Linear Colliders

From physics requirements to today's projects

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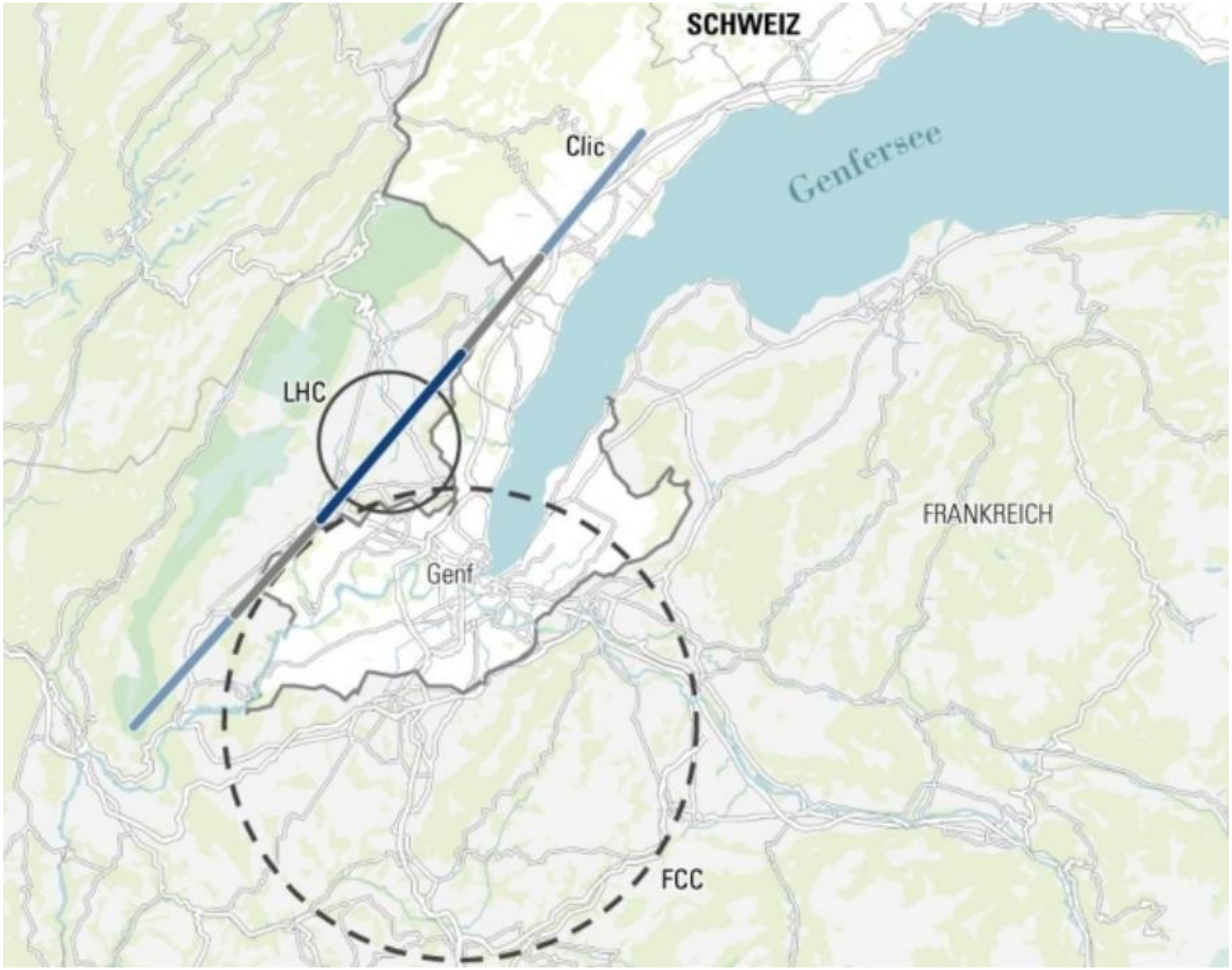
Future directions for particle physics?



Outline

Why a linear collider?

