Beam-beam Effects in Linear Colliders

Daniel Schulte
Single pass poses luminosity challenge

Low emittances are produced in the damping rings

They must be maintained with limited degradation

The beam delivery system (BDS) squeezes the beam as much as possible
ILC

Beam-beam effects in Linear Colliders 3

Damping Rings

E+ source

Ring to Main Linac (RTML) (w. bunch compressors)

e- Main Linac

E+ Main Linac

Parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>C.M. Energy</td>
<td>500 GeV</td>
</tr>
<tr>
<td>Peak luminosity</td>
<td>$1.8 \times 10^{34} , \text{cm}^{-2}\text{s}^{-1}$</td>
</tr>
<tr>
<td>Beam Rep. rate</td>
<td>5 Hz</td>
</tr>
<tr>
<td>Pulse duration</td>
<td>0.73 ms</td>
</tr>
<tr>
<td>Average current</td>
<td>5.8 mA (in pulse)</td>
</tr>
<tr>
<td>E gradient in SCRF acc. cavity</td>
<td>31.5 MV/m +/-20% $Q_0 = 1 \times 10^{10}$</td>
</tr>
</tbody>
</table>
CLIC (at 3TeV)

Drive beam time structure - initial

- 140 µs train length - 24 x 24 sub-pulses
- 4.2 A - 2.4 GeV - 60 cm between bunches

Drive beam time structure - final

- 240 ns - 5.8 µs
- 24 pulses - 101 A - 2.5 cm between bunches

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Beam-beam effects in Linear Colliders
CLIC Staged Approach

- First stage: $E_{\text{cms}}=380\text{GeV}$, $L=1.5 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$, $L_{0.01}/L>0.6$
- Second stage: $E_{\text{cms}}=O(1.5\text{TeV})$
- Final stage: $E_{\text{cms}}=3\text{TeV}$, $L_{0.01}=2 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$, $L_{0.01}/L>0.3$
Linear Collider Experiment

- Measure vertex and short-lived particles
- Measure momentum and charge of charged particles
- Energy measurement of (charged and) neutral particles
- B-field for momentum and charge measurement
- Field return and muon particle identification
- Final steering of nm-size beams

10^9 readout cells

- Measure vertex and Short-lived particles
- 6 m
- 10^9 readout cells

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Beam-beam effects in Linear Colliders

L. Linssen
Vol 1: The CLIC accelerator and site facilities
- CLIC concept with exploration over multi-TeV energy range up to 3 TeV
- Feasibility study of CLIC parameters optimized at 3 TeV (most demanding)
- Consider also 500 GeV, and intermediate energy range
- https://edms.cern.ch/document/1234244/

Vol 2: Physics and detectors at CLIC
- Physics at a multi-TeV CLIC machine can be measured with high precision, despite challenging background conditions
- External review procedure in October 2011
- http://arxiv.org/pdf/1202.5940v1

Vol 3: “CLIC study summary”
- Summary and available for the European Strategy process, including possible implementation stages for a CLIC machine as well as costing and cost-drives
- Proposing objectives and work plan of post CDR phase (2012-16)
- http://arxiv.org/pdf/1209.2543v1

In addition a shorter overview document was submitted as input to the European Strategy update, available at: http://arxiv.org/pdf/1208.1402v1

