Electron-Positron Linear Collider

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Summer Student Lecture

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Schedule

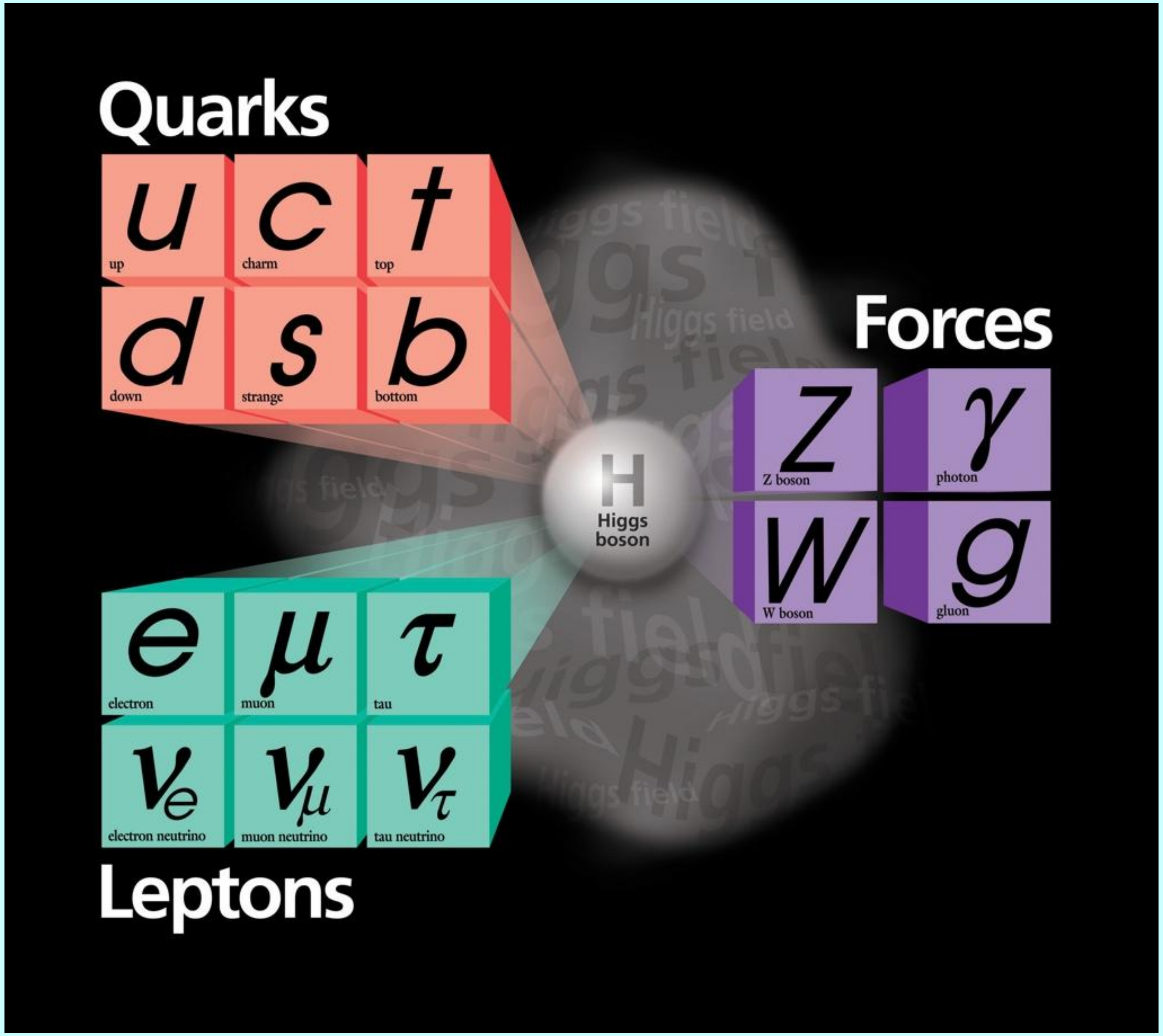
- Introduction
- Global Context
- Physics Case
- ILC Accelerator Design
- CLIC Acceleration Principle
- ILC Detectors
- Outlook

Thanks to Karsten Buesser for using part of his last year's slides, who in turn
thanked P. Wienemann, N. Walker, T. Behnke, B. Foster, J.P. Delahaye and others for letting him stealing some of their plots and slides

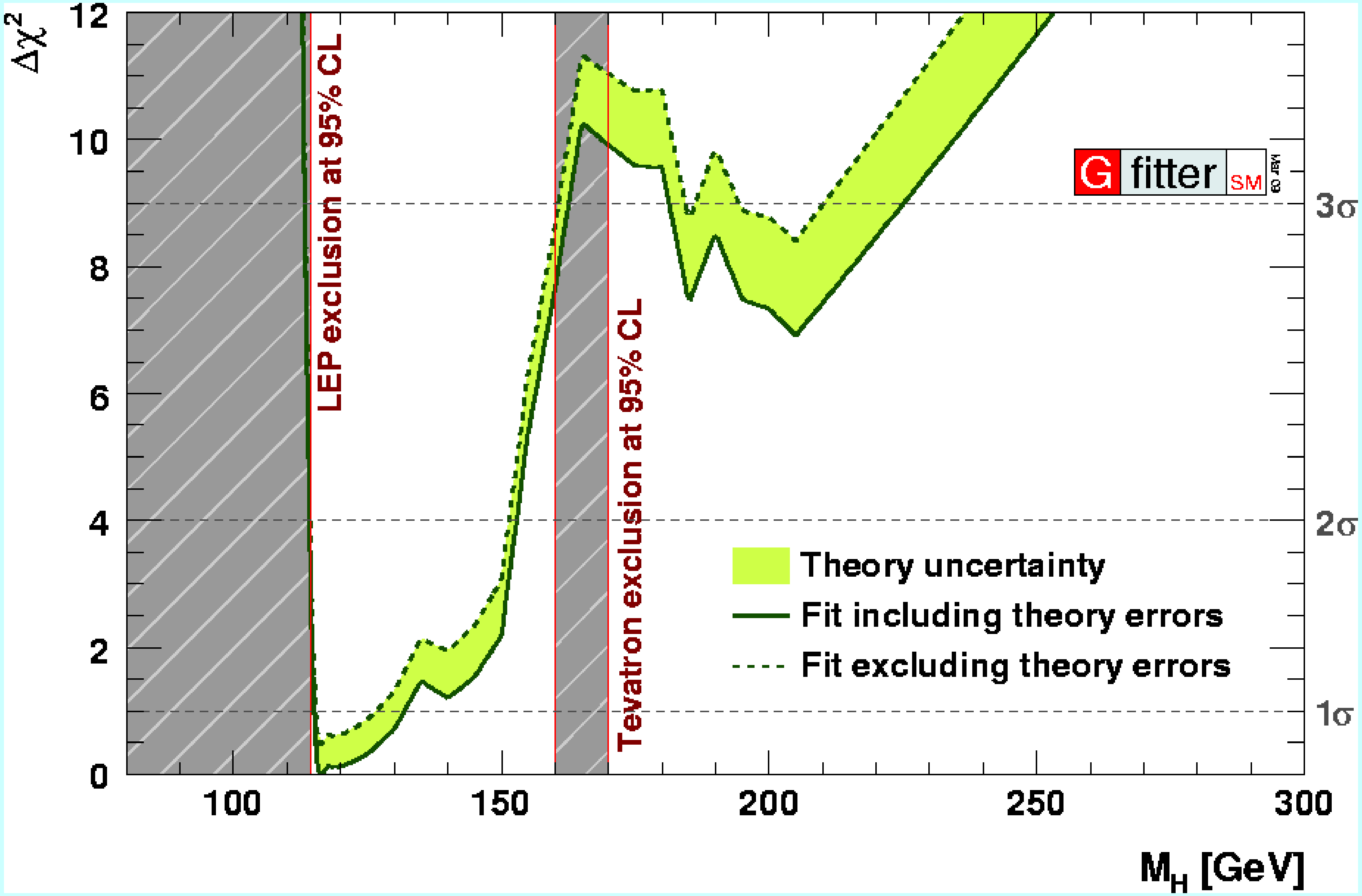
Introduction

The Standard Model of Particle Physics

- Extremely successful description of the microcosm
- 12 matter particles
- 4 force mediators
- 1 missing piece: Higgs Boson
- No significant deviation found in many precision measurements under hypothesis Higgs boson being relatively light



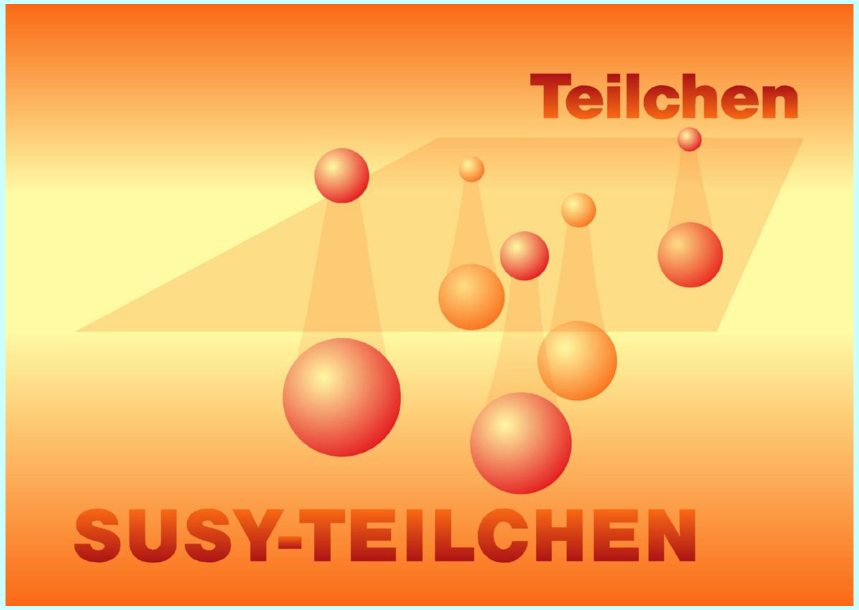
The Higgs-Boson

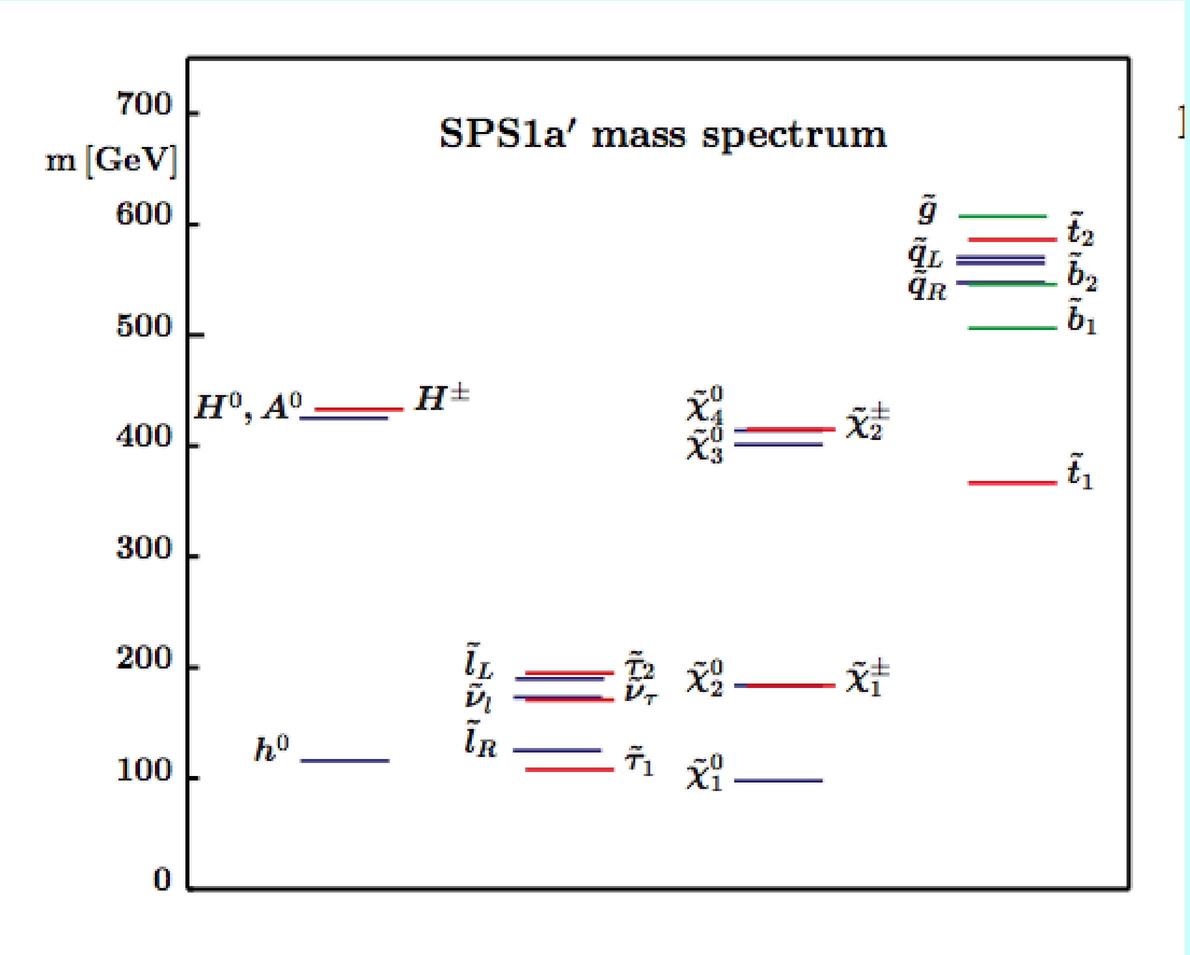


- Where is the Higgs-Boson?
- Direct searches done at LEP, still ongoing at Tevatron and just started at LHC
- Indirect searches point to low mass Higgs

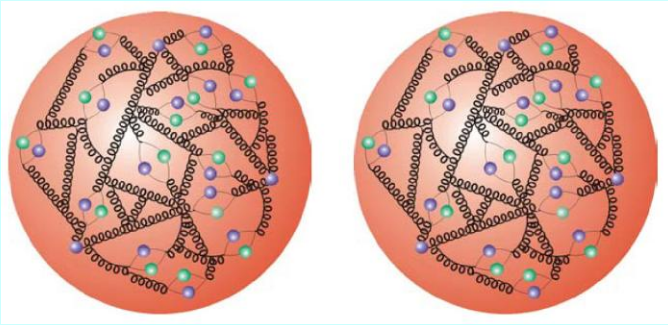
Does SUSY exist?

- Supersymmetry relates bosons and fermions
- It must be a broken symmetry – otherwise we would have found SUSY particles
- New particle spectrum
- Neutral SUSY particles are strong candidate for dark matter!





Hadron and Electron Machines

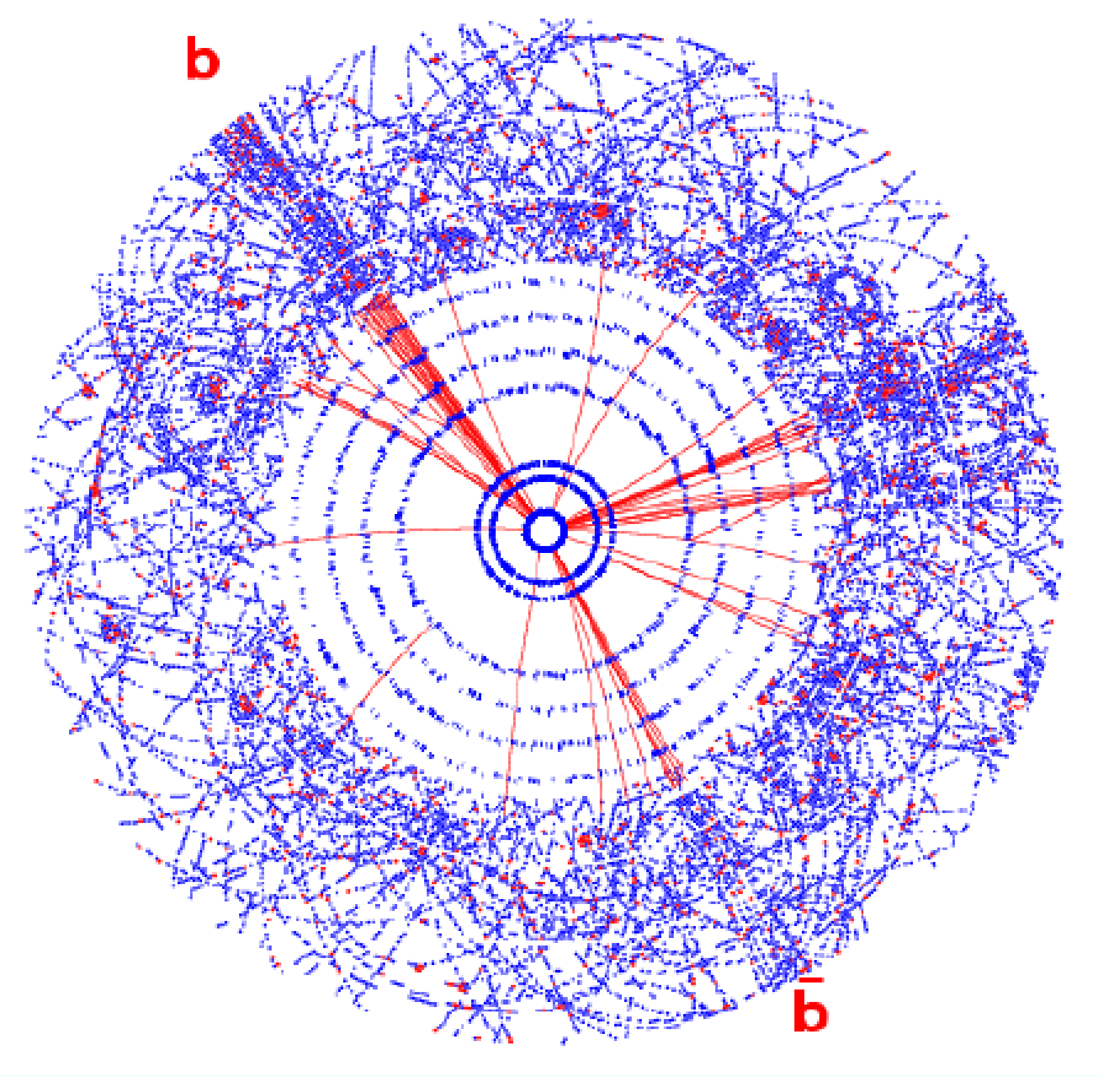
p  p

- Proton (anti-) proton colliders:
- Energy range higher (limited by magnet bending power)
- Composite particles, different initial state constituents and energies in each collision
- Hadronic final states difficult
- Discovery machines
- Excellent for some precision measurements

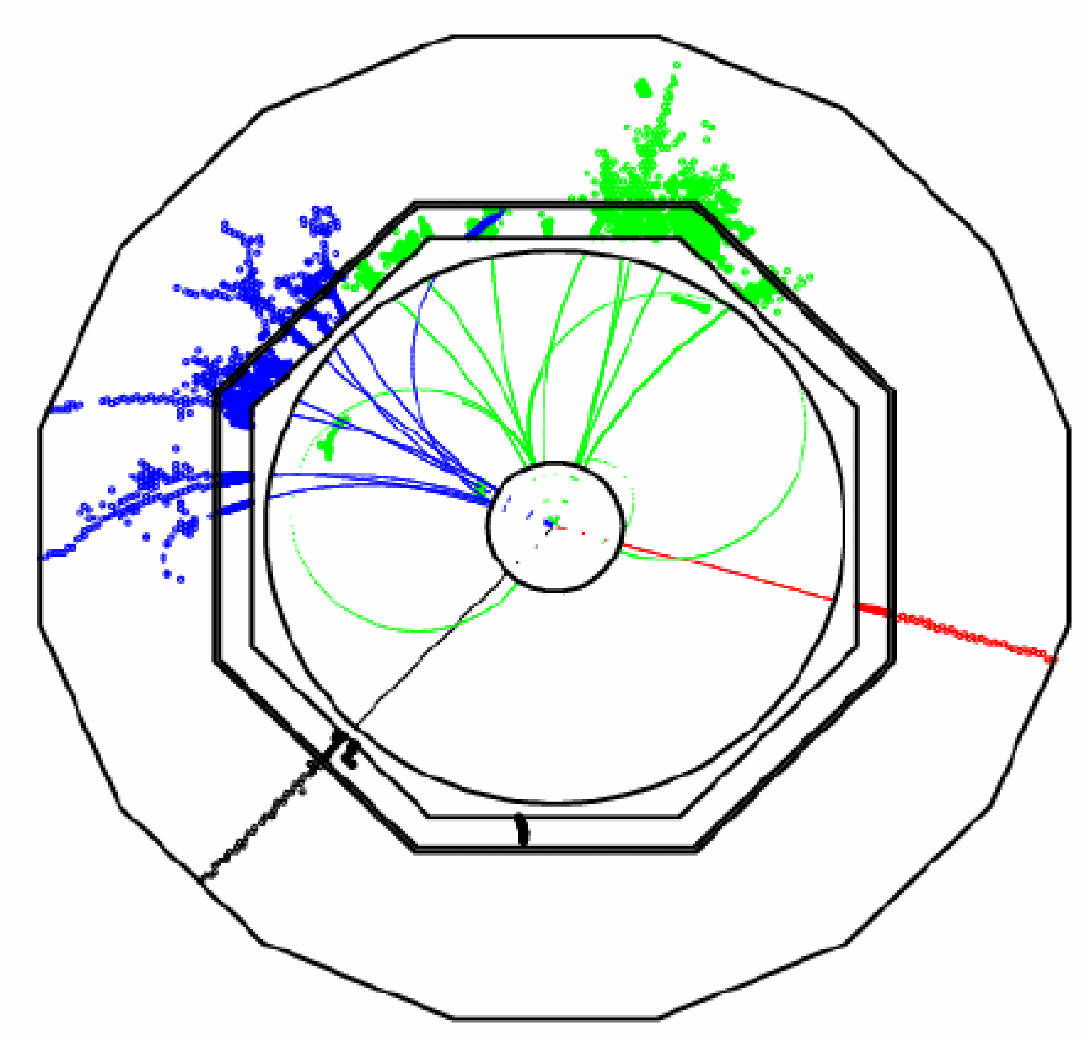
e^+ • • e^-

- 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

Protons vs Electrons



pp ➔ H + X



e^+e^- ➔ HZ

ILC Requirements

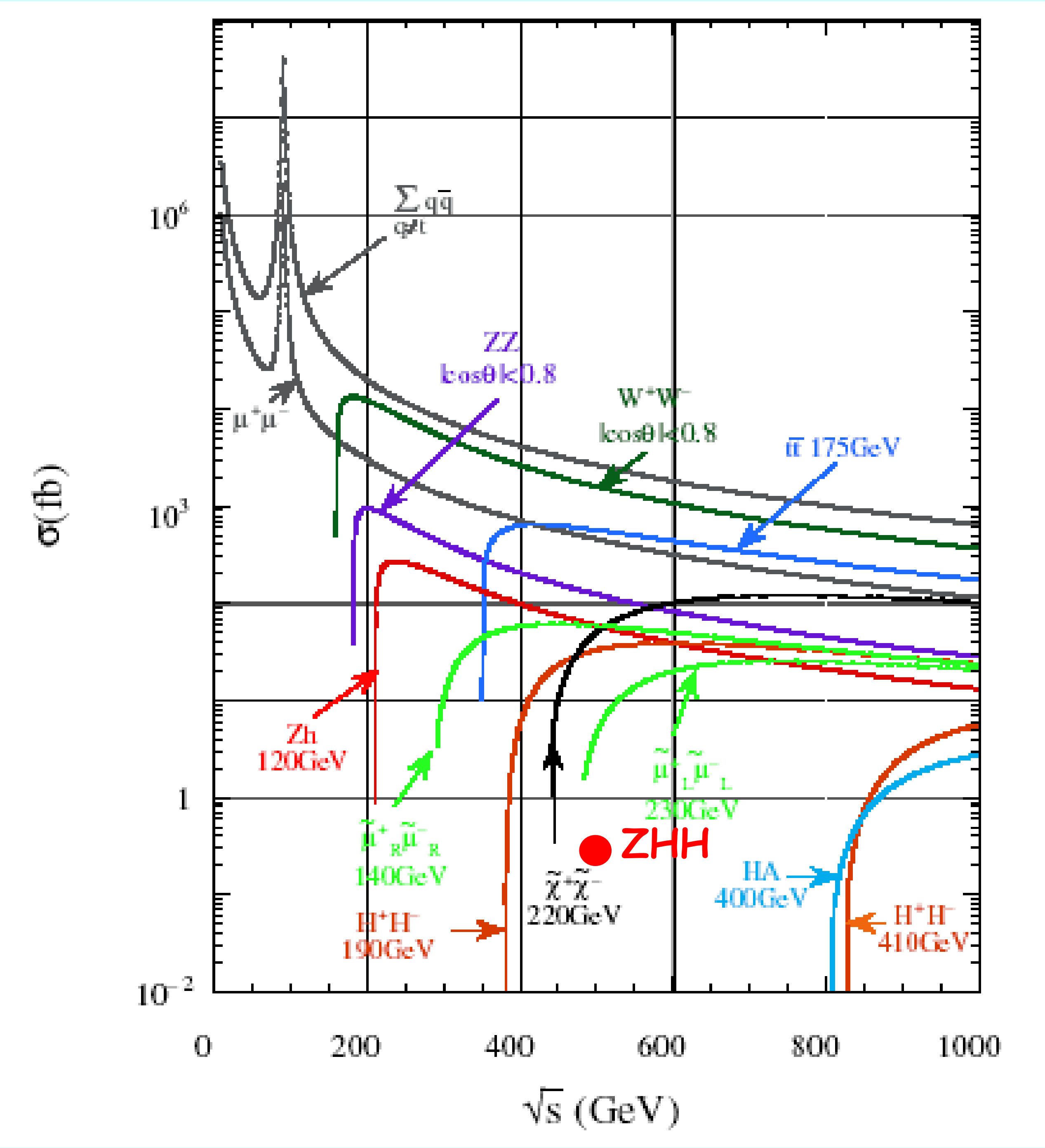
- The e^+e^- cross section drops ~1/s
- The key parameters for a competitive e^+e^- machine are
  - energy reach
  - Luminosity

(LEP2 had integrated luminosity of ~ 700 pb^{-1}/expt; peak luminosity ~10^{32} $cm^{-2}s^{-1}$)

Reminder:

$N_{int} = \sigma \int L dt$

1 pico-barn = 10^{-36} cm^2



ILC baseline parameters

- CMS energy (max.): 500 GeV
- Luminosity (peak): $2 \times 10^{34}\ \mathrm{cm^{-2}s^{-1}}$

  $\int L dt = 500\ \mathrm{fb^{-1}}$ (4 yrs)
- e^- polarisation: ≥ 80%
- One IR with 14 mrad beam crossing angle

Upgrade:

- Energy up to 1 TeV
- $\int L dt = 1\ \mathrm{ab^{-1}}$ (3-4 yrs)

