Beam-beam studies for FCC-ee

K. Ohmi (KEK)

FCC week@Washington

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Thanks to D. Shatilov, Y. Zhang and F. Zimmermann

Simulation Codes

Y. Zhang, CEPC review 2015

- LIFETRAC by D. Shatilov (BINP),

  Quasi-strong-strong method is used: Self-consistent beam size and dynamic beta/emittance (Gaussian Fit)

- BBWS/BBSS by K. Ohmi (KEK),

  Weak-strong sim. with self-consistent σ_z and σ_x, or Strong-strong sim.

- IBB by Y. Zhang (IHEP)

What we can do by simulations at present

- Luminosity evaluation using simplified lattice, in which arc transformation is represented by 6x6 transfer matrix.
  - Effects of Lattice nonlinearity were small for KEKB, but is important in SuperKEKB with very low β^*_y (0.3mm) and complex IR.
- Lifetime evaluation taken into account of beamstrahlung. Determine momentum and betatron acceptance requirement.

Beamstrahlung

- Synchrotron radiation during beam-beam collision
- Beam-beam force and curvature of orbit

$$\Delta p_{x,y} \approx \frac{Nr_e}{\gamma} \frac{1}{\sigma_x + \sigma_y} \qquad \frac{1}{\rho_{xy}} = \frac{\Delta p_{x,y}}{\Delta s} = \frac{4Nr_e}{\sqrt{2\pi}\gamma} \frac{1}{(\sigma_x + \sigma_y)\sigma_z}$$

  – ρ=23.5/19.7m<< ρ_{bend}= 6,094/11,000m (CEPC/TLEP)
  – u_c= 164/194 MeV, N_γ=0.21/0.092

- Formulae for energy spread due to beamstrahlung

$$\langle d\delta_{BS} \rangle = n_\gamma \langle u \rangle / E_0 = 0.864 r_e^3 \gamma \left(\frac{N_e}{\sigma_z(\sigma_x + \sigma_y)} \right)^2 \frac{\sigma_z}{\sqrt{1 + \left(\frac{\theta_c \sigma_z}{\sigma_x} \right)^2}}$$

$$n_\gamma = 2.12 \frac{\alpha r_e N_e}{\sigma_x + \sigma_y} \frac{1}{\sqrt{1 + \left(\frac{\sigma_z \theta_c}{\sigma_x} \right)^2}}$$

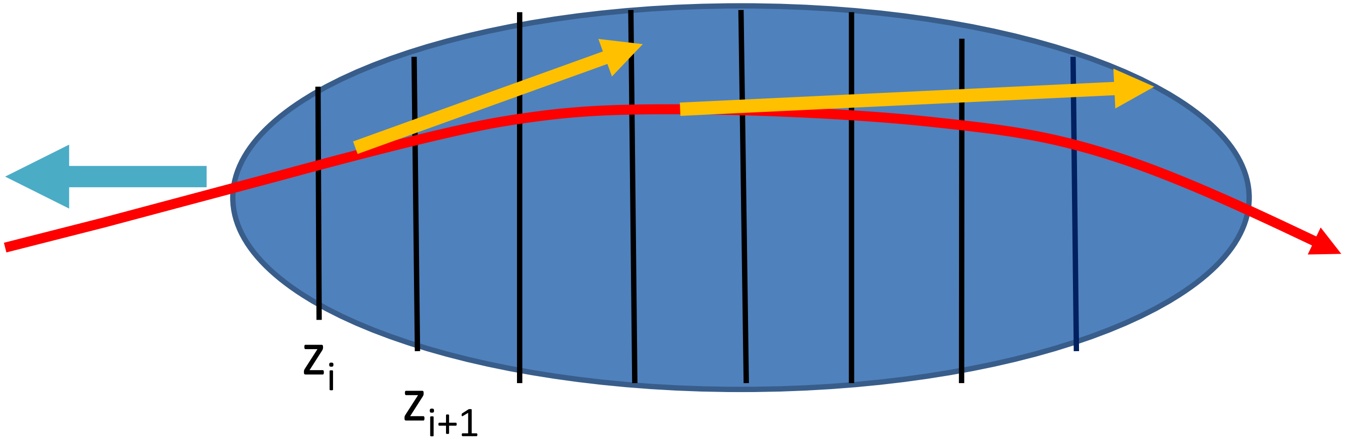
$$\sigma_{\delta,tot} = \sqrt{\sigma_{\delta,SR}^2 + \sigma_{\delta,BS}^2}$$

$$\sqrt{\langle \delta_{BS} \rangle^2} = \langle d\delta_{BS} \rangle \sqrt{0.1639 + \frac{5.129}{n_\gamma}}$$

$$\sigma_{z,tot} = \sigma_{z,SR} \sigma_{\delta,tot} / \sigma_{\delta,SR}$$

Schematic view of the simulation

- Calculate trajectory interacting with colliding beam.
- Particles emit synchrotron radiation due to the momentum kick dp/ds.



$$ds = \frac{z_i - z_{i+1}}{2}$$

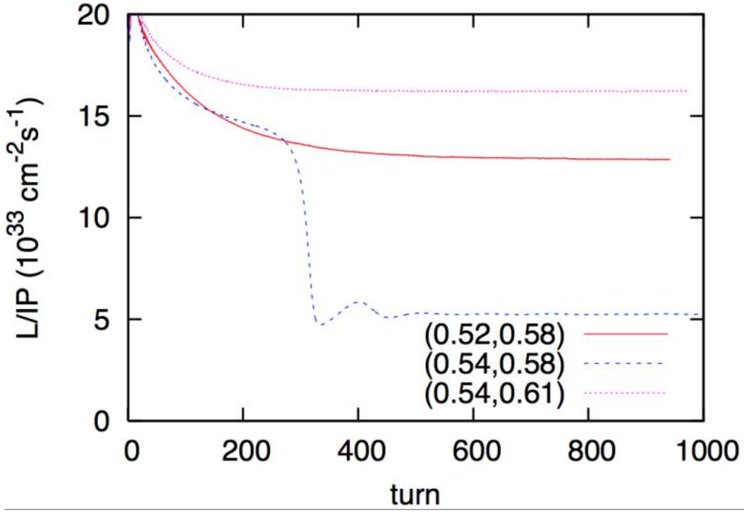
$$\langle\delta\rangle = dn_\gamma \langle u \rangle = \frac{2 r_e \gamma^3}{3\rho^2} ds$$

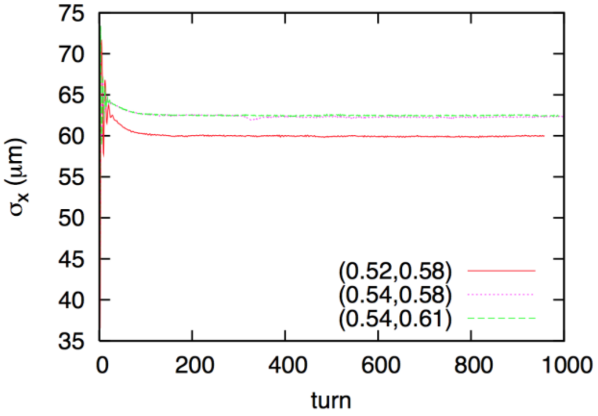
$$\frac{1}{\rho_{x,y}} = \frac{dp_{x,y}}{ds}$$

$$\langle\delta^2\rangle = dn_\gamma \langle u^2 \rangle = \frac{55}{24\sqrt{3}} \frac{r_e \hbar \gamma^5}{mc\rho^3} ds$$

