Linear Colliders (high-energy e+/e- colliders)

- Physics motivation
- Generic Linear Collider Layout
- ILC (International Linear Collider)
- CLIC (Compact Linear Collider)
- CTF3 (CLIC Test Facility)
- Conclusion
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)
Path to higher energy

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

- LHC coming online very soon
- Consensus to build Lin. Collider with $E_{cm} > 500$ GeV to complement LHC physics
  *(European strategy for particle physics by CERN Council)*
Lepton vs. Hadron Collisions

**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

**LHC:**
$H \rightarrow ZZ \rightarrow 4\mu$

**ALICE:**
Ion event

**LEP event:**
$Z^0 \rightarrow 3$ jets
TeV e+e- physics

- **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
The LEP collider

LEP (Large Electron Positron collider) was installed in LHC tunnel

- e+ e- circular collider (27 km) with $E_{cm} = 200$ GeV

- Problem for any ring: Synchrotron radiation

- Emitted power: scales with $E^4$ !! and $1/m_0^3$ (much less for heavy particles)

- This energy loss must be replaced by the RF system !!

- particles lost 3% of their energy each turn!

\[ P = \frac{2}{3} \frac{r_c c}{(m_0 c^2)^3} \frac{E^4}{\rho^2} \]
The next lepton collider

- Solution: LINEAR COLLIDER
- avoid synchrotron radiation
- no bending magnets, huge amount of cavities and RF

![Diagram of CLIC linear collider](image)
Linear Collider vs. Ring

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

\[
L = \frac{n_b N^2 f_{rep}}{4\pi \sigma_x \sigma_y}
\]
What matters in a linear collider?

**Energy reach**

\[ E_{cm} = 2 F_{\text{fill}} L_{\text{linac}} G_{RF} \]

**Luminosity**

\[ L = \frac{n_b N^2 f_{\text{rep}}}{4\pi \sigma_x^* \sigma_y^*} \times H_D \propto \frac{\eta_{\text{beam}}^{AC} P_{AC}}{\varepsilon_y^{1/2}} \delta_{BS}^{1/2} \frac{1}{E_{cm}} \]

- **Acceleration efficiency** \( \eta \)
- **Generation and preservation of small emittance** \( \varepsilon \)
- **Extremely small beam spot at collision point**

\( \sigma_{x,y} = \text{transverse beam size} \)

- damping rings, alignment, stability, wake-fields
- beam delivery system, stability
Generic Linear Collider

Main Linac
Accelerate beam to IP energy without spoiling DR emittance

Electron Gun
Deliver stable beam current

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

Positron Target
Use electrons to pair-produce positrons
First Linear Collider: SLC

SLC – Stanford Linear Collider

Built to study the $Z^0$ and demonstrate linear collider feasibility

Energy = 92 GeV
Luminosity = $2 \times 10^{30}$

Has all the features of a 2nd gen. LC except both $e^+$ and $e^-$ used the same linac

A 10% prototype!

T. Raubenheimer
Linear Collider projects

**ILC (International Linear Collider)**
- Technology decision Aug 2004
- Superconducting RF technology
- 1.3 GHz RF frequency
- ~31 MV/m accelerating gradient
- 500 GeV centre-of-mass energy
- upgrade to 1 TeV possible

**CLIC (Compact Linear Collider)**
- normalconducting technology
- multi-TeV energy range (nom. 3 TeV)
- ~35 km total length
### Parameter comparison