## ILC and CLIC Main Parameters

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<tr>
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<tbody>
<tr>
<td>Centre of mass energy</td>
<td>$E_{cm}$ [GeV]</td>
<td>92</td>
<td>500</td>
<td>380</td>
<td>3000</td>
</tr>
<tr>
<td>Geometric luminosity</td>
<td>$L_{geom}$ [$10^{34}$cm$^{-2}$s$^{-1}$]</td>
<td>0.00015</td>
<td>0.75</td>
<td>0.8</td>
<td>4.3</td>
</tr>
<tr>
<td>Total luminosity</td>
<td>$L$ [$10^{34}$cm$^{-2}$s$^{-1}$]</td>
<td>0.0003</td>
<td>1.8</td>
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<td>6</td>
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<tr>
<td>Luminosity in peak</td>
<td>$L_{0.01}$ [$10^{34}$cm$^{-2}$s$^{-1}$]</td>
<td>0.0003</td>
<td>1</td>
<td>0.9</td>
<td>2</td>
</tr>
<tr>
<td>Gradient</td>
<td>$G$ [MV/m]</td>
<td>20</td>
<td>31.5</td>
<td>72</td>
<td>100</td>
</tr>
<tr>
<td>Particles per bunch</td>
<td>$N$ [$10^9$]</td>
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</tr>
<tr>
<td>Emittance</td>
<td>$\varepsilon_{x,y}$ [$\mu$m/nm]</td>
<td>~3/3000</td>
<td>10/35</td>
<td>0.95/30</td>
<td>0.66/20</td>
</tr>
<tr>
<td>Betafunction</td>
<td>$\beta_{x,y}$ [mm/mm]</td>
<td>~100/10</td>
<td>11/0.48</td>
<td>8.2/0.1</td>
<td>6/0.07</td>
</tr>
<tr>
<td>Bunches per pulse</td>
<td>$n_b$</td>
<td>1</td>
<td>1312</td>
<td>352</td>
<td>312</td>
</tr>
<tr>
<td>Distance between bunches</td>
<td>$\Delta z$ [ns]</td>
<td>-</td>
<td>554</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>$f_r$ [Hz]</td>
<td>120</td>
<td>5</td>
<td>50</td>
<td>50</td>
</tr>
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</table>

There are more parameter sets for ILC and CLIC at different energies.
CLIC at 3TeV has higher order optics and radiation effects.
Luminosity and Parameter Drivers

Can re-write normal luminosity formula (note: no crossing angle assumed)

\[ \mathcal{L} = H_D \frac{N^2}{4\pi \sigma_x \sigma_y} n_b f_r \]

Somewhat simplified view

Beam power

Luminosity spectrum

Beam Quality (+bunch length)
Note: Crossing Angle

Have crossing angles
• ILC: 14 mrad
• CLIC: 20 mrad
• to reduce effects of parasitic crossings
• to extract the spent beam cleanly

Luminosity with crossing angle
\[ \mathcal{L} = \frac{N^2 f_r \eta}{4\pi \sigma_x \sigma_y} \sqrt{\frac{1}{1 + \left( \frac{\sigma_z}{\sigma_x} \tan \frac{\theta_c}{2} \right)^2}} \]

Use crab cavities:

Can ignore crossing angle for beam-beam calculation
But not in detector design

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Beam-beam effects in Linear Colliders
Beam-beam Effect

Bunches are squeezed strongly to maximise luminosity

Electron magnetic fields are very strong

Beam particles travel on curved trajectories

They emit photons \((O(1))\) (beamstrahlung)

They collide with less than nominal energy

Request from physics
\(L_{0.01}/L > 0.6\) below 500 GeV
\(L_{0.01}/L > 0.3\) at 3 TeV

CLIC at 3 TeV

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Beam-beam effects in Linear Colliders
Beam Focusing

Note: The colliding beams are flat to reduce beamstrahlung, we will see later why.

Deflection easy to calculate for:
- small offset to the axis
- no initial angle
- negligible change of trajectory

In each plane core of beam is focused to one point

\[ s = f_x \quad s = f_y \]

\[ r_e \approx 2.8 \times 10^{-15} \text{ m} \]
Disruption Parameter

We define the disruption parameters to compare the focal length of the bunch to its length:

\[ D_x = \frac{\sigma_z}{f_x} = \frac{2Nre\sigma_z}{\gamma(\sigma_x + \sigma_y)\sigma_x} \quad D_y = \frac{\sigma_z}{f_y} = \frac{2Nre\sigma_z}{\gamma(\sigma_x + \sigma_y)\sigma_y} \]

- \( D \ll 1 \):
  - Particles do not move much in beam
  - Thin lens approximation is OK
  - Analytic calculation possible
  - Weak-strong simulation sufficient
  - Typical for x-plane

- \( D \gg 1 \):
  - Particles do move in beam
  - Thin lens assumption has been wrong
  - Analytic calculation tough
  - Strong-strong simulation required
  - Typical for y-plane
## Typical Disruption

