The ILC Project

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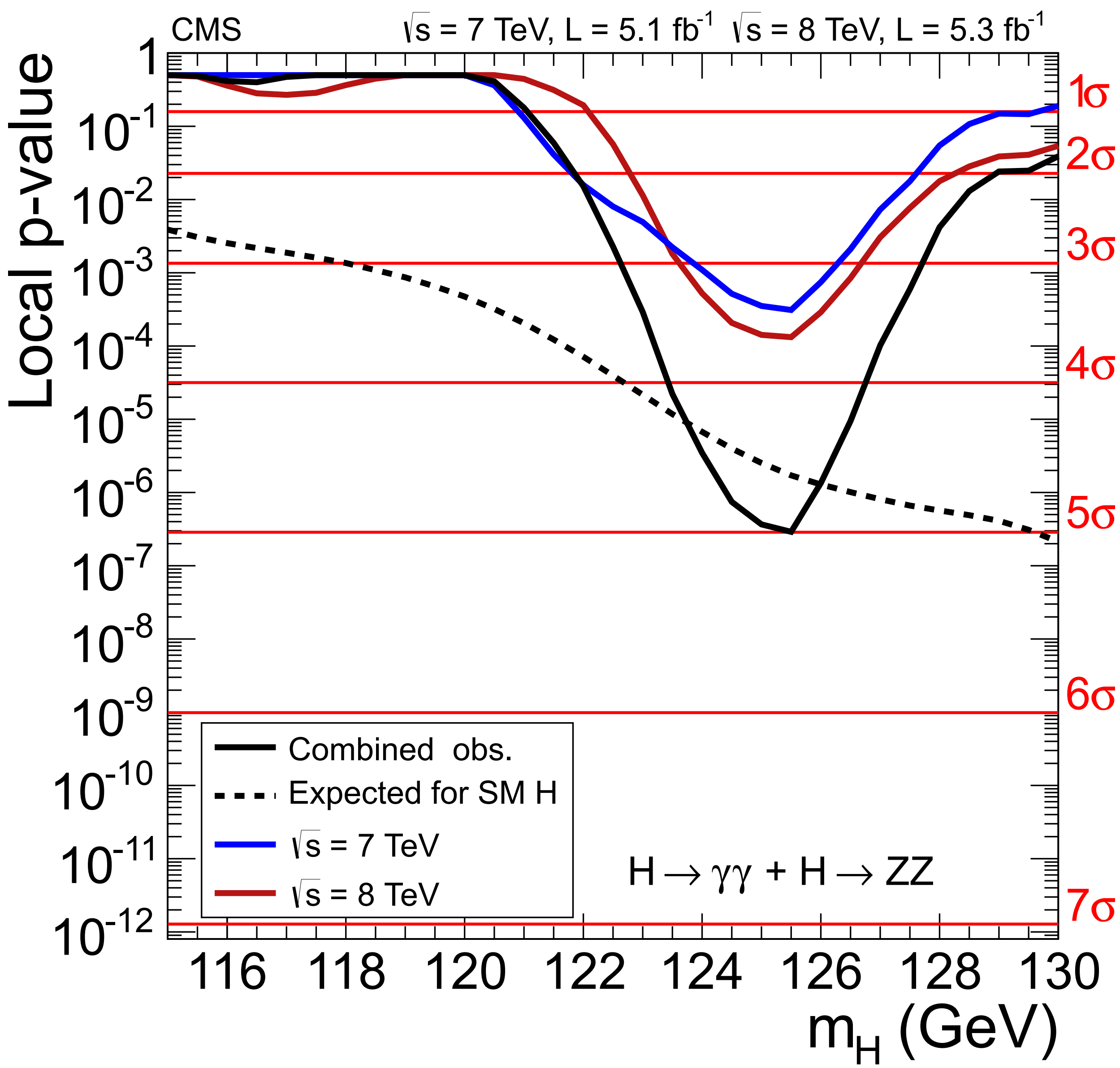
„I hear the roar of a big machine....“
The Sisters of Mercy

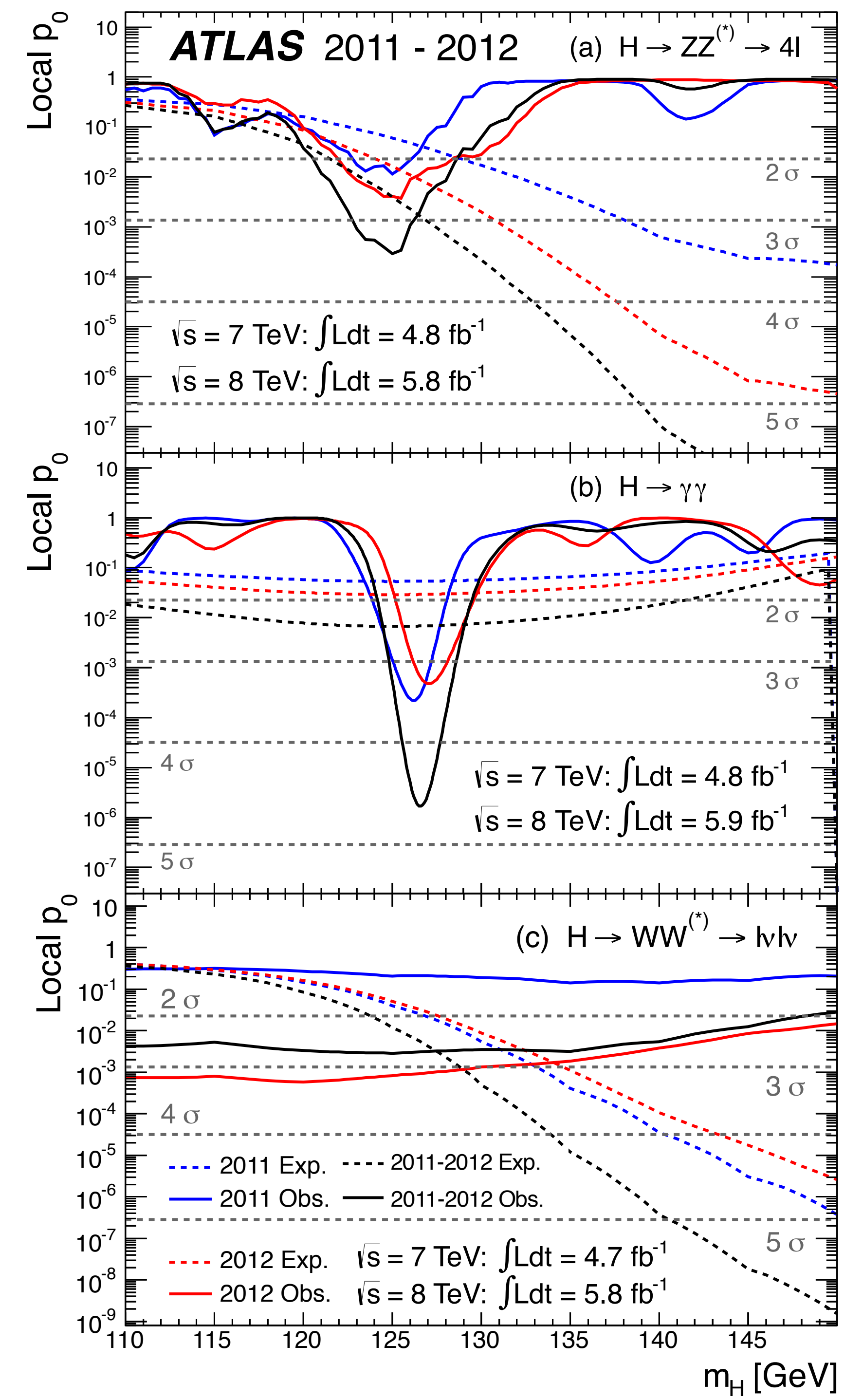
Programme

- Introduction - The International Linear Collider
- ILC Accelerator Design
- ILC Detectors
- Global Context
- Outlook

Introduction

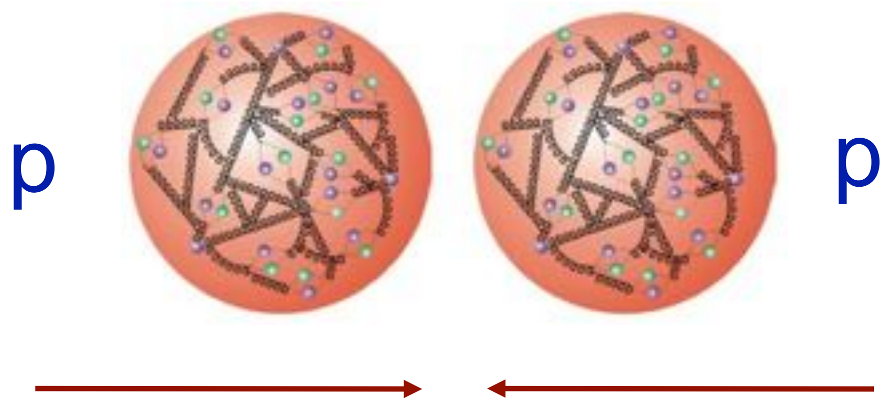
Discovery of a New Boson at 125 GeV

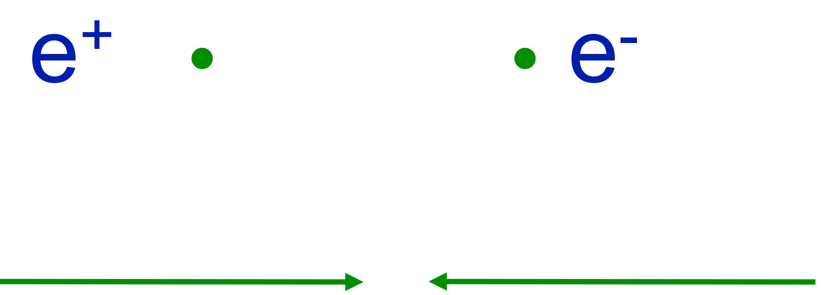




- Now have to establish the nature of the observed boson!

Hadron and Lepton Colliders

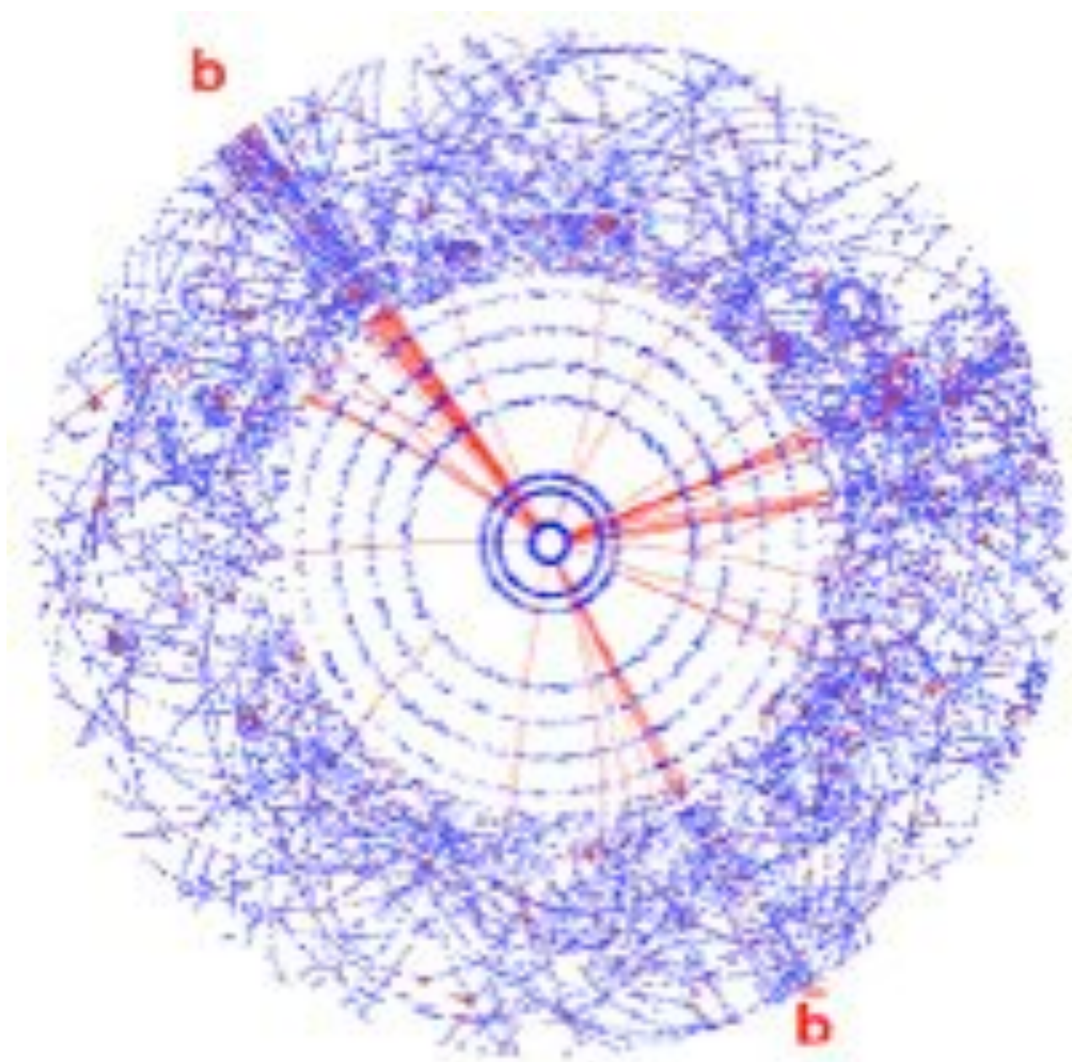




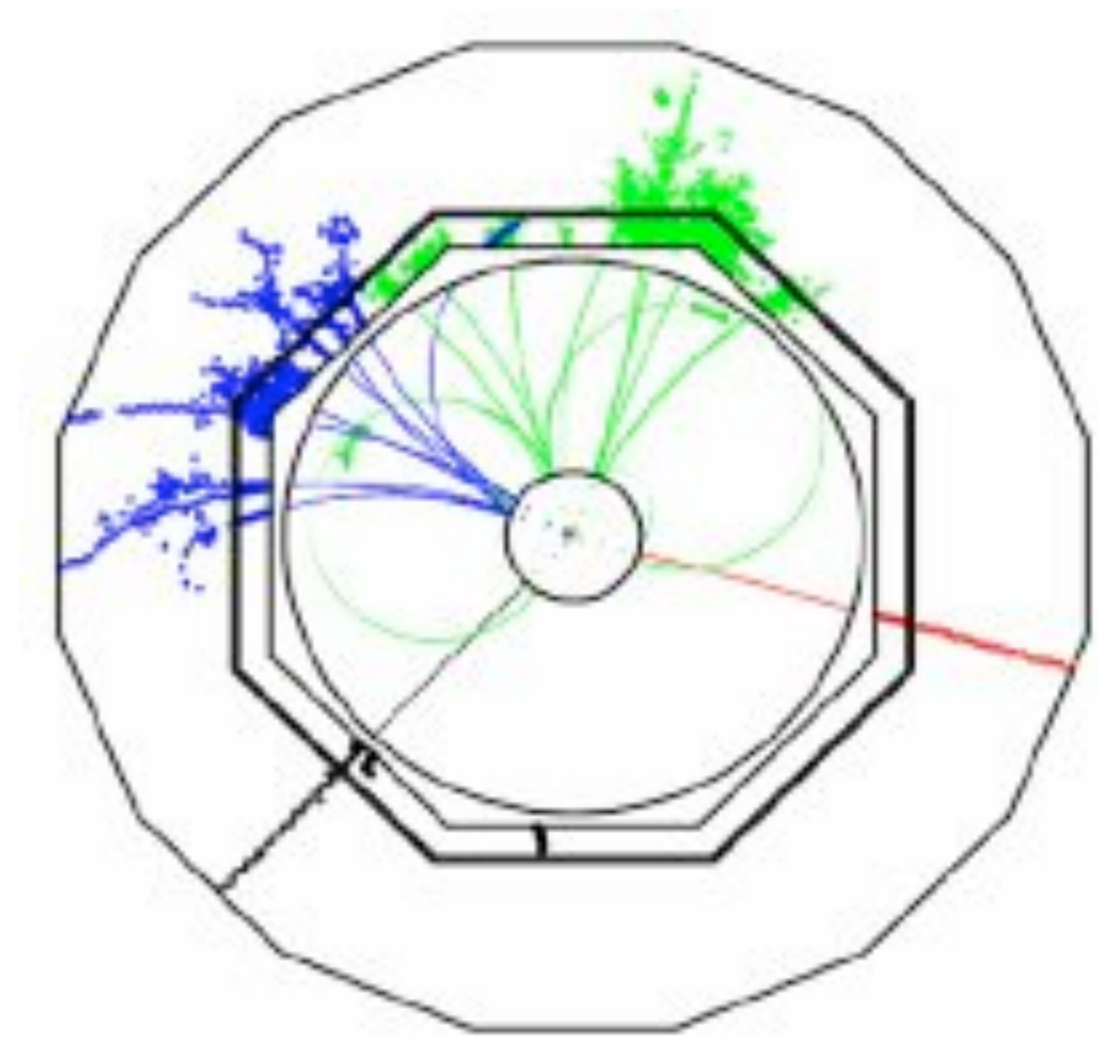
- Proton (anti-) proton colliders:
  - Energy range high (limited by bending magnets power)
  - Composite particles, different initial state constituents and energies in each collision
  - Difficult hadronic final states
- Discovery machines
- Precision measurement potential

- Electron positron colliders:
  - Energy range limited (by RF power)
  - Pointlike particles, well defined initial state quantum numbers and energies
  - Easier final states
- Precision machines
- Discovery potential

Hadron or Lepton Colliders

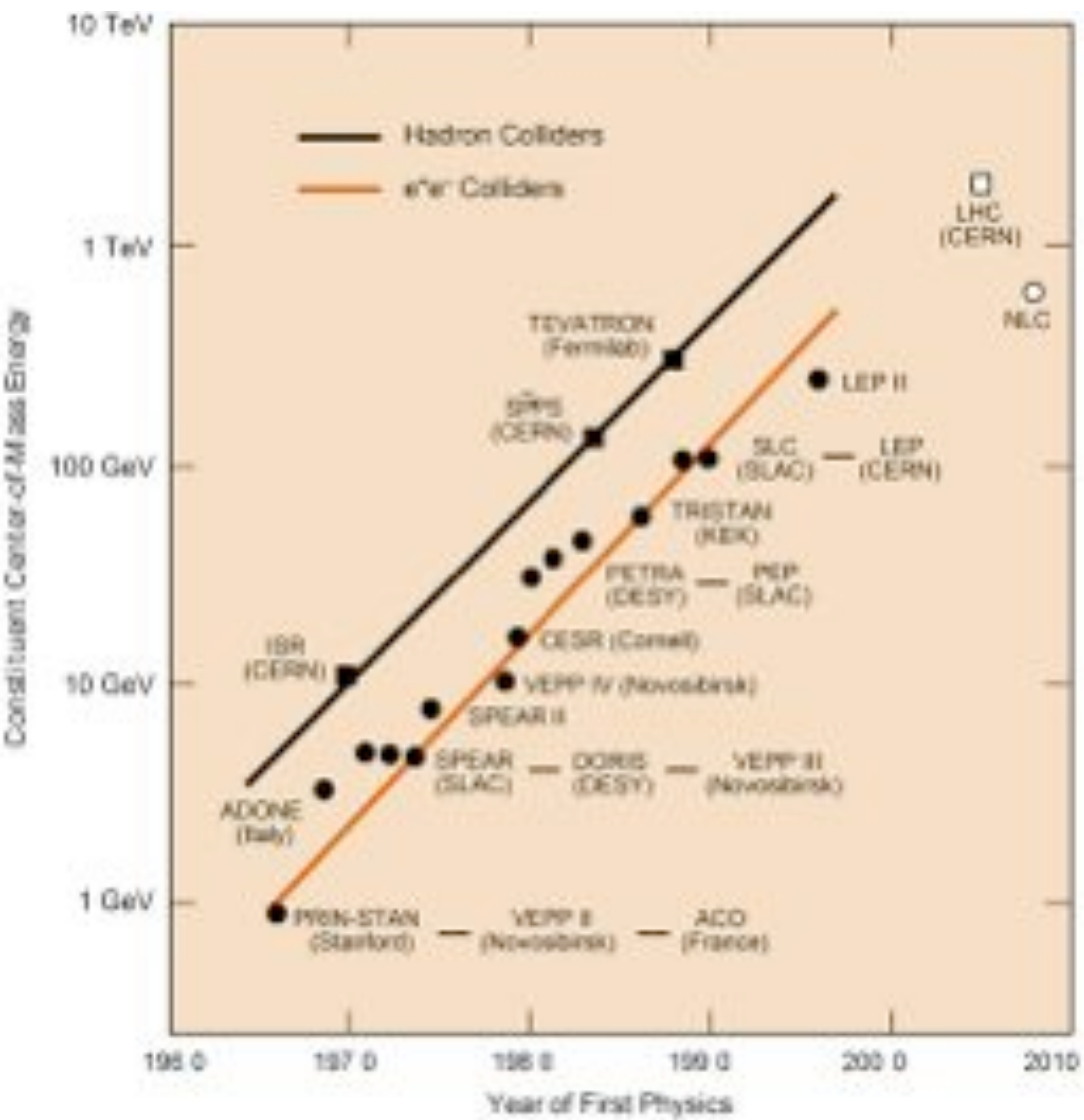


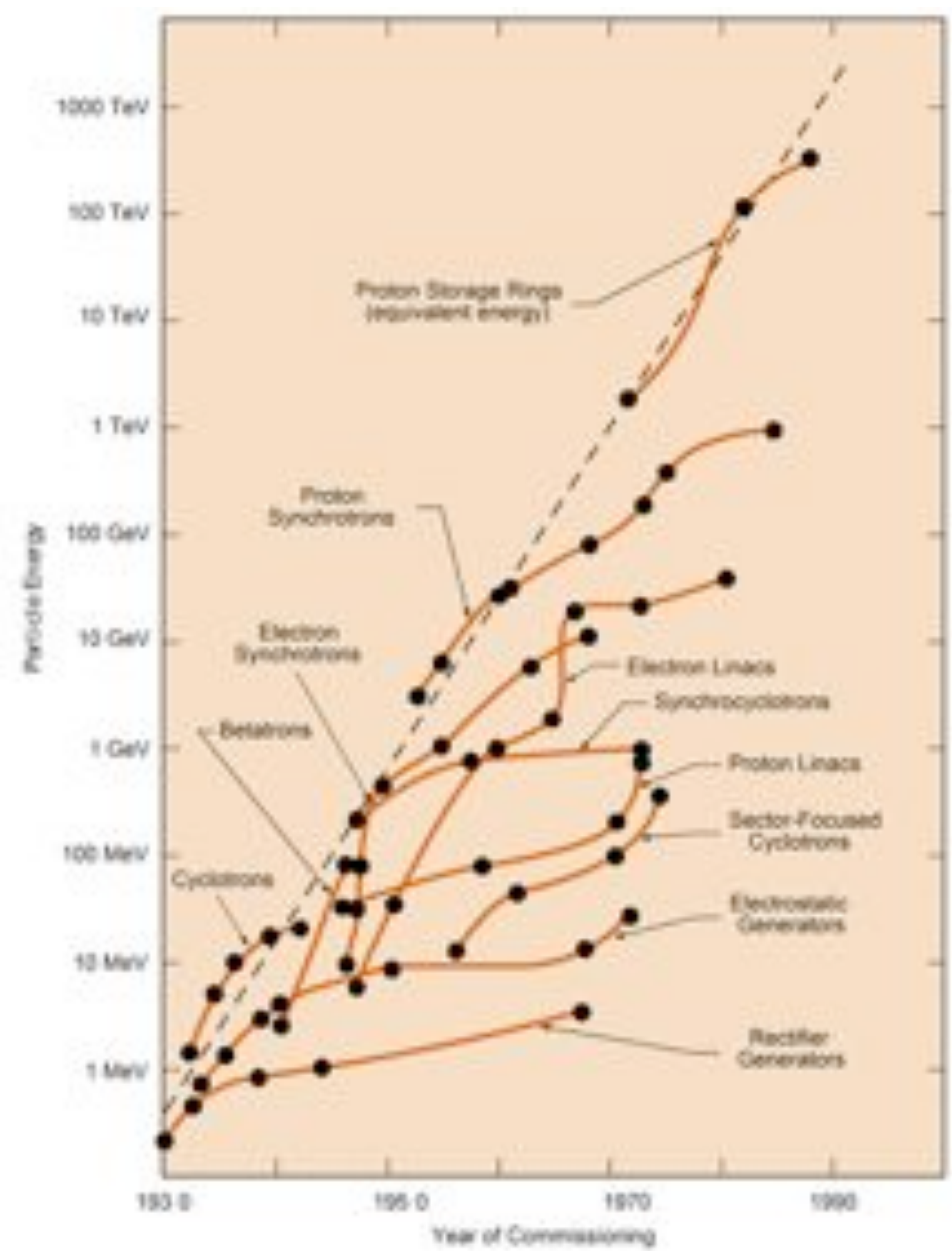
pp ➔ H + X



e^+e^- ➔ HZ

Collider History

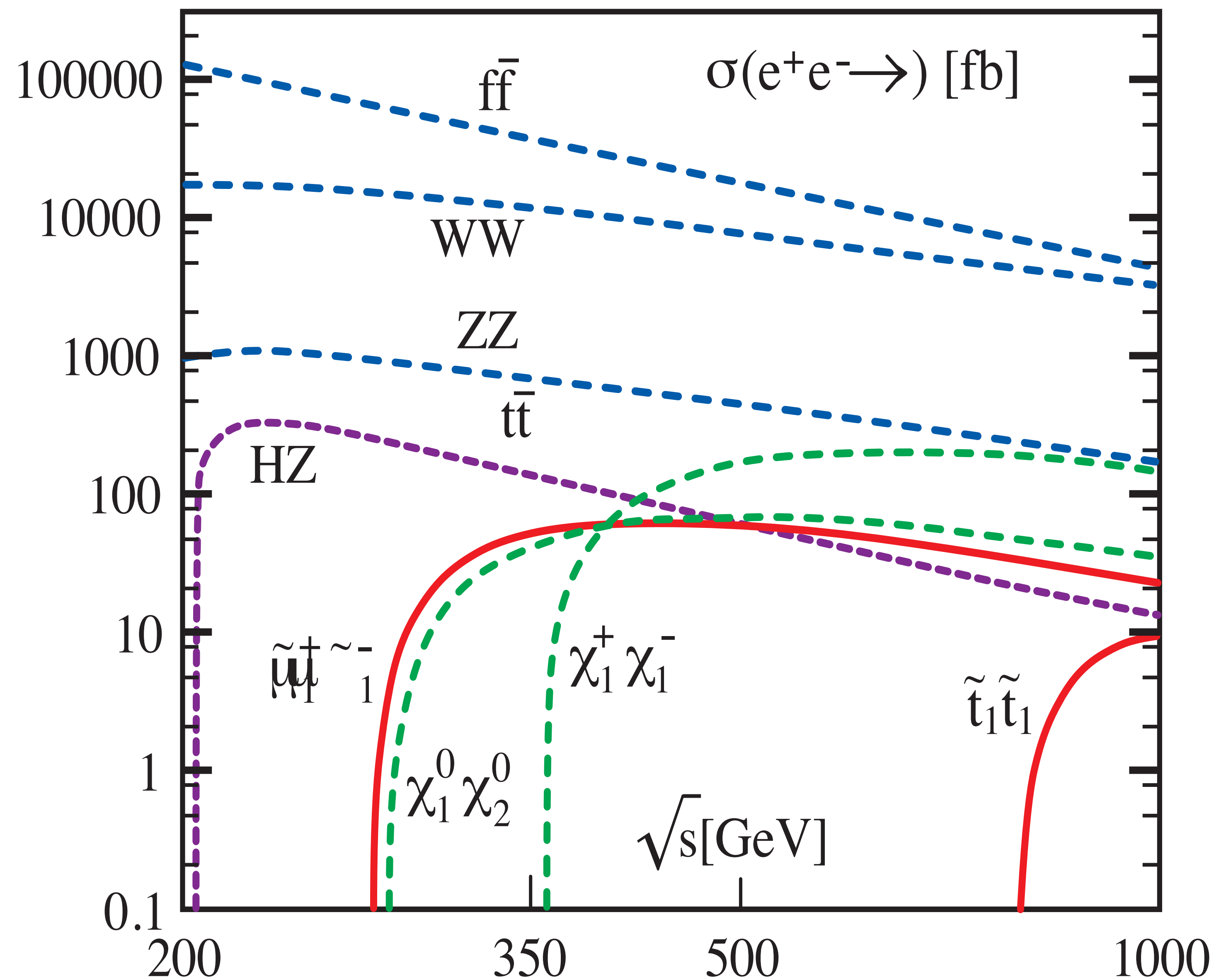




Future Lepton Collider Requirements

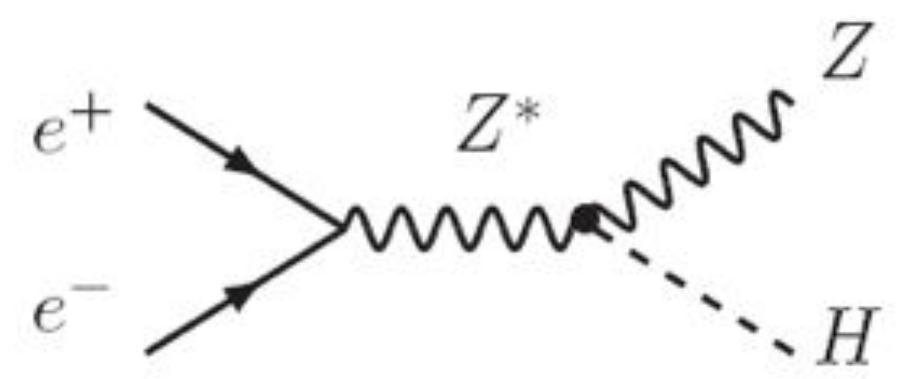
- The e^+e^- cross section drops ~1/s; some t-channel processes rise logarithmically

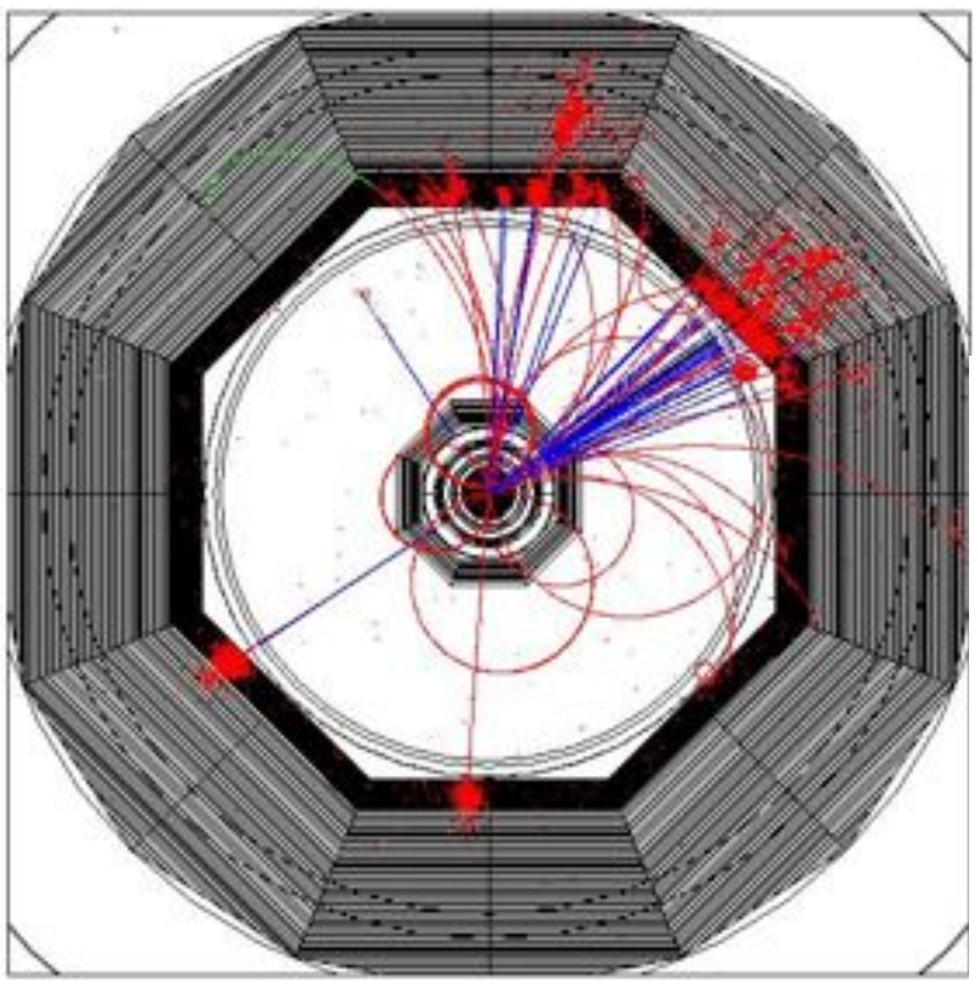
- The key parameters are:
  - the right energy window
  - luminosity



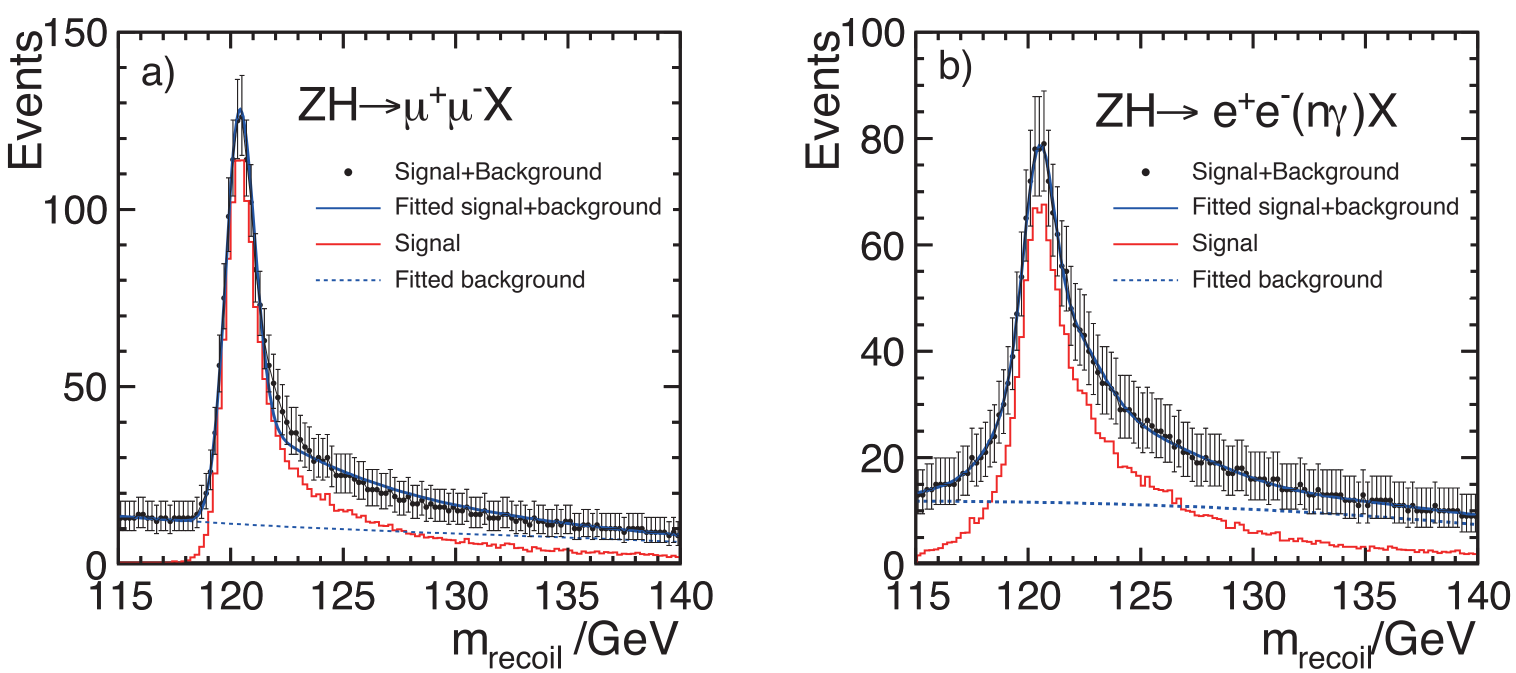
Higgs Physics

- Model independent Higgs measurement
  - recoil independent of branching ratios of Higgs particle



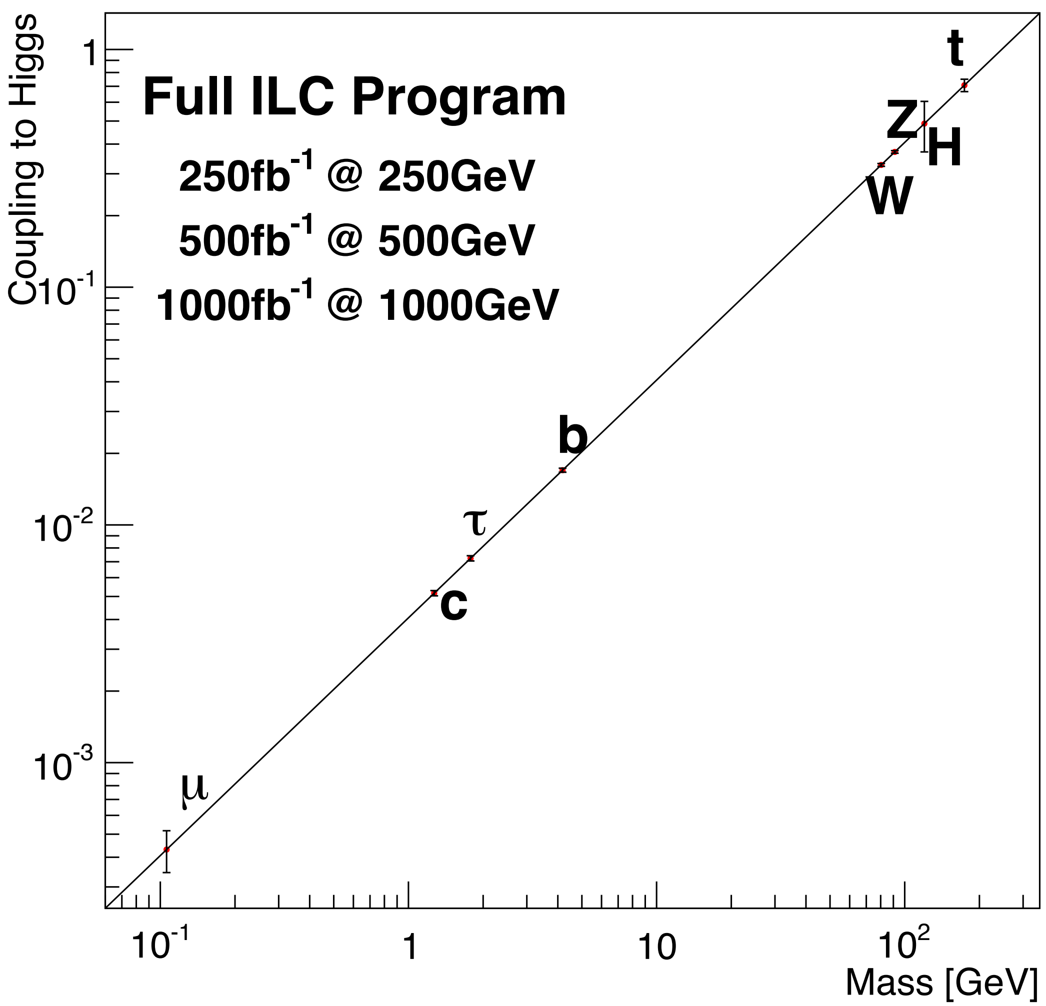


Is this the SM Higgs?

