Collider Accelerator Physics

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My Research

• Projects: CLIC and ILC
• Diagnostics
  • How to measure electron beams
• Laserwire
  • Collide 1 μm high power laser (1 GW) with 1 μm electron beam
• Beam Position Monitors
  • Measure beam position to 10s of nanometers
• EM radiation for charged particles beams

Former life: HERA, QCD, top quark, energy spectrometry
Outline

• Historical overview

• Just enough accelerator physics, scaling and UG physics to understand the problems
  • Acceleration
  • Luminosity production

• Machines to address these problems
  • International Linear Collider (ILC)
  • Compact Linear Collider (CLIC)
  • Muon Collider
  • Large Hadron Collider (LHC) and its upgrade (High Energy; HE & High Luminosity; HL)

• Exotic acceleration
Recent History

• Tevatron shut down
• LHC moving into large scale data collection with higher energy and luminosity
• International efforts towards:
  • High energy or high luminosity LHC
  • ILC, CLIC, Muon Collider
  • Beam and laser driven plasmas
  • Exotics! Dielectric wakefield, meta-materials
Particle Physics

- Need events to perform analysis on
  - Stays remarkably constant

- Not the entire picture as we need to think about:
  - Beam energy
  - Polarisation
  - Composite nature of colliding beams (e.g., protons)
  - Of course complications PDFs etc

```
Number of events = \sigma L = \sigma \int \mathcal{L} \, dt
```

Cross section

```
N = \int \sigma(E_1, E_2, s_1, s_2, ...) \cdot \mathcal{L}(E_1, E_2, s_1, s_2, ...) \, dt
```

Integrated luminosity

Beam energies

Beam polarisation

Thursday, 23 January 14
Cross Sections

• Probe beam wavelength scales as inverse of energy

• Cross section like inverse of energy squared

• Desire to reach high energies based on
  • High mass states, SUSY
  • Decreasing probe wavelength

![Cross-section equation]

\[ \sigma = \lambda^2 \]

De Broglie wavelength

\[ \lambda = \frac{h}{p} \sim \frac{h}{E} \]

Ultra-relativistic

Point-like cross section scales as:

\[ \sigma \sim \frac{1}{E^2} \]

Matter wavelength [m]

Beam momentum

Beam energy
Energy Frontier

- Historical progress has been power law like for most of the last 70 years
- Vast majority of recent machines were synchrotrons
- Notable exceptions
  - SLC
  - NLC/ILC
- LHC

\[
\lambda = \frac{h}{p} \sim \frac{h}{E} \quad \sqrt{s} > 2M_X
\]
Luminosity Frontier

- Need corresponding rise in luminosity
- Higher luminosity brings all the challenges for detectors
  - High event rates
  - Pile up
- Beam-beam interactions
- Beamstrahlung

![Graph showing luminosity vs. center-of-mass energy with markers for different facilities and planned future collider sites.](image-url)
Designing a Machine

- Particle species
  - Electrons/positrons
  - Protons/anti-protons
  - Muons/anti-muons
- Beam energy
- Spin
- Luminosity

- How do you produce anti-particles?
- Once produced how does one keep them? (muon collider)
- Once collided what is done with the spent beams?
- Accelerator and detector protection
Accelerator Much More Than Just...

- Particle production
- Damping, cooling, or preparation
- Injection and extraction
- Acceleration
- Collimation (betatron, energy, etc.)
- Diagnostics and controls
- Machine (and detector) protection
- Beam delivery and luminosity production
- Technology spin off
  - Lowe energy machines, medical applications, applied physics, materials, blah, blah
2nd year electromagnetism

- Electric field (either static, or more commonly, time varying) to accelerate, or more appropriately, increase energy of beam
- Magnetic part of Lorentz force used to guide and focus
  - Dipole magnets: to bend
  - Quadrupole: to focus or defocus
Synchrotron

• Work horse of modern particle physics
• Huge legacy of discovery
  • W/Z, Gluon, Higgs, SUSY?
• Increase energy whilst synchronously increasing bending magnet strength
• Stable storage of high beam current/power
• Magnetic field proportional to momentum

\[ qBv = \frac{m_0 v^2}{\rho} \]

\[ B\rho = p/q \]
Synchrotron

- Time varying electric field:

\[ V(t) = V_0 \sin(\omega_{RF} t + \phi) \]

Angular frequency of accelerating field

- Particle gets a kick every revolution

\[ \frac{1}{f_{\text{ref}}} = n \frac{2\pi}{\omega_{RF}} \]

