Beam-Beam Optimization for Fcc-ee at High Energies (120, 175 GeV)

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Preamble

There are different proposals for FCC-ee collision scheme: head-on, small crossing angle (11 mrad), crab waist (30 mrad). The comparison of head-on and crab waist performed earlier was not perfect, as we used different lattice parameters and different restrictions. Small crossing angle was not checked yet by beam-beam simulations.

Now we have some preliminary lattice design, which we believe will not change too much. So, the time has come to optimize the luminosity with the given set of lattice parameters and compare different collision schemes with the same set of restrictions.

It has been already shown that crab waist provides much higher luminosity at low energies (Z, W). The detailed comparison at these energies will be performed soon, but now the most important question is the comparison at high energies (H, tt). Which factors limit the luminosity there? Do we have some benefits (or drawbacks) from crab waist?

For these studies we used simple model with 4-fold symmetry: 4 IPs with the same phase advances from IP to IP. Of course, tolerance to possible asymmetries needs to be investigated, this will be done later. As for now, a collider with one IP was simulated.

Set of lattice parameters at [120 / 175] GeV

Momentum compaction: $\alpha = 5.7 \cdot 10^{-6}$

Emittance: ε_x = [0.85 / 1.8] nm

Energy spread: σ_E = [0.0011 / 0.0016]

Energy acceptance: $\eta = 0.02$ (optimistic, to be obtained)

Energy loss per turn: U_0 = [1.9 / 8.6] GeV

Damping time: τ_z = [250 / 80] “turns” (one quarter of the ring)

Total number of particles: N_{tot} = [5.45 / 1.2] $\cdot 10^{13}$ (to get P_{tot} = 50 MW)

Total beam current: I_{tot} = [26.3 / 5.8] mA

Beta-function at IP: β_y = 1 mm (2 mm as a possible option)

Restrictions:

Betatron coupling: $\kappa \geq 0.002$

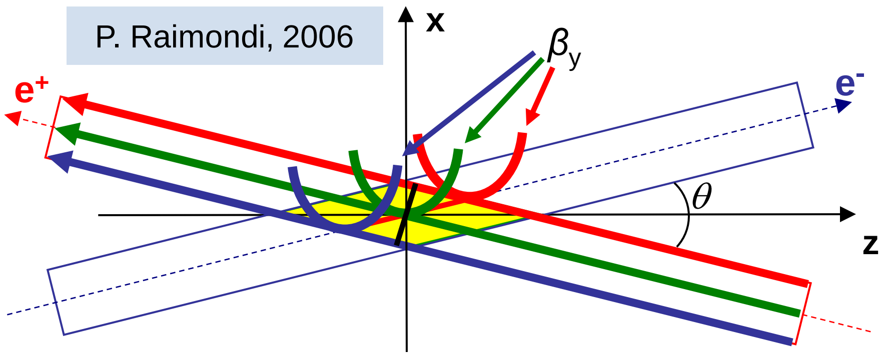
Vertical emittance: $\varepsilon_y \geq 1$ pm

Beamstrahlung & beam-beam lifetime: $\tau_{bs+bb} > 15$ min (beam-beam lifetime is limited by the beam tails and vertical aperture in the final quads)