General considerations

CLIC

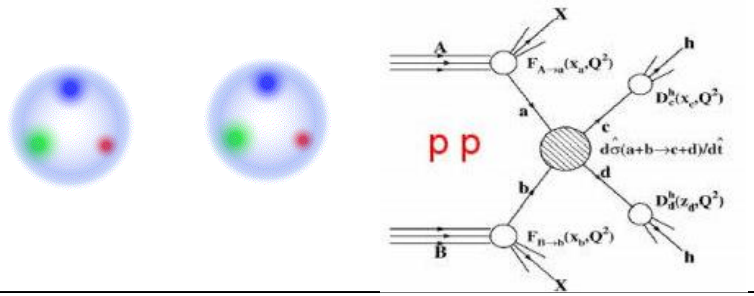
ILC

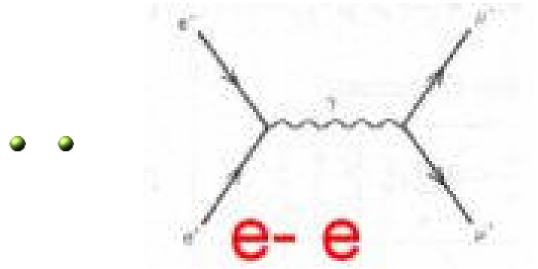
Summary

Hadron versus lepton colliders

Hadrons: composite objects

Leptons: known initial collision state



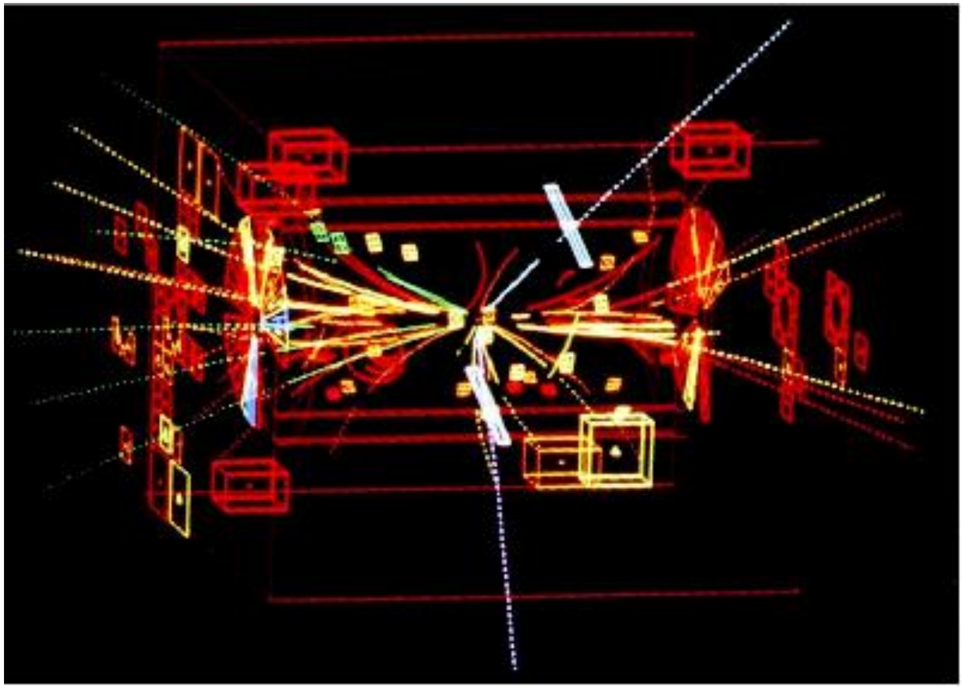


Lepton colliders have significant advantages over hadron colliders :

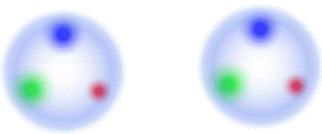
- **cleanliness:** reduced detector background with respect to LHC -> improved detector momentum and energy resolutio
- **democracy:** e+e- annihilation produces pairs of all species, new and exotic, at similar rates. No trigger needed, can measure absolute branching ratios and total width (unlike LHC)
- **calculability:** radioactive corrections more precise for EW interactions (LC) than for QCD (LHC). More precise calculations possible
- **detail:** Reconstruction of complete events, direct measurement of spin-dependence of production and decay processes possible

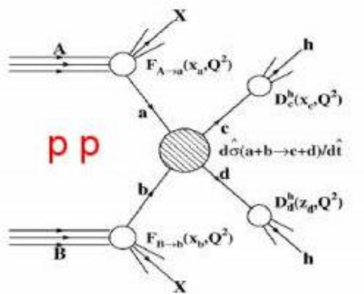
Desirable to operate a lepton collider (most likely electron-positron) operating at the same CoM energy as the LHC (~ TeV collisions). Case will be strengthen further if LHC discovers new physics at the TeV scale.

