Simulation of Beam-Beam Effect & Optimization of Machine Parameters

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Thanks:

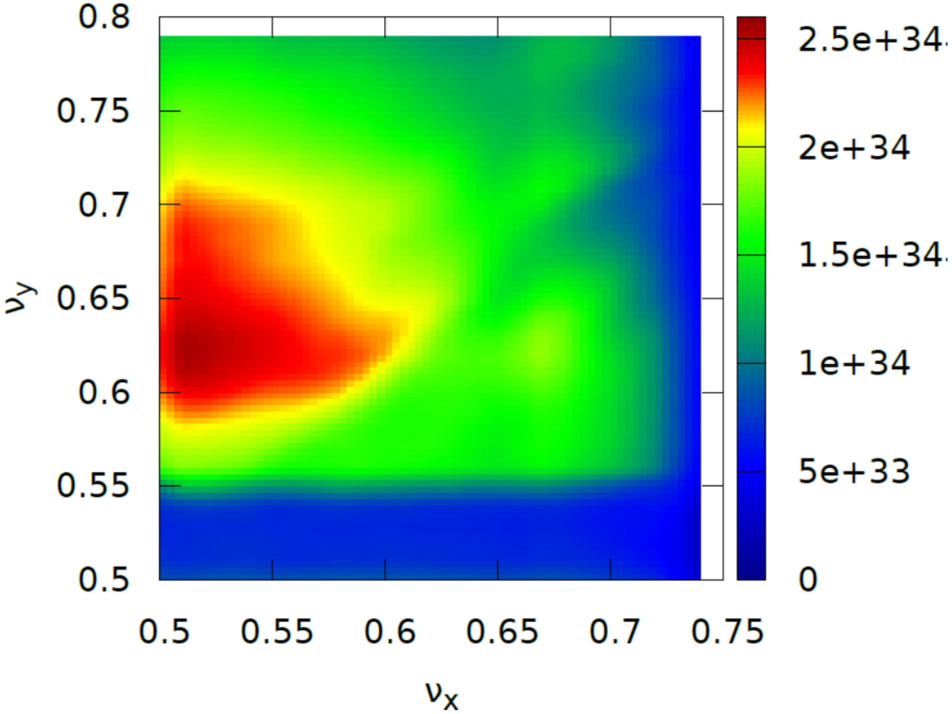
Dmitry Shatilov, Kazuhito Ohmi, Demin Zhou, Huiping Geng, Yuemei Peng, Yuanyuan Guo

Main beam parameters for CEPC at 50km

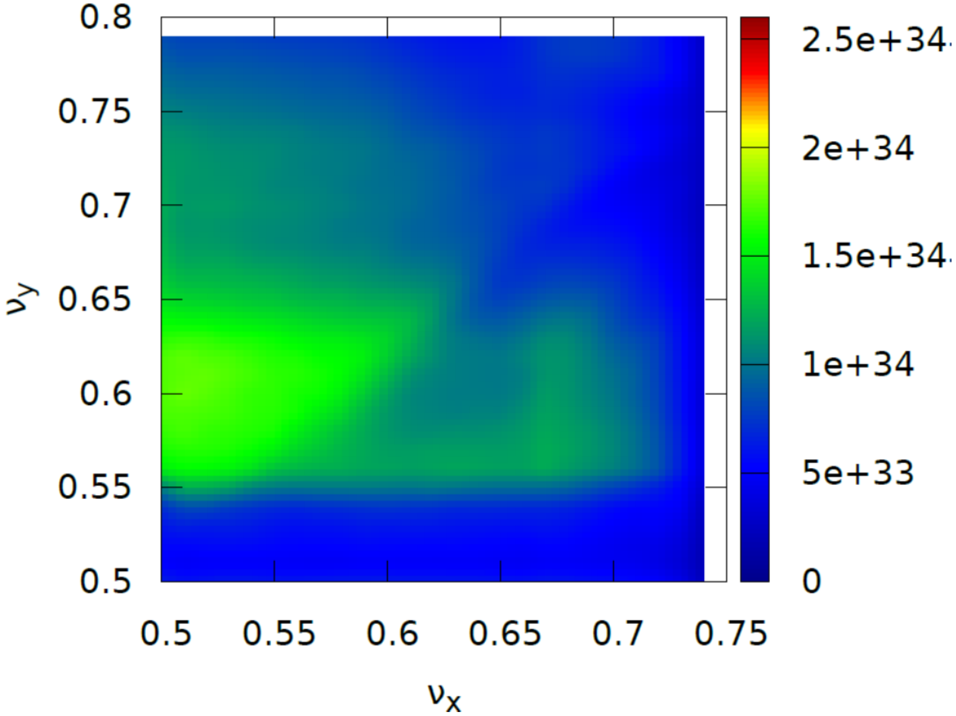
Parameter	Unit	Value	Parameter	Unit	Value
Energy	GeV	120	Circumference	km	50
Number of IP		1	SR loss	(GeV/turn)	2.96
N_e/bunch	1E11	3.52	**N_b/beam**		**50**
Beam current	mA	16.9	SR power/beam	MW	50
Partition Je		2	Long. damp. time	ms	6.7
Dipole field	Tesla	0.065	Bending radius	km	6.2
Dipole length	m	9.978	Bending angle	mrad	1.609
Emittance (x/y)	nm	6.69/0.033	**β_{IP} (x/y)**	**mm**	**200/1**
Trans. size (x/y)	μm	36.6/0.18	Mom. compaction	1E-4	0.4
$\xi_{x,y}$ /IP		**0.1/0.1**	**Bunch length**	**mm**	**3**
RF voltage V_{rf}	GV	4.2	RF frequency f_{rf}	GHz	0.7
Long. tune ν_s		0.13	Harmonic number		116747
Hourglass factor		0.6	n_γ		0.42
Energy spread SR		0.0013	Energy spread BS		0.00014
Energy acceptance	%	2.7	Lifetime BS	hr	1.6
L_0 /IP (10^{34})	**$cm^{-2}s^{-1}$**	**2.65**	**L_{limit} /IP (10^{34})**	**$cm^{-2}s^{-1}$**	**1.26**

