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

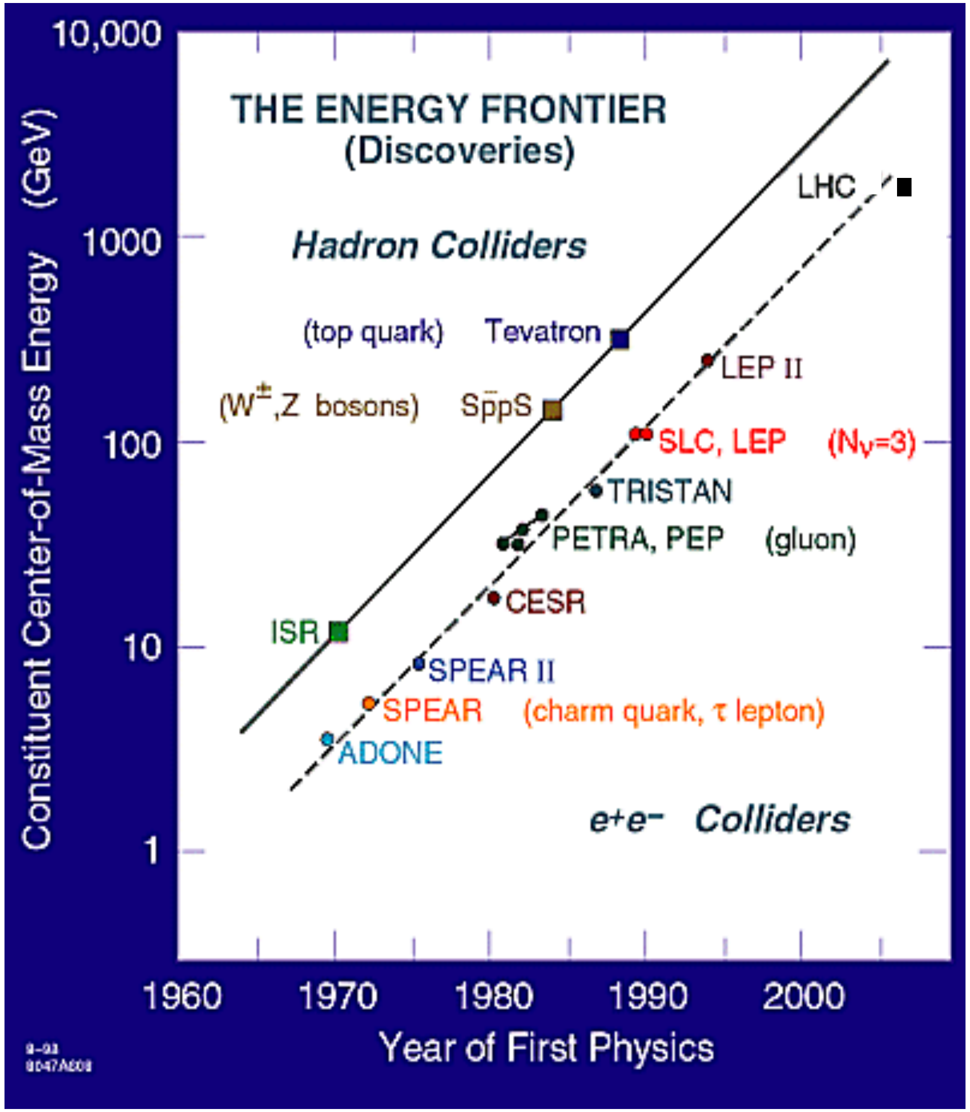
- Complex topic --- but: DON'T PANIC!
- Approach:
  - Explain the fundamental layout of a linear collider and the specific designs based on SuperConducting (**SC**) and normal conducting (**NC**) technology
  - I will not go much into technical details
  - Try to avoid formulae as much as possible
- 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

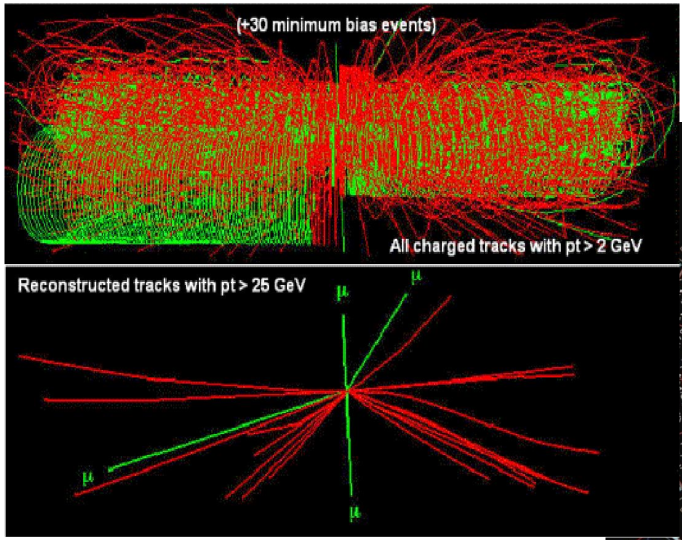
Path to higher energy



- History:
  - Energy constantly increasing with time
  - Hadron Colliders at the energy frontier
  - Lepton Colliders for precision physics
- LHC has found the Higgs with $m_H = 126\ GeV/c^2$
- 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 → ZZ → 4μ



ALICE:
Ion event

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

- Hadron Collider (p, ions):

  - Composite nature of protons
  - Can only use p_t conservation
  - Huge QCD background

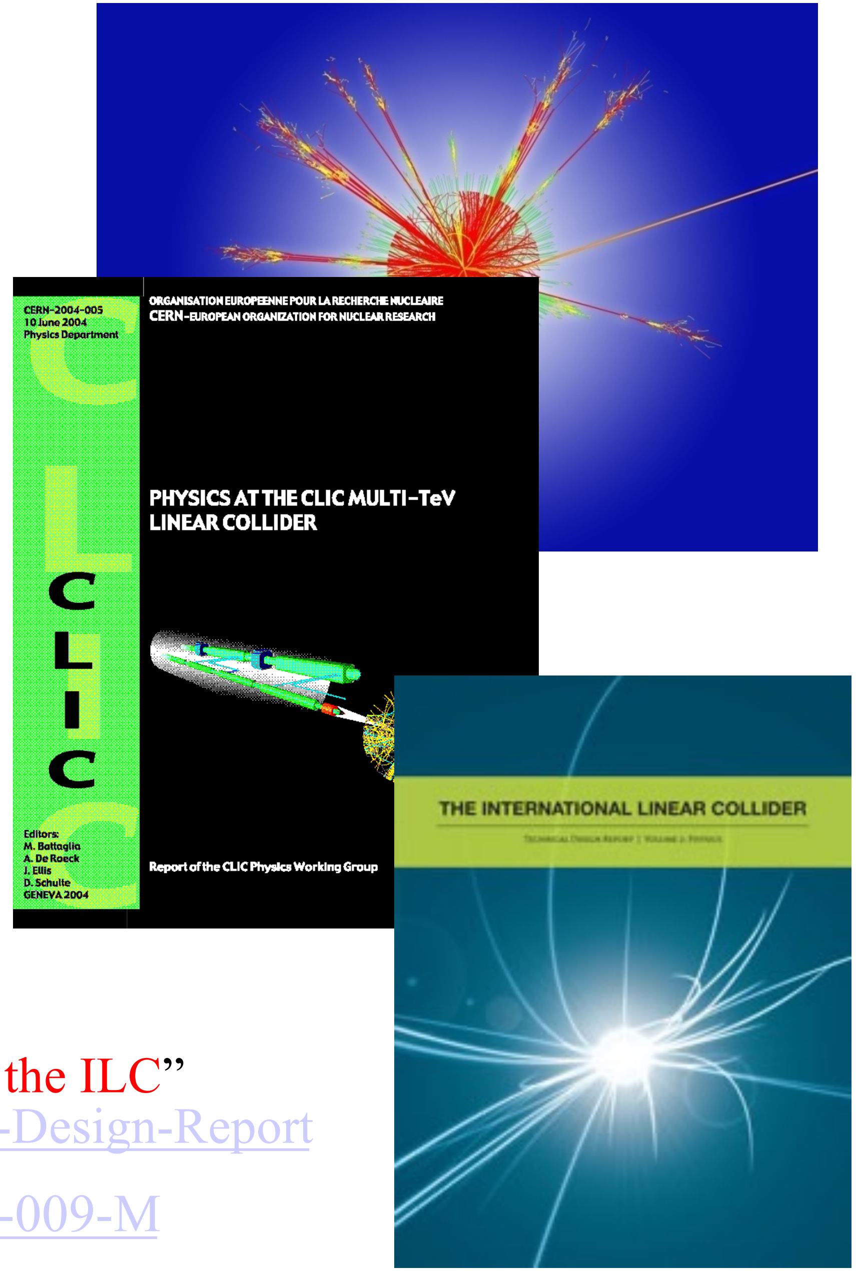
- Lepton Collider:

  - 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

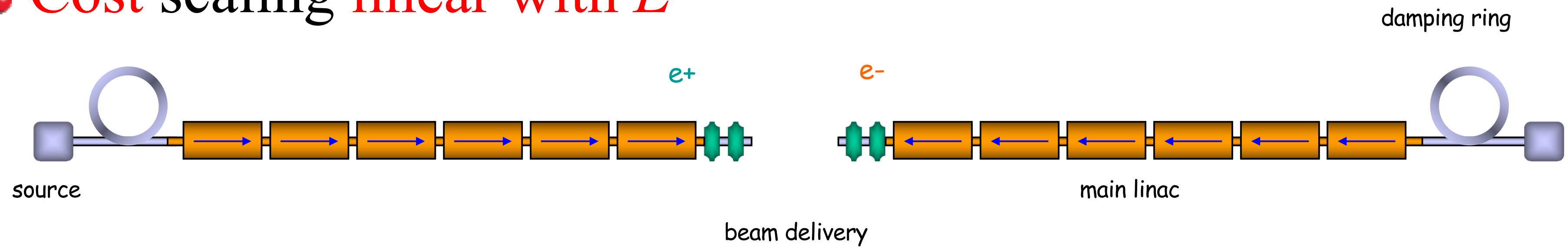
The next lepton collider

- Larger lepton storage ring? LEP-3?? (LEP $L = 27$ km, $E_{cm} = 200$ GeV)
- Remember: Synchrotron radiation
  - Emitted power: $$P = \frac{2}{3} \frac{r_e c}{(m_o c^2)^3} \frac{E^4}{\rho^2}$$ scales with E^4 !!
  - Energy loss/turn: $$U_0 = \frac{4}{3} \pi \frac{r_e}{(m_0 c^2)^3} \frac{E^4}{\rho}$$ 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: $€_{lin} \propto €_{RF} \Rightarrow \rho \propto E^2$
- 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)

