Linear Colliders
4 lectures

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

Preface

- 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

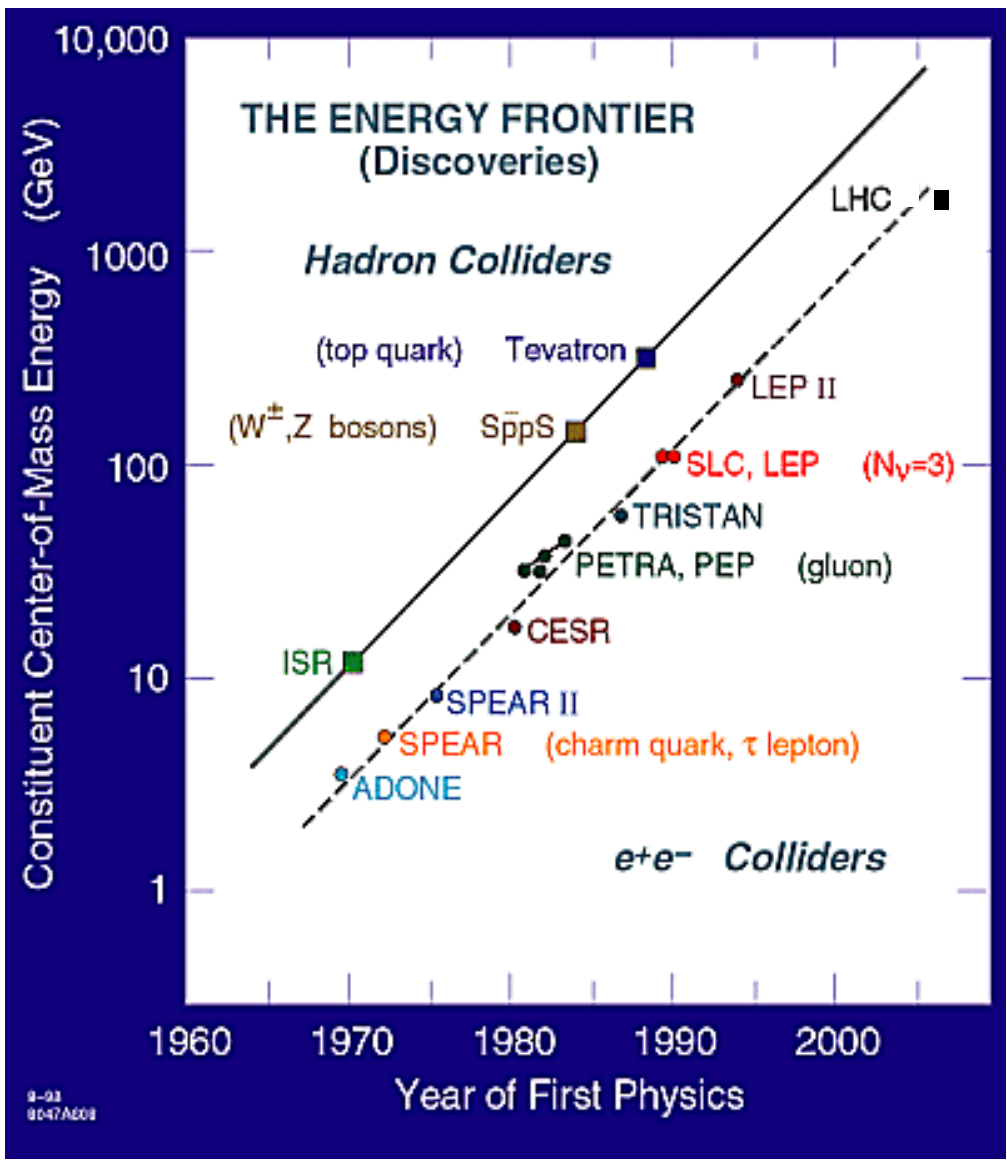- Ask questions at any time! Any comment is useful! (e-mail: tecker@cern.ch)

Linear Colliders
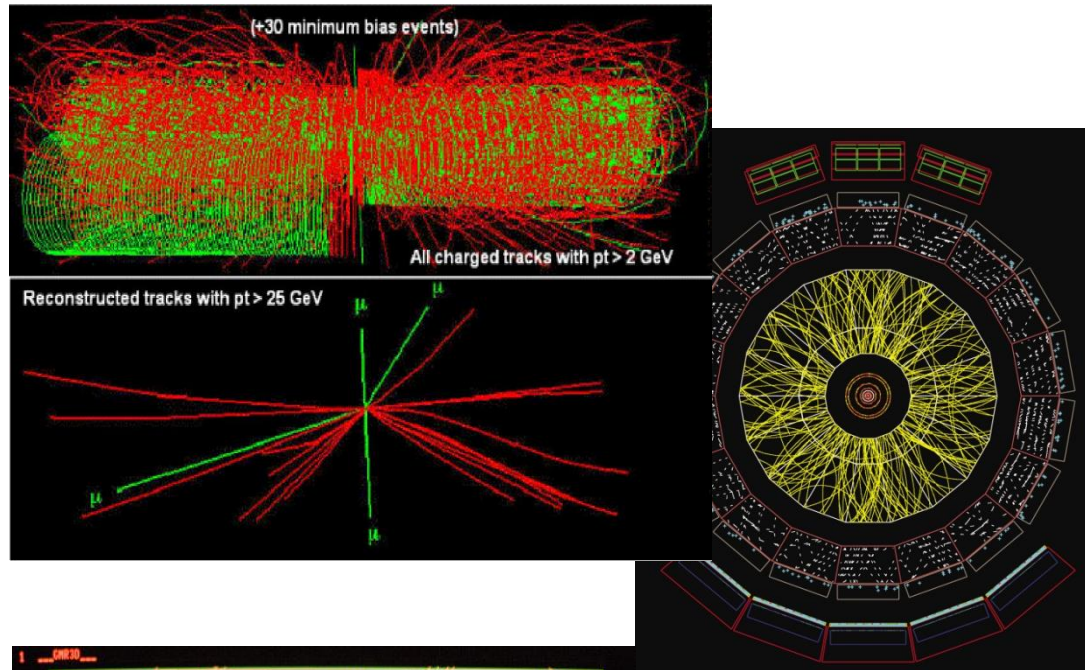# Lecture 1:
Introduction and Overview

Frank Tecker – CERN

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

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

- LHC has found the Higgs with $m_H = 126$ 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: $H \to ZZ \to 4\mu$

(+30 minimum bias events)
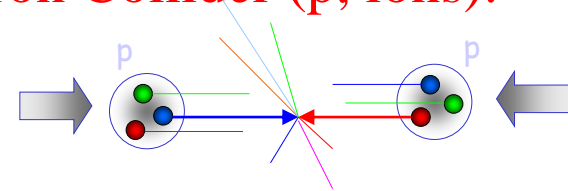All charged tracks with pt > 2 GeV
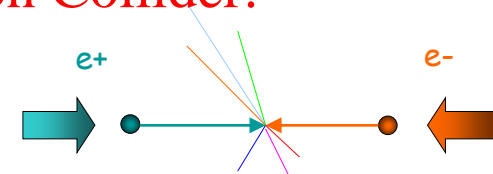Reconstructed tracks with pt > 25 GeV

ALICE:
Ion event

LEP event:
$Z^0 \to 3$ jets

🔴 **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

TeV e+e- physics

- **Higgs** physics
  - LC explore its properties in detail

- **Supersymmetry**

- **Extra** spatial **dimensions**

- New **strong interactions**

- **dark matter, dark energy, . . .**

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

- "Physics at the CLIC Multi-TeV Linear Collider"
  CERN-2004-005, https://cds.cern.ch/record/749219

- "CLIC Conceptual Design Report– Vol.2"
  http://arxiv.org/abs/1202.5940

- "ILC Technical Design Report – Vol.2 – Physics at the ILC"
  www.linearcollider.org/ILC/Publications/Technical-Design-Report

- The CLIC potential for new physics CERN-2018-009-M
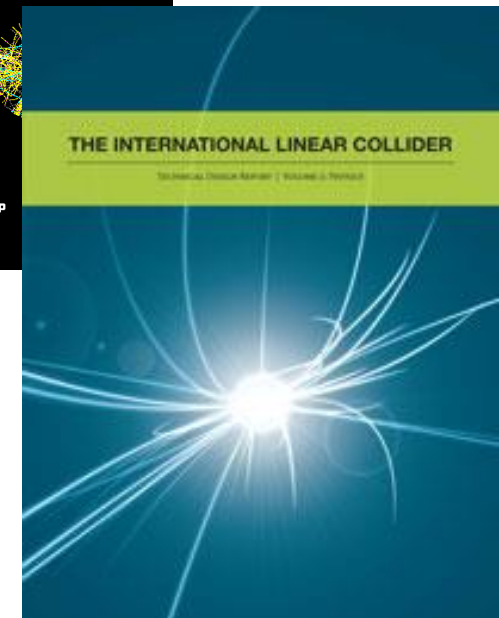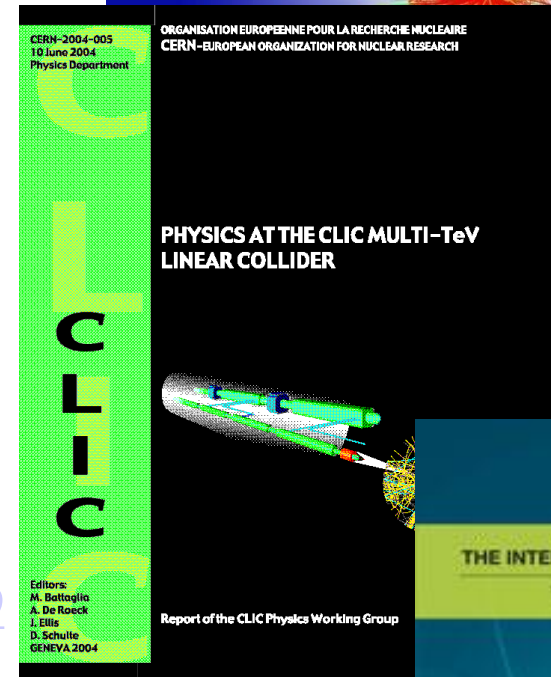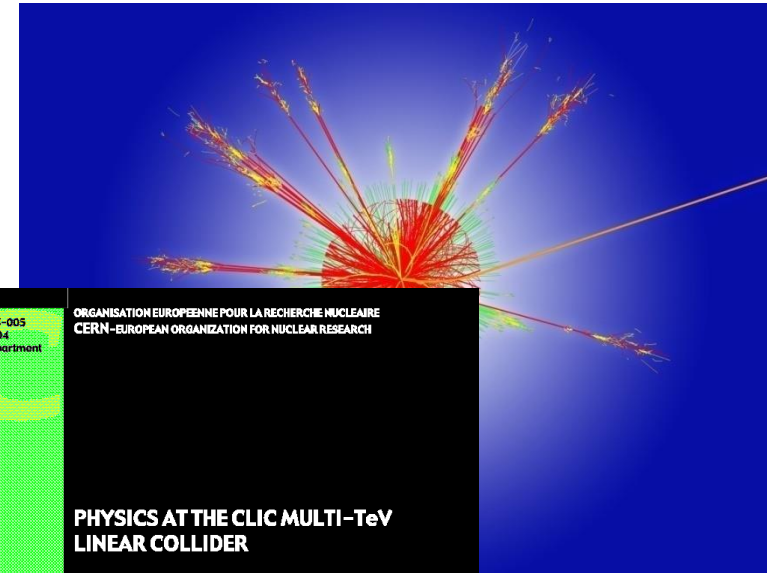
- Larger lepton storage ring?   LEP-3??   (LEP $L = 27$ km, $E_{cm} = 200$ GeV)