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

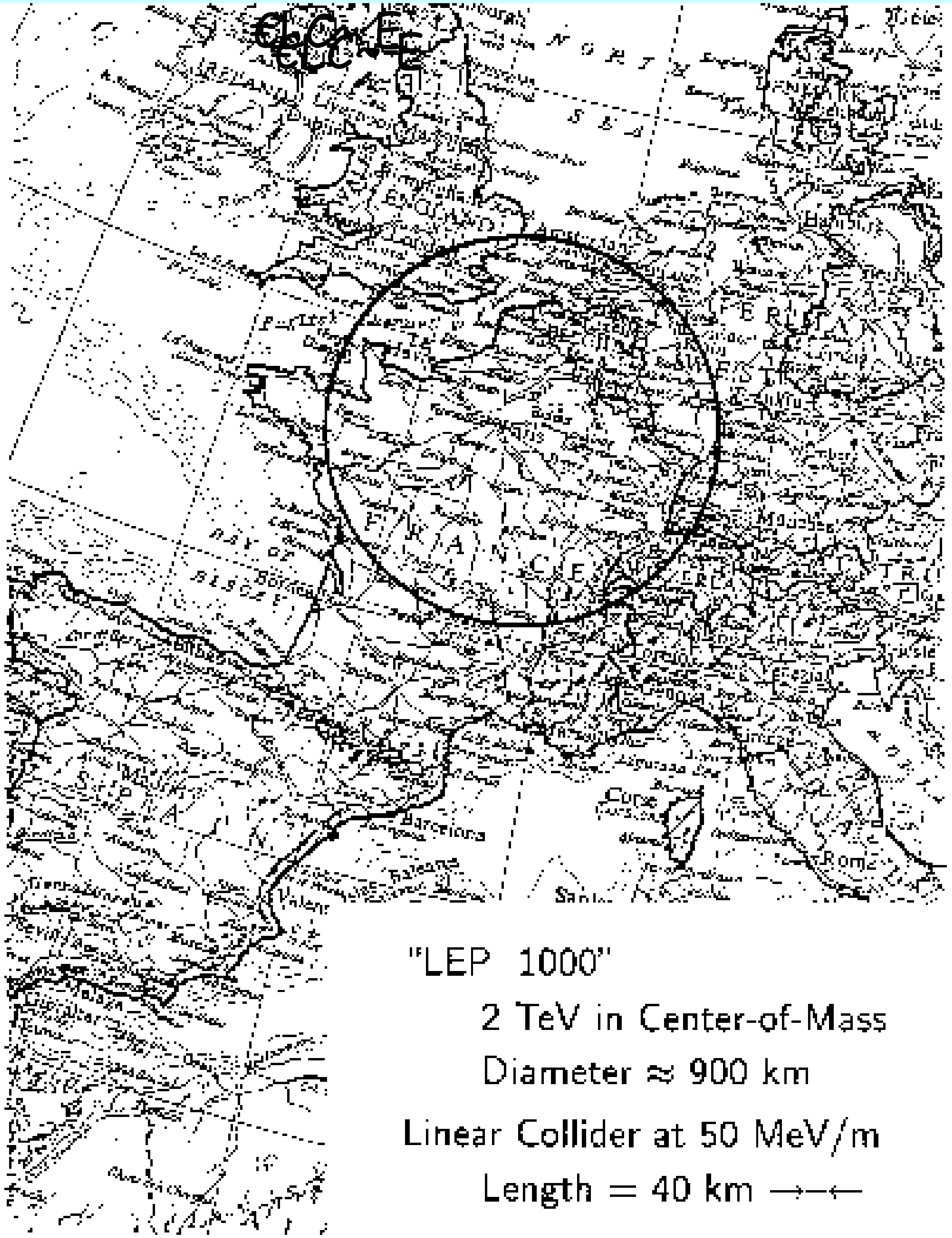


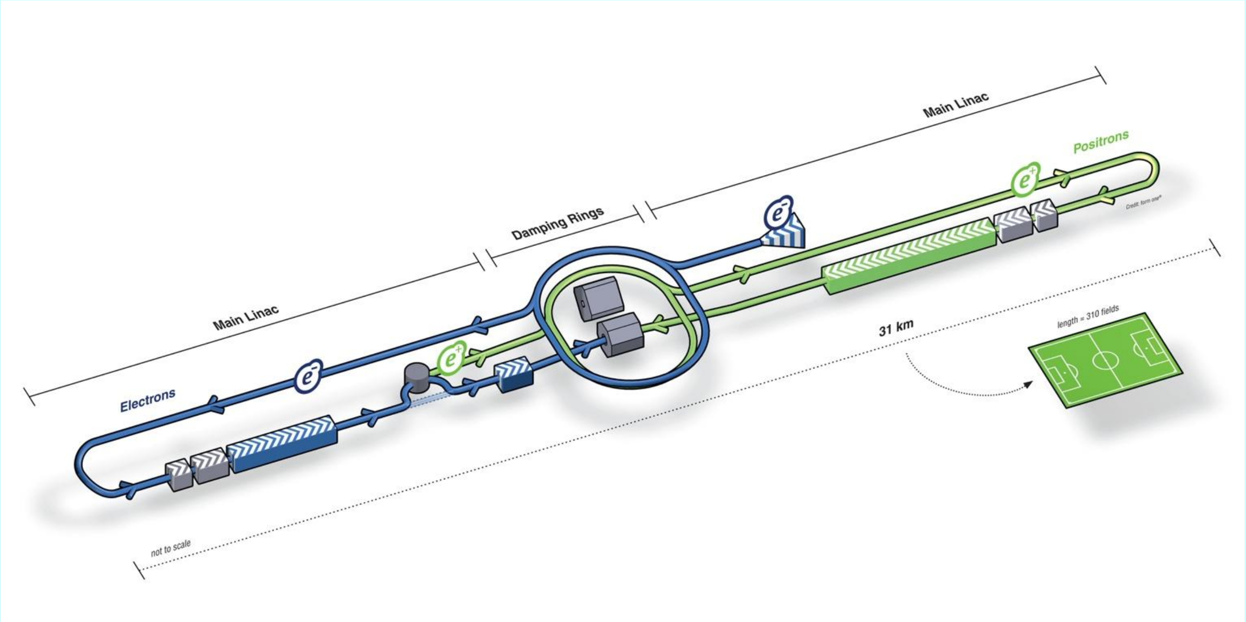
Figure by Gregory Loew

- The next high-energy e+e- collider will have to be linear:
- $€_{LC} \sim E$

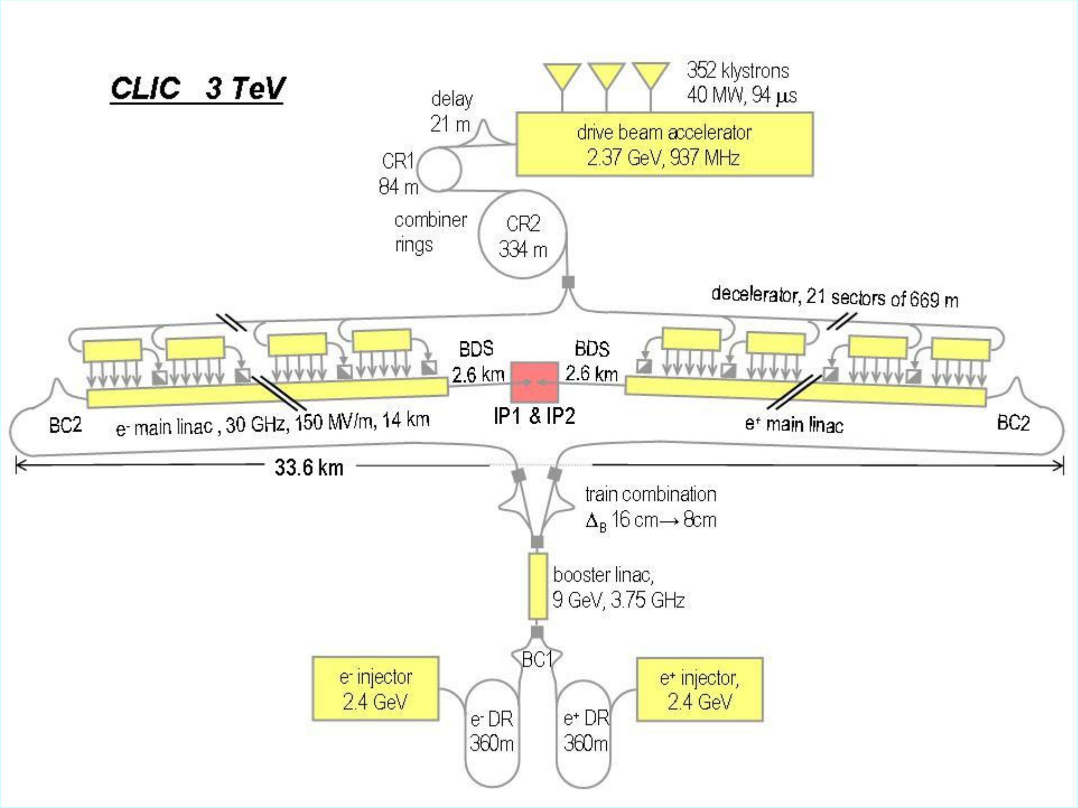
The Global Context

Linear Collider Developments

- International Linear Collider ILC
  - superconducting acceleration
  - 31.5 MeV/m, 1.3 GHz
  - advanced design (c.f. XFEL)
  - 500 GeV (→ 1TeV)
  - Luminosity: $2 \times 10^{34}\ cm^{-2}\ s^{-1}$
  - technology is at hand



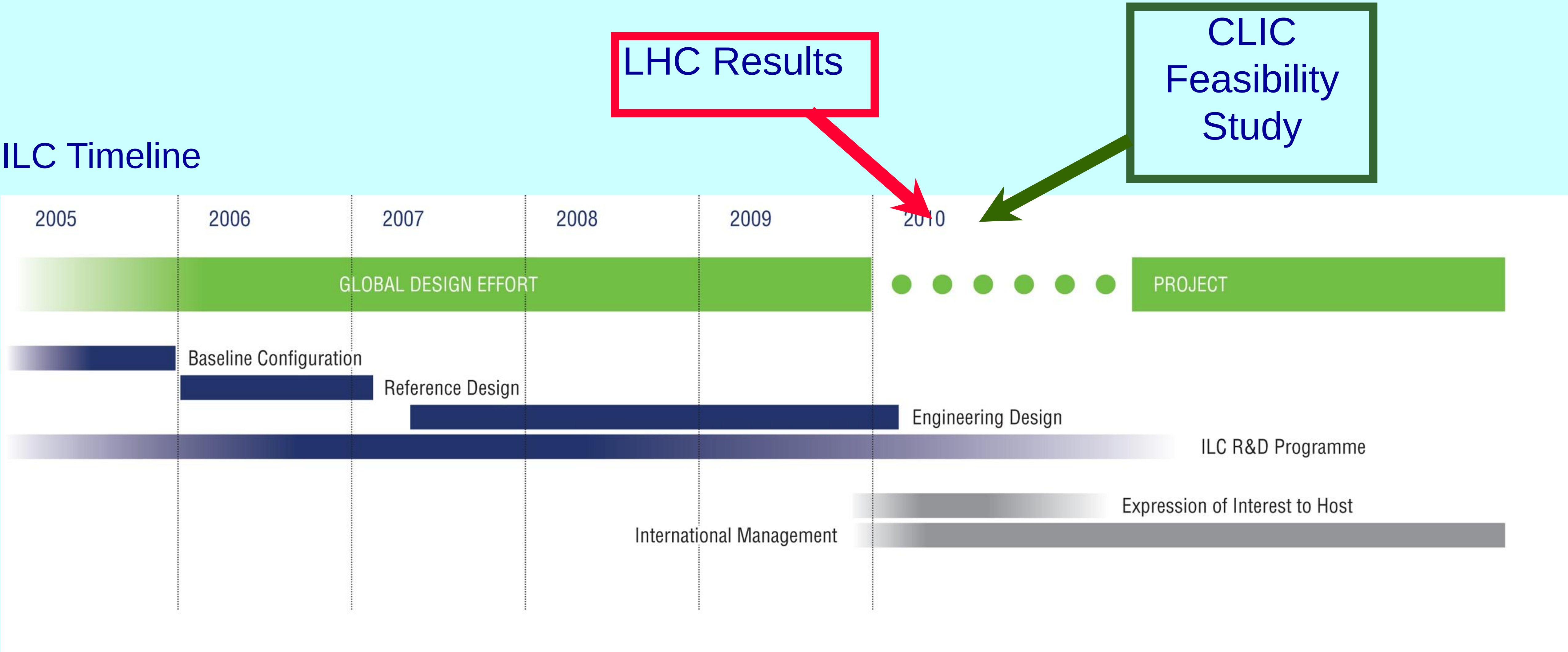
- Compact Linear Collider CLIC
  - normalconducting acceleration
  - 100 MeV/m, 12 GHz
  - two-beam acceleration principle
  - up to several TeV
  - still in fundamental R&D phase



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?

ILC Reference Design Report (2007)

Download it at
www.linearcollider.org

2011: CLIC Conceptual Design Report

Physics Case

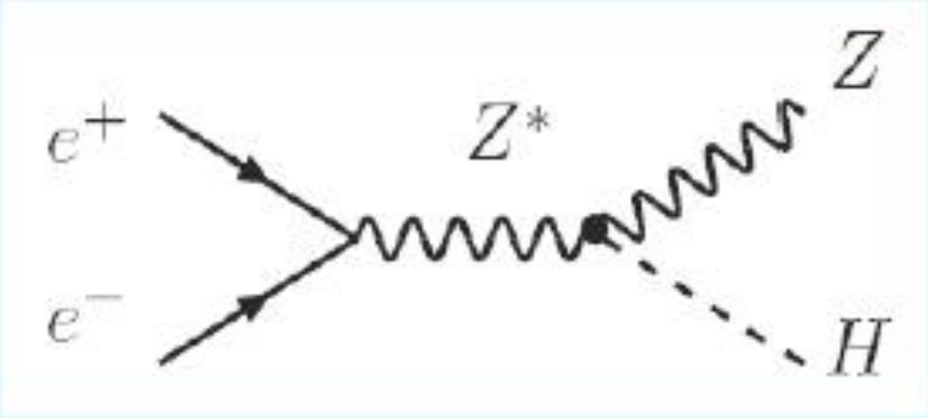
Physics Case

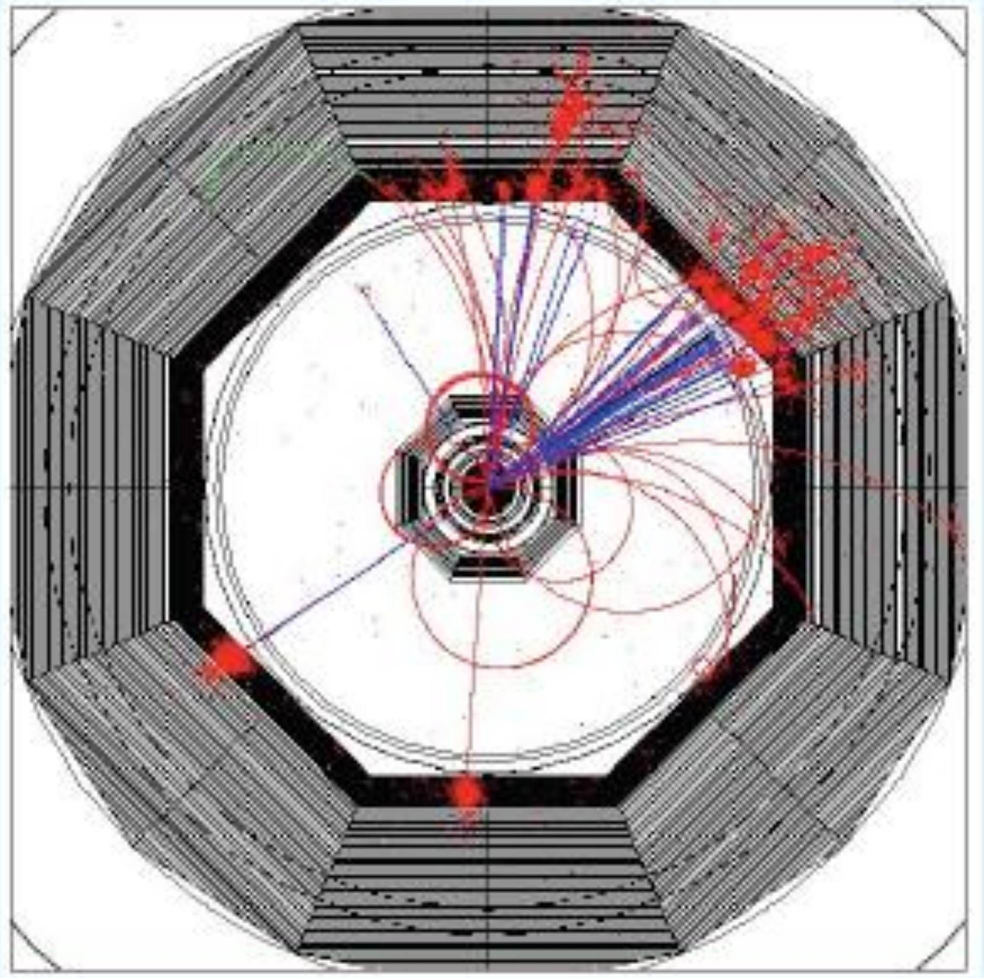
- There are other lectures which deal with the physics of electron-positron collisions
  - Elementary particle physics research - A. Geiser
  - Introduction to elementary particle physics - J. Meyer (HEP-Lectures)
  - Physics at e^+e^- colliders - G. Moortgat-Pick (HEP-Lectures)

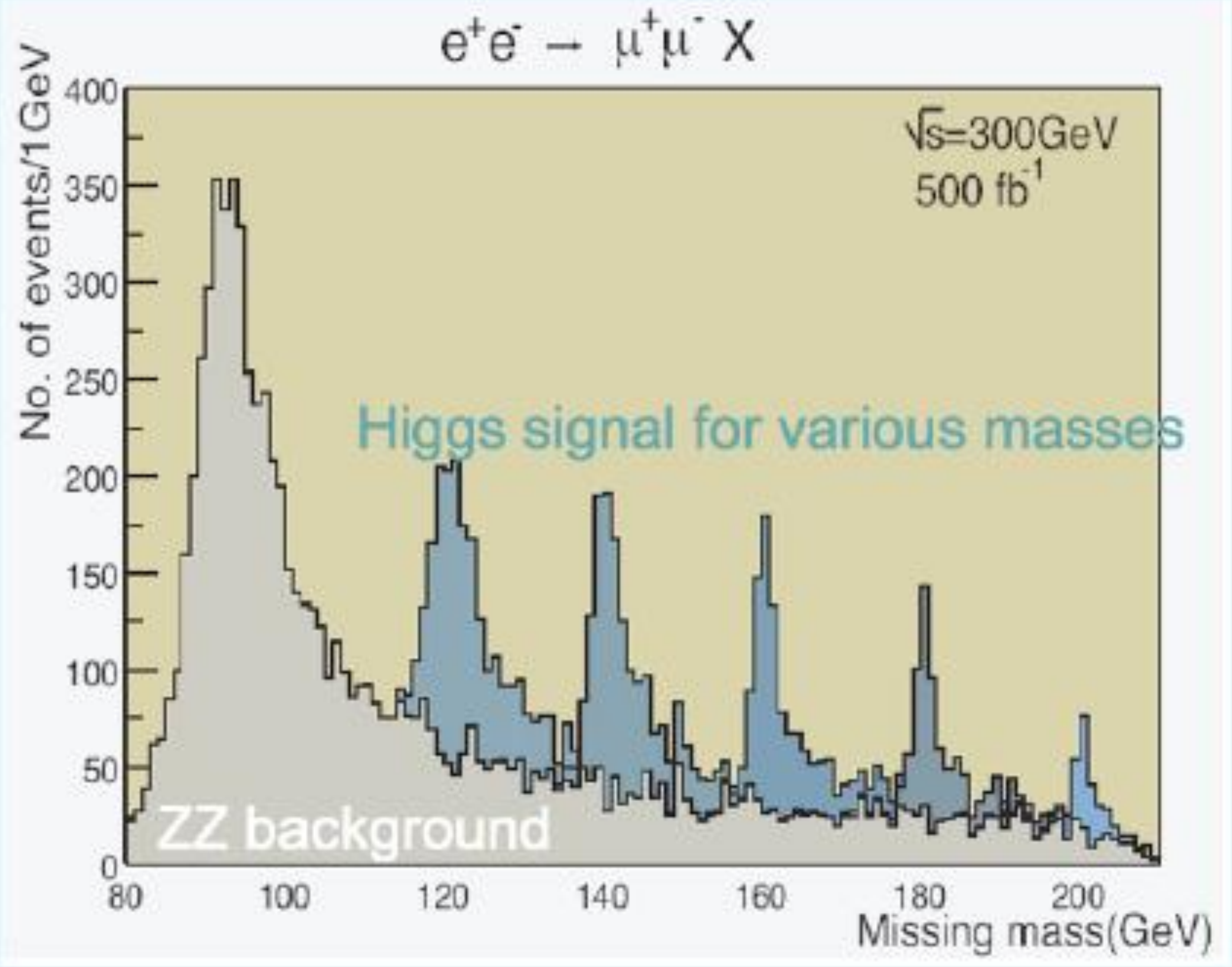
- I will just give one example and will leave the rest to the specialised lectures

