Particle tracking and beam losses in the ILC 20 mrad extraction line

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Introduction

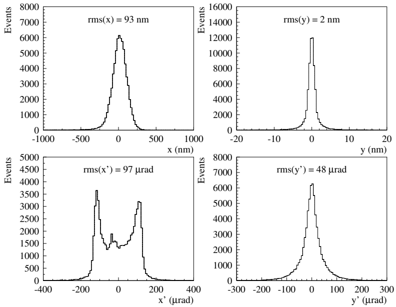
- At high-energy e^+e^- linear colliders, the incoming beams experience strong electromagnetic fields at the interaction point $\rightarrow$ increased angular divergence of the disrupted beam, emission of beamstrahlung photons (thus a larger energy spread) and production of coherent pairs.
- All these particles must be transported to their dump with minimal losses in the extraction line.
- We consider a TeV e^+e^- linear collider with a 20 mrad crossing angle (four luminosity configurations for ILC and one for CLIC).
- Beam losses are studied with DIMAD.

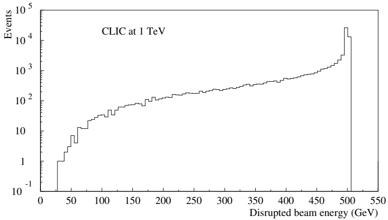
Incoming beam parameters

Configuration at 1 TeV	CLIC	ILC nominal	ILC hl1	ILC hl2	ILC hl3
Particles per bunch (10^{10})	0.256	2.0	2.0	2.4	2.0
Bunches per RF pulse	220	2820	2820	2820	2820
Bunch spacing (ns)	0.267	307.7	307.7	307.7	307.7
Beam current (A)	1.5	0.0104	0.0104	0.0125	0.0104
Repetition frequency (Hz)	150	4	4	4	4
Primary beam power (MW)	6.8	18.1	18.1	21.7	18.1
$(\beta\gamma)\epsilon_x$ in 10^{-6} m.rad	0.660	10	10	10	10
$(\beta\gamma)\epsilon_y$ in 10^{-6} m.rad	0.001	0.04	0.03	0.023	0.023
σ_x in nm	94	554	320	550	470
σ_y in nm	1.0	3.5	2.5	2.7	2.7
σ_z in μm	30.8	300	150	300	300
Luminosity (10^{34} cm^{-2} s^{-1})	2.8	2.8	7.8	5.7	4.6
Photons per e^+ or e^-	0.9	1.4	2.2	1.7	1.7
Beamstrahlung loss δ_B	9.0%	4.8%	17.6%	6.7%	6.5%

Disrupted beam distributions

Strong beam-beam interactions lead to an emittance growth and the apparition of low-energy tails in the disrupted beam.

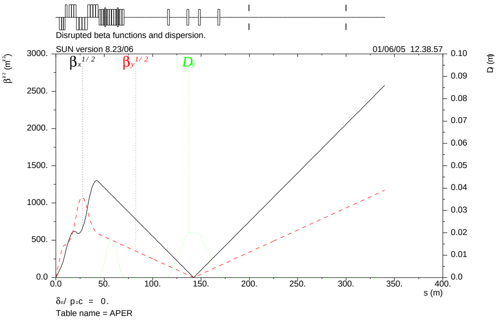




Distributions for CLIC at 1 TeV

The ILC 20 mrad extraction line

The ILC 20 mrad extraction line consists of a DFDF quadruplet, followed by two vertical chicanes for energy and polarization measurements and a field-free region with two collimators at 200 and 300 m downstream of the interaction point.



Estimation of the power losses

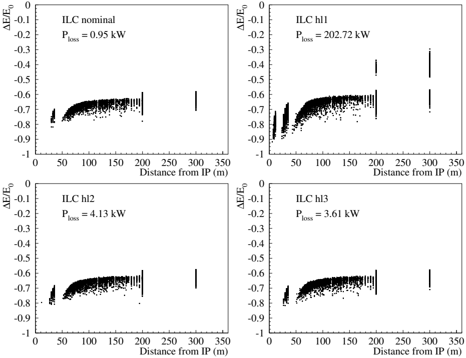
The disrupted beam distributions are tracked with DIMAD, from the interaction point to the dump.
Using the number of lost particles in the extraction line, as well as their energy, one calculates the total beam power loss:

$$P_{loss}[W] = 1.602 \times 10^{-10} \, \frac{N_b \, n \, f}{N_{tracks}} \sum_{i=1}^{N_{loss}} E_i \, .$$

- N_b is the number of particles per bunch,
- n is the number of bunches per RF pulse,
- f is the repetition frequency (in Hz),
- N_{tracks} and N_{lost} are the number of tracked and lost particles,
- E_i is the energy of the particle i (in GeV).

