Large Piwinski angle and crab waist scheme in LHC

K. Ohmi, KEK
CARE-HHH, LHC beam-beam and beam-beam compensation
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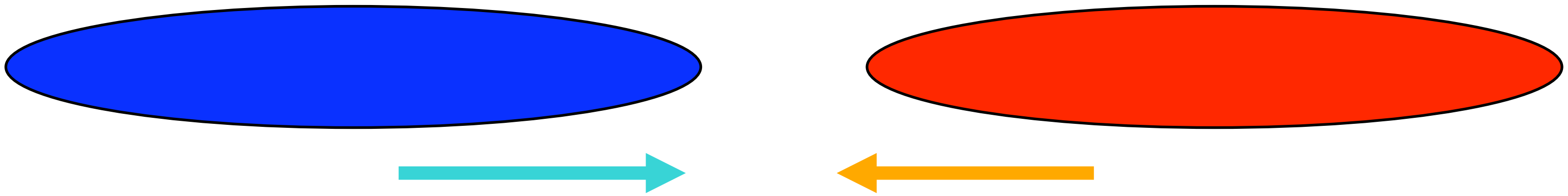
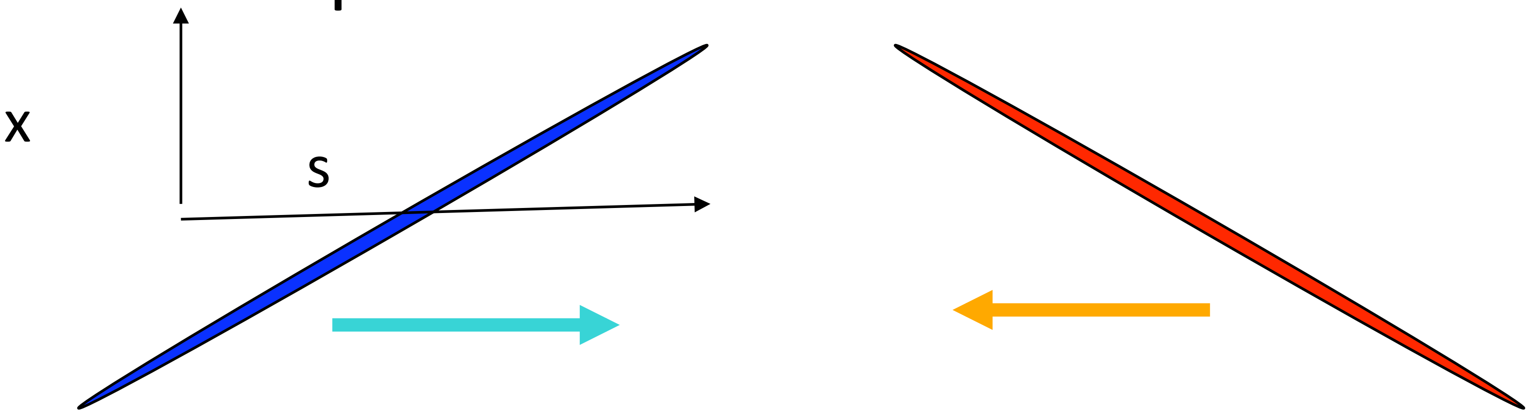
Two approach toward high luminosity in e^+e^- colliders

- High current, high beam-beam parameter.



- Low emittance, low beta, low current, so-called super bunch collision



Tune shift

Short bunch

$$\frac{\sqrt{\varepsilon_x \beta_x}}{\theta_h \sigma_z} \geq 1$$

$$L \sim \frac{N^2}{\sqrt{\varepsilon_x \beta_x \varepsilon_y \beta_y}} \sim \frac{N \xi_y}{\beta_y}$$

$$\xi_x \sim \frac{N}{\varepsilon_x}$$

$$\xi_y \sim N \sqrt{\frac{\beta_y}{\varepsilon_x \beta_x \varepsilon_y}}$$

$$\beta_y > \sigma_z$$

Super-bunch(LPA)

$$\frac{\sqrt{\varepsilon_x \beta_x}}{\theta_h \sigma_z} < 1$$

$$L \sim \frac{N^2}{\theta_h \sigma_z \sqrt{\varepsilon_y \beta_y}} \sim \frac{N \xi_y}{\beta_y}$$

