



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

- 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)



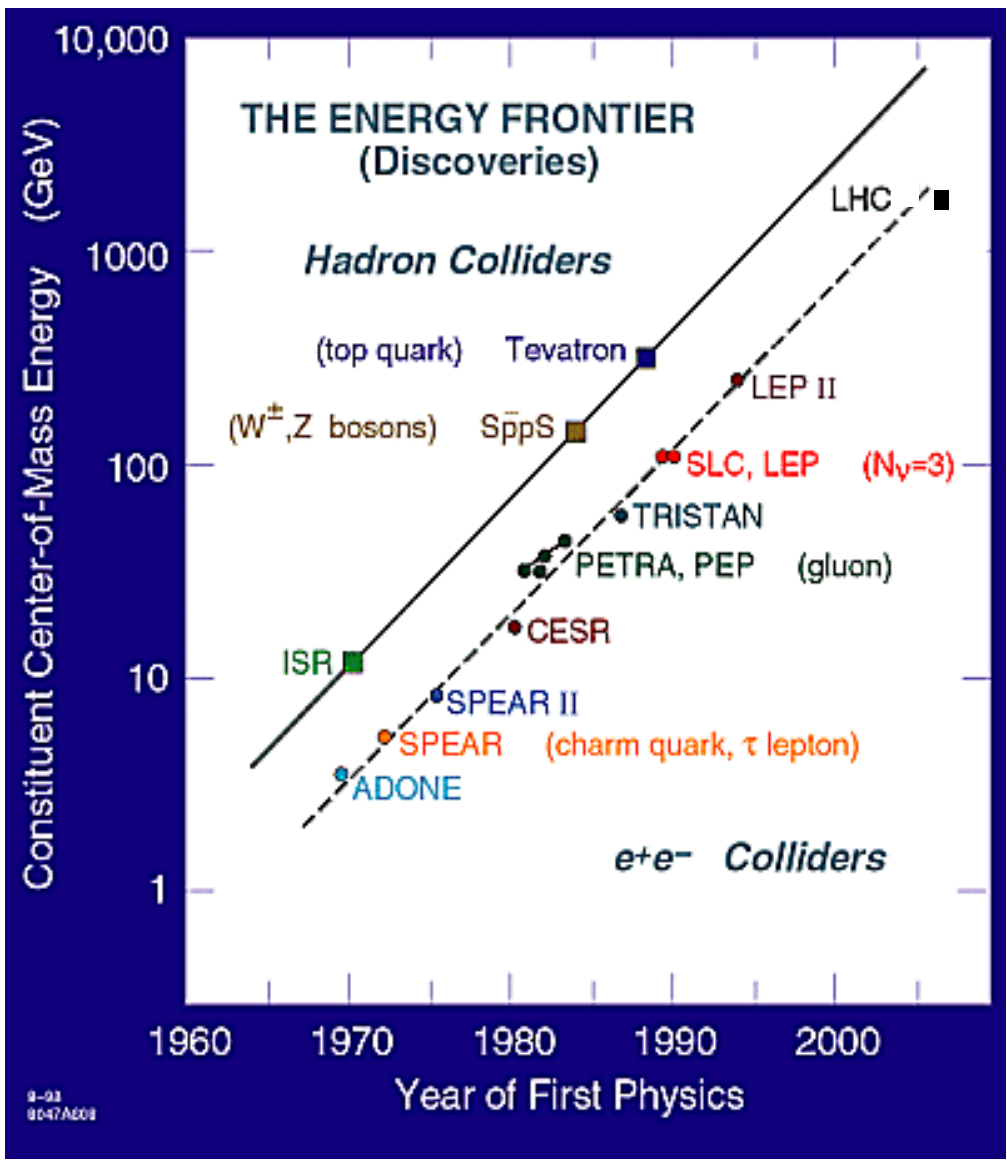
Linear Colliders

Lecture 1: Introduction and Overview



Frank Tecker – CERN

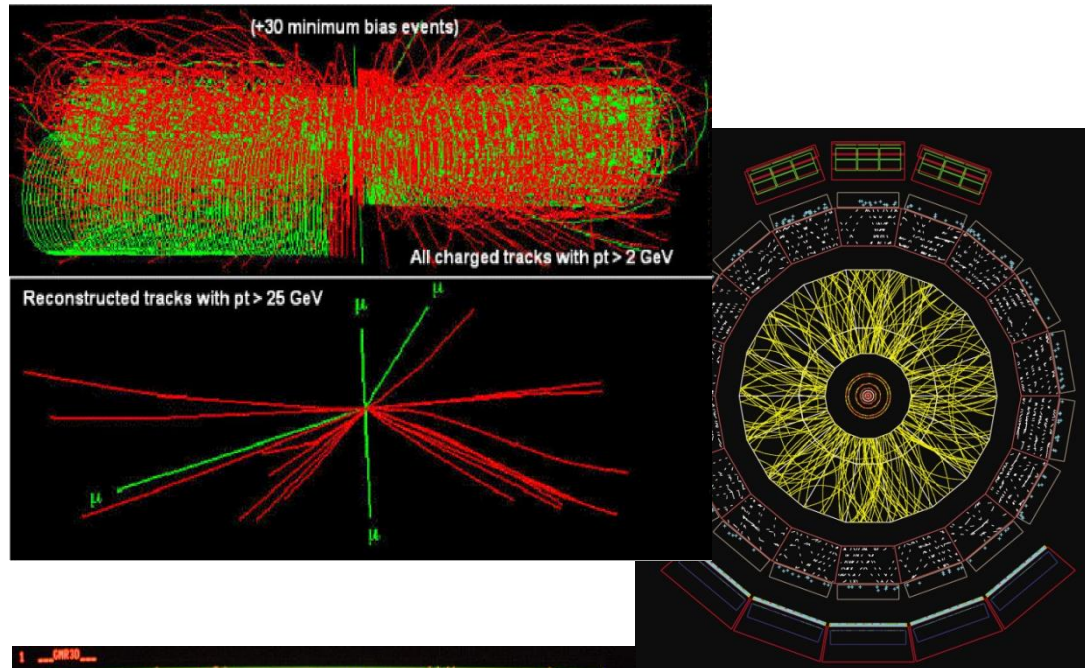
- Path to higher energy
- Cost scaling
- Luminosity
- Generic LC layout
- ILC / CLIC



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

- LHC has found the Higgs with $m_H = 126 \text{ GeV}/c^2$
- A future Lepton Collider would complement LHC physics

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

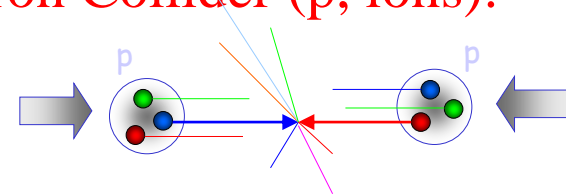


ALICE:
Ion event



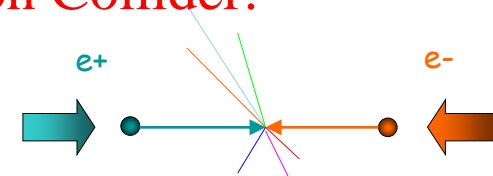
LEP event:
 $Z^0 \rightarrow 3$ jets

● **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

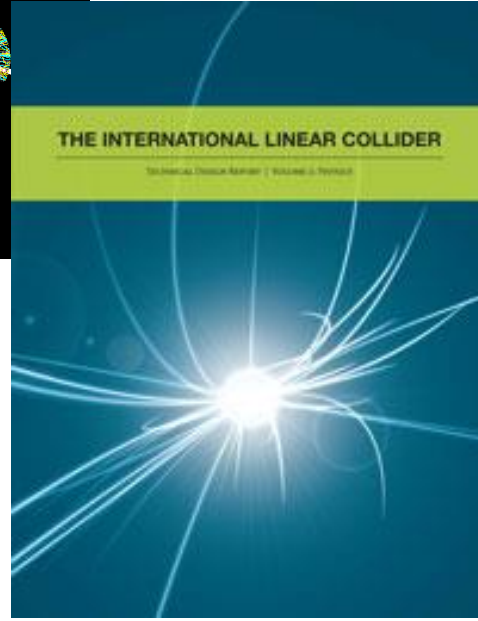
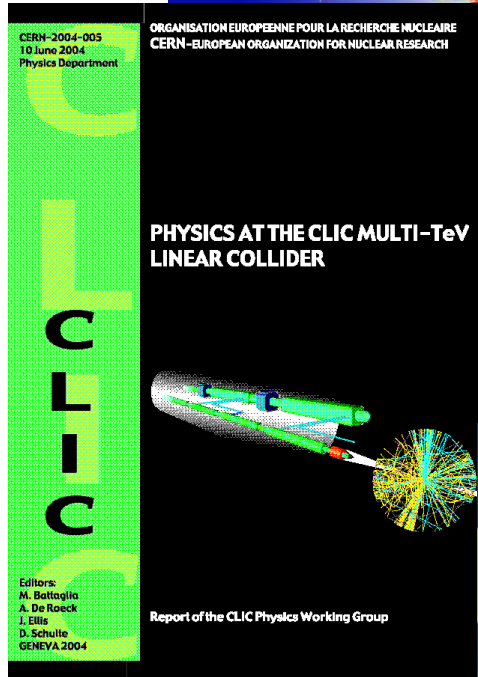
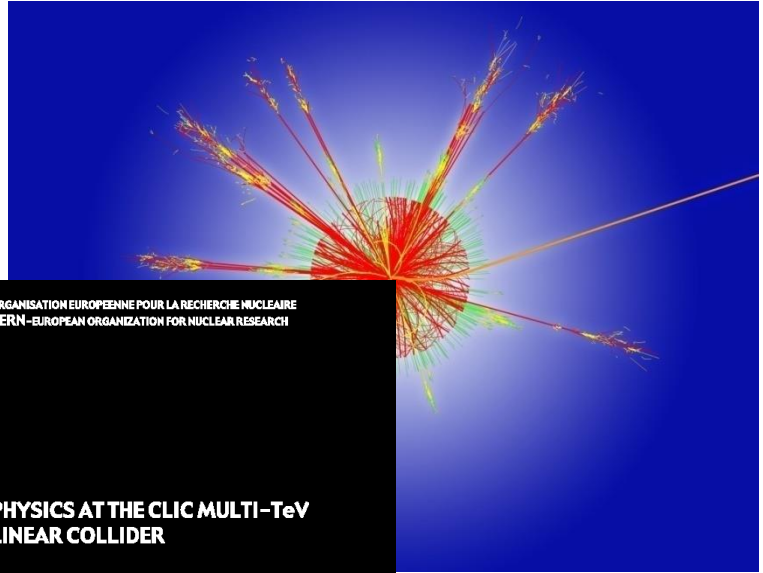
- **Higgs physics**
 - LHC has discovered the Higgs particle
 - LC explore its properties in detail