Tune Scan

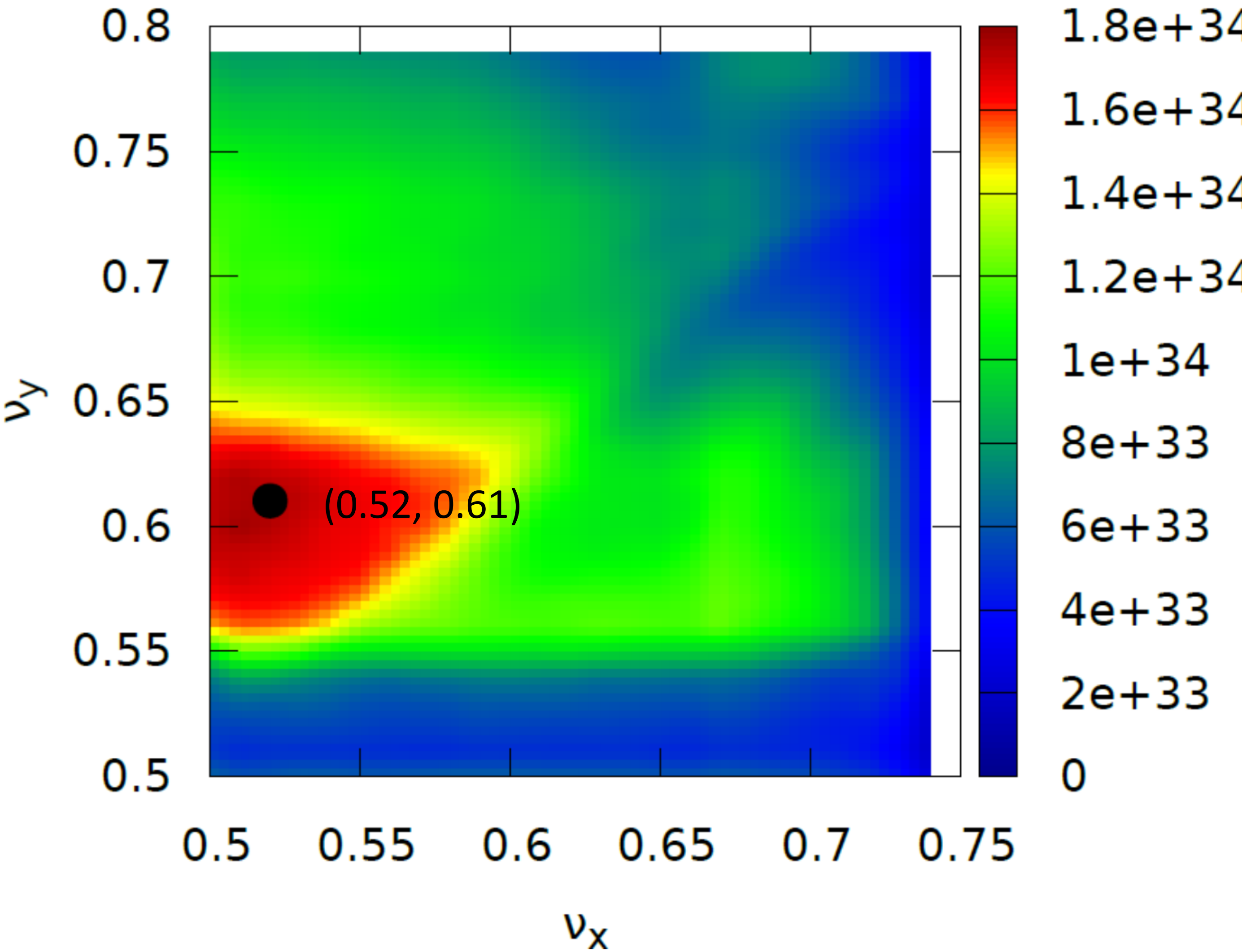
Beamstrahlung OFF



Beamstrahlung ON



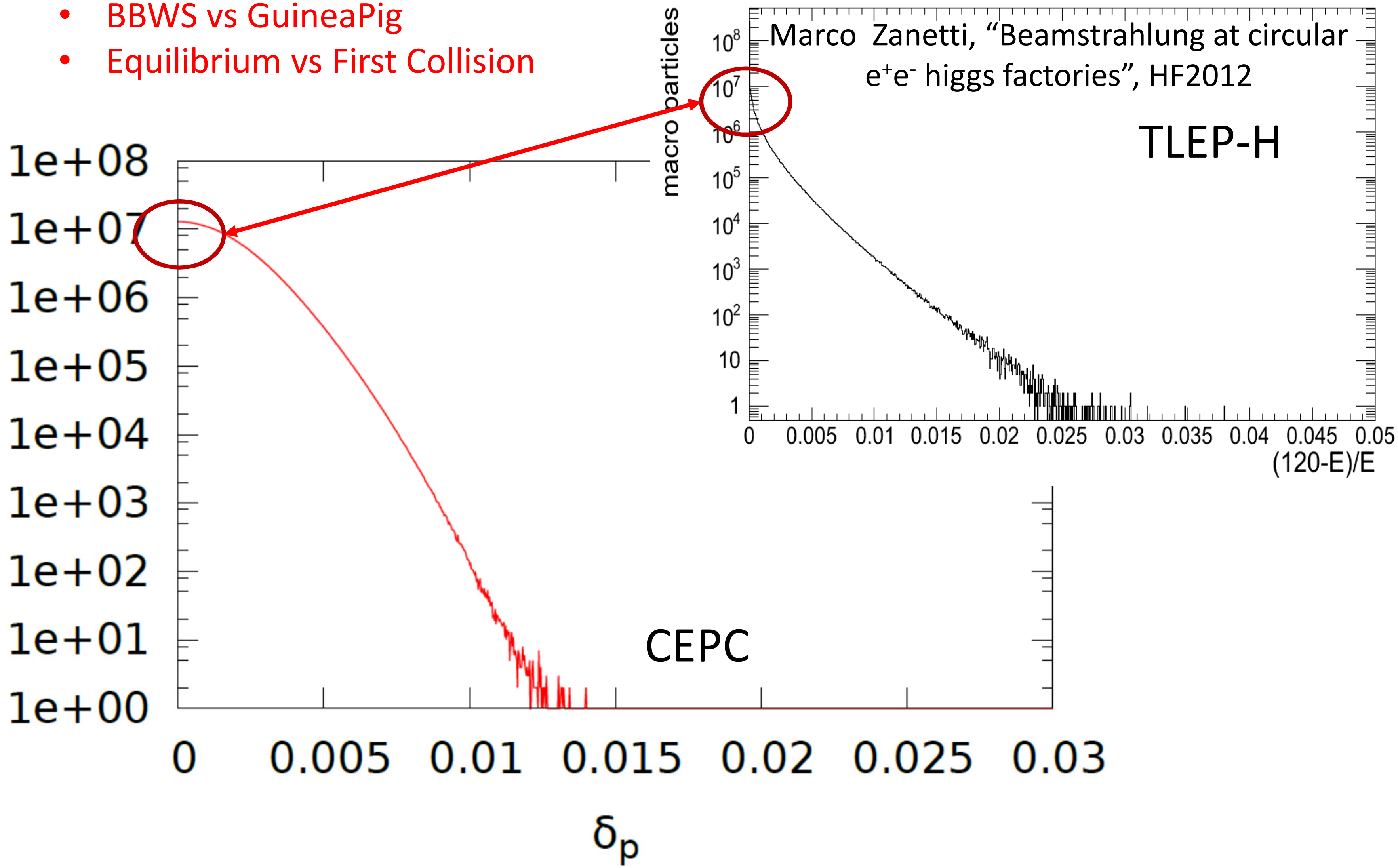
Tune Scan w/ Beamstrahlung