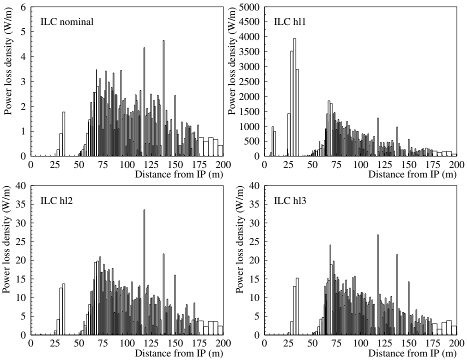
Disrupted beam losses (ILC cases)

Total power losses along the 20 mrad extraction line:



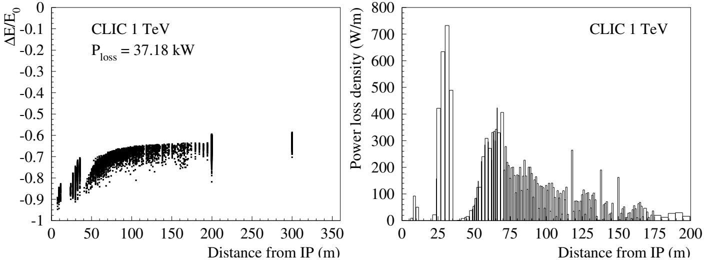
Disrupted beam losses (ILC cases)

Power loss density along the 20 mrad extraction line, upstream of the collimators:



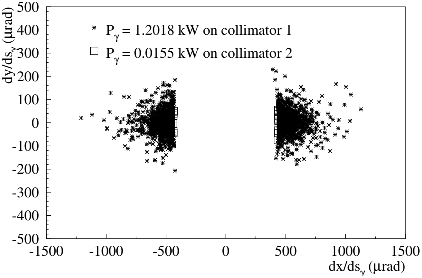
Disrupted beam losses (CLIC case)

Total power losses (left) and loss density (right) along the 20 mrad extraction line, upstream of the collimators:



Beamstrahlung photon losses

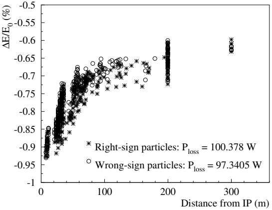
Beamstrahlung photons losses occur on the first collimator, which has an opening angle of 0.44 mrad. Only the ILC hl1 case leads to significant losses ($P_{loss} = 1.2$ kW), due to the large horizontal angular divergence of the photons.

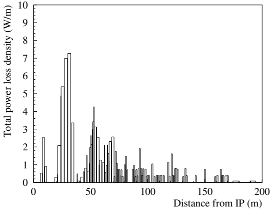


Coherent pair losses

At CLIC (resp. ILC hl1), one expects 5.3×10^5 (resp. 3.6×10^5) coherent pairs per bunch crossing. In all other cases, coherent pair production remains negligible.

About 75% of these particles do not reach the dump, due to their low energy. The corresponding power loss is smaller than 0.2 kW for CLIC (and thus even less in the ILC hl1 case).





Beam-beam effects vs vertical position offset

With ILC or CLIC vertically flat beams, horizontal position offsets have no significant effects.

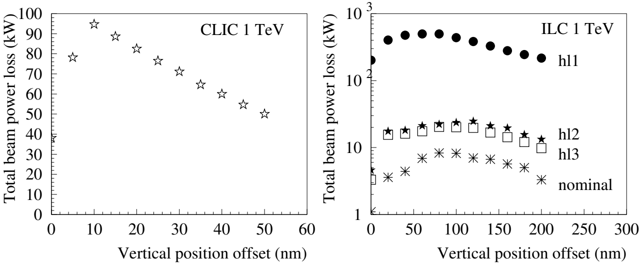
When a vertical position offset Δy is introduced:

- small Δy: the field seen by the bulk of charged particles in one beam increases with the distance to the other beam... and so do disruption, beamstrahlung photon emission and coherent pair production.
- large Δy: the field seen by each bunch gets smaller as the distance between the beams grows, so the disrupted beam distributions converge to the incoming beam distributions... and the beamstrahlung photon emission disappears.