Simulation Technique

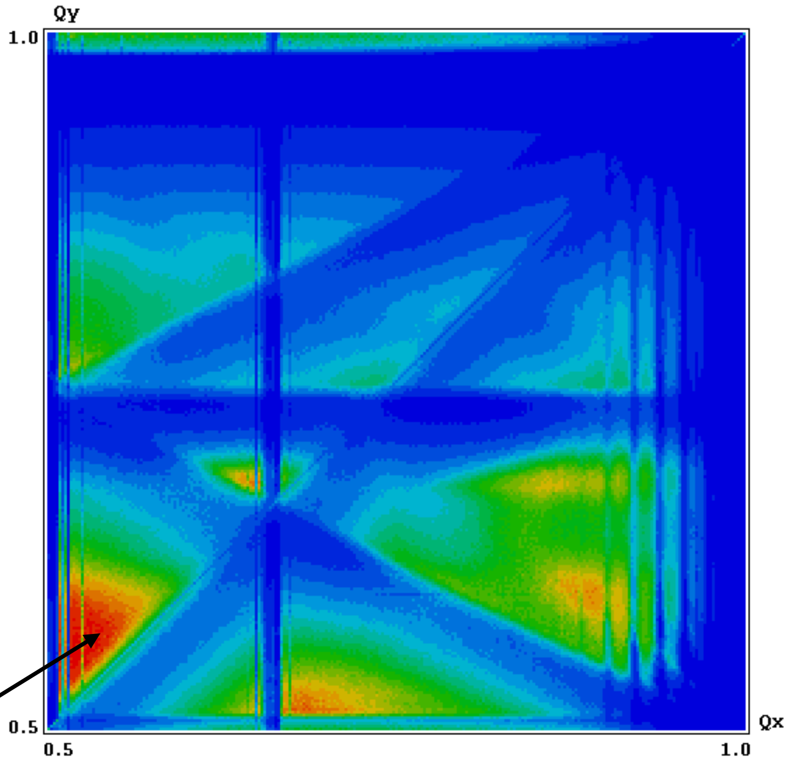
- Beam-beam tracking code `Lifetrac`.
- Linear lattice with RF cavities (and thin crab sextupoles, if required).
- Synchrotron radiation effects: damping and noise.
- Beamstrahlung: the process of photon emission is directly simulated, taking into account the correct spectrum.
- Quasi-strong-strong method: a series of weak-strong simulations, where the weak and the strong beams swap. Converges to equilibrium.
- Account of dynamic betas and emittances (these effects strongly depend on the working point and beam-beam tune shifts).
- Known problem: strong beam's beta-function dependence on the azimuth near IP is treated as for the drift space, but the opposite beam focusing changes $\beta(s)$ behavior. The problem will be resolved in future.
- Output: luminosity, emittances (r.m.s. and Gauss-fit), lifetime, equilibrium distribution in the space of normalized amplitudes (contour plots).

Crab Waist: Choice of Parameters



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



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

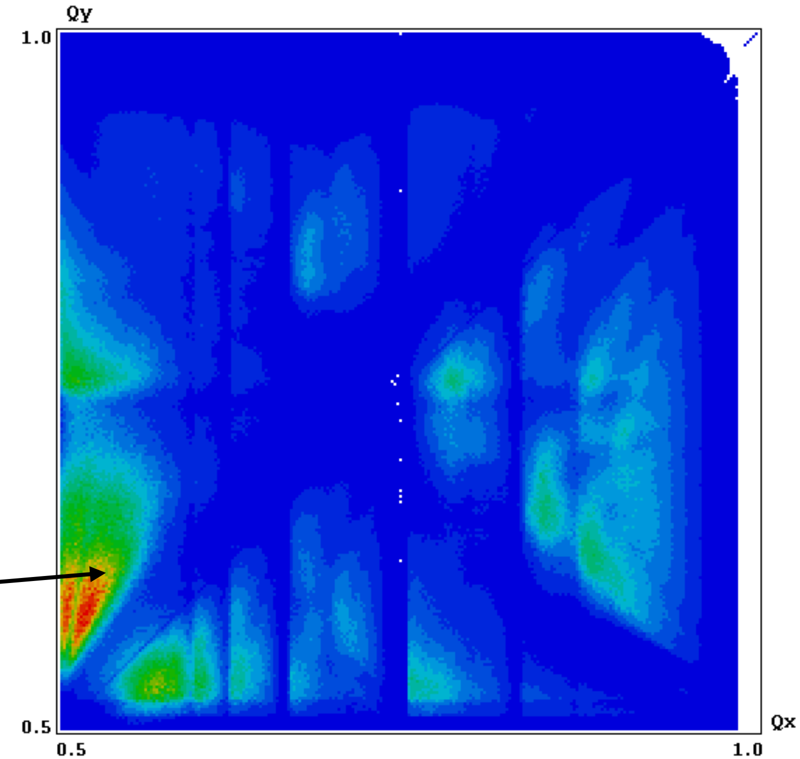
Good working point: (0.54, 0.57). We need to make σ_z larger (to increase ϕ) and ν_s smaller (to avoid synchro-betatron satellites of $\nu_x = 0.5$) => requirements on RF (low voltage, 400 MHz).

Head-on: Choice of Parameters

Both ξ_x and ξ_y are large (and almost equal). The effects of dynamic horizontal beta and emittance become large. Therefore, we should not stay too close to ν_x = 0.5.

Luminosity tune scan was performed in weak-strong (not quasi-strong-strong) mode. However, a good working point can be found by this way. Our choice is (0.54, 0.61), the same working point was adopted for CEPC.

We also need to make σ_z smaller (to decrease hour-glass) => requirements on RF (high voltage, 800 MHz).



