Luminosity and Beam-Beam Effects for Novosibirsk SCTF

D. Shatilov

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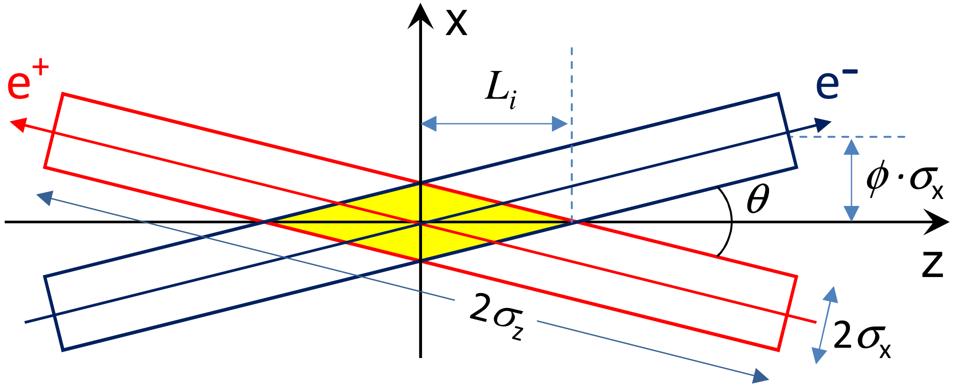
Luminosity and Collision Scheme

Luminosity for flat beams:

$$L = \frac{\gamma}{2er_e} \cdot \frac{I_{tot}\xi_y}{\beta_y^*} \cdot R_H$$



Collision scheme with large Piwinski angle: $\phi = \frac{\sigma_z}{\sigma_x} tg\left(\frac{\theta}{2}\right)$

LPA and Crab Waist

P. Raimondi, 2006

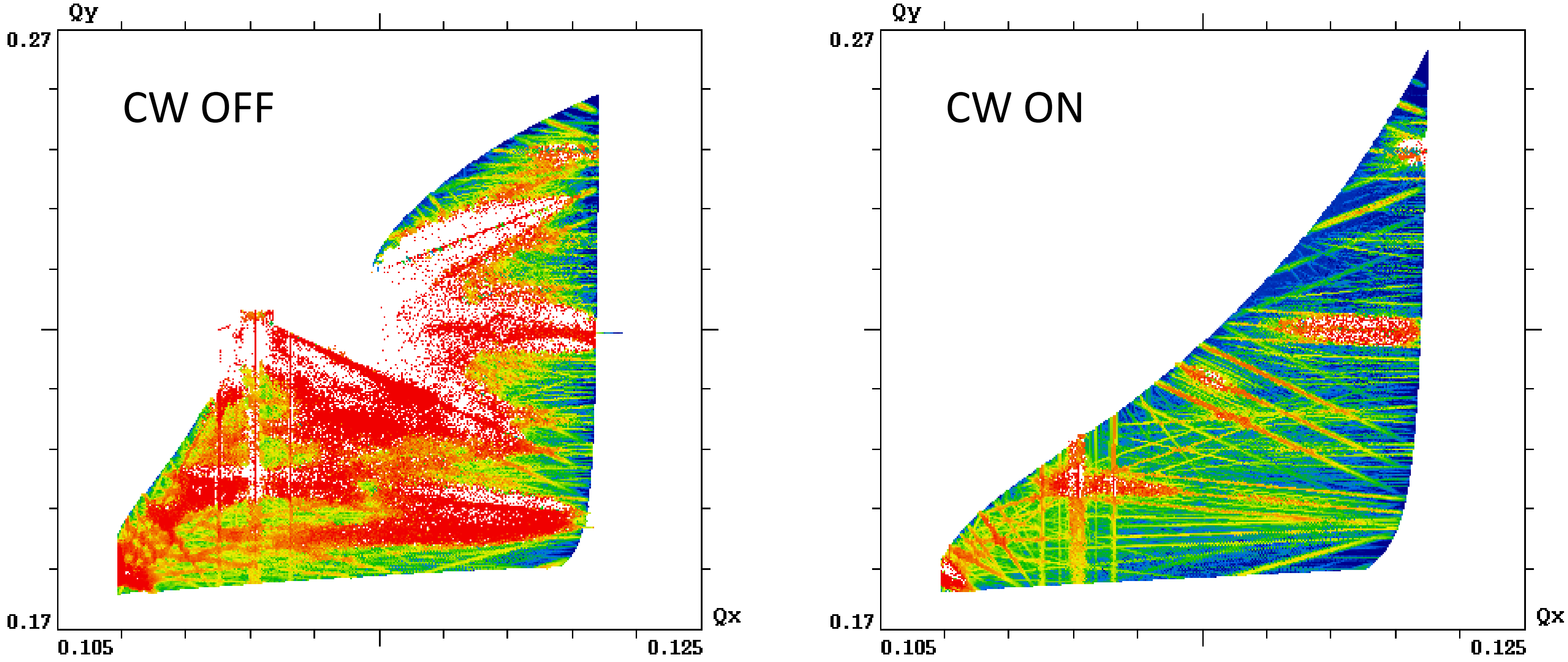
1) Transverse separation at parasitic crossings is huge => bunch spacing is not limited by beam-beam.