- Remember: Synchrotron radiation

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

  - Energy loss/turn:
  $$U_0 = \frac{4}{3} \Box \frac{r_e}{\left(m_0 c^2\right)^3} \frac{E^4}{\rho}$$
  must be replaced by the RF system !!

- RF costs: $€_{RF} \propto U_0 \propto E^4/\rho$

- Linear costs (magnets, tunnel, etc.) : $€_{lin} \propto \rho$

- => Optimum when: $€_{lin} \propto €_{RF} \quad \Rightarrow \quad \rho \propto E^2$

- 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)

The solution: a Linear Collider

- NO bending magnets ⇒ NO synchrotron radiation

- but: A lot of accelerating structures !!!

- Cost scaling linear with E

damping ring

e+   e-

source

beam delivery

main linac
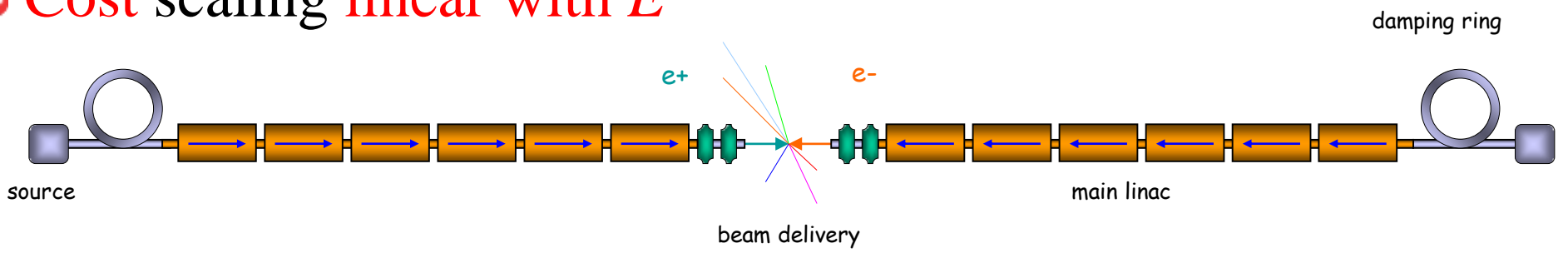
Storage rings:

- accelerate + collide every turn

- 're-use' RF + 're-use' particles

- => efficient

Linear Collider:

- one-pass acceleration + collision => need

- high gradient
- small beam size σ and emittance

to reach high luminosity L (event rate)

- much less limited by beam-beam effect

- Collider luminosity L (cm^{-2} s^{-1}) is approximately given by

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

  where:

  n_b = bunches / train
  N = particles per bunch
  f_{rep} = repetition frequency
  $\sigma_{x,y}$ = transverse beam size at IP
  H_D = beam-beam enhancement factor (linear collider: typical value ~2)

- LHC ring f_{rep} = 11 kHz

- LC f_{rep} = few-100 Hz (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 10^6 gain! needed to obtain high luminosity of a few 10^{34} cm^{-2}s^{-1}

  LEP: $\sigma_x \sigma_y \approx 130 \times 6$ µm^2

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

- Introduce centre-of-mass Energy E_{cm}

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

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

- η_{RF} is RF to beam power efficiency

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

$$L = \frac{\left(n_b N f_{rep} E_{cm}\right) N}{4\rho s_x s_y E_{cm}} H_D$$

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

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

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

- 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

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

- choice of technology (NC vs SC):
  - efficiency
  - available power

- Strong focusing needed for small beam size
  - optical aberrations
  - stability issues and tolerances

- Beam-Beam effects:
  - strong self focusing (pinch effect) ⇒ increases Luminosity
  - beamstrahlung ⇒ photon emission
    - dilutes Luminosity spectrum
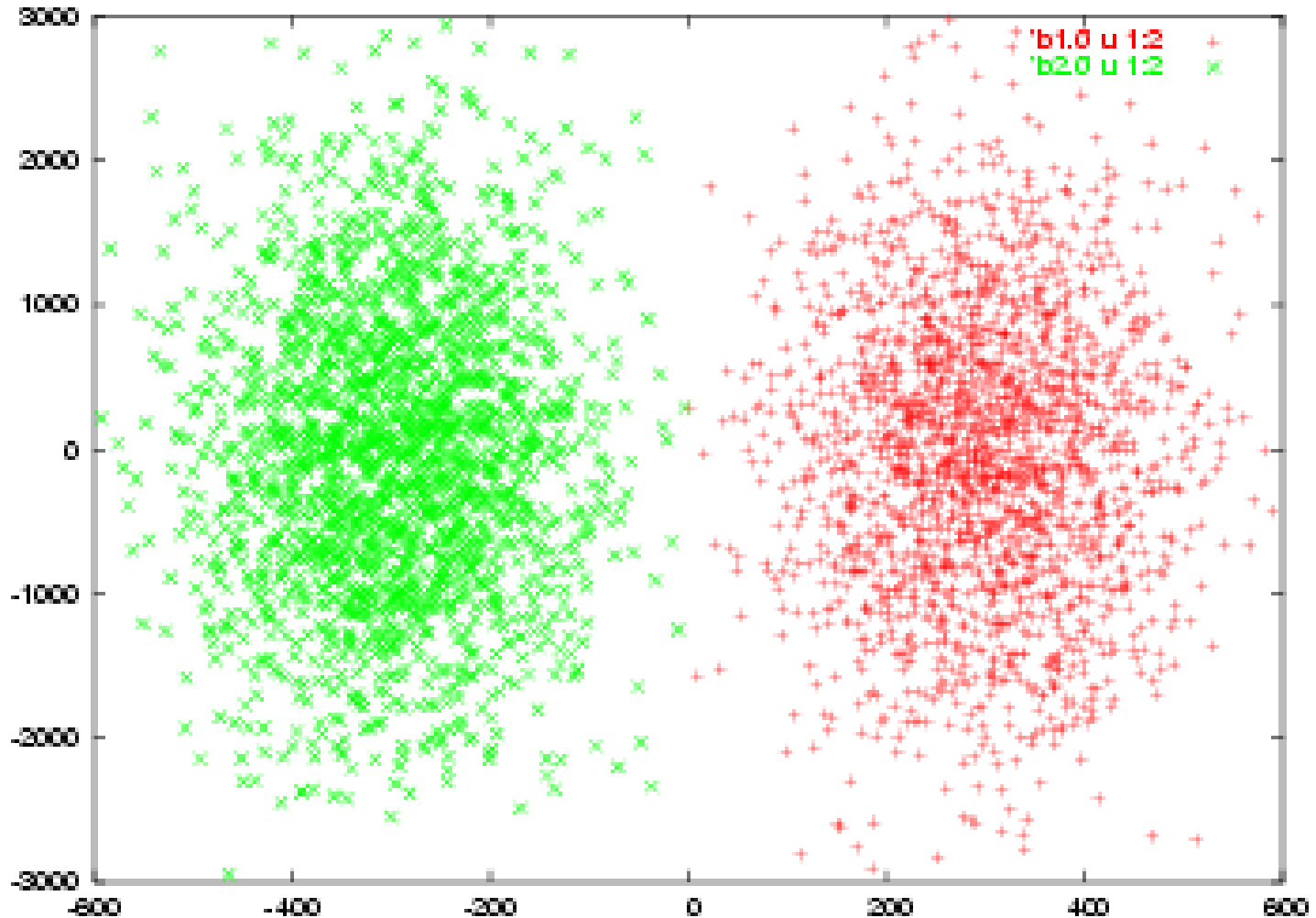   - creates detector background

- Strong electromagnetic field of the opposing bunch:

  - deflects the particles "beam-beam kick"

  - focuses the bunches "pinch effect"