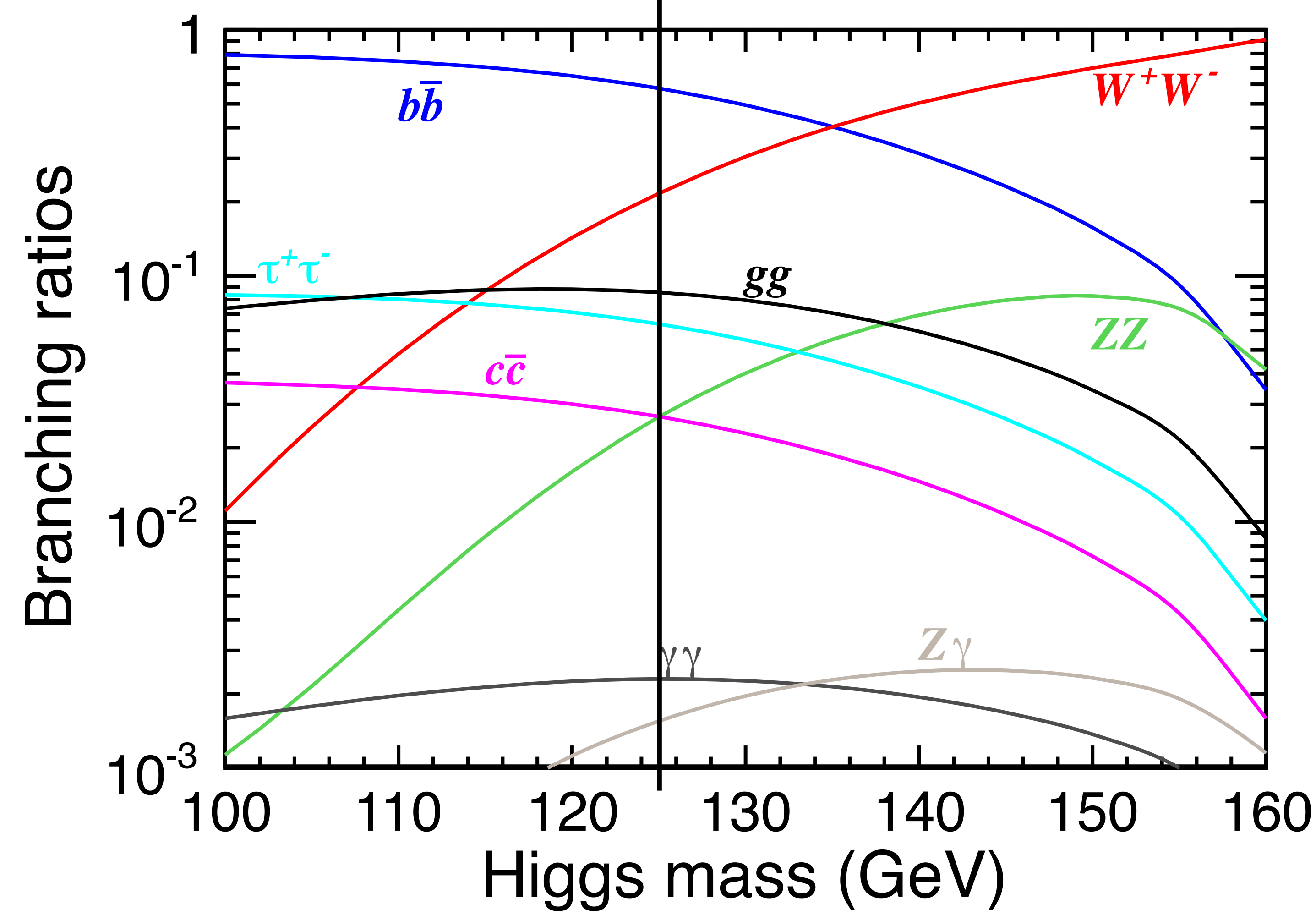


Establishing the Higgs-Mechanism

- Measuring the couplings of the Higgs to massive particles
- Check coupling-mass relation
  - The key feature of the Higgs particle



A Higgs at 125 GeV has favourable BR to several particles



The Need for Precision

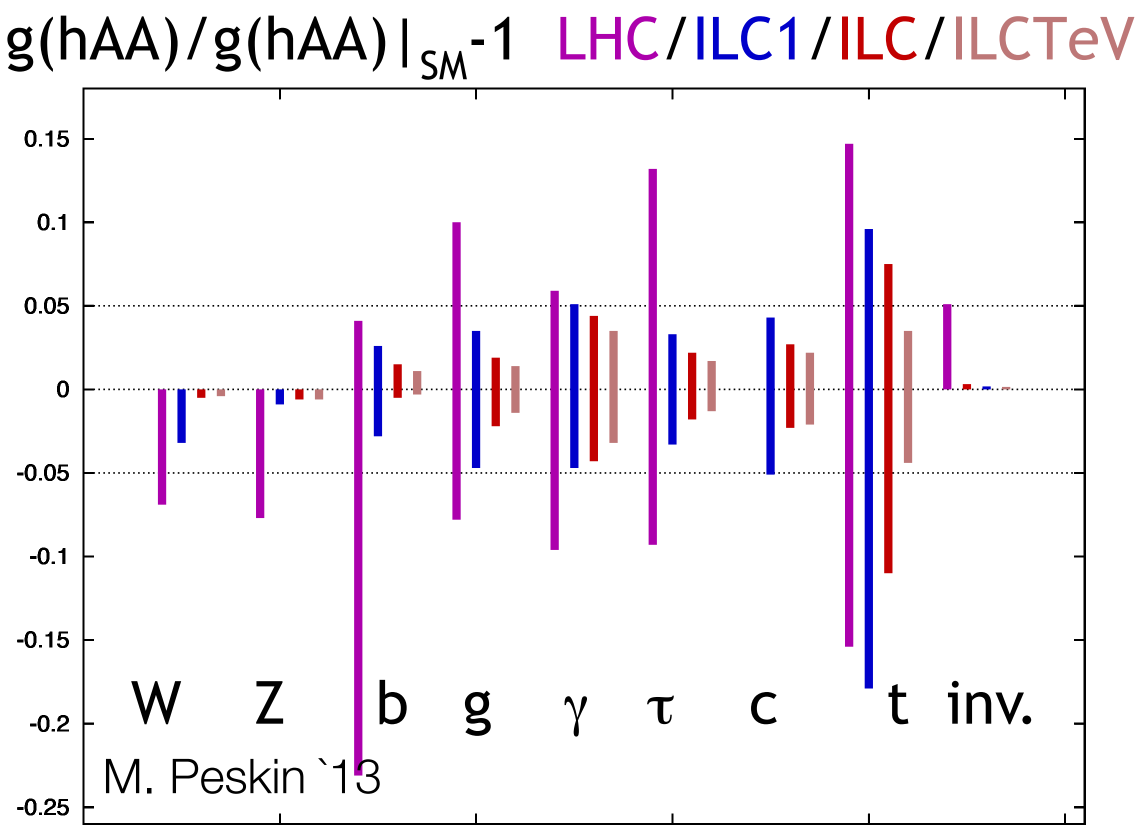
- H. Rzehak (ECFA WS 2013):

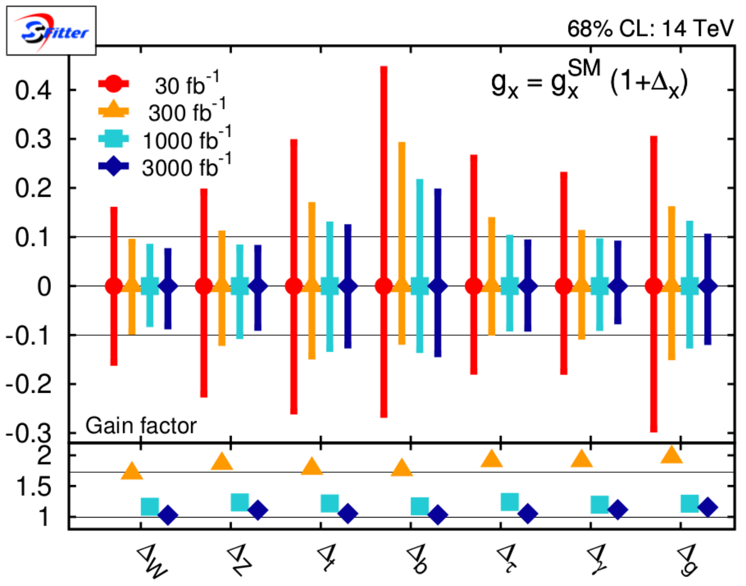
How large can the maximal deviations from the SM Higgs couplings be if no new physics is discovered by the LHC?

The answer in the context of 3 different models:

	$\lvert\Delta hVV\rvert$	$\lvert\Delta h\bar{t}t\rvert$	$\lvert\Delta h\bar{b}b\rvert$	$\lvert\Delta hhh\rvert$
Mixed-in Singlet	6%	6%	6%	18%
Composite Higgs	8%	tens of %	tens of %	tens of %
MSSM	$<1\%$	3%	10%, 100%	2%, 15%

$\tan\beta > 20$ no superpartners; all other cases





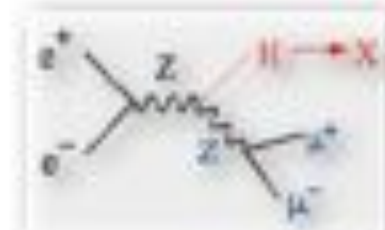
LHC/LHC Upgrades

The ILC-500 Higgs Menu

ZH @ 250 GeV (~mZ+mH+20GeV) :

- Higgs mass, width, J^{PC}
- Gauge quantum numbers
- Absolute measrement of HZZ coupling (recoil mass)
- BR(h->VV,qq,ll,invisible) : V=W/Z(direct), g, γ (loop)

-> couplings to H (other than top)



ttbar @ 340-350GeV (~2mt) : ZH meas. Is also possible

- Threshold scan --> indirect meas. of top Yukawa coupling
- A_{FB}, Top momentum measurements
- Form factor measurements

γγ → HH @ 350GeV possibility

ννH @ 350 - 500GeV :

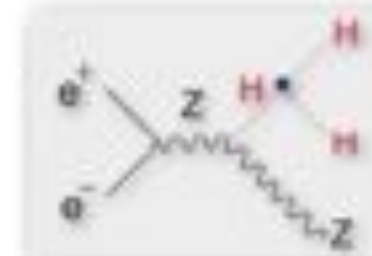
- HWW coupling -> total width --> absolute normalization of couplings

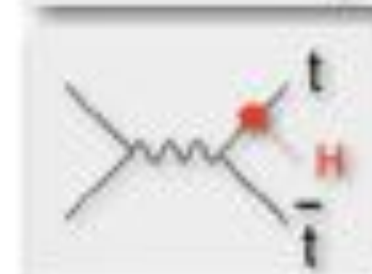
ZHH @ 500GeV (~mZ+2mH+170GeV) :

- Prod. cross section attains its maximum at around 500GeV -> Higgs self-coupling

ttbarH @ 500GeV (~2mt+mH+30GeV) :

- Prod. cross section becomes maximum at around 700GeV.
- QCD threshold correction enhances the cross section -> top Yukawa measurable at 500GeV concurrently with the self-coupling



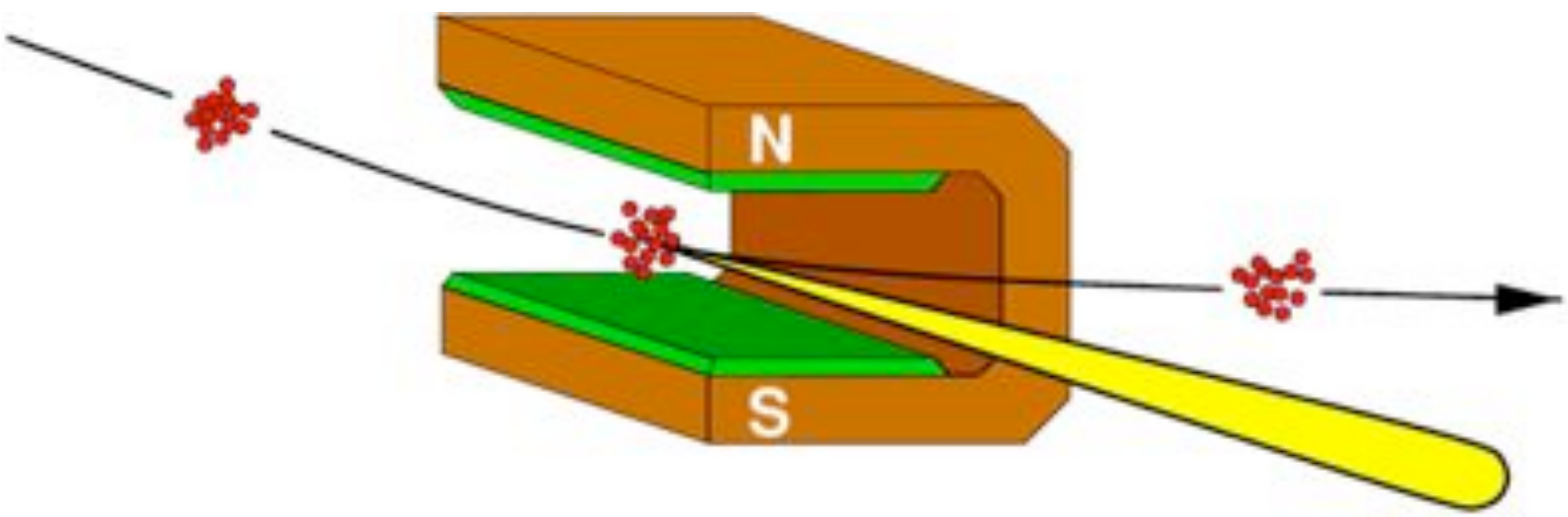


We can complete the mass-coupling plot at ~500GeV!

Accelerator Issues

The Limits of Storage Rings

- Charged particles radiate on curved trajectories



- Energy loss per revolution ~$1/m^4$
- RF power for acceleration: $P_{RF} \sim E^4/r$

Cost Scaling for Storage Rings

- Cost for RF:
  - $€_{RF} \sim E^4/r$
- Linear cost (tunneling, beam lines, etc.):
  - $€_{lin} \sim r$
- Total cost optimum:
  - $€_{tot} = €_{RF} + €_{lin} \sim E^2$
  - $r_{opt} \sim E^2$
- For details: B. Richter, NIM 136 (1976) oo. 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

- The next high energy e^+e^- collider will be linear:
- $€_{LC} \sim E + \text{const.}$

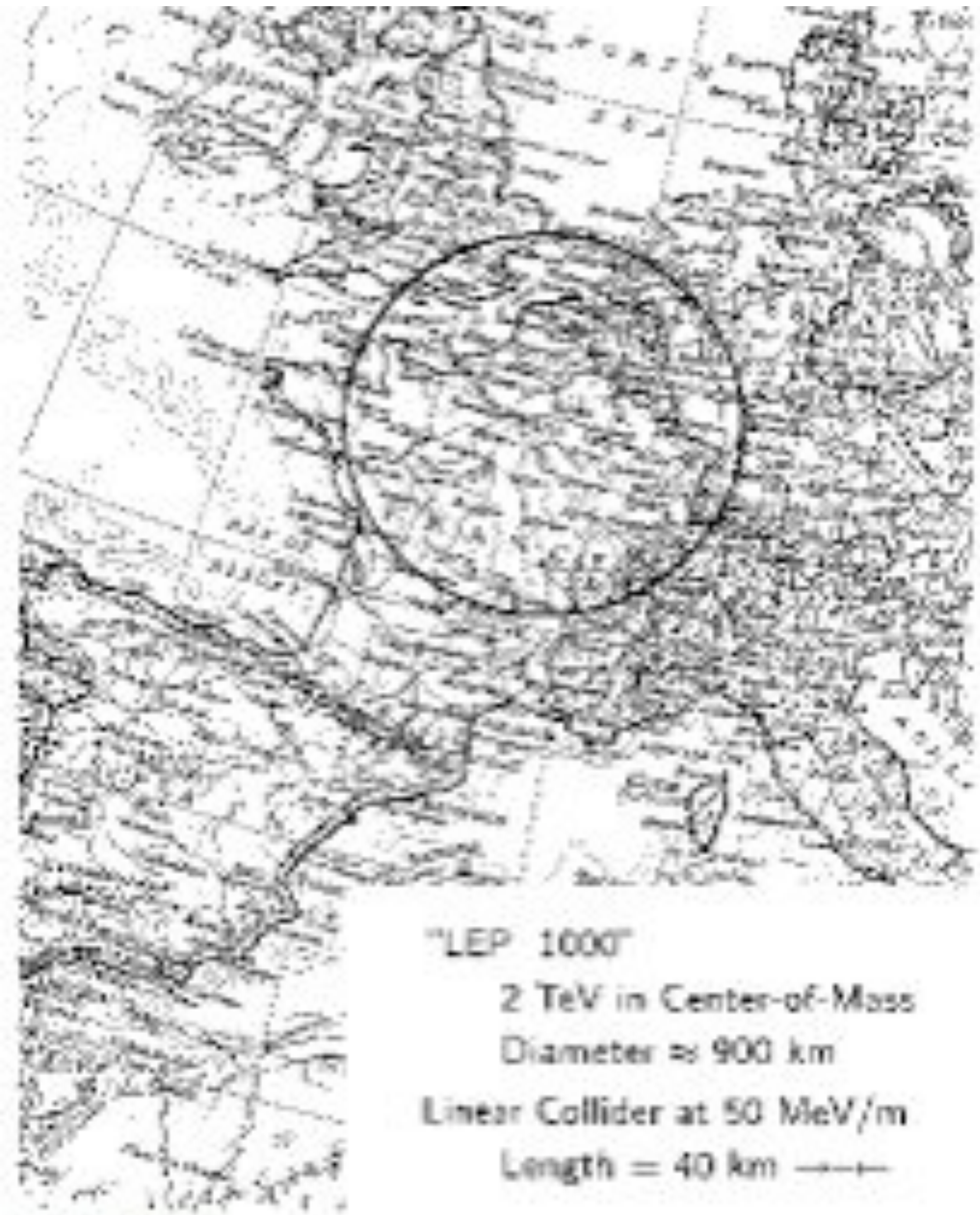
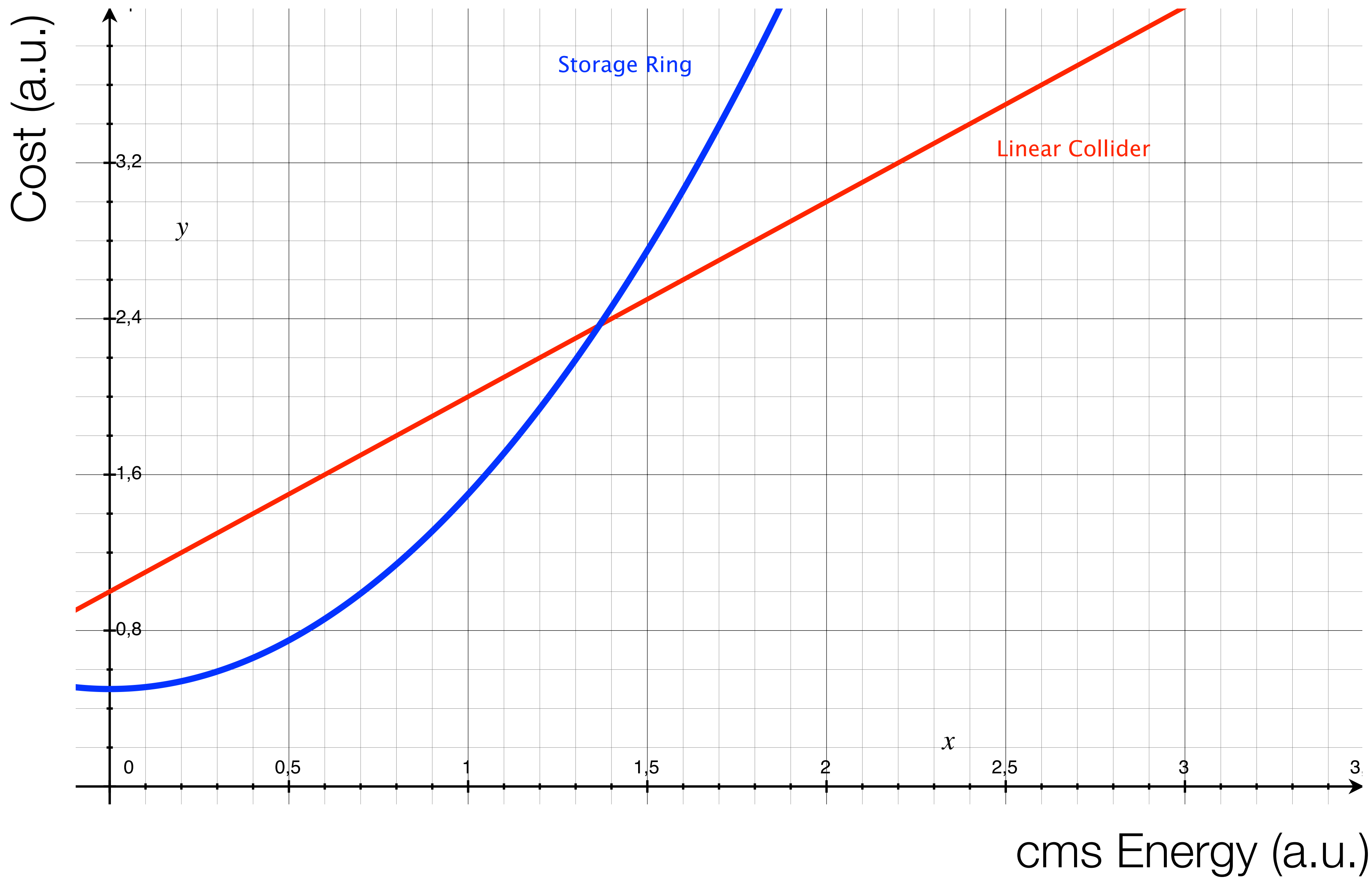


Figure by Gregory Loew

Cost Scaling



- Linear colliders are the economical choice above ~220± GeV cms energy
- TLEP pushes this limit...

Linear Collider - an Old Story

- First e+e- collider: AdA (1961)
- First proposal for a linear collider: M. Tigner (1965)

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

M. Tigner

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

(ricevuto il 2 Febbraio 1965)

- „While the storage ring technique for performing clashing-beam experiments is very elegant in concept it seems worth-wile at the present juncture to investigate other methods which, while less elegant or superficially more complex may prove more tractable.“

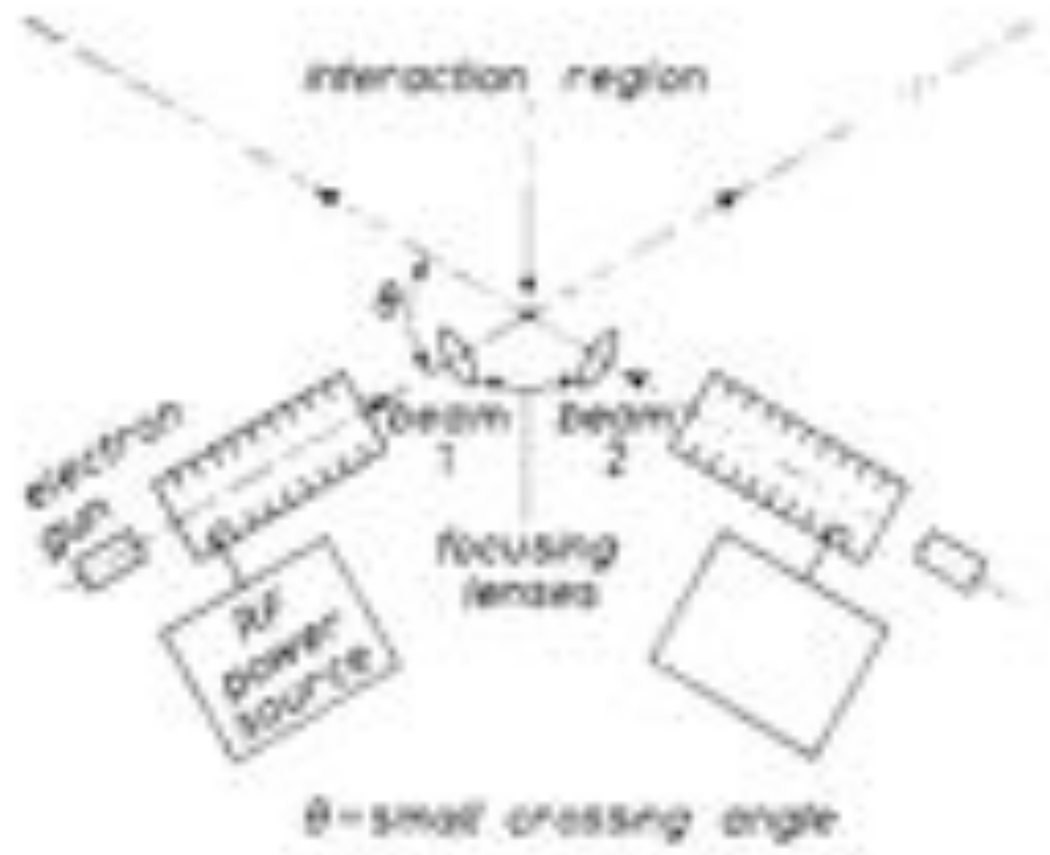
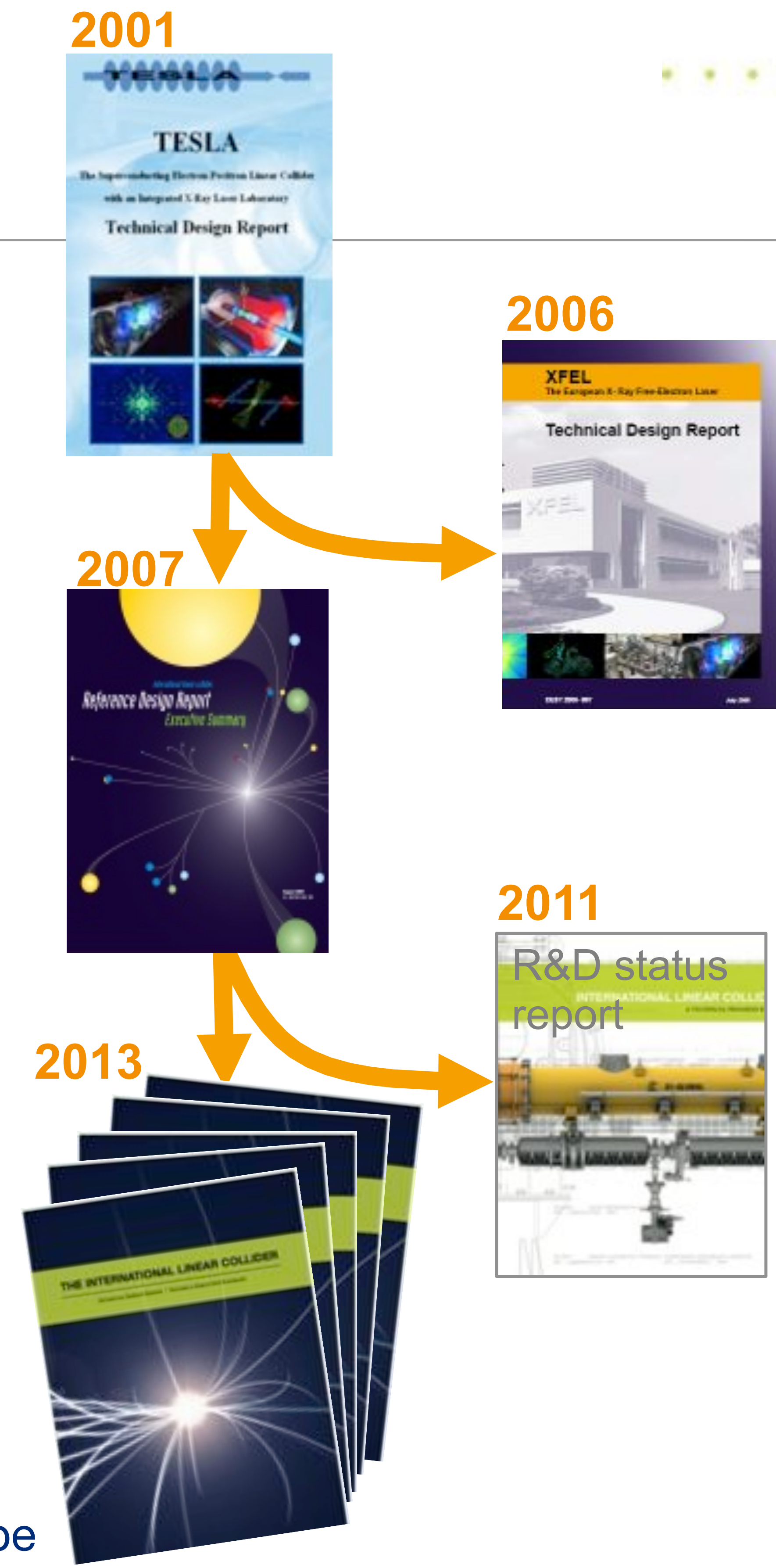


Fig. 1.

ILC History

- Pre-ILC:
  - since early 90s different LC studies
    - TESLA (SCRF)
    - NLC/JLC (normal conducting)
    - CLIC (two beam)
  - 2004: technology decision: SCRF
- since 2005:
  - ILC Global Design Effort founded
  - 2007 ILC Reference Design Report
    - first cost estimate
  - 2012/13 ILC Technical Design Report
    - cost update
- since 2012/13:
  - Linear Collider Collaboration (LCC)
    - ILC: Higgs/Top factory
      - towards possible realisation in Japan
    - CLIC: multi-TeV option on longer timescale
      - option for next energy frontier project in Europe



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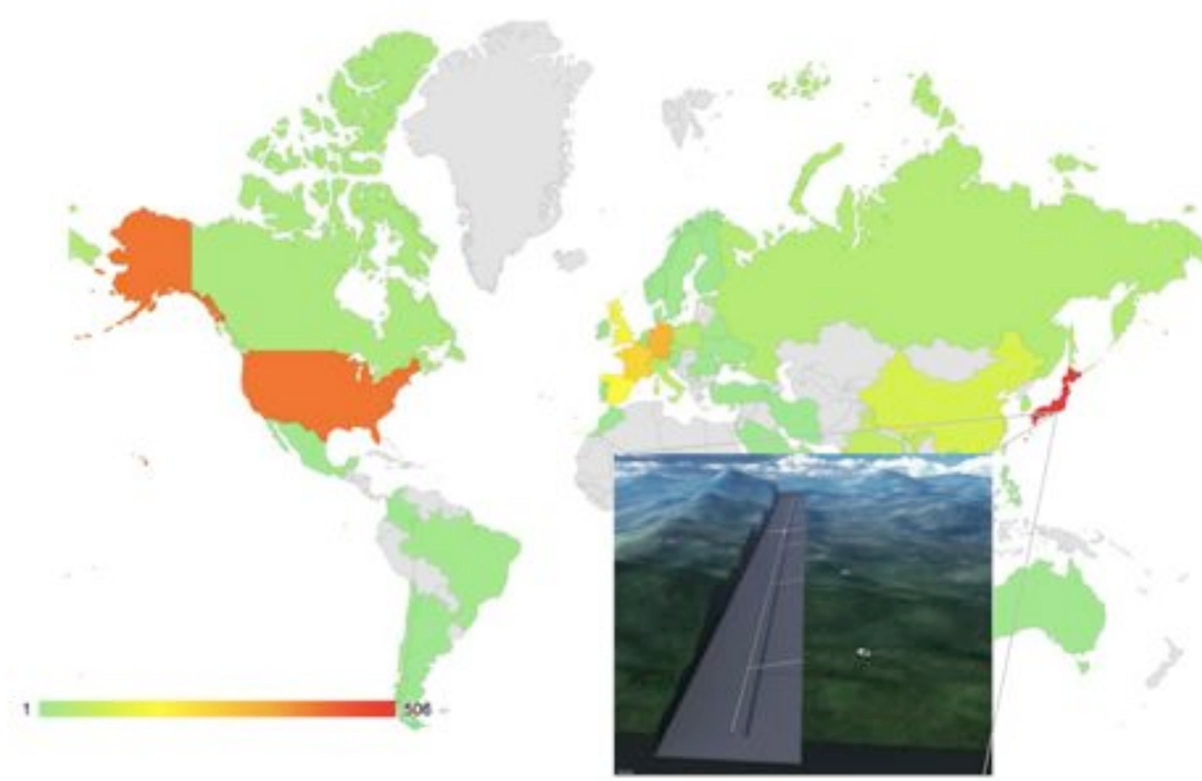
Resources since 2005 (GDE):
~250 FTE/a
~2000 person years
(~5000 person years in total)
~300 M$ globally

2400 signatories for the TDR



The Luminosity Challenge

- 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 per train
- N = particles per bunch
- f_{rep} = repetition frequency
- $4\pi\sigma_x\sigma_y$ = beam cross section at the interaction point
- H_D = beam-beam enhancement factor

The Luminosity Challenge

- Introducing the beam power:

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

- yields

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

- $\eta_{RF\rightarrow beam}$: conversion efficiency RF to beam

RF Power

- Some numbers:
  - E_{cm} = 500 GeV
  - N = 10^{10}
  - n_b = 1000
  - f_{rep} = 10 Hz
  - ⇒ P_{beams} = 8 MW
- adding efficiencies
  - Wall plug ⟶ RF ⟶ beam

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

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

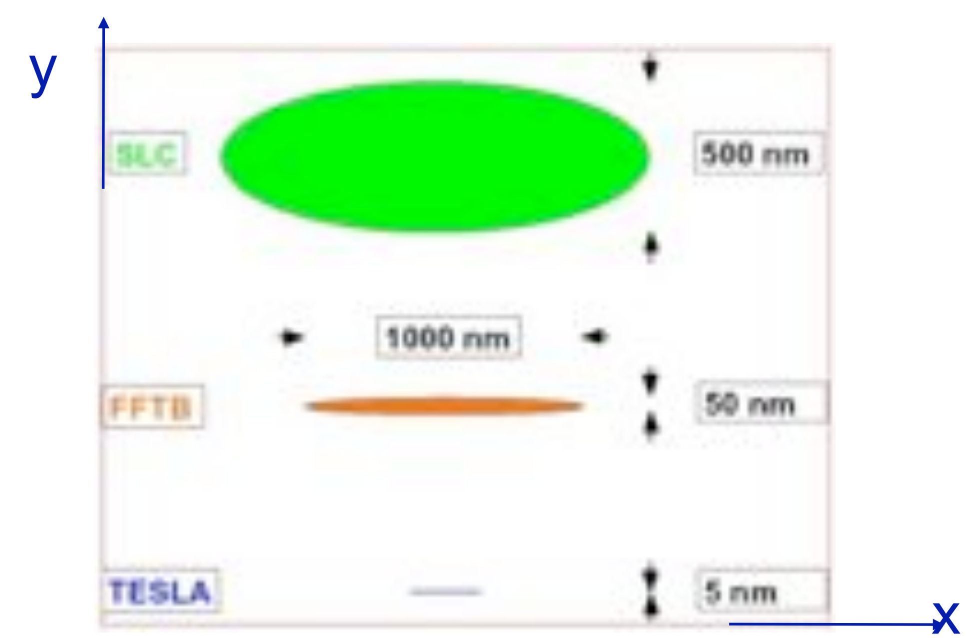
- yields AC power needs >100 MW just to accelerate beams and maintain luminosity!!!