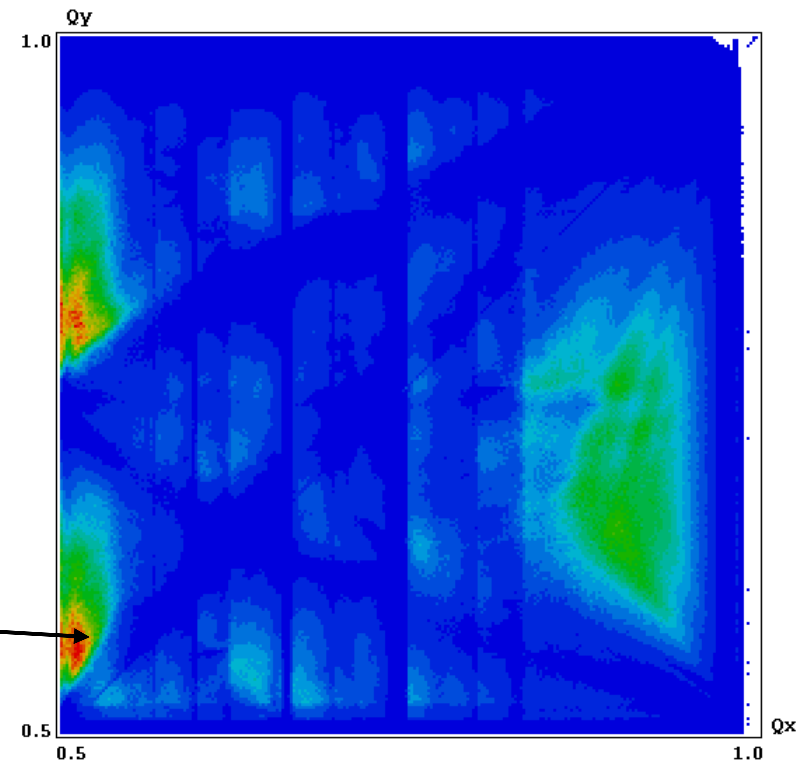
Luminosity tune scan for TLEP at 120 Gev, head-on.

Crossing (11 mrad): Choice of Parameters

Crossing angle with ϕ < 1 excites betatron resonances k · ν_x + m · ν_y = n with odd k numbers (which are suppressed in head-on collision due to symmetry) and synchro-betatron resonances.

Luminosity tune scan was performed in weak-strong (not quasi-strong-strong) mode. Our choice of working point: (0.52, 0.57). Probably, too close to half-integer, so we get an “optimistic estimate” of achievable luminosity.

The RF parameters are the same as for head-on collision.



Luminosity tune scan for TLEP at 120 Gev, crossing angle 11 mrad.

Effect of Dynamical ε_x

Due to betatron coupling, dynamical increase of ε_x results in a proportional growth of ε_y that affects the luminosity and beam-beam lifetime (if it is defined by the vertical tails).

The main contribution to ε_x growth comes from the linear effect, which is proportional to ξ_x and strongly depends on the distance to half-integer resonance $\nu_x = 0.5$:

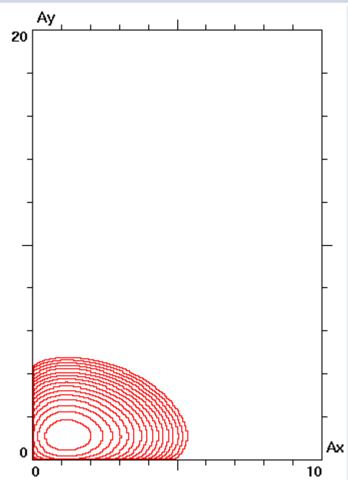
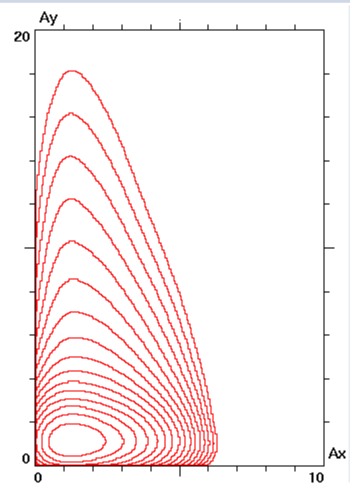
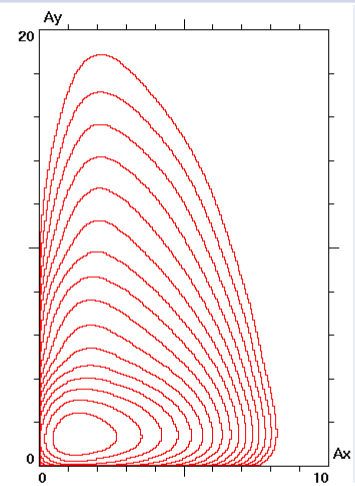
$$\varepsilon_x = \frac{1+2\pi\xi_x \cot\mu_x}{\sqrt{1+4\pi\xi_x \cot\mu_x - 4\pi^2\xi_x^2}}\varepsilon_{x0} \qquad \beta_x = \frac{\beta_x}{\sqrt{1+4\pi\xi_x \cot\mu_x - 4\pi^2\xi_x^2}}$$