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 σ and emittance

  to reach high luminosity L (event rate)
- much less limited by beam-beam effect

Luminosity: LC vs Storage Ring

- 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)

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

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

Luminosity: RF power

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

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

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

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

- η_{RF} is RF to beam power efficiency

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

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

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

- 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

Luminosity: IP effects

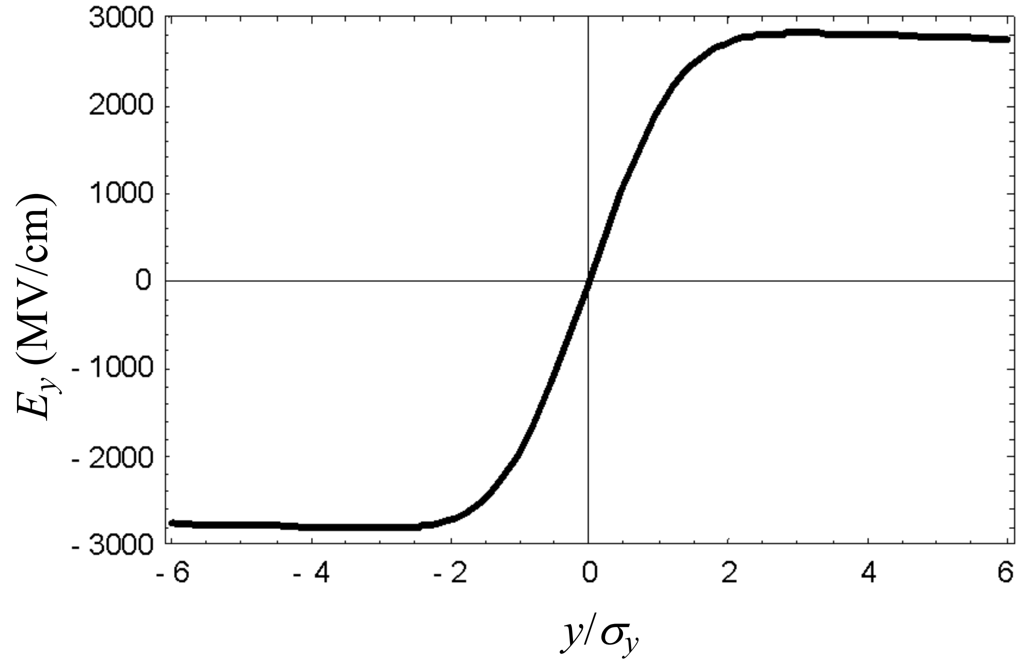
$$L = \frac{1}{4\pi E_{cm}} \left(\eta_{RF} P_{RF} \right) \left(\frac{N}{\sigma_x \sigma_y} H_D \right)$$

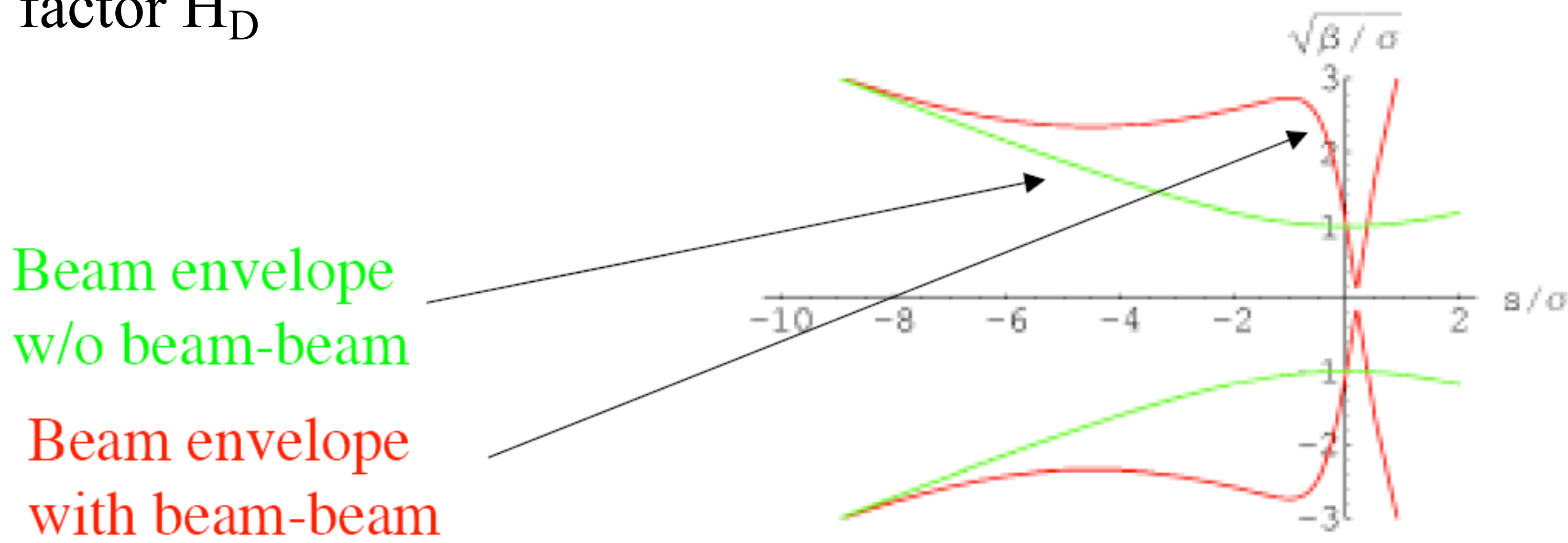
- choice of technology (NC vs SC):
  - efficiency
  - available power

