Challenges of Large Scale Accelerator Facilities

- The ILC and Beyond -

“I hear the roar of a big machine“
The Sisters of Mercy

Karsten Büßer

Accelerators and Detectors at the Technology Frontier

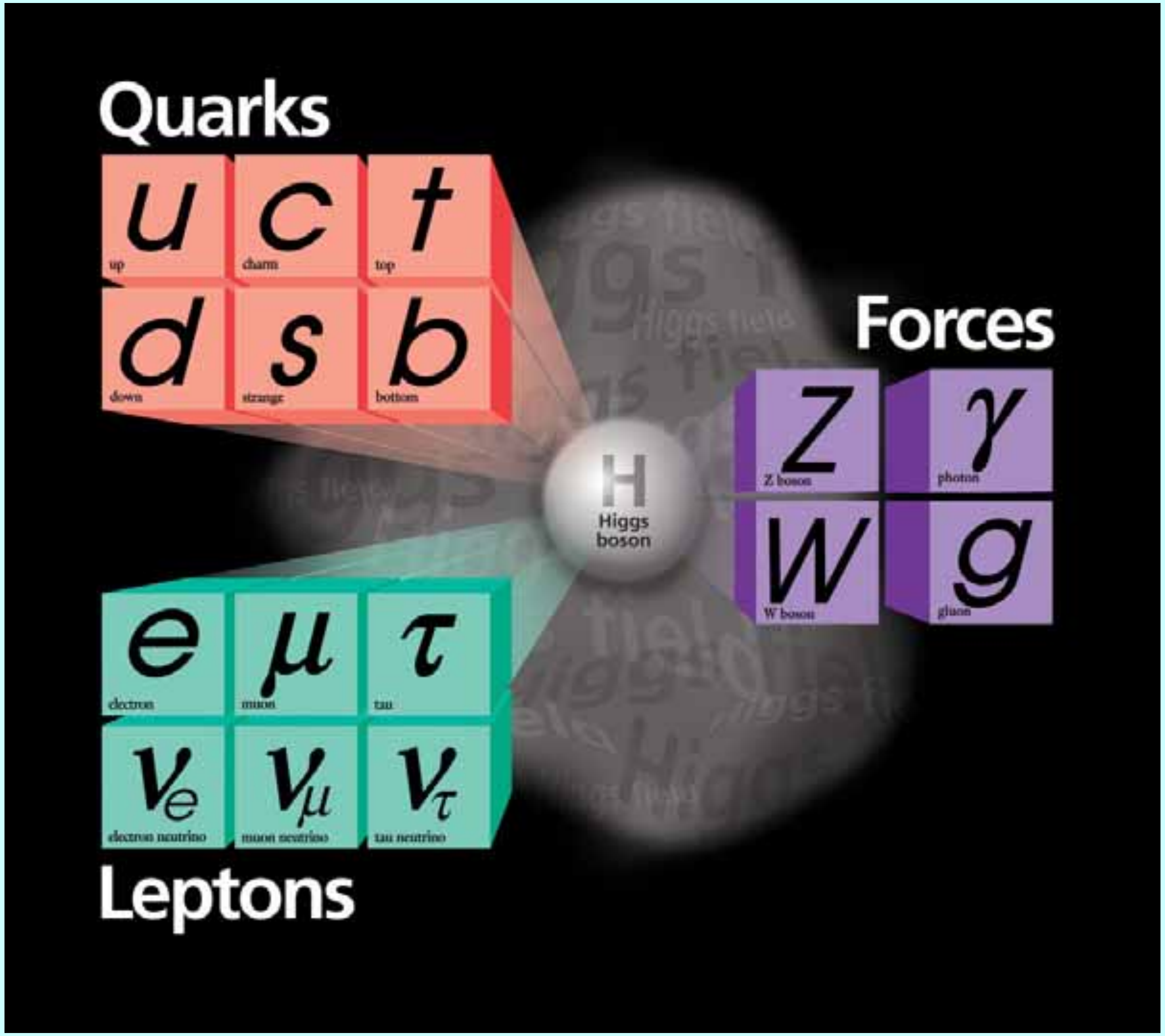
430. Wilhelm und Else Heraeus-Seminar

29.04.2009

The Standard Model of Particle Physics

- Extremely successful description of the microcosm
- 12 matter particles
- 4 force mediators

- 1 missing piece:
  Higgs Boson



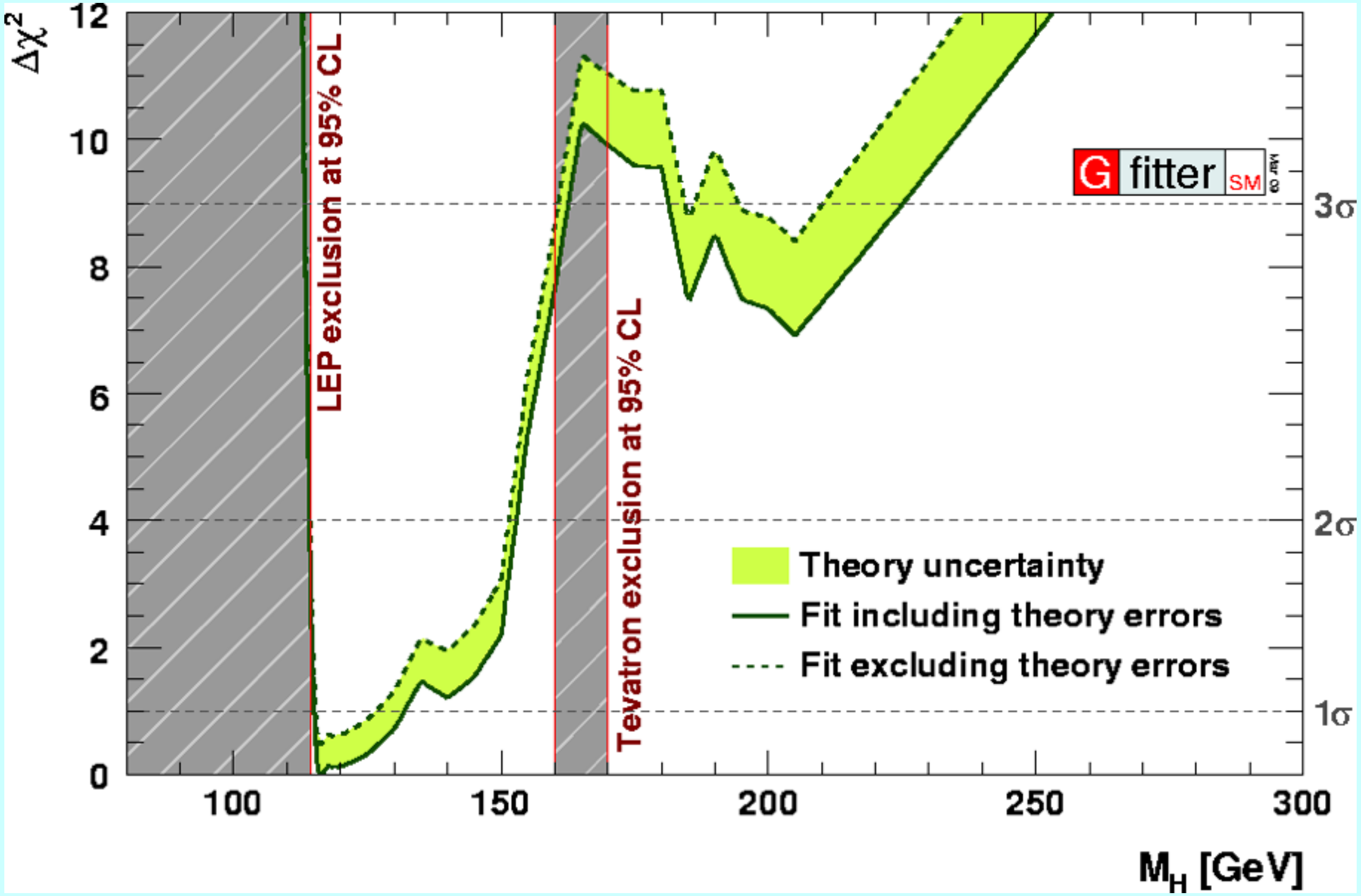
Shortcomings of the Standard Model

The Standard Model of particle physics leaves open questions:

- Where ist the Higgs-Partice?
- Do the forces unite?
- Why are there three generations of particles?
- Why are there 19 free parameters?
- Why do the electric charges of electrons and protons cancel exactly?
- What is the origin of dark matter and dark energy?
- (…)

We are looking for an underlying unifying theory of everything!

The Higgs is Around the Corner (?)



The Large Hadron Collider at CERN

Hadron and Electron Machines

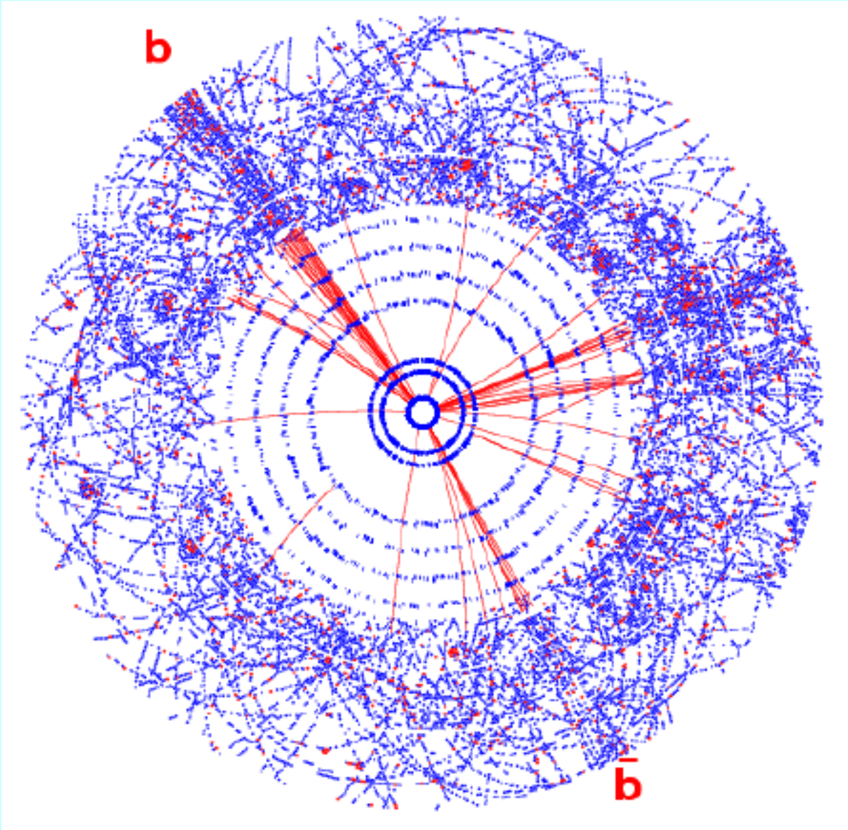
p  p

e^+ • • e^-

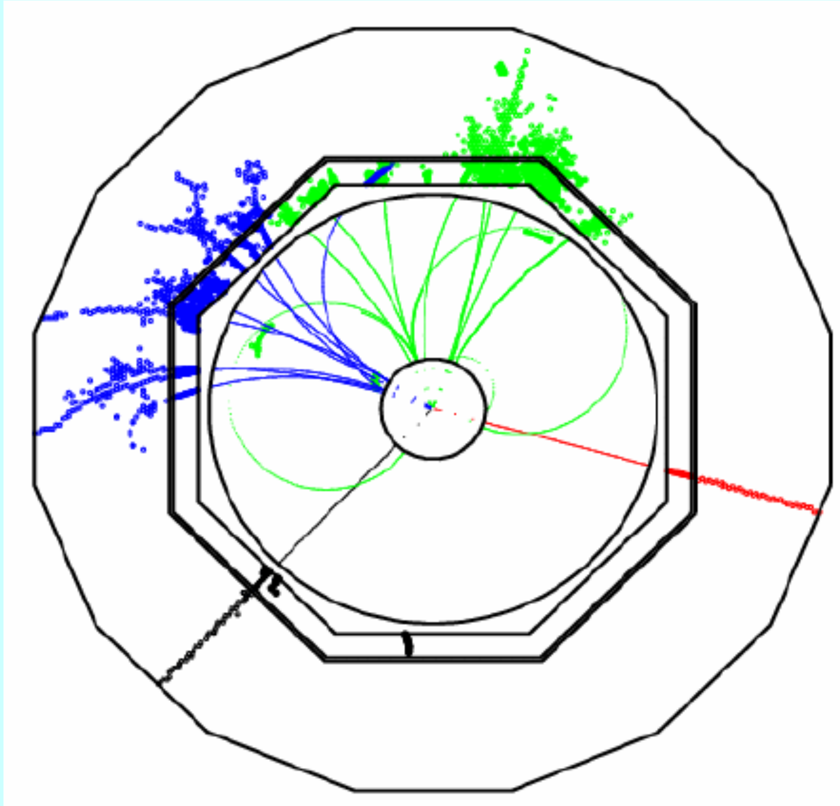
- Proton-proton colliders:
  - Energy range higher (limited by magnet bending power)
  - Composite particles, different initial state constituents and energies in each collision
  - Complicated hadronic final states
- Discovery machines
- Limited abilities for precision measurements

- Electron positron colliders:
  - Energy range limited (by RF power)
  - Point-like particles, exactly defined initial state quantum numbers and energies
  - Hadronic final states easy
- Precision machines
- Discovery potential

Electrons vs Protons

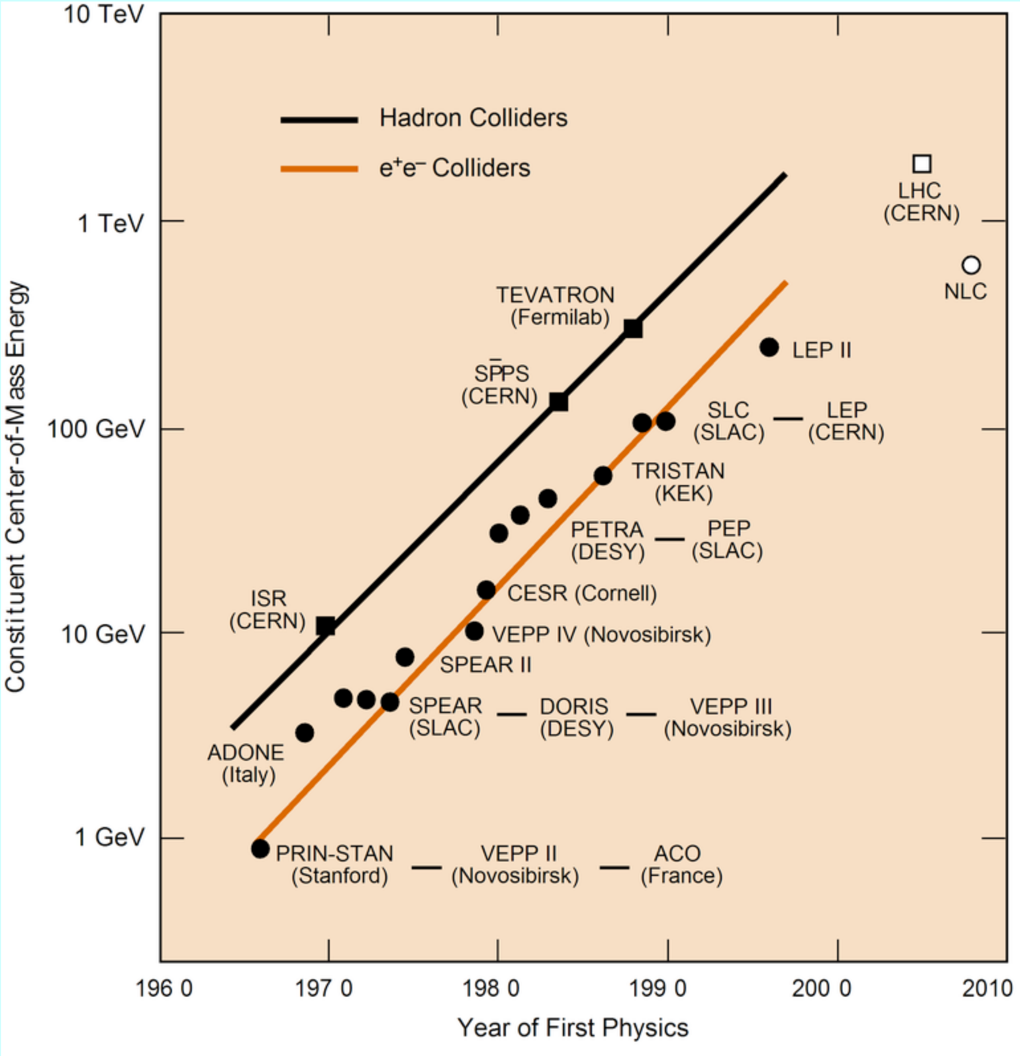


pp → H + X



e^+e^- → HZ

Collider History



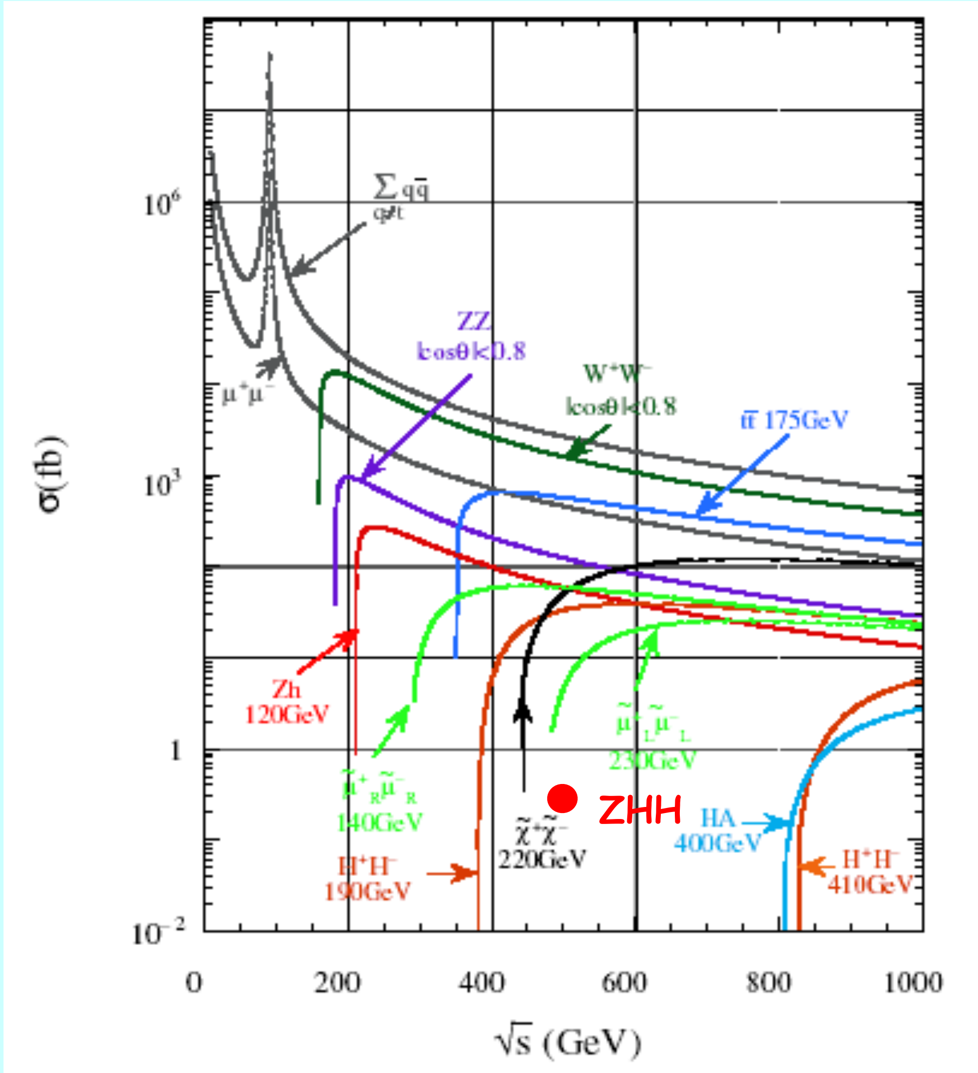
LEP@CERN
E_{max} = 209 GeV
P_{RF} = 30 MW

Requirements for the Next Lepton Collider

The e^+e^- cross section drops ~1/√s

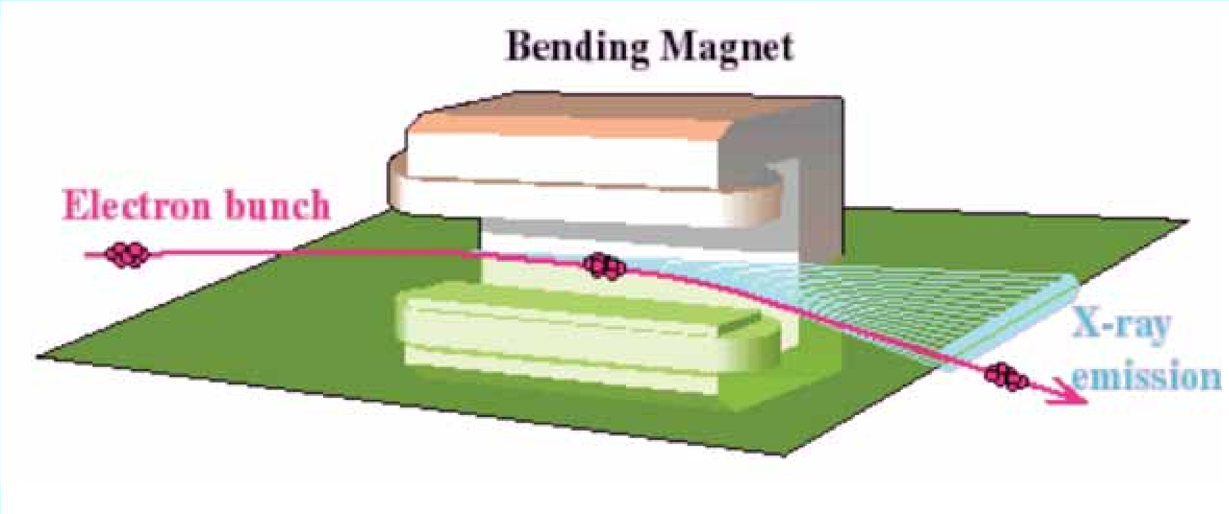
The key parameters for a competitive e^+e^- machine are

- energy reach (TeV region)
- luminosity (~10^{34} cm^{-2} s^{-1})



The Limits of Circular Accelerators

A law of nature: a charged particle on a curved trajectory radiates synchrotron radiation



- Energy loss per revolution ~ $1/m^4$,
- RF Power needed: $P_{RF} \sim E^4/r$

Cost Scalings for Storage Rings

Cost for RF:

$$€_{RF} \sim E^4/r$$

Linear costs (tunnelling, beam line, etc.):

$$€_{lin} \sim r$$

Total cost:

$$€_{tot} = €_{RF} + €_{lin} \sim E^2$$

$$r_{opt} \sim E^2$$

For details check: B. Richter, NIM 136 (1976) pp. 47-60

Scaling LEP

	LEP-II	Super-LEP	HYPER-LEP
E_{cm}	180 GeV	500 GeV	2 TeV
L	27 km	200 km	3200 km
ΔE	1.5 GeV	12 GeV	240 GeV
$€_{tot}$	2 billion	15 billion	240 billion!