$$\xi_x \sim \frac{N \beta_x}{\theta_h^2 \sigma_z^2}$$

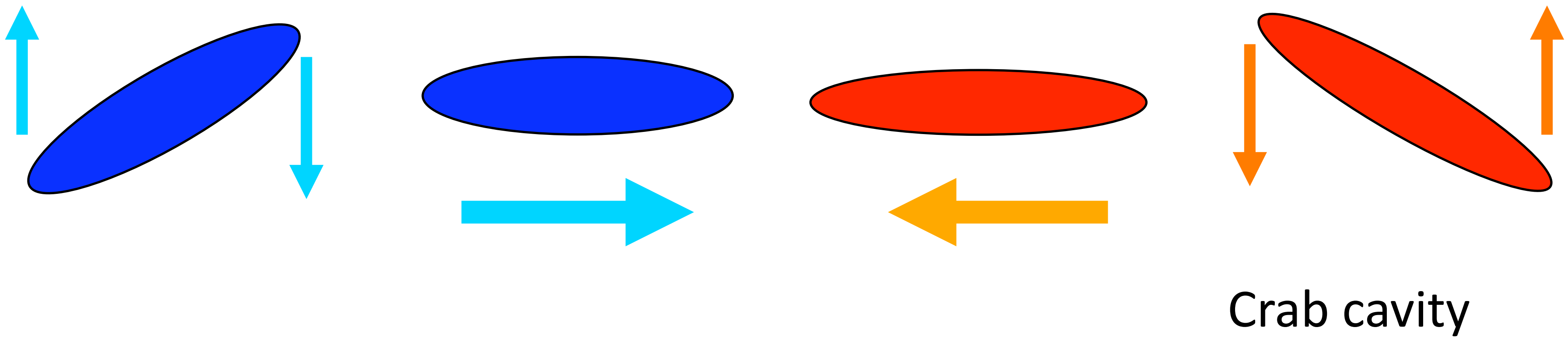
$$\xi_y \sim \frac{N}{\theta_h \sigma_z} \sqrt{\frac{\beta_y}{\varepsilon_y}}$$

$$\beta_y > \frac{\sqrt{\varepsilon_x \beta_x}}{\theta_h}$$

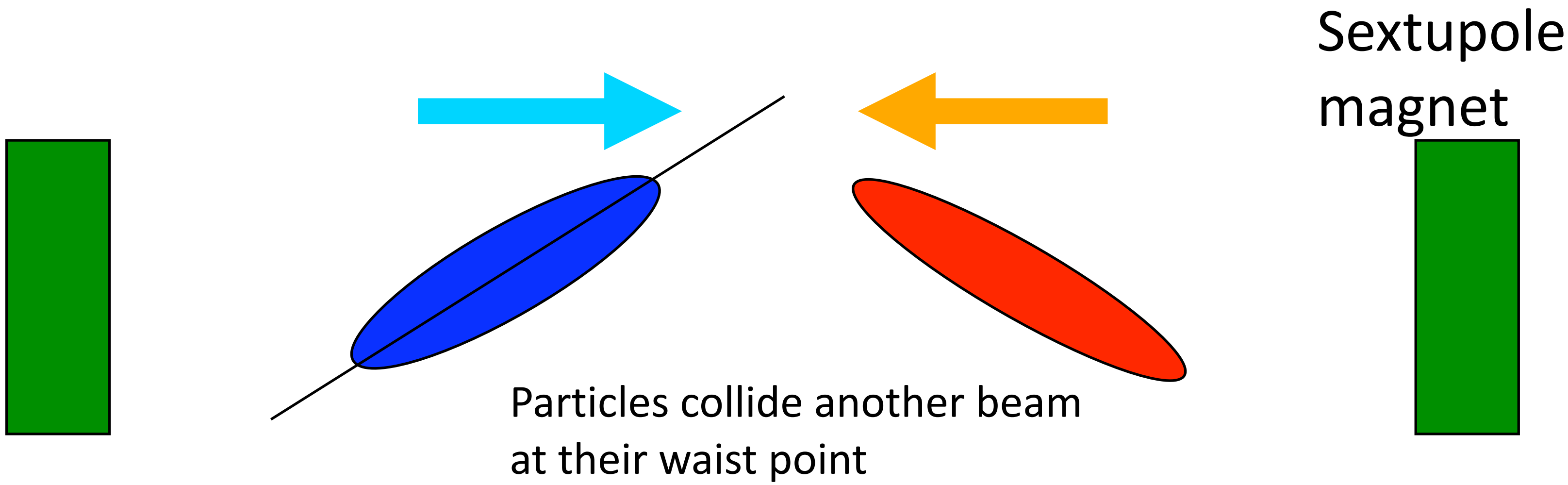
Super B

	SuperKEKB	Middle	SuperB (LNF/SLAC)
εx	9.00E-09	6.00E-09	0.8E-09
εy	4.50E-11	6.00E-11	2E-12
βx (mm)	200	50	9
βy (mm)	3	0.5	0.133
σz (mm)	3	6	6
νs	0.025	0.01	0.012/0.026
ne	5.50E+10	5.50E+10	1.9E+10
np	1.26E+11	1.27E+11	3.3E+10
$\theta/2$ (mrad)	0	15	25
ξx	0.397	0.022	
ξy	0.794->0.24	0.179	
Lum (W.S.)	8E+35	1.00E+36	1.00E+36
Lum (S.S.)	8.25E35	8-9E35	

- Crab crossing



- Crab waist



Crab waist

- Add sextupole magnets at both side of collision point for finite crossing collsion.
- Effective potential is expressed as follows,

  $U(x,y,z)\delta(s-s^*)+Kxp_y^2\delta(s-s^*-\varepsilon)-Kxp_y^2\delta(s-s^*+\varepsilon)$

Put sextupole magnets both side of the collision point at the vertical betatron phase difference, $\pi(2n+1)/2$ and horizontal $m\pi$.