- 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

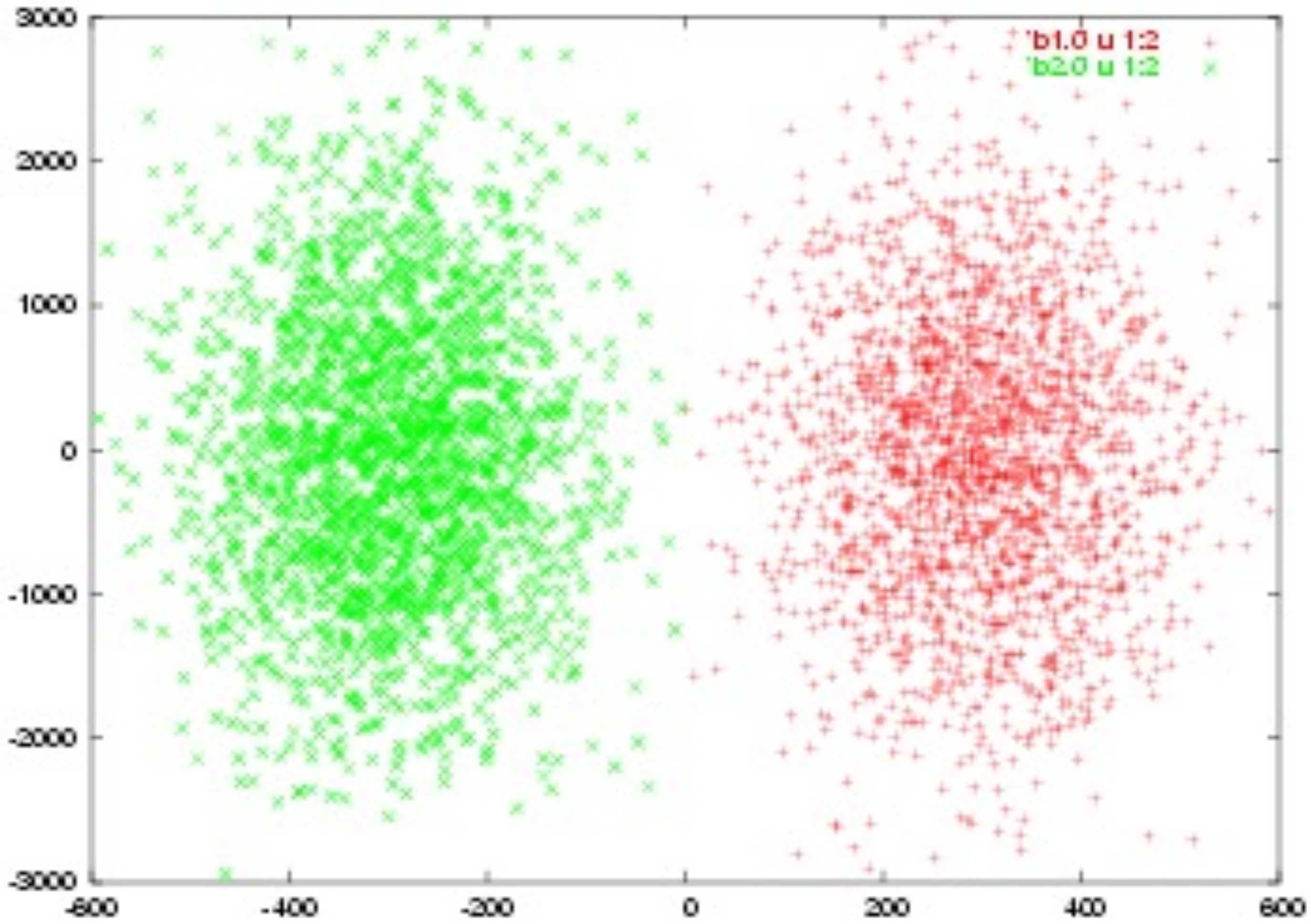
Beam-Beam effects: pinch

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





Collision Simulation

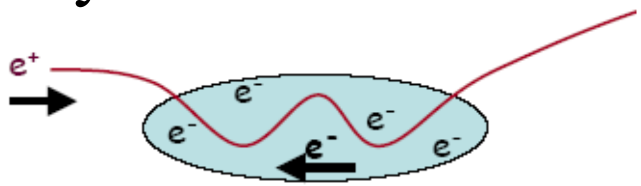


D.Schulte

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

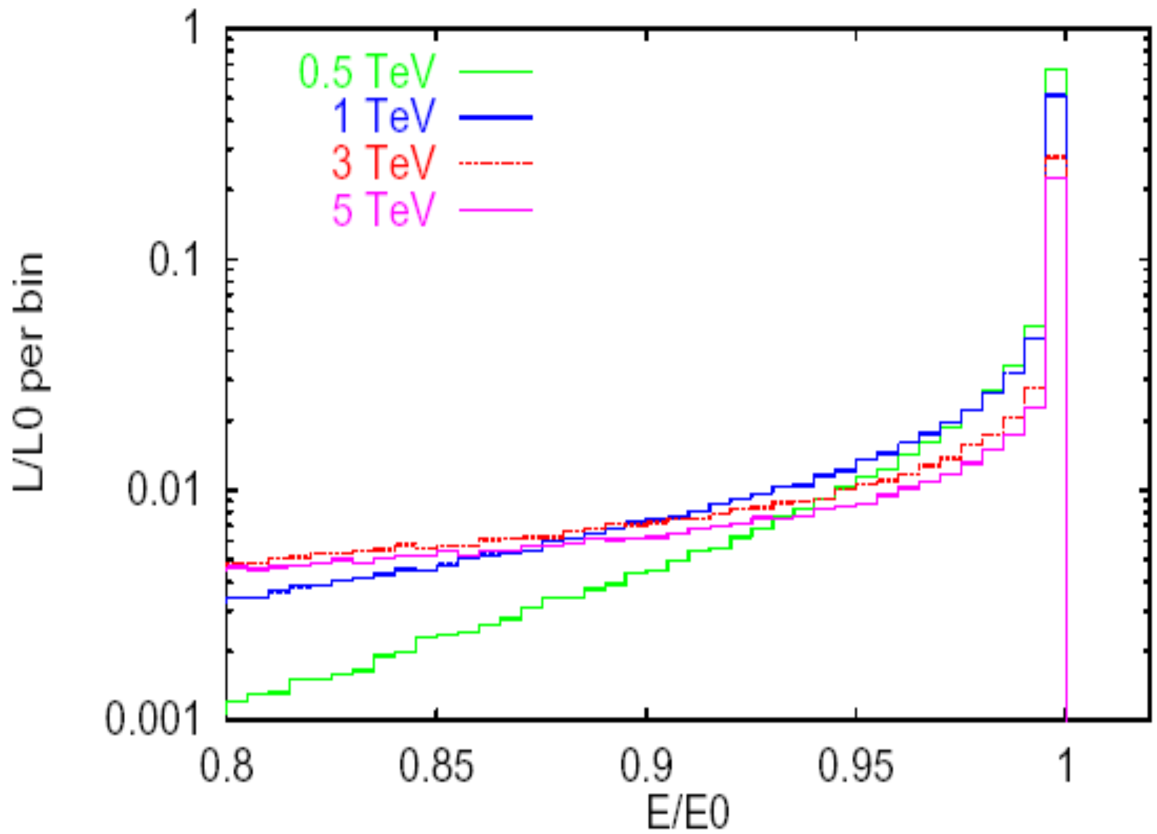
Beamstrahlung

- "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

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

Beamstrahlung: energy loss

- RMS relative energy loss
  beamstrahlung energy loss

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

- 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

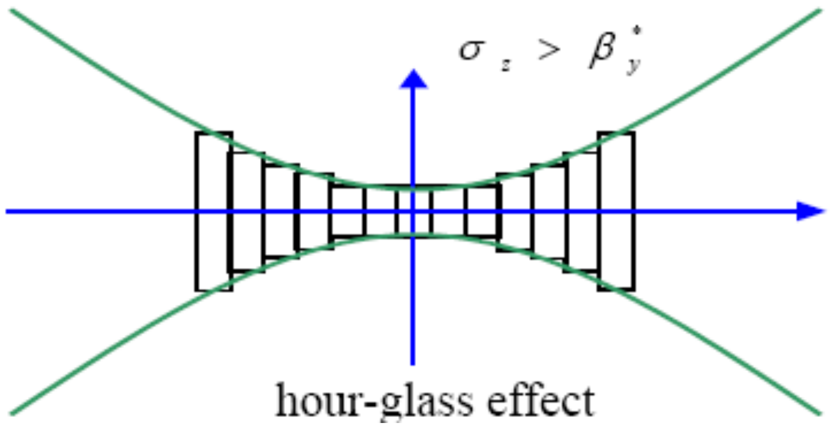
  and minimise δ_{BS} by big σ_x

Limit on beam size: Hourglass effect

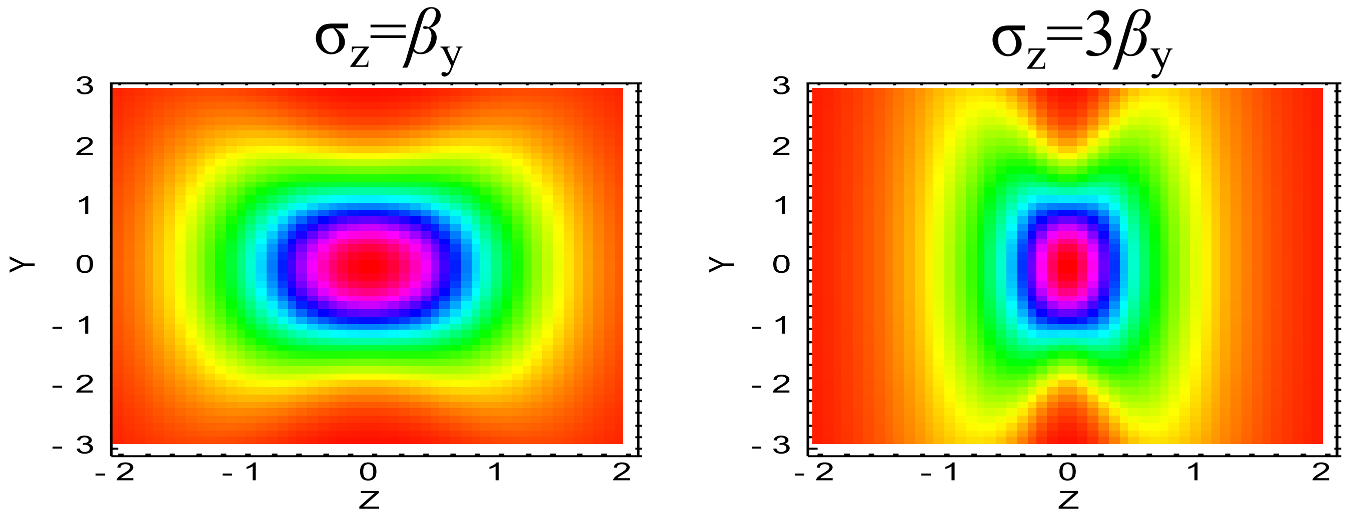
- β-function at the interaction point follows

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

β^* 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



N.Walker

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 $$L \propto \frac{\eta_{RF} P_{RF}}{E_{cm}^{3/2}} \sqrt{\frac{\delta_{BS}\gamma}{\varepsilon_{n,y}}} \sqrt{\frac{\sigma_z}{\beta_y}} \propto \frac{\eta_{RF} P_{RF}}{E_{cm}} \sqrt{\frac{\delta_{BS}}{\varepsilon_{n,y}}} \underbrace{\sqrt{\frac{\sigma_z}{\beta_y}}}_{\sim 1 \text{ (hourglass effect)}}$$

The ‘final’ scaling for LC

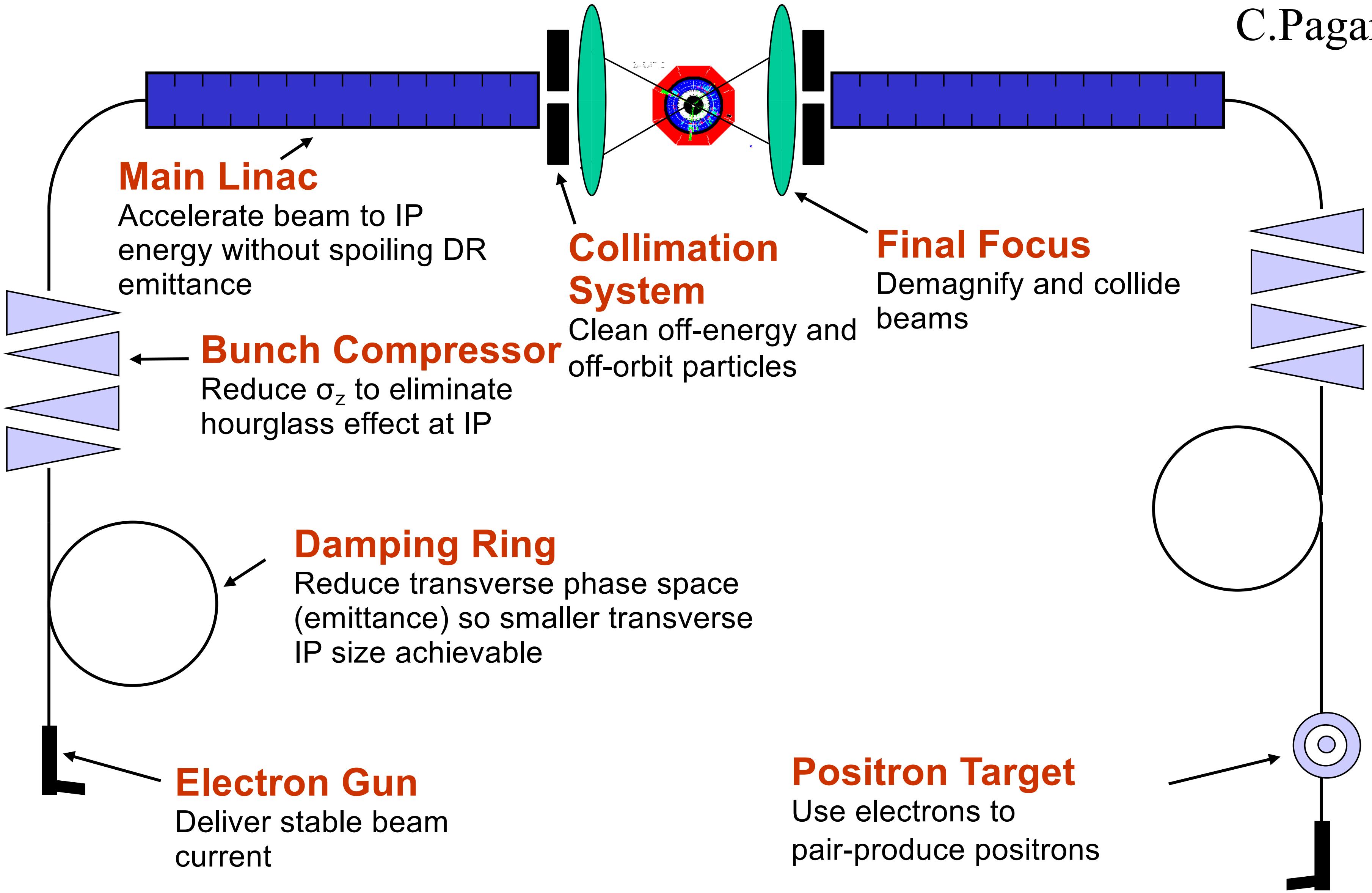
$$L \propto \frac{\eta_{RF} P_{RF}}{E_{cm}} \sqrt{\frac{\delta_{BS}}{\varepsilon_{n,y}}} H_D \qquad \beta_y \approx \sigma_z$$