  - Luminosity enhancement factor H_D
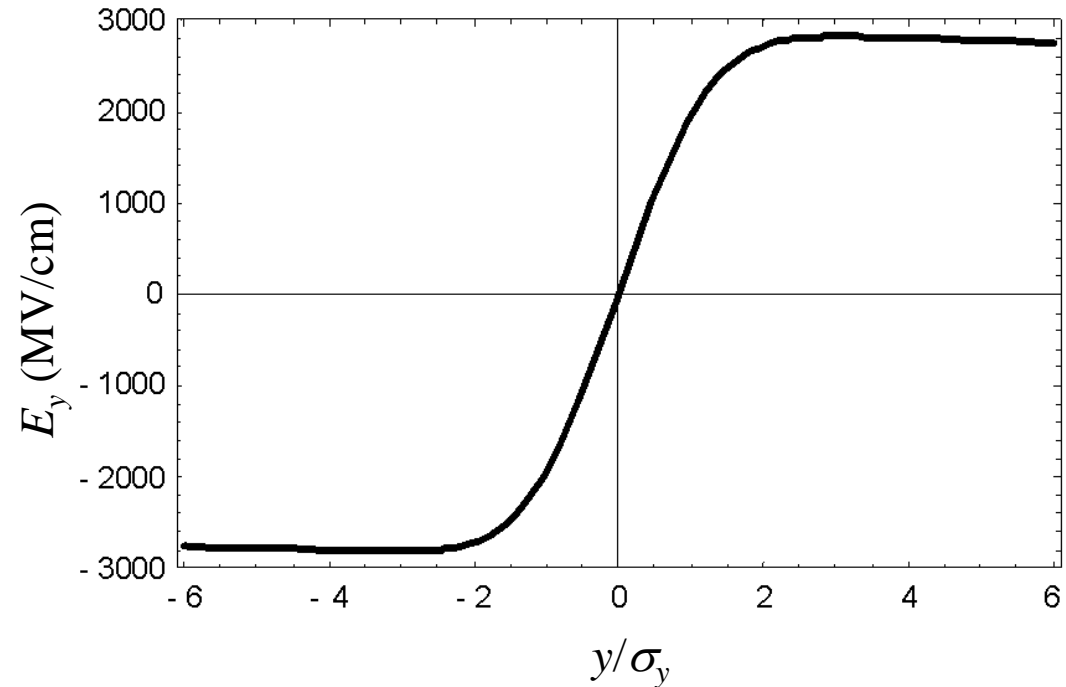
Beam envelope w/o beam-beam

Beam envelope with beam-beam
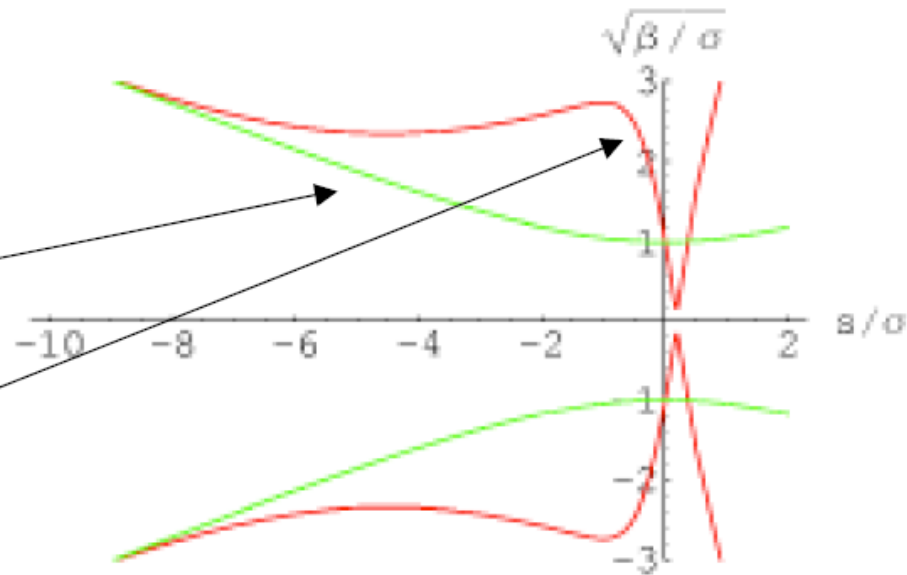
D.Schulte

- beams strongly focused during collision ⇒ Luminosity!

- large divergence after collision ⇒ beam extraction difficult

Beamstrahlung

- "synchrotron radiation" in the field of the opposing bunch
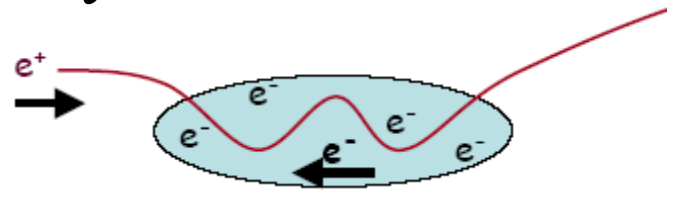
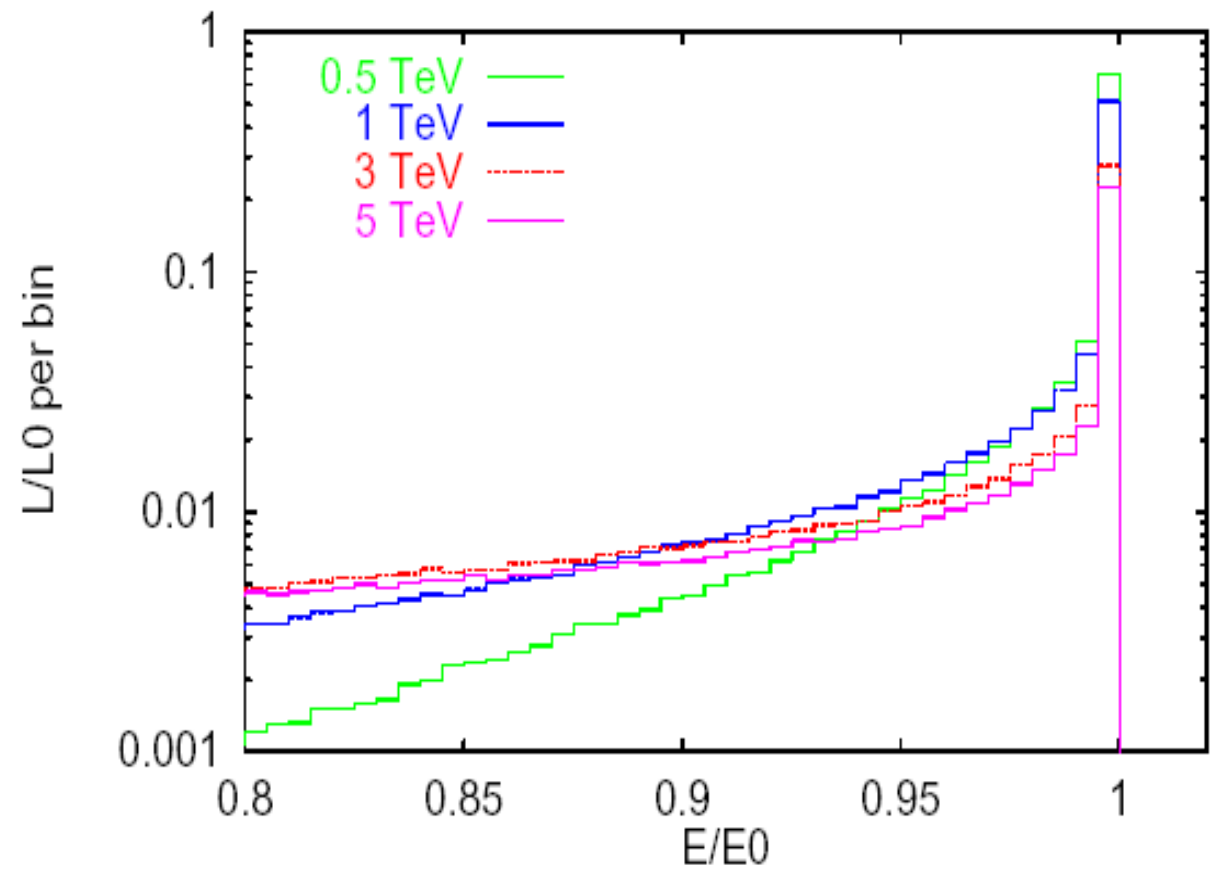=> energy loss

- smears out luminosity spectrum

- creates e⁺e⁻ pairs background in detector

- quantified by Disruption parameter

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

- 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

  - σ_x and σ_y small for high luminosity

  - $(\sigma_x + \sigma_y)$ large for small δ_{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 σ_y

  and minimise δ_{BS} by big σ_x

- β-function at the interaction point follows

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

β^* beta function at the IP

$\sigma_z > \beta^*_y$

hour-glass effect
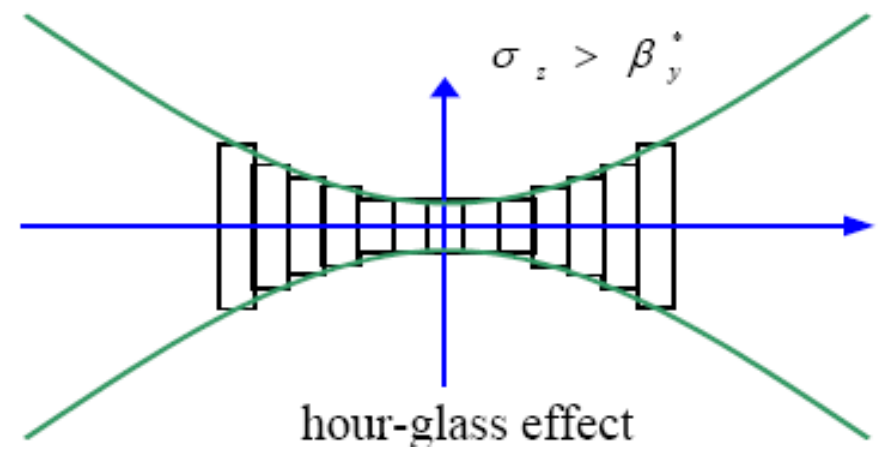
- Luminosity has to be calculated in slices

- desirable to have $\sigma_z \leq \beta_y$ $\Rightarrow$ short bunch length for high luminosity

