Third International Accelerator School for Linear Colliders

October 19 - 29, 2008

Oak Brook Hills Marriott Hotel, Oak Brook, Illinois, U.S.A.

Introduction to the Linear Colliders

Carlo Pagani

University of Milano & INFN Milano-LASA

Course Content

Lecture:

1. Introduction and overview (Carlo Pagani, Milano University & INFN)
2. Sources & bunch compressors (Masao Kuriki, Hiroshima University)
3. Damping Rings (Mark Palmer, Cornell University)
4. Linac (Toshiyasu Higo, KEK)
5. Low-Level and High-Power RF (Stefan Simrock, DESY)
6. Beam Delivery and Beam-Beam (Deepa Angal-Kalinin. Daresbury)
7. Superconducting RF & ILC (Nikolay Solyak, Fermilab)
8. Room temperature RF & CLIC (Frank Tecker, CERN)
9. Instrumentation and Controls (Toshiyuki Okugi (KEK)
10. Muon collider (Bob Palmer, BNL)
11. Operations (Tom Himel, SLAC)
12. Physics and Detectors (Rolf Heuer, DESY/CERN)

Special How the Fermilab accel. complex works (Roger Dixon (Fermilab)

Special Hands-on training (Bob Mau (Fermilab)

Summary of this Lecture

Why LC

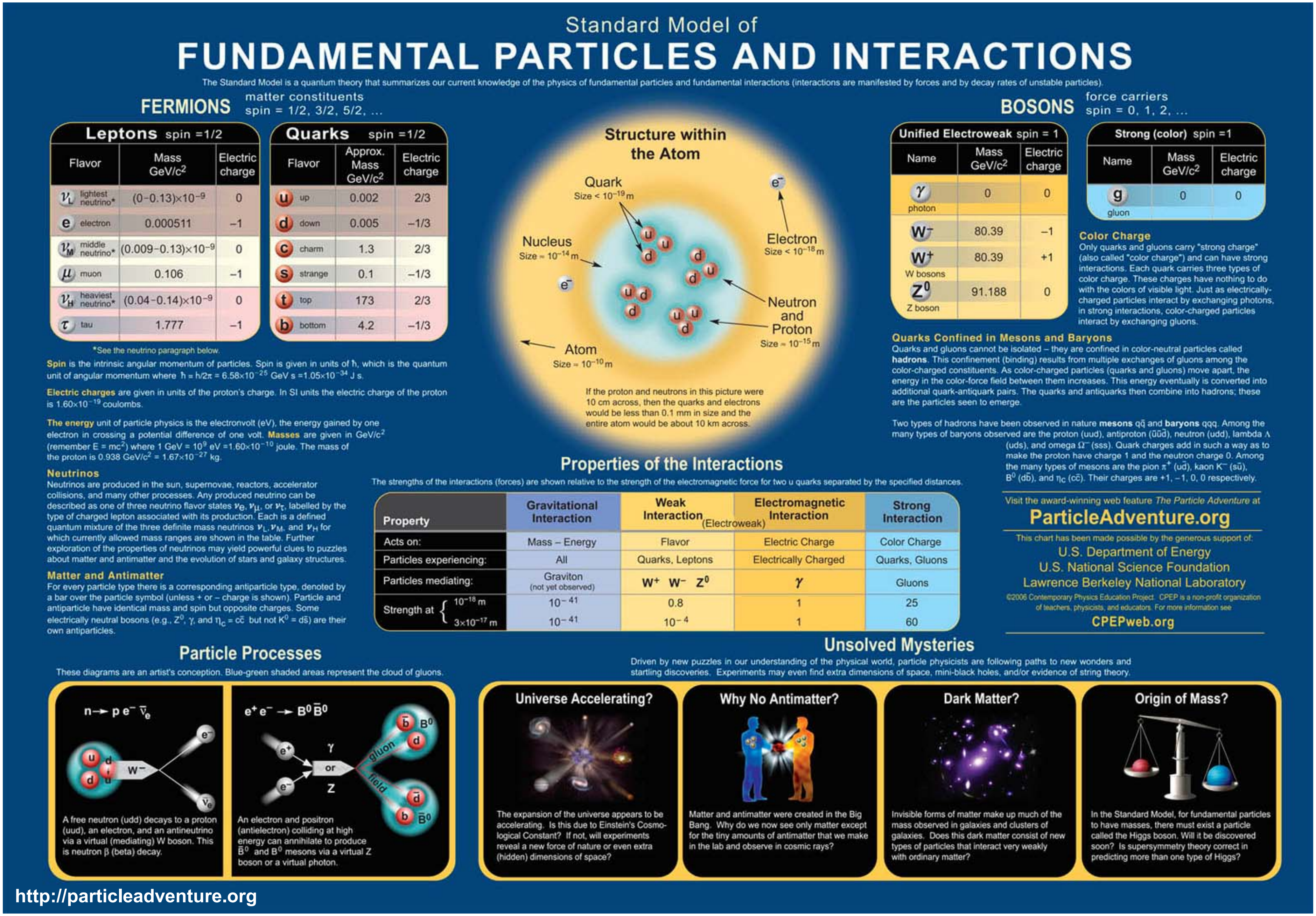
What is ILC

Layout of the ILC

Parameter choices & optimization

Overview of accelerator issues

Other future lepton colliders: CLIC and muon collider


Standard Model of
FUNDAMENTAL PARTICLES AND INTERACTIONS
The Standard Model is a quantum theory that summarizes our current knowledge of the physics of fundamental particles and fundamental interactions (interactions are manifested by forces and by decay rates of unstable particles).
FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...
Leptons spin =1/2
Flavor | Mass GeV/c² | Electric charge
νL lightest neutrino* | (0–0.13)×10⁻⁹ | 0
e electron | 0.000511 | –1
νM middle neutrino* | (0.009–0.13)×10⁻⁹ | 0
μ muon | 0.106 | –1
νH heaviest neutrino* | (0.04–0.14)×10⁻⁹ | 0
τ tau | 1.777 | –1
Quarks spin =1/2
Flavor | Approx. Mass GeV/c² | Electric charge
u up | 0.002 | 2/3
d down | 0.005 | –1/3
c charm | 1.3 | 2/3
s strange | 0.1 | –1/3
t top | 173 | 2/3
b bottom | 4.2 | –1/3
*See the neutrino paragraph below.
Spin is the intrinsic angular momentum of particles. Spin is given in units of ħ, which is the quantum unit of angular momentum where ħ = h/2π = 6.58×10⁻²⁵ GeV s =1.05×10⁻³⁴ J s.
Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10⁻¹⁹ coulombs.
The energy unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. Masses are given in GeV/c² (remember E = mc²) where 1 GeV = 10⁹ eV =1.60×10⁻¹⁰ joule. The mass of the proton is 0.938 GeV/c² = 1.67×10⁻²⁷ kg.
Neutrinos
Neutrinos are produced in the sun, supernovae, reactors, accelerator collisions, and many other processes. Any produced neutrino can be described as one of three neutrino flavor states νe, νμ, or ντ, labelled by the type of charged lepton associated with its production. Each is a defined quantum mixture of the three definite mass neutrinos νL, νM, and νH for which currently allowed mass ranges are shown in the table. Further exploration of the properties of neutrinos may yield powerful clues to puzzles about matter and antimatter and the evolution of stars and galaxy structures.
Matter and Antimatter
For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or – charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z⁰, γ, and ηc = cc̄ but not K⁰ = ds̄) are their own antiparticles.
Structure within the Atom
Quark Size < 10⁻¹⁹ m
Nucleus Size ≈ 10⁻¹⁴ m
Electron Size < 10⁻¹⁸ m
Neutron and Proton Size ≈ 10⁻¹⁵ m
Atom Size ≈ 10⁻¹⁰ m
If the proton and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.
BOSONS force carriers spin = 0, 1, 2, ...
Unified Electroweak spin = 1
Name | Mass GeV/c² | Electric charge
γ photon | 0 | 0
W⁻ | 80.39 | –1
W⁺ W bosons | 80.39 | +1
Z⁰ Z boson | 91.188 | 0
Strong (color) spin =1
Name | Mass GeV/c² | Electric charge
g gluon | 0 | 0
Color Charge
Only quarks and gluons carry "strong charge" (also called "color charge") and can have strong interactions. Each quark carries three types of color charge. These charges have nothing to do with the colors of visible light. Just as electrically-charged particles interact by exchanging photons, in strong interactions, color-charged particles interact by exchanging gluons.
Quarks Confined in Mesons and Baryons
Quarks and gluons cannot be isolated – they are confined in color-neutral particles called hadrons. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs. The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge.
Two types of hadrons have been observed in nature mesons qq̄ and baryons qqq. Among the many types of baryons observed are the proton (uud), antiproton (ūūd̄), neutron (udd), lambda Λ (uds), and omega Ω⁻ (sss). Quark charges add in such a way as to make the proton have charge 1 and the neutron charge 0. Among the many types of mesons are the pion π⁺ (ud̄), kaon K⁻ (sū), B⁰ (db̄), and ηc (cc̄). Their charges are +1, –1, 0, 0 respectively.
Visit the award-winning web feature The Particle Adventure at
ParticleAdventure.org
This chart has been made possible by the generous support of:
U.S. Department of Energy
U.S. National Science Foundation
Lawrence Berkeley National Laboratory
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CPEPweb.org
Properties of the Interactions
The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two u quarks separated by the specified distances.
Property | Gravitational Interaction | Weak Interaction (Electroweak) | Electromagnetic Interaction | Strong Interaction
Acts on: | Mass – Energy | Flavor | Electric Charge | Color Charge
Particles experiencing: | All | Quarks, Leptons | Electrically Charged | Quarks, Gluons
Particles mediating: | Graviton (not yet observed) | W⁺ W⁻ Z⁰ | γ | Gluons
Strength at 10⁻¹⁸ m | 10⁻⁴¹ | 0.8 | 1 | 25
Strength at 3×10⁻¹⁷ m | 10⁻⁴¹ | 10⁻⁴ | 1 | 60
Particle Processes
These diagrams are an artist's conception. Blue-green shaded areas represent the cloud of gluons.
n → p e⁻ ν̄e
A free neutron (udd) decays to a proton (uud), an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β (beta) decay.
e⁺ e⁻ → B⁰ B̄⁰
An electron and positron (antielectron) colliding at high energy can annihilate to produce B̄⁰ and B⁰ mesons via a virtual Z boson or a virtual photon.
Unsolved Mysteries
Driven by new puzzles in our understanding of the physical world, particle physicists are following paths to new wonders and startling discoveries. Experiments may even find extra dimensions of space, mini-black holes, and/or evidence of string theory.
Universe Accelerating?
The expansion of the universe appears to be accelerating. Is this due to Einstein's Cosmological Constant? If not, will experiments reveal a new force of nature or even extra (hidden) dimensions of space?
Why No Antimatter?
Matter and antimatter were created in the Big Bang. Why do we now see only matter except for the tiny amounts of antimatter that we make in the lab and observe in cosmic rays?
Dark Matter?
Invisible forms of matter make up much of the mass observed in galaxies and clusters of galaxies. Does this dark matter consist of new types of particles that interact very weakly with ordinary matter?
Origin of Mass?
In the Standard Model, for fundamental particles to have masses, there must exist a particle called the Higgs boson. Will it be discovered soon? Is supersymmetry theory correct in predicting more than one type of Higgs?
http://particleadventure.org

Glossary

- **Units of Energy** : eV (Electron Volt)
  MeV ; Mega Electron Volt : 10^6 eV
  GeV ; Giga Electron Volt : 10^9 eV
  TeV ; Tera Electron Volt : 10^{12} eV
- **Particle Masses**
  Electron : 0.5 MeV/c^2, Proton : 938 MeV/c^2
- **Cross section** : σ
  nb : 10^{-33} cm^2 , pb : 10^{-36} cm^2 , fb : $10^{-39}$$cm^2$
- **Luminosity** : L
  Number of Particle collisions per unit time per unit area
  e.g. : the KEKB recorded L = 1.6 x10^{34} $cm^{-2}sec^{-1}$
- **Integrated Luminosity** : $\int L$
  Luminosity integrated over some time interval,
  e.g. : the KEKB recorded $\int L$ = $10^{39}cm^{-2}$ = fb^{-1} in a day.

Path to the Standard Model of Particles

Kobayashi, Maskawa
Glashow, Salam, Weinberg
Higgs, Nambu
Gell-Man
Feynman, Schwinger, Tomonaga
Lee, Yang
Yukawa
Dirac
Schroedinger
Einstein
Maxwell
Hewton
Galilei
Aristotle

Great Theories

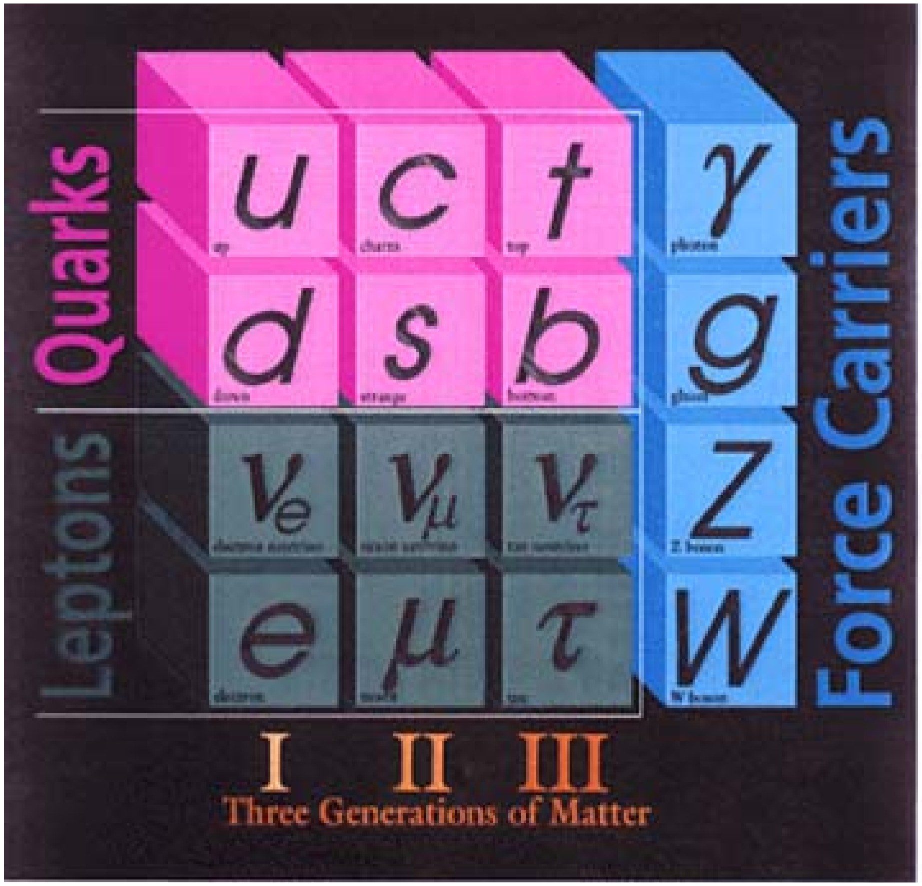
Neutrino mixing
T-quark
W/Z boson
B-meson
D-meson
τ-lepton
μ-Neutrino
Kaon
Pion
Muon
Neutron
Proton
Positron
Electron

Great Discoveries
by particle accelerators

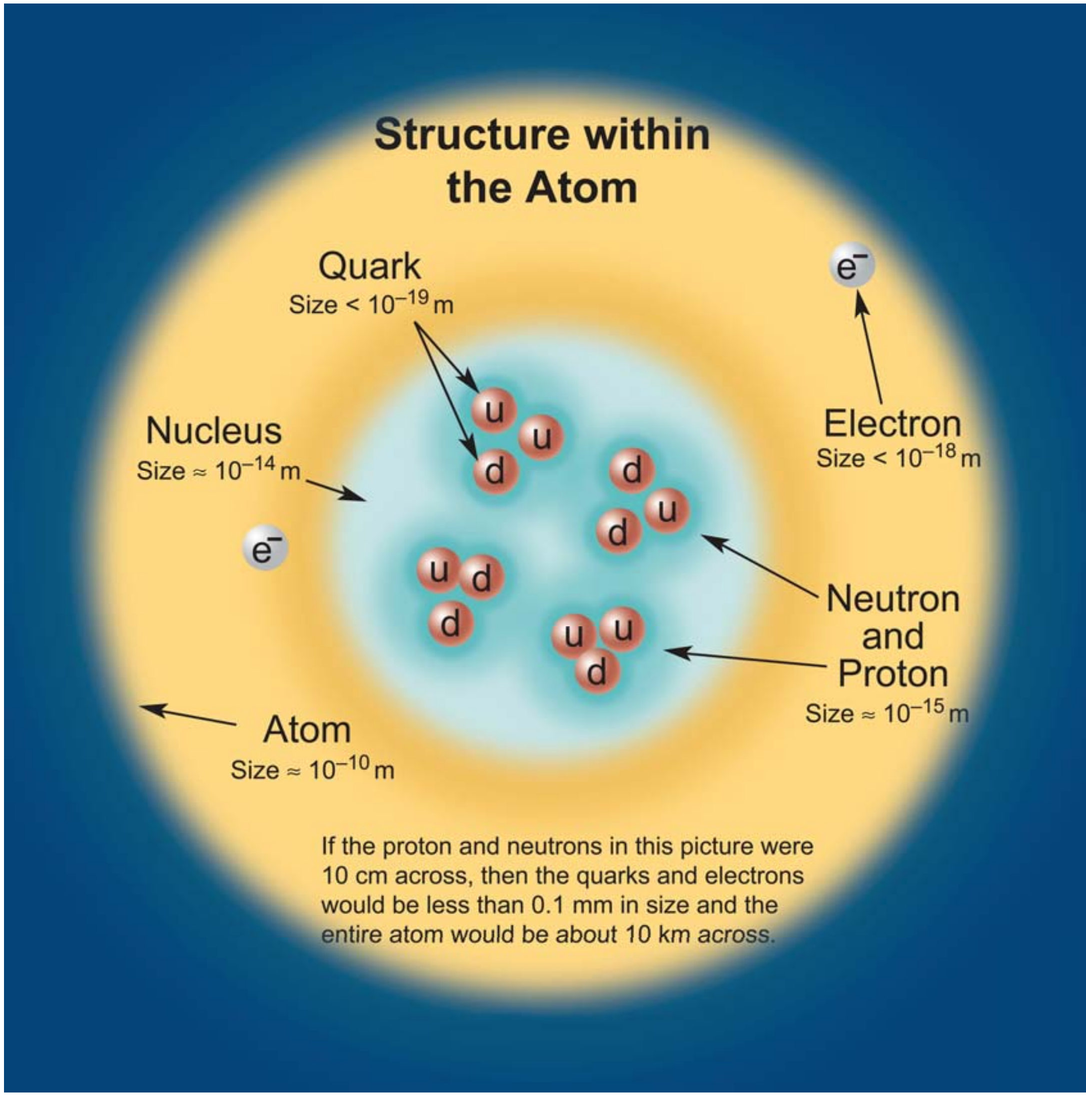
Elementary particles

In the Standard Model

- 3 families of quarks
- 3 families of leptons
- 4 kinds of force carriers



Fermions and Bosons



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Higgs Particles and Higgs Field

Higgs Particles

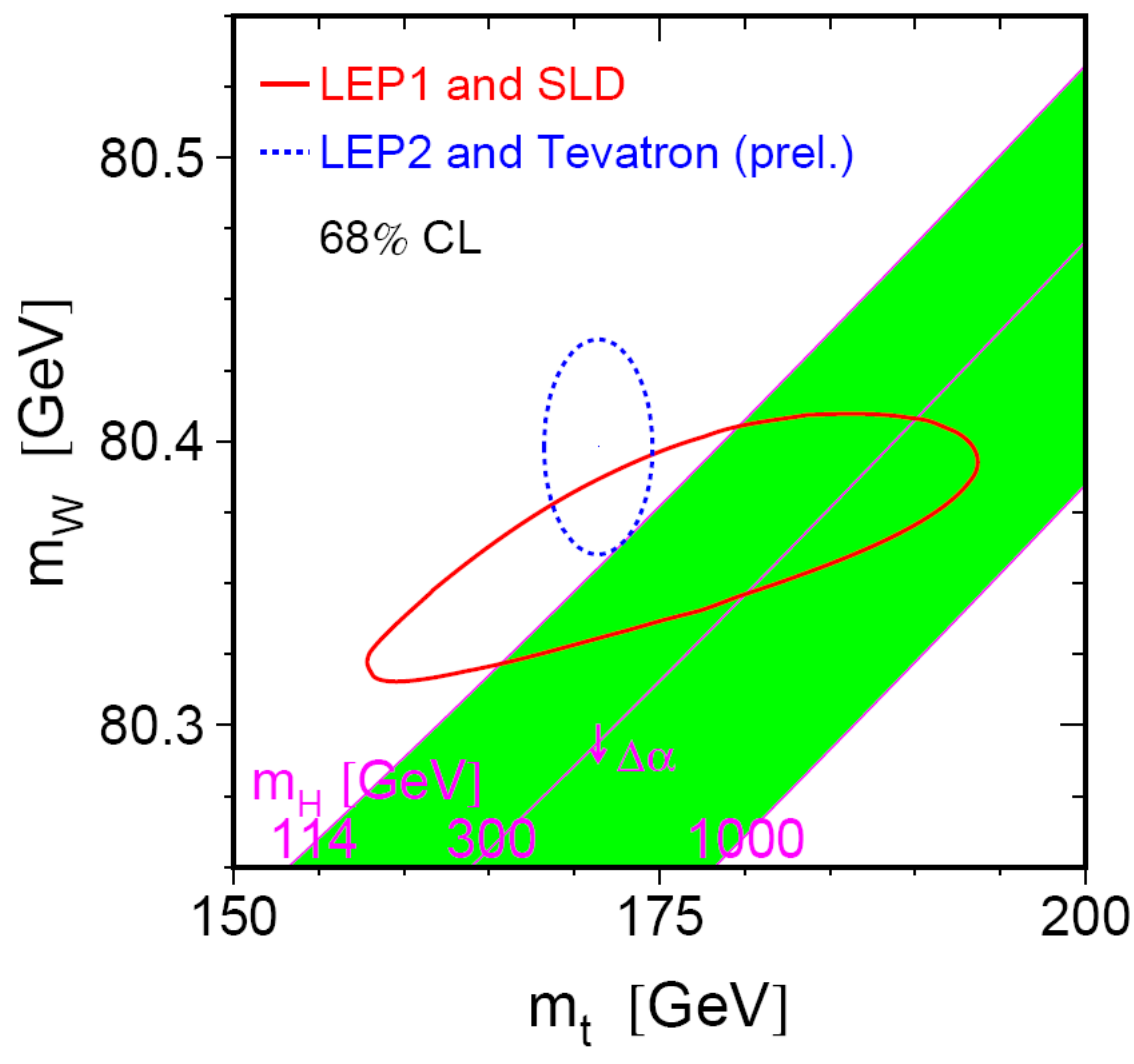
- also called: **God Particles** and **Holy Grail** of Particle Physics
- They are spin=0 Bosons
- **The Higgs is neither matter nor force**
- The Higgs is its own antiparticle
- The **Higgs is just different**
- This would be **the first fundamental scalar ever discovered**

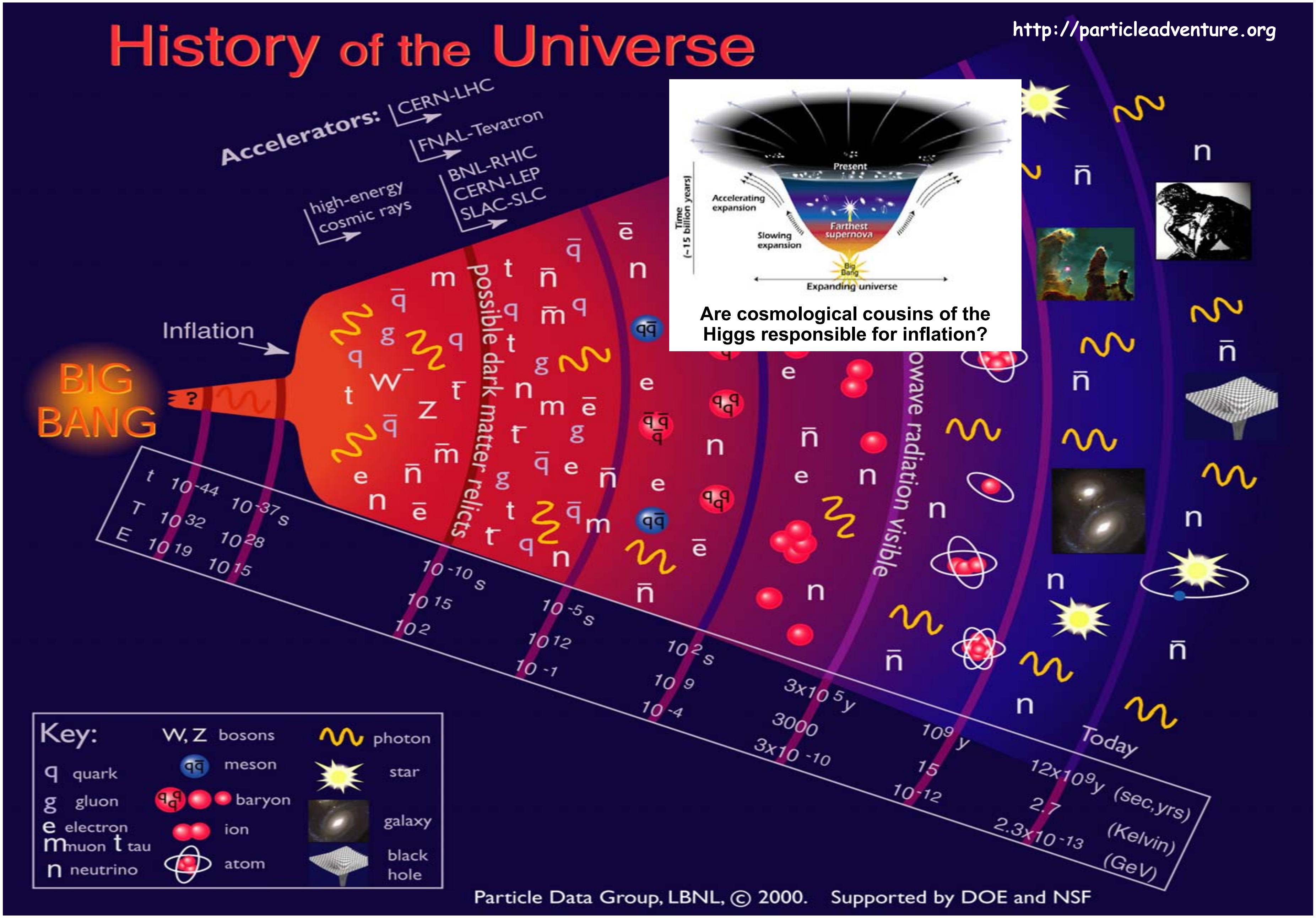
Higgs Field

- **Neutral scalar field that fills the entire universe**
- **Particles** traveling through the universe **interact with this field & become massive**
- Importantly, the W and Z bosons receive mass but not the photon in the Standard Model
- The Higgs field is thought to fill the entire universe.
- Could give a handle on dark energy (scalar field) ?

If discovered, the Higgs is a very powerful probe of new physics

SM Higgs mass from LEP2 & Tevatron




History of the Universe
http://particleadventure.org
Accelerators: CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relics
owave radiation visible
Present
Accelerating expansion
Slowing expansion
Farthest supernova
Big Bang
Expanding universe
Time (~15 billion years)
Are cosmological cousins of the Higgs responsible for inflation?
t 10-44 10-37 s 10-10 s 10-5 s 10 2 s 3x10 5 y 10 9 y 12x10 9 y (sec,yrs)
T 10 32 10 28 10 15 10 12 10 9 3000 15 2.7 (Kelvin)
E 10 19 10 15 10 2 10 -1 10 -4 3x10 -10 10 -12 2.3x10 -13 (GeV)
Today
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

About Orders of Magnitude

Linear Sizes in the Universe

• **Quark**	**10^{-19}**	**m**
• Proton & Neutron	10^{-15}	m
• Atoms	10^{-10}	m
• Cells	10^{-8} - 10^{-3}	m
• **Human being**	**10^{0}**	**m**
• Earth	10^{7}	m
• Sun	10^{9}	m
• Solar System	10^{13}	m
• Milky Way	10^{21}	m
• **Univers**	**10^{26}**	**m**

Just for fun

Linear Ratio between the sizes of
the universe and the quark

$$\frac{\Phi_{universe}}{\Phi_{quark}} \approx 10^{45} \longrightarrow \text{45 digits}$$

60 digits are used for encrypting codes !

The Large Instruments for Physics

Particle Accelerators

- To study what is extremely small
  - Particles are created from energy and analyzed
  - Nuclei are excited and their behavior observed
  - Short wavelength photons and neutrons are indirectly generated to observe the invisible world
- As intense particle sources for applications
  - cancer therapy and radio-isotope production
  - nuclear waste transmutation to reduce toxicity
  - intense photon beams for: micro-lithography, food, catalysis, etc.

Large Telescopes

- To study what is extremely big
  - Viewing far in space and time
  - Observing large phenomena at their extreme conditions

What is a Particle Accelerator ?

- A particle Accelerator is a machine designed to transfer energy to a charged particle beam. In most cases the particle beam extracts energy from an electromagnetic field that is stored or traveling in low losses structures, called cavities.

$E\ [J] = q\ [C] \cdot V\ [Volt]$ or $E\ [eV] = q\ [e] \cdot V\ [Volt]$

- Particles are taking energy from the electric field, $\boldsymbol{E}$, and are guided by the magnetic field, $\boldsymbol{B}$, according to the Lorentz equation:

$$\boldsymbol{F} = q\ (\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B})$$

- The charged accelerated particles can be:
  - electrons (& positrons) [i.e. leptons: “elementary” particles]
  - protons (& antiprotons) [i.e. hadrons, “composite” particles]
  - heavy ions (i.e. ionized atoms)

- An intense primary beam can be used to produce a secondary beam that could not be accelerated: photons, neutrons, neutrinos, etc.

Guiding Forces from Magnetic Field

Expanding the magnetic component of the Lorentz force we have

$$\vec{F}_{mag} = q\left(\vec{v} \times \vec{B}\right) = q \begin{vmatrix} \vec{i} & \vec{j} & \vec{k} \\ v_x & v_y & v_z \\ B_x & B_y & B_z \end{vmatrix} = \vec{i}\,q(v_y B_z - v_z B_y) + \vec{j}\,q(v_z B_x - v_x B_z) + \vec{k}\,q(v_x B_y - v_y B_x)$$

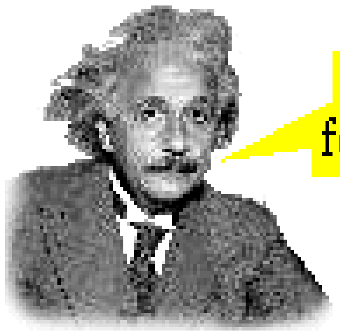
The 3 magnetic field components, properly combined with the 3 beam velocity components are used to produce the forces required to guide the beam in a stable orbit

$$F_x^{mag} = q\left(v_y B_z - v_z B_y\right)$$

$$F_y^{mag} = q\left(v_z B_x - v_x B_z\right)$$

$$F_z^{mag} = q\left(v_x B_y - v_y B_x\right)$$

Energy and Mass



$m = \gamma m_0$ $\qquad E_0 = m_0 c^2$

$\gamma = (1-\beta^2)^{-1/2}$ $\qquad \beta = v/c$

$$E = m c^2$$

Momentum $\quad \mathbf{p} = m\,\mathbf{v} \approx m_0 \gamma\, \mathbf{c}$

Kinetic energy $\quad K = E - E_0 = (\gamma - 1)\, m c^2$

Speed of light: $c \equiv 2.99792458 \cdot 10^8$ ms^{-1}

Energy unit: 1 eV = $1.6021 \cdot 10^{-19}$ J

Electron rest energy: E_0 = 0.511 MeV

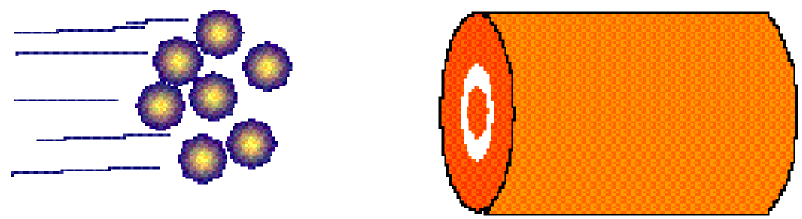
Proton rest energy: E_0 = 938 MeV

Colliding Beams for High Energy

W = Energy available in center-of-mass for making new particles

For fixed target :

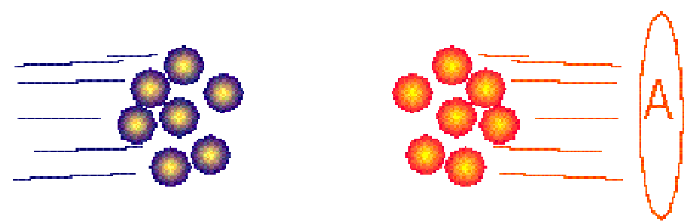
$$E_{c.m} \cong \sqrt{2 m_T E_B}$$



... and we rapidly run out of money trying to gain a factor 10 in c.m. energy

But a storage ring , colliding two beams, gives:

$$E_{c.m.} \cong 2 \; E_B$$

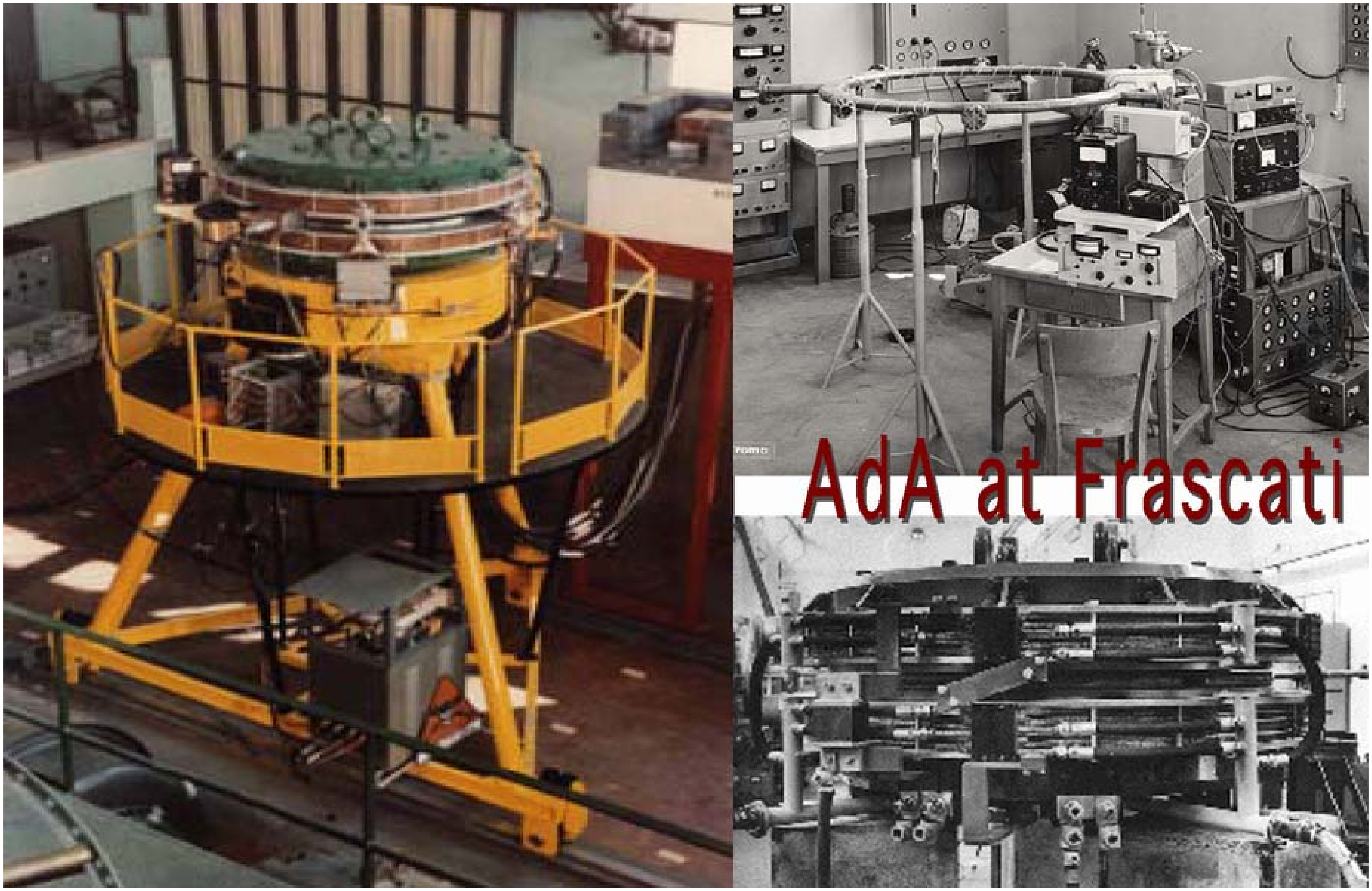


Problem: Smaller probability that accelerated particles collide .... "Luminosity" of a collider

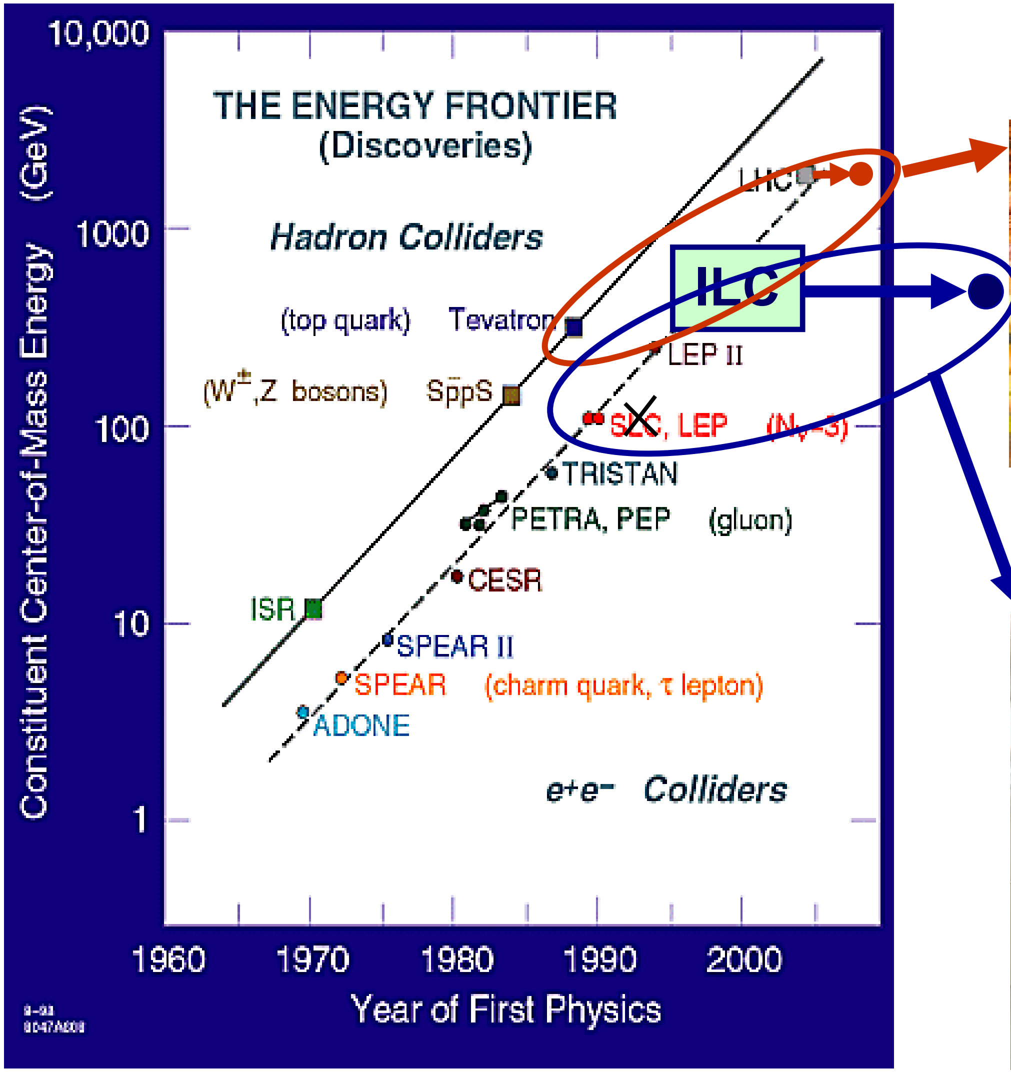
$$L = N_1 N_2 \frac{1}{A} \frac{\beta c}{2\pi R} \approx 10^{29} \ldots 10^{34} \, cm^{-2} s^{-1}$$

© E.J.N. Wilson

The First Collider: AdA @ Frascati

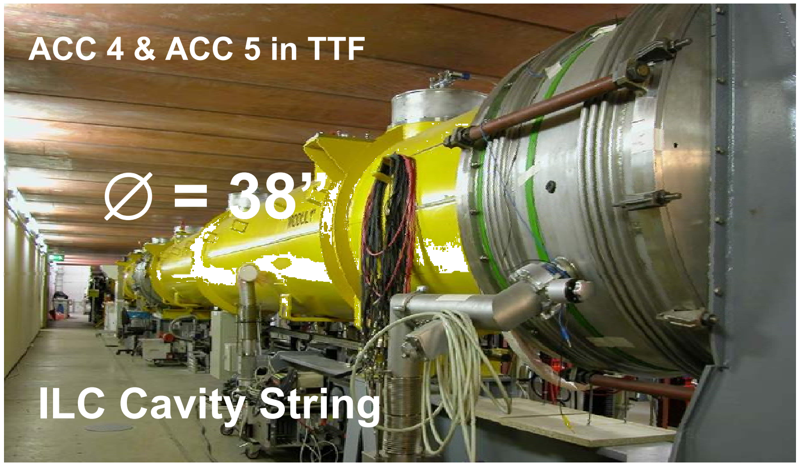


Energy Frontier and Accelerator Tech.