Revolution frequency Integer
Synchrotron Radiation Limits

- Why not just build bigger LEP?
- Reuse accelerating section every revolution of particle bunch
- Power loss due to synchrotron radiation
- LEP2 was practical limit for electron-positron synchrotron

\[ P = \frac{1}{4\pi\varepsilon_0} \frac{e^2v^4}{c^3\rho^2\gamma^4} \]

Energy loss per turn
\[ W = 8.85 \times 10^{-5} \frac{E^4}{\rho} \]
Absolute Limits on Acceleration

- Need to create large on-axis electric fields
- Accelerating structures:
  - Superconducting (~35 MV/m)
  - Normal conducting (~100 MV/m)
- Beyond these values there is high voltage breakdown

\[ S = \frac{E}{q \frac{dV}{ds}} \]

Machine length [m] \quad Beam energy [MeV] \quad Accelerating gradient [MV/m]
Luminosity

- What luminosity is required for measurement?
- Need some knowledge of x-section
- Simple relationship between number of particles, frequency of collision and beam sizes

\[ \mathcal{L} = f \frac{N_1 N_2}{4 \pi \sigma_x \sigma_y} \]

Luminosity [s\(^{-1}\) m\(^{-2}\)]

Bunch populations

Frequency of collisions [Hz]

Beam r.m.s. sizes [m]

Emittance [m]

Beta function [m]

\[ \sigma = \sqrt{\epsilon / \beta} \]
Emittance

- Emittance is an invariant measure of phase space (spatial) occupied by charged particle beam
- Product of spatial width and angular width
- Normalised emittance invariant under forces due to Lorentz

\[ \epsilon^2 = \langle x^2 \rangle \langle x'^2 \rangle - \langle xx' \rangle^2 \]

\[ x' = \frac{\partial x}{\partial s} = \frac{px}{p_s} \]

Distance along accelerator

\[ x' \]

Momentum components
Magnets

- Quadrupole magnets effectively act as lenses
- Focusing in one plane and defocusing in the other plane
Accelerator Magnets

- Normal and superconducting
- Dipoles and quadrupoles
- Beam losses effect superconductors
  - Can cause quench (i.e., superconductor becoming normal)
- High energy large momentum, so big magnets, high currents large resistive losses
Acceleration

- Acceleration only in direction of motion
- Increase longitudinal component of momentum
- Position is untouched
- Overall the emittance is reduced

- Normalised emittance:
  \[ \epsilon_n = \beta \gamma \epsilon \]

\[ x' = \frac{p_x}{p_s + \Delta p} \]
Accelerating Cavities

- Need to create high electric fields
  - LHC has 8 cavities per beam
    - 2 MV, so 16 MeV per turn
      - 11245 turns/s
    - 0.18 TeV/s
  - Ramp time?
Optical Functions

- Beam phase space described in 6 dimensions
  \[ \mathbf{v} = (x, x', y, y', E, t) \]

- Transformation of vector through magnetic elements
  \[ \mathbf{v}' = M \mathbf{v} \]

- Beta functions tell us about relationship between position and angle

- Dispersion between energy and time etc etc
Linear Colliders

- Two different options available
  - International Linear Collider (ILC)
    - 1 TeV: Super conducting
  - Compact Linear Collider (CLIC)
    - 3 TeV: Normal

- Avoid the problem of SR losses
  - ILC problem: No SUSY < 500 GeV
  - CLIC problem: Boundary of technological limits
Linear Collider Accelerator

- Gradients of 35 MV/m required
- ILC uses
  - Niobium cavities
  - 1.2 GHz RF
- Above this the super conductor quenches
- Type II SC, largest magnetic penetration of any element
- Remember Maxwell’s equations
Beam Delivery System

- Major challenge for lepton colliders is the luminosity

\[ \mathcal{L} = \int \frac{N_1 N_2}{4 \pi \sigma_x \sigma_y} \]

<table>
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</tr>
<tr>
<td>Nominal beam divergence at IP, ( \theta^*, x/y )</td>
<td>( \mu )rad</td>
<td>32/14</td>
</tr>
<tr>
<td>Nominal beta-function at IP, ( \beta^*, x/y )</td>
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<td>20/0.4</td>
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<td>Nominal bunch length, ( \sigma_z )</td>
<td>( \mu )m</td>
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<td>Nominal disruption parameters, x/y</td>
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<td>0.17/19.4</td>
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<tr>
<td>Nominal bunch population, N</td>
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<td>( 2 \times 10^{10} )</td>
</tr>
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<td>Beam power in each beam</td>
<td>MW</td>
<td>10.8</td>
</tr>
<tr>
<td>Preferred entrance train to train jitter</td>
<td>( \sigma_y )</td>
<td>&lt; 0.5</td>
</tr>
<tr>
<td>Preferred entrance bunch to bunch jitter</td>
<td>( \sigma_y )</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>Typical nominal collimation aperture, x/y</td>
<td></td>
<td>8–10/60</td>
</tr>
<tr>
<td>Vacuum pressure level, near/far from IP</td>
<td>( n )Torr</td>
<td>1/50</td>
</tr>
</tbody>
</table>
Interaction Point Focusing