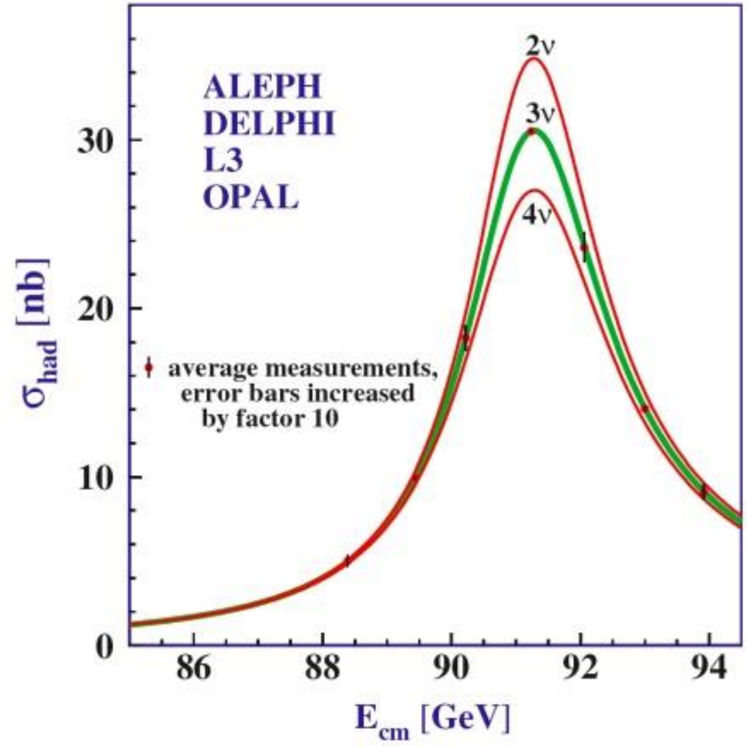
Hadron versus lepton colliders



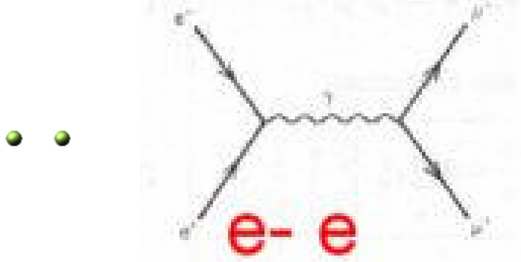
Hadron collider SppS, √s=540 GeV, $W^{+/-}$ and Z^0 discovery







Lepton collider LEP, $\sqrt{s}_{max}$=209 GeV, precision measurements of Z^0 decay width