Crab waist scheme (P. Raimondi et al.)

$$\mathbf{M} = e^{-:H_I:}\mathbf{M}_0 e^{:H_I:}$$

$$H_I = \frac{a}{2} x p_y^2$$

$$\overline{y} = y + \frac{\partial H_I}{\partial P_y} = y + axP_y \qquad \overline{p_x} = p_x - \frac{\partial H}{\partial x} = p_x - ap_y^2$$

- Take linear part for y, since x is constant during collision.

$$\begin{pmatrix} \overline{\beta} & -\overline{\alpha} \\ -\overline{\alpha} & \overline{\gamma} \end{pmatrix} = T \begin{pmatrix} \beta & -\alpha \\ -\alpha & \gamma \end{pmatrix} T^t = \begin{pmatrix} \beta + \frac{a^2 x^2}{\beta} & \frac{ax}{\beta} \\ \frac{ax}{\beta} & \frac{1}{\beta} \end{pmatrix}$$

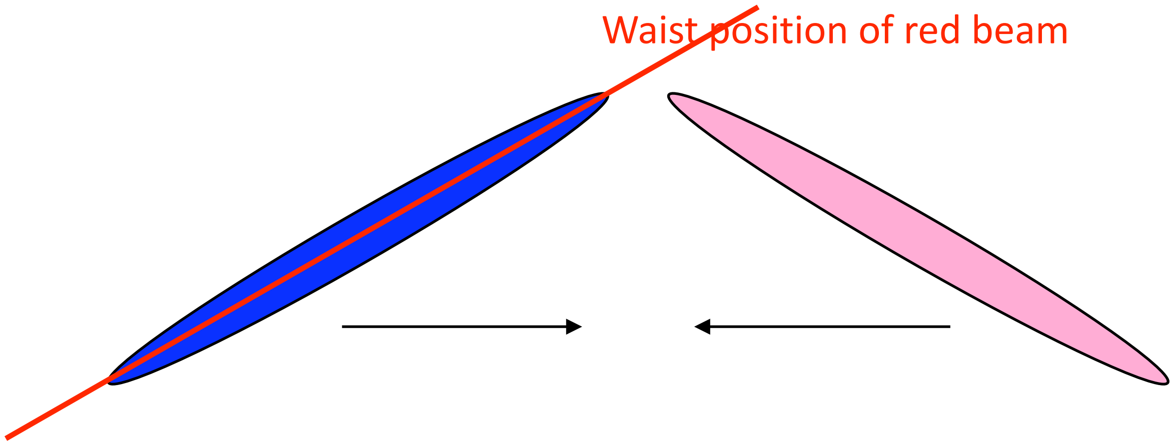
$$T = \begin{pmatrix} 1 & ax \\ 0 & 1 \end{pmatrix}$$

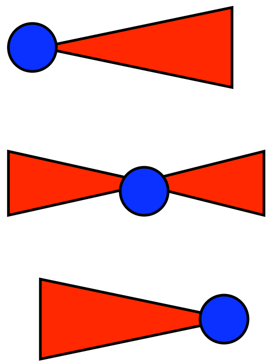
$$M(s)\begin{pmatrix} \beta+\dfrac{a^2x^2}{\beta} & \dfrac{ax}{\beta} \\ \dfrac{ax}{\beta} & \dfrac{1}{\beta} \end{pmatrix} M^t(s) = \begin{pmatrix} \beta+\dfrac{(s+ax)^2}{\beta} & \dfrac{s+ax}{\beta} \\ \dfrac{s+ax}{\beta} & \dfrac{1}{\beta} \end{pmatrix}$$

β waist is shifted to s=-ax

Taking $a=1/2\theta_h$

- Beam particles with various x collides with other beam at their waist.



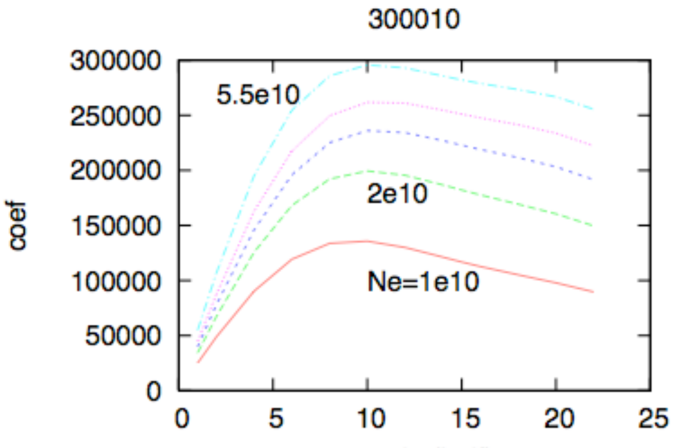


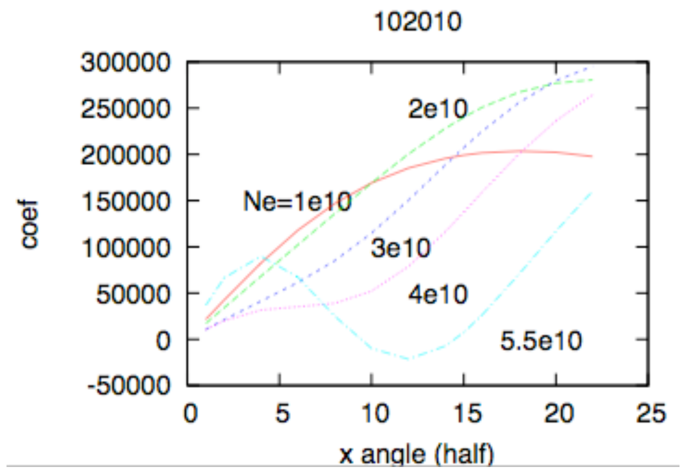
Beam shape is not Gaussian, but is like triangle at IP.

