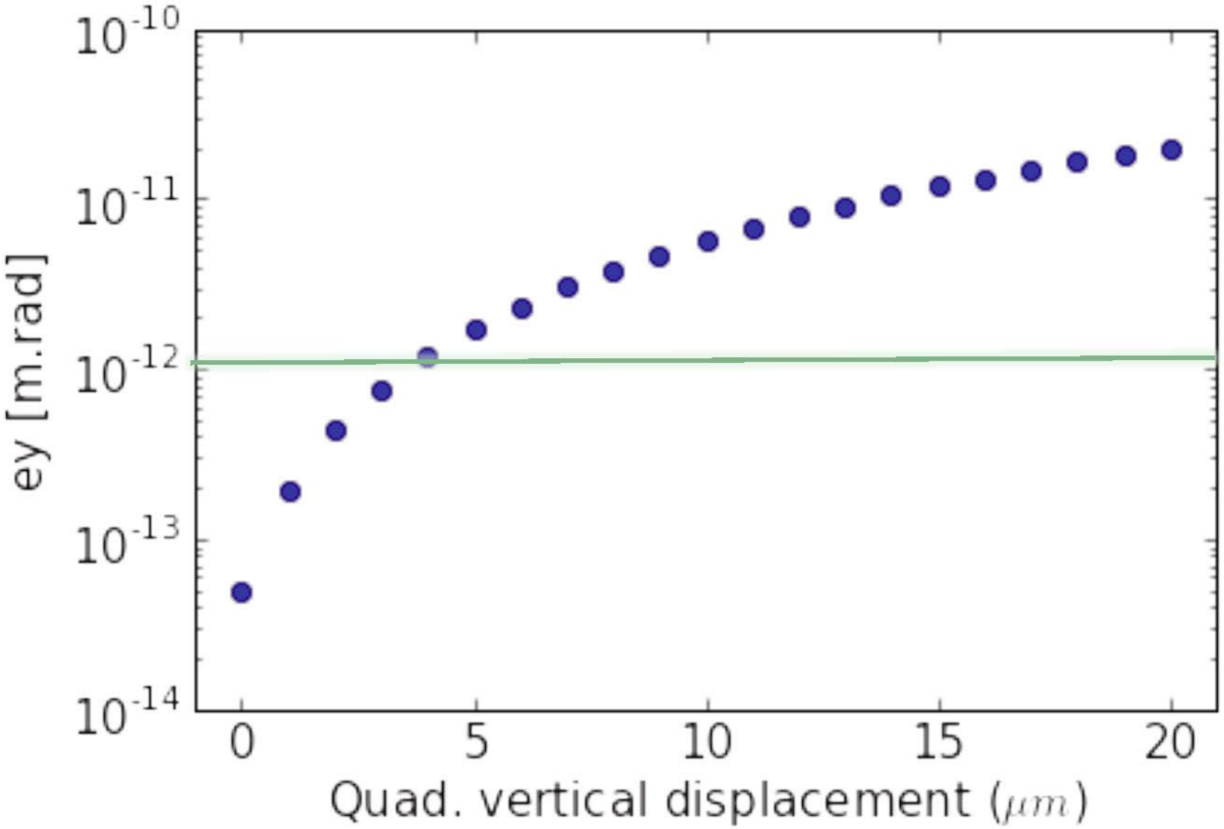


Effects	Included?	Significance for DA
Synchrotron motion	✓	**Essential**
Radiation damping (turn-by-turn)	✓	**Essential**, increases DA
Radiation damping (each element)*	✓	**Essential**, decreases DA
Tapering	✓	**Essential**
Crab-waist	✓	**Essential**, decreases DA,
Solenoids	✓	Minimal, if locally compensated
Maxwellian fringe fields	✓	Small
Kinetic terms	✓	Small
Errors / misalignments	✗	**Essential**, correction schemes must be developed

* No fluctuations yet.

L. Medina, K. Oide

dispersion-free steering for FCC-ee



lattice errors have huge impact on D_y & ε_y, due to the beta-function in the IRs, very sensitive ; presently developing lattice correction methods, adaptation to 100 km machine is still on going ;
DFS + local dispersion correction in IR looks promising

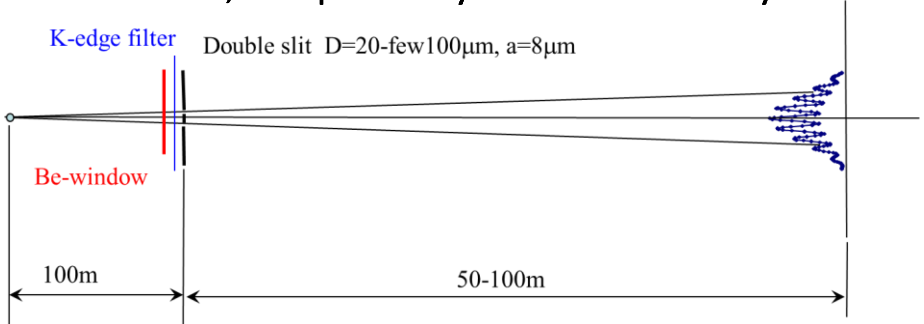
S. Aumon

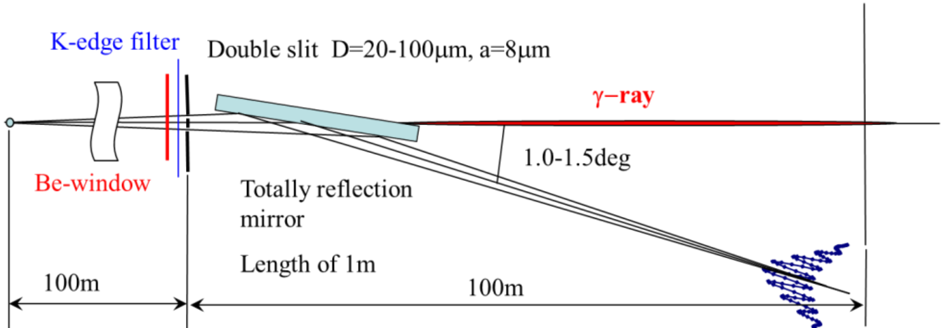
FCC-ee SR monitor

T. Mitsuhashi

method	wavelength	measurable minimum beme size in angular diameter in μrad	Corresponding size in 100m in μm	Corresponding size in 1000m in μm
Visible light imaging	500nm	50	500	5000
X-ray pinhole	0.1nm	0. 5	50	500
FZP imaging Of soft X-ray	0.35nm	0.3	30	300
Visible light interferometry	400nm	0.47	47	470
Coded aperture	0.3nm	0.5 0.1 (estimation)	50 10	500 100
X-ray Interferometry (new method)	0.1nm	0.01	1	10μm