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<tr>
<td>Vertical emittance</td>
<td>$\varepsilon_{x,y}$ [nm]</td>
<td>3000</td>
<td>35</td>
<td>40</td>
<td>20</td>
</tr>
<tr>
<td>Horizontal disruption</td>
<td>$D_x$</td>
<td>0.6</td>
<td>0.3</td>
<td>0.24</td>
<td>0.2</td>
</tr>
<tr>
<td>Vertical disruption</td>
<td>$D_y$</td>
<td>1.7</td>
<td>24.3</td>
<td>12.5</td>
<td>7.6</td>
</tr>
</tbody>
</table>

\[ D_x \ll 1 \text{ and } D_y \gg 1 \]

Need to resort to strong-strong simulation
Simulation Codes

Need strong-strong code

- CAIN (K. Yokoya et al.)
- GUINEA-PIG (D. Schulte et al.)

- Beams => macro particles
- Beams => slices
- Slices => cells
- The simulation is performed in a number of time steps in each of them
- The macro-particle charges are distributed over the cells
  - The forces at the cell locations are calculated
  - The forces are applied to the macro particles
  - The particles are advanced

All simulation performed with GUINEA-PIG
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Beam-beam force switched off
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Beam-beam force switched off

Y direction

Z direction

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Beam-beam effects in Linear Colliders
The Spent Beam

Particles move little in the horizontal plane
⇒ Can see the field profile

They start to oscillate in the vertical plane
⇒ Final angle depends also on the phase that they happen to have at the end of the collision
Beamstrahlung

Similar to synchrotron radiation

From local trajectory curvature calculate critical

Define beamstrahlung parameter Upsilon

Average Upsilon is approximately given by

\[
\begin{align*}
\hbar \omega_c &= \frac{3}{2} \frac{\gamma^3 \hbar c}{\rho} \\
\Upsilon &= \frac{2}{3} \frac{\hbar \omega_c}{E_0} \\
\langle \Upsilon \rangle &= \frac{5}{6} \frac{N r_e^2 \gamma}{\alpha (\sigma_x + \sigma_y) \sigma_z}
\end{align*}
\]
The spectrum is given by

\[
\frac{d\dot{w}}{d\omega} = \frac{\alpha}{\sqrt{3\pi} \gamma^2} \left[ \int_{x}^{\infty} K_{\frac{5}{3}}(x')dx' + \frac{\hbar \omega}{E} \frac{\hbar \omega}{E - \hbar \omega} K_{\frac{2}{3}}(x) \right]
\]

With modified Bessel functions \(K_{\frac{5}{3}}\) and \(K_{\frac{2}{3}}\)

\[
x = \frac{\omega}{\omega_c} \frac{E}{E - \hbar \omega}
\]

Classical regime \(\gamma \ll 1\)

ILC \(\gamma = 0.06\)

CLIC at 380 GeV \(\gamma = 0.17\)

Quantum regime \(\gamma \gg 1\)

CLIC at 3 TeV \(\gamma = 5\)
Photons in the Classical Regime $\gamma \ll 1$

Number of photons Dominates $L/L_{0.01}$

Energy of photons Defines shape of tail

\[ n_\gamma \propto \frac{N}{\sigma_x + \sigma_y} \]

\[ \mathcal{L} \propto \frac{N}{\sigma_x \sigma_y} \]

\[ \sigma_x \gg \sigma_y \]

\[ \sigma_x + \sigma_y \approx \sigma_x \]

Determined by beamstrahlung

\[ \frac{E_\gamma}{E_0} \propto \frac{N}{\sigma_x + \sigma_y \sigma_z} \gamma \]

\[ \mathcal{L} \propto H_D \left( \frac{N}{\sigma_x} \right) N n_b f_r \frac{1}{\sigma_y} \]

