Beam-beam effect for collision with Large Piwinski angle scheme and high frequency crab cavity in LHC

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CARE-HHH, LHC beam-beam and beam-beam compensation

28 Aug.,2008

Thanks to F. Zimmermann, J.P. Koutchouk, O. Bruning, R. Calaga, R. Tomas, Y. Sun, A. Morita, M. Aiba

F. Zimmermann, PAC07, J.P. Koutchouk, EPAC08

Table 1: Parameters for the (1) nominal and (2) ultimate LHC compared with those for three upgrade scenarios with (3) shorter bunches at 12.5-ns spacing [old baseline], (4) more strongly focused ultimate bunches with early separation at 25-ns spacing [ES], (5) longer intense flat bunches at 50-ns spacing in a regime of large Piwinski angle [LPA]. The numbers refer to the performance without luminosity leveling.

parameter	symbol	nominal	ultimate	old	ES	LPA	LPA-II
number of bunches	n_b	2808	2808	5616	2808	1404	2808
protons per bunch	N_b [10^{11}]	1.15	1.7	1.7	1.7	4.9	2.5
bunch spacing	$\Delta t_{\rm sep}$ [ns]	25	25	12.5	25	50	25
average current	I [A]	0.58	0.86	1.72	0.86	1.22	1.22
normalized transverse emittance	$\gamma\epsilon$ [μm]	3.75	3.75	3.75	3.75	3.75	3.75
longitudinal profile		Gaussian	Gaussian	Gaussian	Gaussian	uniform	Gaussian
rms bunch length	σ_z [cm]	7.55	7.55	3.78	7.55	11.8	7.55
beta function at IP1&5	β^* [m]	0.55	0.5	0.25	0.08	0.25	0.14
(effective) crossing angle	θ_c [μrad]	285	315	445	0	381	786
Piwinski angle	ϕ	0.4	0.75	0.75	0	2.01	
hourglass factor	$F_{\rm hg}$	1.00	1.00	1.00	0.86	0.99	
peak luminosity	$\hat{L}$ [10^{34} cm^{-2}s^{-1}]	1.0	2.3	9.2	15.5	10.6	
events per crossing		19	44	88	294	403	
rms length of luminous region	$\sigma_{\rm lum}$ [mm]	45	43	21	53	37	
initial luminosity lifetime	τ_L [h]	22.2	14.3	7.2	2.2	4.5	
average luminosity ($T_{\rm ta} = 10$ h)	$L_{\rm av}$ [10^{34} cm^{-2}s^{-1}]	0.5	0.9	2.7	2.4	2.5	
optimum run time ($T_{\rm ta} = 10$ h)	$T_{\rm run}$ [h]	21.2	17.0	12.0	6.6	9.5	
average luminosity ($T_{\rm ta} = 5$ h)	$L_{\rm av}$ [10^{34} cm^{-2}s^{-1}]	0.6	1.2	3.7	3.6	3.5	
optimum run time ($T_{\rm ta} = 5$ h)	$T_{\rm run}$ [h]	15.0	12.0	8.5	4.6	6.7	
e-cloud heat load for $\delta_{\rm max} = 1.4$	$P_{\rm ec}$ [W/m]	1.07	1.04	13.3	1.0	0.4	
e-cloud heat load for $\delta_{\rm max} = 1.3$	$P_{\rm ec}$ [W/m]	0.44	0.6	7.9	0.6	0.1	
SR heat load	$P_{\rm SR}$ [W/m]	0.17	0.25	0.5	0.25	0.36	
image-current heat load	$P_{\rm ic}$ [W/m]	0.15	0.33	1.85	0.33	0.70	

LPA or crab cavity

$$L = \frac{I\gamma}{r_p e\beta}\xi_N$$

- For a target Luminosity, there are choices for keeping ξ, β and I.

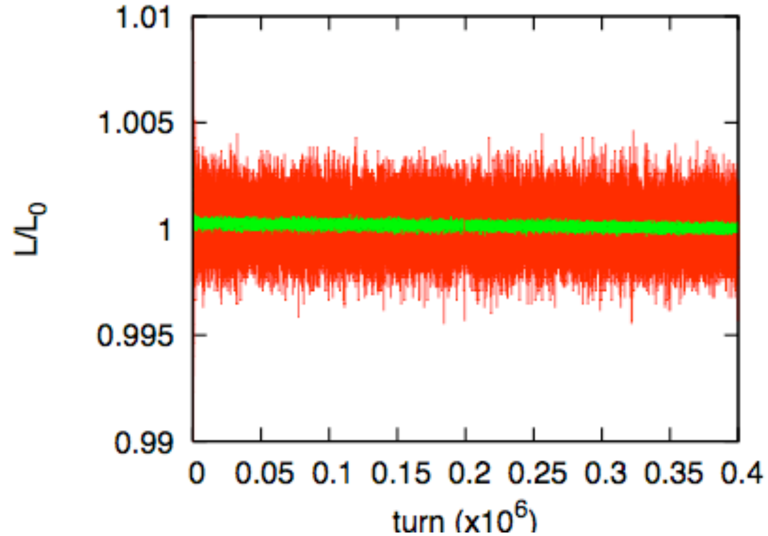
1. Design with the head-on collision condition using well-known formula
2. Increasing Piwinski (crossing) angle and bunch population can keep ξ. To keep I, bunch repetition is decreased.

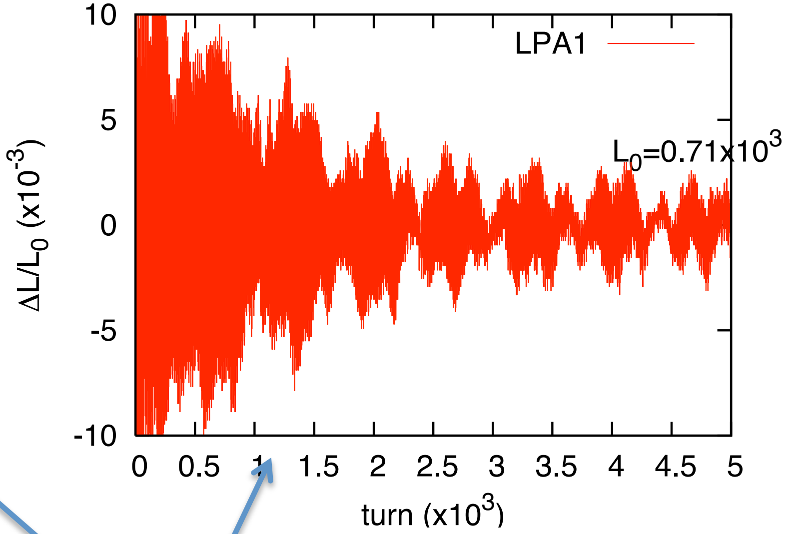
- The choice depends on other conditions for $\beta_{xy}>\sigma_z$, if crossing angle does not affect the beam-beam performance. For example, a large bunch spacing is gain for avoiding parasitic interaction depending on arrangement of separation magnet and wires. Electron cloud…
- Both scheme are examined with simulations.