<table>
<thead>
<tr>
<th>Parameter</th>
<th>SLC</th>
<th>TESLA</th>
<th>ILC</th>
<th>J/NLC</th>
<th>CLIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology</td>
<td>NC</td>
<td>Supercond.</td>
<td>Supercond.</td>
<td>NC</td>
<td>NC</td>
</tr>
<tr>
<td>Gradient [MeV/m]</td>
<td>20</td>
<td>25</td>
<td>31.5</td>
<td>50</td>
<td>100</td>
</tr>
<tr>
<td>CMS Energy E [GeV]</td>
<td>92</td>
<td>500-800</td>
<td>500-1000</td>
<td>500-1000</td>
<td>500-3000</td>
</tr>
<tr>
<td>RF frequency $f$ [GHz]</td>
<td>2.8</td>
<td>1.3</td>
<td>1.3</td>
<td>11.4</td>
<td>12.0</td>
</tr>
<tr>
<td>Luminosity $L$ [$10^{33}$ cm$^{-2}$s$^{-1}$]</td>
<td>0.003</td>
<td>34</td>
<td>20</td>
<td>20</td>
<td>21</td>
</tr>
<tr>
<td>Beam power $P_{beam}$ [MW]</td>
<td>0.035</td>
<td>11.3</td>
<td>10.8</td>
<td>6.9</td>
<td>5</td>
</tr>
<tr>
<td>Grid power $P_{AC}$ [MW]</td>
<td>140</td>
<td>230</td>
<td>195</td>
<td>130</td>
<td></td>
</tr>
<tr>
<td>Bunch length $\sigma_z^*$ [mm]</td>
<td>~1</td>
<td>0.3</td>
<td>0.3</td>
<td>0.11</td>
<td>0.03</td>
</tr>
<tr>
<td>Vert. emittance $\gamma\varepsilon_y$ [10$^{-8}$m]</td>
<td>300</td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>2.5</td>
</tr>
<tr>
<td>Vert. beta function $\beta_y^*$ [mm]</td>
<td>~1.5</td>
<td>0.4</td>
<td>0.4</td>
<td>0.11</td>
<td>0.1</td>
</tr>
<tr>
<td>Vert. beam size $\sigma_y^*$ [nm]</td>
<td>650</td>
<td>5</td>
<td>5.7</td>
<td>3</td>
<td>2.3</td>
</tr>
</tbody>
</table>

Parameters (except SLC) at 500 GeV
ICL 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
SC Technology

- In the past, SC gradient typically 5 MV/m and expensive cryogenic equipment
- TESLA development: new material specs, new cleaning and fabrication techniques, new processing techniques
- Significant cost reduction
- Gradient substantially increased
- Electropolishing technique has reached ~35 MV/m in 9-cell cavities
- Still requires essential work
- 31.5 MV/m ILC baseline

Chemical polish  Electropolishing
Recent progress by R&D programme to systematically understand and set procedures for the production process

- goal to reach a 50% yield at 35 MV/m by the end of 2010
- already approaching that goal
- 90% yield foreseen later
R&D of SCRF cavities

TESLA Nine-Cells: (Proof-of-Principle)
Best tests of 9 best Cavities (Vertical Test Results)

Derived From TESLA Collaboration

New cavity shapes

New preparation techniques

60mm-Aperture Re-Entrant Cavity, 58 MV/m!
KEK/Cornell Collaboration

New material
Large grains
Higher perf
Lower cost

Frank Tecker
Linear Colliders – CAS Darmstadt
1.10.2009
Accelerating gradient

- Superconducting cavities fundamentally limited in gradient by critical magnetic field => become normal conducting above

- Normal conducting cavities limited in pulse length + gradient by
  - “Pulsed surface heating” => can lead to fatigue
  - RF breakdowns (field collapses => no acceleration, deflection of beam)

- Normal conducting cavities: higher gradient with shorter RF pulse length

- Superconducting cavities: lower gradient with long RF pulse
Develop technology for linear e+/e- collider with the requirements:

- $E_{cm}$ should cover range from ILC to LHC maximum reach and beyond $\Rightarrow E_{cm} = 0.5 - 3$ TeV
- Luminosity > few $10^{34}$ cm$^{-2}$ with acceptable background and energy spread
  - $E_{cm}$ and $L$ to be reviewed once LHC results are available

- Design compatible with maximum length $\sim 50$ km
- Affordable
- Total power consumption $< 500$ MW

Present goal: Demonstrate all key feasibility issues and document in a CDR by 2010 (possibly TDR by 2016)
World-wide CLIC&CTF3 Collaboration