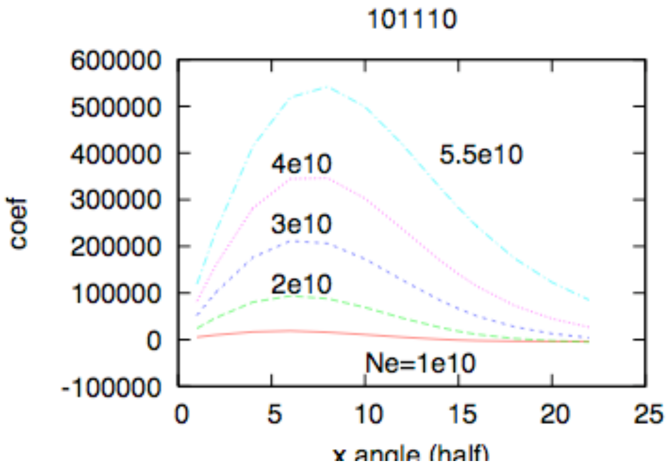
Beam shape on red beam frame

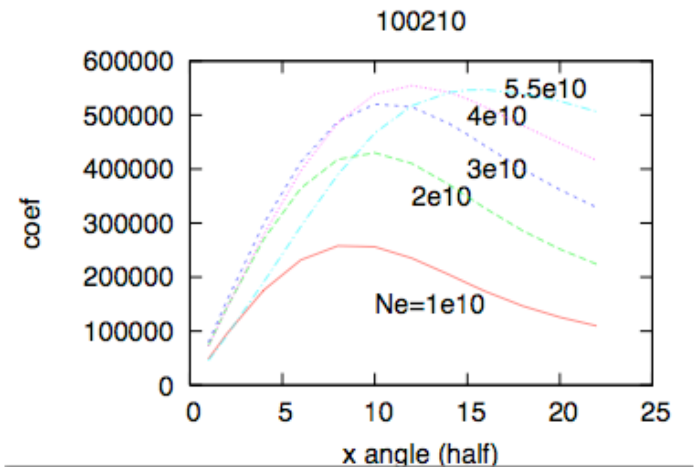
Taylor map analysis for KEKB

- Resonance line ν_x-2ν_y=k is effective for the beam-beam limit in e^+e^- colliders.