- We need strong foci
- Strong magnets (lenses)
- Short focal length
- Large beam size on input

Generally need large demagnification
300 ILC

Need small size, set
Sets optical system length

\[ M = \frac{f_1}{f_2} \]

\[ L^* = 2 \text{ m} \]

\[ f_2 = 600 \text{ m} \]
Accelerator Test Facility (ATF) 2

- Facility to test ideas of beam focusing
- Aim to achieve 35 nm vertical beam size
- Using 1.3 GeV electron beam
Beam Power

- Another way to look at luminosity
- Look at it in terms of beam power and efficiency
- How do we pay for luminosity?
- Luminosity directly proportional to input power and efficiency

- £££ or $$$ or €€€ or CHF or JPY

\[ \mathcal{L} = N_b f \frac{N_1 N_2}{4\pi \sigma_x \sigma_y} H_D \]

Grid power

\[ P_{\text{beam}} = f E N_b N_1 = \eta P_{\text{grid}} \]

Efficiency

\[ \mathcal{L} = \frac{N}{4\pi \sigma_x \sigma_y} H_D \frac{\eta P_{\text{grid}}}{E} \]

\[ \mathcal{L} \sim \frac{P_{\text{beam}}}{E_{CM}} = \frac{\eta P_{\text{grid}}}{E_{CM}} \]
Compact Linear Collider

- **Getting to TeV**
  - Super conducting acceleration even with 50 MeV/m
  - 60 km in length!
  - Cryogenic power, RF power
  - Need more efficient method of making beam power
- **Novel power transformation systems**
Muons are difficult to:
- Make enough of them
- Accelerate quickly
- 200 times more massive than electron
- No SR losses
Muon Production

- High power/current proton driver
- Target must take ~4 MW of power
  - Mercury jet
  - Solid tungsten
  - Small tungsten spheres, with cooling
  - Powder jet of tungsten??
- Magnetically levitated rotation toroid???
- Transverse momentum of muons?

\[ L = f \frac{N_1 N_2}{4\pi \sqrt{\epsilon_x \beta_x^* \epsilon_y \beta_y^*}} \]

autical and driven by linear motors

\[ p \rightarrow \pi^\pm \rightarrow \nu_\mu \rightarrow \mu \]

rotating toroid

\[ \text{toroid at 2300 K radiates heat to water-cooled surroundings} \]

ISIS at RAL
Muon Emittance and Cooling

• Cooling needed for most facilities ILC, CLIC, LHC, Muon
  • Methods differ, radiation damping, stochastic cooling....
  • Ionisation

\[ \mathcal{L} = f \frac{N_1 N_2}{4\pi \sqrt{\epsilon_x \beta_x \epsilon_y \beta_y}} \]

MICE experiment at RAL

Thursday, 23 January 14
Fast Acceleration of Muons

- Synchrotron does not work for Muon acceleration
- Need to accelerate quickly
  \[ \tau = \gamma \tau_0 \]
- Can’t because
  \[ B \rho = p/q \]
- Typically
  \[ B \propto I \]
### Options for LHC upgrade
- High luminosity
- High energy

#### Summary of the LHC parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>‘white book’</th>
<th>nominal</th>
<th>ultimate</th>
</tr>
</thead>
<tbody>
<tr>
<td># bunches</td>
<td>3564</td>
<td>2808</td>
<td>2808</td>
</tr>
<tr>
<td>ppb</td>
<td>$0.34 \times 10^{11}$</td>
<td>$1.15 \times 10^{11}$</td>
<td>$1.7 \times 10^{11}$</td>
</tr>
<tr>
<td>$\beta^*$</td>
<td>1 m</td>
<td>0.55 m</td>
<td>0.5 m</td>
</tr>
<tr>
<td>$\varepsilon / \gamma$</td>
<td>1.07 $\mu$m</td>
<td>3.75 $\mu$m</td>
<td>3.75 $\mu$m</td>
</tr>
<tr>
<td>full crossing angle</td>
<td>100 $\mu$rad</td>
<td>285 $\mu$rad</td>
<td>315 $\mu$rad</td>
</tr>
<tr>
<td>events / crossing</td>
<td>1 &lt;-&gt; 4</td>
<td>19.2</td>
<td>44.2</td>
</tr>
<tr>
<td>L [$\text{cm}^{-2} \text{sec}^{-1}$]</td>
<td>$0.1 \times 10^{34}$</td>
<td>$1 \times 10^{34}$</td>
<td>$2.4 \times 10^{34}$</td>
</tr>
<tr>
<td>luminosity lifetime*</td>
<td>56 h</td>
<td>15 h</td>
<td>10 h</td>
</tr>
<tr>
<td>stored beam energy</td>
<td>121 MJ</td>
<td>366 MJ</td>
<td>541 MJ</td>
</tr>
</tbody>
</table>
Collimation