Storage Ring vs Linear Collider

- LEP f_{rep}: 44 kHz
- ILC f_{rep}: few to 100 Hz (power limited)

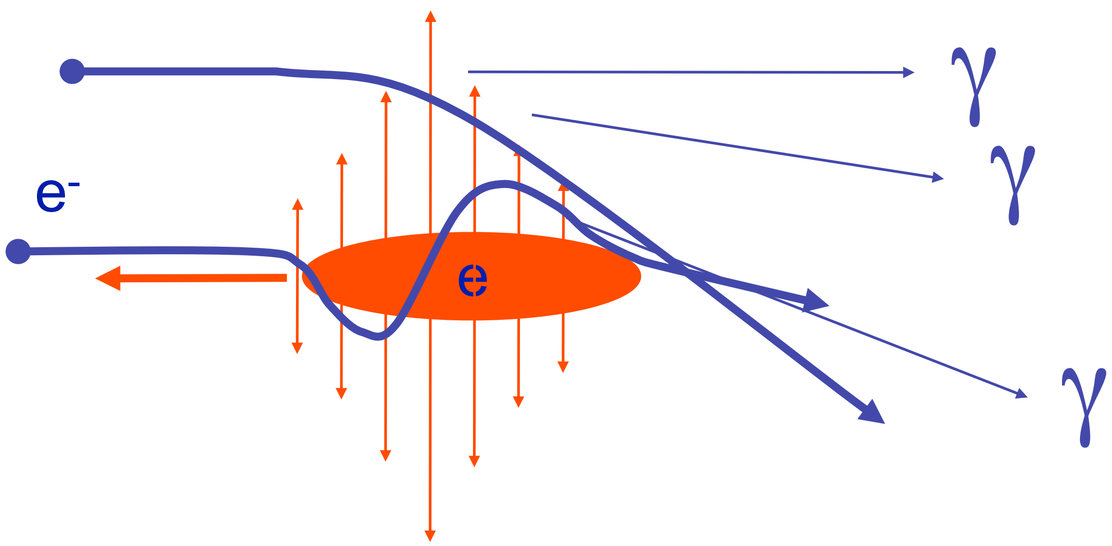
- Factor ~1000 in Luminosity already lost!
- Recover by pushing hard on the beam spot sizes at collision:
  - LEP: 130 x 6 μm^2
  - ILC: 500 x 5 nm^2
- Needed to achieve $L=O(10^{34}\ cm^{-2}\ s^{-1})$

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



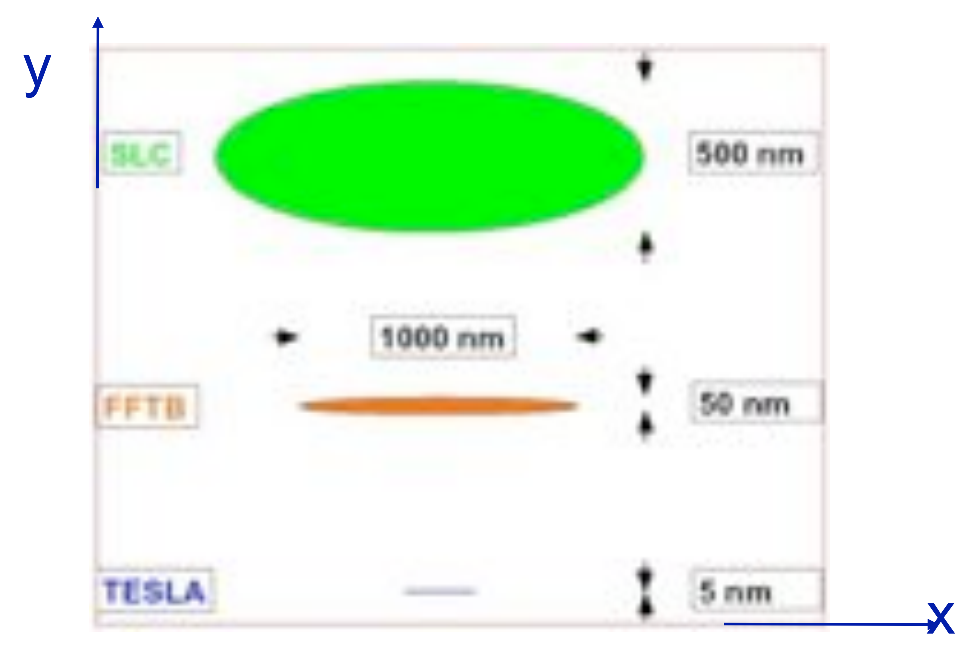
Beamstrahlung

- Strong mutual focusing of beam gives rise to significant luminosity enhancement ($H_d \approx 2$): pinch effect
- electrons/positrons pass through intense field of opposite beam, radiate hard photons: Beamstrahlung



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

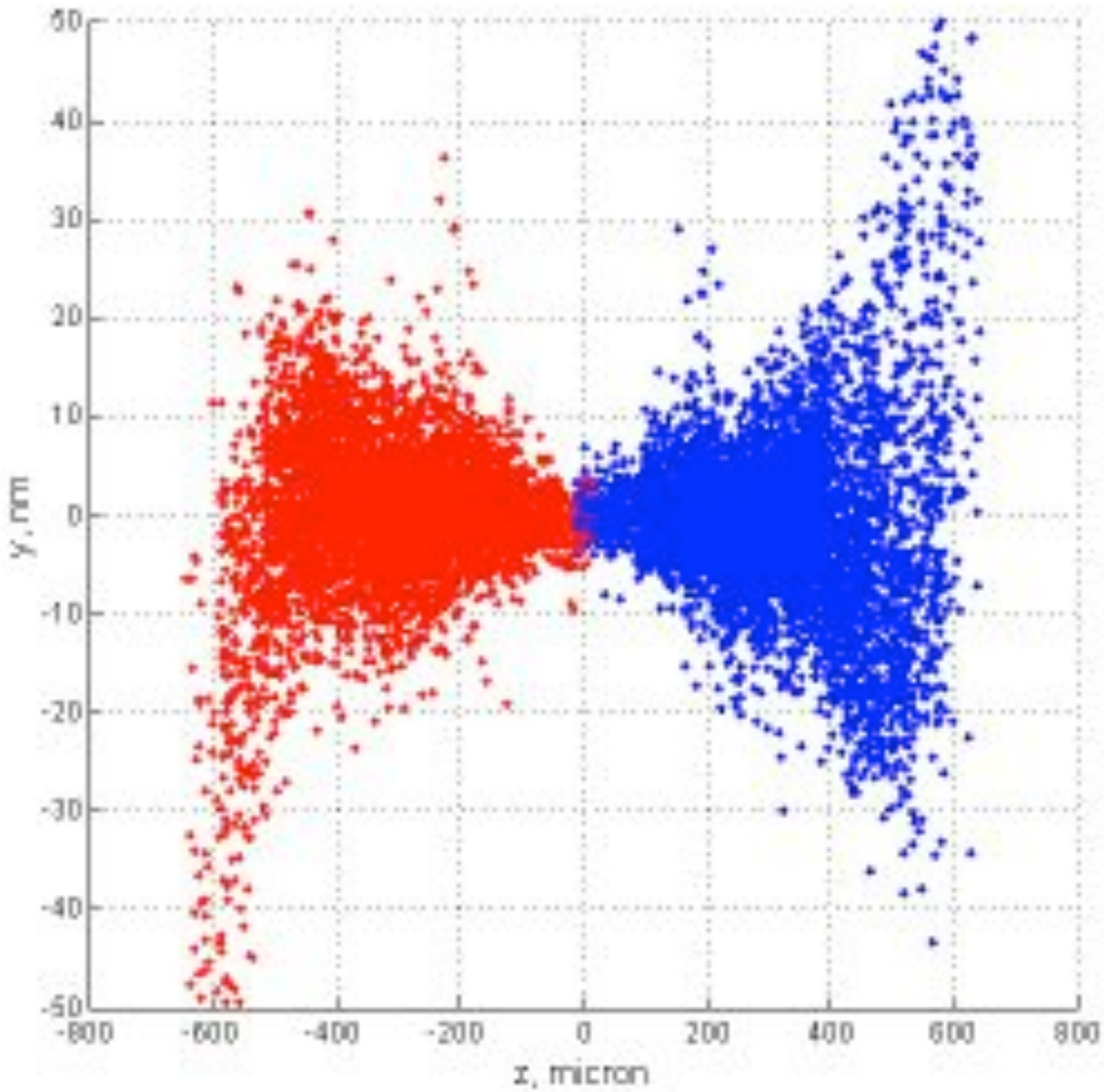
$$L = \frac{n_b N^2 f_{rep}}{4\pi \sigma_x \sigma_y} H_D$$



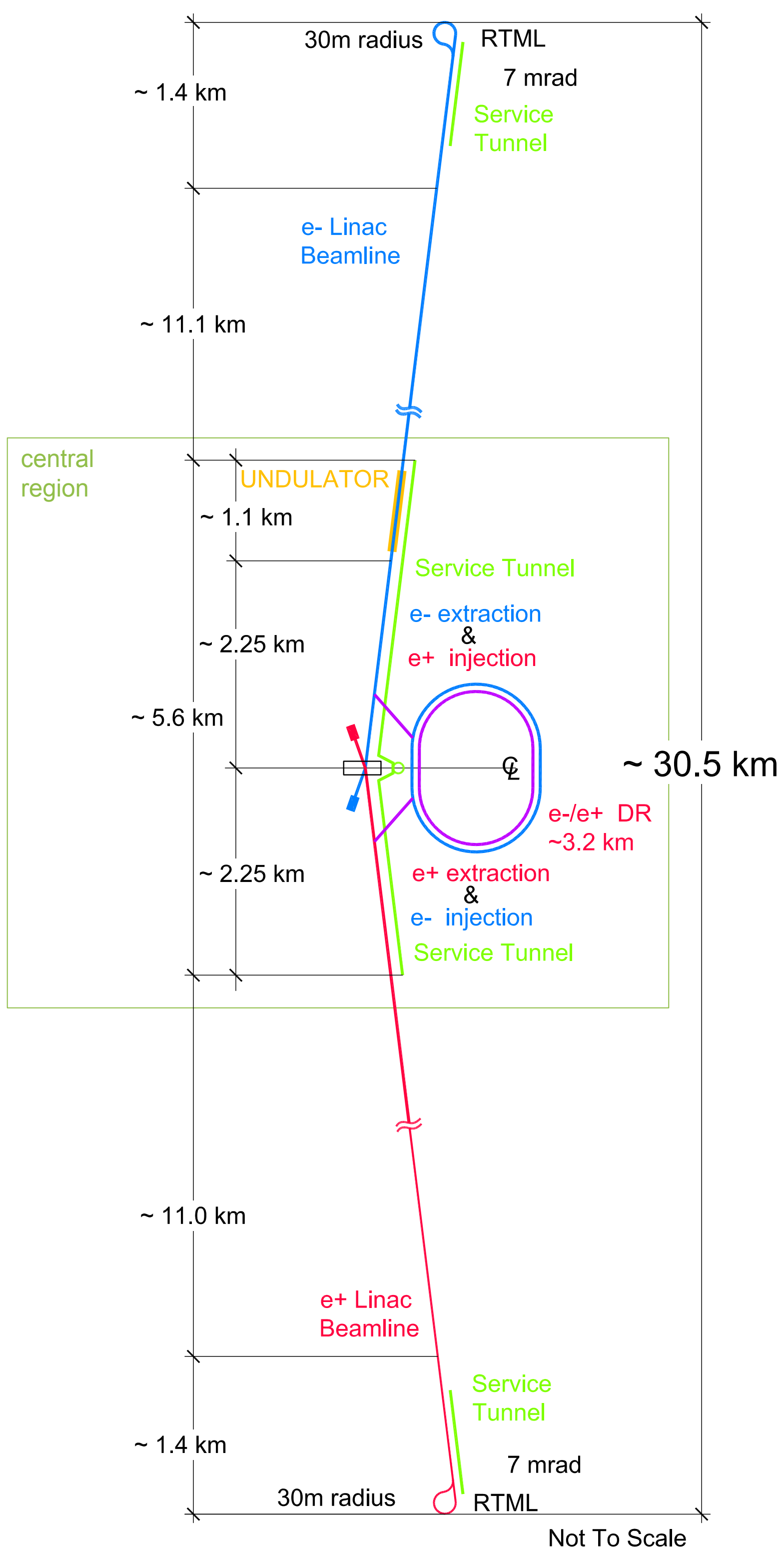
Chose flat beams!

Beam-Beam Interaction

Beam-Beam Interaction



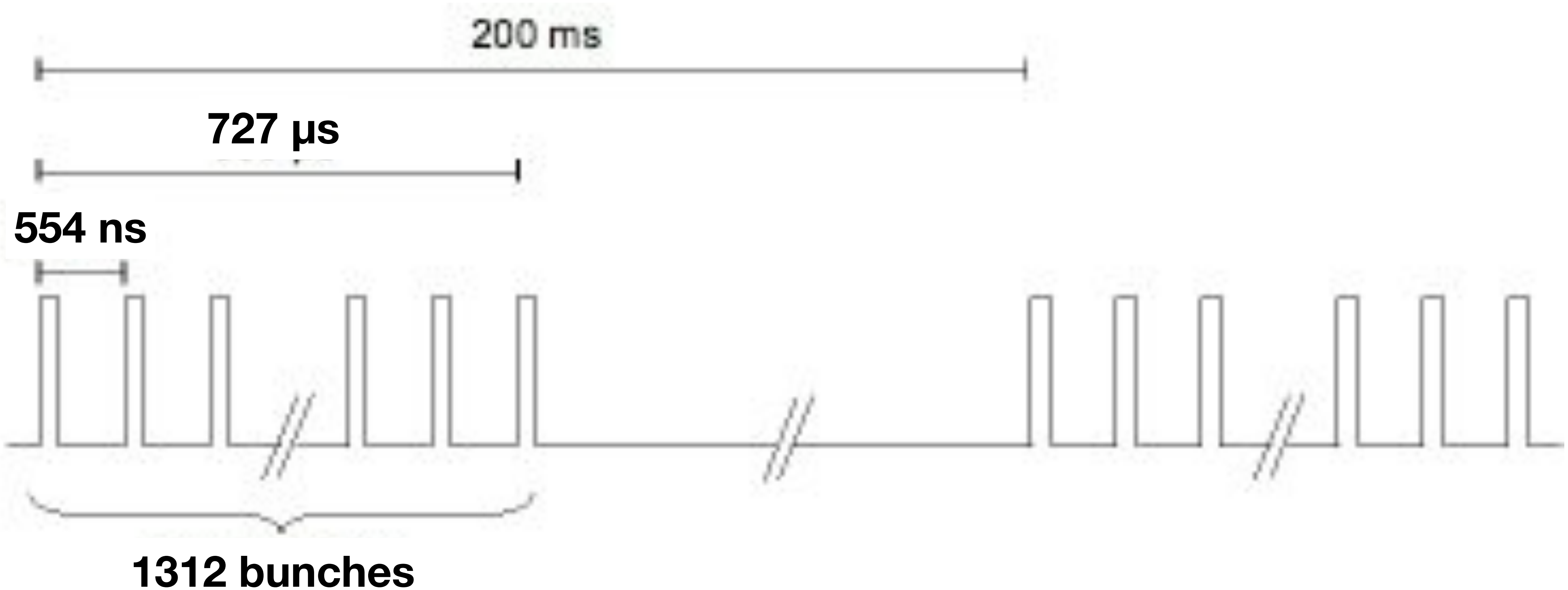
ILC Baseline Design (500 GeV)



Physics	Max. E_{cm}	500 GeV
	Luminosity	1.8×10^{34} $cm^{-2}s^{-1}$
	Polarisation (e-/e+)	80% / 30%
	δ_{BS}	4.5%
Beam (interaction point)	σ_x / σ_y	574 nm / 6 nm
	σ_z	300 μm
	$\gamma\epsilon_x$ / $\gamma\epsilon_y$	10 μm / 35 nm
	β_x / β_y	11 mm / 0.48 mm
	bunch charge	2×10^{10}
Beam (time structure)	Number of bunches / pulse	1312
	Bunch spacing	554 ns
	Pulse current	5.8 mA
	Beam pulse length	727 μs
	Pulse repetition rate	5 Hz
Accelerator (general)	Average beam power	10.5 MW (total)
	Total AC power	163 MW
	(linacs AC power	107 MW)

ILC Bunch Structure

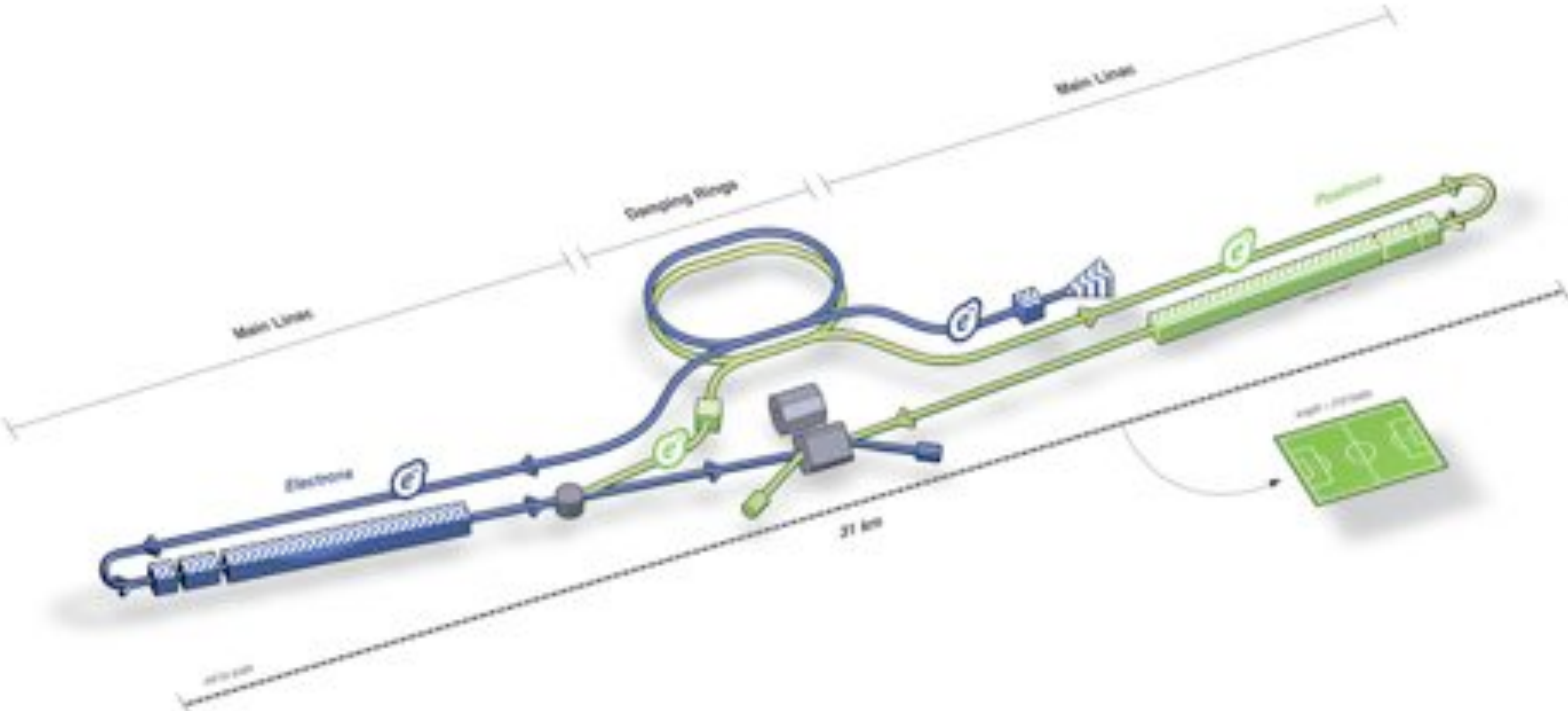
- Superconducting RF has small dissipation losses in cavity walls
- ⇒ long pulses (~1ms) with large bunch spacing



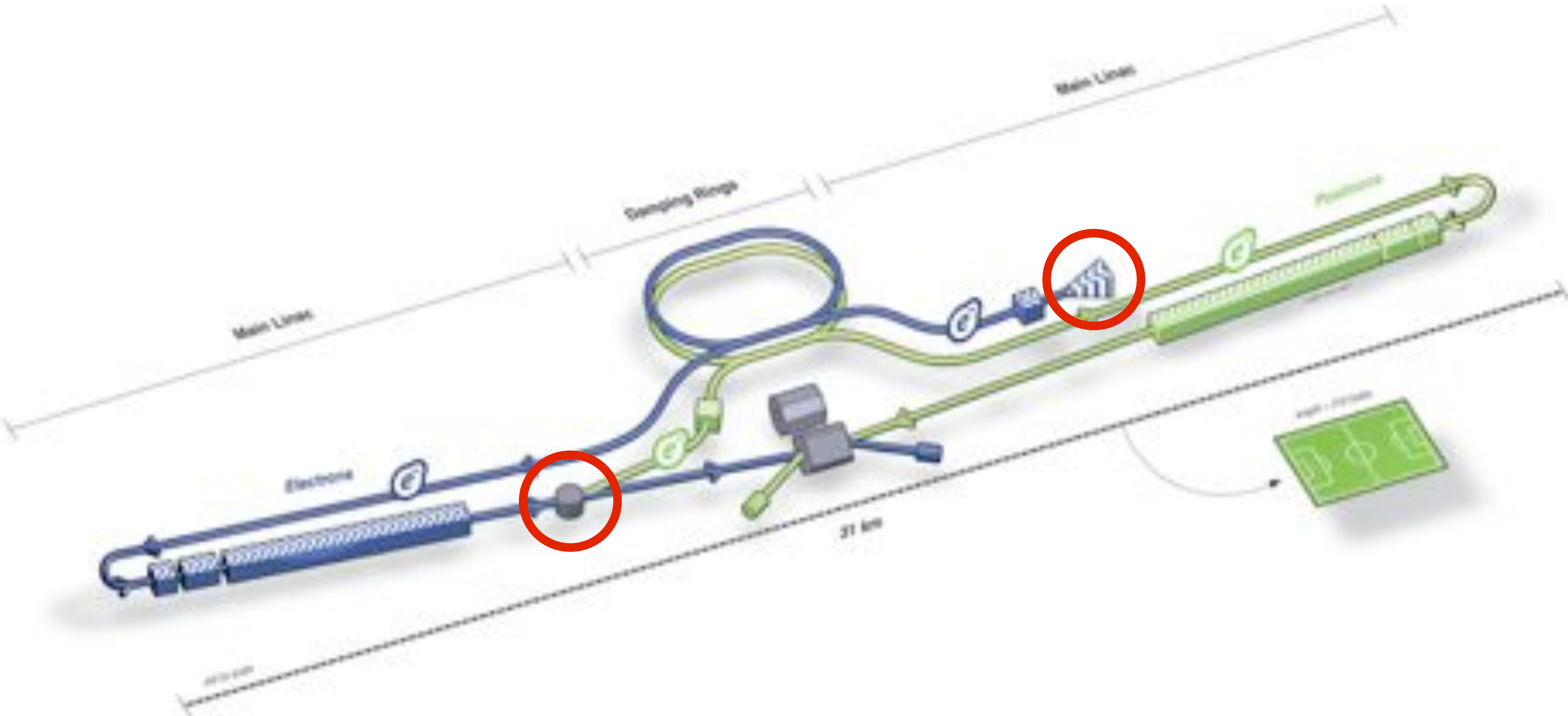
ILC Beam Parameters

Centre-of-mass energy	E_{CM}	GeV	200	230	250	350	500
Luminosity pulse repetition rate		Hz	5	5	5	5	5
Positron production mode			10 Hz	10 Hz	10 Hz	nom.	nom.
Estimated AC power	P_{AC}	MW	114	119	122	121	163
Bunch population	N	$\times 10^{10}$	2	2	2	2	2
Number of bunches	n_b		1312	1312	1312	1312	1312
Linac bunch interval	Δt_b	ns	554	554	554	554	554
RMS bunch length	σ_z	μm	300	300	300	300	300
Normalized horizontal emittance at IP	$\gamma\epsilon_x$	μm	10	10	10	10	10
Normalized vertical emittance at IP	$\gamma\epsilon_y$	nm	35	35	35	35	35
Horizontal beta function at IP	β_x^*	mm	16	14	13	16	11
Vertical beta function at IP	β_y^*	mm	0.34	0.38	0.41	0.34	0.48
RMS horizontal beam size at IP	σ_x^*	nm	904	789	729	684	474
RMS vertical beam size at IP	σ_y^*	nm	7.8	7.7	7.7	5.9	5.9
Vertical disruption parameter	D_y		24.3	24.5	24.5	24.3	24.6
Fractional RMS energy loss to beamstrahlung	δ_{BS}	%	0.65	0.83	0.97	1.9	4.5
Luminosity	L	$\times 10^{34}$ cm^{-2} s^{-1}	0.56	0.67	0.75	1.0	1.8
Fraction of L in top 1% E_{CM}	$L_{0.01}$	%	91	89	87	77	58
Electron polarisation	P_-	%	80	80	80	80	80
Positron polarisation	P_+	%	30	30	30	30	30
Electron relative energy spread at IP	$\Delta p/p$	%	0.20	0.19	0.19	0.16	0.13
Positron relative energy spread at IP	$\Delta p/p$	%	0.19	0.17	0.15	0.10	0.07

Sources

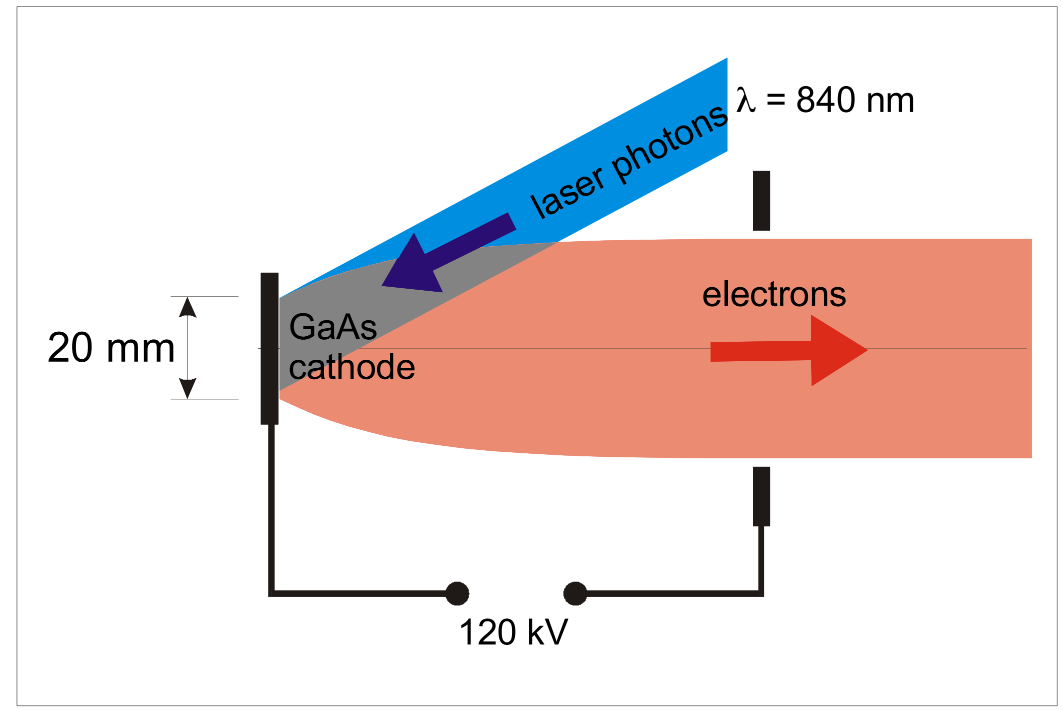

Main Linac
Damping Rings
Main Linac
Positrons
Electrons
31 km

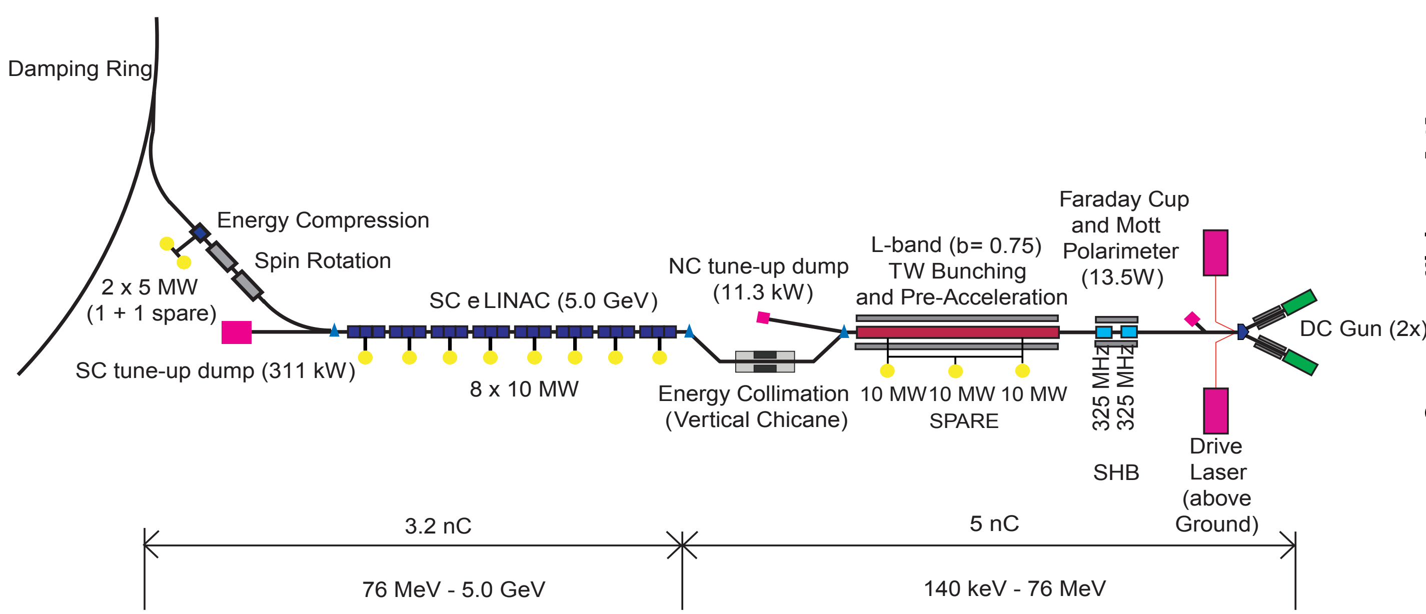
Sources

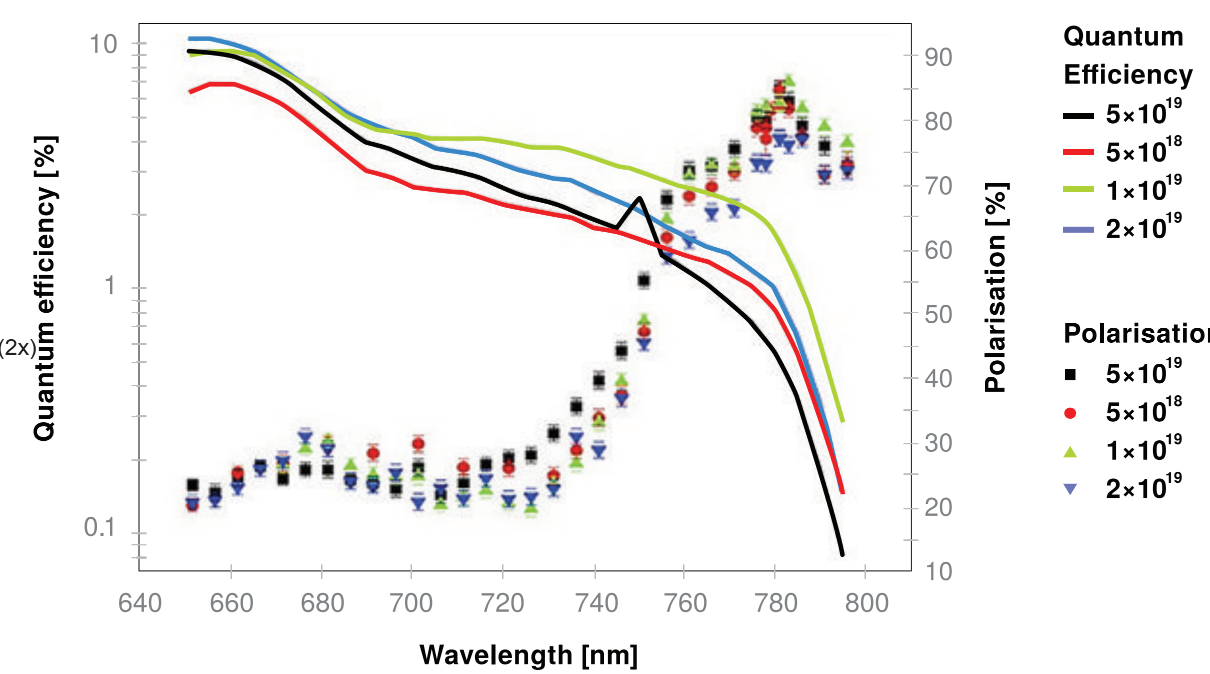


Electron Source

- Laser driven photo injector based on SLC design
- Circular polarised photons on GaAs cathode produce longitudinal polarised electrons
- very high vacuum requirements to protect cathode from impurities and ion backdrift
- 140 keV electron energy at exit
- 1ns bunch length at 2 MHz
- ~5 nC/ns peak current

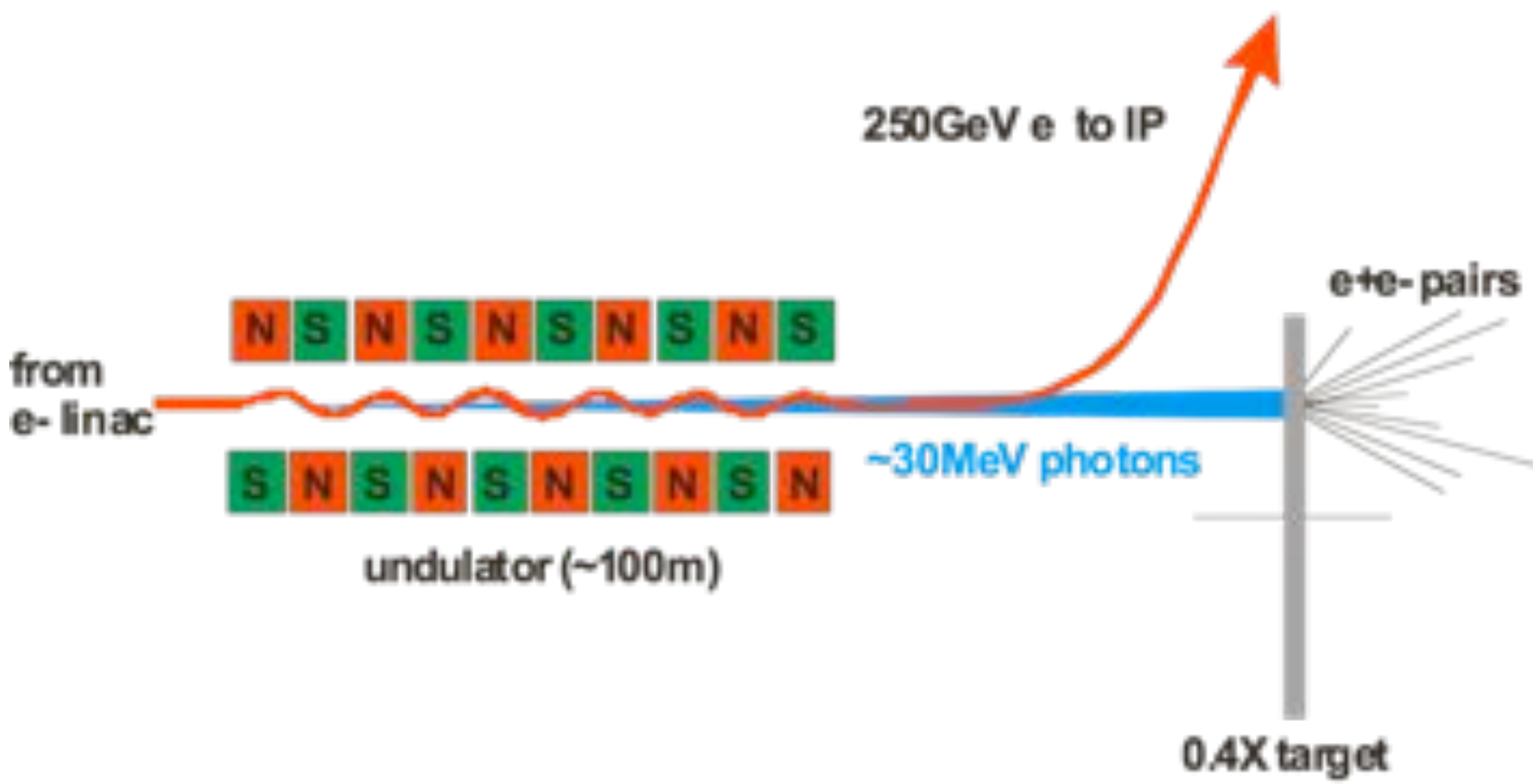




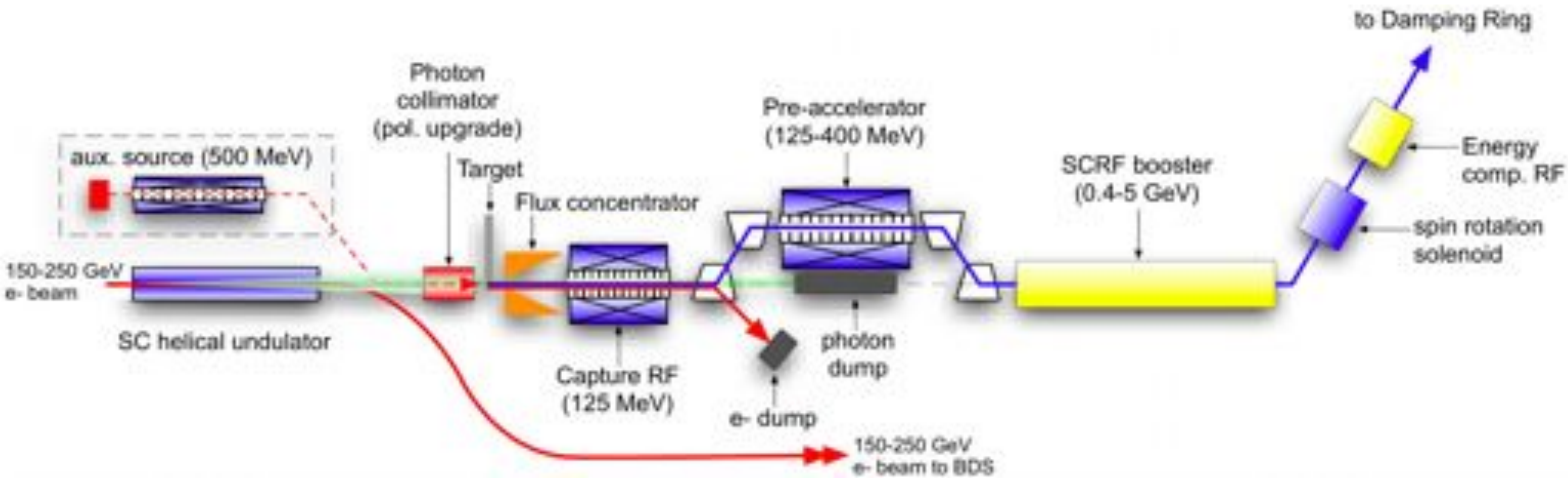


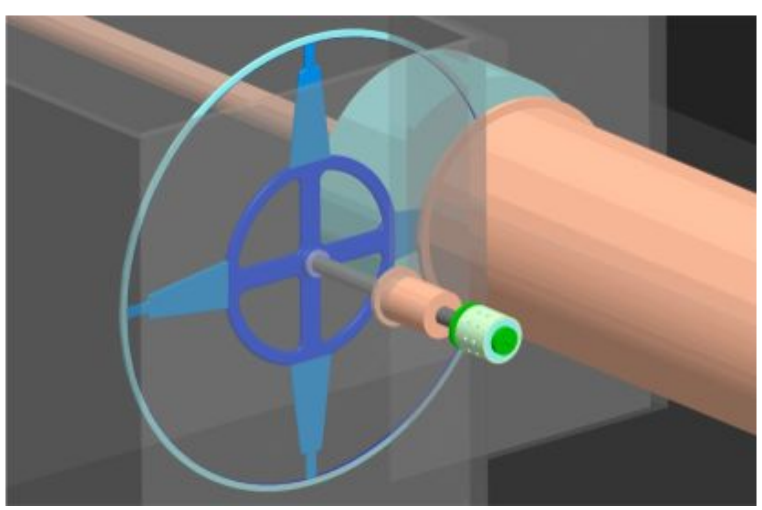
Positron Source

- Production of $e^{\pm}$ pairs from 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