- 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

Generic Linear Collider

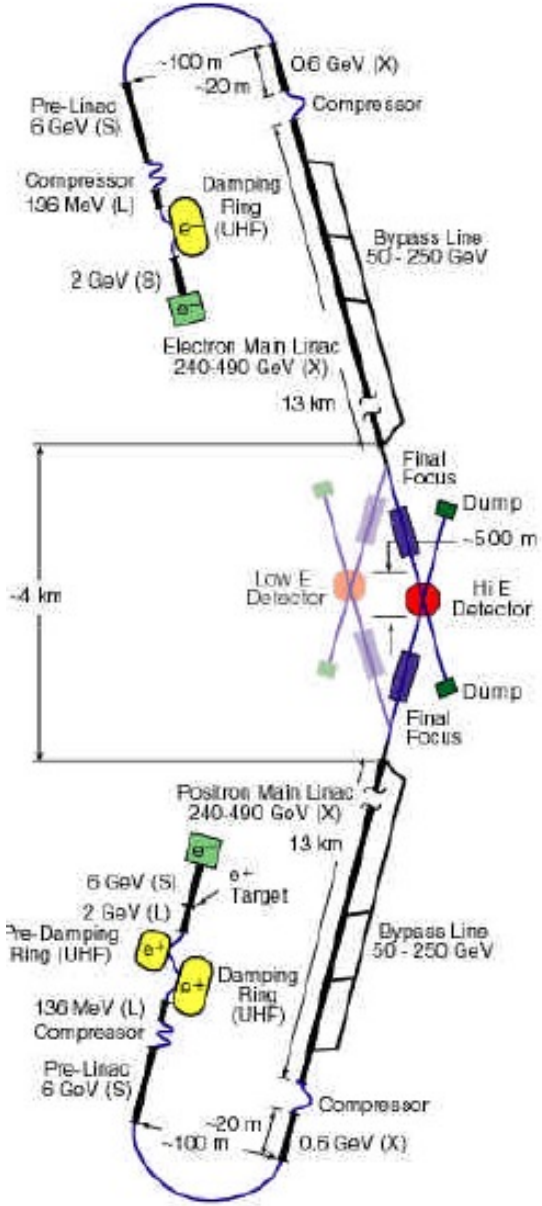
C.Pagani



- will see the different elements in the following…

The real designs: JLC/NLC

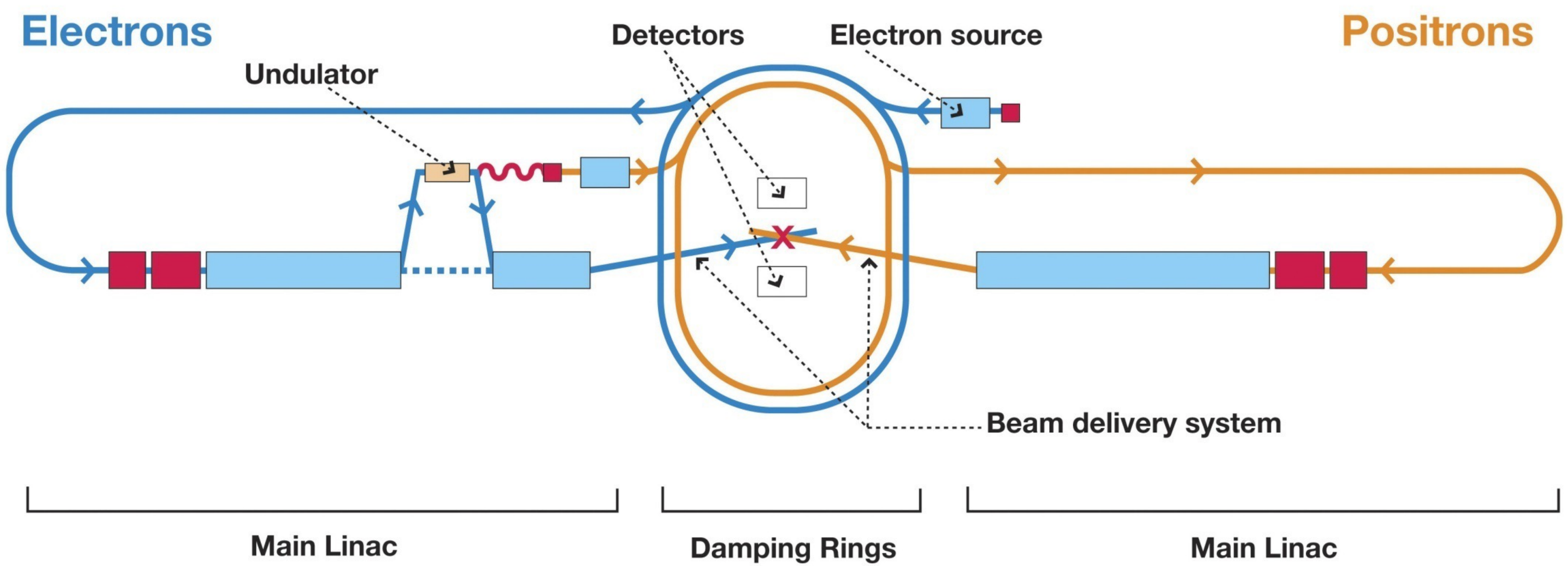
- **NLC (Next Linear Collider)**
- **JLC (Japanese Linear Collider)**:
  - 500 – 1000 GeV
  - Normal conducting RF
  - 11.4 GHz
  - 65 MV/m gradient
- not followed up any more
- technology decision in Aug 2004 for superconducting technology



The real designs: TESLA -> ILC

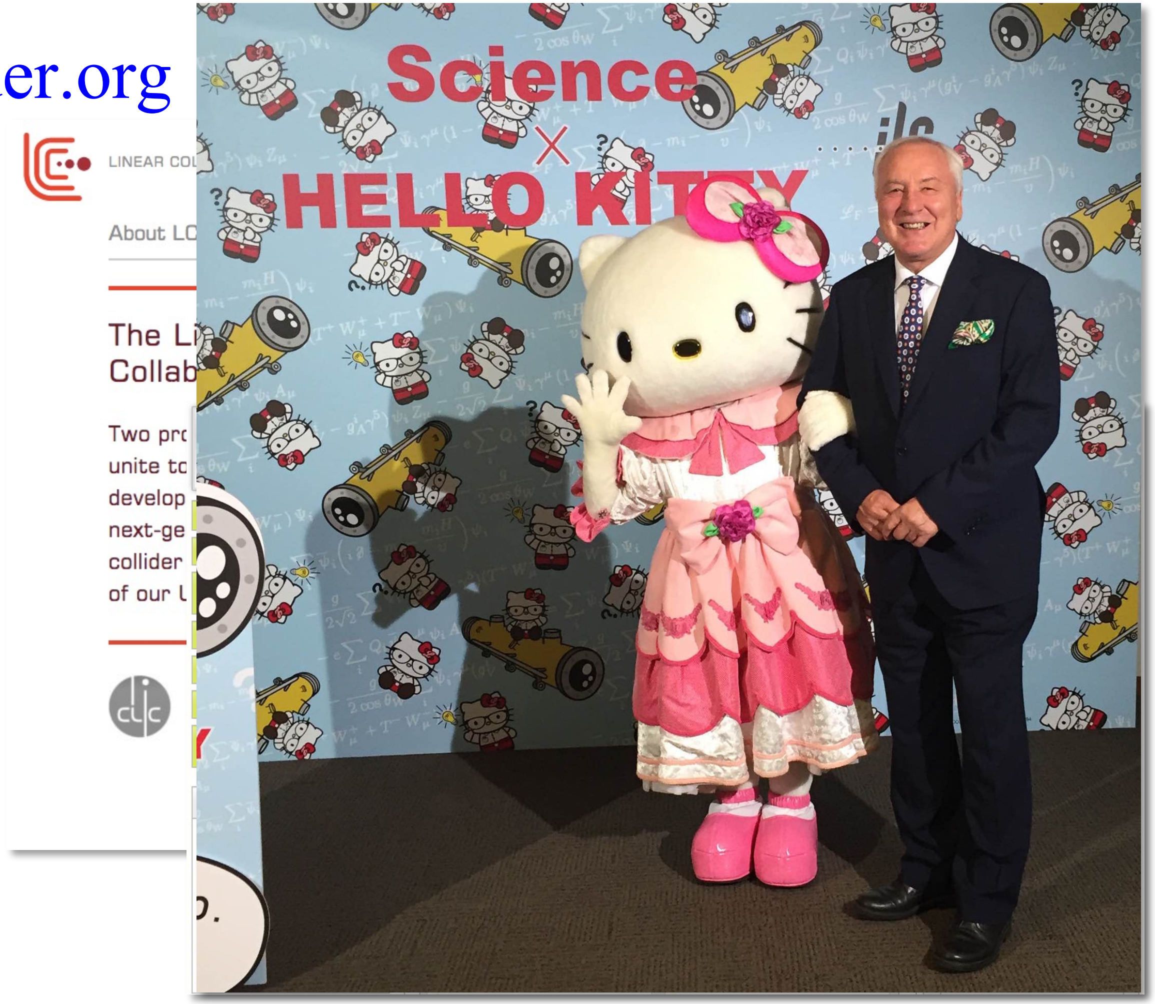
- **TESLA**:
  - Superconducting cavities
  - 1.3 GHz
  - 35 MV/m gradient
  - 500 – 800 GeV
- **ILC** (Internat. Linear Collider):
  - Superconducting cavities
  - 31.5 MV/m gradient
  - 500 GeV
  - Upgrade to 1000 GeV possible