Superconducting Dipoles

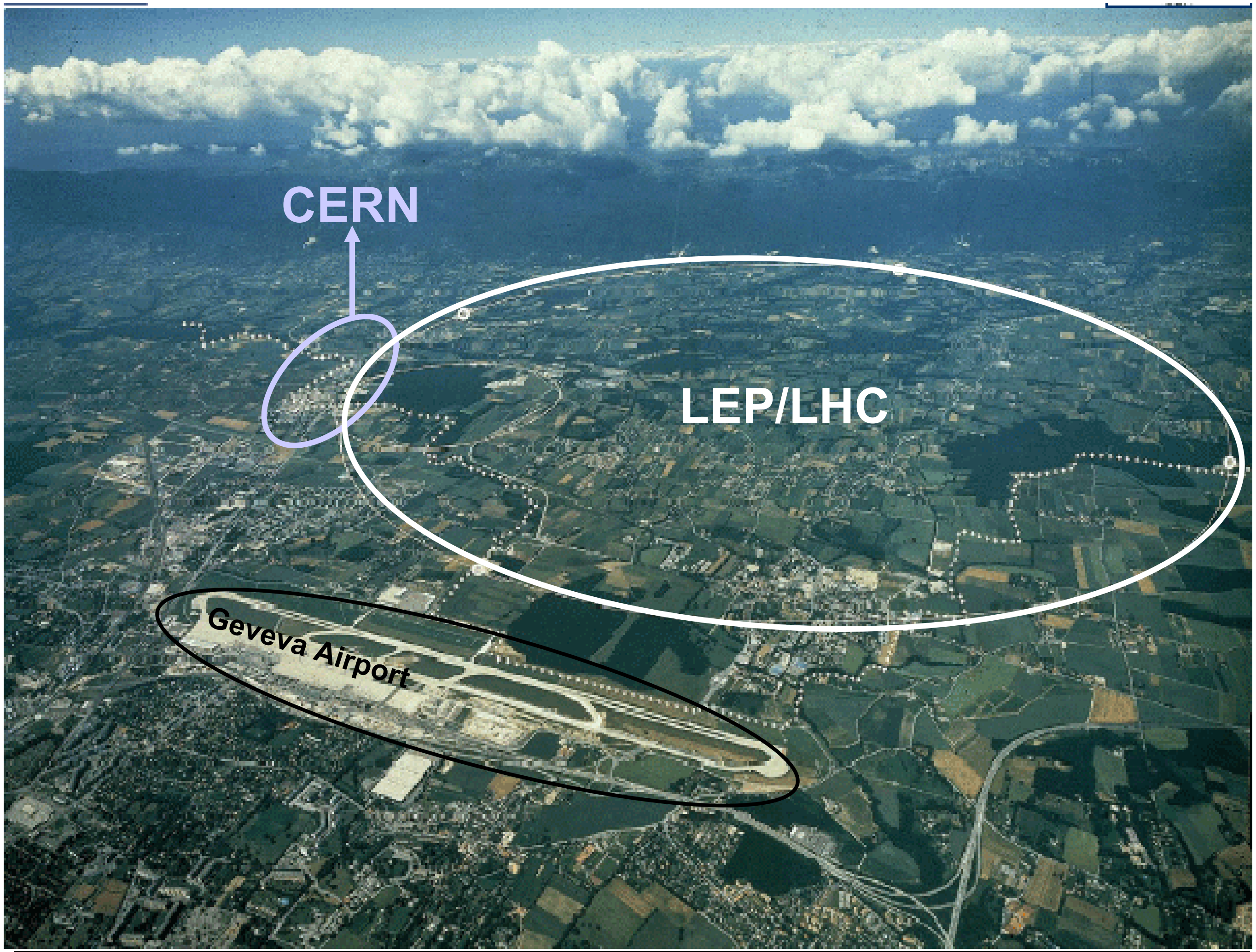
Superconducting RF Cavities



Aerial view of the CERN area

W.Van Doninck Collisions Namur 22/11/2001

LEP @ LHC in the CERN area

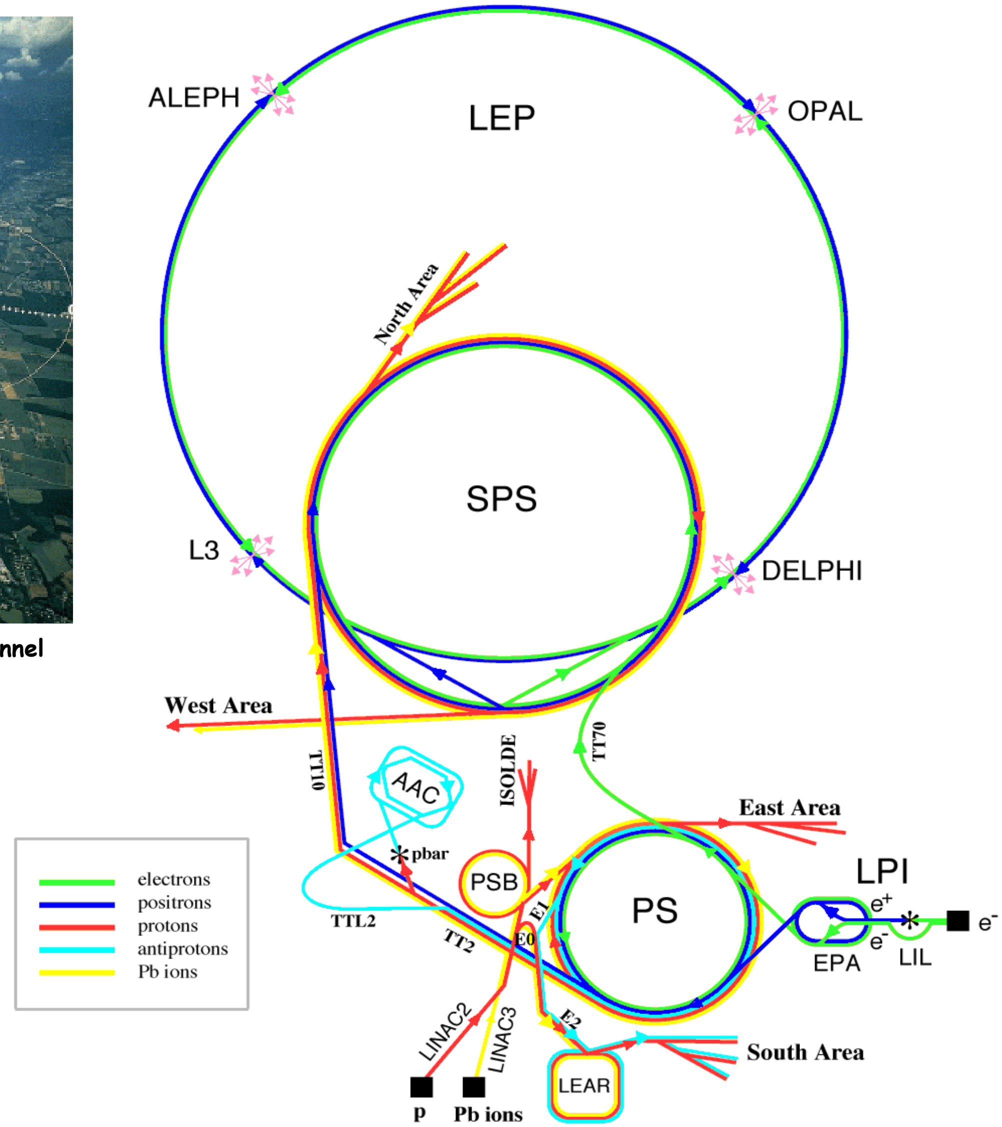


W.Van Doninck Collisions Namur 22/11/2001

The LEP Accelerator Complex @ CERN

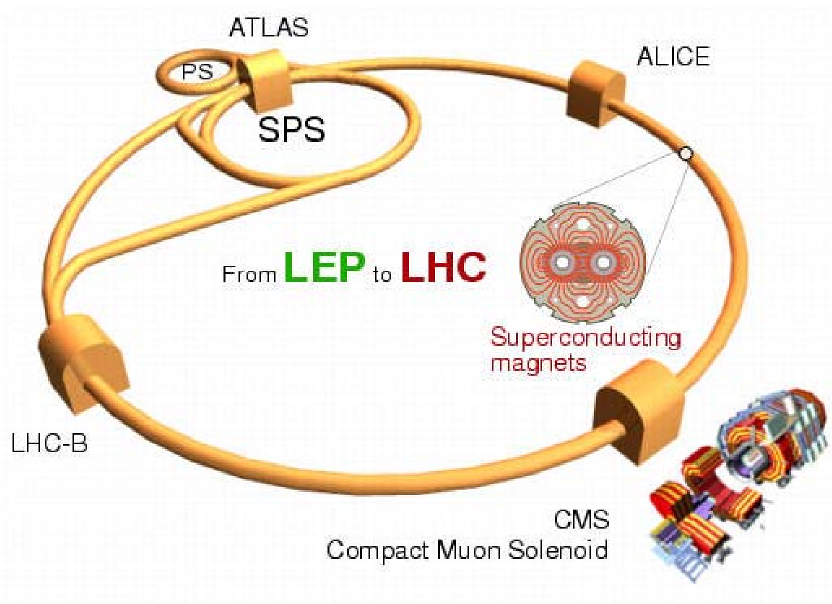
Aerial view of the CERN site with an indication of the circular LEP tunnel

- Linacs and synchrotrons were used to inject in the 28 km synchrotron where both electron and positrons were accelerated up to 100 GeV to collide with a centre of mass energy of 200 GeV
- LHC now in commissioning is making use of most of the LEP injection accelerator complex



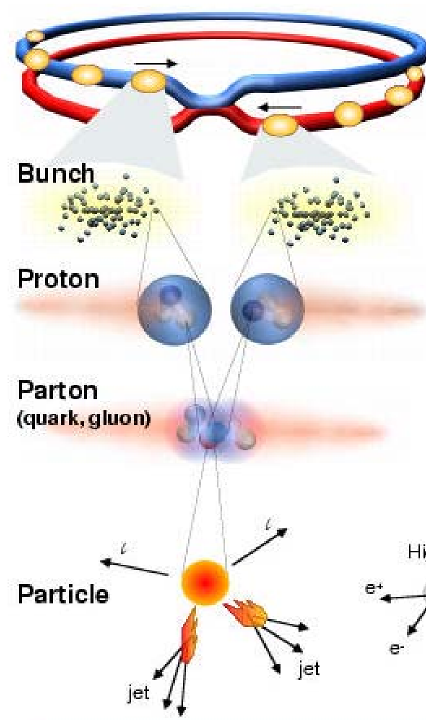
From LEP to LHC

The Large Hadron Collider (LHC)



	Beams	Energy		Luminosity
LEP	e+ e-	200	GeV	10^{32} cm^{-2}s^{-1}
LHC	p p	14	TeV	10^{34}
	Pb Pb	1312	TeV	10^{27}

Collisions at LHC



Proton-Proton	(2835 x 2835 bunches)
Protons/bunch	10^{11}
Beam energy	7 TeV (7x10^{12} eV)
Luminosity	10^{34} cm^{-2} s^{-1}
Crossing rate	40 MHz
Collisions ≈	10^7 - 10^9 Hz

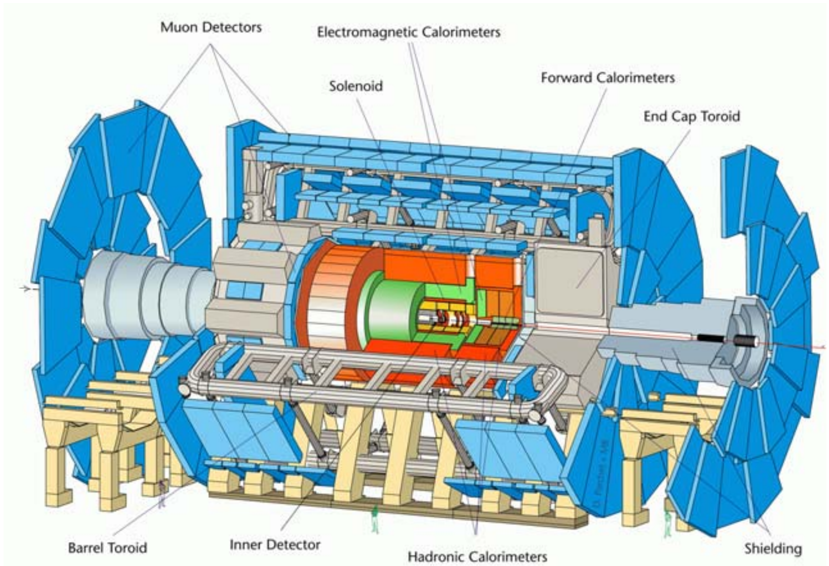
Selection of 1 in 10,000,000,000,000

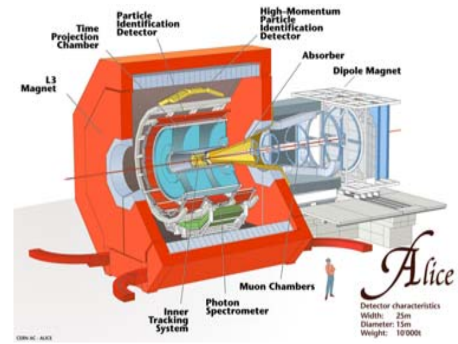
LHC General Parameters (protons)

LHC General Parameters		
Energy at collision	7	TeV
Energy at injection	450	GeV
Dipole field at 7 TeV	8.33	T
Coil inner diameter	56	mm
Distance between aperture axes (1.9 K)	194	mm
Luminosity	1	E34 $cm^{-2}s^{-1}$
Beam beam parameter	3.6	E-3
DC beam current	0.56	A
Bunch spacing	7.48	m
Bunch separation	24.95	ns
Number of particles per bunch	1.1	E11
Normalized transverse emittance (r.m.s.)	3.75	µm
Total crossing angle	300	µrad
Luminosity lifetime	10	h
Energy loss per turn	7	keV
Critical photon energy	44.1	eV
Total radiated power per beam	3.8	kW
Stored energy per beam	350	MJ
Filling time per ring	4.3	min

The LHC Detectors

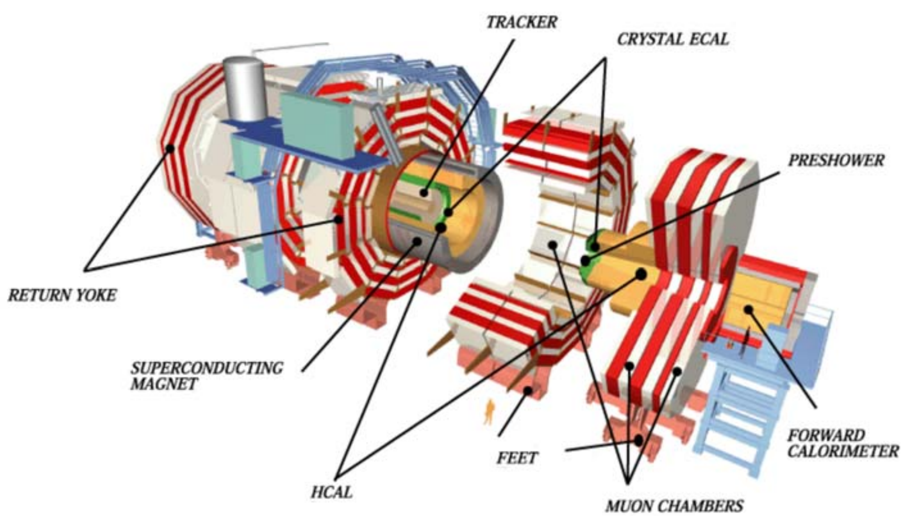
ATLAS

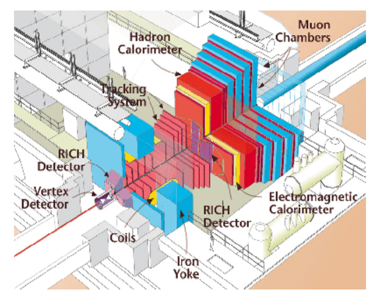




ALICE

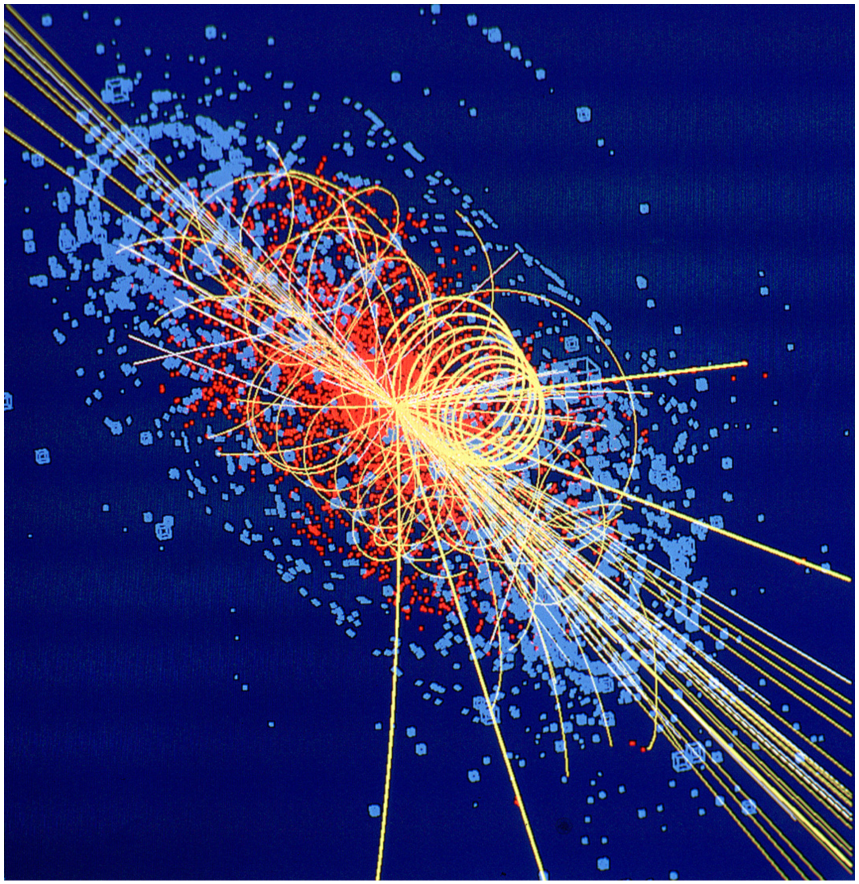
CMS



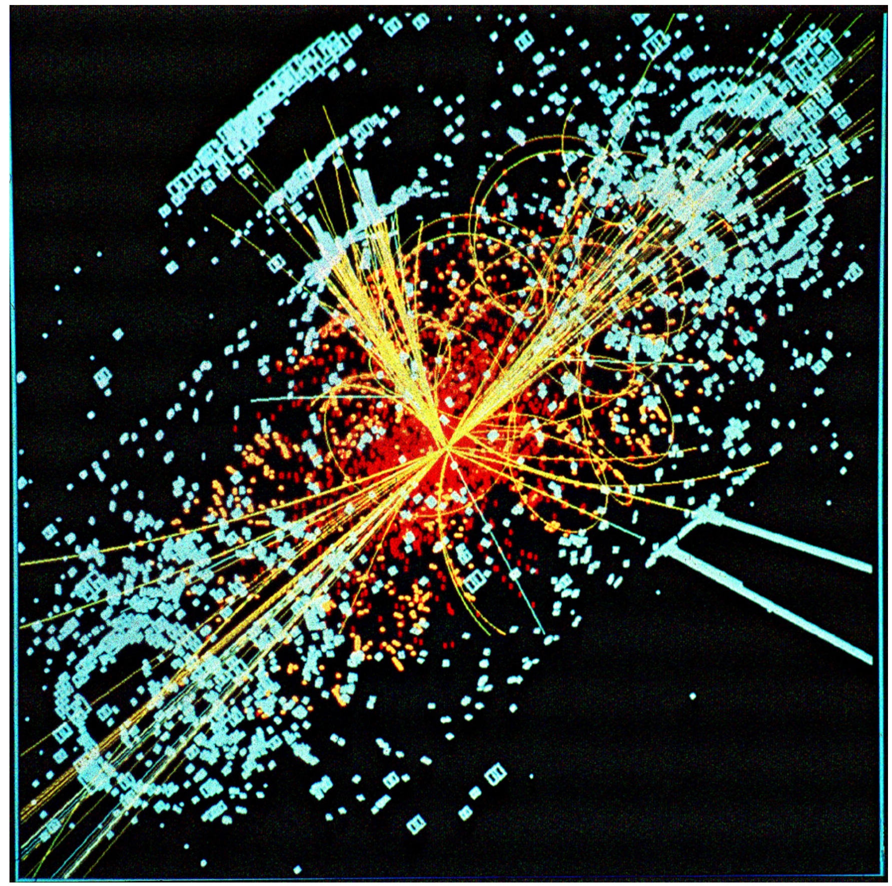


LHC 'B'

Simulations of Higgs events at CMS

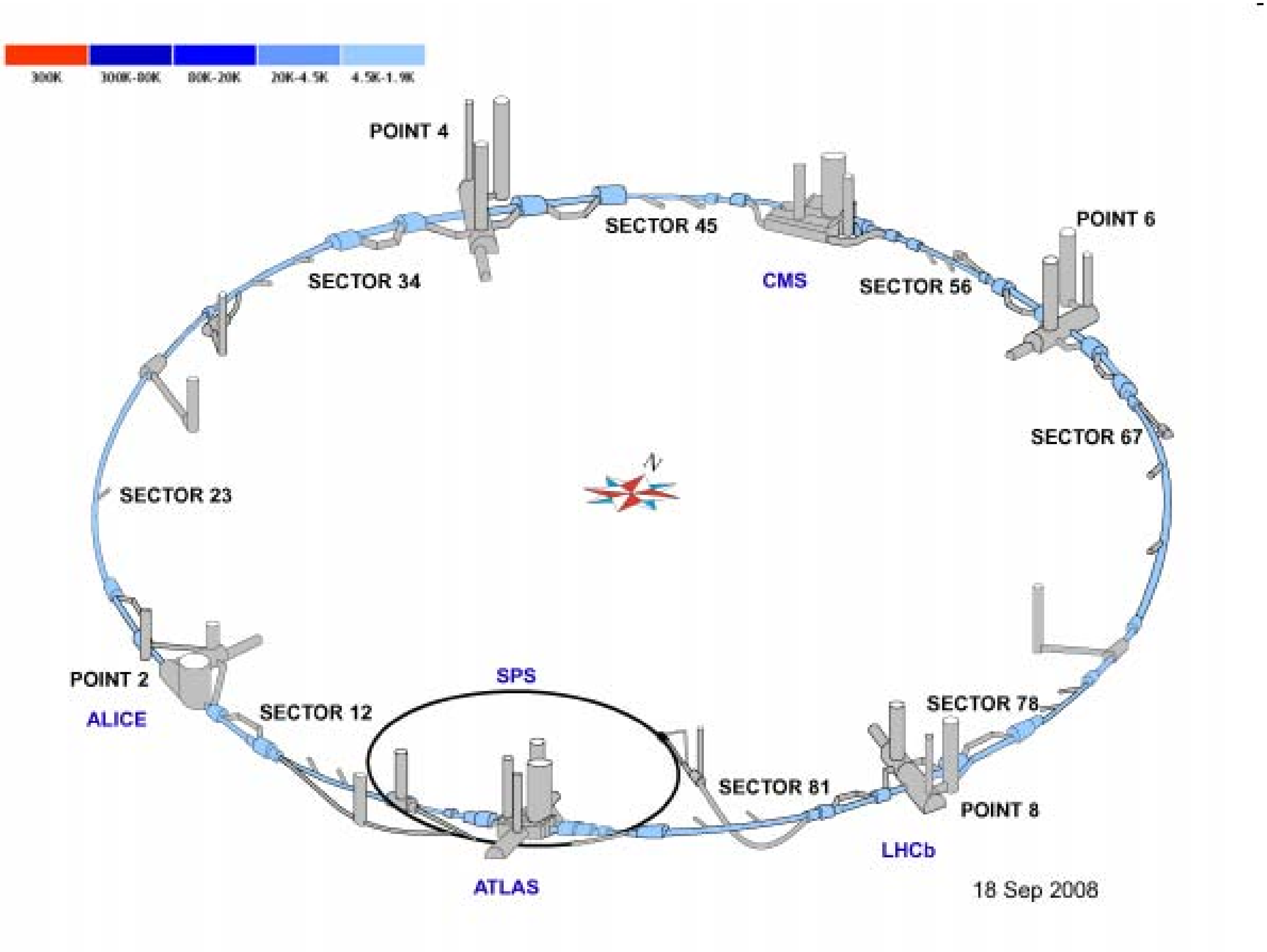


CERN-EX-9710002_05



CERN-EX-9710002_10

LHC cold under beam commissionig

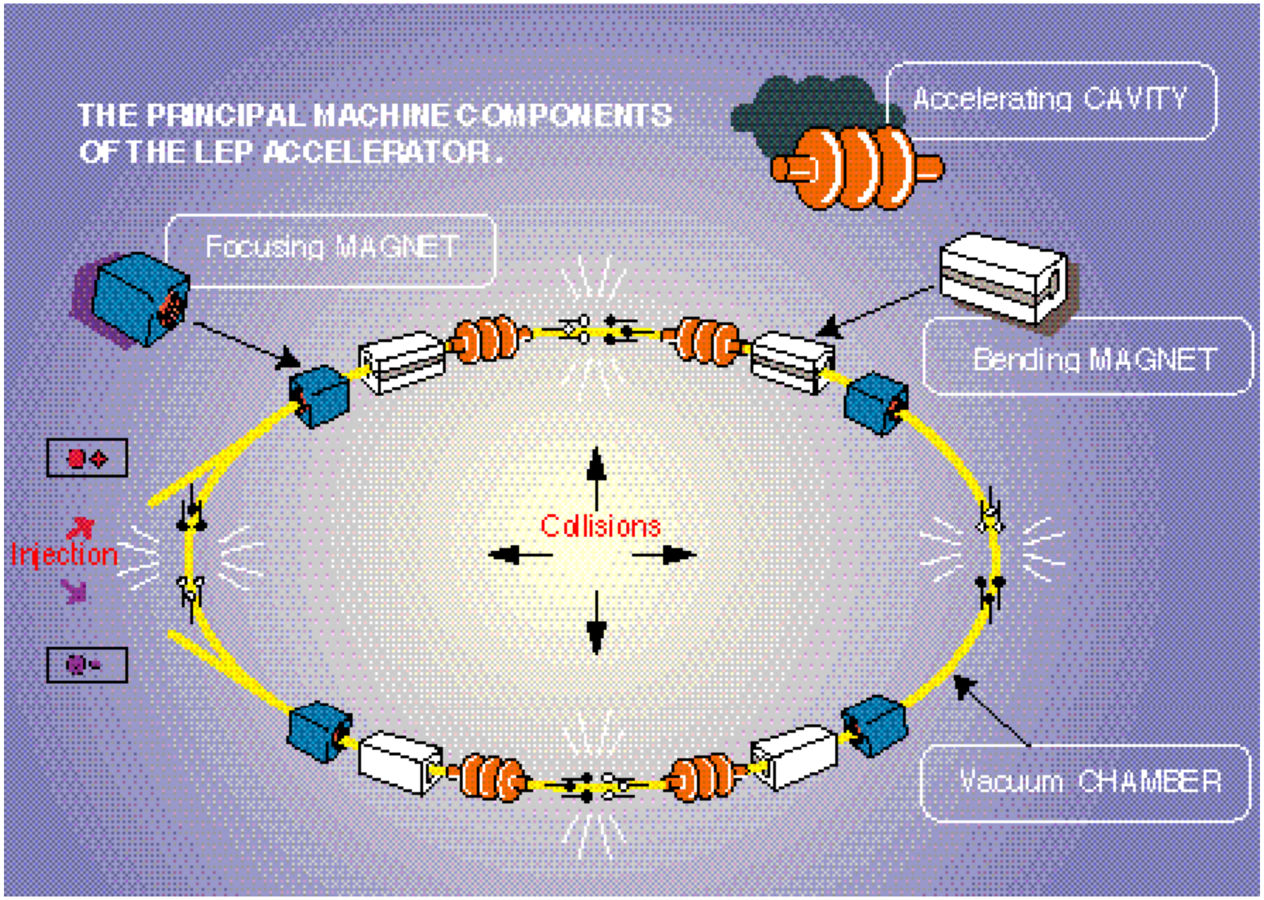


RF acceleration: Synchrotron

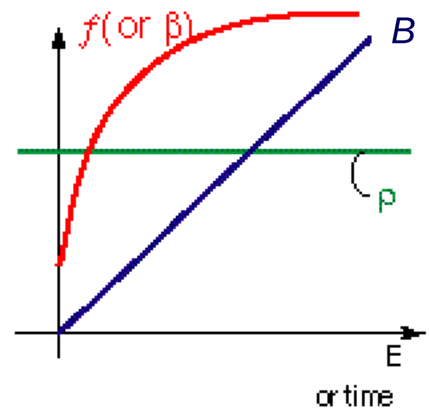
The LEP Example

Cyclotron: constant B Synchrotron: constant ρ

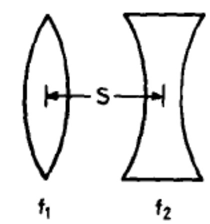
$$B\rho = \frac{mv}{q} = \frac{p}{q}$$



Accelerating cycle



Strong focusing concept

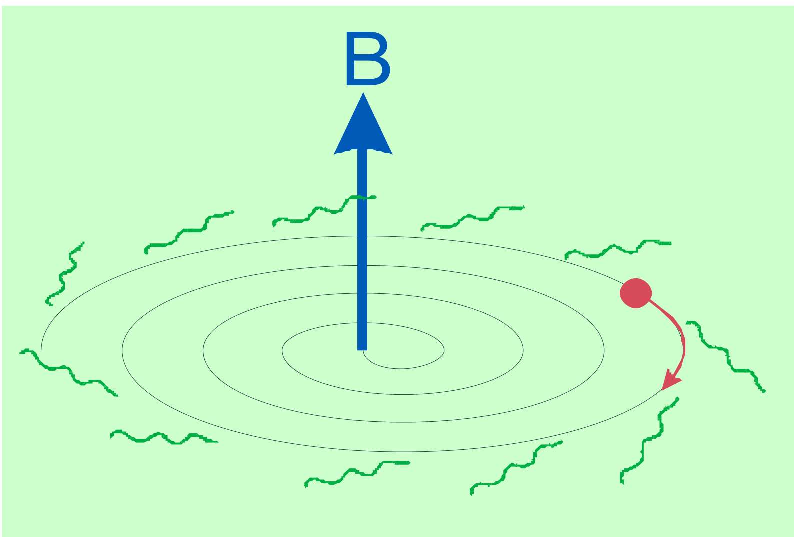


$$\frac{1}{F} = \frac{1}{f_1} + \frac{1}{f_2} - \frac{S}{f_1 \cdot f_2}$$

For $v \approx c$ ⟶ $E\,[GeV] \approx 0.3\,B\,[T] \cdot \rho\,[m]$

No Circular e^+e^- Collider after LEP

Synchrotron Radiation:
charged particle in a magnetic field:



Energy loss replaced by RF power
cost scaling $ ∝ E_{cm}^2

Energy loss dramatic for electrons

$$U_{SR}[\text{GeV}] = 6 \cdot 10^{-21} \cdot \gamma^4 \cdot 1/r[km]$$

$$\gamma_{\text{proton}} / \gamma_{\text{electron}} \approx 2000$$

Impractical scaling of LEP II to
E_{cm} = 500 GeV and **$L = 2 \cdot 10^{34}$**

- **170 km** around
- **13 GeV/turn** lost
- **1 A** current/beam
- **26 GW RF power**
- **Plug power request > Germany**

Origin of the Linear Collider Idea

M. Tigner,
Nuovo Cimento **37** (1965) 1228

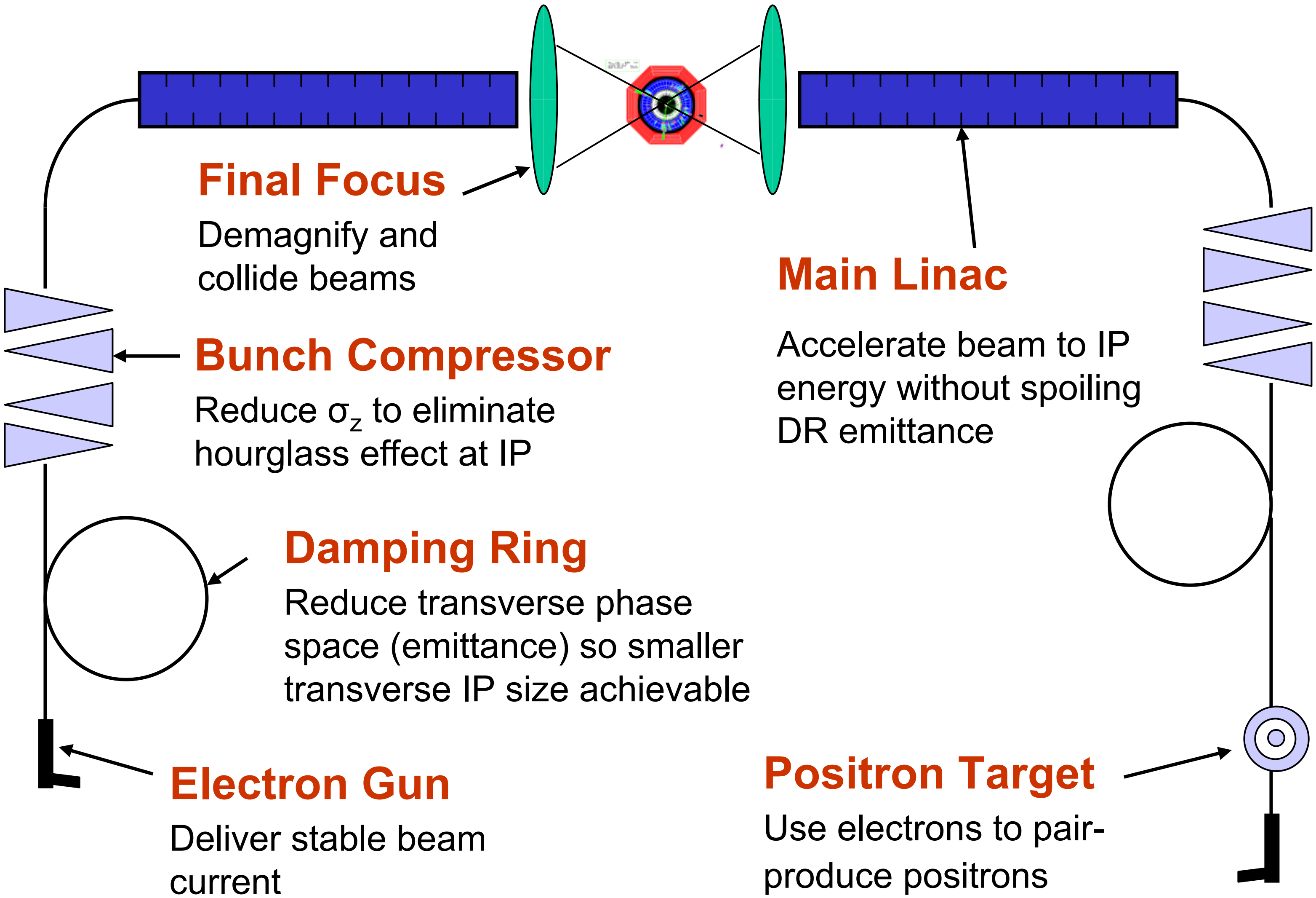
A Possible Apparatus for Electron-Clashing Experiments (*).

M. Tigner

Laboratory of Nuclear Studies. Cornell University - Ithaca, N.Y.

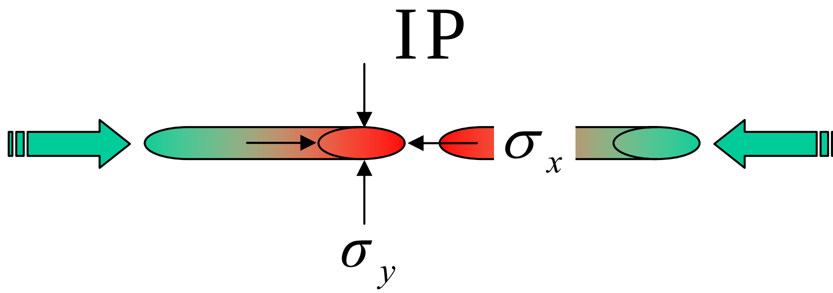
"While the storage ring concept for providing clashing-beam experiments ([1]) is very elegant in concept it seems worth-while at the present juncture to investigate other methods which, while less elegant and superficially more complex may prove more tractable."

Linear Collider Conceptual Scheme



Fighting for Luminosity

$$L \propto \frac{N_e^2}{\sigma_x \sigma_y}$$



$$L \propto n_b \times f_{rep}$$

L = Luminosity
N_e = # of electrons per bunch
$\sigma_{x,y}$ = beam sizes at IP
IP = interaction point

$$L \propto \frac{P_b}{E_{c.m.}} \times \frac{N_e}{\sigma_x \sigma_y}$$

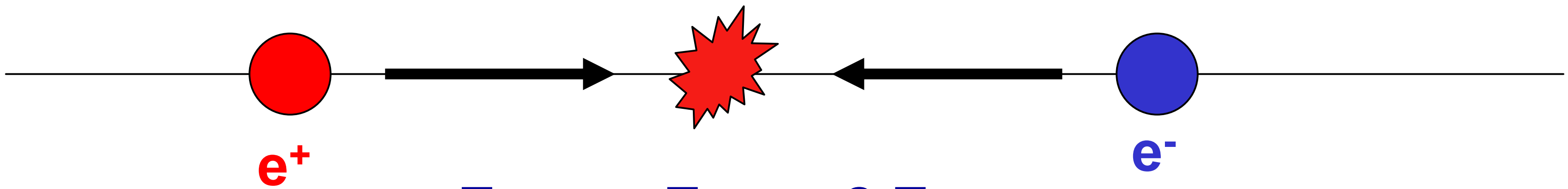
n_b = # of bunches per pulse
f_{rep} = pulse repetition rate
P_b = beam power
$E_{c.m.}$ = center of mass energy

Parameters to play with

- ↓ Reduce **beam emittance** ($\varepsilon_x \cdot \varepsilon_y$) for smaller beam size ($\sigma_x \cdot \sigma_y$)
- ↑ Increase bunch population N_e
- ↑ Increase beam power $P_b \propto N_e \times n_b \times f_{rep}$
- ↑ Increase **beam to-plug power efficiency** for cost

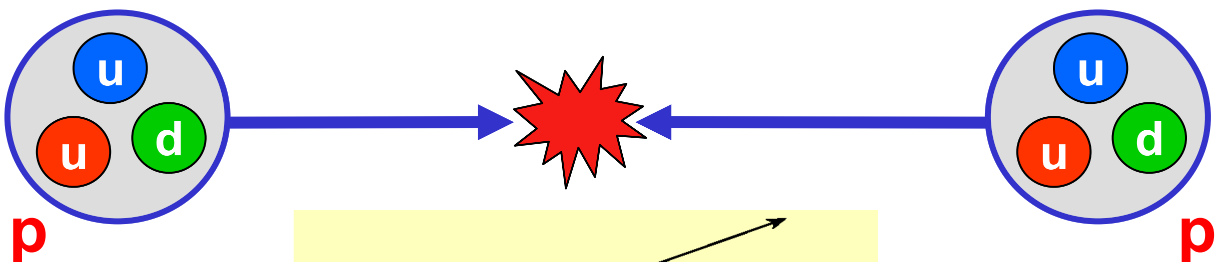
Why we insist for leptons ?