2) The length of interaction area $L_i << \sigma_z$ => small $\beta_y^* << \sigma_z$ without hourglass.

3) Crab waist suppresses betatron and synchro-betatron coupling resonances => $\xi_y \sim 0.2$

Crab Waist at Work

Crab Waist was successfully tested at DAΦNE Φ-factory (INFN-LNF, Italy) providing a significant increase in luminosity.



Footprint (FMA) for DAΦNE with and without CW.
Blue color corresponds to regular trajectories, red color – stochastic.

Requirements and Limitations

$$\xi_y = \frac{r_e}{2\pi\gamma} \cdot \frac{N_p}{\sigma_x} \cdot \sqrt{\frac{\beta_y^*}{\varepsilon_y(1+\phi^2)}}$$

We need at a "standard" bunch population N_p to make $\phi >> 1$, reduce β_y^* (by about ϕ times), and increase ξ_y several-fold. This is possible only with a significant decrease in the transverse dimensions of the beam.

In CW collision, beam-beam interaction [almost] does not cause beam sizes blowup, long tails in the equilibrium distribution, etc. **The main limitations are associated with obtaining the design values for lattice and beam parameters**:

- Very small β_y^* (FF design, DA, energy acceptance, etc.)
- Very small emittances with high populated bunches (IBS, feedback noises, Toucshek lifetime, etc.)

Besides, two limitations related to beam-beam interaction with LPA were found:

- Bunch crabbing in X-Z plane
- Coherent beam-beam instability

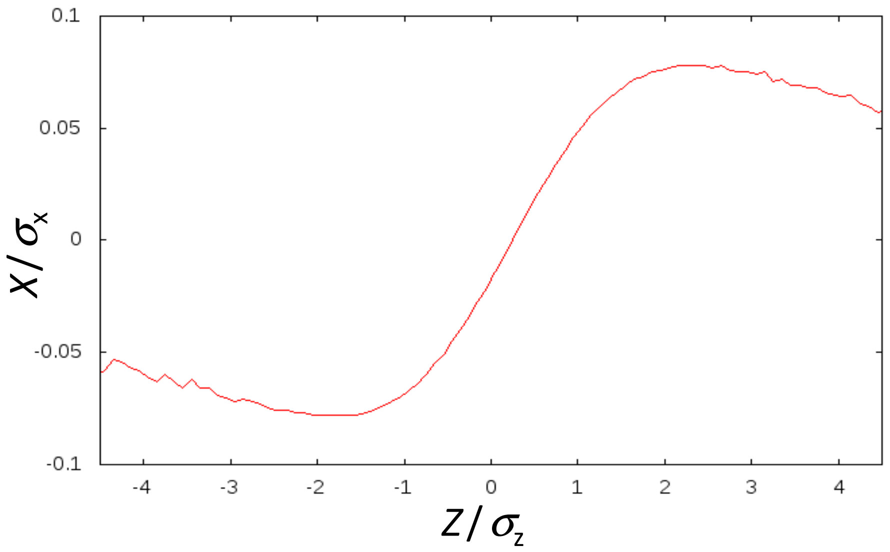
Both of them can be mitigated by a proper choice of parameters.

Bunch Crabbing

Beam-beam interaction in collision with LPA leads to crabbing of bunches in X-Z plane.