~31 km total length (500 GeV)

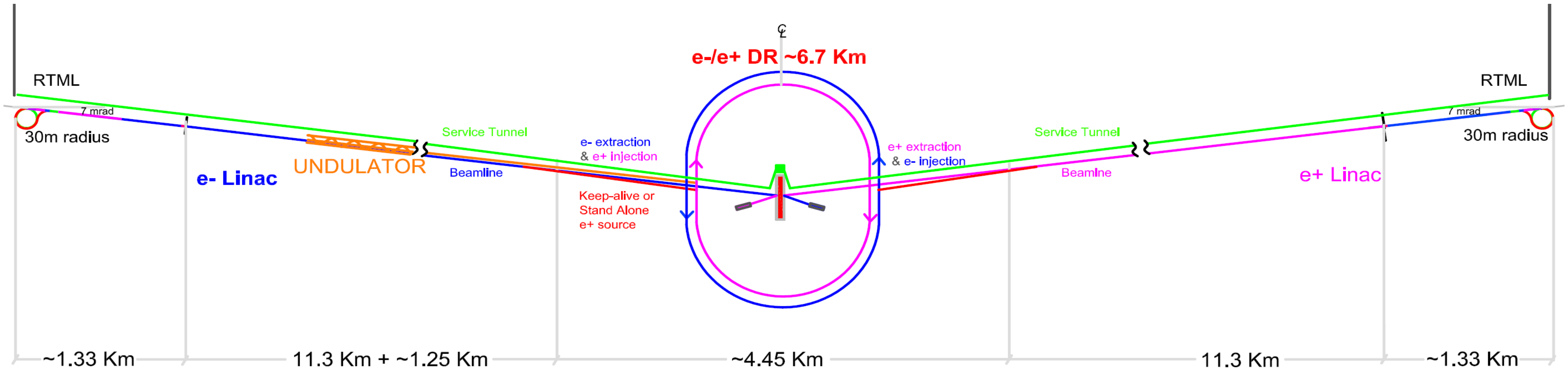


ILC - Global Design Effort - LCC

- 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

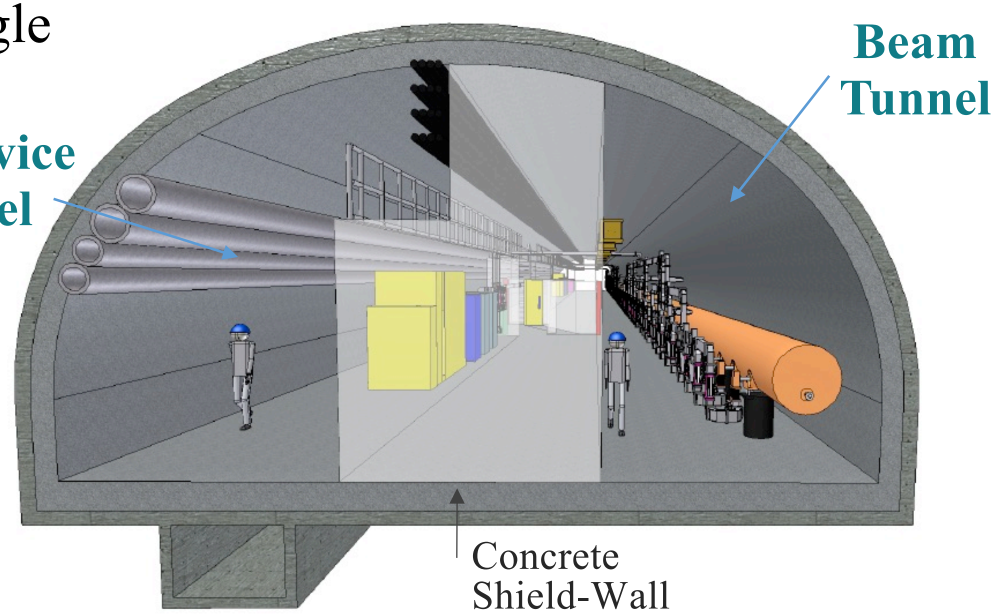


ILC Schematic



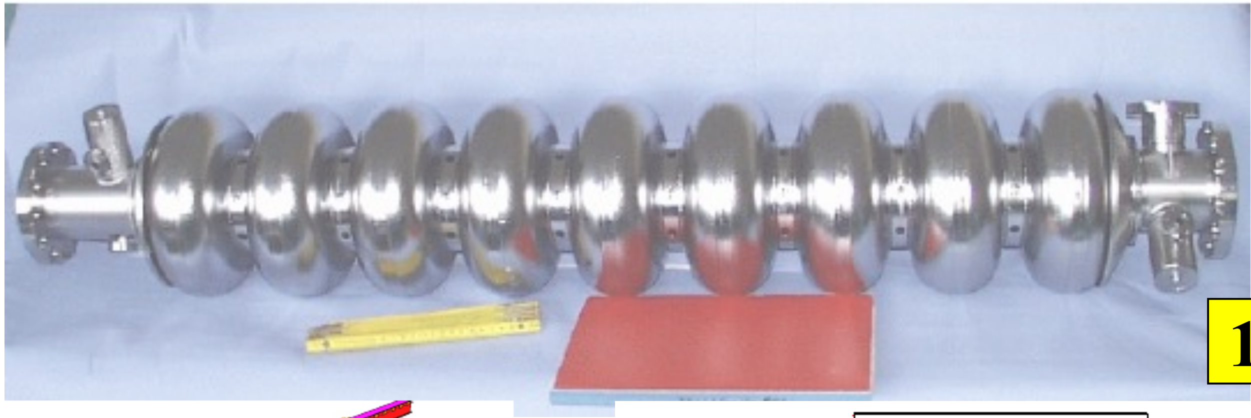
Schematic Layout of the 500 GeV Machine

- 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



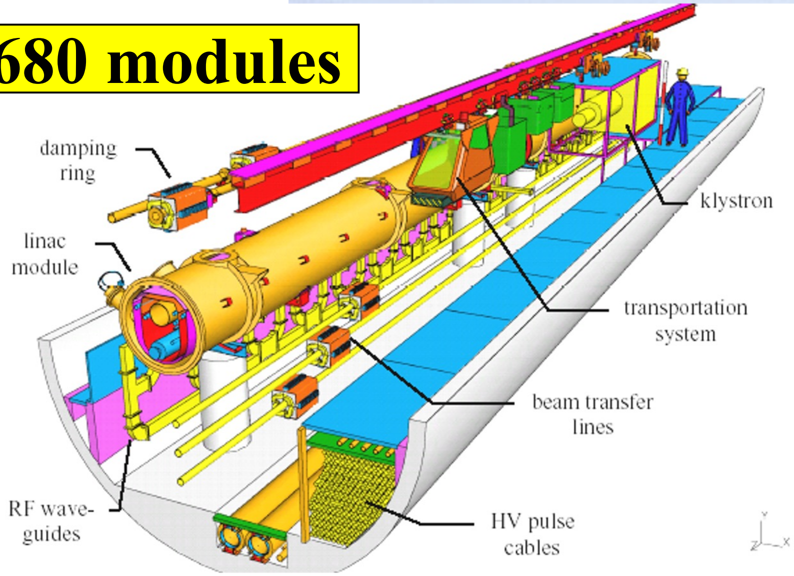
ILC Super-conducting technology

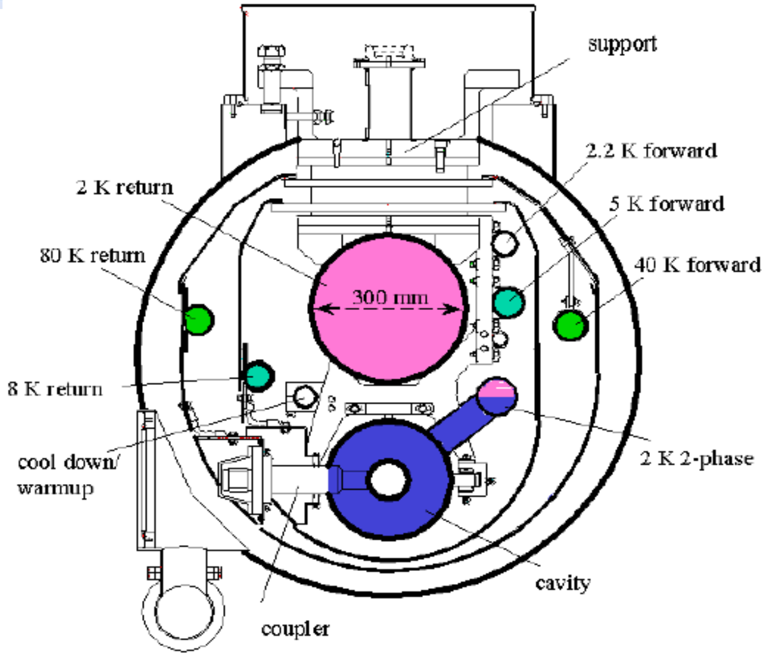
The core technology for the ILC is 1.3GHz superconducting RF cavity intensely developed in the TESLA collaboration, and recommended for the ILC by the ITRP on 2004 August.
The cavities are installed in a long cryostat cooled at 2K, and operated at gradient 31.5MV/m.