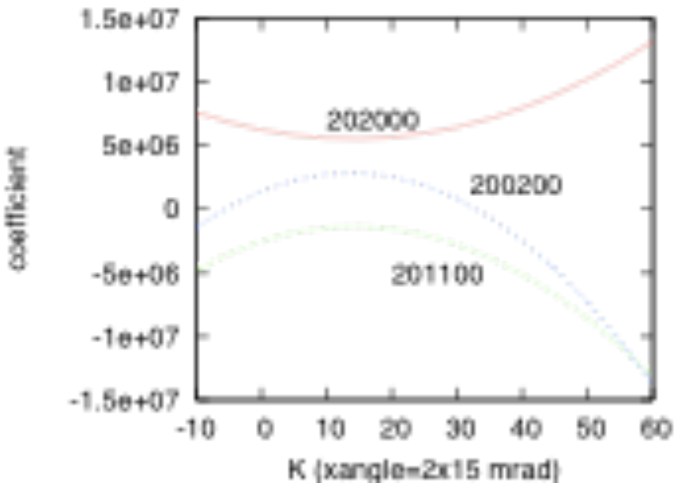


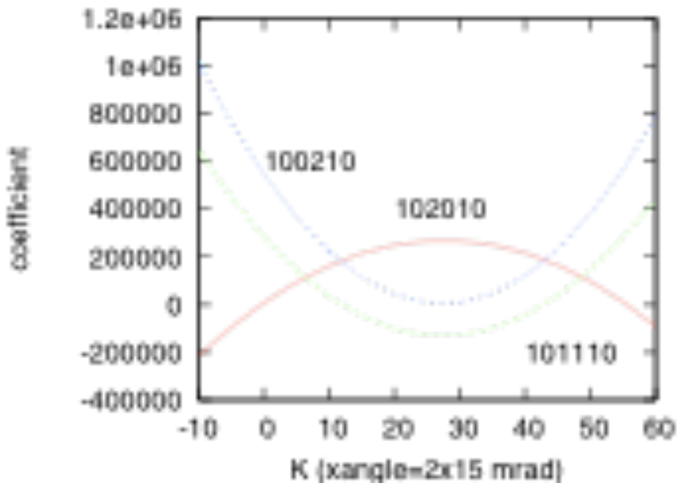


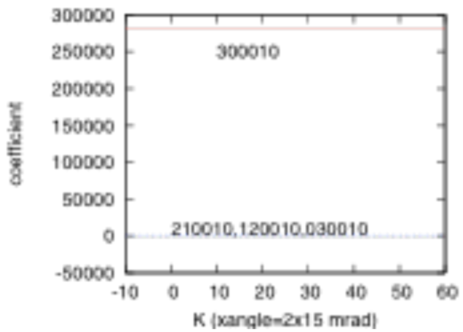


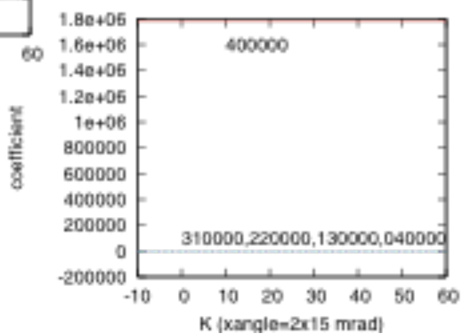


4-th order Coefficients as a function of crab sextupole strength, KEKB





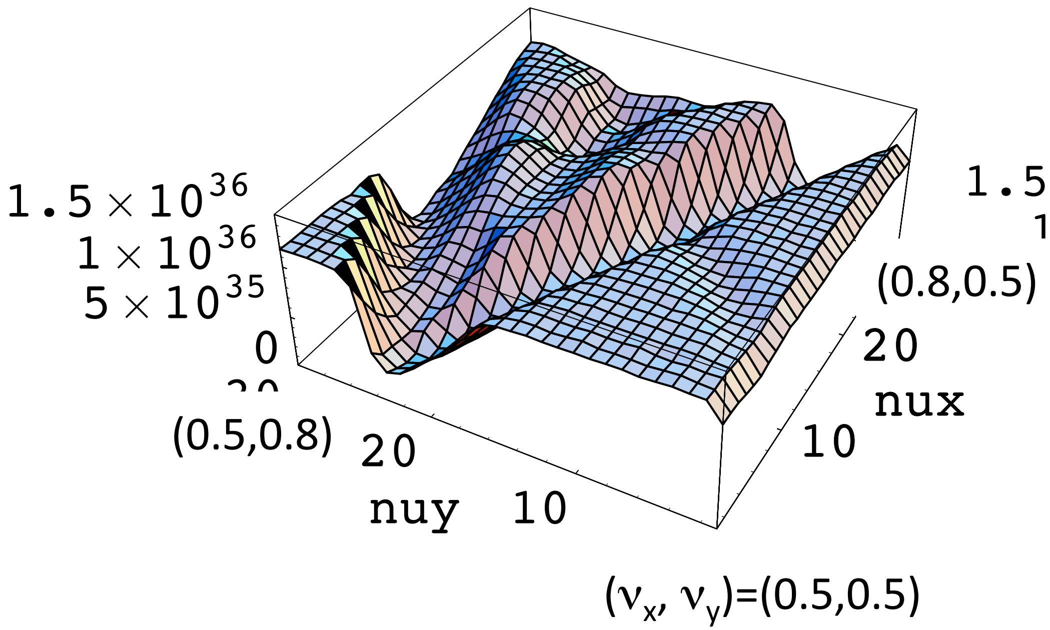


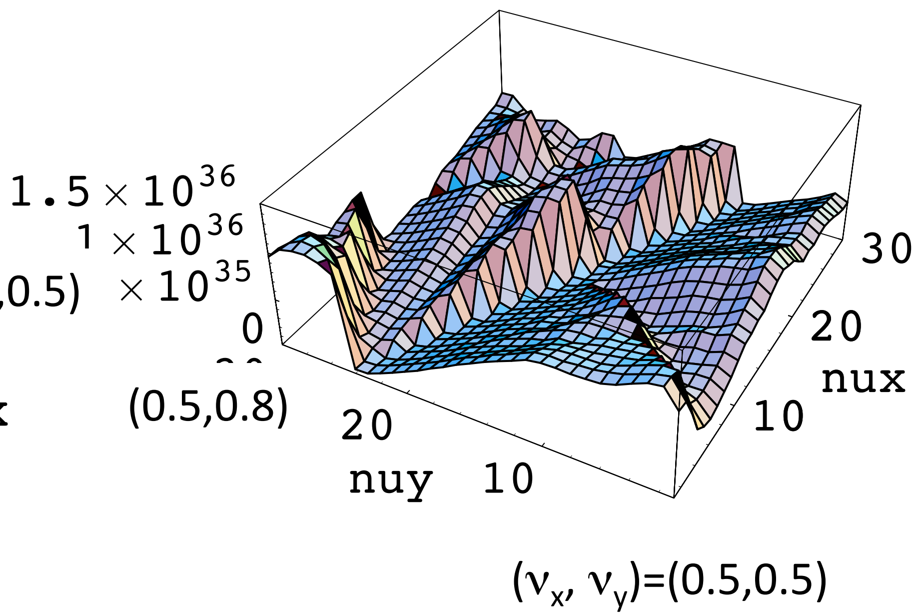


- $H=K \times p_y^2/2$, theoretical optimum, K=1/xangle.
- Clear structure- 220,121
- Flat for sextupole strength- 400, 301, 040