Higgs Physics

- Model independent Higgs measurement

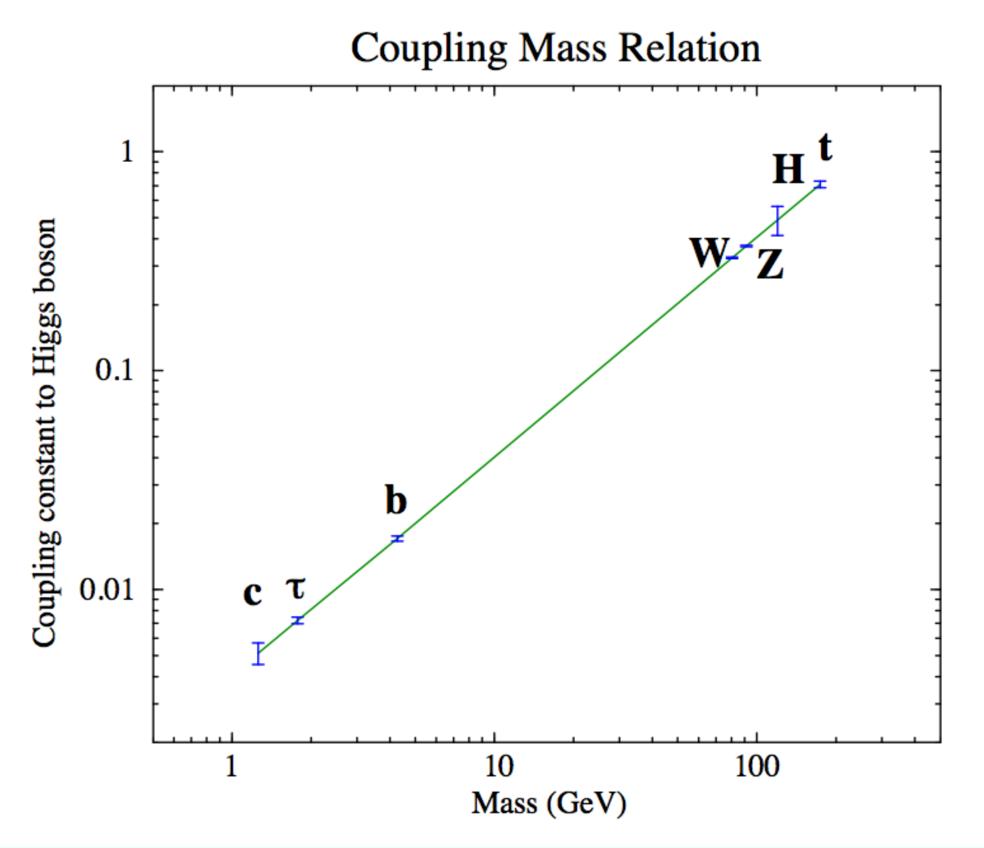


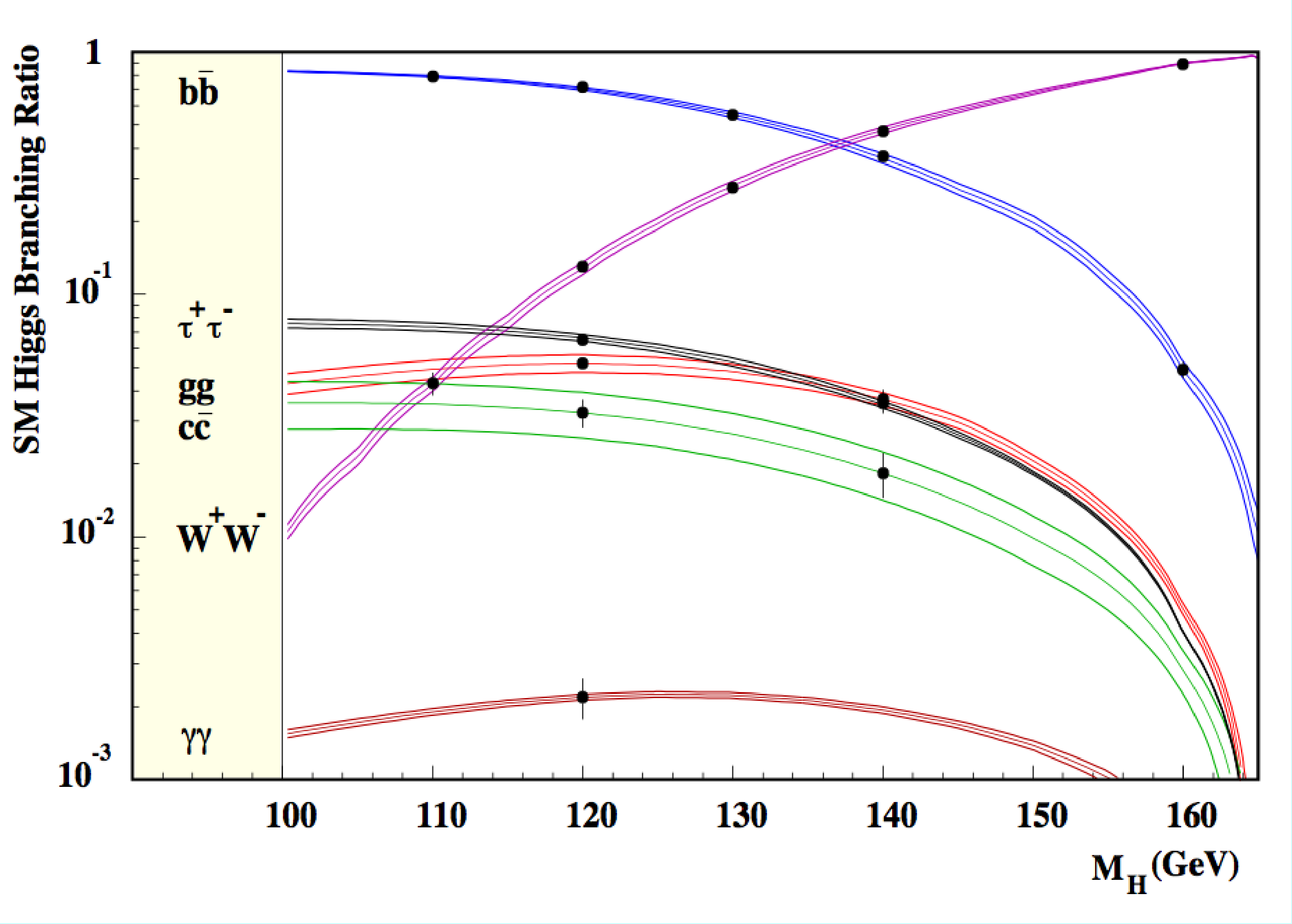




Establishing the Higgs-Mechanism

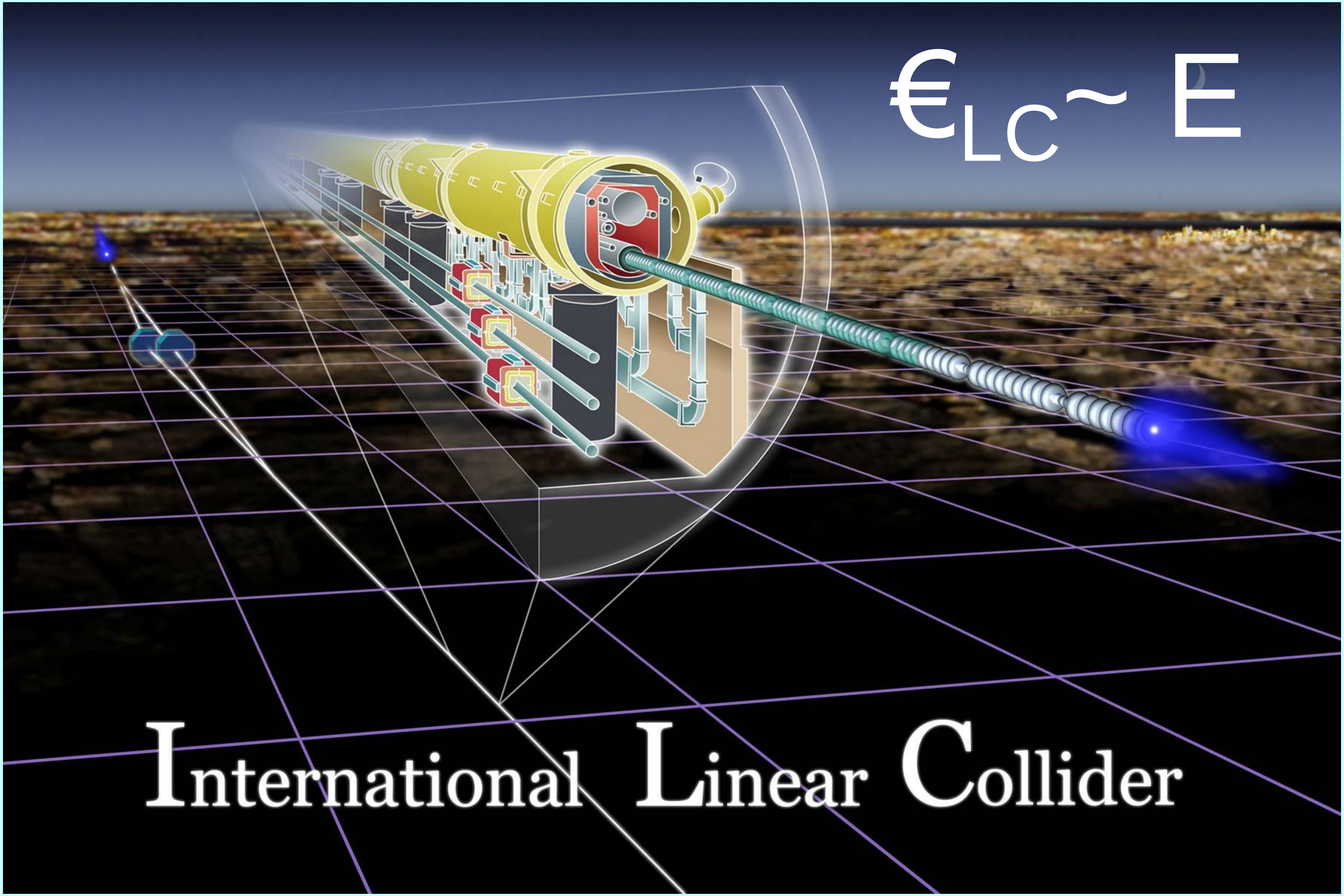
- Measuring the couplings of the Higgs to massive particles
- Check coupling-mass relation
  - The smoking gun!





ILC Accelerator Design

The Future is Linear



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-100 Hz (power limited)

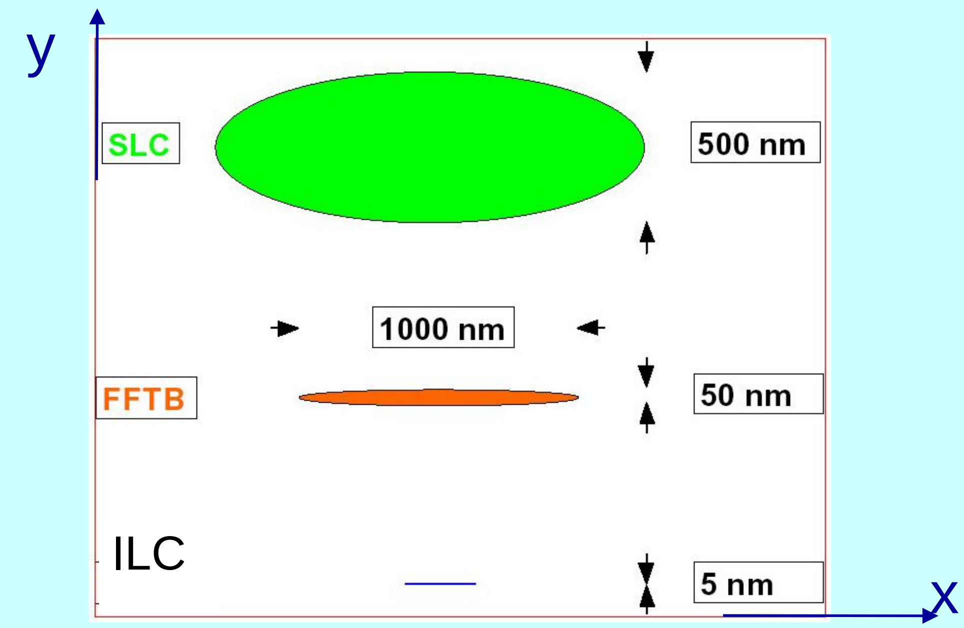
$$L = \frac{n_b N^2 f_{rep}}{4\pi \sigma_x \sigma_y} H_D$$

- Factor ~ 400 in *L* already lost!
- Recover by pushing hard on the beam spot sizes at collision:

LEP: 130 x 6 μm^2

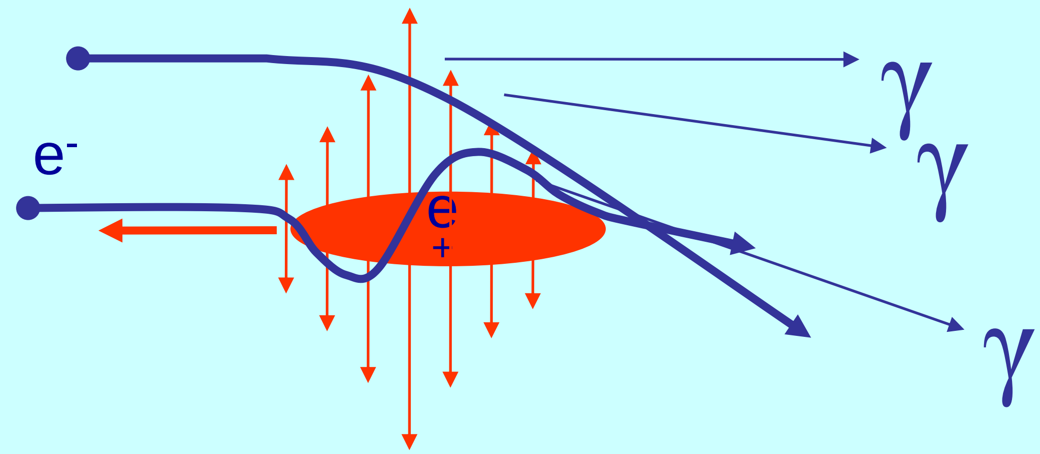
ILC: 500 x 5 nm^2

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



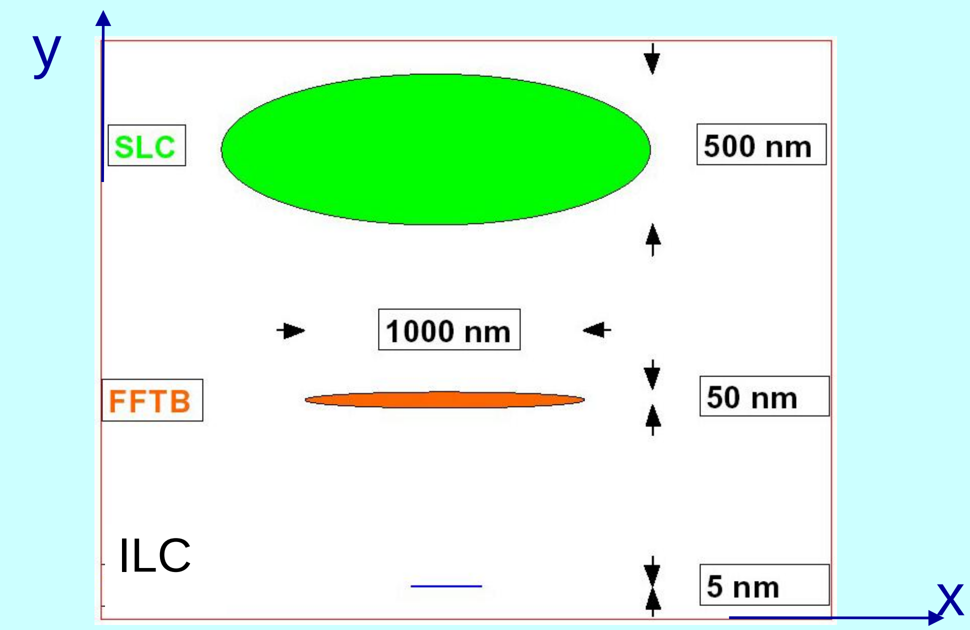
Beamstrahlung

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



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

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



Choose flat beams!

Luminosity Scaling Law

- Choose 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:

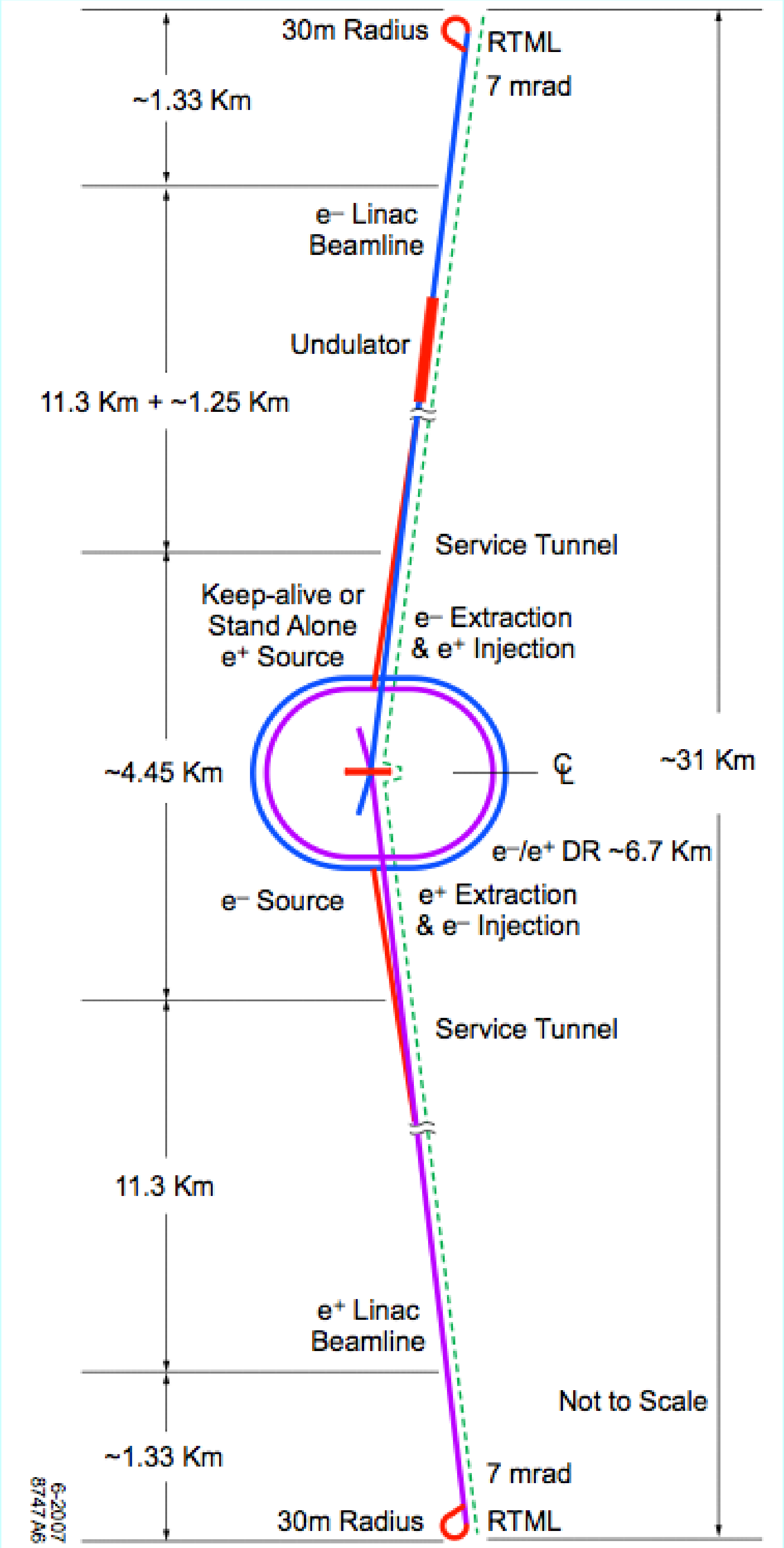
$$L \propto \frac{\eta_{RF} P_{RF}}{E_{cm}^{3/2}} \frac{\sqrt{\delta_{BS} \sigma_z}}{\sigma_y}$$

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

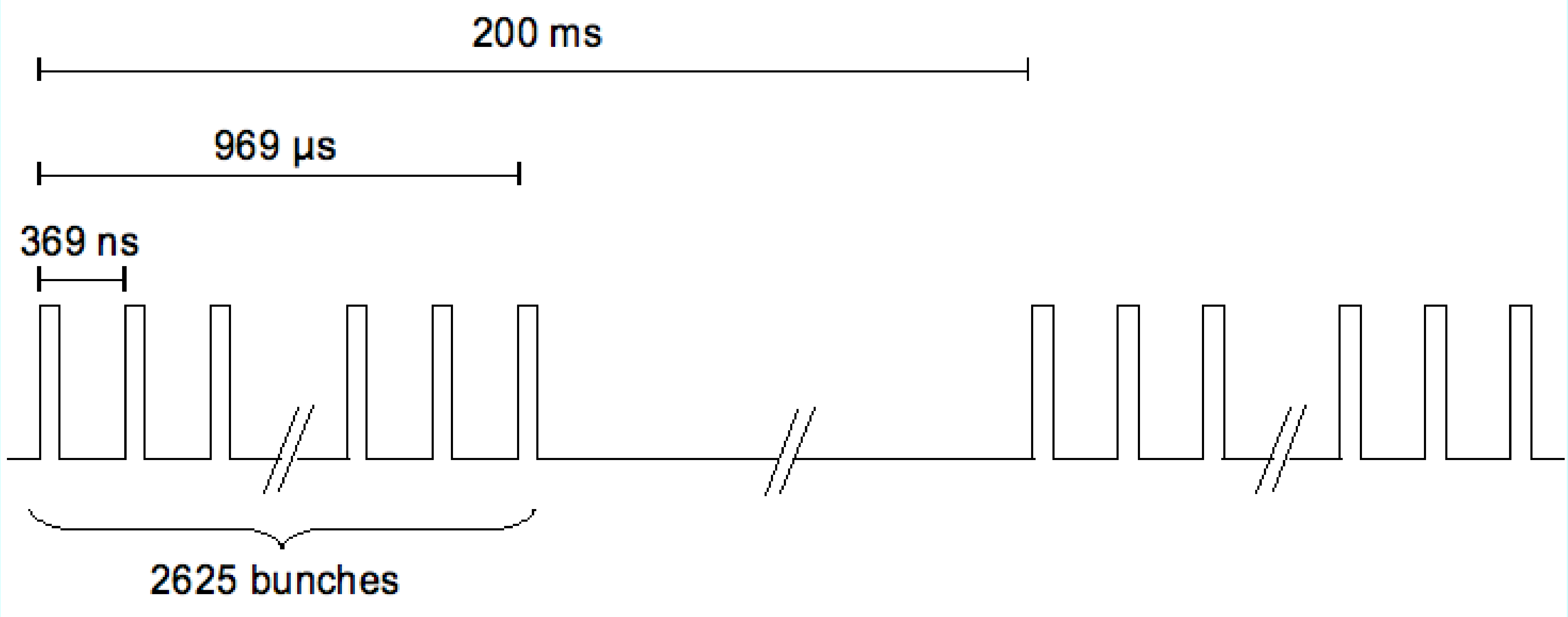
ILC Baseline Design



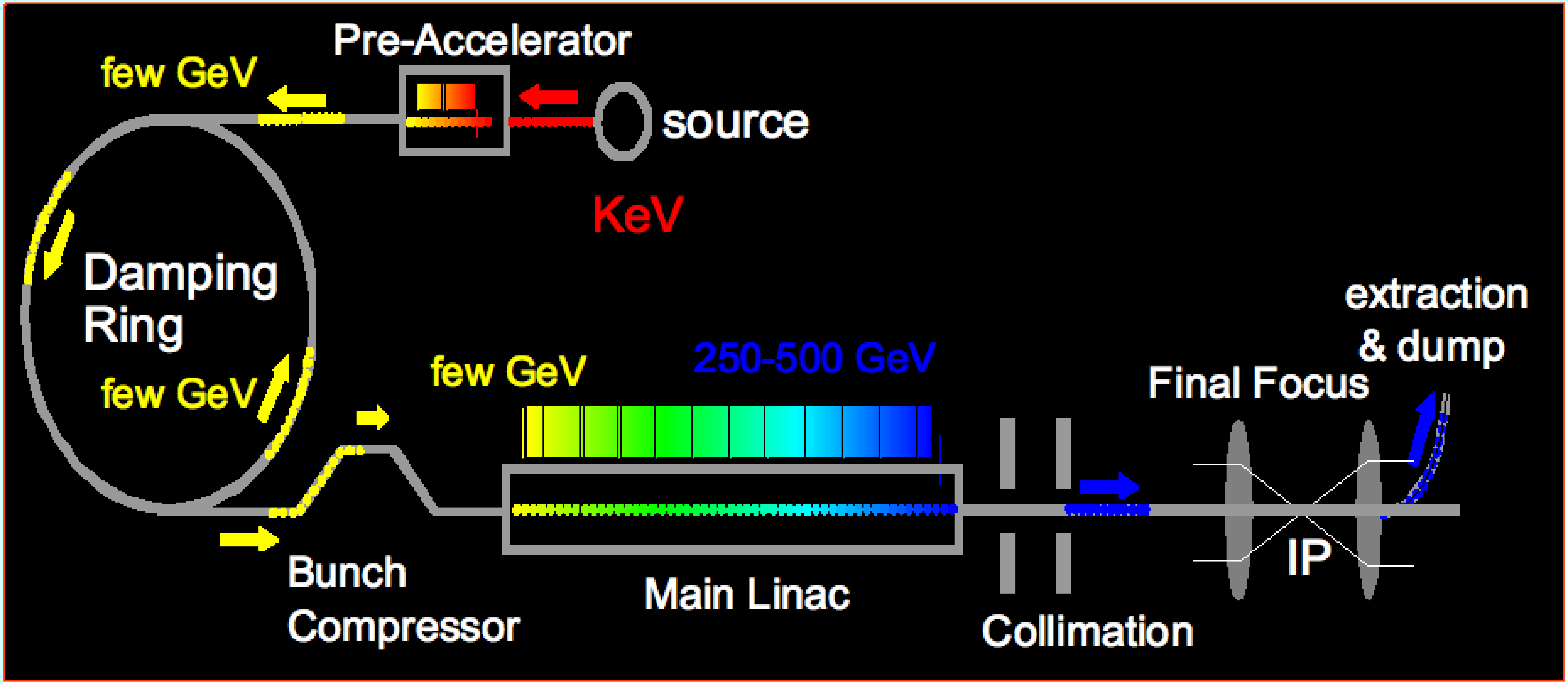
Parameter	Unit		ILC/LEP
Center-of-mass energy range	GeV	200 - 500	2.5
Peak luminosity[a)]	$cm^{-2}s^{-1}$	2×10^{34}	200
Average beam current in pulse	mA	9.0	2
Pulse rate	Hz	5.0	0.0001
Pulse length (beam)	ms	~ 1	
Number of bunches per pulse		1000 - 5400	~3000
Charge per bunch	nC	1.6 - 3.2	~0.05
Accelerating 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 Bunch Structure

- Superconducting RF has small dissipation losses in cavity walls → long pulses with large bunch spacing possible



ILC Technical Systems

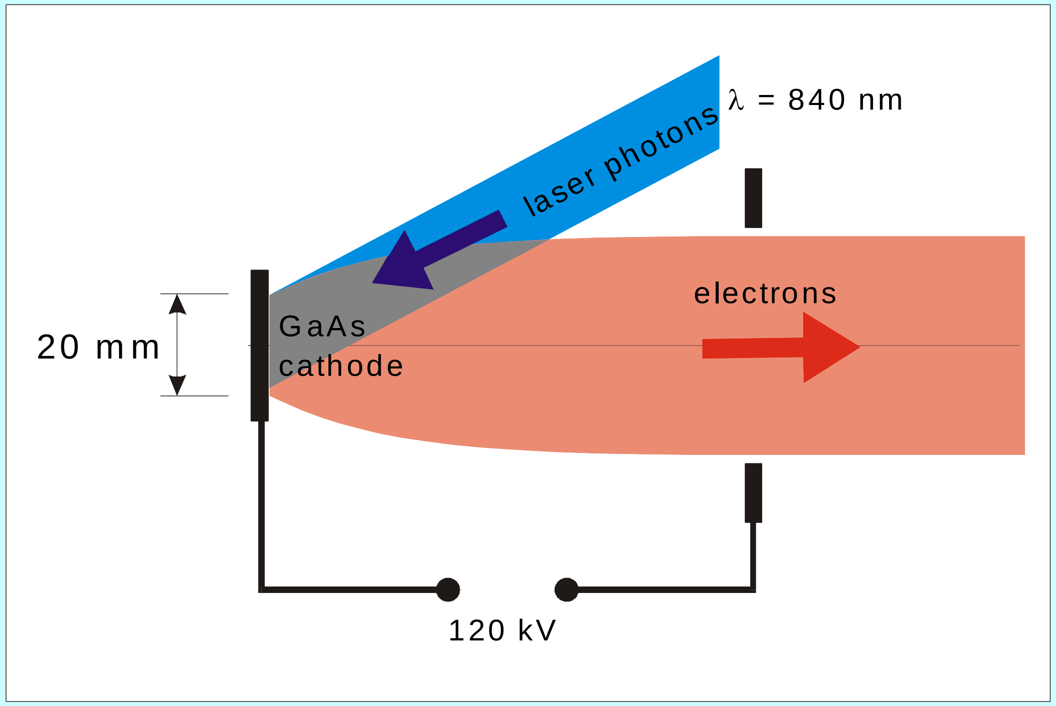


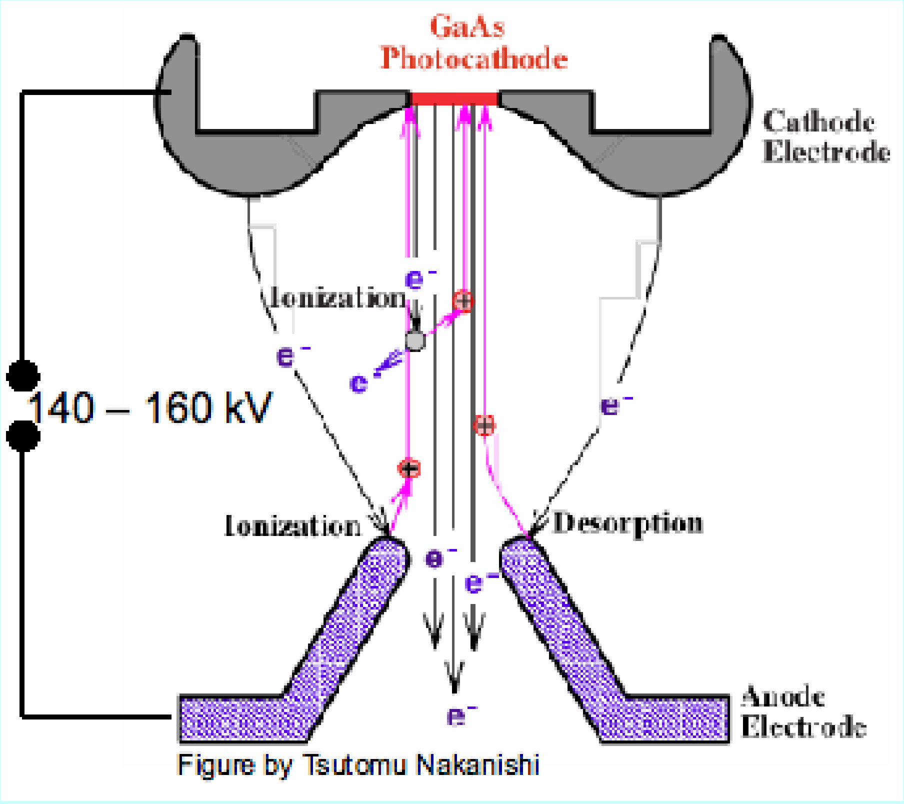
Sources

- 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

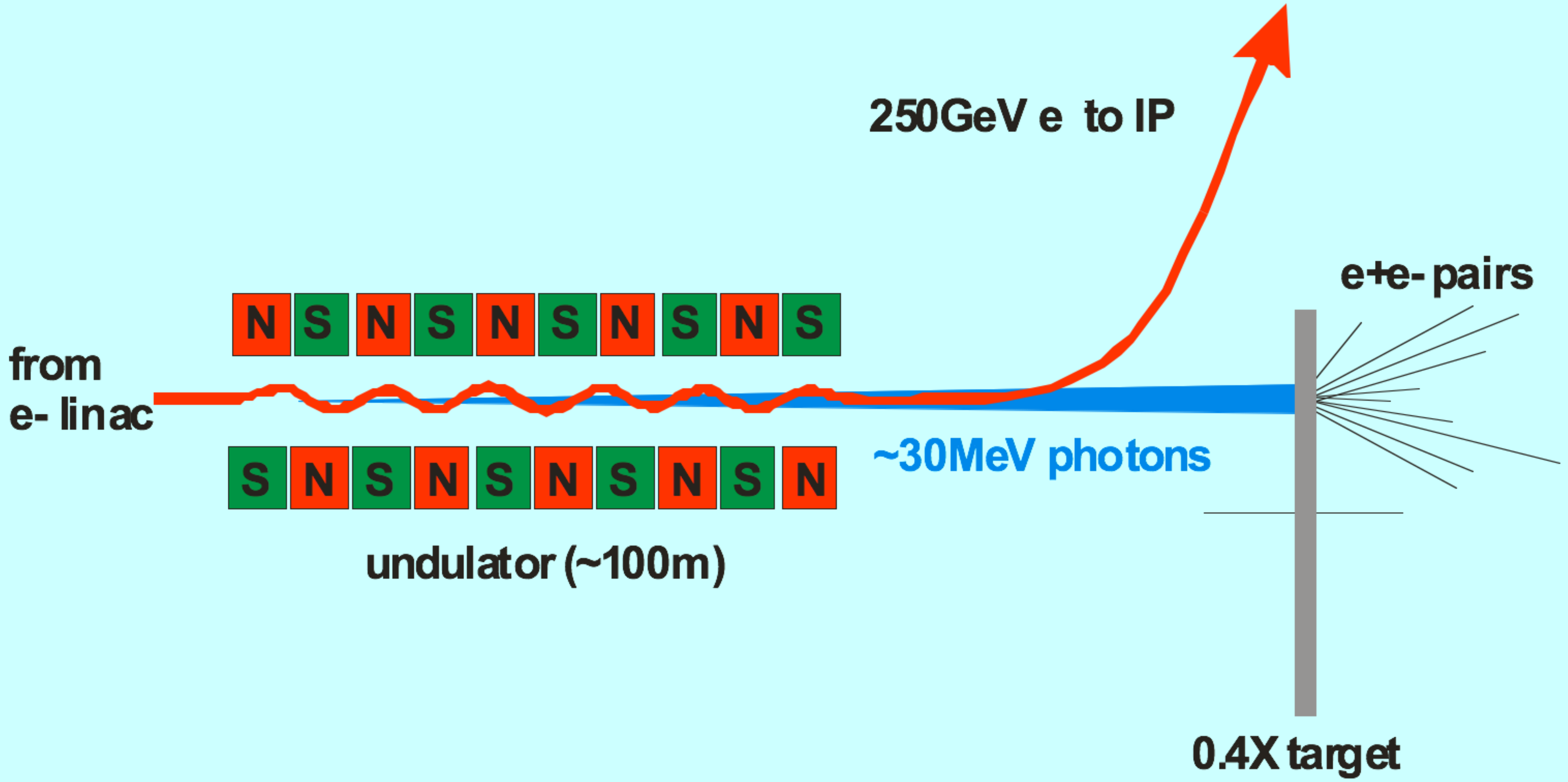
- Laser driven photo injector based on SLC design
- Circular polarised photons on GaAs cathode → longitudinal polarised electrons
- very high vacuum requirements (< 10^{-11} mbar) to protect cathode from impurities and ion backdrift
- 140-160 keV electron kinetic energy at exit
- 1ns bunch length at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