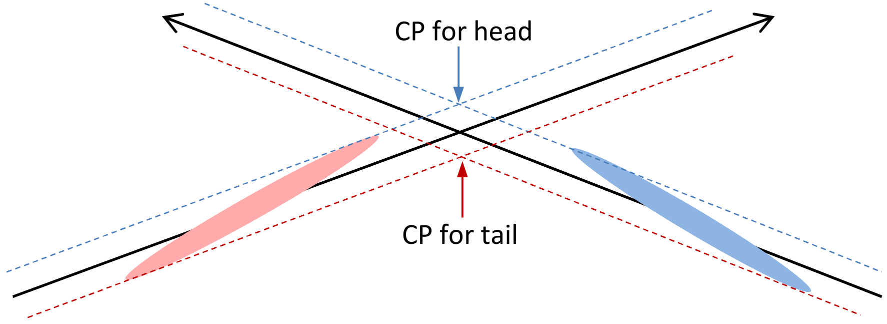
E. Perevedentsev, 2001

Bunch shape in X-Z plane (tracking)



Tilt angle at IP: $\phi \propto \beta_x^* \cdot ctg(\pi\nu_x)$

Bunch crabbing can destroy CW



“Collision Point” for particles with $Z \neq 0$ shifts away from the axis and also shifts longitudinally, away from the β_y waist.

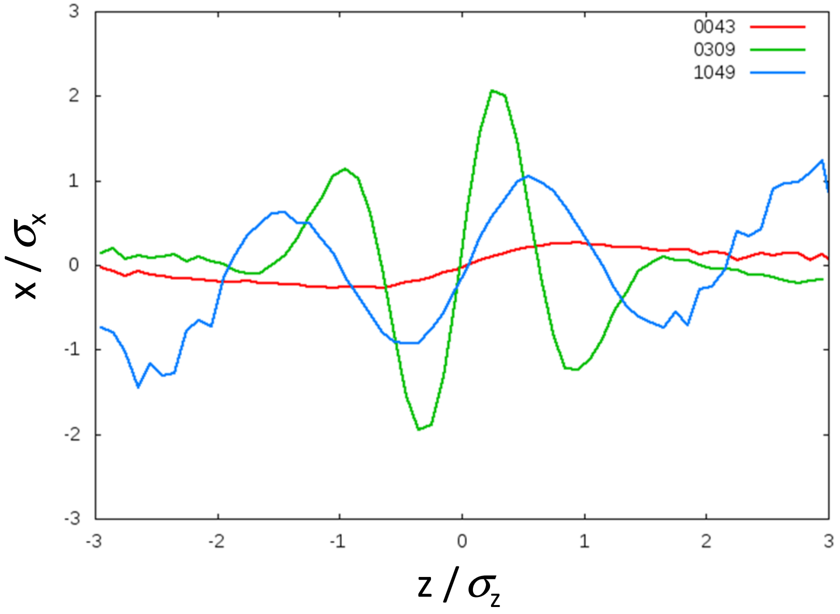
Mitigation: ν_x close to half-integer and small β_x^*

Coherent Beam-beam Instability

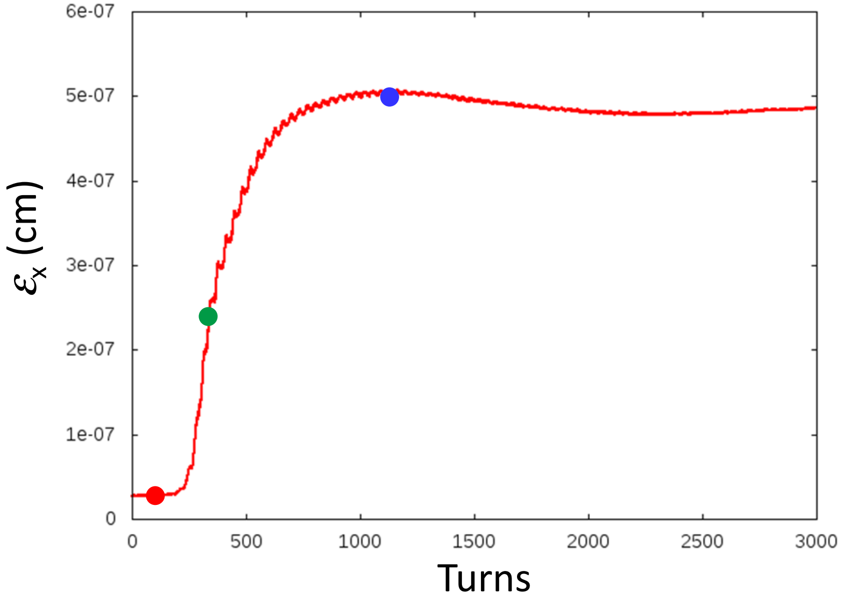
Discovered by K. Ohmi in strong-strong simulations (`BBSS`). Reproduced in quasi-strong-strong simulations (`Lifetrac`). There is a good agreement between the two codes.