X-ray double-slit interferometry (1930's technology) can measure few μm beam size at FCC-ee, simple easy-to-construct system

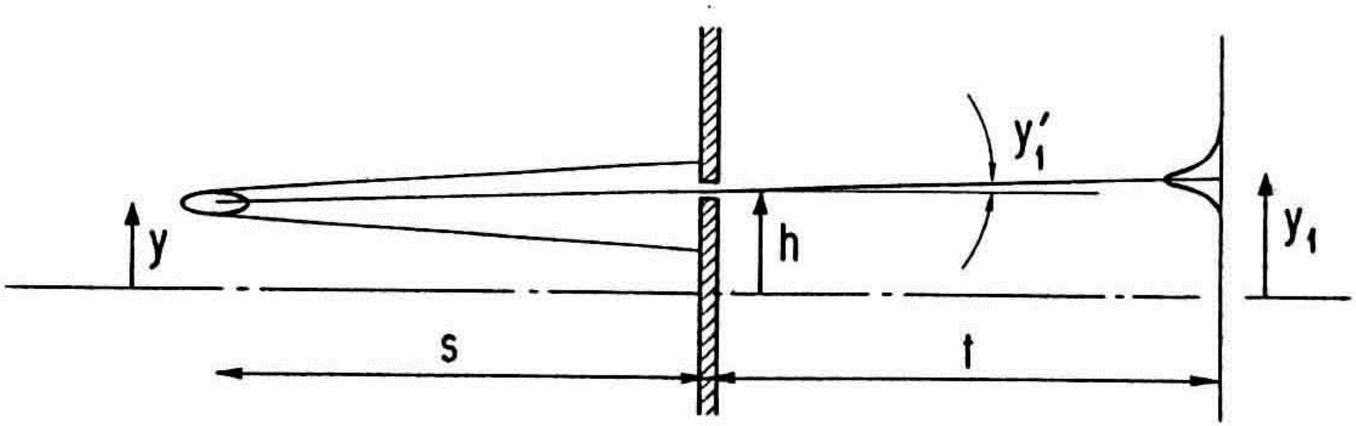




FCC-hh SR monitor

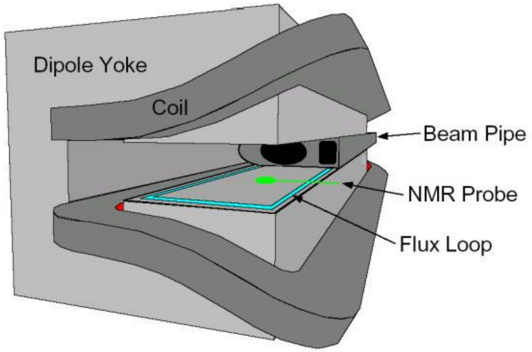
We can use visible SR for all energy range for diagnostics.
Hard X-rays are available at beam energies > 40TeV
Various diagnostics system using visible SR like in the LHC will be useable for entire range.
Simple pinhole camera should be convenient for beam size measurement at 40-50TeV.

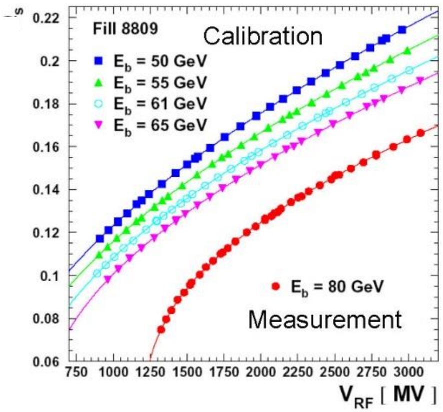
1. **For the pinhole camera, we need to optimize lattice parameter at the source point.**
2. **For the convenience of diagnostics, we need *high β-section* to obtain a large beam size at the source point.**
3. **Dedicated source point such as chicane will be necessary in *high β-section.***



T. Mitsuhashi

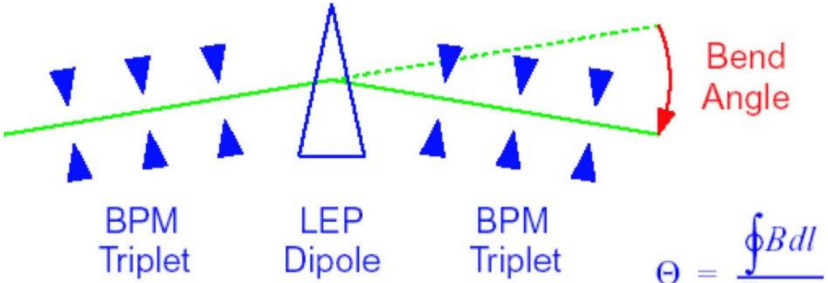
LEP energy calibration – lessons for FCC-ee





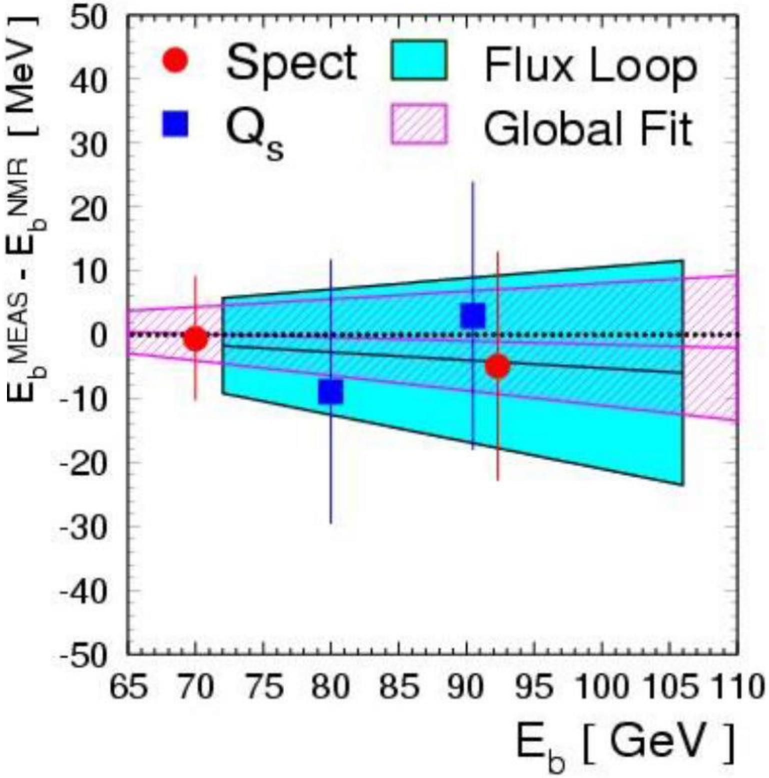
The LEP in-line spectrometer

First proposed in 1997; installed close to IP3 and commissioned in 1999; data taking for E_b measurements in 2000.