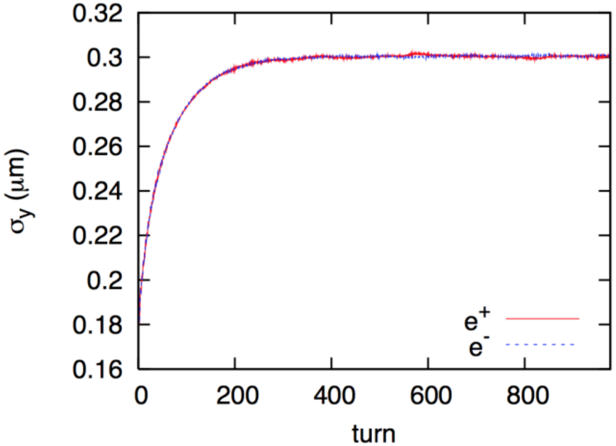
Example of simulation

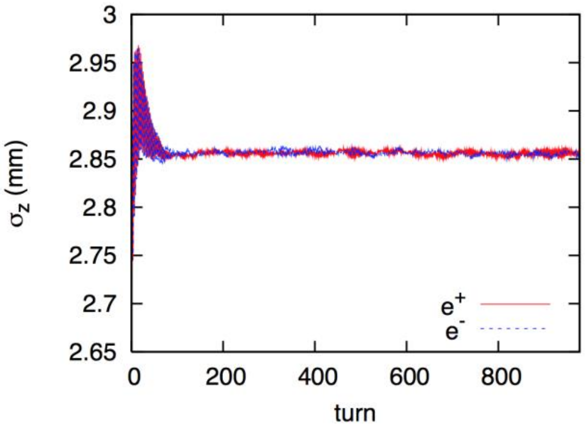
- Luminosity evolution in a strong-strong simulation.





- Beam size evolution of e-/e+ beam

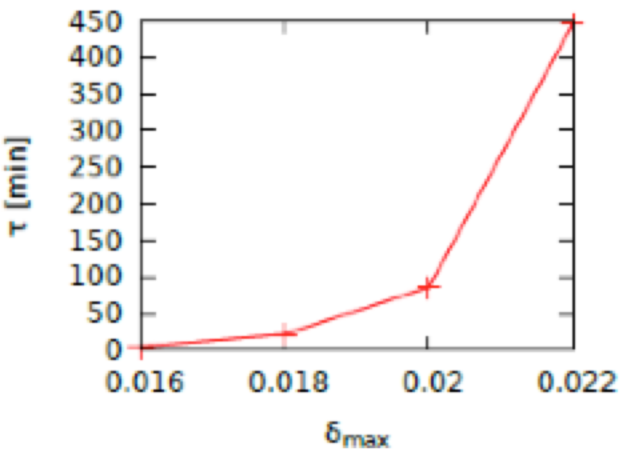




Lifetime evaluation

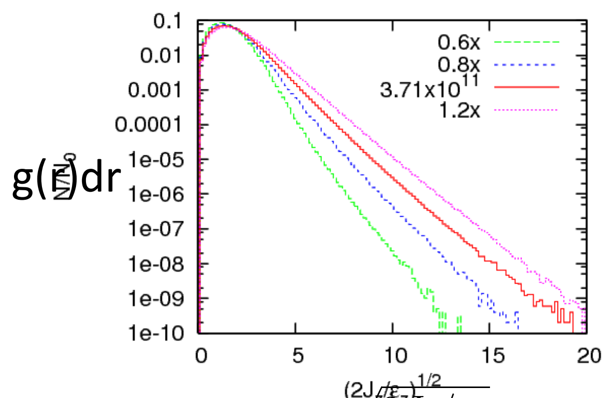
- High energy photon emission due to beamstrahlung induces beam halo in longitudinal.
- Two methods are used on the simulations
  - direct count beam loss
  - evaluate from equilibrium beam distribution (M. Sands)

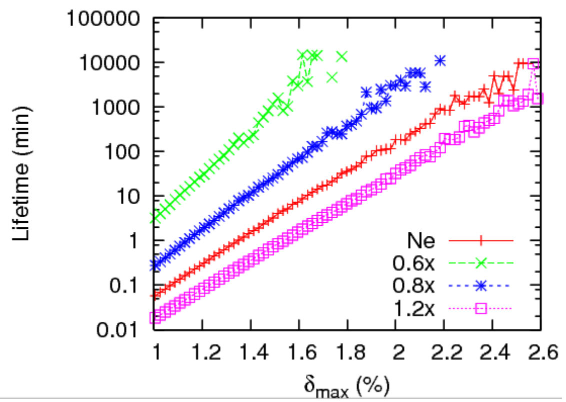
CEPC: 2% momentum acceptance is required.



LIFETRAC

$$\tau = \frac{\tau_z}{r_z g(r_z)}$$





$$r_z = \sqrt{2J_z/\varepsilon_z}$$

Analytic formula (Telnov, Bogomyagkov)

$$\tau_{\mathrm{bs,Telnov}} = \frac{\mathbf{10}}{f_0}\frac{4\sqrt{\pi}}{3}\sqrt{\frac{\eta}{\alpha r_e}} \times \exp\left(\frac{2}{3}\frac{\eta\alpha}{r_e\gamma^2}\times\frac{\gamma\sigma_x\sigma_z}{\mathbf{2}r_eN_p}\right)\frac{\mathbf{2}}{\sigma_z\gamma^2}\left(\frac{\gamma\sigma_x\sigma_z}{\mathbf{2}r_eN_p}\right)$$

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

1 is necessary

$\eta = \delta_{max} = 1.5\%$

Table 2: Expected and simulated BS lifetime.

τ_{BS} [min]	TLEP-H	TLEP-t	CepC
analytical [9]	310	3.6	113
analytical [8]	1400	3.3	619
weak-strong (loss)	26	0.3	5.5
weak-strong (distr.)	33	0.3	~5

- The lifetime in simulations is shorter than analytical estimates.
- Analytical formula considering dynamic beta agree with simulation results (M. Koratzinos).