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Photon Production

Horizontal plane

Vertical plane
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<td>$L$ [$10^{34}$cm$^{-2}$s$^{-1}$]</td>
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<td>1.5</td>
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</tr>
<tr>
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<td>$L_{0.01}$ [$10^{34}$cm$^{-2}$s$^{-1}$]</td>
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</tr>
<tr>
<td>Photons per beam particle</td>
<td>$n_{\gamma}$</td>
<td>1.9</td>
<td>1.5</td>
<td>2.1</td>
</tr>
<tr>
<td>Average photon energy</td>
<td>$&lt;E_{\gamma}/E_0&gt;$ [%]</td>
<td>2.4</td>
<td>4.5</td>
<td>13</td>
</tr>
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</table>

Photon numbers and $L_{0.01}/L$ are similar for ILC and CLIC at low energies

Average photon energy does not seem to matter too much for $L_{0.01}$
Luminosity spectrum for ILC, CLIC at 380GeV looks similar (beam energy spread is ignored)

Luminosity $L_{0.01}$ above 99% of nominal CMS energy is $L_{0.01}/L = 60\%$

For CLIC380, this has been the design criterion

But why did the experiments chose $L_{0.01}/L > 60\%$?
Electrons often emit a photon before the collision
⇒ Initial State Radiation

The electron can be replaced by a spectrum of electrons

This yields a luminosity spectrum

About 65% probability of collision with more than 99% of nominal energy
The total luminosity $L$ varies strongly with beta-function.

But $L_{0.01}$ does not change so much.

Hard to push beta-functions that low.

So tend to use $L_{0.01}/L = 60\%$ as criterion.

Reasonable compromise for most physics studies.
Using the naïve luminosity calculation with beta-function at the IP we find that the luminosity can be increased by reducing $\beta_y$

$$\mathcal{L} = \frac{N^2}{4\pi \sigma_x \sigma_y} n_b f_r$$

There are two limits:

The lattice design tends to find a practical lower limit a bit below $\beta_y=100 \, \mu m$
CLIC at 3TeV has $\beta_y=70 \, \mu m$ but strong geometric aberrations

Luminosity actually increases not as predicted

Not excluded that this can be improved but people worked on it for years

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**Hourglass Effect**

Taking into account hourglass effect

\[
\beta(s) = \sqrt{\beta(0) + \frac{s^2}{\beta(0)}}
\]

Luminosity does not improve much below \( \beta_y < \sigma_z \)

For flat beams, the optimum is around \( \beta_y \approx 0.25 \times \sigma_z \)

Note: This is different for round beams.
Including pinch effect

\[ \mathcal{L} = H_D \frac{N^2}{4\pi \sigma_x \sigma_y} n_b f_r \]

There is an optimum value for beta

For smaller beta-function the geometric luminosity increases but the enhancement is reduced

Small beta-functions lead to
High chromaticity
⇒ Optics is difficult
Large divergence
⇒ Quadrupole aperture is limited
Focusing before IP leads to more luminosity (D.S.)

For CLIC and ILC ~10% luminosity gain
Note: ILC Full Optimisation

For ILC could consider smaller vertical beta-functions

Smaller beta-functions profit more from waist shift  \( \Rightarrow 0.24\text{mm} \) seems best

Would gain 15\% luminosity

But still more difficult to produce (larger divergence)
And tolerances become tighter
Luminosity and Offset

Luminosity loss for rigid bunches with offset

$$\frac{\mathcal{L}}{\mathcal{L}_0} = \exp\left(\frac{-\Delta y^2}{4\sigma_y^2}\right)$$

Actual loss depends strongly on disruption

Note: the simulations suffer from noise (use of macroparticles)

Need to enforce symmetric charge distribution to simulate high disruption

Can you trust the results in real life?
Luminosity and Offset

Luminosity loss for beam offsets depends strongly on disruption parameter

\[ \Delta y = 0.4 \sigma_y \]

\[ L = 0.71 L_0 \quad D_y \sim 24 \]

\[ L = 0.92 L_0 \quad D_y \sim 12 \]
Luminosity loss for beam offsets depends strongly on disruption parameter

\[ \Delta y = 2 \sigma_y \]

\[ L = 0.38 L_0 \]

\[ L = 0.59 L_0 \]
Luminosity and Offset

Luminosity loss for beam offsets depends strongly on disruption parameter

\[ \Delta y = 4 \sigma_y \]

\[ L = 0.26 L_0 \]
Beam-beam Deflection

Strong deflection allows to easily measure and correct offset.