Leptons (e^-, e^+, μ^-, μ^+) are **Fermions,** i.e. **matter constituents**

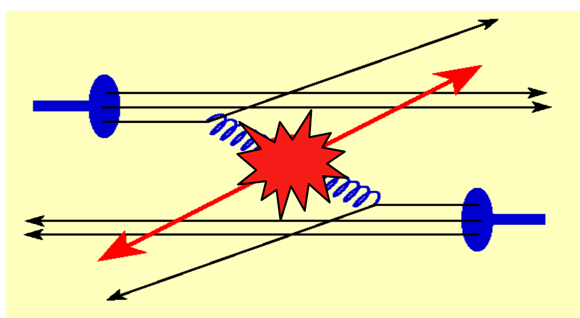


$$E_{react.} = E_{c.m.} = 2\ E_{beam}$$

Hadrons (p, $\overline{p}$, ions) are complex **composite particles**



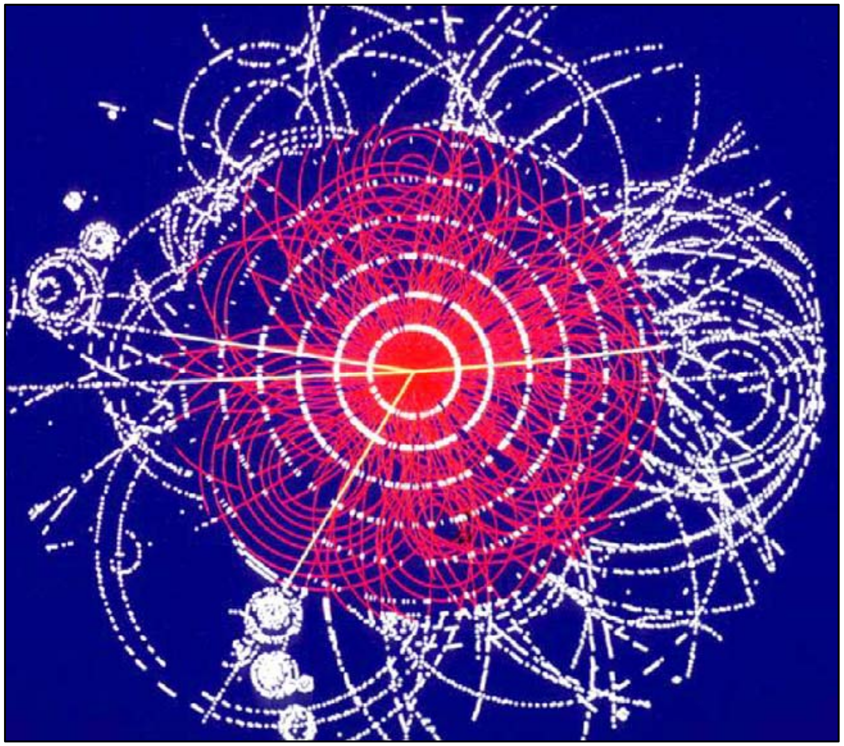
$E_{react.} \ll 2\ E_{beam}$



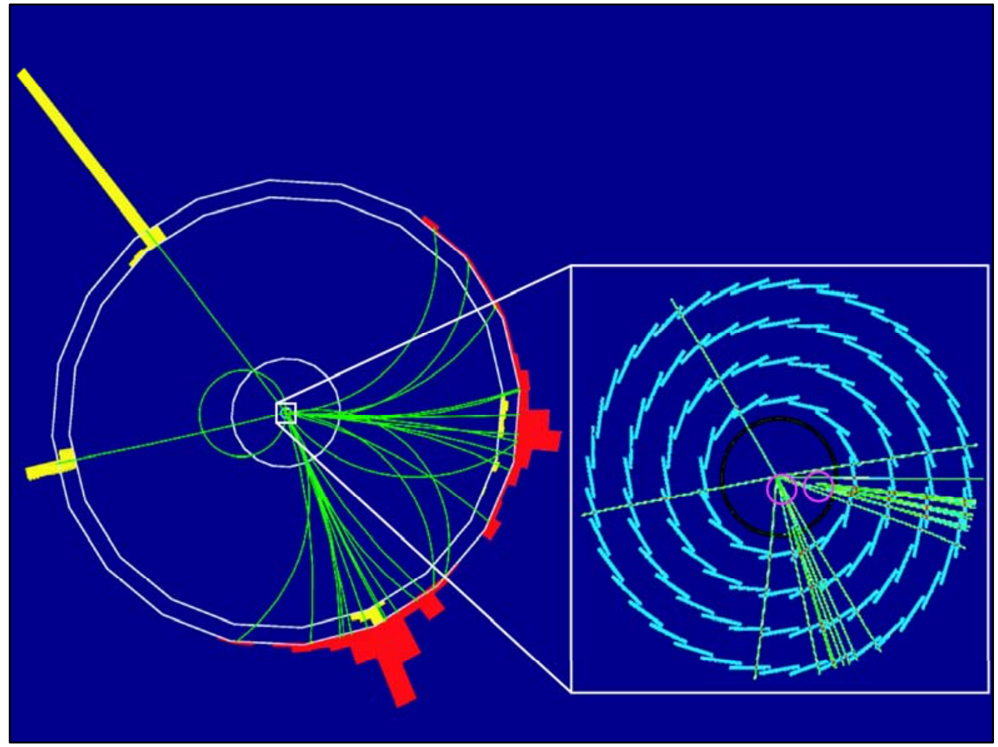
Gluon-Gluon Collision

$E_{react.}$ **cannot be controlled and it is unknown**

Higgs event Simulation Comparison



LHC



ILC

$e^+ e^- \rightarrow Z H$

$Z \rightarrow e^+ e^-, H \rightarrow b \bar{b}$

Relation of LHC and ILC

Since the ILC will start after the start of LHC, it **must add significant amount of information**. **This is the case!**

Neither LC nor HC's can draw the whole picture alone. ILC will add new discoveries and precision of ILC will be essential for a better understanding of the underlying physics.

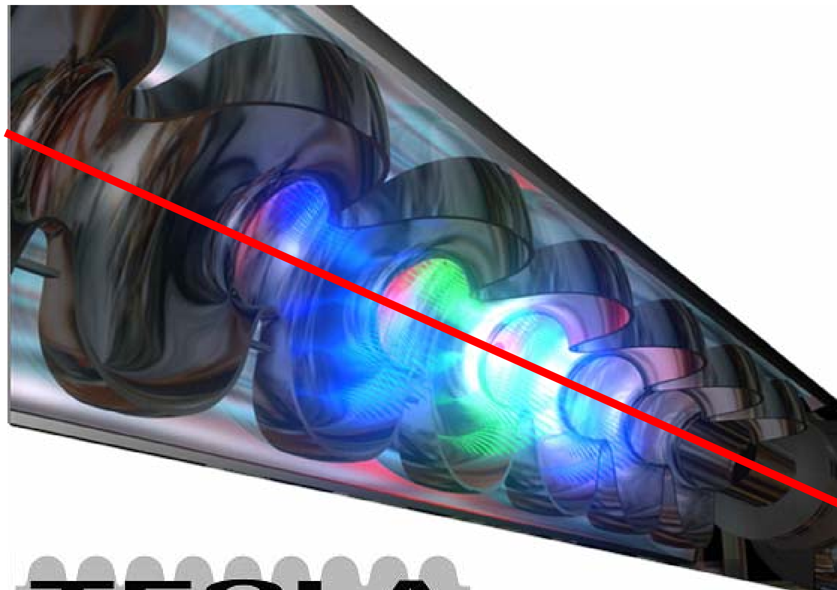
There are probably pieces which can only be explored by the LHC due to the higher mass reach. **Joint interpretation of the results** will improve the overall picture

In the Higgs Boson Scenario

LHC will make the **discovery**

ILC will behave as a **Higgs Boson factory** to precisely determine its properties and the consequences for physics beyond the standard model

Competing technologies for the ILC

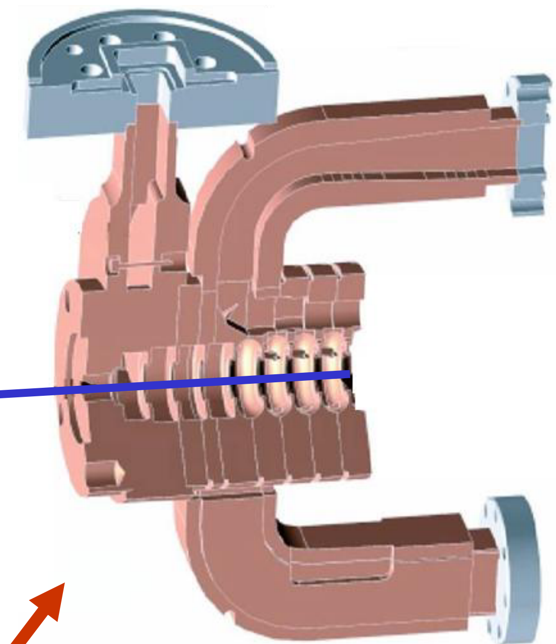


TESLA

1.3 GHz - Cold

Evolution from: CEBAF & LEPII
+ TRISTAN, HERA, etc.

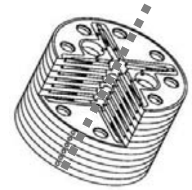
Evolution from: SLAC & SLC



NLC

JLC

11.4 GHz - Warm



CLIC

12 GHz - Warm

Technology Choice:
NLC/JLC or TESLA

The International Linear Collider Steering Committee (ILCSC) selected the twelve members of the International Technology Recommendation Panel (**ITRP**) at the end of 2003:

Asia:	Europe:	North America:
G.S. Lee	J-E Augustin	J. Bagger
A. Masaike	G. Bellettini	**B. Barish (Chair)**
K. Oide	G. Kalmus	P. Grannis
H. Sugawara	V. Soergel	N. Holtkamp

Mission: one technology by end 2004

The 3 Project Leaders were asked to follow the ITRP process as "Technology Experts": Dave Burke (NLC), Kaoru Yokoya (GLC) & Carlo Pagani (TESLA)

Result: recommendation on 19 August 2004

Cold that is TESLA like

From the ILC Birthday

The Recommendation

- **We recommend that the linear collider be based on superconducting rf technology (from Exec. Summary)**
  - This recommendation is made with the understanding that we are recommending a technology, not a design. We expect the final design to be developed by a team drawn from the combined warm and cold linear collider communities, taking full advantage of the experience and expertise of both (from the Executive Summary).
  - We submit the Executive Summary today to ILCSC & ICFA
  - Details of the assessment will be presented in the body of the ITRP report to be published around mid September
  - The superconducting technology has features that tipped the balance in its favor. They follow in part from the low rf frequency.

19-Aug-04 ITRP - LC Technology Recommendation 13

Basic parameters for the ILC

E_{cm} adjustable from 200 – 500 GeV

Luminosity → $\int L dt$ = 500 fb^{-1} in 4 years

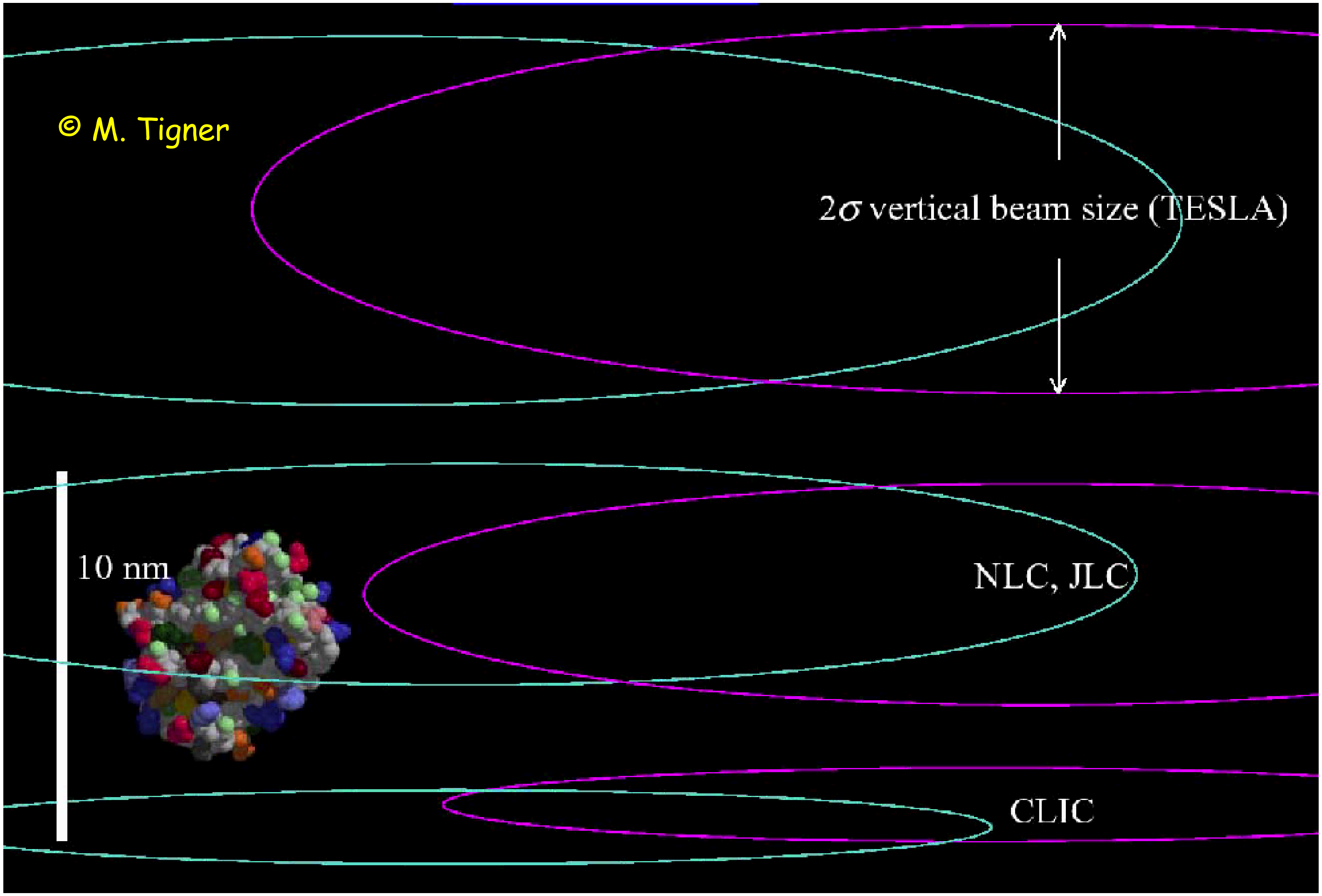
Ability to scan between 200 and 500 GeV

Energy stability and precision below 0.1%

Electron polarization of at least 80%

Machine upgradeable to 1 TeV

Beam Sizes: Pictorial View



The TESLA Collaboration Mission

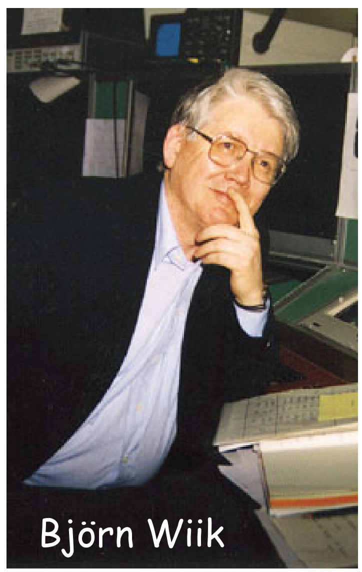
Develop SRF for the future TeV Linear Collider

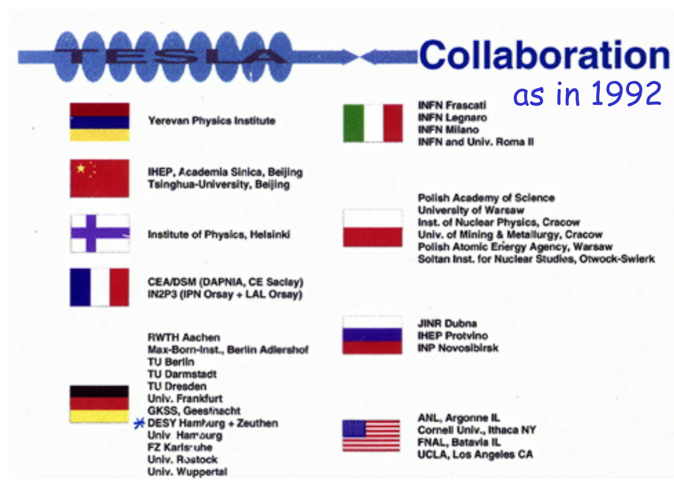
Basic goals

- **Increase gradient by a factor of 5** (Physical limit for Nb at ~ 50 MV/m)
- **Reduce cost per MV by a factor 20** (New cryomodule concept and Industrialization)
- **Make possible pulsed operation** (Combine SRF and mechanical engineering)

Major advantages vs NC Technology

- **Higher conversion efficiency**: more beam power for less plug power consumption
- **Lower RF frequency**: relaxed tolerances and smaller emittance dilution





TESLA Coll. Milestones before 08/2004

February **1992** – **1° TESLA Collaboration Board Meeting @ DESY**

March **1993** - “A Proposal to Construct and Test Prototype Superconducting RF Structures for Linear Colliders”

April **1995** – **25 MV/m in multi-cell cavity**

May **1996** – **First beam at TTF**

March **2001** – **First SASE-FEL Saturation at TTF**

March **2001** – **TESLA Technical Design Report**

February **2003** –**TESLA X-FEL** proposed as an European Facility,
50% funding from Germany

March **2004** – TTF II/**FLASH** Commissioning start

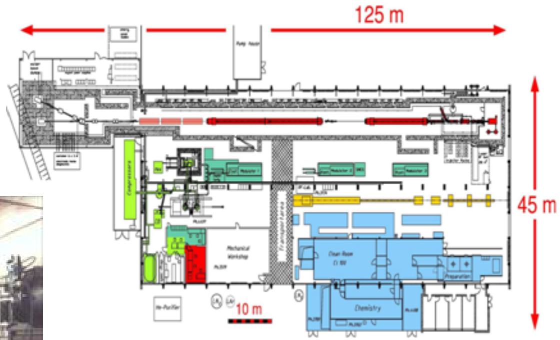
April **2004** - **35 MV/m with beam**

August **2004** – **TESLA Technology chosen for ILC**

August **2005** – **ILC-GDE Formed** for design and costing

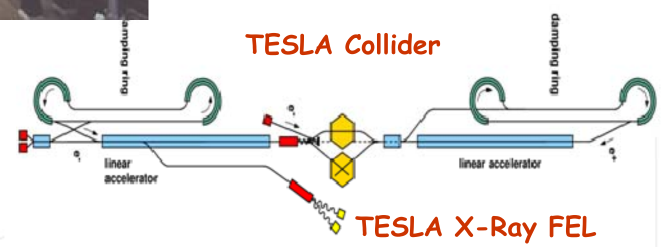
June **2007** – **European XFEL Project Starts**

Infrastructure @ DESY in Hall 3

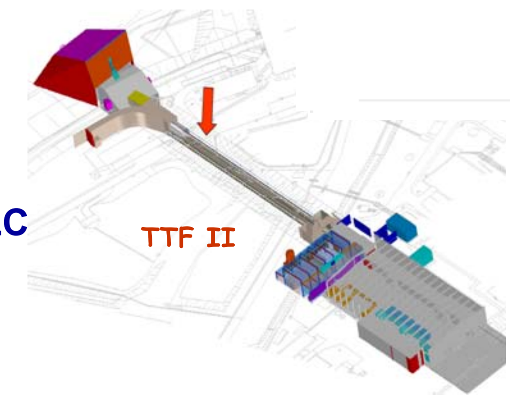


TTF I

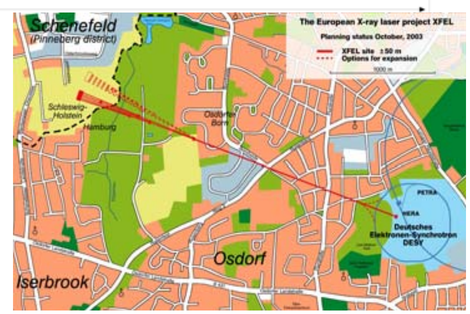
TESLA Collider



TESLA X-Ray FEL



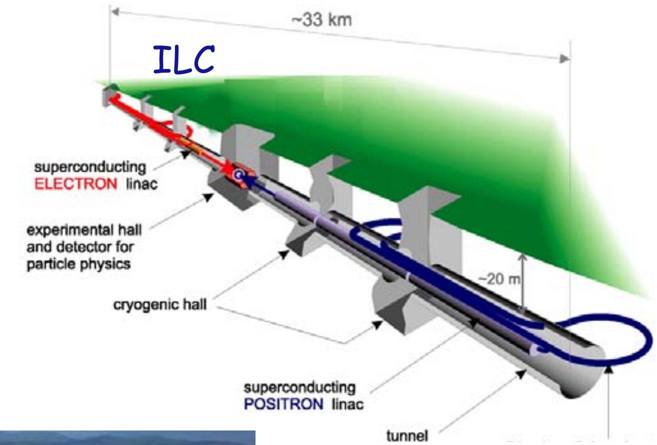
TTF II



Great Impulse from TESLA Results

High Energy Physics: Leptons and Hadrons

- **ILC** is growing cold
- IFMIF for ITER
- Project X @ Fermilab
- SPL for CERN: neutrinos and LHC upgrade
- Electron coolers



Nuclear Physics: Ions and Electrons

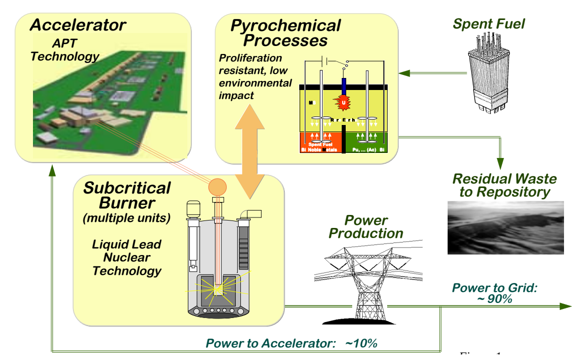
- Spiral 2
- RIA
- Eurisol
- Spes
- CEBAF Upgrade
- ……

Applied Physics: Electrons and Neutrons

- Spallation Neutron Sources: SNS, ESS
- 4th Generation Light Sources: **European X-FEL**
- Storage Rings
- Energy Recovery Linacs: 4GLS in Europe and many others
- ……

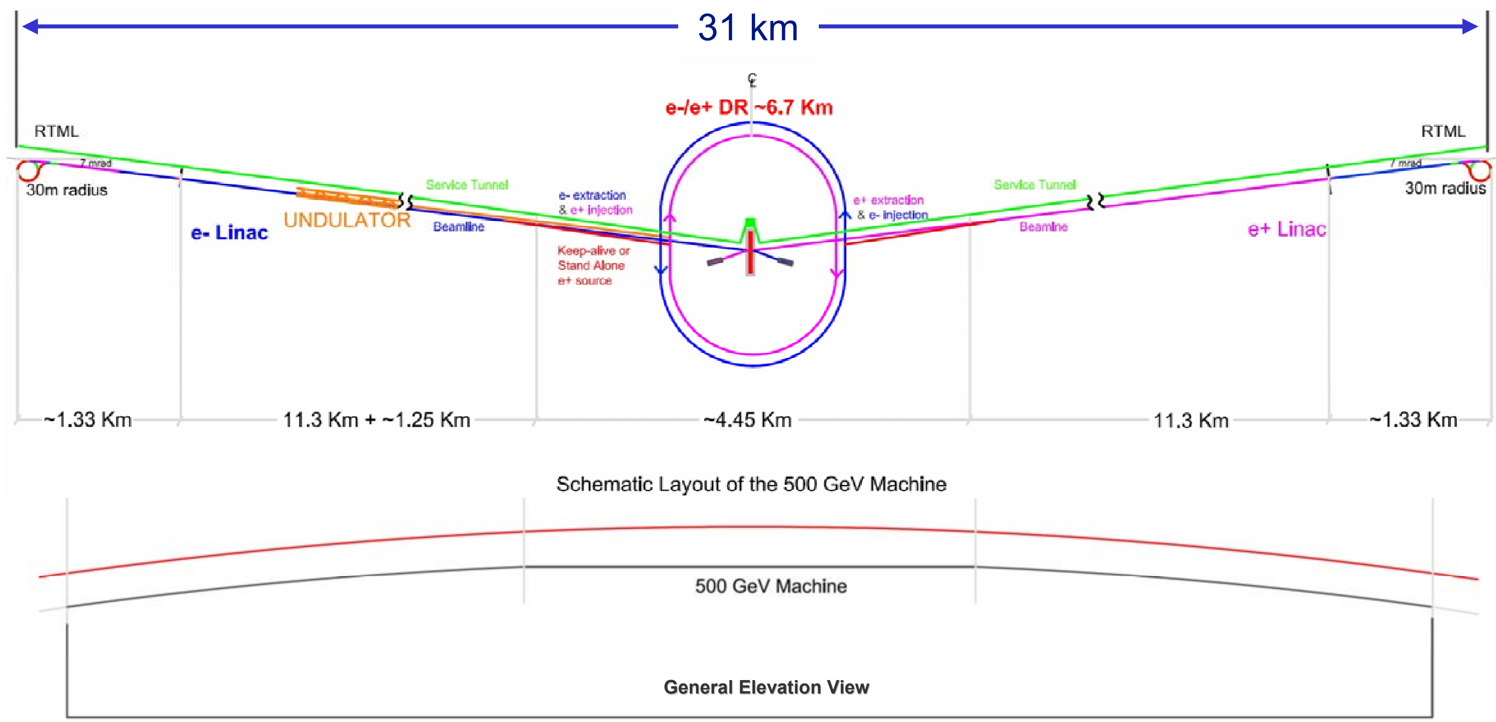
ADS for Nuclear Waste Transmutation

- EuroTrans

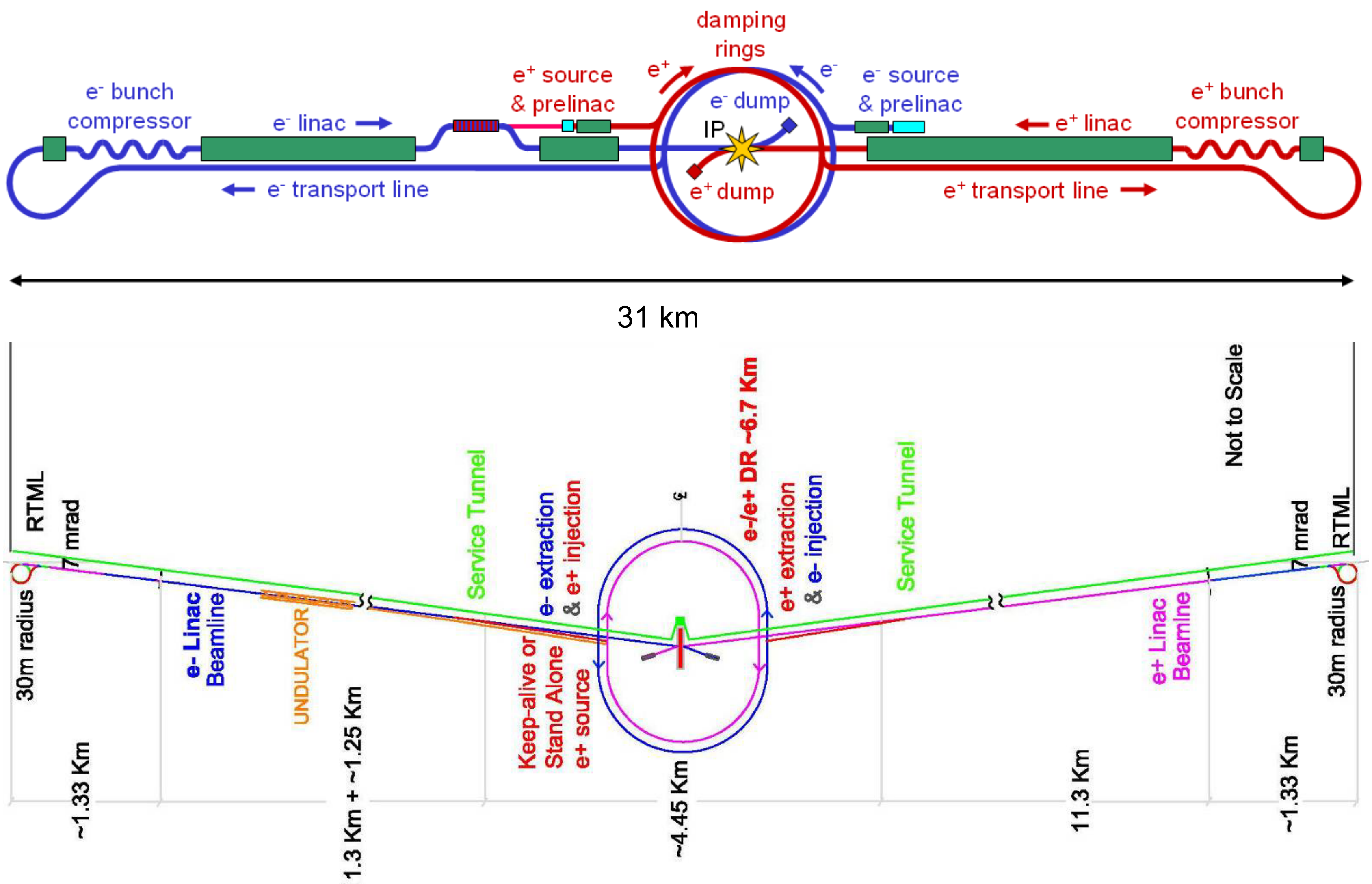


Schematic of the ILC *(RDR Feb. 2007)*

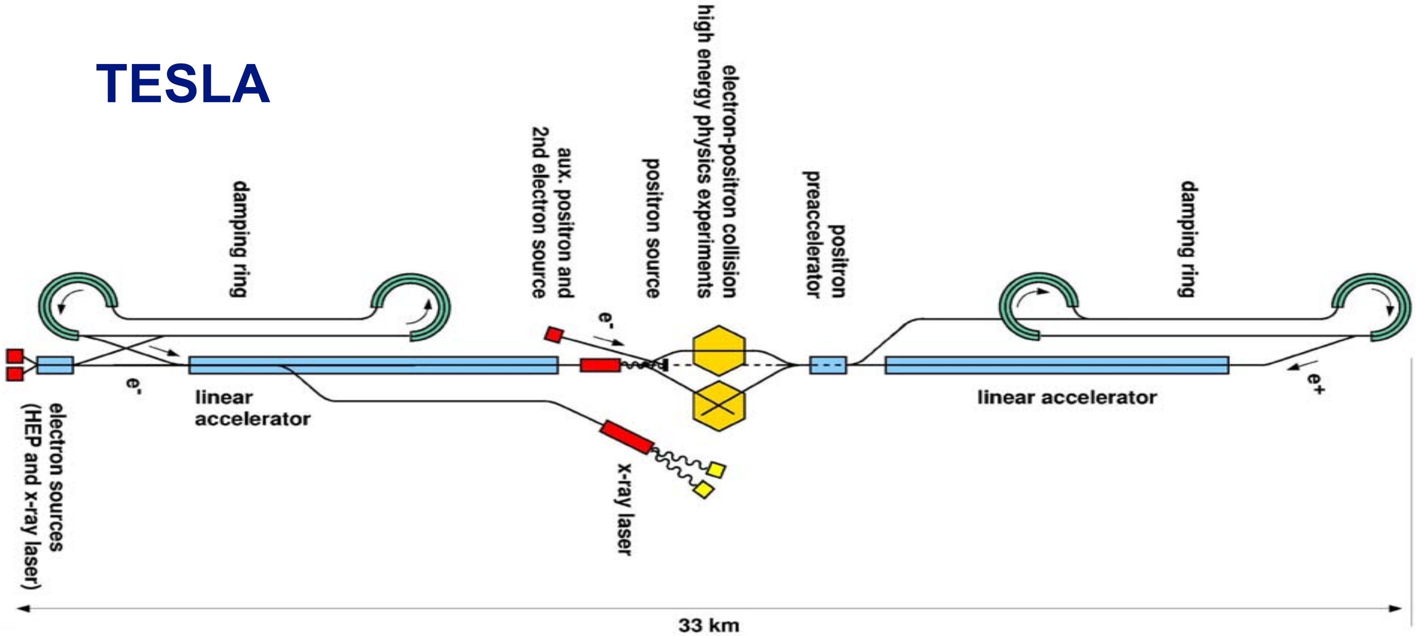
- 11km SC linacs operating at 31.5 MV/m for 500 GeV
- Centralized injector
  - Circular damping rings for electrons and positrons
  - Undulator-based positron source
- Single IR with 14 mrad crossing angle
- Dual tunnel configuration for safety and availability

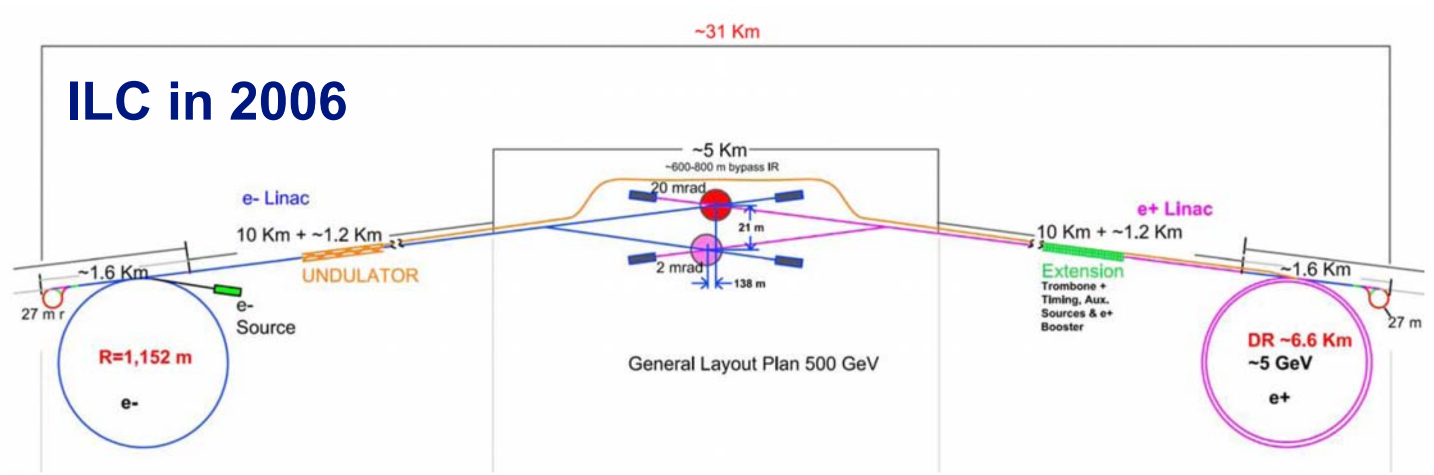


The ILC Footprint



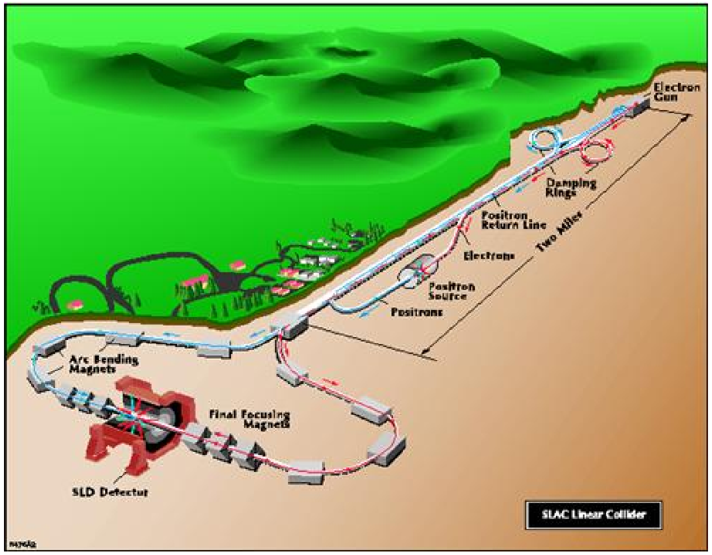
ILC Design Evolution

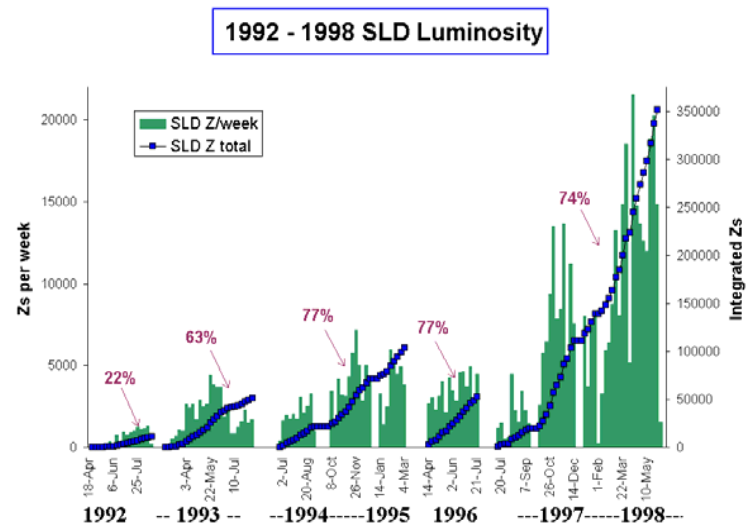


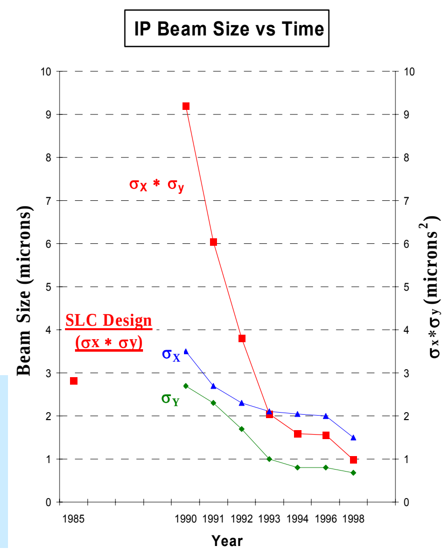


Lessons from SLC : the 1st Linear Collider

SLC = SLAC Linear Collider







New Territory in Accelerator Design and Operation

- Sophisticated on-line modeling of non-linear beam physics.
- Correction techniques (trajectory and emittance), from hands-on by operators to fully automated control.
- Slow/fast feedback theory and practice.