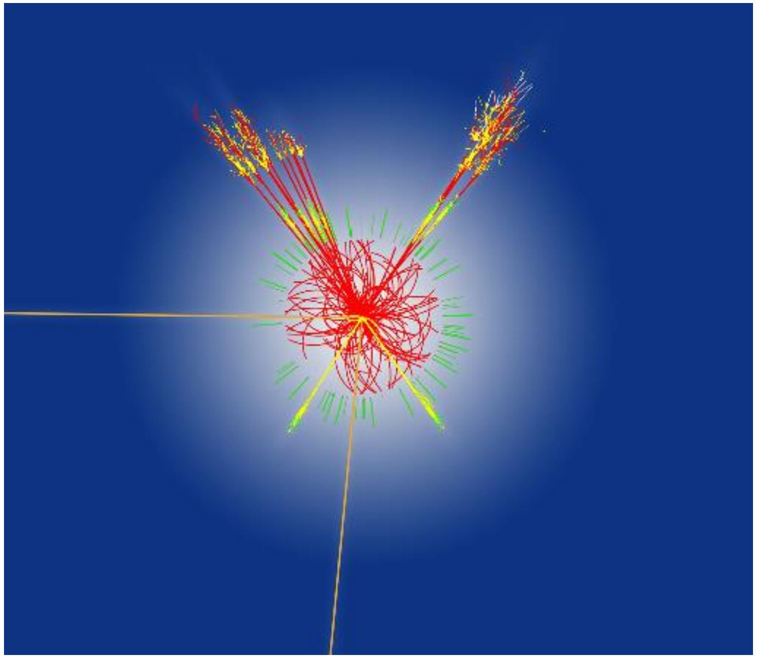


LHC versus future colliders

Example: Higgs physics

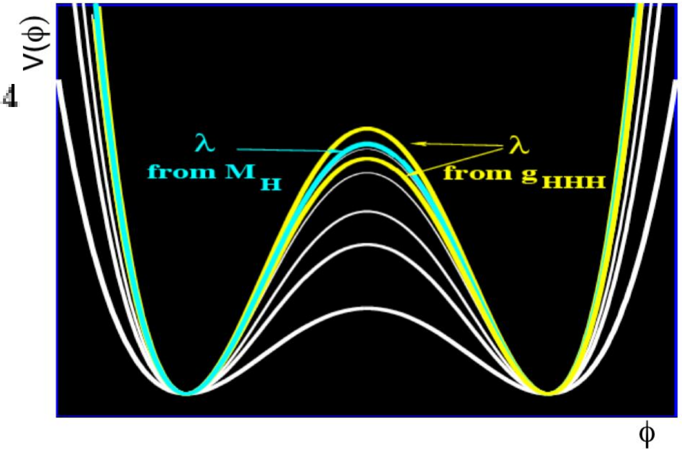
Standard Model Higgs:
- **scalar spin-0 particle**
- **specific form of scalar potential :**

$$V(\eta) = \lambda v \eta^3 + \frac{1}{4}\lambda\eta^4$$

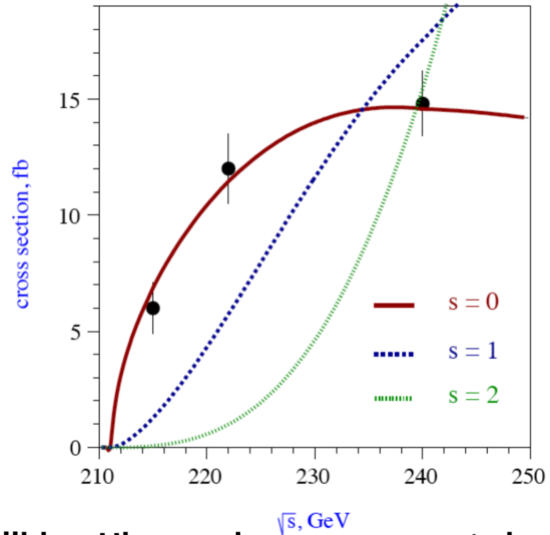


ATLAS and CMS@LHC, discovery of a Higgs boson confirmed in 2012. LHC continues to study properties of the Higgs boson. Precision numbers are key (e.g. mass measurements expected to 0.1% precision after 300 fb^{-1})

A linear collider can perform complementary Higgs physics.