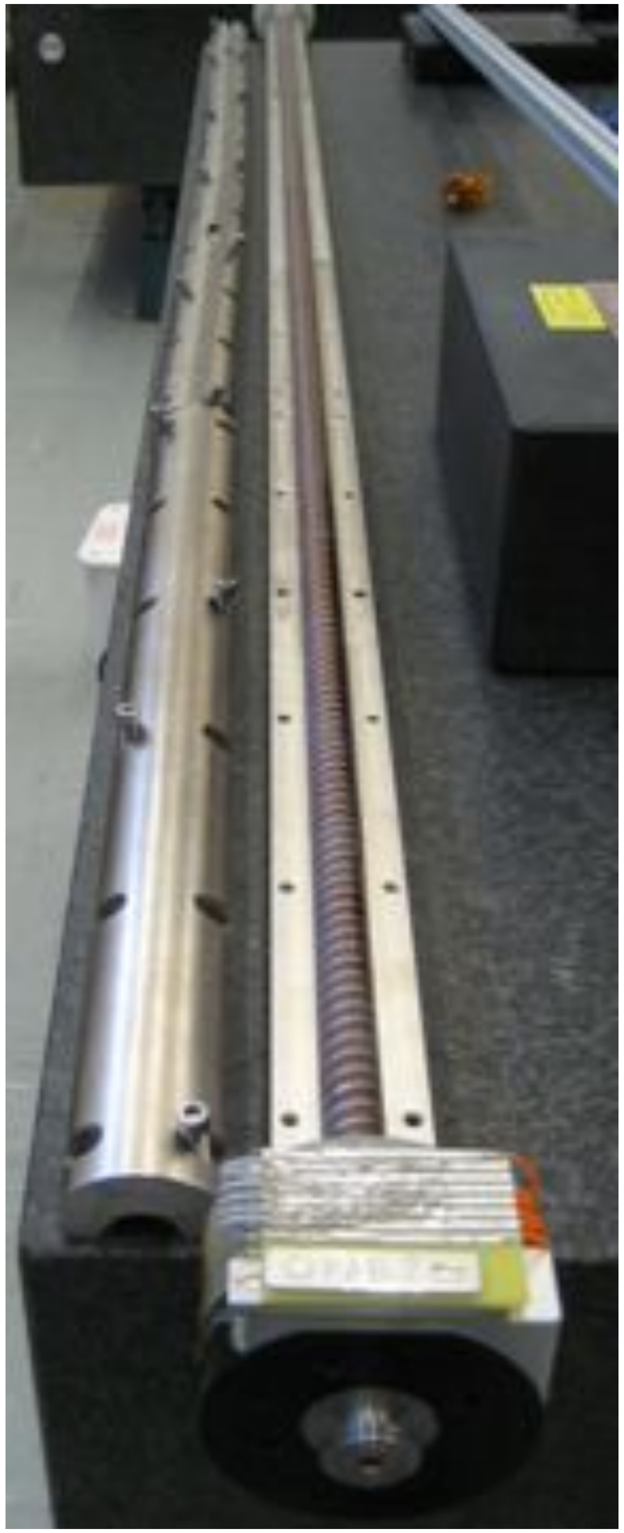
Positron Source Design



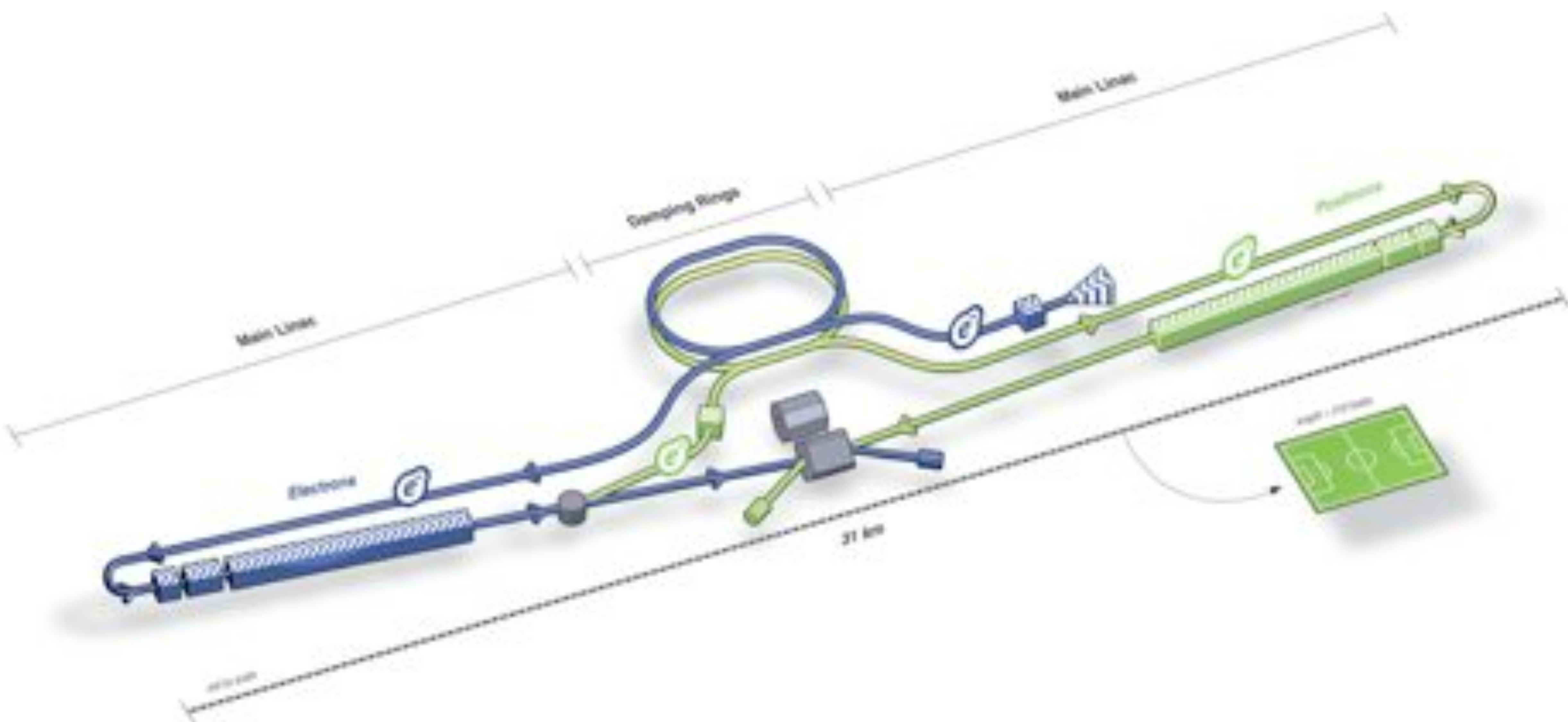


Positrons/bunch	2 x 10^{10}
Undulator length	147 m
Undulator period	1.15 cm
Photon energy	10-40 MeV
Positron polarisation	~30%

Positron Source Prototyping

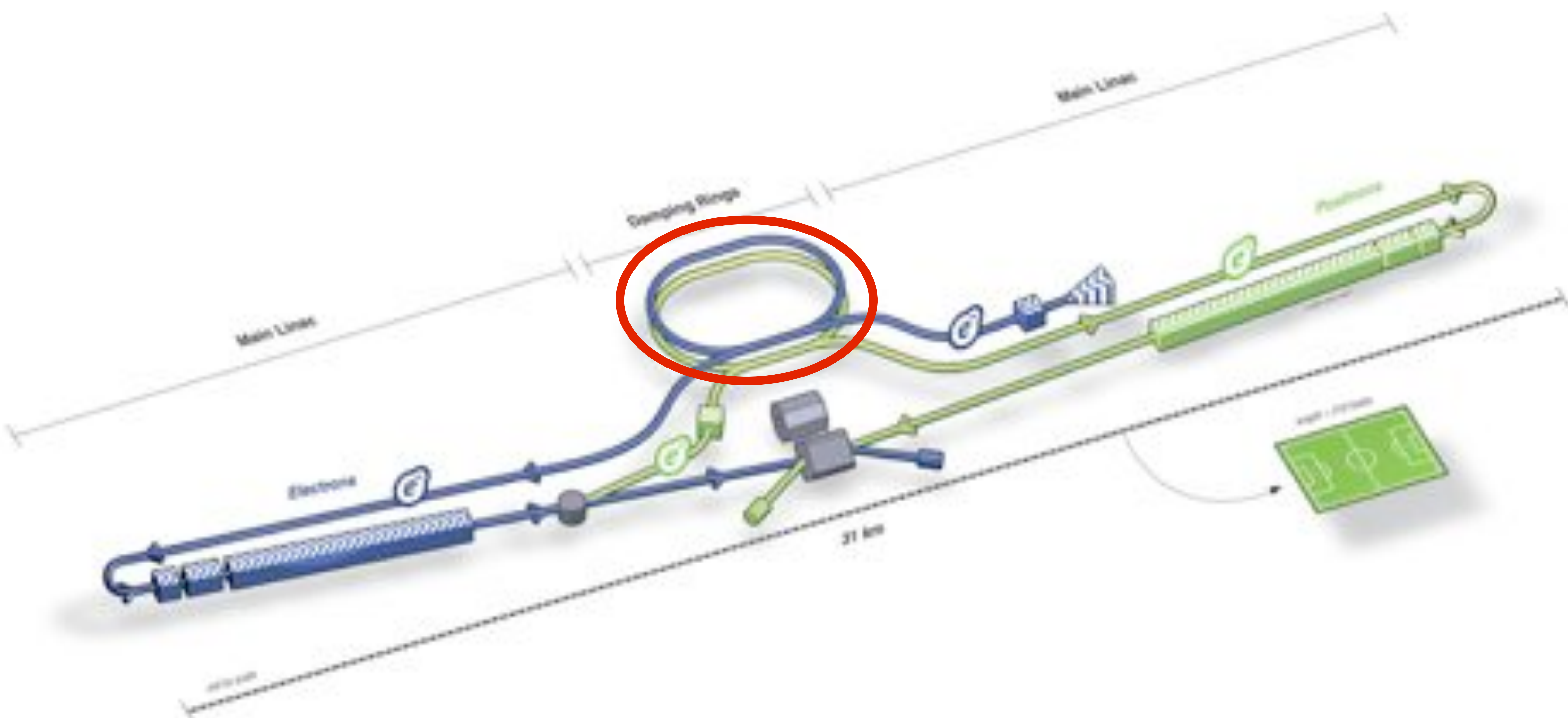


Damping Rings



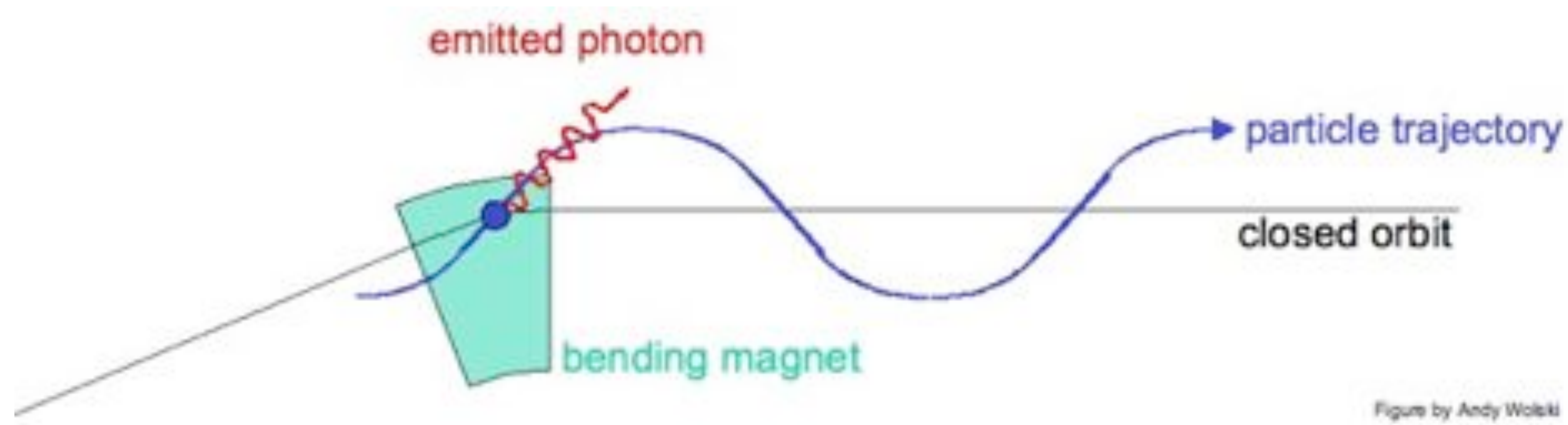
ILC Schema | © www.form-one.de

Damping Rings

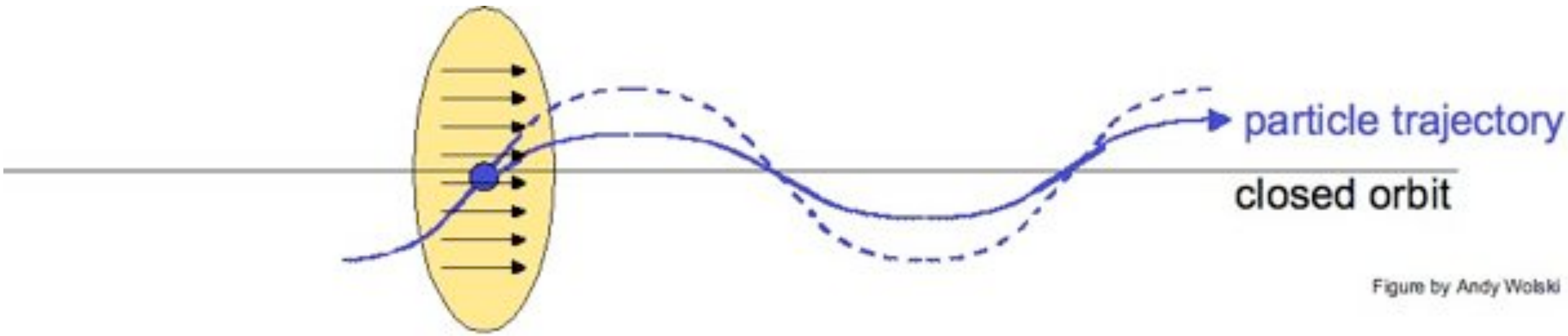


Damping Rings Purpose

- Emittance of beams from the sources are orders of magnitudes too big
- Beams need to be cooled
- Use synchrotron radiation in damping rings to cool beams
  - Particles lose longitudinal and transverse momentum
  - replenish only longitudinal momentum

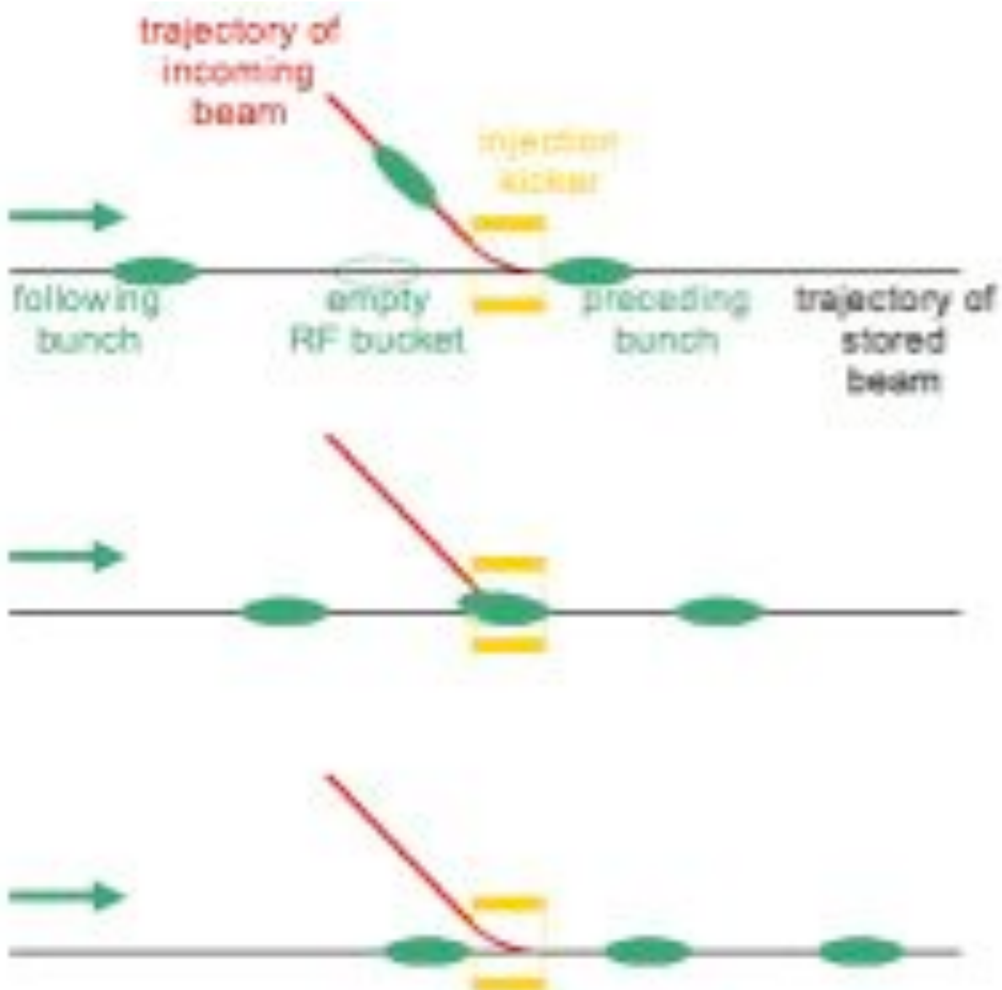


Damping Rings

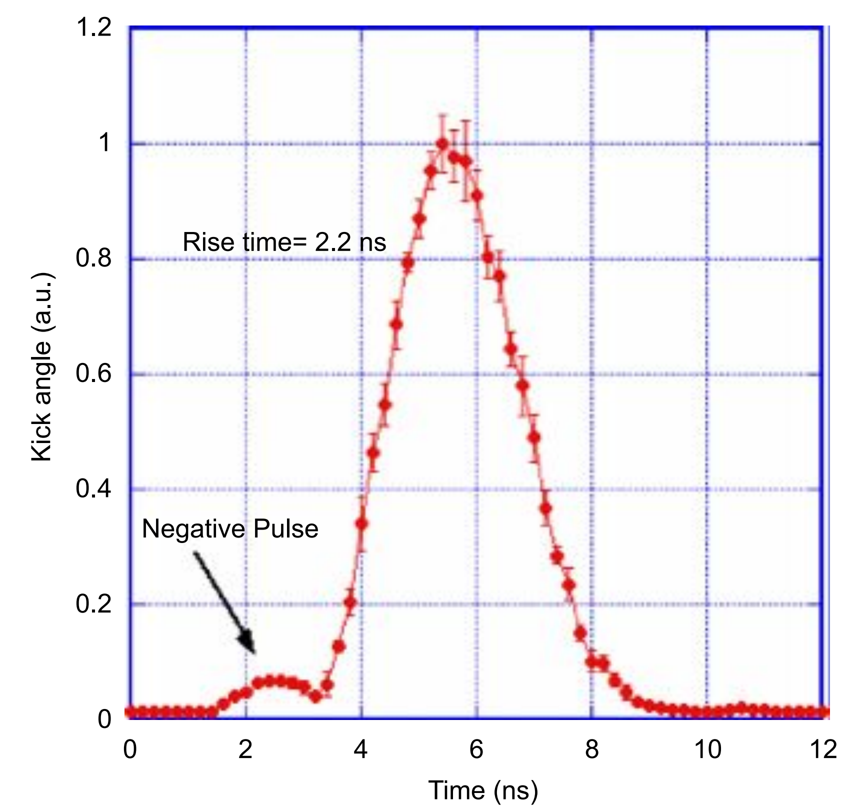


- RF system in damping rings accelerates beam particles in longitudinal direction
- Interplay between radiation and RF reduces transverse emittance!
- Typical damping times are of order 100 ms
  - Linac RD pulse length is 1ms!
  - Whole bunch train (200 km @ 560 ns) needs to be stored in a damping ring O(3 km)!
  - Bunch train, i.e. bunch-bunch spacing, needs to be compressed in damping ring

DR Injection/Extraction



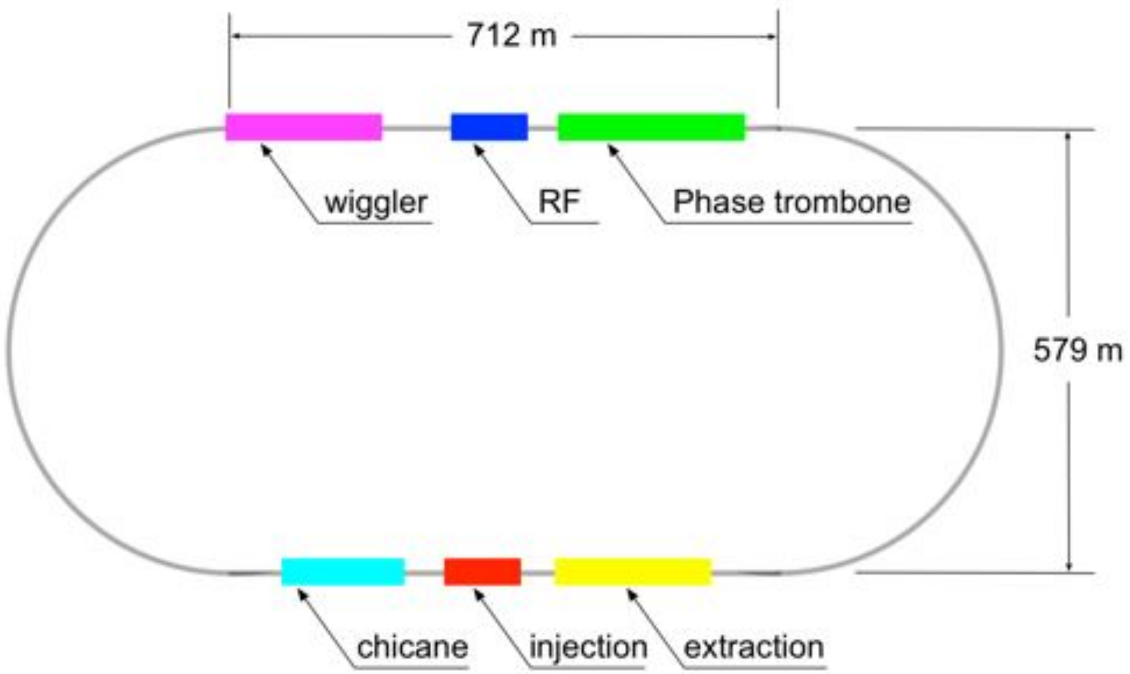
1. Kicker is off. "Preceding" bunch exits kicker electrodes. Kicker starts to turn on.
2. Kicker is on. "Incoming" bunch is deflected by kicker. Kicker starts to turn off.
3. Kicker is off by the time the following bunch reaches the kicker.

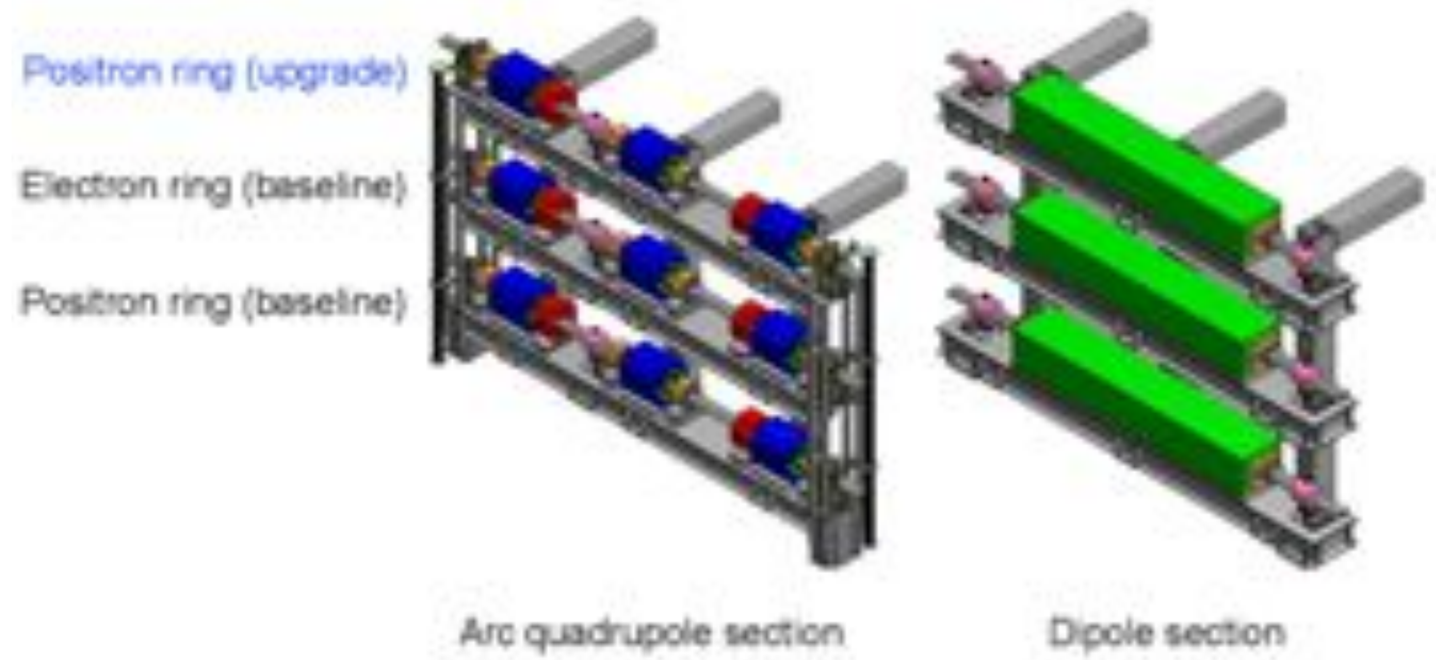


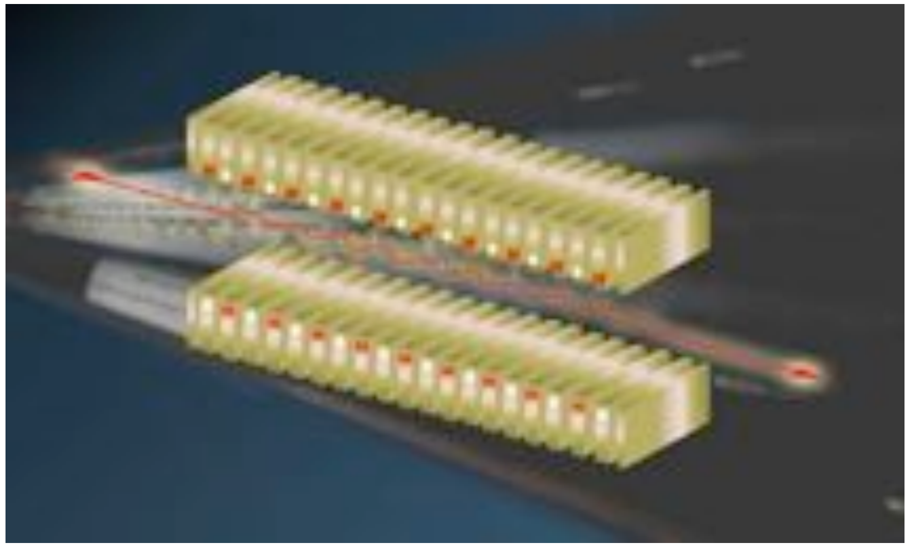
T. Naito et al., NIM A 571 (2007) 559

Slide by Andy Wolski

ILC Damping Ring Design

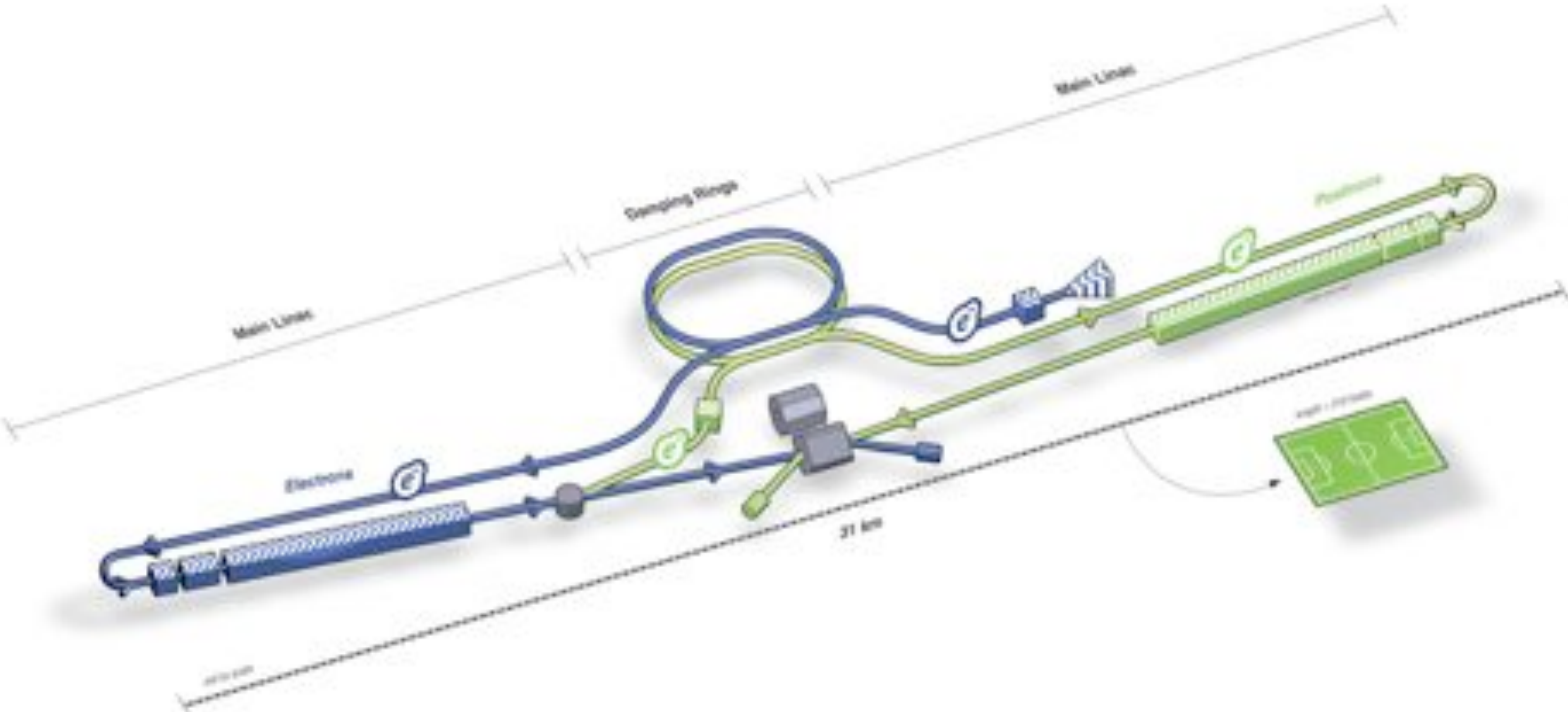




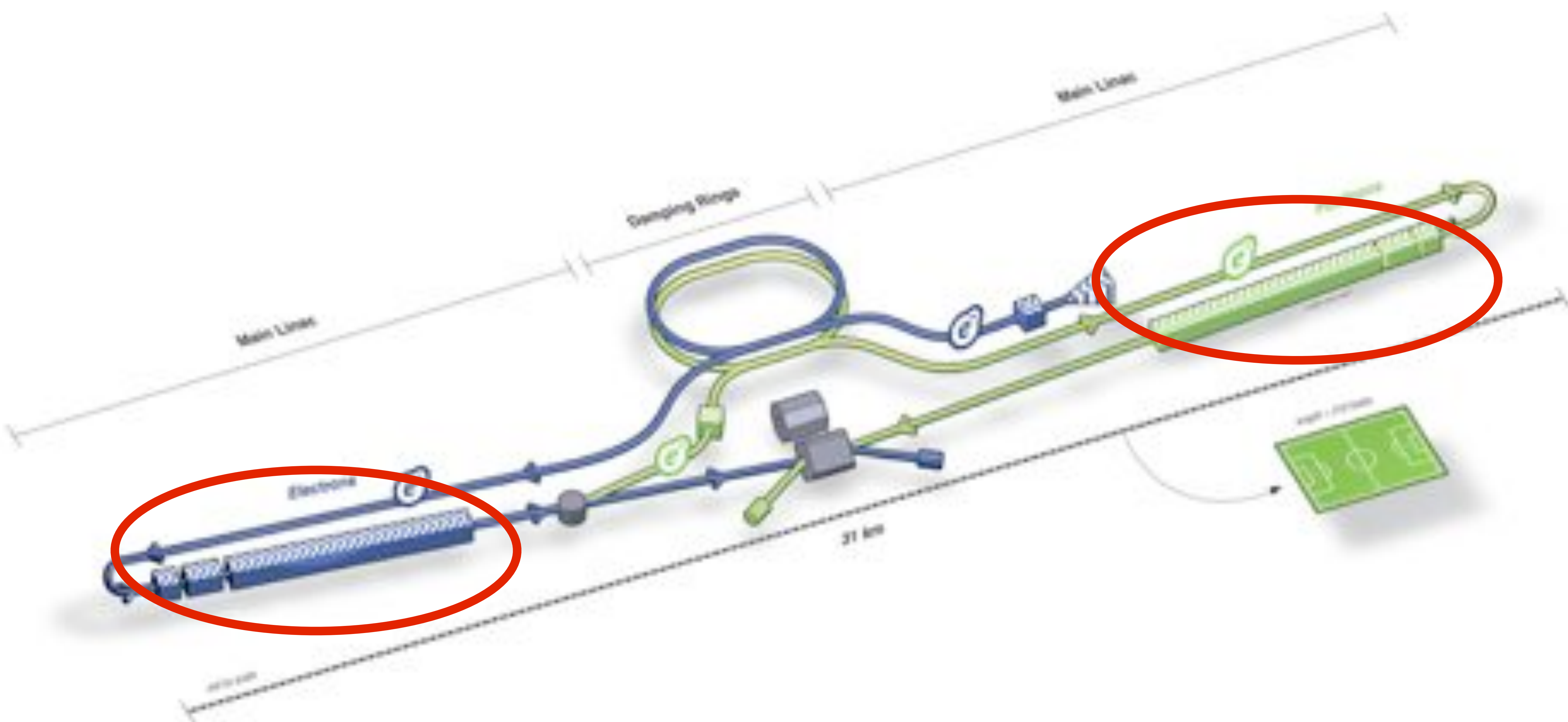


- Damping time by SR from bending magnets too large O(400ms)
- Include damping wigglers in the beam to reduce damping time to ~25ms

Main Linacs

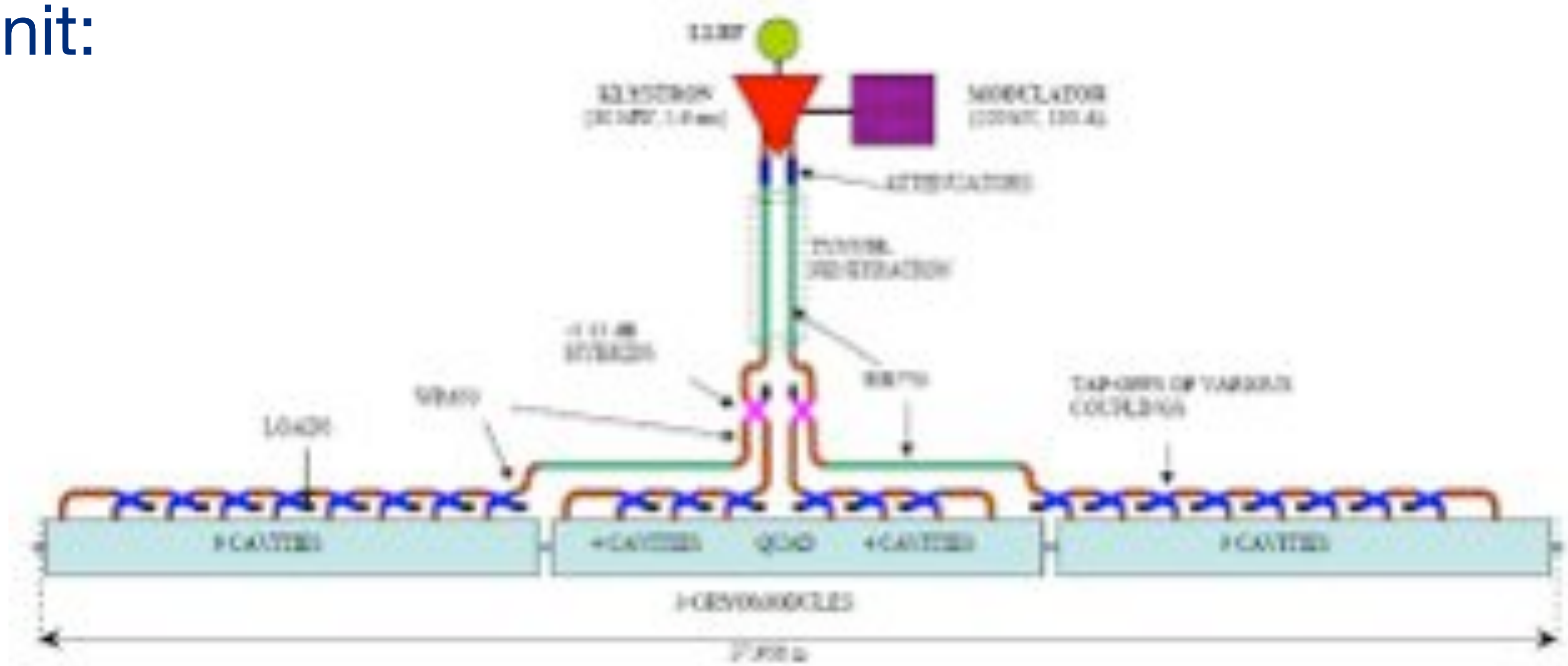

Main Linac
Damping Rings
Main Linac
Positrons
Electrons
31 km

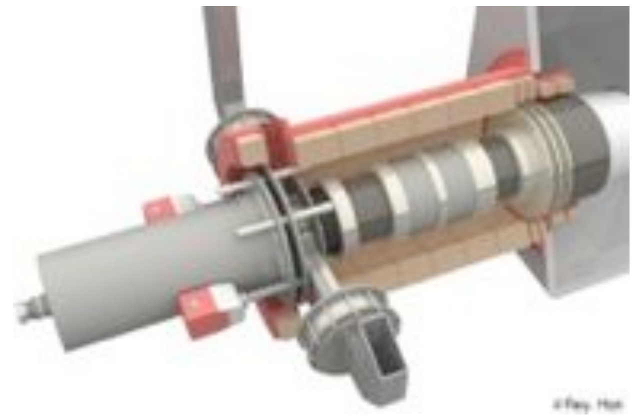
Main Linacs



Main Linac Components

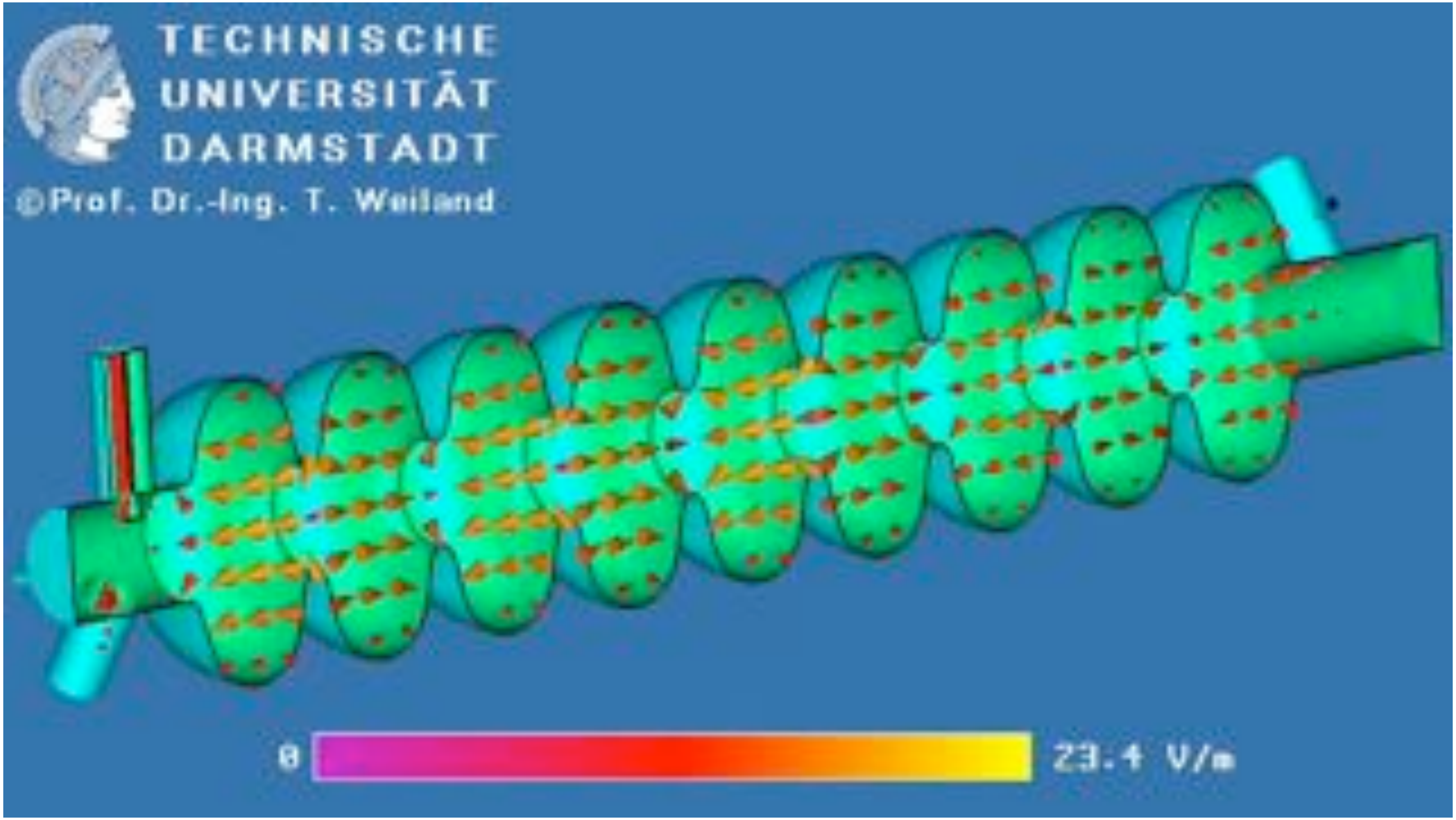
- One RF Unit:





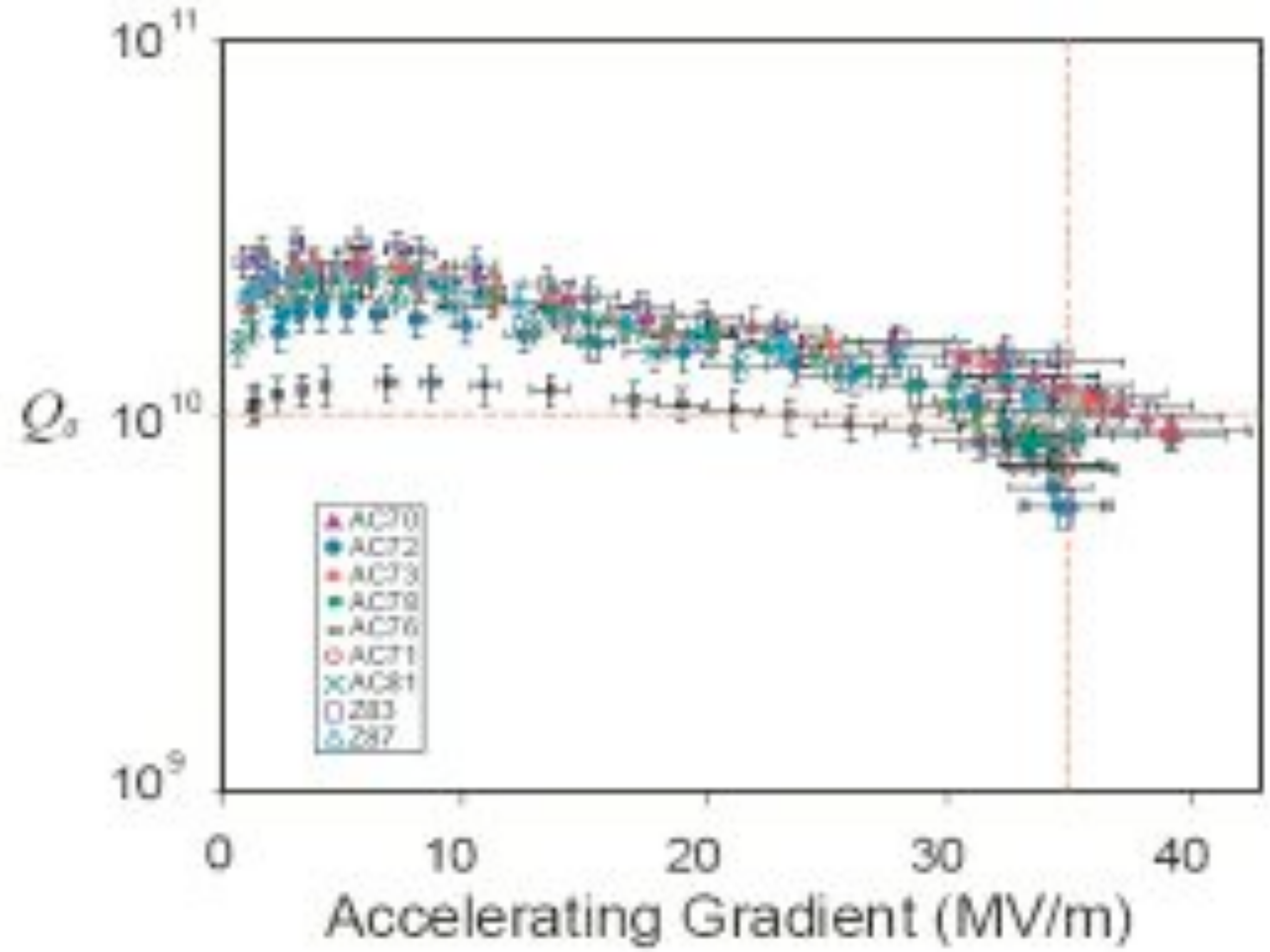
SCRF Cavities

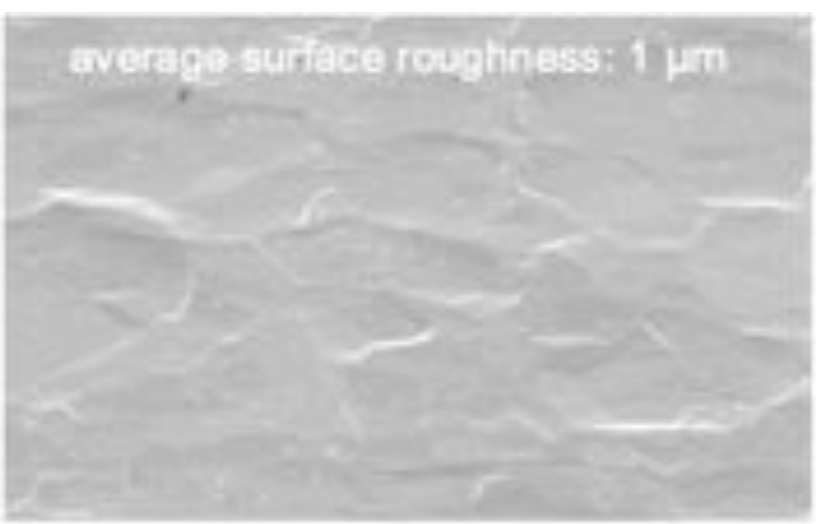
RF Field Simulation



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





buffered chemical polishing

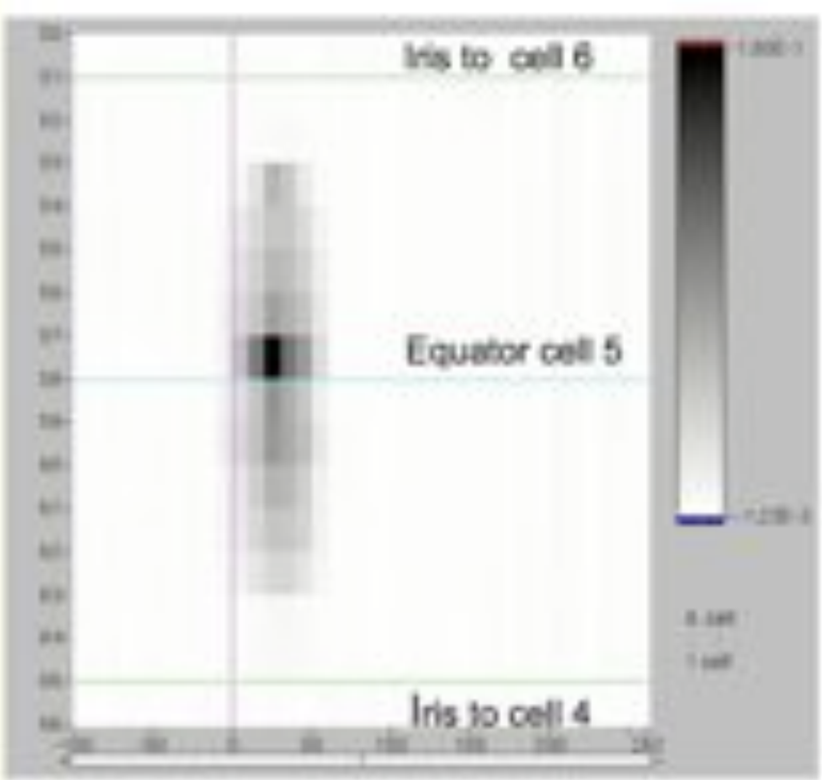
electrolytic polishing

Q Factor

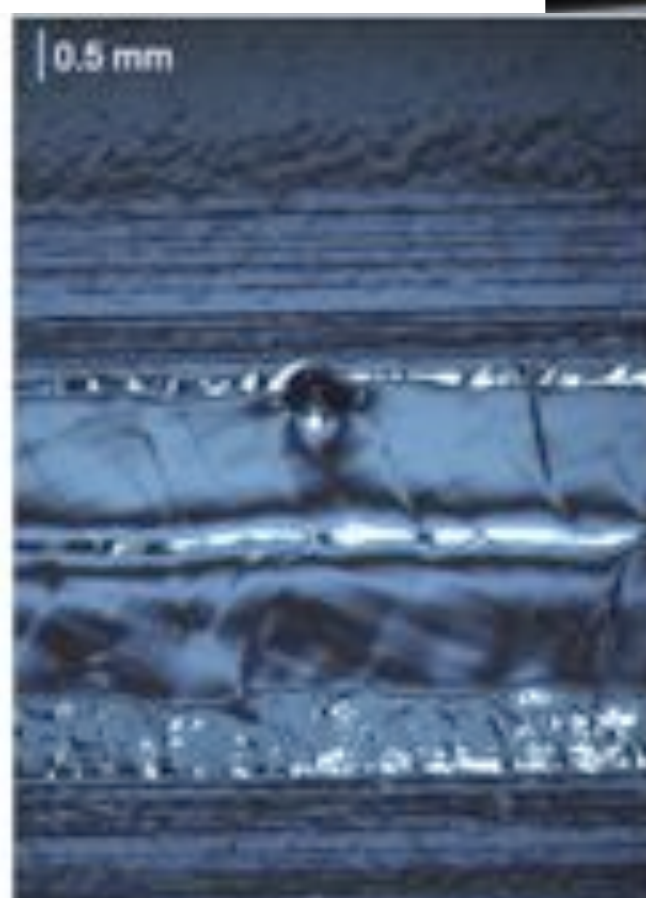
- Superconducting cavity:
  - surface resistance ~0
  - $Q_0 \sim 1/\delta$
  - $Q_0 > 10^{10}$
  - decay times of seconds even at 1.3 GHz
- A church bell (300 Hz) with $Q_0 = 5 \times 10^{10}$ would ring – once excited – longer than one year!

Cavity Diagnostics

- Quality control and assurance
- Need 18.000 9 cell cavities for ILC
- Yield of 80% means to throw away 3600....
- Identifiying and reprocessing defunct cavities might help

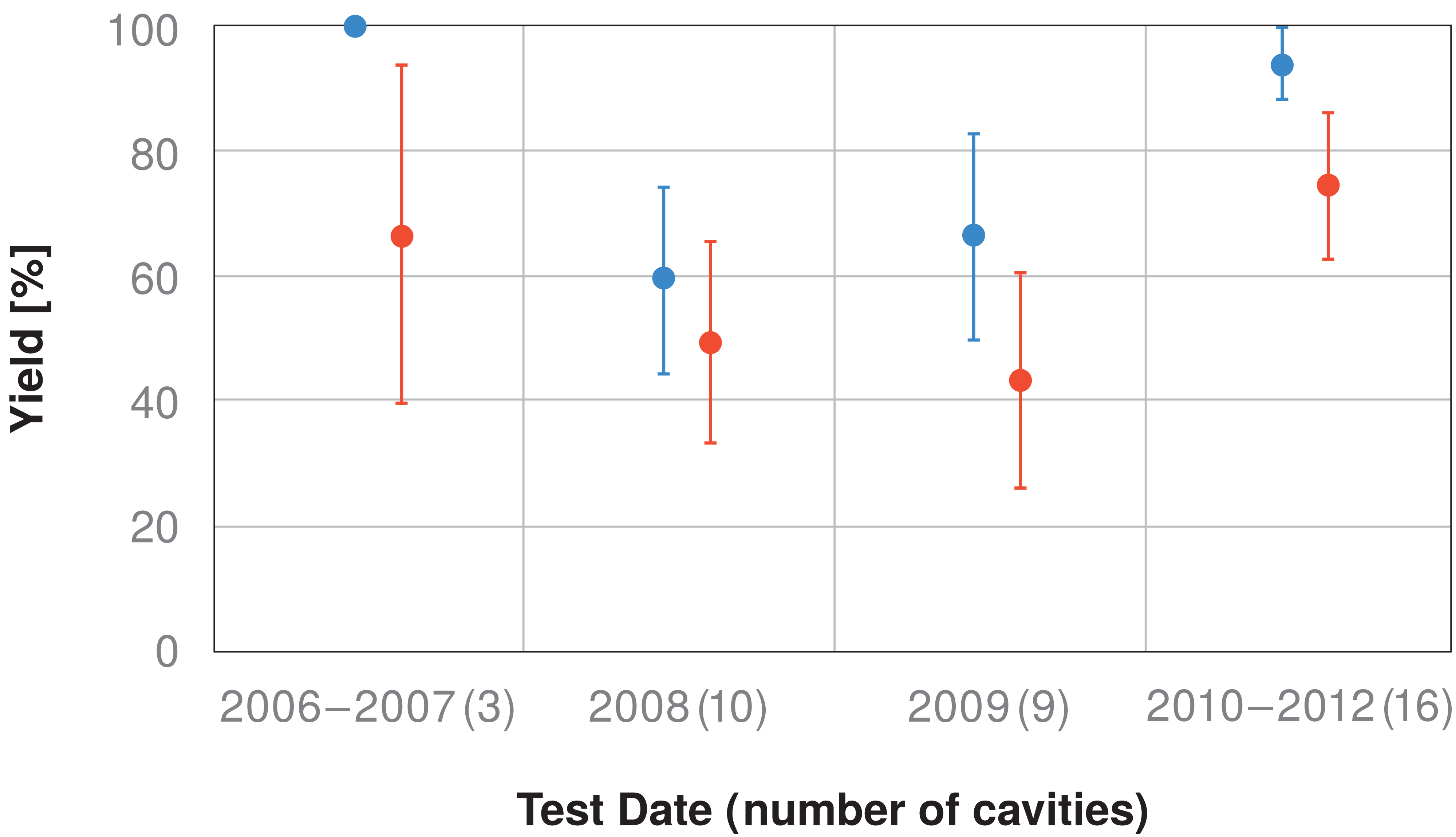


Z130: Quench in 3π/9-mode at 22 MV/m



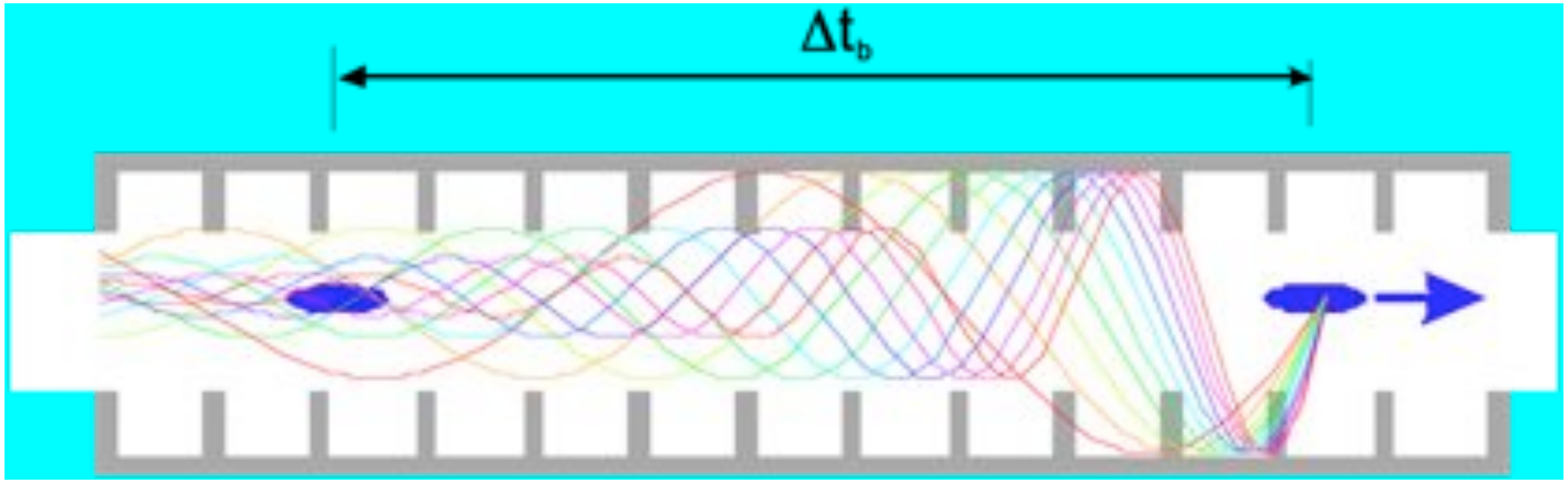
Picture at same location

Cavity Production Yield



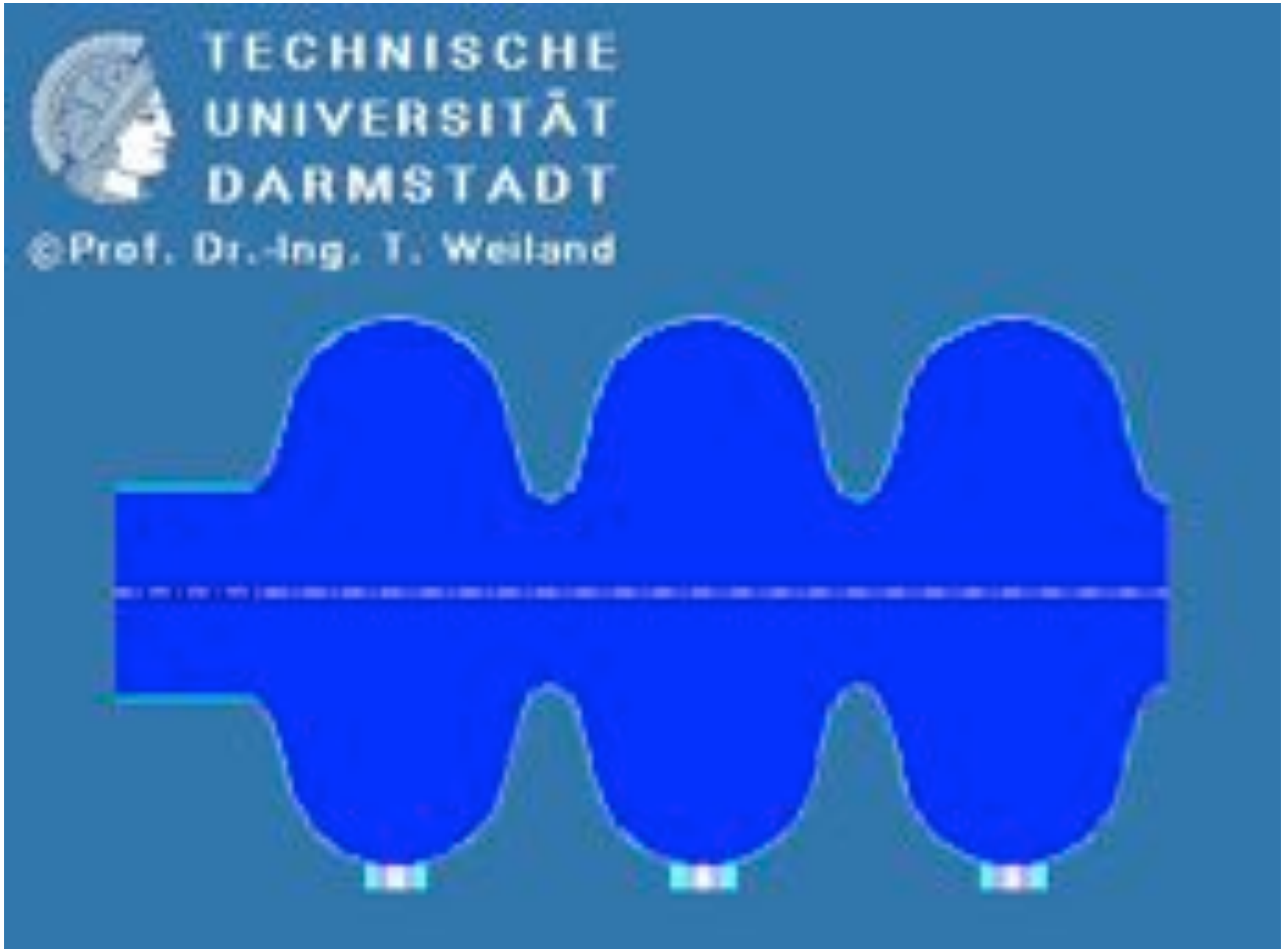
Transverse Wakefields

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

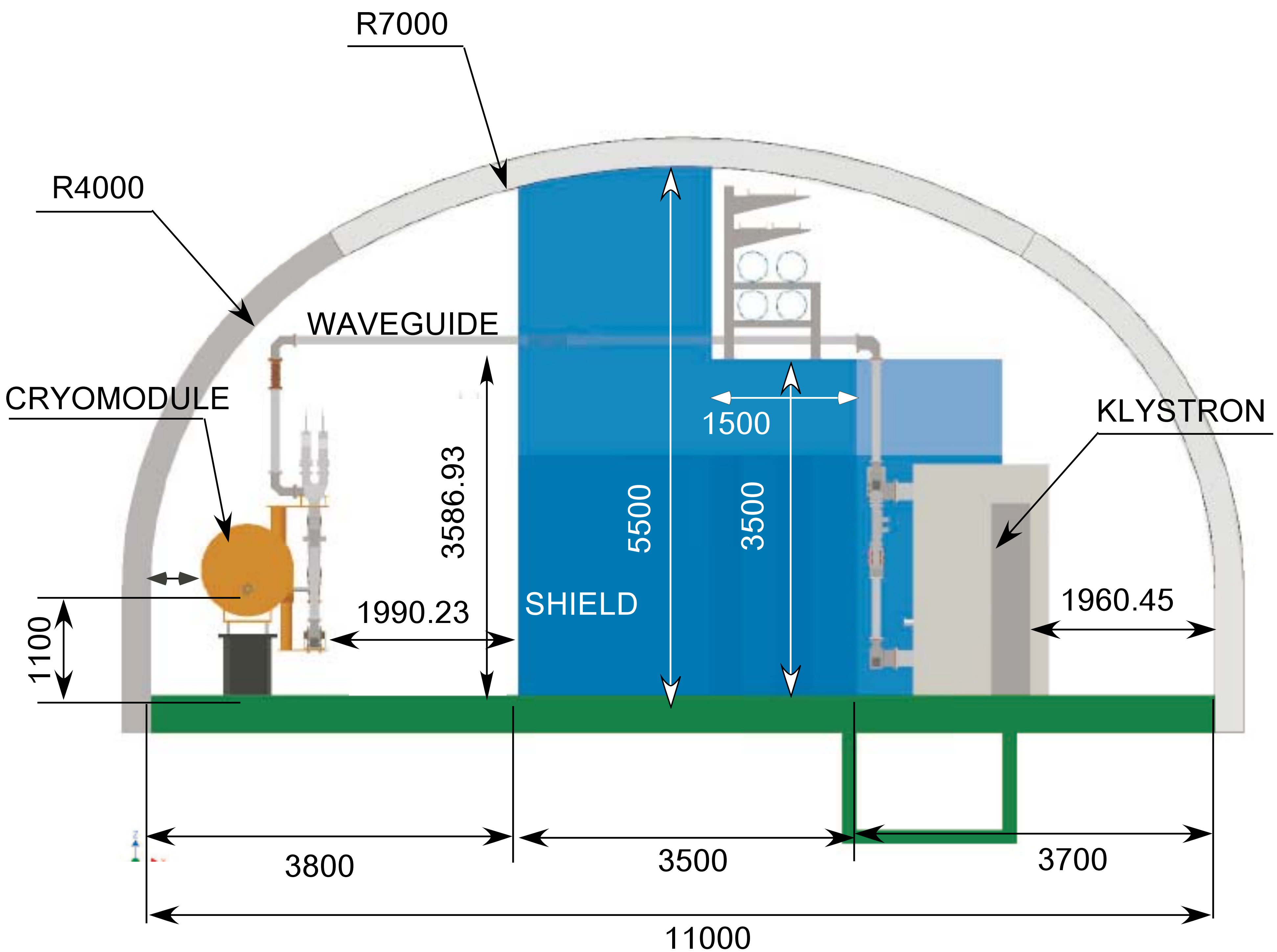


- Fields build up resonantly and kick later bunches transversely
- Dilutes Emittance!

Wakefield Simulation

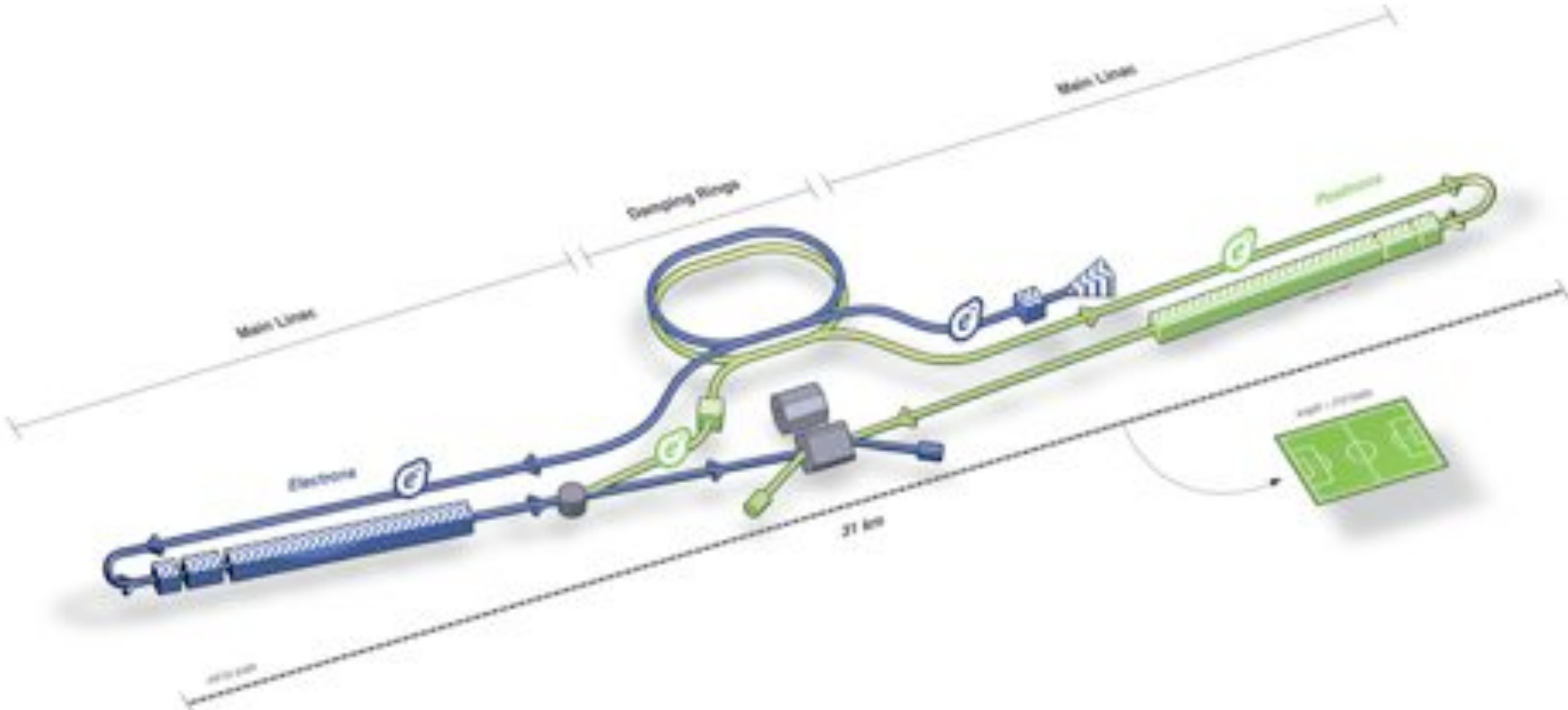


Tunnel Profile

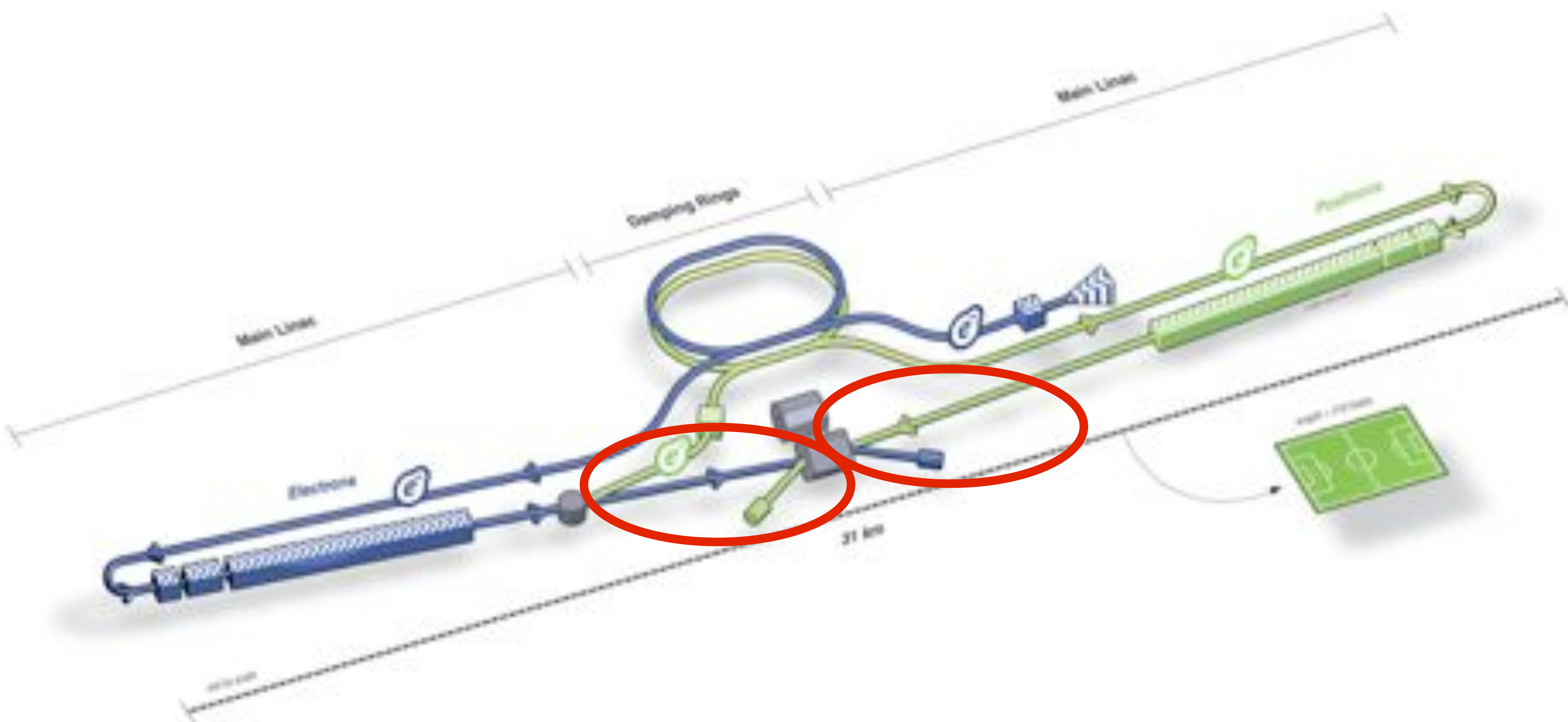


Tunnel View (Simulation)

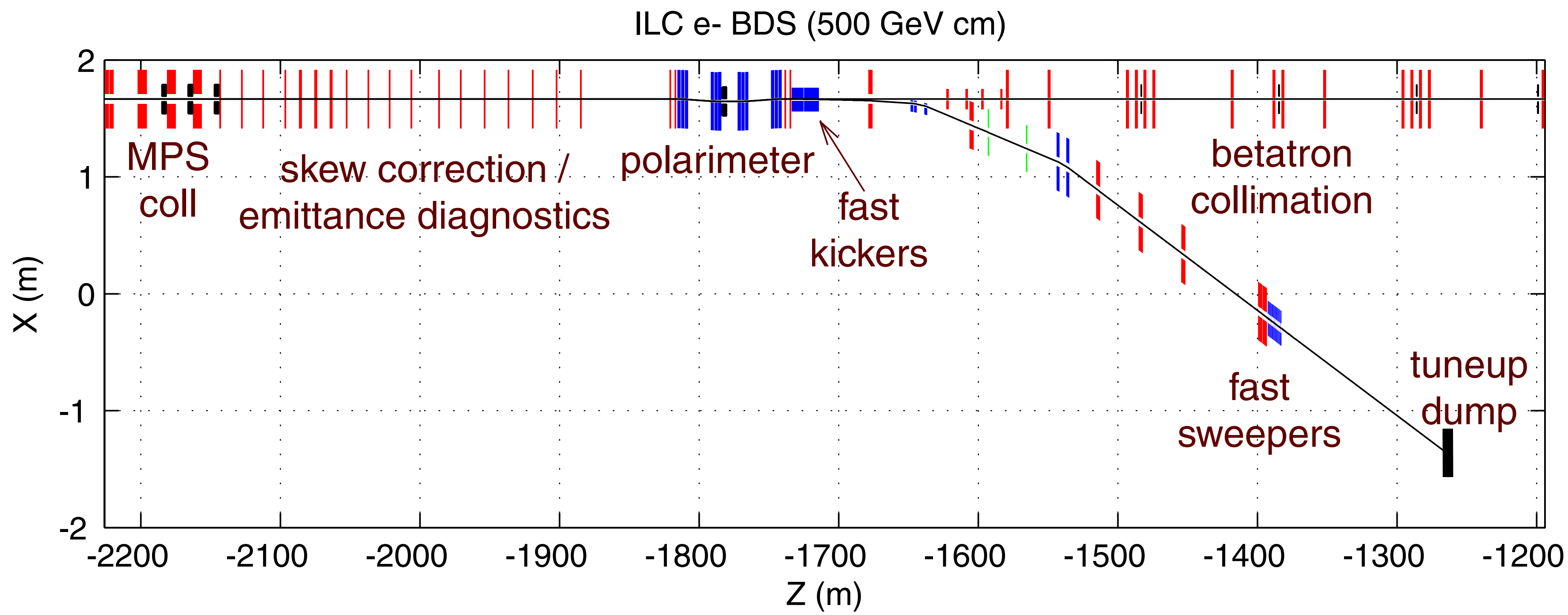
Beam Delivery Systems

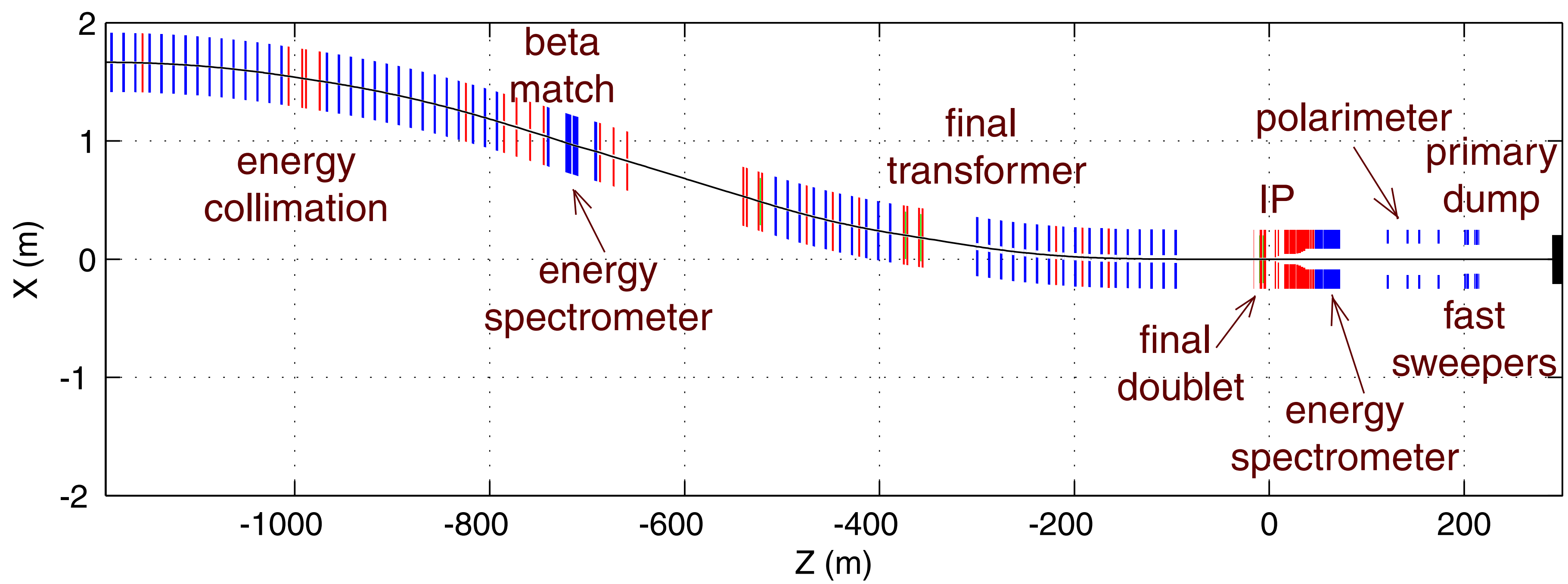


Beam Delivery Systems



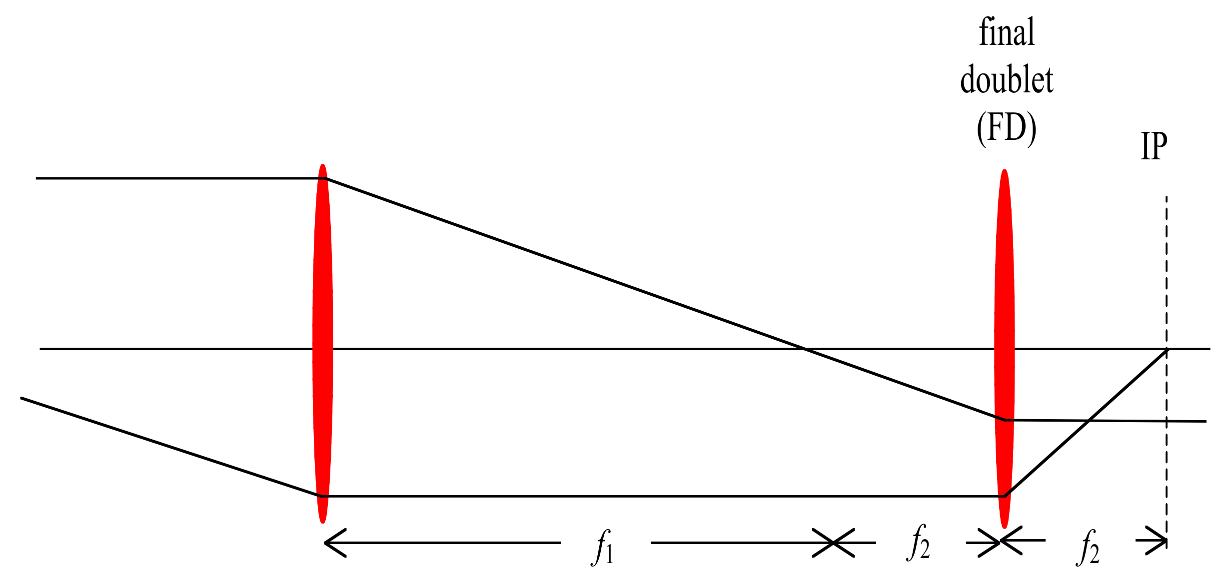
BDS Optics

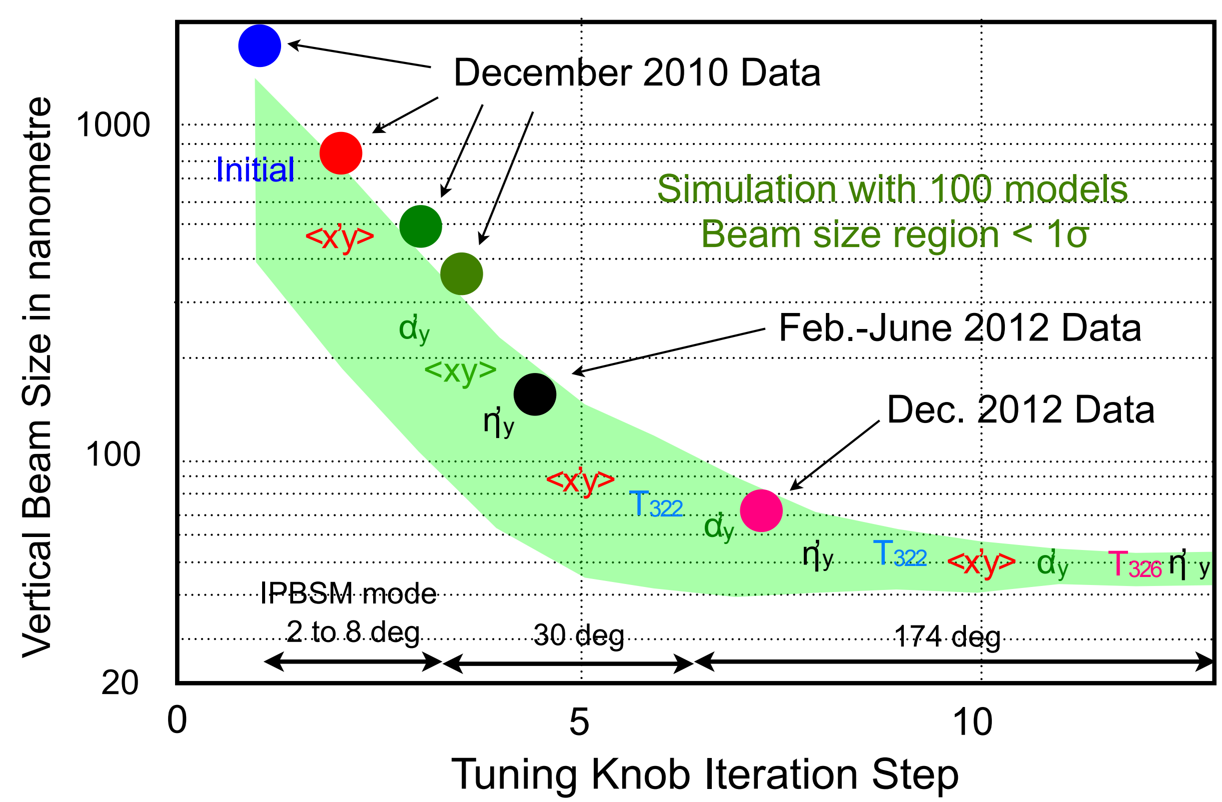

ILC e- BDS (500 GeV cm)
X (m)
Z (m)
2
1
0
-1
-2
-2200
-2100
-2000
-1900
-1800
-1700
-1600
-1500
-1400
-1300
-1200
MPS coll
skew correction / emittance diagnostics
polarimeter
fast kickers
betatron collimation
fast sweepers
tuneup dump