E_{cm} = 92 GeV

$L = 3 \cdot 10^{30}\ cm^{-2}s^{-1}$

Luminosity: Beam Size & Beam Power

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

$f_{rep} \cdot n_b$ tends to be low in a linear collider

	L [cm^{-2} s^{-1}]	f_{rep} [s^{-1}]	n_b	N [10^{10}]	σ_x [μm]	σ_y [μm]
ILC	**$2 \cdot 10^{34}$**	**5**	**3000**	**2**	**0.5**	**0.005**
SLC	$2 \cdot 10^{30}$	120	1	4	1.5	0.5
LEP II	$5 \cdot 10^{31}$	10,000	8	30	240	4
PEP II	$1 \cdot 10^{34}$	140,000	1700	6	155	4

The beam-beam tune shift limit is much looser in a linear collider than a storage rings → achieve luminosity with spot size and bunch charge

- Small spots mean small emittances, $\varepsilon_{x,y}$ and small β-functions, $\beta_{x,y}$

$$\sigma_{x,y} = \sqrt{\beta_{x,y} \cdot \varepsilon_{x,y}}$$

Phase Space

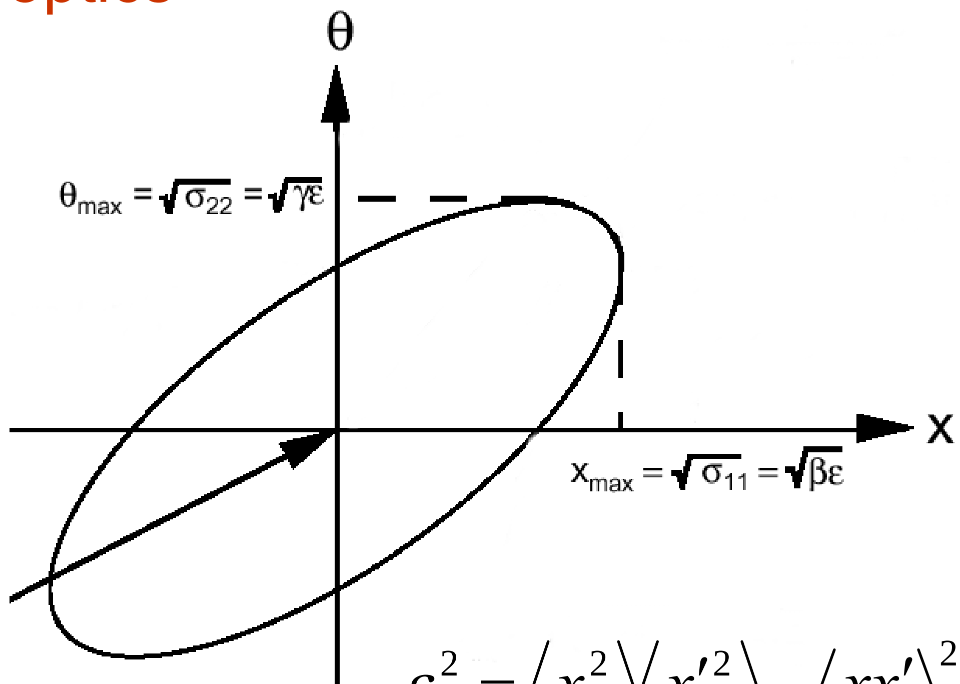
Beta function β characterize optics

Emittance ε is phase space volume of the beam – optics analogy is the wavelength

Tilt is parameterized with α

Beam size: $(\varepsilon\ \beta)^{1/2}$

Divergence: $(\varepsilon\ /\beta)^{1/2}$



$$\varepsilon^2 = \langle x^2 \rangle \langle x'^2 \rangle - \langle xx' \rangle^2$$

Squeeze on beam size → increase angular divergence

Beam emittance is not conserved during acceleration → normalized emittance should be $\gamma\varepsilon$

The Luminosity Issue: Aiming for 2x10^34

Collider luminosity [cm^{-2} s^{-1}] is approximately given by

$$L = \frac{n_b N^2 f_{rep}}{A} H_D$$

where:

- n_b = bunches / train
- N = particles per bunch
- f_{rep} = repetition frequency
- A = beam cross-section at IP
- H_D = beam-beam enhancement factor

For a Gaussian beam distribution luminosity is usually written

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

LC Parameter Evolution (1)

status at first LC-TRC

End 1995 E_{cm} = 500 GeV

	TESLA	SBLC	JLC-S	JLC-C	JLC-X	NLC	VLEPP	CLIC
f [GHz]	1.3	3.0	2.8	5.7	11.4	11.4	14.0	30.0
$L \times 10^{33}$ [$cm^{-2}s^{-1}$]	6	4	4	9	5	7	9	1-5
P_{beam} [MW]	16.5	7.3	1.3	4.3	3.2	4.2	2.4	1-4
P_{AC} [MW]	164	139	118	209	114	103	57	100
$\gamma\varepsilon_y$ [$\times 10^{-8}$m]	100	50	4.8	4.8	4.8	5	7.5	15
σ_y^* [nm]	64	28	3	3	3	3.2	4	7.4

LC Parameter Evolution (2)
status at second LC-TRC

January 2003 E_{cm}= 500 GeV

	TESLA	SBLC	JLC-S	JLC-C	JLC-X/NLC	VLEPP	CLIC
f [GHz]	1.3			5.7	11.4		30.0
$L \times 10^{33}$ [$cm^{-2}s^{-1}$]	34			14	20		21
P_{beam} [MW]	11.3			5.8	6.9		4.9
P_{AC} [MW]	140			233	195		175
$\gamma\varepsilon_y$ [$\times 10^{-8}$m]	3			4	4		1
σ_y^* [nm]	5			4	3		1.2

LC Parameter Evolution (3)

second to first LC-TRC comparison

2003 vs. 1995 $E_{cm} = 500$ GeV

	TESLA 2003	TESLA 1994	JLC/NLC 2003	<JLC/NLC> 1994	CLIC 2003	CLIC 1994
f [GHz]	1.3	1.3	11.4	11.4	30.0	30.0
$L \times 10^{33}$ [$cm^{-2}s^{-1}$]	34	6	20	6	21	1-5
P_{beam} [MW]	11.3	16.5	6.9	3.7	4.9	1-4
P_{AC} [MW]	140	164	195	110	175	100
$\gamma\varepsilon_y$ [$\times 10^{-8}$m]	3	100	4	5	1	15
σ_y^* [nm]	5	64	3	3	1.2	7.5

ILC Parameters

		nominal	low N	High L
N	$\times 10^{10}$	**2**	1	2
n_b		**2820**	5640	2820
$\varepsilon_{x,y}$	μm - nm	**9.6 - 40**	10 - 30	10 - 30
$\beta_{x,y}$	cm - mm	**2 - 0.4**	1.2 - 0.2	1 - 0.2
$\sigma_{x,y}$	nm	**543 - 5.7**	495 - 3.5	452 - 3.5
D_y		**18.5**	10	22
δ_{BS}	%	**2.2**	1.8	7
σ_z	μm	**300**	150	150
P_{beam}	MW	**11**	11	11

Parameter range established to allow for operational optimization

The Luminosity Issue: RF Power

Introducing the

centre of mass energy, E_{cm}

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

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

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

η_{RF} Is the RF to beam Power Efficiency

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

i.e. for a given E_{cm}

Luminosity **is proportional to the *RF Power***

The Luminosity Issue: RF Power

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

Using some rough **ILC** numbers

E_{cm} = 500 GeV
N = 2 x 10^{10}
n_b = 3000
f_{rep} = 5 Hz

P_{beam} **~ 2** x **10 MW**

Taking into account conversion efficiencies

$\eta_{RF \to beam}$ ~ 60% (SCRF)

$\eta_{PlugPower \to RF}$ ~ 50%

It turns out that **~70 MW** of average **AC Power** are required **to accelerate the 2 beams to 250 GeV, achieving *Luminosity***

The Luminosity Issue: LEP vs ILC

LEP f_{rep} = 44 kHz

ILC f_{rep} = 5 Hz
(power limited)

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

⇒ **factor 8800 in *L* already lost!**

Must push very hard on beam cross-section at collision:

LEP:	$\sigma_x\sigma_y \approx 130\times 6\ \mu m^2$
ILC:	$\sigma_x\sigma_y \approx 500\times(3\text{-}5)\ nm^2$

factor of 10^6 gain!
Needed to obtain high luminosity of a few $10^{34}\ cm^{-2}s^{-1}$

Luminosity *Issue: intense beams at IP*

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

choice of linac technology:

- efficiency
- available power

Beam-Beam effects:

- beamstrahlung
- disruption

Strong focusing

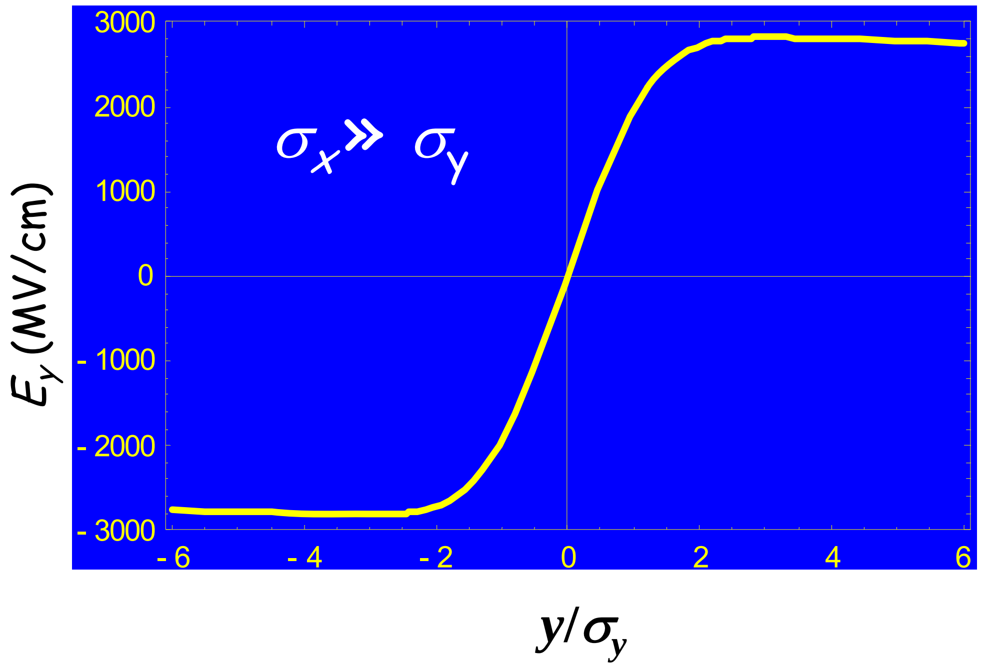
- optical aberrations
- stability issues and tolerances

Beam size comparison at the Interaction Point

LEP	$\sigma_x \sigma_y \approx 130 \times 6\ \mu m^2$
ILC	$\sigma_x \sigma_y \approx (200\text{-}500) \times (3\text{-}5)\ nm^2$

Luminosity *Issue: Beam-Beam - 1*

- strong mutual focusing of beams (pinch) gives rise to luminosity enhancement H_D
- As $e^{\pm}$ pass through intense field of opposing beam, they radiate hard photons [beamstrahlung] and loose energy ⟶ Flat Beam
- Interaction of beamstrahlung photons with intense field causes copious e^+e^- pair production [background]



Luminosity *Issue: Beam-Beam - 2*

beam-beam characterised by ***Disruption Parameter****:*

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

σ_z = bunch length,

f_{beam} = focal length of beam-lens

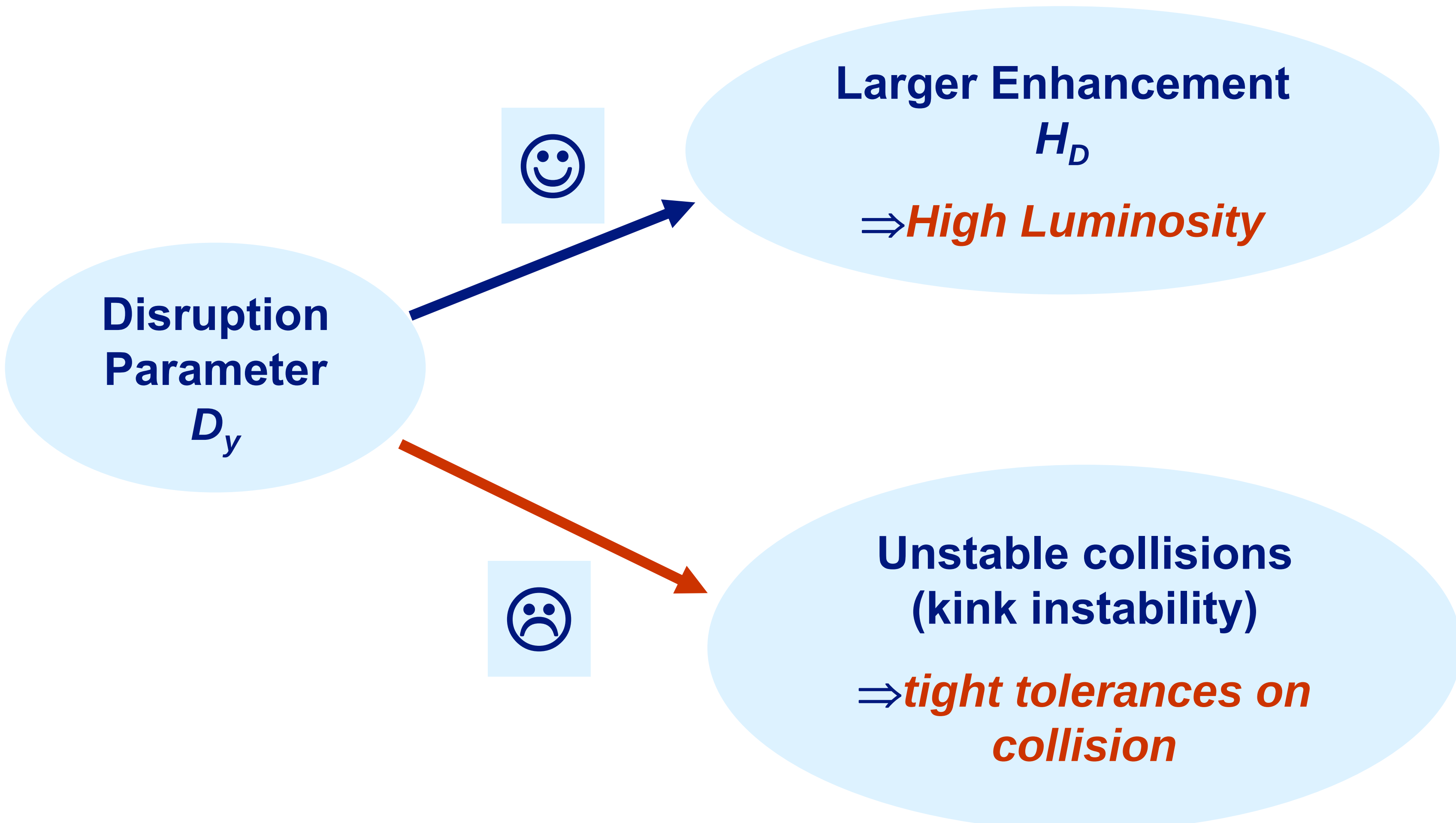
for storage rings, $f_{beam} >> \sigma_z$ and $D_{x,y} << 1$

for a LC, $D_{x,y} \approx 10 \div 20$ hence $f_{beam} < \sigma_z$

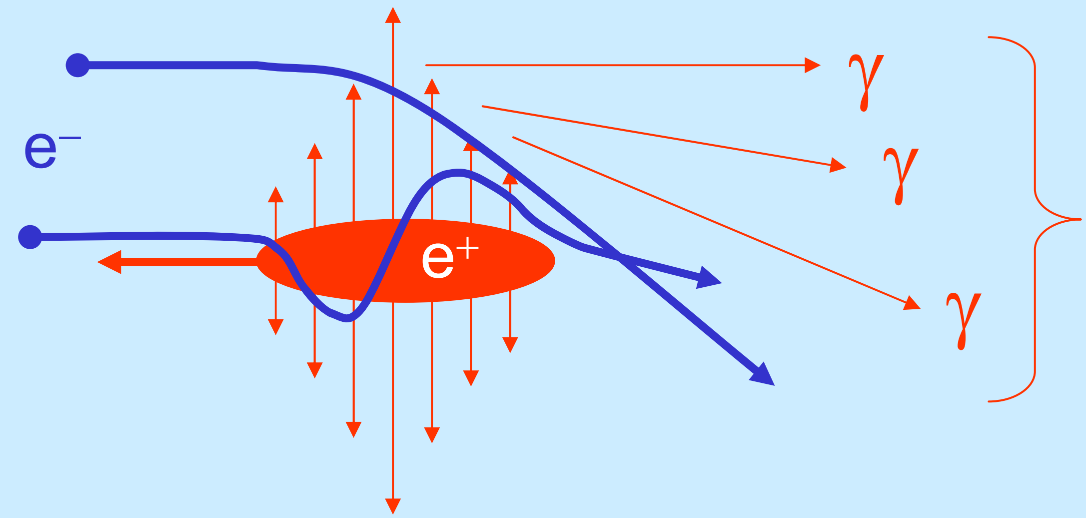
Enhancement factor (typically H_D ~ 1.5 ÷ 2) is given by:

$$H_{Dx,y} = 1 + D_{x,y}^{1/4}\left(\frac{D_{x,y}^3}{1+D_{x,y}^3}\right)\left[\ln\left(\sqrt{D_{x,y}} + 1\right) + 2\ln\left(\frac{0.8\beta_{x.y}}{\sigma_z}\right)\right]$$

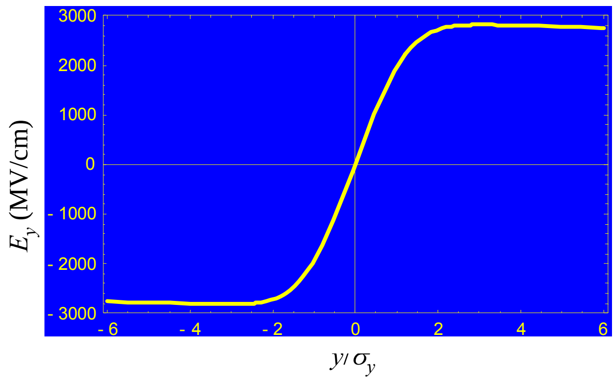
The Luminosity *Issue: Beam-Beam - 3*



The Luminosity Issue: Beamstrahlung - 1



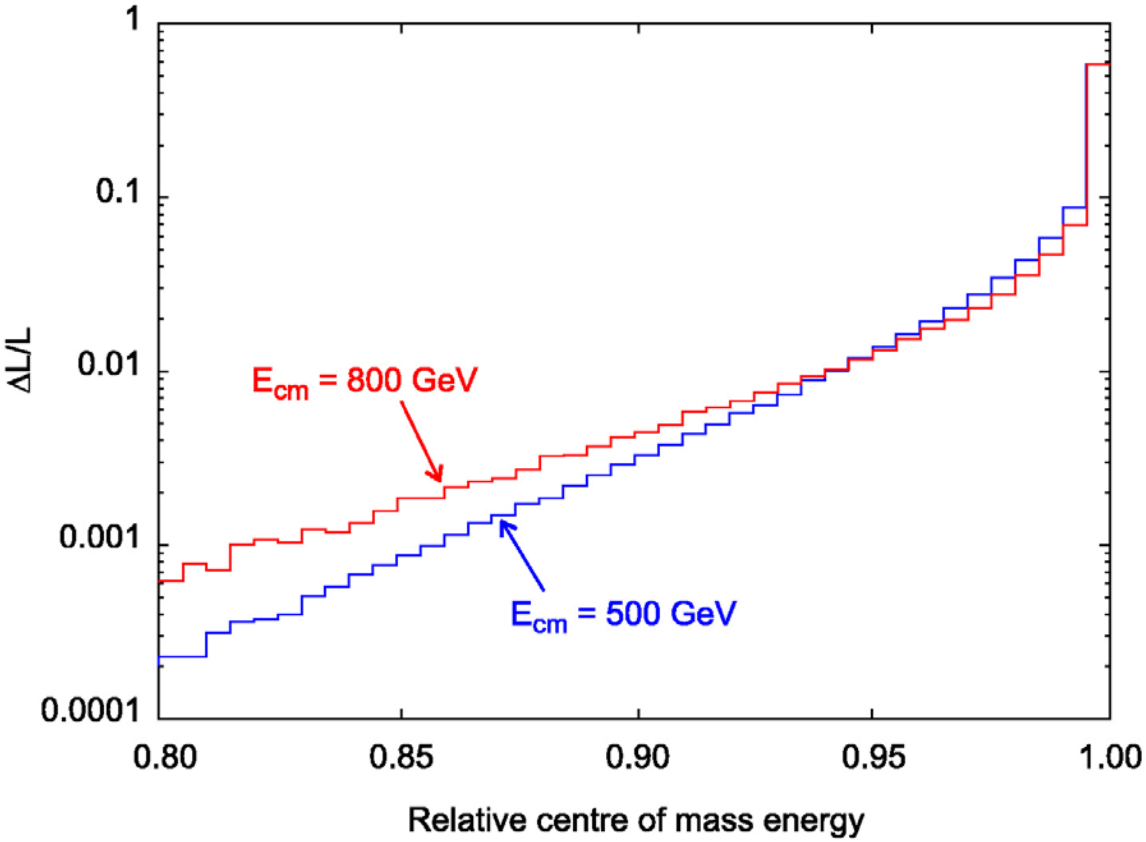
hard γs radiated by intense electric field = ***Beamstrahlung***



Gives rise to

- average energy loss
- increase in RMS energy spread in the beams

The Luminosity Issue: Beamstrahlung - 2



Emission of high-energy photons causes a degradation in the ***Luminosity spectrum***

Characteristic long low-energy tail

Example taken from the TESLA Technical Design Report

The Luminosity Issue: Beamstrahlung - 3

rms relative energy loss induced by Beamstrahlung

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

we would like to make $(\sigma_x\ \sigma_y)$ small to maximise luminosity

and keep $(\sigma_x + \sigma_y)$ large to reduce δ_{SB}

Trick: use "flat beams" with $\sigma_x >> \sigma_y$

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

Rule:

- make $\boldsymbol{\sigma_x}$ **large to limit** $\boldsymbol{\delta_{BS}}$ to few % for background
- make $\boldsymbol{\sigma_y}$ **as small as possible** to achieve high luminosity.

For **ILC**, δ_{BS} **~ 2.4%**

The Luminosity Issue: Beamstrahlung - 4

Returning to our L scaling law, and ignoring H_D

$$L \propto \frac{\eta_{RF} P_{RF}}{E_{cm}} \left(\frac{N}{\sigma_x} \right) \frac{1}{\sigma_y}$$

From flat-beam beamstrahlung

$$\frac{N}{\sigma_x} \propto \sqrt{\frac{\delta_{BS} \sigma_z}{E_{cm}}}$$

hence

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

Luminosity Issue: story so far

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

For high Luminosity we need:

- high RF-beam conversion efficiency η_{RF}
- high RF power P_{RF}
- small vertical beam size σ_y
- large bunch length σ_z (will come back to this one)
- could also allow higher beamstrahlung δ_{BS} if willing to live with the consequences

Next question: ***how to make a small*** σ_y ⟶ ***Damping Rings***

Luminosity Issue: A final scaling law?

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

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

where $\varepsilon_{n,y}$ is the normalised vertical emittance, and β_y is the vertical β-function at the IP. Substituting:

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

hour glass constraint

β_y is the same 'depth of focus' β for hour-glass effect. Hence

Luminosity Issue: A final scaling law?

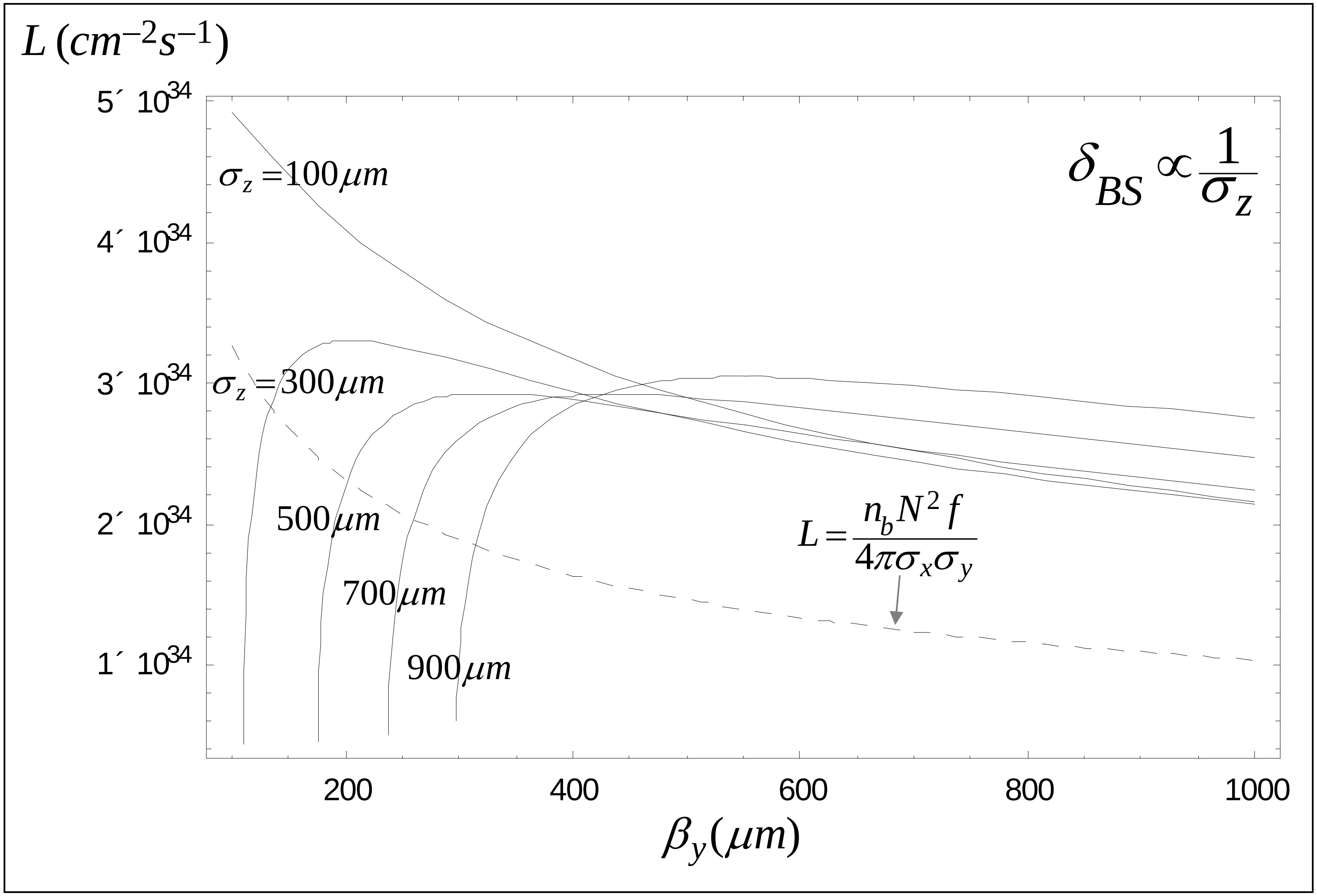
$$L \propto \frac{\eta_{RF} P_{RF}}{E_{cm}} \sqrt{\frac{\delta_{BS}}{\varepsilon_{n,y}}} H_D \qquad \beta_y \approx \sigma_z$$

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

Above result is for the **low beamstrahlung regime** where δ_{BS} ~ few %

Slightly different result for **high beamstrahlung regime**

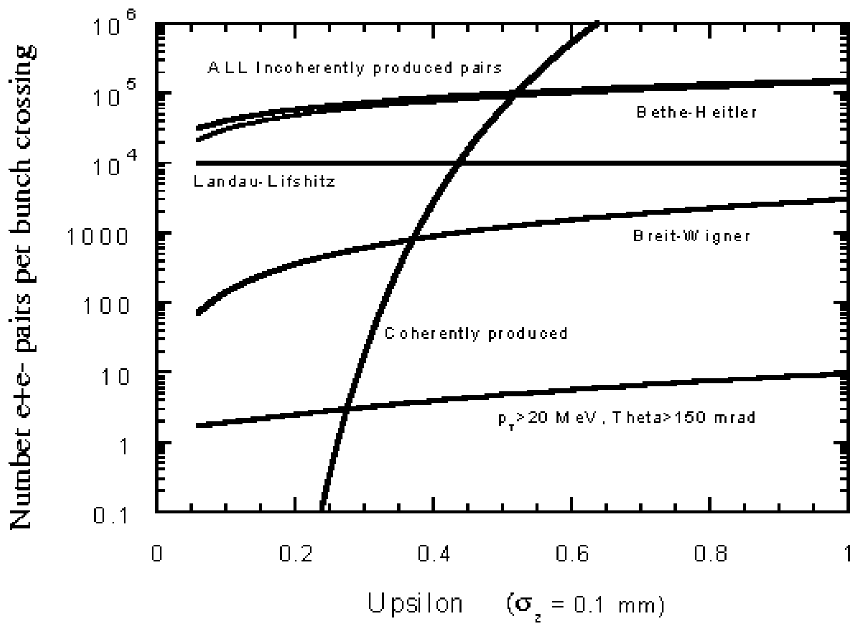
Luminosity as a function of β_y



Pair Production (1)

The beamstrahlung photons can create e^+e^- pairs

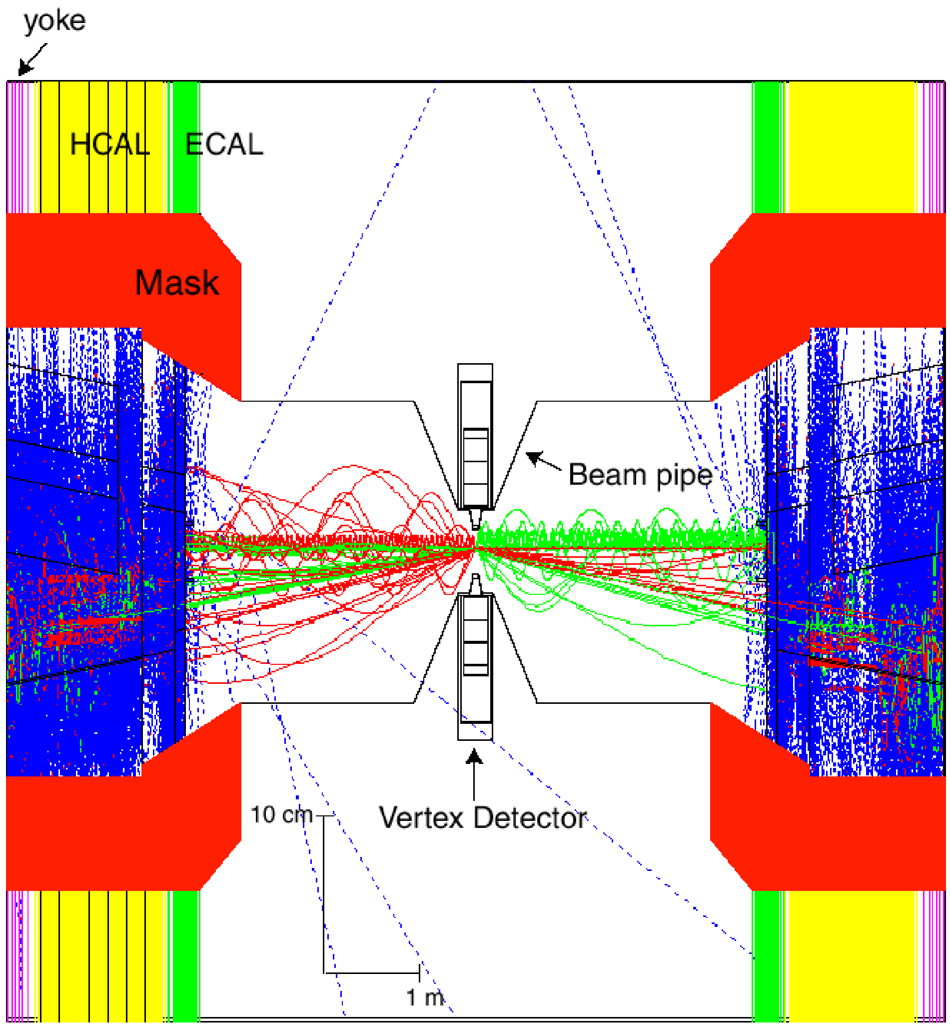
- Incoherent pair production – arises from photons scattering off of beam particles
  - Multiple channels but typically relatively few pairs ~10^5
- Coherent pair production – arises from photon scattering off collective fields of the beam
  - With Y ~ 1, as many pairs as beam particles



Pair Production (2)

Pairs are a significant source of background

- Relatively low energy particles are given large transverse deflections by the beam fields
- Can be partly controlled with strong solenoidal field at the IP but need to be careful with detector design to constrain the particles and secondary interactions



Single Bunch Kink (1)

Single bunch kink is a two-stream instability

- Small offsets are amplified by very strong beam-beam forces

Potential limitation at high disruption parameters

- Why high disruption?
- Luminosity expression can be re-written in terms of D_y

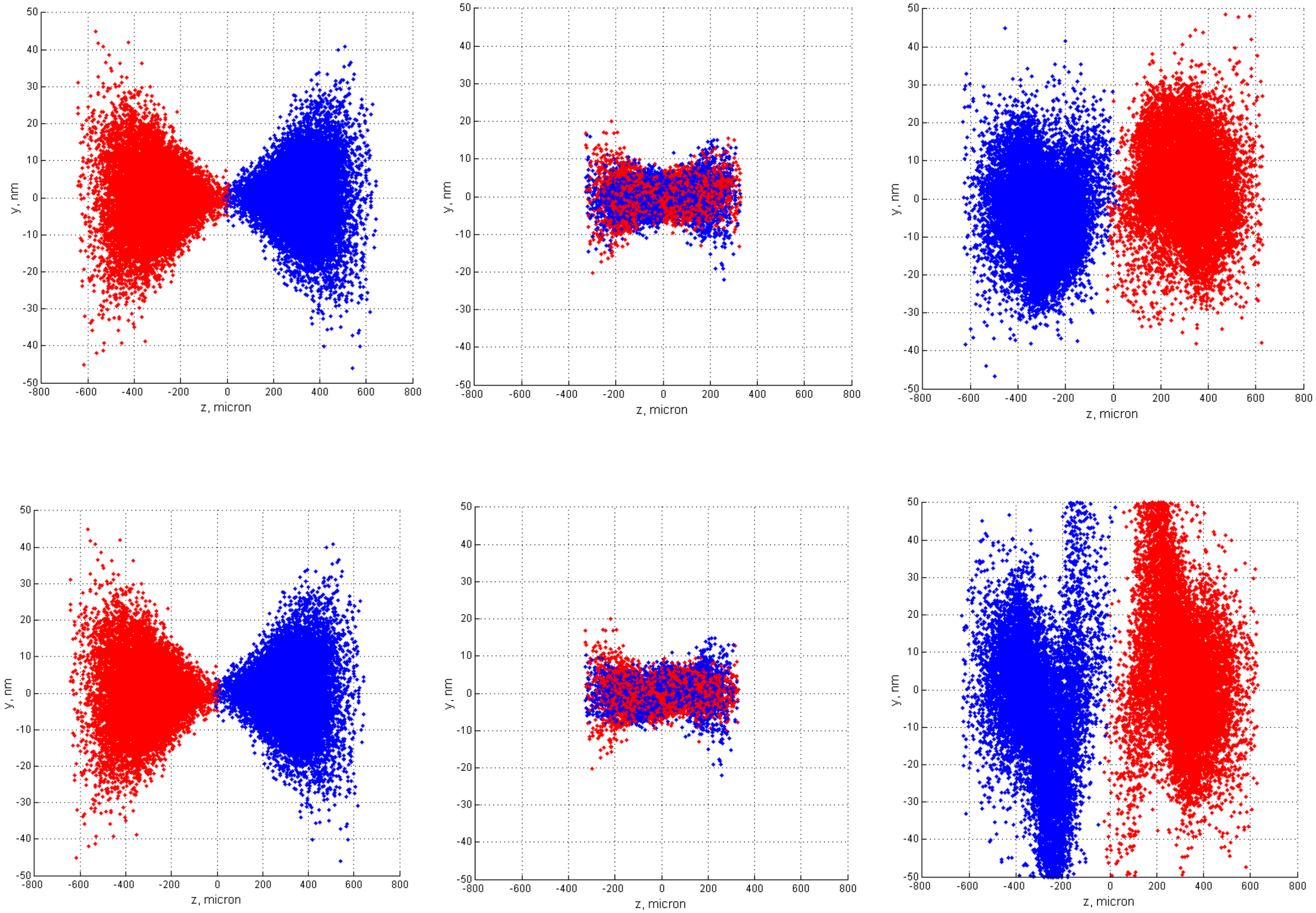
$$L \propto \frac{P_{beam}}{E_{cms}} \frac{D_y}{\sigma_z} H_D \qquad \delta_B \propto D_y^2 \sigma_y^2 \left(\frac{\gamma}{\sigma_z} \right)^3$$

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

- If there is a practical limit on the maximum disruption → luminosity can be increased by shortening the bunch
- Hard to avoid larger beamstrahlung

Single Bunch Kink (2)

Single bunch kink due to 1% initial offset between beams



$D_y = 12$

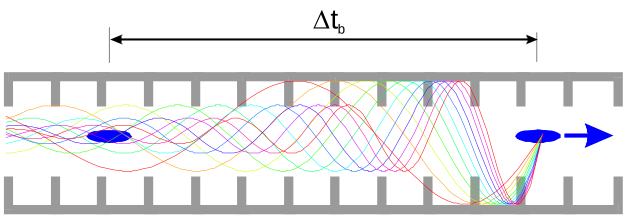
$D_y = 24$

Transverse Wakes: The Emittance Killer!

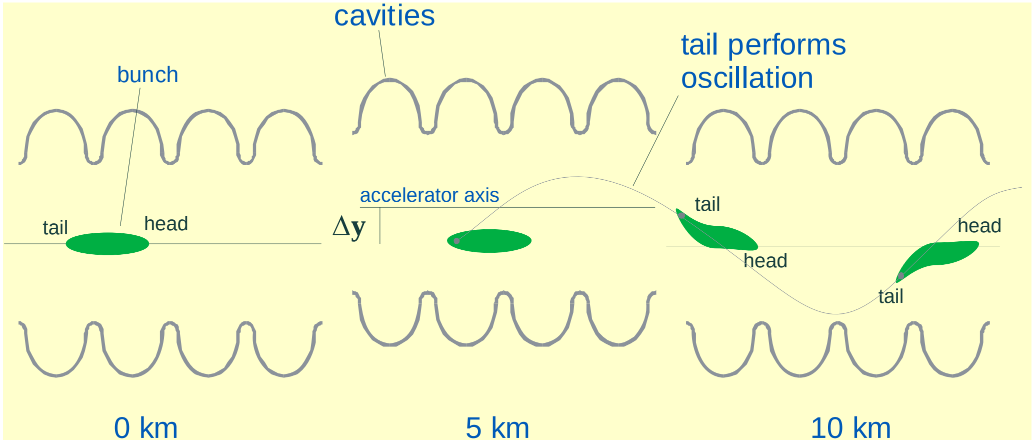
Alignment tolerance δY_{RMS} determines the emittance grow

Low frequency is preferred: For a given $\Delta\varepsilon$, δY_{RMS} scales as

$$\delta Y_{RMS} \propto \frac{f^{-3}}{N} \sqrt{\frac{E_{acc}}{\beta}}$$



Wake Fields in a TW structure



- Bunch current also generates transverse deflecting modes when bunches are not on cavity axis
- Fields build up resonantly: latter bunches are kicked transversely
- $\Rightarrow$ multi- and single-bunch beam breakup (MBBU, SBBU)

Beam Parameters

Requirements:

- High luminosity – set by physics needs
- Low backgrounds (small IP effects)
- Forced to high beam power and small vertical spots

Details of technology determine other limitations

- RF cavities and power sources → 10 mA beam current
- Damping rings → beam emittances and number of bunches
- Bunch compressors → IP bunch length
- Cryogenic systems → duty cycle
- Extensive cost optimization is required to balance systems

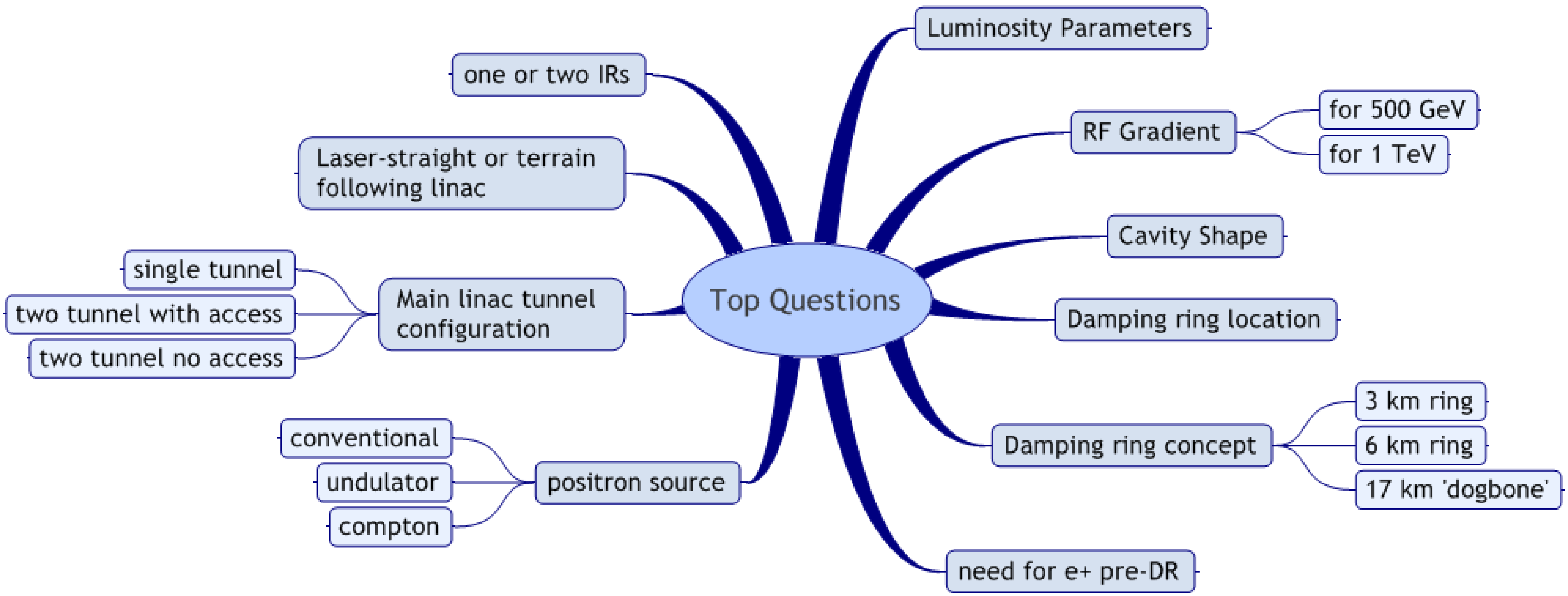
Linear collider will push many technological and beam-physics limits

- Need to have operational flexibility to overcome unexpected problems

IP Parameters

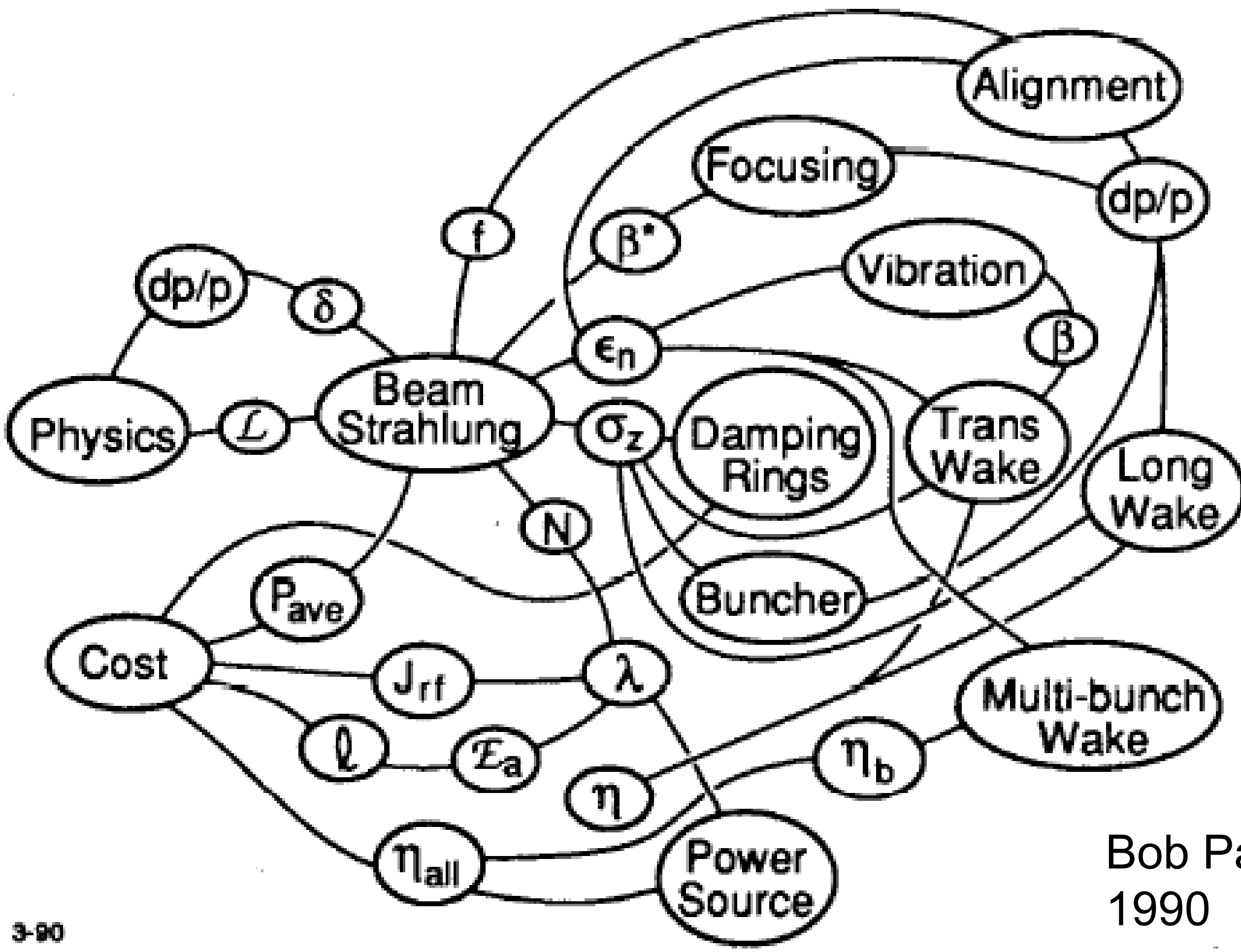
IP parameters determine basic beam structure

- Charge per bunch
- Beam power
- IP spot sizes
- All parameters are linked



Linear Collider Parameters

Model for linear collider design!