33 Institutes involving 21 funding agencies and 18 countries

- Aarhus University (Denmark)
- Ankara University (Turkey)
- Argonne National Laboratory (USA)
- Athens University (Greece)
- BINP (Russia)
- CERN
- Ciemat (Spain)
- Cockcroft Institute (UK)
- Gazi Universities (Turkey)
- Helsinki Institute of Physics (Finland)
- IAP (Russia)
- IAP NASU (Ukraine)
- INFN / LNF (Italy)
- Instituto de Fisica Corpuscular (Spain)
- IRFU / Saclay (France)
- Jefferson Lab (USA)
- John Adams Institute (UK)
- JINR (Russia)
- Karlsruhe University (Germany)
- KEK (Japan)
- LAL / Orsay (France)
- LAPP / ESIA (France)
- NCP (Pakistan)
- North-West. Univ. Illinois (USA)
- Oslo University (Norway)
- Patras University (Greece)
- Polytech. University of Catalonia (Spain)
- PSI (Switzerland)
- RAL (UK)
- RRCAT / Indore (India)
- SLAC (USA)
- Thrace University (Greece)
- Uppsala University (Sweden)
CLIC – basic features

- High acceleration gradient
  - “Compact” collider – total length < 50 km
  - Normal conducting acceleration structures
  - High acceleration frequency (12 GHz)

- Two-Beam Acceleration Scheme
  - High charge Drive Beam (low energy)
  - Low charge Main Beam (high collision energy)
  - ⇒ Simple tunnel, no active elements
  - ⇒ Modular, easy energy upgrade in stages

Main beam – 1 A, 156 ns from 9 GeV to 1.5 TeV

Drive beam - 101 A, 240 ns from 2.4 GeV to 240 MeV
CLIC Layout at various energies

**0.5 TeV Stage**

**1 TeV Stage**

**3 TeV Stage**
CLIC – overall layout – 3 TeV

Drive beam

Main beam

Drive Beam Generation Complex

Main Beam Generation Complex
### CLIC main parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center-of-mass energy</td>
<td>3 TeV</td>
</tr>
<tr>
<td>Peak Luminosity</td>
<td>$6 \cdot 10^{34}$ cm$^{-2}$ s$^{-1}$</td>
</tr>
<tr>
<td>Peak luminosity (in 1% of energy)</td>
<td>$2 \cdot 10^{34}$ cm$^{-2}$ s$^{-1}$</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Loaded accelerating gradient</td>
<td>100 MV/m</td>
</tr>
<tr>
<td>Main linac RF frequency</td>
<td>12 GHz</td>
</tr>
<tr>
<td>Overall two-linac length</td>
<td>42 km</td>
</tr>
<tr>
<td>Bunch charge</td>
<td>$3.7 \cdot 10^9$</td>
</tr>
<tr>
<td>Beam pulse length</td>
<td>156 ns</td>
</tr>
<tr>
<td>Average current in pulse</td>
<td>1 A</td>
</tr>
<tr>
<td>Hor./vert. normalized emittance</td>
<td>660 / 20 nm rad</td>
</tr>
<tr>
<td>Hor./vert. IP beam size before pinch</td>
<td>45 / ~1 nm</td>
</tr>
<tr>
<td>Total site length</td>
<td>48.3 km</td>
</tr>
<tr>
<td>Total power consumption</td>
<td>415 MW</td>
</tr>
</tbody>
</table>
CLIC drive beam scheme

- **Very high gradients** possible with NC accelerating structures at high RF frequencies (30 GHz → 12 GHz) and short RF pulses (~100 ns)
- Extract required high RF power from an intense e- “drive beam”
- Generate **efficiently** long beam pulse and compress it (in power + frequency)

**Klystrons**
- Low frequency
- High efficiency

**Accelerating Structures**
- High Frequency - High field

**Power stored in electron beam**

**Power extracted from beam in resonant structures**

**Electron beam manipulation**
- Power compression
- Frequency multiplication

**Long RF Pulses**
- $P_0$, $\nu_0$, $\tau_0$

**Short RF Pulses**
- $P_A = P_0 \times N_1$
- $\tau_A = \tau_0 / N_2$
- $\nu_A = \nu_0 \times N_3$
**Efficient acceleration**

