Beam-Beam and Lifetime Modeling at FCC-ee

D. Shatilov

Acknowledgements: K. Ohmi, K. Oide, Y. Zhang

FUTURE CIRCULAR COLLIDER
Innovation Study

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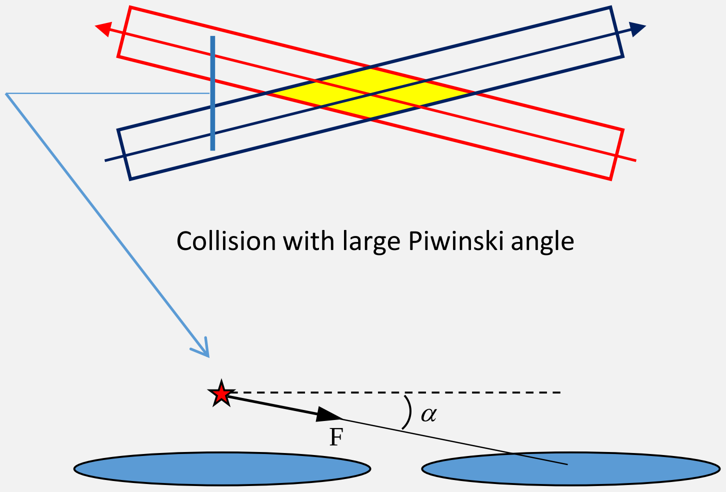
Disruption Parameter

At IPs, both bunches act on each other. Is it necessary to take into account the change in their distribution functions *during collision*?

- Beam-beam kicks depend on the distribution of transverse coordinates of the oncoming beam, and [almost] does not depend on the distribution of transverse momenta.
- The kicks change the transverse momenta, not the coordinates. However, during the interaction, $\Delta p_{x,y}$ will have time to transfer into Δx, Δy.
- The magnitude of change in the transverse coordinates during collision is described by the disruption parameter (here $\xi_{x,y}$ refers to one IP):

$$D_{x,y} = 4\pi\xi_{x,y}\frac{\sigma_z}{\beta^*_{x,y}}$$

- In crab waist collision, we have D_x << 1, but large ξ_y and β_y^* << σ_z. Does it mean that D_y >> 1? No, **σ_z in the above formula should be replaced by $L_i \approx \beta_y^*$, so we have $D_y \sim 1$.**
- Relatively small disruption parameter ($D_{x,y} \leq 1$) means that the distribution of coordinates remains almost unaffected during interaction.
- Examples of $D_{x,y}$ >> 1: linear colliders (ILC, CLIC).



Collision with large Piwinski angle

Vertical plane: kick from the opposite bunch (slice)

If the horizontal distance between slices is greater than several σ_x, then the force is directed to the center of the opposite slice and falls as 1/r, and $\alpha \propto \sigma_y/\sigma_x$ << 1. The vertical kick: $F_y = F{\cdot}\sin(\alpha)$ << F.

Therefore, the vertical kick is localized in the overlap region of the two beams (marked in yellow).

Simulation Models

Interaction with the opposite bunch

1) **Weak-strong (WS)**

   The opposite (strong) bunch is not affected during long-term (many turns) tracking. This is a simple and fast model. It is always recommended to start with it.

2) **Strong-strong (SS)**

   Both bunches are affected and updated <u>during</u> each collision. This is a complex and time-consuming model, but we must use it when $D_{x,y} >> 1$. Simplified variant (to avoid solving Poisson equation): take into account the barycenter of each slice (transverse displacements) and fit the transverse distribution to Gaussian.

3) **Quasi-strong-strong (QSS)**

   Swap the "weak" and the "strong" bunches every *n-th* turn, and thus update the parameters of the opposite bunch. More realistic and more complex option: simulate two beams simultaneously (in parallel) and exchange data every turn. The opposite bunch is *frozen* (not affected by beam-beam) during collision. This is much faster than SS, but cannot be used when $D_{x,y} >> 1$.

Particle tracking between IP(s)

1) **Linear lattice (constant transport matrix, can be with coupling)**

   A simplified model for chromaticity, impedance, etc. can also be included. This model is simple, fast, and most flexible. If beam-beam is considered as the major nonlinearity, it is recommended to start with this approach.

2) **Realistic nonlinear lattice**

   This is more time-consuming, but correctly accounts chromaticity, DA and momentum acceptance, interference between beam-beam and lattice-driven resonances (especially when considering misalignments and errors).

Plus space charge, IBS, electron clouds, impedance, etc.

