Frank Tecker – CERN

1: Introduction, Overview, Scaling
2: Subsystems: source, DR, BC, main linac
3: Subsystems: linac, wakefields, RF, alignment
4: Real designs: Parameters, NC/SC, CLIC
Complex topic --- but: DON’T PANIC!

Approach:

- Explain the fundamental layout of a linear collider and the specific designs based on SuperConducting (SC) and normal conducting (NC) technology
- I will not go much into technical details
- Try to avoid formulae as much as possible

Goal: You understand

- Basic principles
- Some driving forces and limitations in linear collider design
- The basic building blocks of CLIC

Ask questions at any time! Any comment is useful! (e-mail: tecker@cern.ch)
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- Path to higher energy
- Cost scaling
- Luminosity
- Generic LC layout
- ILC / CLIC
Path to higher energy

- History:
  - Energy constantly increasing with time
  - Hadron Collider at the energy frontier
  - Lepton Collider for precision physics

- LHC has come online
- Consensus to build LC with $E_{cm} > 500$ GeV to complement LHC physics

*(European strategy for particle physics by CERN Council)*
Lepton vs. Hadron Collisions

LHC: \[ H \rightarrow ZZ \rightarrow 4\mu \]

Hadron Collider (p, ions):
- Composite nature of protons
- Can only use \( p_t \) conservation
- Huge QCD background

Lepton Collider:
- Elementary particles
- Well defined initial state
- Beam polarization
- Produces particles democratically
- Momentum conservation eases decay product analysis

ALICE: Ion event

LEP event: \( Z^0 \rightarrow 3 \) jets
Higgs physics
- Tevatron/LHC should discover Higgs (or something else)
- LC explore its properties in detail

Supersymmetry
- LC will complement the LHC particle spectrum

Extra spatial dimensions

New strong interactions

... => a lot of new territory to discover beyond the standard model

"Physics at the CLIC Multi-TeV Linear Collider"
CERN-2004-005

"ILC Reference Design Report – Vol.2 – Physics at the ILC"
www.linearcollider.org/rdr
Larger lepton storage ring? SUPER-LEP?? (LEP $L=27$ km $E_{cm}=200$ GeV)

Remember: Synchrotron radiation

Emitted power: $P = \frac{2}{3} \frac{r_e c}{(m_0 c^2)^3} \frac{E^4}{\rho^2}$ scales with $E^4$ !!

Energy loss/turn: $U_0 = \frac{4}{3} \pi \frac{r_e}{(m_0 c^2)^3} \frac{E^4}{\rho}$

This energy loss must be replaced by the RF system !!
Cost and Scalings

- Linear costs (magnets, tunnel, etc.):
  \[ \epsilon_{\text{lin}} \propto \rho \]

- RF costs:
  \[ \epsilon_{\text{RF}} \propto U_0 \propto E^4/\rho \]

- Optimum when:
  \[ \epsilon_{\text{lin}} \propto \epsilon_{\text{RF}} \Rightarrow \rho \propto E^2 \]

- The size and the optimized cost scale as \( E^2 \)

- Also the energy loss per turn scales as \( E^2 \)
The solution: a Linear Collider

- NO bending magnets ⇒ NO synchrotron radiation
- but: A lot of accelerating structures !!!
- Cost scaling linear with $E$

Storage rings:
- accelerate + collide every turn
- ‘re-use’ RF + ‘re-use’ particles
⇒ efficient

Linear Collider:
- one-pass acceleration + collision ⇒ need
- high gradient
- small beam size $\sigma$ and emittance

⇒ to reach high luminosity $L$ (event rate)
- much less limited by beam-beam effect
Collider luminosity $(\text{cm}^2 \text{ s}^{-1})$ is approximately given by

$$L = \frac{n_b N^2 f_{\text{rep}}}{A} H_D$$

where:

- $n_b = \text{bunches / train}$
- $N = \text{particles per bunch}$
- $f_{\text{rep}} = \text{repetition frequency}$
- $A = \text{beam cross-section at IP}$
- $H_D = \text{beam-beam enhancement factor}$
  (linear collider: typical value $\sim 2$)

For Gaussian beam distribution:

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

$\sigma_{x,y} = \text{transverse beam size}$
Luminosity: LC vs Storage Ring

- **LEP** \( f_{rep} = 11 \text{ kHz} \)
- **LC** \( f_{rep} = \text{few-100 Hz} \)
  (power limited)

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

⇒ factor \( \sim 100 \) in \( L \) already lost!