To relax beamstrahlung

- For given current and beam-beam parameter,

$$L = \frac{\gamma}{2er_e}\frac{I\xi_y}{\beta_y}$$

- zero crossing angle

$$\langle d\delta_{BS}\rangle = 34.1 r_e \gamma^3 \left(\frac{\xi_y \sigma_y}{\beta_y}\right)^2 \frac{1}{\sigma_z} \qquad N_\gamma = 13.3 \alpha r_e \gamma_e \frac{\xi_y \sigma_y}{\beta_y}$$

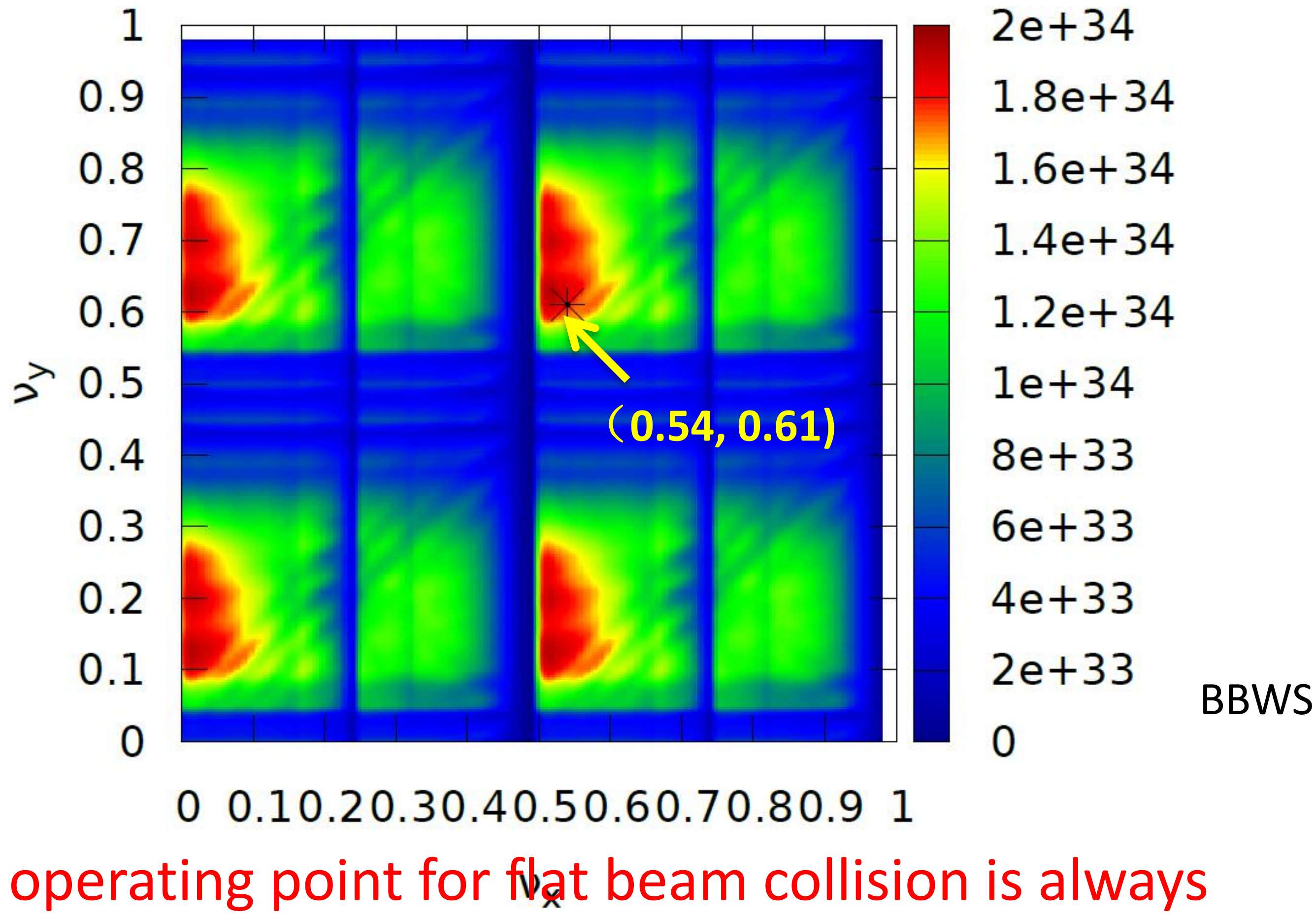
- Small σ_y is better. It means small N_e keeping ξ_y and coupling, that is, more bunch is better.
- Effect of beamstrahlung is prominent for CEPC, because number of bunch is 48, while 1000 for FCC

Parameters based on Head-on collision

		CEPC	TLEP-H ('14)	TLEP-H ('15)
circumference	C (km)	54.7	100	100
energy	E (GeV)	120	120	120
bunch population	N_e (10^{10})	37.9	4.6	4.6
emittance	$\varepsilon_x/\varepsilon_y$ (nm)	6.79/0.02	0.94/0.0019	0.94/0.0019
beta at IP	β_x/β_y (m)	0.8/0.0012	0.5/0.001	0.5/0.001
bunch length	σ_z(mm)	2.14(2.65)	0.81(1.17)	1.6(1.8)
energy spread	σ_δ(%)	0.13 (0.16)	0.10(0.14)	0.139 (0.154)
damping time (turn)	τ_x/τ_z	78/39	142/71	142/71
number of IP	N_{IP}	2	4	4/2
number of bunch	N_{bunch}	48	1360	1360/1046
Luminosity	L/IP (10^{34}cm^{-2}s^{-1})	2	6	5.3-7
Lumi (simulation)		2	7.6	5.9-7.6

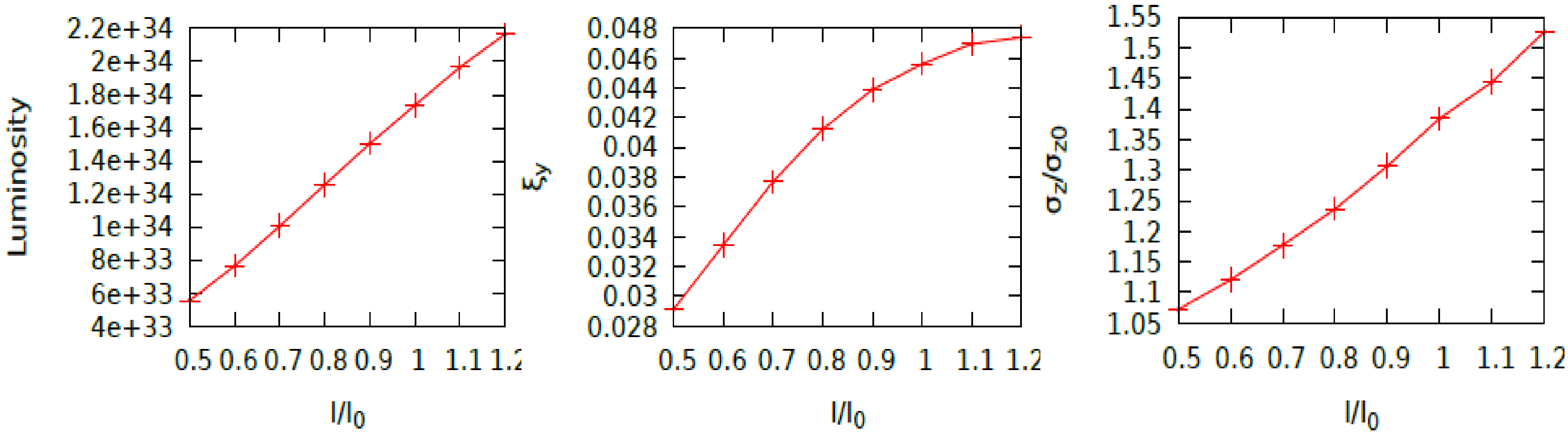
Tune scan using weak-strong simulation Choice of Working Point (CEPC)

By Y. Zhang



The best operating point for flat beam collision is always ν_x=0.5+ε, ν_y~0.6, K. Ohmi, J. Plasma Fusion Res., 91,2015.