Crab Waist was discovered in WS, coherent beam-beam instability – in SS, and then confirmed in QSS. In all cases – linear lattice between IPs.

Simulation Codes

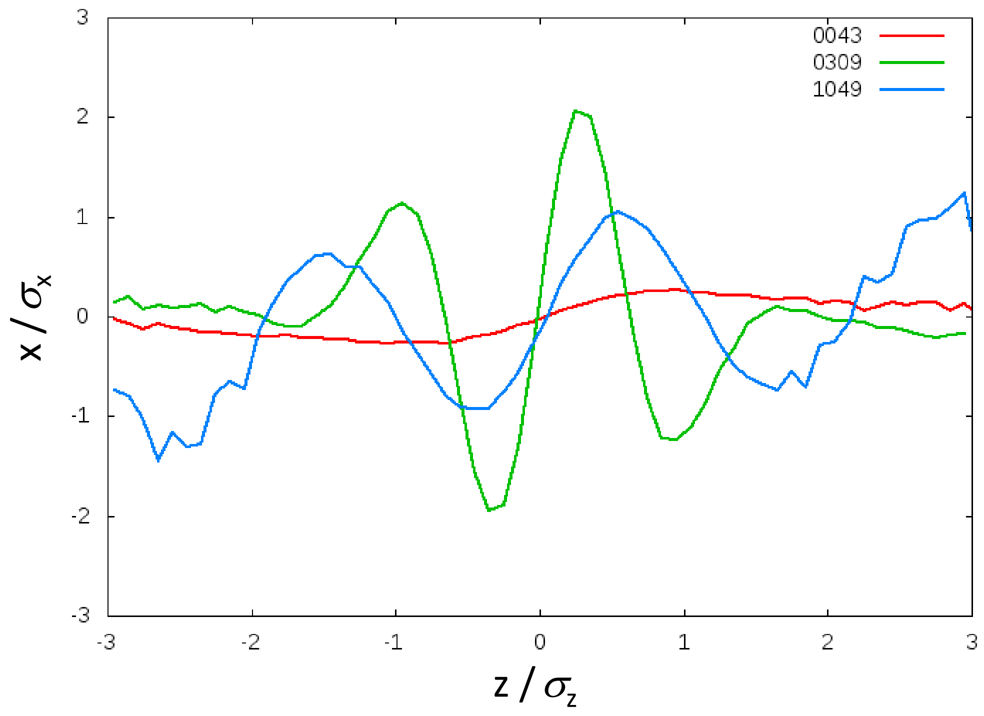
1. Lifetrac (D. Shatilov)
   - WS and QSS simulations
   - Realistic lattice with errors, misalignments and corrections
   - Upcoming updates: tapering, realistic SR in all magnets
2. BBWS, BBSS (K. Ohmi)
   - WS and SS simulations
   - Linear lattice with possible consideration of chromaticity, impedance, etc.
3. SAD (K. Oide et al.) + BBWS
   - Realistic lattice with errors, misalignments and corrections
   - Tapering, realistic SR in all magnets, spin tracking, etc.
   - Beam-beam (WS) is provided by BBWS code
4. IBB (Y. Zhang)
   - WS, SS and QSS simulations
   - Linear lattice with possible consideration of chromaticity, impedance, etc.
   - Next steps: realistic lattice with errors, misalignments, SR in all magnets
5. Xsuite (P. Kicsiny, X. Buffat et al.)
   - WS, SS and QSS simulations (now testing, work in progress)
   - Realistic lattice with all effects included

The functionality of different codes is not completely the same, but there are large areas of overlap where cross-checking can be done.

Example: Coherent Beam-Beam Instability (TMCI type)

discovered by K. Ohmi in SS simulations

QSS (Lifetrac): bunch shape in the horizontal plane at some turns



The shape (barycenter of slices) changes every turn due to betatron and synchrotron oscillations.