- Collimation is to remove unwanted particles
- Off position-angle
- Off energy
- Smallest beta functions, beam size at IR regions
- Loose particles into detector
- Worse damage accelerator
LHC Upgrades

• What would you do with the LHC?
• Need to start thinking now
• High energy
• Access to heavier states
• Higher luminosity
• More precise measurements
• Need more particles, smaller beam size and higher frequency collisions

\[ \mathcal{L} = \frac{f N_1 N_2}{4\pi \sigma_x \sigma_y} \]

1) Upgrade pre-accelerators
2) Injection system
3) Reduce beta functions or emittance
4) Crab crossing system
5) Change RF and timing systems... experimental triggers?

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High Energy LHC

\[ B\rho = \frac{p}{q} \]

To reach higher energies require stronger magnetic fields

- Research in new SC magnet technology

SPS+, 1.3 TeV, 2030-33

HE-LHC 2030-33

2-GeV Booster
High Luminosity LHC

IR upgrade
(detectors, low-b quad’s, crab cavities, etc)
\(~2020-21\)

Booster energy upgrade
\(1.4 \rightarrow 2 \text{ GeV}, \sim2015\)

SPS enhancements
(anti e-cloud coating, RF, impedance), \(2012-2021\)

\[ \mathcal{L} = \frac{f \cdot N_1 N_2}{4\pi \sqrt{\epsilon_x \beta_x^* \epsilon_y \beta_y^*}} \]
IR Upgrade ($L^*$ & Crab Crossing)

- Squeeze the beta functions at the IR point
  - Smaller beam sizes
  - Collimation will change
  - Larger beam power
  - Detector and machine protection
- Interesting point is crab crossing
  - Extra luminosity
Crab Crossing Angle

- Fraction of nominal luminosity

\[
\frac{L(\theta_c)}{L_0} \approx \left[ 1 + \left( \frac{\sigma_z}{\sigma_x} \tan(\theta_c/2) \right)^2 \right]^{1/2}
\]

- Recover luminosity by rotating bunches
- Much like a grab walking
Exotic Acceleration

- Compact acceleration
  - Need higher gradients
  - Plasma
  - Dielectric wake-fields
  - Photonic crystals
  - Direct laser
- Principle is still power transformation need better efficiency and less break-down

FIG. 3. A symmetric waveguide.

using sapphire rods with copper end-plates

Penrose (5-fold sym) Dodecagonal triangular lattice

outer dielectric: $\varepsilon = 10$
inner dielectric: $\varepsilon = 37$

$E_z$

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Plasma Wakefield Acceleration

- Break down limits electron acceleration ~few TeV
- Higher efficiency

Experiments at the SLAC Final Focus Test Beam (FFTB) Facility demonstrated high-gradient acceleration over meter scale distances. A single bunch of 42GeV electrons produced by the 3km SLAC linac was used to both drive and sample the wakefield in an 85cm long lithium plasma of density 2.7 x 1017 e-/cm3. Particles in the front of the bunch lost energy driving the wake while particles in the back of the bunch were accelerated to over 85GeV in just 85cm. The accelerated electrons were dispersed in energy by a magnetic field in a region of air. The Cherenkov light emitted by the electrons passing through the air was imaged onto a CCD camera to record the beam spectrum.
Summary

• Many different technologies and ideas
  • Talk focused on lepton colliders
  • What about proton/ion-electron, what about high-L, low-E lepton like B-factories, g-2, etc

• Ability to decode technical issues with future colliders
  • LHC upgrades
  • Future lepton colliders (electron and muon)

• Accelerator physics here applies well
  • Machines that might be built in the next 2 decades is unclear
  • Laser or beam PWA possible, but technically difficult
ACCELERATOR DESCRIPTION

TABLE XIV. Baseline parameters for high- and low-energy muon colliders. Higgs factory of the parameters of various muon colliders includ-
known as a Higgs factory.