$\sigma_z = \beta_y$

$\sigma_z = 3\beta_y$
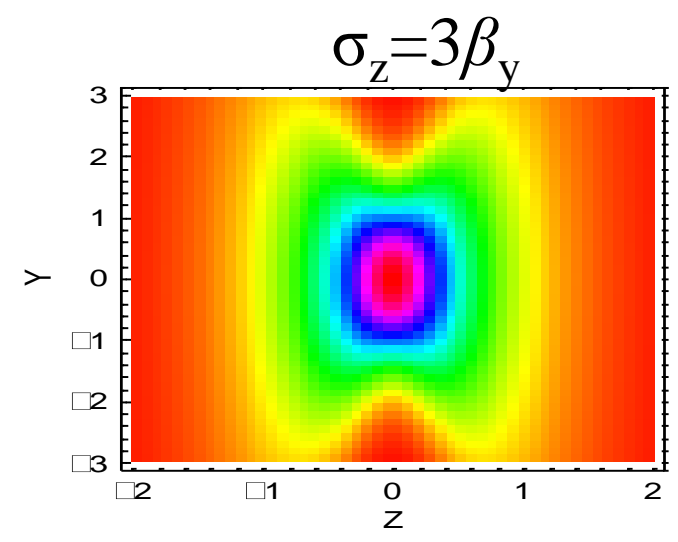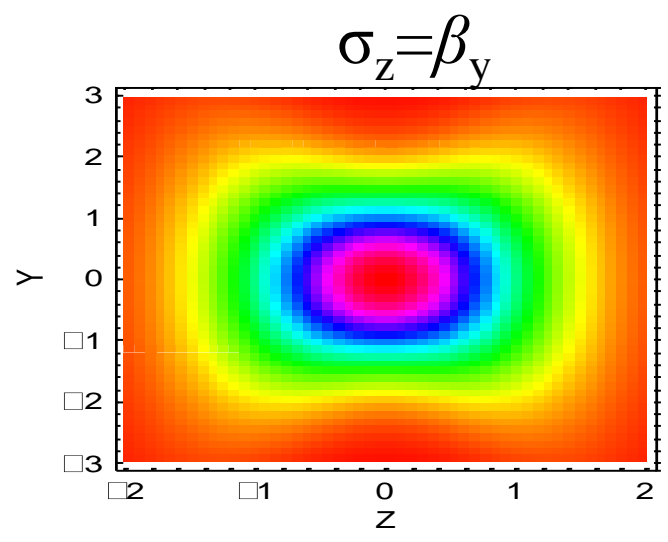
N.Walker

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

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

- now use $\sigma_y = \sqrt{\dfrac{\beta_y \varepsilon_{n,y}}{\gamma}}$ (assuming $\beta_{rel} \sim 1$)
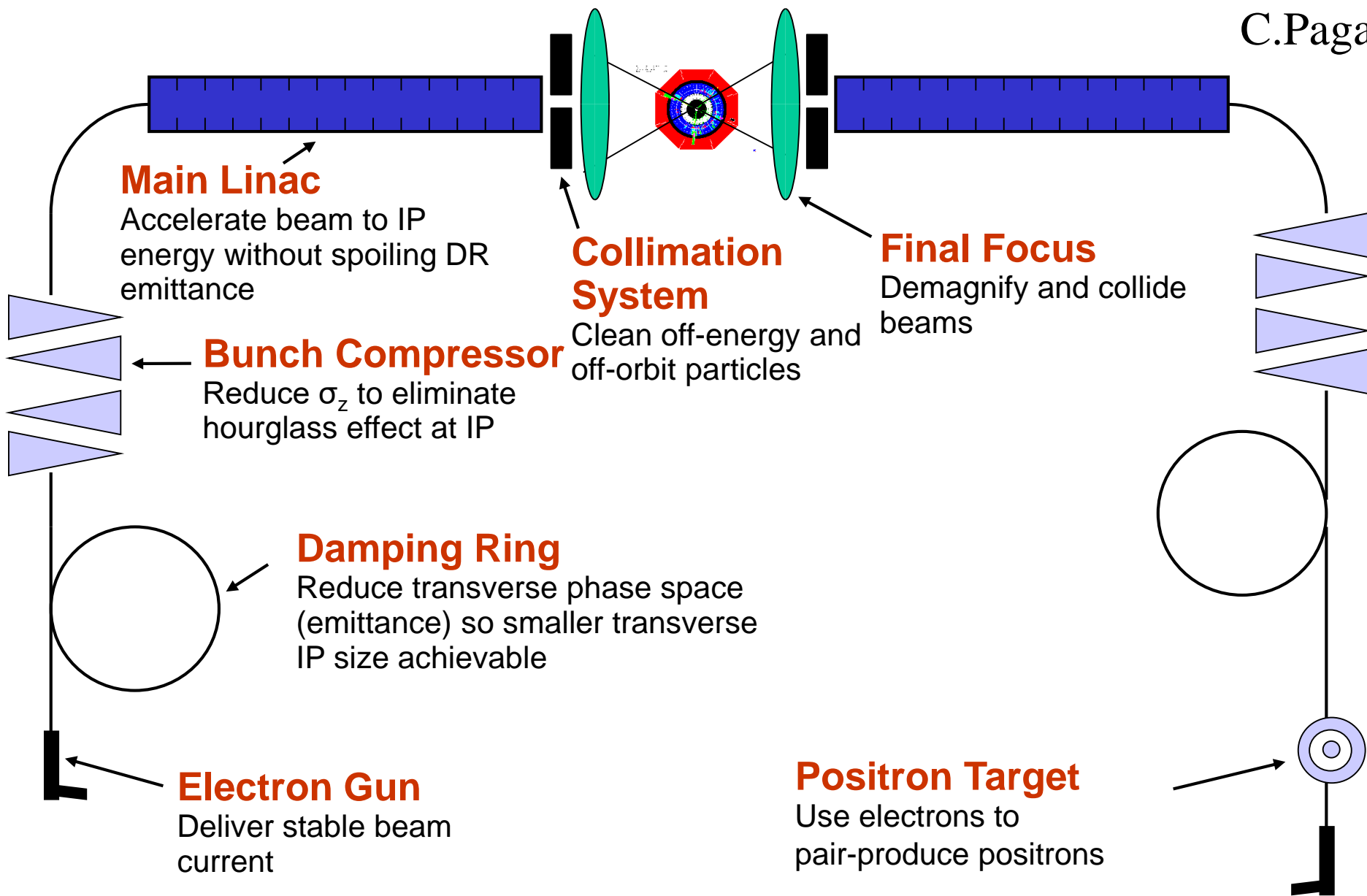
- then $L \propto \dfrac{\eta_{RF} P_{RF}}{E_{cm}^{3/2}}\sqrt{\dfrac{\delta_{BS}\gamma}{\varepsilon_{n,y}}}\sqrt{\dfrac{\sigma_z}{\beta_y}} \propto \dfrac{\eta_{RF} P_{RF}}{E_{cm}}\sqrt{\dfrac{\delta_{BS}}{\varepsilon_{n,y}}}\underbrace{\sqrt{\dfrac{\sigma_z}{\beta_y}}}$

~ 1 (hour glass effect)

The 'final' scaling for LC

$$L \propto \frac{\eta_{RF} P_{RF}}{E_{cm}} \sqrt{\frac{\delta_{BS}}{\varepsilon_{n,y}}} H_D \qquad b_y \gg s_z$$

- we want high RF-beam conversion efficiency η_{RF}

- need high RF power P_{RF}

- small normalised vertical emittance $\varepsilon_{n,y}$

- strong focusing at IP (small β_y and hence small σ_z)

- could also allow higher beamstrahlung δ_{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

Frank Tecker   Slide 18   John Adams Institute

Generic Linear Collider

C.Pagani

Main Linac
Accelerate beam to IP energy without spoiling DR emittance

Bunch Compressor
Reduce σ_z to eliminate hourglass effect at IP

Collimation System
Clean off-energy and off-orbit particles

Final Focus
Demagnify and collide beams

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

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
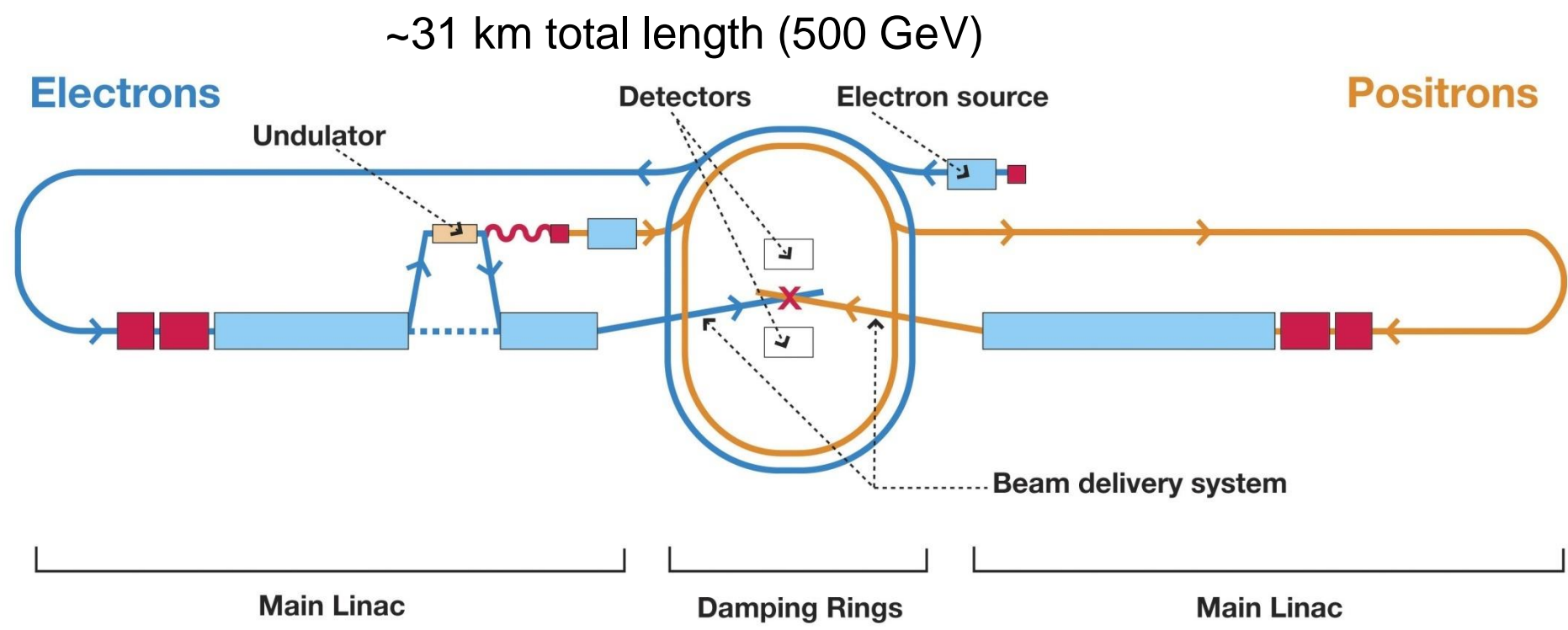
The real designs: TESLA -> ILC
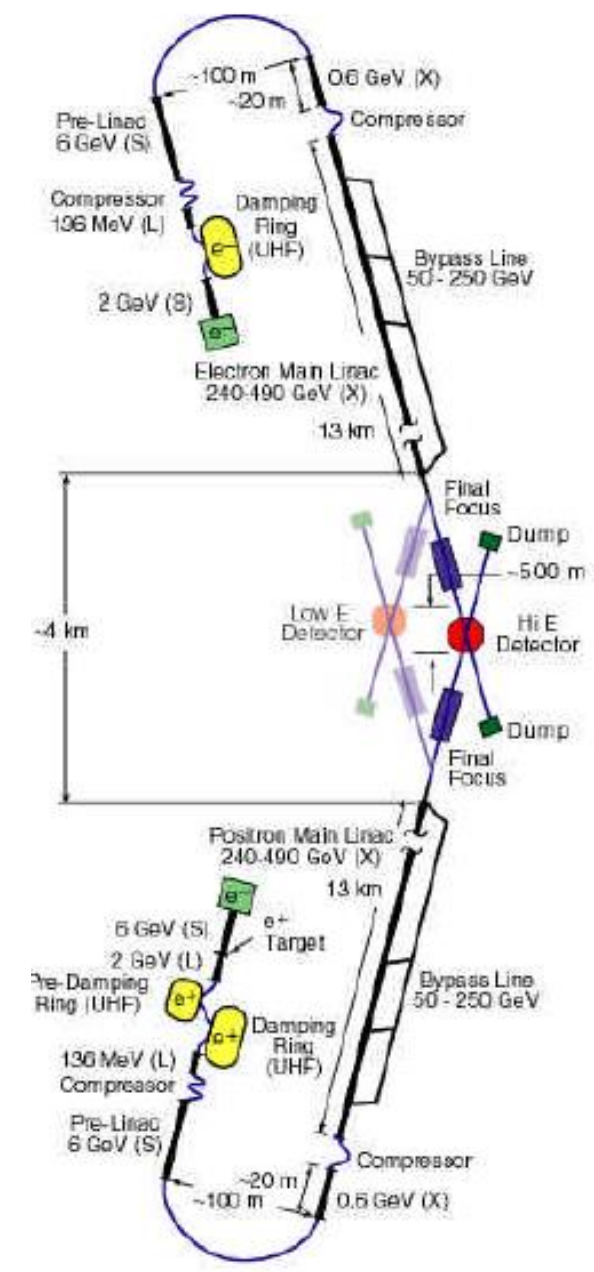
TESLA:

- 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

~31 km total length (500 GeV)

- 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
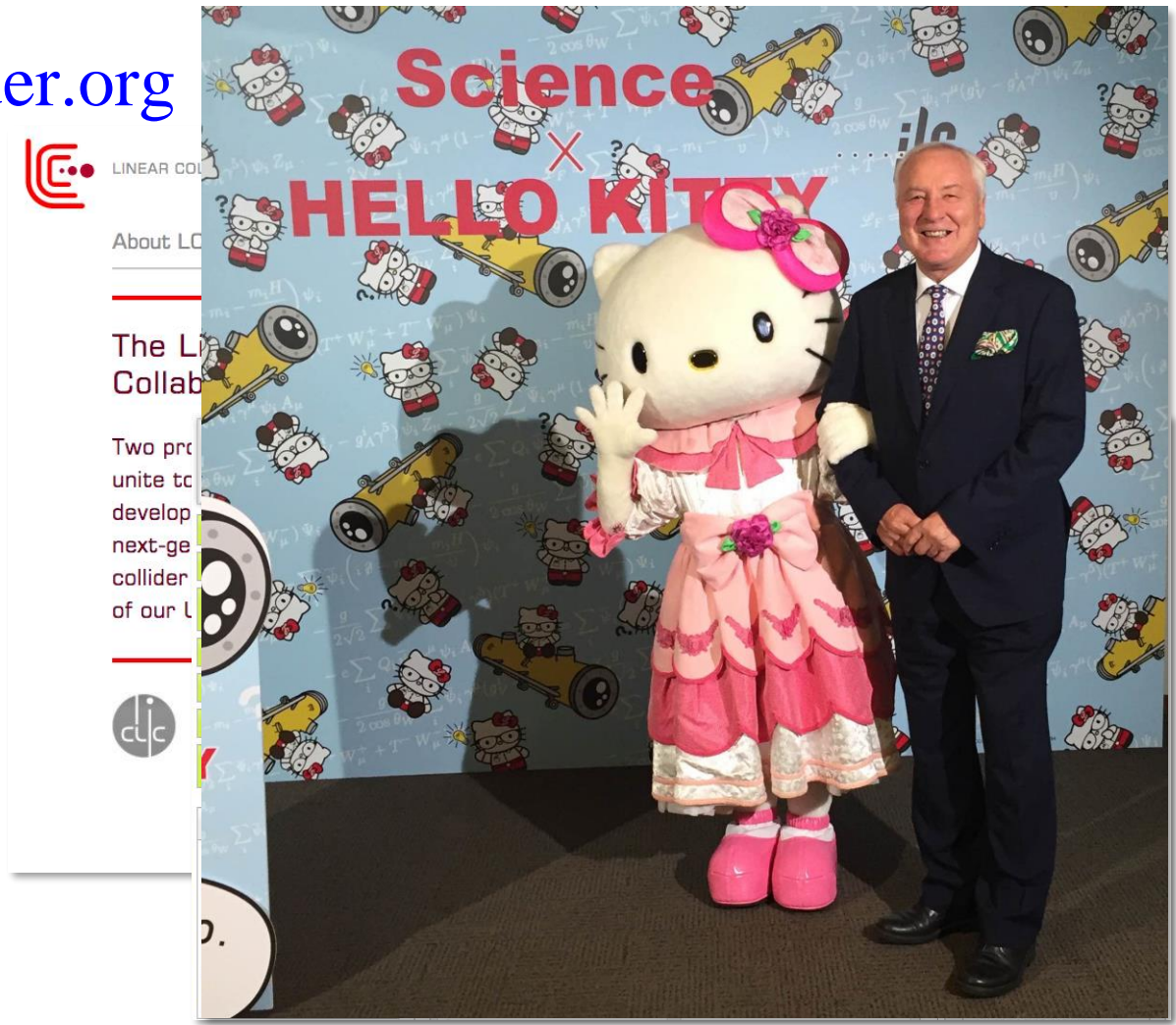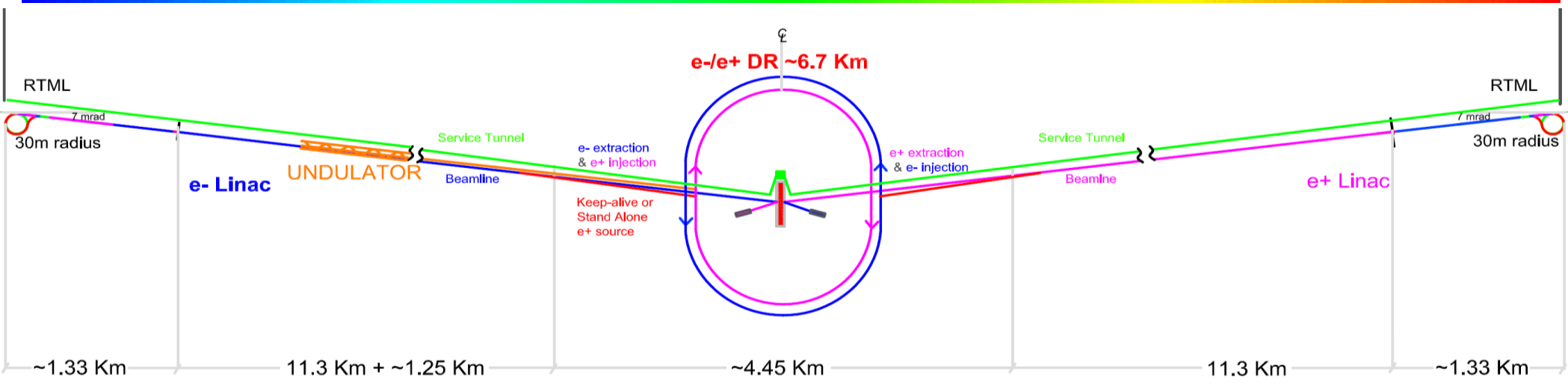
ILC Schematic