Table by James Jones

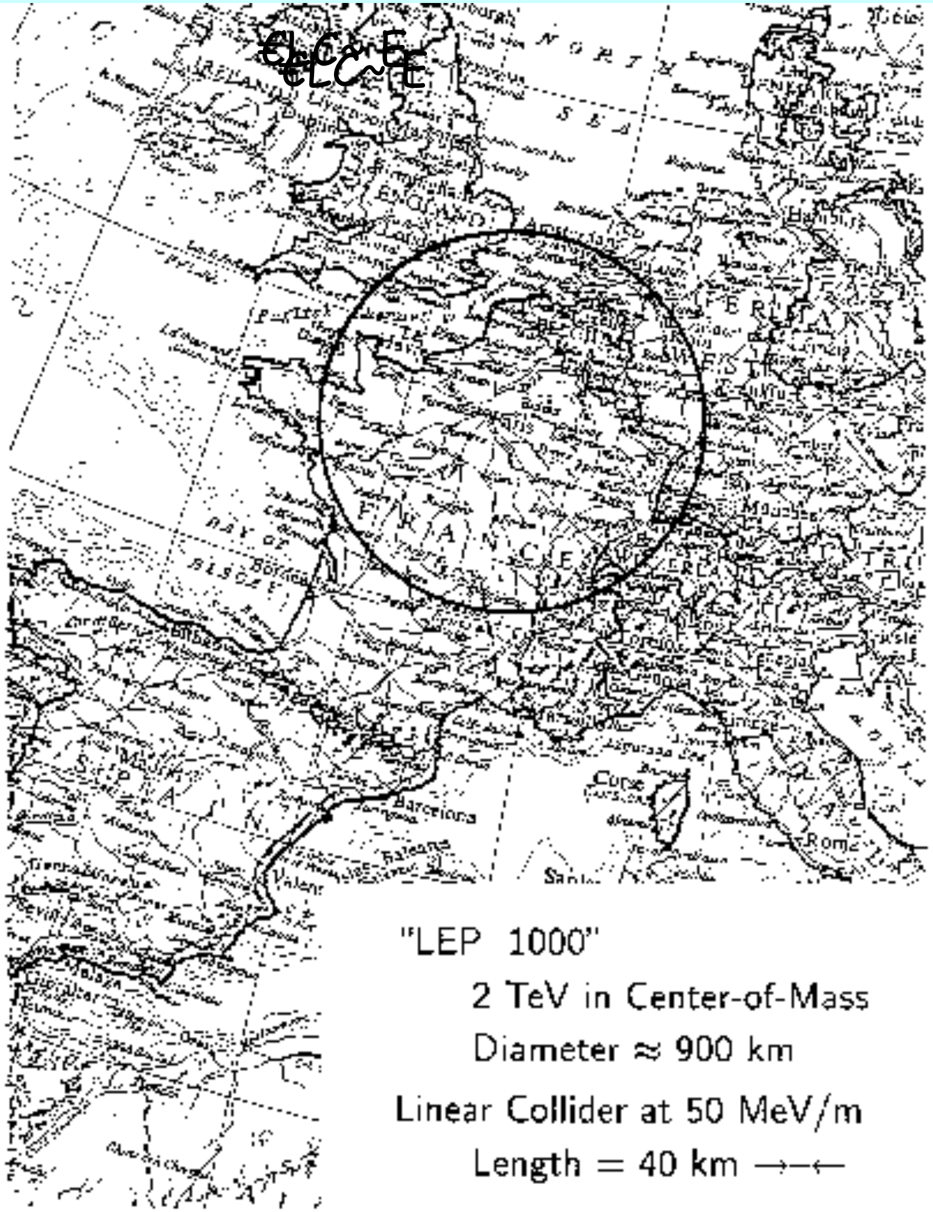
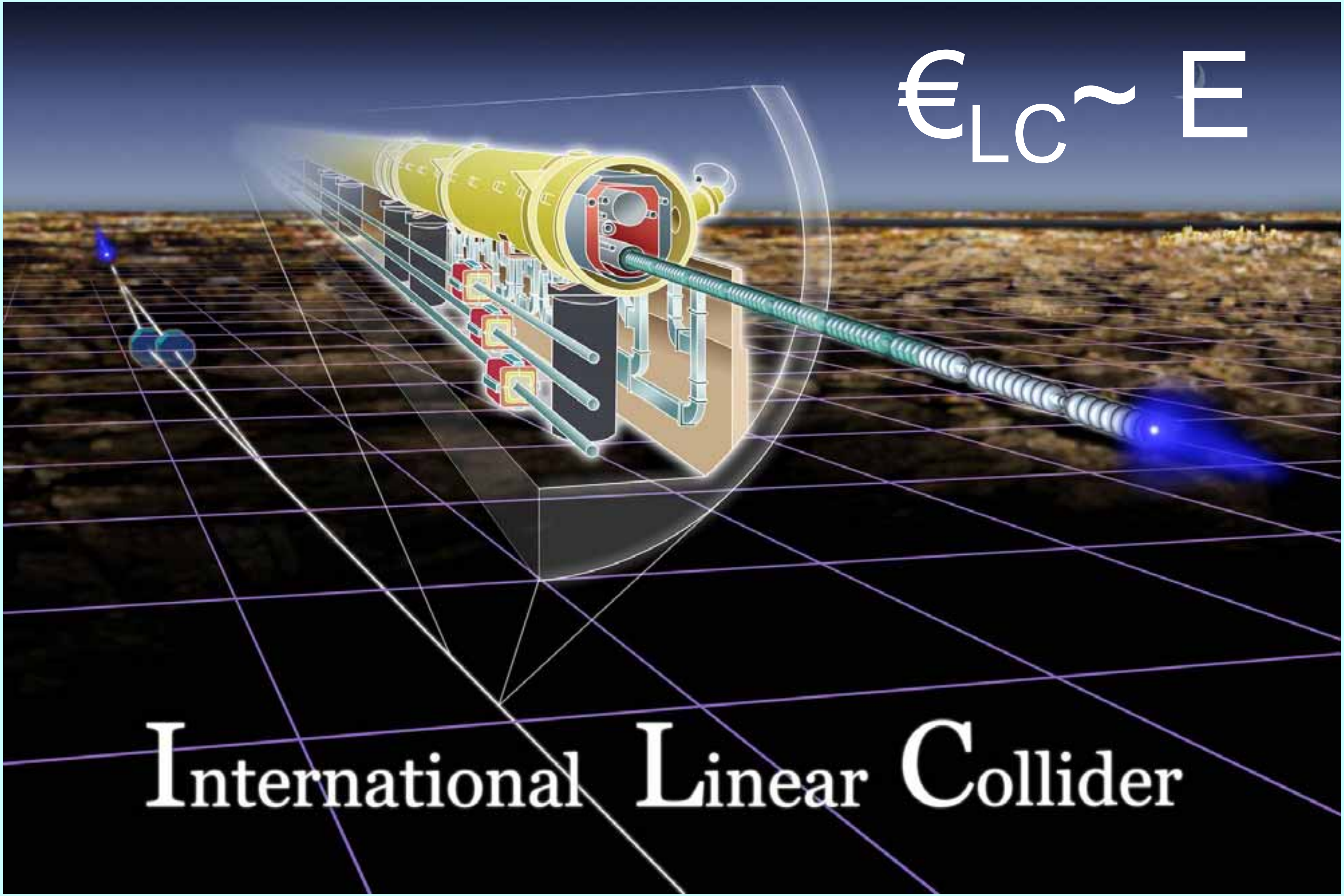


Figure by Gregory Loew

The next e^+e^- collider will be linear:

$€_{LC} \sim E$

The Future is Linear



Not a New Idea!

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

M. Tigner

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

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

"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."

The Luminosity Issue

The Luminosity ($cm^{-2}\ s^{-1}$) for a collider with Gaussian beams is given by:

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

n_b = bunches / train

N = particles per bunch

f_{rep} = repetition frequency

$4\pi\sigma_x\sigma_y$ = beam cross-section at IP

H_D = beam-beam enhancement factor

The Luminosity Issue: RF Power

Introducing the Beam Power:

$$n_b N f_{rep} E_{cm} = P_{beams}$$
$$= \eta_{RF \to beam} P_{RF}$$

yields

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

RF Power

Some numbers:

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

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

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

→ P_{beams} = 8 MW

Adding efficiencies Wall plug → RF → beam

yields AC power needs > 100 MW just to accelerate beams and maintain luminosity!

Storage Ring vs Linear Collider

LEP f_{rep} 44 kHz

ILC f_{rep} few Hz (power limited)

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

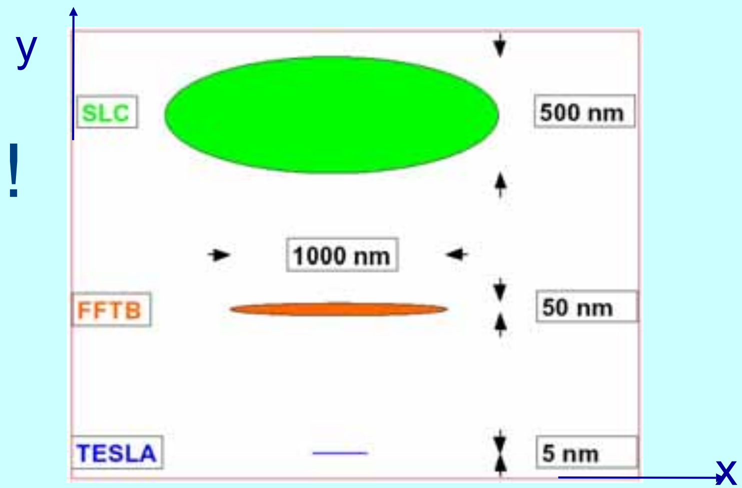
Factor ~ 4000 in *L* already lost!

Recover by pushing hard on the beam spot sizes at collision:

LEP: 130 x 6 μm^2

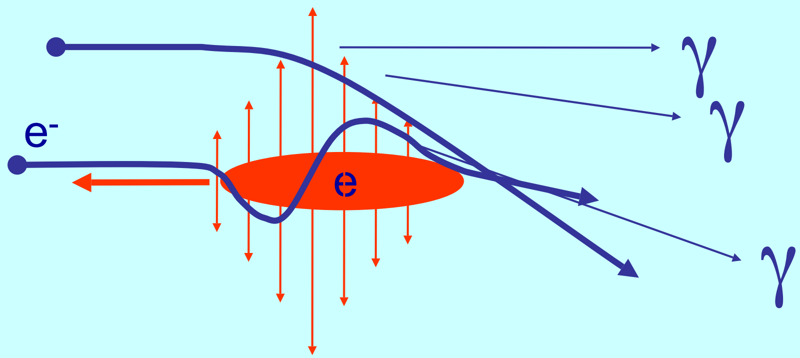
ILC: 500 x 5 nm

Needed to achieve L~ O(10^{34} cm^{-2} s^{-1})!



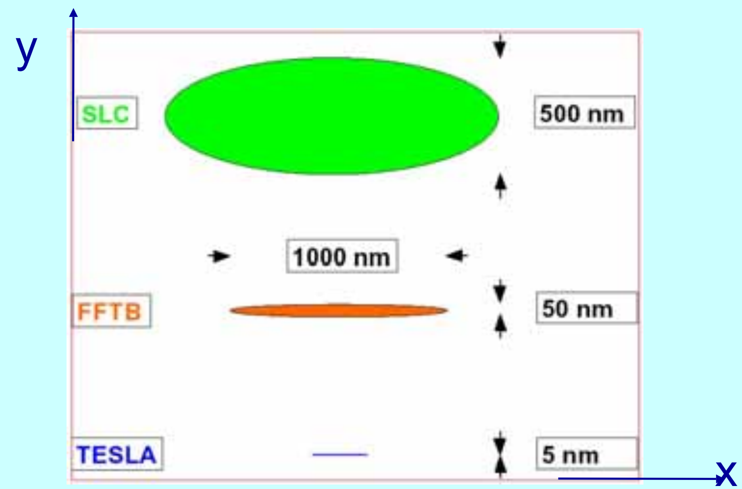
Beamstrahlung

- Strong mutual focusing of beams gives rise to significant luminosity enhancement ($H_d \approx 2$): Pinch effect
- e± pass through intense field of opposite beam, radiate hard photons: Beamstrahlung



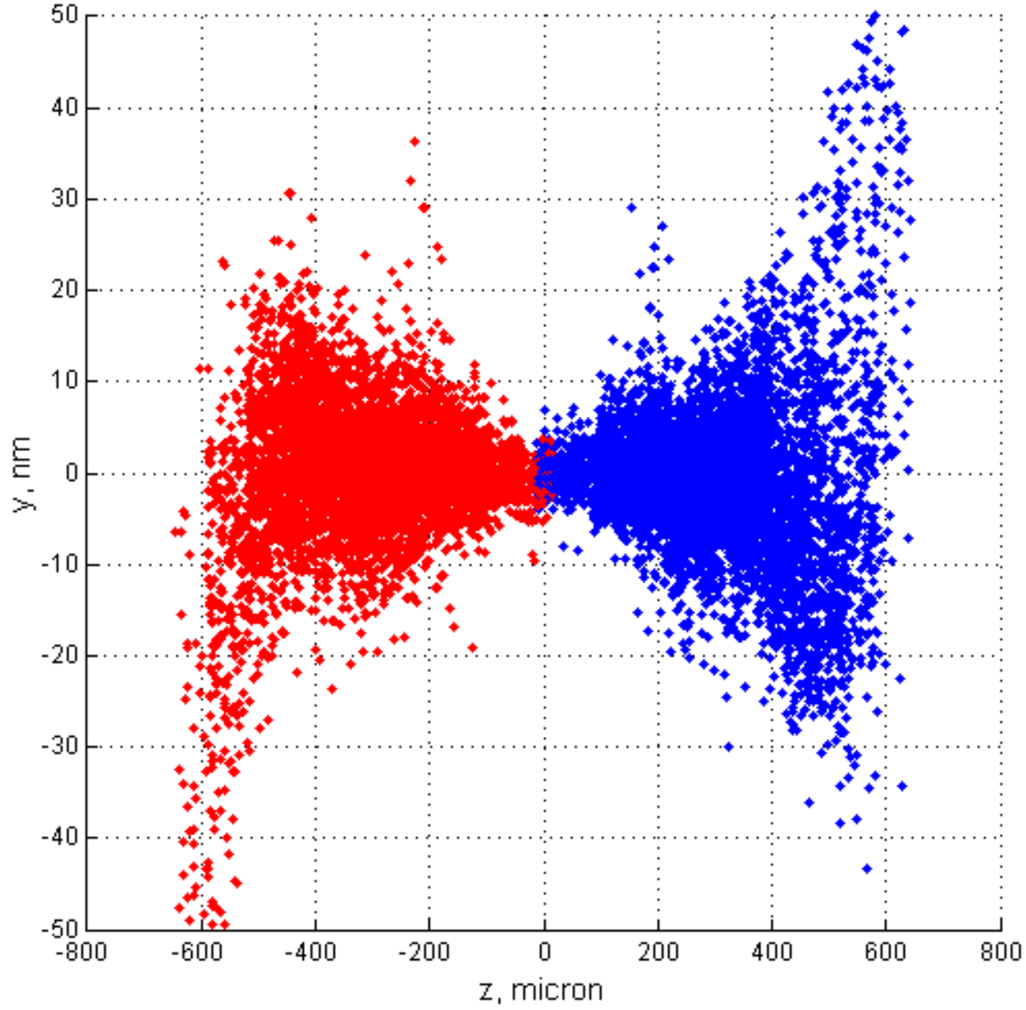
$$\delta_{BS} \approx 0.86 \frac{e r_e^3}{2 m_0 c^2} \left(\frac{E_{cm}}{\sigma_z} \right) \frac{N^2}{(\sigma_x + \sigma_y)^2}$$

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



Chose flat beams!

