The TESLA Linear Collider

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(based on last years lecture by Nick Walker)

Energy Frontier $e^+e^-$ Colliders

LEP at CERN, CH
$E_{cm} = 180$ GeV
$P_{RF} = 30$ MW
Why a Linear Collider?

Synchrotron Radiation from an electron in a magnetic field:

\[ P_\gamma = \frac{e^2 c^2}{2\pi} C_\gamma E^2 B^2 \]

Energy loss per turn of a machine with an average bending radius \( \rho \):

\[ C_\gamma \propto \left( \frac{m_0 c^2}{E} \right)^4 \]

\[ \Delta E / \text{rev} = \frac{C_\gamma E^4}{\rho} \]

Energy loss must be replaced by RF system

Cost Scaling

- Linear Costs (tunnel, magnets etc): \( $_{\text{lin}} \propto \rho \)
- RF costs: \( $_{RF} \propto \Delta E \propto E^4 / \rho \)
- Optimum at \( $_{\text{lin}} = $_{RF} \)
- Optimised cost \( ($_{\text{lin}} + $_{RF}) \propto E^2 \)

- LINAC: optimised cost \( ($_{\text{lin}} + $_{RF}) \propto E \)
Linear Collider
No Bends, but lots of RF!

For a $E_{cm} = 500$ GeV:
Effective gradient: 25 MV/m

A Little History

A Possible Apparatus for Electron-Clashing Experiments (*).

M. Tigner

Laboratory of Nuclear Studies, Cornell University - Ithaca, N.Y.

- SLC (SLAC, 1988-98)
- NLCTA (SLAC, 1991-)
- TTF (DESY, 1994-)
- ATF (KEK, 1991-)
- FFTB (SLAC, 1992-1995)
- SBTF (DESY, 1994-1998)
- CLIC CTF1,2,3 (CERN, 1994-)

Over 15 Years of Linear Collider R&D

Nuovo Cimento 37 (1965) 1228
The Luminosity Issue

Particles per bunch

No. bunches in bunch train

Repetition rate

Beam-beam enhancement factor

(typically 2)

\[ L = \frac{n_b N^2 f_{\text{rep}}}{4\pi \sigma_x \sigma_y} \times H_D \]

LEP $f_{\text{rep}} = 40$ kHz

LC $f_{\text{rep}} = 5 - 200$ Hz!

LEP: $130 \times 6$ $\mu$m$^2$

LC: $550 \times 5$ nm$^2$

Requirements for Next Generation LC:

$P_{\text{beam}}$ typically 5-8 MW

\[ L \geq 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \]

$E_{\text{cm}} = 0.5 - 1$ TeV
The Luminosity Issue

Efficiency
- RF→beam: 20-60%
- Wall plug→RF: 28-40%

\[ L = \frac{1}{4\pi E_{cm}} \left( \eta P_{AC} \right) \left( \frac{N}{\sigma_x \sigma_y^*} H_D \right) \]

Beam-Beam effects:
- beamstrahlung, disruption

Strong focusing:
- optical aberrations, stability issues

Beam Beam Effects

RMS Energy Loss for a flat beam
\( (\sigma_z >> \sigma_y) \)

\[ \delta_{BS} \propto \frac{E_{cm}}{\sigma_z} \left( \frac{N}{\sigma_y^*} \right)^2 \]
Limit on $\beta^*$

$\beta(s) = \beta^* + \frac{s^2}{\beta^*}$, $\beta^* = \beta(s = 0)$

$\beta^*$ = “depth of focus”
reasonable lower limit for $\beta^*$ is bunch length $\sigma_z$
Thus set $\beta^* = \sigma_z$

$\Rightarrow \sigma_y = \sqrt{\epsilon_y \sigma_z}$

Beam-Beam Simulation
('Banana' Effect)

- Instability driven by vertical beam profile distortion
- Strong for high disruption
- Distortion caused by transverse wakefields and quad offset – only a few percent emittance growth
- Tuning can remove static part

Nominal TESLA Beam Parameters + y-z correlation (equivalent to few % projected emittance growth)
Beam centroids head on
Final Luminosity Scaling Law

\[ L \propto \left( \frac{n P_{RF}}{E_{cm}} \right) \left( \frac{\delta_{BS}}{\varepsilon_y} \right)^{\frac{1}{2}} \]