Tune scan of luminosity for super B

- Crab waist ON　　　　　　　　　　OFF





A simple picture of the crab waist

$$H_I = \frac{a}{2} x p_y^2$$

$$y(s) = y_0 + axp_y + p_y s \approx axp_y + p_y s \qquad \beta_y << \sigma_z$$

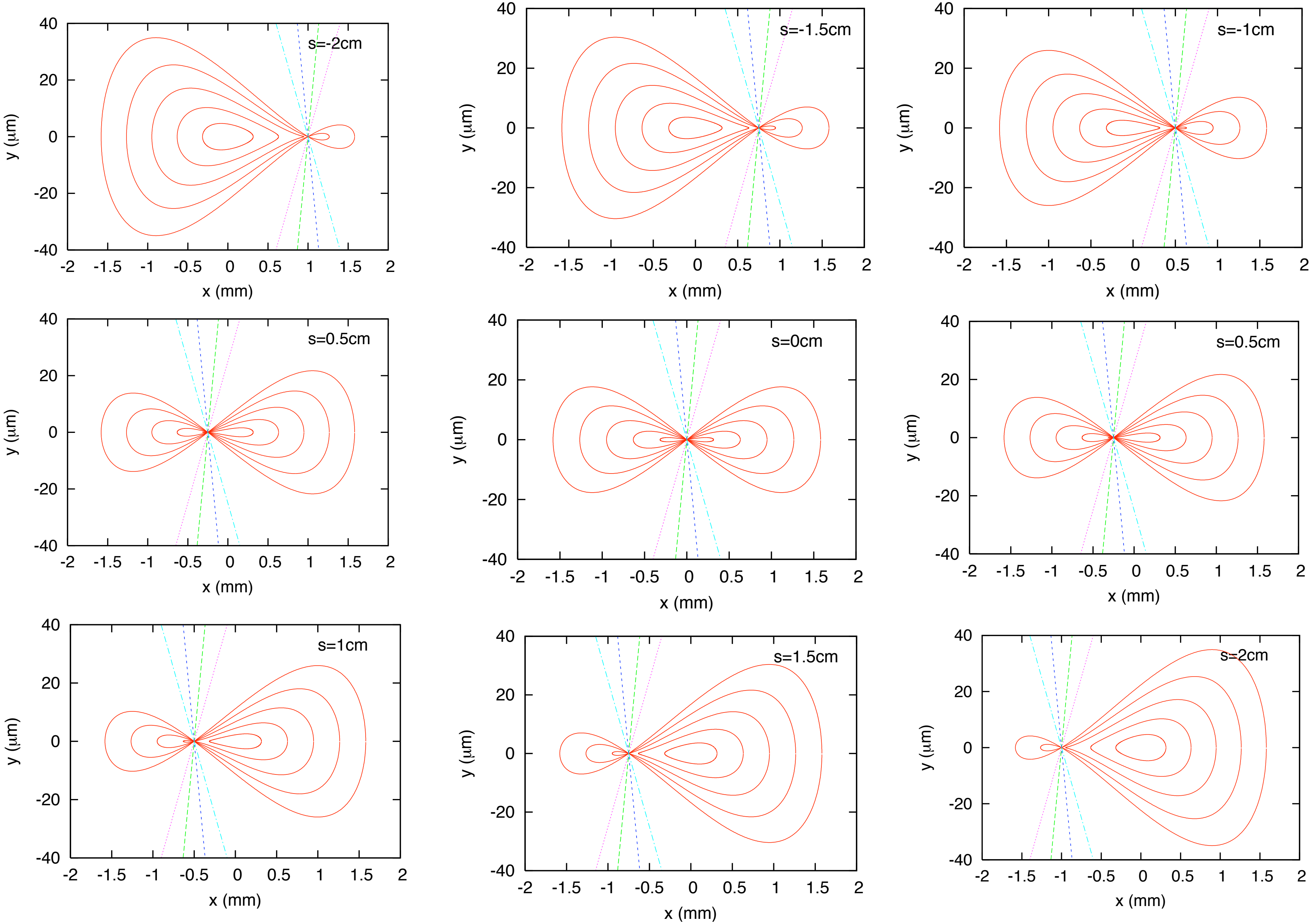
$$x(s) = x_0 + p_x s \approx x_0 \qquad \beta_x > \sigma_z$$

- The distribution is Gaussian for x_0 and p_{y0}.
- Non-Gaussian distribution for x(s),y(s).
- $y(s)=y_0$ for

$$a = -\frac{s}{x} = -\frac{1}{2\theta_h}$$

s independent because of $x=s\theta_h$

Beam distribution at s



Strength of Crab waist sextupole

- Sextuples are located a position where the betatron phase difference is $n\pi$ and $(n+1/2)\pi$ for horizontal and vertical, respectively. The strength is

$$K_2 = \frac{B''L}{p/e} = \frac{1}{2\theta_h}\frac{1}{\beta_y\beta_y^*}\sqrt{\frac{\beta_x^*}{\beta_x}}$$

- For LHC, $\beta_x=\beta_y=2000$m, $\beta_x^*=\beta_y^*=0.25$m and $\theta_h=140\mu$rad, $K_2=0.08$.
- This value is not very large, since the strength of the normal sextupoles

$$|K_2| = \left|\frac{B''L}{B\rho}\right| \approx 0.05$$

Crab waist scheme at LHC

- The waist position can be shifted along the axis of the colliding beam. However the gain is week for $\beta_{xy}>\sigma_z$.
- Betatron phase of x and y varies simultaneously in the round beam.

Possible condition for crab waist in LHC

An example

- ϕ=3.5 in LPA option. β_y can be squeezed to σ_x/ϕ=2.1cm. L increases $(14/2.1)^{1/2}$=2.6 times. ξ_y decreases and ξ_x is small for LPA.
- Crab waist has an opportunity to work.