In CLIC an offset $\Delta y = 0.1\sigma_y = 0.1\text{nm}$

$\Rightarrow$ 3m downstream of IP 40$\mu\text{m}$ beam offset.

Get great signals for the BPMs.
Note: The Banana Effect

a) Wakefields + dispersion can create banana-shaped bunch in main linac

b) Do not model with projected emittance

c) The correct shape should be used

For large disruption (ILC) banana can reduce luminosity

Study done for TESLA
Similar disruption as ILC
Goal is to maximise $L_{0.01}$
And $L_{0.01}/L > 0.3$

$\gamma \gg 1$

$$n_\gamma \propto \left(\frac{\sigma_z}{\gamma}\right)^{\frac{1}{3}} \left(\frac{N}{\sigma_x + \sigma_y}\right)^{\frac{2}{3}}$$

$$\mathcal{L} \propto \frac{n_\gamma^{3/2}}{\sqrt{\sigma_z}} \eta P_{wall} \frac{1}{\sigma_y} \cdot H_D$$
Coherent Pair Creation

Beam fields in the rest system of a photon can reach the Schwinger Critical Field
⇒ The quantum electrodynamics becomes non-linear

A photon in a very strong field can form an electron-positron pair
⇒ Coherent pair creation

\[ \frac{\gamma B}{B_c} = \gamma \]

\[ B_c \approx 4.4 \times 10^9 \text{T} \]

Produce 6.8x10^8 pairs
Average particle energy 0.3TeV
Spent Beam Divergence

Beam particles are focused by oncoming beam

Photons are radiated into direction of beam particles

Coherent pair particles can be focused or defocused by the beams but deflection limited due to their high energy

-> Extraction hole angle should be significantly larger than 6 mradian

We chose 10 mradian for CLIC

-> 20 mradian crossing angle

ILC requires 14 mradian crossing angle
The last focusing magnet of the machine is inside of the detector
CLIC Inner Detector Layout

Increased ratio $x/s$

10 mradian
For the beam

10 mradian
To fit the quadrupole
Colliding photons can produce electron-positron pairs (incoherent pair production) \(O(10^5)\) per bunch crossing.
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<td>$N_{coh}$</td>
<td>-</td>
<td>-</td>
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<td>Their energy</td>
<td>$E_{coh}$ [TeV]</td>
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<td>-</td>
<td>2.1$\times10^8$</td>
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<tr>
<td>Incoherent pairs</td>
<td>$N_{incoh}$</td>
<td>196$\times10^3$</td>
<td>58$\times10^3$</td>
<td>300$\times10^3$</td>
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<tr>
<td>Their energy</td>
<td>$E_{incoh}$ [TeV]</td>
<td>484</td>
<td>187</td>
<td>2.3$\times10^4$</td>
</tr>
</tbody>
</table>
Incoherent pairs can be strongly deflected by the beam-beam interaction. The maximum deflection angle depends on their energy.
Impact on Vertex Detector

To vertex detector can identify particles originating from decays of other particles.

Need a certain angular coverage.

Hit density from pairs depends on radius and field. Edge is due to beam-beam deflection.

Limit $O(1 \text{mm}^{-2})$.
Conclusion

• Beam-beam effects have critical impact on luminosity in linear colliders
  – Strong pinching enhances luminosity
  – Simulations tool are important
  – Beamstrahlung requires flat beams and gives lower limit on horizontal size
    • Has impact on experiment performance
  – For high disruption collisions can be unstable
    • Very good beam-beam stability is required
  – Non-linear QED can appear at high energies
    • Beam charge can increase by $O(10\%)$

• Machine background poses important constraints on the experiment
  – Minimum vertex detector radius is given by beam parameters
Reserve
Higgs Physics in e+e- Collisions

- **Precision Higgs measurements**
- **Model-independent**
  - Higgs couplings
  - Higgs mass
- Large energy span of linear colliders allows to collect a maximum of information:
  - ILC: 500 GeV (1 TeV)
  - CLIC: ~350 GeV – 3 TeV

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Beam-beam effects in Linear Colliders
Invisible Higgs Decays

Can we check that the Higgs does not decay into something invisible, e.g. neutrinos?