Full beam-loading acceleration in traveling wave sections

- High beam current
- Most of RF power to the beam
- “short” structure - low Ohmic losses

**Frequency multiplication**

Beam combination/separation by transverse RF deflectors

- $P_0, \nu_0$
- $2 \times P_0, 2 \times \nu_0$
- Deflecting Field
Beam combination by RF deflectors

Transverse
RF Deflector, \( \nu_0 \)

Deflecting Field

\[ 2 \times P_0, 2 \times \nu_0 \]
Beam separation by RF deflectors

Transverse RF Deflector, $\nu_0/2$

Deflecting Field

$P_0/2, \nu_0/2$

$P_0/2, \nu_0/2$

$P_0, \nu_0$
Drive Beam Accelerator
- efficient acceleration in fully loaded linac

Drive Beam Decelerator Section (2 × 24 in total)
- pulse compression & frequency multiplication

Combiner Ring × 4
- pulse compression & frequency multiplication

Combiner Ring × 3
- pulse compression & frequency multiplication

Delay Loop × 2
- gap creation, pulse compression & frequency multiplication

CLIC RF POWER SOURCE LAYOUT

Drive beam time structure - initial
- 240 ns
- 140 μs train length - 24 × 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
CTF 3

- Demonstrate Drive Beam generation (fully loaded acceleration, bunch frequency multiplication 8x)
- Test CLIC accelerating structures
- Test power production structures (PETS)

30 GHz "PETS Line"
Linac
Bunch length chicane
RF deflector
Delay Loop – 42m
Combiner Ring – 84m

Injector

Laser

30 GHz test area

4A – 1.2µs
150 MeV

32A – 140ns
150 MeV

CLEX

TL1

TL2

10 m
Fully loaded operation

- **efficient** power transfer from RF to the beam needed

**“Standard”** situation:
- **small** beam loading
- power at structure exit lost in load

**“Efficient”** situation:
- **high** beam current
- **high** beam loading
- no power flows into load
- \( V_{\text{ACC}} \approx \frac{1}{2} V_{\text{unloaded}} \)
CTF3 linac acceleration structures

- 3 GHz $2\pi/3$ traveling wave structure
- constant aperture
- slotted-iris damping + detuning with nose cones
- up to 4 A 1.4 µs beam pulse stably accelerated

Measured RF-to-beam efficiency 95.3%

Theory 96% (~ 4 % ohmic losses)
Delay Loop Principle

- double repetition frequency and current
- parts of bunch train delayed in loop
- RF deflector combines the bunches

Acceleration 3 GHz

Deflection 1.5 GHz

180° phase switch in SHB

140 ns sub-pulse length

odd buckets even buckets

20 cm between bunches

140 ns pulse length 140 ns pulse gap odd even buckets

10 cm between bunches
3.3 A after chicane => < 6 A after combination (satellites)
demonstrated in CTF3
RF injection in combiner ring

- combination factors up to 5 reachable in a ring

\[ C_{\text{ring}} = (n + \frac{1}{4}) \lambda \]

1\textsuperscript{st} turn
- injection line
- septum
- 1\textsuperscript{st} deflector
- local inner orbits
- 2\textsuperscript{nd} deflector
- \( \lambda_o \)

2\textsuperscript{nd}

3\textsuperscript{rd}

4\textsuperscript{rd}
- \( \lambda_o / 4 \)
Demonstration of frequency multiplication

Combination factor 5

CTF3 - PRELIMINARY PHASE
2001/2002

Successful low-charge demonstration of electron pulse combination and bunch frequency multiplication by up to factor 5

Beam structure after combination

Streak camera image of beam time structure evolution

Beam time structure in linac

420 ns (ring revolution time)

Beam Current 0.3 A

Bunch spacing 333 ps

Beam Current 1.5 A

Bunch spacing 66 ps

5th turn

λ₀/5 (2 cm)

λ₀ = 10 cm

5th turn

RF deflectors

streak camera measurement

Streak camera image of beam time structure evolution
A first ring combination test was performed in 2002, *at low current and short pulse*, in the CERN Electron-Positron Accumulator (EPA), properly modified.
CTF3 combiner ring
Combiner ring - latest status