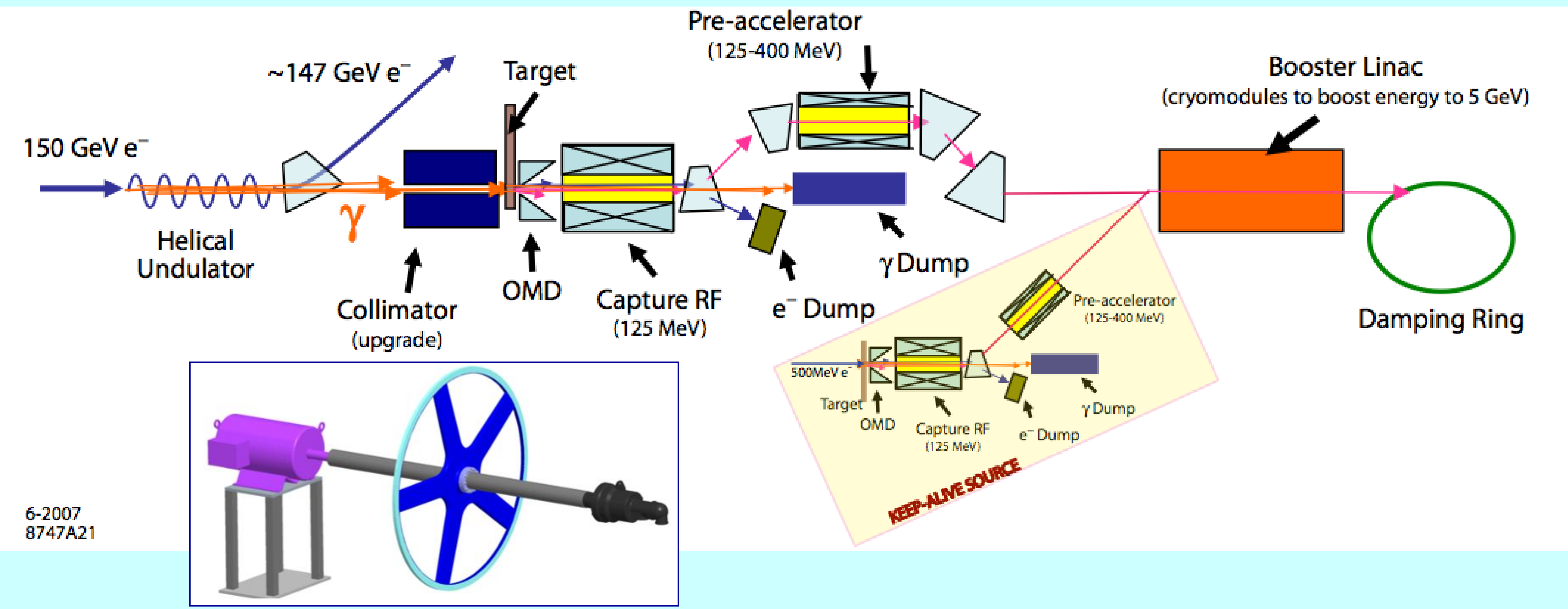
Positron Source

- 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!

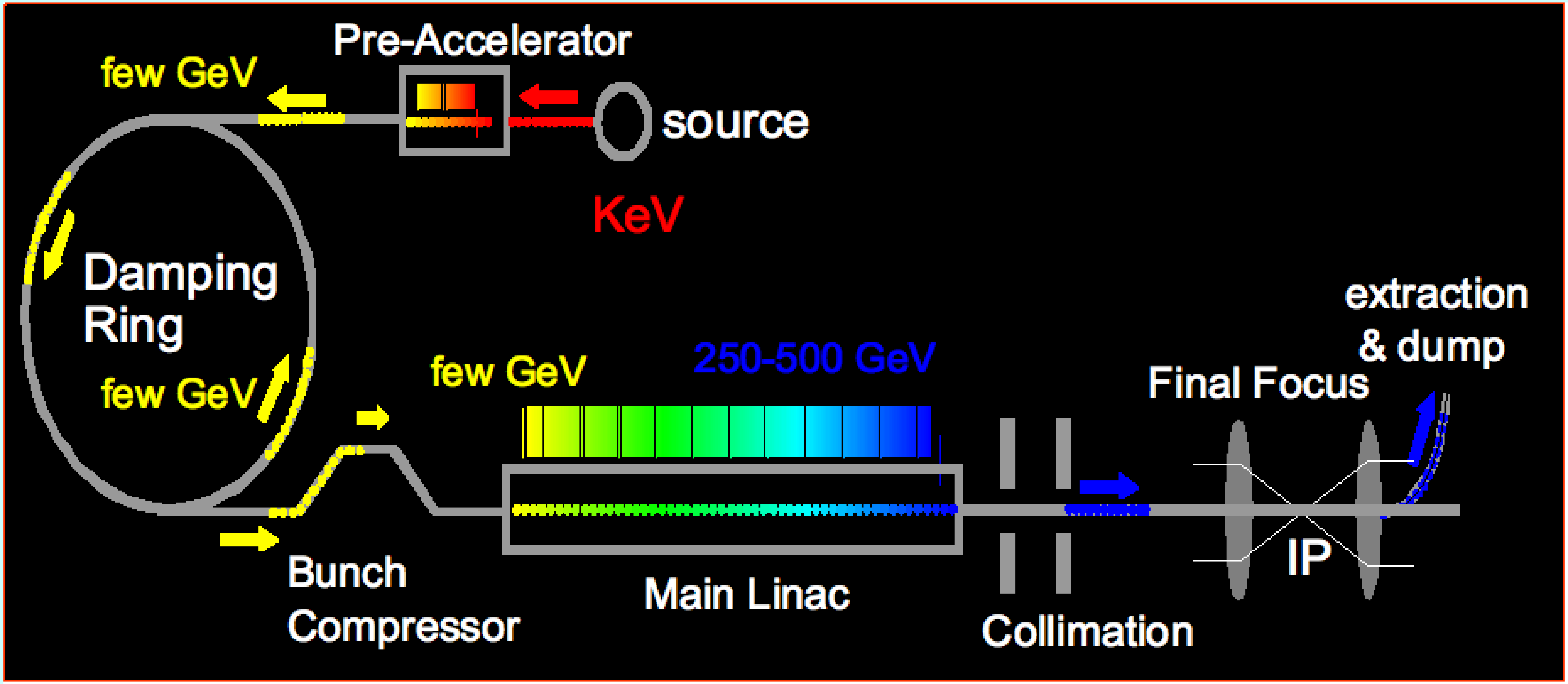


Positron Source Design

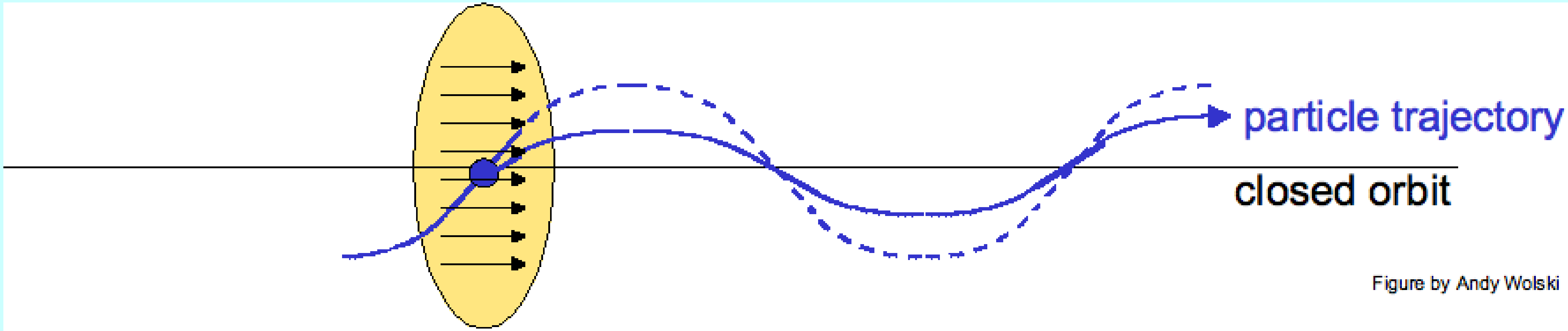
- Using a helical undulator allows the production of polarised positrons!
- Positron source links electron and positron linac
- Keep-alive positron source planned



Damping Rings

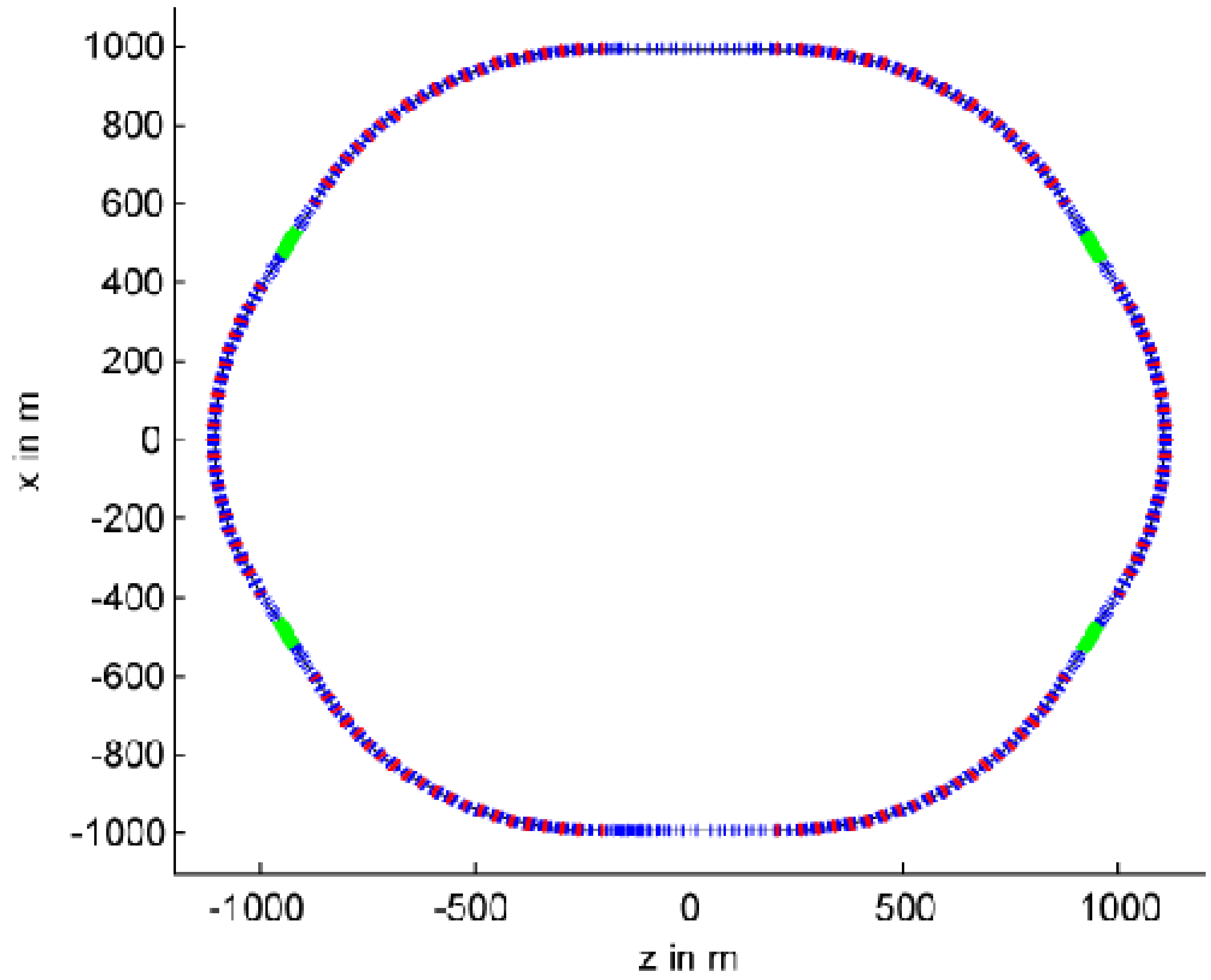


Damping Rings



- 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 100 ms
  - Linac RD 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

ILC Damping Ring Design



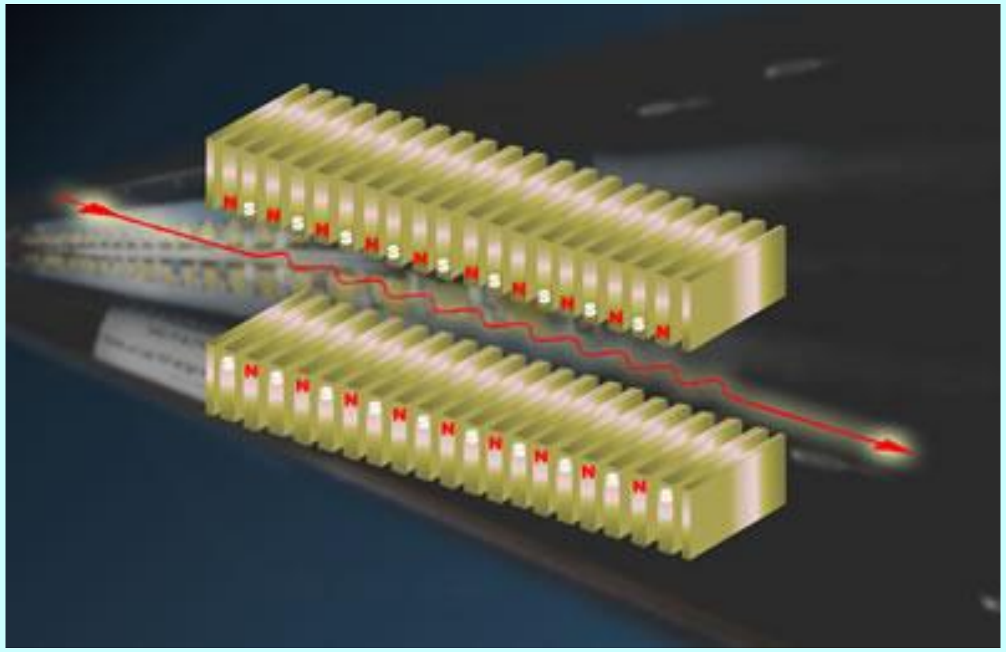
1 electron and 1 positron damping ring in common tunnel

6.7 km circumference

5 GeV beam energy

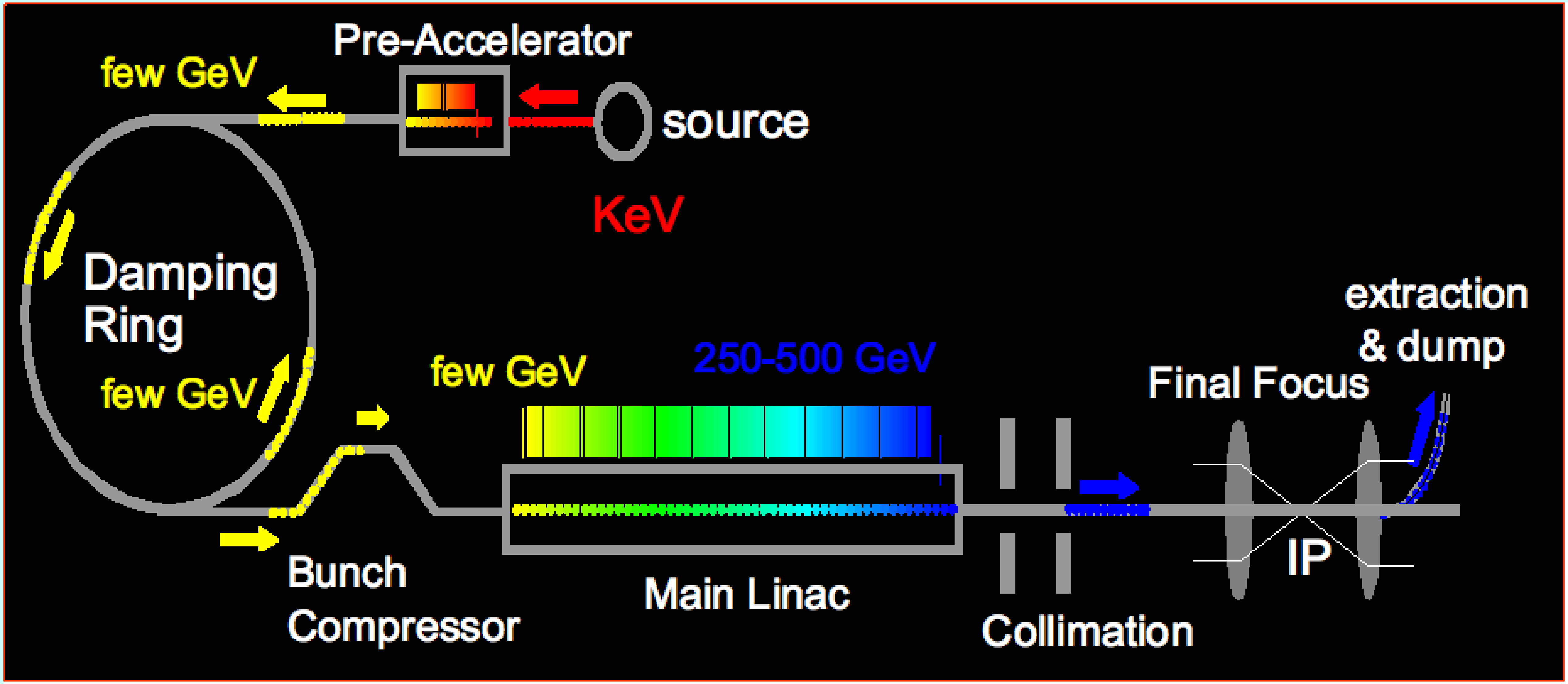
6 arcs, 6 straight sections

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

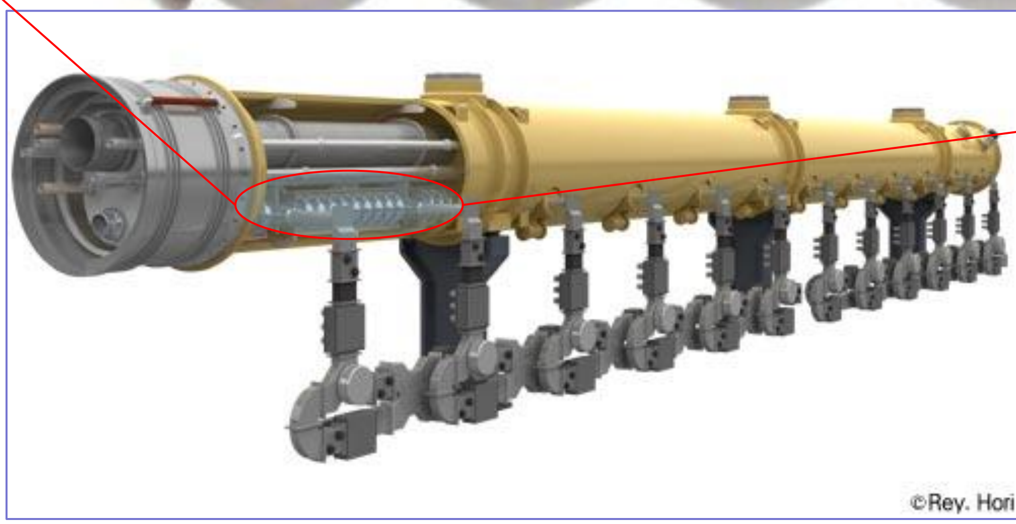


- Damping time by SR from bending magnets would be too large O(400ms)
- Include damping wigglers in the beam to reduce damping time to ~25 ms

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

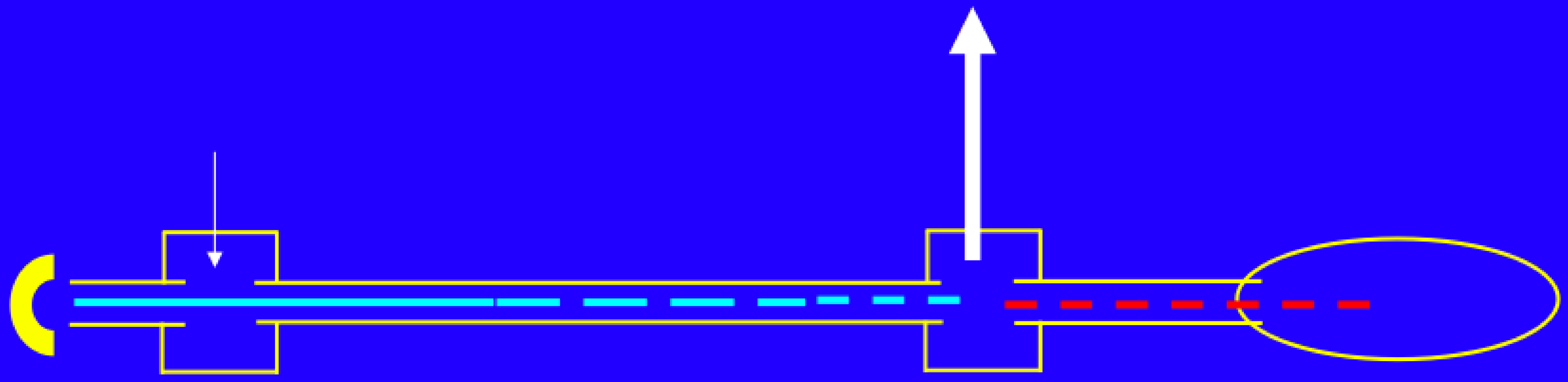
ILC's Workhorse - SCRF



Parameter	Value
C.M. Energy	500 GeV
Peak luminosity	2x10^{34} cm^{-2}s^{-1}
Beam Rep. rate	5 Hz
Pulse time duration	1 ms
Average beam current	9 mA (in pulse)
Av. field gradient	**31.5 MV/m**
# 9-cell cavity	**14,560**
# cryomodule	**1,680**
# RF units	**560**

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.



