Beam-Beam Effects for FCC-ee at Different Energies: Crab Waist vs. Head-on

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Beamstrahlung

Luminosity of high energy e+e- colliders is limited by beamstrahlung (radiation in the field of the opposing beam), because emission of single high energy photons in the tail of the beamstrahlung spectra determines the beam lifetime.
V.Telnov, PRL 110,114801 (2013)

The lifetime (due to beamstrahlung) is proportional to: $\tau_{bs} \sim \exp\left(\frac{2\eta\alpha\rho}{3r_e\gamma^2}\right)\cdot\frac{\rho^{3/2}}{L\gamma^2}$
where L is the interaction length, η - energy acceptance,
ρ - [average] bending radius of particle's trajectory at IP.

$\Downarrow$

η must be increased as much as possible (the goal: 2%)

At "high" energies (H, tt) we should increase ρ in order to keep acceptable lifetime. At "low" energies (Z, W) we can make ρ smaller, that is beneficial for luminosity. As a result, the relative contribution of beamstrahlung to the total energy spread (and bunch length) is larger at low energies.

The main impact of beamstrahlung on luminosity limit:

Low energies: bunch lengthening

High energies: beam lifetime

Luminosity

For flat beams (both head-on and crossing angle collision): $L = \frac{\gamma}{2er_e} \cdot \frac{I\xi_y}{\beta_y^*} \cdot H$

I – total beam current, defined by SR power of 50 MW

ξ_y – vertical betatron tune shift, its limit depends on the collision scheme

H – hour-glass factor: H ≈ [0.86, 0.7, 0.6] for σ_z / β_y^* = [1, 2, 3]

β_y^* should be minimized as much as possible, but there are some restrictions:

– beta-function at the final quads raises as $1/\beta_y^2$ that limits dynamic aperture and can create problems with chromaticity corrections

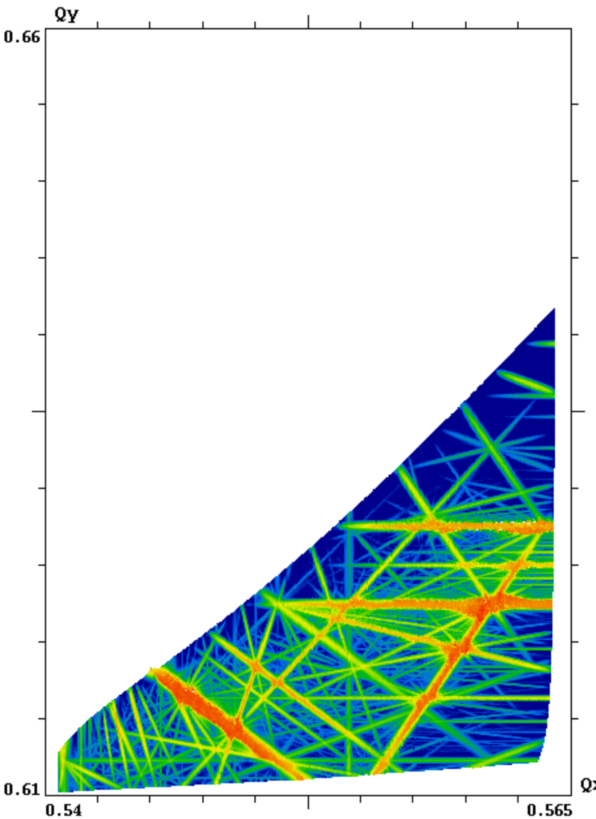
– bunch length should be squeezed too, preferably to $\sigma_z \sim \beta_y^*$

We will assume $\beta_y = 1$ mm, as it was chosen for the current FCC-ee design (see FCC-ACC-SPS-0004). The SR bunch length for TLEP Z is 1.64 mm, with account of beamstrahlung it becomes $\sigma_z \approx 3$ mm.