- **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
- **“CLIC Conceptual Design Report– Vol.2”**
<http://lcd.web.cern.ch/LCD/CDR/CDR.html>
- **“ILC Technical Design Report – Vol.2 – Physics at the ILC”**
www.linearcollider.org/ILC/Publications/Technical-Design-Report



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

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

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

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

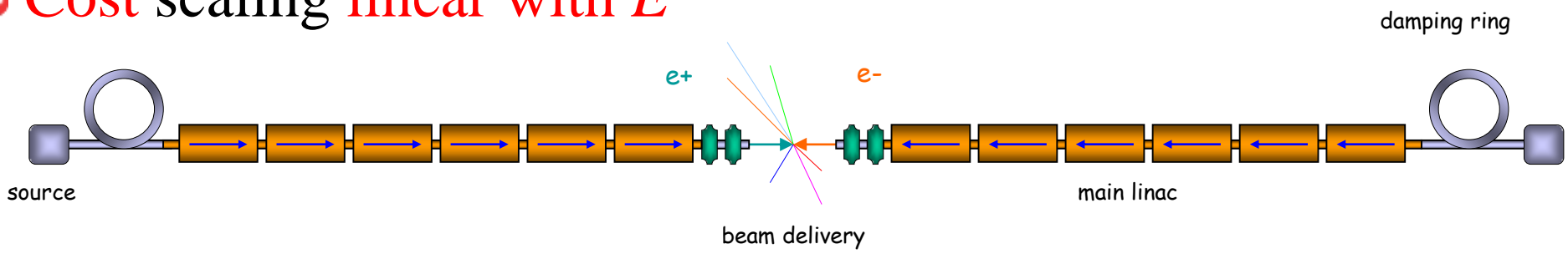
- Linear costs (magnets, tunnel, etc.): $\epsilon_{lin} \propto \rho$

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

- 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)

- NO bending magnets \Rightarrow **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
- \Rightarrow efficient

• **Linear Collider:**

- one-pass acceleration + collision \Rightarrow 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 ($\text{cm}^{-2} \text{s}^{-1}$) 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 $f_{rep} = 11 \text{ kHz}$

- LC $f_{rep} = \text{few-100 Hz}$ (power limited)

\Rightarrow factor $\sim 100-1000$ 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 $10^{34} \text{ cm}^{-2} \text{s}^{-1}$

LEP: $\sigma_x \sigma_y \approx 130 \times 6 \mu\text{m}^2$

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

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

$$n_b N f_{rep} E_{cm} = P_{beams}$$

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

- η_{RF} is RF to beam power efficiency

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

$$L = \frac{(n_b N f_{rep} E_{cm}) N}{4\rho S_x S_y E_{cm}} H_D$$

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

- Some numbers:

E_{cm}	= 500 GeV
N	= 10^{10}
n_b	= 100
f_{rep}	= 100 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%

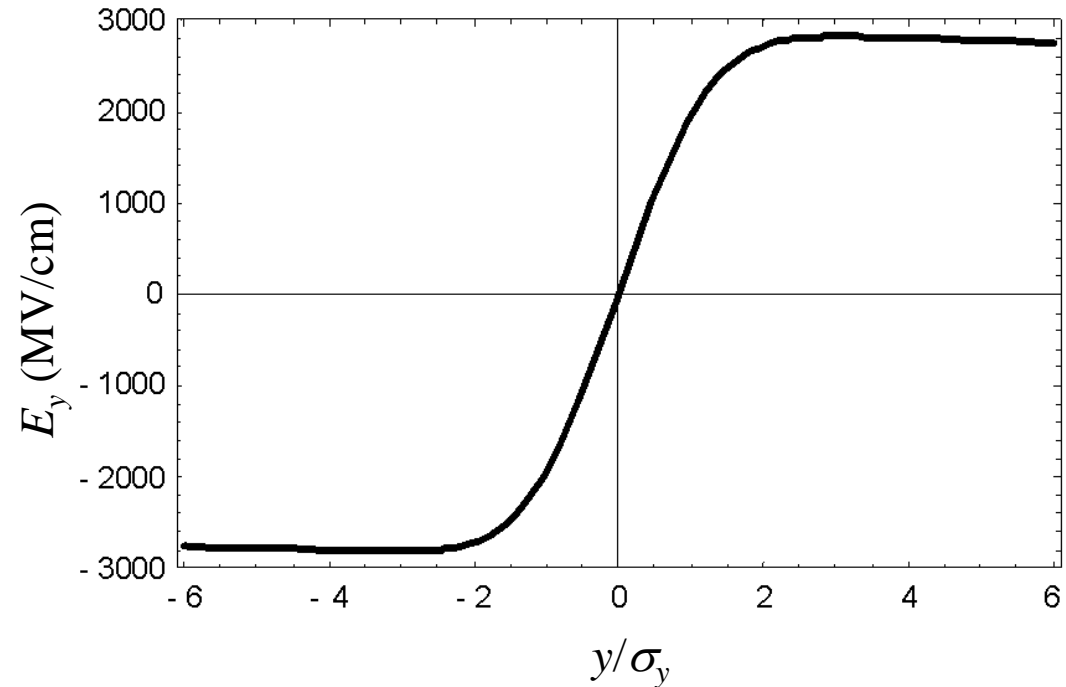
- **AC power:** a few hundred MW to accelerate beams for a high luminosity
- this limits the practically achievable energy and luminosity

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

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

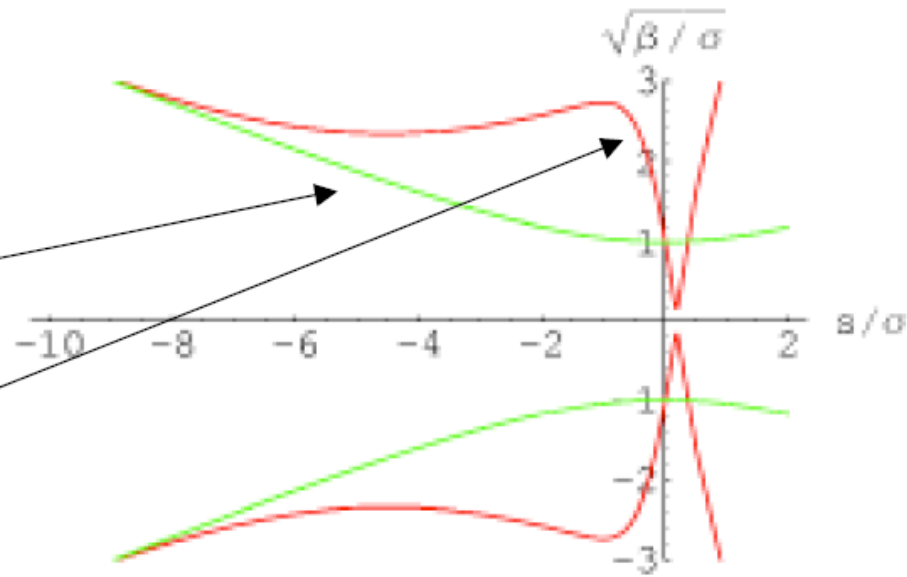
- **Strong focusing** needed for small beam size
 - optical aberrations
 - stability issues and tolerances
- **Beam-Beam effects:**
 - strong self focusing (pinch effect) \Rightarrow increases Luminosity
 - beamstrahlung \Rightarrow photon emission
 - dilutes Luminosity spectrum
 - creates detector background