- as high as possible
- \( \approx 100 \text{ MW} \)
- background
- 0.5 – 1.0 TeV
- as small as possible

The *Luminosity* Issue

- High Beam Power
- Small IP vertical beam size
- High current \( (n_b \, N) \)
- High efficiency \( (P_{RF} \rightarrow P_{beam}) \)
- Small emittance \( \varepsilon_y \)
- strong focusing \( (\text{small } \beta^*_y) \)
The Luminosity Issue

- High current ($n_b \, N$)
- High efficiency ($P_{RF} \rightarrow P_{beam}$)
- Small emittance $\varepsilon_y$
- Strong focusing ($\beta^{*}_y$)

Superconducting RF Technology

The Superconducting Advantage

- Low RF losses in resonator walls ($Q_0 = 10^{10}$ compared to Cu = $10^4$)
  - High efficiency $\eta_{AC \rightarrow beam}$
  - Long beam pulses (many bunches) $\rightarrow$ low RF peak power
  - Large bunch spacing allowing feedback correction within bunch train.
The Superconducting Advantage

- Low-frequency accelerating structures (1.3 GHz, for Cu 6-30 GHz)
  - very small wakefields
  - relaxed alignment tolerances
  - high beam stability

Wake Fields
- Electromagnetic fields produced by charge and changes in the surrounding environment
- Act back on the same bunch ==> transverse and longitudinal deformation
- Interact with subsequent bunches ==> position and energy variation along train
Wakefields (alignment tolerances)

TESLA superconducting (T=2K) 9-cell Niobium cavity
The TESLA Test Facility (TTF)

Cavity strings are prepared and assembled in ultra-clean room environment at TTF

lecture on sc in accelerators

The TESLA Test Facility (TTF)

TTF Test Linac constructed from completed Cryomodules
The TESLA Linac

- Damping Ring
- Cryomodule
- Cavities

The TESLA Linac

- Klystrons mounted inside tunnel

Klystrons

- damping ring
- linac module
- transportation system
- beam transfer lines
- RF waveguides
- HV pulse cables
The TESLA Linac

1. 9-cell 1.3GHz Niobium Cavity

The TESLA Linac

12 9-cell 1.3GHz Niobium Cavity
1 Cryomodule
The TESLA Linac

36 9-cell 1.3GHz Niobium Cavity
3 Cryomodule
1 10MW Multi-Beam Klystron

Per Linac ($E_{cm} = 500$ GeV):

- 10,296 Cavities
- 858 Cryomodules
- 286 Klystrons
- Gradient: 23.4 MV/m (inc. 2% overhead)
- LENGTH 14.4km (fill factor: 74%)
Cryoplants

- Each linac divided into 6 Cryo-units (~140 cryomodules)
- 7 refrigeration (liquid He) plants housed in 7 surface halls (~5km)

Cryohalls

- Refrigerators
- LINAC tunnel
The LINAC is only one part of a linear collider!

The SC linac can:
• Efficiently accelerate a high charge to high energies (high RF→beam power transfer efficiency)
• Preserve the required small bunch volumes (small emittance) because of low wakefields
• Has relatively relaxed tolerances

BUT how do we:
• Produce the electron charge?
• Produce the positron charge?
• Make small emittance beams?
• Focus the beam down to 5nm at the IP?
The LINAC is only one part of a linear collider!

Machine Overview
$e^-$ Source

- laser-driven photo injector
- circ. polarised photons on GaAs cathode → long. polarised $e^-$
- laser pulse modulated to give required time structure
- very high vacuum requirements for GaAs ($<10^{-11}$ mbar)
- beam quality is dominated by space charge (note $v \approx 0.2c$)

\[ \varepsilon \approx 10^{-5} m \]

factor 10 in $x$ plane
factor ~500 in $y$ plane

$e^-$ Source: pre-acceleration

- $E = 12$ MeV
- $E = 76$ MeV
$e^+$ Source

Photon conversion to $e^\pm$ pairs in target material

Standard method is $e^-$ beam on 'thick' target (em-shower)

$e^+\ Source:\ undulator-based$

250GeV $e$ to IP

$\sim$30MeV photons

undulator (~100m)

$e^+e^-$ pairs

$\varepsilon$=10^{-2} m

$P_T$= 5kW
Damping Rings

- beam is damped down due to synchrotron radiation effects

\[ \gamma \epsilon_x = 10^{-7} \text{ m} \]
\[ \gamma \epsilon_y = 3 \times 10^{-8} \text{ m} \]