From this point of view, the best scheme is crab waist, as ξ_x is small when $\phi \gg 1$. The worst scheme is "11 mrad", since the good working point is too close to $2\nu_x = n$.

Dynamical beta-functions and emittances were accounted in the performed simulations. However, in our simplified model there is no explicit coupling, so the vertical emittance was created "independently" by the corresponding noise and damping.

More realistic tracking through the real lattice with some coupling (e.g. skew-quads) will be performed later.

Summary Table (120 GeV , β_y= 1 mm)

	Crab Waist	× Head-on ×	Crossing (11 mrad)
RF voltage [GV]	2.3	5.5	5.5
RF frequency [MHz]	400	800	800
Tunes $\nu_x / \nu_y / \nu_s$	0.54 / 0.57 / 0.009	0.54 / 0.61 / 0.0255	0.52 / 0.57 / 0.0255
Bunch length [mm]	2.76 / 6.77	0.98 / 1.47	0.98 / 1.62
Bunch population	$3.5 \cdot 10^{11}$	$5 \cdot 10^{10}$	$6 \cdot 10^{10}$
Footprint size $\Delta\nu_x / \Delta\nu_y$	0.019 / 0.126	0.087 / 0.128	0.063 / 0.104
Lifetime bb+bs [min]	17	120	200
Luminosity [$cm^{-2}s^{-1}$]	$9.8 \cdot 10^{34}$	$7.2 \cdot 10^{34}$	$5.8 \cdot 10^{34}$
Luminosity (β_y = 2 mm)	$8.3 \cdot 10^{34}$	$6.8 \cdot 10^{34}$	$5.0 \cdot 10^{34}$
Density contour plots			

Summary (120 GeV)

- In head-on and crossing (11 mrad) schemes the luminosity is limited mainly by beam-beam. In crab waist scheme it is limited by beamstrahlung only – this is one of the reasons why it is higher.
- Crab waist scheme has a potential to provide even higher luminosity if we could reduce the betatron coupling below 0.2%, or increase the energy acceptance above 2%.
- If additional ε_y growth due to coupling and dynamical ε_x is accounted, crab waist would become even better.
- The transverse beam distribution is much better in crab waist scheme, that is important for detector background, reduces SR from the final quads, etc.
- Inevitable asymmetry between 4 IPs and the arcs between them will result in emersion of new series of resonances. On this evidence crab waist should be better, as it is dedicated to suppress resonances, and there is larger “room for imperfections” since we are significantly below the beam-beam limit.
- Relaxing β_y to 2 mm is possible, luminosity drops by ~15% only.

Parameters Optimization at 175 GeV

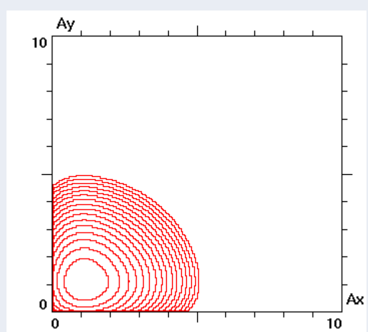
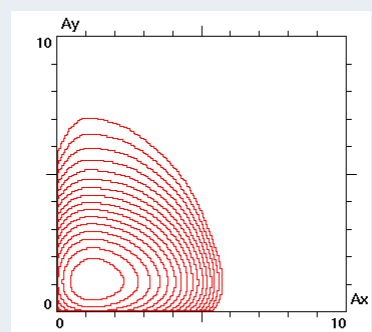
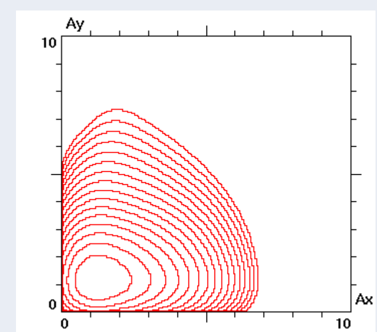
The lifetime is limited by beamstrahlung: $\tau_{bs} \sim \exp\left(\frac{2\eta\alpha\rho}{3r_e\gamma^2}\right)\cdot\frac{\rho^{3/2}}{L\gamma^2}$