- factor 4 combination achieved with 13 A, 280 ns,
Power extraction structure PETS

- must extract efficiently >100 MW power from high current drive beam
- passive microwave device in which bunches of the drive beam interact with the impedance of the periodically loaded waveguide and generate RF power
- periodically corrugated structure with low impedance (big a/λ)
- ON/OFF mechanism

The power produced by the bunched ($\omega_0$) beam in a constant impedance structure:

$$ P = I^2 L^2 F_b^2 \omega_0 \frac{R/Q}{V_g^4} $$

**Design input parameters**
- $P$ - RF power, determined by the accelerating structure needs and the module layout.
- $I$ - Drive beam current
- $L$ - Active length of the PETS
- $F_b$ - single bunch form factor ($\approx 1$)
Simulation of RF Power Transfer

The induced fields travel along the PETS structure and build up resonantly.

**PETS structure**

**Accelerating structure**

T3P models realistic, complex accelerator structures with unprecedented accuracy.

Low group velocity requires simulations with 100k time steps.

Arno Candel, SLAC
Bunches induce wakefields in the accelerating cavities.

Later bunches are perturbed by the Higher Order Modes (HOM).

Can lead to emittance growth and instabilities!!!

Effect depends on $a/\lambda$ ($a$ iris aperture) and structure design details.

Transverse wakefields roughly scale as $W_\perp \propto f^3$.

Less important for lower frequency: Super-Conducting (SW) cavities suffer less from wakefields.

Long-range wakefields minimised by structure design.
• Structures built from discs
• Slight detuning between cells makes HOMs decohere quickly
• Each cell damped by 4 radial WG
• terminated by SiC RF loads
• HOM enter WG
• Long-range wakefields efficiently damped
CRUCIAL FOR LUMINOSITY: EMISSANCE

- CLIC aims at smaller beam size than other designs

**Implications:**
- Generate small emittance in the Damping Rings
- Transport the beam to the IP without significant blow-up
- Wakefield control
- Very good alignment
- Precise instrumentation
- Beam based corrections and feed-backs

**R.M.S. Beam Sizes at Collision in Linear Colliders**

- **ATF2**
- **SLC**
- **FFTB**
- **CLIC 500 GeV**
- **CLIC 3 TeV**
- **ILC GeV 500**

**Diagram:**
- Vertical Beam Size (nm)
- Horizontal Beam Size (nm)
Beam Delivery System

- reduce the beam size to a few x a few tens of nanometers
- many common issues for ILC and CLIC
- diagnostics, emittance measurement, energy measurement, …
- collimation, crab cavities, beam-beam feedback, beam extraction, beam dump
World-wide Consensus for a Lepton Linear Collider as the next HEP facility to complement LHC at the energy frontier

Presently two Linear Collider Projects:

- International Linear Collider based on Super- Conducting RF technology with extensive R&D in world-wide collaboration:
  - First phase at 500 GeV beam collision energy, upgrade to 1 TeV
  - in Technical Design phase
- CLIC technology only possible scheme to extend collider beam energy into Multi-TeV energy range
  - Very promising results but not mature yet, requires challenging R&D
  - CLIC-related key issues addressed in CTF3 by 2010

Possible decision from 2010-12 based on LHC results
Looking forward to a successful LHC operation
Documentation

- ILC information: http://www.linearcollider.org
- General documentation about the CLIC study: http://cern.ch/CLIC-Study/
- CLIC Physics: http://clicphysics.web.cern.ch/CLICphysics/
- CLIC technological challenges (CERN Academic Training): http://indico.cern.ch/conferenceDisplay.py?confId=a057972
- CLIC Workshop 2008 (most actual information): http://cern.ch/CLIC08
- EDMS: http://edms.cern.ch/nav/CERN-0000060014
- CLIC ACE (advisory committee meeting): http://indico.cern.ch/conferenceDisplay.py?confId=58072
- CLIC meeting (parameter table): http://cern.ch/clic-meeting
- CLIC notes: http://cdsweb.cern.ch/collection/CLIC%20Notes