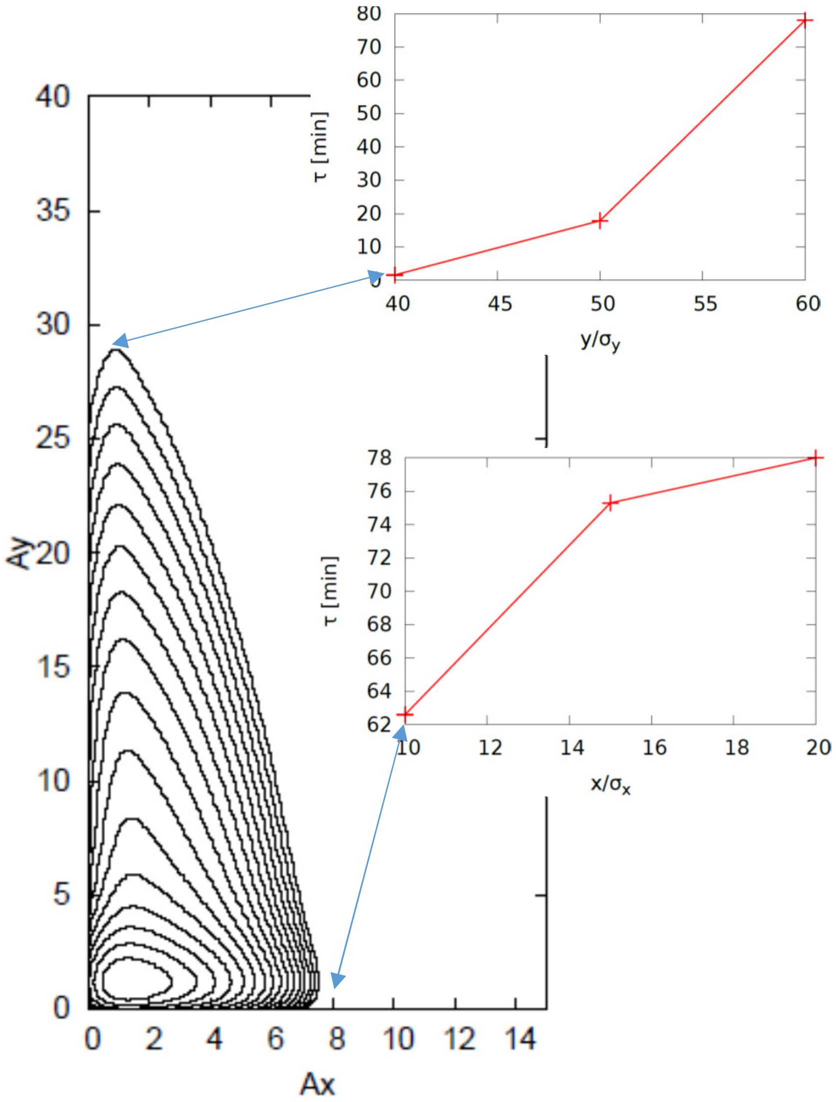
16.9mA*16.9mA,
50bunches,
BBWS,
Luminosity ~ 1.6e34
But ……
Quasi-Strong-Strong simulation only shows Luminosity ~ 1.1e34