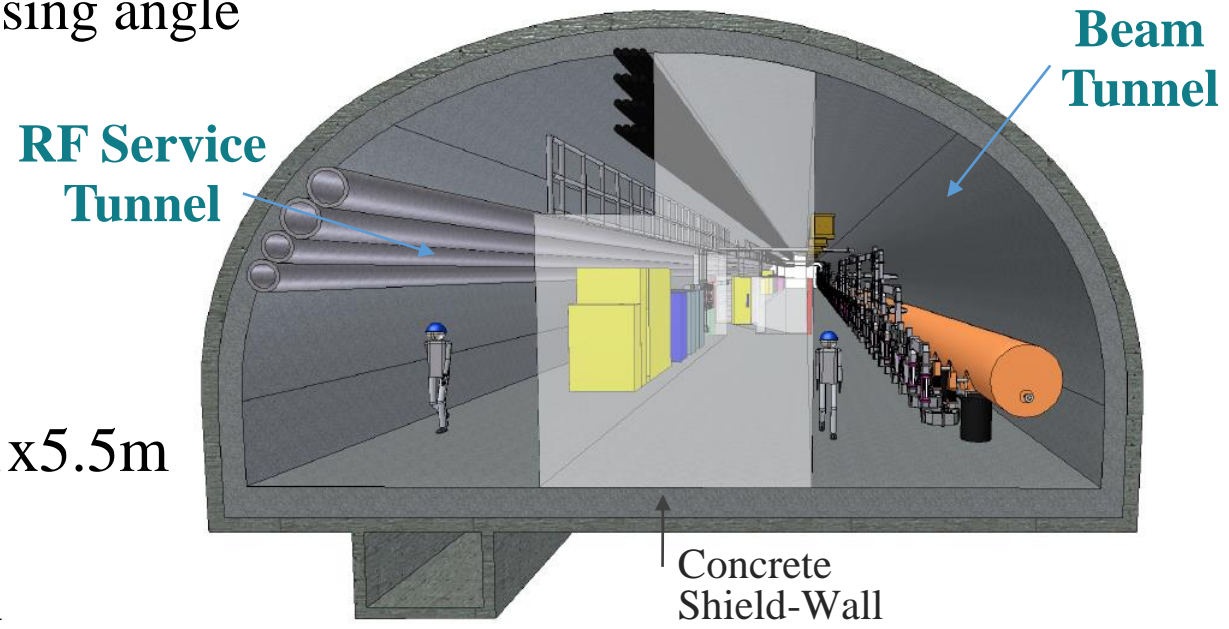Schematic Layout of the 500 GeV Machine

- 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
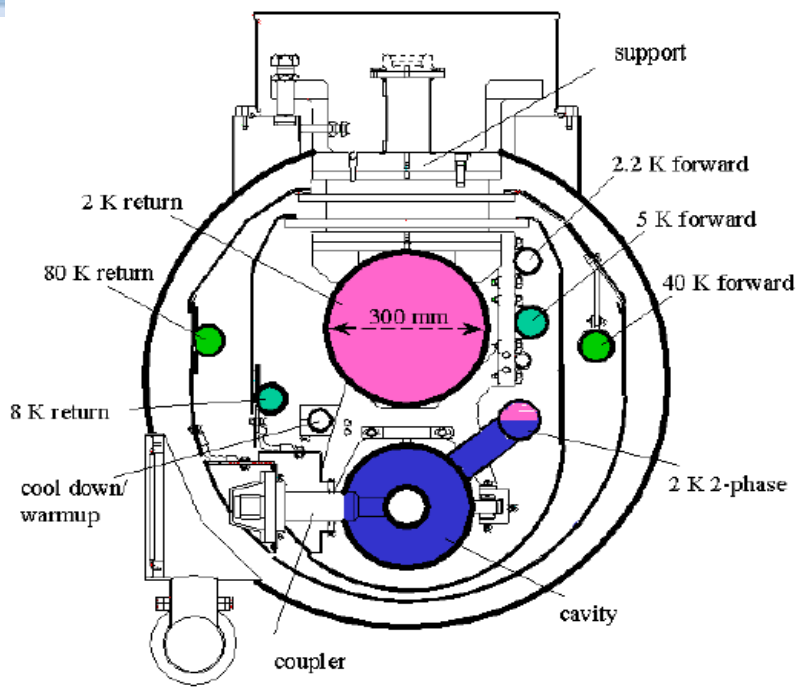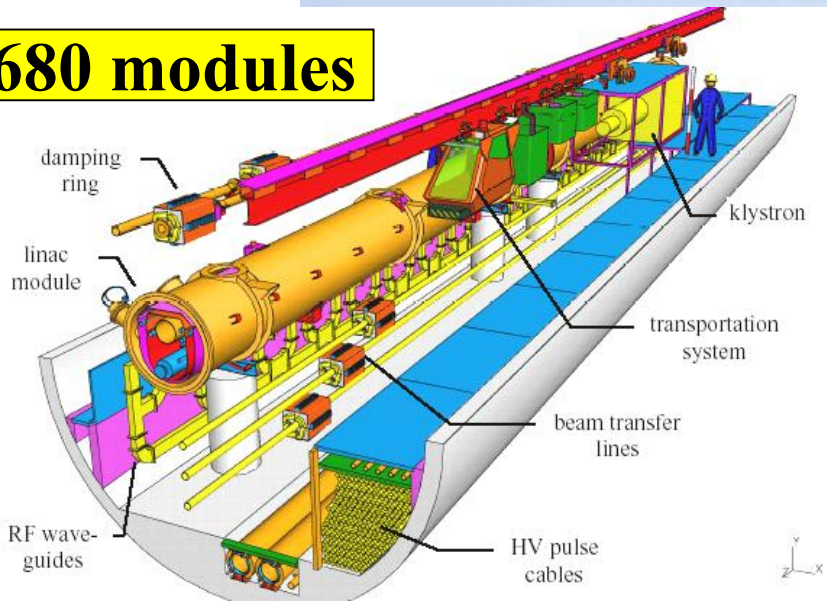 - 3.5m shield wall reduction being investigated

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.

14560 cavities

1680 modules

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**
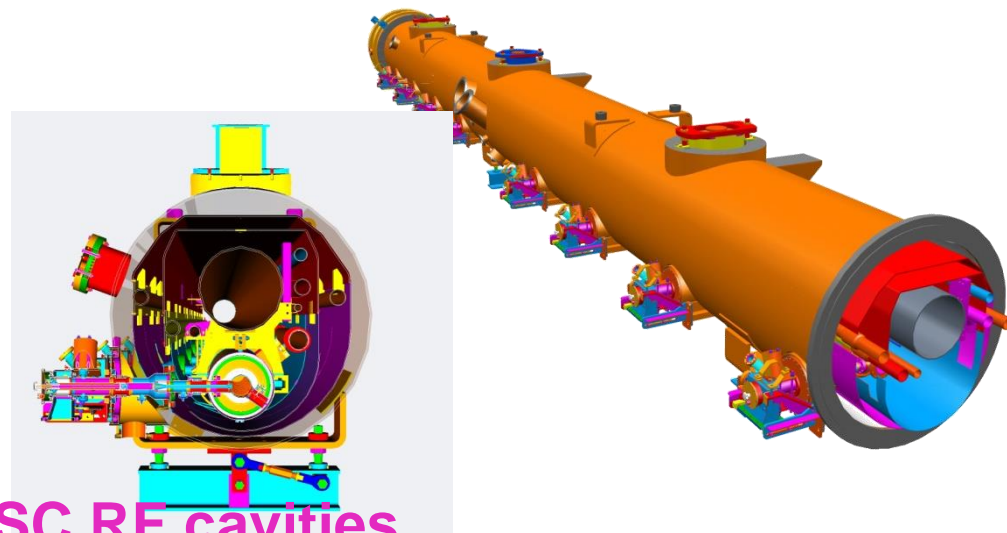
Total of 1680 cryomodules and 14 560 SC RF cavities

cryomodule connection   cryomodule connection

Linear RF Power distribution
with circulator & stub or EH tuner for every
cavity input

3MW Line   3MW Line   splitter   circulator   coupler pump   beam-line pump

stub tuner   cryomodule pump

10MW Multi-beam
Klystron,
socket assembly

1:12 Pulse Trans

Bouncer Modulator

Front end electronics

ILC Main Linac RF distribution
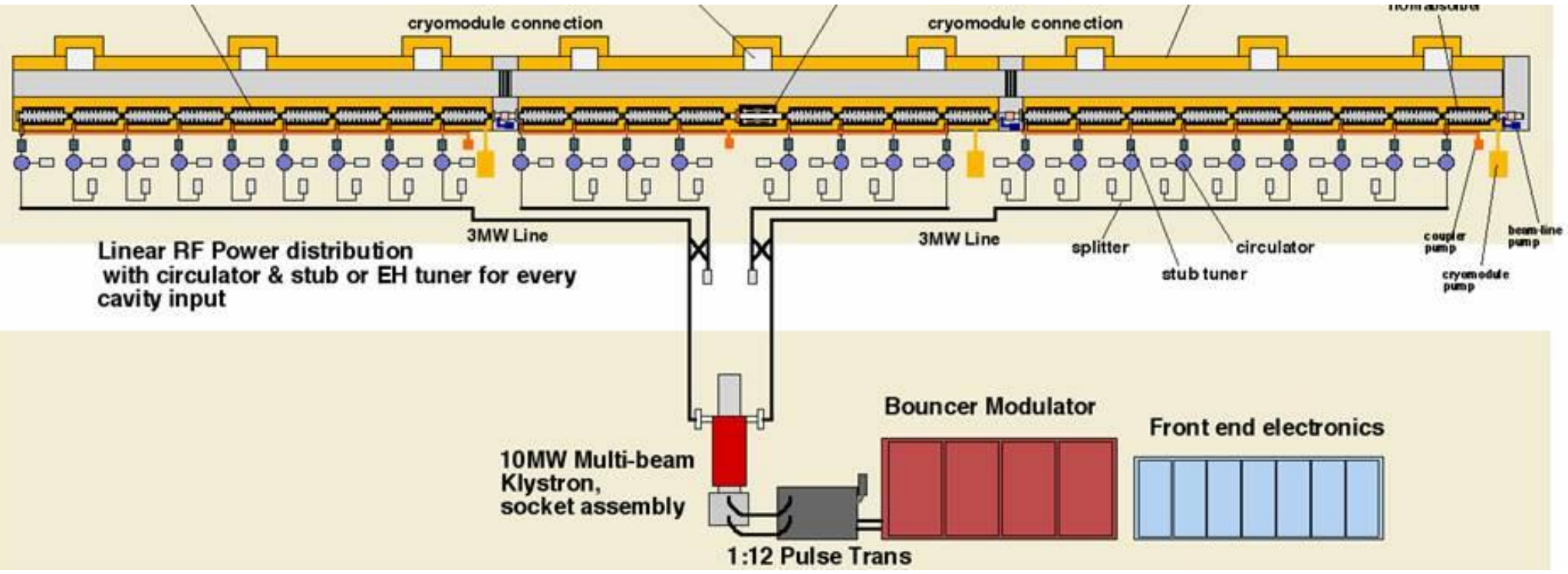
surface rf power cluster building
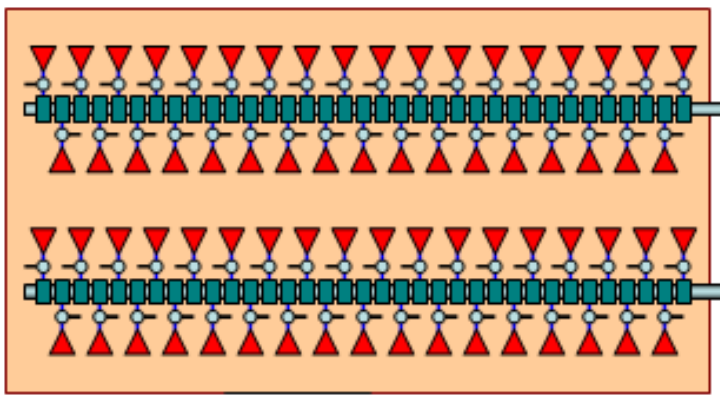
- Either many small klystrons in the tunnel
- or few clusters of higher power klystrons
- O(10TW) instantaneous power