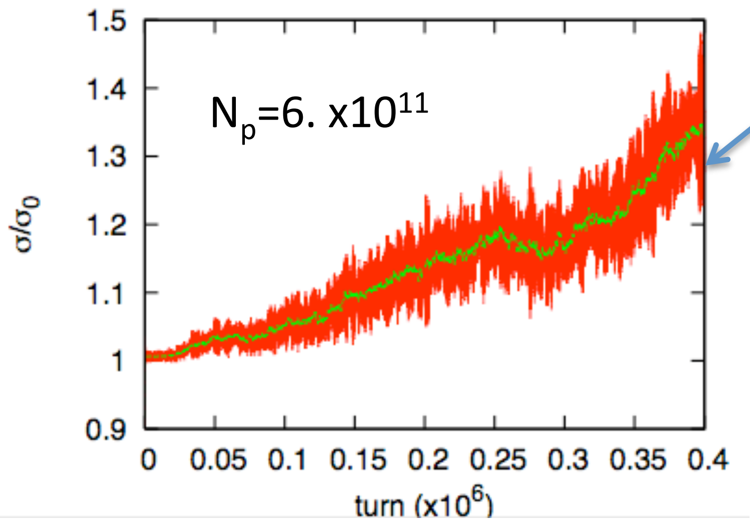
Simulations for LPA

- Weak-strong and strong-strong simulations were performed.
- A bunch is sliced many pieces (15) for LPA scheme.
- The calculation time linearly increase for the number of slices in the weak-strong simulation.
- While it is square of the number of slices in the strong-strong simulations, .

Simulation for LPA -I







- Weak-strong (strong beam is uniform)
- strong-strong, miss-matching is seen.
- Emittance growth due to parasitic interaction is seen in high bunch population (WS).

Large Piwinski angle option-II

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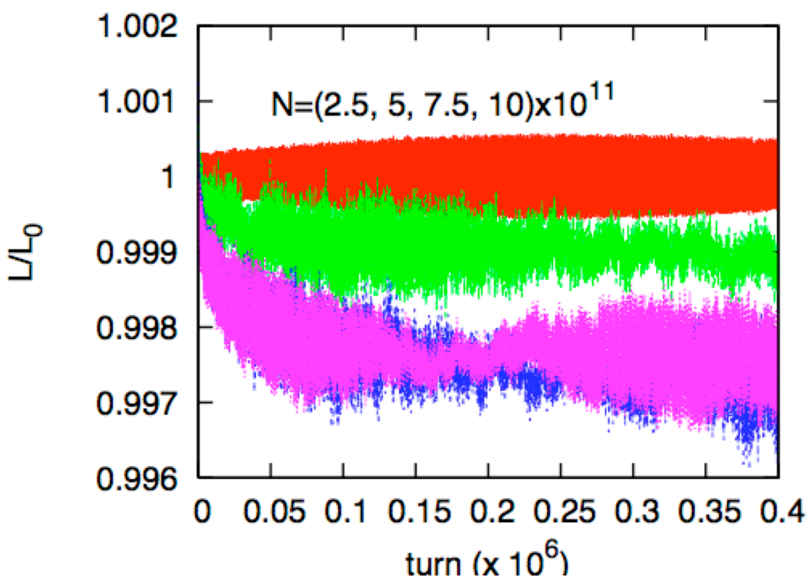
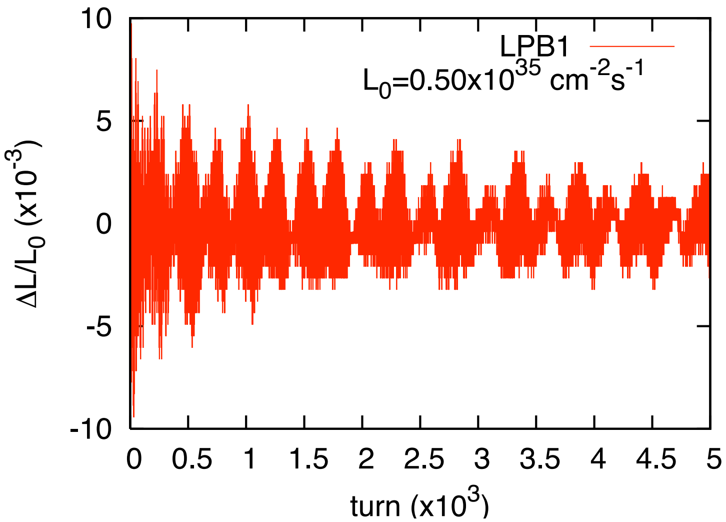
- $N=2.5x10^{11}$ /bunch , β^*=14 cm, σ_z=7.5 cm, , θ_h(half xangle) =393 μrad, Piwinski angle = 3.5, HV crossing, no parasitic

Weak-strong

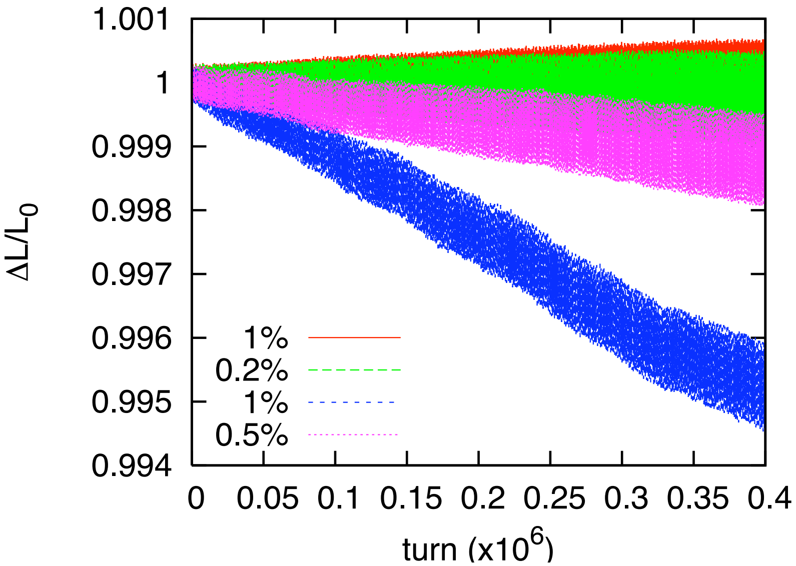


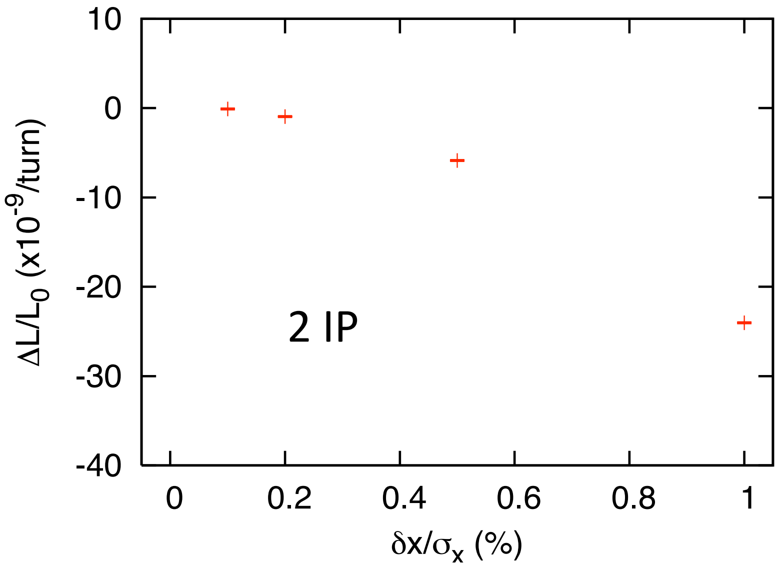
Strong-strong
(design bunch population)



Noise tolerance in LPA

- For LPA-II, the noise tolerance is $\delta x=0.1\%\sigma_x$.