The beam-beam effects are largest when $\Delta y = 10 \to 30\sigma_y$.

Disrupted beam losses vs vertical position offset

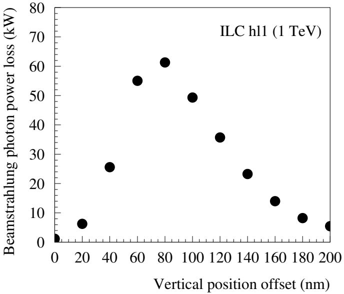
As a result of the increased emittance and energy spread that are induced by the vertical position offset, one expects larger power losses for the disrupted beams in the extraction line.



Other losses vs vertical position offset

Beamstrahlung photons lead to significant losses in the ILC hl1 case only.

The losses are maximal when $\Delta y = 12\sigma_y$.



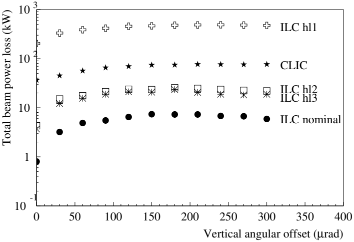
The contribution of coherent pairs remains negligible even when a vertical position offset is introduced.

Disrupted beam losses vs vertical angular offset

Horizontal angular offsets lead to a diminution of the luminosity and thus to less power losses in the extraction beam line.

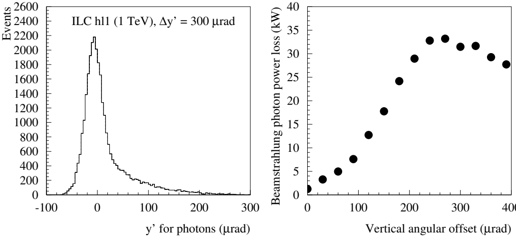
The disrupted beam losses due a vertical angular offset $\Delta y'$ first increase, before reaching some saturation at 0.1-0.2 mrad.

The maximal losses obtained here are usually slightly lower than (or comparable to) those due to a vertical position offset.



Other losses vs vertical angular offset

Beamstrahlung photon losses increase when there is a vertical angular offset due to the apparition of tails in the y'-distribution.



The contribution of coherent pairs remains negligible even when a vertical angular offset is introduced.

Conclusion and outlooks

- In the nominal ILC configuration, the power losses seem to be acceptable. Also, the recently proposed ILC hl2 and hl3 configurations for reaching high luminosity should lead to acceptable losses. On the other hand, the power losses become too large in the ILC hl1 and CLIC configurations.
- Further studies should include a more detailed magnet design, more collimators to reduce the loss densities and simulations of the interaction between lost particles and surrounding matter (BDSIM).
- The next task at Uppsala University is to perform a design study of the post-collision line for CLIC at 3 TeV, where the most serious challenges are the long low-energy tails and the much larger amount of coherent pairs.

Introduction

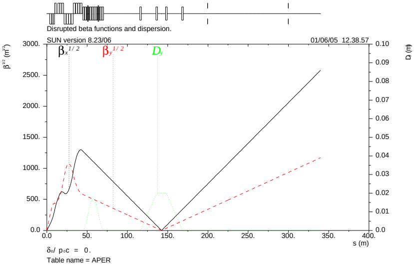
ILC → two configurations for the beam crossing angle:

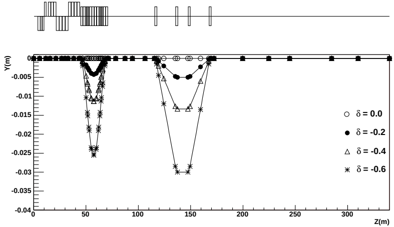
- 2 mrad crossing angle: extraction of the disrupted beam off-center in the first large super-conducting defocusing quadrupole of the final focus beam line, as well as in the two nearby sextupoles.
- 20 mrad crossing angle: crab-crossing corrections, beam passing through the solenoid field with an angle.