How $\beta$-damping works

- $\delta p$ replaced by RF such that $\Delta p_x = \delta p$.
- since $y' = dy/ds = p_z/p_x$,
- we have a reduction in amplitude:
  \[ \delta y' = -\delta p y' \]

\[ \epsilon_f = \epsilon_{eq} + (\epsilon_i - \epsilon_{eq})e^{-2T/\tau_p} \]
- initial emittance
- final emittance
- equilibrium emittance
- damping time ~ 28 ms

\( y' \) not changed by photon

- dipole
- RF cavity

\( \delta p \)
**TESLA Damping Rings**

- Long pulse: $950\text{ms} \times c = 285\text{km}!!$
- Compress bunch train into 18km “ring”
- Minimum circumference set by speed of ejection/injection kicker ($\sim 20\text{ns}$)
- Unique “dog-bone” design: 90% of ‘circumference’ in linac tunnel.

**Bunch Compression**

bunch length:
- after DR 6 mm at IP 300 $\mu\text{m}$
Bunch Compression

Damping ring (~ppm)

After compression
(300 µm)

Damping ring

6 mm

ΔE/E

2.8%

5 GeV: 2.8%
250 GeV: 0.6‰

Final Focus System for small $\beta^*$

• Optical telescope required to strongly demagnify the beam
  ($M_x \approx 1/100$, $M_y \approx 1/500$)

• Strong focusing leads to unacceptable chromatic aberrations [non-linear optics]

• Require 2nd-order optical correction

$\sigma_y = 50 \text{nm}$

$\sigma_y = 5 \text{nm}$

uses non-linear elements (sextupoles)
Positron Production System

\( \sigma_y = 3 \, \mu\text{m} \)

Beam Delivery System

Demagnification: \( \times 636 \)

\( \sigma_y = 5 \, \text{nm} \)

Collimation System

Final Focus System

Stability

- Tiny (emittance) beams
- Tight component tolerances
  - Field quality
  - Alignment
- Vibration and Ground Motion issues
- Active stabilisation
- Feedback systems

Linear Collider will be “Fly By Wire”
Stability: some numbers

- Cavity alignment (RMS): 500 \( \mu \text{m} \)
- Linac magnets: 100 nm
- BDS magnets: 10-100 nm
- Final “lens”: \( \sim \) nm !!!

Parallel-to-Point focusing

IP Fast (orbit) Feedback

Long bunch train:
- 2820 bunches
- \( t_0 = 337 \) ns

Beam-beam kick
IP Fast (orbit) Feedback

Systems successfully tested at TTF

Long Term Stability

IP Feedback & slow orbit feedback

No Feedback
Proposed Site

Experimental Area (Ellerhoop)
Thanks for listening and have a lot of fun here at DESY
The Linear Accelerator (LINAC)

- Gradient given by shunt impedance:
  \[ E_z = \sqrt{P_{RF} R_s} \]
  - \( P_{RF} \): RF power / unit length
  - \( R_s \): shunt impedance / unit length

- The cavity \( Q \) defines the fill time: \( t_{\text{fill}} = \begin{cases} \frac{2Q}{\omega} & \text{SW} \\ 2\pi Q/\omega = \frac{l_s}{v_g} & \text{TW} \end{cases} \)
  - \( v_g \): group velocity
  - \( l_s \): structure length

- For TW, \( \tau \) is the structure attenuation constant:

- RF power lost along structure (TW):
  \[ \frac{dP_{RF}}{dz} = \frac{E_z^2}{R_s} i_b E_z \]
  - power lost to structure
  - beam loading

\[ \eta_{RF} \]
would like \( R_s \) to be as high as possible
\[ R_s \propto \sqrt{\omega} \]

Basic Optics 1: Phase Space and Emittance

- Electron optics analogous to light optics (quadrupole magnets instead of lenses)
Basic Optics 1: Phase Space and Emittance

Particle trajectories map out an area in the phase plane. Integral over y-y’ space is the **emittance**, which is a constant.