Emittance growth in LPA

- Weak-strong simulations did not show any emittance growth and halo formation for the design bunch population.
- The emittance growth for 5×10^{11} population is 10^{-9} or slightly higher than the requirement (1day life time).
- Fluctuation of luminosity is larger than the nominal case. Miss-match? There was no fluctuation in a low population.
- The accelerator lattice should be included. A. Morita can do it with SAD.
- Simulations of 5000-10000 turns is limit for the strong-strong, where the number of slice is 15. The prediction power for the emittance growth is poor in the present computers.
- Tolerance for fast noise is similar as the nominal LHC.
- There were no clear problem in LPA scheme as far as these simulations.

Crab cavity scheme in LHC

- Choice of cavity frequency, 800 MHz or 400MHz.
- σ_z=7.5 cm, $\omega\sigma_z/c$=1.25 or 0.63.
- The voltage slope may not be negligible. Beam distributes with snake shape.
- Study of collision of snake shape beams.

Effective Hamiltonian of crab cavity

- H at crab cavity

$$H_c = \frac{V_c}{E_0} x \sin(kz + \phi)$$

$$k = \frac{\omega_c}{c}$$

$$\bar{p}_x = p_x - \frac{V_c}{E_0} \sin(kz + \phi)$$

$$\bar{\delta} = \delta - \frac{V_c}{E_0} kx \cos(kz + \phi)$$

- H at collision point, horizontal betatron phase difference between crab and IP is chosen $\pi/2$.

$$H_c = \frac{\theta}{k} p_x \sin(kz + \phi)$$

$$\theta = \frac{\omega_c}{c} \frac{V_c}{E_0} \sqrt{\beta_{x,c} \beta_x^*}$$

$$\bar{x} = x + \frac{\theta}{k} \sin(kz + \phi)$$

$$\bar{\delta} = \delta - \theta p_x \cos(kz + \phi)$$

Weak-strong beam-beam simulation with the crab cavity

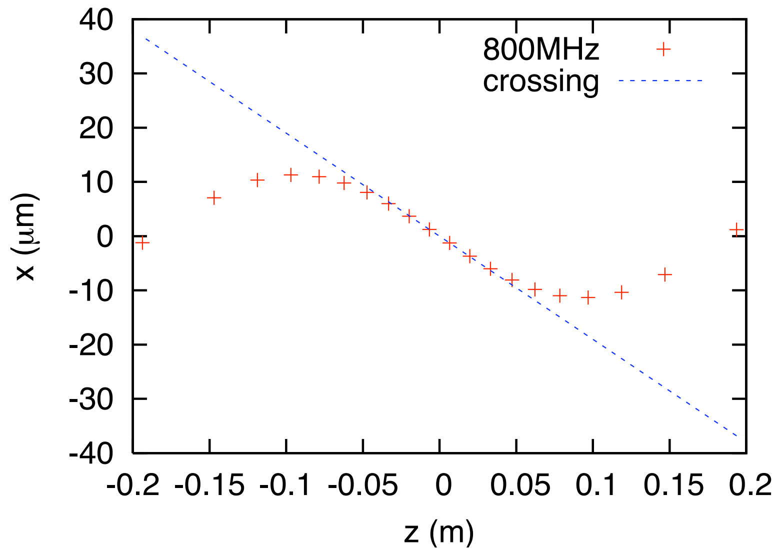
- Weak beam is transferred with H_c.
- Beam envelope of the strong beam is sliced in longitudinal direction.

$$R_{ij} = \left\langle x_i x_j \right\rangle_c$$

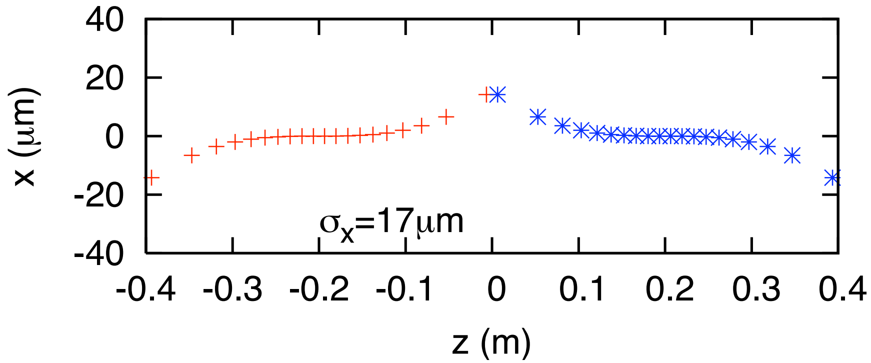
- 4x4 beam envelope is kept, but the dipole moment is