L is the interaction length, η - energy acceptance,

ρ - [average] bending radius of a particle's trajectory at the IP: $\frac{1}{\rho} \sim \frac{\xi_y}{L}\sqrt{\frac{\varepsilon_y}{\beta_y}}$

- In order to increase τ_{bs}, L can be increased in head-on and 11 mrad schemes by the bunch lengthening. Since damping is very strong and we are below the beam-beam limit, $\sigma_z \sim 2\beta_y$ looks acceptable.
- RF voltage can be decreased to 9.5 GV, but this is not enough. A better solution: reduce RF frequency from 800 to 400 MHz. After that, decrease of RF voltage does not help: luminosity saturates due to hour-glass while the vertical beam tails grow.
- Since hour-glass is large when β_y = 1 mm, and ξ_y is below the limit, increasing β_y up to 2 mm keeps the luminosity [almost] unchanged.
- In crab waist scheme we need large σ_z to get ϕ >> 1, but L does not depend on σ_z and it is a little bit smaller than in head-on.

Summary Table (175 GeV, β_y= 2 mm)

	Crab Waist	× Head-on ×	Crossing (11 mrad)
RF voltage [GV]	9.5	11	11
RF frequency [MHz]	400	400	400
Tunes $\nu_x / \nu_y / \nu_s$	0.54 / 0.57 / 0.0132	0.54 / 0.61 / 0.0172	0.52 / 0.57 / 0.0172
Bunch length [mm]	2.75 / 3.74	2.11 / 2.56	2.11 / 2.68
Bunch population	$2.0 \cdot 10^{11}$	$1.1 \cdot 10^{11}$	$1.2 \cdot 10^{11}$
Footprint size $\Delta\nu_x / \Delta\nu_y$	0.023 / 0.079	0.071 / 0.137	0.047 / 0.106
Lifetime τ_{bs} [min]	18	35	25
Luminosity [$cm^{-2}s^{-1}$]	$1.15 \cdot 10^{34}$	$1.3 \cdot 10^{34}$	$1.2 \cdot 10^{34}$
Luminosity (β_y = 1 mm)	$1.25 \cdot 10^{34}$	$1.3 \cdot 10^{34}$ (800 MHz)	$1.25 \cdot 10^{34}$ (800 MHz)
Density contour plots			

If additional ε_y growth due to coupling and dynamical ε_x is accounted, crab waist could become the best.

Summary (175 GeV)

- Short bunches are not needed even for head-on collision, so 400 MHz RF is OK and RF voltage can be lowered.
- β_y can be relaxed to 2 mm without luminosity loss (about 9% loss in crab waist).
- In all schemes the luminosity is limited by beamstrahlung lifetime – this is the main reason why it is almost the same.
- If additional ε_y growth due to coupling and dynamical ε_x is accounted, crab waist has some advantage.

Dispersion at the IP

Beamstrahlung results in emittance growth when there is a dispersion at the IP.

For example, η' = [0.01, 0.02] leads to ε_x increase by [35%, 140%], η = 5 mm leads to ε_x increase by $\sim$ 60% – tested by weak-strong (not self-consistent) simulations at 120 GeV. These numbers can be used as rough estimates.

Due to betatron coupling, ε_y will increase in the same proportion, and luminosity drops as 1/sqrt(ε_y).

We cannot afford large enough dispersion in the final quads to facilitate the chromaticity correction, so it would be better to nullify η, η' at the IP.

Conclusion

- Crab waist collision scheme is much better than head-on and ordinary crossing (11 mrad) at low energies (Z, W), significantly better at 120 Gev, and not worse at 175 GeV. It should be adopted as the basic scheme for all 4 energy points.
- Dispersion (and its derivative) must be nullified at the IP.
- More realistic simulations with the real nonlinear lattice are required. This can be done only when the necessary energy acceptance & dynamic aperture are obtained.
- Next steps: tolerances to imperfections, asymmetry between 4 quarters of the ring, asymmetry between bunches (longitudinal flip-flop ?), etc.
- Cross-check of `Lifetrac` simulations (Ohmi-san ?).