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TABLE XIII. Transverse and longitudinal emittances at the end of the decay channel, study-
Higgs factory cooler 0.14 9
Emittance at end of Transverse emittance (μm mrad) 30 / 62
Longitudinal emittance (μm) 30 / 62

<table>
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<tr>
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</thead>
<tbody>
<tr>
<td>Number of structures per linac</td>
<td>ND</td>
<td>22</td>
</tr>
<tr>
<td>Number of drive-beams/linac</td>
<td>NΔ</td>
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<tr>
<td>Number of structures per linac</td>
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<tr>
<td>AC-to-RF efficiency</td>
<td>ηAC</td>
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<tr>
<td>RF-to-beam efficiency</td>
<td>ηRF</td>
<td>24.4%</td>
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<tr>
<td>AC-to-beam efficiency</td>
<td>ηAC</td>
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<tr>
<td>AC power for RF production</td>
<td>PAC</td>
<td>300 MW</td>
</tr>
</tbody>
</table>
Revision II

The status report [9] outlines the details of the acceleration and collider ring for the 0.1 TeV Higgs factory, shown schematically in Fig. 33. Table XIV gives a summary of the parameters of various muon colliders including three different modes of running the Higgs collider that have varying beam momentum spreads. Additional information about the muon collider can be found in [133,134].

B. Longitudinal cooling

At the time of writing of the status report [9] there was no satisfactory solution for the emittance exchange problem and this remained a major stumbling block towards realizing a muon collider. However, ring coolers have been found to hold significant promise in cooling in 6D phase space. Another advantage of ring coolers is that one can circulate the muons many turns, thereby reusing the cooling-channel elements. Several meetings on emittance exchange were held [135] and a successful workshop [136] was held in 2001, where we explored in some depth several kinds of ring coolers. These options differ primarily in the type of focusing used to contain the beam. We describe the current status of our understanding of three types of ring coolers here.

<table>
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<th>TABLE XII. Transverse and longitudinal emittances at the end of the decay channel, study-II cooling channel, and the Higgs factory cooling channel.</th>
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<td>Emittance at end of Transverse emittance (/.0025 mm)</td>
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FIG. 33. (Color) Plan of a 0.1-TeV -CoM muon collider, also known as a Higgs factory.

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<tr>
<th>TABLE XIV. Baseline parameters for high- and low-energy muon colliders. Higgs/year assumes a cross section $\sigma = 5 \times 10^4$ fb; a Higgs width $\Gamma = 2.7$ MeV; 1 yr = $10^7$ s.</th>
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<tr>
<td>CoM energy (TeV)</td>
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<tr>
<td>$p$ energy (GeV)</td>
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<tr>
<td>$p$'s/bunch</td>
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<tr>
<td>Bunches/fill</td>
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<td>Repetition rate (Hz)</td>
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<tr>
<td>$p$ power (MW)</td>
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<td>$\mu$/bunch</td>
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<td>$\mu$ power (MW)</td>
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<td>Wall power (MW)</td>
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<td>Collider circumference (m)</td>
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<td>Average bending field (T)</td>
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<td>rms $\Delta p / p%$</td>
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<tr>
<td>6D $\epsilon_{6, N}$ (πm)$^3$</td>
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<td>rms $\epsilon_n$ (π mm mrad)</td>
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<tr>
<td>$\beta^*$ (cm)</td>
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<tr>
<td>$\sigma_z$ (cm)</td>
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<tr>
<td>$\sigma_r$ spot (μm)</td>
</tr>
<tr>
<td>$\sigma_\theta$ IP (mrad)</td>
</tr>
<tr>
<td>Tune shift</td>
</tr>
<tr>
<td>$n_{\text{turns}}$ (effective)</td>
</tr>
<tr>
<td>Luminosity cm$^{-2}$ s$^{-1}$</td>
</tr>
<tr>
<td>Higgs/year</td>
</tr>
</tbody>
</table>
References

• ILC
  • http://tesla.desy.de/new_pages/TDR_CD/start.html
  • http://www.linearcollider.org/about/Publications/Reference-Design-Report

• CLIC
  • http://clic-study.web.cern.ch/clic-study/

• Muon collider
  • http://mice.iit.edu/
  • http://www.fnal.gov/pub/muonCollider/resources.html

• LHC
  • Proceedings of LHC-LUMI-05

• Exotic acceleration
  • https://slacportal.slac.stanford.edu/sites/ard_public/facet/Pages/Default.aspx/
  • http://www.ireap.umd.edu/AAC2010/