$$\left\langle x(z) \right\rangle = \frac{\theta}{k} \sin(kz + \phi)$$

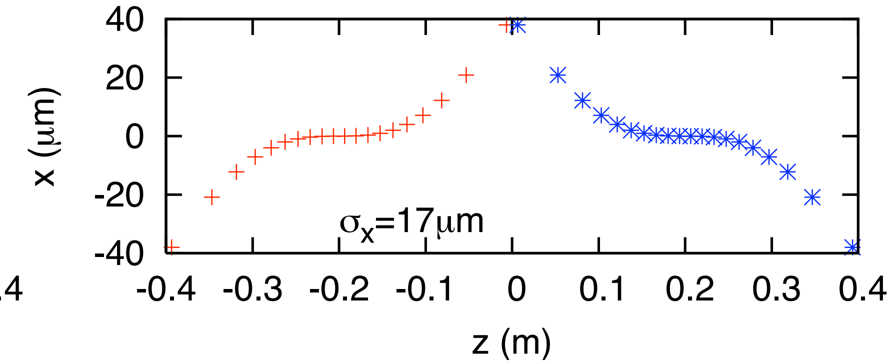
Crab kick for two frequencies



400 MHz

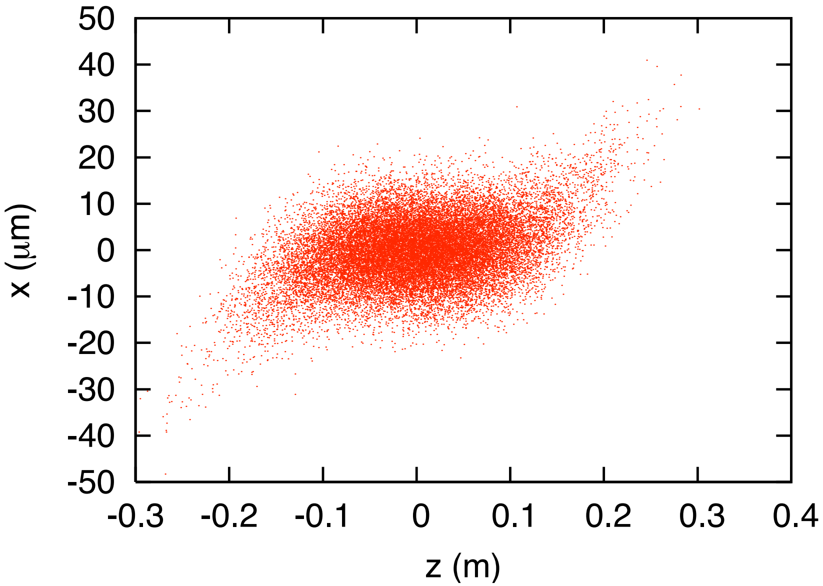


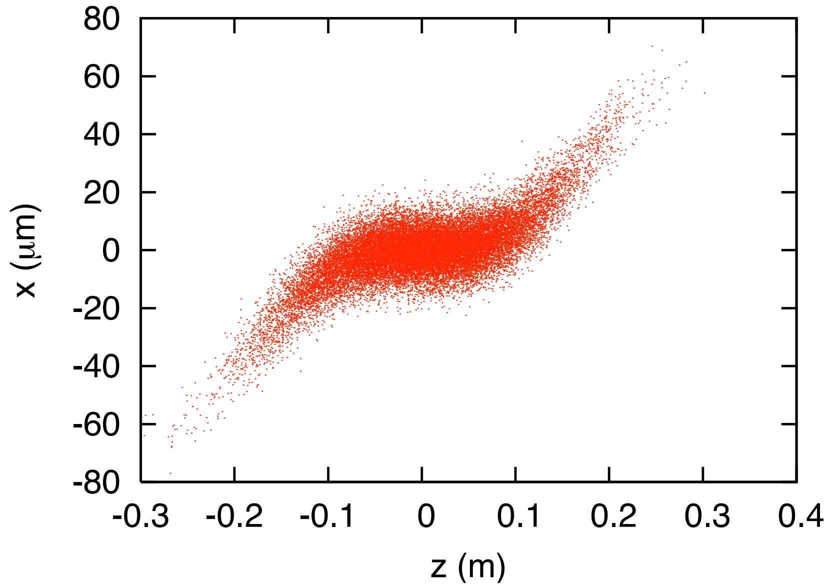
800 MHz



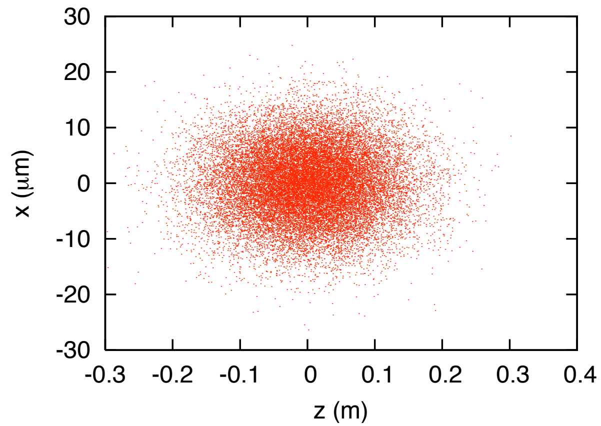
Beam distribution of the weak beam

- 400MHz 800MHz

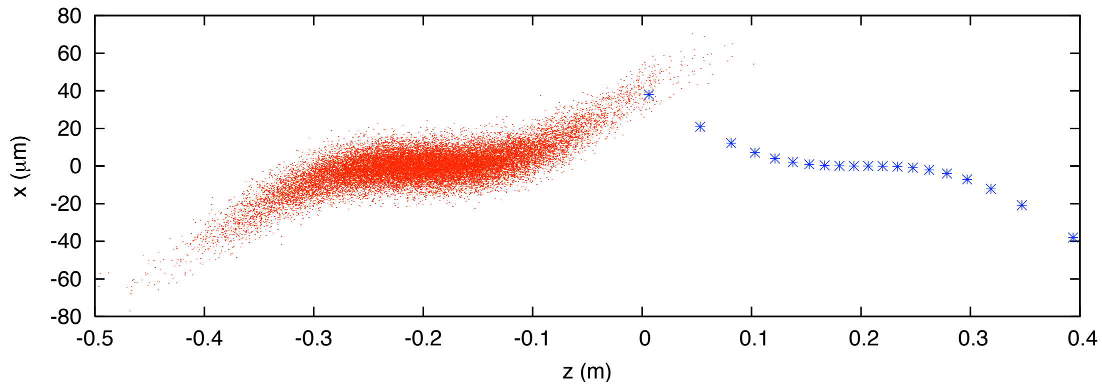




Outside of Crab cavity