surface

shaft

- **service tunnel eliminated**
- **underground heat load greatly reduced**

~1.06 km ⬅ upstream

downstream ➡ ~1.06 km

accelerator tunnel

CTO

TE$_{01}$ waveguide

WAVEGUIDE DISTRIBUTION SYSTEM

TAP-OFFS

WAVEGUIDE DISTRIBUTION SYSTEM

TAP-OFFS

WAVEGUIDE DISTRIBUTION SYSTEM

9 CAVITIES	4 CAVITIES QUAD 4 CAVITIES	9 CAVITIES
3 CRYOMODULES		
37.956 m		

9 CAVITIES	4 CAVITIES QUAD 4 CAVITIES	9 CAVITIES
3 CRYOMODULES		
37.956 m		

9 CAVITIES	4 CAVITIES QUAD
3 CRYOMODUL	
37.956 m	

CLIC – overall layout – 3 TeV
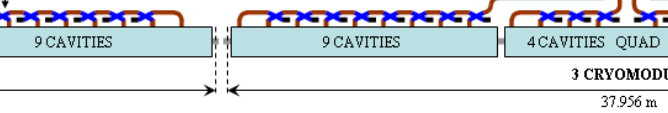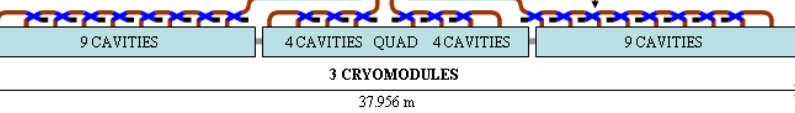
- **CLIC** (Compact Linear Collider): only multi-TeV design

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

Drive Beam

540 klystrons
20 MW, 148 µs

drive beam accelerator
2.4 GeV, 1.0 GHz

2.5 km

circumferences
delay loop 73 m
CR1 293 m
CR2 439 m

540 klystrons
20 MW, 148 µs

drive beam accelerator
2.4 GeV, 1.0 GHz

2.5 km

delay loop

CR1

CR2

CR2

CR1

delay loop

decelerator, 25 sectors of 878 m

BC2

BC2

BDS
2.75 km

IP

BDS
2.75 km

e⁻ main linac, 12 GHz, 72/100 MV/m, 21 km

e⁺ main linac

TA

TA

50 km

CR   combiner ring
TA   turnaround
DR   damping ring
PDR   predamping ring
BC   bunch compressor
BDS   beam delivery system
IP   interaction point
       dump

booster linac
2.86 to 9 GeV

Main Beam

BC1

e⁻ injector
2.86 GeV

e⁻
DR
427 m

e⁺
DR
427 m

e⁺
PDR
389 m

e⁺ injector
2.86 GeV

CLIC two beam 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
  380 GeV => ~1.5 TeV => 3 TeV

CLIC TUNNEL
CROSS-SECTION

**Drive beam** - 101 A, 240 ns
from 2.4 GeV to 240 MeV
power-extraction and transfer structure (PETS)

quadrupole

quadrupole

accelerating structures

RF

12 GHz, 68 MW

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

BPM

Transfer lines

Drive Beam   Main Beam

5.6 m diameter
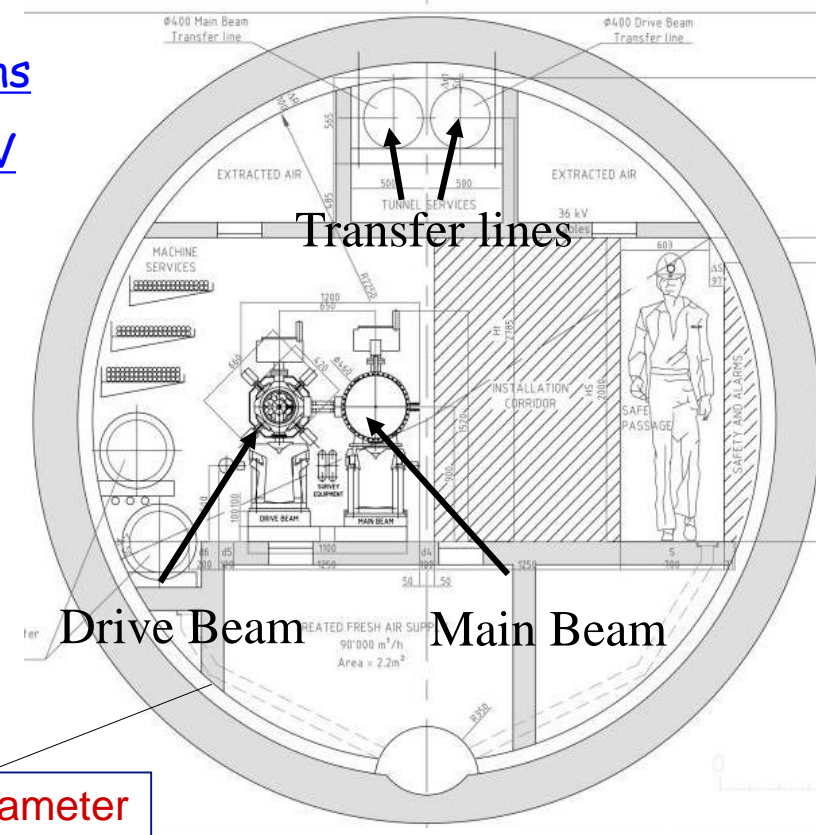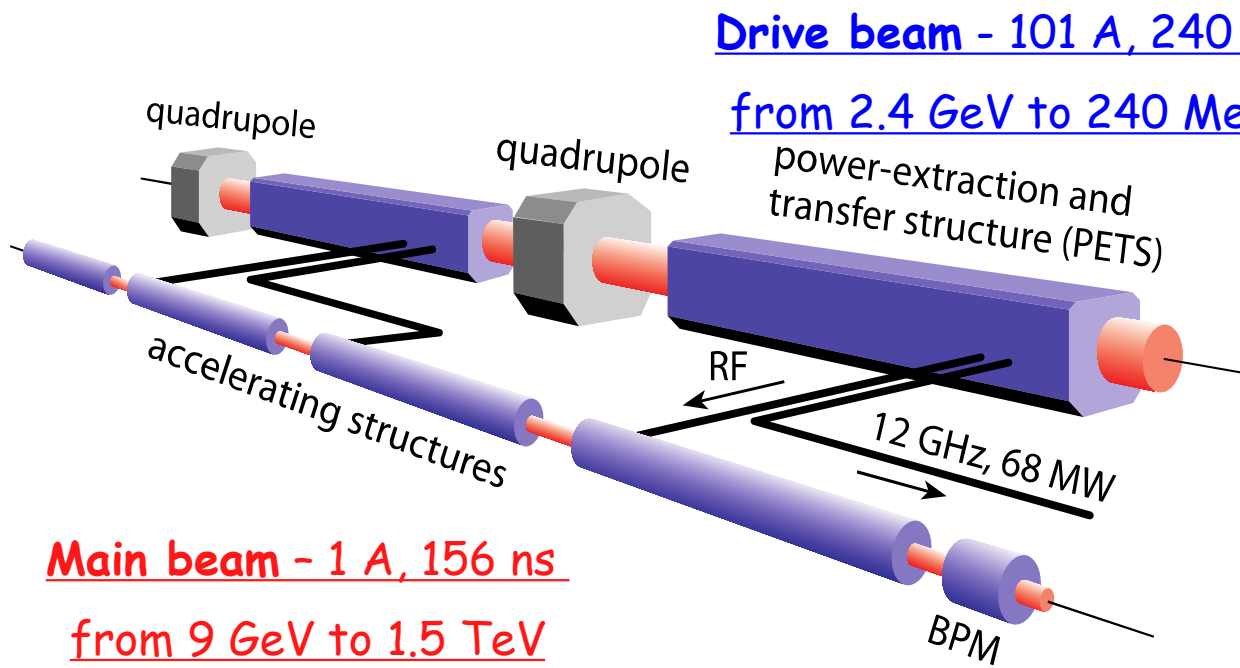
Compact Linear Collider (CLIC)

- ▬ **380 GeV** - 11.4 km (CLIC380)
- ▬ **1.5 TeV** - 29.0 km (CLIC1500)
- ▬ **3.0 TeV** - 50.1 km (CLIC3000)