Recently it was observed at SuperKEKB (K. Ohmi).

Bunch shape in the horizontal plane at some turns



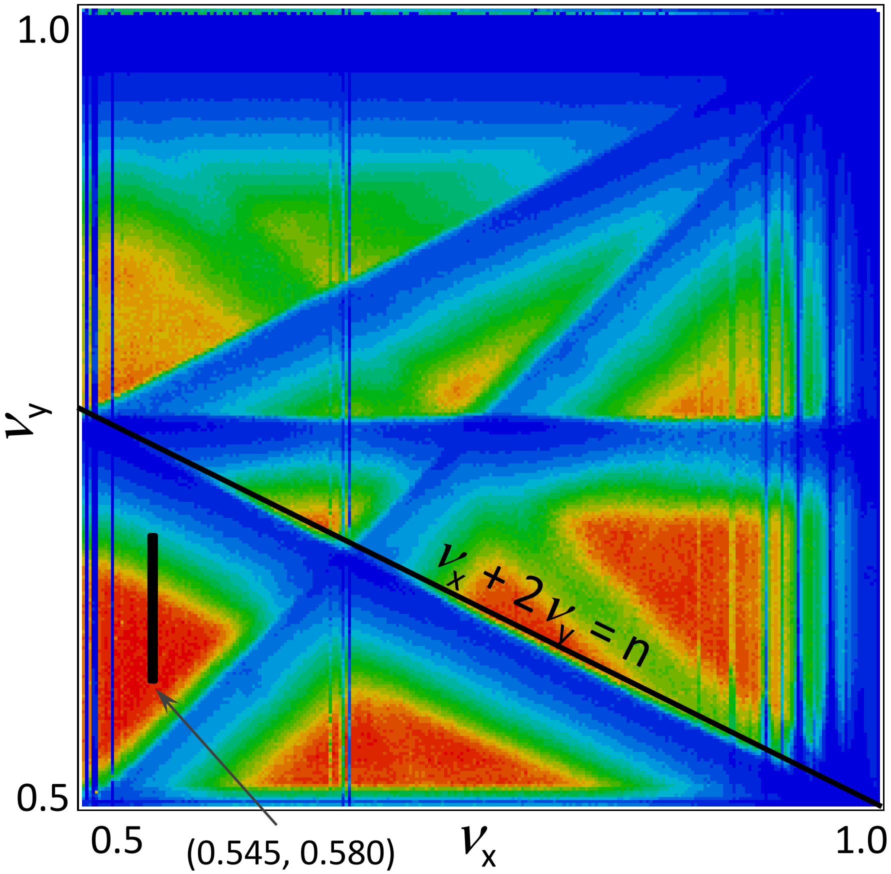
Evolution of the horizontal emittance



The effect is 2D, ε_x increases several times. Then betatron coupling leads to ε_y growth in the same proportion, and luminosity falls. This instability cannot be mitigated by feedback. The only solution: find conditions under which it does not arise.