$$\Theta = \frac{\oint B\,dl}{E_{Beam}}$$

Three methods give consistent results and validate NMR model



Offset to NMR model at 100 GeV -2 ± 10 MeV

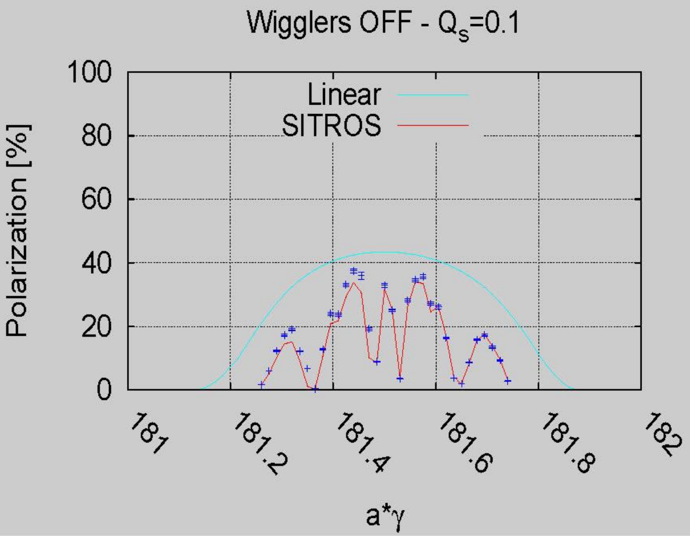
"At FCC-ee, continuous RDP during physics operation, and polarisation in the W+W- regime (if achieved) will ameliorate many problems that LEP faced"

G. Wilkinson

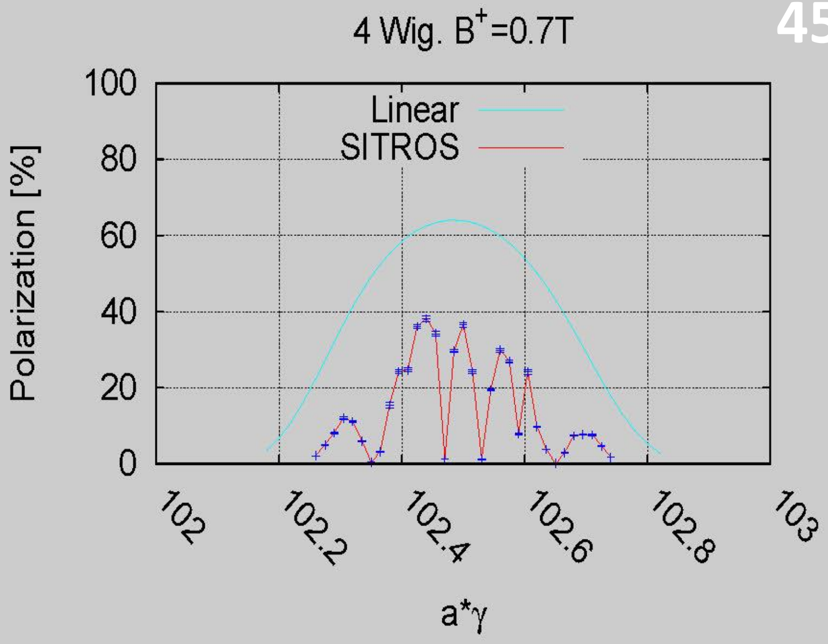
simulations for FCC-ee self polarization

- 45 GeV
  - limit ΔE=50 MeV (extrapolating from LEP)
  - 4 wigglers with B^{+}= 0.7 T
  - 10% polarization in 2.9 h for energy calibration
- 80 GeV
  - no wigglers
  - 10% polarization in 1.6 h for energy calibration
- BPMs errors added to quadrupole misalignments