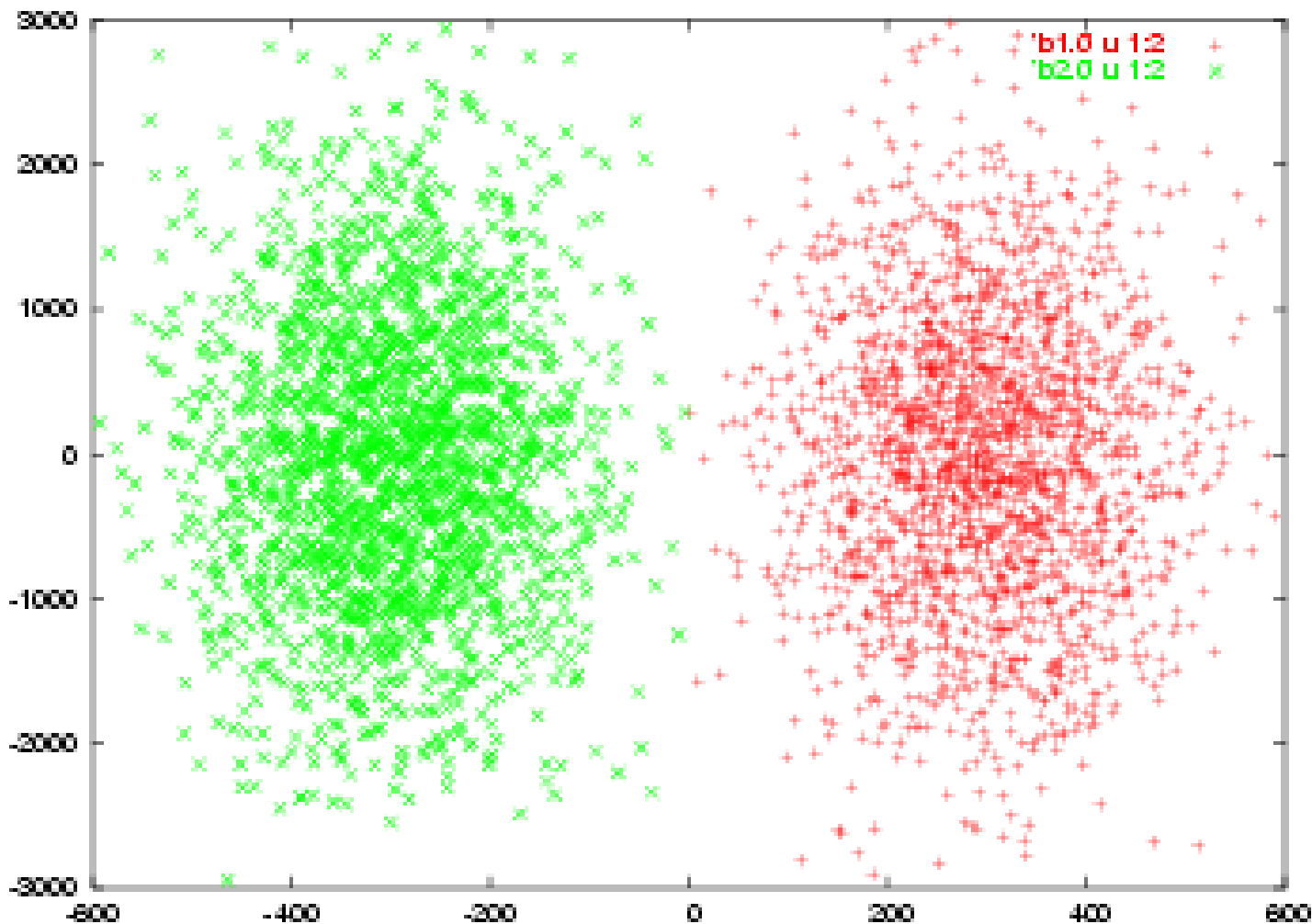
- Strong electromagnetic field of the opposing bunch:
 - deflects the particles “beam-beam kick”
 - focuses the bunches “pinch effect”
 - Luminosity enhancement factor H_D



Beam envelope w/o beam-beam

Beam envelope with beam-beam

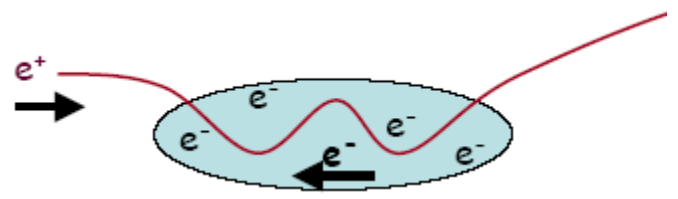




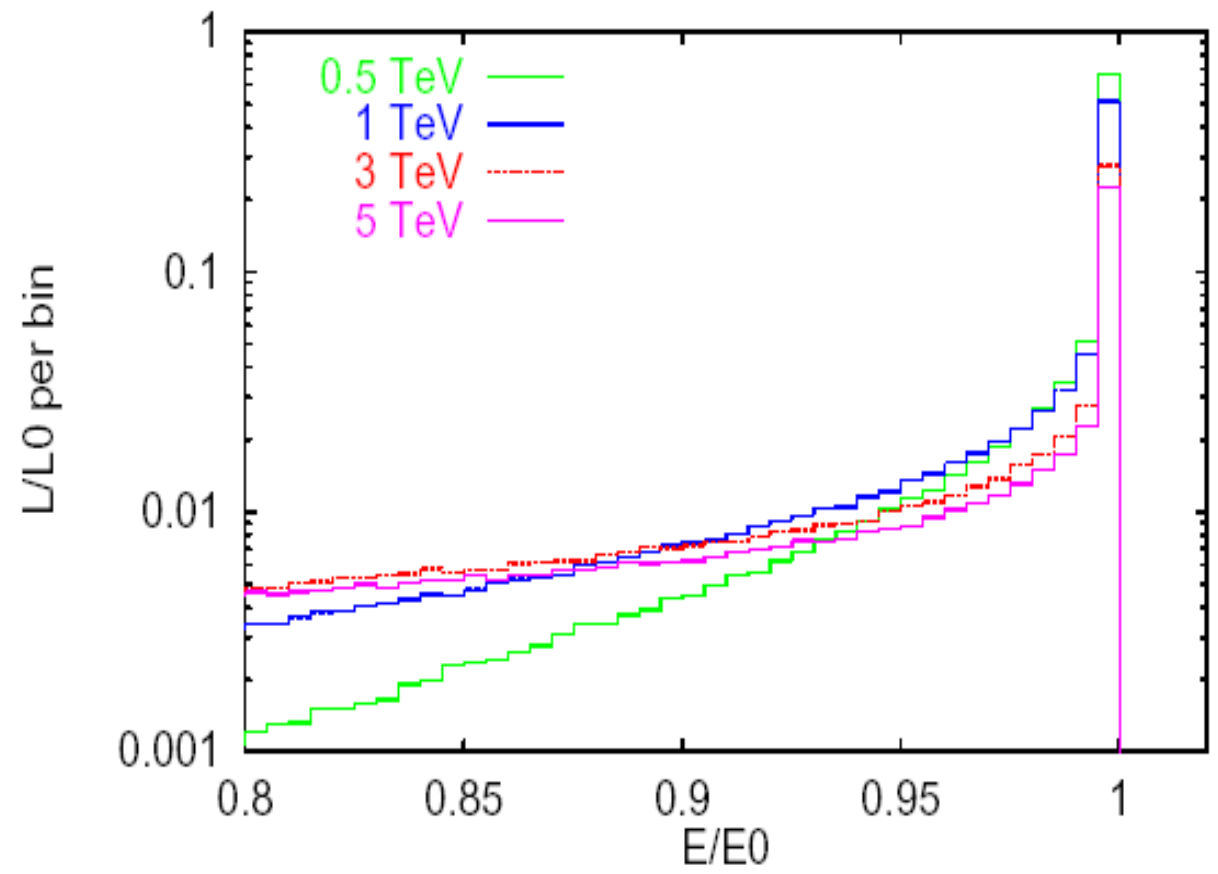
D.Schulte

- beams strongly focused during collision \Rightarrow **Luminosity!**
- large divergence after collision \Rightarrow beam extraction difficult

- “synchrotron radiation” in the field of the opposing bunch



- smears out luminosity spectrum
- creates e^+e^- pairs background in detector



- quantified by Disruption parameter

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

- 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} (\Rightarrow **better luminosity spectrum**)

- use flat beams with $\sigma_x \gg \sigma_y$

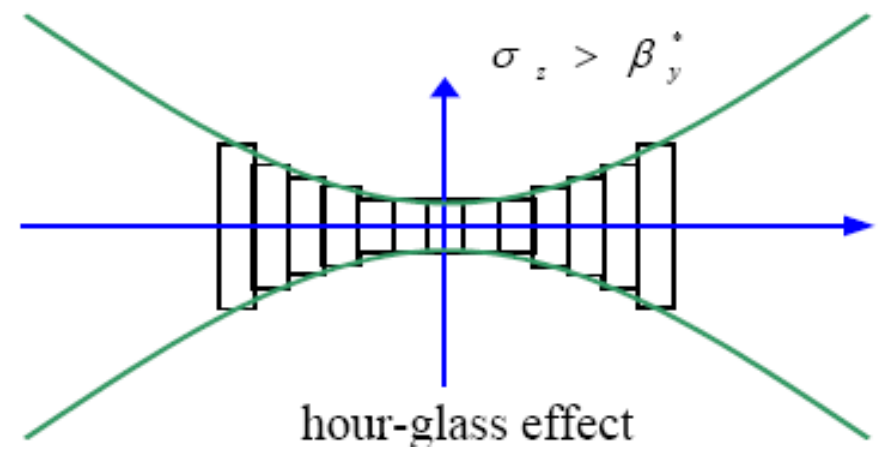
$$\delta_{BS} \propto \left(\frac{E_{cm}}{\sigma_z} \right) \frac{N^2}{\sigma_x^2}$$