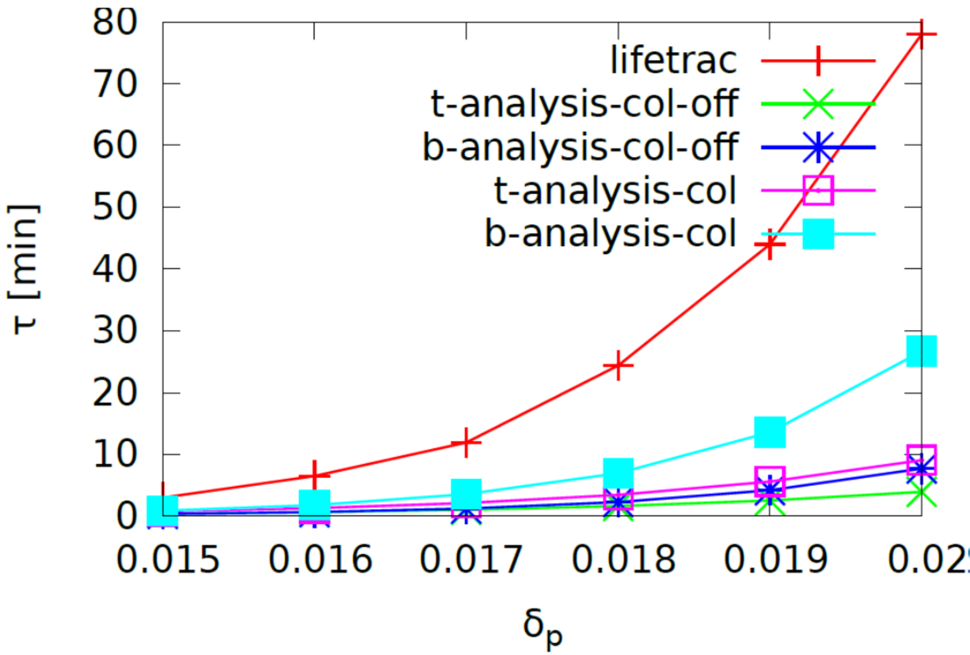
Energy Distribution

- BBWS vs GuineaPig
- Equilibrium vs First Collision



Beam Lifetime vs dynamic aperture





Simulation & analysis not consistent?

Difficulity of SuperKEKB & TLEP

K. Oide, "Final Focus & Injection", FCC Kick-off Meeting, Feb 13, 2014

Scaling of final quads (cont'd)

$$L_0 = \frac{c_f B\rho}{c_Q B_0}\sqrt{\frac{2J_{x,y}}{\beta^*_{x,y}}}$$

$$L > \frac{L_0}{2}\left(1 + \sqrt{1 + 4\frac{\beta^{*2}_{x,y}}{L_0^2}}\right)$$

$$\xi_y = \frac{c_f L}{\beta^*_y}$$

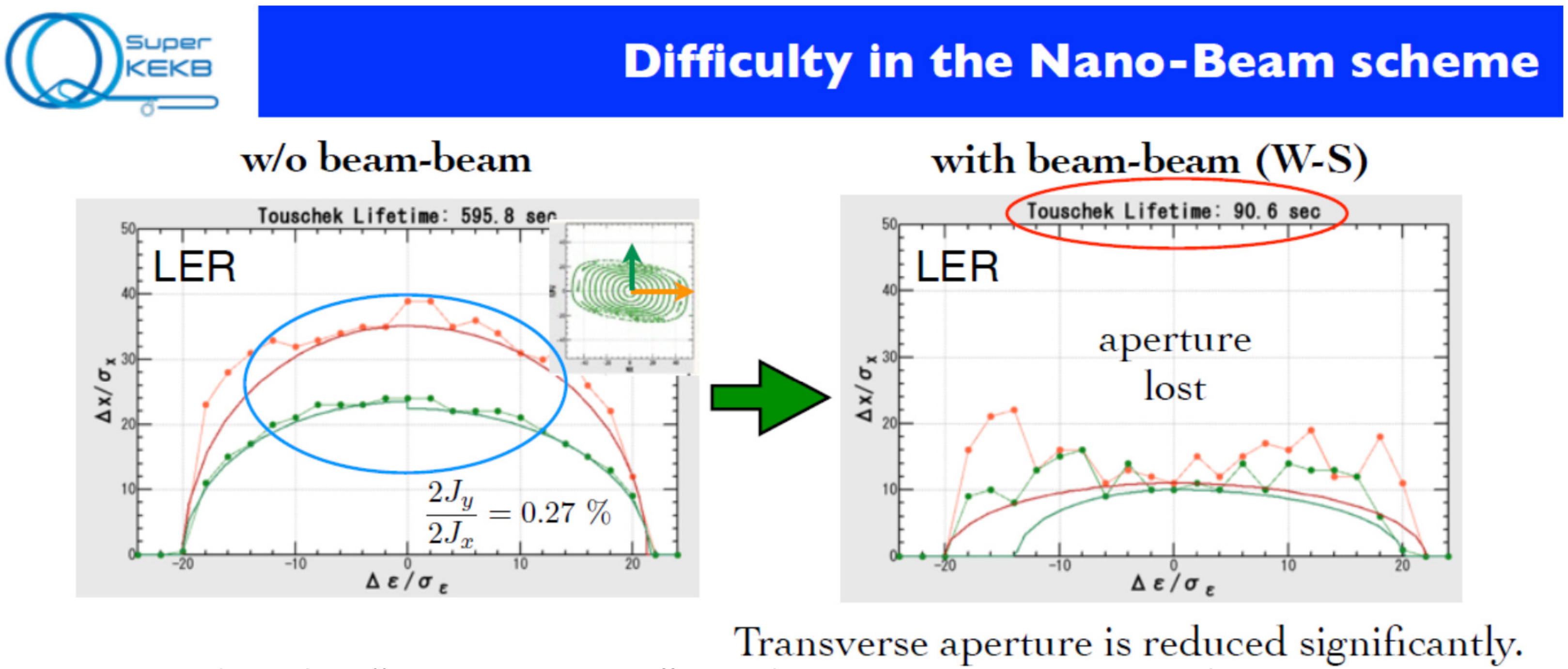
Rings	SuperKEKB LER	TLEP Z	TLEP tt	
Beam energy	4	46	175	GeV
$B\rho$	13.3	153	584	Tm
B_0	0.7	⇐		T
$c_f \equiv k_1 L$	1.56	⇐		
$c_Q \equiv L_Q/L$	0.35	0.35	0.7	
β^*_x	32	500	1000	mm
β^*_y	0.27	1	1	mm
$2J_x$	3.7	⇐		μm
$2J_y$	10	0.87	0.23	nm
L_0	0.935	2.65	3.58	m
L	0.935	2.74	3.84	m
L_Q	0.33	0.96	2.69	m
b	10	7.4	7.4	mm
ξ_y	5,400	4,200	6,000	

$J_{x,y}$ assumes similar injected beams.