Another possibility

Waist control for parasitic collision

- Betatron phase of beam particles rotate ~π/2 at parasitic collision points.

$$H = \frac{a}{6} p_x^3 + \frac{b}{2} p_x p_y^2$$

$$\beta_y << s$$

$$x(s) = x_0 + \frac{a}{2} p_x^2 + \frac{b}{2} p_y^2 + p_x s$$

$$y(s) = y_0 + b p_x p_y + p_y s$$

- The distribution is Gaussian for p_x and p_y.
- Non-Gaussian distribution for x(s) and y(s).
- Choosing a and b, beam distribution can be distorted at parasitic collision points.

- $x(s)=x_0$
- $y(s)=y_0$

$$\frac{a}{2}p_x^2 + \frac{b}{2}p_y^2 + p_x s = 0 \qquad a = -\frac{2s}{p_x} - b\frac{p_y^2}{p_x^2}$$

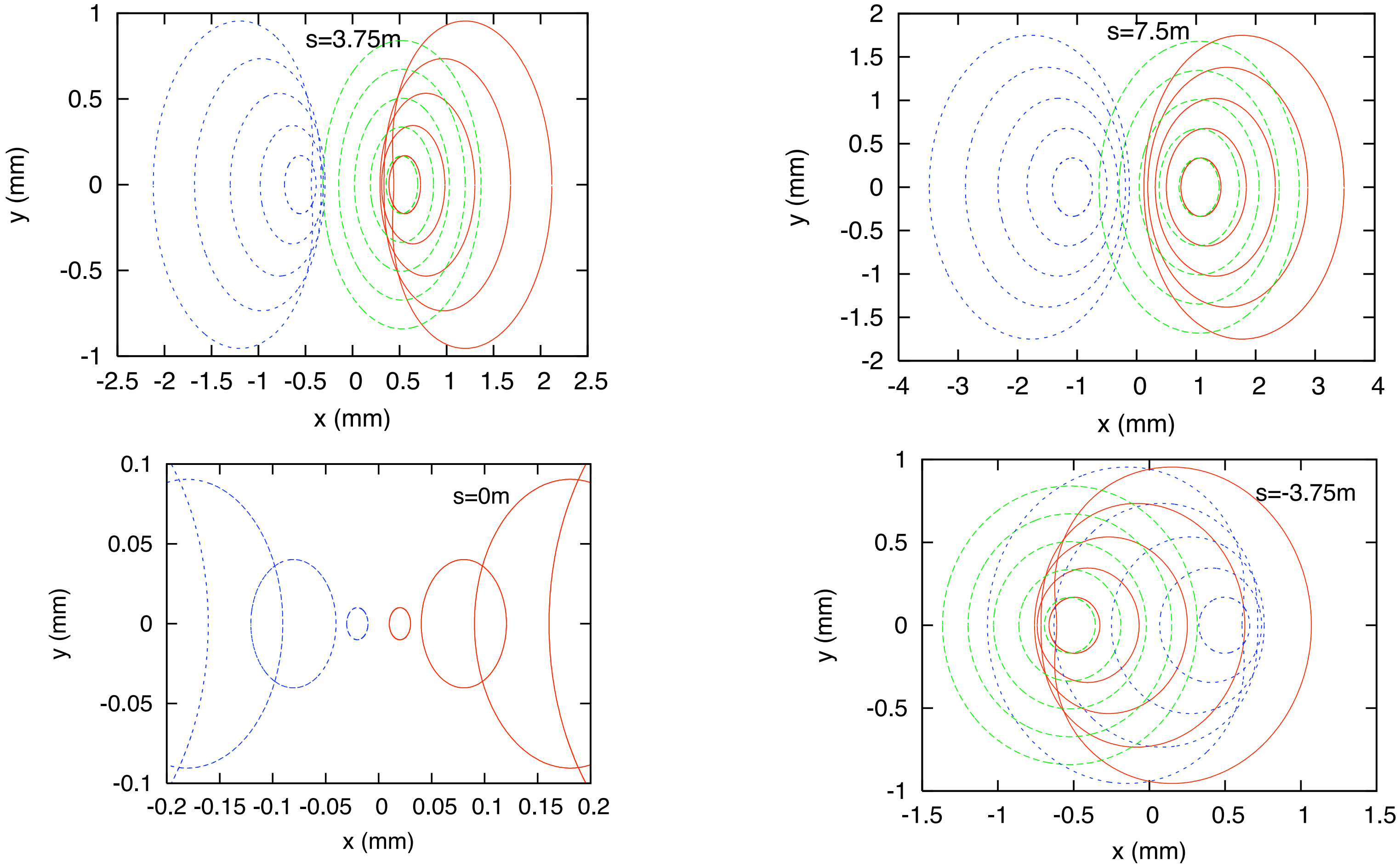
$$b p_x p_y + p_y s = 0 \qquad b = -\frac{s}{p_x}\left(= -\frac{s}{2\theta}\right)$$

- $p_x=1/2\theta$ for parasitic encounter.
- The condition is s dependent and coupled for x and y.
- For s=>-s, the condition break.

- But this is Garbage idea.