Luminosity versus bunch current for CEPC



- For flat beam, the achieved beam-beam parameter can be defined as

$$\xi_y \equiv \frac{2r_e\beta_y L}{\gamma N_e f_{col}}$$

The effective beam-beam parameter is only about 0.045 with design parameters and the saturation is very clear near the design bunch current.

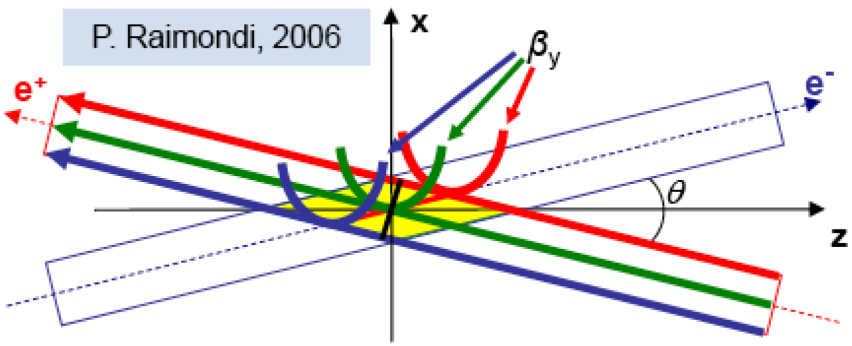
- The bunch length is nearly 3 times of , which entails strong hourglass effect.

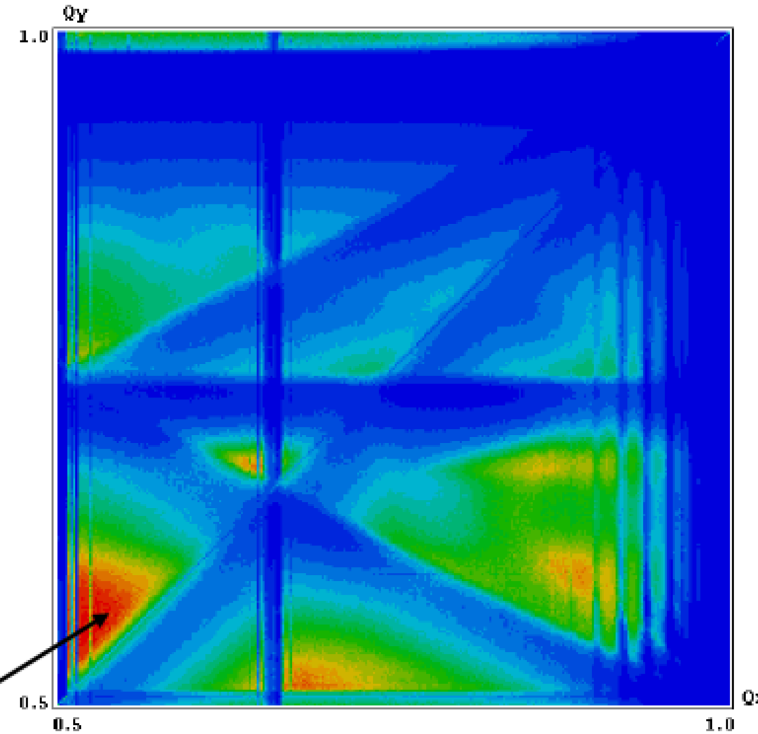
LIFETRAC

Crab waist scheme

Crab Waist: Choice of Parameters

D. Shatilov





Luminosity tune scan for Super c-τ factory, $\xi_y \sim 0.21$
(typical picture for crab waist scheme)

$$\phi = \frac{\sigma_z}{\sigma_x} tg\left(\frac{\theta}{2}\right)$$ – Piwinski angle, should be >> 1

For $\phi >> 1$, $\xi_x \propto 1/\phi^2$ and $\xi_y \propto 1/\phi$, so we have $\xi_x << \xi_y$ and footprint looks like a thin vertical bar.

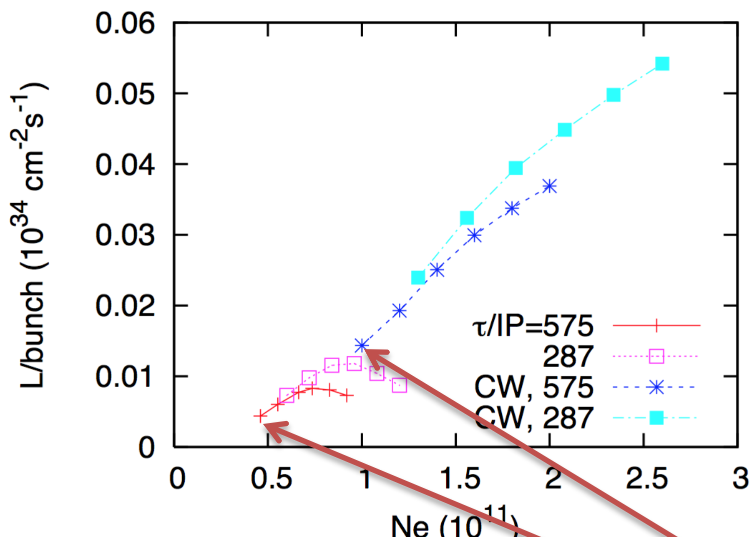
Good working point: (0.54, 0.57). We need to make σ_z larger (to increase ϕ) and ν_s smaller (to avoid synchro-betatron satellites of $\nu_x = 0.5$) => requirements on RF (low voltage, 400 MHz).