Basic Optics 2: RMS Emittance

Take statistical 2\textsuperscript{nd}-order moments of phase space coordinates

\[
\begin{pmatrix}
\langle y^2 \rangle & \langle yy' \rangle \\
\langle yy' \rangle & \langle y'^2 \rangle
\end{pmatrix} = \begin{pmatrix}
\beta_y & -\alpha_y \\
-\alpha_y & (1+\alpha_y^2)/\beta_y
\end{pmatrix} \epsilon_y
\]

\[
det = \epsilon_y^2, \quad det = 1
\]

define \( \epsilon_y = \sqrt{\langle y^2 \rangle \langle y'^2 \rangle - \langle yy' \rangle^2} \)

\[
\frac{(1+\alpha_y^2)}{\beta_y} y^2 + 2\alpha_y yy' + \beta_y y'^2 = \epsilon_y
\]

equation of an ellipse which bounds one standard deviation of the bivariate distribution

RMS emittance is conserved by linear optics.
Basic Optics 3: Phase Advance

The parameters $\beta = \beta(s)$ and $\alpha = \alpha(s)$ are functions of the magnetic lattice (optics). $s$ is the distance along the system (magnetic axis).

At any point $s = s_1$, we can transform the phase space ellipse into a circle (floquet transformation)

$y(s) = a \sqrt{\beta_y(s)} \cos \left( \phi_y(s) + \phi_z(0) \right)$

‘betatron’ oscillation

Basic Optics 4: Emittance and Acceleration

high-energy (relativistic) optics is based on very small angle approximations.

Hence we assume $p_z \perp p_y$ and thus

$p_z = |P|$

$y' = \frac{dy}{dz} \approx \frac{p_y}{p_z} \approx \frac{p_y}{|P|}$

hence for ultra-relativistic beams

$y' \propto \frac{1}{\gamma}$

$\gamma = E/m$

$\gamma y' = \text{const.}$

$\Rightarrow \gamma e_{y_z} = \text{const.} \equiv \text{normalised emittance}$
Beam-Beam

beam-beam characterised by Disruption Parameter:

\[ D_{x,y} = \frac{2r N \sigma_z}{\gamma \sigma_{x,y} (\sigma_{x} + \sigma_{y})} \approx \frac{\sigma_z}{f_{beam}} \]

\( \sigma_z \) = bunch length,

\( f_{beam} \) = focal length of beam-lens

for storage rings, \( f_{beam} \gg \sigma_z \) and \( D_{x,y} \ll 1 \)

In a LC, \( D_y \approx 10-20 \) hence \( f_{beam} < \sigma_z \)

Enhancement factor (typically \( H_D \approx 2 \)):

\[ H_{D_{x,y}} = 1 + D_{x,y}^{1/4} \left[ \frac{D_{z,x,y}^3}{1 + D_{x,y}} \right] \ln \left( \sqrt{D_{x,y}} + 1 \right) + 2 \ln \left( \frac{0.81 \ln 12}{\sigma_z} \right) \]

‘hour glass’ effect

Beamstrahlung

RMS relative energy loss \( \delta_{SB} \approx 0.86 \frac{e r x^3}{2 m c^2} \left( \frac{E_{cm}}{\sigma_z} \right) \left( \frac{N^2}{\sigma_z^2 + \sigma_x^2} \right) \)

we would like to make \( \sigma_x, \sigma_y \) small to maximise luminosity

BUT keep \( (\sigma_x + \sigma_y) \) large to reduce \( \delta_{SB} \).

Trick: use “flat beams” with \( \sigma_x \gg \sigma_y \)

\[ \delta_{SB} \propto \left( \frac{E_{cm}}{\sigma_z} \right) \left( \frac{N^2}{\sigma_x^2} \right) \]

Now we set \( \sigma_x \) to fix \( \delta_{SB} \), and make \( \sigma_y \) as small as possible to achieve high luminosity.

For most LC designs, \( \delta_{SB} \approx 3-10\% \)
Beamstrahlung

Returning to our $L$ scaling law, and ignoring $H_D$

$$L \propto \eta_{RF} P_{RF} \frac{N}{\sigma_x} \left(\frac{1}{\sigma_y}\right)$$

From flat-beam beamstrahlung

$$\frac{N}{\sigma_x} \propto \sqrt{\frac{\sigma_z \delta_{BS}}{E_{cm}}}$$

hence

$$L \propto \eta_{RF} P_{RF} \frac{\sqrt{\delta_{BS} \sigma_z}}{E_{cm}^{3/2} \sigma_y}$$