

Frank Tecker – CERN

- 1: Introduction, Overview, Scaling, ILC/CLIC
- 2: Subsystems: source, DR, BC, main linac
- 3: Subsystems: linac, wakefields, RF, alignment
- 4: 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)



# Linear Colliders Lecture 1: Introduction and Overview



Frank Tecker – CERN

- Path to higher energy
- Cost scaling
- Luminosity
- Generic LC layout
- ILC / CLIC



# Path to higher energy





### • History:

- Energy constantly increasing with time
- Hadron Colliders at the energy frontier
- Lepton Colliders for precision physics
- LHC has found the Higgs with  $m_{\rm H} = 126 \text{ GeV/c}^2$
- A future Lepton Collider would complement LHC physics
- Recommended in the 2020
   Update of the European Strategy for Particle Physics



# Lepton vs. Hadron Collisions



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



Hadron Collider (p, ions):



- Composite nature of protons
- Can only use p<sub>t</sub> conservation
- Huge QCD background

• Lepton Collider:



- Elementary particles
- Well defined initial state
- Beam polarization
- produces particles democratically
- Momentum conservation eases decay product analysis





Higgs physics

[A]

- LC explore its properties in detail
- Supersymmetry
- 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, <u>https://cds.cern.ch/record/749219</u>
- "CLIC Conceptual Design Report– Vol.2" <u>http://arxiv.org/abs/1202.5940</u>
- "ILC Technical Design Report Vol.2 Physics at the ILC" www.linearcollider.org/ILC/Publications/Technical-Design-Report
- The CLIC potential for new physics <u>CERN-2018-009-M</u>







- Larger lepton storage ring? LEP-3?? (LEP  $L = 27 \text{ km}, E_{cm} = 200 \text{ GeV}$ )
- Remember: Synchrotron radiation
  - Emitted power:

Energy loss/turn:



 $U_{0} = \frac{4}{3} \Box \frac{r_{e}}{(m_{e}c^{2})^{3}} \frac{E^{4}}{\rho}$ 

scales with  $E^4$  !!

must be replaced by the RF system !!

• RF costs:

- $\label{eq:RF} \bigotimes U_0 \propto E^4/\rho$
- Linear costs (magnets, tunnel, etc.) :  $\in_{\text{lin}} \propto \rho$
- => Optimum when:  $e_{\text{lin}} \propto e_{\text{RF}} \Rightarrow \rho \propto E^2$
- Increase radius quadratically with energy

=> The size and the optimized cost scale as  $E^2$ as well as the energy loss per turn (was already 3% at LEP)



**Frank Tecker** 





 Collider luminosity L (cm<sup>-2</sup> s<sup>-1</sup>) is approximately given by

where:

- $n_b$  = bunches / train
- $\tilde{N}$  = particles per bunch
- $f_{rep}$  = repetition frequency
- $\sigma_{x,y}$  = transverse beam size at IP
- $\tilde{H}_D$  = beam-beam enhancement factor (linear collider: typical value ~2)
- LHC ring  $f_{rep} = 11 \text{ kHz}$
- LC  $f_{rep} = \text{few-100 Hz} \text{ (power limited)}$

 $\Rightarrow$  factor ~100-1000 in *L* already lost for the LC!

- Must push very hard on beam cross-section at collision:
- factor of 10<sup>6</sup> gain! needed to obtain high luminosity of a few 10<sup>34</sup> cm<sup>-2</sup>s<sup>-1</sup>

LEP:  $\sigma_x \sigma_y \approx 130 \times 6 \,\mu m^2$ 

LC:  $\sigma_x \sigma_y \approx (60-550) \times (1-5) \text{ nm}^2$ 

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



## Luminosity: RF power



• Introduce centre-of-mass Energy  $E_{\rm cm}$ 

 $n_b N f_{rep} E_{cm} = P_{beams}$  (beam power)

$$=\eta_{RF\to beam}P_{RF}$$

• /  $_{RF}$  is RF to beam power efficiency

$$L = \frac{n_b N^2 f_{rep}}{4\pi \sigma_x \sigma_y} H_D$$
$$L = \frac{\left(n_b N f_{rep} E_{cm}\right) N}{4\rho S_x S_y E_{cm}} H_D$$