- Must push very hard on beam cross-section at collision:

- factor of \( 10^6 \) gain! needed
  to obtain high luminosity of a few \( 10^{34} \text{ cm}^{-2}\text{s}^{-1} \)

<table>
<thead>
<tr>
<th></th>
<th>LEP:</th>
<th>LC:</th>
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<tbody>
<tr>
<td>( \sigma_x \sigma_y \approx )</td>
<td>( 130 \times 6 \ \mu\text{m}^2 )</td>
<td>( (60-550) \times (1-5) \ \text{nm}^2 )</td>
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</table>
Introduce centre of mass energy $E_{cm}$

$$n_b N f_{rep} E_{cm} = P_{beams} = \eta_{RF \rightarrow beam} P_{RF}$$

- $\eta_{RF}$ is RF to beam power efficiency
- *Luminosity* is proportional to the RF power and efficiency for a given $E_{cm}$

$$L = \frac{n_b N^2 f_{rep} H_D}{4\pi \sigma_x \sigma_y E_{cm}}$$

$$L = \frac{(E_{cm} n_b N f_{rep}) N H_D}{4\pi \sigma_x \sigma_y E_{cm}}$$
Luminosity: RF power limit

- Some numbers:
  \[ E_{cm} = 500 \text{ GeV} \]
  \[ N = 10^{10} \]
  \[ n_b = 100 \]
  \[ f_{rep} = 100 \text{ Hz} \]

- Need to include efficiencies:
  - RF→beam: range 20-60%
  - Wall plug→RF: range 28-40%

- AC power > 100 MW to accelerate beams for a high luminosity
- this limits the practically achievable energy and luminosity
Luminosity: IP effects

\[ L = \frac{1}{4\pi E_{cm}} \left( \eta_{RF} P_{RF} \right) \left( \frac{N}{\sigma_x \sigma_y} H_D \right) \]

- **Beam-Beam effects:**
  - strong self focusing (pinch effect) \( \Rightarrow \) increases Luminosity
  - beamstrahlung \( \Rightarrow \) photon emission
    - dilutes Luminosity spectrum
    - creates detector background
  - **Strong focusing** needed for small beam size
    - optical aberrations
    - stability issues and tolerances

- **choice of technology (NC vs SC):**
  - efficiency
  - available power
Beam-Beam effects: pinch

- Strong electromagnetic field of the opposing bunch:
  - deflects the particles “beam-beam kick”
  - focuses the bunches “pinch effect”
  - Luminosity enhancement factor $H_D$

 Beam envelope w/o beam-beam
 Beam envelope with beam-beam
Collision Simulation

- beams strongly focused during collision ⇒ Luminosity!
- large divergence after collision ⇒ beam extraction difficult
Beamstrahlung

- “synchrotron radiation” in the field of the opposing bunch
- smears out luminosity spectrum
- creates $e^+e^-$ pairs background in detector

- quantified by Disruption parameter

$$D_{x,y} = \frac{2r_e N \sigma_z}{\gamma \sigma_{x,y} (\sigma_x + \sigma_y)}$$
Beamstrahlung: energy loss

- RMS relative energy loss
- we want
  - $\sigma_x$ and $\sigma_y$ small for high luminosity
  - $(\sigma_x + \sigma_y)$ large for small $\delta_{BS}$ (=> better luminosity spectrum)
- use flat beams with $\sigma_x \gg \sigma_y$

$$\delta_{BS} \approx 0.86 \frac{r_e^3}{2m_0c^2} \left( \frac{E_{cm}}{\sigma_z} \right) \frac{N^2}{(\sigma_x + \sigma_y)^2}$$

$$\delta_{BS} \propto \left( \frac{E_{cm}}{\sigma_z} \right) \frac{N^2}{\sigma_x^2}$$

- Can increase luminosity by small $\sigma_y$
- and minimise $\delta_{BS}$ by big $\sigma_x$
Limit on beam size: Hour-glass effect

- $\beta$-function at the interaction point follows

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

- $\beta^*$ bet function at the IP

- Luminosity has to be calculated in slices

- desirable to have $\sigma_z \leq \beta_y \Rightarrow$ short bunch length
**Hour-glass effect**

Enhancement factor $H_D$ (round beam)

$H_{Dx,y} = 1 + D_{x,y}^{1/4} \left( \frac{D_{x,y}^3}{1 + D_{x,y}^3} \right) \ln \left( \sqrt{D_{x,y}} + 1 \right) + 2 \ln \left( \frac{0.8 \beta_{x,y}}{\sigma_z} \right)$

$H_D$ (flat) $\approx H_D$ (round)$^{1/3}$

‘hour glass’ effect
Luminosity: more scaling ...

- substitute $\delta_{BS} \propto \left( \frac{E_{cm}}{\sigma_z} \right) \frac{N^2}{\sigma_x^2}$ into 

$$L = \frac{1}{4\pi E_{cm}} \left( \eta_{RF} P_{RF} \right) \left( \frac{N}{\sigma_x \sigma_y} H_D \right)$$

- we get 

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

- now use 

$$\sigma_y = \sqrt{\frac{\beta_y \epsilon_{n,y}}{\gamma}}$$

- then 

$$L \propto \frac{\eta_{RF} P_{RF}}{E_{cm}^{3/2}} \sqrt{\delta_{BS} \gamma} \sqrt{\frac{\sigma_z}{\beta_y}} \propto \frac{\eta_{RF} P_{RF}}{E_{cm}} \sqrt{\epsilon_{n,y}} \sqrt{\frac{\delta_{BS}}{\beta_y}} \sqrt{\frac{\sigma_z}{\beta_y}} \sim 1 \text{ (hour glass effect)}$$
The ‘final’ scaling for LC

\[ L \propto \frac{\eta_{RF} P_{RF}}{E_{cm}} \sqrt{\frac{\delta_{BS}}{\varepsilon_{n,y}}} H_D \]

\[ \beta_y = \sigma_z \]