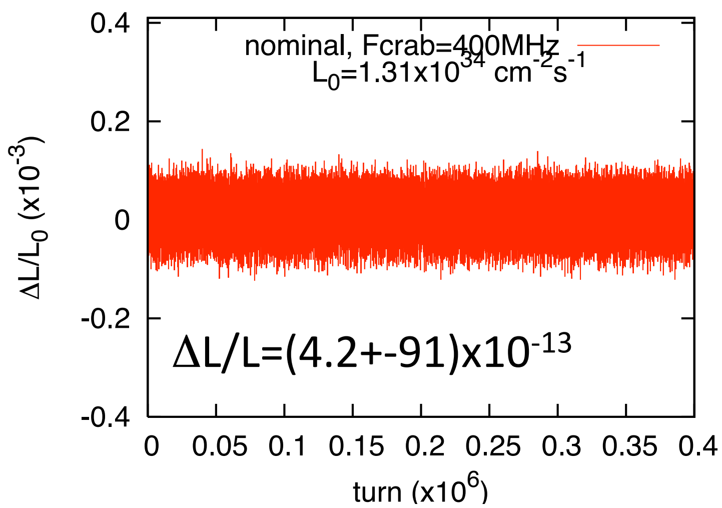


Simulation results of weak-strong

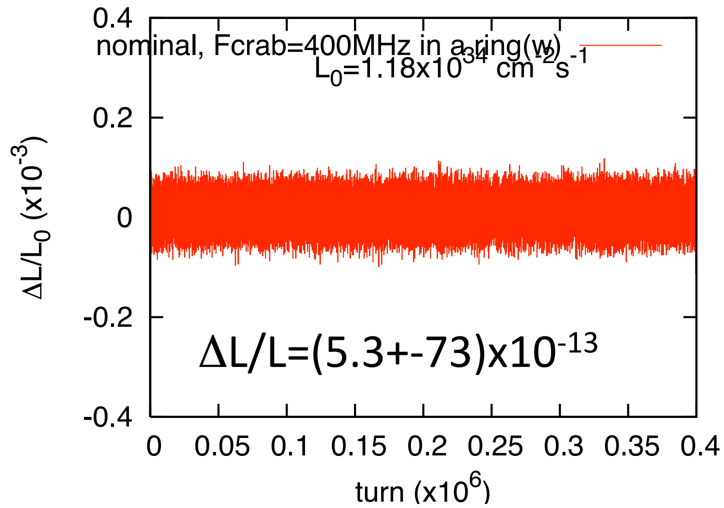


- Luminosity evolution for LHC nominal

2 crab

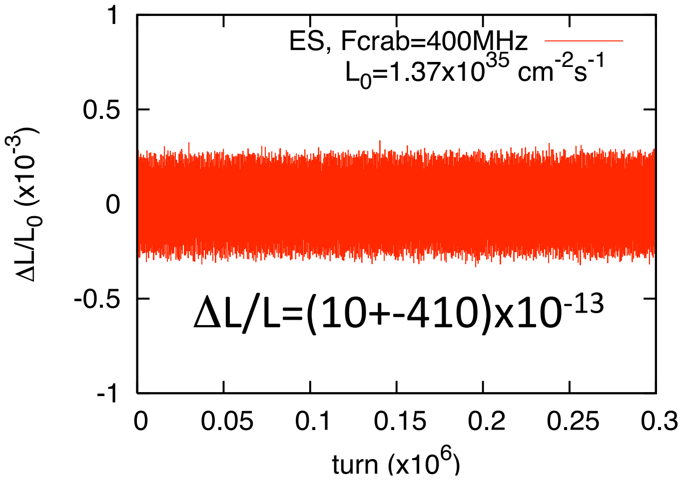


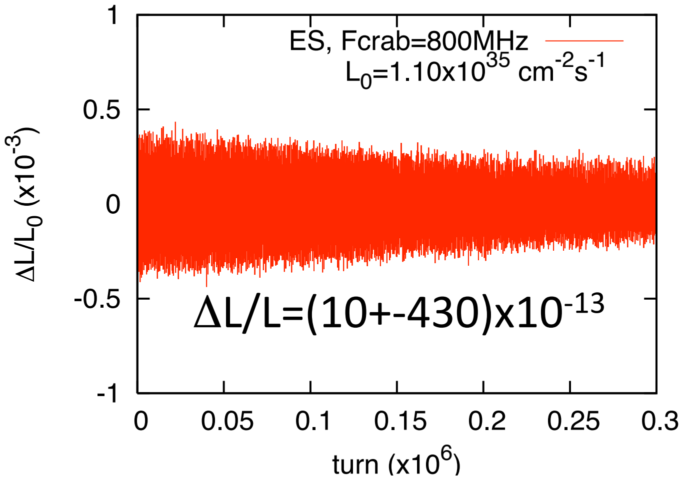
1 crab

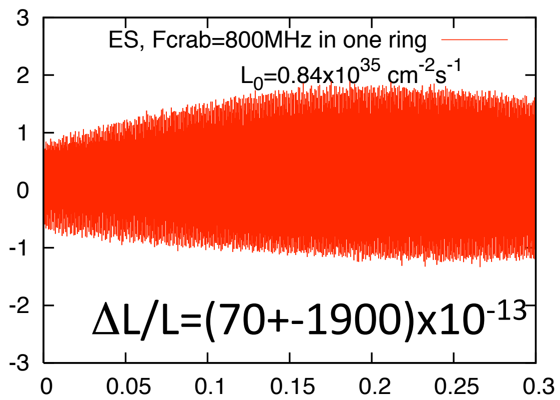


Simulation results of weak-strong

- Early Separation scheme
- Emittance growth is negligible $\Delta L/L_0<10^{-9}$.