Betatron Tunes

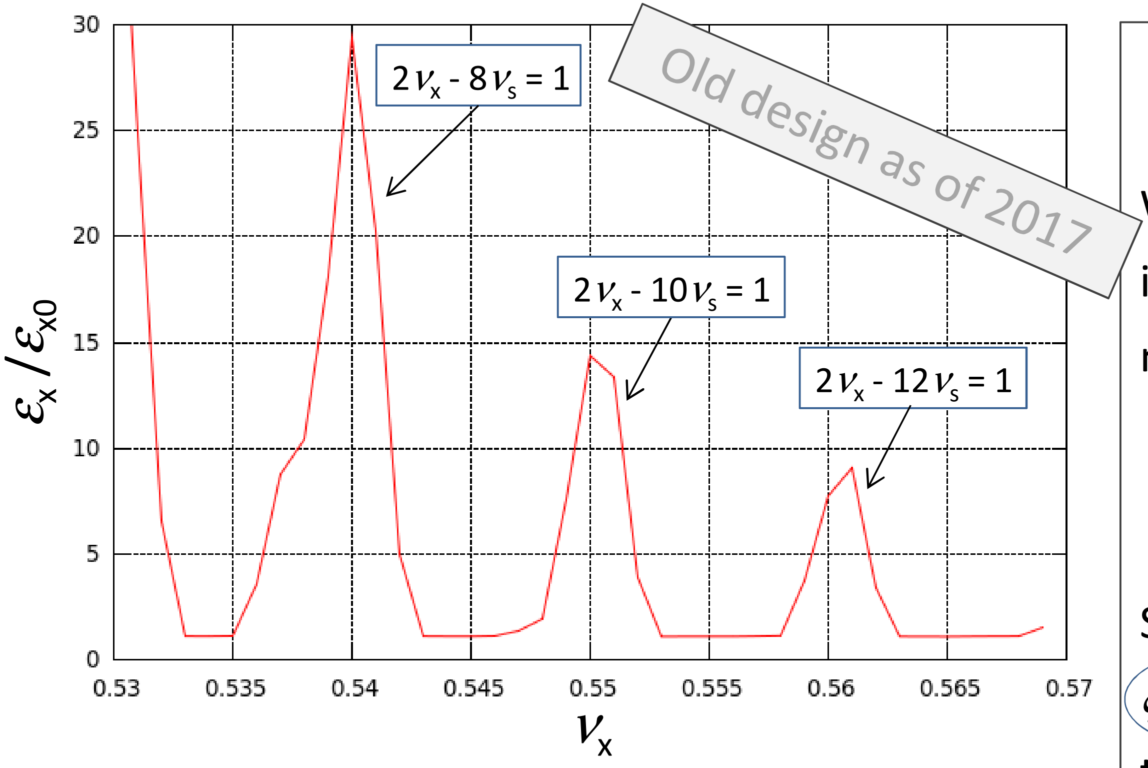
Luminosity vs. betatron tunes, simplified model, weak-strong simulations. Colors from zero (blue) to 10^{35} cm^{-2}c^{-1} (red).



- Good area: red triangle in the bottom-left corner, ν_x close to half-integer. The bunch crabbing is small here.
- Only low-order resonances are visible, the others are suppressed by CW.
- High order synchrotron satellites of half-integer resonance are visible only in [quasi]-strong-strong model (next slide).
- The range of permissible ν_x for large ξ_y is bounded on the right by 0.57÷0.58.

Synchro-Betatron Resonances

Coherent beam-beam instability: ε_x dependence on ν_x and ν_s at 2 GeV. Quasi-strong-strong simulations.



The distance between resonances is ν_s. The width depends on ξ_x and the order of resonance.

Mitigation:

We need to reduce ξ_x / ν_s ratio and increase the order of resonances near the working point.

$$\xi_x = \frac{2r_e}{\pi\gamma} \cdot \frac{N_p \beta_x^*}{\theta^2 \sigma_z^2} \quad \text{for } \phi >> 1$$

Small β_x^* has a key role. We have $\xi_x \approx \nu_s / 3$, precisely because of this there are regions between resonances free of instability.

Optimization for Current Design

In the current design, compared to the previous one:

- β_x^* increased from 4 to 5 cm => increase in ξ_x
- Perimeter decreased 1.7 times => decrease in ν_s

As a result, the ratio ξ_x / ν_s increased, and it can cause problems.