Beam-Beam Interaction



Luminosity Scaling Law

Chose flat beam ($\sigma_y << \sigma_x$):

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

Luminosity law:

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

yields:

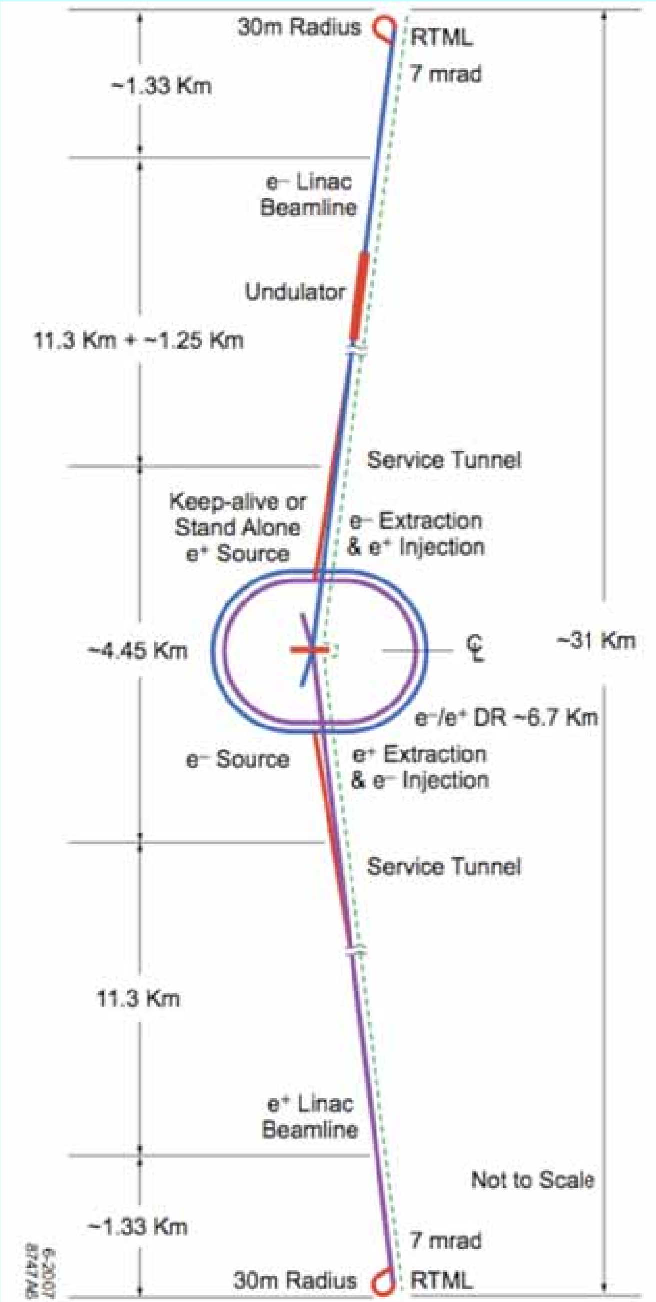
$$L \propto \frac{\eta_{RF} P_{RF}}{E_{cm}^{3/2}} \frac{\sqrt{\delta_{BS} \sigma_z}}{\sigma_y}$$

How to Maximise Luminosity

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

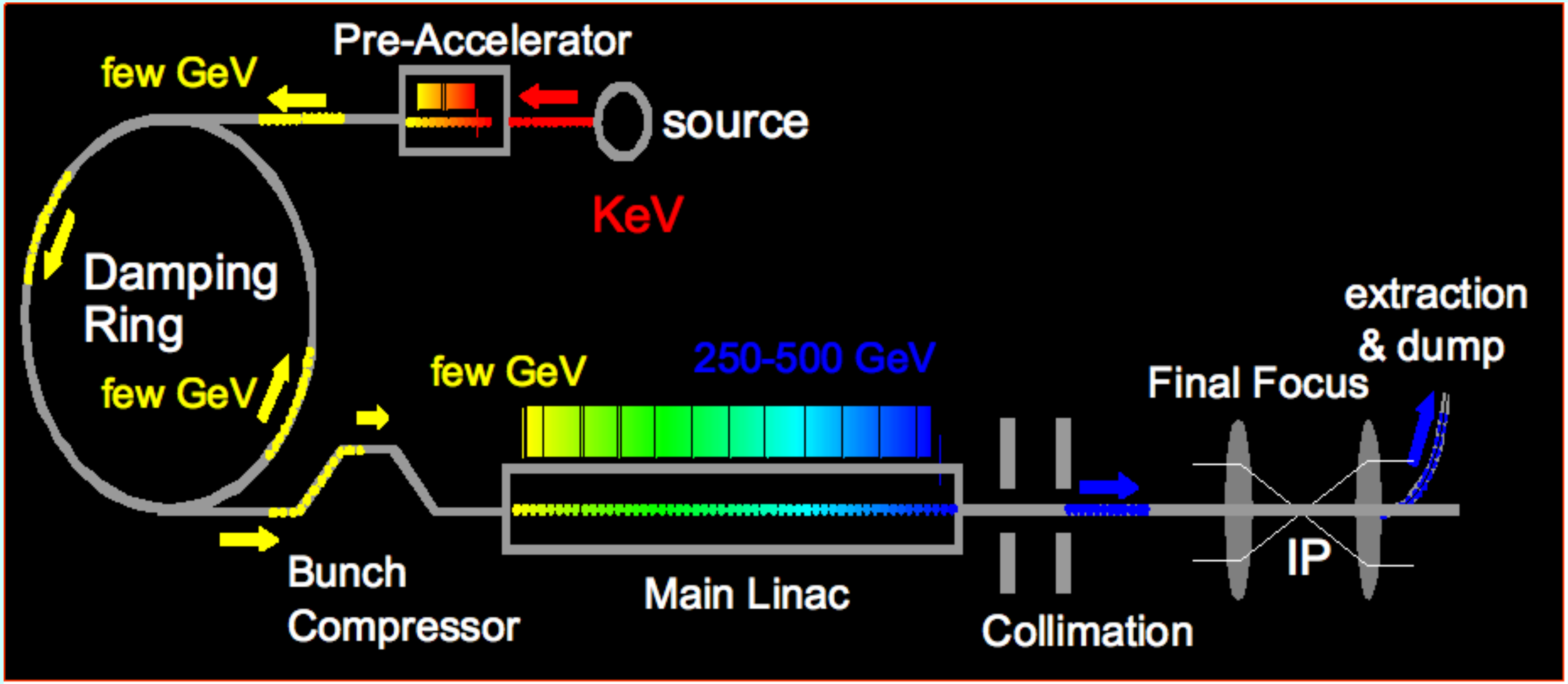
- high RF beam-power conversion efficiency η_{RF}
- high RF power P_{RF}
- small vertical beam size σ_y
- large bunch length σ_z
- could go to higher beamstrahlung δ_{BS}, if willing to live with consequences

ILC Baseline Design



Parameter	Unit		ILC/LEP
Center-of-mass energy range	GeV	200 - 500	2.5
Peak luminosity[a)]	$cm^{-2}s^{-1}$	2×10^{34}	200
Average beam current in pulse	mA	9.0	2
Pulse rate	Hz	5.0	0.0001
Pulse length (beam)	ms	~ 1	
Number of bunches per pulse		1000 - 5400	~3000
Charge per bunch	nC	1.6 - 3.2	~0.05
Accelerating gradient[a)]	MV/m	31.5	4.5
RF pulse length	ms	1.6	
Beam power (per beam)[a)]	MW	10.8	
Typical beam size at IP[a)] $(h \times v)$	nm	640×5.7	
Total AC Power consumption[a)]	MW	230	

ILC Technical Systems



Sources

Requirements:

Produce long bunch trains of high charge bunches

- ~3000 bunches per train
- 5 trains per second

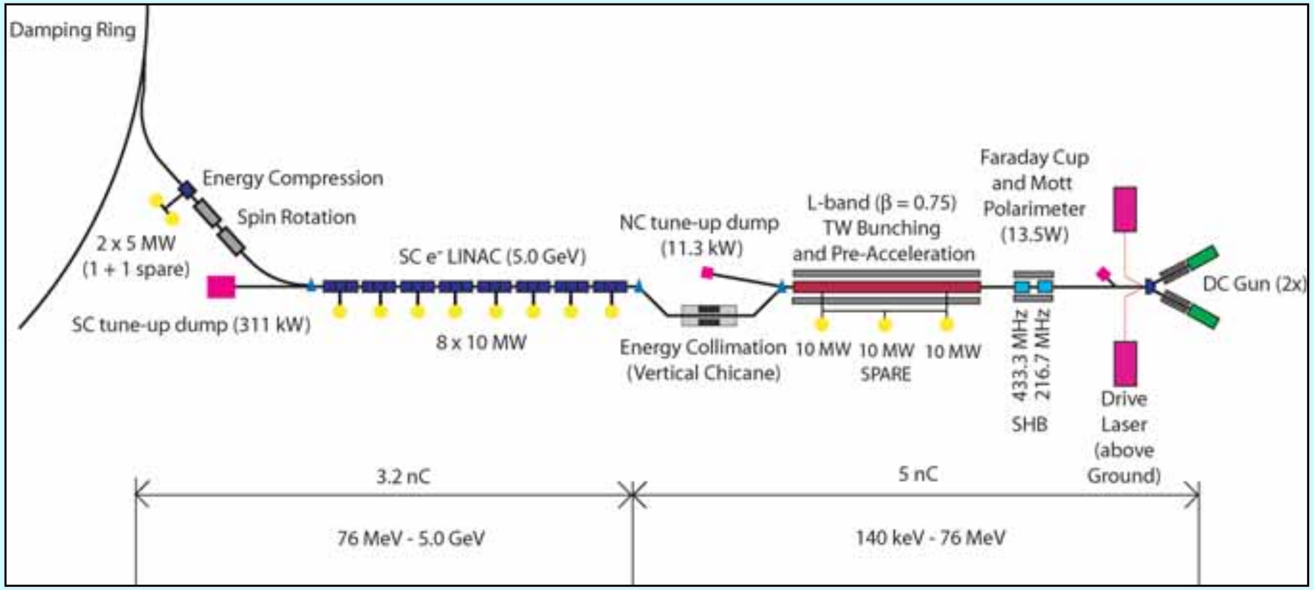
With small emittances

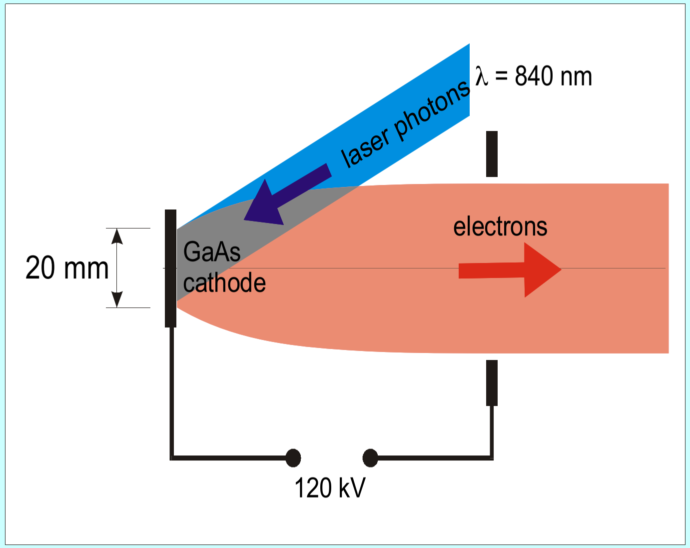
And polarisarion:

- mandatory for electrons
- nice to have for positrons

Electron Source

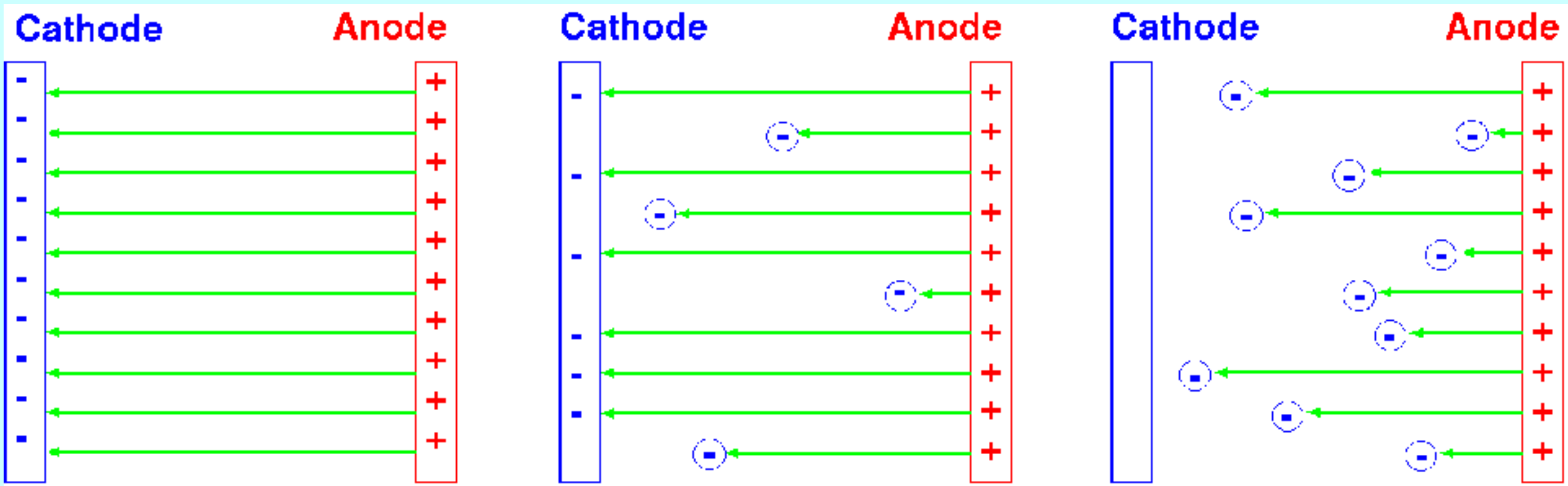
- Laser driven photo injector based on SLC design
- Circular polarised photons on GaAs cathode ⇒ longitudinal polarised electrons
- very high vacuum requirements (< 10^{-11} mbar) to protect cathode from impurities and ion backdrift
- 140-160 keV electron kinetic energy at exit
- 1ns bunch length at 3 MHz
- Peak current: 4.5-5 nC/ns (needed at IP 1.6-3.2 nC), space charge limited





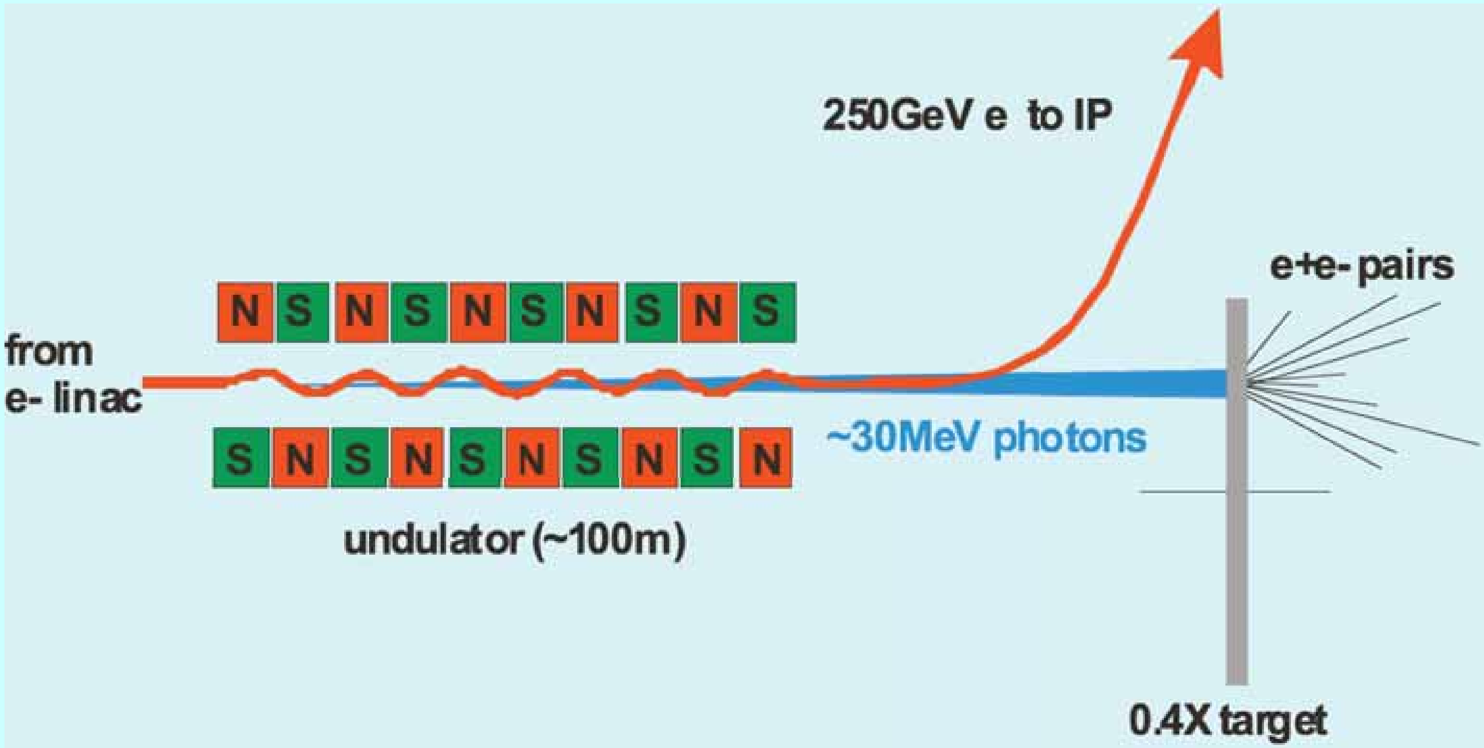
Space Charge Limit

- Electrons terminate electric flux (Gauss law)
- Electric field is screened by electrons
- At space charge limit: no field in front of the cathode



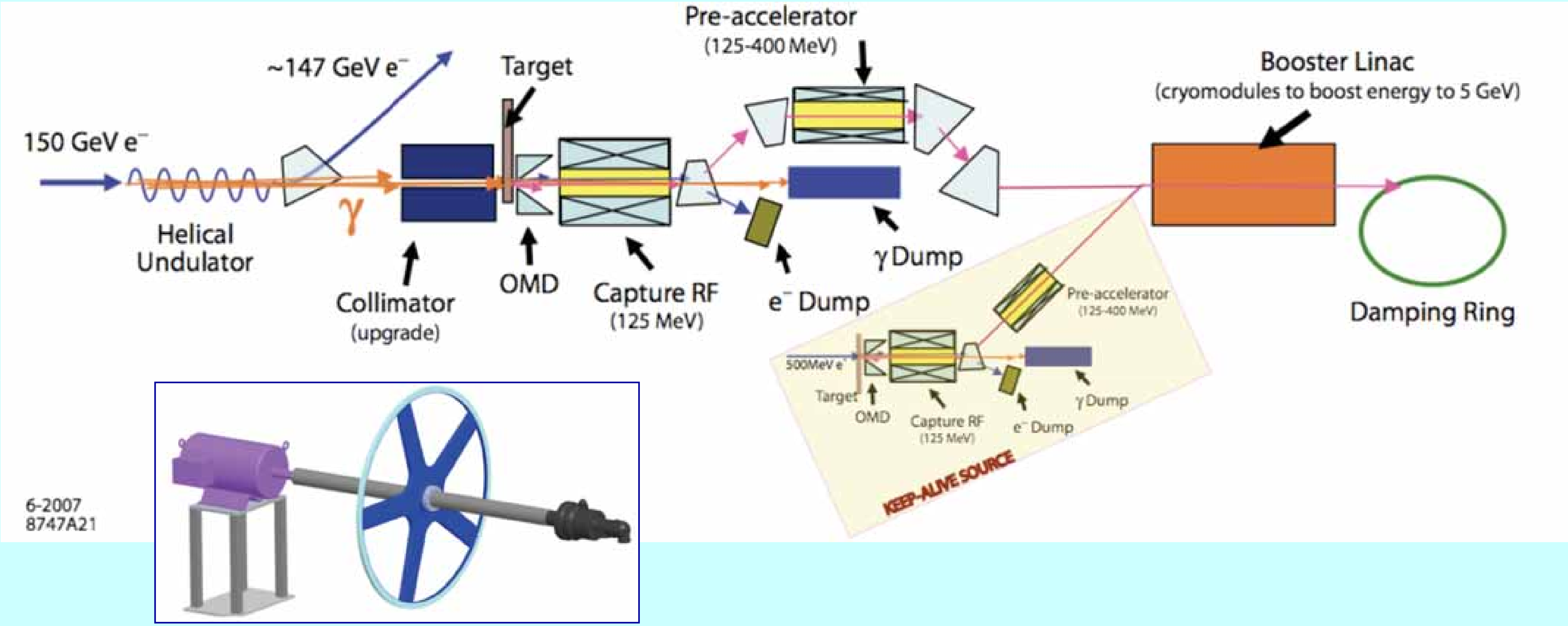
Positron Source

- Production of $e^{\pm}$ pairs by ~30 MeV undulator photons hitting a thin (0.4 X_0) target
- Thin target reduces multiple scattering, hence better emittance
- Needs >150 GeV electrons in undulator!