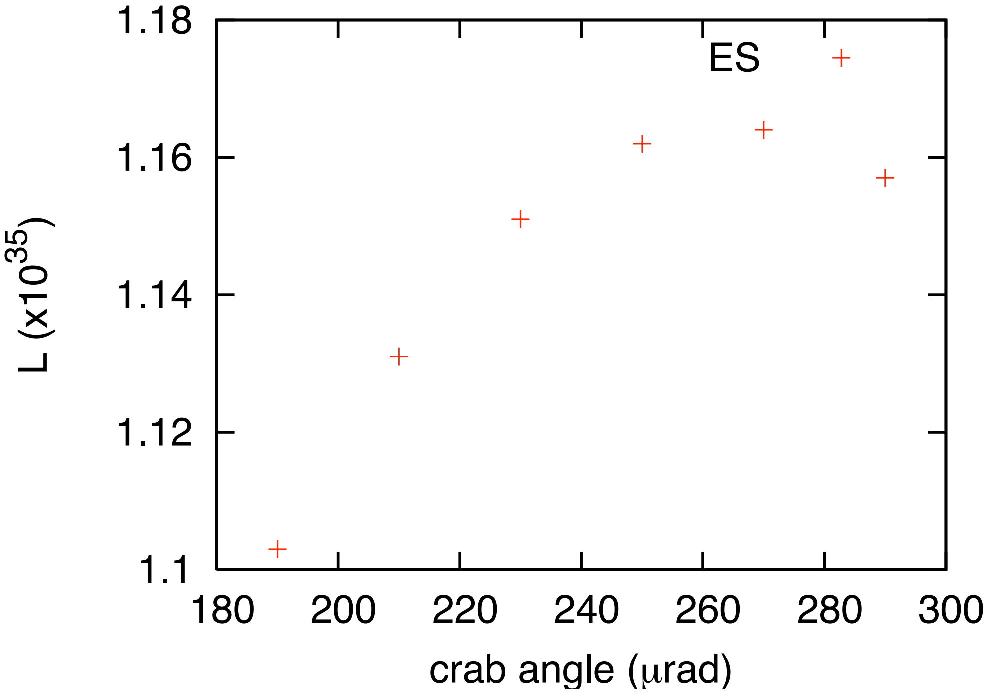




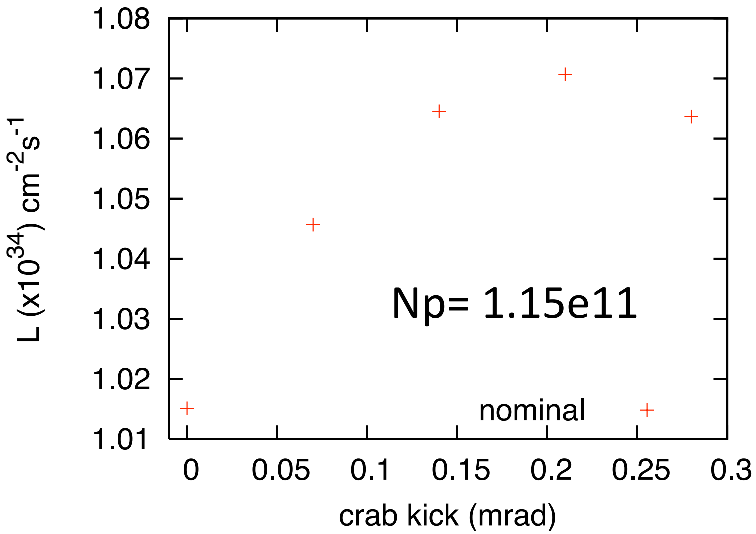


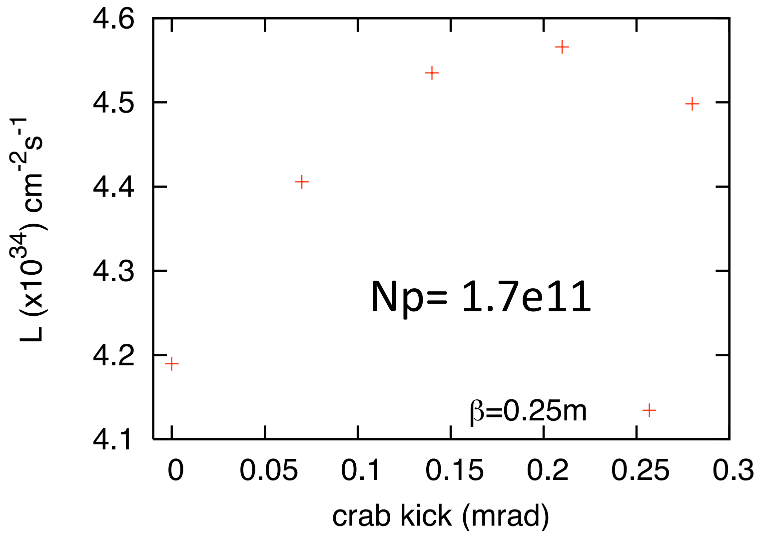
Luminosity for crab in Early Separation scheme

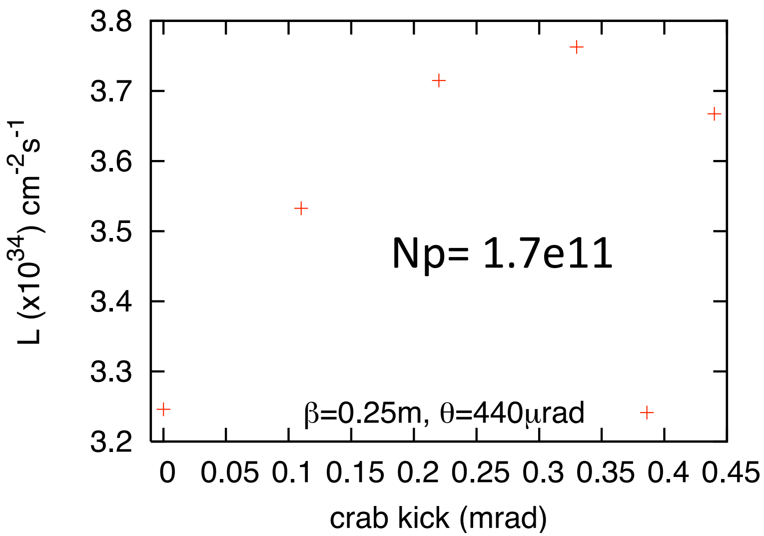
- L vs Crab angle (2 crab cavity)



Luminosity for single crab cavity







- nominal Np= 1.15e11, β=0.55m, θ=280 μrad
- upgrade Np=1.7e11, β=0.25m, θ=280 μrad
- upgrade Np=1.7e11, β=0.25m, θ=440 μrad

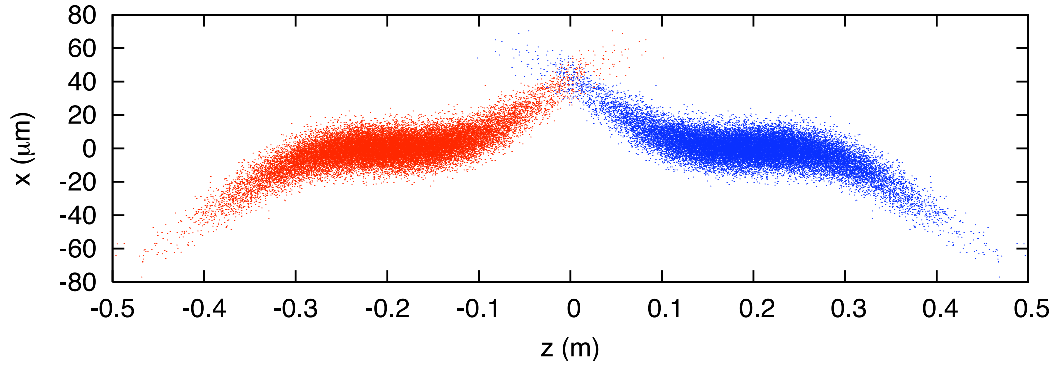
Strong-strong simulation

- Both beams are transferred with

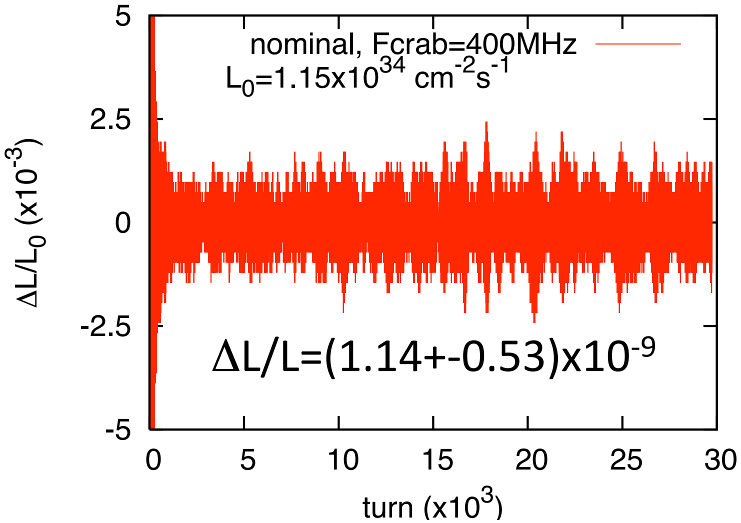
$$H_c = \frac{\theta}{k} p_x \sin(kz + \phi)$$

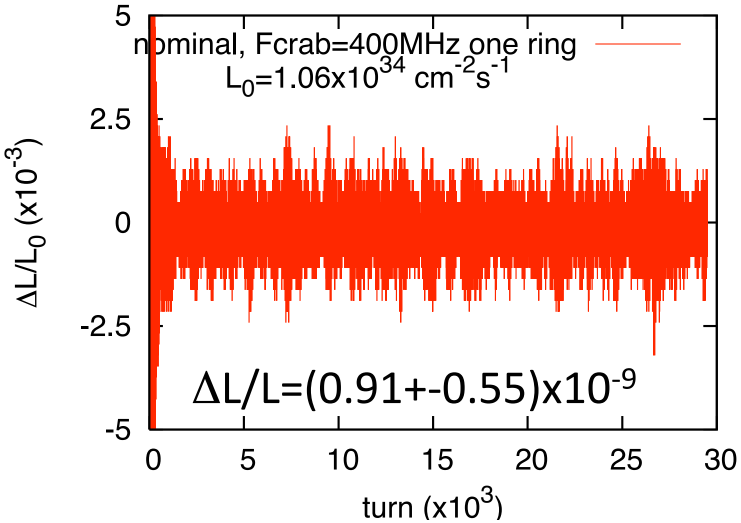
- A bunch is sliced into 10 parts. Sliced beam interacts with another sliced beam 10x10 times in one collision.
- Number of revolutions is limited in the strong-strong simulation, 30000 turns.