X (m)
Z (m)
2
1
0
-1
-2
-1000
-800
-600
-400
-200
0
200
energy collimation
beta match
energy spectrometer
final transformer
IP
polarimeter
primary dump
final doublet
energy spectrometer
fast sweepers

Final Focus

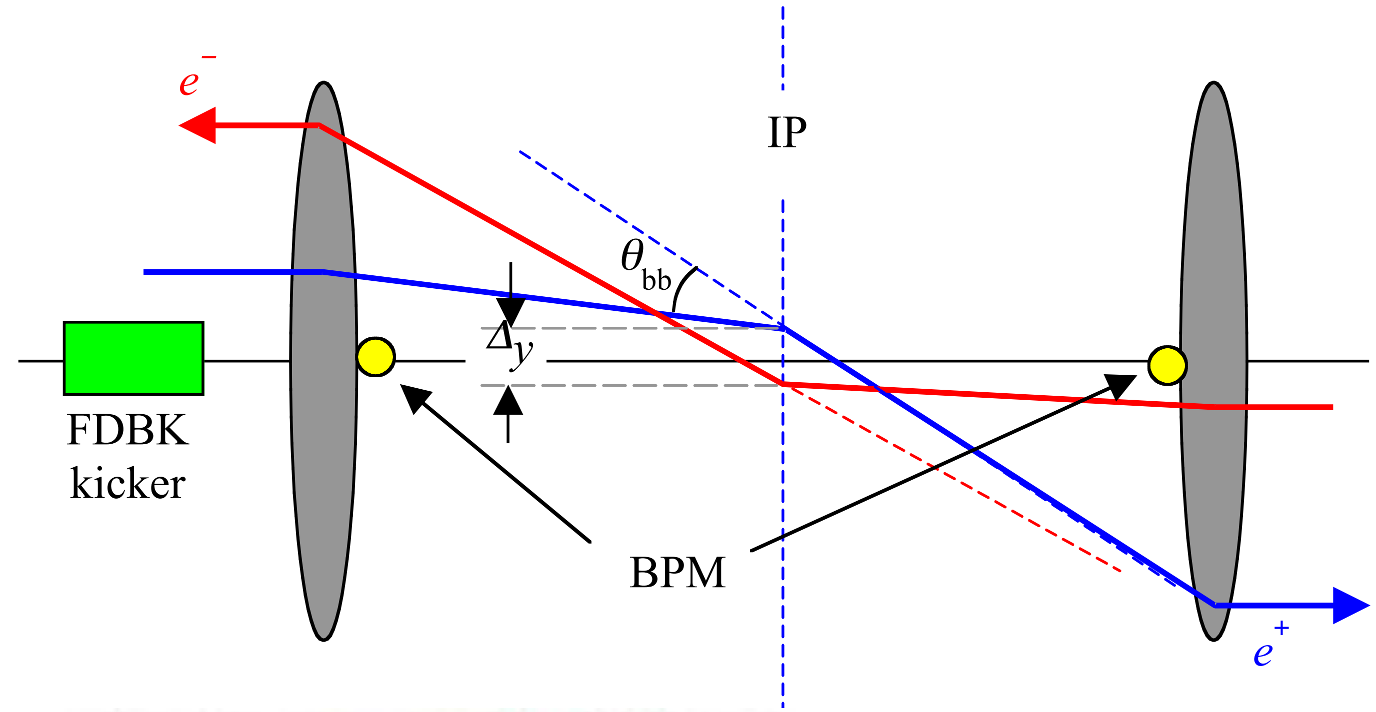
- Use telescope optics to de-magnify beam by factor $m = f_1/f_2$
  - typically m=300
  - f2 = 3m ⇒ f1 = 900m
- More complicated: corrections for chromatic and geometric abberations
- Final-focus test experiment at ATF2 facility at KEK
  - reached ~64 nm spot size, design is 37 nm
  - on-going work

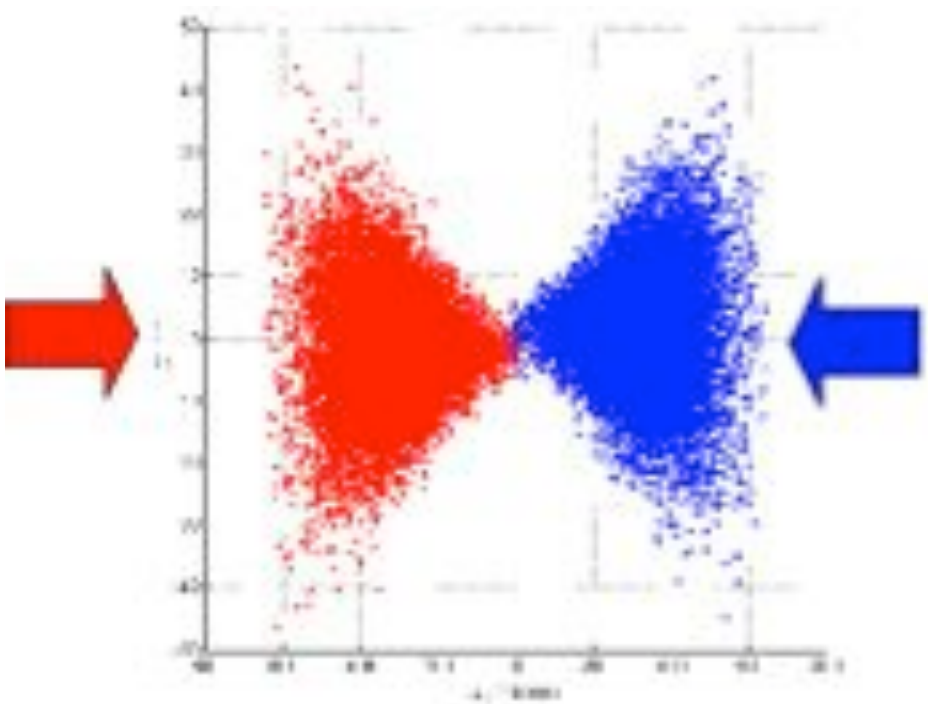


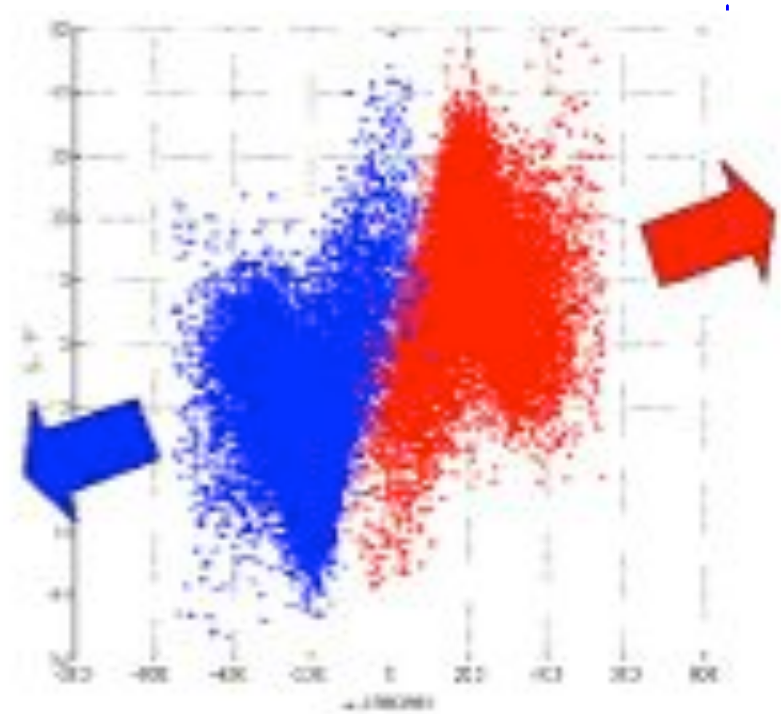


Beam-Beam Orbit Feedback

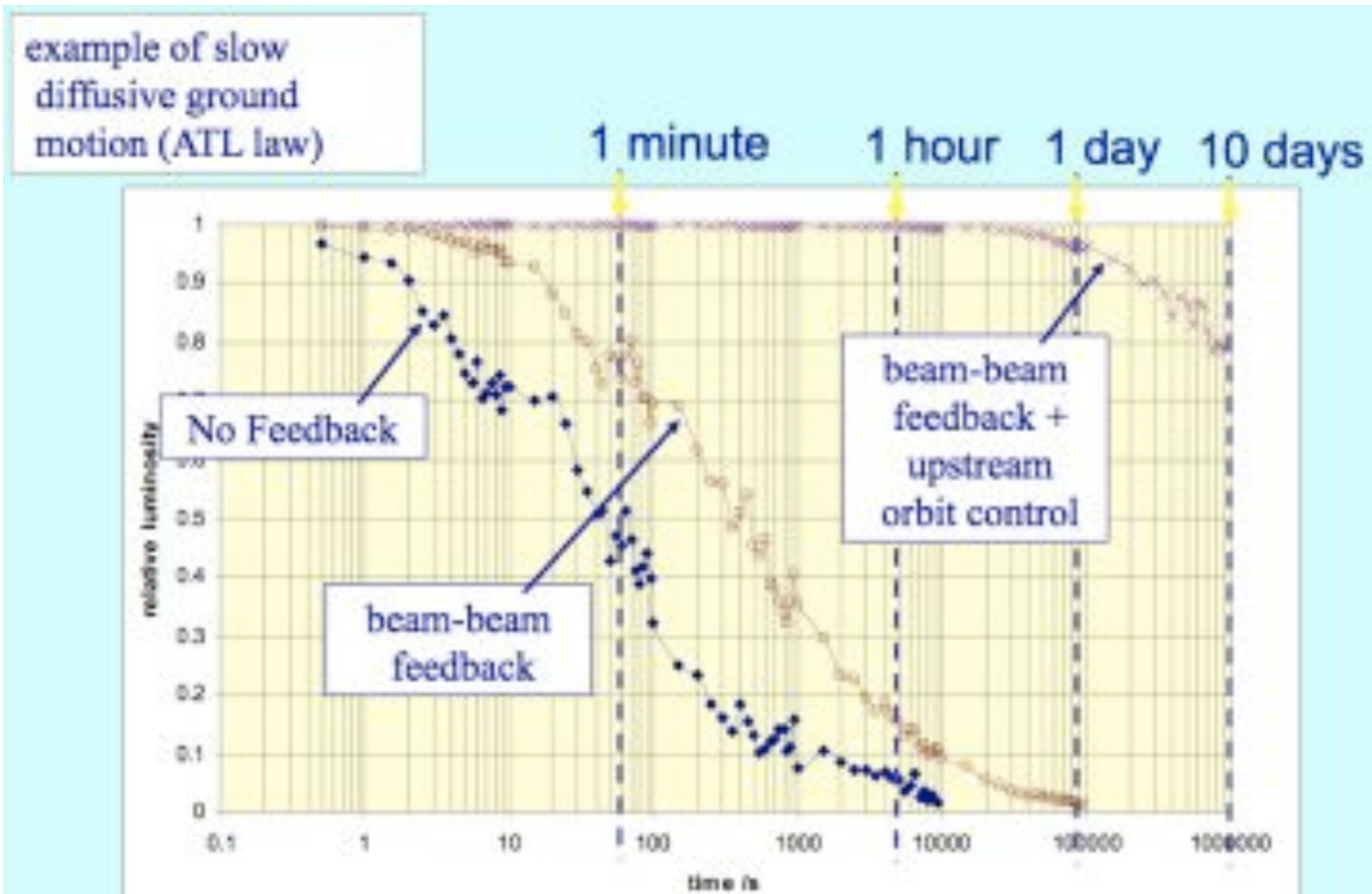
- Beam-beam kick transforms nanometre offsets at the IP to large measurable effects downstream
- Used in feedback system to optimise luminosity



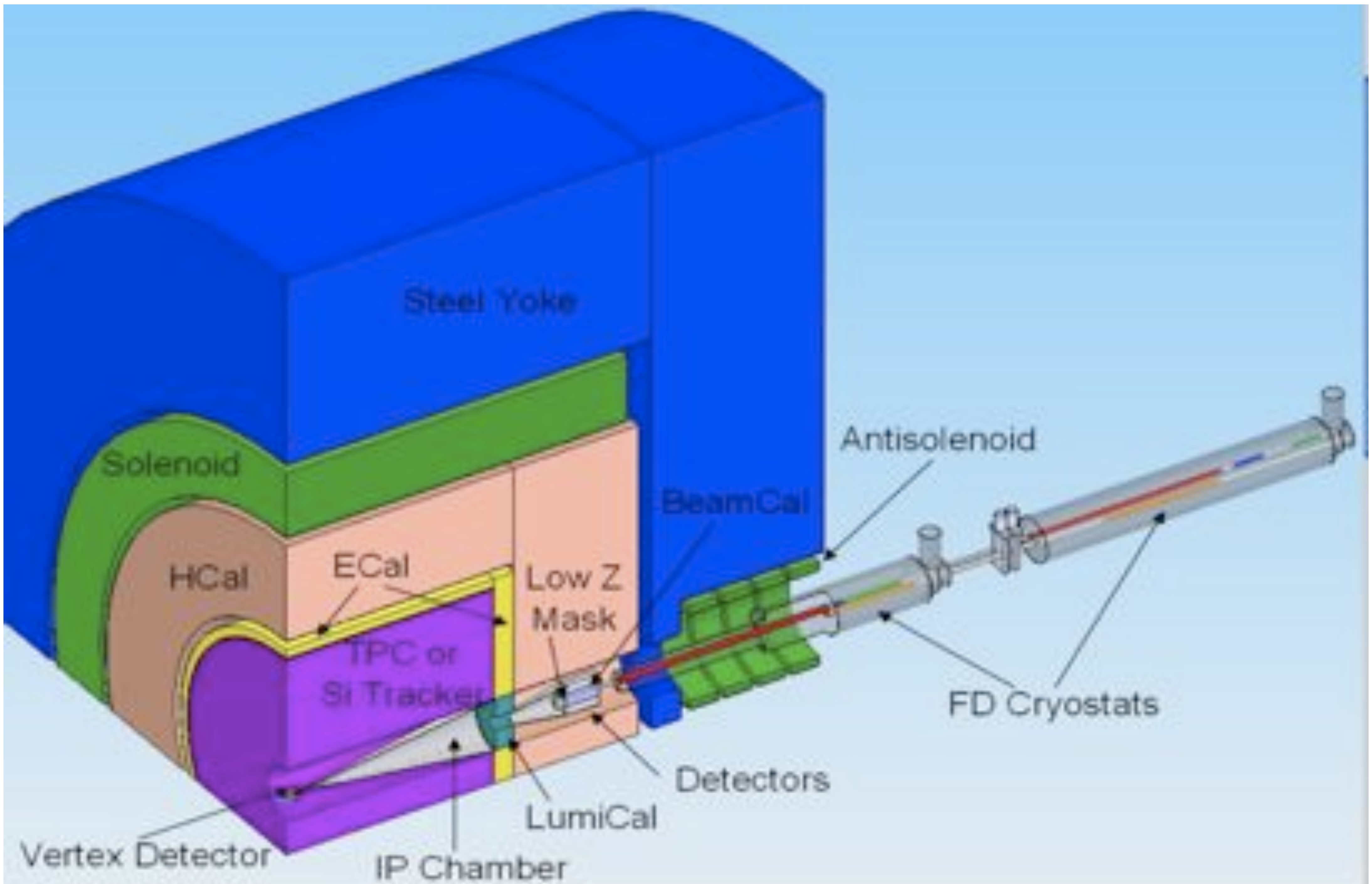




Long Term Stability



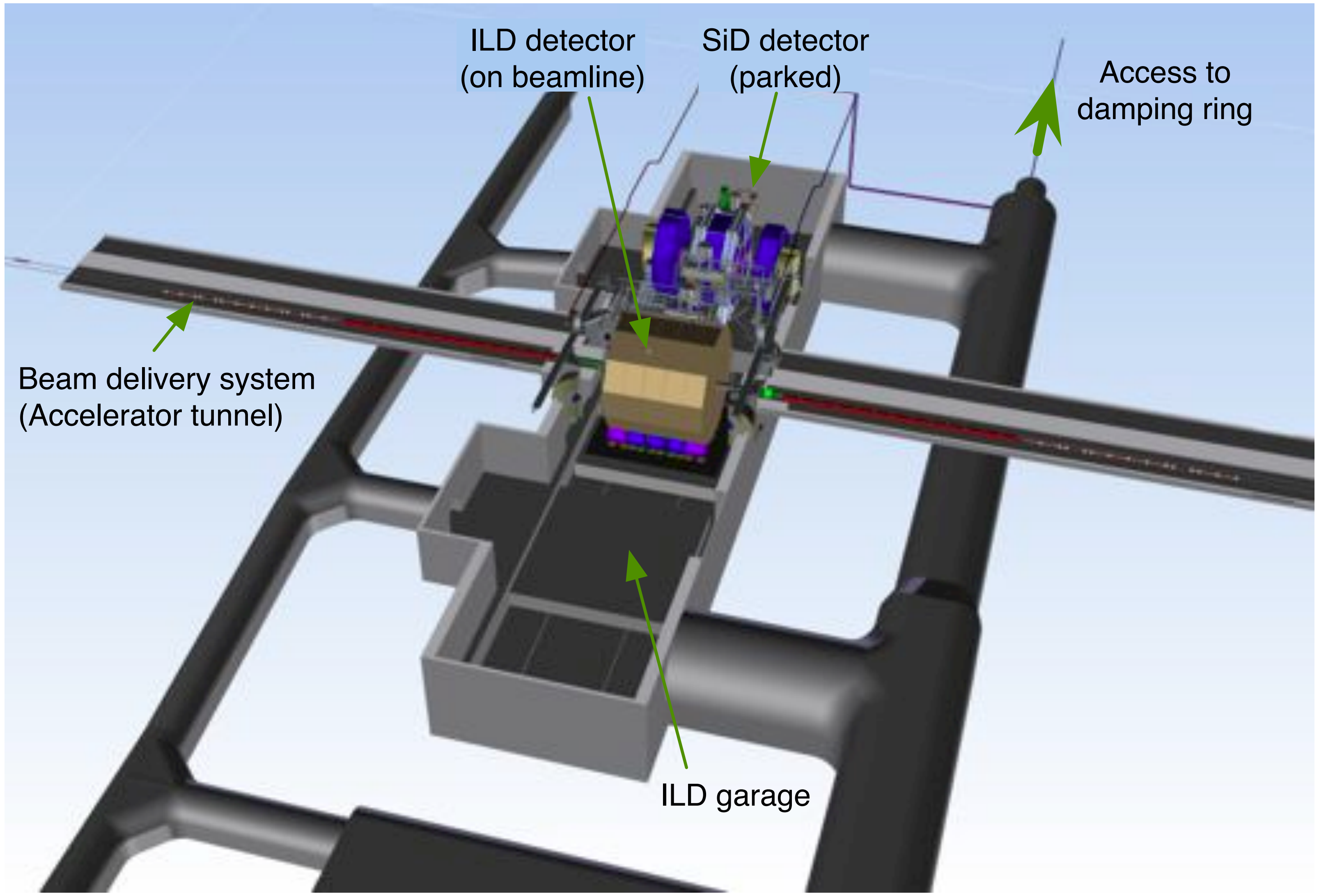
IP Region


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

Detectors and Push/Pull

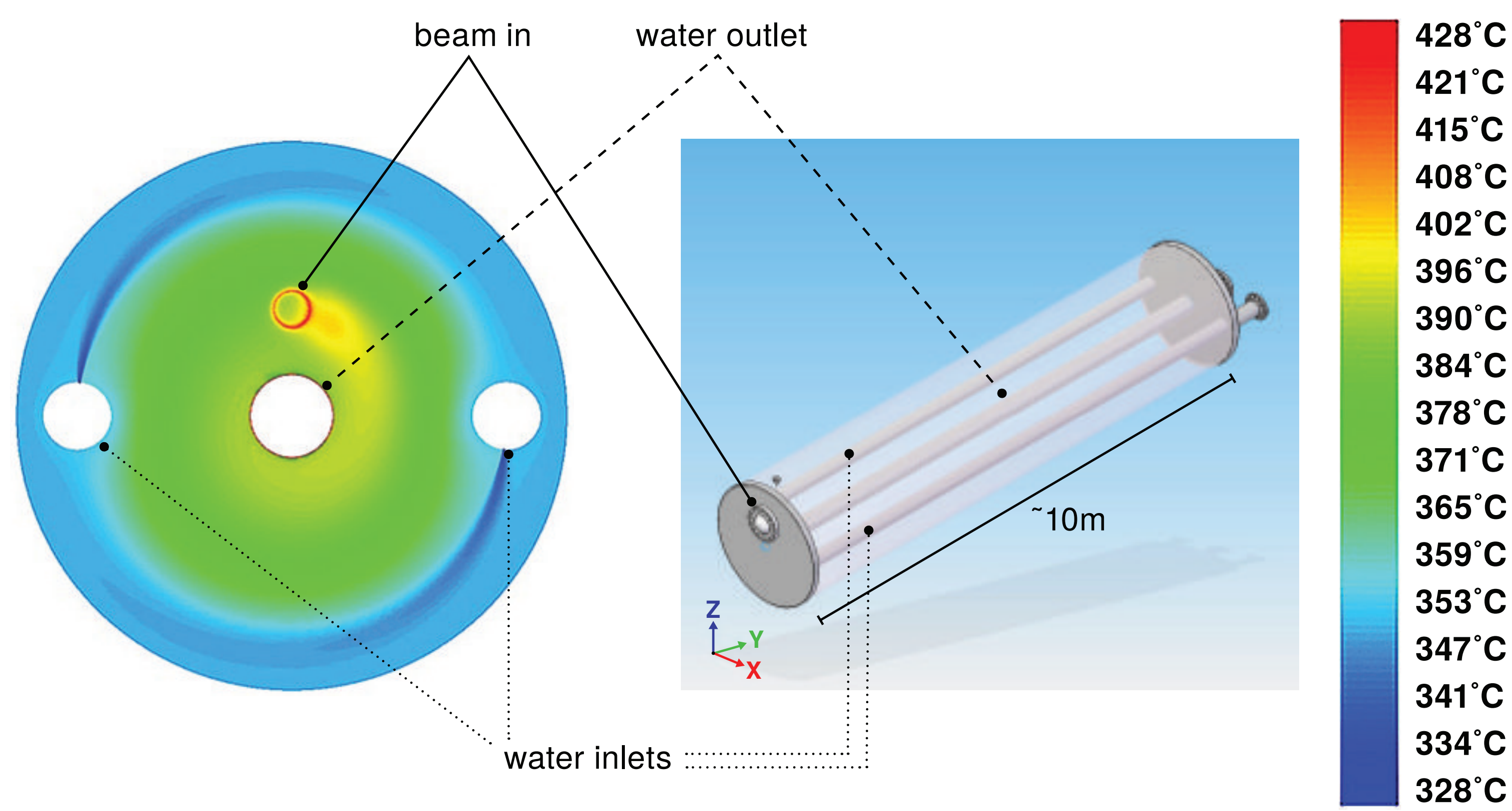
- Integrated luminosity at linear colliders does not scale with the number of interaction regions
- ILC has just one interaction beam line (cost issue) but should have two detectors
- Two detectors share one interaction region

  → 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



FLASH@DESY

FLASH/TTF

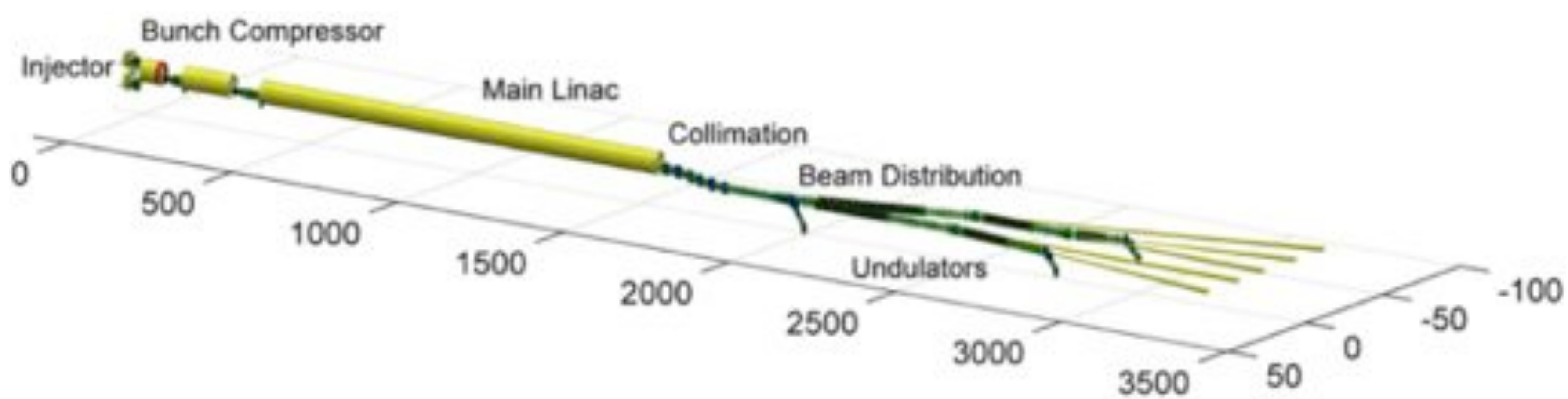
- Complete System Test
- 1 GeV e^- Linac
- 9 mA beams have been accelerated
- ILC-like pulse structure
- 0.5% prototype for the ILC....

- User facility:
  - UV Free Electron Laser

The European XFEL

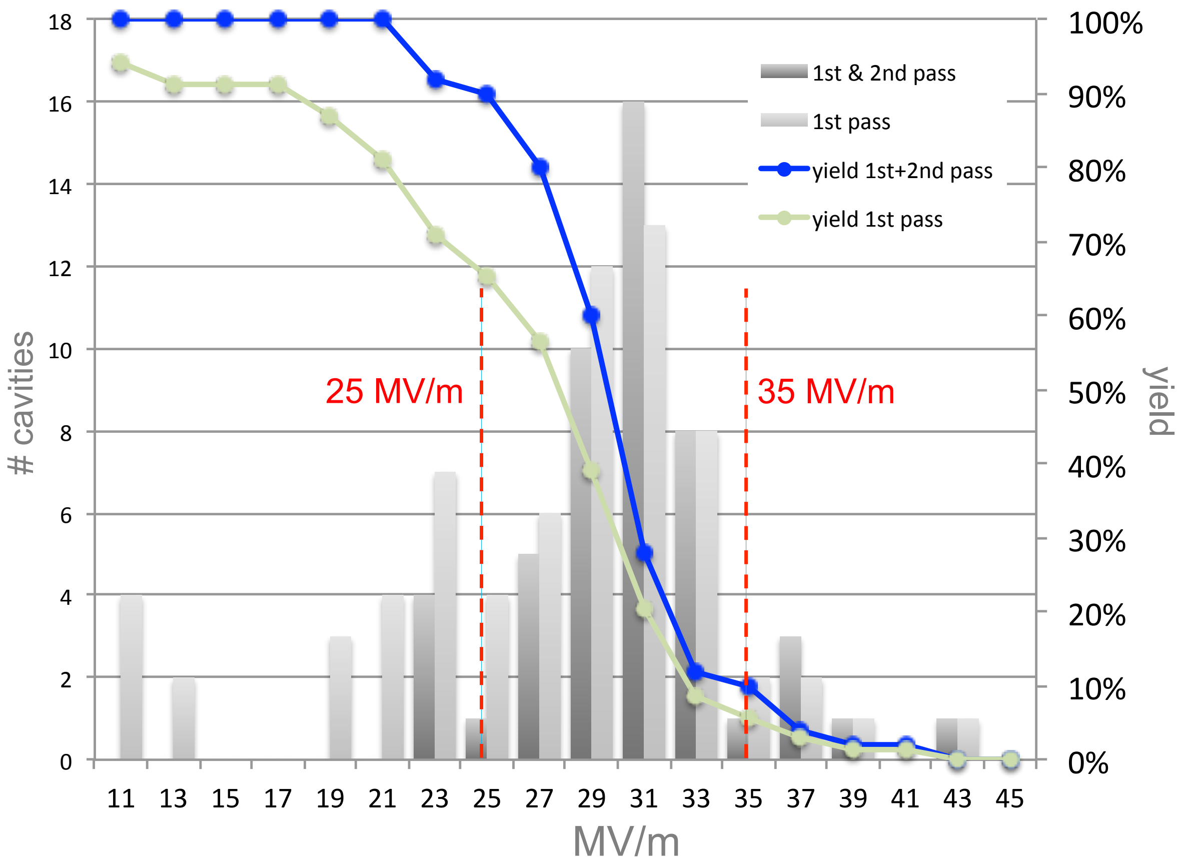
X-Ray Free Electron Laser

- ILC technology
- Length: 3,4 km
- Beam energy: 17,5 GeV
- Laser wavelength: 0,085 - 6 nm
- Laser pulse length: < 100 fs
- Construction start: 2009
- First beam: 2015
- Applied material research
- Linac: 10% prototype for ILC.....



Industrialisation for XFEL

- Mass production has started:
    - 100 cryomodules
    - 800 cavities
- Largest deployment of this SCRF technology to date....
- Large unbiased sample
    - critical for ILC



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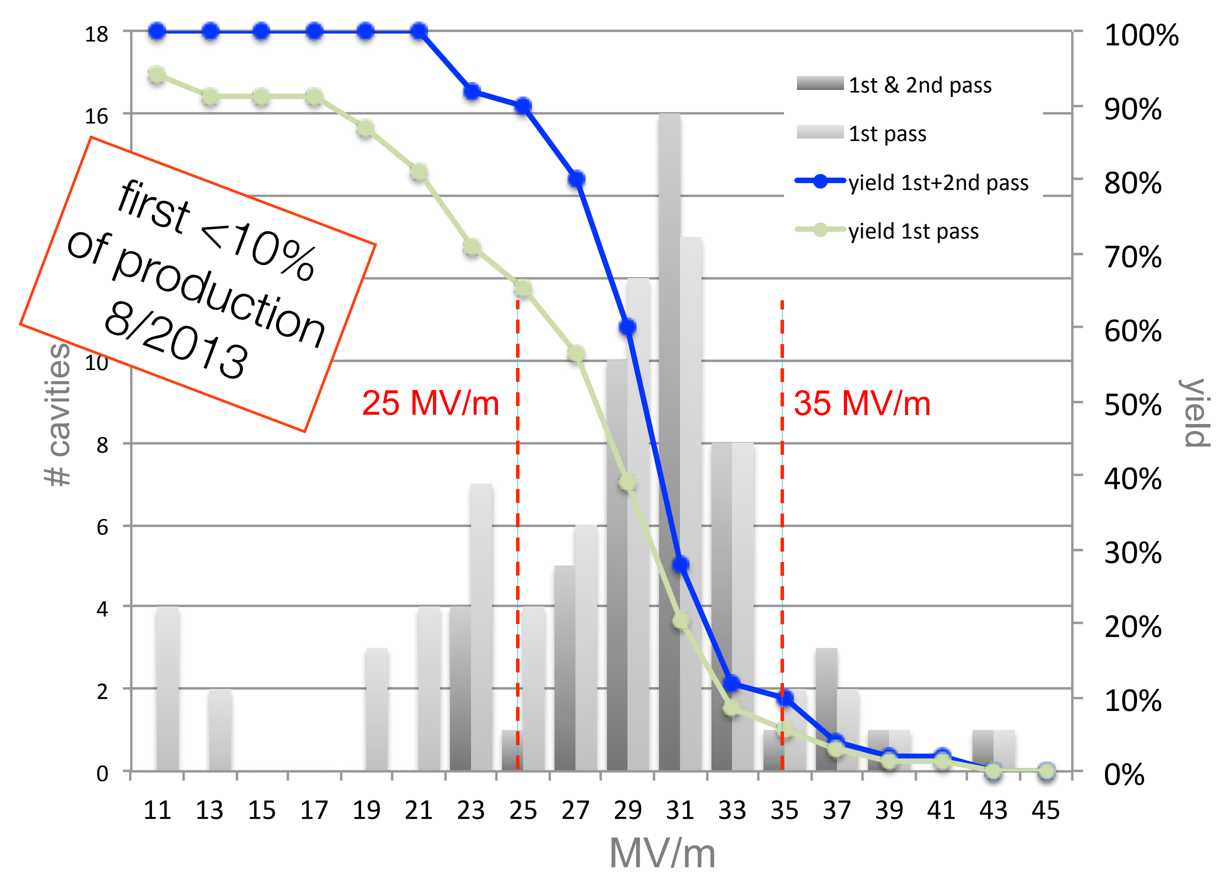