- Can **increase luminosity** by **small σ_y**
and **minimise δ_{BS}** by **big σ_x**

- β -function at the interaction point follows

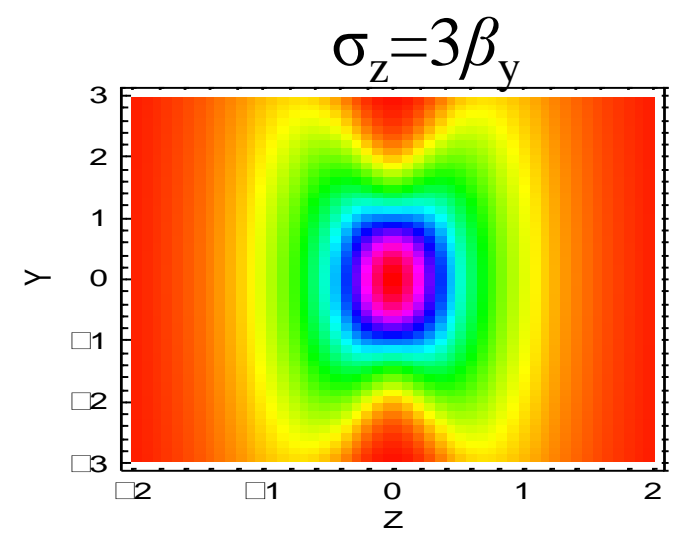
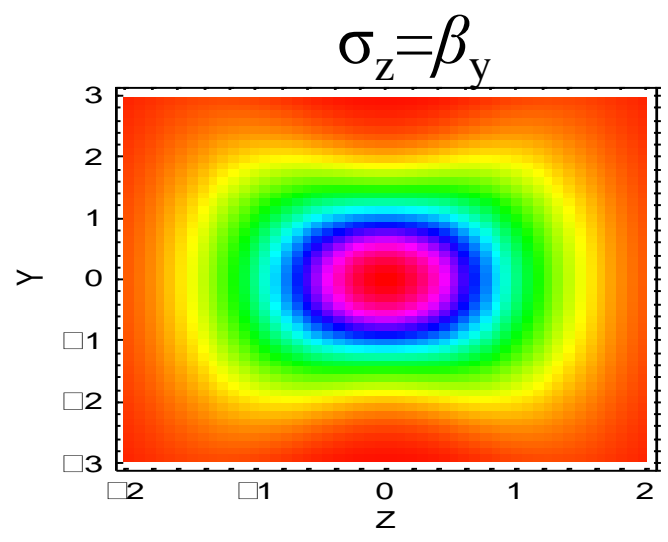
$$\beta(s) = \beta^* + \frac{s^2}{\beta^*}$$

β^* beta function at the IP



- Luminosity has to be calculated in slices

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



N.Walker

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

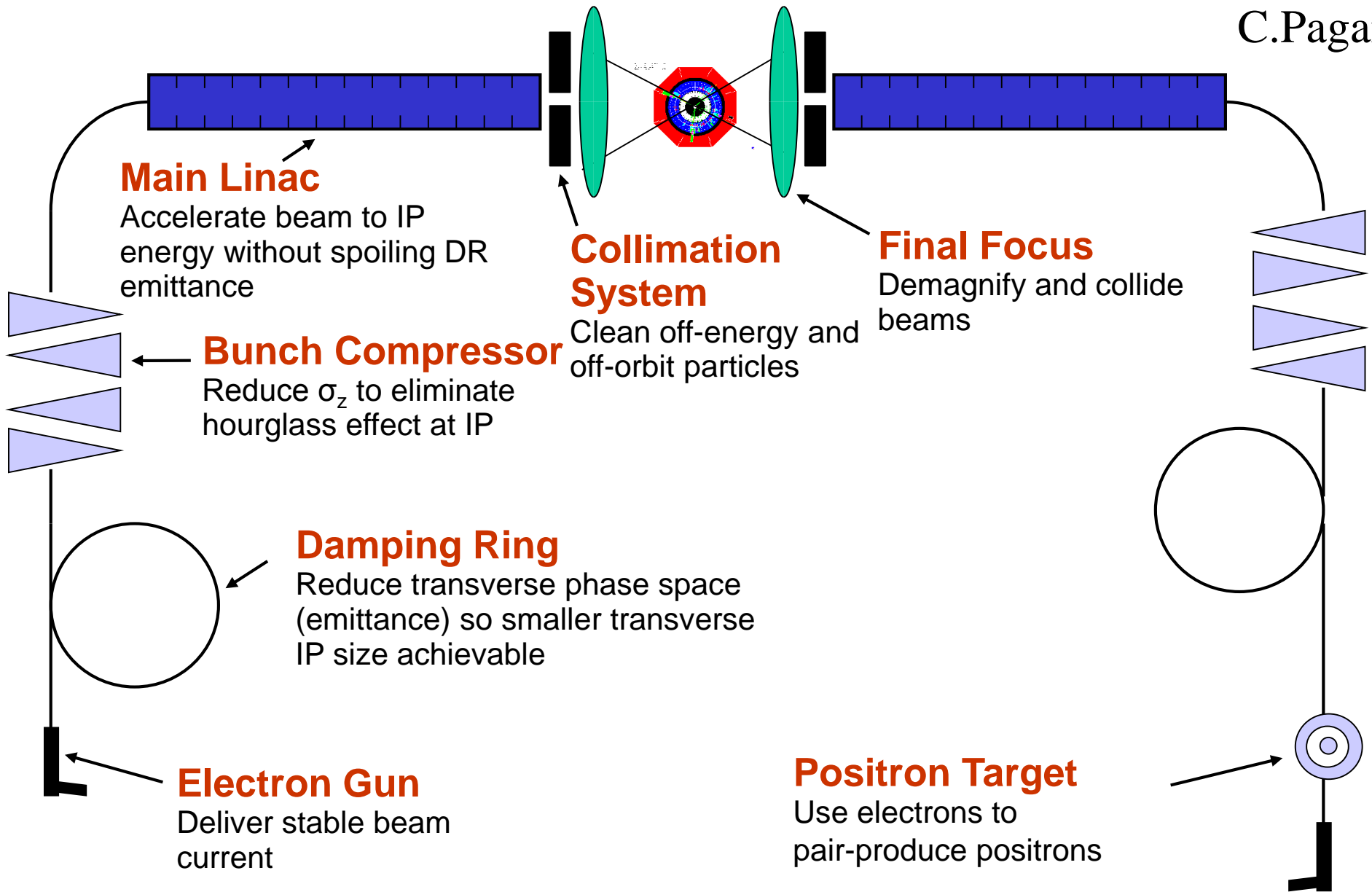
• then $L \propto \frac{\eta_{RF} P_{RF}}{E_{cm}^{3/2}} \sqrt{\frac{\delta_{BS} \gamma}{\varepsilon_{n,y}}} \sqrt{\frac{\sigma_z}{\beta_y}} \propto \frac{\eta_{RF} P_{RF}}{E_{cm}} \underbrace{\sqrt{\frac{\delta_{BS}}{\varepsilon_{n,y}} \frac{\sigma_z}{\beta_y}}}_{\sim 1 \text{ (hour glass effect)}}$

$$L \propto \frac{\eta_{RF} P_{RF}}{E_{cm}} \sqrt{\frac{\delta_{BS}}{\epsilon_{n,y}}} H_D$$

$$b_y \gg S_z$$

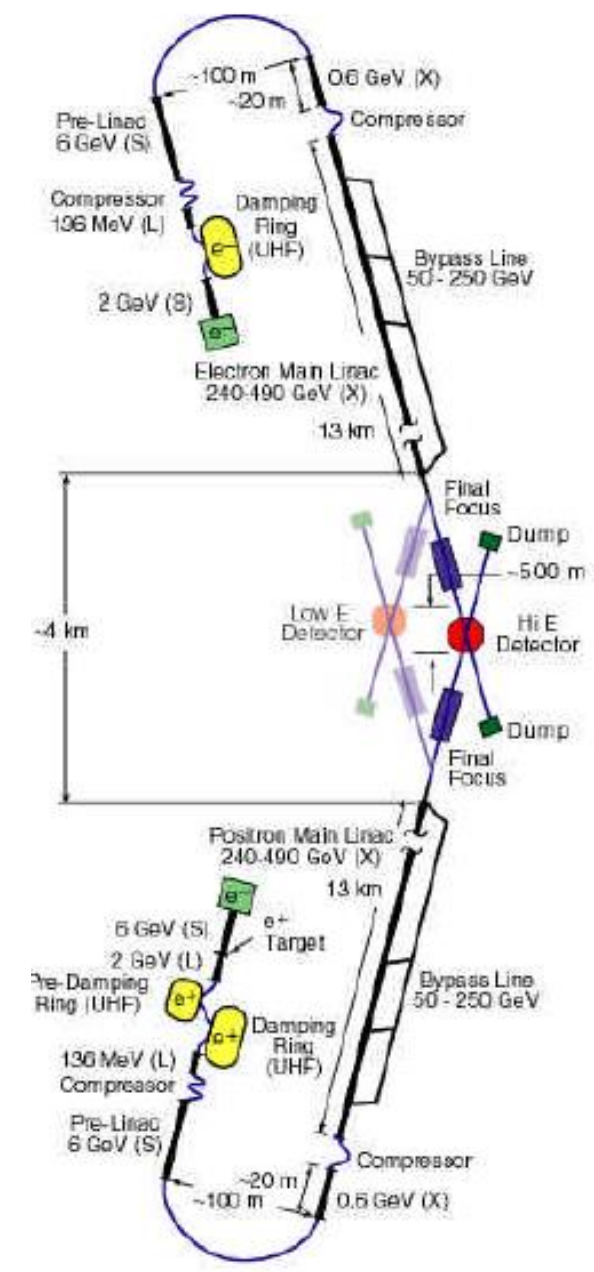
- we want **high RF-beam conversion efficiency** / $_{RF}$
- need **high RF power** P_{RF}
- **small** normalised **vertical emittance** $\Sigma_{n,y}$
- **strong focusing at IP** (small β_y and hence **small** σ_z)
- could also allow higher beamstrahlung δ_{BS} if willing to live with the consequences (Luminosity spread and background)
 - Above result is for the **low** beamstrahlung regime where $\delta_{BS} \sim \text{few } \%$
 - Slightly different result for **high** beamstrahlung regime

C.Pagani



● will see the different elements in the following...