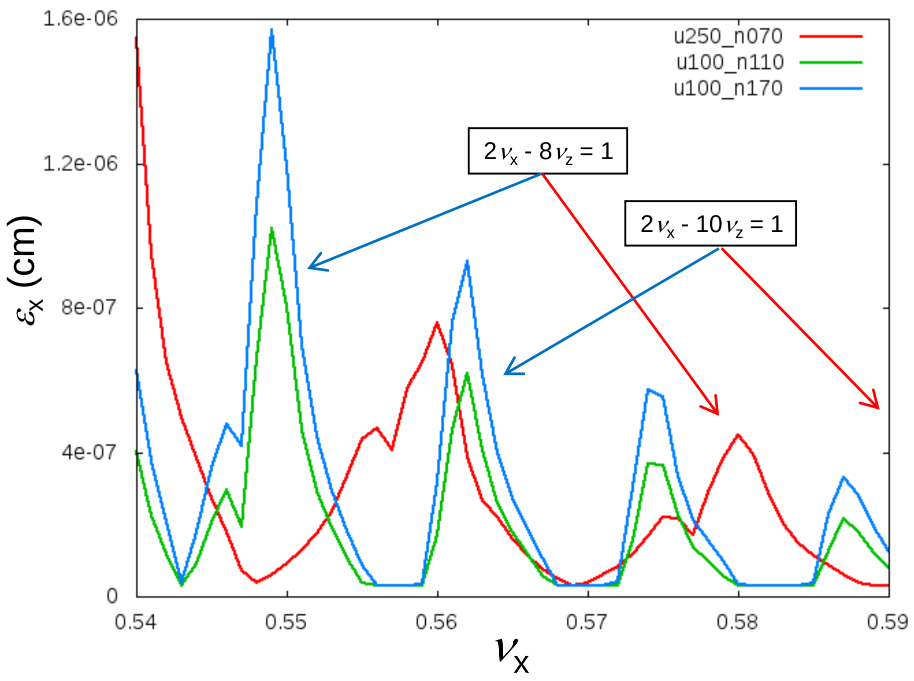
QSS simulations:

- Opposite bunch is represented as a sequence of several hundred slices with individual horizontal displacements.
- Two colliding bunches are tracked simultaneously in parallel, and their shapes (transverse emittances and shifts of slices) are updated every turn.
- Particles collide with slices (not slices with slices!) for both bunches. Since D_x is small, the bunch shape in X-Z plane does not change during collision.
- The transverse distribution of slices is assumed to be Gaussian, but $\sigma_{x,y}$ depend on the azimuth.
- This instability leads to an increase in ε_x which has little *direct* effect on the luminosity. But the explicit betatron coupling changes the situation.

Very good agreement was obtained between SS and QSS simulations.

Coherent Beam-Beam Instability: Mitigation

Old lattice example at Z: ε_x dependence on ν_x and ν_z.
U_{RF} = 250 MV (red) and 100 MV (green, blue).



The distance between resonances is ν_z. The width depends on ξ_x and the order of resonance.
We need to reduce ξ_x / ν_z ratio and increase the order of resonances near the working point.

- Increase in the momentum compaction factor: ν_z and σ_z grow, ξ_x decreases.

  This is done by changing FODO arc cell, which also leads to an increase in ε_x. Besides, the threshold of microwave instability is raised.

- Decrease in β_x^* (and thus ξ_x).

  However, this leads to a decrease in the energy acceptance.

- Reduce the RF voltage.

  This decreases ν_z and ξ_x in the same proportion, but increases the order of resonances near the W.P.