Bob Palmer
1990

ILC Parameters for L = 2 x 10^{32} [cm^{-2} s^{-1}]

		nominal	low N	High L
N	$\times 10^{10}$	**2**	1	2
n_b		**2820**	5640	2820
$\varepsilon_{x,y}$	μm - nm	**9.6 - 40**	10 - 30	10 - 30
$\beta_{x,y}$	cm - mm	**2 - 0.4**	1.2 - 0.2	1 - 0.2
$\sigma_{x,y}$	nm	**543 - 5.7**	495 - 3.5	452 - 3.5
D_y		**18.5**	10	22
δ_{BS}	%	**2.2**	1.8	7
σ_z	μm	**300**	150	150
P_{beam}	MW	**11**	11	11

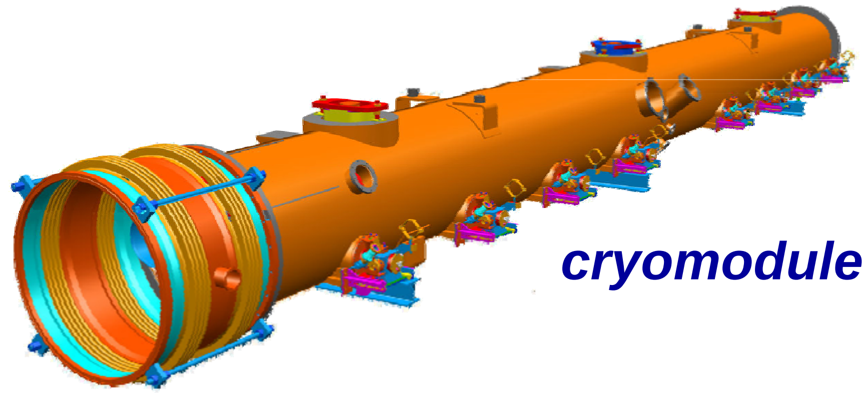
Parameter range established to allow for operational optimization

ILC Parameter List as in the RDR

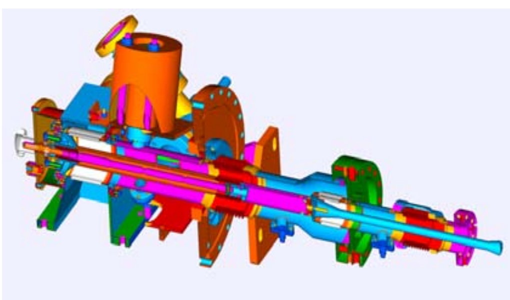
		Nominal	Low N	Large Y	Low P
Repetition rate	f_{rep} (Hz)	5	5	5	5
Number of particles per bunch	N (10^{10})	2	1	2	2
Number of bunches per pulse	n_b	2625	5120	2625	1320
Bunch interval in the main linac	t_b (ns)	369.2	189.2	369.2	480.0
in units of RF buckets		480	246	480	624
Average current in the main linac	I_{ave} (mA)	9.0	9.0	9.0	6.8
Normalized emittance at IP	$\gamma\epsilon_x^*$ (mm·rad)	10	10	12	10
Normalized emittance at IP	$\gamma\epsilon_y^*$ (mm·rad)	0.04	0.03	0.08	0.035
Beta function at IP	β_x^* (mm)	20	11	11	11
Beta function at IP	β_y^* (mm)	0.4	0.2	0.6	0.2
R.m.s. beam size at IP	σ_x^* (nm)	639	474	474	474
R.m.s. beam size at IP	σ_y^* (nm)	5.7	3.5	9.9	3.8
R.m.s. bunch length	σ_z (μm)	300	200	500	200
Disruption parameter	D_x	0.17	0.11	0.52	0.21
Disruption parameter	D_y	19.4	14.6	24.9	26.1
Beamstrahlung parameter	Υ_{ave}	0.048	0.050	0.038	0.097
Energy loss by beamstrahlung	δ_{BS}	0.024	0.017	0.027	0.055
Number of beamstrahlung photons	n_γ	1.32	0.91	1.77	1.72
Luminosity enhancement factor	H_D	1.71	1.48	2.18	1.64
Geometric luminosity	$\mathcal{L}_{geo}$ $10^{34}/\text{cm}^2/\text{s}$	1.20	1.35	0.94	1.21
Luminosity	$\mathcal{L}$ $10^{34}/\text{cm}^2/\text{s}$	2	2	2	2

Superconducting RF Linac Technology

cavity

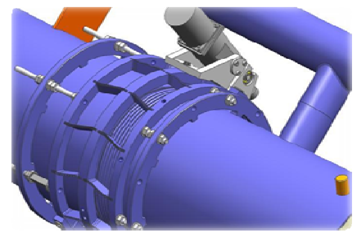


cryomodule



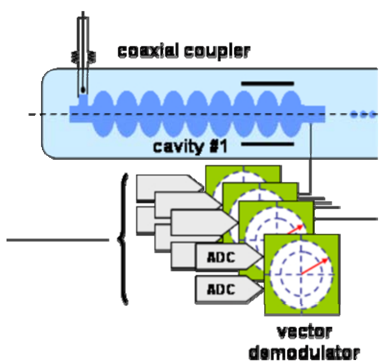
coupler

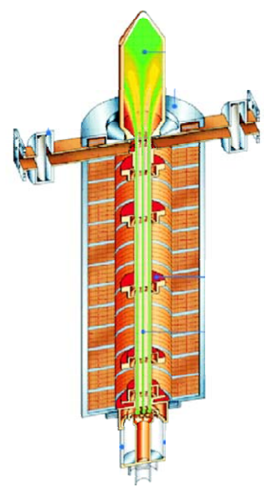
SCRF Linac Technology



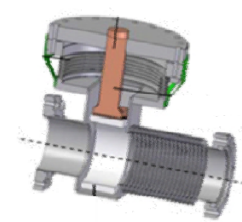
tuner

LLRF





RF



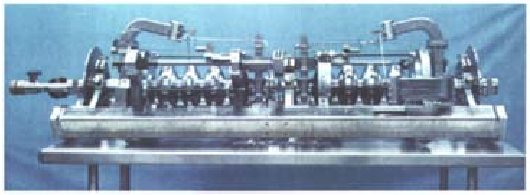
HOMs

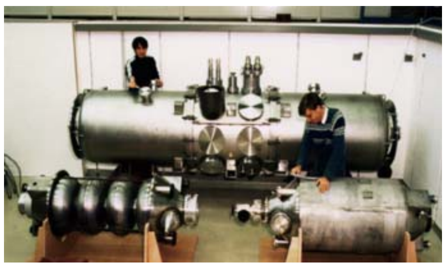
SRF before TESLA / ILC

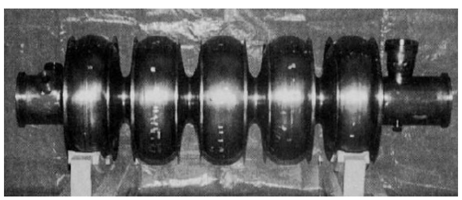
“Livingston Plot” from Hasan Padamsee

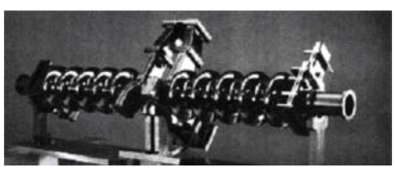
Total Installation > 1000 m

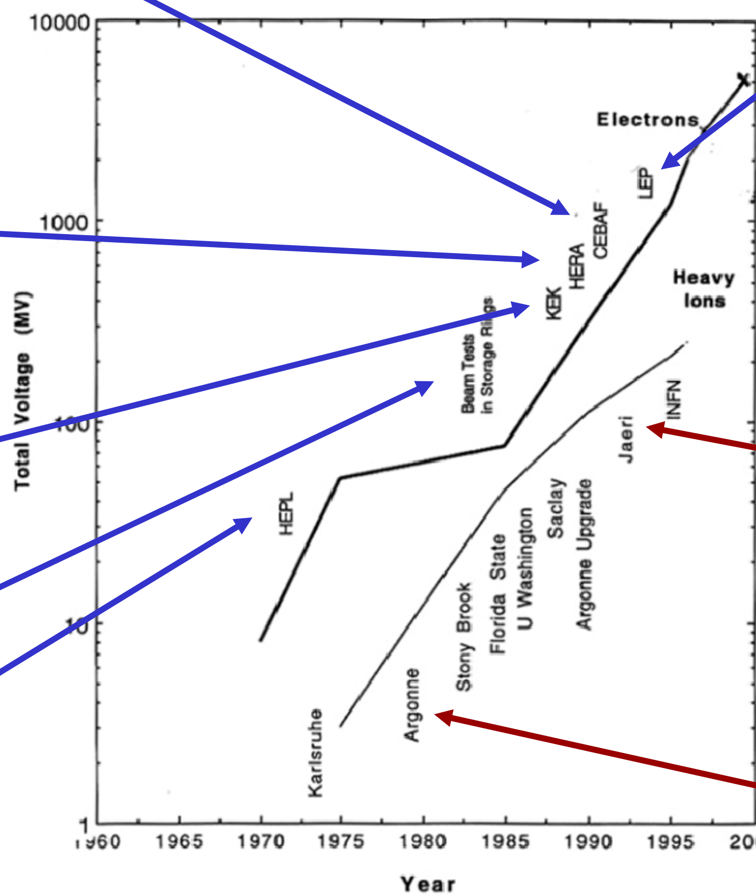
Provided > 5 GV











The TESLA Mission

Develop SRF Technology for the future Linear Collider

Basic goals on SRF Technology

- **Increase gradient by a factor of 5: from 5 to 25 MV/m** (Physical magnetic field limit for Nb is ~ 180 mT)
  - Push cavity performances close to the physical limit, understanding practical limits
  - Set all the required quality control for reproducibility and industrial production
- **Make possible pulsed operation: Lorentz force detuning**
  - Combine SRF and mechanical engineering in cavity design
  - Develop efficient Modulators and Klystrons
  - Develop slow and fast tuners
  - Develop appropriate couplers
- **Reduce cost per MV by a factor 20: to make the LC feasible**
  - New cryomodule concept for cryolosses, cost and filling factor (for real estate gradient)
  - All subsystems designed for large scale production
  - **Reliability and quality control as a general guide line**

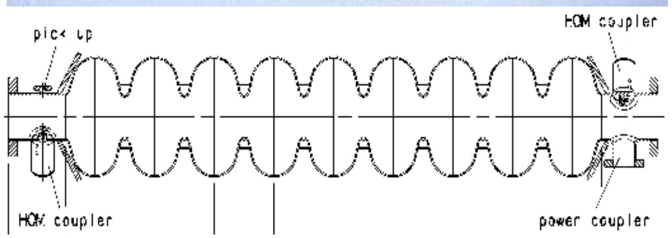
Basic goals on Machine Design

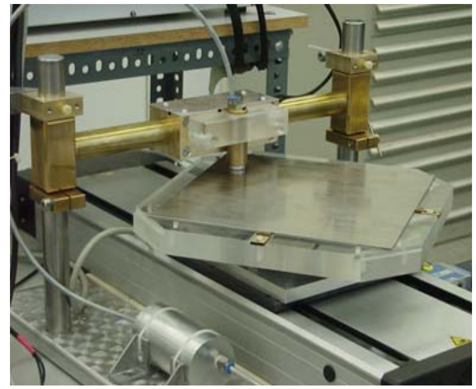
- **Design a Linear Collider based on the Cold Linac peculiarities**
- **Maximize Luminosity and optimize cost for a given plug power**
- **Design and quote major subsystems:** DR, Positron Source, BDS, etc.
- **Put all together in a consistent TDR, including cost estimation**

Optimized Cavity Design and Rules

Major contributions from: CERN, Cornell, DESY, CEA-Saclay & INFN-LASA

Bulk Nb, 9-cell, 1.3 GHz





Eddy-current scanning system for niobium sheets

Cleanroom handling of niobium cavities

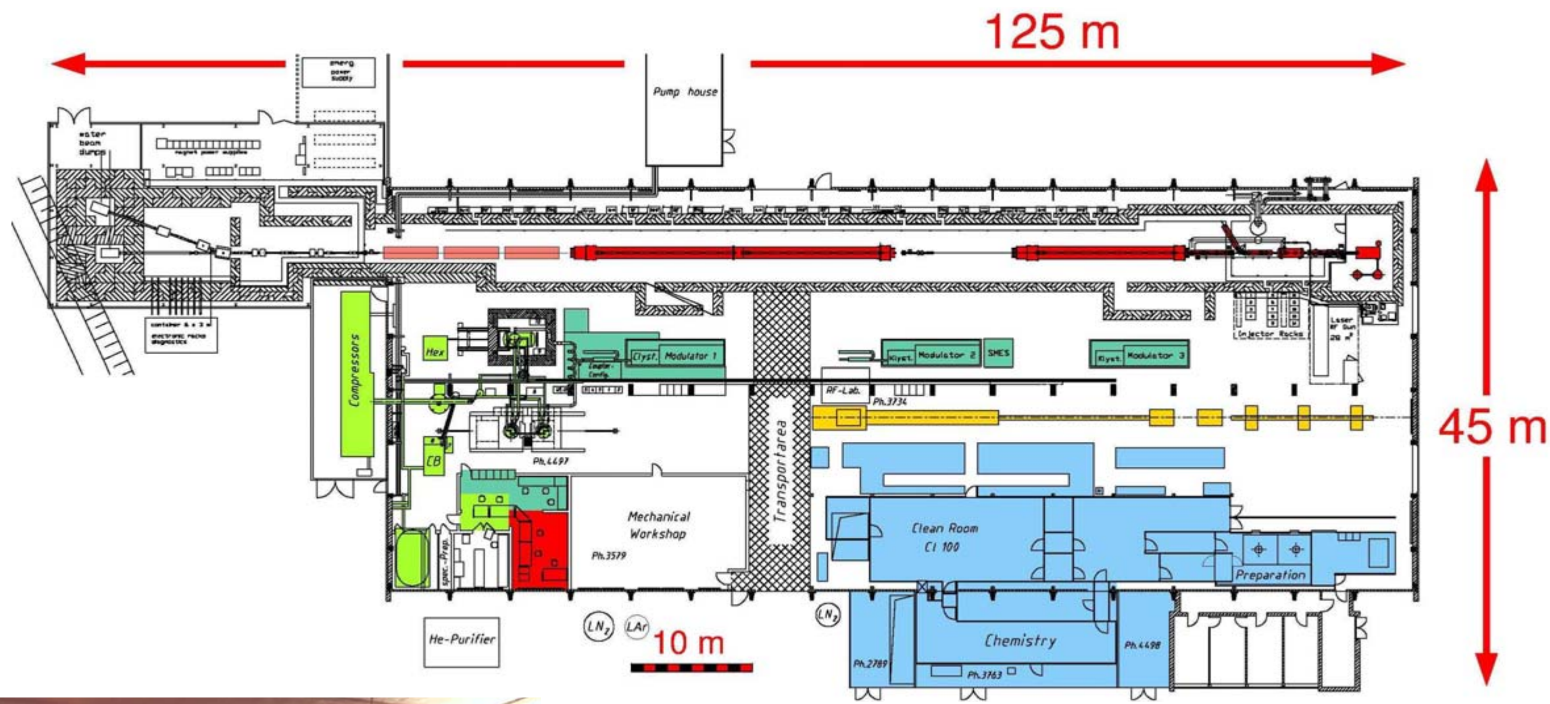
TESLA cavity parameters

R/Q	1036	W
E_{peak}/E_{acc}	2.0	
B_{peak}/E_{acc}	4.26	mT/(MV/m)
$\Delta f/\Delta l$	315	kHz/mm
$K_{Lorentz}$	≈ -1	$Hz/(MV/m)^2$

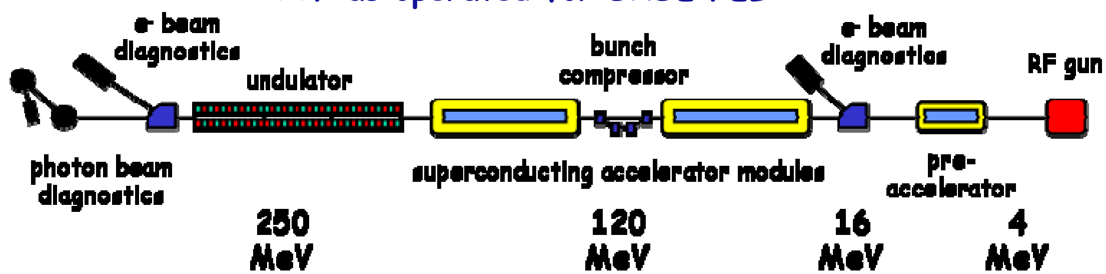
Preparation Sequence

- Niobium sheets (RRR=300) are scanned by eddy-currents to detect avoid foreign material inclusions like tantalum and iron
- Industrial production of full nine-cell cavities:
  - Deep-drawing of subunits (half-cells, etc.) from niobium sheets
  - Chemical preparation for welding, cleanroom preparation
  - Electron-beam welding according to detailed specification
- 800 °C high temperature heat treatment to stress anneal the Nb and to remove hydrogen from the Nb
- 1400 °C high temperature heat treatment with titanium getter layer to increase the thermal conductivity (RRR=500)
- Cleanroom handling:
  - Chemical etching to remove damage layer and titanium getter layer
  - High pressure water rinsing as final treatment to avoid particle contamination

TTF infrastructure at DESY



TTF as operated for SASE FEL



Chemistry, HPR and String Assembly

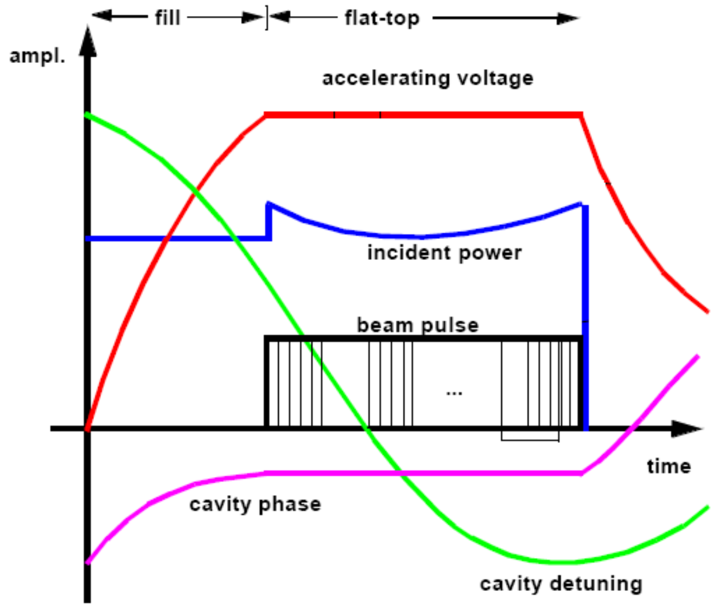
The ILC Linac Technology: Cavity

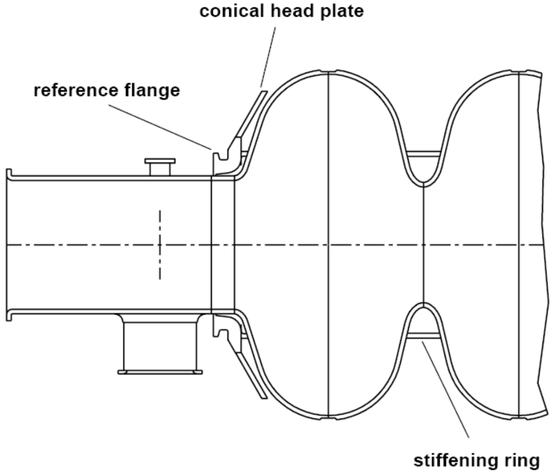
The TESLA resonator

- **Nb 9-cell**, operated at **2 K** temperature
- **1.3 GHz** frequency, TM_{010} EM mode
- Typical nominal $\mathbf{Q_0 \geq 10^{10}}$
- $\mathbf{E_{acc}}$ **of 31.5 MV/m** for ILC, 35 MV/m for qualification tests
- Q_L of 10^6 and $\mathbf{\Delta f_{FWHM}}$ **of 370 Hz** with beam and coupler

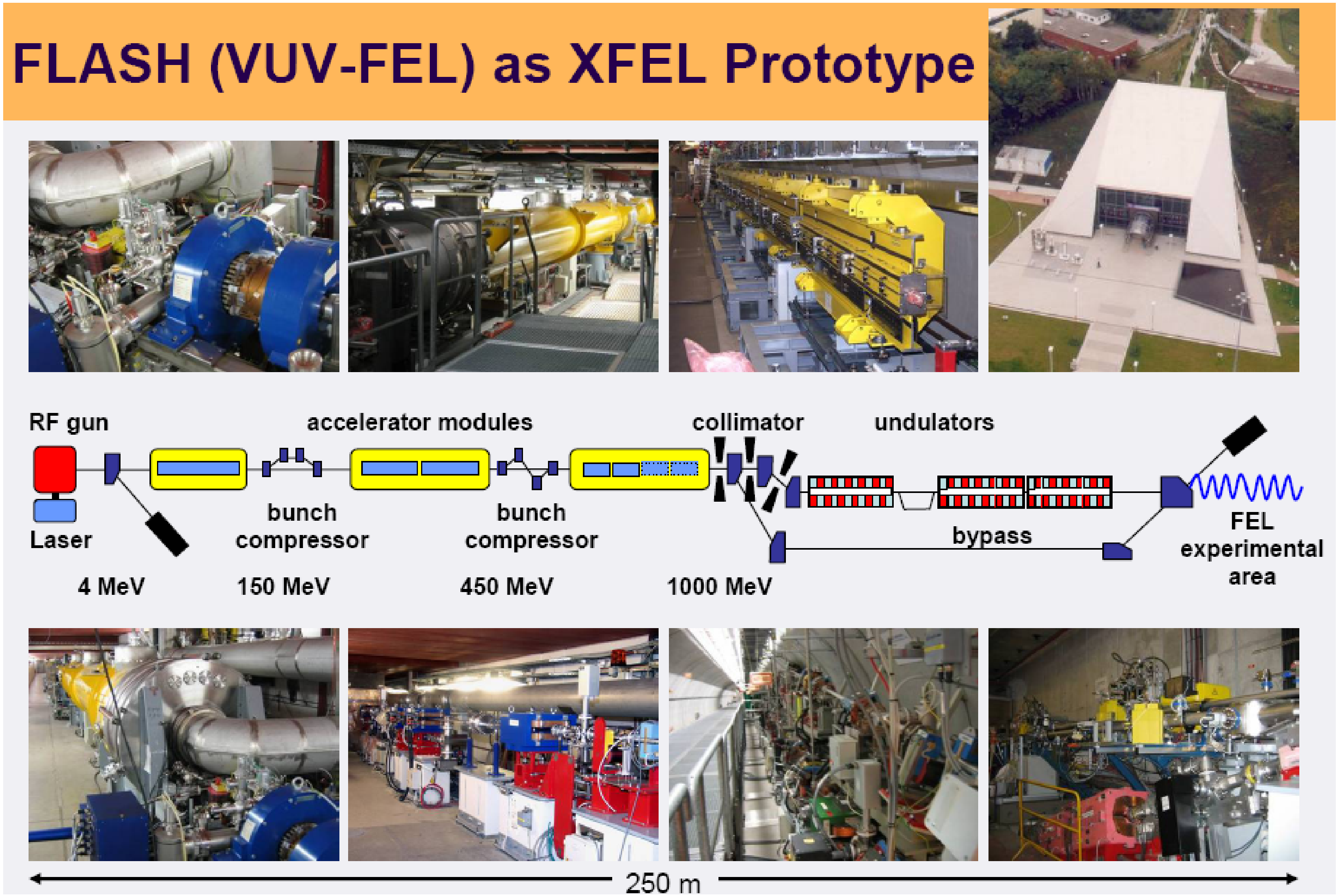
Pulsed operations

- 5 Hz repetition rate, 1.6 ms pulse length

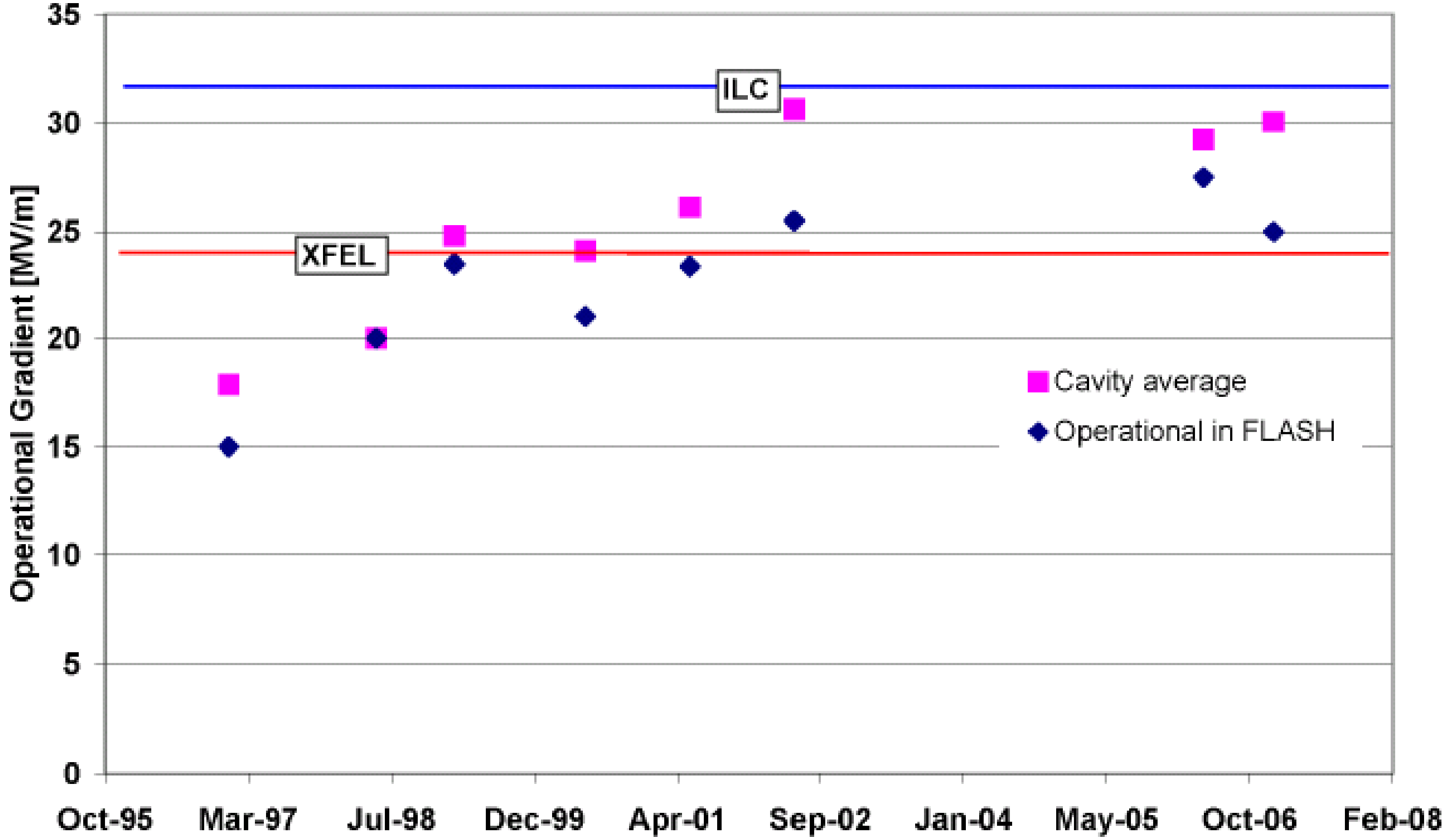




The Existing FLASH at DESY



TTF-FLASH Cryomodule Performances



A more flexible RF Distribution System will allow higher operation gradient

RF to transfer Energy to the Beam

To give energy to a charged particle beam, apart from "details", you need to let him move across a region in which an electric field exists and is directed as the particle motion.

$$\Delta E_{particle} = \int \vec{F}_{Lorentz} \cdot d\vec{s} = q \int \vec{E} \cdot \vec{v}\, dt$$

In the accelerator world RF takes care of all the variety of items that are required to accomplish this task of creating a region filled of electromagnetic energy that can be sucked by the beam while crossing it.

An "RF power source" is used to fill, via a "coupler", the "RF cavity", or resonator that is the e.m. energy container from which the beam is taking its energy.

What we ask to a good cavity?

High Q for losses:

- U = stored energy
- P_{diss} = dissipated power

$$Q = \omega \frac{U}{P_{diss}}$$

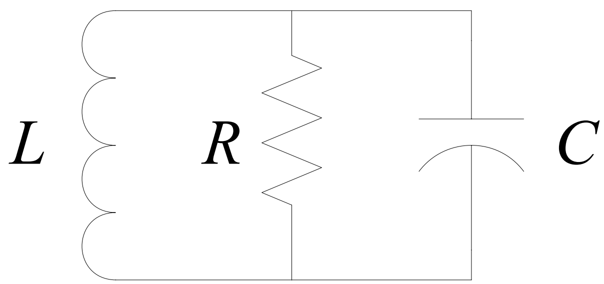
Small R_s for high Q:

- R_s = surface resistance
- G = cavity geometrical factor

$$Q = \frac{G}{R_s}$$

Cavity lumped circuit model and R_S

- A cavity at the fundamental mode has an equivalent resonant lumped circuit



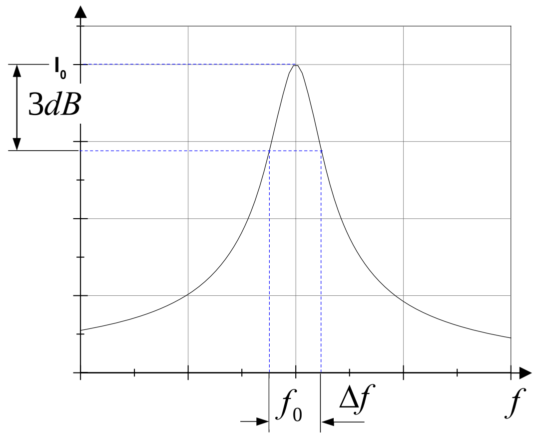
$$\omega_0 = \frac{1}{\sqrt{LC}} \qquad Q = \omega_0 RC$$

$$\omega_0 = 2\pi f_0$$

$$P_{diss} = \frac{V^2}{2R}$$

- Q determines the frequency band Δf

$$\Delta f = \frac{f_0}{Q}$$



- R proportional to Q determines P_{diss}

$$R \propto Q$$

- R depends inversely from the cavity R_s through a geometrical factor

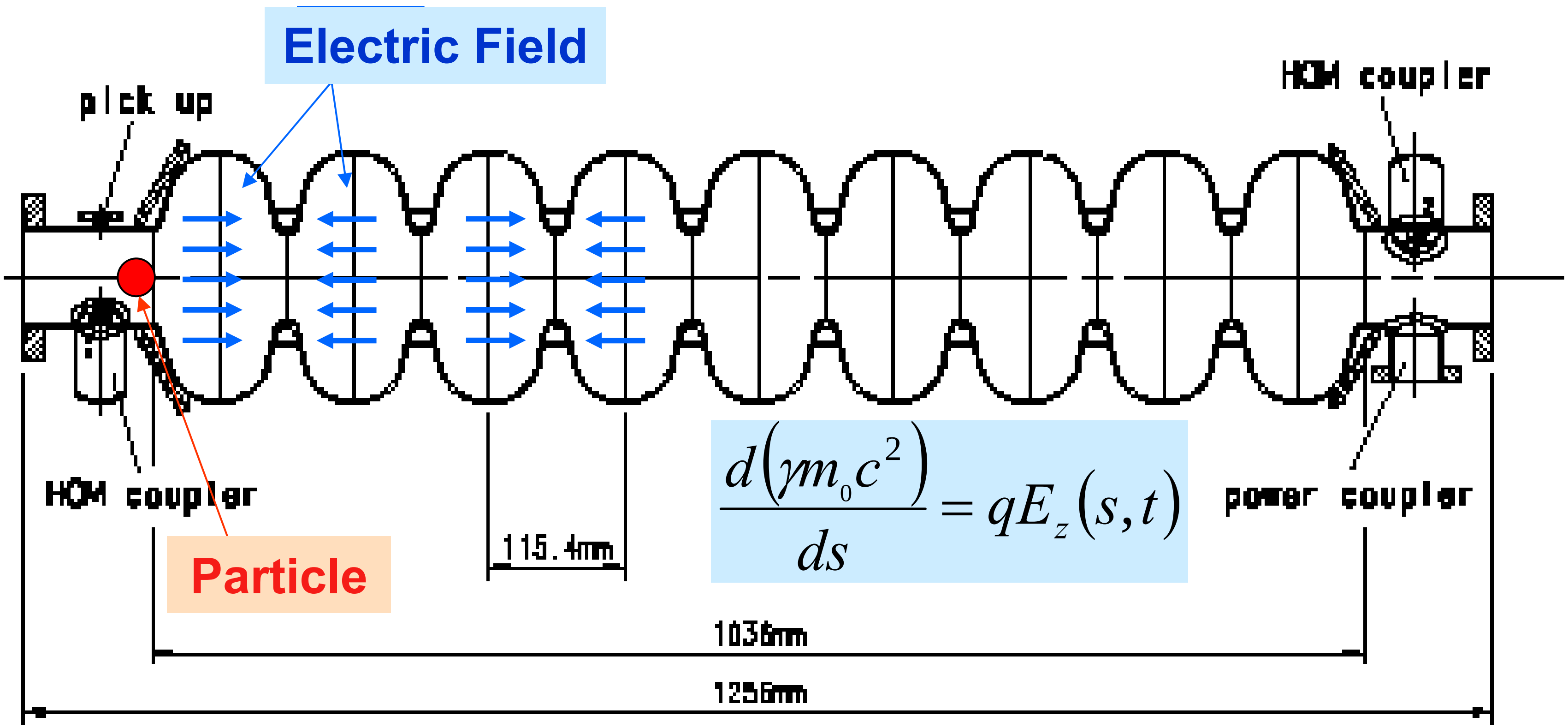
$$R \propto \frac{1}{R_s}$$

- In practice, for a given geometry and a given accelerating field the surface resistance R_s plays the crucial role of determining the dissipated power, that is the power required to sustain the field

$$R_s$$

Acceleration inside an ILC Cavity

- An electromagnetic field is resonating inside the “cavity”. The electric field inverts its direction according to the frequency determined by the cavity resonator shape.
- If the charged particle beam has the proper synchronism, moving from one cell to the other it sees always the field in the right direction and gains energy: $E_{gain} = q \times V$



$$\frac{d\left(\gamma m_0 c^2\right)}{ds} = qE_z(s,t)$$

Maxwell Equations and Waves

Electromagnetic fields are described by Maxwell Equations that in empty space are:

$$\begin{cases} \nabla \cdot \vec{E} = 0 \\ \nabla \cdot \vec{B} = 0 \\ \nabla \times \vec{E} = -\dfrac{\partial \vec{B}}{\partial t} \\ \nabla \times \vec{B} = \mu_0 \varepsilon_0 \dfrac{\partial \vec{E}}{\partial t} \end{cases}$$

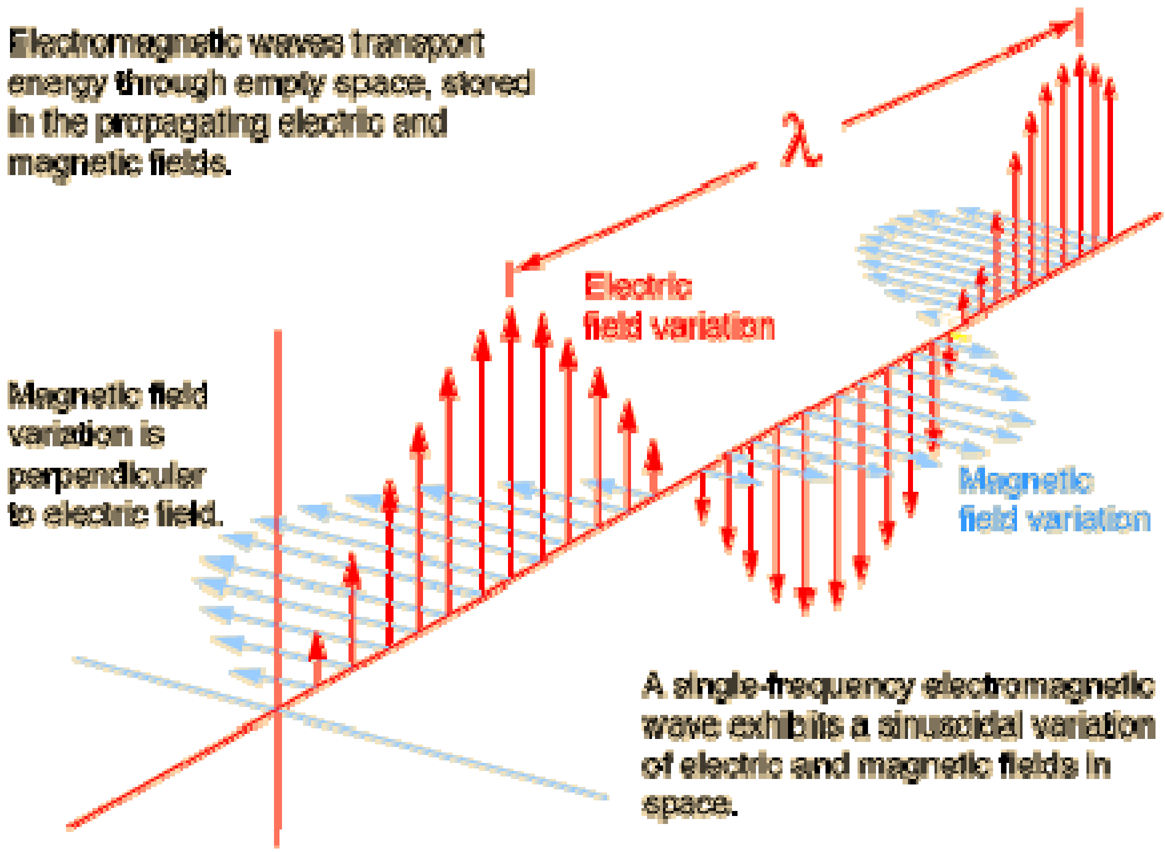
From Maxwell Equation we obtain the Wave Equations for Electric and Magnetic Fields

$$\nabla^2 \begin{Bmatrix} \vec{E} \\ \vec{B} \end{Bmatrix} - \frac{1}{c^2} \frac{\partial^2}{\partial t^2} \begin{Bmatrix} \vec{E} \\ \vec{B} \end{Bmatrix} = 0$$

where: $c = \dfrac{1}{\sqrt{\mu_0 \varepsilon_0}}$

Planar Wave: Pictorial View

Planar wave in empty space: **no acceleration is possible**



The energy transport per unit area is described by the Poynting vector ***S***

$$\vec{S} = \frac{1}{\mu_0} \vec{E} \times \vec{B}$$

$$c = \frac{1}{\sqrt{\varepsilon_0 \mu_0}}$$

ε_0 = electric permittivity
μ_0 = magnetic permeability

The Phase velocity V_{ph} is the velocity of an observer sitting at constant phase

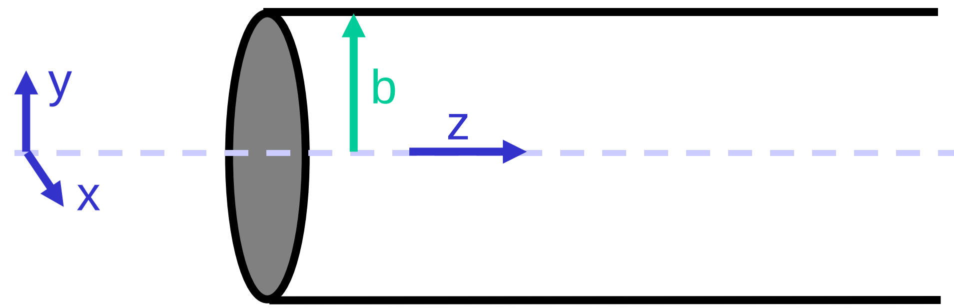
Group velocity V_{gr} is the velocity of the energy propagation

$$v_{ph} = v_{gr} = c$$

Bounded Solution, Perfect Conductor -1

Apply some kind of boundaries in *x* and *y*, so that non-zero *x* and *y* derivatives of the electric field can cancel z derivative (i.e. permits non-zero $E_{0,z}$ while still obeying Maxwell).