14560 cavities

1680 modules

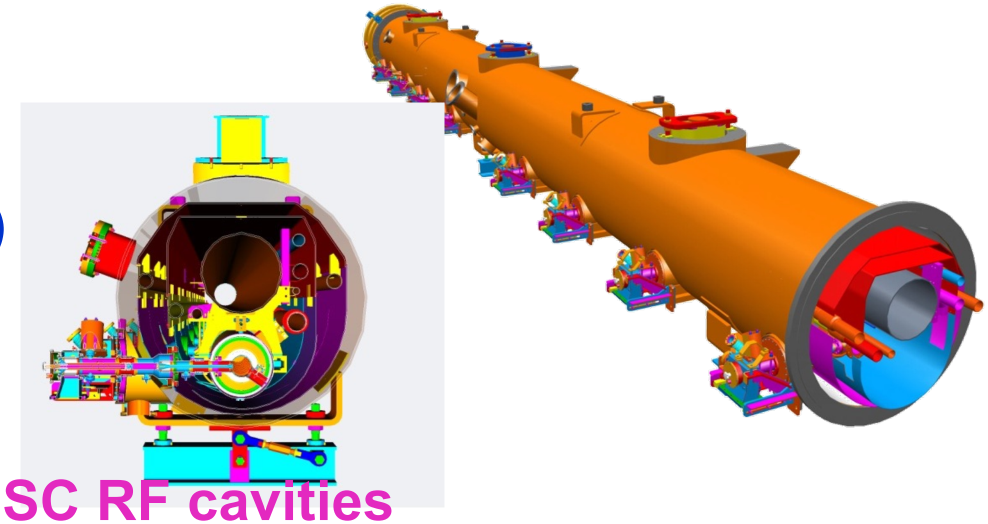




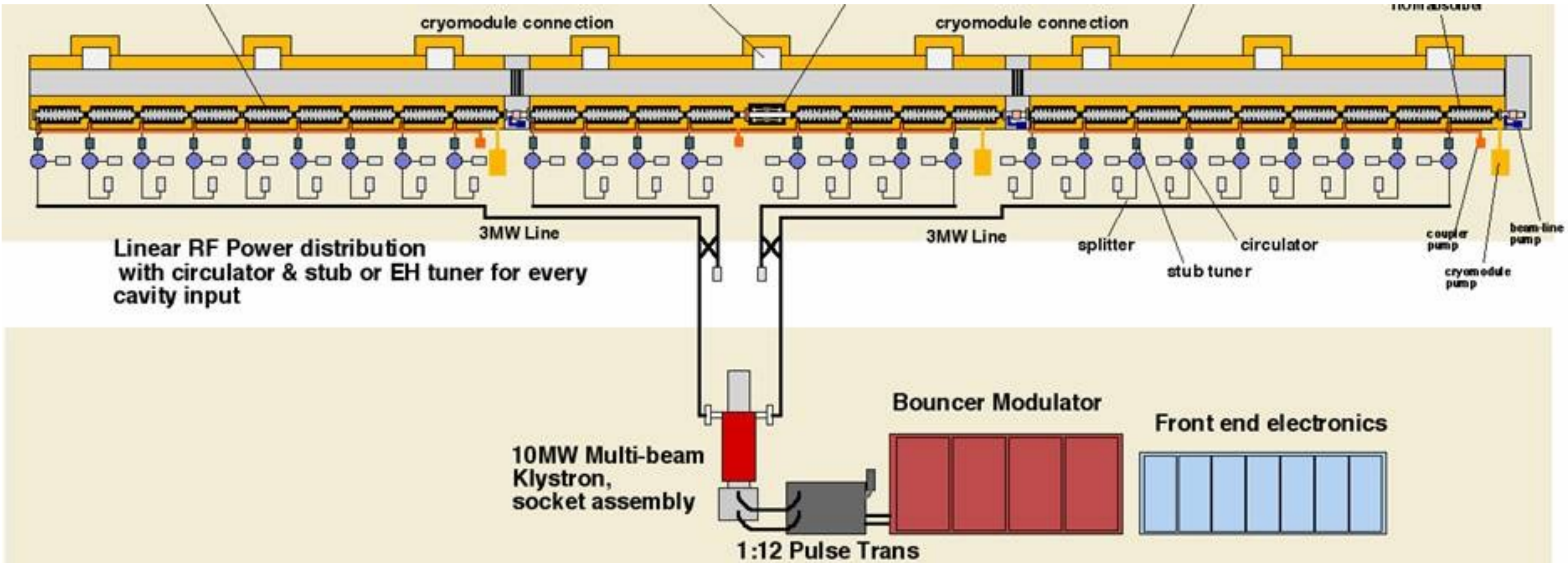
ILC Main Linac RF Unit

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

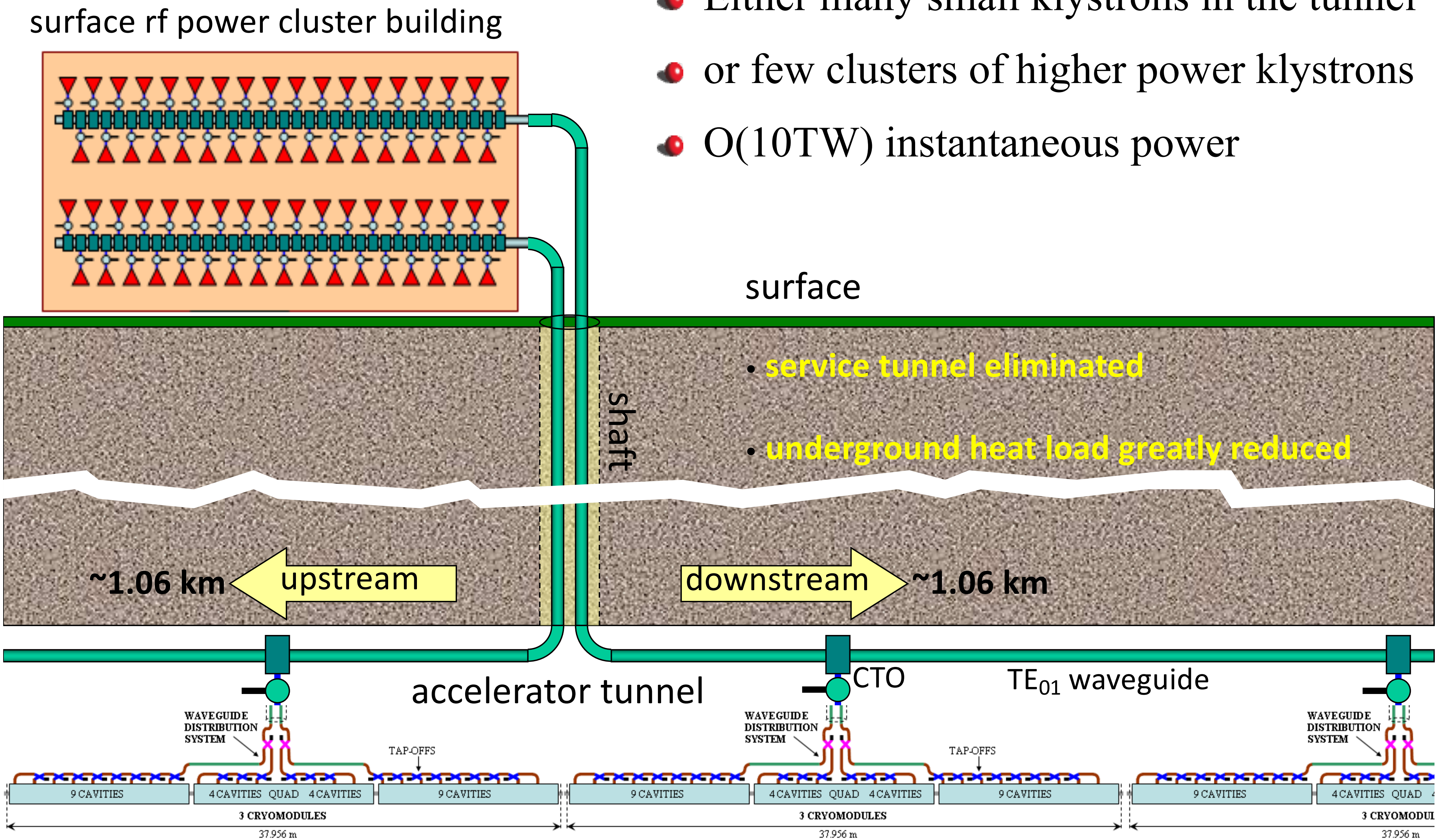


Total of 1680 cryomodules and 14 560 SC RF cavities



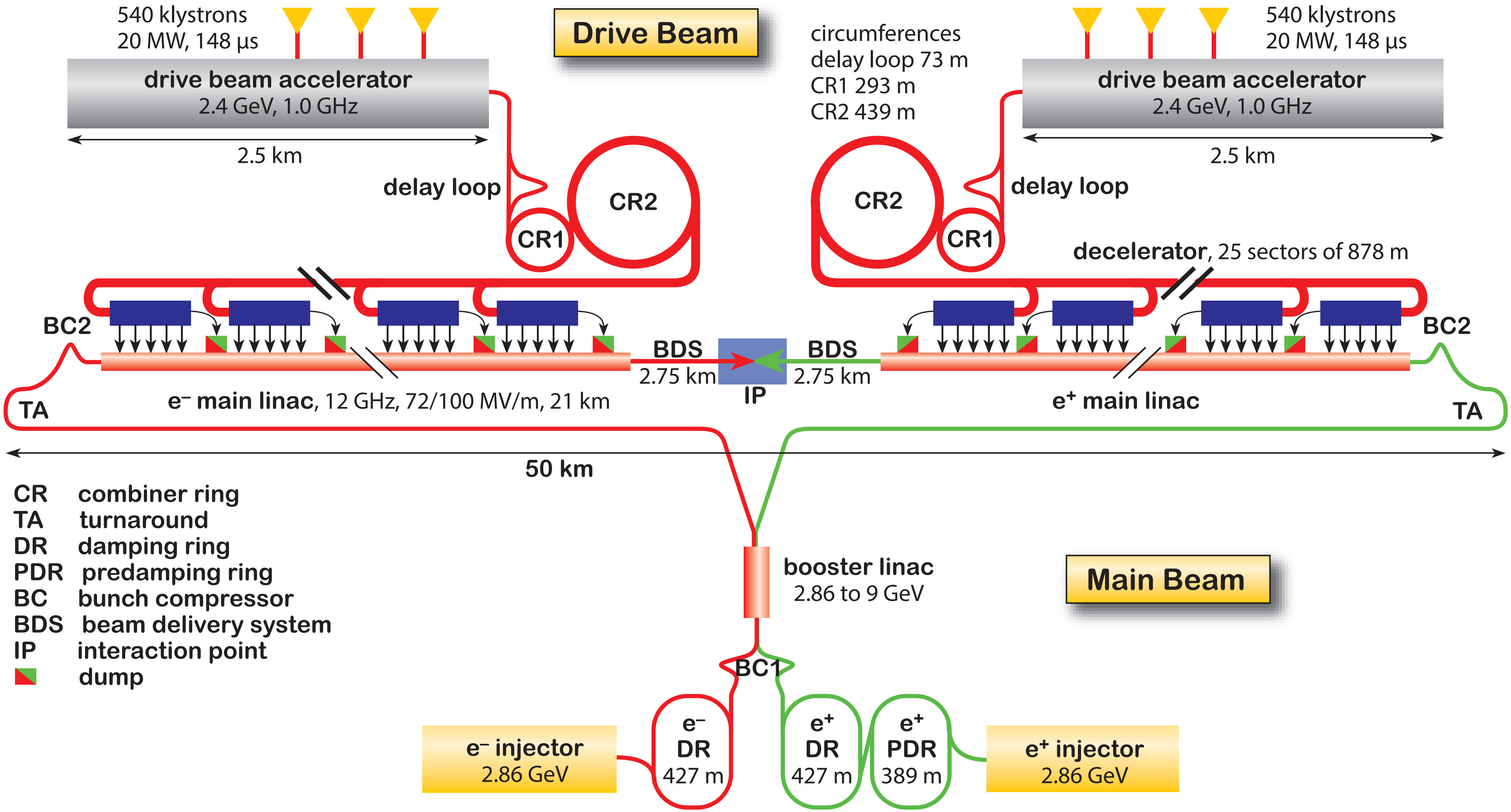
ILC Main Linac RF distribution

- Either many small klystrons in the tunnel
- or few clusters of higher power klystrons
- O(10TW) instantaneous power