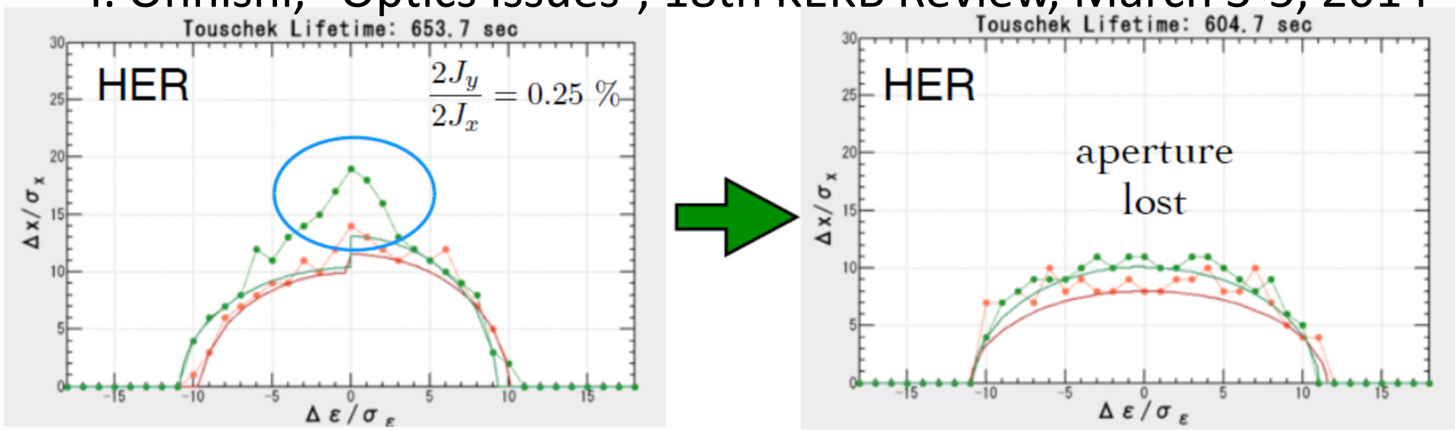
Similar level of difficulty!

If TLEP uses a chromaticity correction similar to SuperKEKB, the resulting momentum acceptance will be similar, about ±1.4%.