- Luminosity is proportional to the *RF power* and *efficiency* for a given  $E_{cm}$
- Some numbers:
- $\begin{array}{l} E_{cm} = 500 \; {\rm GeV} \\ N = 10^{10} \\ n_b = 100 \\ f_{rep} = 100 \; {\rm Hz} \end{array}$

$$L = \frac{\eta_{RF} P_{RF} N}{4\pi \sigma_x \sigma_y E_{cm}} H_D$$

- Need to include efficiencies: RF→beam: range 20-60% Wall plug→RF: range 28-40%
- AC power: a few hundred MW to accelerate beams for a high luminosity
- this limits the practically achievable energy and luminosity



stability issues and tolerances

### Beam-Beam effects:

• strong self focusing (pinch effect)  $\Rightarrow$  increases Luminosity

• beamstrahlung  $\Rightarrow$  photon emission

- dilutes Luminosity spectrum
- creates detector background





- Strong electromagnetic field of the opposing bunch:
  - deflects the particles
     "beam-beam kick"
  - focuses the bunches "pinch effect"

Beam envelope

w/o beam-beam

Beam envelope

with beam-beam

 Luminosity enhancement factor H<sub>D</sub>



Frank Tecker







• beams strongly focused during collision  $\Rightarrow$  Luminosity!

• large divergence after collision  $\Rightarrow$  beam extraction difficult





• "synchrotron radiation" in the field of the opposing bunch

- => energy loss
- smears out luminosity spectrum
- creates e<sup>+</sup>e<sup>-</sup> pairs
   background in detector



 quantified by Disruption parameter



Frank Tecker





RMS relative energy loss
 beamstrahlung energy loss

$$\delta_{BS} \approx 0.86 \frac{r_e^3}{2m_0 c^2} \left(\frac{E_{cm}}{\sigma_z}\right) \frac{N^2}{(\sigma_x + \sigma_y)^2}$$

we want

AI

- $\sigma_x$  and  $\sigma_y$  small for high luminosity •  $(\sigma_x + \sigma_y)$  large for small  $\delta_{BS}$  (=> better luminosity spectrum) • use flat beams with  $\sigma_x \gg \sigma_y$  $\delta_{BS} \propto \left(\frac{E_{cm}}{\sigma_z}\right) \frac{N^2}{\sigma_x^2}$
- Can increase luminosity by small  $\sigma_y$ and minimise  $\delta_{BS}$  by big  $\sigma_x$

# JAL Limit on beam size: Hour-glass effect

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

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

 $\beta^*$  beta function at the IP



- Luminosity has to be calculated in slices
- desirable to have  $\sigma_z \leq \beta_y \Rightarrow$  short bunch length for high luminosity



Frank Tecker



Luminosity: more scaling ...



• substitute 
$$\delta_{BS} \propto \left(\frac{E_{cm}}{\sigma_z}\right) \frac{N^2}{\sigma_x^2}$$
 into  $L = \frac{1}{4\pi E_{cm}} (\eta_{RF} P_{RF}) \left(\frac{N}{\sigma_x \sigma_y} H_D\right)$ 

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

• now use 
$$\sigma_y = \sqrt{\frac{\beta_y \varepsilon_{n,y}}{\gamma}}$$

(assuming  $\beta_{rel} \sim 1$ )

• then 
$$L \propto \frac{\eta_{RF} P_{RF}}{E_{cm}^{3/2}} \sqrt{\frac{\delta_{BS} \gamma}{\varepsilon_{n,y}}} \sqrt{\frac{\sigma_z}{\beta_y}} \propto \frac{\eta_{RF} P_{RF}}{E_{cm}} \sqrt{\frac{\delta_{BS}}{\varepsilon_{n,y}}} \sqrt{\frac{\sigma_z}{\beta_y}} \sqrt{\frac{\sigma_z}{$$







- we want high RF-beam conversion efficiency  $/_{RF}$
- need high RF power  $P_{RF}$
- small normalised vertical emittance  $\sum_{n,y}$
- strong focusing at IP (small  $\beta_v$  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  $\delta_{BS}$  ~ few %
  - Slightly different result for high beamstrahlung regime