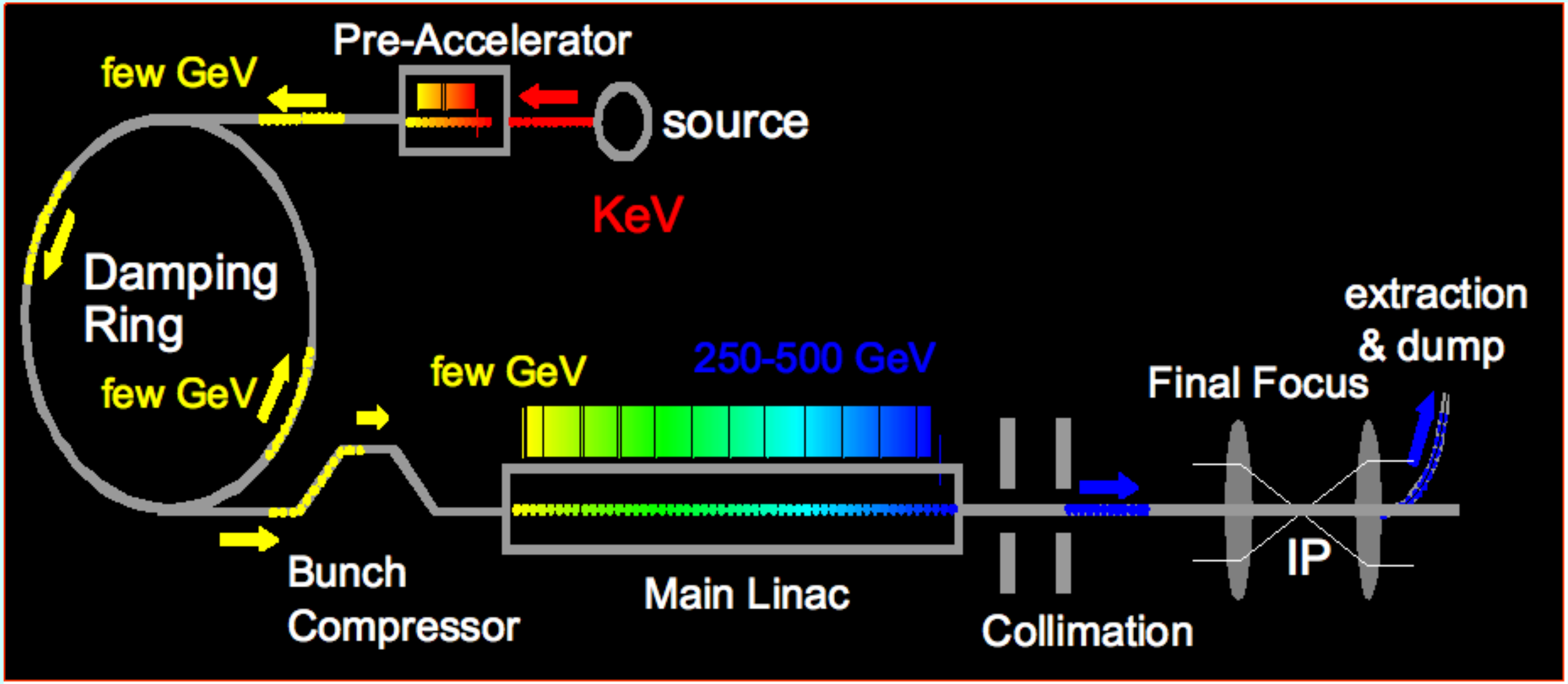
Positron Source Design

- Using a helical undulator allows the production of polarised positrons!
- Positron source links electron and positron linac
- Keep-alive positron source planned



Positron Source Prototyping

Damping Rings



Damping Rings Purpose

- Emittance of beams coming out of the sources are orders of magnitudes too big
- Beams need to be cooled
- Beams in damping rings radiate photons via synchrotron radiation
- Particles lose longitudinal and transverse momentum

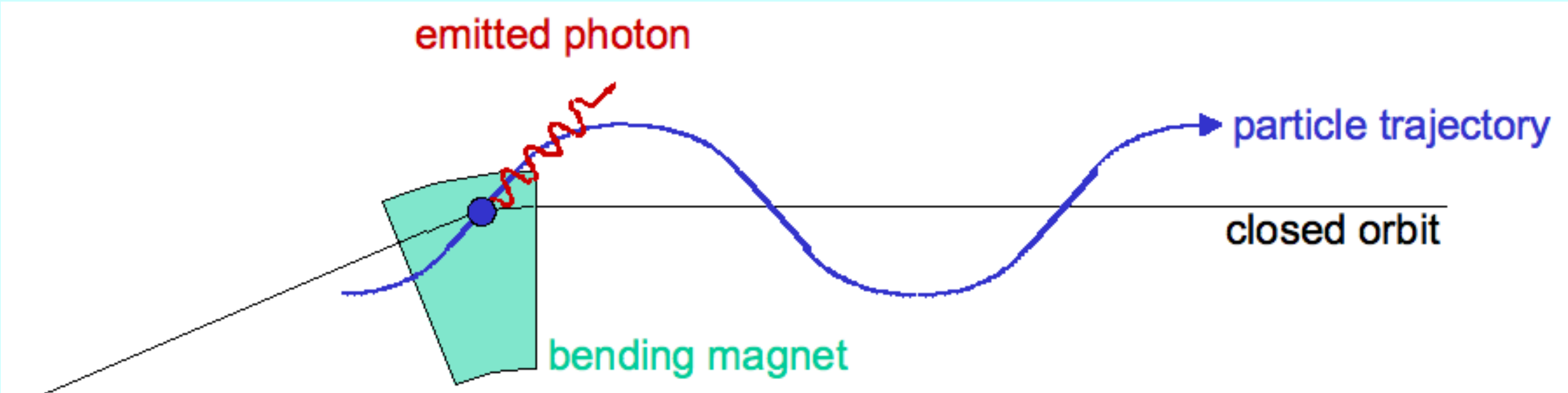
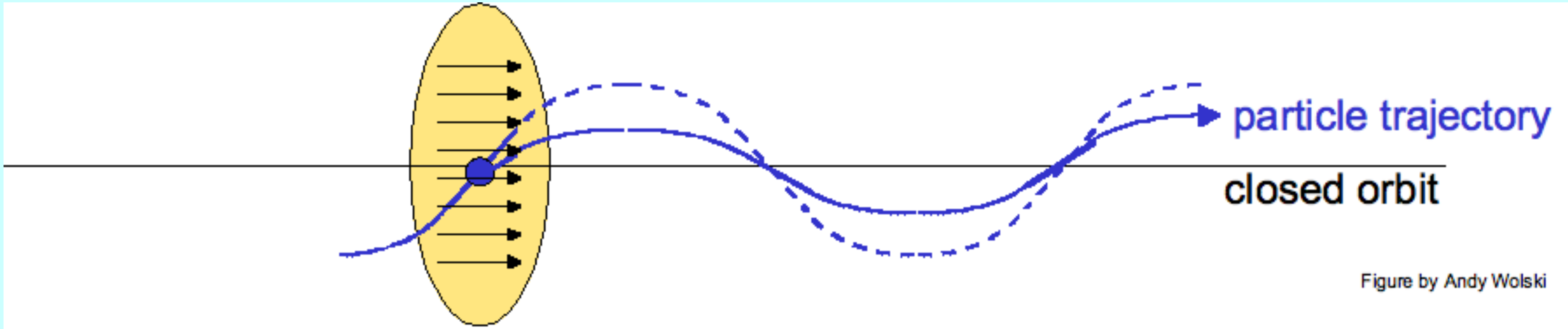


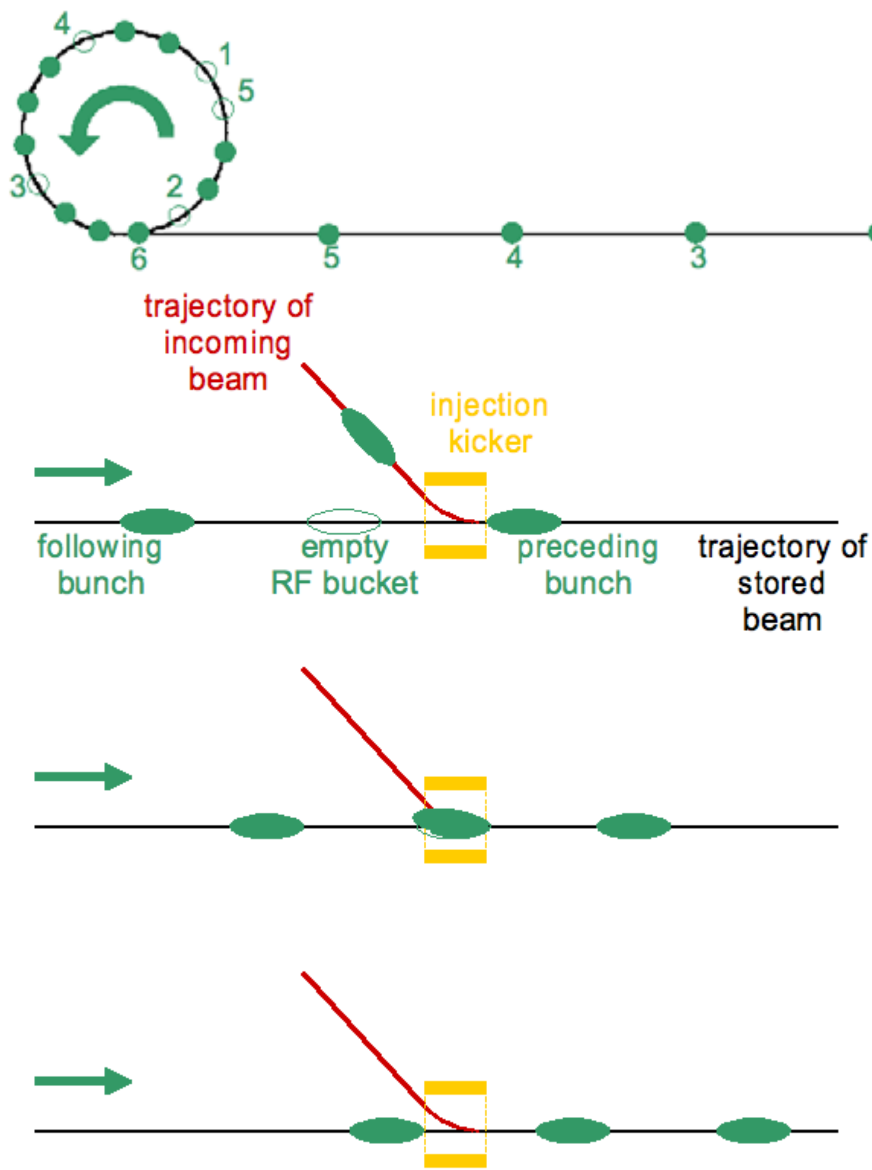
Figure by Andy Wolski

Damping Rings



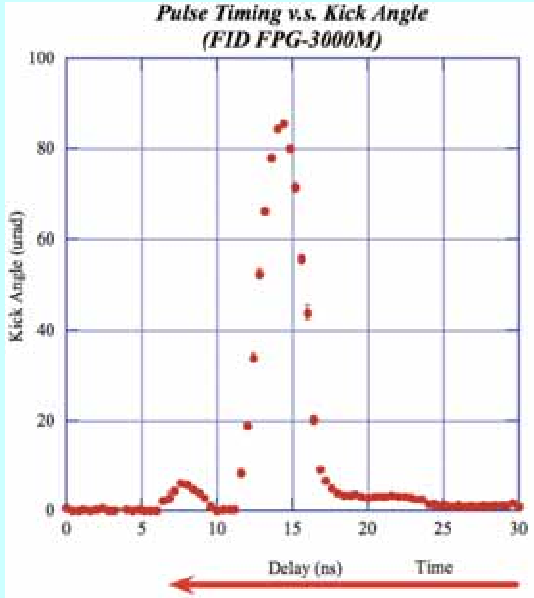
- RF system in damping rings accelerates beam particles in longitudinal direction
- Interplay between radiation and RF reduces transverse emittance!
- Typical damping times are of order 100ms
  - Linac RF pulse length is 1ms!
  - Whole bunch train (300 km @ 300ns) needs to be stored in a damping ring O(10km)!
  - Bunch train needs to be compressed in damping ring

DR Injection/Extraction

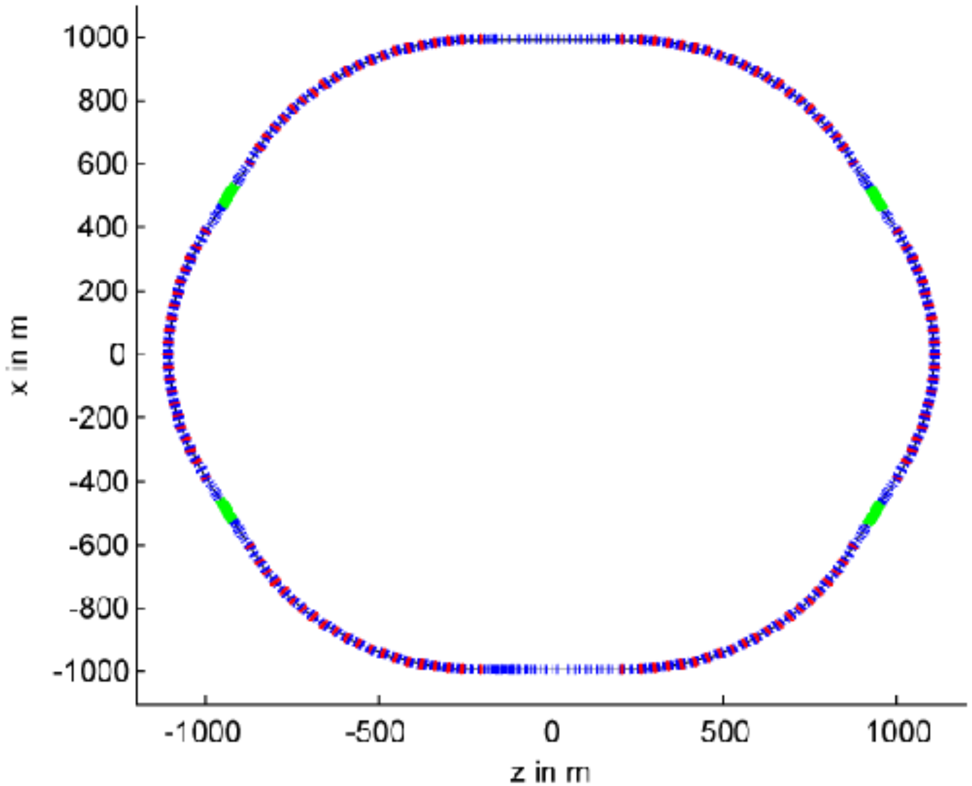


1. Kicker is off. “Preceding” bunch exits kicker electrodes.
   Kicker starts to turn on.
2. Kicker is on.
   “Incoming” bunch is deflected by kicker.
   Kicker starts to turn off.
3. Kicker is off by the time the following bunch reaches the kicker.

Slide by Andy Wolski



ILC Damping Ring Design



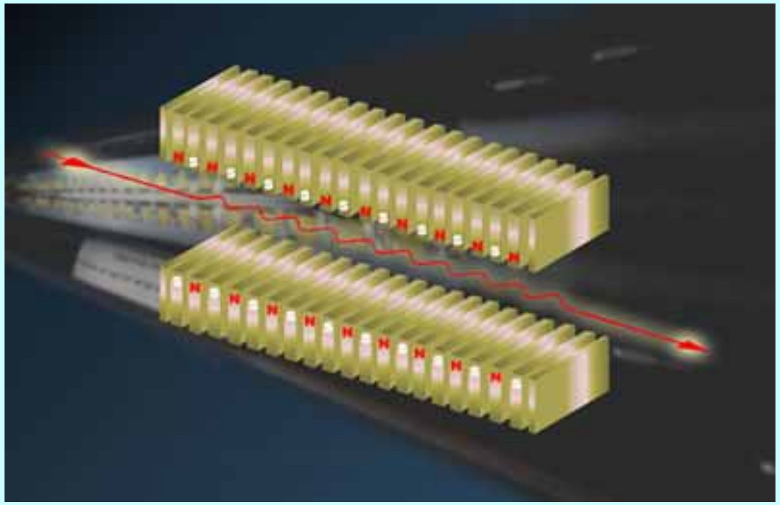
1 electron and 1 positron damping ring in common tunnel

6.7 km circumference

5 GeV beam energy

6 arcs, 6 straight sections

straight sections contain damping wigglers, RF cavities, and injection/extraction sections



- Damping time by SR from bending magnets would be too large O(400ms)
- Include damping wigglers in the beam to reduce damping time to ~25ms

Damping Ring Instabilities (Exmpl. Electron Cloud)

Electron cloud:

- Photons emitted by beam particles generate electrons by hitting the beam pipe
- Electron cloud is a source of instability for positron beam
- Reducing secondary electron yield should help
  → NEG materials, grooves

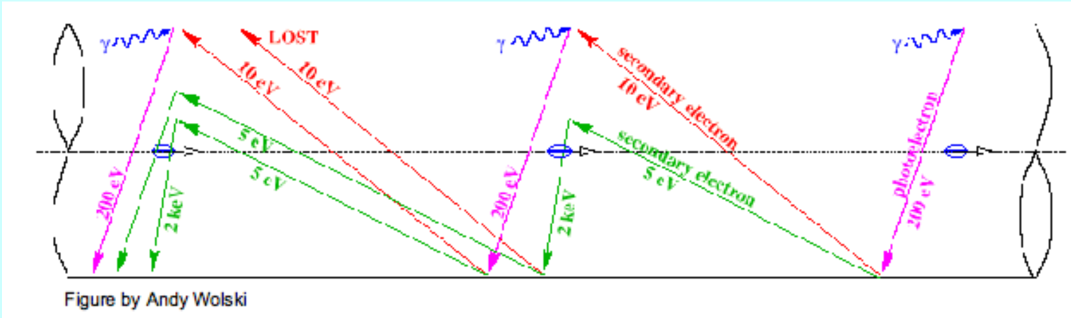
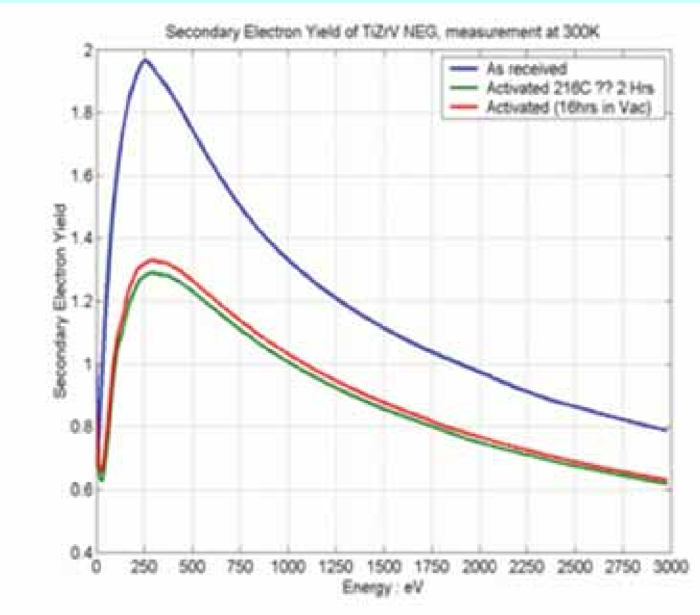
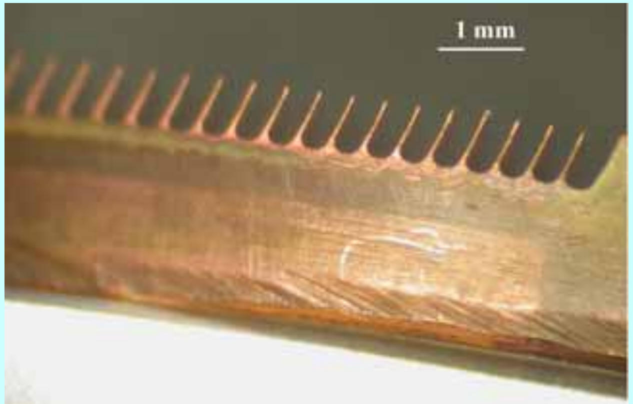
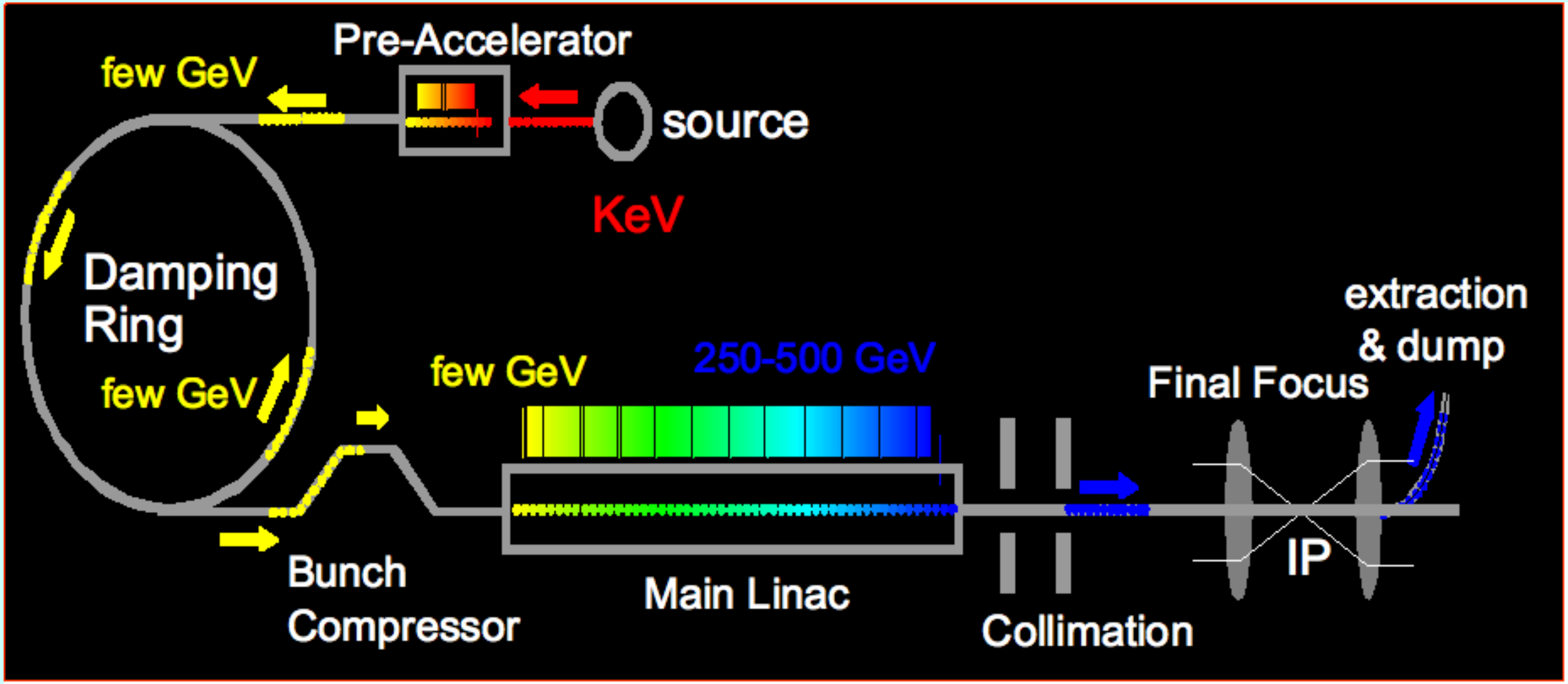