Simulation results (strong-strong)



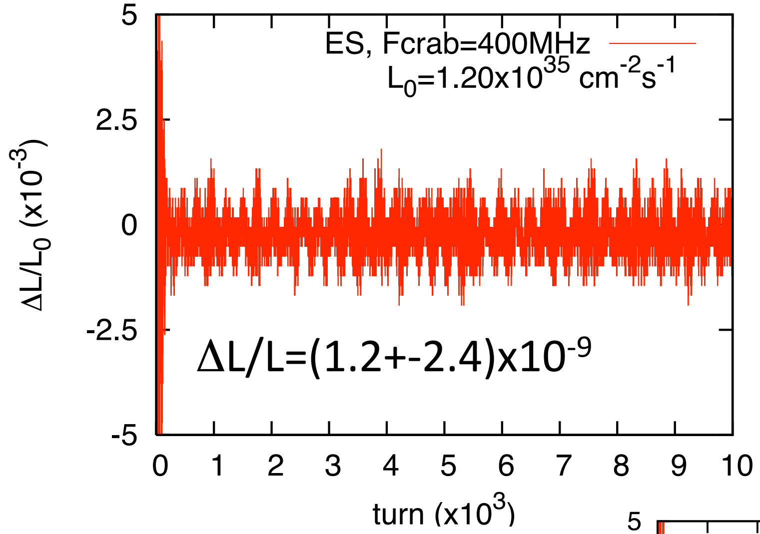
- Luminosity evolution for nominal LHC

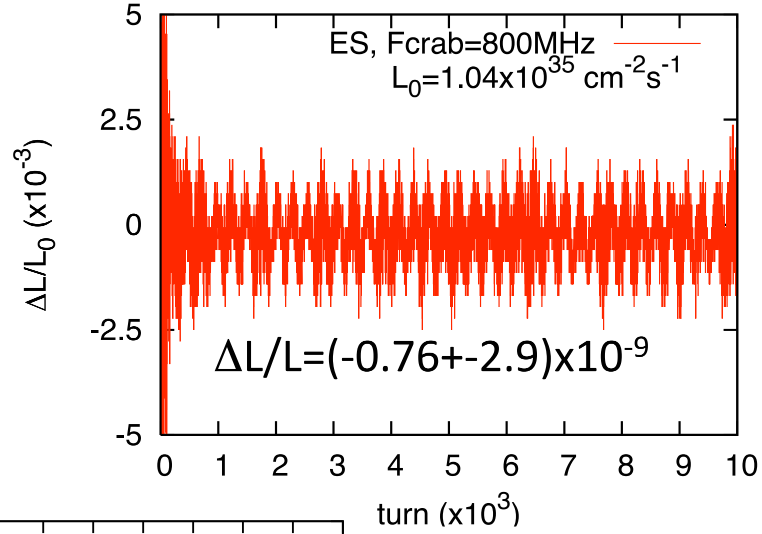


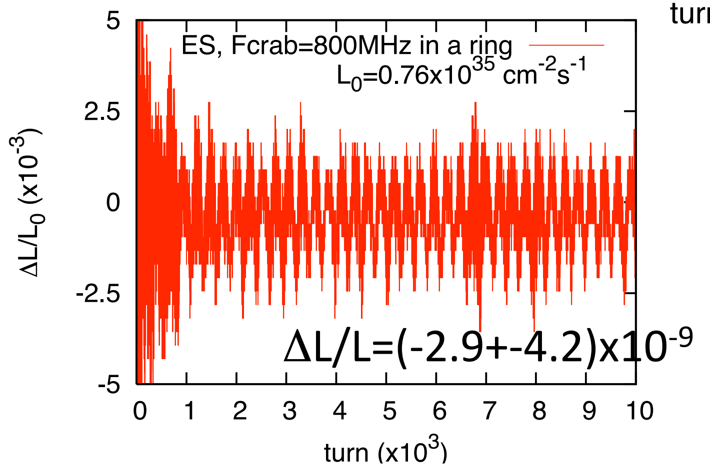


Simulation results (strong-strong)

- Early Separation scheme

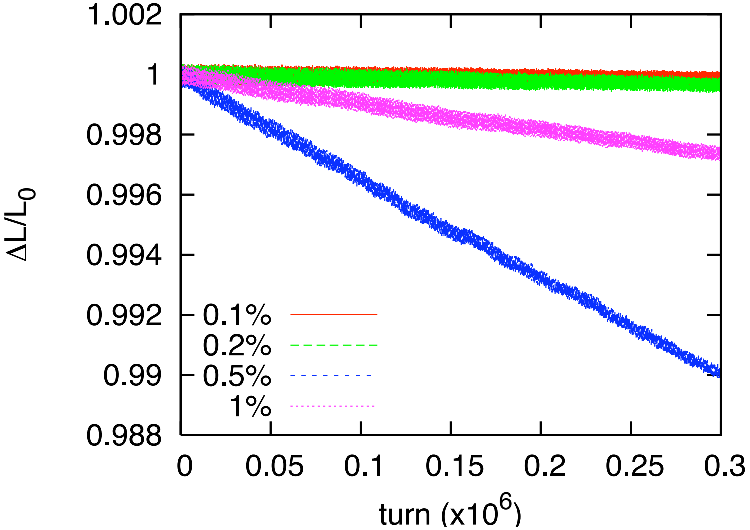


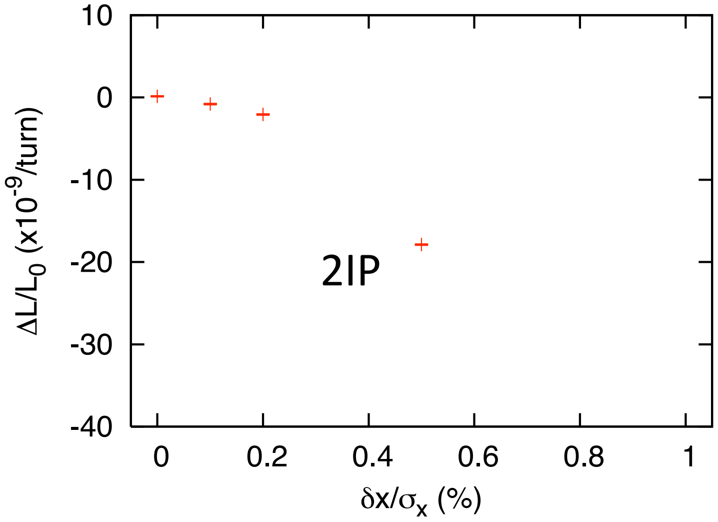




Tolerance for fast noise weak-strong

- For 800 MHz crab cavity, 0.1% noise is limit.