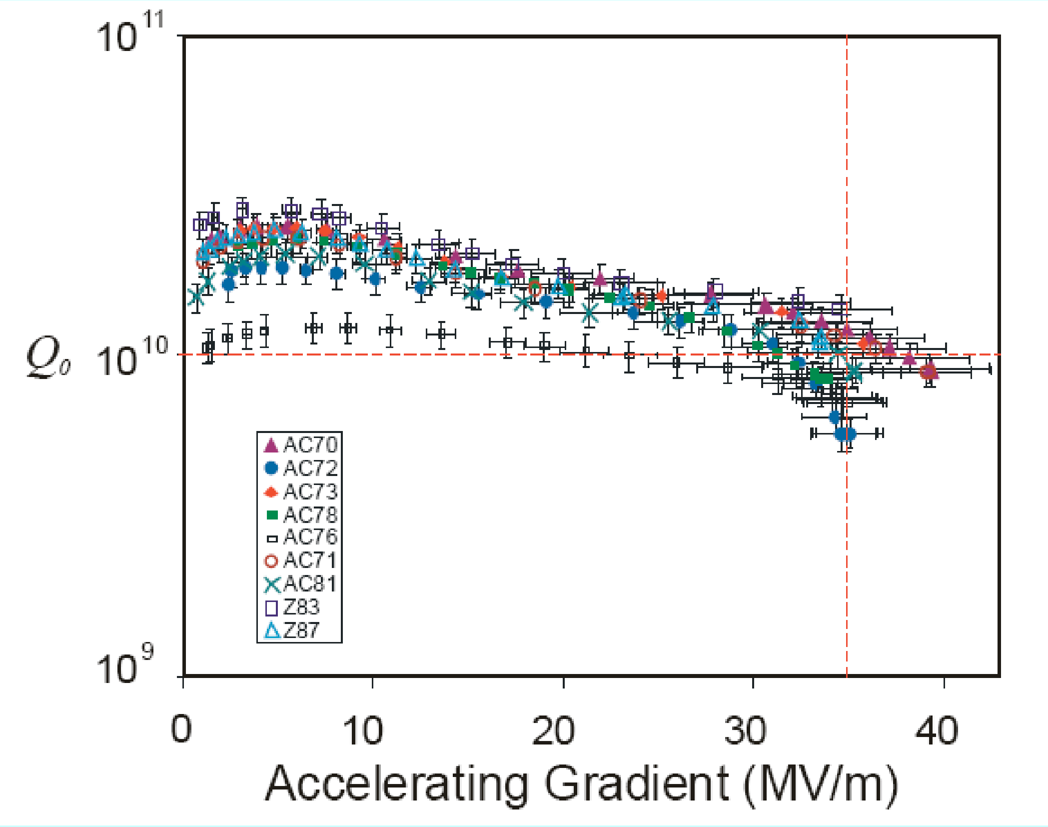
ILC Klystrons

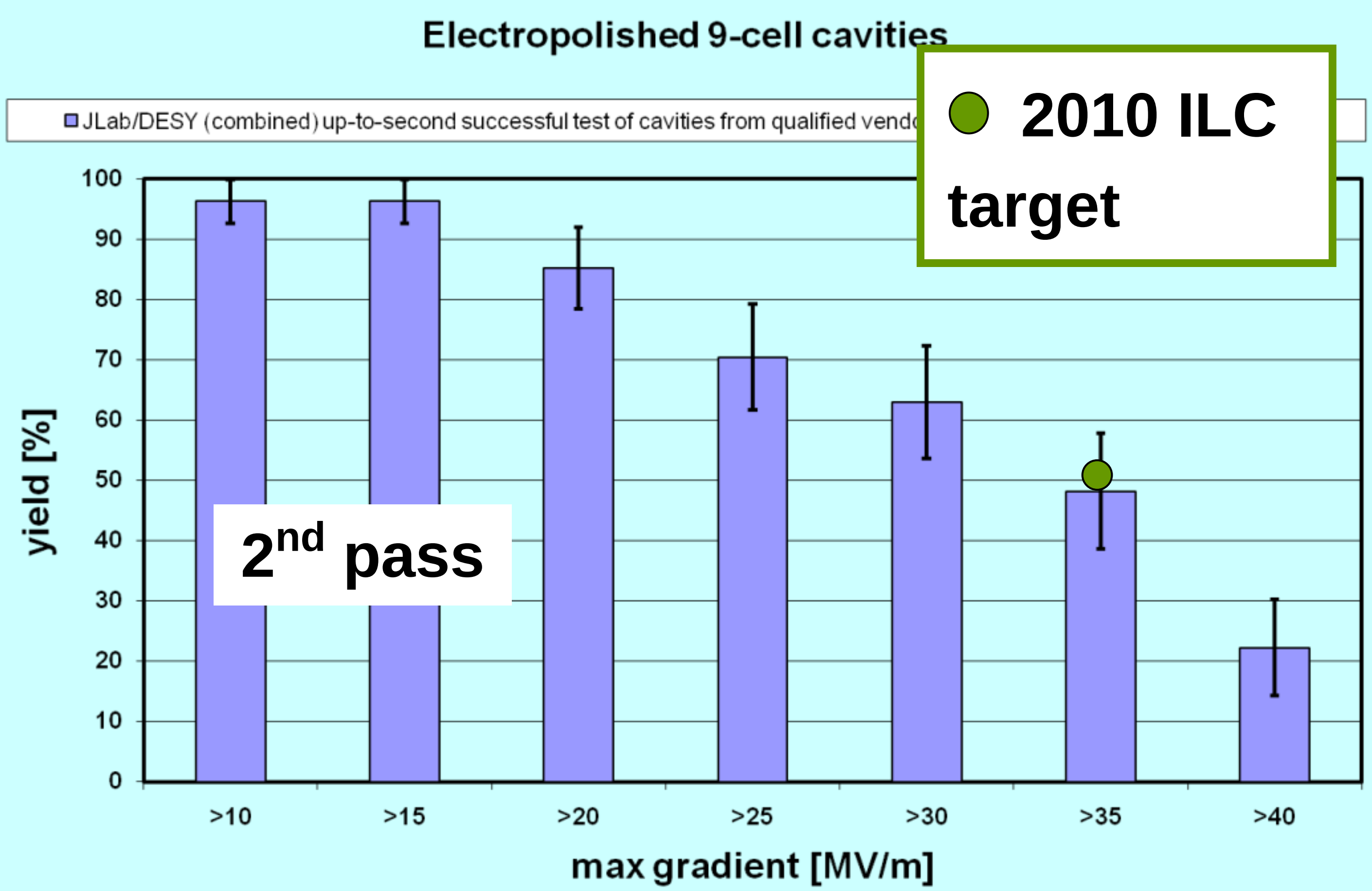
- 10 MW multibeam klystron

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	≥47 db
Instantaneous 1 db BW	>3 MHz
Cathode Voltage	≤120 kV
Cathode Current	≤140 A
Power Asymmetry	≤1%
Lifetime	>40,000 hours

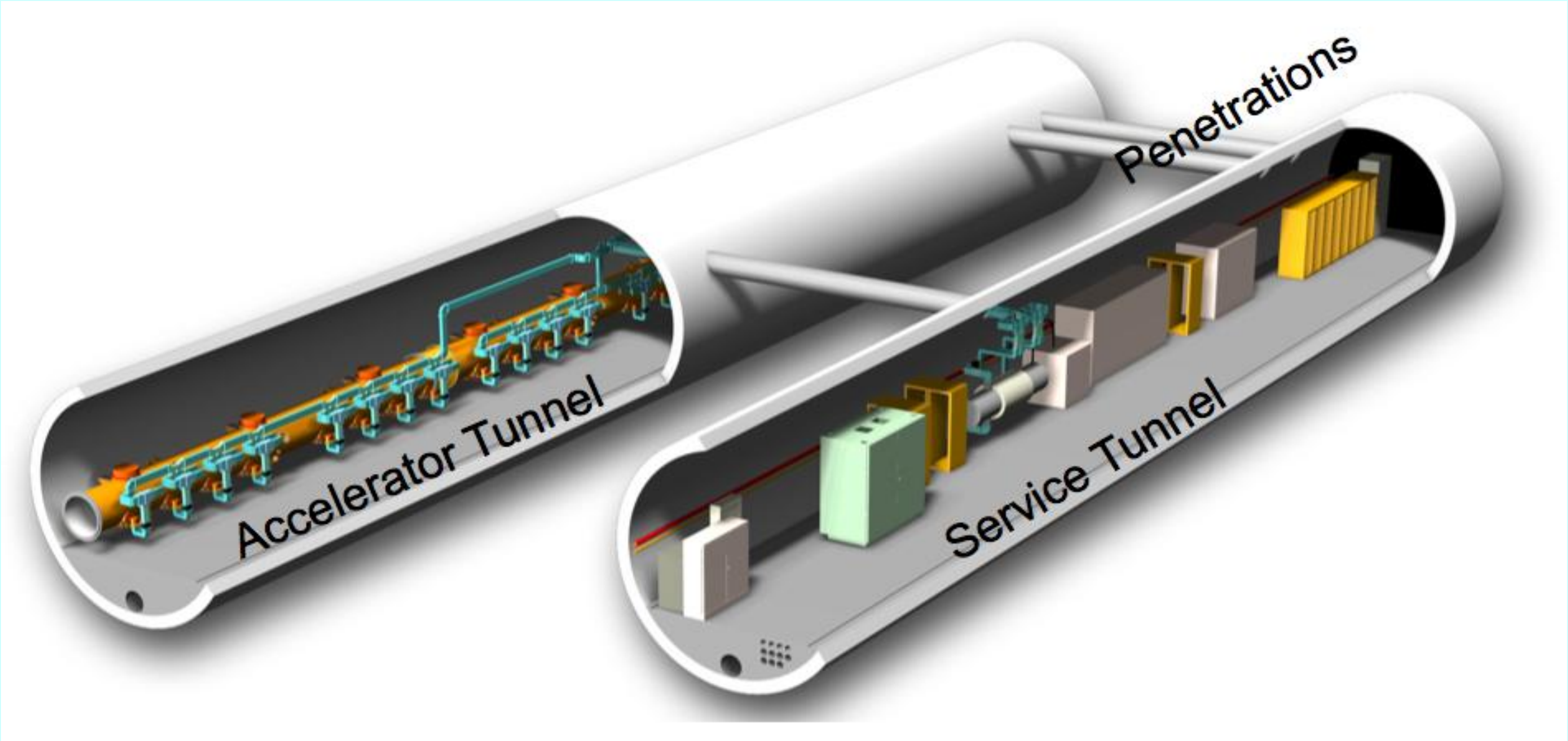
ILC Cavities

- 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





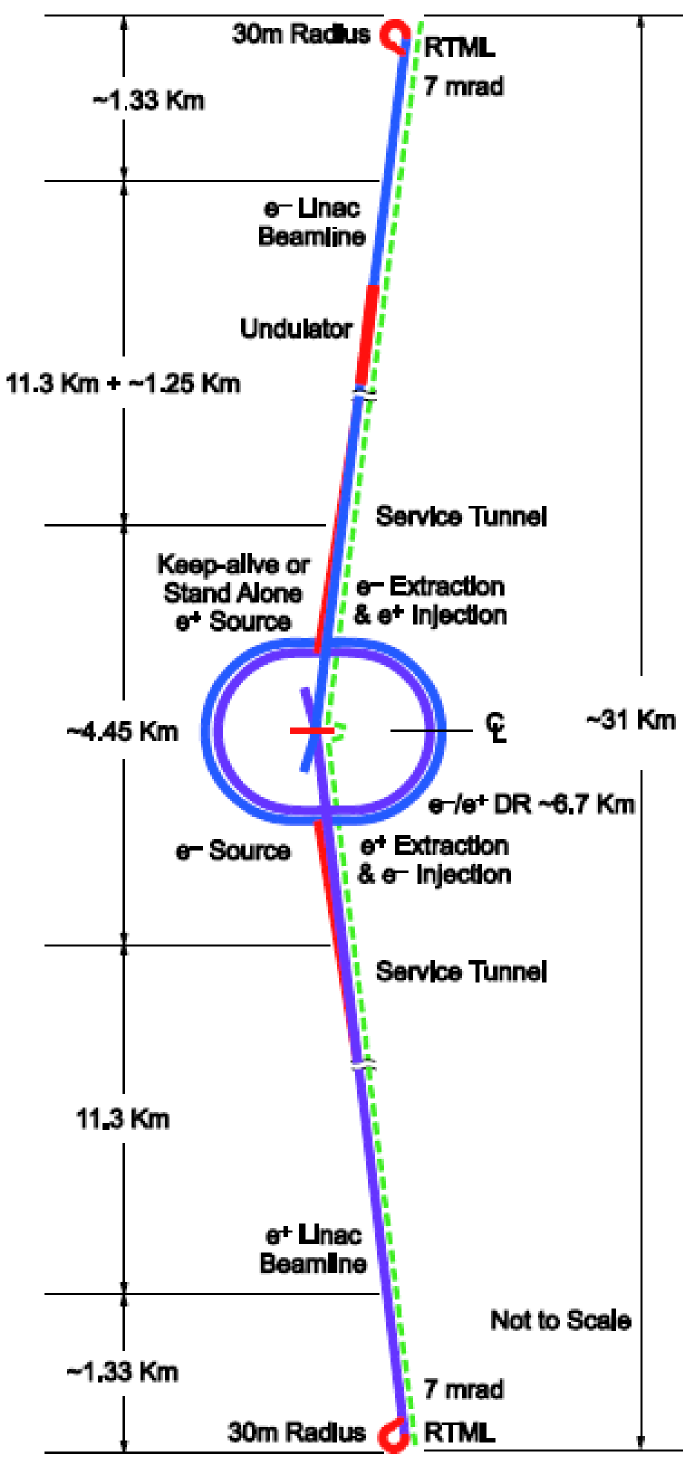
Tunnel Configuration



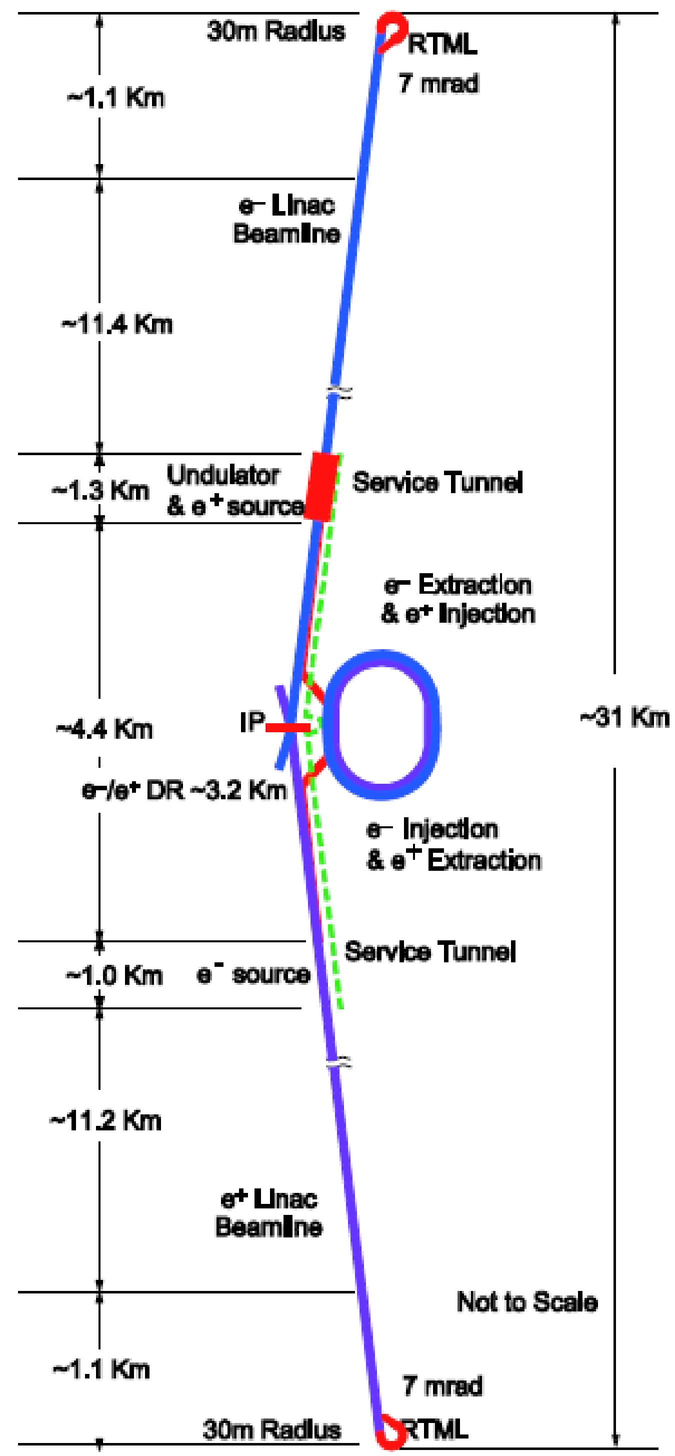
- Two tunnel solution:
  - Three RF/cable penetrations every rf unit
  - Safety crossovers every 500 m
  - 34 kV power distribution
  - 72.5 km tunnels
  - 13 major shafts > 9 meter diameter
  - 443 K cu. m. underground excavation: caverns, alcoves, halls
- Or is one tunnel better (XFEL-like)?

From RDR -> SB2009

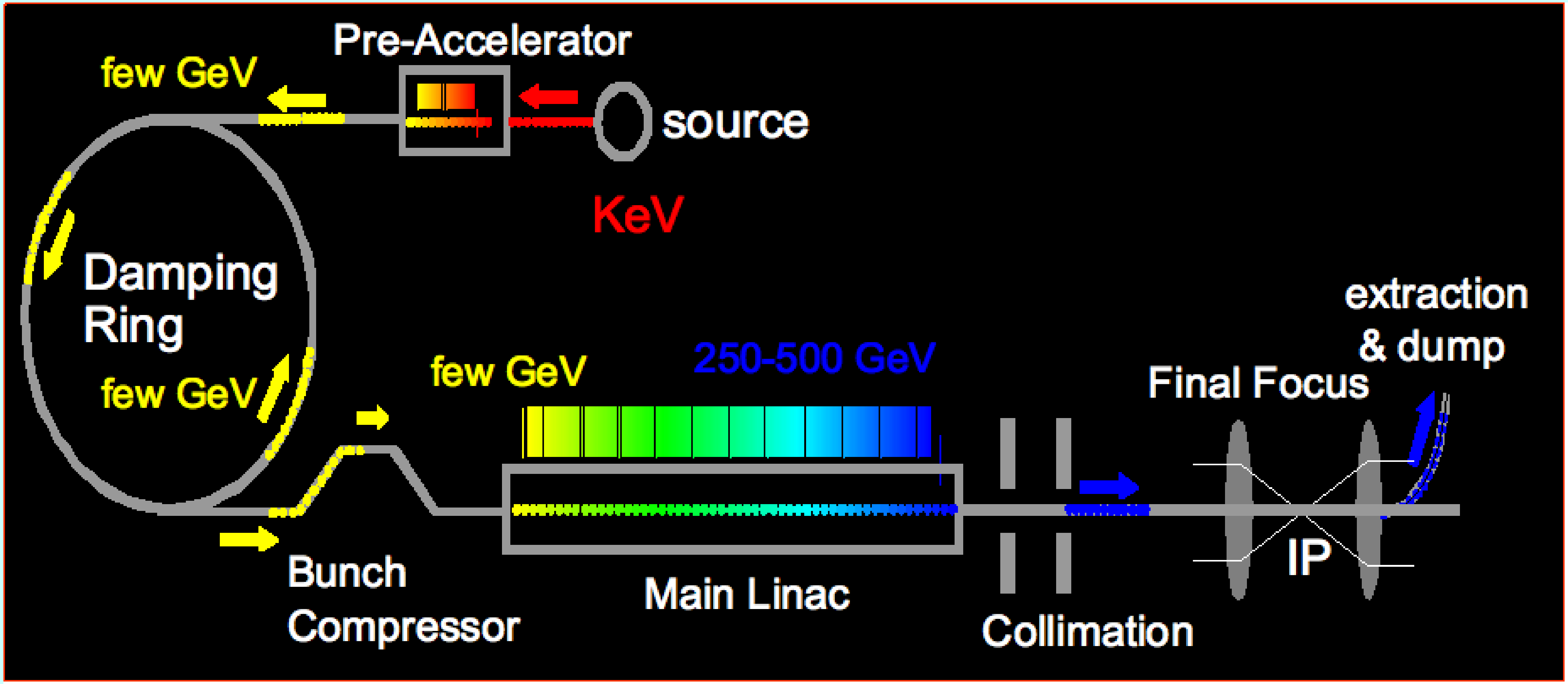
RDR



SB2009



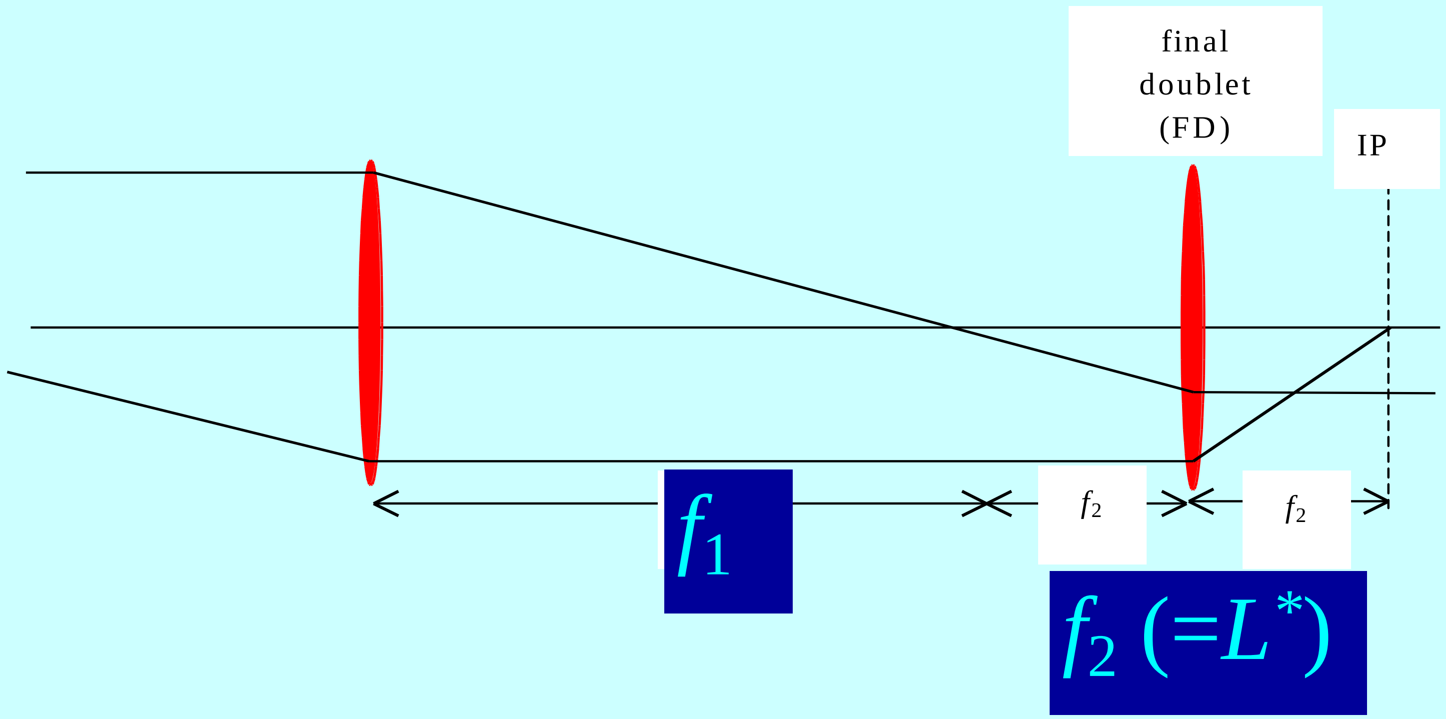
- Single Tunnel for main linac
- Move positron source to end of linac
- Reduce number of bunches factor of two (lower power)
- Reduce size of damping rings (3.2km)
- Integrate central region
- Single stage bunch compressor


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

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

Final Focus



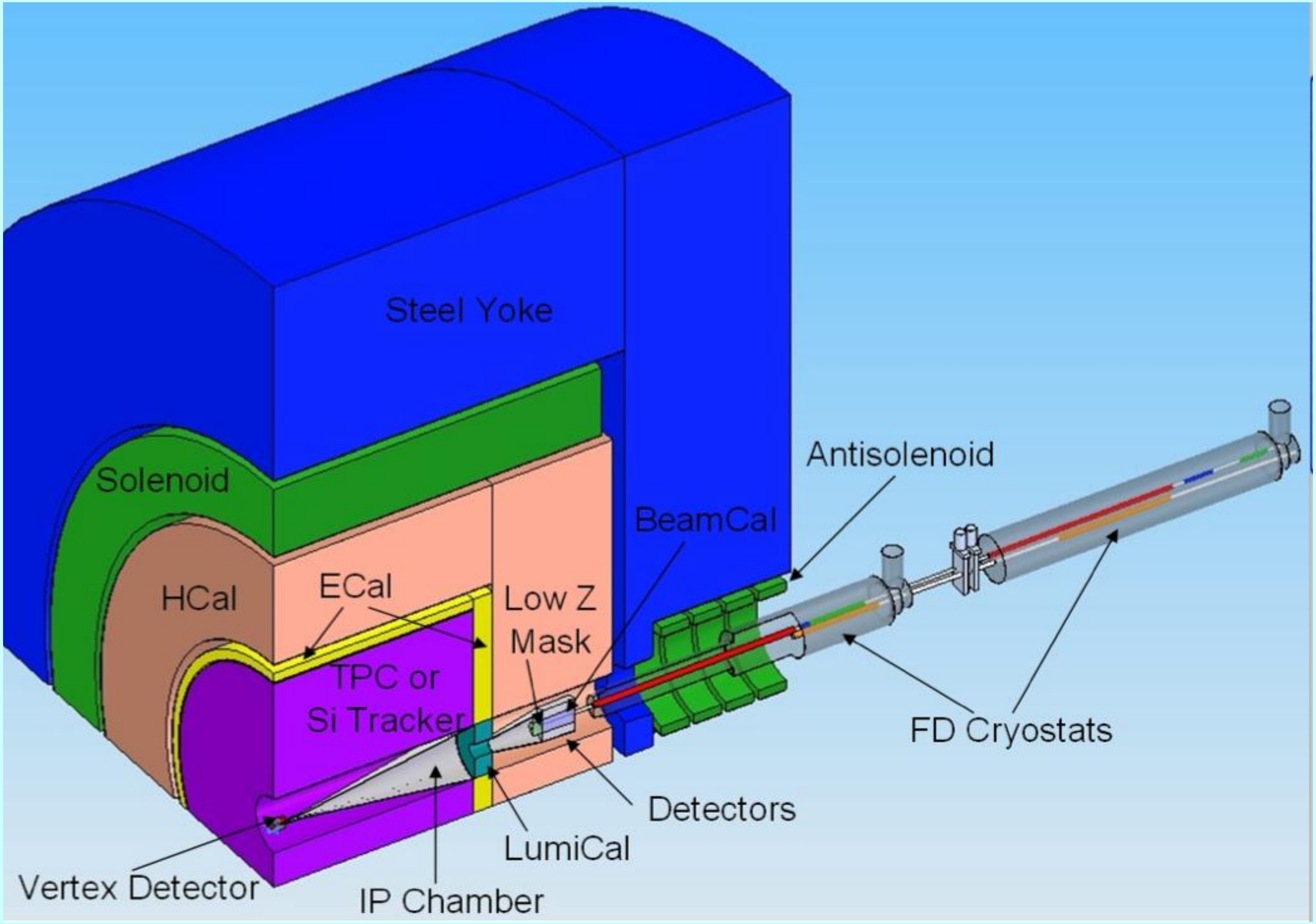
Use telescope optics to de-magnify beam by factor $m = f_1/f_2 = f_1/L^*$