Dynamic aperture w/o and w/ beam-beam interaction@SuperKEKB



Y. Ohnishi, “Optics Issues”, 18th KEKB Review, March 3-5, 2014



SuperKEKB, http://www-superkekb.kek.jp/index.html

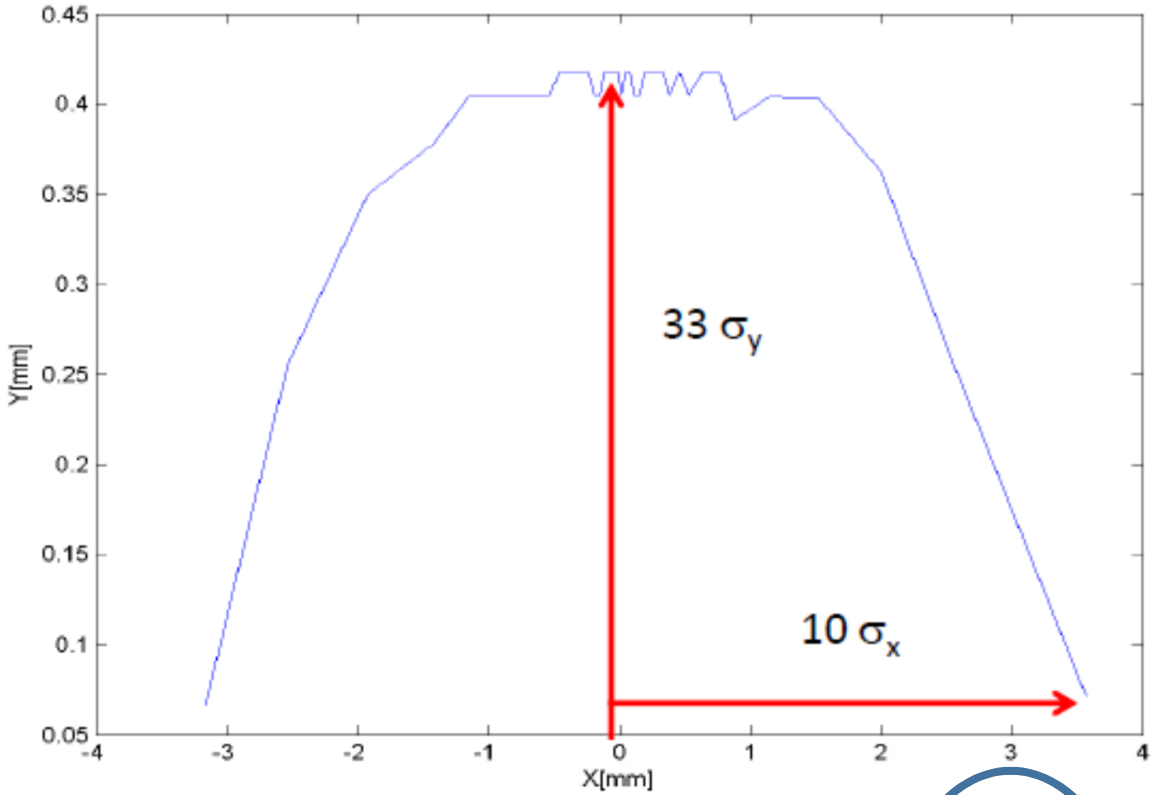
Machine Parameters

2013/July/29	LER	HER	unit	
E	4.000	7.007	GeV	
I	3.6	2.6	A	
Number of bunches	2,500			
Bunch Current	1.44	1.04	mA	
Circumference	3,016.315		m	
$\varepsilon_x/\varepsilon_y$	3.2(1.9)/8.64(2.8)	4.6(4.4)/12.9(1.5)	nm/pm	():zero current
Coupling	0.27	0.28		includes beam-beam
β_x^*/β_y^*	32/0.27	25/0.30	mm	
Crossing angle	83		mrad	
α_p	3.18×10^{-4}	4.53×10^{-4}		
σ_δ	$8.10(7.73)\times10^{-4}$	$6.37(6.30)\times10^{-4}$		():zero current
V_c	9.4	15.0	MV	
σ_z	6.0(5.0)	5(4.9)	mm	():zero current
ν_s	-0.0244	-0.0280		
ν_x/ν_y	44.53/46.57	45.53/43.57		
U_0	1.86	2.43	MeV	
$\tau_{x,y}/\tau_s$	43.2/21.6	58.0/29.0	msec	
ξ_x/ξ_y	0.0028/0.0881	0.0012/0.0807		
Luminosity	8×10^{35}		$cm^{-2}s^{-1}$	

ϵ_x~7nm

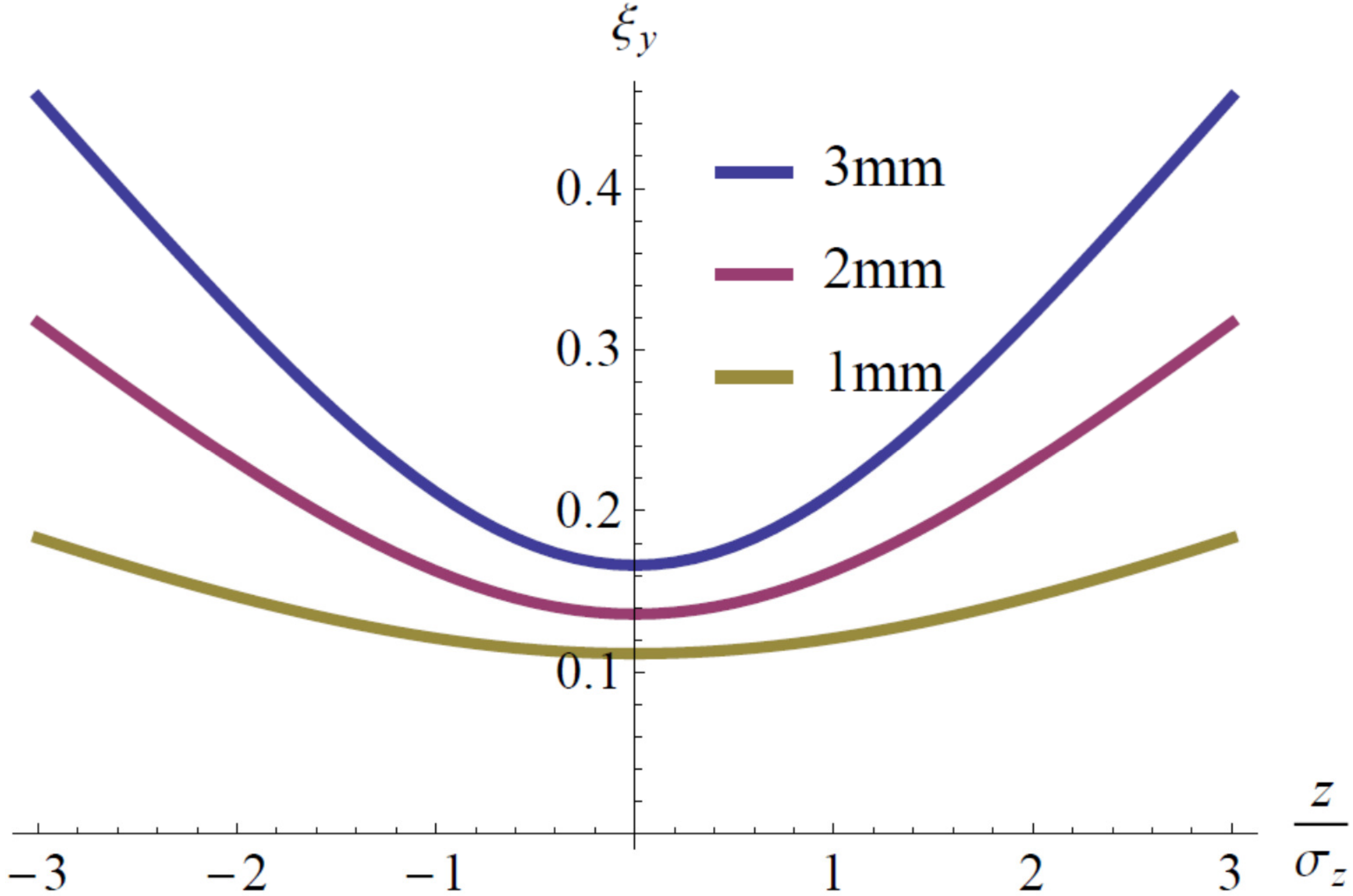
For CEPC baseline parameters

Dynamic Aperture for On-Momentum Particles



Horizontal emittance [nm]	48	4.3
Vertical emittance [nm]	0.25	0.0108
Momentum compaction factor	$18.5\text{x}10^{-5}$	$2.4\text{x}10^{-5}$
β_x* [mm]	1500	100
β_y* [mm]	50	1