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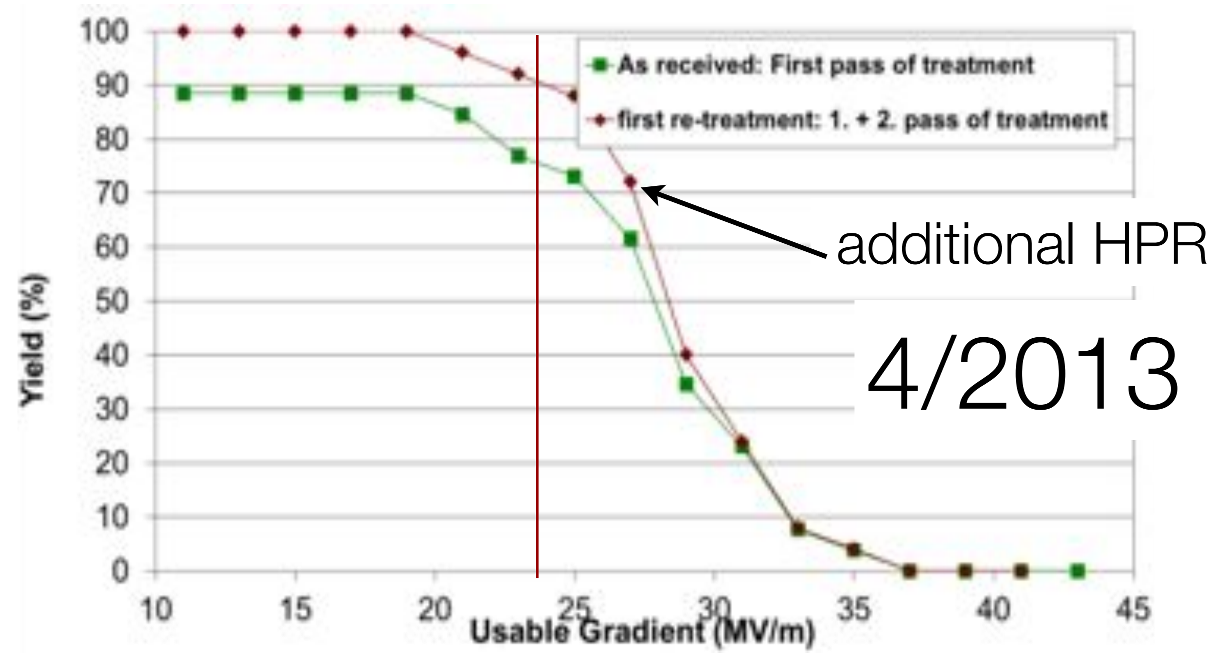
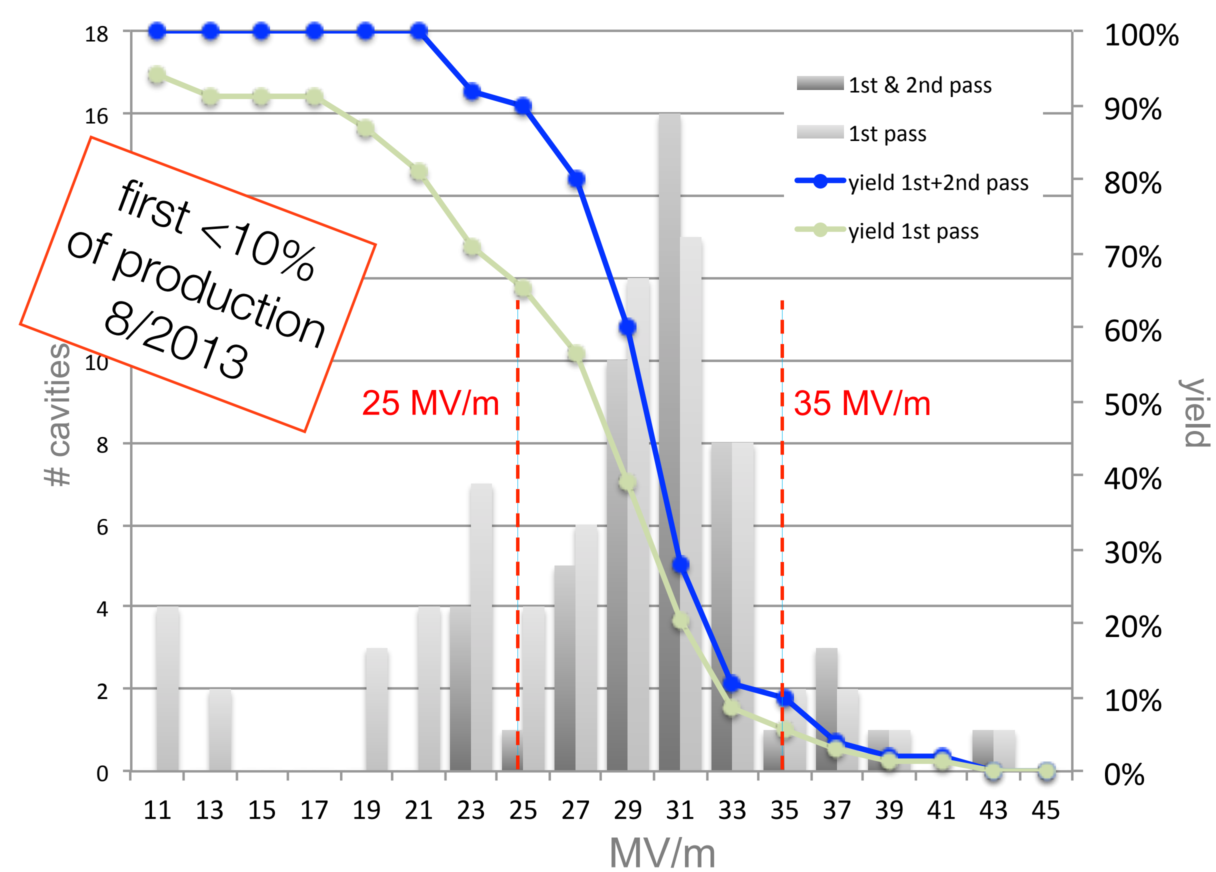




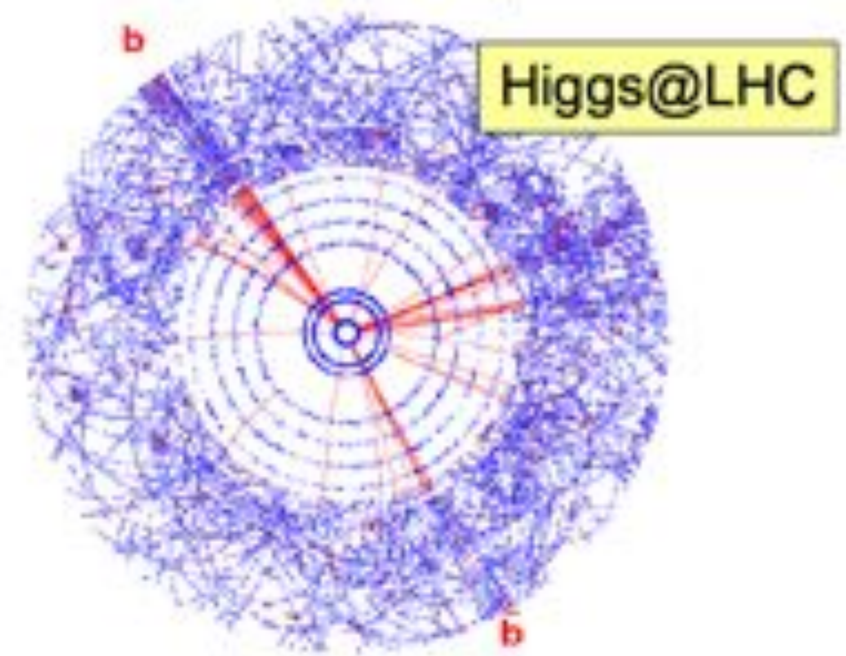
Detector Issues

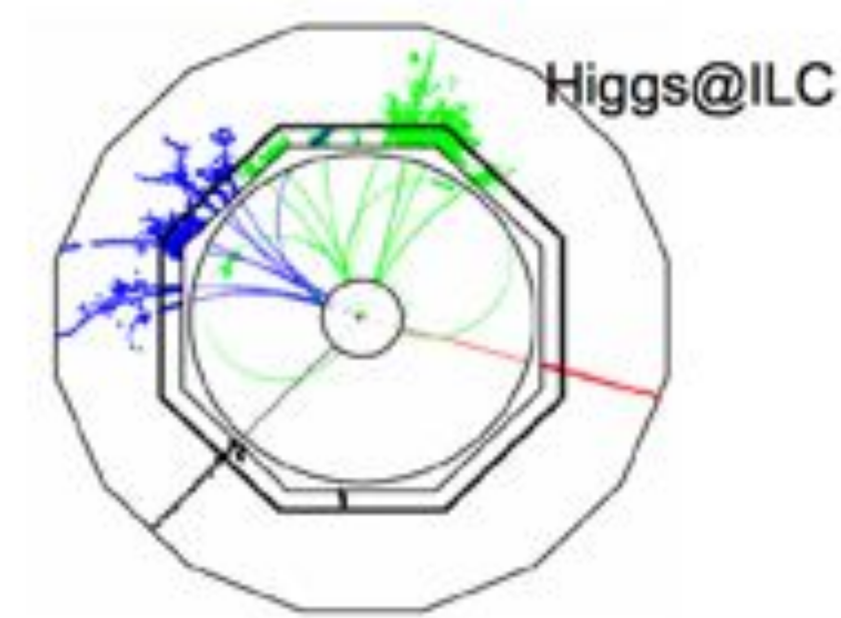
Why not copy LHC detectors?

LHC detectors were primarily designed to survive the harsh LHC environment (radiation hardness) and to cope with the short bunch spacing (25 ns).

ILC detector design is driven by precision:

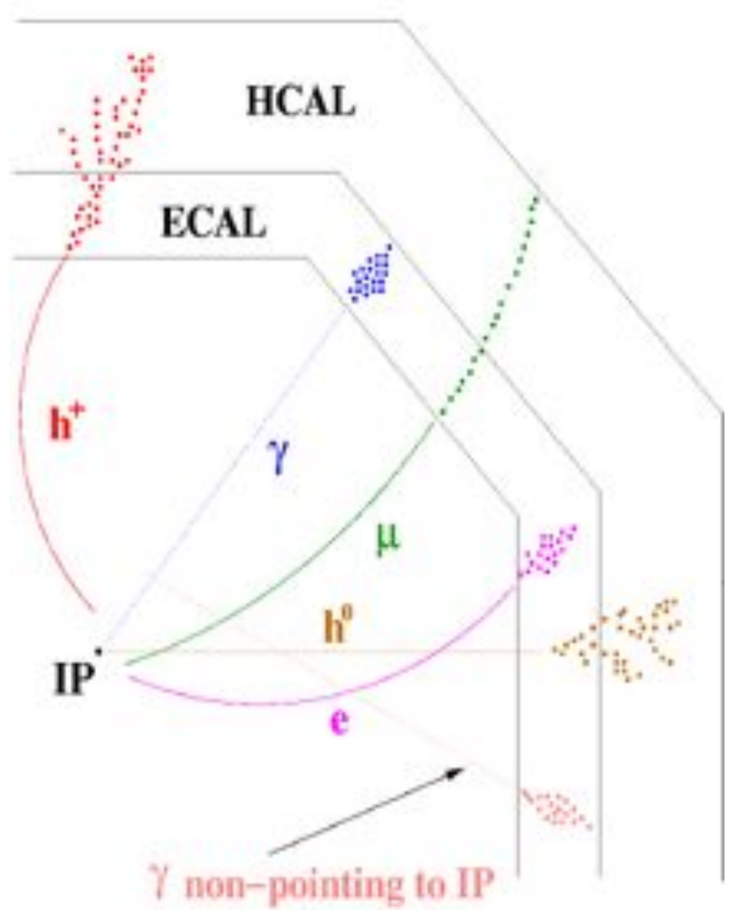
- Inner vertex layer ~3-6 times closer to IP
- Vertex pixel size ~30 times smaller
- Vertex detector layer ~30 times thinner
- Material in tracker ~30 times less
- Track momentum resolution ~10 better
- Granularity in electromagnetic calorimeter ~200 times better

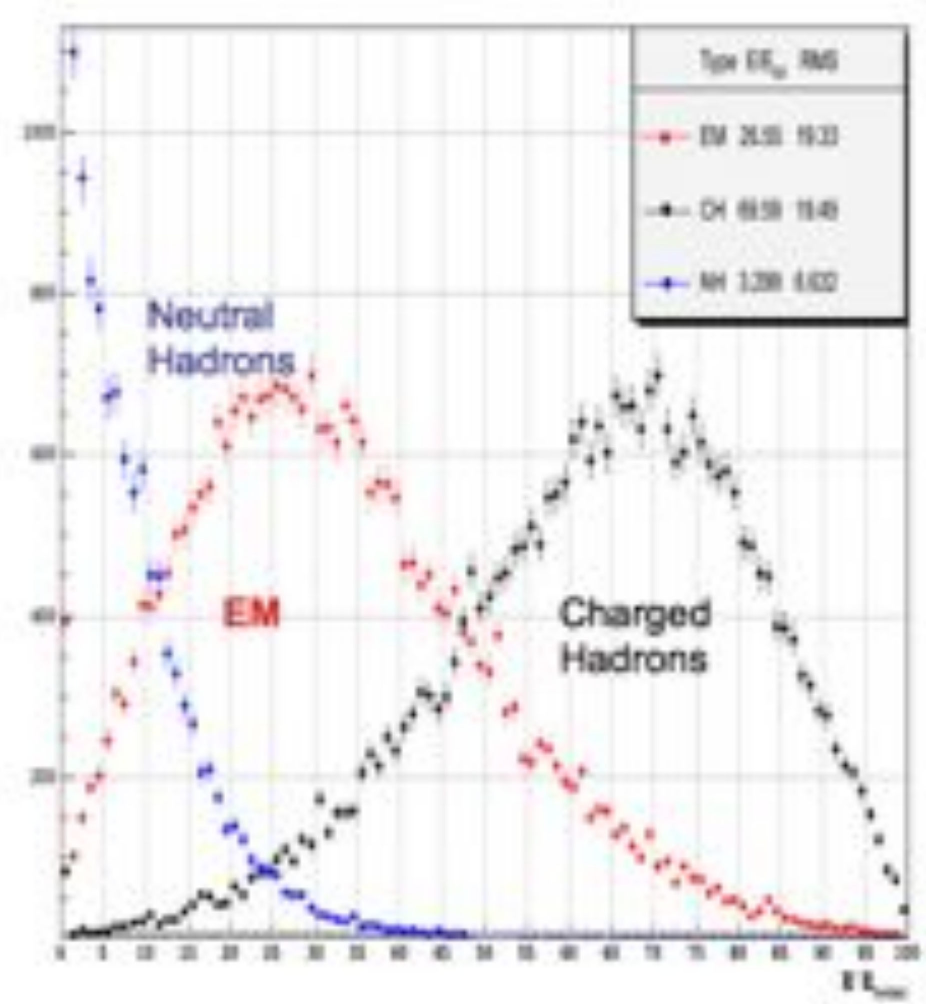




Calorimetry

- Typical jet:
  - 65% visible jet energy from charged hadrons
  - 25% photons (from $\pi^0 \rightarrow \gamma\gamma$)
  - 10% neutral hadrons
- Traditional approach:
  - measure total visible jet energy in ECAL and HCAL
  - Problem: large fluctuations

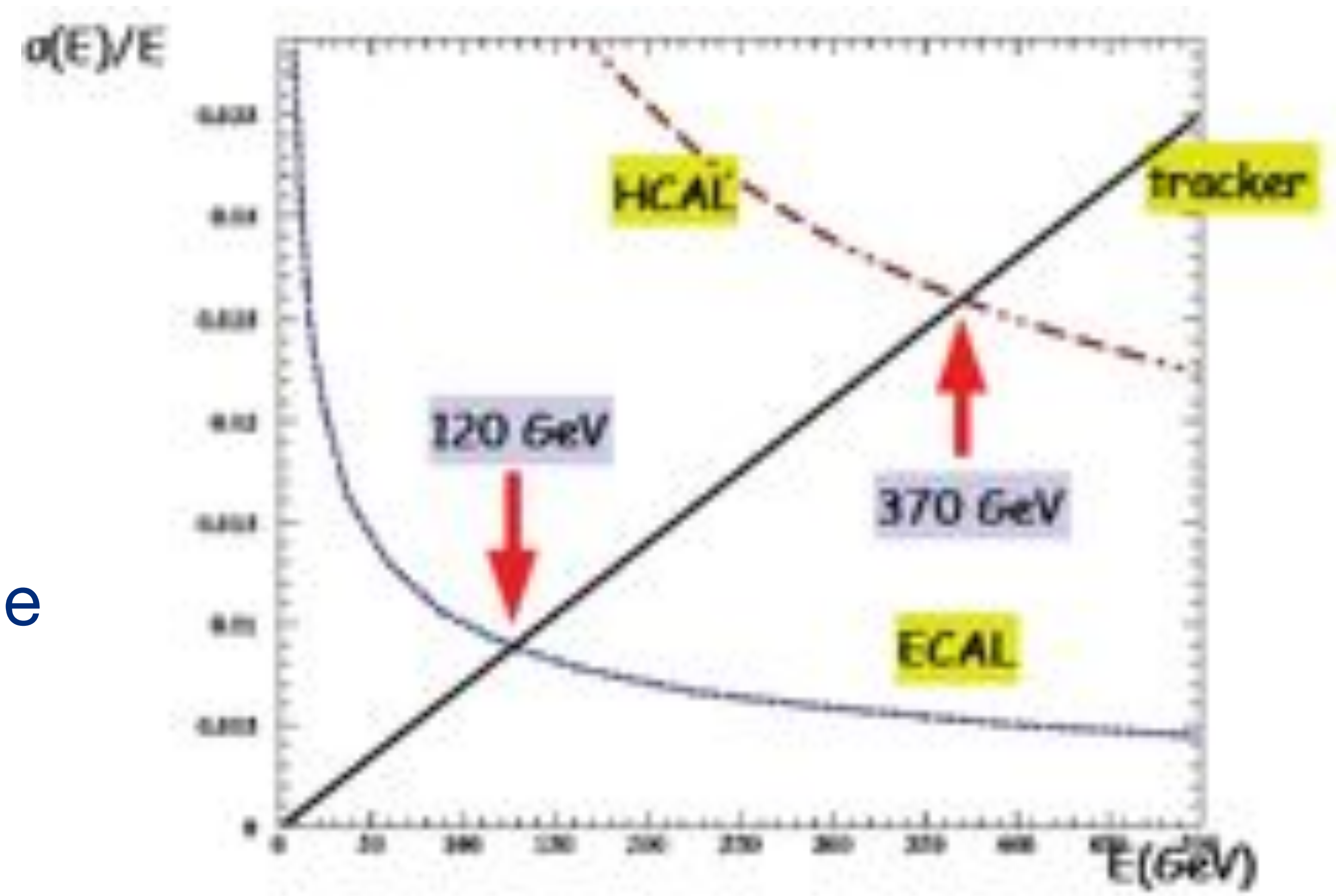




The Particle Flow Concept

- Idea: use the sub-detector with the best resolution for the energy measurement!
- Charged particles: tracking system
- Photons: ECAL
- Neutral Hadrons: HCAL

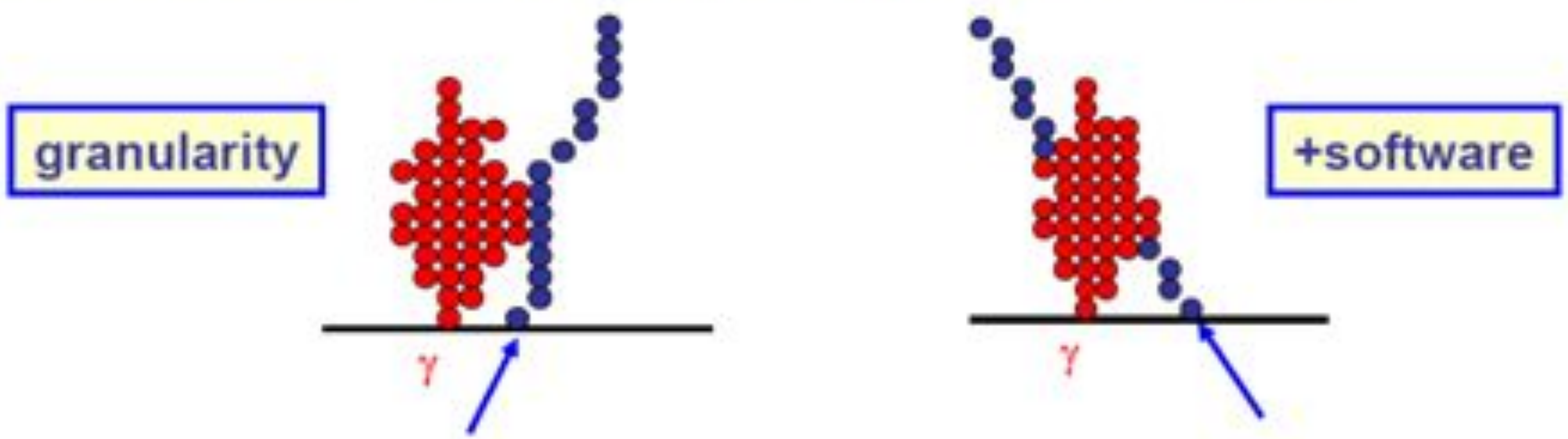
- Avoid double counting!
  - Trace every single particle through the detector
- $E_{jet} = E_{charged} + E_{photons} + E_{neutral\ hadr.}$
- $\sigma^2(E_{jet}) = \sigma^2(E_{charged}) + \sigma^2(E_{photons}) + \sigma^2(E_{neutral\ hadr.}) + \sigma^2_{confusion}$



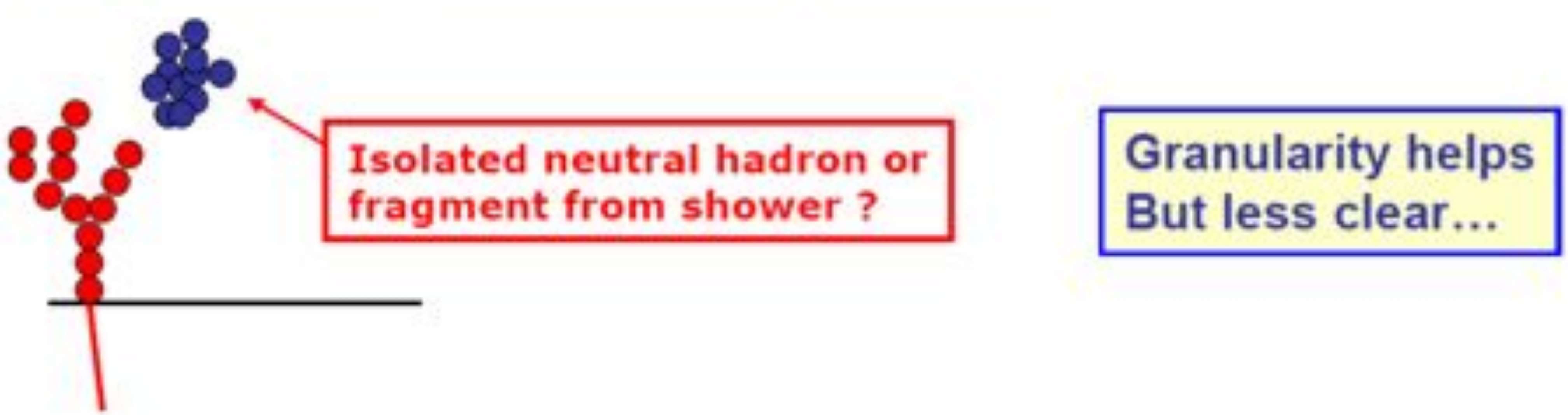
Particle Flow Challenge

Separate energy deposits and avoid double counting

Example: need to separate "tracks" (charged hadrons) from photons

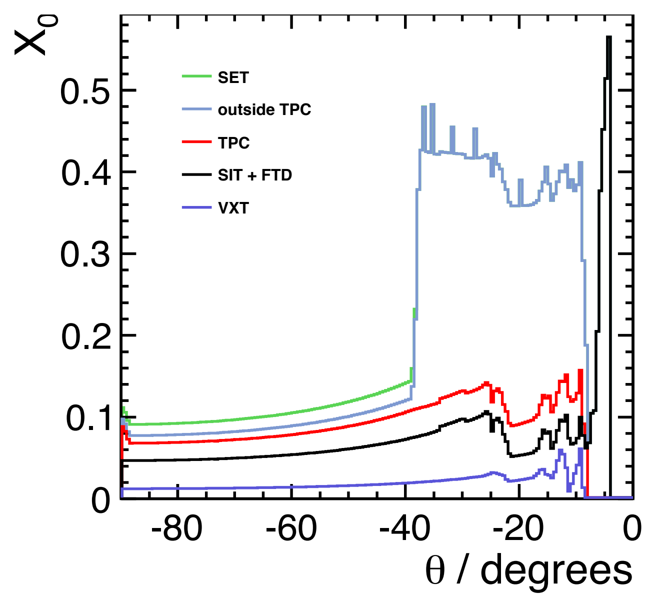


Need to separate neutral hadrons from charged hadrons

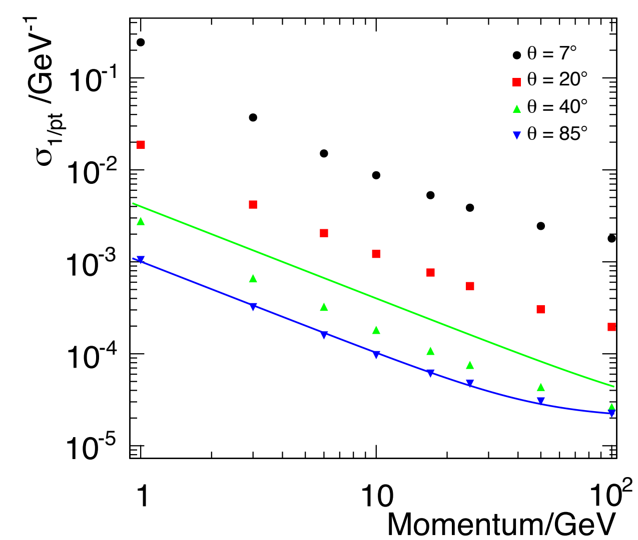


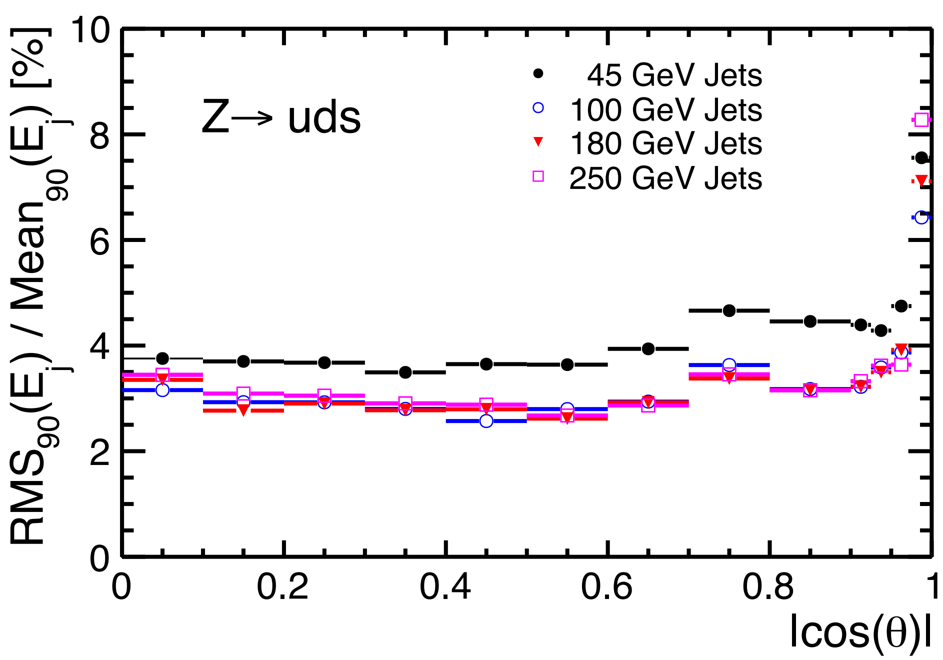
Detector Performance

Material Budget

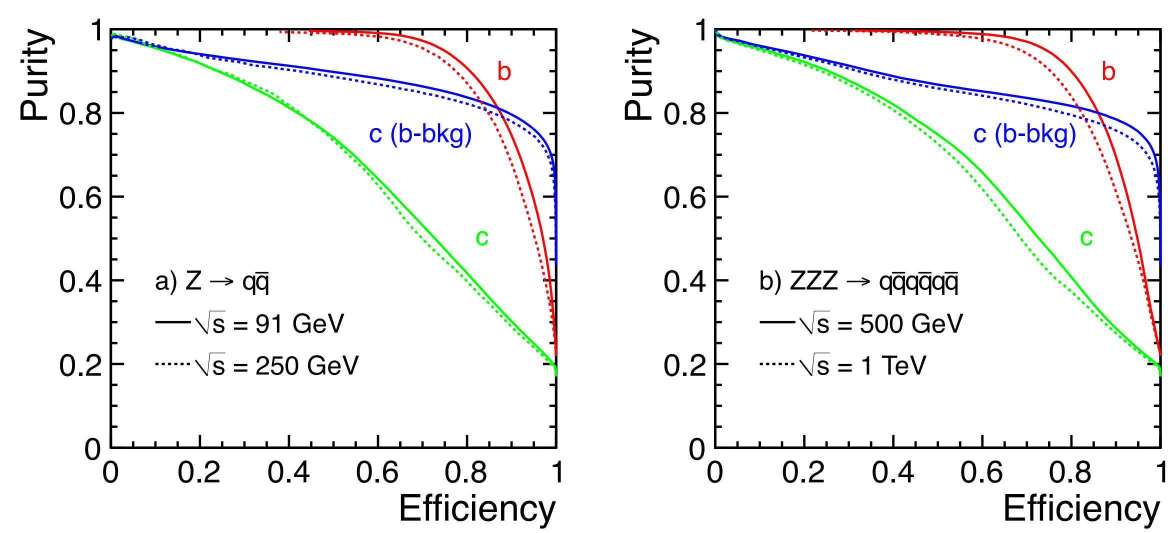


Momentum Resolution



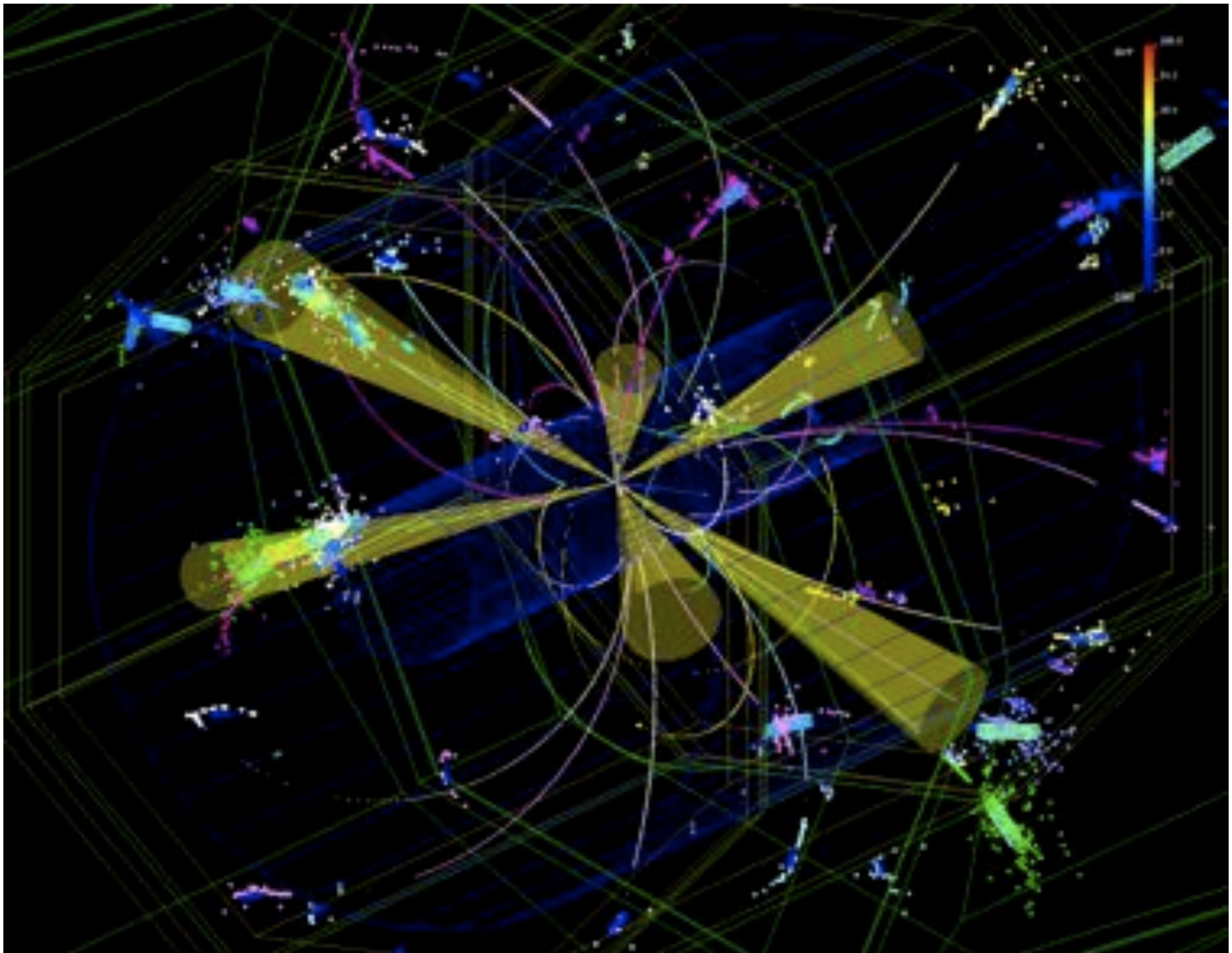


Jet Energy Resolution



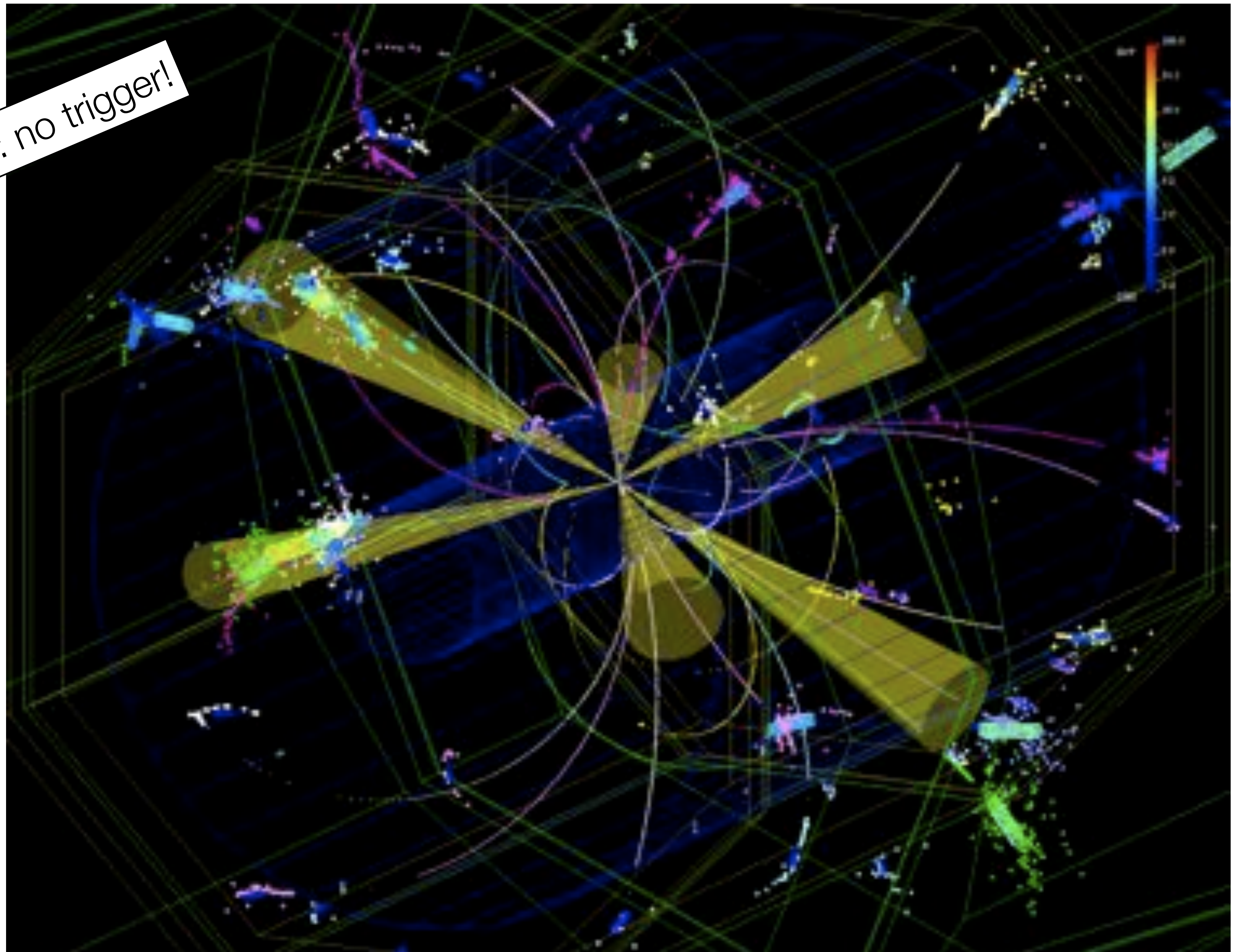
Flavour Tagging

Imaging Detector

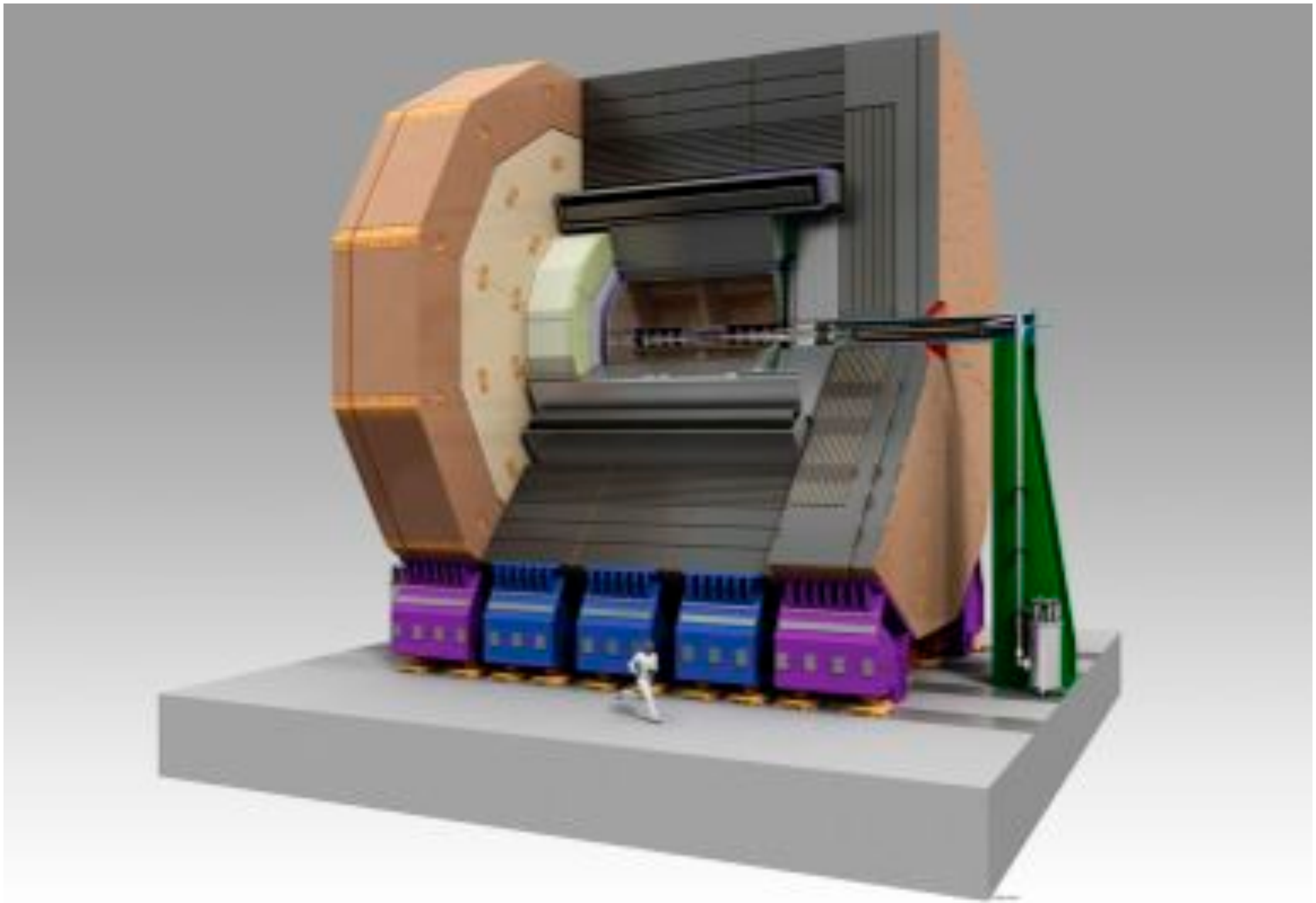


Imaging Detector

btw: no trigger!