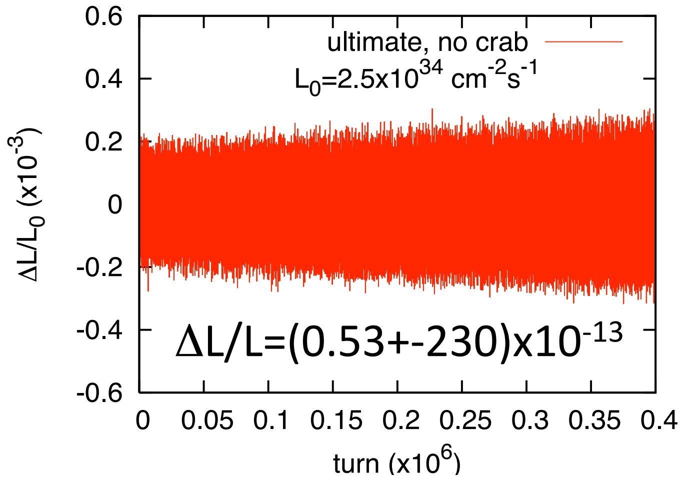


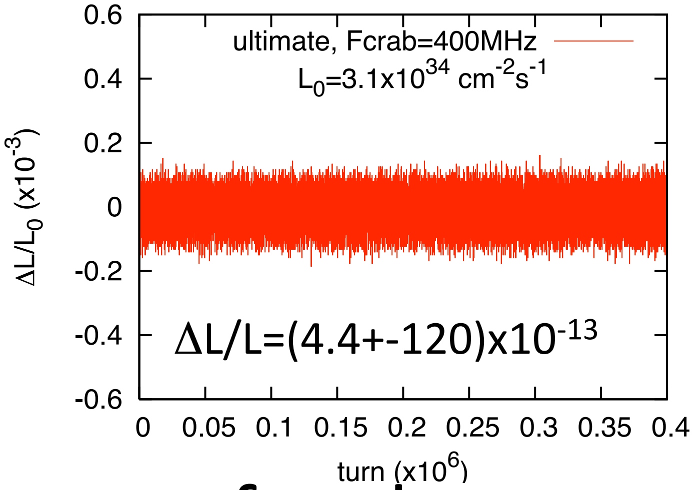
- The tolerance is a little severe than LPA. Considering the higher beam-beam parameter, it is reasonable.

Summary

- Any problem was not found in both of LPA and crab cavity schemes even high crab cavity frequency, 800 MHz.
- Only geometric effects are seen in these simulations for the design population.
- Tolerance for fast noise is similar level as the nominal LHC (~0.1%).

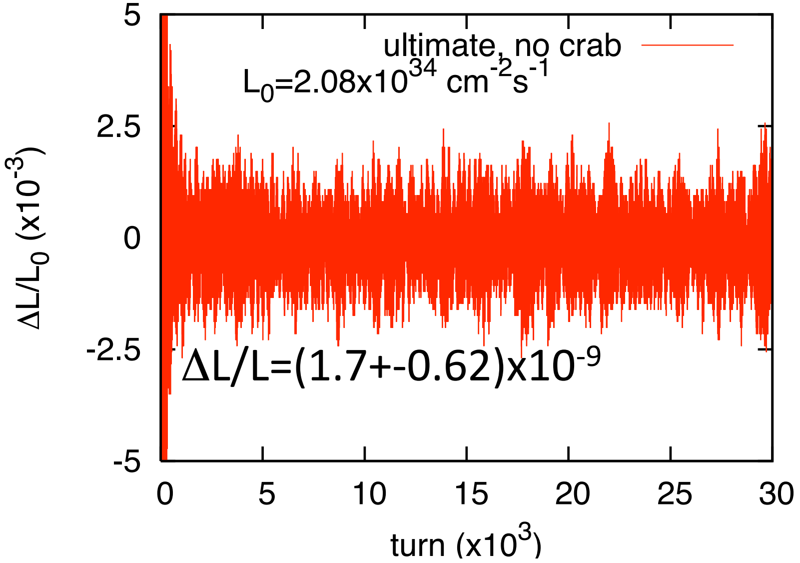
- Ultimate



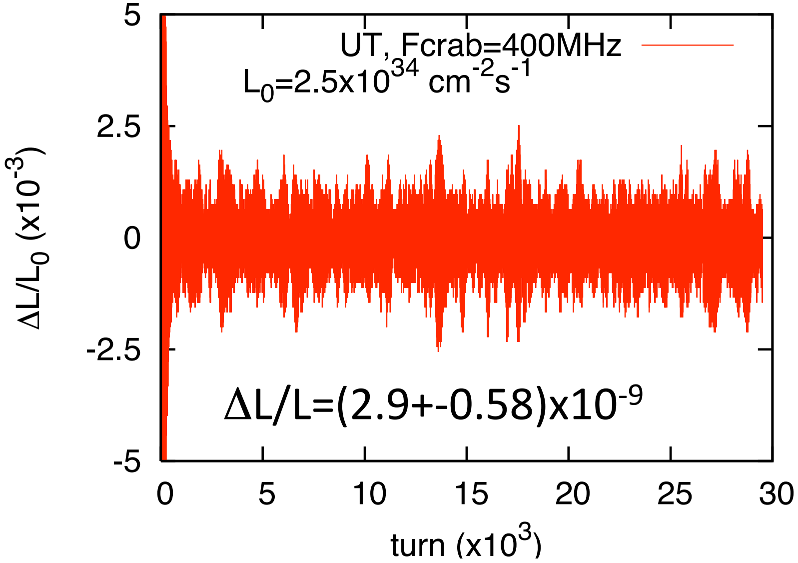


- The luminosity decrements for al cases are very small in the weak-strong simulation.

- Ultimate



ultimate, no crab
L0=2.08x10^34 cm^-2s^-1
ΔL/L=(1.7+-0.62)x10^-9
ΔL/L0 (x10^-3)
turn (x10^3)



UT, Fcrab=400MHz
L0=2.5x10^34 cm^-2s^-1
ΔL/L=(2.9+-0.58)x10^-9
ΔL/L0 (x10^-3)
turn (x10^3)

Local crab or global crab

- Local crab

$$\exp(-:H_{bb}:)e^{-:H_c:}e^{-:H_{arc}:}e^{:H_c:}$$

$$e^{:H_c:}\exp(-:H_{bb}:)e^{-:H_c:}$$

- Global crab

$$e^{-:H_c:}e^{-:H_{arc}:}e^{:H_c:} = e^{-:H_c:}e^{:\exp(-:H_{arc}:)H_c:}e^{-:H_{arc}:}$$