LHC

CLIC380

CLIC1500

CERN

CLIC3000

Geneva

CLIC two-beam scheme
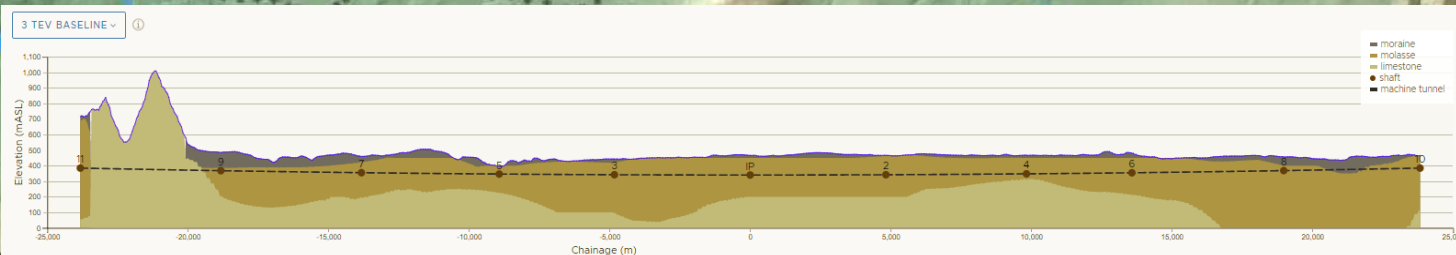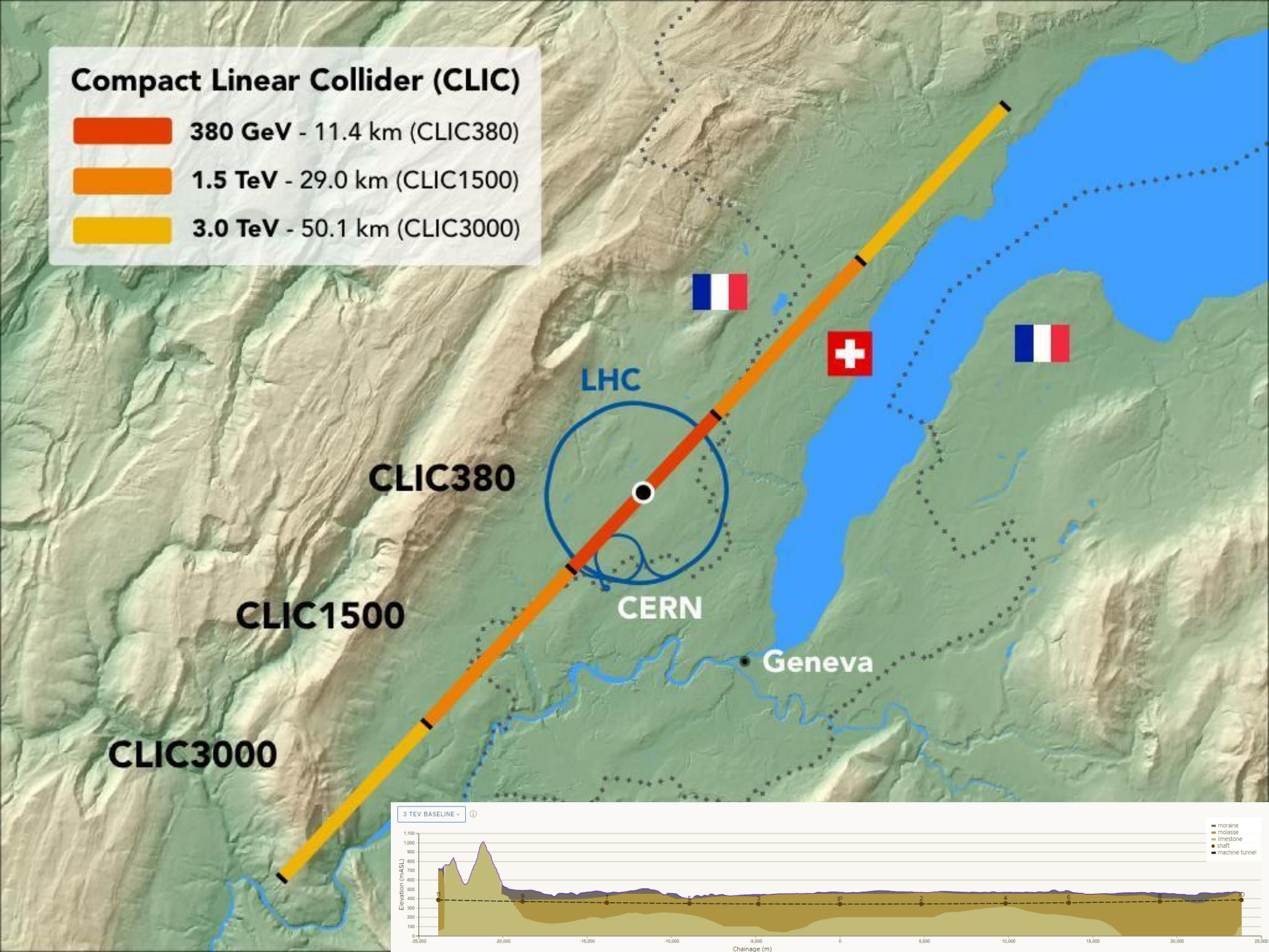
- RF power is produced by drive beam

- Drive beam:
  100 A current, 2.4 GeV

- Main beam:
  1 A, 1500 GeV
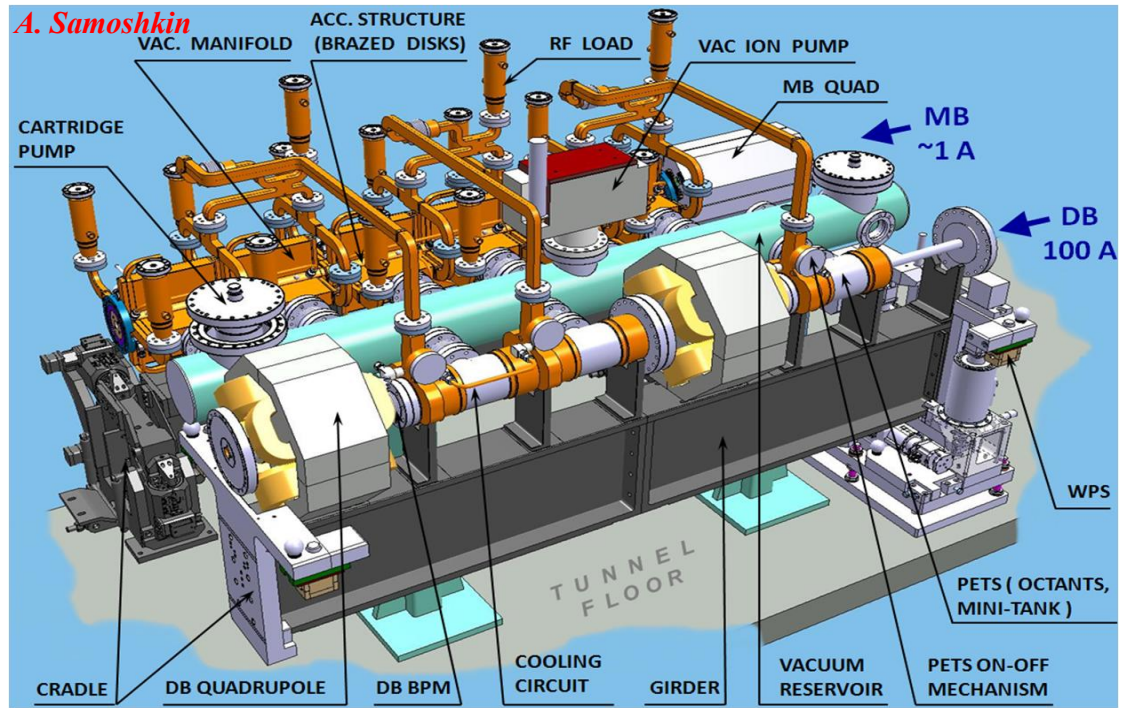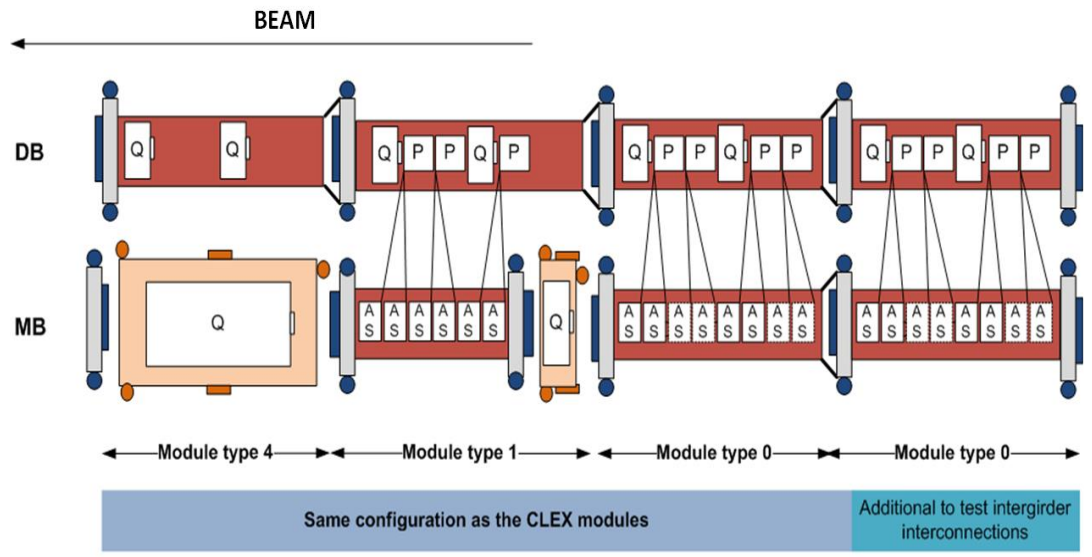
- RF Power per structure ~ 65MW

- No of structures ~140,000

- Total instantaneous power ~ 9.1 PW

Built to study the Z^0 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} cm^{-2}s^{-1}]	0.003	34	20	20	23
Beam power P_{beam} [MW]	0.035	11.3	10.8	6.9	4.9
Grid power P_{AC} [MW]		140	230	195	270
Bunch length $\int_z^*$ [mm]	~1	0.3	0.3	0.11	0.07
Vert. emittance $\copyright\sum_y$ [10^{-8}m]	300	3	4	4	2.5
Vert. beta function $\mathcal{R}_y^*$ [mm]	~1.5	0.4	0.4	0.11	0.1
Vert. beam size $\int_y^*$ [nm]	650	5	5.7	3	2.3

Parameters (except SLC) at 500 GeV

Documentation about ILC/CLIC

- ILC International Development Team — http://linearcollider.org

- ILC Newsline — http://newsline.linearcollider.org

- General documentation about the CLIC study: — http://cern.ch/clic-study / http://clic.cern

- Int. Linear Collider Workshop 2021 — https://indico.cern.ch/event/995633

- CLIC Workshop 2019 (most actual info) — http://indico.cern.ch/event/753671

- International school for Linear Colliders: — https://agenda.linearcollider.org/event/7333

- CLIC detector and physics study: — http://cern.ch/clicdp

- CLIC conceptual design report: — http://clic-study.web.cern.ch/content/conceptual-design-report

- CLIC scheme description: — http://cds.cern.ch/record/461450/files/CERN-2000-008.pdf

- CLIC Test Facility: CTF3 — https://clic-study.web.cern.ch/organization/ctf3

- CERN Academic Trainings:
  - CLIC technological challenges — http://indico.cern.ch/conferenceDisplay.py?confId=a057972
  - CLIC (2018) — http://indico.cern.ch/event/668147

- CLIC project meetings — http://indico.cern.ch/category/3589/

- CLIC notes — http://cdsweb.cern.ch/collection/CLIC%20Notes