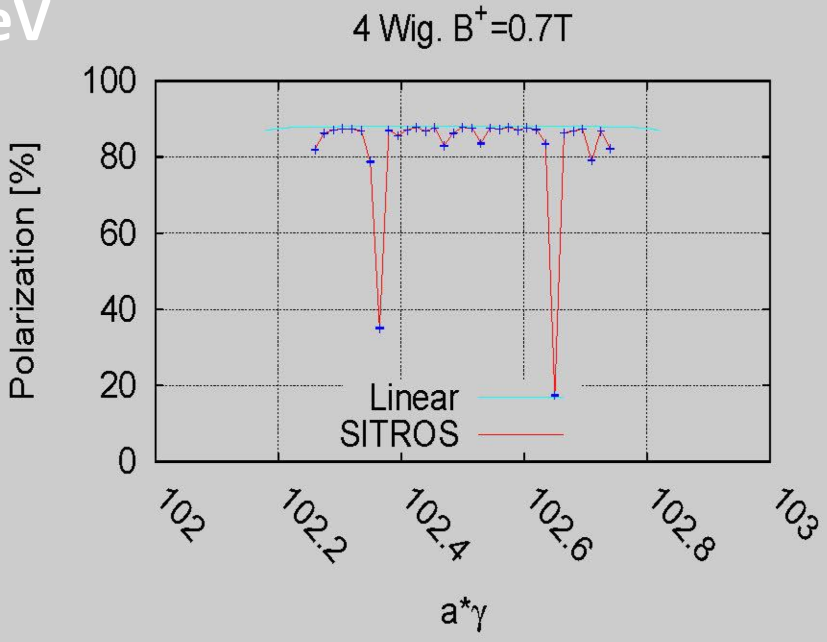
80 GeV



45 GeV



SVD



SVD + harmonic bumps

E. Gianfelice

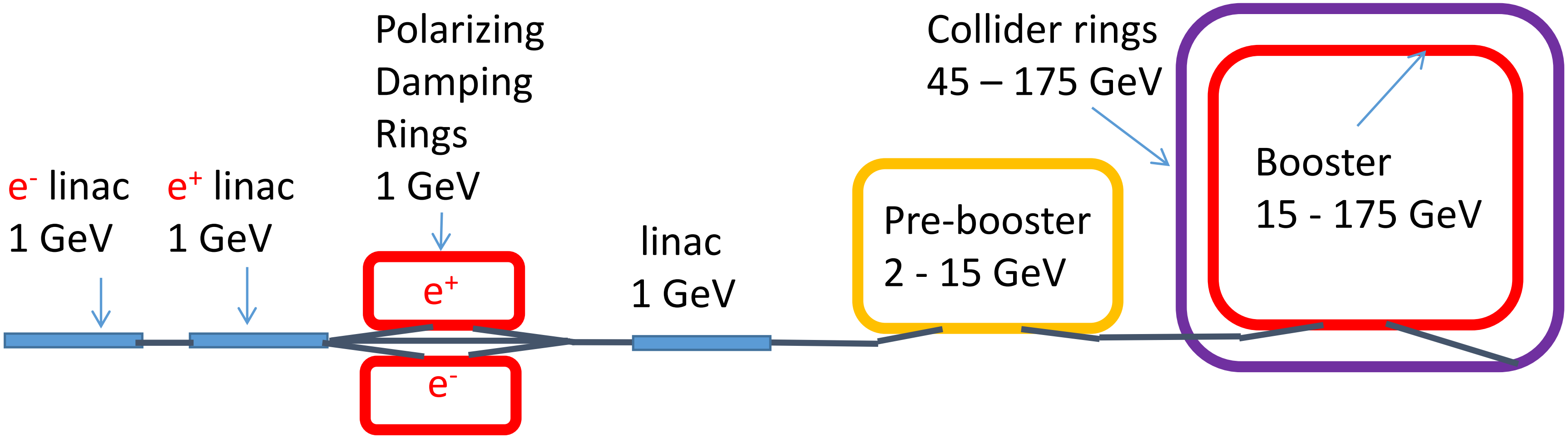
old/new Monte-Carlo spin tracking codes

Code\features	orbit map	Photon emission	Speed
SITROS	2nd order matrix	“Big photon” localized at several points	
SLICKTRACK	1st order matrix	“Big photon” localized at several points	
PTC	nonlinear symplectic integrator	at each integration step of each dipole.	much slower compared to the others.

Simulation tool based on PTC has been developed and benchmarked.
Simulation study of a model ring for CEPC is underway.