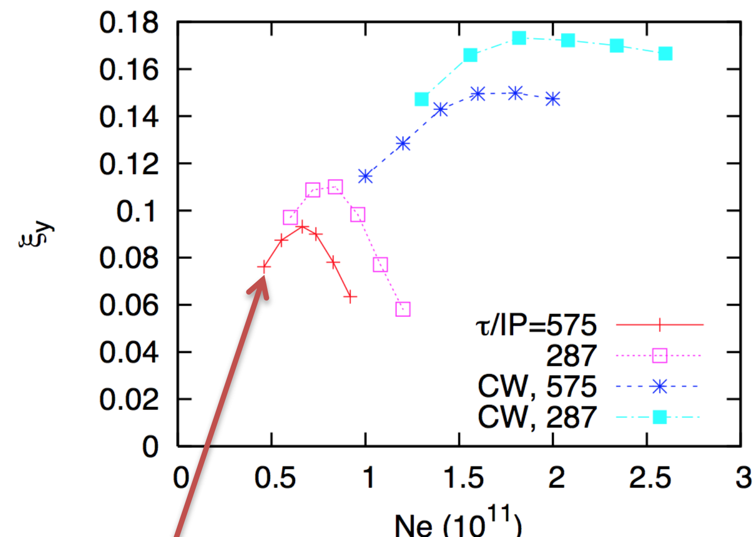
Crab waist

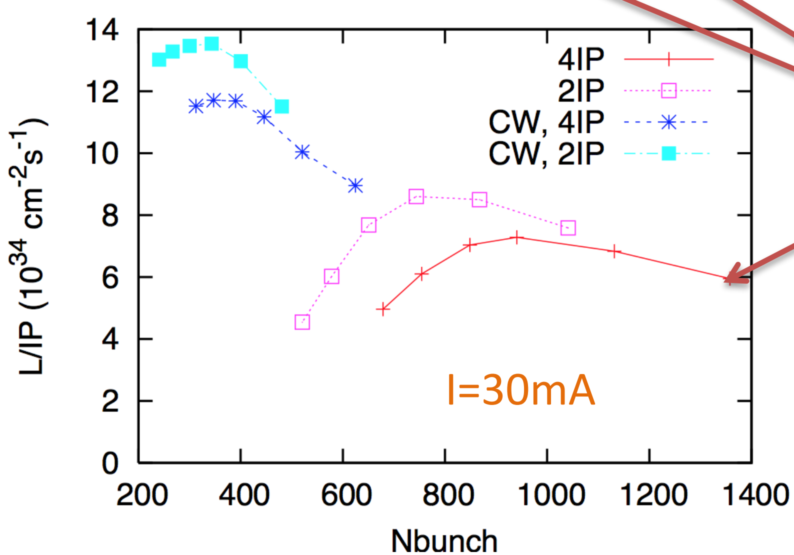
	TLEP-Z('14)	TLEP-Z('15)	TLEP-H('14)	TLEP-H('15)
Ne (10^{10})	10	5	35	10
$\varepsilon x/\varepsilon y$ (nm)	0.14/0.001	0.13/0.001	0.85/0.0018	0.94/0.001
$\beta x/\beta y$ (m)	0.5/0.001	0.5/0.001	0.5/0.001	0.5/0.001
σz(mm)	2.7(5.9)	0.97(3.7)	2.76 (6.77)	2.1(2.6)
$\sigma\delta$(%)	0.05(0.12)	0.037 (0.124)	0.11(0.27)	0.139 (0.172)
$\tau x/\tau z$	2640/1320	2640/1320	142/71	142/71
half cros. angle, θ_c	0.015	0.015	0.015	0.015
NIP	4	4	4	4(2)
Nbunch	29791	59581	127	1360
L/IP ($10^{34}cm^{-2}s^{-1}$)	212	215	9.24	5.3-7
L/IP (simulation)	200	143	9.8	5.9-7.6

TLEPs('14) are given by A.Bogomyagkov, E. Levichev, D. Shatilov, PRST
TLEPs('15) are in a talk of F. Zimmermann, FCCweek'15.

Luminosity and beam-beam parameter for H





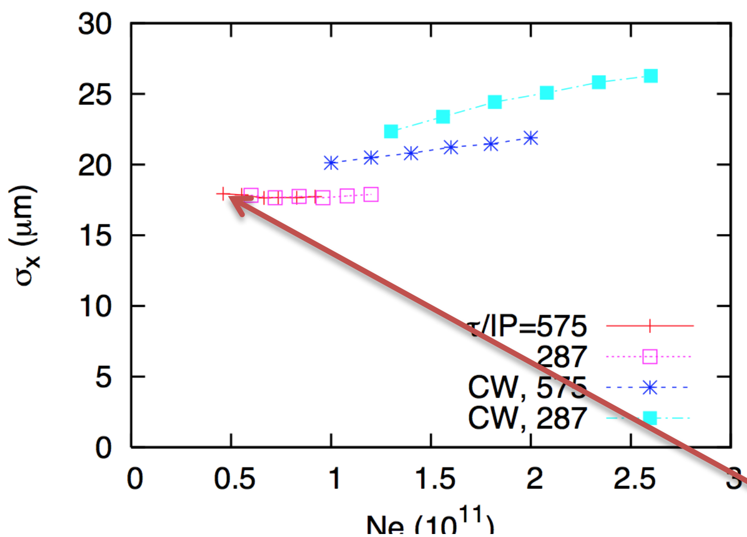


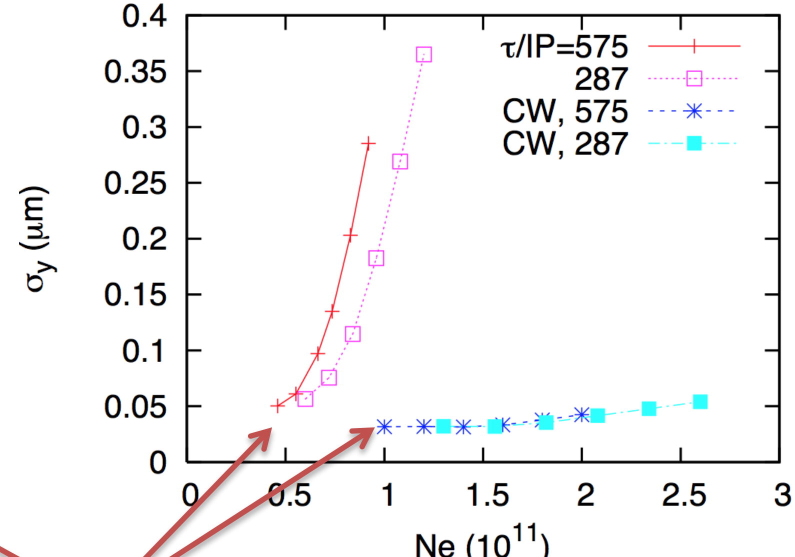
$$\xi_y \equiv \frac{2 r_e \beta_y L}{\gamma N_e f_{col}}$$

Design Ne: the lowest value in figure

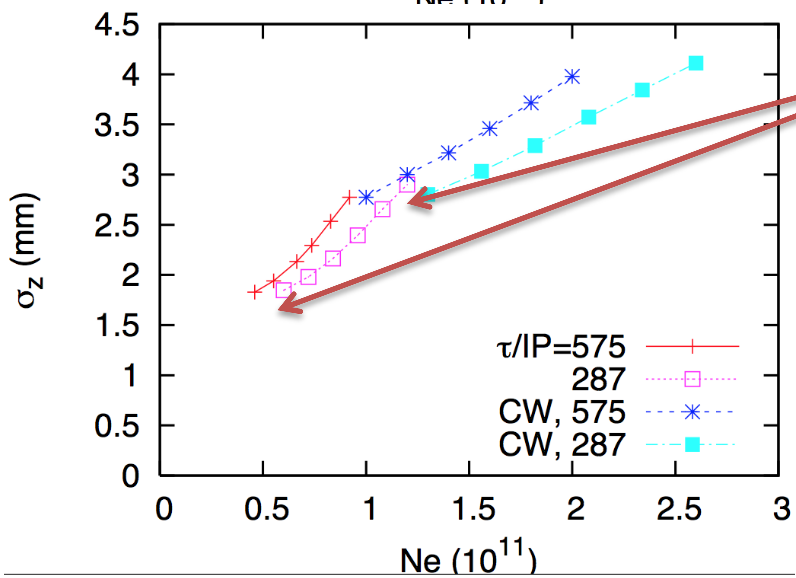
Highest luminosity performance is achieved at the peak of ξ.