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

IP Region

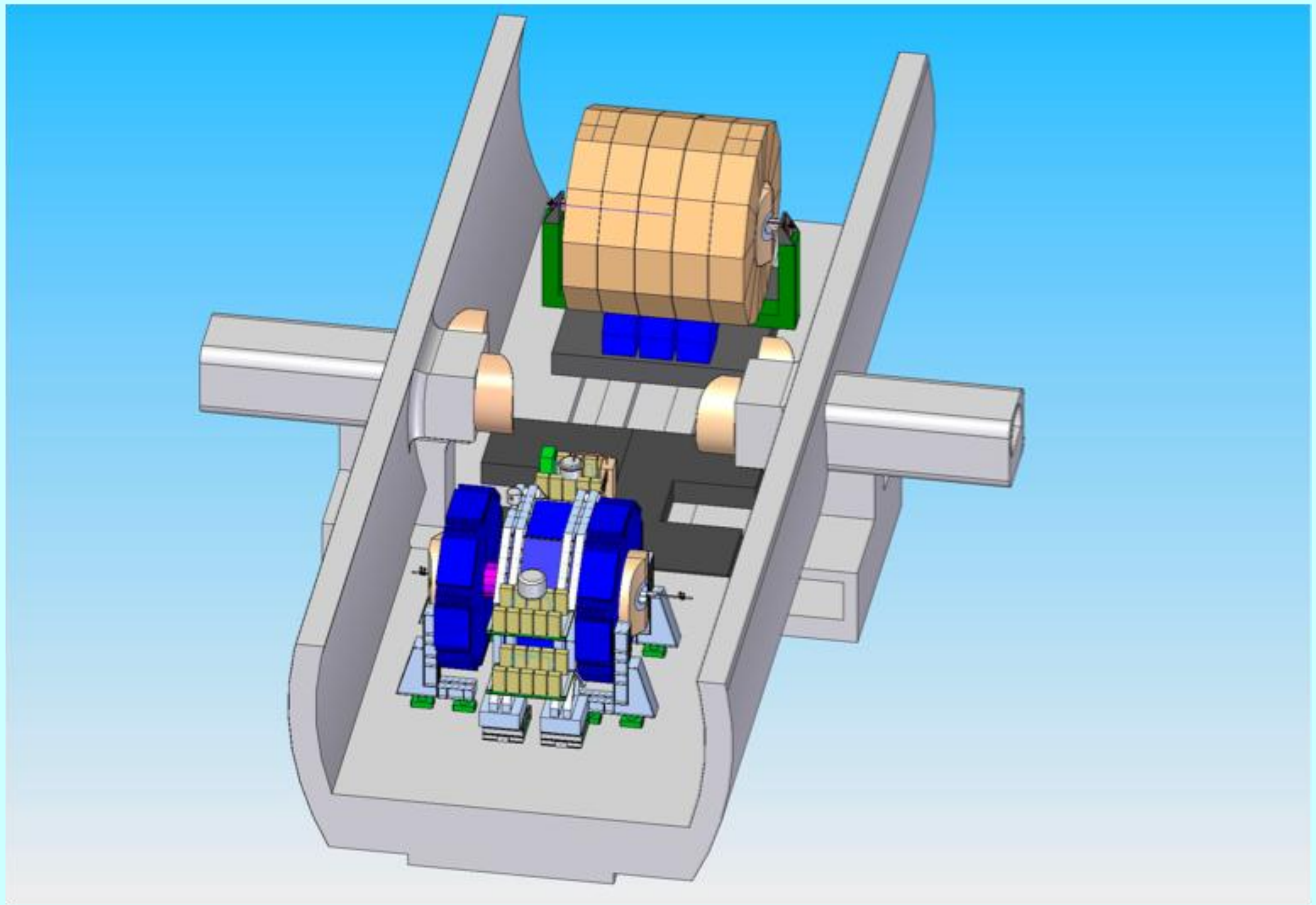


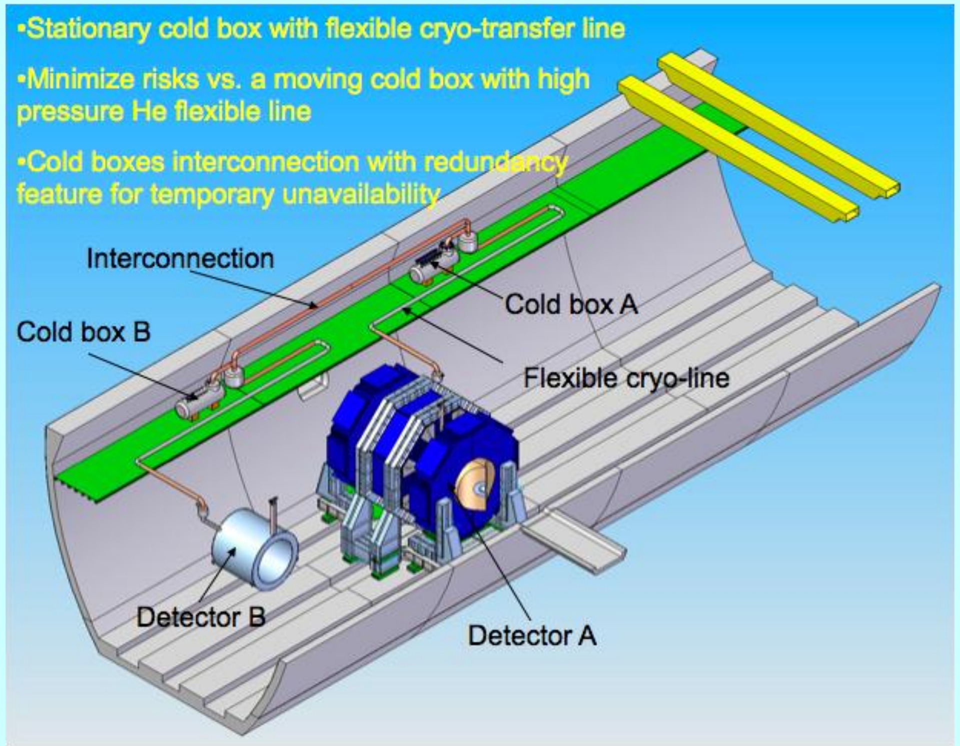
Steel Yoke
Solenoid
HCal
ECal
Low Z
Mask
TPC or
Si Tracker
BeamCal
Antisolenoid
FD Cryostats
Detectors
LumiCal
Vertex Detector
IP Chamber

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

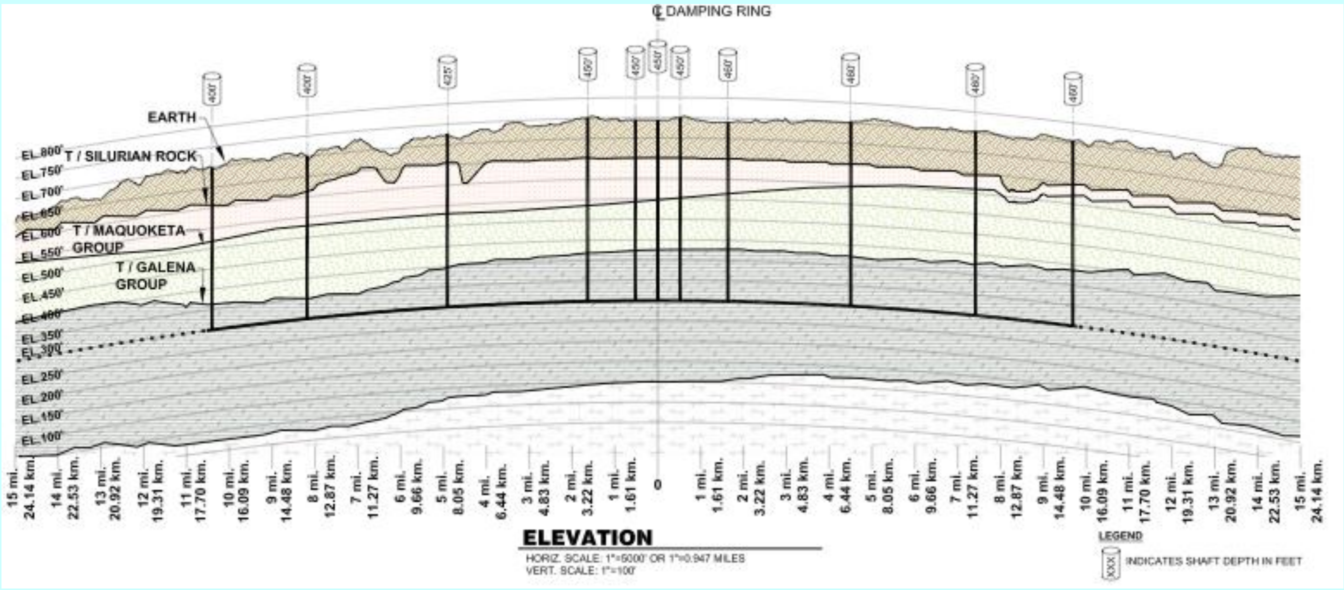
  → Push/Pull System

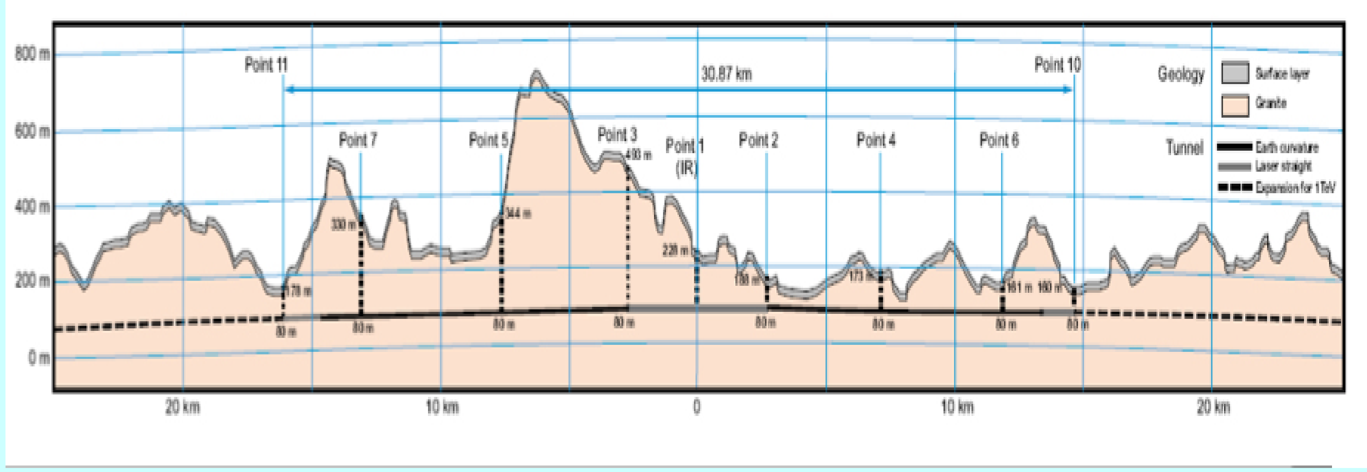


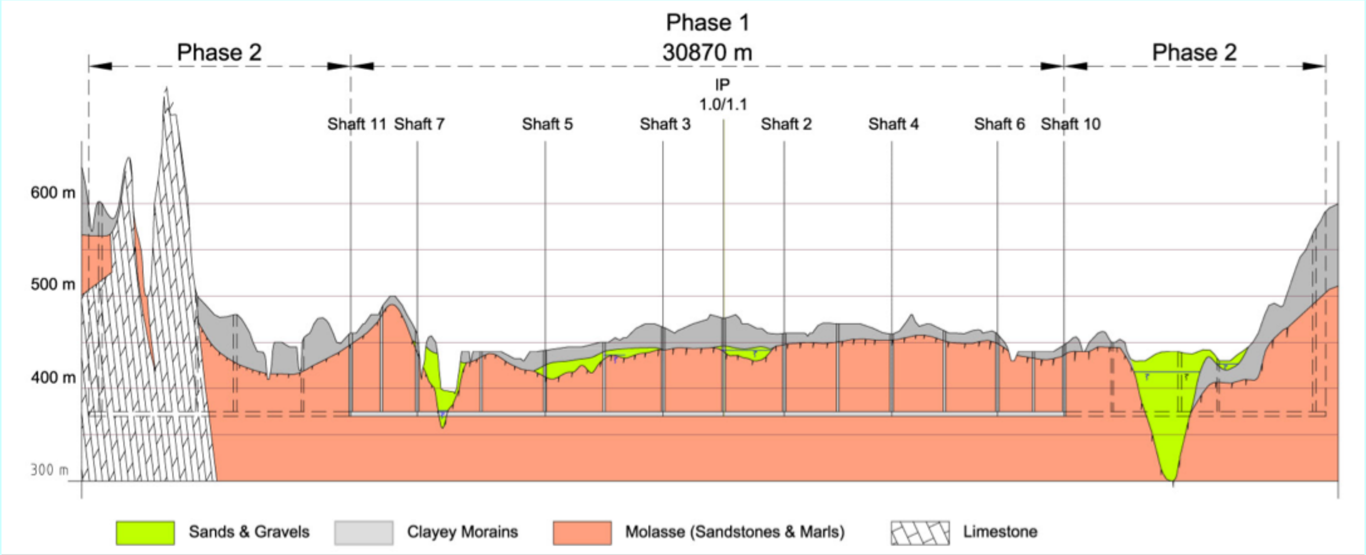


Sample Sites

- 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!







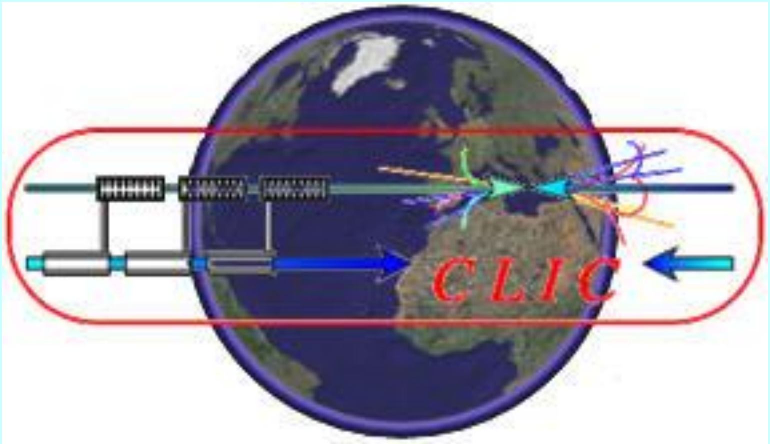
CLIC Technology

What if we need to go way beyond 1 TeV?

- 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 Luminosity Challenge

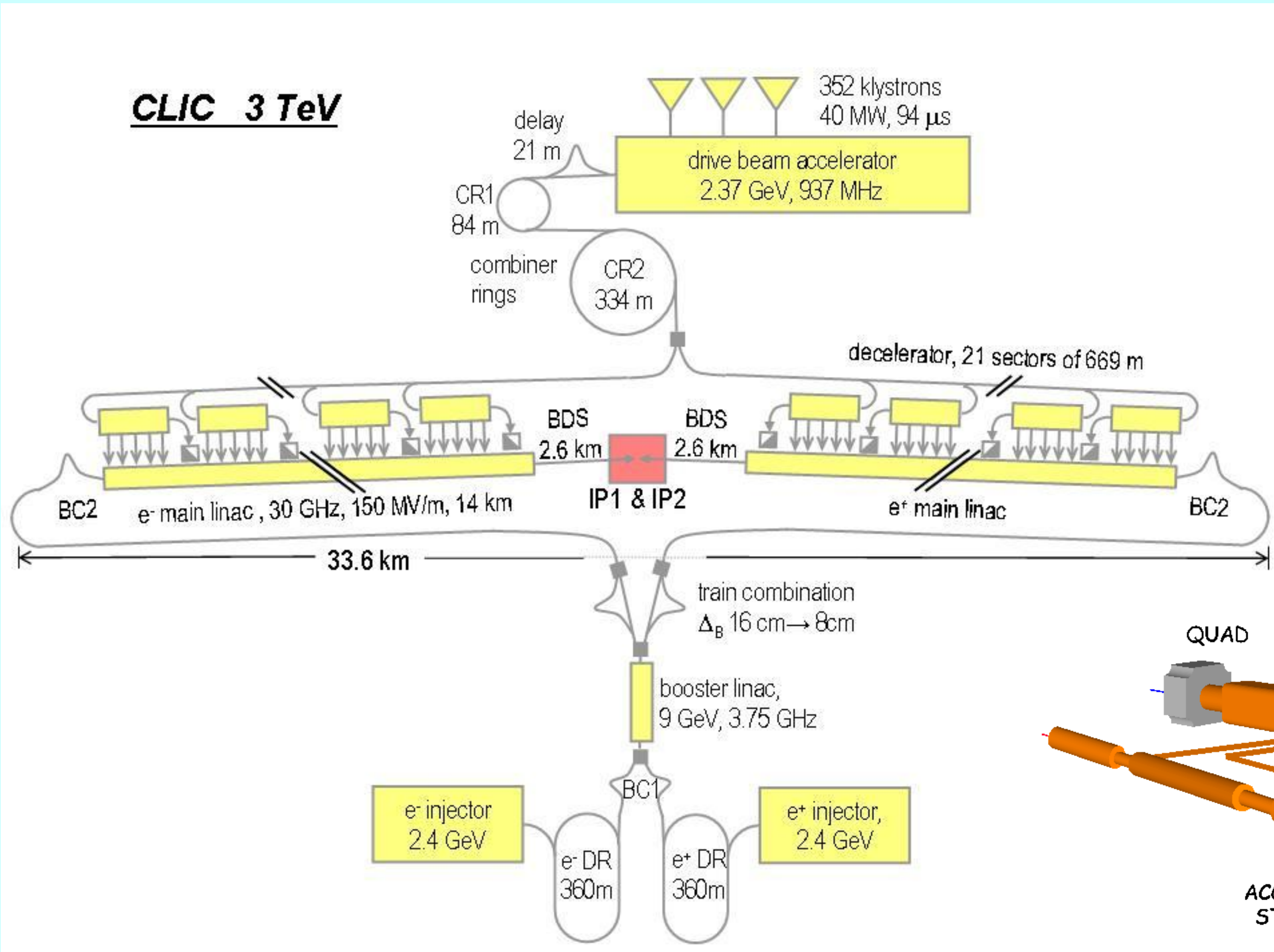
- Remember:

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

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

Two-beam Acceleration

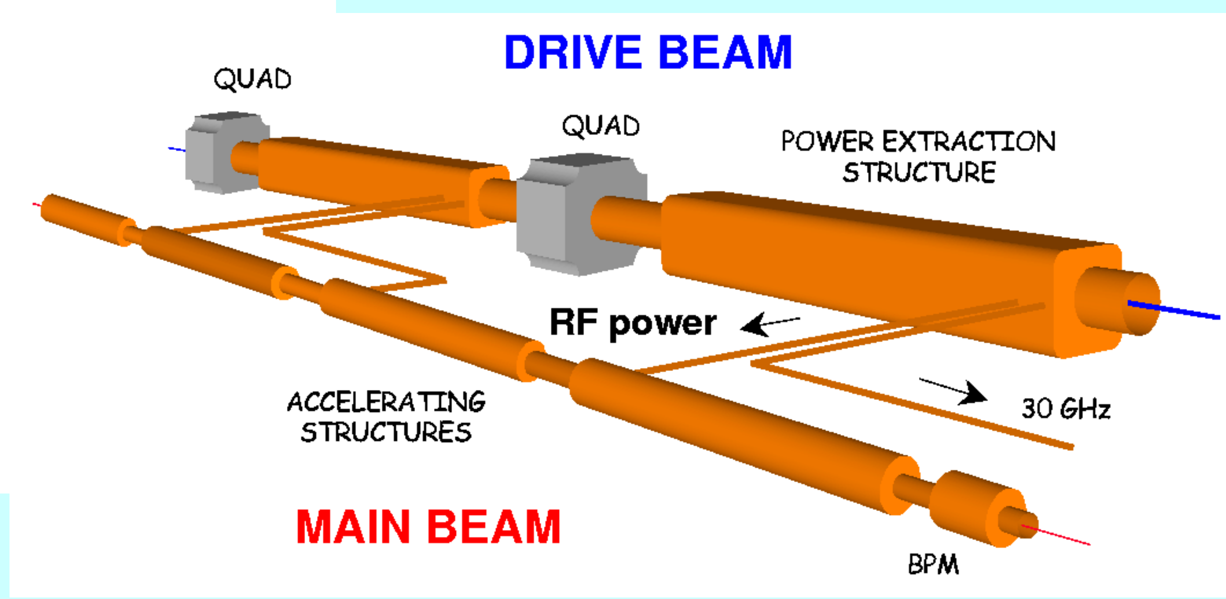
- Use low-energy high-current electron drive-beam as klystron replacement:



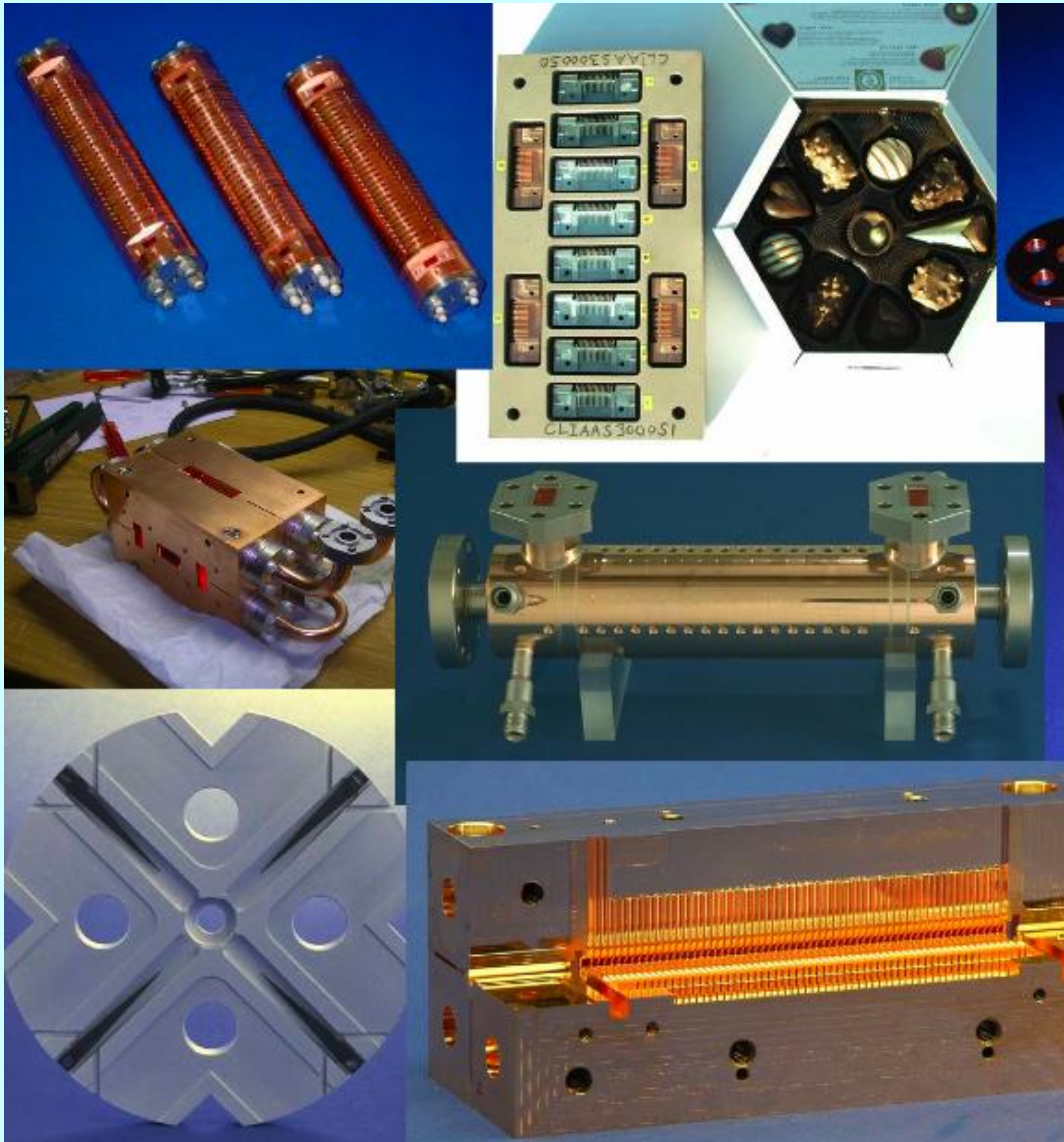
Two Beam Scheme:

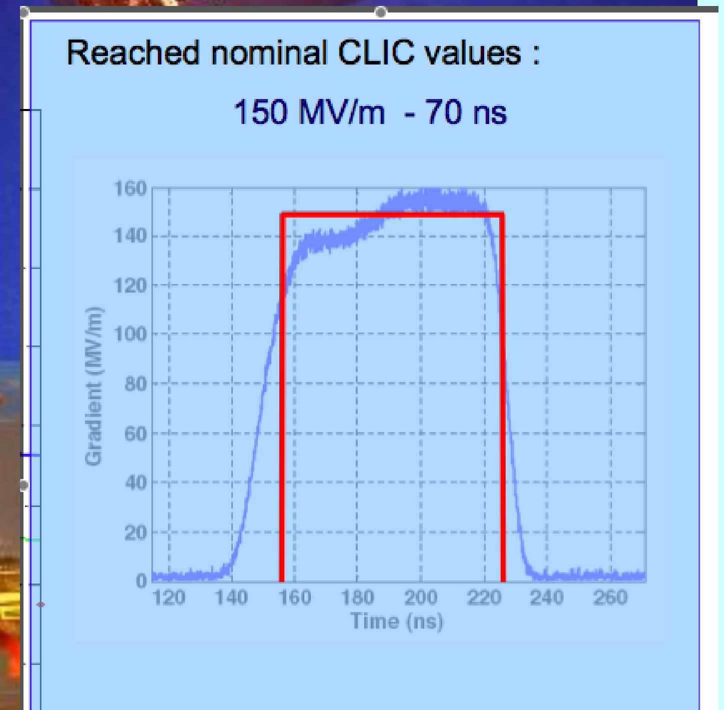
Drive Beam supplies RF power
- 12 GHz bunch structure
- low energy (2.4 GeV - 240 MeV)
- high current (100A)