Z. Duan

accelerating & injecting polarized beams



e^- linac
1 GeV

e^+ linac
1 GeV

Polarizing
Damping
Rings
1 GeV

e^+

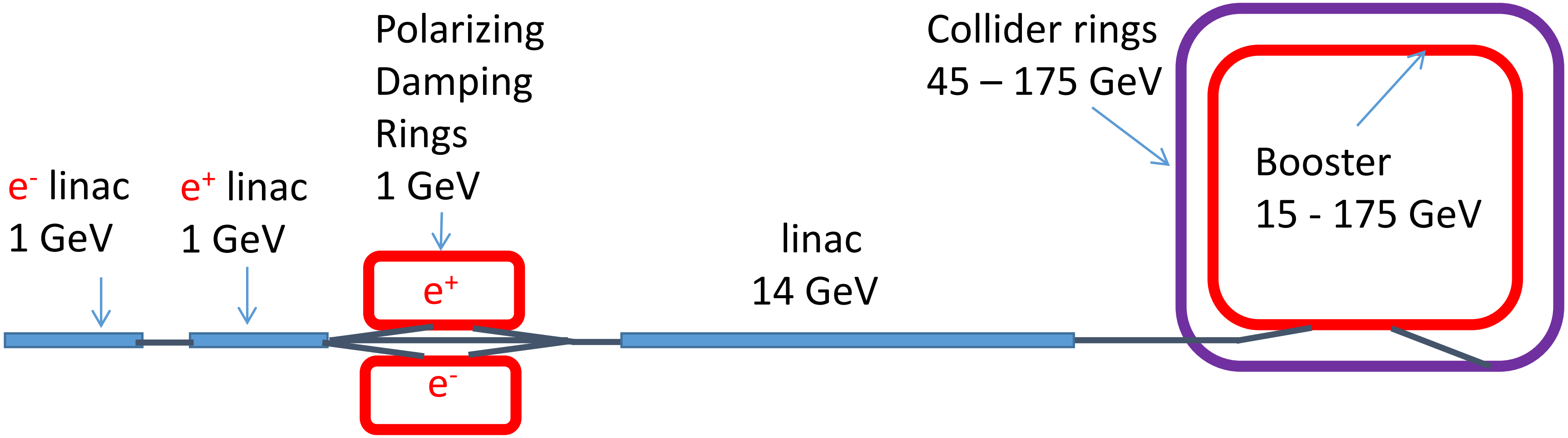
e^-

linac
1 GeV

Pre-booster
2 - 15 GeV

Collider rings
45 – 175 GeV

Booster
15 - 175 GeV



e^- linac
1 GeV

e^+ linac
1 GeV

Polarizing
Damping
Rings
1 GeV

e^+

e^-

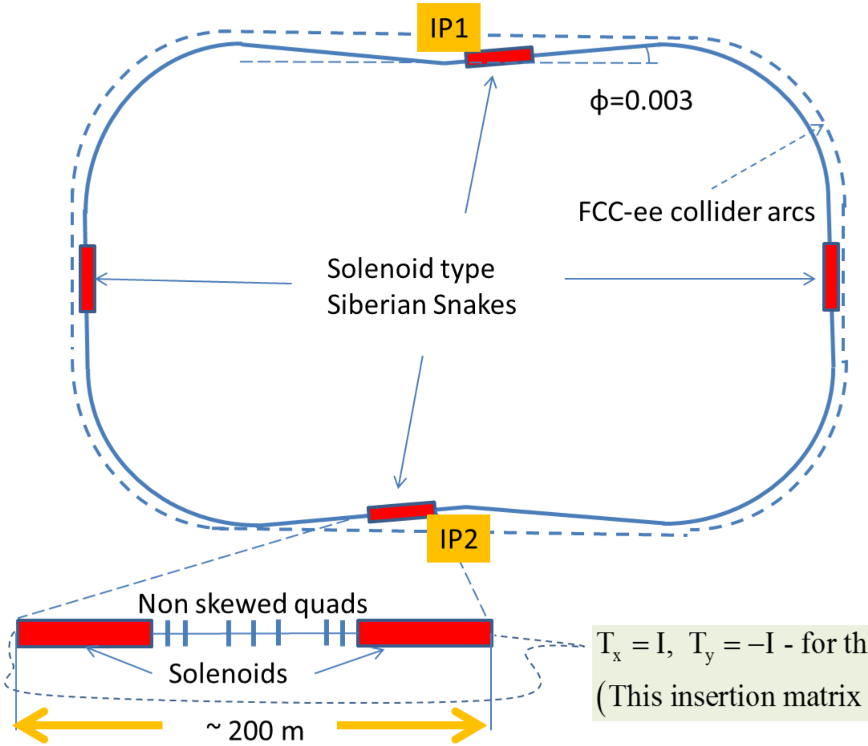
linac
14 GeV

Collider rings
45 – 175 GeV

Booster
15 - 175 GeV

I. Koop

accelerating & injecting polarized beams



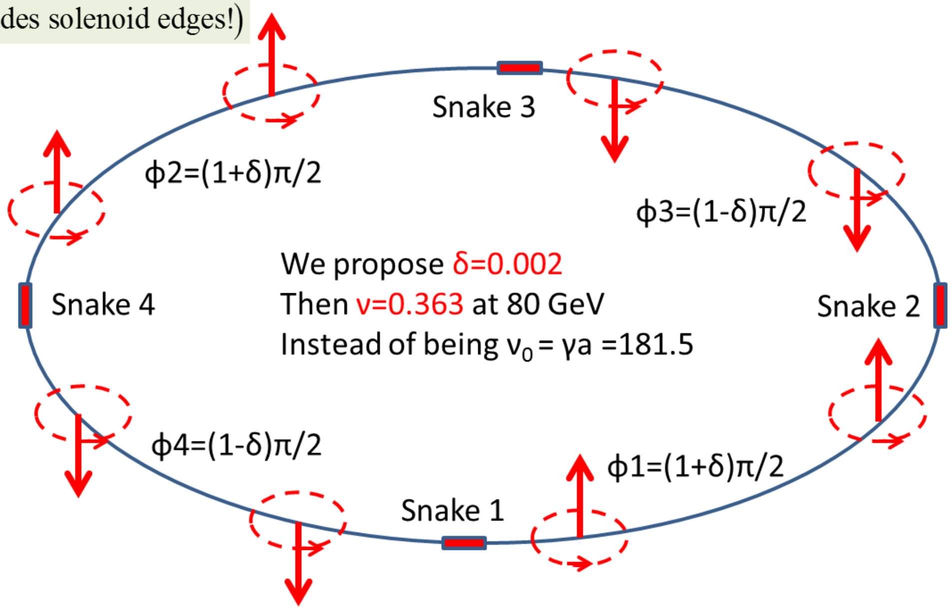
Four snakes spaced by the azimuthal angle $\pi/2 \pm \phi$ from each other reduce the spin precession tune by a factor $2\phi/\pi$

With $\phi=0.003$
$\nu=0.36$ at E=80 GeV
instead of be $\nu_0=181.5$
without snakes

booster ring for FCC-ee top up injection with polarized beams

$T_x = I,\ T_y = -I$ - for the spin transparency!

(This insertion matrix includes solenoid edges!)

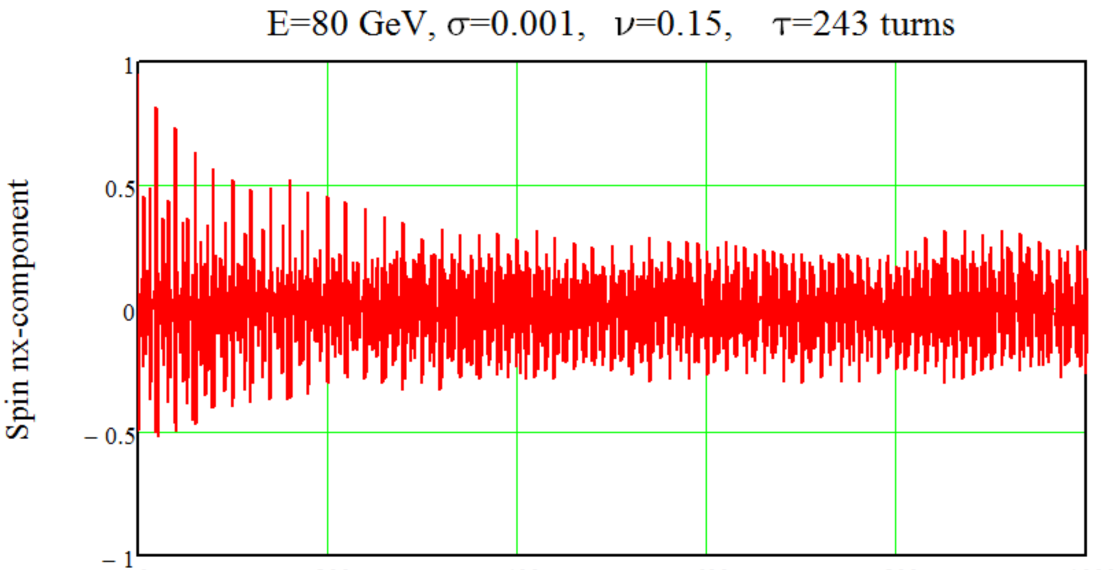


We propose $\delta=0.002$
Then $\nu=0.363$ at 80 GeV
Instead of being $\nu_0 = \gamma a = 181.5$