Equilibrium Beam sizes for H

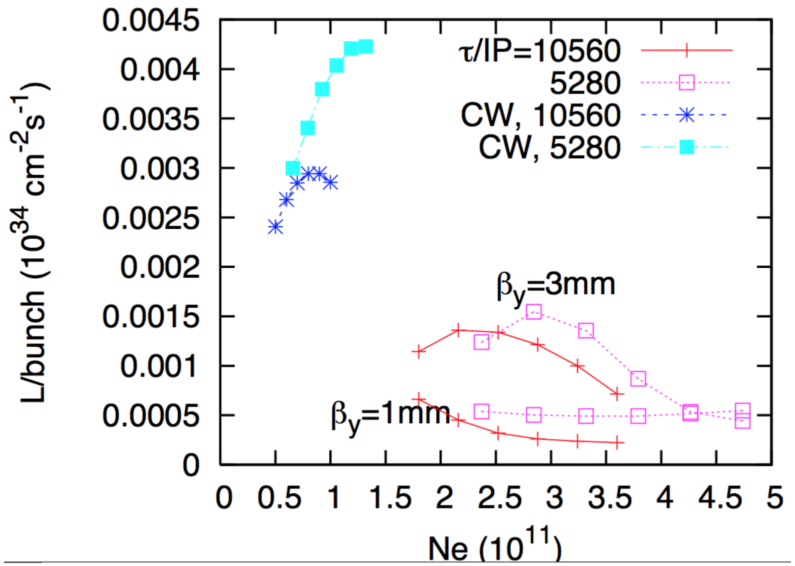


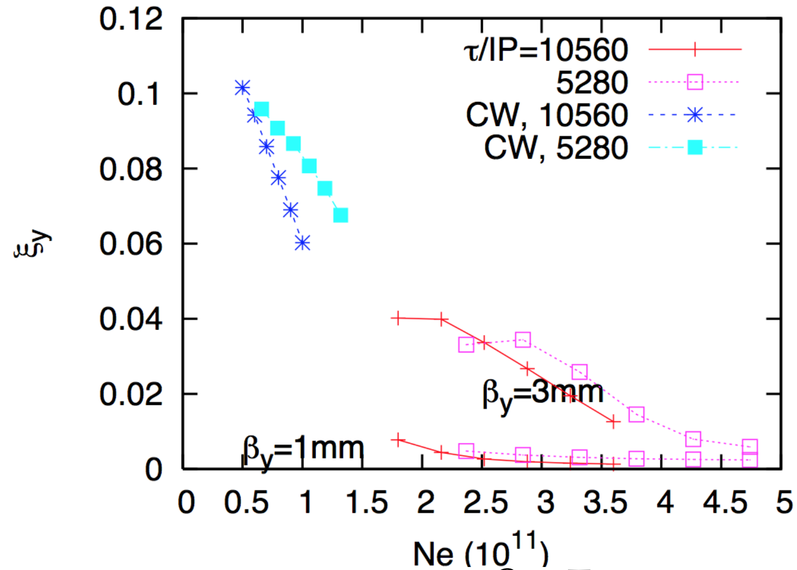


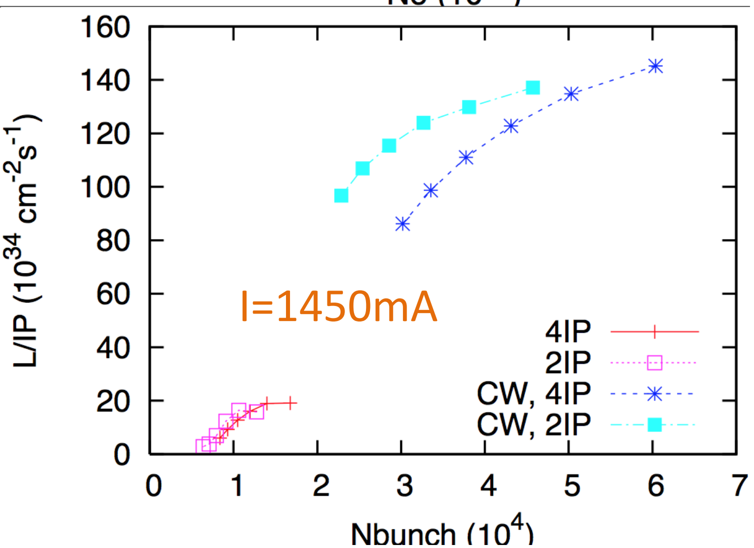
- Design



Luminosity and beam-beam parameter for Z



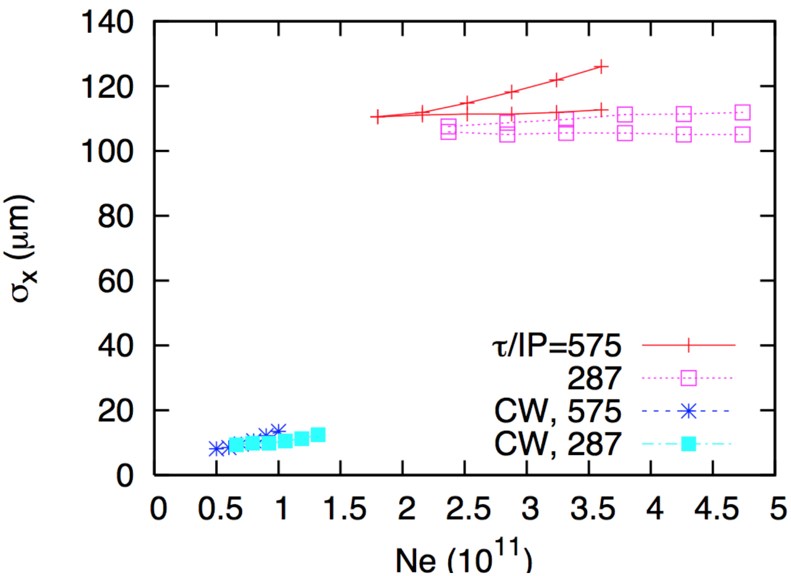


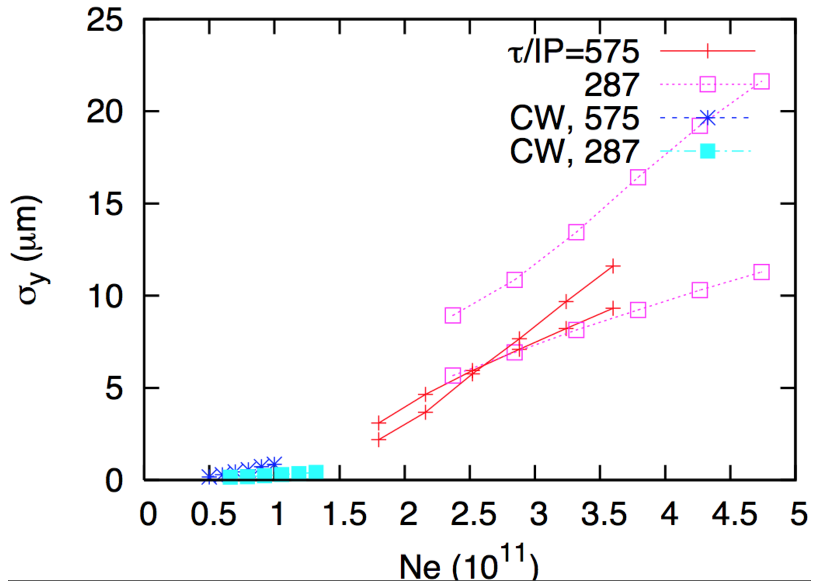


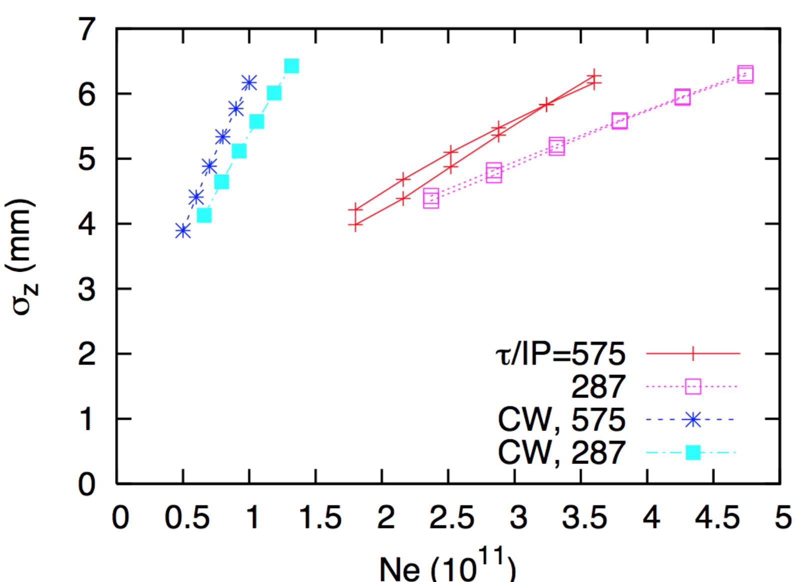