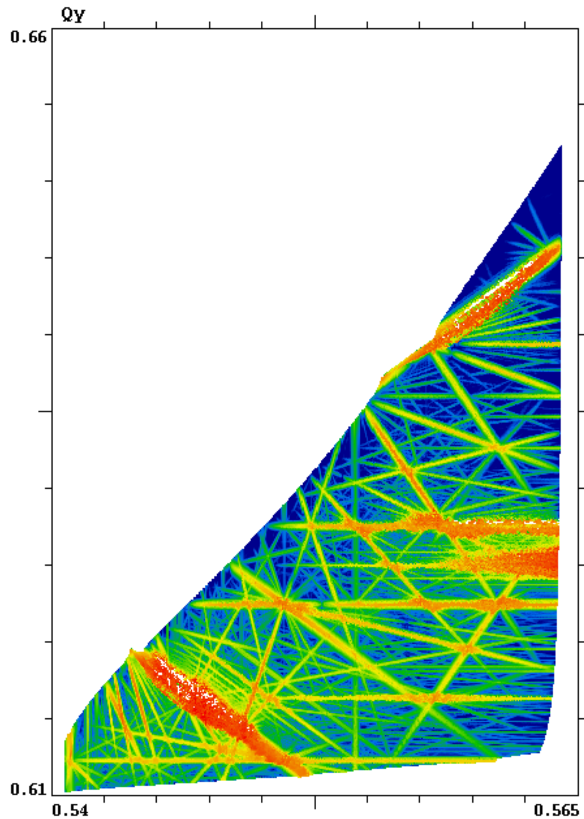
The main consequences of $\sigma_z / \beta_y >> 1$:

- Hour-glass factor H decreases
- The actual vertical tune shift increases
- Enhancement of synchro-betatron resonances (depends on damping!)