Figure by Andy Wolski





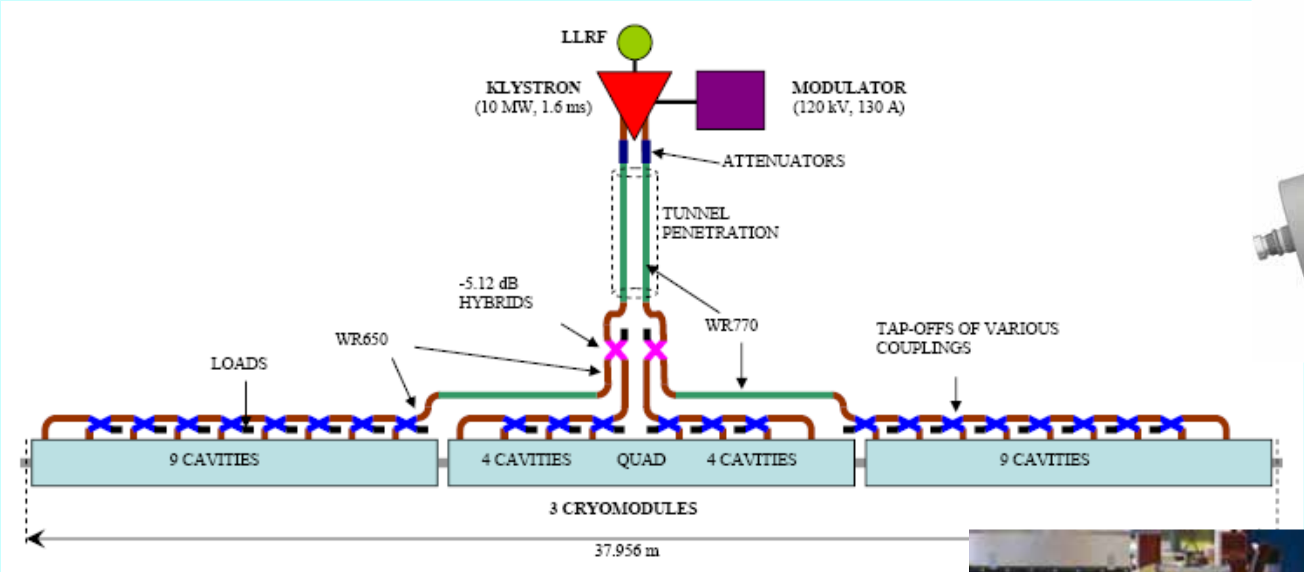
Main Linac

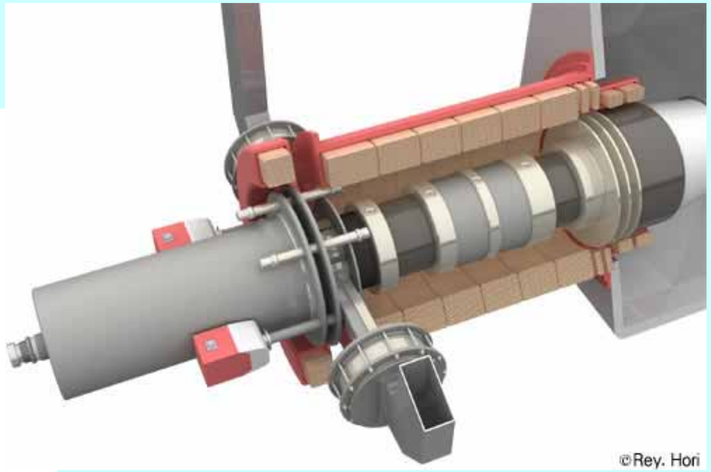


Pre-Accelerator
few GeV
source
KeV
Damping
Ring
few GeV
few GeV
250-500 GeV
extraction
& dump
Final Focus
IP
Bunch
Compressor
Main Linac
Collimation

Main Linac Components

One RF Unit:

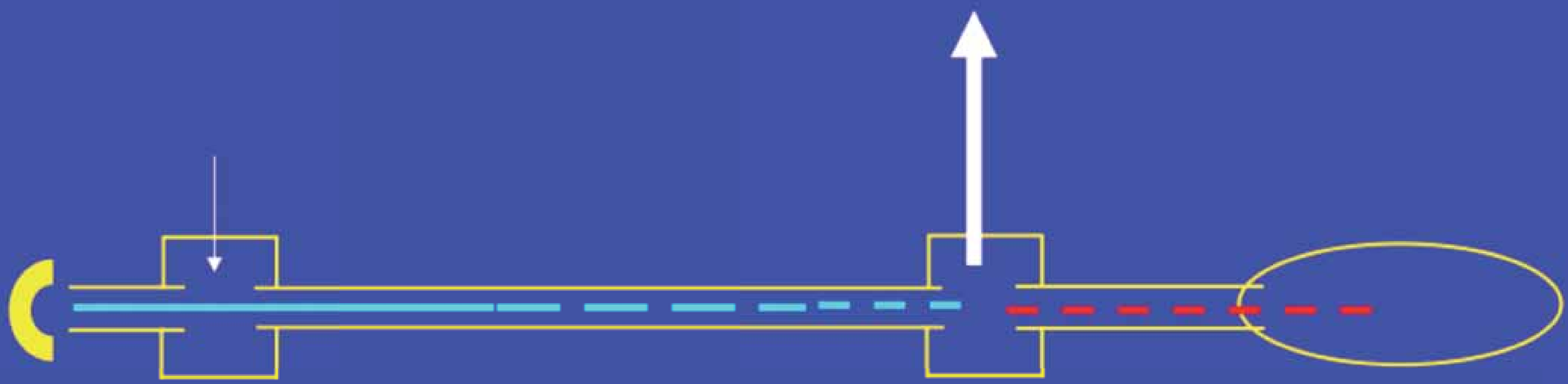




560 RF units in main linac (+86 elsewhere)

How does a Klystron work?

- DC Beam at high voltage (<500 kV, <500 A) is emitted from the gun
- A low-power signal at the design frequency excites the input cavity
- Particles are accelerated or decelerated in the input cavity, depending on phase/arrival time
- Velocity modulation becomes time modulation in the long drift tube (beam is bunched at drive frequency)
- Bunched beam excites output cavity at design frequency (beam loading)
- Spent beam is stopped in the collector.



Klystron Animation

ILC Klystrons

10 MW multibeam klystron

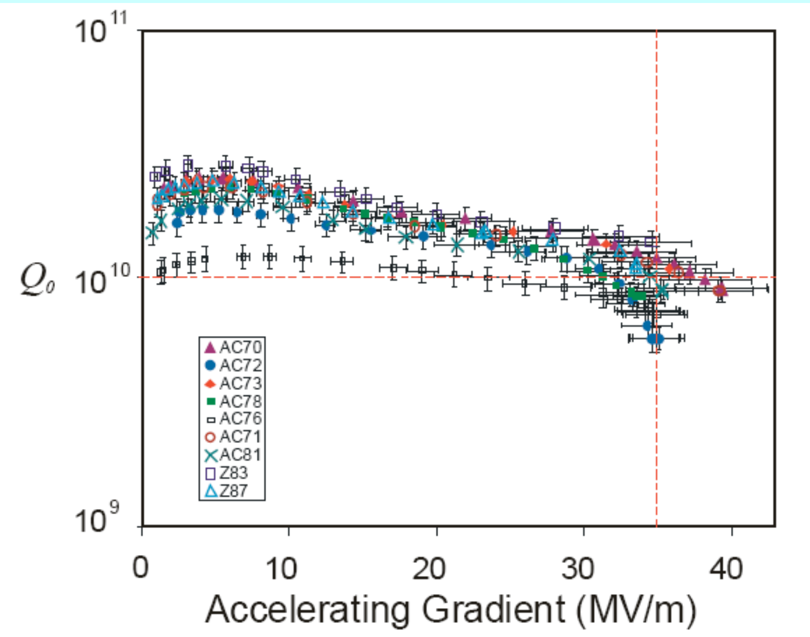
Parameter	Specification
Frequency	1.3 GHz
Peak Power Output	10 MW
RF Pulse Width	1.565 ms
Repetition Rate	5 Hz
Average Power Output	78 kW
Efficiency	65%
Saturated Gain	$\geq$47 db
Instantaneous 1 db BW	>3 MHz
Cathode Voltage	$\leq$120 kV
Cathode Current	$\leq$140 A
Power Asymmetry	$\leq$1%
Lifetime	>40,000 hours

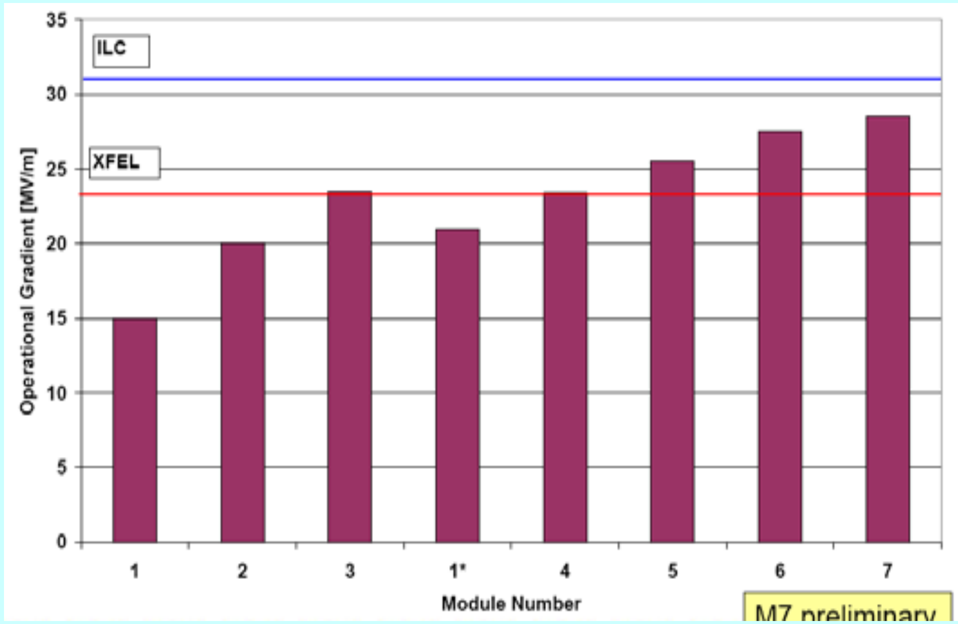


ILC Cavities

Acceleration gradient goal:

- 35 MV/m in 9-cell cavities with production yield >80%
- 50 MV/m have been reached with single cavities
- Mass production reliability is the key problem





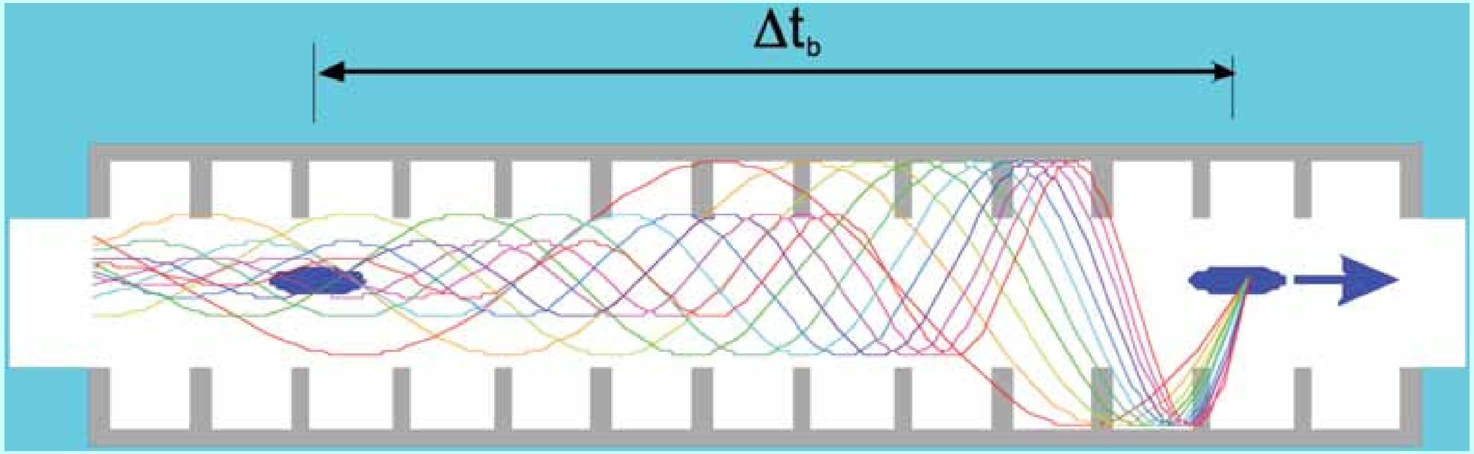
Q Factor

Superconducting cavity: $Q>10^{10}$

A church bell (300 Hz) with $Q=5 \times 10^{10}$ would ring – once excited – longer than one year!

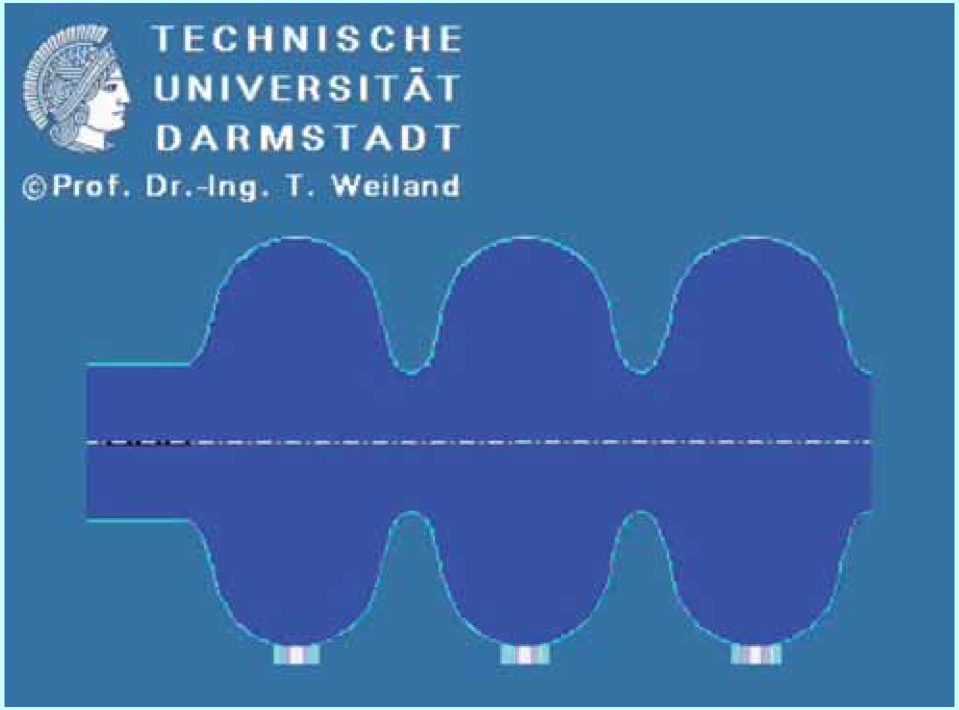
Transverse Wakefields

Bunch currents generate transverse deflecting modes when bunches are not on cavity axis:

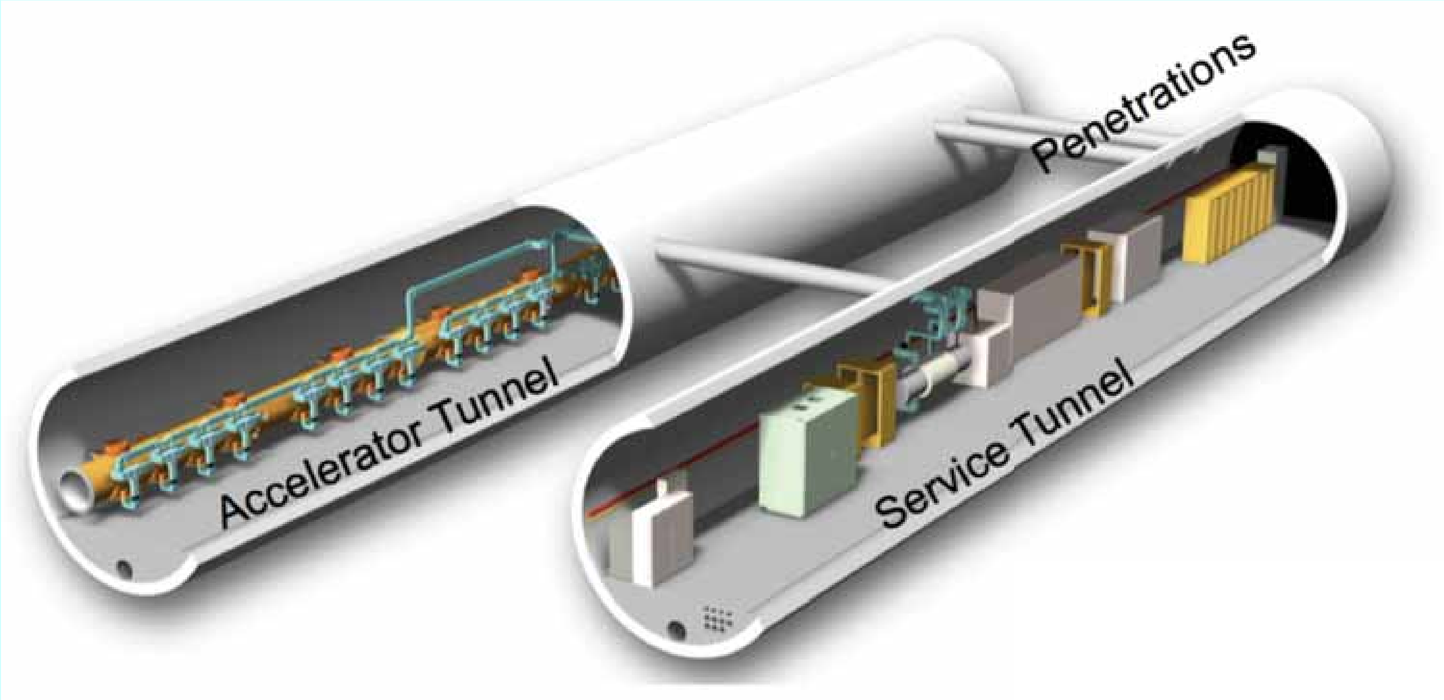


- Fields build up resonantly and kick later bunches transversely
- Dilutes Emittance!