BDSIM is a new package that computes the particle trajectories inside beam line elements, with an interface to GEANT4 to fully simulate interactions with the surrounding matter.
→ Benchmarking of its tracking procedure by a comparison with DIMAD for the nominal ILC at 500 GeV.

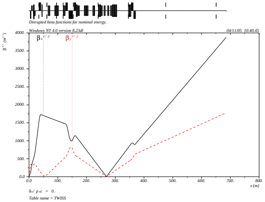
Single off-momentum particle in the 20 mrad case

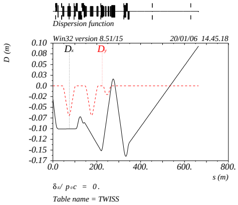
Perfect agreement between DIMAD and BDSIM for single off-momentum particles in the 20 mrad ILC extraction line.

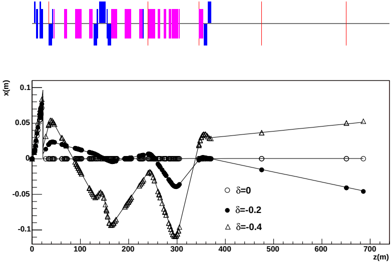




Single off-momentum particle in the 2 mrad case



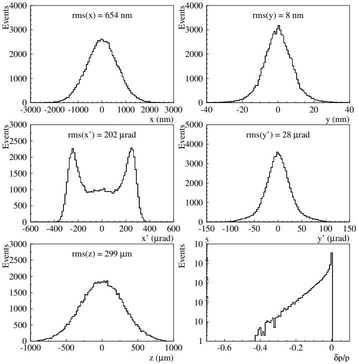




Perfect agreement between DIMAD and BDSIM for single off-momentum particles in the 2 mrad ILC extraction line.

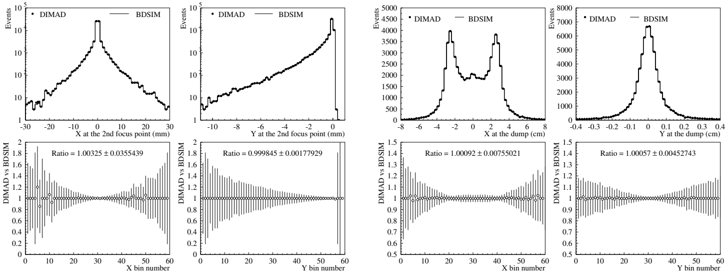
Complete phase space: outgoing beam distributions

ILC nominal case at 500 GeV → no significant losses in the extraction lines → useful to benchmark the tracking procedures.



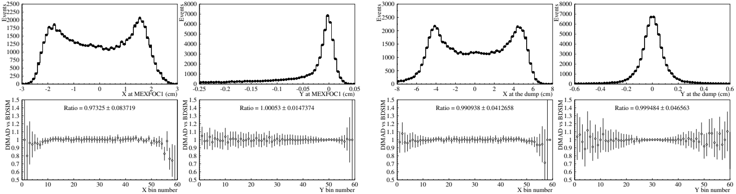
Complete phase space: 20 mrad case

A comparison bin by bin at the 2nd focus point and the dump shows a good agreement between DIMAD and BDSIM.



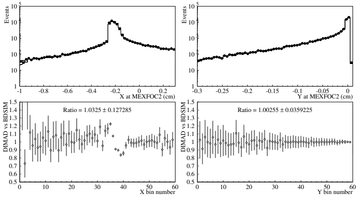
Complete phase space: 2 mrad case (1)

A comparison bin by bin at MEXFOC1 and the dump shows a good agreement between DIMAD and BDSIM...



Complete phase space: 2 mrad case (2)

... however some discrepancy is observed at the secondary focus point MEXFOC2!
This may be due to the differing treatments of high-order effects in the optical transport for non-linear elements.



Conclusion and outlooks

- BDSIM and DIMAD mostly give an equivalent description of the beam transport along the post-collision lines.
- A similar benchmarking study is being performed to compare the power losses obtained with DIMAD and BDSIM in the 2 mrad and 20 mrad post-collision lines.
- A more comprehensive simulation study of the backgrounds from secondary particles will follow.