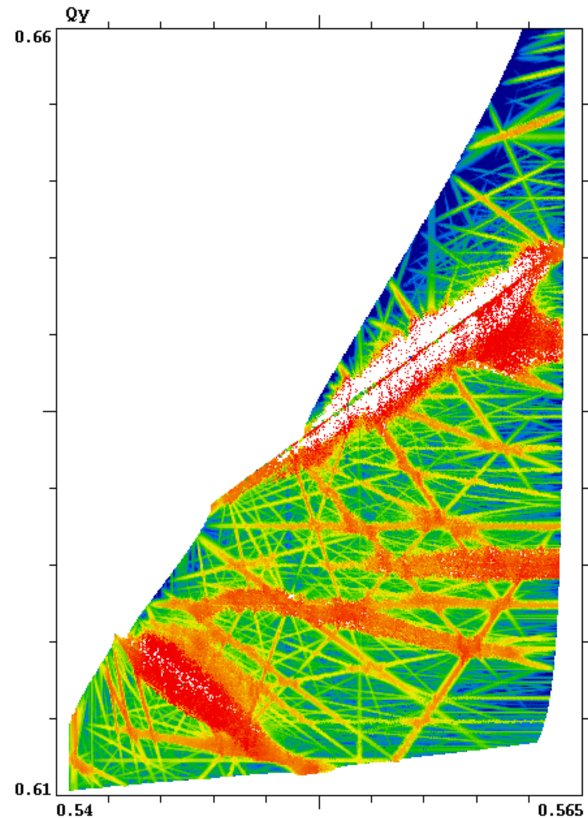
Impact of Bunch Lengthening



$\sigma_z = \beta_y$



$\sigma_z = 2\beta_y$

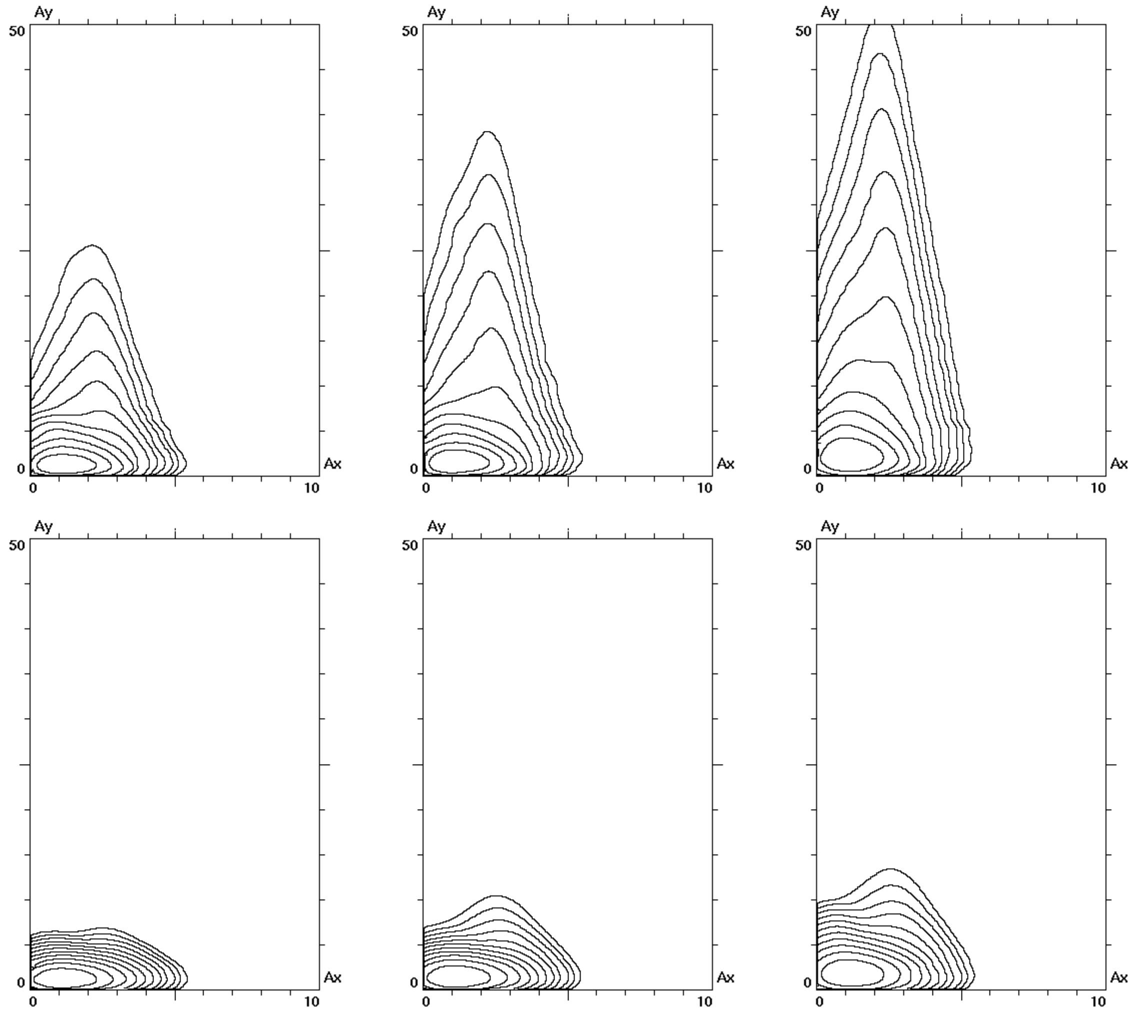


$\sigma_z = 3\beta_y$

FMA footprints in the plane of betatron tunes, synchrotron amplitude: A_s=1 sigma.

Parameters as for TLEP Z from FCC-ACC-SPS-0004, $\xi_x \approx \xi_y \approx 0.03$ (nominal).

Impact of Bunch Lengthening vs. Damping



$\sigma_z = \beta_y$, H ≈ 0.86 $\sigma_z = 2\beta_y$, H ≈ 0.7 $\sigma_z = 3\beta_y$, H ≈ 0.6

Damping as for TLEP Z

Damping as for TLEP H
(20 times stronger)

Contour plots of equilibrium distribution in the plane of normalized betatron amplitudes

Head-on Collision for TLEP Z

1) Beamstrahlung results in significant bunch lengthening.
2) Actual tune shift increases, synchro-betatron resonances are excited.
3) In respect that damping is weak, this leads to beam blowup.
4) It sets a limit on β_y (cannot be too small) and/or ξ_y (cannot be too large).

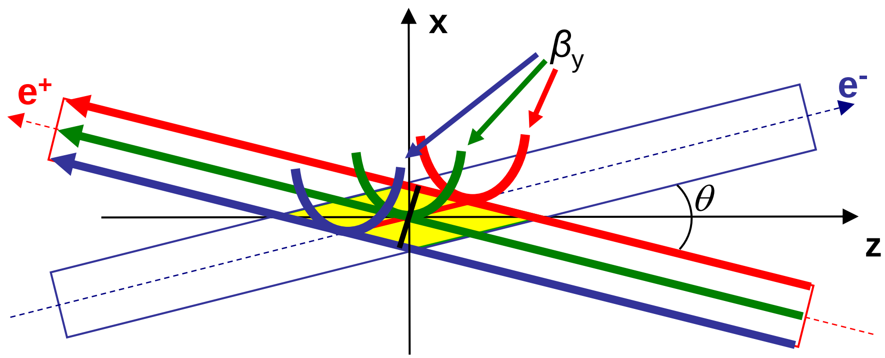
Thus we have a limit on achievable luminosity, which seems to be impossible to overcome in head-on collision.