- we want high RF-beam conversion efficiency \( \eta_{RF} \)
- need high RF power \( P_{RF} \)
- small normalised vertical emittance \( \varepsilon_{n,y} \)
- strong focusing at IP (small \( \beta_y \) and hence small \( \sigma_z \))
- could also allow higher beamstrahlung \( \delta_{BS} \) if willing to live with the consequences (Luminosity spread and background)

Above result is for the low beamstrahlung regime where \( \delta_{BS} \sim \) few %

Slightly different result for high beamstrahlung regime
Generic Linear Collider

Main Linac
Accelerate beam to IP energy without spoiling DR emittance

Bunch Compressor
Reduce $\sigma_z$ to eliminate hourglass effect at IP

Damping Ring
Reduce transverse phase space (emittance) so smaller transverse IP size achievable

Collimation System
Clean off-energy and off-orbit particles

Final Focus
Demagnify and collide beams

Electron Gun
 Deliver stable beam current

Positron Target
Use electrons to pair-produce positrons

will see the different elements in the following…
The real designs: JLC/NLC

- NLC (Next Linear Collider)
  - JLC (Japanese Linear Collider):
    - 500 – 1000 GeV
    - Normal conducting RF
    - 11.4 GHz
    - 65 MV/m gradient

- not followed up any more
- technology decision in Aug 2004 for superconducting technology
The real designs: TESLA -> ILC

**TESLA:**
- Superconducting cavities
- 1.3 GHz
- 35 MV/m gradient
- 500 – 800 GeV

**ILC (Internat. Linear Collider):**
- Superconducting cavities
- 31.5 MV/m gradient
- 500 GeV
- Upgrade to 1000 GeV possible

~35 km total length
ILC Global Design Effort

- ~700 contributors from 84 institutes in the RDR
- Web site: www.linearcollider.org
Two 250 Gev linacs arranged to produce nearly head on $e^+e^-$ collisions
- Single IR with 14 mrad crossing angle
- Centralized injector
  - Circular 6.7 km damping rings
  - Undulator-based positron source
- Dual tunnel configuration for safety and availability
The core technology for the ILC is 1.3GHz superconducting RF cavity intensely developed in the TESLA collaboration, and recommended for the ILC by the ITRP on 2004 August. The cavities are installed in a long cryostat cooled at 2K, and operated at gradient 31.5MV/m.
560 RF units each one composed of:

- 1 Bouncer type modulator
- 1 Multibeam klystron (10 MW, 1.6 ms)
- 3 Cryostats (9+8+9 = 26 cavities)
- 1 Quadrupole at the center

Total of 1680 cryomodules and 14 560 SC RF cavities
**CLIC (Compact Linear Collider): only multi-TeV design**

3 TeV, 100 MV/m, warm technology, 12 GHz, two beam scheme

- **Drive beam acceleration complex**
  - Drive beam accelerator: 2.38 GeV, 1.0 GHz
  - Circumferences:
    - CR1: 146.1 m
    - CR2: 438.3 m
  - Delay loop: 73.0 m
  - Decelerator: 24 sectors of 876 m
  - 326 klystrons: 33 MW, 139 µs

- **Main beam acceleration complex**
  - Drive beam accelerator: 2.38 GeV, 1.0 GHz
  - Circumferences:
    - CR1: 146.1 m
    - CR2: 438.3 m
  - Delay loop: 1 km
  - Decelerator: 24 sectors of 876 m
  - 326 klystrons: 33 MW, 139 µs

**Beam Transport System**

- **Drive beam**
  - e⁻ injector: 2.86 GeV
  - e⁻ main linac: 12 GHz, 100 MV/m, 21.02 km
  - BDS: 2.75 km
  - IP: Interaction point
  - TA: Turnaround
definition: radius = 120 m

- **Main beam**
  - e⁺ main linac: 2.38 GeV, 1.0 GHz
  - BDS: 2.75 km
  - IP: Interaction point
  - TA: Turnaround
definition: radius = 120 m

**Main Beam Generation Complex**

- Booster linac: 6.14 GeV
- e⁻ injector: 2.86 GeV
- e⁻ PDR: 398 m
e⁺ DR: 493 m
e⁺ PDR: 398 m
- e⁻ PDR: 398 m
e⁺ DR: 493 m
e⁺ PDR: 398 m

**Main Beam Generation System**

- e⁻ injector: 2.86 GeV
- e⁻ PDR: 398 m
- e⁺ DR: 493 m
- e⁺ PDR: 398 m

**Beam Transport System**

- e⁺ injector: 2.86 GeV
- e⁺ PDR: 398 m
- e⁺ DR: 493 m
- e⁺ PDR: 398 m

**Beam Distribution System**

- BDS: 2.75 km
- IP: Interaction point
- TA: Turnaround
definition: radius = 120 m

**CLIC – overall layout – 3 TeV**