Wakefield Simulation

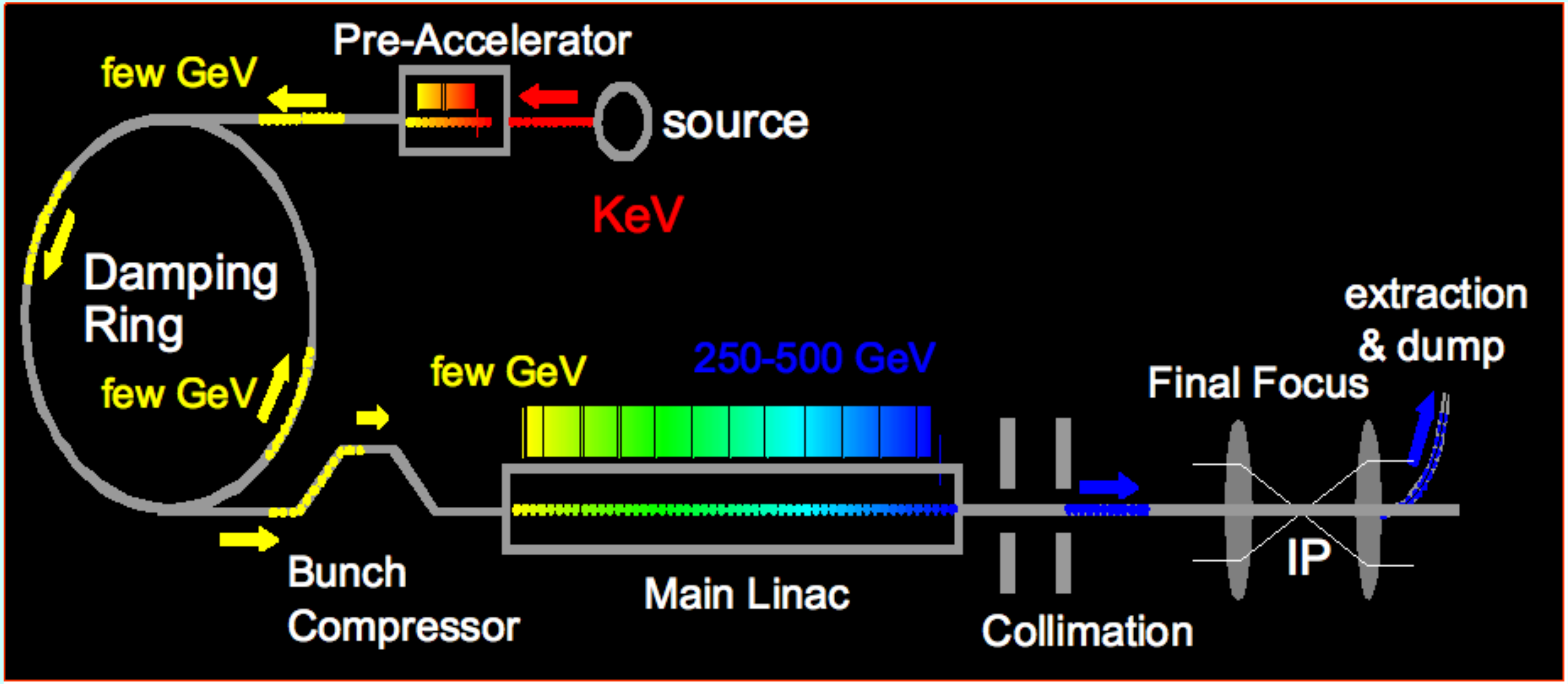


Tunnel Configuration



- Three RF/cable penetrations for every RF unit
- Safety crossovers every 500 m
- 34 kV power distribution
- 72.5 km tunnels
- 13 major shafts > 9 meter diameter
- 443000 m^3 underground excavation: caverns, alcoves, halls
- Alternative solutions (single tunnel à la XFEL) under study

Beam Delivery System

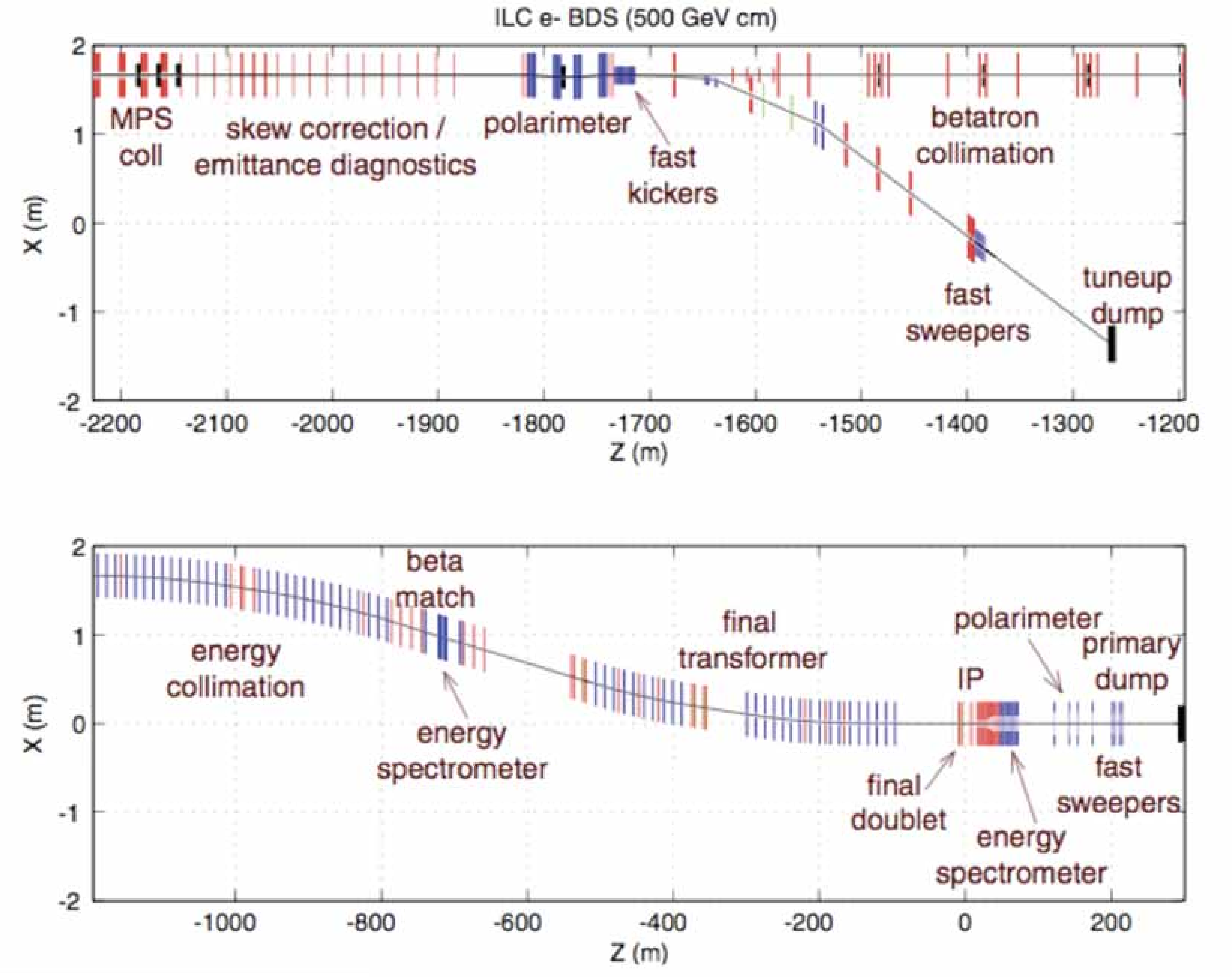


Beam Delivery System Tasks

The main tasks of the Beam Delivery System are:

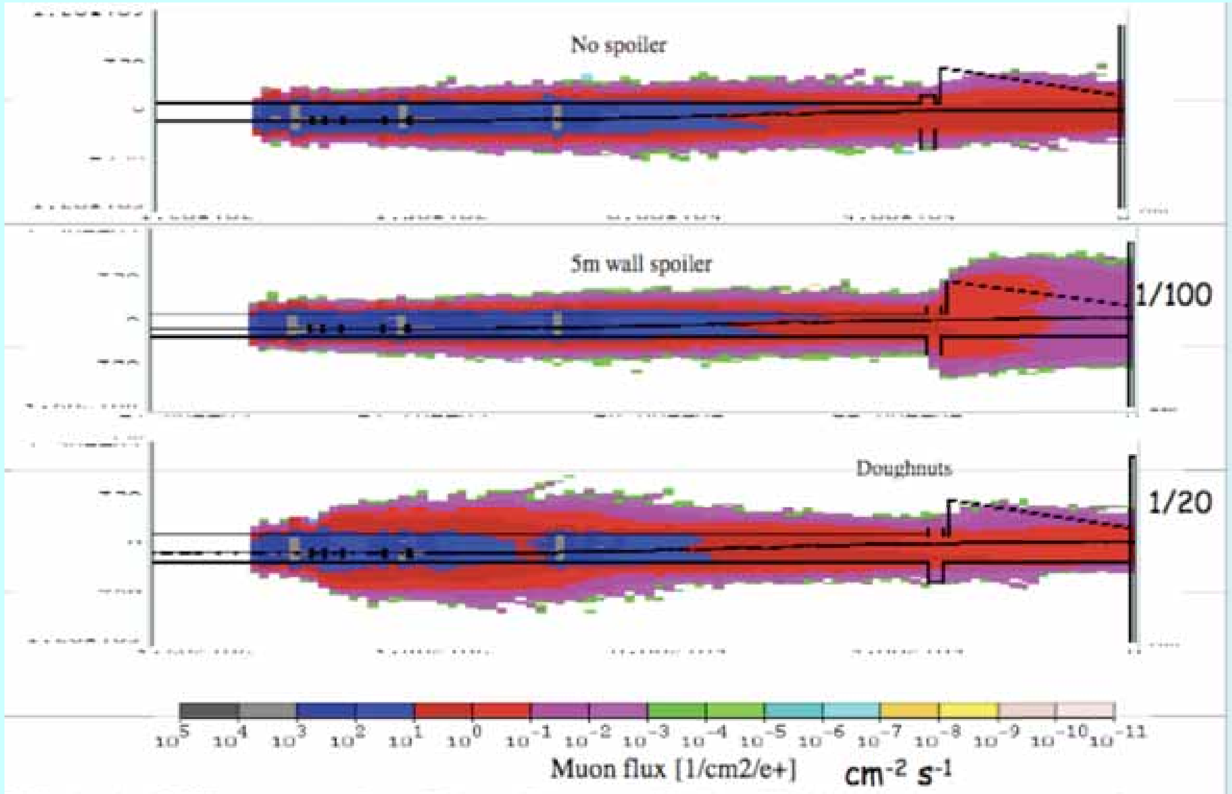
- Collimation: remove the beam halo to reduce background
- Beam diagnostics (up- and downstream of the IP)
- Final Focus System: squeeze the beams to nanometre sizes to provide luminosity at the IP
- Beam dumps: dispose spent beams after the collision

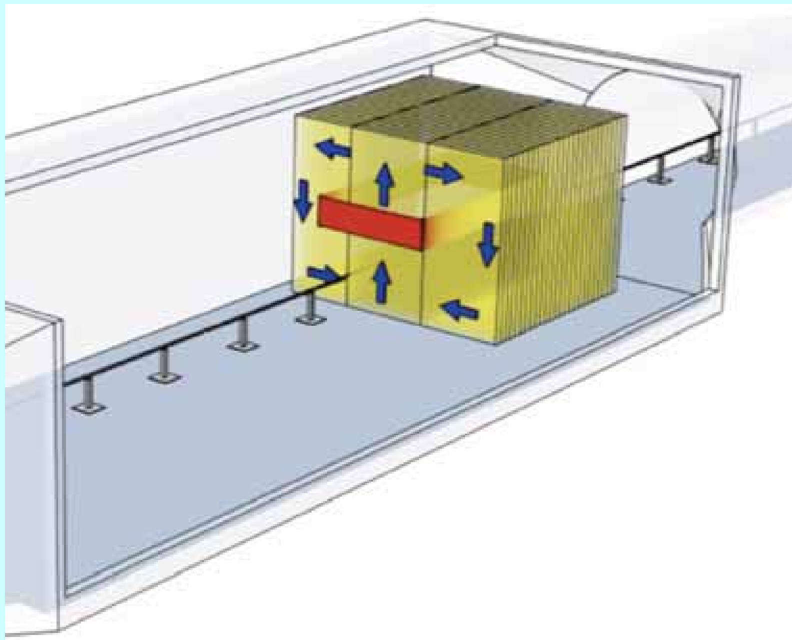
BDS Optics


ILC e- BDS (500 GeV cm)
MPS
coll
skew correction /
emittance diagnostics
polarimeter
fast
kickers
betatron
collimation
fast
sweepers
tuneup
dump
X (m)
Z (m)
beta
match
energy
collimation
energy
spectrometer
final
transformer
polarimeter
primary
dump
IP
final
doublet
fast
sweepers
energy
spectrometer

Collimation System

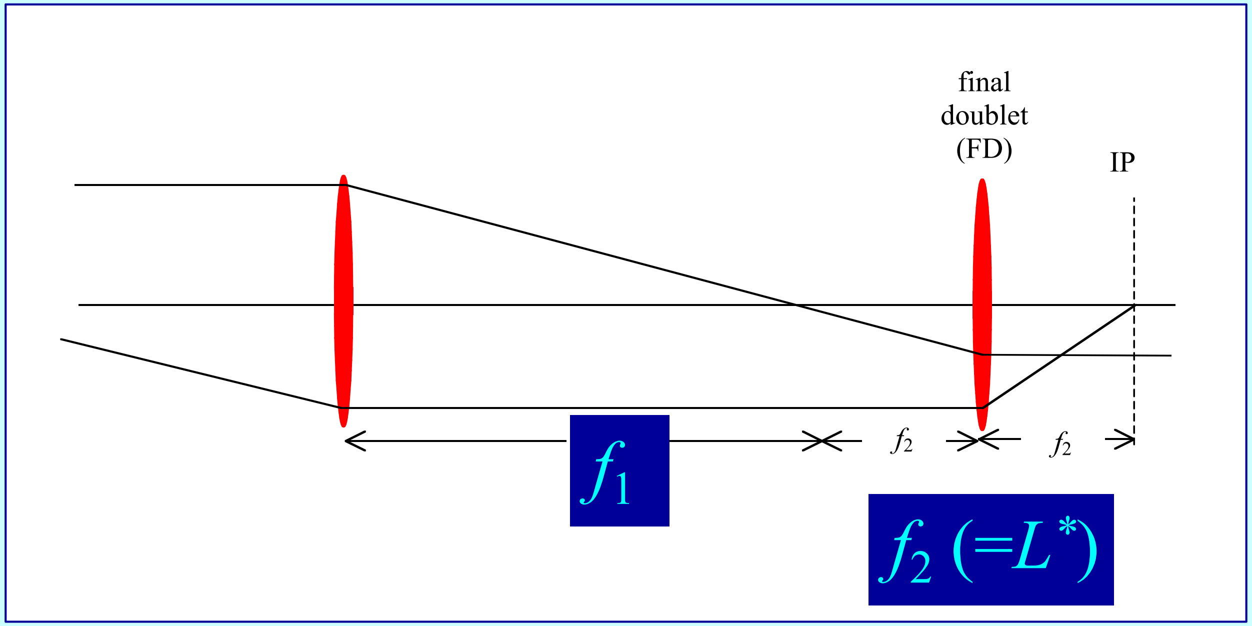
- Collimators scrap away halo outside ~8-10 σ_x and ~60-80 σ_y
- Removes potential background at the IP but is a source of muon background itself





5m thick magnetised muon shield

Final Focus



Use telescope optics to de-magnify beam by factor $m = f_1/f_2 = f_1/L^*$

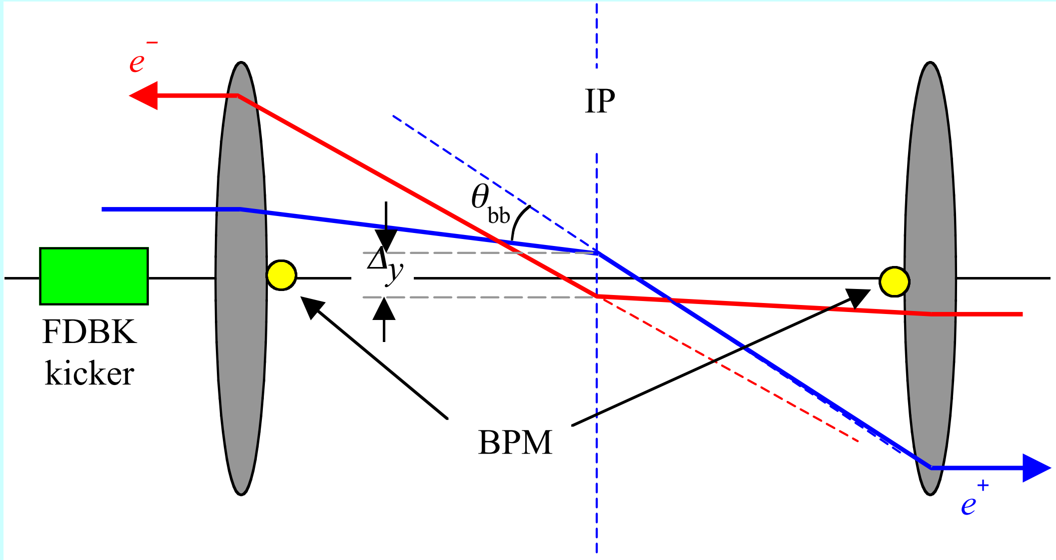
Need typically $m = 300$

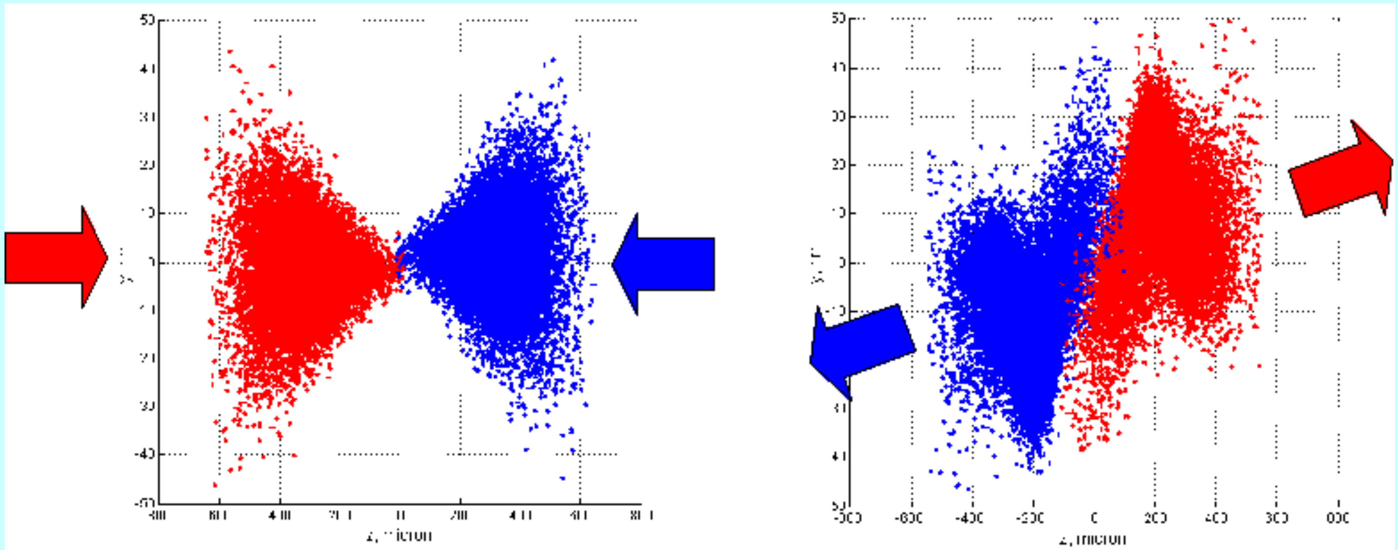
putting $L^* = 2\text{m} \Rightarrow f_1 = 600\text{m}$

In real life much more complicated: correction for large chromatic and geometric aberrations needed → principle design challenge

Beam-Beam Orbit Feedback

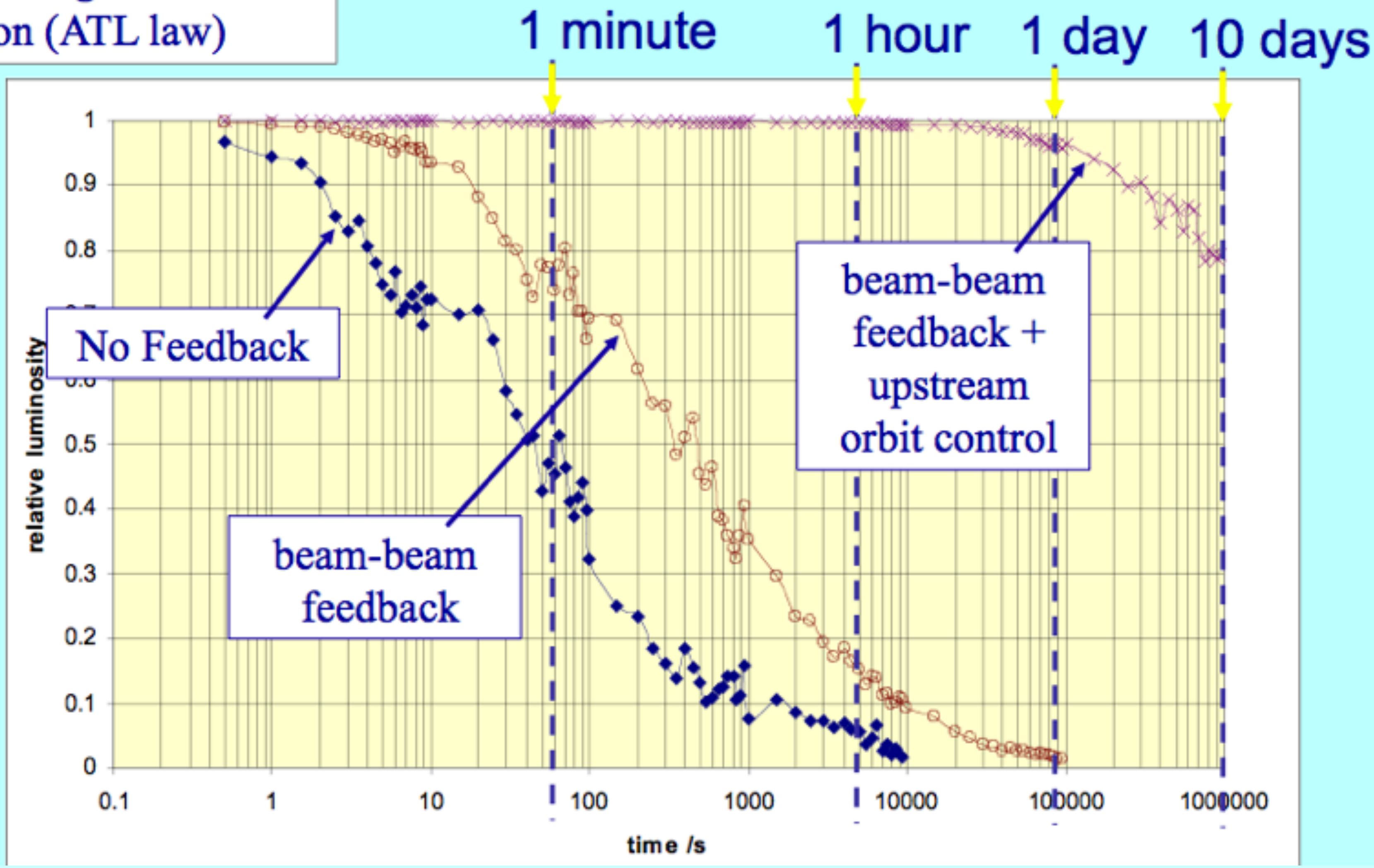
- Beam-beam kick transforms nanometre offsets at the IP to large measurable effects downstream
- Used for a feedback system