$$\xi_y \equiv \frac{2r_e\beta_y L}{\gamma N_e f_{col}}$$

$$L = \frac{\gamma}{2er_e}\frac{I\xi_y}{\beta_y}$$

Equilibrium Beam sizes for z



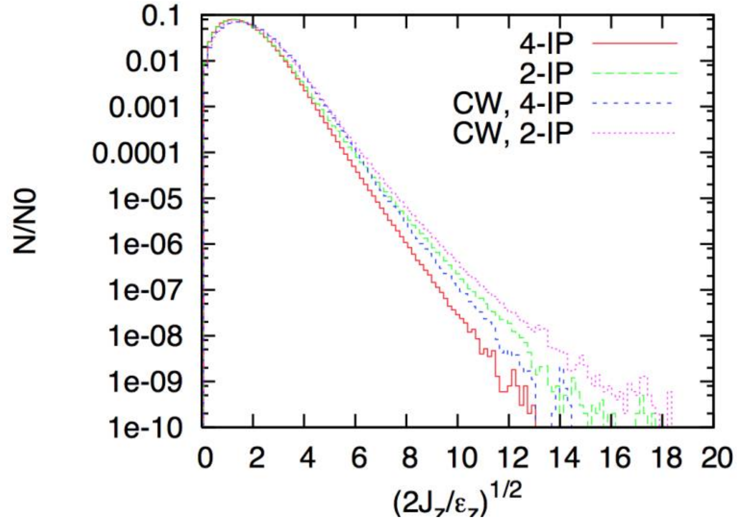


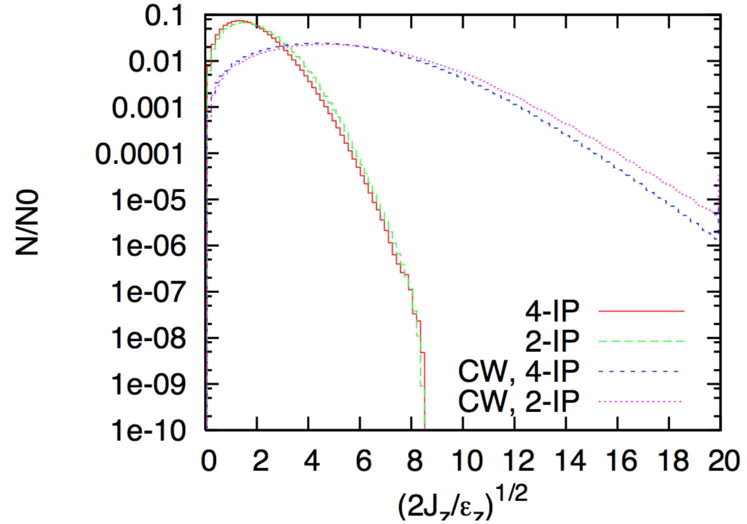


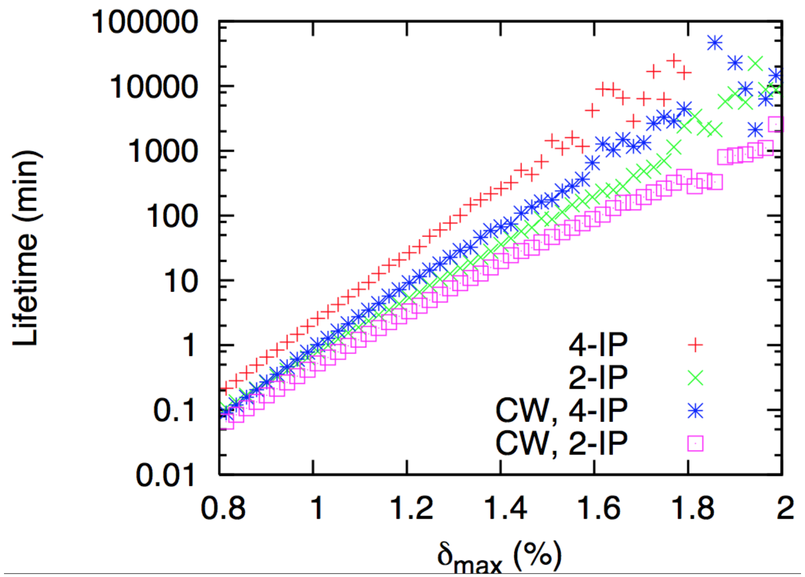
- Ne's in table are the lowest points.