Main beam for physics
- high energy (9 GeV – 1.5 TeV)
- current 1.2 A



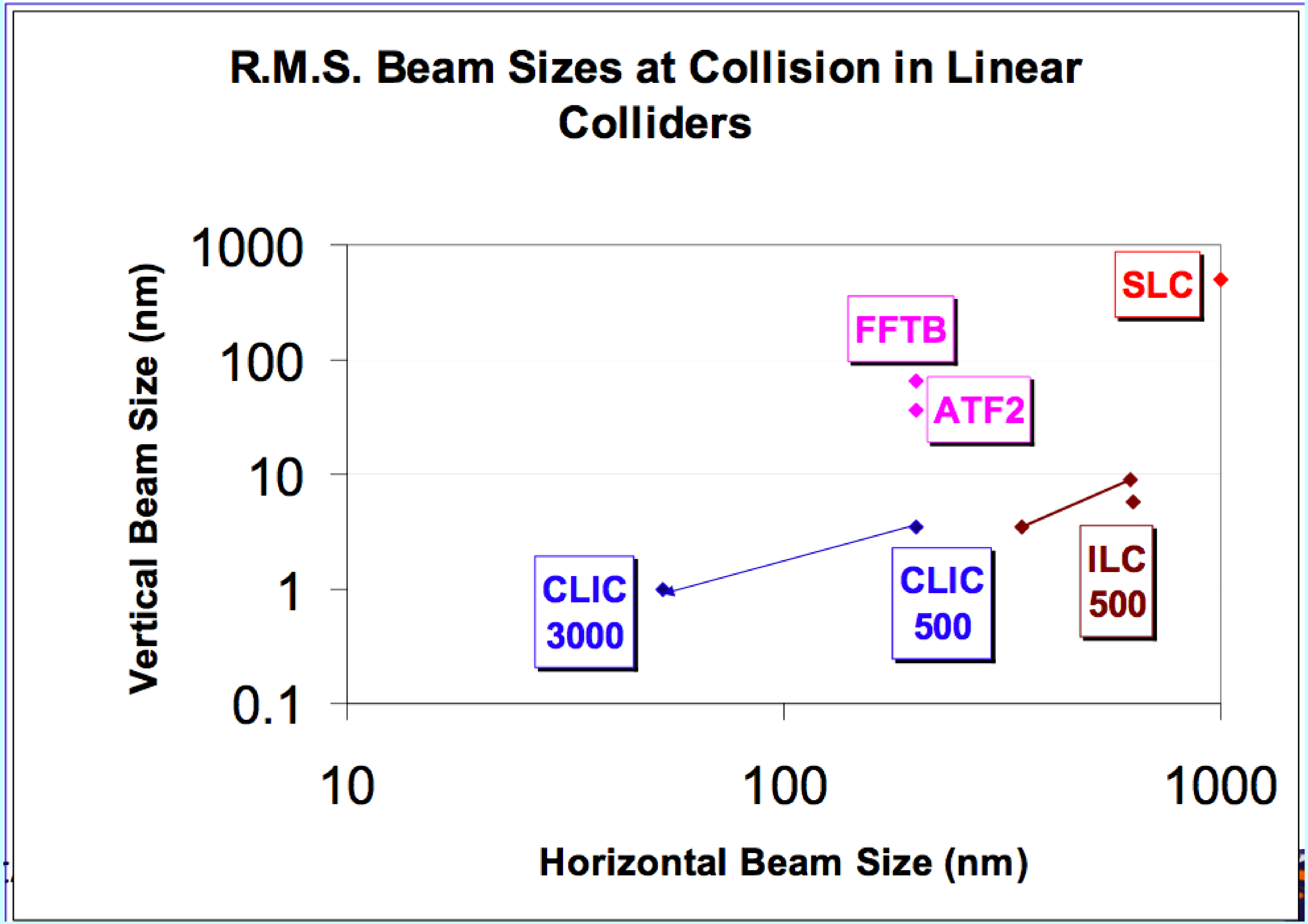
Copper Acceleration Cavities





Breakdown Rate not compatible with LC operation

Beam Spot Sizes

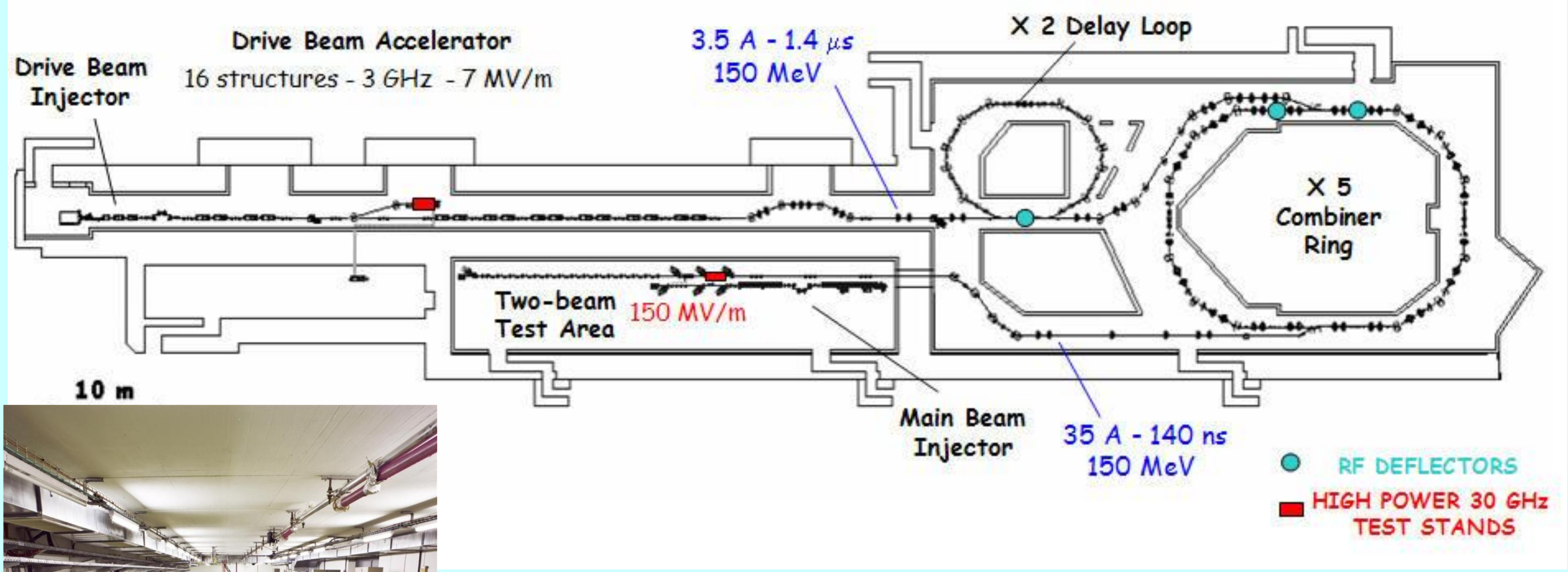


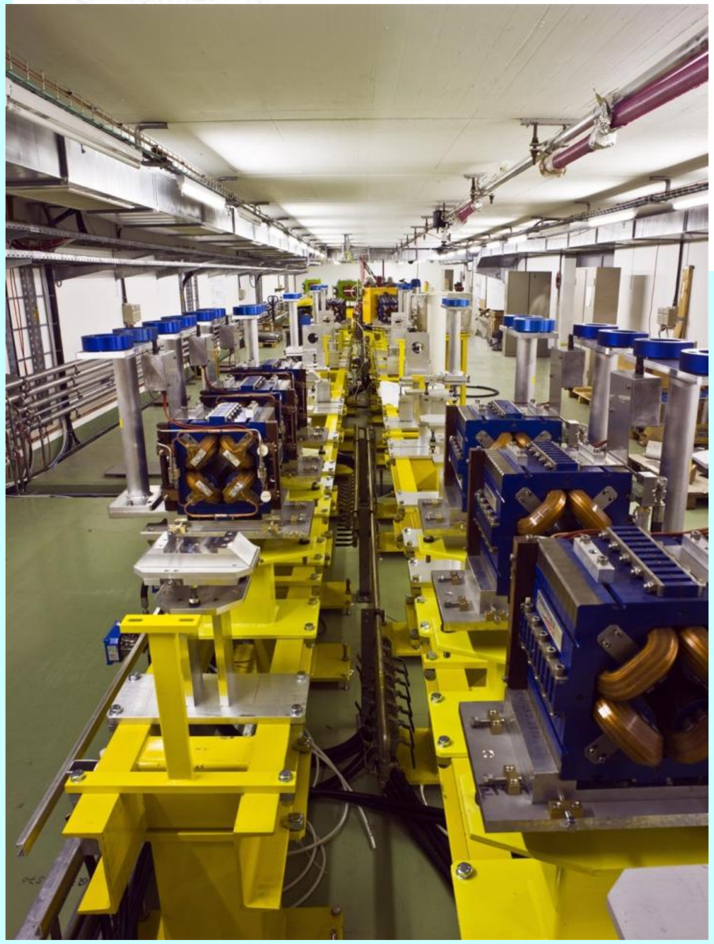
ILC/CLIC parameters

Center-of-mass energy	ILC 500 GeV	CLIC 500 GeV	CLIC 3 TeV
Total (Peak 1%) luminosity [$\cdot 10^{34}$]	2(1.5)	2.3 (1.4)	5.9 (2.0)
Repetition rate (Hz)	5	50	
Loaded accel. gradient MV/m	32	80	100
Main linac RF frequency GHz	1.3	12	
Bunch charge [$\cdot 10^{9}$]	2.4	6.8	3.7
Bunch separation (ns)	370	0.5	
Beam pulse duration (ns)	950μs	177	156
Beam power/beam (MWatts)		4.9	14
Hor./vert. IP beam size (nm)	600 / 6	200 / 2.3	40 / 1.0
Hadronic events/crossing at IP	0.12	0.2	2.7
Incoherent pairs at IP	$1 \cdot 10^{5}$	$1.7\cdot 10^{5}$	$3\cdot 10^{5}$
BDS length (km) (2 x)	2.25	1.87	2.75
Total site length km	31	13	48
Total power consumption MW	230	130	415

Crossing Angle 20 mrad (ILC 14 mrad)

CLIC Test Facility CTF3

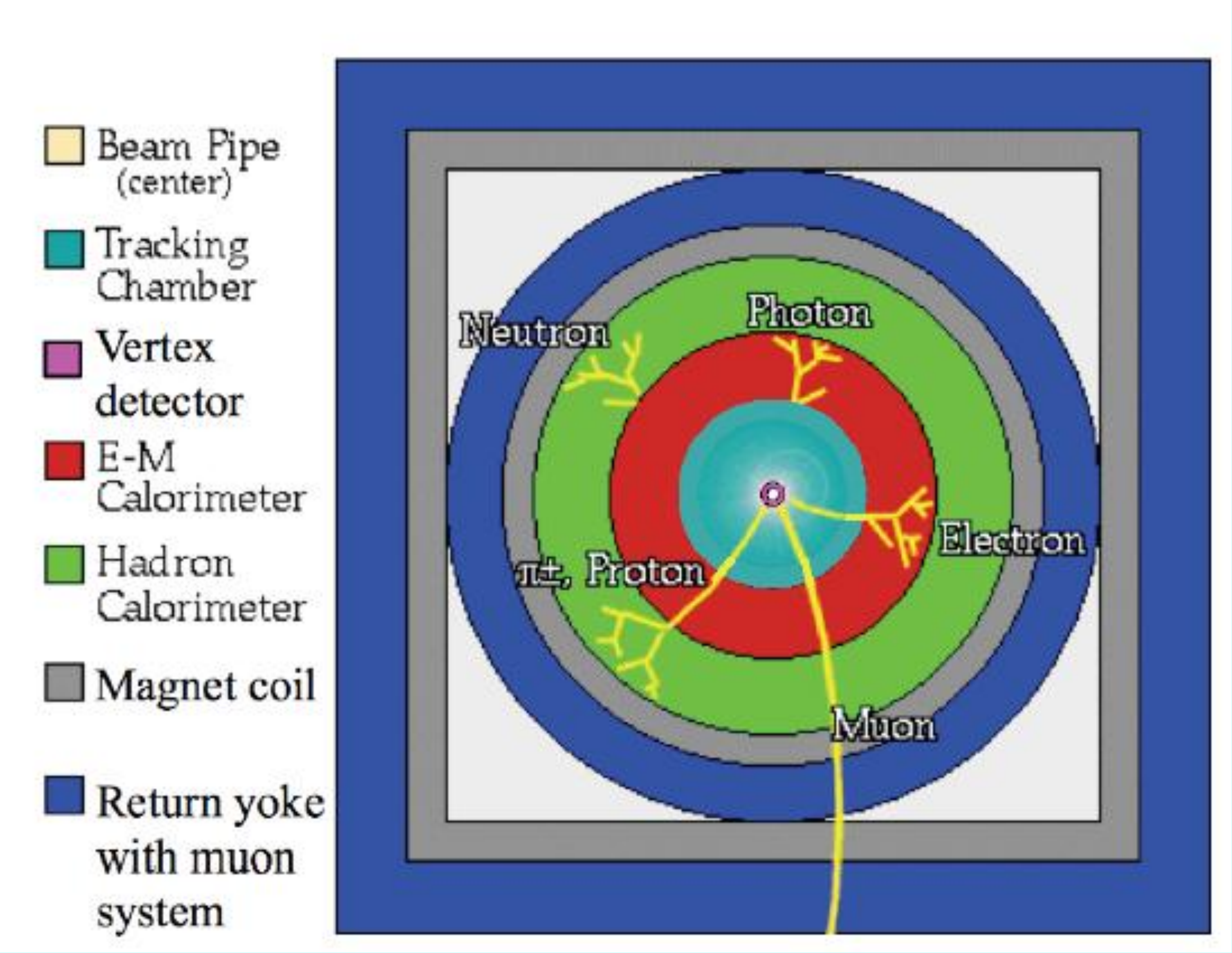




- Show CLIC feasibility by 2010

ILC Detectors

Generic Detector



Basic detector design concept

(and compared to LEP detector)

- Performance goal (common to all det. concepts)
  - Vertex Detector: $$\delta(IP) \leq 5 \oplus 10 / p \sin^{3/2}\theta$$ [μm]

    (ILC 5x better than LEP)
  - Tracking: $$\delta p_t / p_t^2 \leq 5 \times 10^{-5}$$ [GeV^{-1}]

    (ILC: 10x better) (CMS: 1.5 10^{-4})
  - Jet energy res.: $$\delta E / E \leq 0.3 / \sqrt{E}$$ [E in GeV]

    (ILC: 2x better)

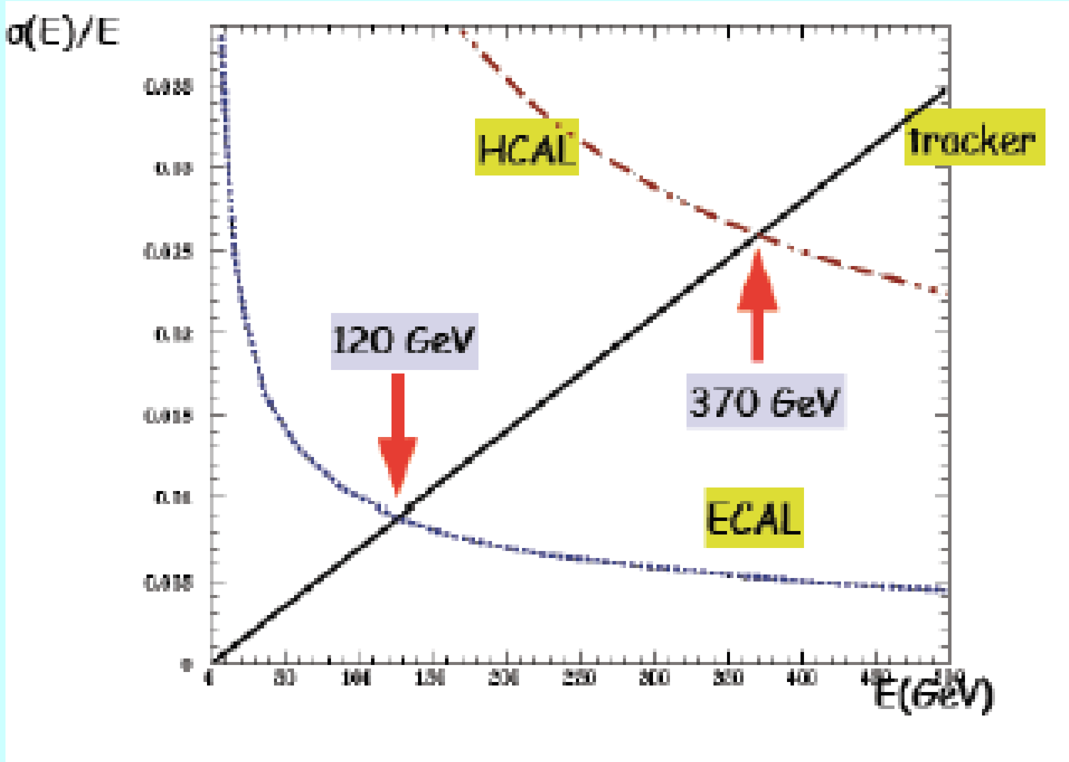
    ➔ Detector optimized for Particle Flow Algorithm (PFA)

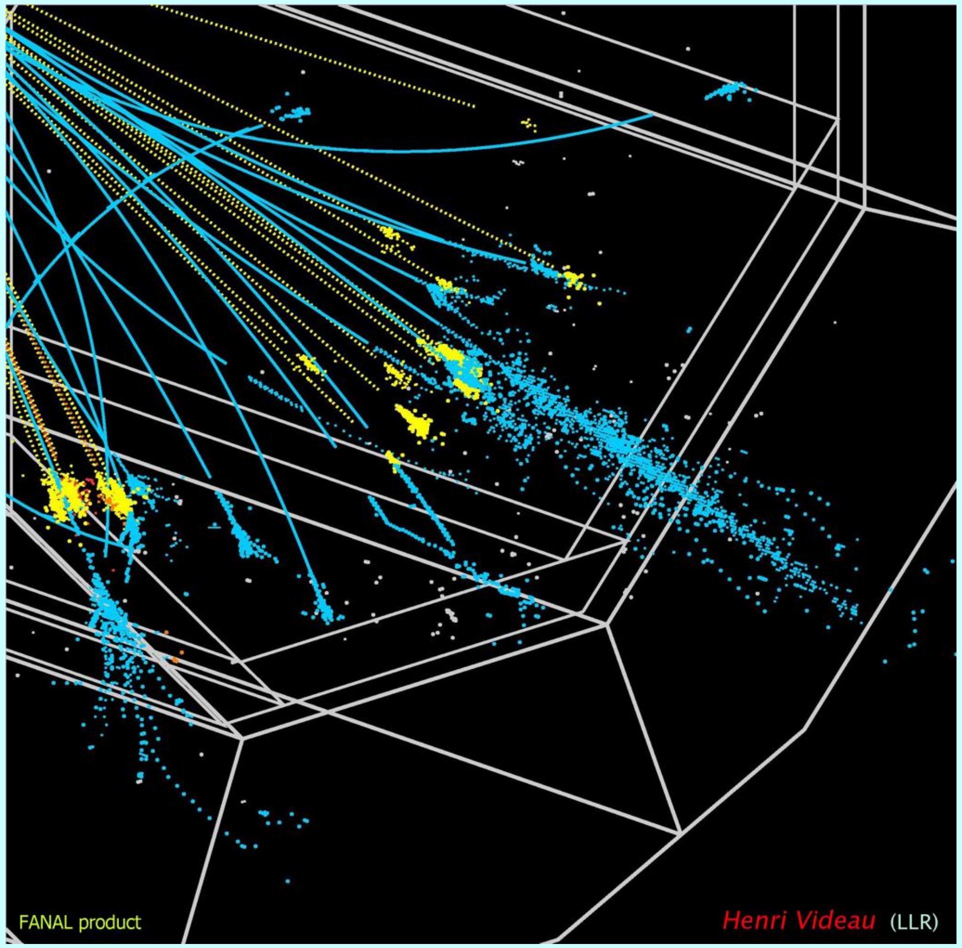
The Particle Flow Concept

- Idea: use the sub-detector with the best resolution for the energy measurement!
- Charged particles: tracking system (~65% of jet energy)
- Photons: ECAL (~25%)
- Neutral Hadrons: HCAL (~10%)

- Avoid double counting!
  - Trace every single particle through the detector

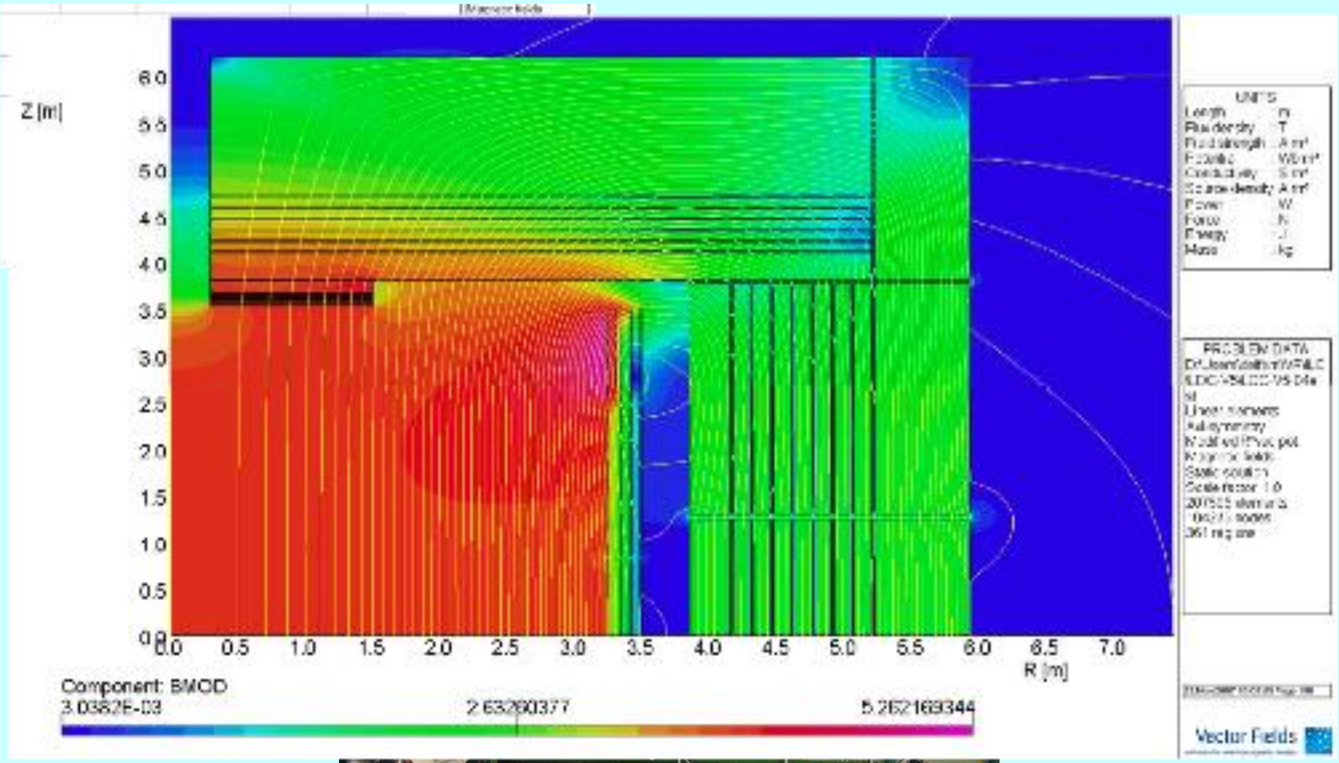
- $E_{jet} = E_{charged} + E_{photons} + E_{neutral\ hadr.}$
- $\sigma^2(E_{jet}) = \sigma^2(E_{charged}) + \sigma^2(E_{photons}) + \sigma^2(E_{neutral\ hadr.}) + \sigma^2_{confusion}$





Detector Solenoid

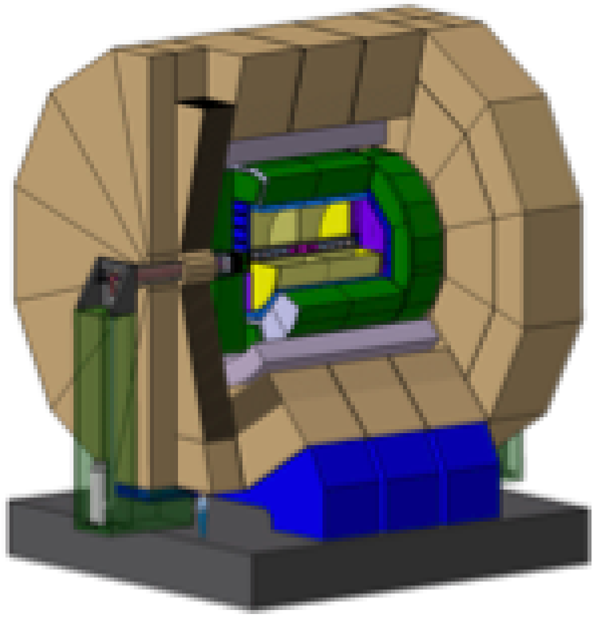
- High magnetic field needed for precision in momentum measurement:
  - 3.5 - 4 T
- Field homogeneity is crucial for TPC operation
- Coil is a major cost driver for the experiments!
- CMS coil (4T) is the model



Validated ILC concepts

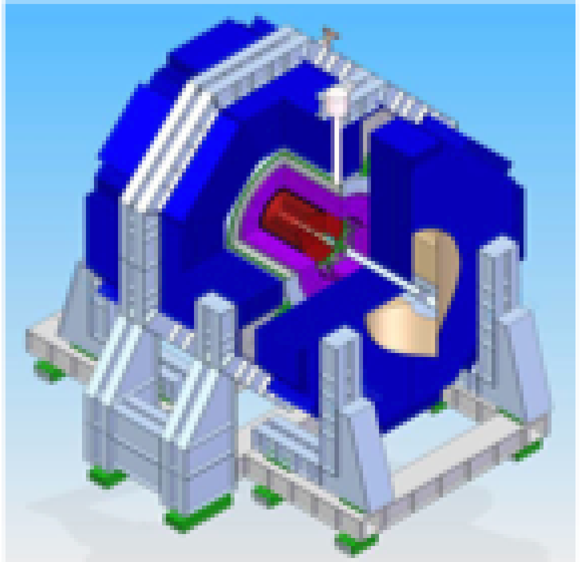
ILD: International Large Detector

"Large" : tracker radius 1.8m
B-field : 3.5 T
Tracker : TPC + Silicon
Calorimetry : high granularity particle flow
ECAL + HCAL inside large solenoid



SiD: Silicon Detector

"Small" : tracker radius 1.2m
B-field : 5 T
Tracker : Silicon
Calorimetry : high granularity particle flow
ECAL + HCAL inside large solenoid

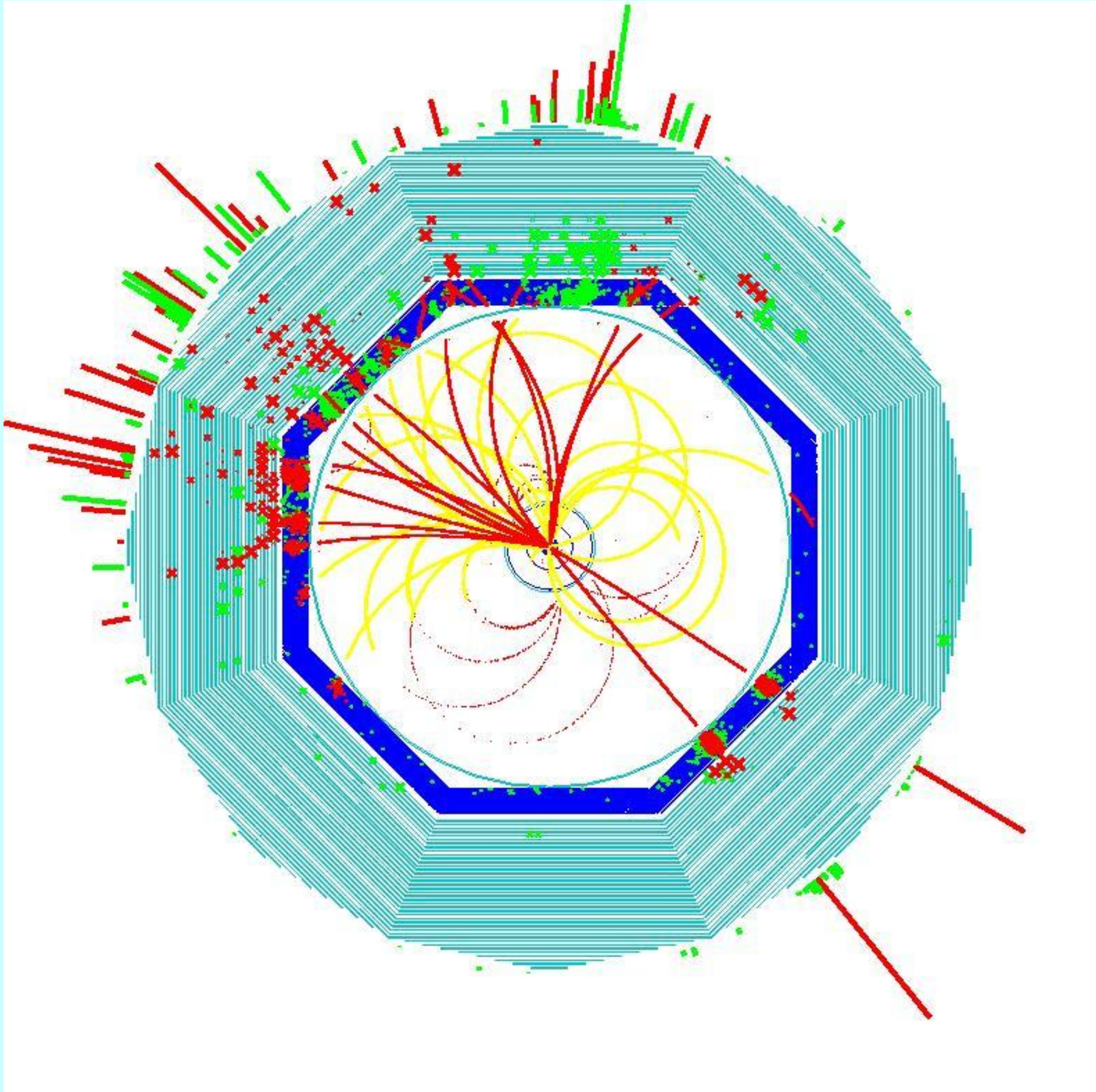


CLIC detector concepts will be based on SiD and ILD.