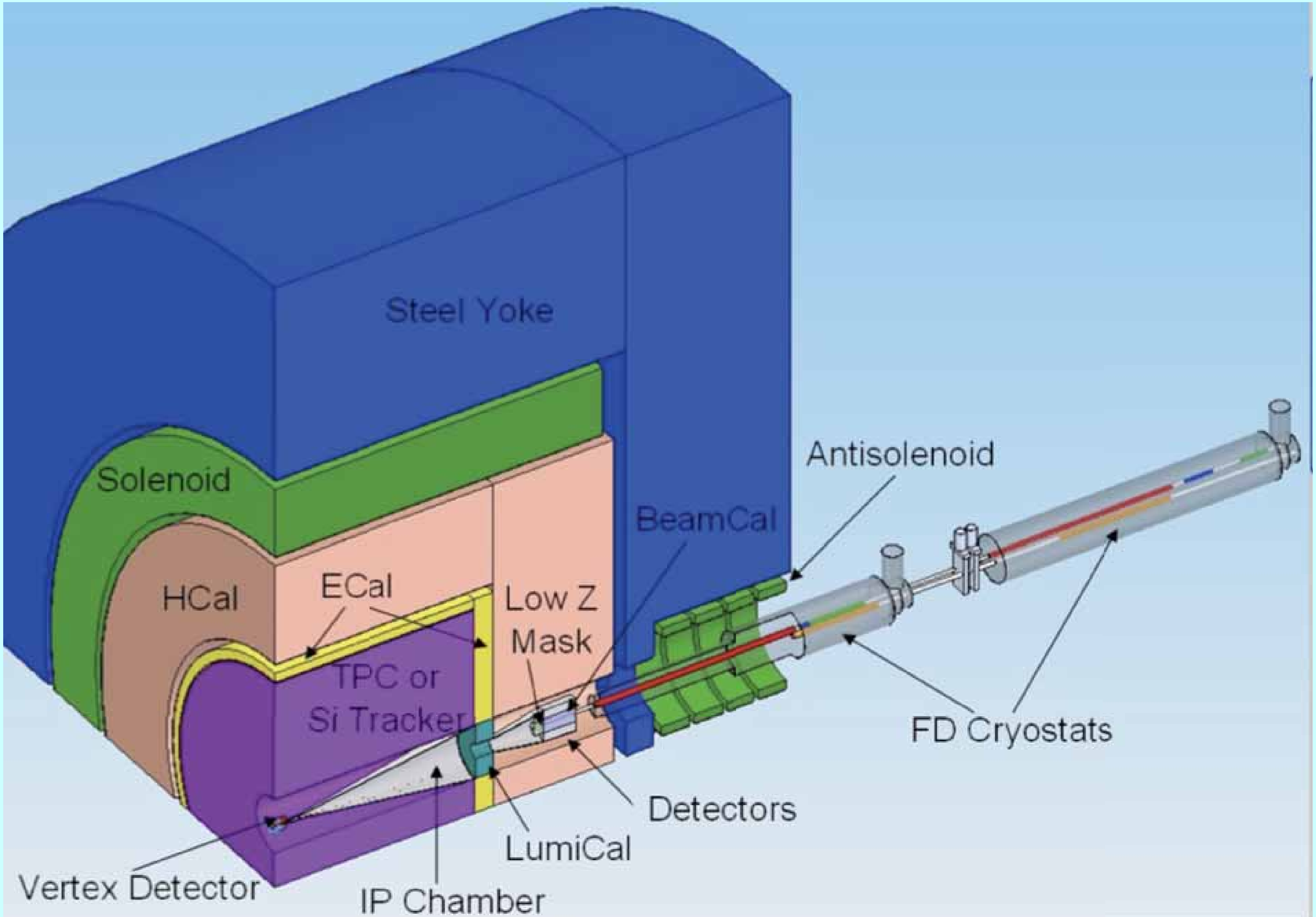


Long Term Stability

example of slow diffusive ground motion (ATL law)

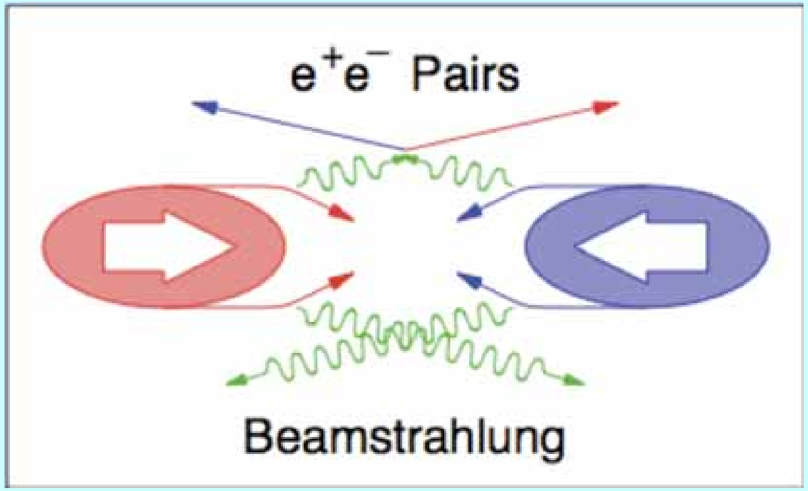


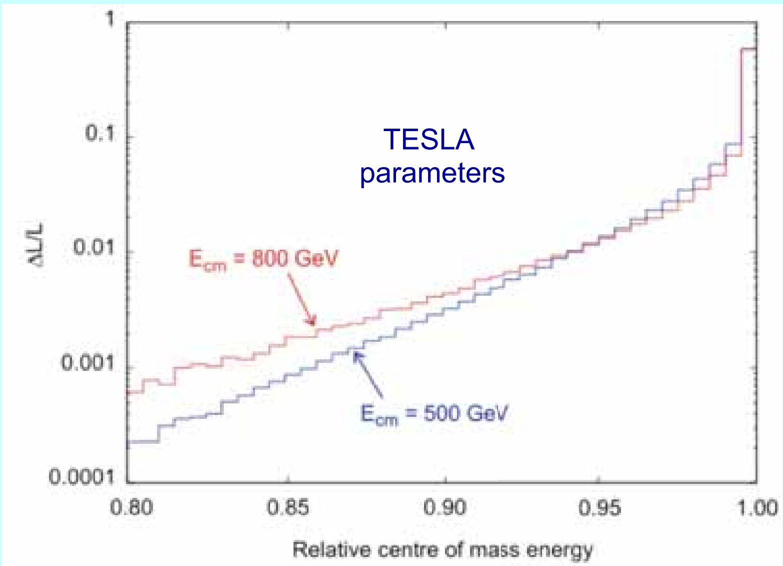
IP Region

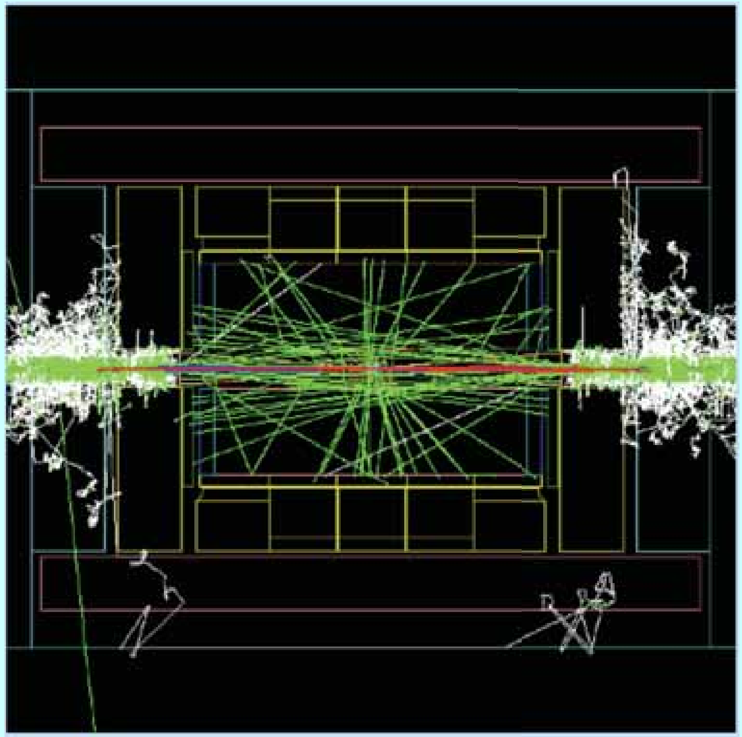

Steel Yoke
Solenoid
HCal
ECal
Low Z
Mask
BeamCal
Antisolenoid
TPC or
Si Tracker
FD Cryostats
Detectors
LumiCal
Vertex Detector
IP Chamber

Beamstrahlung Revisited

- Beam-beam effect leads to the production of beamstrahlung
- Beamstrahlung dilutes luminosity spectrum of the collider
- Beamstrahlung photons can produce e± pairs which generate detector background







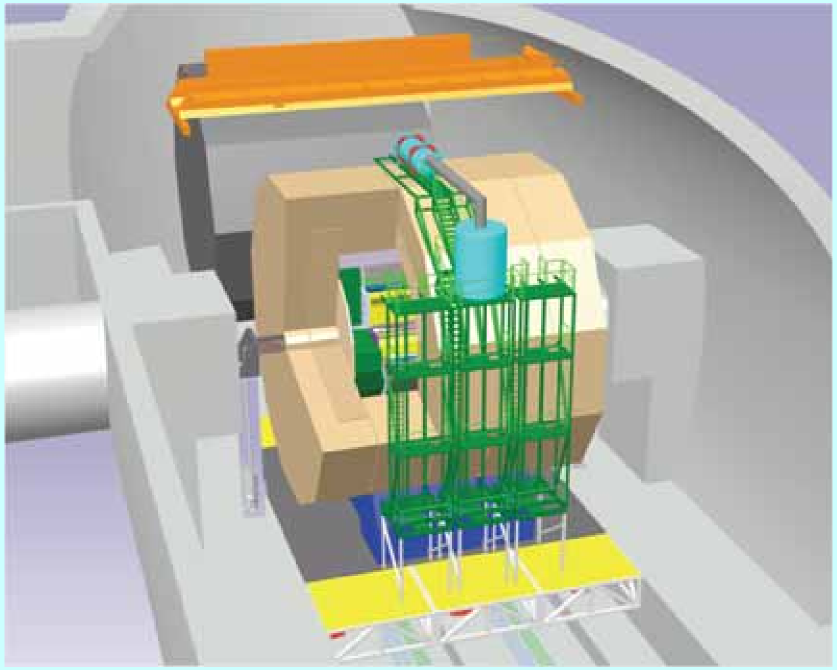
Detectors and Push/Pull

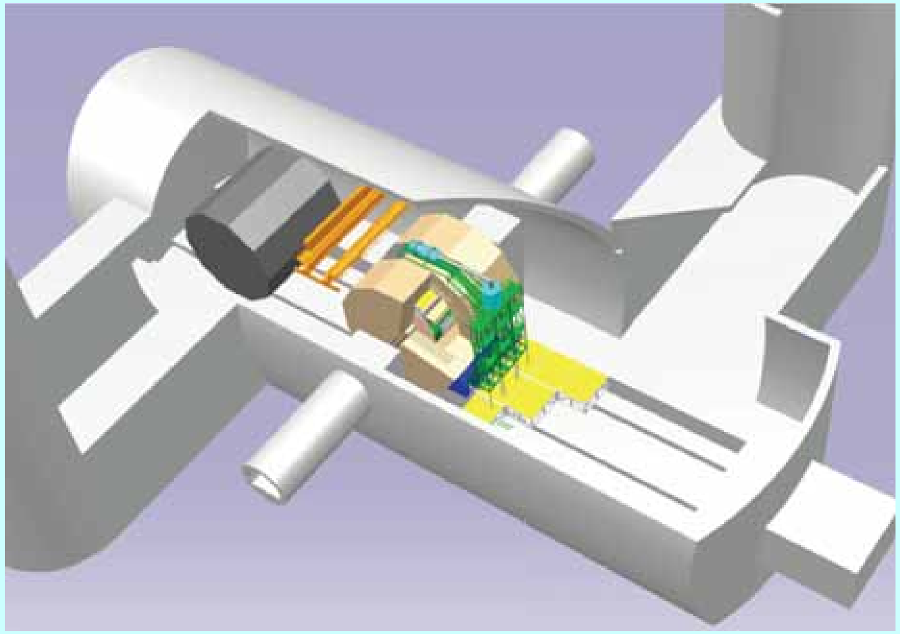
- Integrated luminosity at linear colliders scales not with the number of interaction regions

- ILC has just one interaction beam line (cost issue) but should have two detectors

- Try to find a solution where two detectors share one interaction region

  → Push/Pull System

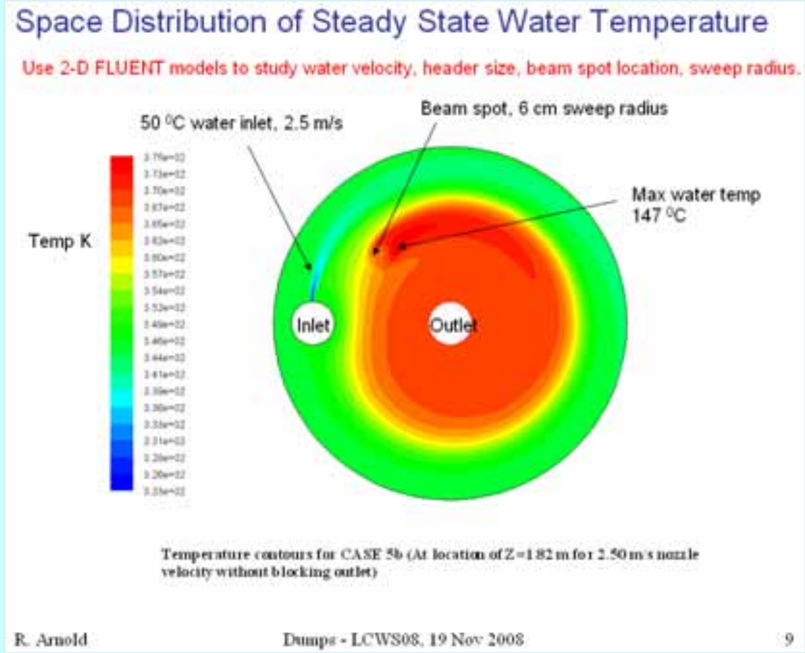


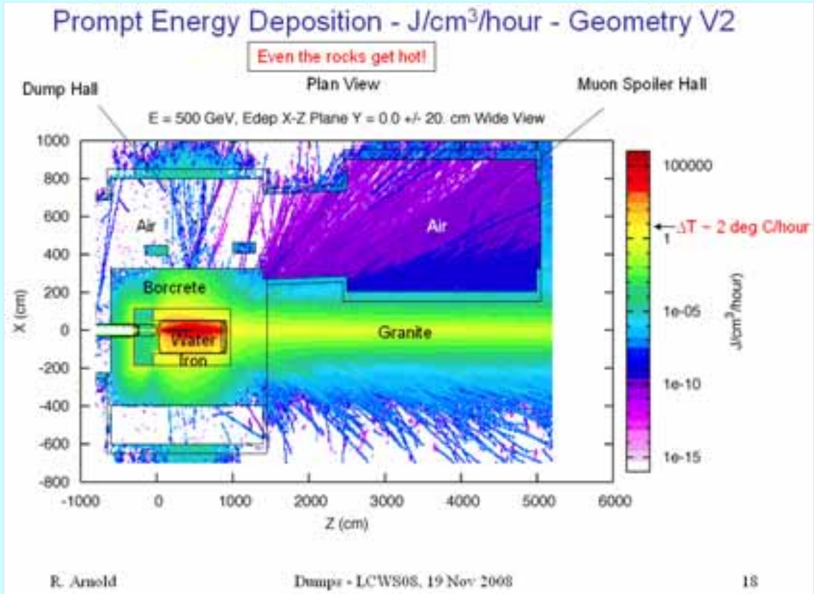


Beam Dumps

- Beam dumps designed for 1 TeV machine: 18 MW (!)
- 10 bar pressurised water (avoid boiling) plus copper sandwich
- Beam sweeped over entry window
- Heat exchange system (8500 l/min) removes power

- Significant challenges:
  - Tritium production
  - H_2O Radiolysis

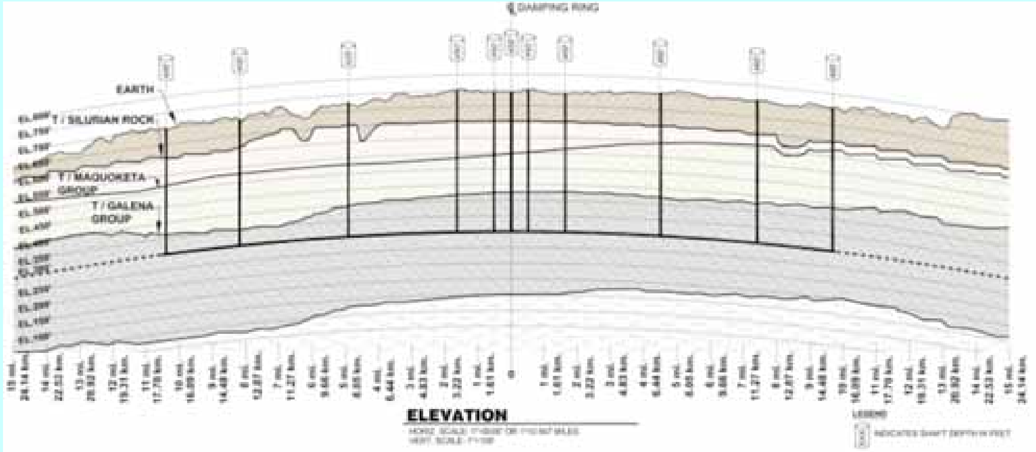




Sample Sites

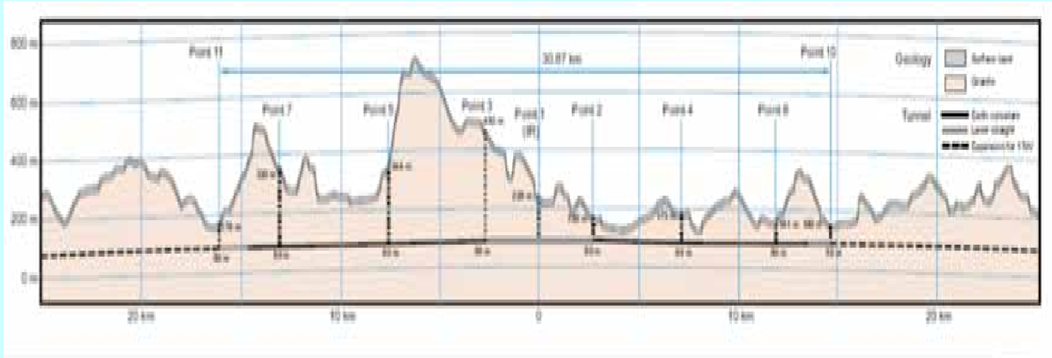
Three deep sites under study:

- Americas: Fermilab
- Asia: Japan
- Europe: CERN



Two shallow sites:

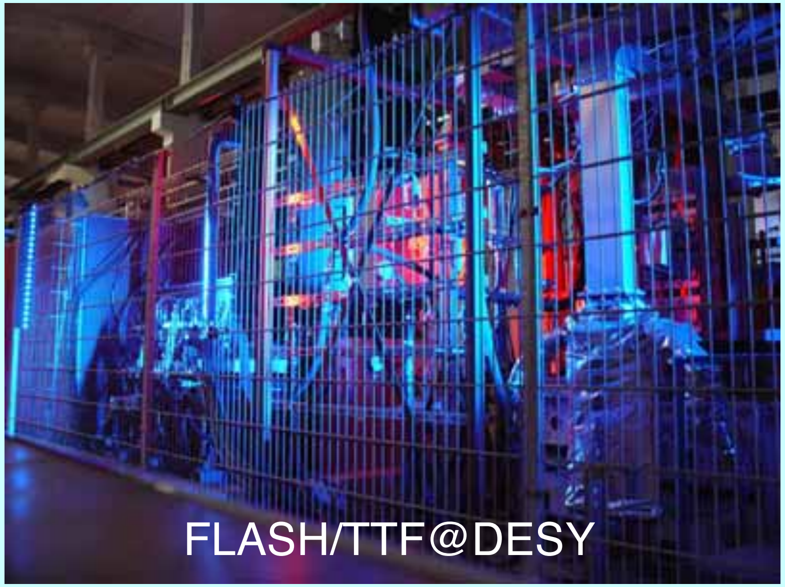
- DESY
- Dubna



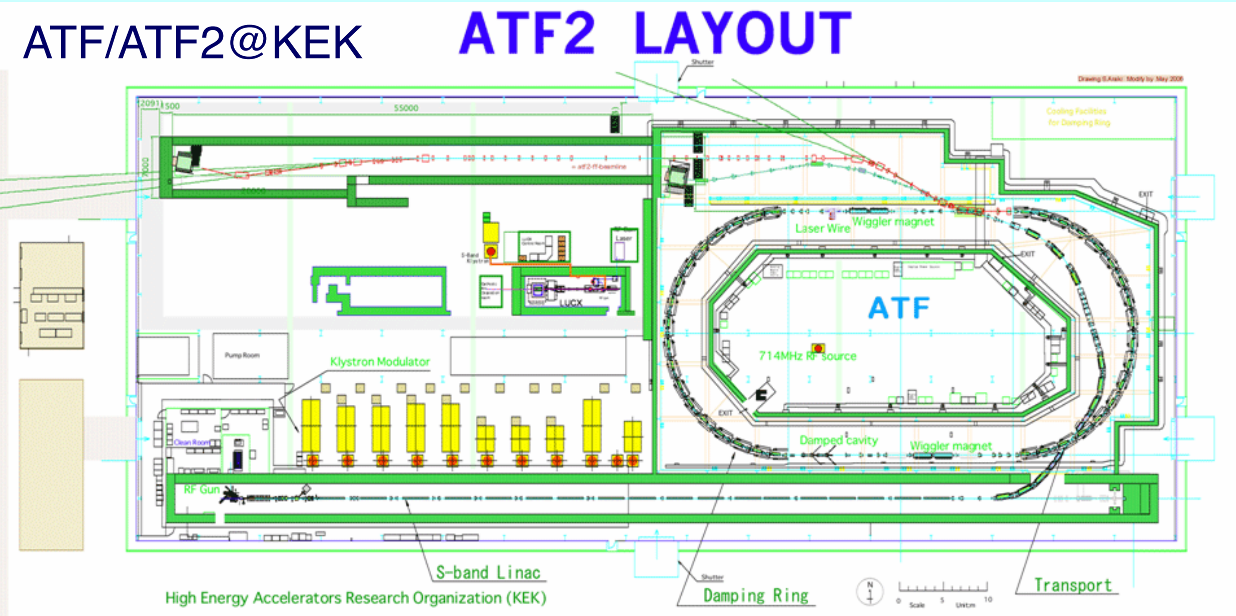
Sample sites are studied for technical reasons.