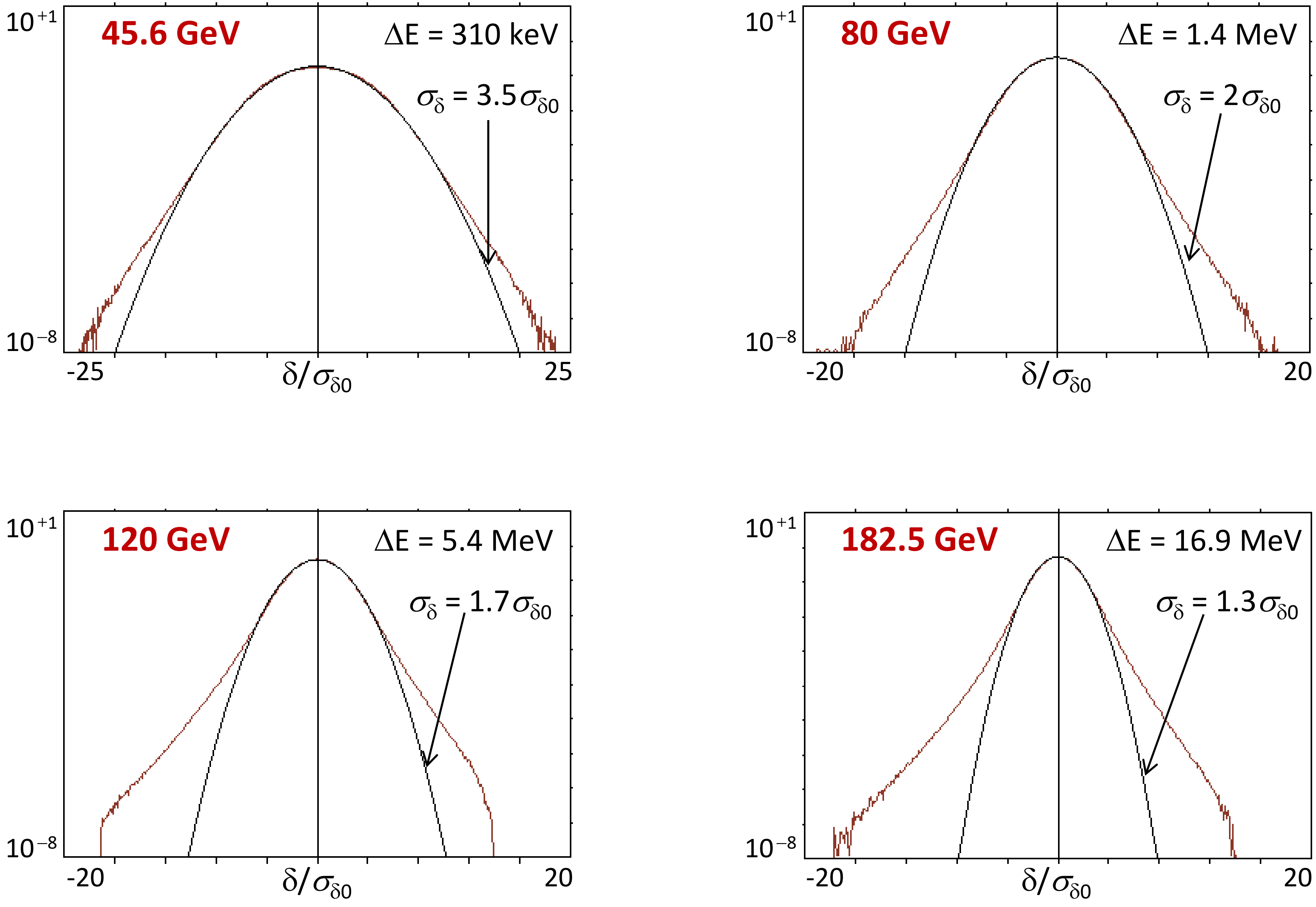
- Neat choice of ν_x between synchro-betatron resonances.

Scan of ν_x consists of 50 points (step is 0.001). It takes about one day of QSS simulations.

Many scans were made to perform parameter optimization. If we do this in SS model, then the time would be too long.

At several points (stable and unstable) the results have been checked by SS code and the match with QSS is very good.

Beamstrahlung and the Energy Spread



Old parameters from the CDR, 2 IPs. Self-consistent results obtained in QSS simulations.

Energy distributions are shown in a logarithmic scale.

The black lines (parabola) correspond to Gaussian distributions fitted to the beam core.

The large momentum acceptance is required at all energies!

3D Flip-Flop

1) Asymmetry in the bunch currents leads to asymmetry in σ_z due to beamstrahlung (BS).
2) In collision with LPA, asymmetry in σ_z:
   a. Enhances synchrotron modulation of the horizontal kick for a longer (weak) bunch, thus amplifying synchro-betatron resonances.
   b. ξ_x^w grows quadratically and ξ_y^w – linearly with decrease of σ_z^s, so the footprint expands and can cross more resonances.

   All this leads to an increase in both transverse emittances of the weak bunch.
3) An increase in ε_x^w has two consequences:
   1. Weakening of BS for the strong bunch, which makes it shorter and thereby enhances BS for the weak bunch. **This is one positive feedback loop.**
   2. Growth of ε_y^w due to betatron coupling, which leads to asymmetry in the vertical beam sizes.
4) Asymmetry in σ_y enhances BS for the weak bunch and its lengthening, while BS for the opposite bunch weakens and σ_z^s shrinks. Thus the asymmetry in σ_z increases even more. **This is another positive feedback loop.**