- **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**

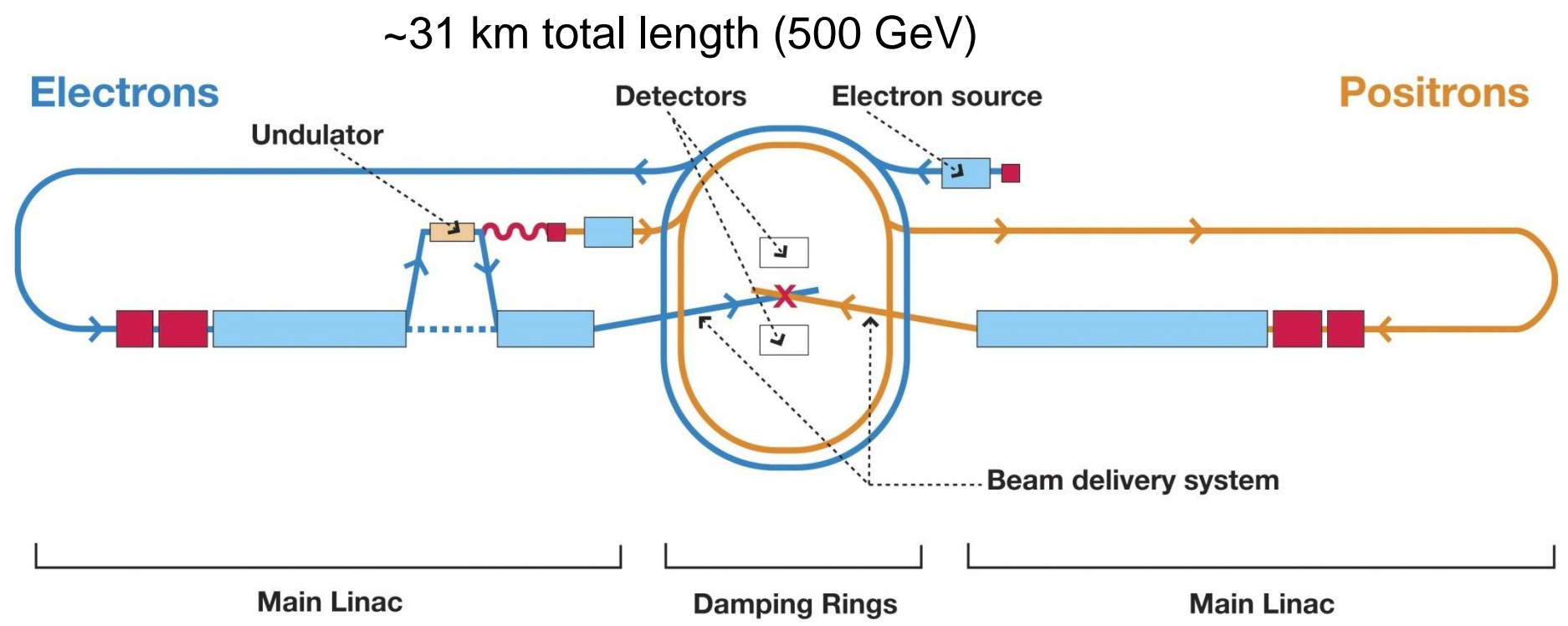


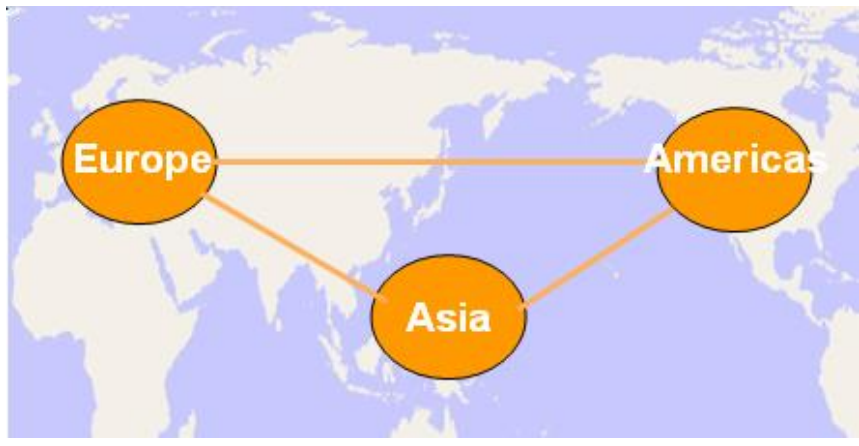
• TESLA:

- 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

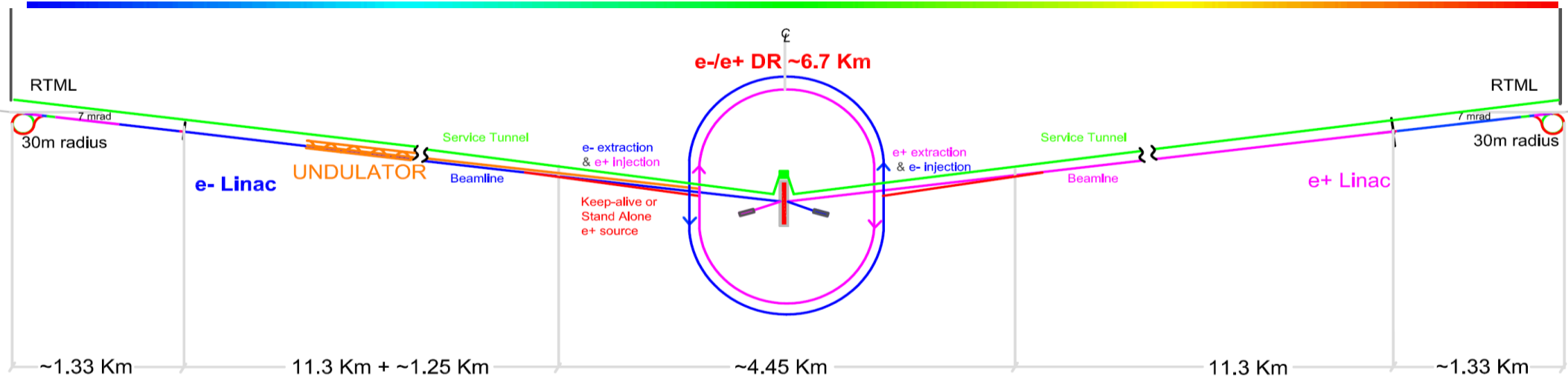




- Reference Design Report 2007
- Technical Design Report 2013
- Web site: www.linearcollider.org

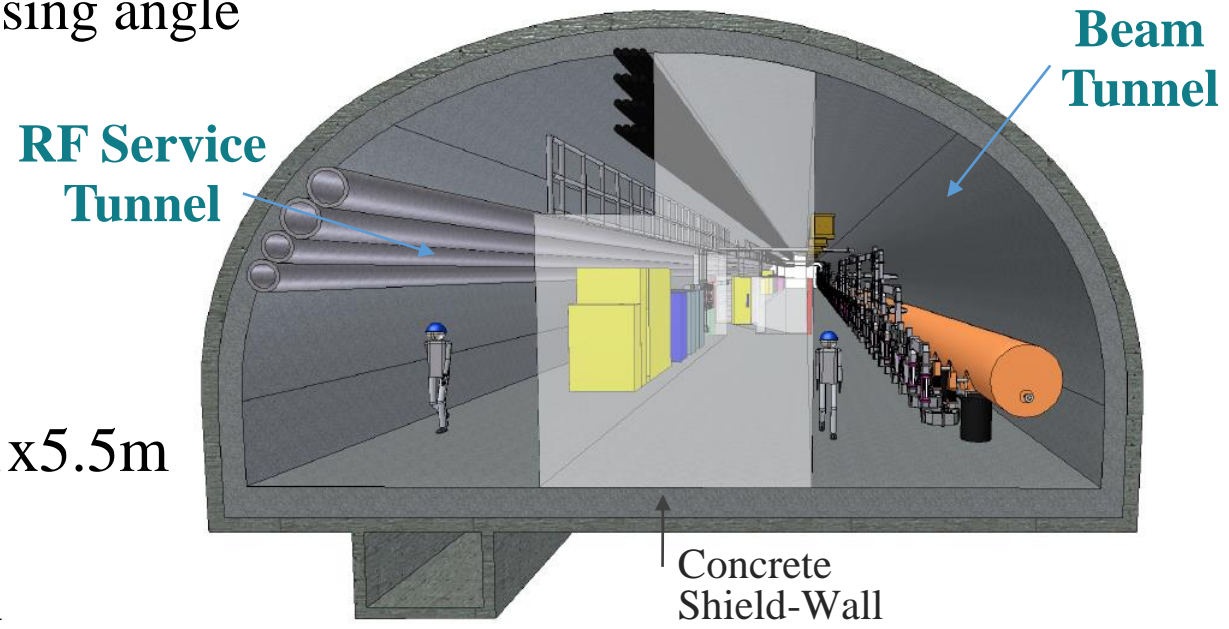
- Linear Collider Collaboration (LCC) continues design effort until project approval
- Japan has expressed interest in hosting ILC
- preferred candidate site selected: Kitakami (north Japan)