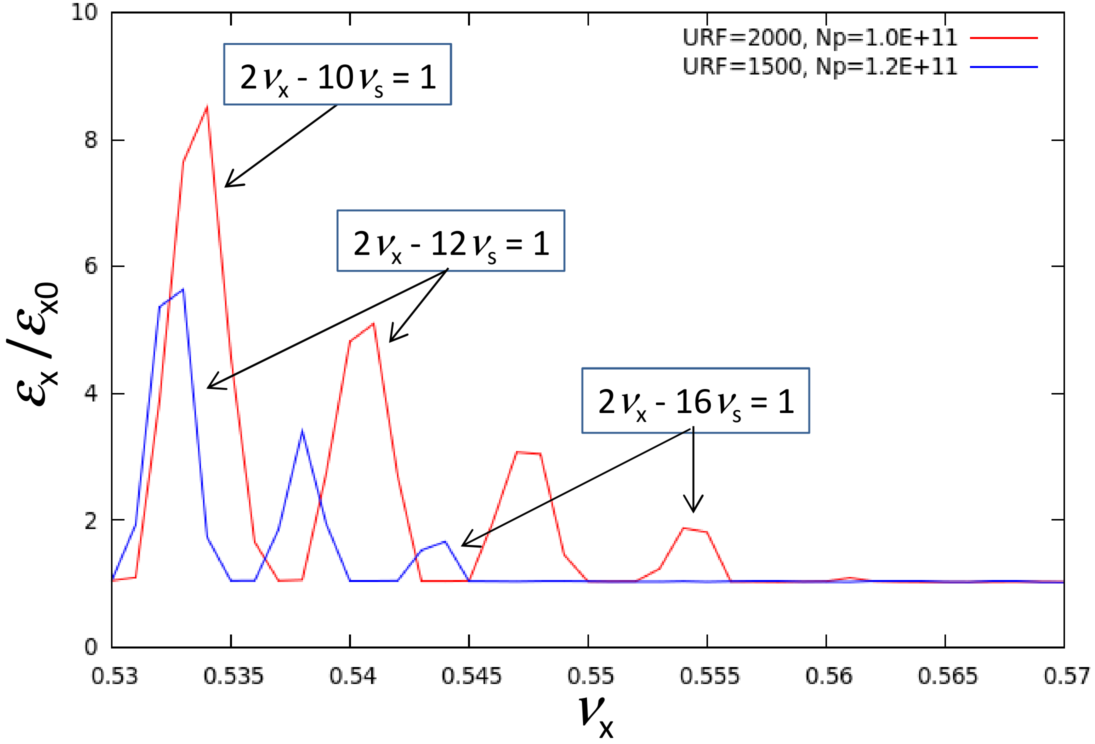
Another important issue is Touschek lifetime, which is mainly determined by the momentum acceptance. Currently it is below 1%, but work is ongoing and it is improving slightly. The goal is 1.5÷2%.

Further I will assume that the momentum acceptance is 1.2%. Under these conditions, the parameter optimization is as follows:

1) Select RF voltage so that RF acceptance is equal to the momentum acceptance. Small U_{RF} helps to mitigate coherent beam-beam instability.
2) Select the bunch population N_p so that Touschek lifetime is acceptable. Further I will consider that the restriction is 10 minutes.
3) Neat choice of ν_x to avoid coherent instability. This becomes important only for large enough N_p.

Beam Energy: 3 GeV

Coherent beam-beam instability: ε_x dependence on ν_x and ν_s. Quasi-strong-strong simulations.



These simulations were performed in linear lattice, so the momentum acceptance was ignored.

IBS and Touschek lifetime were obtained by MADX with realistic nonlinear lattice, but only RF acceptance is taken into account.

U_{RF} = 2 MV, N_p = 1.0E+11, $I = 2$ A

***L* = 1.4E+35**

Lifetime ~ 30 min

U_{RF} = 1.5 MV, N_p = 1.2E+11, $I = 2$ A

***L* = 1.4E+35**, ξ_x / ν_s is the same!

Lifetime ~ 10 min

Beam-beam simulations with realistic nonlinear lattice were also performed, and no problems were found. However, direct modeling of IBS is not yet implemented in the tracking code. This will be done soon, then simulation results will be more accurate.

Beam Energy: 2 and 1.5 GeV

E (GeV)	U_{RF} (KV)	N_p (10^{10})	N_b	I_{tot} (A)	L (10^{34})
2	500	3	500	1.51	4.2
1.5	300	2.5	500	1.26	2.3

Luminosity at low energies is greatly limited by Touschek lifetime.
Now the beam-beam tune shifts are far below the limits.

We need to increase the momentum acceptance!

The length of interaction area at low energies is 0.7÷0.8 mm (when N_p is large enough), so there is no need to have $\beta_y^* = 0.5$ mm. By relaxing β_y^* we can simplify chromaticity correction and obtain a larger momentum acceptance.

If we manage to increase momentum acceptance, the bunch population will be higher, and we also need to increase U_{RF} accordingly. Then the coherent beam-beam instability becomes critical again. Possible mitigation: increase the momentum compaction factor. The drawback of this approach is that the natural emittance will increase, but the full emittance (which is mainly formed by IBS) will not be much affected.

Summary

- Beam-beam simulations with realistic nonlinear lattice were performed.
- The parameter optimization procedure was developed and the main limitations were found.
- U_{RF} should be adjusted according to the momentum acceptance.
- In the present design, luminosity is restricted by insufficient momentum acceptance. Further lattice optimization is required.