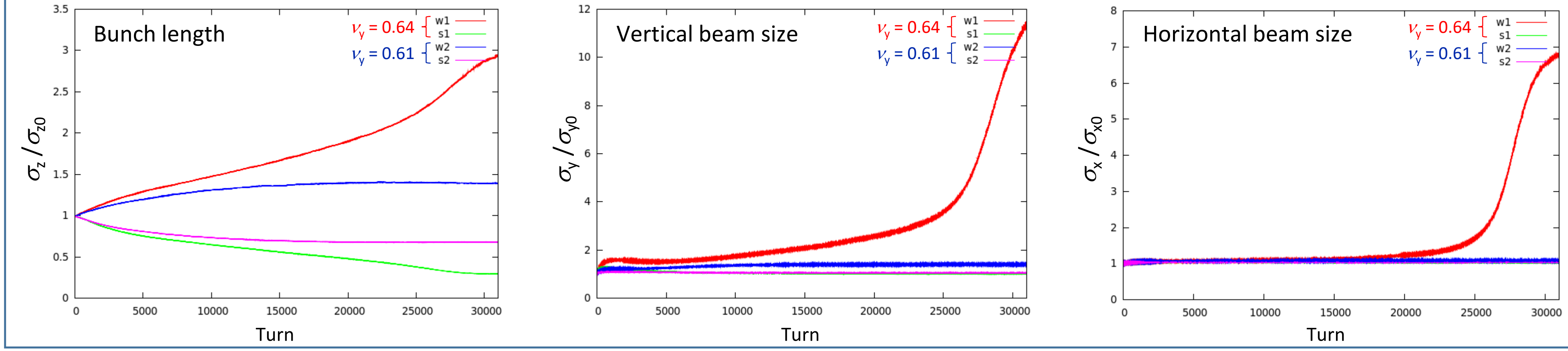
There are many possible scenarios for 3D flip-flop:

1) Starts from asymmetry in the bunch populations.
2) Starts from ε_x^w growth (e.g. synchro-betatron resonances $2\nu_x - k\nu_z = 1$), then ε_y^w increases due to betatron coupling.
3) Starts from ε_y^w growth (e.g. non-optimal ν_y or strength of crab sextupoles). After σ_z^s is sufficiently reduced, and ξ_x^w increased, the resonances $2\nu_x - k\nu_z = 1$ lead to ε_x^w blowup.

In all cases, beamstrahlung plays a key role: σ_z strongly depend on [asymmetry in] emittances, and $\xi_{x,y}$ depend on σ_z^s.

Mitigation:

- Minimize asymmetry in the population of colliding bunches.
- Avoid the vertical blowup: good choice of the working point, CW strength, etc.
- Avoid and mitigate the horizontal synchro-betatron resonances.



Example of 3D flip-flop. Small asymmetry in the bunch populations plus non-optimal vertical betatron tune.

Analytical Formulation for 3D Flip-Flop?

Can we develop an analytical model to predict 3D flip-flop?

- The dynamical system is very complicated and all parameters (bunch length, tune shifts, emittances) are mutually dependent.
- Analytical model can only be based on known dependencies. These dependencies are complex, non-linear and depend on many other parameters. How can we get these dependencies? Only from tracking.
- But if we have tracking code, then we can get the answer about flip-flop directly. Why then do we need analytics?
- It is highly doubtful that a self-consistent analytical model for 3D flip-flop can be created. We need to rely on simulation, as has long been done for conventional beam-beam effects and other complex dynamical systems.

Lifetime Modeling

Simplified model (as in the CDR)

- Transverse aperture was set "by hand" to 15 $\sigma_x \times 70\ \sigma_y$.
- Momentum acceptance was set "by hand" to the value obtained in DA optimizations by SAD.
- Long-term tracking in linear lattice, WS model. Many particles and many turns. Every turn check every particle weather it is outside the aperture or not.
- Counting the number of lost particles per a given number of turns. And this determines the lifetime.

More realistic model

- Nonlinear lattice with misalignments, errors and corrections. This determines the 6D dynamic aperture, so there is no need to set it manually.
- Tapering and SR in all magnets including quadrupoles.
- Long-term tracking in WS model. Every turn check every particle weather it is outside the aperture or not.
- Counting the number of lost particles per a given number of turns. And this determines the lifetime.

Current Activity and Next Steps

- It has been found that misalignments and lattice errors can lead to a significant decrease in DA and momentum acceptance. We are currently looking for ways to reduce misalignments (i.e. beam based alignment) and to perform efficient corrections. A special group has been created for this, and progress is already being made (see “Tuning” session tomorrow).
- It is necessary to conduct massive beam-beam simulations in a realistic model, taking into account all nonlinearities and collective effects. We have several codes that are ready (or almost ready) for this.
- Some important results are expected in the coming months. They will clarify the question of what luminosity can be obtained for a given error and misalignment tolerance.