The screenshot shows the ILC website interface. At the top is the 'ilc international linear collider' logo. Below it are navigation tabs: 'FOR COLLABORATORS', 'FOR THE PRESS', 'FOR COMMUNICATORS', and 'FOR STUDENTS AND EDUCATORS'. A search bar is on the right. The main content area features a large image of a cryomodule with the caption 'A cryomodule's view inside the cave during the construction of Fermilab's ILC Test Area'. To the left is a sidebar menu with links like 'What is the ILC?', 'Global Design Effort', and 'ILC Jobs'. Below the main image are sections for 'Current News' (with a link to a Daily Herald article) and 'Features' (with a link to 'ILC NewsLine').



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



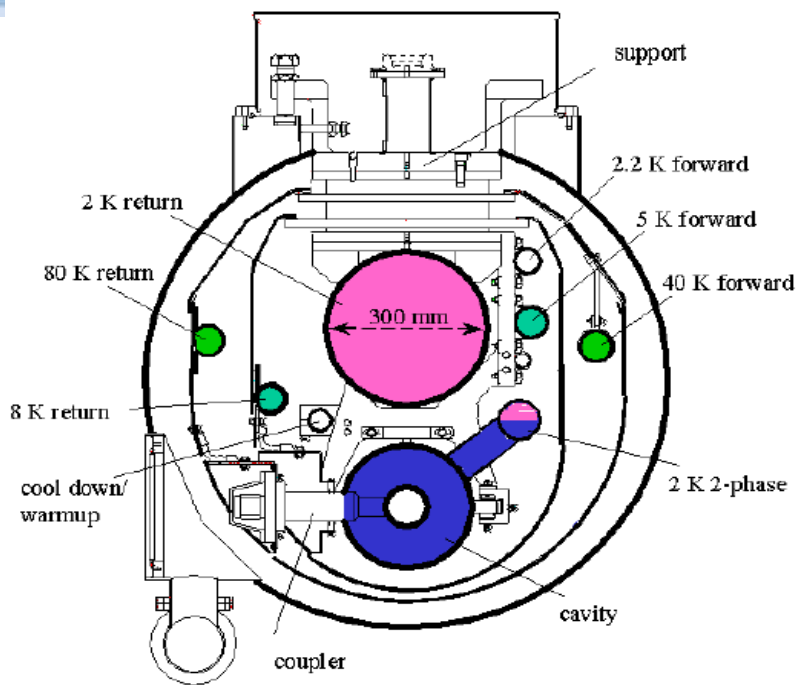
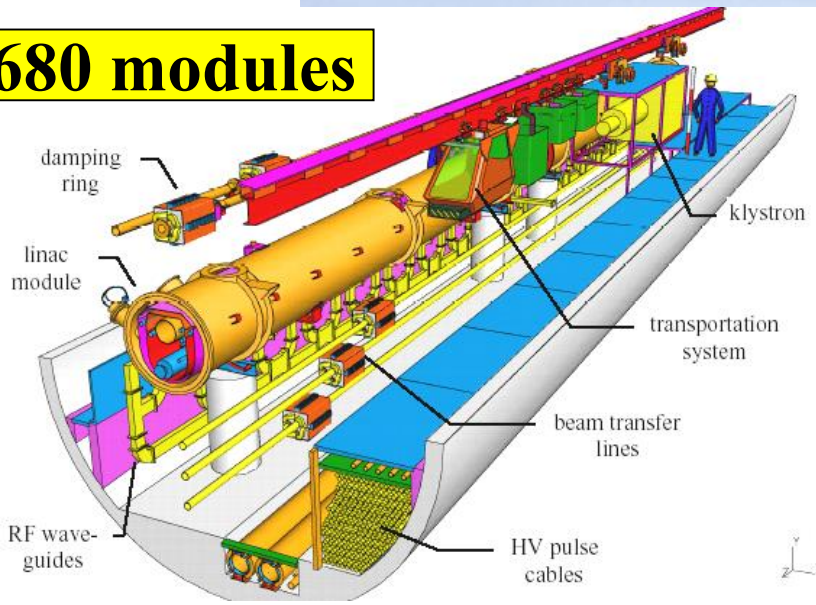
The core technology for the ILC is 1.3GHz superconducting RF cavity intensely developed in the TESLA collaboration, and recommended for the ILC by the ITRP on 2004 August.

The cavities are installed in a long cryostat cooled at 2K, and operated at gradient 31.5MV/m.