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



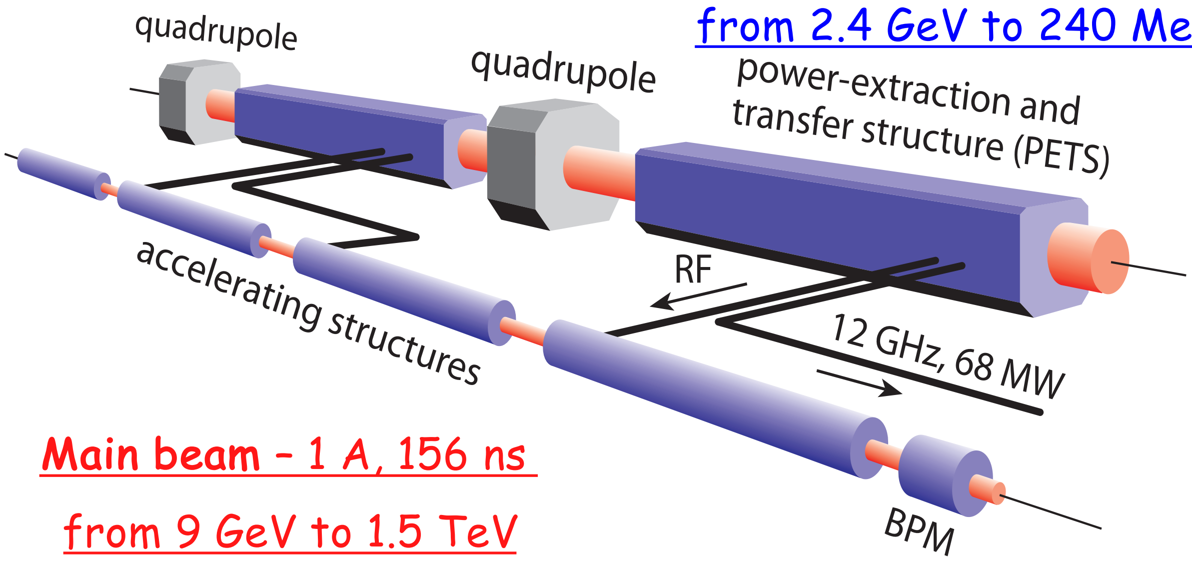
CLIC two beam scheme

- 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

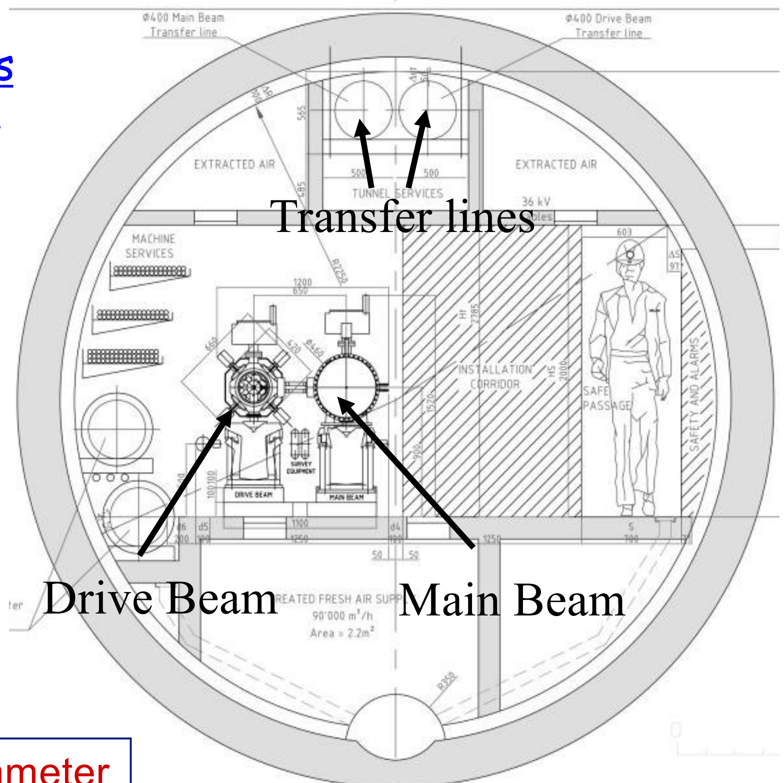
Drive beam - 101 A, 240 ns

from 2.4 GeV to 240 MeV

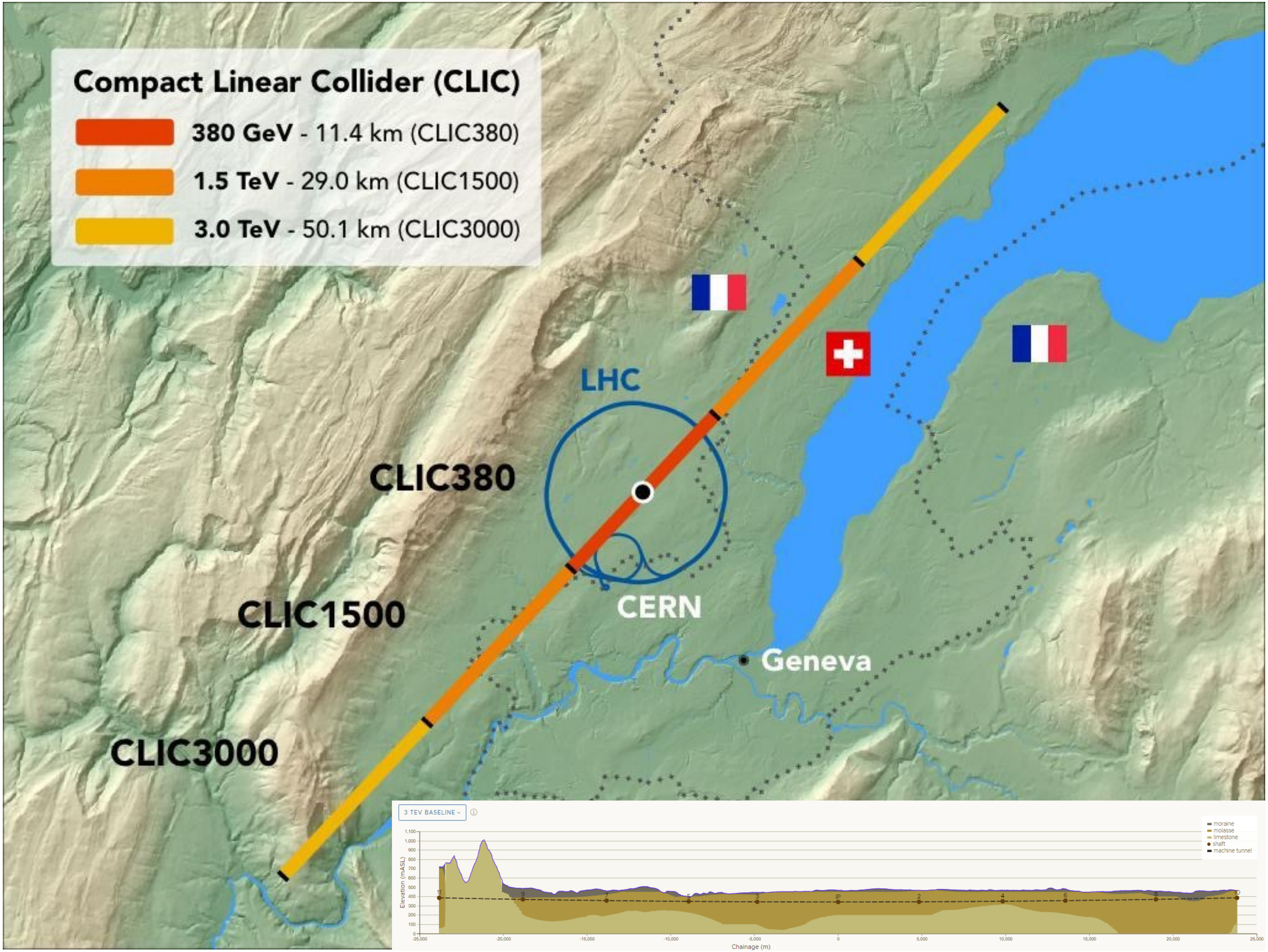


Main beam – 1 A, 156 ns

from 9 GeV to 1.5 TeV

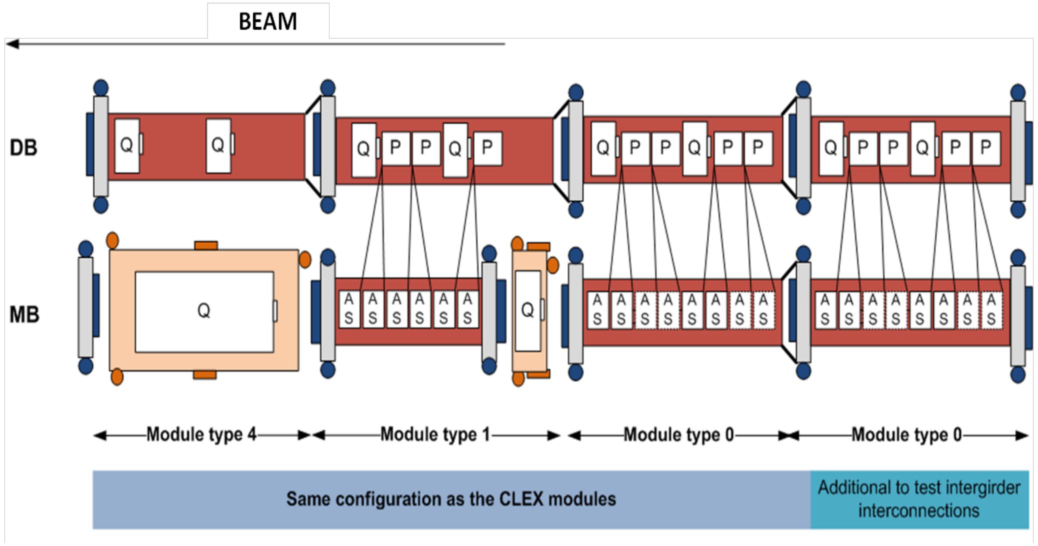


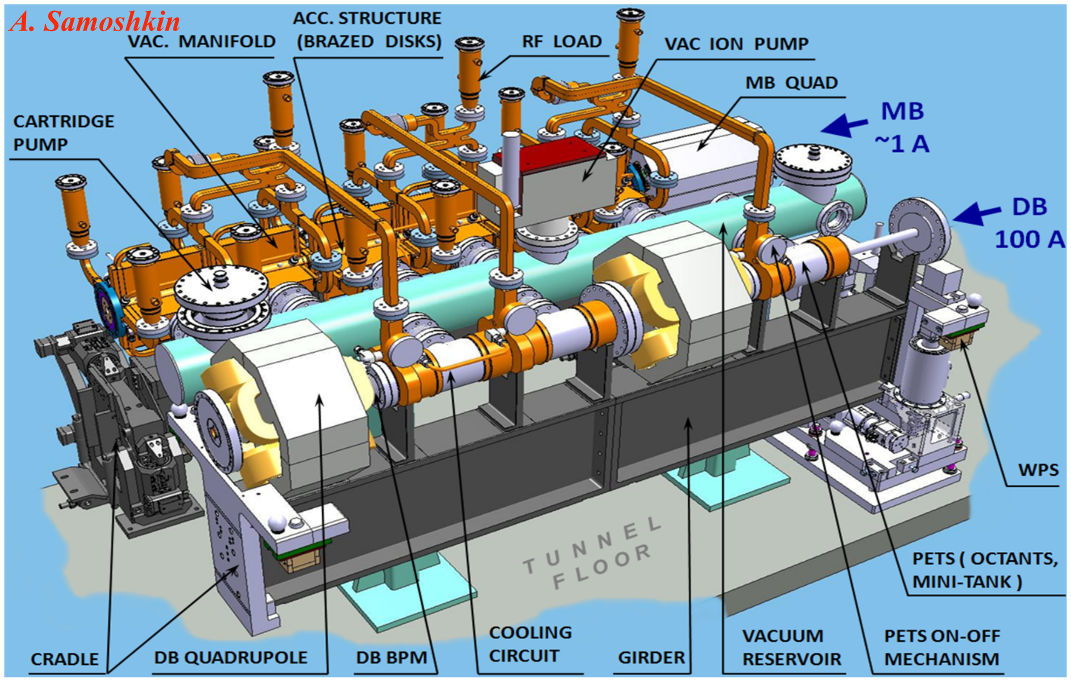
5.6 m diameter


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
CLIC3000
CERN
Geneva
3 TEV BASELINE
moraine
molasse
limestone
shaft
machine tunnel
Elevation (mASL)
Chainage (m)

CLIC two-beam scheme

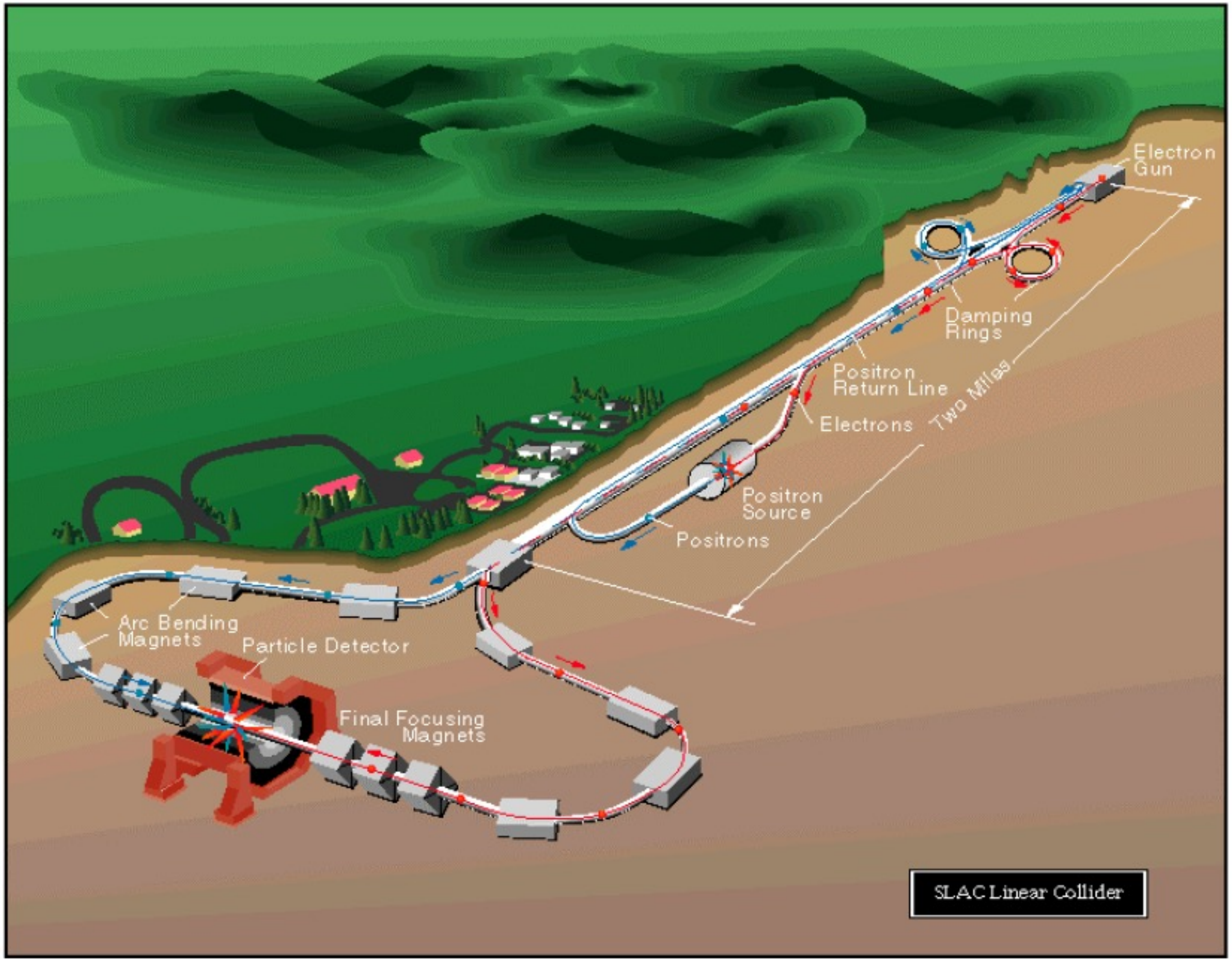
- RF power is produced by drive beam
- Drive beam:
  100 A current, 2.4 GeV
- Main beam:
  1 A, 1500 GeV





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

First LC: SLC



Built to study the Z^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 σ_z* [mm]	~1	0.3	0.3	0.11	0.07
Vert. emittance $\gamma\varepsilon_y$ [10^{-8}m]	300	3	4	4	2.5
Vert. beta function β_y* [mm]	~1.5	0.4	0.4	0.11	0.1
Vert. beam size σ_y* [nm]	650	5	5.7	3	2.3

Parameters (except SLC) at 500 GeV

Documentation about ILC/CLIC

- Linear Collider Vision Community event 2025 https://indico.cern.ch/event/1471891
- 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
- CLIC Mini Week 2023 https://indico.cern.ch/event/1335148
- Int. Linear Collider Workshop 2024 https://agenda.linearcollider.org/event/10134/
- CLIC Workshop 2019 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 https://indico.cern.ch/event/428136/
  - 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