There is a very good solution to solve the problem:

Crab Waist

P. Raimondi, 2006

Crab Waist Scheme



$$\phi = \frac{\sigma_z}{\sigma_x} tg\left(\frac{\theta}{2}\right)$$ – Piwinski angle

1) Large Piwinski angle: ϕ >> 1

2) β_y approx. equals to overlapping area: $\beta_y \sim \sigma_z / \phi$

3) Crab Waist: minimum of β_y along the axis of the opposite beam

Advantages:

- ✓ Impact of hour-glass is small and does not depend on bunch lengthening
- ✓ Suppression of betatron coupling resonances allows to achieve $\xi_y \sim 0.2$
- ✓ As a result, luminosity can be significantly increased

Luminosity at Low Energies (Z, W)

Energy	TLEP Z		TLEP W	
Collision scheme	Head-on	Crab Waist	Head-on	Crab Waist
Np [10^{11}]	1.8	1.0	0.7	4.0
θ [mrad]	0	30	0	30
σ_z (SR / total) mm]	1.64 / **3.0**	2.77 / **7.63**	1.01 / **1.76**	4.13 / **11.6**
ε_x [nm]	29.2	0.14	3.3	0.44
ε_y [pm]	60.0	1.0	7.0	1.0
ξ_x / ξ_y [nominal]	0.03 / 0.03	0.02 / 0.14	0.06 / 0.06	0.02 / 0.20
L [10^{34} cm^{-2}s^{-1}]	**17**	**180**	**13**	**45**

Head-on: parameters taken from FCC-ACC-SPS-0004

Crab Waist scheme requires low emittances. This can be achieved by keeping the same lattice as for high energies (i.e. $\varepsilon_x \sim \gamma^2$).

The numbers obtained in simulations are shown in blue.

For TLEP Z ξ_y can be raised up to 0.2. If we try to achieve this by 50% increase of N_p, additional bunch lengthening will occur due to beamstrahlung, so ξ_y increases by 15% only. Decrease of ε_y would be more efficient, since for flat bunches beamstrahlung does not depend on the vertical beam size.

One of the main limitations: very small vertical emittance is required. *Is it possible to achieve ε_y < 1 pm?*

The energy acceptance can be decreased from 2% to 1% (for Z) and 1.7% (for W).

Luminosity at High Energies (H, tt)

Energy	TLEP H		TLEP tt	
Collision scheme	Head-on	Crab Waist	Head-on	Crab Waist
Np [10^{11}]	0.46	4.7	1.4	4.0
θ [mrad]	0	30	0	30
σ_z (SR / total) [mm]	0.81 / **1.29**	4.82 / **9.33**	1.16 / **1.60**	5.25 / **6.78**
ε_x [nm]	0.94	1.0	2.0	2.13
ε_y [pm]	1.9	2.0	2.0	4.25
ξ_x / ξ_y [nominal]	0.093 / 0.093	0.02 / 0.13	0.092 / 0.092	0.03 / 0.07
τ_{bs} [min]	**> 500**	**70**	**2**	**20**
L [10^{34} cm^{-2}s^{-1}]	**7.4**	**8.4**	**2.1**	**1.3**

Bending radius at IP:

$$\frac{1}{\rho} \sim \frac{\xi_y}{L}\sqrt{\frac{\varepsilon_y}{\beta_y}}$$

L – interaction length (for crab waist – overlapping area)

To keep acceptable τ_{bs}, we need to make L larger than β_y (for tt – by a factor of ~2)

Again, very small vertical emittance is of crucial importance.

ξ_y can be raised by decreasing ε_y, but it requires the betatron coupling of ~0.1%. *Is it possible*?

In general, head-on and crab waist provide similar luminosity at high energies.

Since L > β_y and ξ_y is below the limit, we can increase β_y and luminosity will drop slowly than $1/\sqrt{\beta_y}$. E.g. increase of β_y to 1.5 (2) mm lowers the luminosity by 2.5% (7.5%) for TLEP H, and by 1.5% (5%) for TLEP tt.

Conclusions

- At low energies (Z, W) crab waist scheme can provide much higher luminosity than head-on collision.
- At high energies (H, tt) both schemes are of equal efficiency.
- Very small vertical emittance is required at all energies.
- At low energies the energy acceptance can be decreased, at high energies β_y can be increased.