Modified to meet CLIC requirements

Imaging Detector

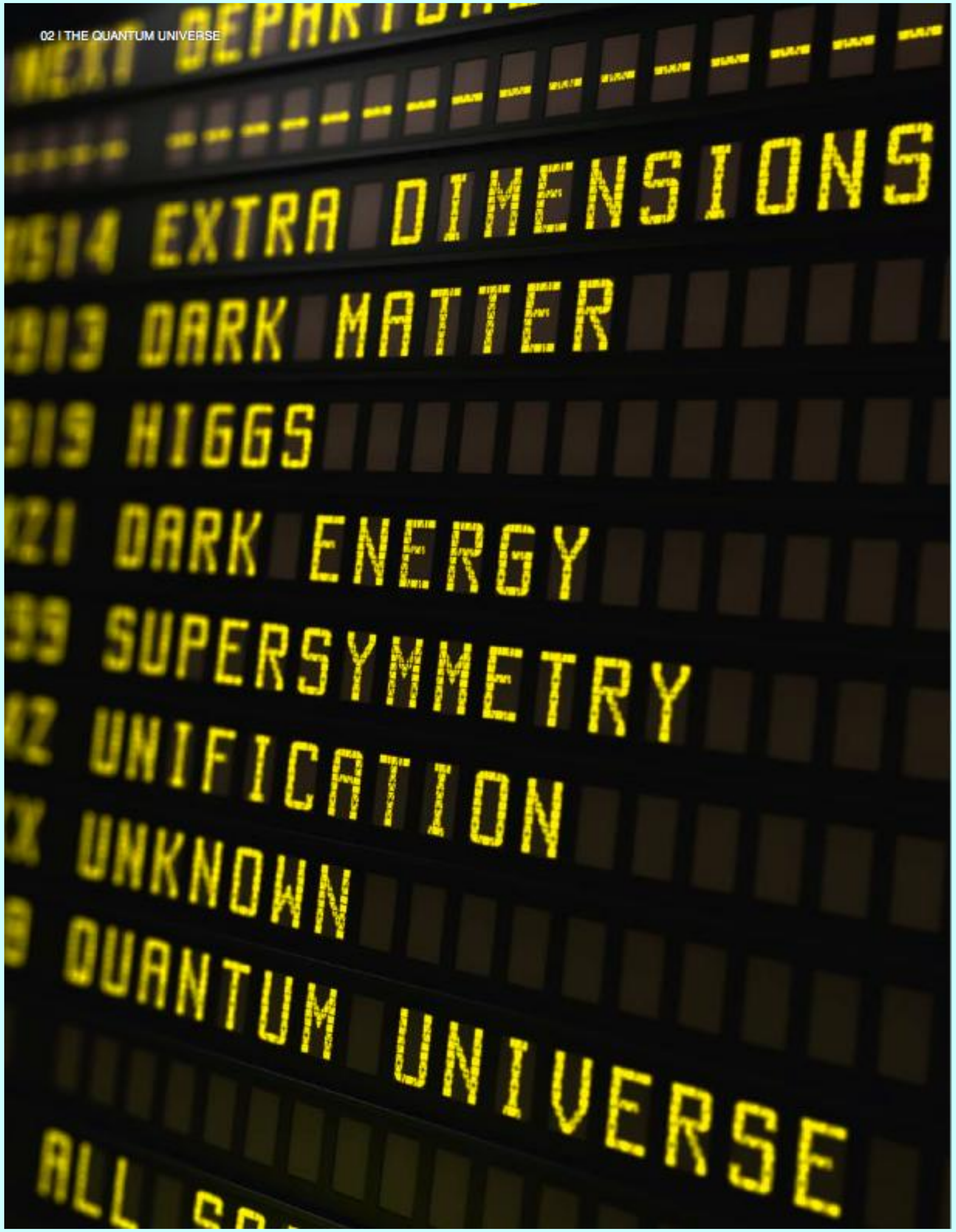
- $e^+e^- \to ZH$



Conclusion

Conclusion

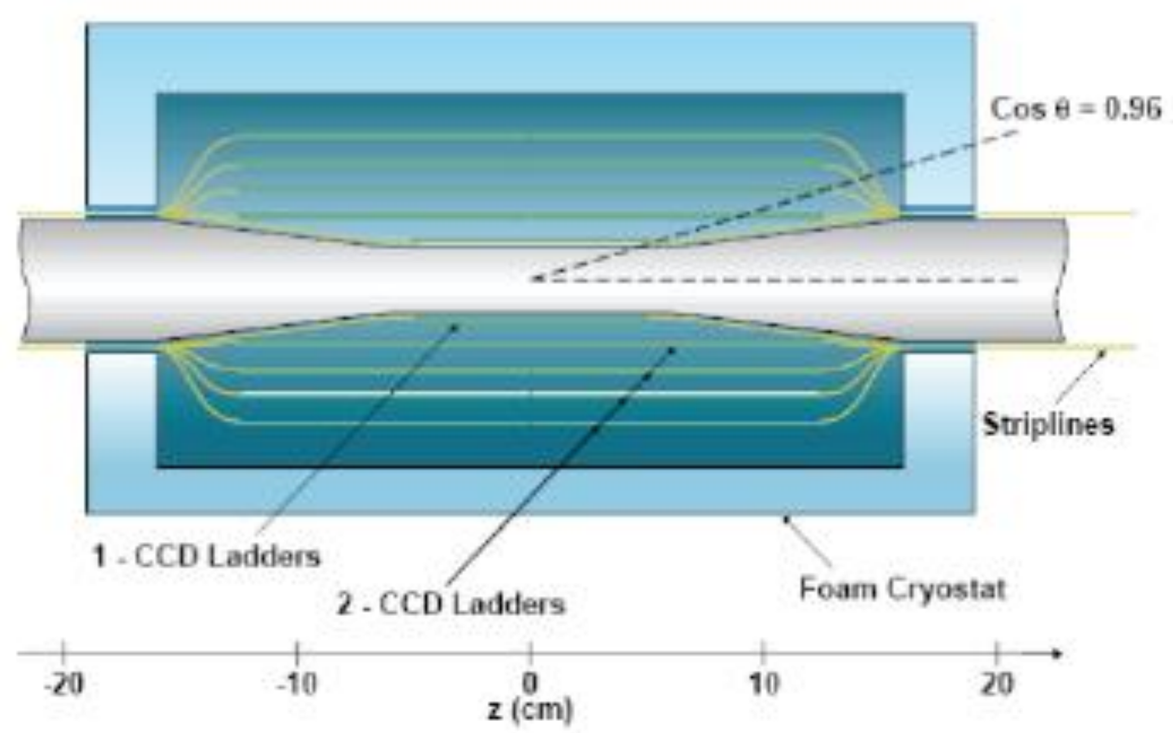
- The LHC will need to be complemented by an electron-positron collider for precision measurements
- LHC results will tell the parameter needs
- ILC is the far most advanced collider design
- CLIC could be a high-energy option
  - on a much longer timescale though...
- Machine and experiments demand high-tech solutions on yet untested scales

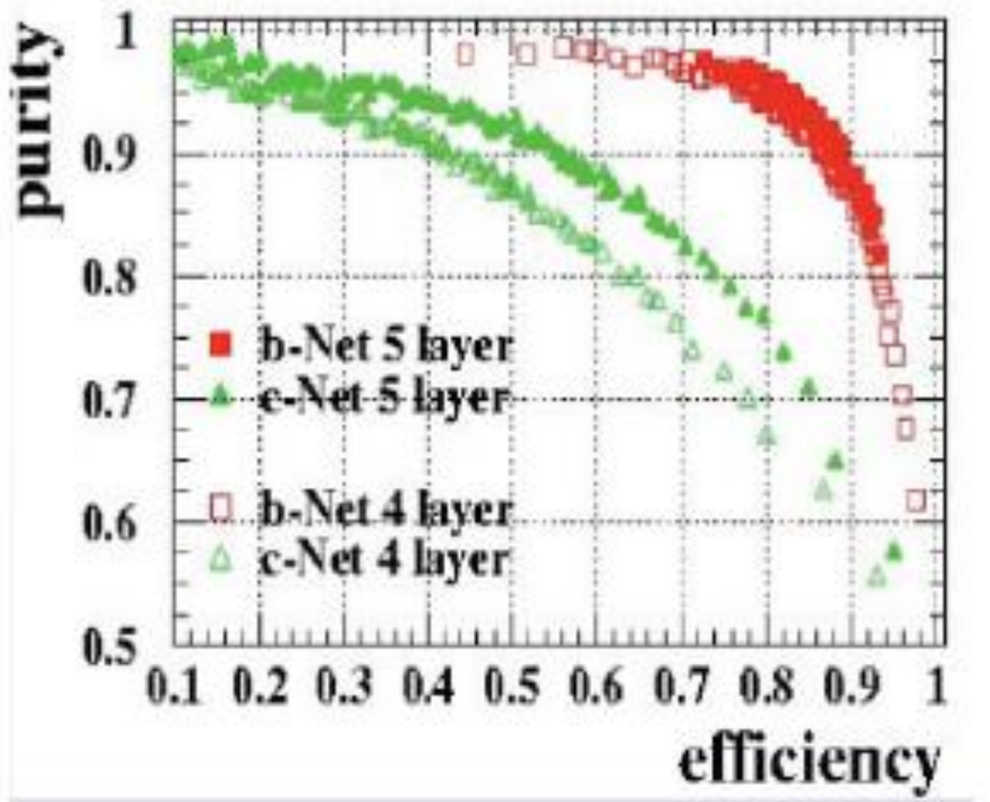


Backup detector slides

Vertex Detector

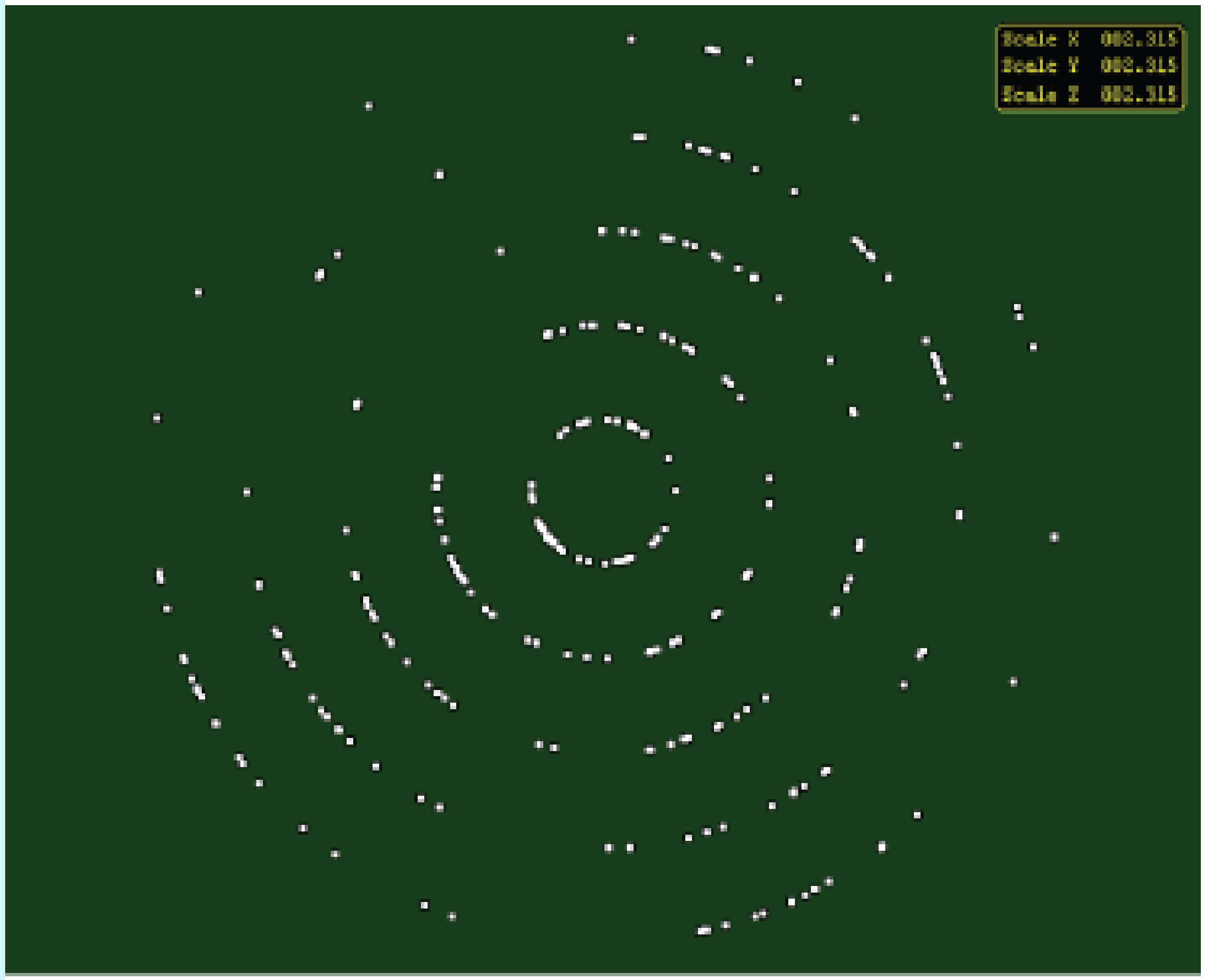
- Requirements:
  - excellent point resolution <4μm
  - small pixel sizes: 20 x 20 μm^2
  - ~10^9 channels
  - low material budget: ~0.1% X_0
  - fast read-out to minimise pile-up
  - immune against EMI effects
- Flavour tagging is crucial
  - b-tagging easier than c-tagging
- Many technologies under study





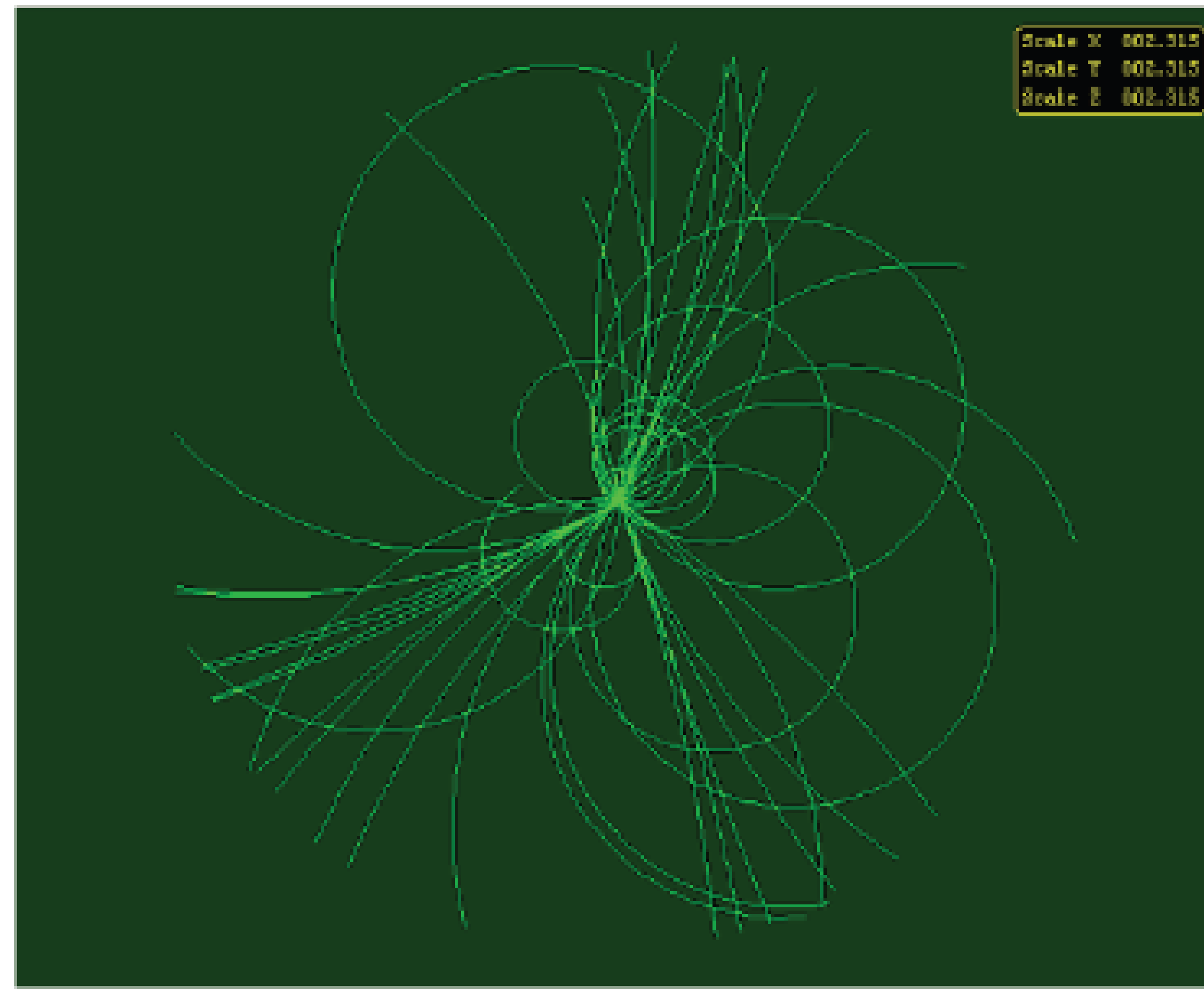
Tracking Options: Pixelated or Gaseuos?

Silicon tracker



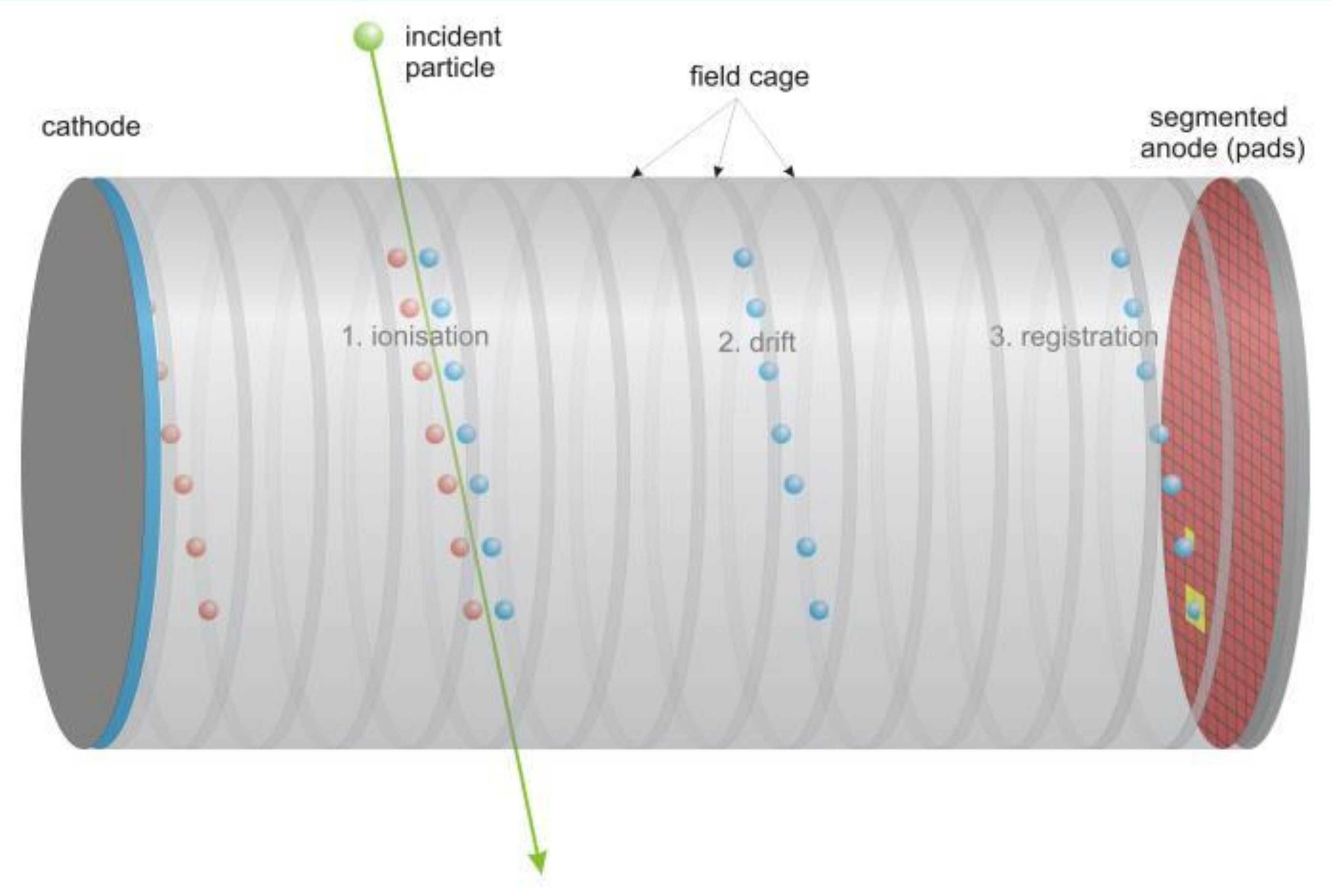
a few space points with extreme precision

Gaseous tracker



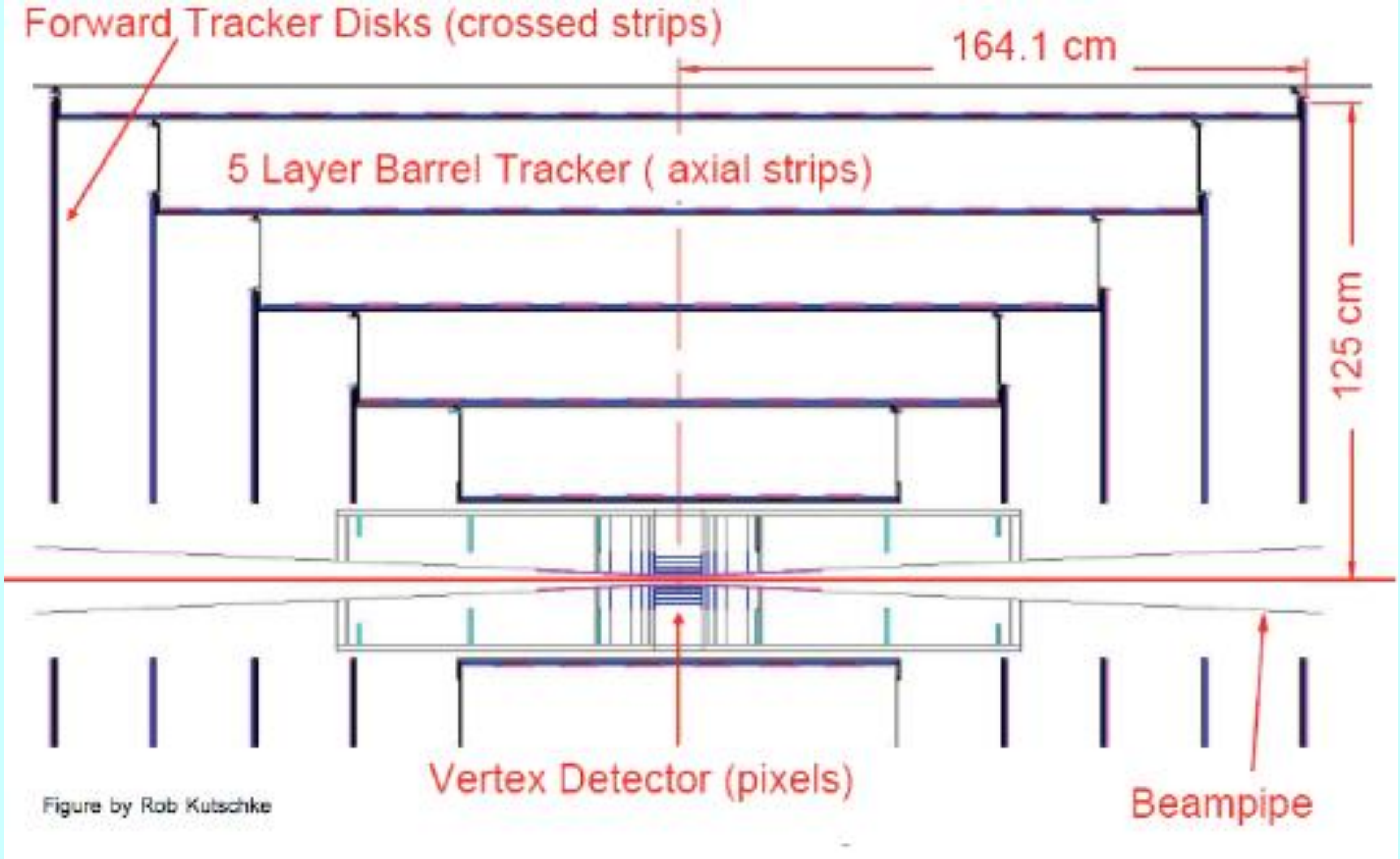
many space points with moderate precision

Tracking System Option: Time Projection Chamber



- Genuine 3d trajectory measurement
- Spacepoint resolution ~100μm
- Minimal amount of material in front of calorimeters
- Rather slow: 150 bunch crossings per picture

Tracking System Option: Silicon Tracker



- Axial strips, no z information
- $r\varphi$ resolution: < 7μm
- p_t resolution: $\Delta p_t/p_t^2 < 2 \times 10^{-5}$ GeV^{-1}

ILD Detector Concept