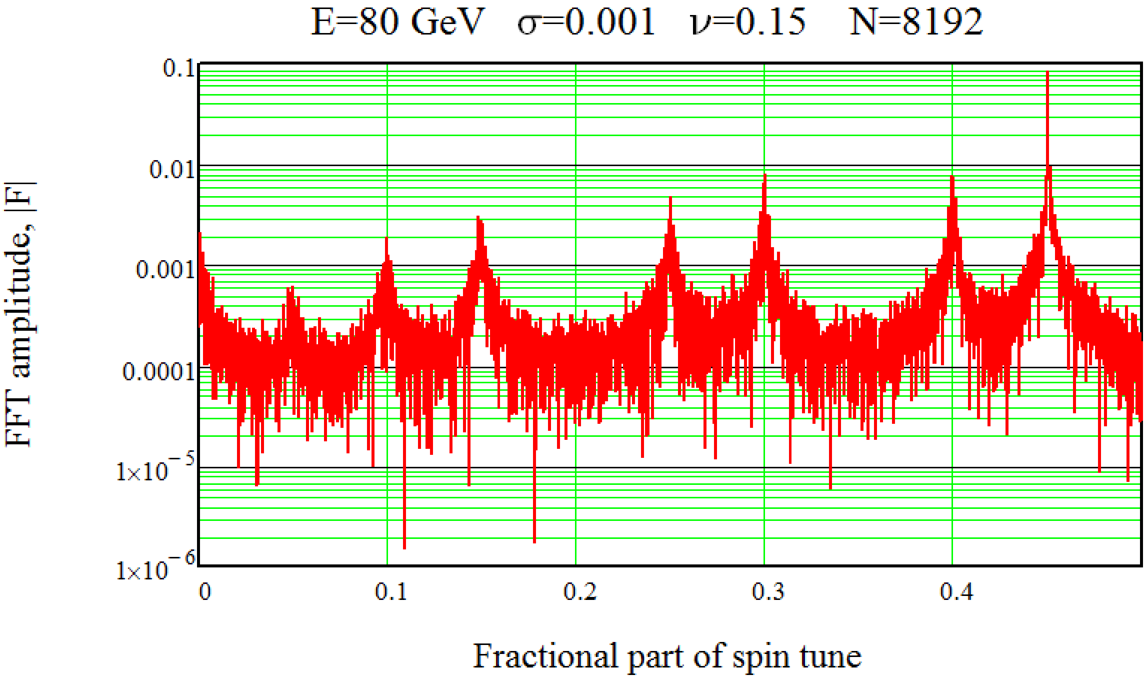
closed spin orbit in a ring with 4 snakes

I. Koop

measuring free spin precession at injection



one example



experimental
test at VEPP-4?

I. Koop

KEKB & SuperKEKB injector requirements

K. Furukawa

Stage	KEKB (final)		Present Phase-I		SuperKEKB (final	
Beam	e+	e–	e+	e–	e+	e–
Energy	3.5 GeV	8.0 GeV	4.0 GeV	7.0 GeV	4.0 GeV	7.0 GeV
Stored current	1.6 A	1.1 A	1 A	1 A	3.6 A	2.6 A
Life time	150 min.	200 min.	100 min.	100 min.	**6 min.**	**6 min.**
Bunch charge	Primary e- 10nC →1 nC	1 nC	Primary e- 8nC →0.4 nC	1 nC	Primary e- 10nC →4 nC	5 nC
Norm. Emittance (γβε) (μrad)	2100	200	2400	150	100/20 (Hor./Ver.)	50/20 (Hor./Ver.
Energy spread	0.125%	0.125%	0.5%	0.5%	0.1%	0.1%
No. Bunch / Pulse	2	2	2	2	2	2
Repetition rate	**50 Hz**		25 / 50 Hz		50 Hz	
Simultaneous top-up injection (PPM)	**3 rings** (KEKB e–/e+, PF)		No top-up		4+1 rings (SuperKEKB e–/e+, DR, PF, PF-AR)	

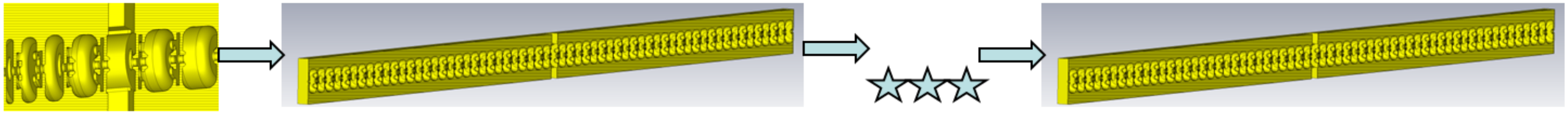
example FCC-ee injector parameters w. SPS

Accelerator	FCCee-Z		FCCee-W		FCCee-H		FCCee-tt	
Energy [GeV]	45.6		80		120		175	
Type of filling	Full	Top-up	Full	Top-up	Full	Top-up	Full	Top-up
LINAC # bunches	915		530		195		81	
LINAC repetition rate [Hz]	50							
LINAC RF freq [MHz]	2000							
LINAC bunch population [10^9]	3.3	0.38	3.3	0.38	3.3	0.38	3.3	0.38
# of LINAC injections	5		5		4		5	
SPS/BR bunch spacing [MHz]	400							
SPS bunches/injection	183		106		39		16	
SPS bunch population [10^{10}]	1.7	0.19	1.7	0.19	1.7	0.19	1.7	0.19
SPS duty factor	0.5						0.17	
SPS / BR # of bunches	915/4575		530/2650		156/780		81/81	
SPS / BR cycle time [s]	1.2 / 12						1.2 / 7.2	
Number of BR cycles	50	9	10	2	7	2	3	1
Transfer efficiency	0.8							
Total number of bunches	91500		5260		780		81	
Filling time (both species) [sec]	1200	216	240	48	168	48	43.2	14.4
Injected bunch population [10^{10}]	1.7	0.19	1.7	0.19	1.7	0.19	1.7	0.19

Y. Papaphilippou

preliminary injector linac design

RF-gun **10-20 regular sections for 2 GeV in total (3000 or 2000 MHz)**



3000 MHz **or** **2000 MHz** **?**

π/2 mode, st. wave
12 BAS periods
~60 cm of length
12 MeV output
350 kV/cm on axe
(for ~50 nC)

Not enough place
for first coupling cell !
side coupling should
be used

π/2 mode, st. wave
61 BAS periods
305 cm length
400/600/900 kV/cm
70/105/160 MeV
per section