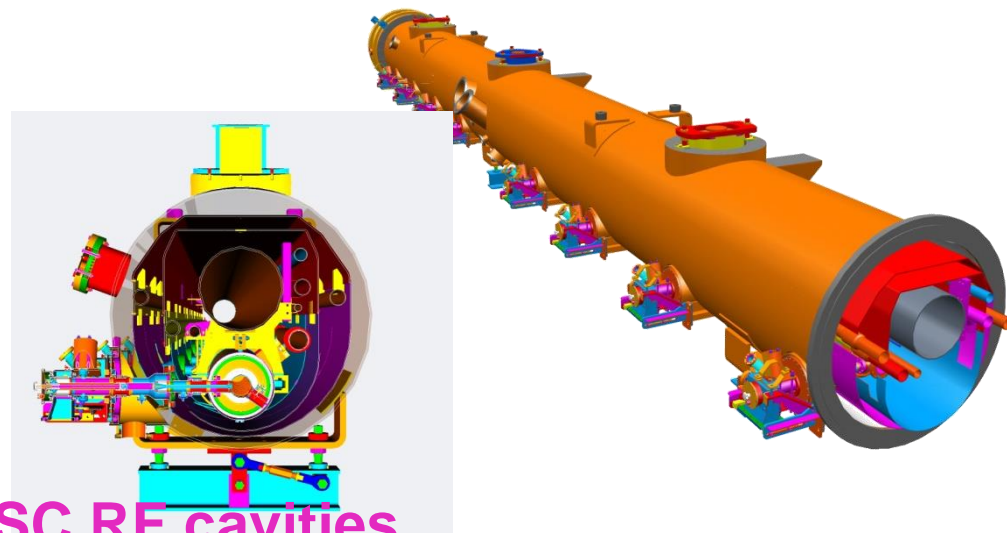
14560 cavities

1680 modules

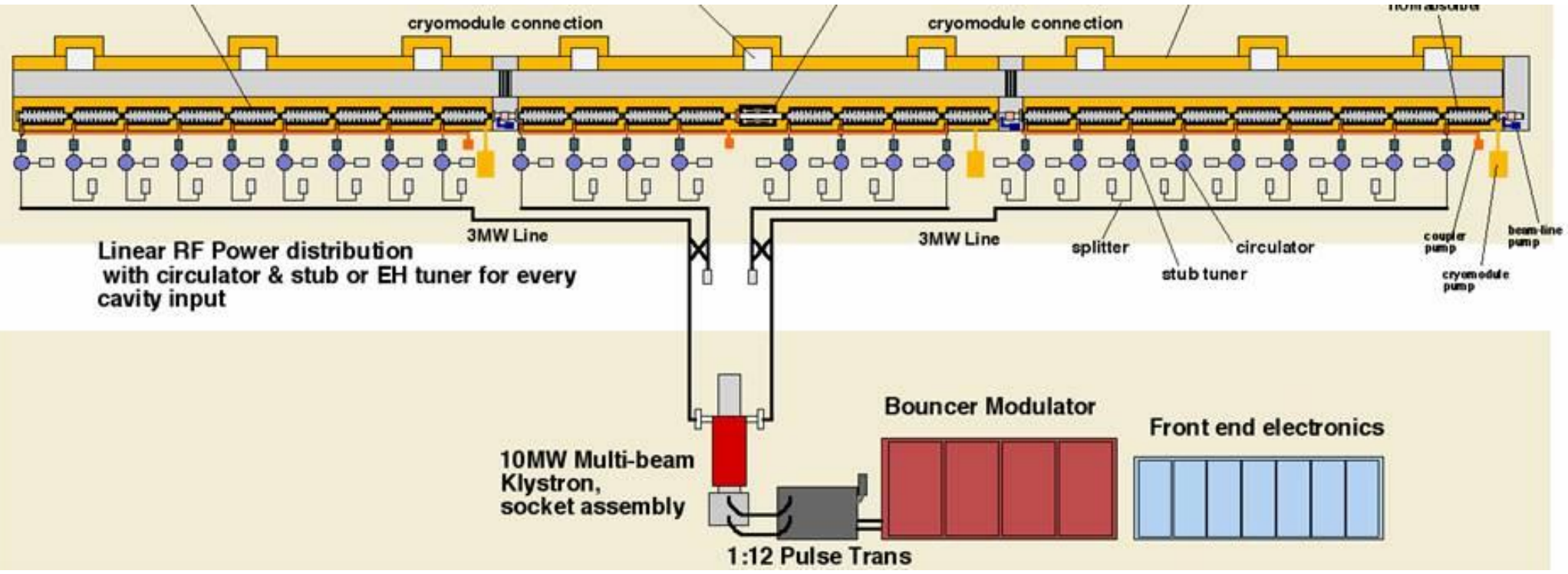


560 RF units each one composed of:

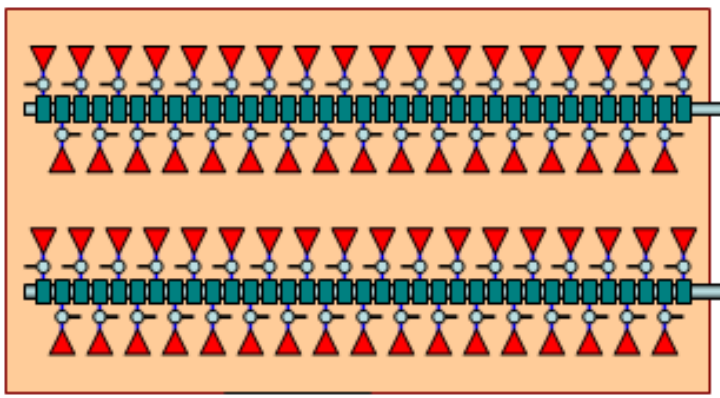
- 1 Bouncer type modulator
- 1 Multibeam klystron (10 MW, 1.6 ms)
- 3 Cryostats (9+8+9 = 26 cavities)
- 1 Quadrupole at the center



Total of 1680 cryomodules and 14 560 SC RF cavities



surface rf power cluster building



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

surface

- service tunnel eliminated
- underground heat load greatly reduced

shaft

~1.06 km ← upstream

downstream → ~1.06 km

accelerator tunnel

CTO

TE_{01} waveguide

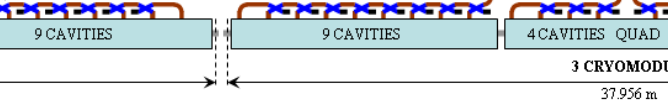
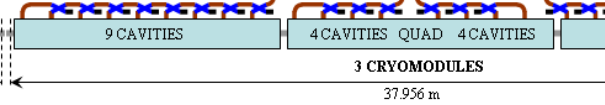
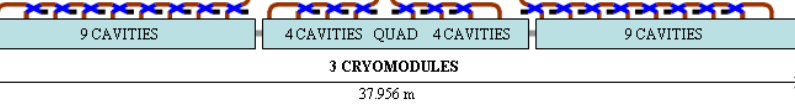
WAVEGUIDE DISTRIBUTION SYSTEM