Effective Beam-Beam Parameter versus z for different bunch length



FCC-ACC-SPC-0004

	LEP1	LEP2	TLEP Z	TLEP W	TLEP H	TLEP tt
Circumference [km]	26.7		100			
Bending radius [km]	3.1		11			
Beam energy [GeV]	45.4	104	45.5	80	120	175
Beam current [mA]	2.6	3.04	1450	152	30	6.6
Bunches / beam	12	4	16700	4490	1360	98
Bunch population [10^{11}]	1.8	4.2	1.8	0.7	0.46	1.4
Transverse emittance e - Horizontal [nm] - Vertical [pm]	 20 400	 22 250	 29.2 60	 3.3 7	 0.94 1.9	 2 2
Momentum comp. [10^{-5}]	18.6	14	18	2	0.5	0.5
Betatron function at IP b* - Horizontal [m] - Vertical [mm]	 2 50	 1.2 50	 0.5 1	 0.5 1	 0.5 1	 1 1
Beam size at IP s* [mm] - -						
Ener... - -						
Bunc... - - Total	 8.6	 11.5	 2.56	 1.49	 1.17	 1.49
Energy loss / turn [GeV]	0.12(1)	3.34	0.03	0.33	1.67	7.55
SR power / beam [MW]	0.3(1)	11	50			
Total RF voltage [GV]	0.24	3.5	2.5	4	5.5	11
RF frequency [MHz]	352		800			
Longitudinal damping time t_E [turns]	371	31	1320	243	72	23
Energy acceptance RF [%]	1.7	0.8	2.7	7.2	11.2	7.1
Synchrotron tune Q_s	0.065	0.083	0.65	0.21	0.096	0.10
Polarization time t_p [min]	252	4	11200	672	89	13
Hourglass factor H	1	1	0.64	0.77	0.83	0.78
Luminosity/IP [10^{34} cm^{-2}s^{-1}]	0.002	0.012	28.0	12.0	6.0	1.8
Beam-beam parameter - Horizontal - Vertical	 0.044 0.044	 0.040 0.060	 0.031 0.030	 0.060 0.059	 0.093 0.093	 0.092 0.092
Luminosity lifetime [min](2)	1250	310	213	52	21	15
Beamstrahlung critical	No		No	No	Yes	Yes

	BX/BY	σ_z	ϵ_x	N_p	Coupling	N_b
TLEP-H	0.5m/1mm	0.81mm	0.94nm	0.46e11	0.2%	1360
CEPC	0.2m/1mm	3mm	6.69nm	3.52e11	0.5%	50

Beamstrahlung lifetime

A. Bogomyagkov,* E. Levichev,† and D. Shatilov arxiv, 1311.1580, 2013

$$\tau_{bs} = \frac{1}{f_0}\frac{4\sqrt{\pi}}{3}\sqrt{\frac{\eta}{\alpha r_e}}\exp\left(\frac{2}{3}\frac{\eta\alpha}{r_e\gamma^2}\times\frac{\gamma\sigma_x\sigma_s}{\sqrt{2}r_eN_p}\right)\frac{\sqrt{2}}{\sqrt{\pi}\sigma_s\gamma^2}\left(\frac{\gamma\sigma_x\sigma_s}{\sqrt{2}r_eN_p}\right)^{3/2},$$

V.I.Telnov Phys. Rev. Lett. **110**, 114801 (2013).

$$\tau_{bs} = \frac{10}{f_0}\frac{4\sqrt{\pi}}{3}\sqrt{\frac{\eta}{\alpha r_e}}\exp\left(\frac{2}{3}\frac{\eta\alpha}{r_e\gamma^2}\times\frac{\gamma\sigma_x\sigma_s}{2r_eN_p}\right)\frac{2}{\sigma_s\gamma^2}\left(\frac{\gamma\sigma_x\sigma_s}{2r_eN_p}\right)^{3/2}.$$

The lifetime can be represented by a function: $\tau(\eta, \sigma_s, \frac{\sigma_x\sigma_s}{N_p})$,

- Larger momentum acceptance η is preferred, but lattice design
- Longer bunch length σ_s is preferred, but hourglass effect!
- Larger $\frac{\sigma_x\sigma_s}{N_p} \sim \frac{\sqrt{\beta_x}\sigma_s}{\sqrt{\epsilon_x}}$ is preferred => Large β_x and small ϵ_x is preferred!

Phase Advance: 60º -> 90º

- Since $\alpha_p \propto \frac{1}{Q_x^2}$, Phase advance per cell in horizontal direction: 60º -> 90º .

  α_p : 4e-5 ($\times \frac{1}{1.5^2}$) -> 1.8e-5
- $\sigma_{z,0} \propto \alpha_p^{\frac{1}{2}} \propto \frac{1}{Q_x}$.

  $\sigma_{z,0}$: 3mm ($\times \frac{1}{1.5}$) -> 2mm
- $\epsilon_x \propto \sim \frac{1}{Q_x^3}$,

  ϵ_x : 6.69nm ($\times \frac{1}{3}$) -> 2.23 nm
- Bunch population $N_p \propto \epsilon_x$

  N_p: 3.52e11 ($\times \frac{1}{3}$) -> 1.17e11; N_b: 50 ($\times$ 3)-> 150
- If β_x, β_y keep unchanged, Energy acceptance > 0.02 for 20min lifetime
- If $\beta_x = 0.5m, \beta_y = 1mm$, Coupling 0.2%, Energy acceptance > 0.012 for 20min lifetime, L0/IP=2.65 -> 3.2e34

Everything seems OK, But the bunch number 150 is too much for one ring!