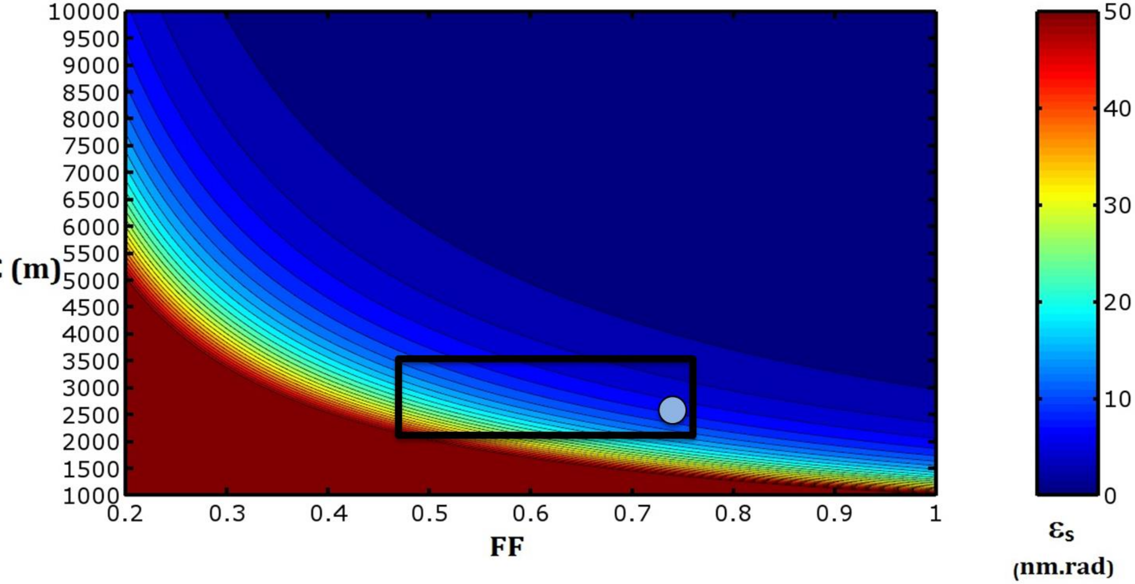
π/2 mode, st. wave
41 BAS periods
307.5 cm length
400/600/900 kV/cm
75/110/170 MeV
per section

High (12-14 %) coupling coefficient to achieve high group velocity and low time of transient process!!!

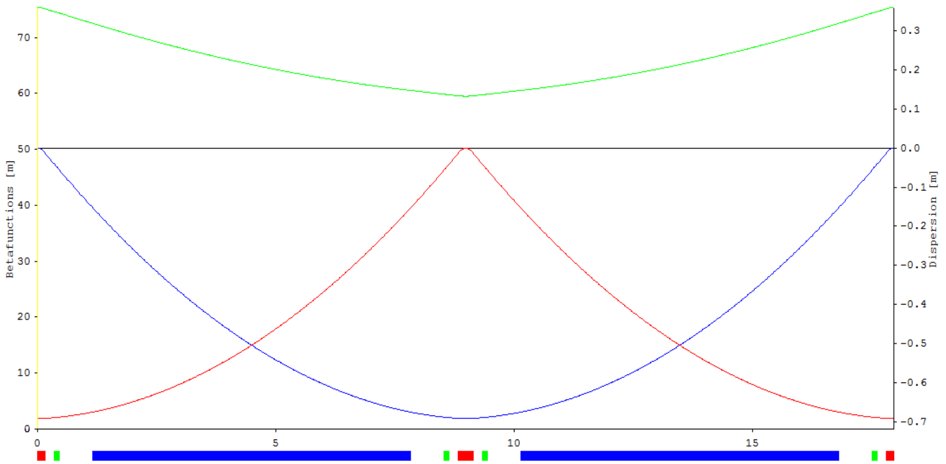
S. Polozov

design pre-booster (btw linac and booster)

O. Etisken



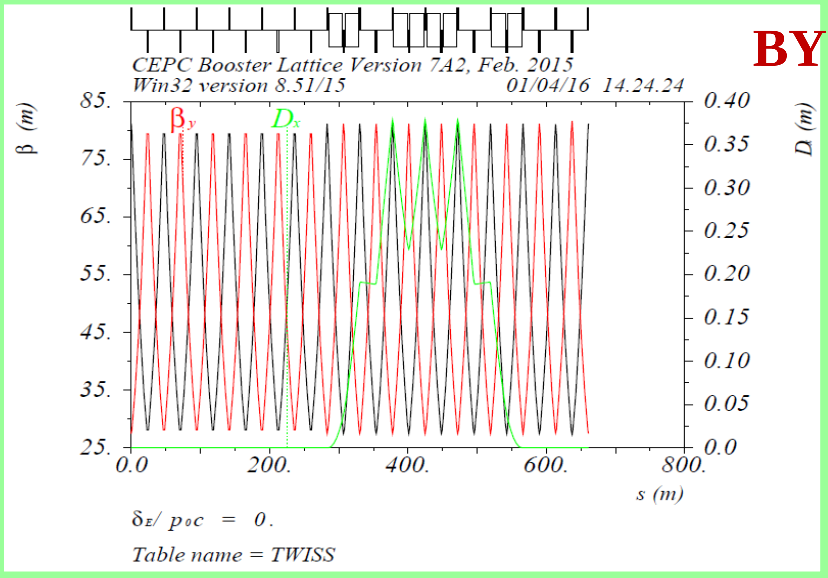
- For the area we remarked before, the values are nice for emittance.
- It is around 10 nm.rad on the point for around FF:0.7 and C:2.5km

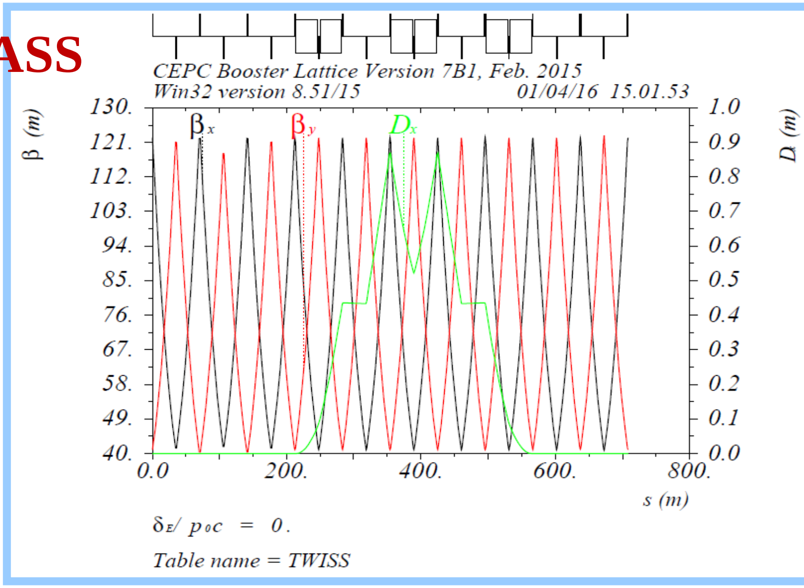


	6 GeV	20 GeV
C (m)	2388.7 m	2388.7 m
Emittance (nm.rad)	0.674	11.965
E. Spread	0.277	1.019
Chrom X	-124.487	-106.562
Chrom Y	-124.351	-106.402
Uo (keV)	331.9	50045.2
TauX (ms)	347.861	6.373
TauY (ms)	347.664	6.368
TauE (ms)	173.783	3.183