WAVEGUIDE DISTRIBUTION SYSTEM

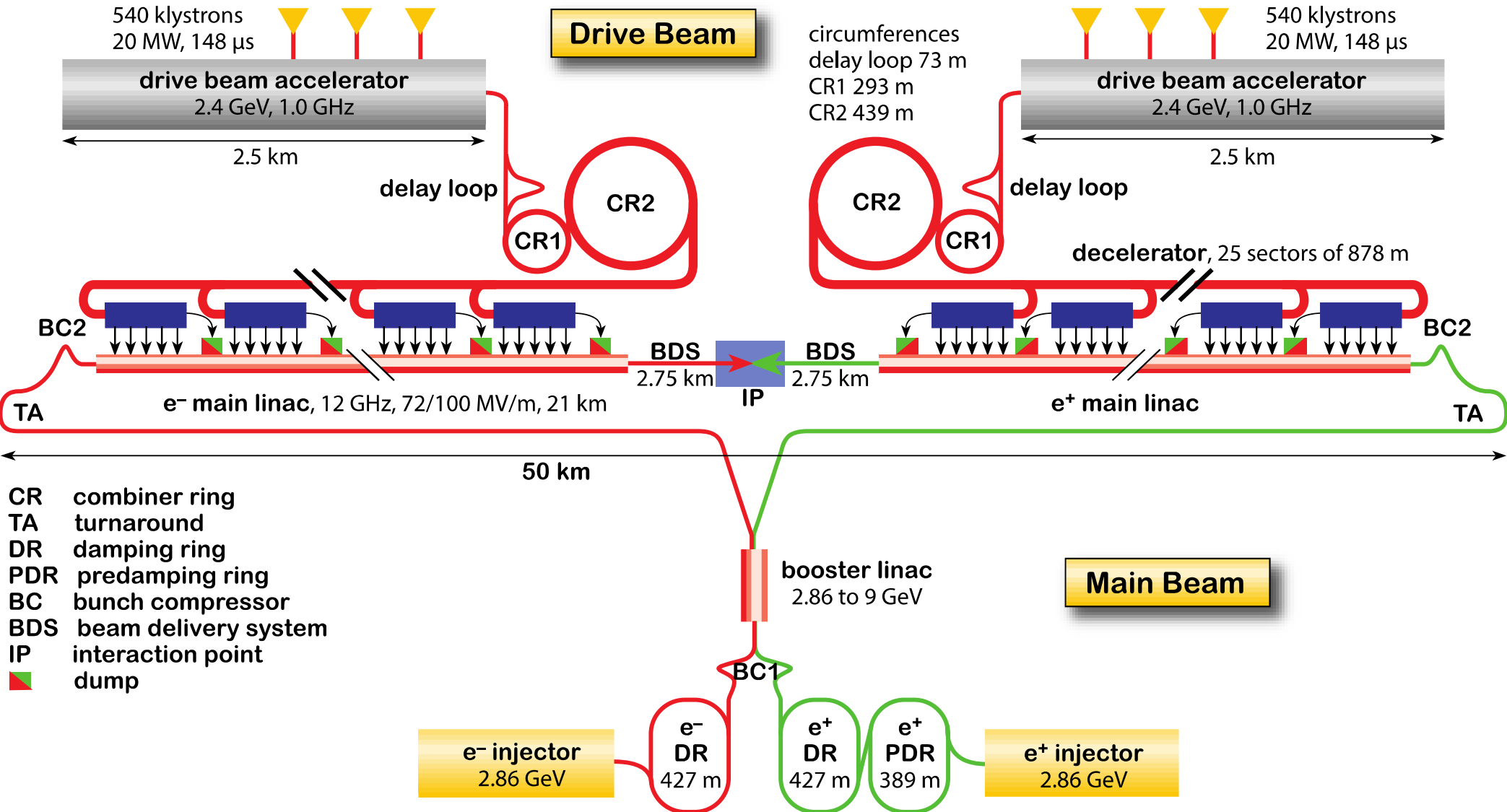
WAVEGUIDE DISTRIBUTION SYSTEM

TAP-OFFS

TAP-OFFS

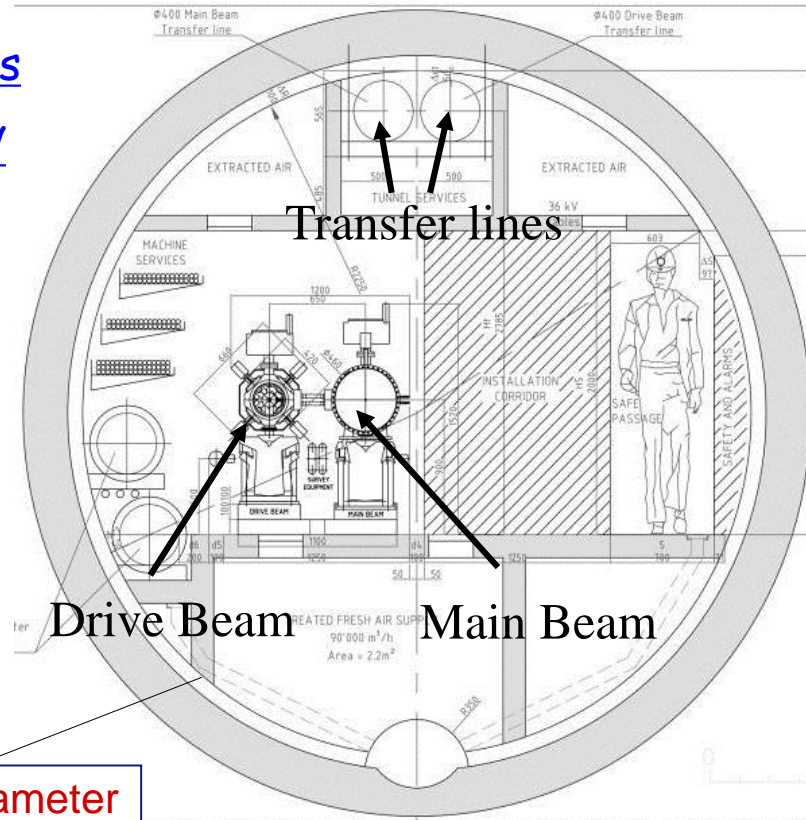
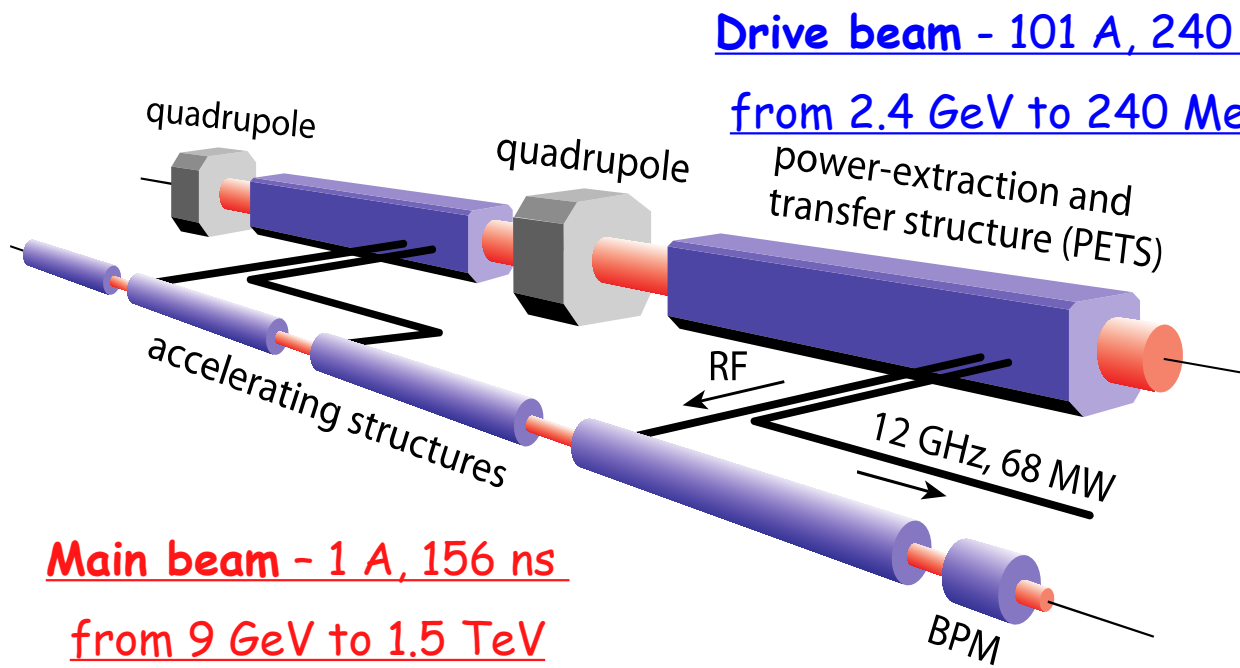


- **CLIC (Compact Linear Collider): only multi-TeV design**
 3 TeV, 100 MV/m, warm technology, 12 GHz, two beam scheme

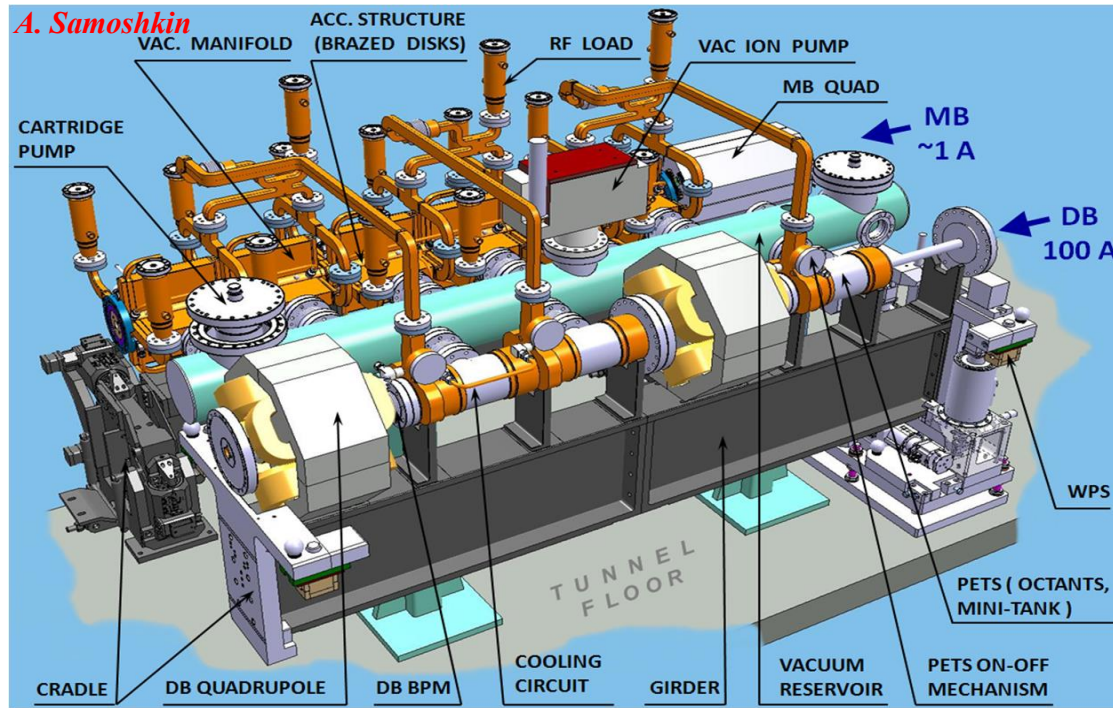
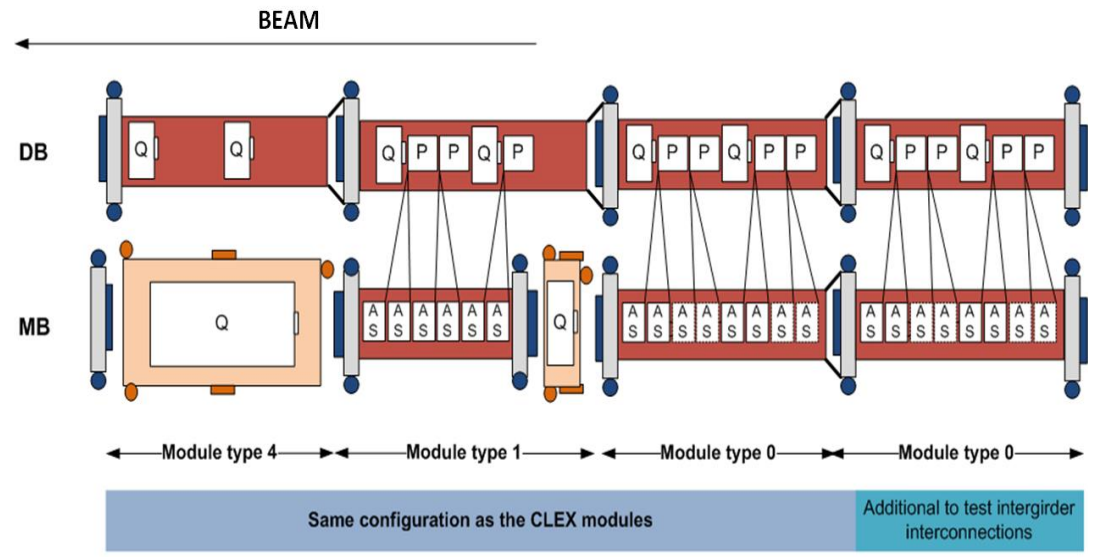


- High charge **Drive Beam** (low energy)
- Low charge **Main Beam** (high collision energy)
- => Simple tunnel, no active elements
- => Modular, easy energy upgrade in stages
380 GeV => 1.5 TeV => 3 TeV

CLIC TUNNEL CROSS-SECTION



- 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 $\sim 65\text{MW}$
- No of structures $\sim 140,000$
- Total instantaneous power $\sim 9.1\text{PW}$



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

	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_{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 $\mathcal{C}\Sigma_y$ [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

- Linear Collider Collaboration <http://linearcollider.org>
- General documentation about the ILC: <http://linearcollider.org/ILC>
- General documentation about the CLIC study: <http://cern.ch/clic-study>
- Int. Linear Collider Workshop 2016 (most actual info) <http://lcws2016.sgk.iwate-u.ac.jp>
- CLIC Workshop 2016 <http://indico.cern.ch/event/449801>
- International school for Linear Colliders: <http://linearcollider.org/school>
- Linear Collider Detector: <http://cern.ch/lcd>
- CLIC conceptual design report: <http://clic-study.web.cern.ch/content/conceptual-design-report>
- CLIC scheme description: <http://preprints.cern.ch/yellowrep/2000/2000-008/p1.pdf>
- CERN Bulletin
article: <http://cdsweb.cern.ch/journal/article?issue=28/2009&name=CERNBulletin&category=News%20Articles&number=1&ln=en>
- CLIC Test Facility: CTF3 <http://ctf3.home.cern.ch/ctf3/CTFindex.htm>
- CLIC technological challenges (CERN Academic Training) <http://indico.cern.ch/conferenceDisplay.py?confId=a057972>
- CLIC project meetings <http://indico.cern.ch/category/3589/>
- CLIC notes <http://cdsweb.cern.ch/collection/CLIC%20Notes>