Yes, missing mass (or recoil mass) analysis:

1) Measure the Z, e.g. from produced jets

2) Subtract Z momentum from initial state
\[(E_{cm},0,0,0)-(E_Z, P_{Z,x}, P_{Z,y}, P_{Z,z})=(E_H, P_{H,x}, P_{H,y}, P_{H,z})\]

3) Result is mass and momentum of other particle
Even if we do not see it

So we know the missing particle
Automatic Parameter Determination

Structure design fixed by few parameters
\[ a_1, a_2, d_1, d_2, N_c, \phi, G \]

Beam parameters derived automatically to reach specific energy and luminosity

Consistency of structure with RF constraints is checked

Repeat for 1.7 billion cases

Design choices and specific studies

- Use 50Hz operation for beam stability
- Scale horizontal emittance with charge to keep the same risk in damping ring
- Scale for constant local stability in main linac, i.e. tolerances vary but stay above CDR values
- BDS design similar to CDR, use improved $\beta_x$-reach as reserve
Many thanks to the rebaselining team that provided the models that are integrated in the code.

Luminosity goal significantly impact minimum cost
For $L = 1 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$ to $L = 2 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$:
Costs 0.5 a.u.
And $O(100\text{MW})$

Cheapest machine is close to lowest power consumption => small potential for trade-off
Can reach high electron-positron centre-of-mass energies
• almost no synchrotron radiation

Single pass, hence two main challenges
• gradient
• luminosity
Note: Luminosity Enhancement

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol [unit]</th>
<th>ILC</th>
<th>CLIC</th>
<th>CLIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centre of mass energy</td>
<td>$E_{cm}$ [GeV]</td>
<td>500</td>
<td>380</td>
<td>3000</td>
</tr>
<tr>
<td>Total luminosity</td>
<td>$L$ [$10^{34}$ cm$^{-2}$s$^{-1}$]</td>
<td>1.8</td>
<td>1.5</td>
<td>6</td>
</tr>
<tr>
<td>Luminosity in peak</td>
<td>$L_{0.01}$ [$10^{34}$ cm$^{-2}$s$^{-1}$]</td>
<td>1</td>
<td>0.9</td>
<td>2</td>
</tr>
<tr>
<td>Particles per bunch</td>
<td>$N$ [$10^9$]</td>
<td>20</td>
<td>5.2</td>
<td>3.72</td>
</tr>
<tr>
<td>Bunch length</td>
<td>$\sigma_z$ [$\mu$m]</td>
<td>300</td>
<td>70</td>
<td>44</td>
</tr>
<tr>
<td>Collision beam size</td>
<td>$\sigma_{x,y}$ [nm/nm]</td>
<td>474/5.9</td>
<td>149/2.9</td>
<td>40/1</td>
</tr>
<tr>
<td>Vertical emittance</td>
<td>$\varepsilon_{x,y}$ [nm]</td>
<td>35</td>
<td>40</td>
<td>20</td>
</tr>
<tr>
<td>Geometric luminosity</td>
<td>$L_{geom}$ [$10^{34}$ cm$^{-2}$s$^{-1}$]</td>
<td>0.75</td>
<td>0.8</td>
<td>4.3</td>
</tr>
<tr>
<td>Enhancement factor</td>
<td>$H_D$</td>
<td>2.4</td>
<td>1.9</td>
<td>1.5</td>
</tr>
</tbody>
</table>
Top production at threshold is strongly affected by beam energy spread and beamstrahlung.

For $L_{0.01} > 0.6 L$ impact of beamstrahlung is comparable to ISR.

But depends on physics.
Travelling focus (Balakin):
We focus each slice of the beam on one point of the oncoming beam, e.g. $2\sigma_z$ before the centre.

The beam-beam forces keep the beam small.

Additional gain of 10% in luminosity.

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Beam-beam effects in Linear Colliders
Note: ILC with $\beta_y=0.24\text{mm}$

Even stronger offset dependence for smaller beta-function

So in practice less gain than expected