## Generic Linear Collider





Frank Tecker

Slide 19





- 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







## • 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





- ILC Reference / Technical Design Reports 2007 / 2013
- Linear Collider Collaboration (LCC) continues ILC design effort until project approval
- Web site: www.linearcollider.org
- Japan has expressed interest in hosting ILC, evaluation by government
- preferred candidate site selected: Kitakami (north Japan)
- First stage of 2x125 GeV as Higgs-Factory





Schematic Layout of the 500 GeV Machine

• Two 250 Gev linacs arranged to produce nearly head on e+e- collisions

Single IR with 14 mrad crossing angle

Centralized injector

- Circular 6.5 km / 3.2 km damping rings
- Undulator-based positron source

Dual tunnel configuration 11x5.5m

3.5m shield wall reduction being investigated



**Frank Tecker** 





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.





#### Frank Tecker

JAI





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



# JAL. ILC Main Linac RF distribution





**Frank Tecker** 

Slide 26

# CLIC – overall layout – 3 TeV



CLIC (Compact Linear Collider): only multi-TeV design
 3 TeV, 100 MV/m, warm technology, 12 GHz, two beam scheme



**Frank Tecker** 

JAI

Slide 27





- High charge Drive Beam (low energy)
- Low charge Main Beam (high collision energy)
- Simple tunnel, no active elements
- => Modular, easy energy upgrade in stages
   380 GeV => ~1.5 TeV => 3 TeV









# CLIC two-beam scheme



- RF power is produced by drive beam
- Drive beam: 100 A current, 2.4 GeV
- Main beam:
   1 A, 1500 GeV





- RF Power per structure ~ 65MW
- No of structures ~140,000
- Total instantaneous power
   ~ 9.1 PW



## First LC: SLC





Built to study the Z<sup>0</sup> and demonstrate linear collider feasibility

Energy = 92 GeV Luminosity = 2e30

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

A 10% prototype!

-T.Raubenheimer



## Parameter comparison



	SLC	TESLA	ILC	J/NLC	CLIC
Technology	NC	Supercond.	Supercond.	NC	NC
Gradient [MeV/m]	20	25	31.5	50	100
CMS Energy E [GeV]	92	500-800	500-1000	500-1000	500-3000
RF frequency f [GHz]	2.8	1.3	1.3	11.4	12.0
Luminosity $L [10^{33} \text{ cm}^{-2} \text{s}^{-1}]$	0.003	34	20	20	23
Beam power P <sub>beam</sub> [MW]	0.035	11.3	10.8	6.9	4.9
Grid power <i>P<sub>AC</sub></i> [MW]		140	230	195	270
<b>Bunch length</b> $\int_{z}^{*} [mm]$	~1	0.3	0.3	0.11	0.07
Vert. emittance ©∑, [10 <sup>-8</sup> m]	300	3	4	4	2.5
Vert. beta function @* [mm]	~1.5	0.4	0.4	0.11	0.1
<b>Vert. beam size</b> $\int_{y}^{*}$ [nm]	650	5	5.7	3	2.3

Parameters (except SLC) at 500 GeV

# JAL Documentation about ILC/CLIC



- ILC International Development Team
- ILC Newsline
- General documentation about the CLIC study:
- Int. Linear Collider Workshop 2021
- CLIC Workshop 2019 (most actual info)
- International school for Linear Colliders:
- CLIC detector and physics study:
- CLIC conceptual design report:
- CLIC scheme description:
- CLIC Test Facility: CTF3
- CERN Academic Trainings: CLIC technological challenges CLIC (2018)
- CLIC project meetings
- CLIC notes

#### http://linearcollider.org

- http://newsline.linearcollider.org
- http://cern.ch/clic-study / http://clic.cern
- https://indico.cern.ch/event/995633
- http://indico.cern.ch/event/753671
- https://agenda.linearcollider.org/event/7333
- http://cern.ch/clicdp
- http://clic-study.web.cern.ch/content/conceptual-design-report
- http://cds.cern.ch/record/461450/files/CERN-2000-008.pdf
  - https://clic-study.web.cern.ch/organization/ctf3
  - http://indico.cern.ch/conferenceDisplay.py?confId=a057972 http://indico.cern.ch/event/668147
  - http://indico.cern.ch/category/3589/
  - http://cdsweb.cern.ch/collection/CLIC%20Notes