Try a conducting pipe of radius b, oriented along z axis:



$$\vec{E} = \vec{E}_0 e^{i(\omega t - kz)}$$

$$\vec{H} = \vec{H}_0 e^{i(\omega t - kz)}$$

This time vectors $\boldsymbol{E}_0$ and $\boldsymbol{H}_0$ are functions of transverse coordinates *x* and *y* (or *r* and *θ*) but not *z* or *t*. Thus we can simplify some derivatives:

$$\frac{\partial}{\partial z} = -ik, \frac{\partial^2}{\partial z^2} = -k^2$$

$$\frac{\partial}{\partial t} = +i\omega, \frac{\partial^2}{t^2} = -\omega^2$$

Perfect Conductor Solution - 2

Using cylindrical coordinates we have,

- at the boundary, i.e. at $r=b$, the *normal* component of $\mathbf{B}$ and the *tangential* component of $\mathbf{E}$ are continuous.
- if the conductor is perfect, then *within* the conductor the electric and magnetic field are identically zero. Thus at $r=b$, H_r, E_z, and $E_\theta = 0$.
- since $E_\theta=0$, the θ component of the magnetic curl equation must go to zero.

$$\begin{cases} \vec{\mathrm{n}} \cdot \vec{\mathrm{B}} = 0 \\ \vec{\mathrm{n}} \times \vec{\mathrm{E}} = 0 \end{cases}$$

In total

$$E_\theta = E_z = H_r = \frac{\partial H_z}{\partial r} = 0$$

With some algebra and canceling the common complex component (time dependence) we get from the wave equation the longitudinal electric field:

$$\nabla^2 \vec{E} = \frac{1}{c^2} \frac{\partial^2}{\partial t^2} \vec{E}_0 e^{i(\omega t - kz)}$$

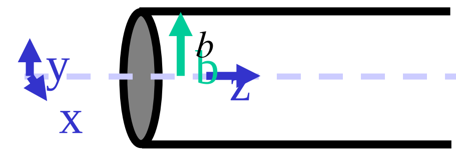
$$E_{0,z} = \sum_{n=0}^{\infty} a_n J_n(k_c r) \cos(n\theta + \theta_n)$$

Where: J_n are the Bessel functions

$$k_c^2 \equiv \left(\frac{\omega^2}{c^2} - k^2\right)$$

n must be is an integer

Perfect Conductor Solution - 3



Because: $E_z=0$ @ $r=b$,

We can set: $k_c b = z_{np}$, where z_{np} is the p^{th} zero of J_n.

As a result: $k_c > 0$

$$E_{0,z} = \sum_{p=1}^{\infty}\sum_{n=0}^{\infty} a_{np} J_n(k_{c,np} r)\cos(n\theta+\theta_{np})$$

$$k_{c,np} = \frac{z_{np}}{b} = \sqrt{\frac{\omega^2}{c^2} - k^2}$$

$k^2 \geq 0$ because k must be real for propagation and for $k = 0$ we have the cutoff frequency:

$$\nabla^2 \vec{E} = \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\vec{E}_0 e^{i(\omega t - kz)}$$

$$\omega_{c,np} = c\frac{z_{np}}{b} = \omega_c$$

Cutoff frequency

$\omega > \omega_c$ Traveling wave: propagation

$\omega < \omega_c$ Evanescent wave: can't propagate

But we also get the phase and the group velocities:

$$v_{ph} = \frac{\omega}{k} = \sqrt{c^2 + \frac{\omega_c^2}{k^2}} > c$$

$$v_{gr} = \frac{\partial\omega}{\partial k} = c\cdot\frac{\sqrt{\omega^2 - \omega_c^2}}{\omega} < c$$

TM and TE Modes

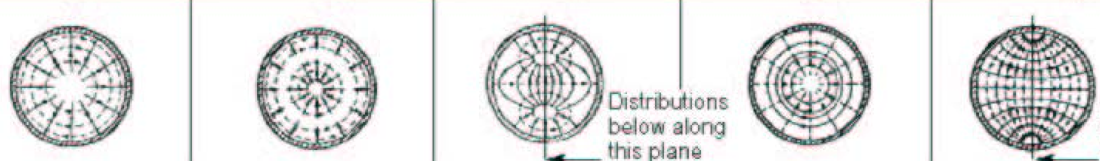
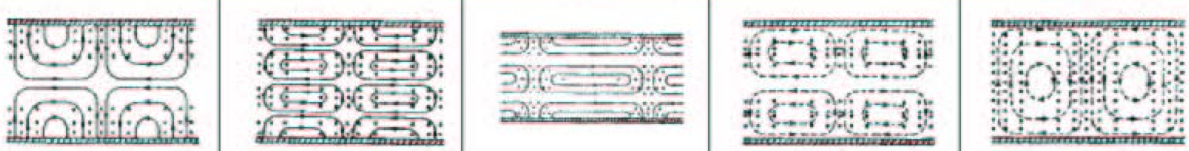
A similar solution is available for the magnetic field vector $\boldsymbol{B}$

In general a wave with a given phase and group velocity cannot have both a longitudinal electric field and a longitudinal magnetic field!

Waves with $H_{0,z} \equiv 0$ are called TM (transverse magnetic) modes; waves with $E_{0,z} \equiv 0$ are called TE (transverse electric) modes. Usually the modes are referred to with their index numbers, TE_{uv} or TM_{np}

TM01 mode has nonzero E_z, E_r, H_θ components only

Table 3 Mode Patterns in Circular Waveguide.

Wave Type	TM_{01}	TM_{02}	TM_{11}	TE_{01}	TE_{11}
Field distributions in cross-sectional plane, at plane of maximum transverse fields			Distributions below along this plane		Distributions below along this plane
Field distributions along guide					
Field components present	E_z, E_r, H_ϕ	E_z, E_r, H_ϕ	E_z, E_r, E_ϕ, H_r, H_ϕ	H_z, H_r, E_ϕ	H_z, H_r, H_ϕ, E_r, E_ϕ

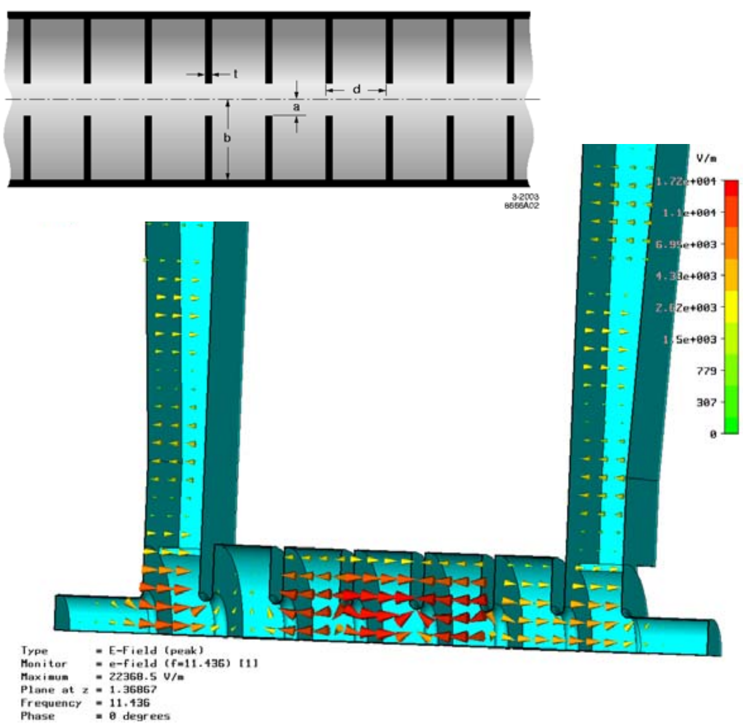
7–98
8365A213

Real Accelerating Structures: Cavities

Imposing boundary condition in the longitudinal direction, z, we have for each mode (for example the TM_{01}) two waves: rightward-propagating (+z) wave and a leftward-propagating wave The combination can give a wave with phase velocity $v_{ph} \leq c$

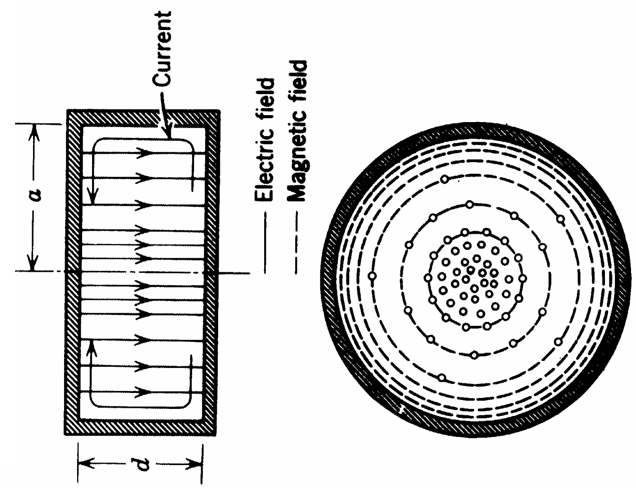
Traveling wave structure

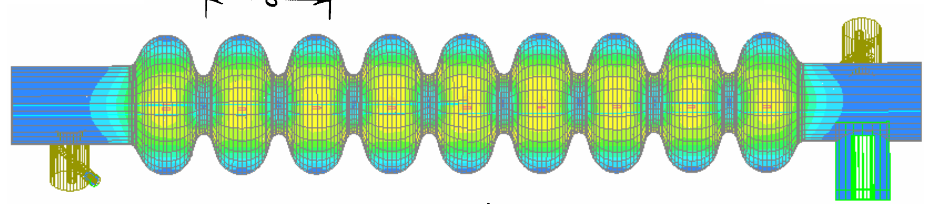
$V_{ph} \approx c$ and $Vg < c$



Standing wave structure

$V_{ph} = 0$ and $Vg = 0$



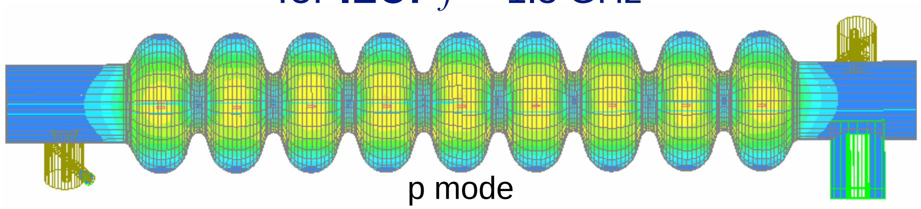


π mode

The ILC technology choice

Standing wave: $v_{ph} = 0$ and $v_g = 0$

for **ILC:** f = 1.3 GHz



The power is deposited at the operating temperature of few K

We need to guarantee and preserve the 2 K environment

- Cavity is sensitive to pressure variations, only viable environment is sub-atmospheric vapor saturated He II bath

We need a thermal "machine" that performs work at room temperature to extract the heat deposited at cold

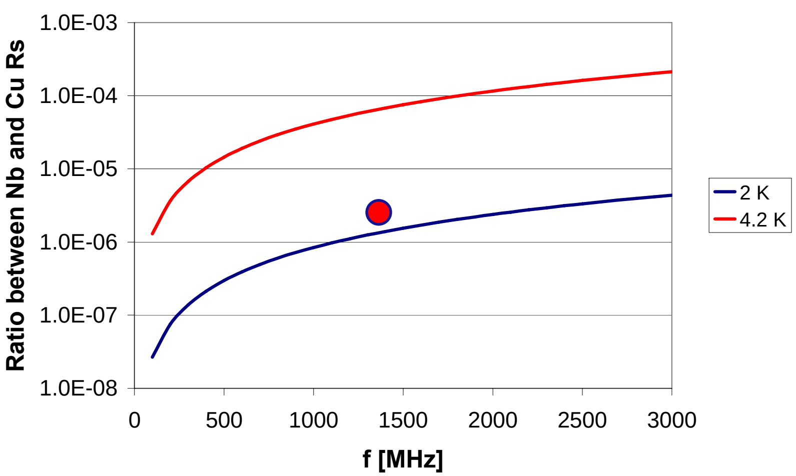
- We can't beat Carnot efficiency!

Remembering that the power dissipated on the cavity walls to sustain a field is:

$$P_{diss} = \frac{R_s}{2} \int_S H^2 dS$$

standing wave case

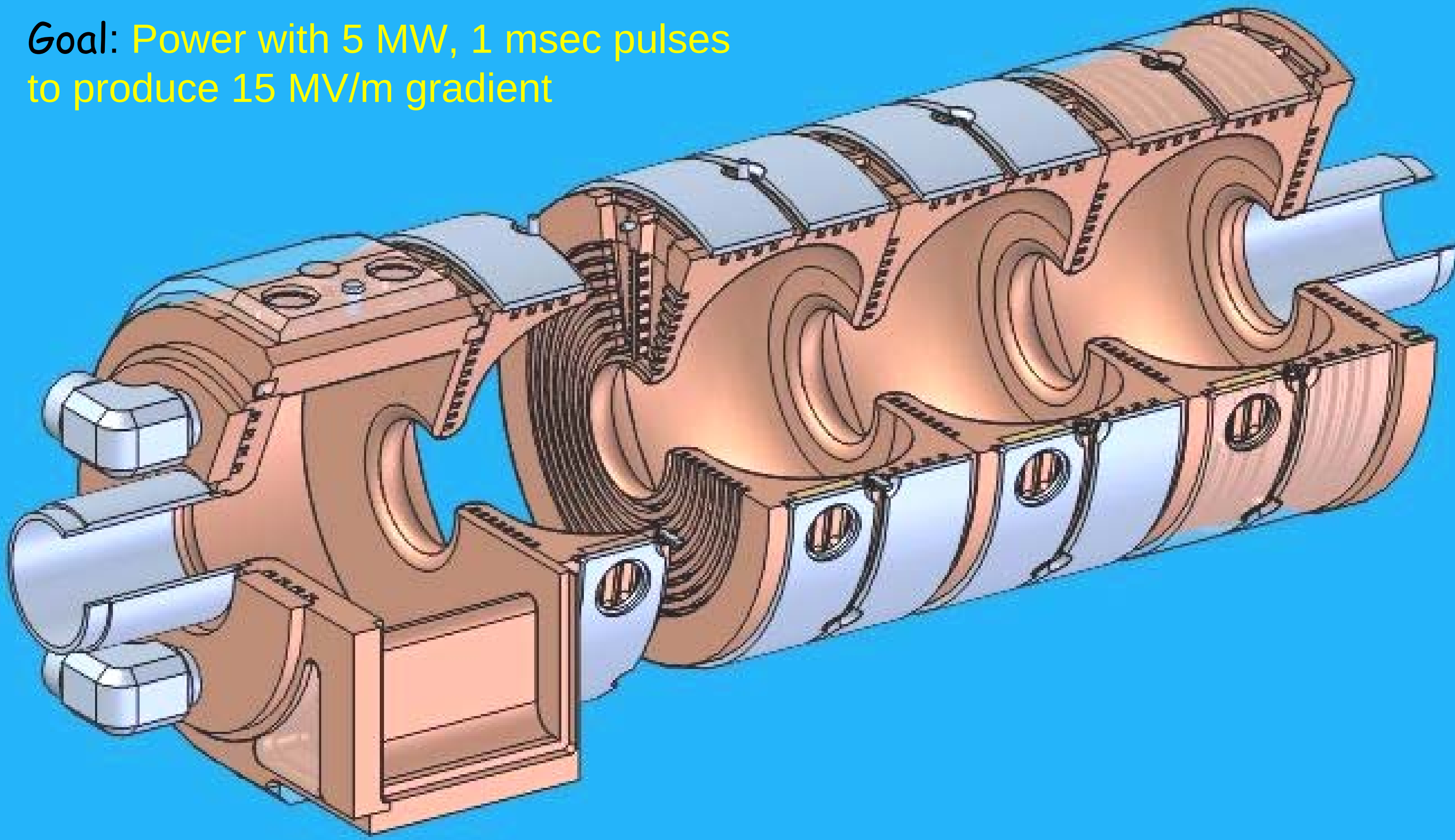
a pulsed operation is required to reduce the time in which the maximum allowable field is produced to accelerate the particles



→ Cryogenics and cryomodules

ILC Positron Capture Cavity Prototype

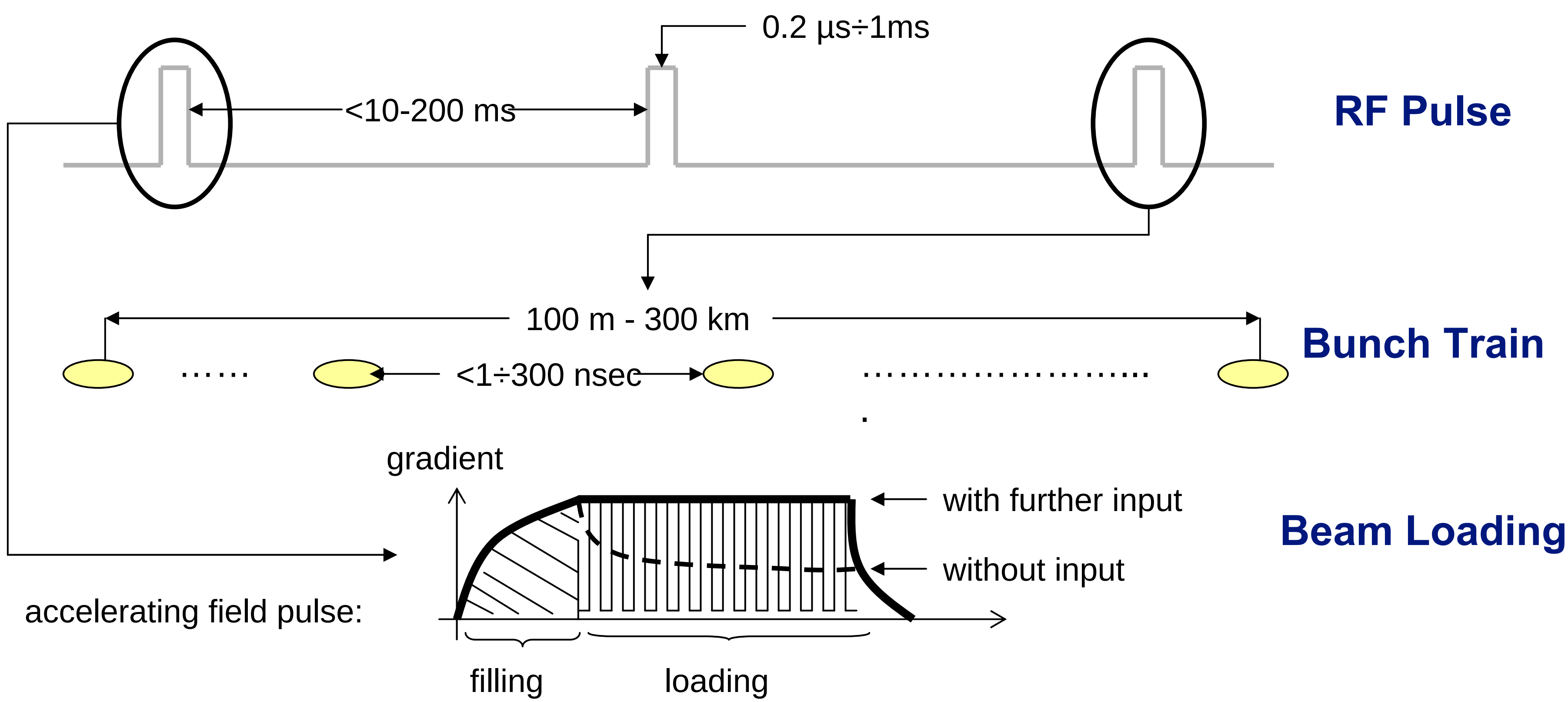
Goal: Power with 5 MW, 1 msec pulses to produce 15 MV/m gradient



Linear Colliders are pulsed

All **LCs are pulsed machines to improve efficiency**. As a result:

- duty factors are small
- pulse peak powers can be very large



How is spent the cold advantage?

The gain in RF power dissipation with respect to a normalconducting structure is spent in different ways

$$W \geq Q \frac{T_h - T_c}{T_c}$$

Paying the price of supplying coolant at 2K

- This include ideal Carnot cycle efficiency
- Mechanical efficiency of compressors and refrigeration items
- Cryo-losses for supplying and transport of cryogenics coolants
- Static losses to maintain the linac cold

Increasing of the duty cycle (percentage of RF field on)

- Longer beam pulses, larger bunch separation, but also
- Larger and more challenging Damping Rings

Increasing the beam power (for the same plug power)

- Good for Luminosity

Cryogenics and Cryomodules

Cryomodule (it contains several SC Cavities)

It's the building block of all SC accelerators: ILC but also LHC

The cryomodule provides:

- cryogenic environment for the SC active elements
- thermal shielding to mitigate static losses
- structural support

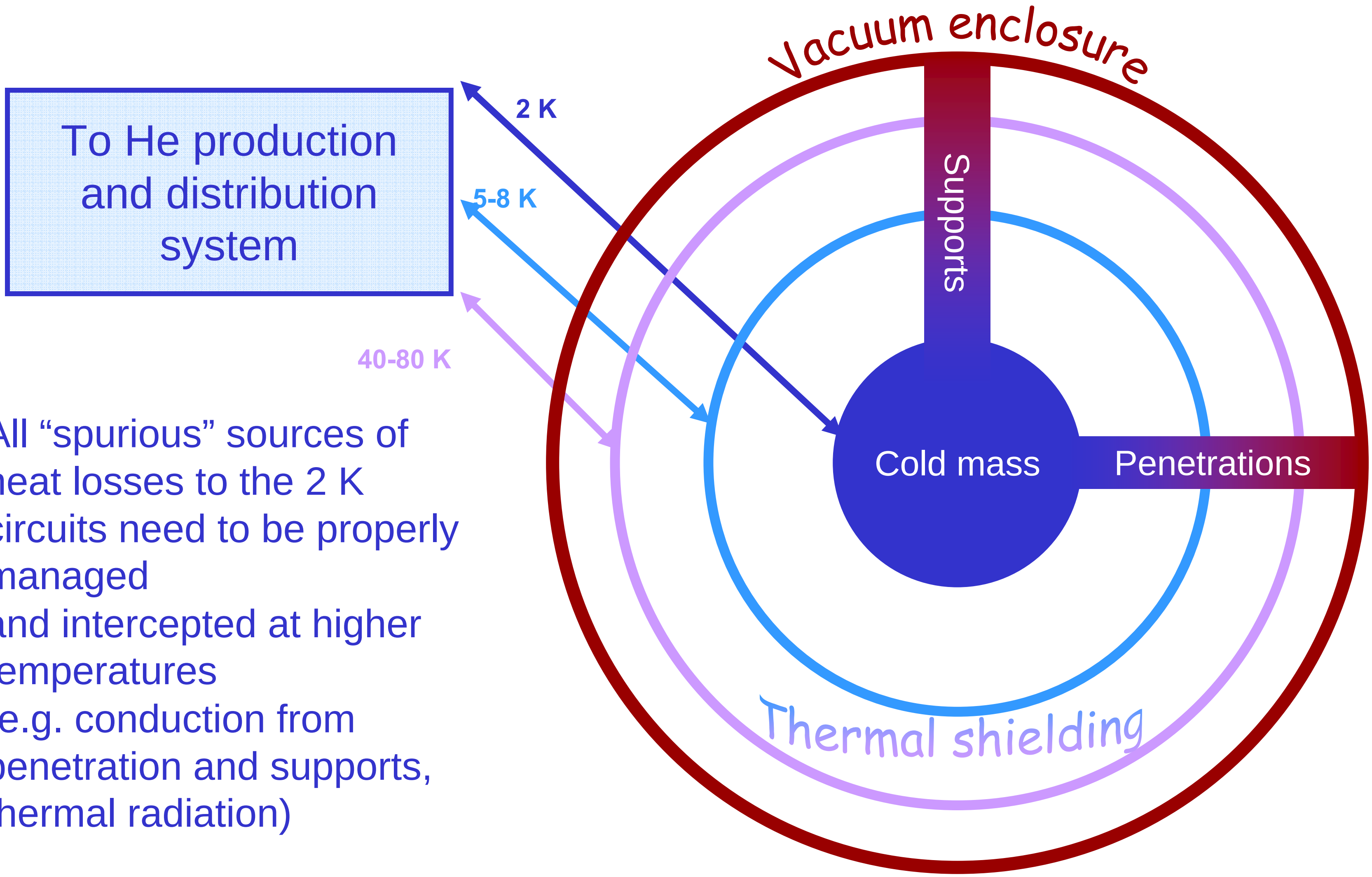
Cryogenics

Refrigeration Plants:

- Transform plug power into cooling power at cryogenics temperatures
  - from MW to kW
  - from 300 K to few K
  - from water to Helium

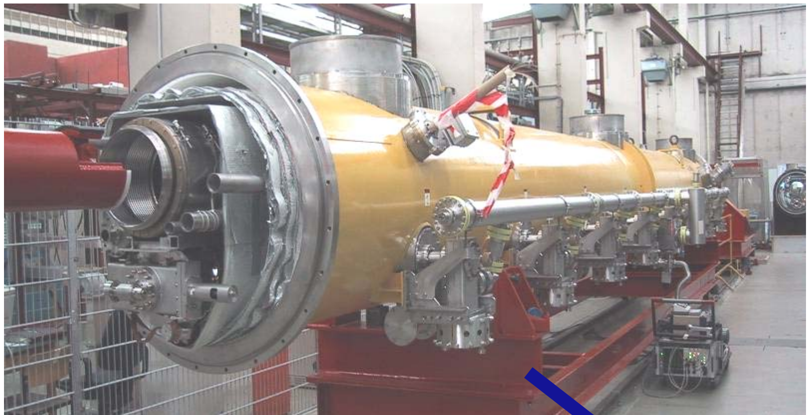
Distribution and Recovery of cryogenics coolants

"Cartoon" view of Cryogenic system



All "spurious" sources of heat losses to the 2 K circuits need to be properly managed
and intercepted at higher temperatures
(e.g. conduction from penetration and supports, thermal radiation)

TTF Type 3, the ILC Reference Cryomodule



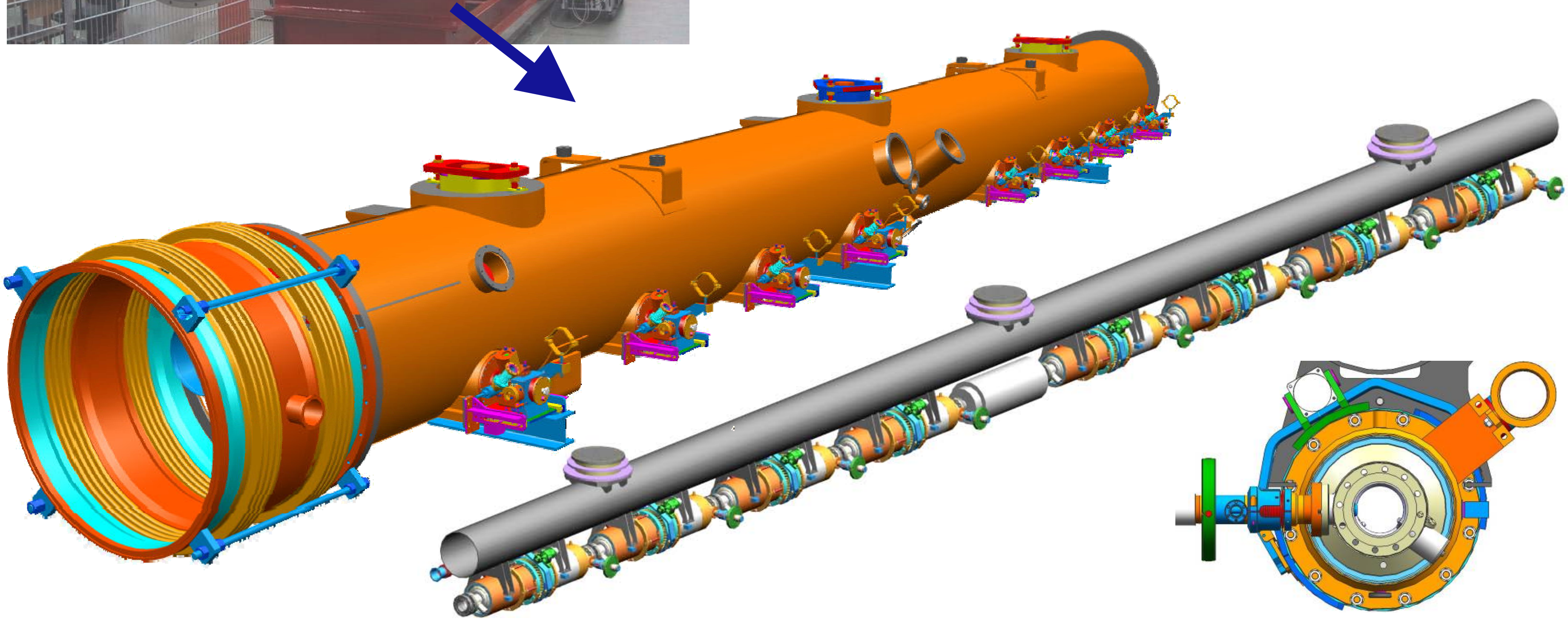
Developed by INFN for TTF-TESLA

3rd generation of improvements

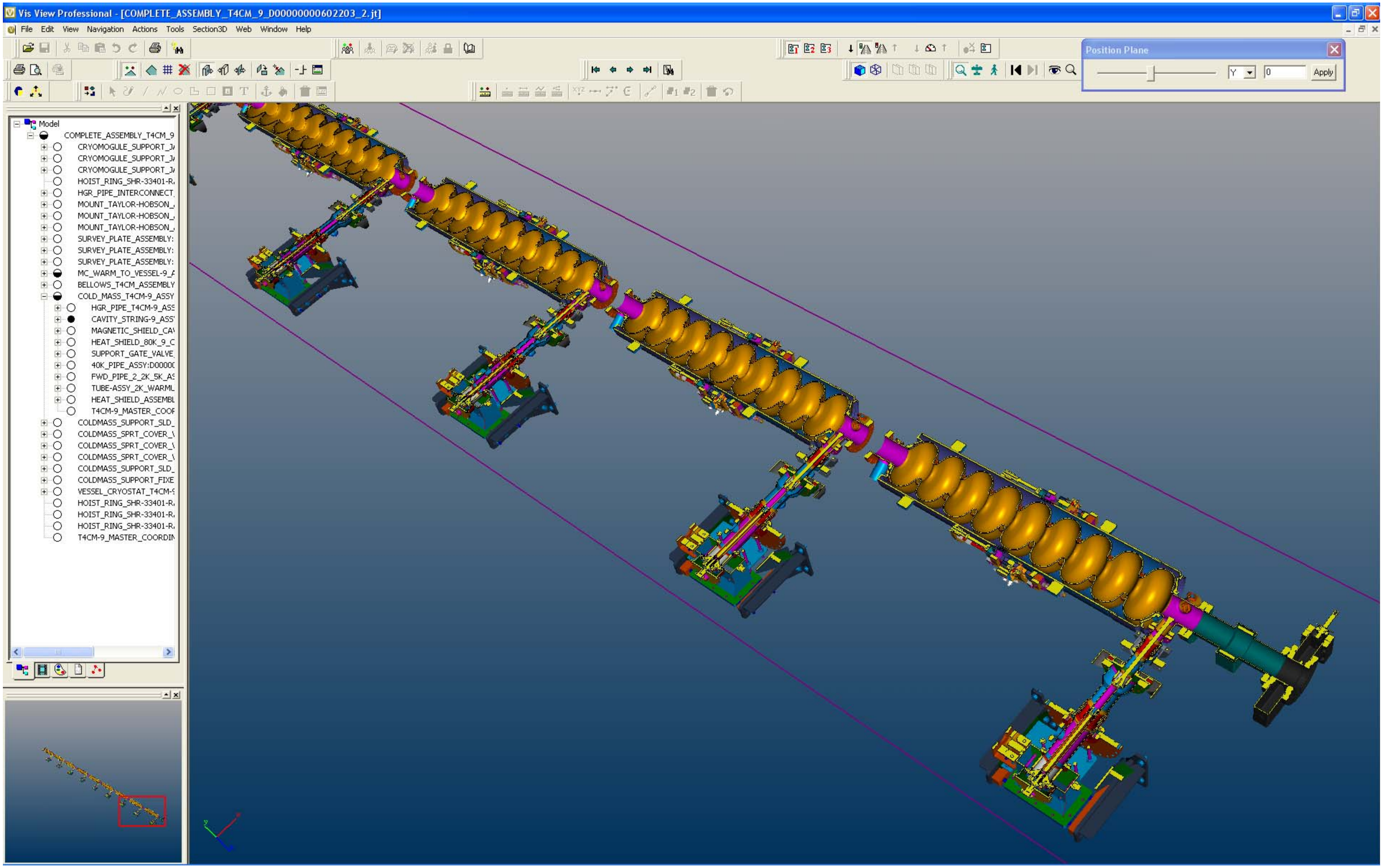
Many years of successful operation

Baseline for XFEL and ILC

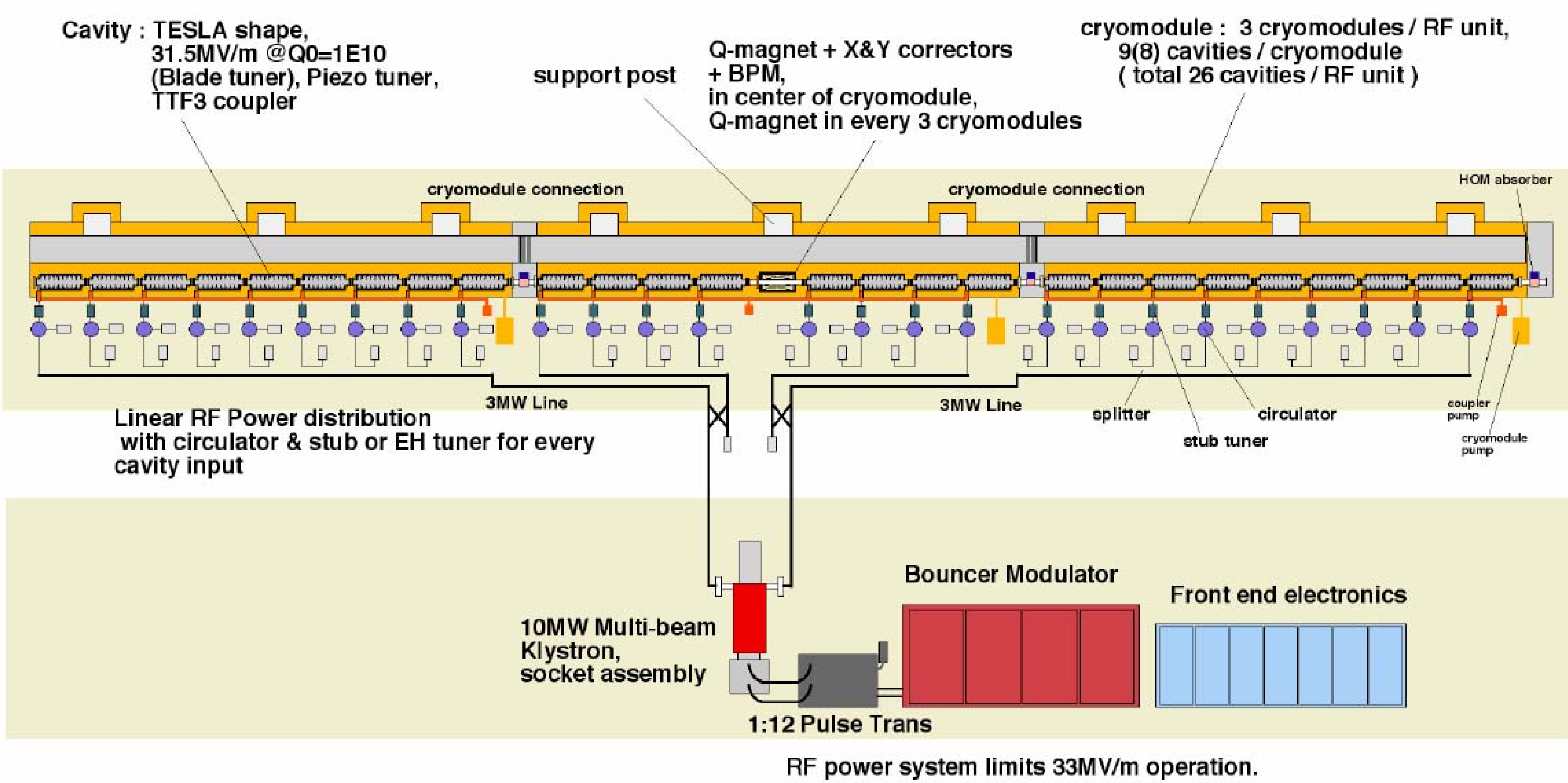
Reference for others (Project X, etc)



From the ILC Cryomodule drawings



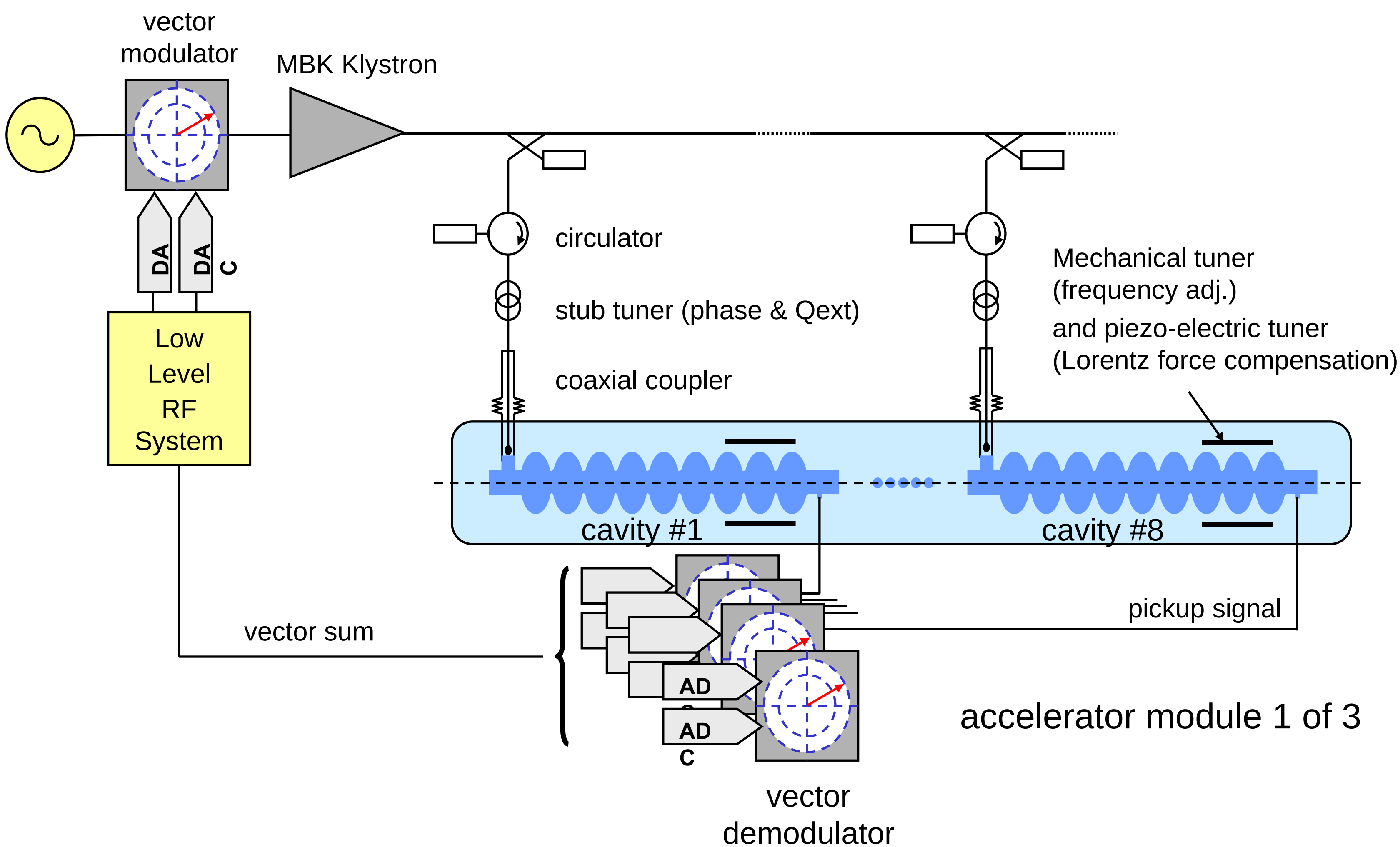
One ILC Linac RF Unit



RDR configuration

Standard ILC RF Unit

1 klystron for 3 accelerating modules, 9-8-9 nine-cell cavities each



Some Context for ILC Re-planning

Building close collaboration with XFEL. It will provide all SCRF development, except high gradient and ILC scale mass production, including a full systems test in 2013, industrialization, etc.