Real site choice will be a political decision!

ILC Test Facilities (Examples)



ATF/ATF2@KEK

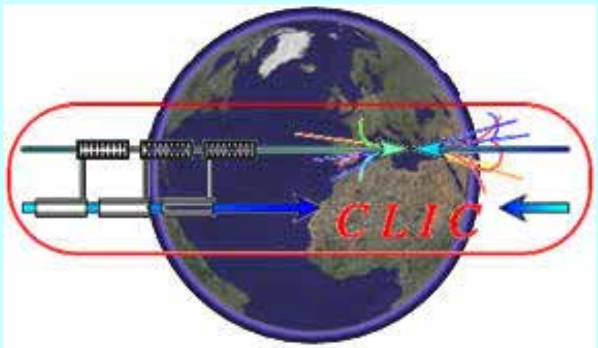


What if 1 TeV is not enough?

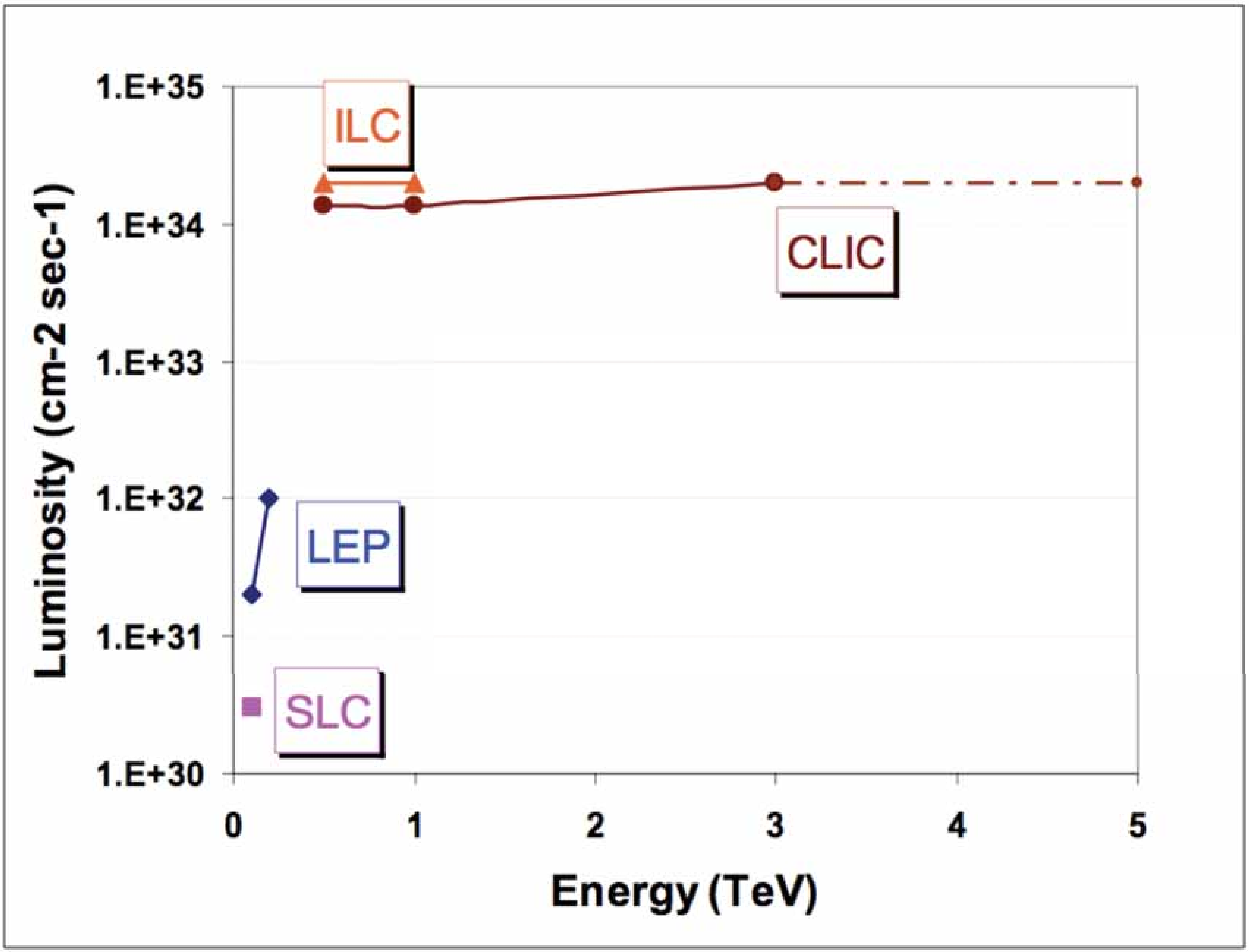
- LHC will tell us the region of the interesting physics ahead
- All seems to hint to the <1TeV region
- But what if the interesting area is the multi-TeV region?

- A Linear Collider with multi-TeV energy reach will be needed then!

- The CLIC technology opens the path to the multi-TeV regime.



The CLIC Challenge



The Luminosity Challenge

Remember:

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

Challenge: Luminosity of 10^{34} $cm^{-2}s^{-1}$ at 3-5 TeV!

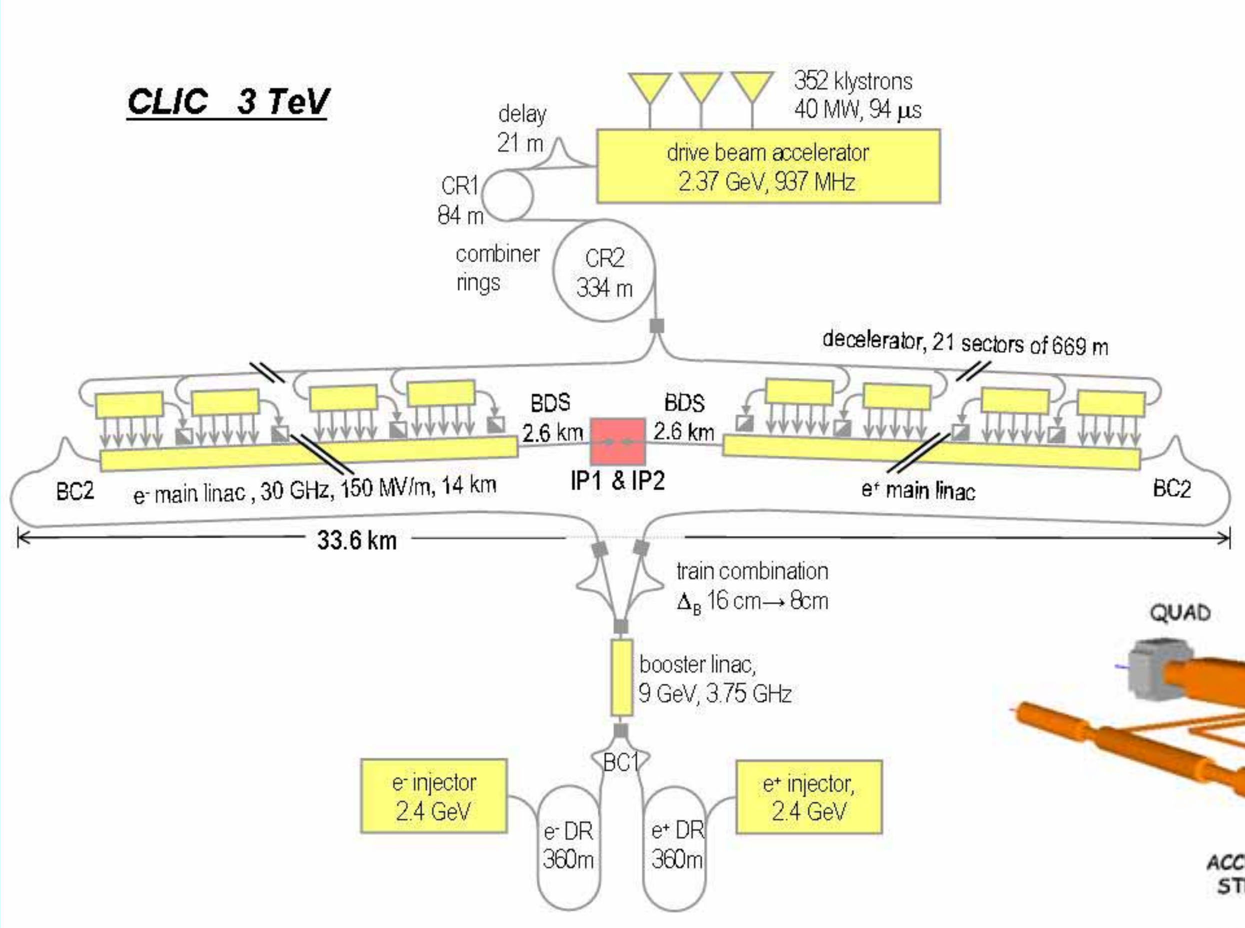
- Need high RF power P_{RF}
- Need high RF efficiency η_{RF}
- Need very small bunch sizes at the IP

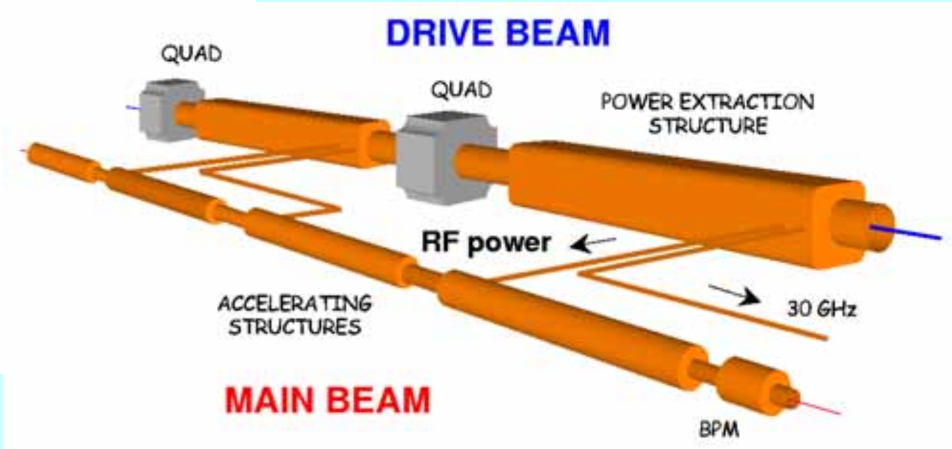
Challenge: Energy of 3-5 TeV on reasonble length (50km)

- Acceleration gradients ~100 MV/m
- Impossible with superconducting cavities (limit around 40-50 MV/m)
- Normalconducting copper cavities needed
  - lower RF efficienies, more RF power needed!

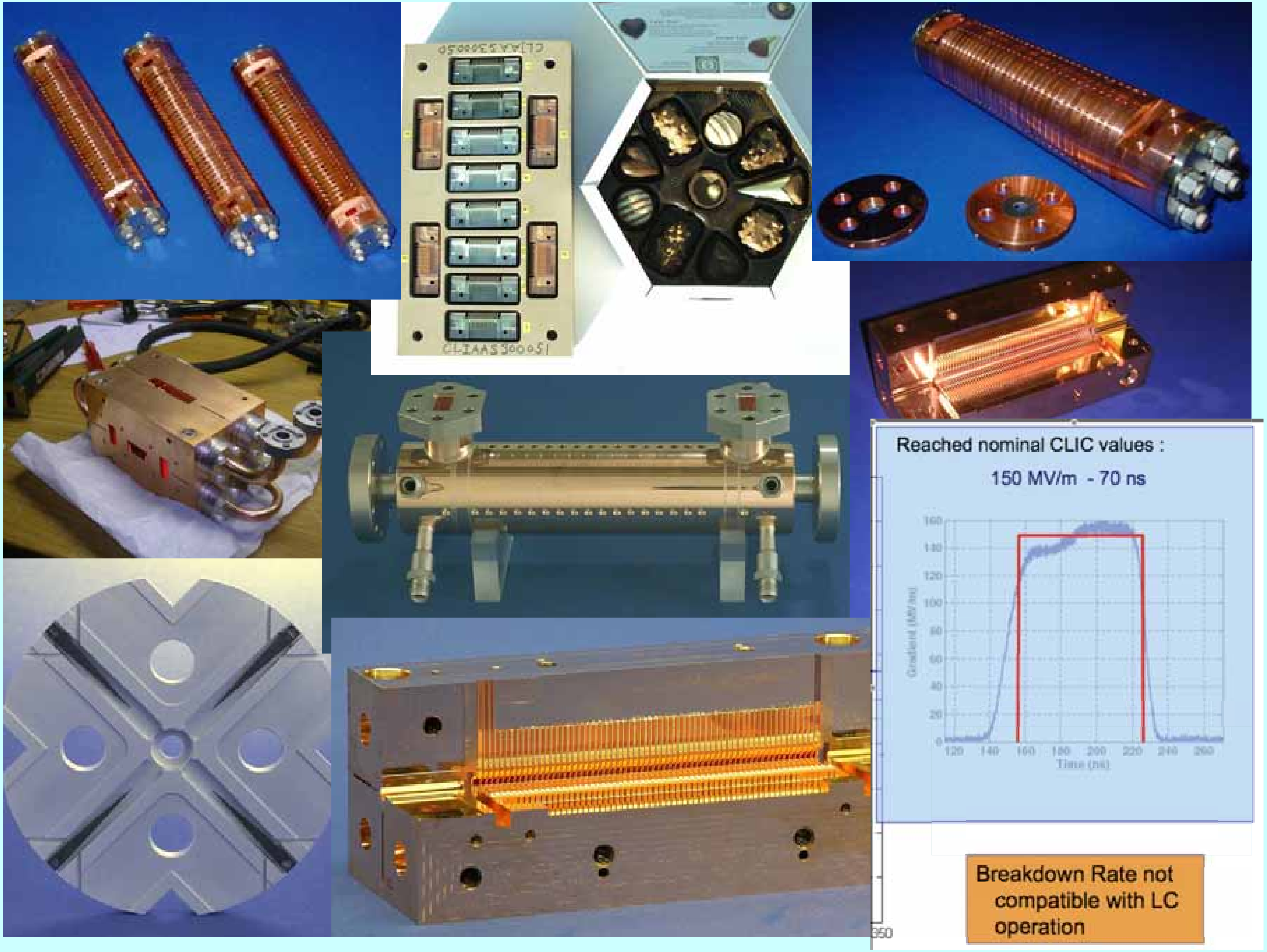
Two-beam Acceleration

Use low-energy high-current electron drive-beam as klystron replacement:





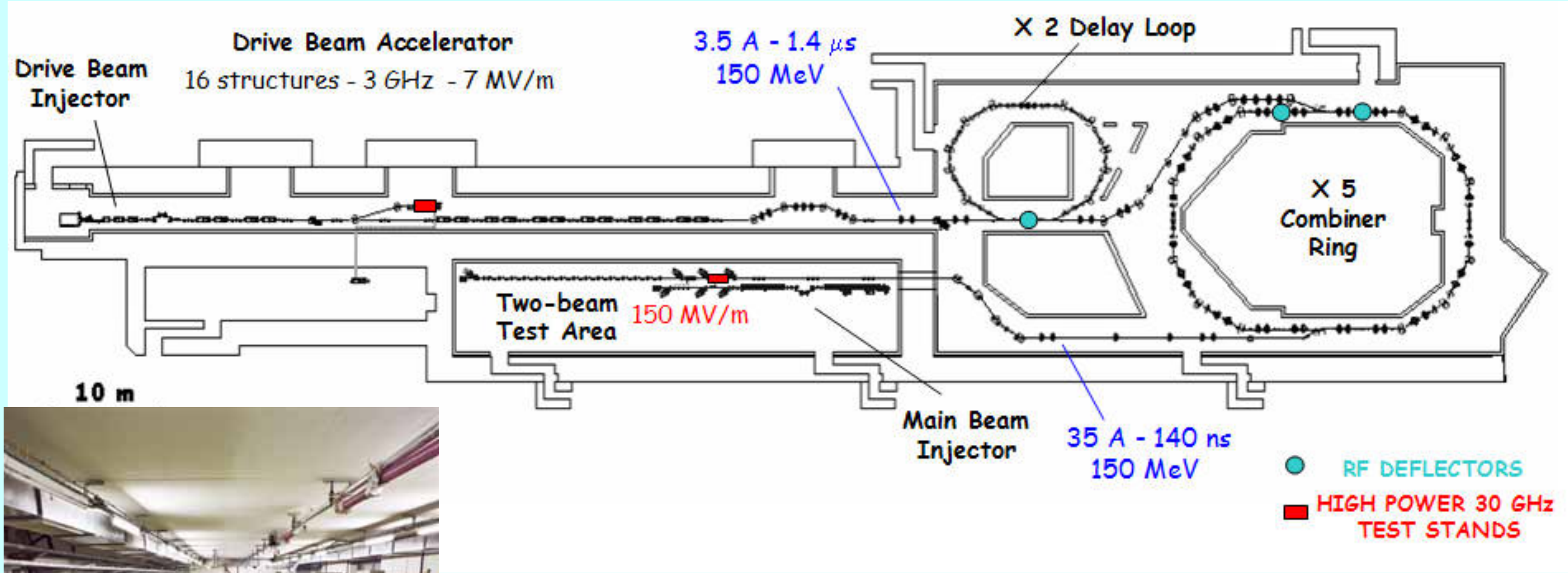
Copper Acceleration Cavities



CLIC Parameters

Center-of-mass energy	3 TeV
Peak Luminosity	$7 \cdot 10^{34}$ cm^{-2} s^{-1}
Peak luminosity (in 1% of energy)	$2 \cdot 10^{34}$ cm^{-2} s^{-1}
Repetition rate	50 Hz
Loaded accelerating gradient	100 MV/m
Main linac RF frequency	12 GHz
Overall two-linac length	42 km
Bunch charge	$3.72 \cdot 10^{9}$
Bunch separation	0.5 ns
Beam pulse duration	156 ns
Beam power/beam	14 MWatts
Hor./vert. normalized emittance	660 / 20 nm rad
Hor./vert. IP beam size bef. pinch	40 / ~1 nm
Total site length	48 km
Total power consumption	322 MW

CLIC Test Facility CTF3



Under construction at CERN
Show CLIC feasibility by 2010

Timeline

- Physics will decide the way forward!
  - LHC will tell us which energy reach will be needed

ILC Timeline

- Years around 2012 will be the decision years on how to proceed:
  - ILC, CLIC, LHC-Upgrades, something completely different?

Summary

- The LHC will tell us very soon about where to look for the answers of the most pressing questions in particle physics
  - Higgs particle and mass generation in the Standard Model
  - Does Supersymmetry exist? Is it the source of the cold dark matter in the universe?
  - Do we live in more than four dimensions?
  - ...
- The ILC is the only available design for a TeV electron-positron linear collider which is mature enough to allow a construction start in a timely manner after the emerging first LHC results
- CLIC might open the path to the multi-TeV region, but it comes on a different time scale
- The next Linear Colllider will be the most complicated machine in the world

- The Technical Design Report for the ILC will be published in 2012
  - This will serve as a construction proposal