z distribution and Lifetime for

- H beamstrahlung Z







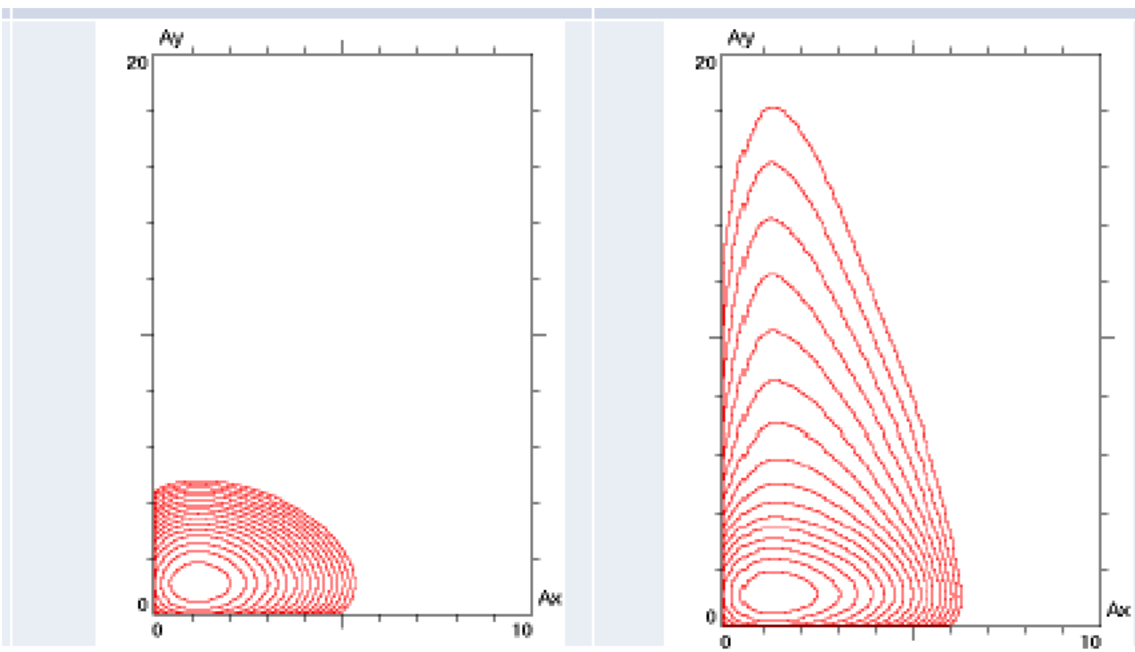
Lifetime for Z is very long.

Momentum acceptance is 1.5% for latest lattice.

Vertical tail and lifetime from vertical aperture

D. Shatilov

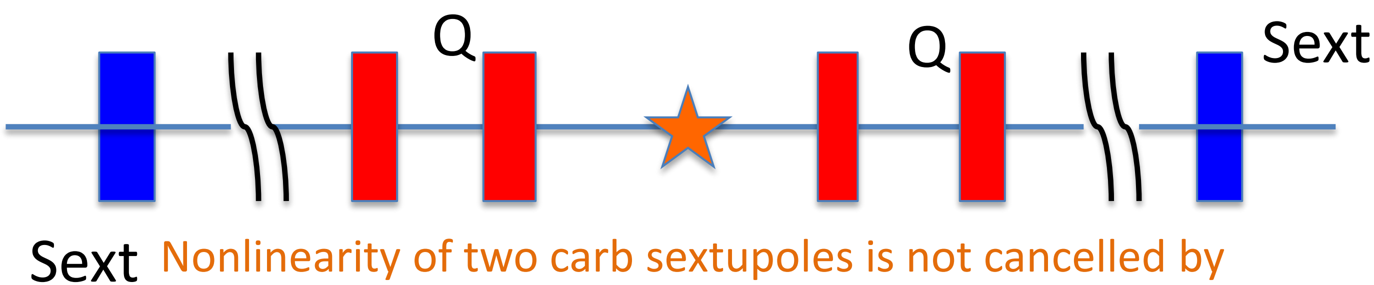
- Crab waist   without crossing angle



- Crab waist shows an excellent performance in consideration of only beam-beam.

Dynamic aperture issue in crab waist

- Crab sextupoles are located at both end of IR, which contains strong nonlinearity (kinematical and Q fringe at very high β).
- Management of the nonlinearity was given up in SuperKEKB (β_y*=0.3mm.)
- BINP team is designing IR without aperture loss in crab waist scheme for FCC, and is going well to getting solution.



Nonlinearity of two carb sextupoles is not cancelled by strong IR nonlinearity.

Summary

- Beam-beam simulations have been performed with weak-strong and strong-strong considering beamstrahlung using BINP, KEK, IHEP codes for FCC/CEPC.
- The simulations can predict luminosity, beam-beam tune shift limit, bunch lengthening and lifetime. Required aperture and momentum acceptance are determined.

- Crab waist works very clear, especially in Z, in the beam-beam simulation without complex IR nonlinearity.
- Management of IR nonlinearity is essential for crab waist.

Thank you for your attention

Parameters for baseline

F. Zimmermann

	4-IP		2-IP	
	Z	H		
E	45	120	45	120
Ne	1.80E+11	4.60E+10	2.37E+11	6.00E+10
εx	2.90E−08	9.40E−10	2.90E−08	9.40E−10
εy	6.00E−11	2.00E−12	6.00E−11	2.00E−12
βx	0.5	0.5	0.5	0.5
βy	0.001	0.001	0.001	0.001
νs	0.458	0.068	0.458	0.068
σz	0.00329	0.00162	0.00329	0.00162
$\sigma\delta$	5.20E−04	1.39E−03	5.20E−04	1.39E−03
εz	1.71E−06	2.25E−06	1.71E−06	2.25E−06
βz	6.3269	1.1655	6.3269	1.1655
θc	0	0	0	0
σz,BS	0.0038	0.0018	0.00384	0.00181
$\sigma\delta$,BS	6.10E−04	1.54E−03	6.10E−04	1.55E−03
Nb	16700	1360	12846	1046

Parameters for crab waist option

- Z & H

F. Zimmermann

	CW 4-IP Z	H	2-IP	
E	45	120	45	120
Ne	5.00E+10	1.00E+11	6.60E+10	1.30E+11
εx	1.30E-10	9.40E-10	1.30E-10	9.40E-10
εy	1.00E-12	1.00E-12	1.00E-12	1.00E-12
βx	0.5	0.5	0.5	0.5
βy	0.001	0.001	0.001	0.001
νs	0.03	0.053	0.03	0.053
σz	0.00097	0.00208	0.00097	0.00208
σδ	3.70E-04	1.39E-03	3.70E-04	1.39E-03
εz	3.59E-07	2.89E-06	3.59E-07	2.89E-06
βz	2.6216	1.4964	2.6216	1.4964
θc	0.015	0.015	0.015	0.015
	1.80E+00	1.44E+00	1.80E+00	1.44E+00
σz,BS	0.0037	0.00258	0.0033	0.00261
σδ,BS	1.24E-03	1.72E-03	1.27E-03	1.74E-03
Nb	59581	625	45154	474

Simulation

- Weak-strong simulation
- Tune/IP=(0.54,0.61)
- Beamstrahlung is taken into account.
- sigz is self-consistent, but sigx or sigy are not.
- The difference between 2 and 4-IP are in damping time and synchrotron tune.

Luminosity and beam-beam parameter for t

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