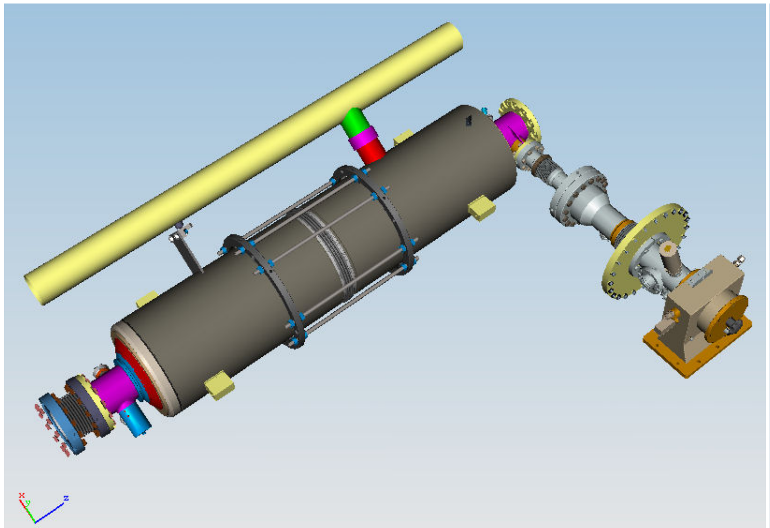
We plan to take advantage of alignments and synergies where they will exist with US generic SCRF program, Project X development, etc.

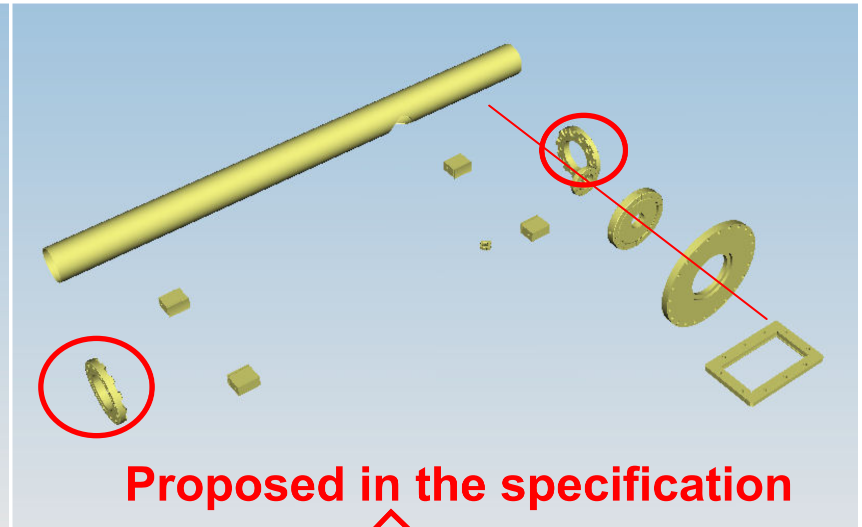
Undertaking steps to integrate linear collider (ILC and CLIC) R&D efforts, where beneficial to both efforts (meeting on 8-Feb, 13-May). Examples – sources, beam delivery, conventional facilities, detectors, costing, …..

SCRF Global Cavity Program

Americas	US FY06 (actual)	US FY07 (actual)	US FY08	US FY09	US FY10	TDP-1 Totals*	US FY11	US FY12
Cavity orders	22	12		10	10	**52**	10	10
Total 'process and test' cycles		40	5	45	30	**113**	30	30
Asia	**JFY06 (actual)**	**JFY07 (actual)**	**JFY08**	**JFY09**	**JFY10**		**JFY11**	**JFY12**
Cavity orders	8	7	8	25	15	**44**	39	39
Total 'process and test' cycles		21	40	75	45	**147**	117	117
Europe	**CY06 (actual)**	**CY07 (actual)**	**CY08**	**CY09**	**CY10**		**CY11**	**CY12**
Cavity orders	60**	8		834*		**8**		
Total 'process and test' cycles		14	18	26	30	**73**	380	406
Global totals								
Global totals - cavity fabrication	90	27	8	869	25	103	49	49
Global totals - cavity tests		75	65	135	175	333	501	501

Plug Compatibility Concept



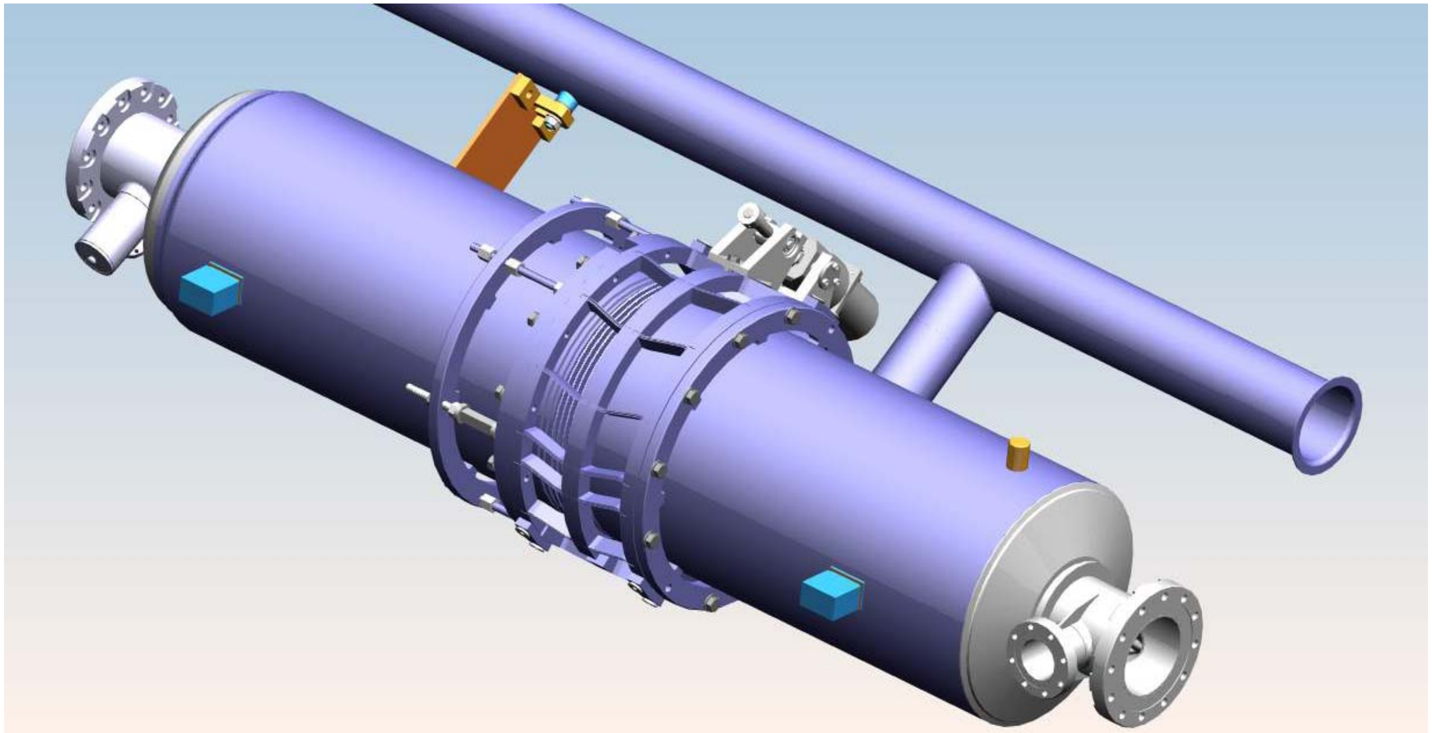


Helium Vessel Body		KEK-STF-BL	KEK-STF-LL	FNAL-T4CM	DESY-XFEL
Helium Jacket	Material	Ti	SUS	Ti	Ti
	Slot length, mm	1337	1337	1326.7	(1382:Type3)
	Distance between beam pipe flanges, m	1258.6	1254.5	1247.4	1283.4
	Distance between bellows flanges, mm	78.4	85.2	80.49 (cold)	
	Outer diameter, mm	242	236	240	240
Beam Pipe Flange	Material	NbTi	Ti	NbTi	NbTi
	Outer diameter, mm	130	140	140	140
	Inner diameter, mm	84	80	82.8	82.8
	Thickness, mm	14	17.5	17.5	17.5
	PCD, bolts	ϕ115, 16-ϕ9	ϕ120, 16-ϕ9	12, M8 SS studs	12, M8 SS studs
	Sealing	Helicoflex	M-O seal	Al Hex Seals	Hexagonal Al ring
	Distances between the connection surface and input coupler axis	62, -1196.6	58.1, -1213.9	60.6, -1186.8	60.6, -1222.8

ILC-XFEL Plug Compatible Cavity

Cavity with Helium Tank, Tuner and pipe connections

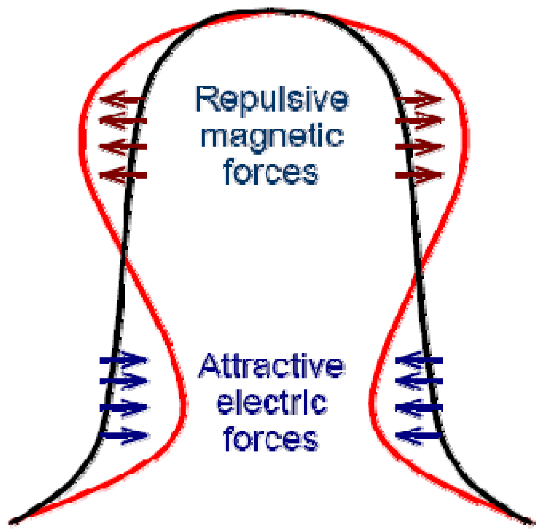
- Plug Compatible with the 3 Regional Infrastructures
- Plug Compatible with the FLASH and XFEL Cryomodules



Sources of dynamic detuning

The Lorentz force detuning, LFD

- **LF** on cavity walls shielding currents induced by EM fields
- **μm level** complex deformation of the cavity shape
- **Scaling as E_{acc}^2**
- Depends on both cavity stiffness and on external stiffness
- **Time-varying** for pulsed operations
- **Repetitive**, synchronous to RF pulses

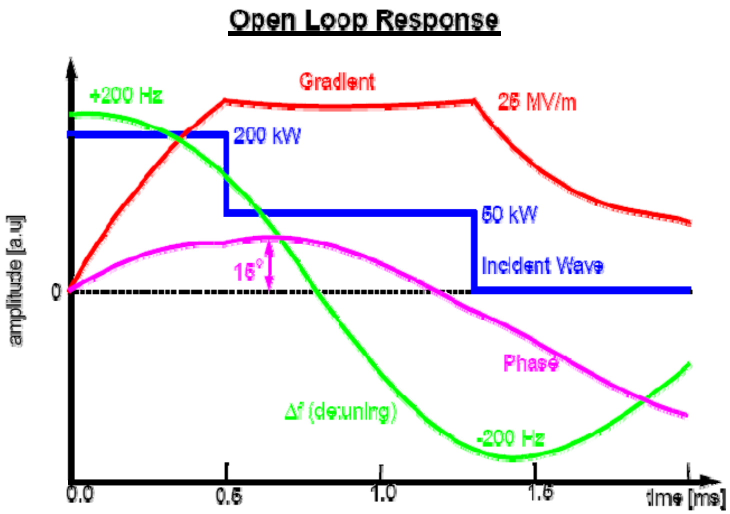


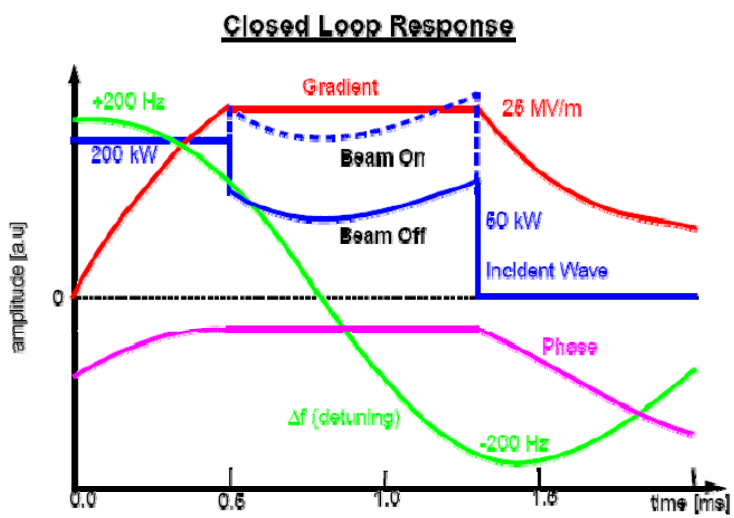
$$P_R = \frac{1}{4}\left(\mu_0|\mathbf{H}|^2 - \varepsilon_0|\mathbf{E}|^2\right)$$

Microphonics, MP

- **Stochastic**, strongly correlated to He bath pressure fluctuations
- **Low amplitude**, about 30 Hz rms

Slow and Fast cavity tuning



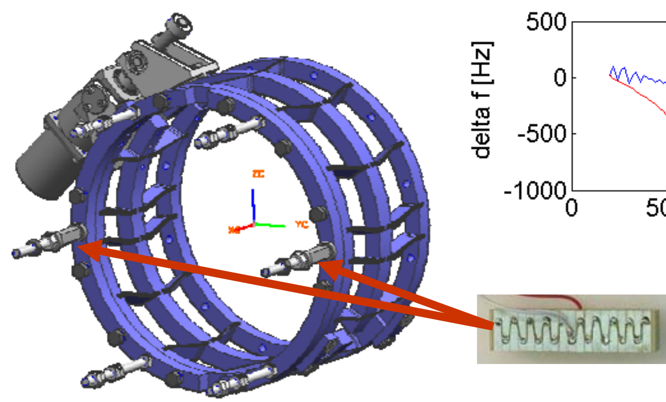


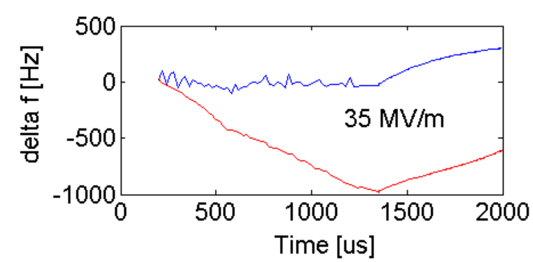
$$P_g = V_{acc} I_b \left[1 + \frac{1}{4} \left(\frac{\Delta f_{acc}}{f_{1/2}} \right)^2 \right]$$

- **Biquadratic** dependence of RF power overhead from cavity E_{acc}
- **10 %** maximum RF power overhead (ILC RDR) to limit the cost of the RF system

RF power overhead w/o compensation	
ILC pulse, RDR K_L', 31.5 MV/m	**+ 32 %**
ILC pulse, ACC6 K_L', 31.5 MV/m	+ 42 %

A fast detuning compensation required





Piezoelectric actuators

10 MW Multi Beam Klystrons

Peak Power Output	10	MW (min)
Ave. Power Output	150	kW (min)
RF Pulse Duration:	1.5	ms (min)

≥ 65% DC to RF Efficiency

TH1801 by **Thales**

VKL-8301 by **CPI**

E3736 MBK by **Toshiba**

e^+e^- *Sources*

Requirements:

- Produce a huge number of particles/second
- produce long bunch trains of high charge bunches
- with small emittances
- and *spin* polarisation (needed for physics)

~10^{14} e^+ and **e^-** per second

~3000 bunches of **few nC** @ **5 Hz**

$\varepsilon_{nx,y}$ **~ 10^{-6},10^{-8} m**

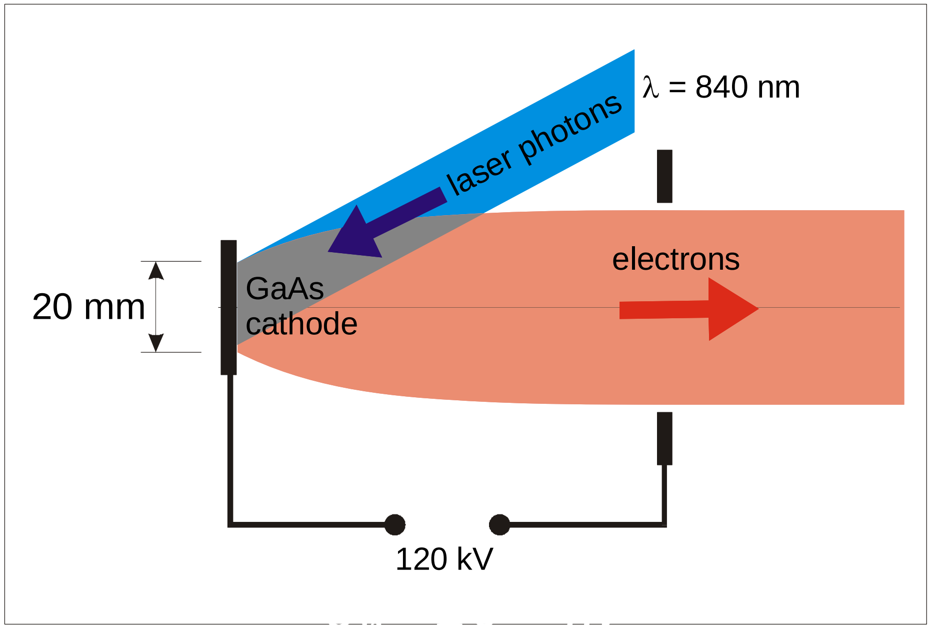
mandatory for *e^-*, nice for *e^+*

Remember *L* scaling:

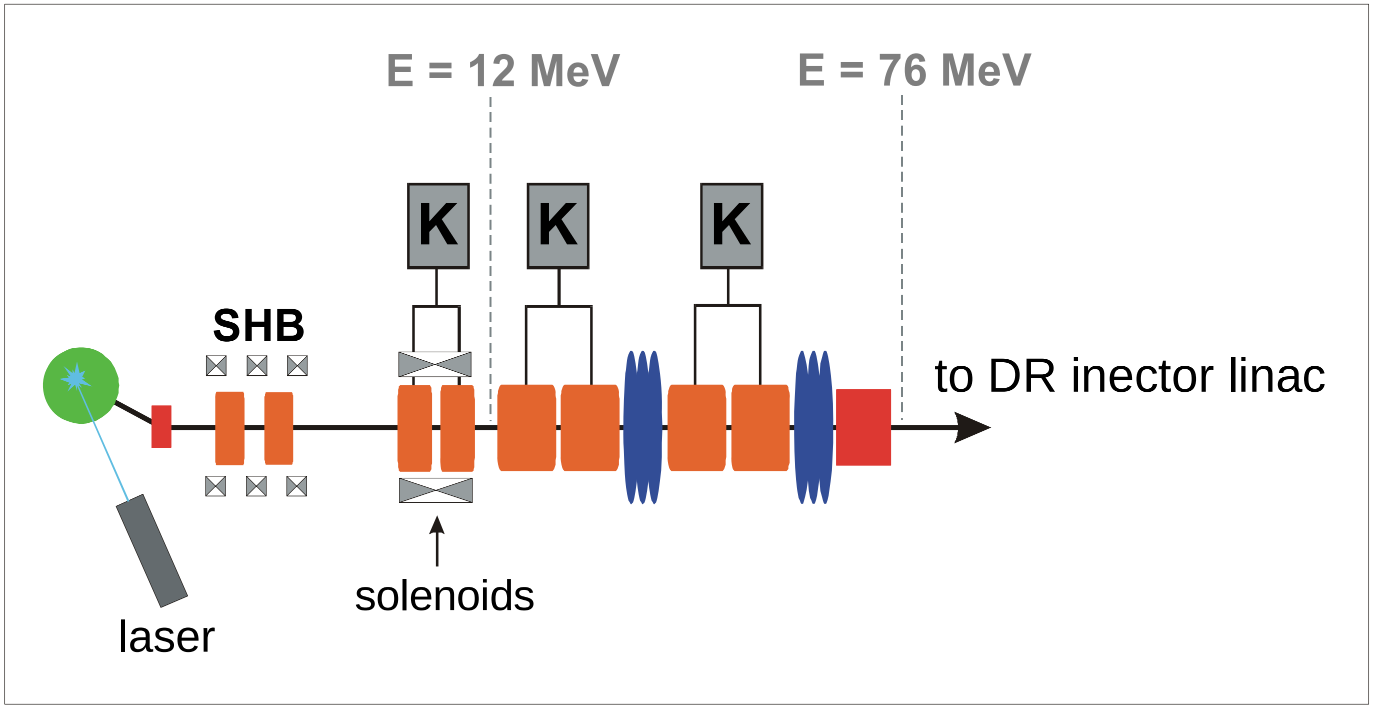
$$L \propto \frac{n_b N^2}{\sqrt{\varepsilon_n}}$$

e^- Source: Laser driven DC Gun

- **laser-driven photo injector**
- circularly polarised photons on GaAs cathode
  $\rightarrow$ long. polarised e^-
- laser pulse modulated to give required time structure
- **very ultra high vacuum** requirements for GaAs (<10^{-11} mbar)
- beam quality is dominated by ***space charge***
  (note v ~ *0.2*÷0.4 *c*)

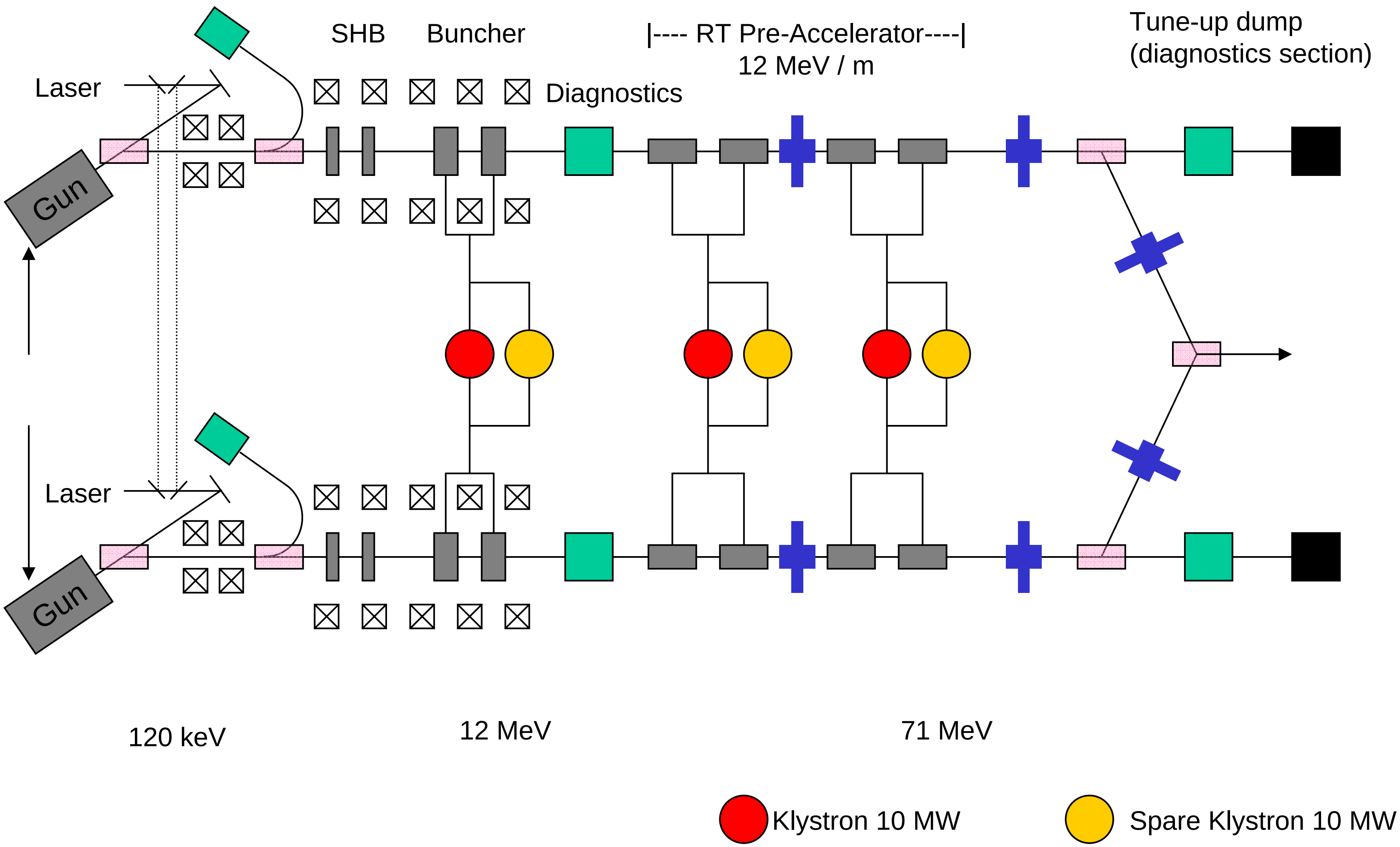


e- Source: pre-acceleration

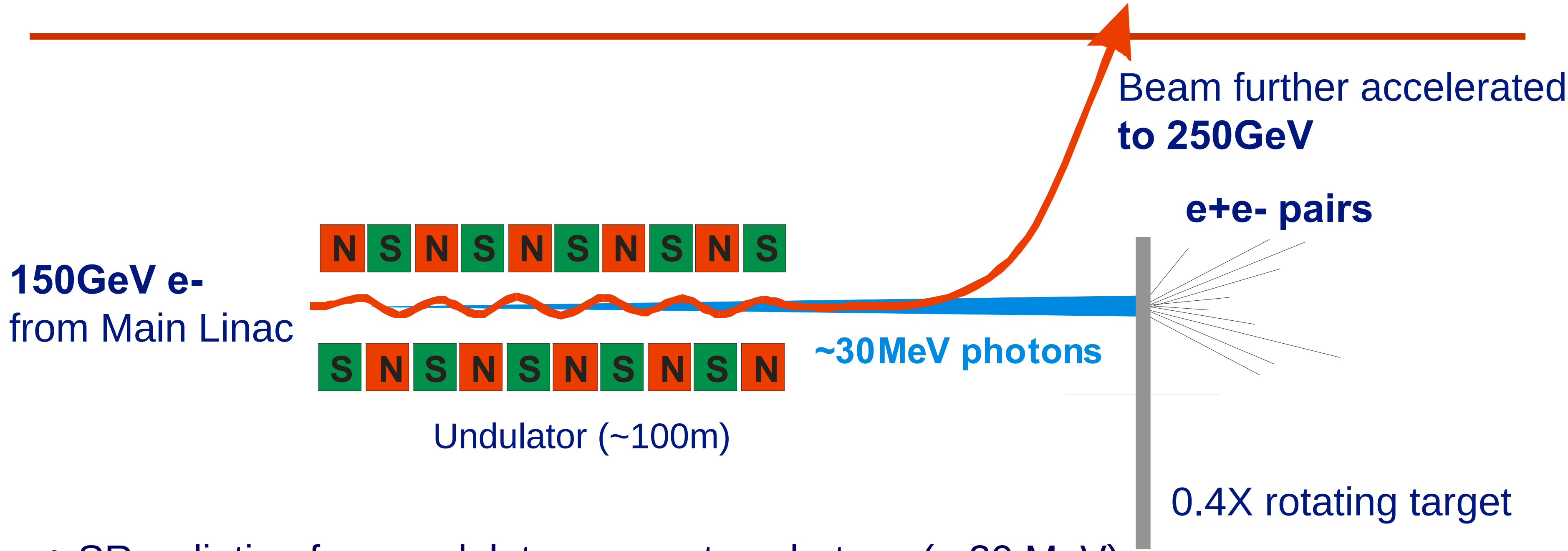


- SHB = sub-harmonic buncher. Typical bunch length from gun is ~ns (too long for electron linac with *f* ~ 1.3 GHz, need tens of ps)
- High-brightness RF guns as used in light sources would be significantly better, but vacuum conditions are generally to poor for polarised gun (cathodes)
- SC RF is an option – but remains an R&D project

ILC Electron Source



e^+ *Source: undulator-based*



- SR radiation from undulator generates photons (~ 30 MeV)
- no need for 'thick' target to generate shower
- thin target reduces multiple-Coulomb scattering: hence better emittance (but still much bigger than needed, ~ 10^{-2} m)
- less power deposited in target (no need for mult. systems), ~ 5 kW
- Achilles heel: needs initial electron energy > 150 GeV!
- Other possibilities to generate high-energy photons: Compton scattering of laser beams

Damping Ring Emittances (1)

Details in Lecture 3

- See also M. Sand, "Physics of Electron Storage Rings," SLAC-121 (1972).Two competing processes: radiation damping and quantum excitation

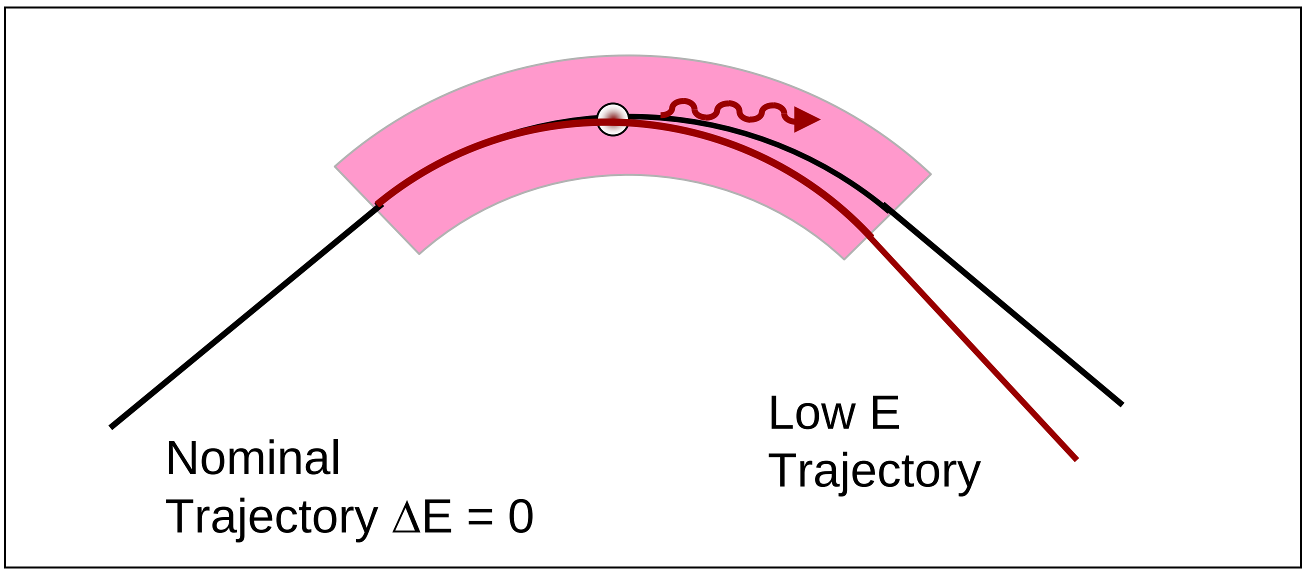
Radiation damping:

- Longitudinal phase space
  - Higher energy particles radiate more energy than low energy particles in the bends
- Transverse phase space
  - Radiation is emitted in a narrow cone centered on the *instantaneous* direction of motion
    - – Transverse momentum is radiated away
  - Energy is restored by the RF cavities *longitudinally*
  - Combined effect of radiation and RF is a loss in transverse momentum

Damping Ring Emittances (2)

Quantum excitation

- Radiation is emitted in discrete quanta
- Number and energy distribution etc. of photons obey statistical laws
- Radiation process can be modeled as a series of “kicks” that excite longitudinal and transverse oscillations



Start to oscillate about nominal trajectory

Damping Ring Emittances (3)

Quantum excitation occurs in the horizontal plane

Two effects determine the vertical emittance:

- Opening angle of the SR – typically limits at about 10% of design emittance
- Alignment errors which couple the horizontal to the vertical
  - Vertical bending due to orbit errors
  - Skew quadrupole fields due to quadrupole rotations or vertical sextupole misalignments
  - Tolerances are very tight – frequently a few microns

Combined effect of radiation damping and excitation:

$$\frac{\mathrm{d}\varepsilon}{\mathrm{d}t} = \varepsilon_{\mathrm{inj}} \mathrm{e}^{-2t/\tau} + \varepsilon_{\mathrm{equ}} \left(1 - \mathrm{e}^{-2t/\tau}\right)$$

ε_{inj} = injected emittance

ε_{equ} = equilibrium emittance

τ = radiation damping time

Issues in the Damping Rings

Emittance tuning and error correction

- Orbit correction and component stabilization

Injection/extraction of individual bunches

- Kicker rise/fall time – very large rings to store 3000 bunches

Dynamic aperture

- Long wigglers needed if the ring is too big

Single-bunch intensity

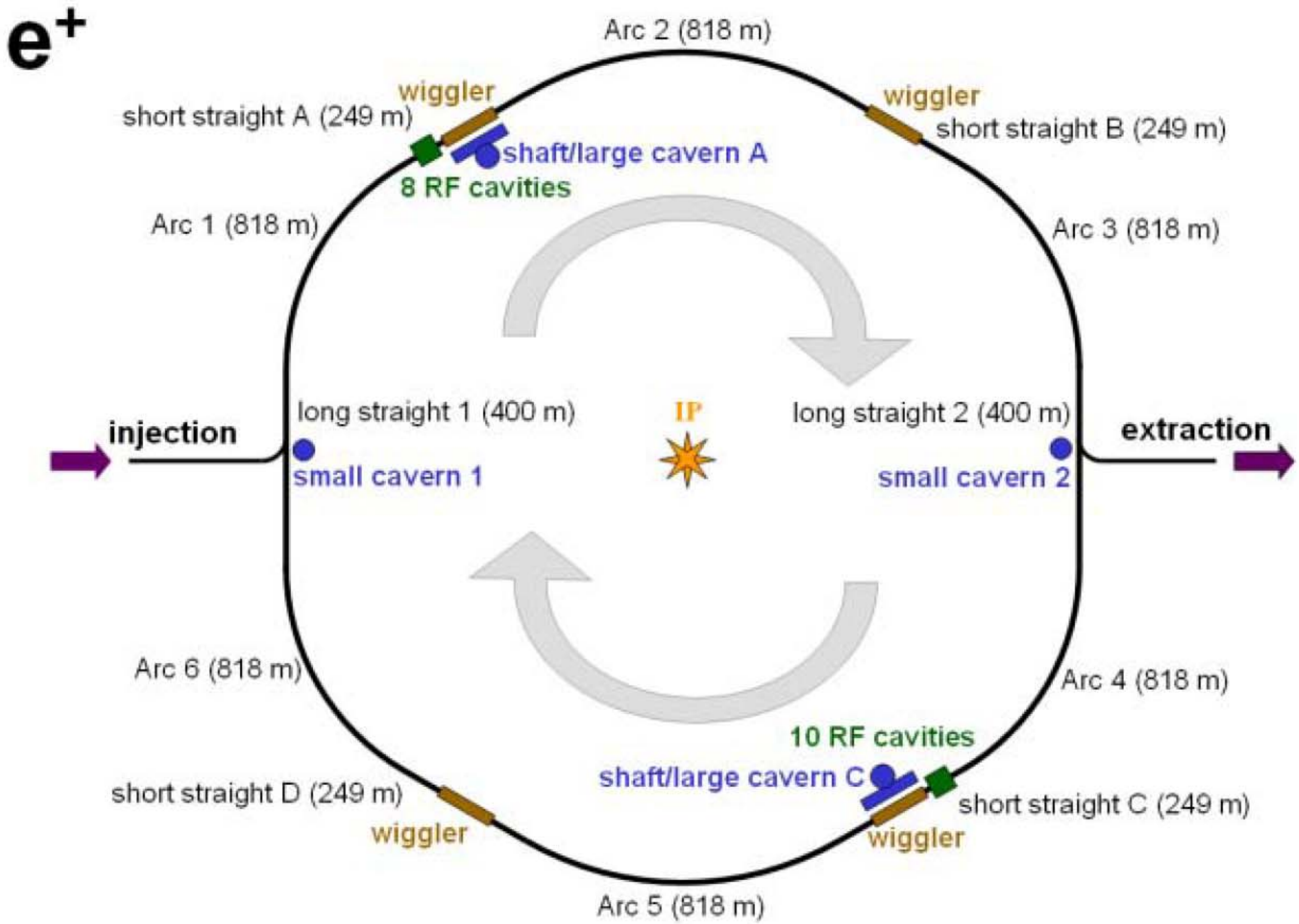
- Tune shift by self-Coulomb force (space charge)

Instabilities (mainly average current)

- Electron cloud instability
- Fast ion instability
- Classical collective instabilities

Rings operate in a new regime with fast damping and very small beam emittances

Layout of the positron Damping Ring



Bunch Compressors

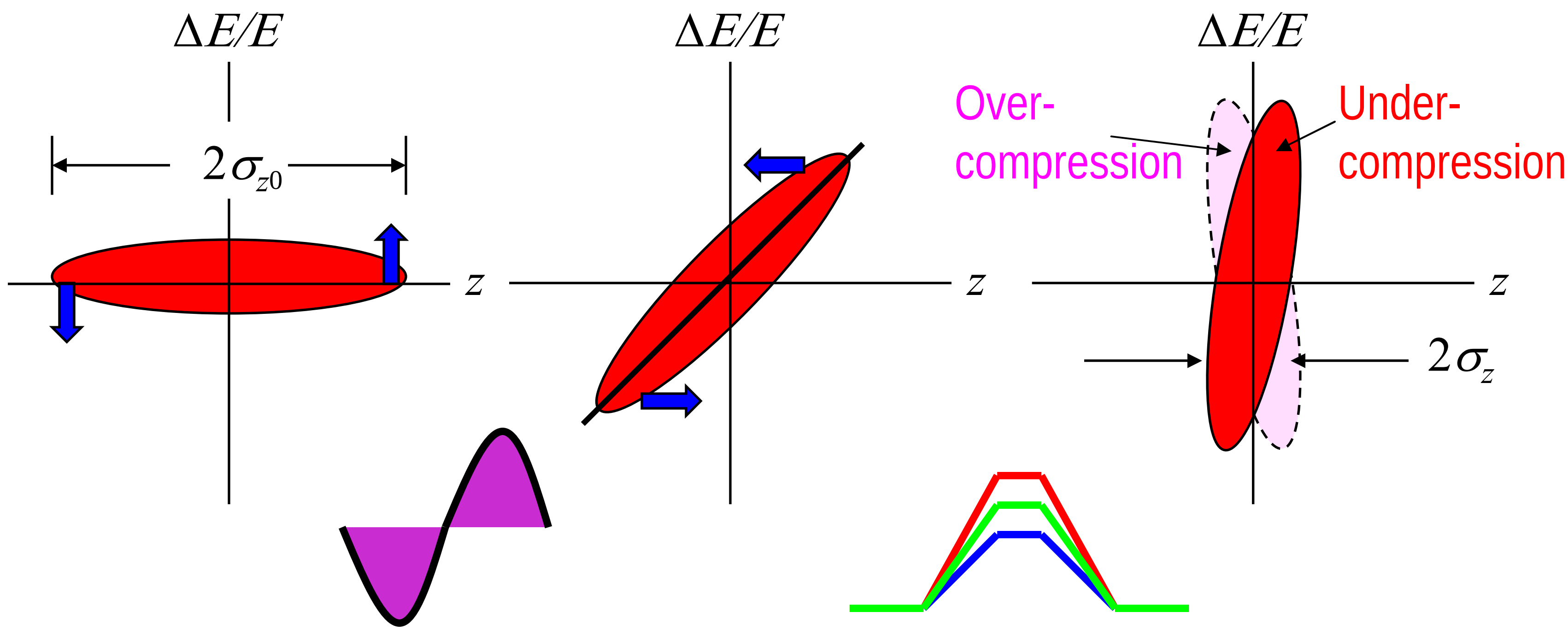
Bunch lengths in damping rings are ~1cm

- Seen that for high luminosity, would like short bunches at the IP

Compress bunches in magnetic bunch compressors after the damping rings

- Three problems:
  - Magnetic bunch compressors operate by bending the beam → synchrotron radiation can dilute the beam emittances
    - Normalized emittance growth scales as γ^6 in transport line
  - Longitudinal phase space is conserved → shortening the bunch length will increase the energy spread
    - Large energy spread in the linacs makes preserving the beam emittance more difficult $\Delta\varepsilon \sim (\Delta E/E)^2$
  - Longitudinal nonlinearities make compressing by more than 10~20x difficult in any single stage

Magnetic bunch compression



$V = V_0 \sin(\omega\tau)$

$\Delta z = R_{56} \Delta E/E$

RF Accelerating Voltage

Path Length-Energy Dependent Beamline

ILC BC Solution

Want capability of compressing from 6mm → 150 μm

Factor of 40 too large for a simple single-stage system

- Dual stage system:
  - Compress just after damping ring at 5 GeV by ~6x
  - Compress again at ~15 GeV point by another factor of ~8x
  - Provides large operating range while limiting the energy spread in the linacs → less emittance dilution than in a single-stage

Bunch compressor system also includes:

- Transverse and longitudinal collimation
- Spin rotation
- Skew correction to correct errors from damping ring or in the spin rotation system
- Extensive diagnostics before launching the beam into the linac

Linac Beam Dynamics

Main issues in the linac are:

- Short-range wakefields
- Dispersive emittance dilutions

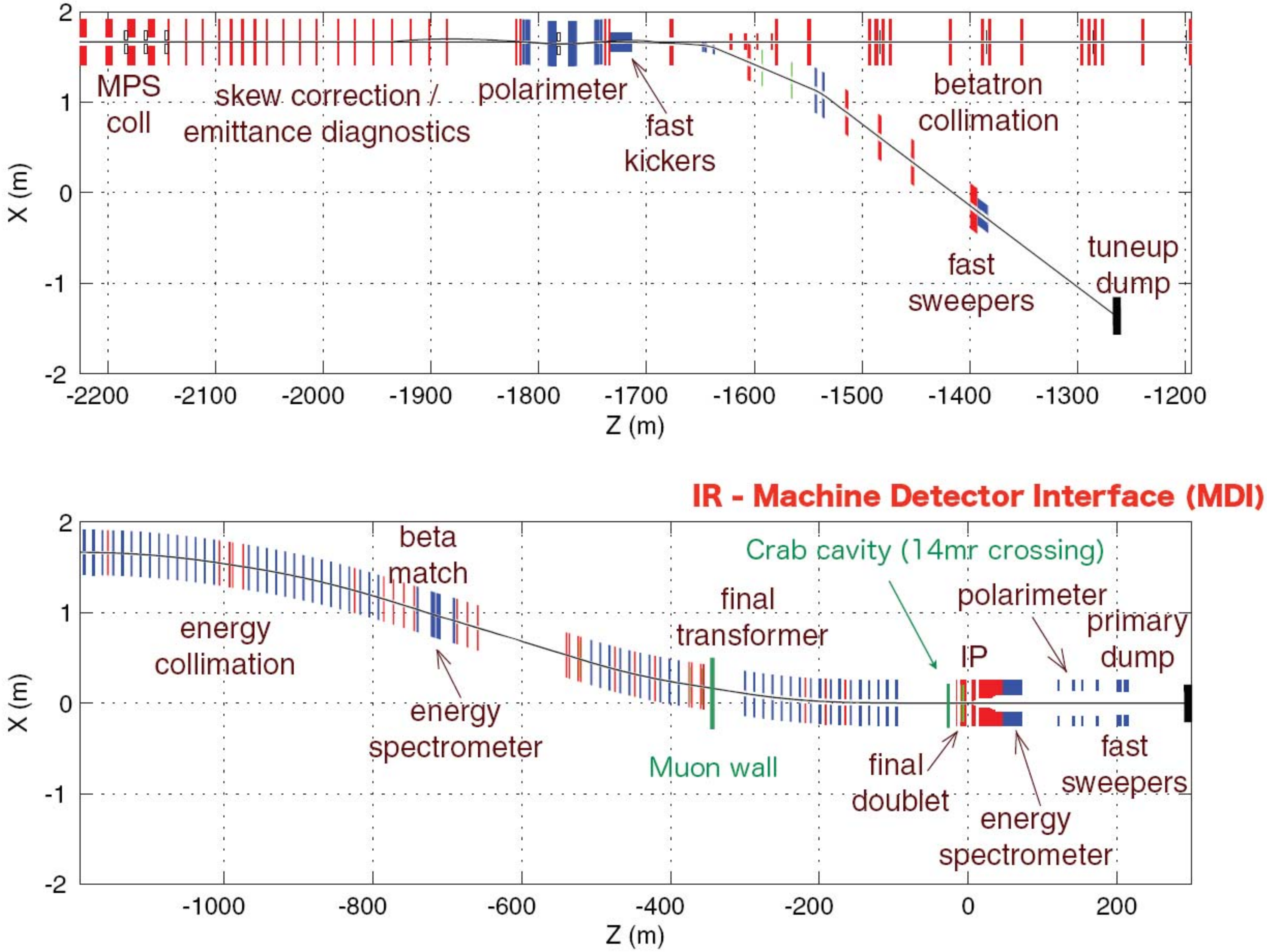
Superconducting linac has relatively loose tolerances for wakefield dilutions

- Cavity alignment at the 300 μm level

Need to be careful on alignment at the low energy ends of the linac due to the dispersive dilutions

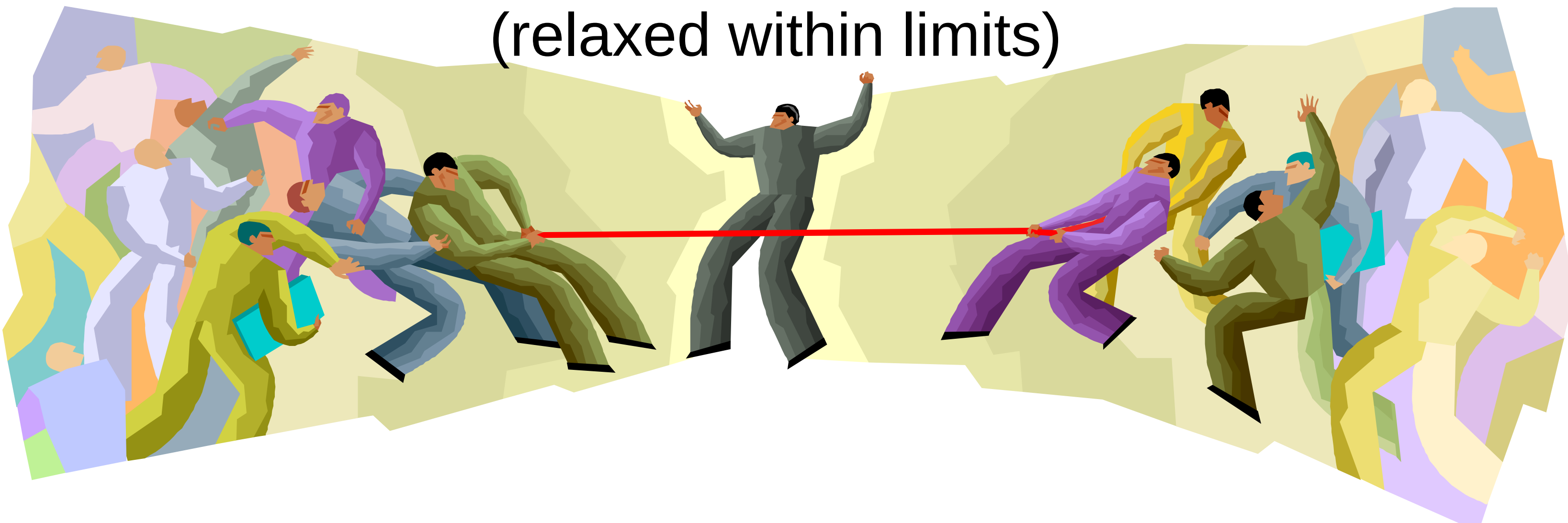
- Must align the quadrupoles at the 25 μm level to avoid dispersive dilutions: $\Delta\varepsilon \sim (\Delta E/E)^2$
- Requires beam-based alignment techniques

Beam Delivery System



Linac Parameter Trades

Linac
(relaxed within limits)



Damping Ring
(sources)

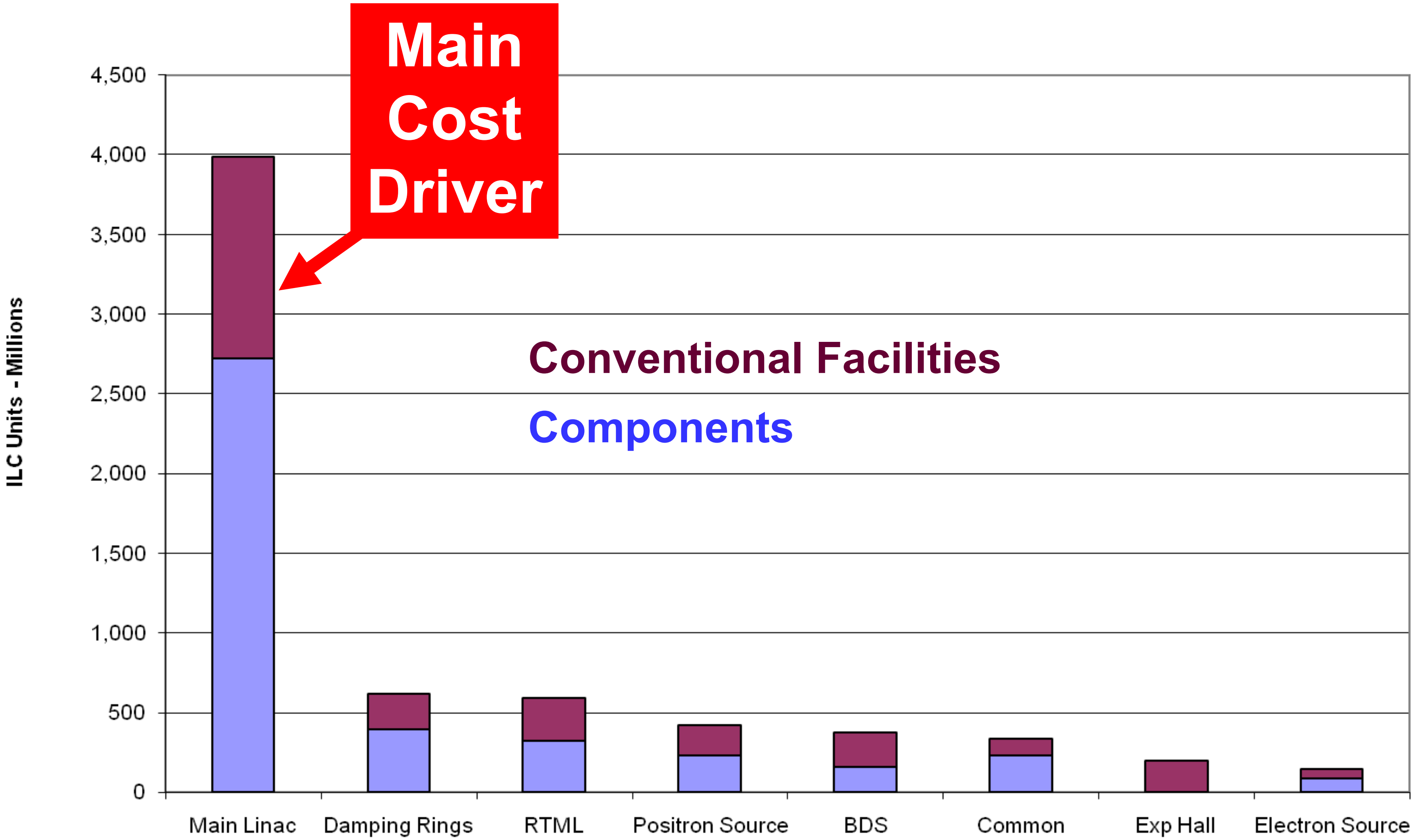
IR (IP)
Beam extraction

© Nick Walker, Snowmass 2005

RDR Design Parameters

Max. Center-of-mass energy	500	GeV
Peak Luminosity	~2x10^{34}	1/cm^{2}s
Beam Current	9.0	mA
Repetition rate	5	Hz
Average accelerating gradient	31.5	MV/m
Beam pulse length	0.95	ms
Total Site Length	31	km
Total AC Power Consumption	~230	MW

ILC Value – by Area Systems



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The Main Linac

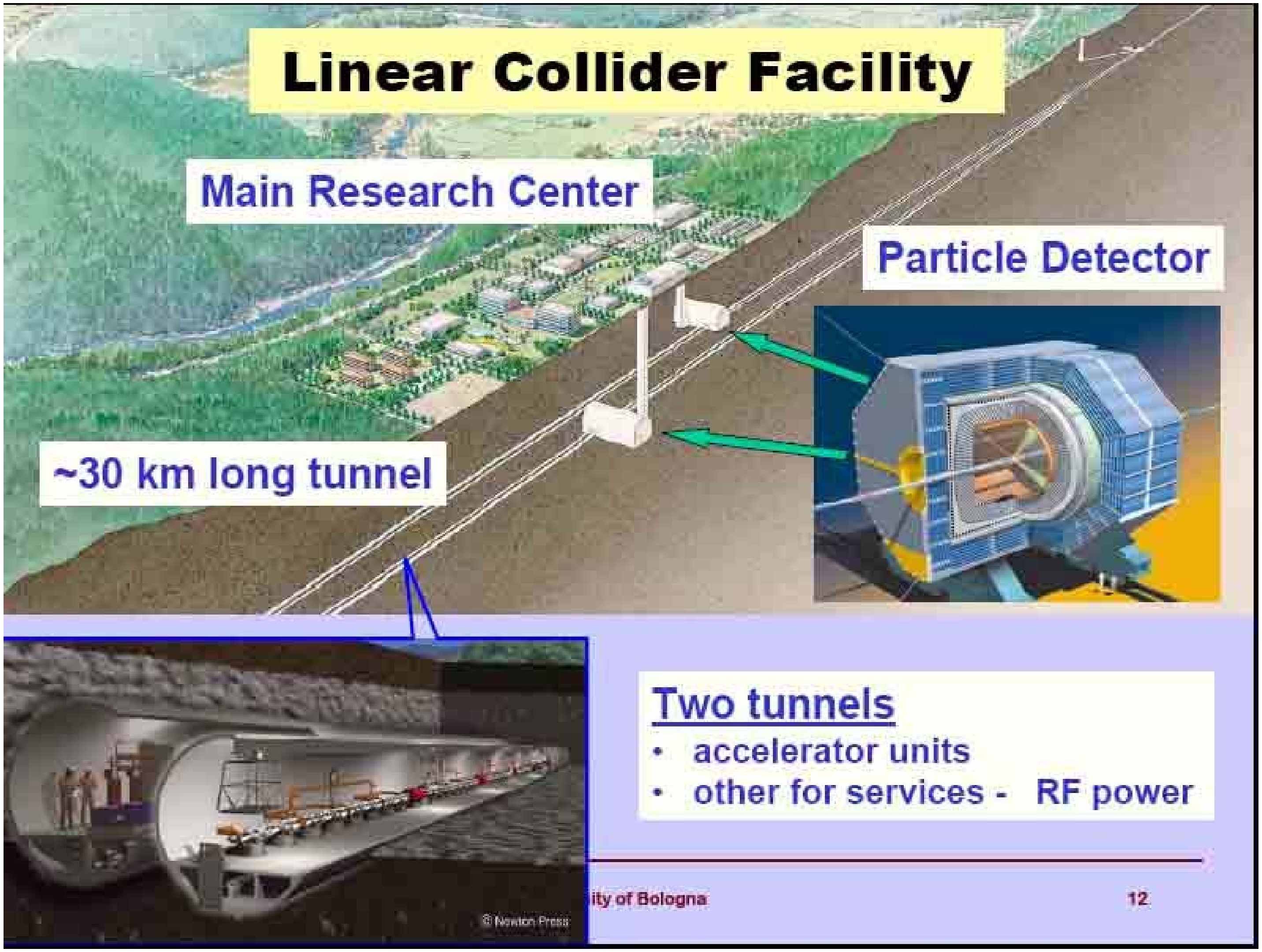
Subdivision	Length (m)	Number
Cavities (9 cells + ends)	1.326	14,560
Cryomodule (9 cavities or 8 cavities + quad)	12.652	1,680
RF unit (3 cryomodules)	37.956	560
Cryo-string of 4 RF units (3 RF units)	154.3 (116.4)	71 (6)
Cryogenic unit with 10 to 16 strings	1,546 to 2,472	10
Electron (positron) linac	10,917 (10,770)	1 (1)

Costs have been estimated regionally and can be compared.

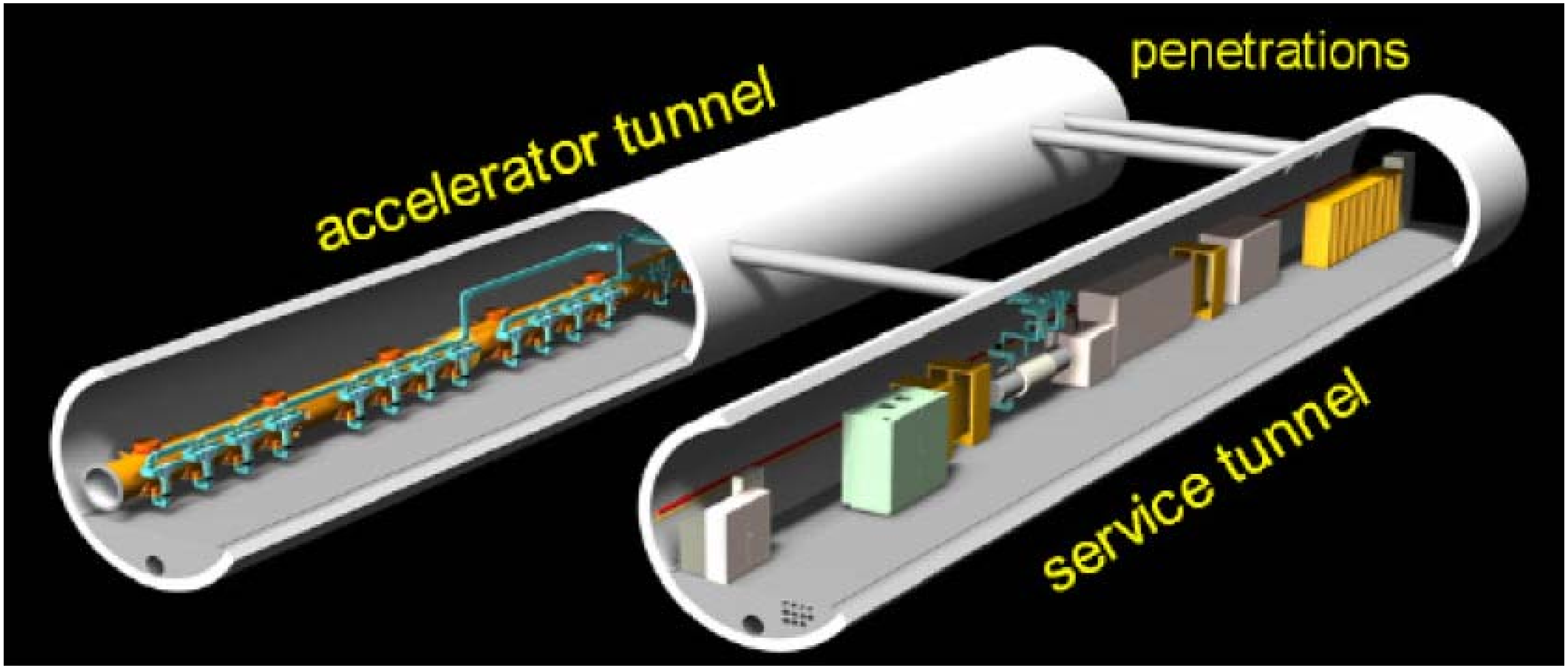
- Understanding differences requires detail comparisons – industrial experience, differences in design or technical specifications, labor rates, assumptions regarding quantity discounts, etc.

Important experience is expected from the European XFEL that is a 1/10 scale prototype of each of the two ILC Linacs

ILC Facility Overview



The ILC Linac in a Double Tunnel



- Three RF/cable penetrations every rf unit
- Safety crossovers every 500 m
- 34 kV power distribution

Summary of Conventional Facilities

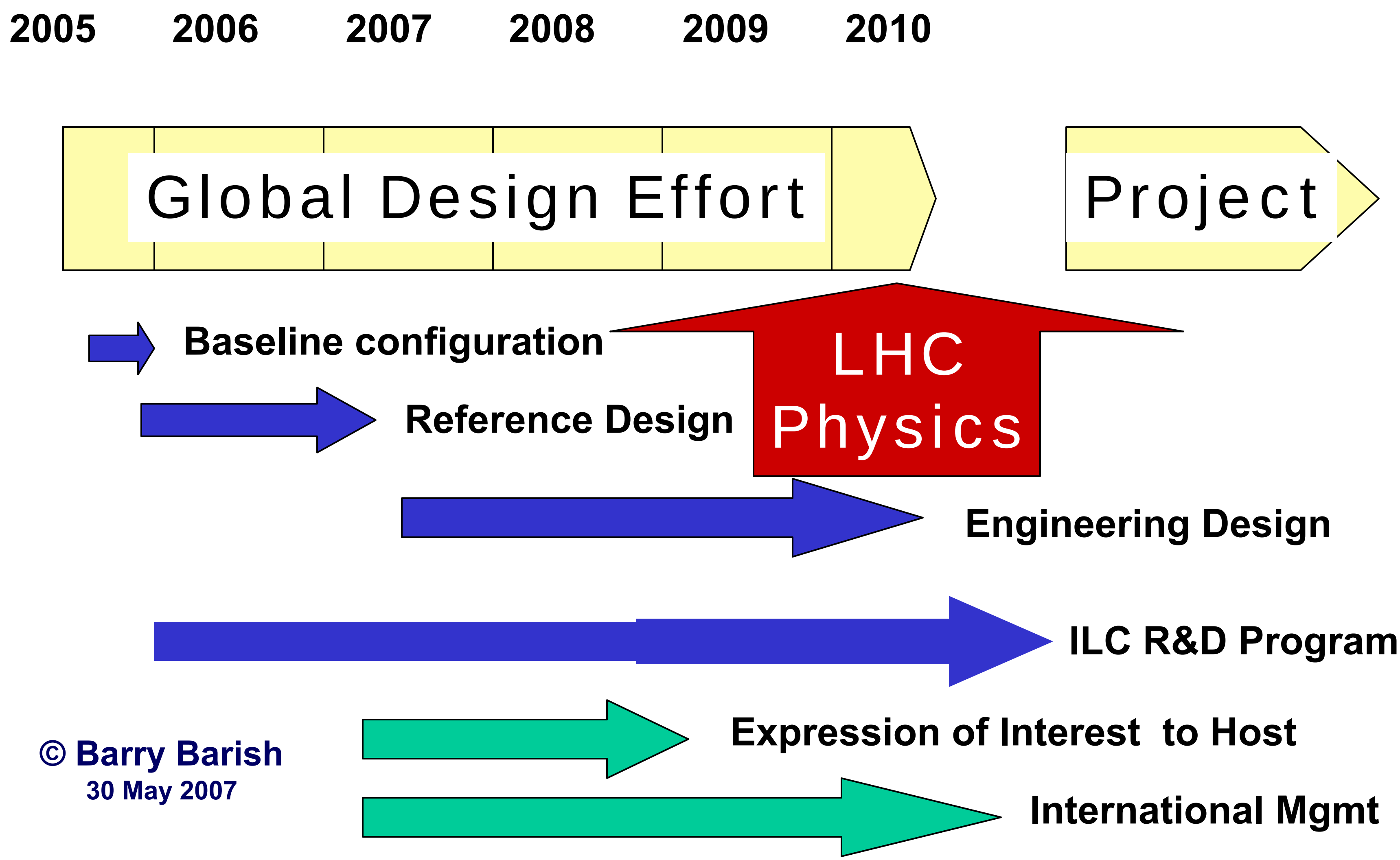
72.5 km tunnels ~ 100-150 meters underground

13 major shafts ≥ 9 meter diameter

443,000 m^3. underground excavation: caverns, alcoves, halls

92 surface "buildings", 52,000 m^2

ILC – Global Design Phase



© Barry Barish
30 May 2007

ILC site power: ~ 230MW

Main Linacs
140 MW

Sub-Systems
90 MW

RF
100 MW

78%

Cryogenics:
40 MW

Injectors

Damping rings

BDS

Auxiliaries

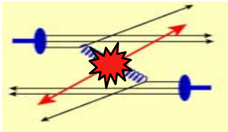
65%

60%

Beam Power
22 MW

TeV Scale Lepton Collider Strategies

The LHC

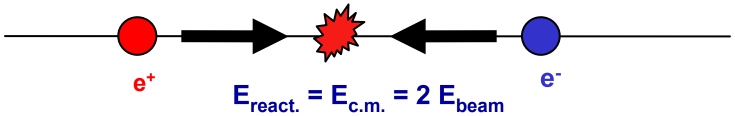


- will lead the way and has large reach
- **gluon-gluon,** quark-quark and quark-gluon collisions at **0.5 - 5 TeV**
- **Broadband initial state**

Complementary lepton collider for precision measurements

The ILC is the choice based of the expected LHC physics discovery

- A second view with high precision
- Electron-positron collisions with fixed energies, adjustable between **0.1 and 1.0 TeV**
- **Well defined initial state**



If LHC physics demands a > 1 TeV machine, a different lepton collider is required and 2 are the options presently under development

- **CLIC** that may be the answer with a longer time scale, depending on “feasibility” study (ILC + 5÷10 years for E_{cm} < 3 TeV)
- **Muon Collider** that is also a long term possibility, if “FEASIBLE” (ILC + 15 years for for E_{cm} < 4 TeV)

Aim of the CLIC study

develop technology for e-/e+ linear collider with the requirements:

- E_{cm} should cover range from ILC to LHC maximum reach and beyond $\Rightarrow$ **E_{cm} = 0.5-3 TeV**, (some physicists keep saying that 5 TeV would be better)
- L > few **10^{34} cm^{-2}** with acceptable background and energy spread
- E_{CM} and L to be reviewed once LHC physics results are available
- Design compatible with maximum length ~ **50 km**
- Affordable
- Total power consumption < **500 MW**

Physics motivation:

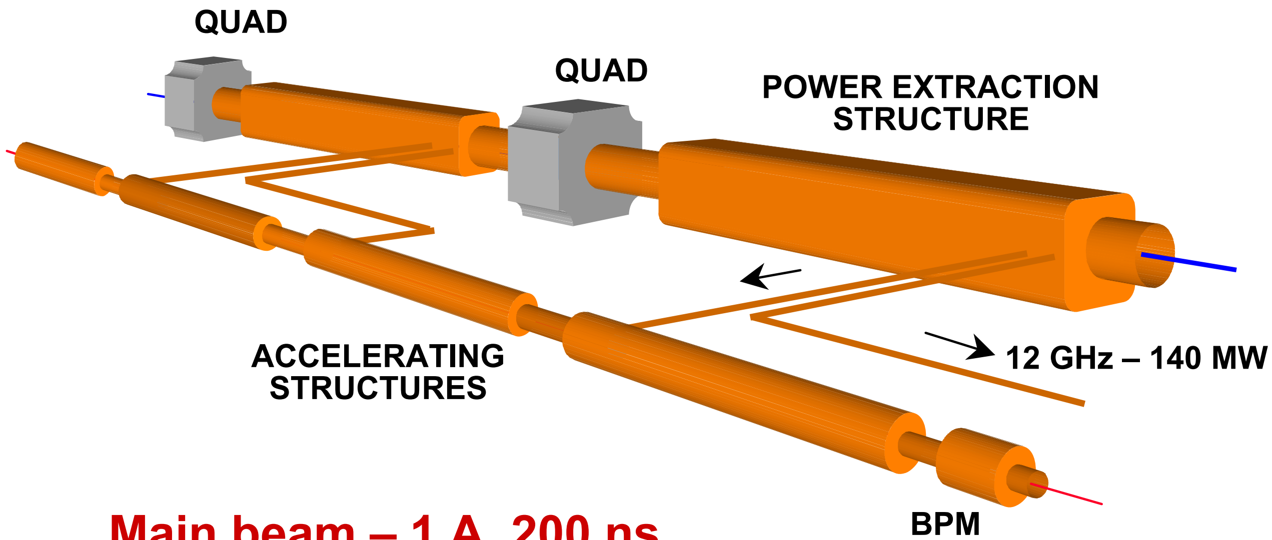
"Physics at the CLIC Multi-TeV Linear Collider: report of the CLIC Physics Working Group", ***CERN report 2004-5***

Present goal:

Demonstrate all key feasibility issues and document in a CDR by 2010 (possibly TDR by 2015)

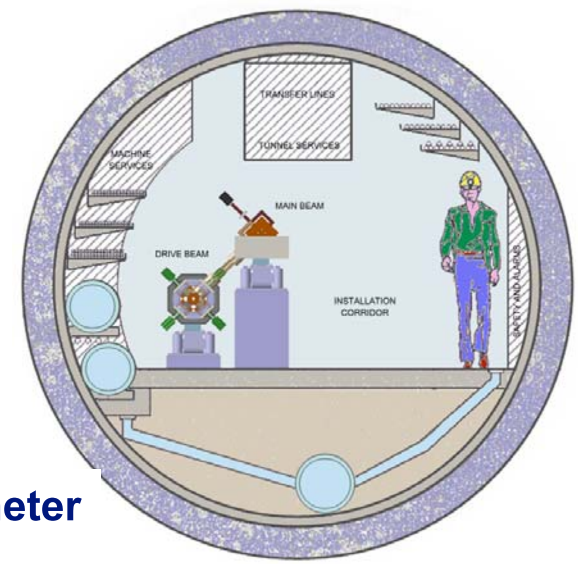
CLIC Two-Beam scheme

Drive beam - 95 A, 300 ns
from 2.4 GeV to 240 MeV



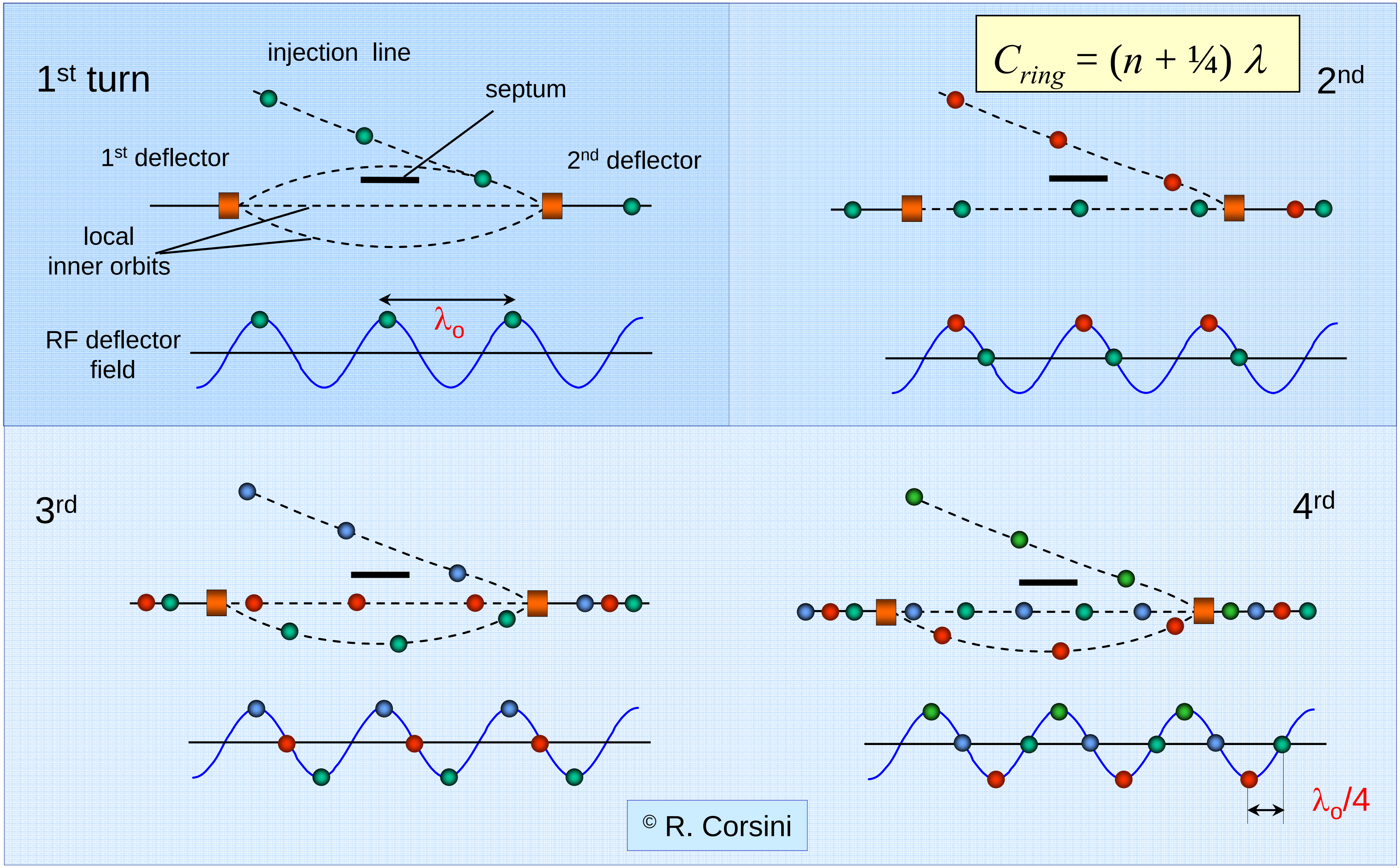
Main beam – 1 A, 200 ns
from 9 GeV to 1.5 TeV

CLIC TUNNEL CROSS-SECTION

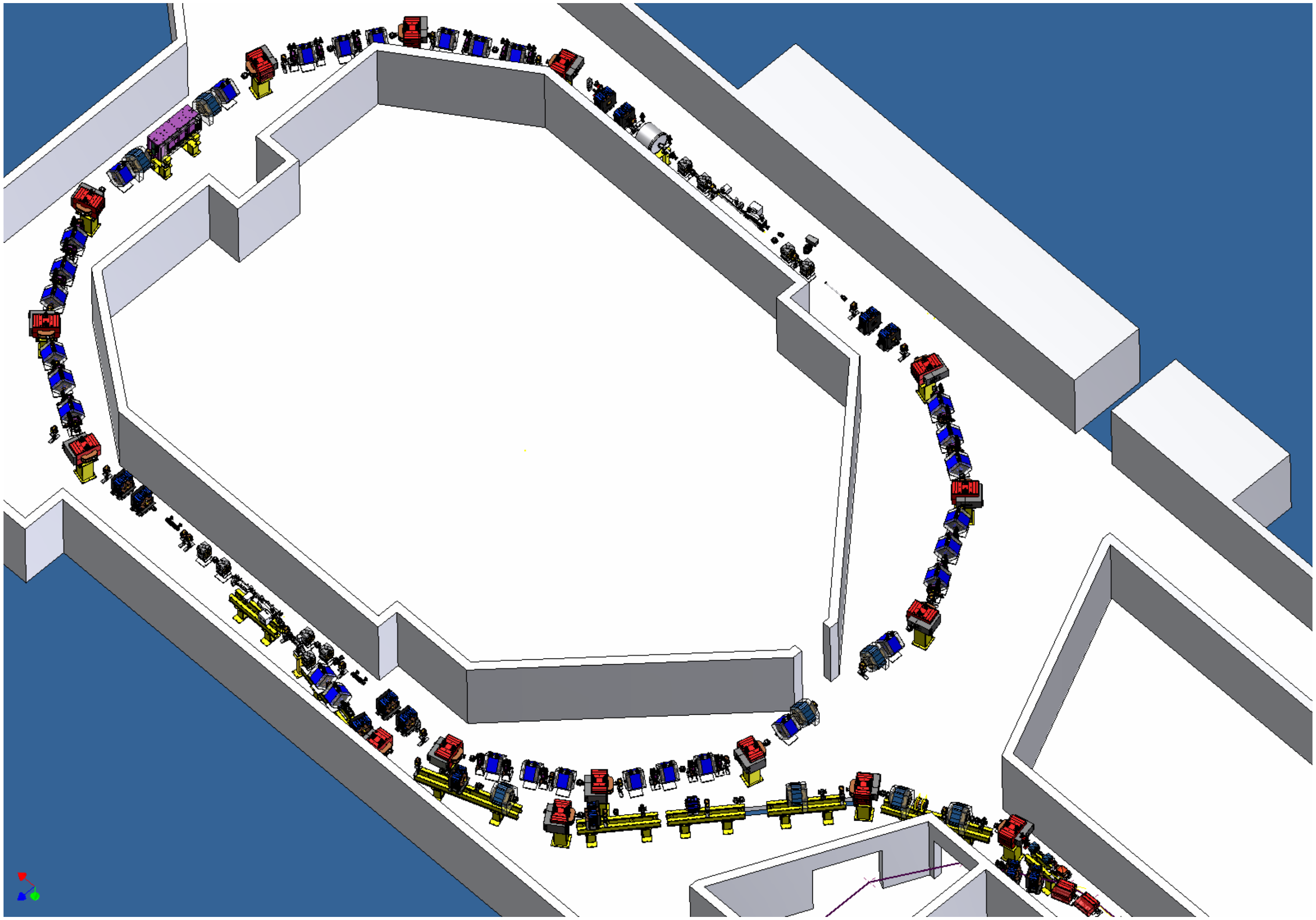


4.5 m diameter

RF injection in combiner ring

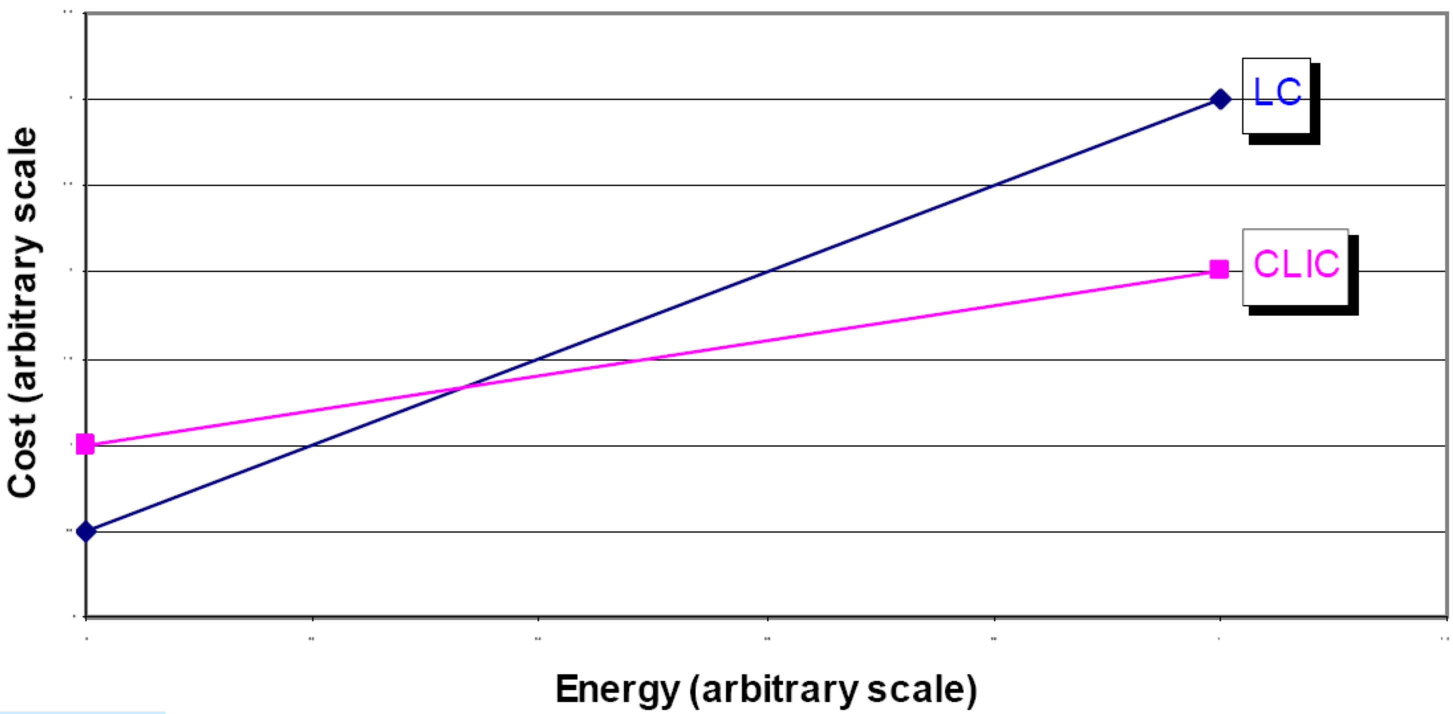


The combiner Ring of CTF3



ILC/CLIC Cost comparison

This pictorial graph want to show that, above a certain Centre of mass Energy, the CLIC Technology should be less costly than the ILC one. At the few TeV scale this possible advantage could became the decision driver



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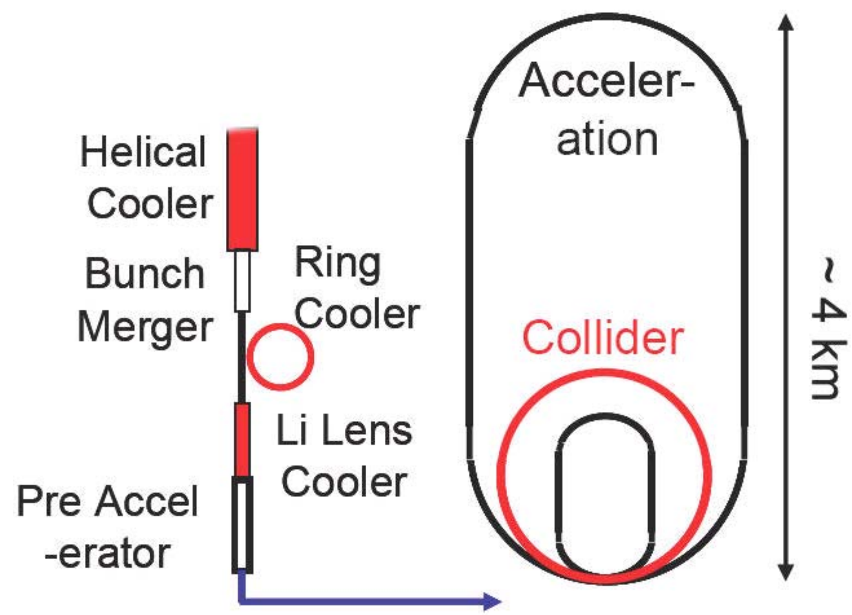
Muon Collider

Some properties of the muon, μ

- is an elementary particle: a **fermion** (matter constituent) of the **lepton** family
- has **negative electric charge** and **spin ½**, as the electron
- has a **mass of 105.7 MeV/c2**, which is **206.7 times the electron mass**.
- is not stable, having a **mean life time of 2.2 μs**

Some of the Muon Collider Issues

- Produce the required large amount of muons
- Cool them at the necessary small emittance (value less stringent but DR concept not applicable)
- Accelerate them very fast to have a longer life time in the lab frame
- and finally let them collide in a ring for at least a thousand of turns



Summary

The Physics Case must be proven by the LHC

Basic beam parameters are determined from the luminosity requirements

- ILC design then follows trying to meet those requirements
- CLIC and Muon Collider are also trying to do the same

Constrains arise from:

- IP physics (luminosity, beamstrahlung, disruption, depth of focus)
- Damping rings, bunch compressor and positron source
- Superconducting RF Linac Technology for ILC
- The complex of new sophisticated technologies for CLIC and Muon Colliders