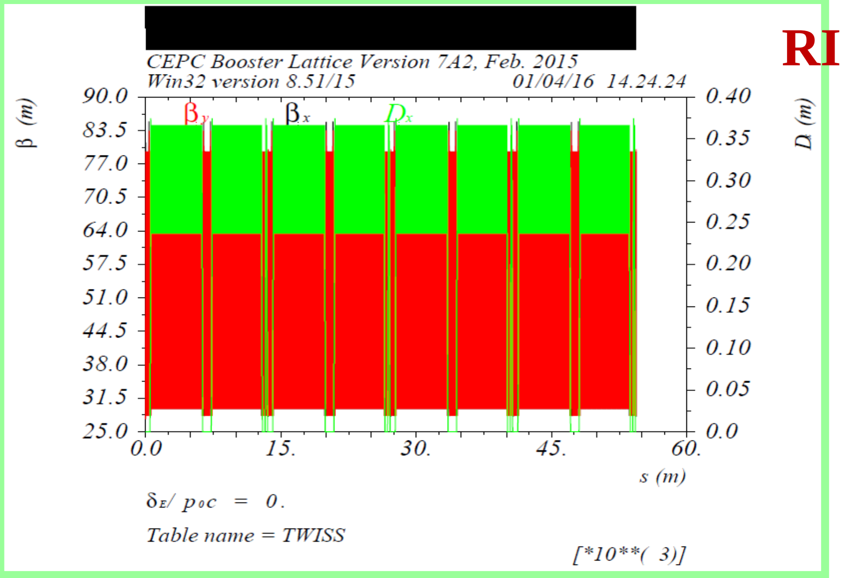
CEPC booster design

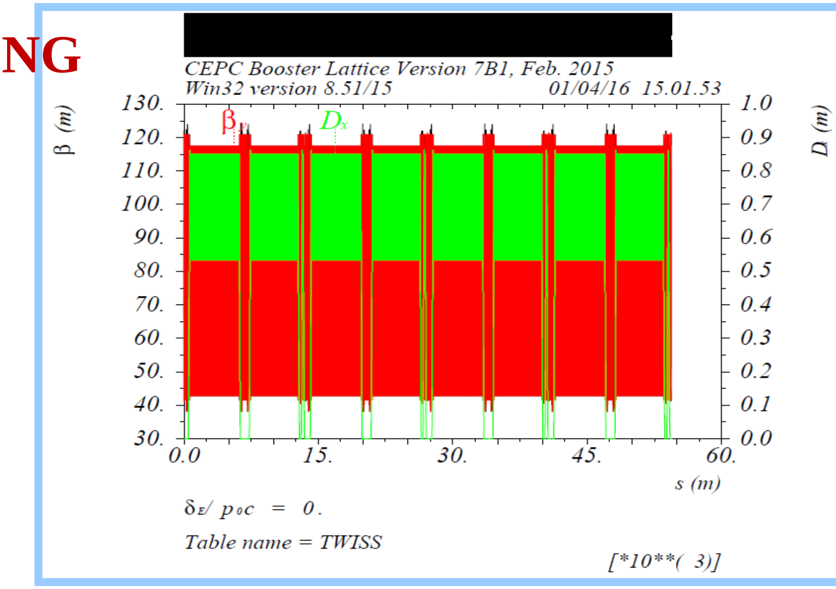
BYPASS





RING





X. Cui

top-up injection schemes for FCC-ee

two schemes feasible, possible optics presented

	Conventional	Multipole kicker
Residual oscillation (Injection beam)	Betatron / Synchrotron (On energy / Off energy)	Betatron / Synchrotron (On energy / Off energy)
Disturbance (Stored beam)	Betatron oscillation (in practice)	Emittance growth (intrinsic)
Wire septum	Essential	Mitigate emittance growth
Kicker specification	Feasible	Feasible
Separation, stored beam to septum	~15σ (5σ at the time of injection)	15σ

M. Aiba

next: modeling injection with beam-beam effects

summary of ee summary – 1

FCC-ee optics - *in excellent shape*

layout perfectly matches FCC-hh, flexible IR optics (allowing lower β*), low photon energies upstream IP, good dynamic aperture on/off momentum, solution for booster bypass, IR shielding and compensating solenoids & realistic quadrupoles, IR SR masks,…

next steps: more simulations with errors, corrections, and tuning schemes to assess vertical emittance reach

Beam-beam + dynamic aperture - *OK*

weak-strong simulations with full lattice nonlinearities confirm the baseline performance and suggest lowering beta* (x,y); crab waist helps at all energies …

quasi-strong simulations including charge imbalance suggests using β*'s of (0.5 m, 1 mm) and larger horizontal emittance at the lower energies; this should also suppress <xz> modulation seen in recent strong-strong simulations

Single-beam collective effects - *under control*

resistive-wall and cavities (with tapers) → large impedance source; distributed photon stops in elliptical chamber ruled out for impedance reasons, new design round with slots ; electron cloud mitigation requires antechamber and low SEY microwave instability is a concern, but a refined impedance model is needed for quantitative conclusions; res.-wall driven CBI & ion instability require transverse feedback with damping time <10 turns ; such feedbacks are considered feasible for a ring of large size…

Polarization and energy calibration – *looking good*

simulations with large errors and wigglers indicate possible high levels of polarization at Z and W, plus reasonable pol. times; alternative interesting scheme with injection of polarized beams ..

Injector complex – *work ongoing at several places*

many options, subsystem design started; SuperKEKB injector as proof-of-principle…

thank you for the great collaboration!