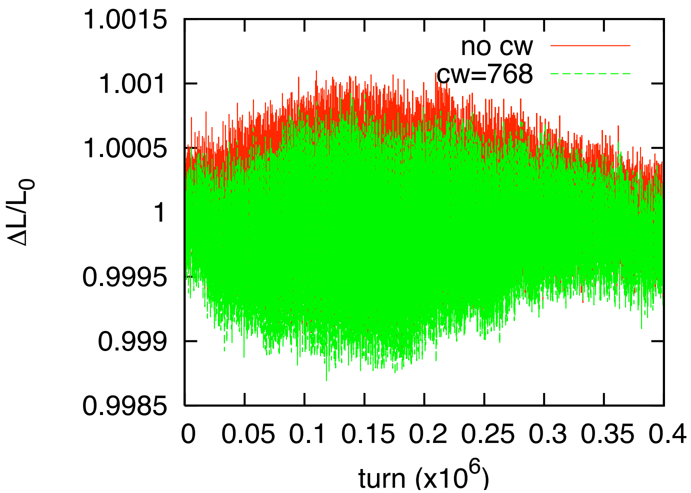
β=0.25m, 140μrad

- a=30000, b=10000. Sorry for showing garbage.



Crab waist in the nominal and upgrade LHC

- Crab waist sextupoles may have some effects on halo in nominal or upgrade LHC.
- In the beam intensity, the effects are not seen.
- The effects in higher intensity ($Np=10^{12}$) is investigated.



Large Piwinski Angle scheme

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

- For a target Luminosity, there are choices for keeping ξ, β and I.
- For example, increasing Piwinski (crossing) angle and bunch population can keep ξ. To keep I, bunch repetition is decreased.
- This is gain for avoiding parasitic interaction depending on arrangement of separation magnet and wires.

LPA or crab cavity scheme

- For $\sigma_z<\beta_{xy}$, both scheme seems to be compatible.
- Crab waist scheme works well for $\sigma_z>\beta_y$.
- Crab cavity installed in LPA scheme can deliver the same or more luminosity. If the beam-beam parameter becomes too high due to the crab cavity, the bunch population is decreased.
- Luminosity leveling.

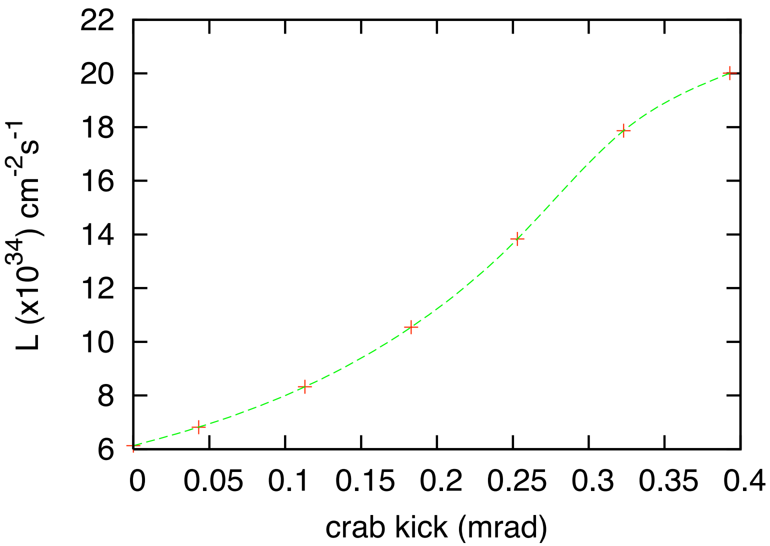
F. Zimmermann, PAC07, J.P. Koutchek, EPAC08

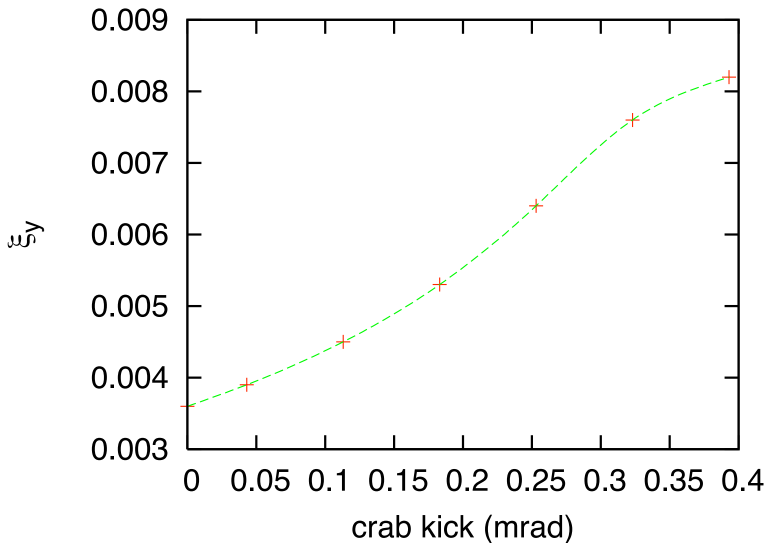
Table 1: Parameters for the (1) nominal and (2) ultimate LHC compared with those for three upgrade scenarios with (3) shorter bunches at 12.5-ns spacing [old baseline], (4) more strongly focused ultimate bunches with early separation at 25-ns spacing [ES], (5) longer intense flat bunches at 50-ns spacing 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	$\tau_{\rm L}$ [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	

Luminosity with crab cavity in LPA-II

- Luminosity and beam-beam parameter for LPA-II (393x2 μrad) with crab cavity





Summary

- We could not find good solution for the crab waist scheme in LHC yet.