ILD Detector



The Global Context

Timeline

- We live in interesting times for particle physics!
  - The 125 GeV „Higgs“ sets the first energy scale for possible new physics

  - European Strategy for Particle Physics (CERN Council) supports the ILC in Japan as a Higgs factory
  - The US „Snowmass Process“ concluded similarly
  - ACFA/AsiaHEP statement along the same lines
  - -> towards a global HEP strategy

The Staged Linear Collider

- In principle, the ILC can run on any energy between ~90 GeV and several TeV
  - linear colliders are scalable, it is mostly a question of cost....
- Develop a staged approach
  - start where interesting physics is guaranteed, extend to higher energies later

- ILC$_{250}$: Higgs measurements (mass, spin, couplings), EW physics, (...)
- ILC$_{350}$: Top physics, (...)
- ILC$_{500}$: Higgs self coupling, Top-Higgs Yukawa coupling, (...)
- ILC$_{1000+}$: SUSY, whatever comes, (...)
- CLIC as multi-TeV option

The Staged Linear Collider

- In principle, the ILC can run on any energy between ~90 GeV and several TeV
  - linear colliders are scalable, it is mostly a question of cost....
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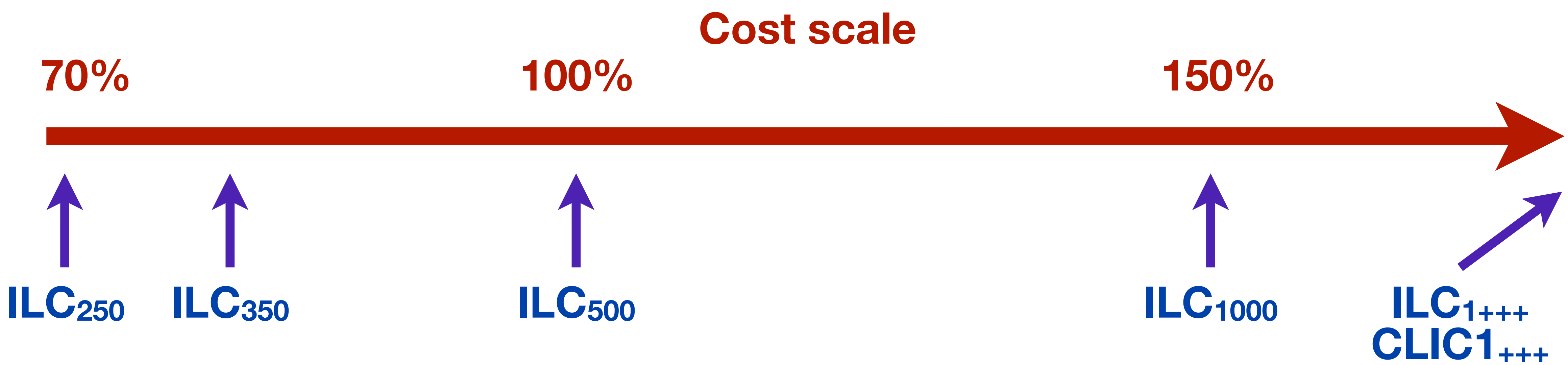

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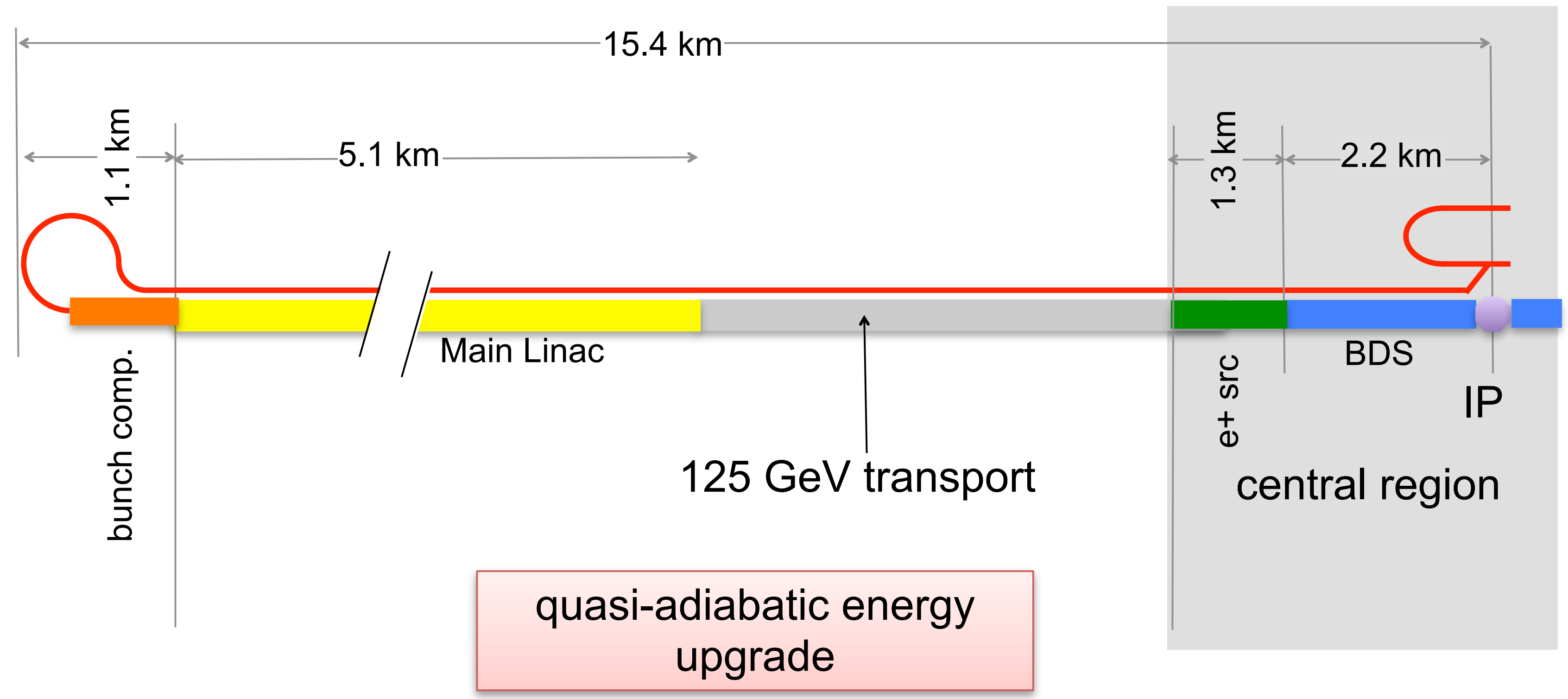
- ILC$_{350}$: Top physics, (...)
- ILC$_{500}$: Higgs self coupling, Top-Higgs Yukawa coupling, (...)
- ILC$_{1000+}$: SUSY, whatever comes, (...)
- CLIC as multi-TeV option

Staged construction: 250 GeV First Phase

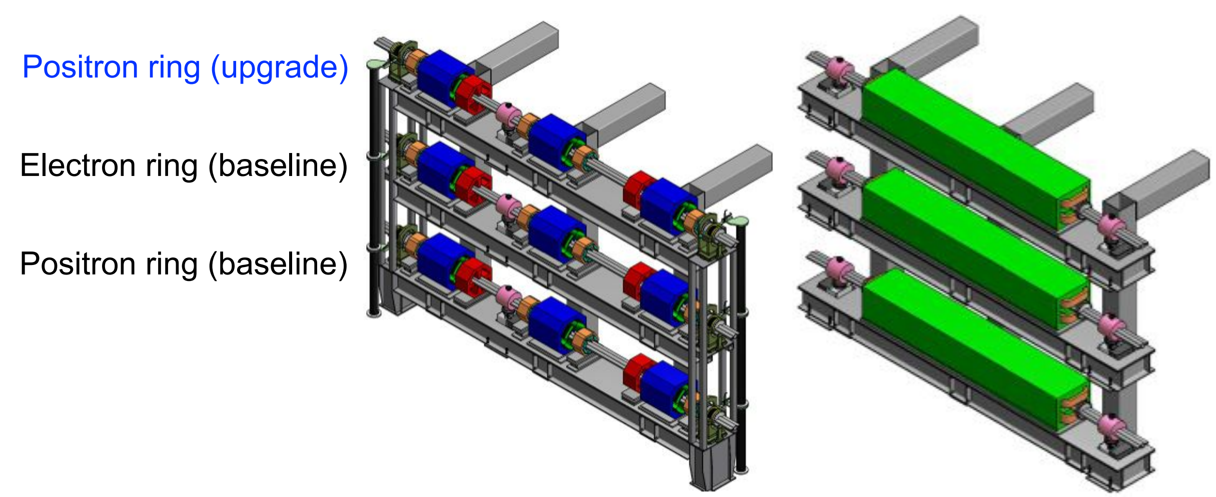


- Complete civil construction for 500 GeV machine
- Install 50% of linacs for first stage (capital savings 25-30%)
- Adiabatic energy upgrade towards 500 GeV (lower rate cryomodule production)

Luminosity Upgrade

- Doubling the luminosity:
  - doubling the number of bunches per train
  - need more RF power (klystrons, modulators)
  - possibly need third damping ring

				1st	L	TeV Upgrade	
			Baseline	Stage	Upgrade	A	B
Centre-of-mass energy	E_{CM}	GeV	500	250	500	1000	1000
Collision rate	f_{rep}	Hz	5	5	5	4	4
Electron linac rate	f_{linac}	Hz	5	10	5	4	4
Number of bunches	n_b		1312	1312	2625	2450	2450
Bunch population	N	$\times 10^{10}$	2.0	2.0	2.0	1.74	1.74
Bunch separation	Δt_b	ns	554	554	366	366	366
Pulse current	I_{beam}	mA	5.79	5.8	8.75	7.6	7.6
Average total beam power	P_{beam}	MW	10.5	5.9	21.0	27.2	27.2
Estimated AC power	P_{AC}	MW	163	129	204	300	300
RMS bunch length	σ_z	mm	0.3	0.3	0.3	0.250	0.225
Electron RMS energy spread	$\Delta p/p$	%	0.124	0.190	0.124	0.083	0.085
Positron RMS energy spread	$\Delta p/p$	%	0.070	0.152	0.070	0.043	0.047
Electron polarisation	P_-	%	80	80	80	80	80
Positron polarisation	P_+	%	30	30	30	20	20
Horizontal emittance	$\gamma\epsilon_x$	μm	10	10	10	10	10
Vertical emittance	$\gamma\epsilon_y$	nm	35	35	35	30	30
IP horizontal beta function	β_x^*	mm	11.0	13.0	11.0	22.6	11.0
IP vertical beta function (no TF)	β_y^*	mm	0.48	0.41	0.48	0.25	0.23
IP RMS horizontal beam size	σ_x^*	nm	474	729	474	481	335
IP RMS veritcal beam size (no TF)	σ_y^*	nm	5.9	7.7	5.9	2.8	2.7
Luminosity (inc. waist shift)	L	$\times 10^{34}$ cm^{-2}s^{-1}	1.8	0.75	3.6	3.6	4.9
Fraction of luminosity in top 1%	$L_{0.01}/L$		58.3%	87.1%	58.3%	59.2%	44.5%
Average energy loss	δ_{BS}		4.5%	0.97%	4.5%	5.6%	10.5%
Number of pairs per bunch crossing	N_{pairs}	$\times 10^3$	139.0	62.4	139.0	200.5	382.6
Total pair energy per bunch crossing	E_{pairs}	TeV	344.1	46.5	344.1	1338.0	3441.0



Arc quadrupole section

Dipole section

Energy Upgrade Beyond 500 GeV

- Need longer tunnel
  - and more cryomodules, etc.
- Adiabatic transformation possible
- Proposed sites are large enough for 1 TeV machine

			Baseline	1st Stage	L Upgrade	TeV Upgrade A	TeV Upgrade B
Centre-of-mass energy	E_{CM}	GeV	500	250	500	1000	1000
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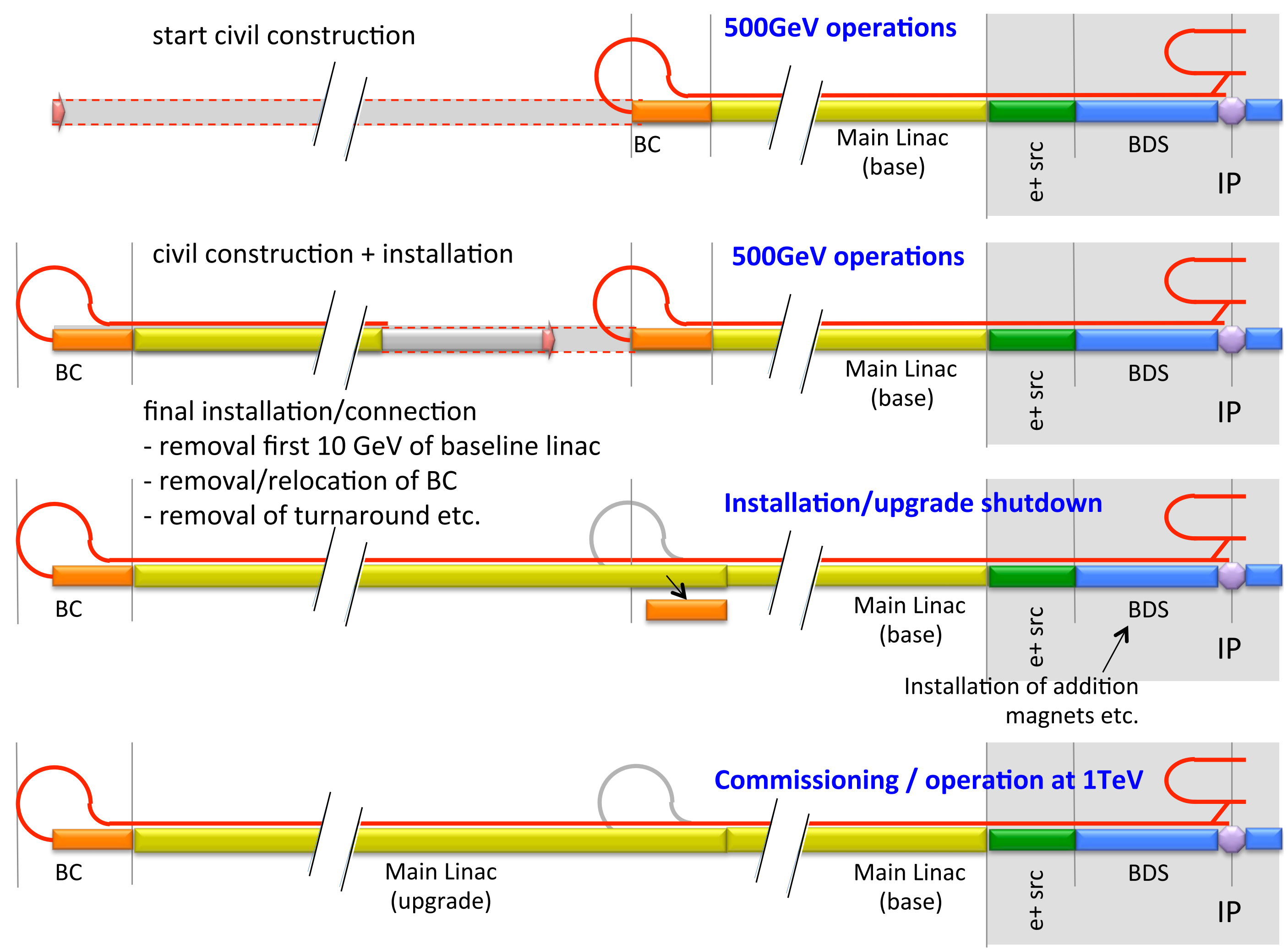
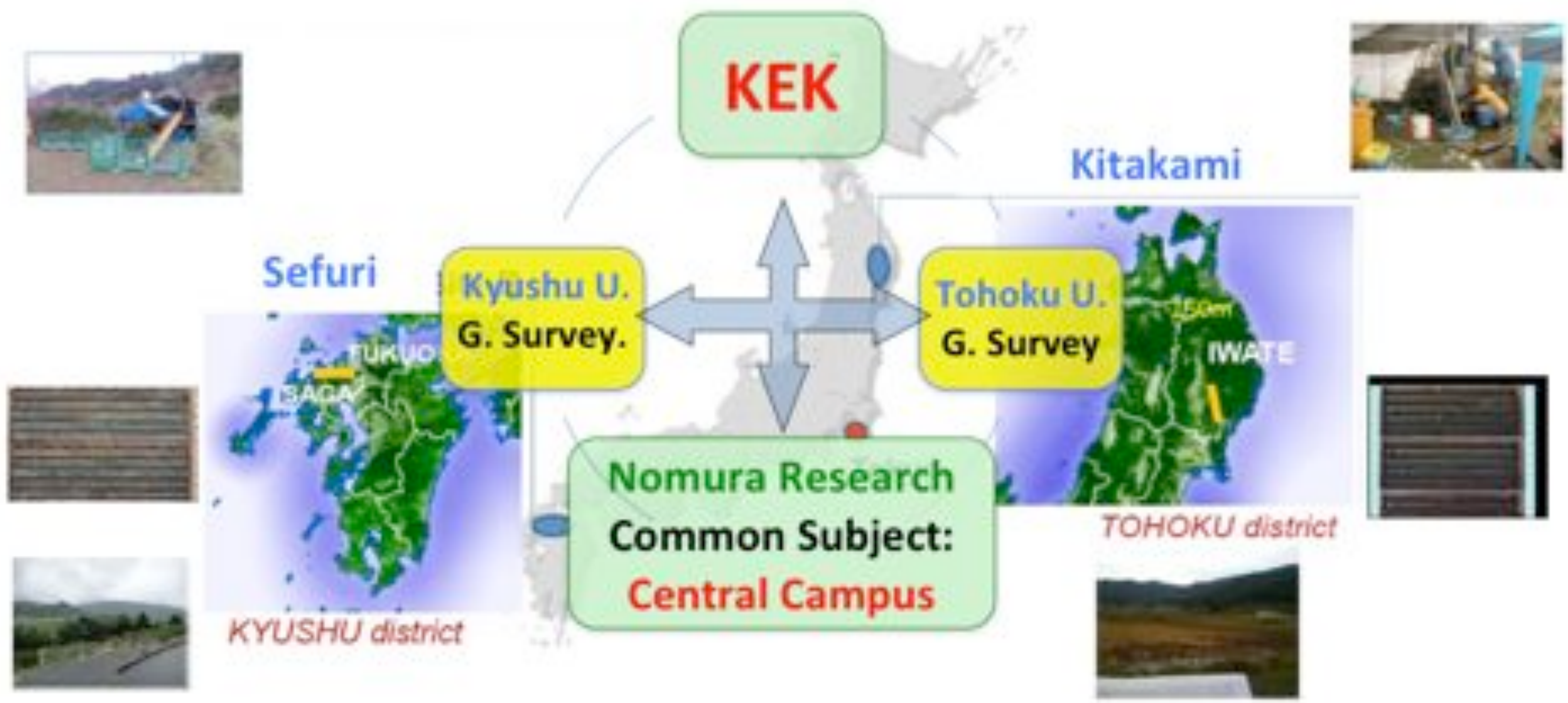


Pushing the Luminosity

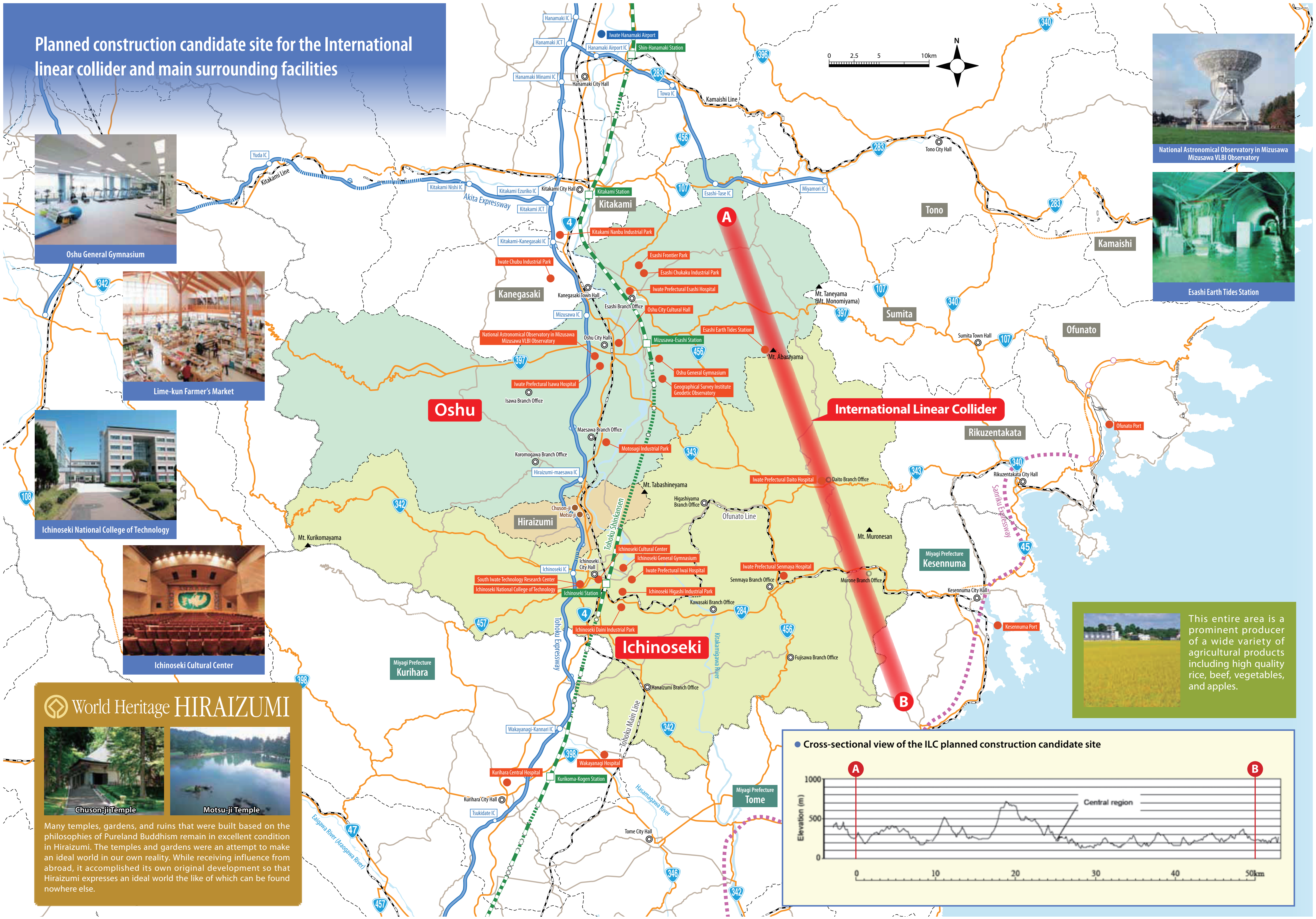
- If one accepts higher energy consumptions, the luminosity at the ILC can be pushed to higher values (e.g. if physics requires):
  - 250 GeV: increase by factor 4: $3x10^{34}cm^{-2}s^{-1}$
    - double number of bunches, double repetition rate
    - 120 → 200 MW wall plug power
  - 500 GeV: increase by factor 2: $3.6x10^{34}cm^{-2}s^{-1}$
    - double number of bunches
    - 160 → 200 MW wall plug power
  - 1 TeV: increase by factor 1.4: $5x10^{34}cm^{-2}s^{-1}$
    - aggressive beam parameters
    - same wall plug power (300 MW)
    - Polarisation gives another factor of 2 for W-fusion....

Japanese Candidate Sites



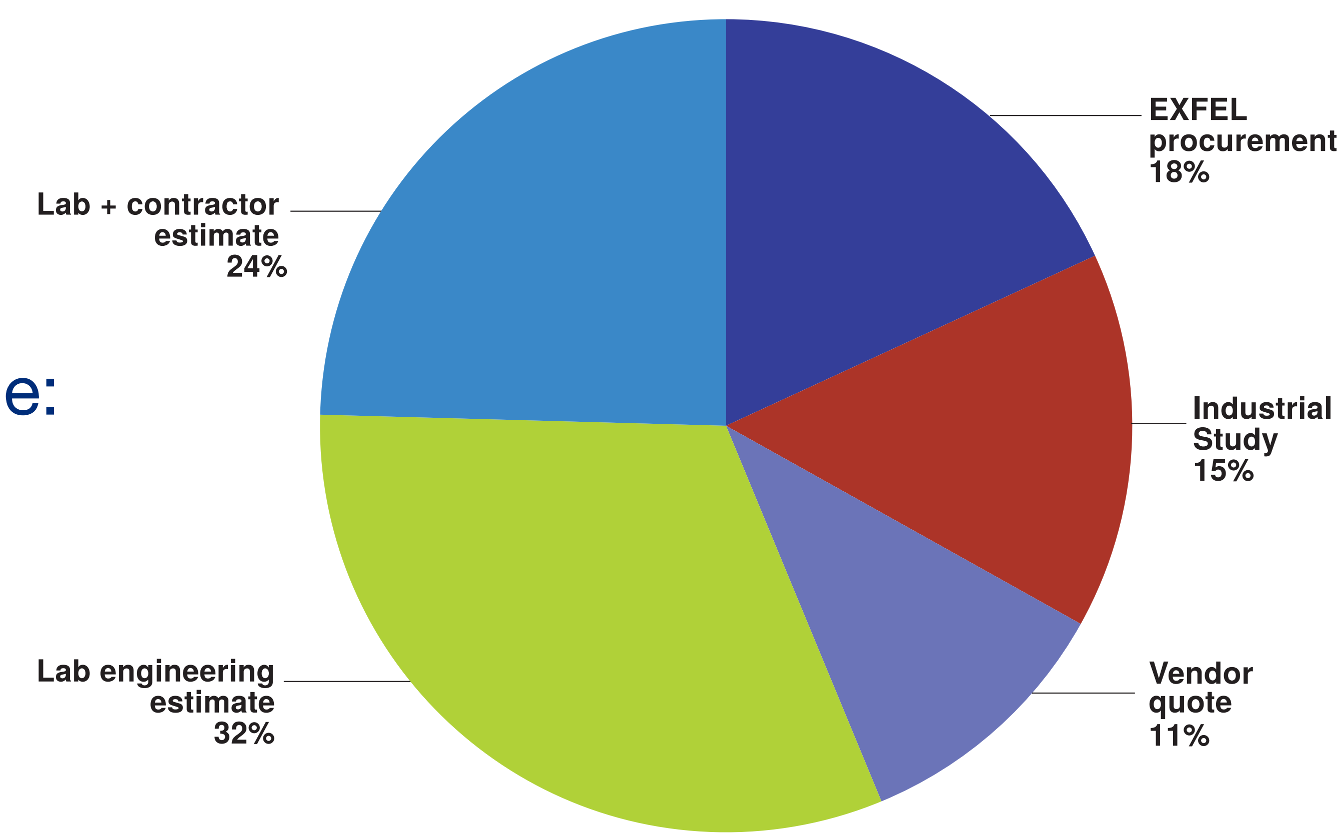
- Intense competition between both regions
- „Winner“ has been announced on August 23rd: Kitakami
  - decision based on technical issues, no government statement

Kitakami Site (Japan)



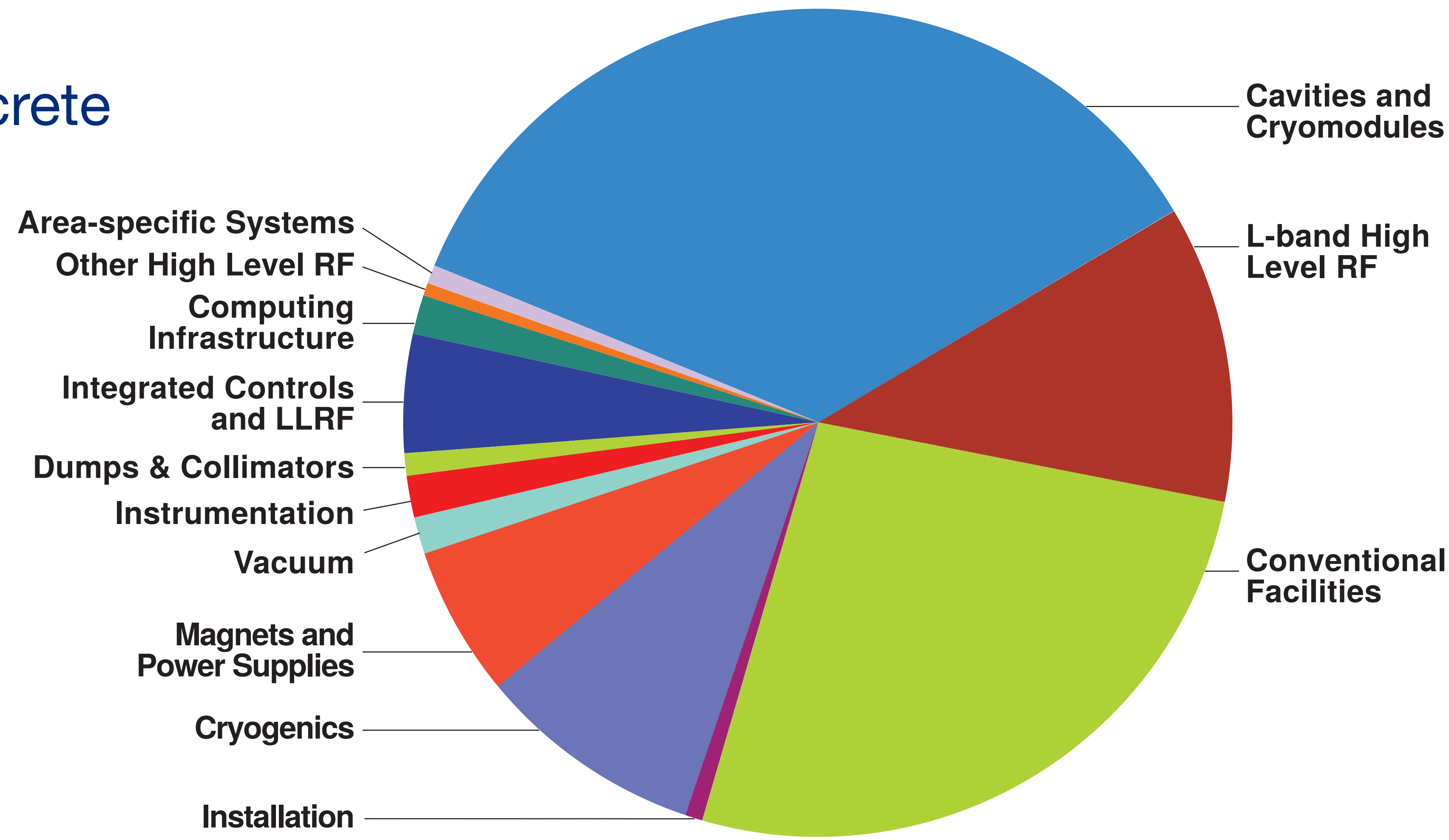
The Cost

- Costing is a very complicated exercise in a global project....
- Technical Design Report (2012) cost estimate:
  - 7.8 BILCUs (1 ILCU = 1 US$ in 2012)
  - 22.6 Mh person labour
- Value estimate as real as possible:
  - existing machines
  - industrial studies
  - vendour quotes
  - lab/contractor estimates



Cost Distribution

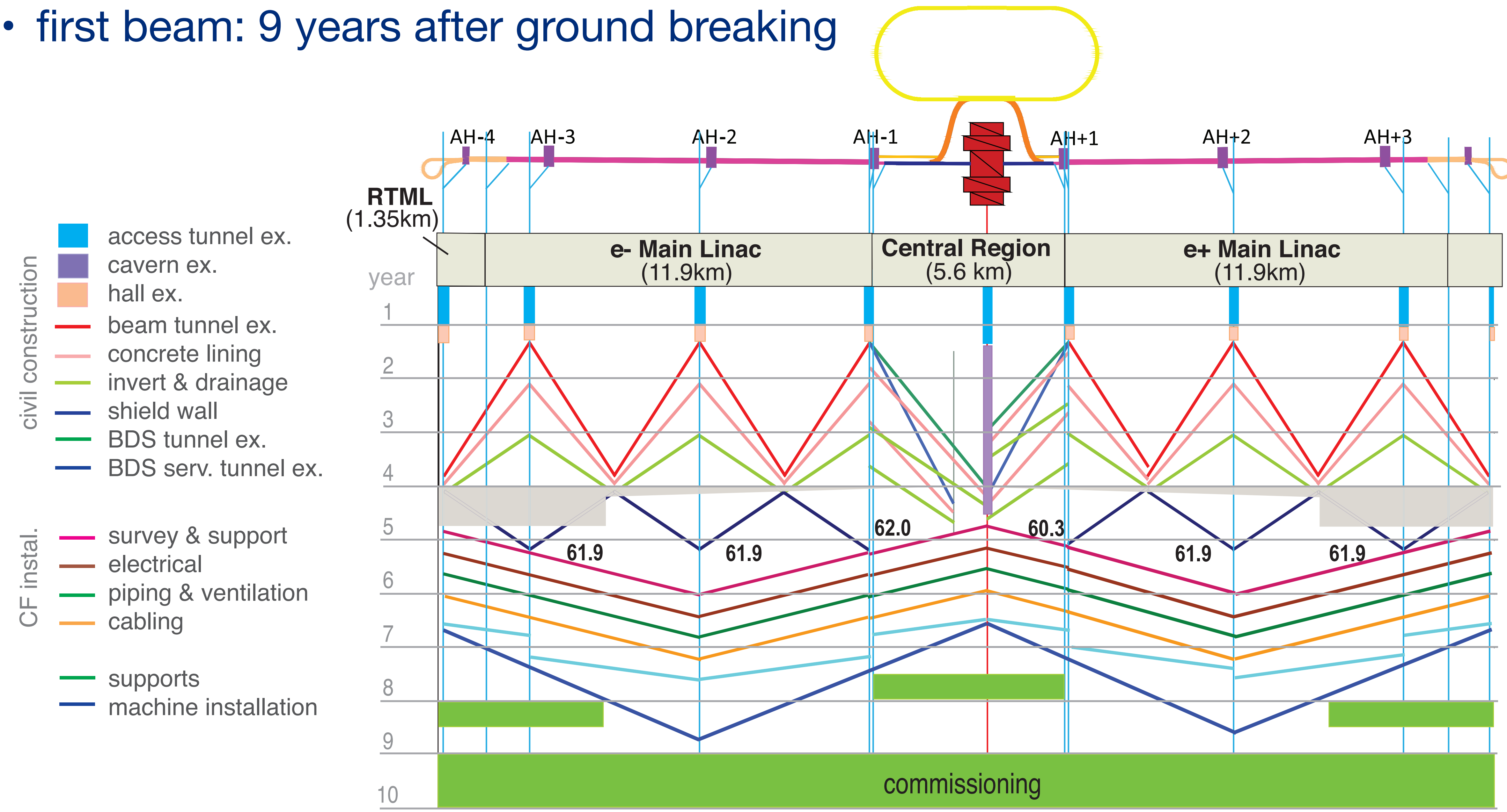
- Most expensive:
  - civil facilities:
    - tunnel, halls, concrete
  - technology:
    - cavities and cryomodules
    - klystrons



plus two detectors....

Construction Schedule

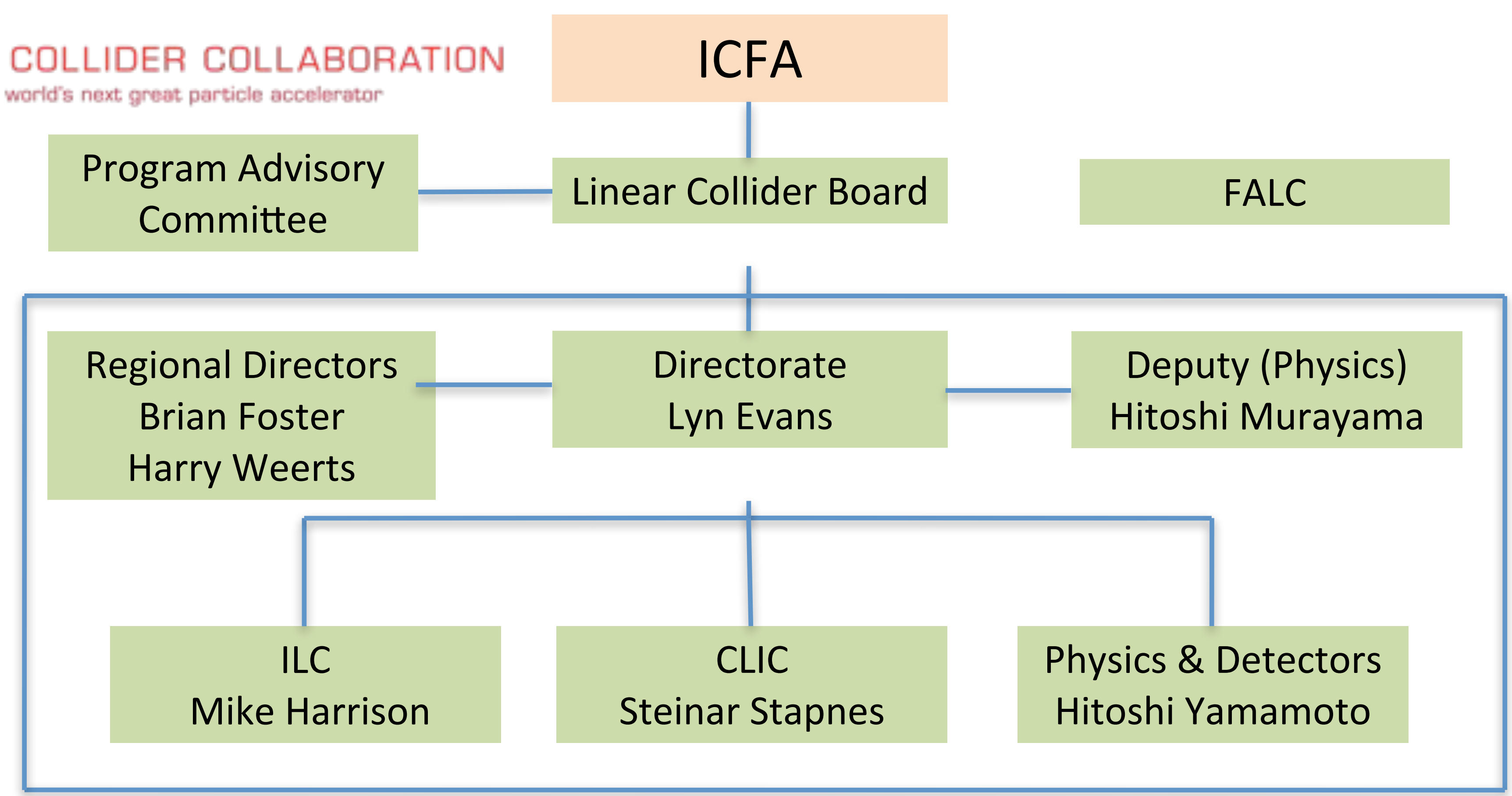
- first beam: 9 years after ground breaking



The Linear Collider Project

- The ILC is the most advanced future project for research at the energy frontier
- CLIC is a possible high-energy option (→ lecture by Lucie Linssen)
- New organisation under the supervision of ICFA: the Linear Collider Collaboration
  - director: Lyn Evans (CERN)

LINEAR COLLIDER COLLABORATION
Designing the world's next great particle accelerator



Conclusion

- LHC will need to be complemented by an e^+e^-- collider for precision measurements
- LHC has established the energy scale of the Higgs; this requires an e^+e^--collider at 250-500 (1000) GeV energies
- ILC is the most advanced collider design and ready for construction
  - 20 year history of system R&D
- CLIC could be a high-energy option
  - on a longer timescale though...
- Machine and experiments demand high-tech solutions on yet untested scales