Phase Advance: 60º -> 90º + Damping Partition Number

- In general, $$\epsilon_x = \frac{55}{32\sqrt{3}} \frac{\hbar}{mc} \frac{\gamma^2}{1-\mathcal{D}} \frac{\oint ds \frac{\mathcal{H}}{|\rho|^3}}{\oint ds \frac{ds}{\rho^2}}$$

  J_x: 1-> 0.5, ϵ_x: 6.69nm ($\times \frac{1}{3} \times 2$) -> 4.46 nm

- Energy spread, $$\sigma_\delta^2 = \frac{55}{32\sqrt{3}} \frac{\hbar}{mc} \frac{\gamma^2}{2+\mathcal{D}} \frac{\oint \frac{ds}{|\rho|^3}}{\oint \frac{ds}{\rho^2}}$$

  $$\sigma_z = \frac{\beta_s c|\eta|}{\omega_s}\sigma_\delta$$

  σ_δ: 1.3e-3 $\left(\times \sqrt{\frac{2}{2+0.5}}\right)$ -> 1.01e-3

  σ_z: 3mm ($\times \frac{1}{1.5} \times \sqrt{\frac{2}{2+0.5}}$) -> 1.79mm (It is assumed α_p remain unchanged)

- $\beta_x = 0.5m, \beta_y = 1mm$, Coupling 0.2%, N_p: 3.52e11 ($\times \frac{1}{3} \times 2$) -> 2.35e11, N_b: 50 $\left(\times 3 \times \frac{1}{2}\right)$-> 75

  Energy acceptance > 0.02 for 20min lifetime, L0/IP=2.65 -> 3.15e34 😐

- $\beta_x = 0.5m, \beta_y = 1.5mm$, Coupling 0.2%, N_p: 3.52e11 ($\times \frac{1}{3} \times 2 \times \frac{1}{\sqrt{1.5}}$) -> 1.92e11, bunch number: 92,

  Energy acceptance > 0.016 for 20min lifetime, xix0/xiy0=0.08/0.10, L0/IP=2.59e34 ☺

- $\beta_x = 0.5m, \beta_y = 1.5mm$, Coupling 0.3%, N_p: 3.52e11 ($\times \frac{1}{3} \times 2 \times \frac{1}{\sqrt{1.5}} \times \sqrt{\frac{0.3}{0.2}}$) -> 2.35e11, bunch number: 75,

  Energy acceptance > 0.02 for 20min lifetime, L0/IP=2.58e34 😐

Phase Advance: 60º -> 72º

- Since $\alpha_p \propto \frac{1}{Q_x^2}$, Phase advance per cell in horizontal direction: 60º -> 90º .

  α_p : 4e-5 ($\times \frac{1}{1.2^2}$) -> 2.78e-5
- $\sigma_{z,0} \propto \alpha_p^{\frac{1}{2}} \propto \frac{1}{Q_x}$.

  $\sigma_{z,0}$: 3mm ($\times \frac{1}{1.2}$) -> 2.5mm
- $\epsilon_x \propto \sim \frac{1}{Q_x^3}$,

  ϵ_x : 6.69nm ($\times \frac{3}{5}$) -> 4.01 nm
- If $\beta_x = 0.5m, \beta_y = 1.5\ mm$, Coupling 0.3%, N_p: 3.52e11 ($\times \frac{3}{5}$) -> 2.11e11, N_b: 50 $\left(\times \frac{5}{3}\right)$-> 83
- Energy acceptance > 0.013 for 20min lifetime, L0/IP=2.65 -> 2.3e34 ☺

Optimization Summary

	Phase Advance per Cell	Bx/By	Emittance, Coupling	σ_z [mm]	$N_p \times 10^{11}$	N_b	η (Analysis)	η Simulation	Vertical Dynamic Aperture	J_x	Lum/IP
Case 1	72°	0.5m/ 1.5mm	4.01nm 0.3%	2.5	2.11	83	0.013	0.015 277min	$40\sigma_y$ 19min	1	1.6e34
Case 2	90°	0.5m/ 1.5mm	4.46nm 0.2%	1.79	1.92	92	0.016	0.015 153min	$40\sigma_y$ 1480min	0.5	2.6e34
Case 3	90°	0.5m/ 1.5mm	4.46nm 0.3%	1.79	2.35	75	0.020	0.015 27min	$40\sigma_y$ 177min	0.5	2.5e34

① Lum is calculated by quasi-strong-strong simulation
② Dynamic Aperture is for 20min beamstrahlung lifetime

Error tolerance

K. Ohmi, D. Zhou (KEK)
SuperKEKB MAC
Feb. 7-9, 2011

Summary – tolerance for parameters with 20% luminosity degradation

Parameter	w/ crab waist	w/o crab waist
r_1^* (mrad)	±5.3	±3.5
r_2^* (mm)	±0.18	±0.13
r_3^* (m^{-1})	±44	±15
r_4^* (rad)	±1.4	±0.4
$\partial r_1^* / \partial\delta$ (rad)	±2.4	±2.1
$\partial r_2^* / \partial\delta$ (m)	±0.086	±0.074
$\partial r_3^* / \partial\delta$ (m^{-1})	$\pm 1.0\times 10^4$	±8400
$\partial r_4^* / \partial\delta$ (rad)	±400	±290
η_y^* (μm)	±62	±31
$\eta_y'^*$	±0.73	±0.23

Δx (μm) collision offset	10	10
Δs (μm) waist error	100	100
Δy,Δy'(μm,μrad) collision offset 0.02 (100)		
δx (μm) turn by turn noise	0.5	0.5
δy (nm)	4	4

The degradation is roughly quadratic

σx=6-10μm σy=50 nm

Summary & Discussion

- Beamstrahlung model in different codes(BBWS, LIFETRAC, GUINEA-PIG)
- We still don’t know if the first few collisions is more critical for beam loss
- Lifetime calculation, analyais & simulation does not agree ?
- If we could not shorten the bunch length, it is not wise to suppress by* to 1mm. 1.5mm is more attractive for us.
- Is it possible to achieve 0.2 or 0.3% coupling. Optics measurement & correction by simulation with error should be studied.
- ~100 bunches in one ring is achievable?
- The result should be checked
- More questions to be answered (If xiy > 0.1?). If aperture with beam-beam is a problem? In the following time, some visitors will attend ihep. We wish a fruitful April.

- Thanks for your attention!