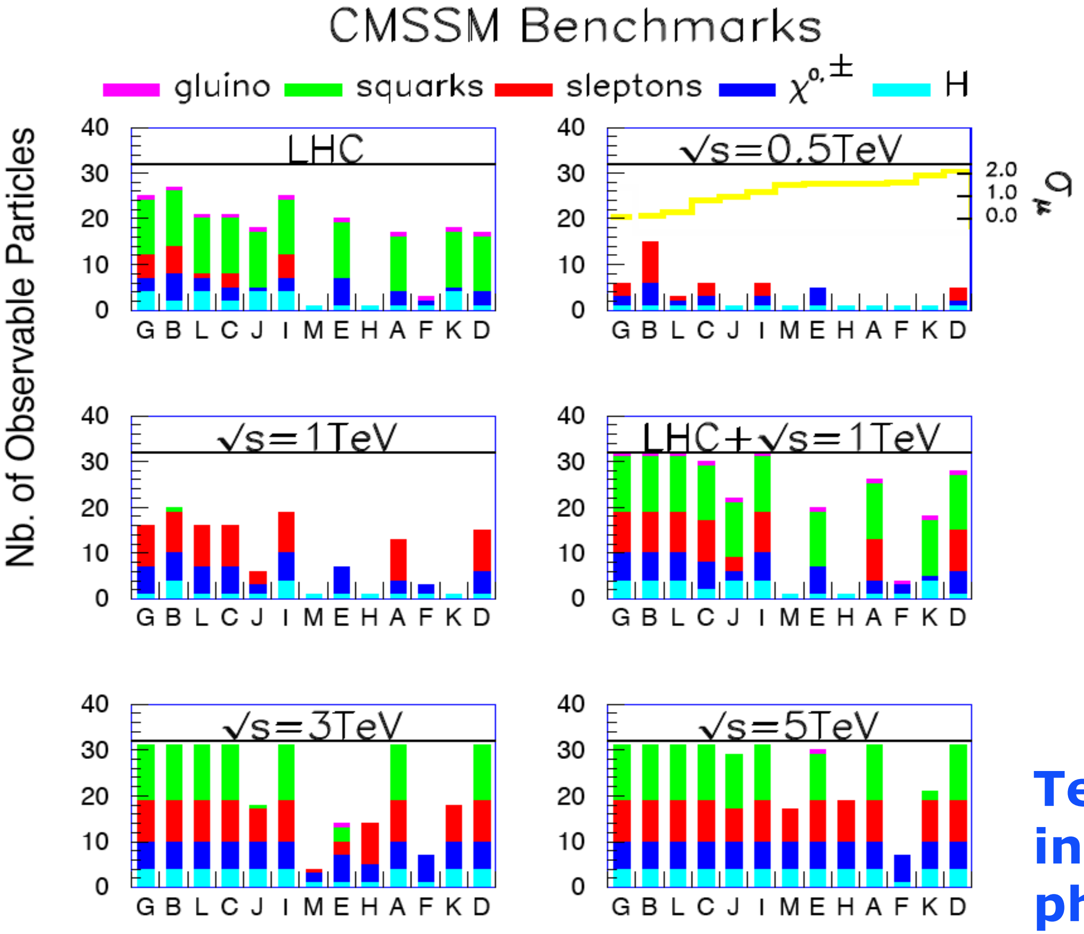
Linear Collider: Precision measurements if the trilinear HHH-coupling (Courtesy of M. Battaglia)



Linear Collider: Higgs spin measurements by energy scan (spin 0 established by LHC by other techniques)

Supersymmetry and new physics

LHC will indicate what physics, and at which energy scale. Depending on the new physics, the case for a Multi-TeV lepton collider may become even stronger.



SUSY reach for an e+e- collider

Supersymmetry:

- Extensive reach to measure SUSY particles

In addition:

- Probe for theories of extra dimensions
- New heavy gauge bosons (e.g. Z')
- Excited quarks or leptons

TeV-scale e- e+ collisions most interesting, depending on new physics.

http://lcd.web.cern.ch/LCD

Lepton collider energy limitation in rings

Synchrotron radiation power loss :

$$\boxed{P_e = \frac{e^2 c}{6\pi\varepsilon_0}\frac{1}{(m_0c^2)^4}\frac{E^4}{R^2}}$$

Any charged particle undergoing acceleration radiates, and looses energy.

U: energy loss per turn

$$\Delta U = \oint P dt = \frac{e^2}{3\varepsilon_0}\frac{1}{(m_0c^2)^4}\frac{E^4}{R}$$

C: cost of circular machine

$$\frac{\partial C_{\text{ring}}}{\partial R} = \frac{\partial}{\partial R}(R + \frac{E^4}{R}) = 0 \Rightarrow R \propto E^2$$

- **Limiting factor** for the LEP energy ($E_{cm,max}$ = 209 GeV)
- Total **cost scaling** for rings, as you scale energy **: ~E^2**
- With linear acceleration : ~E with respect to E^2 for rings
- **TeV e- e+ collisions**: circular colliders not a practical option. The main driver for linear collider research.

Outline

Why a linear collider

General considerations

CLIC

ILC

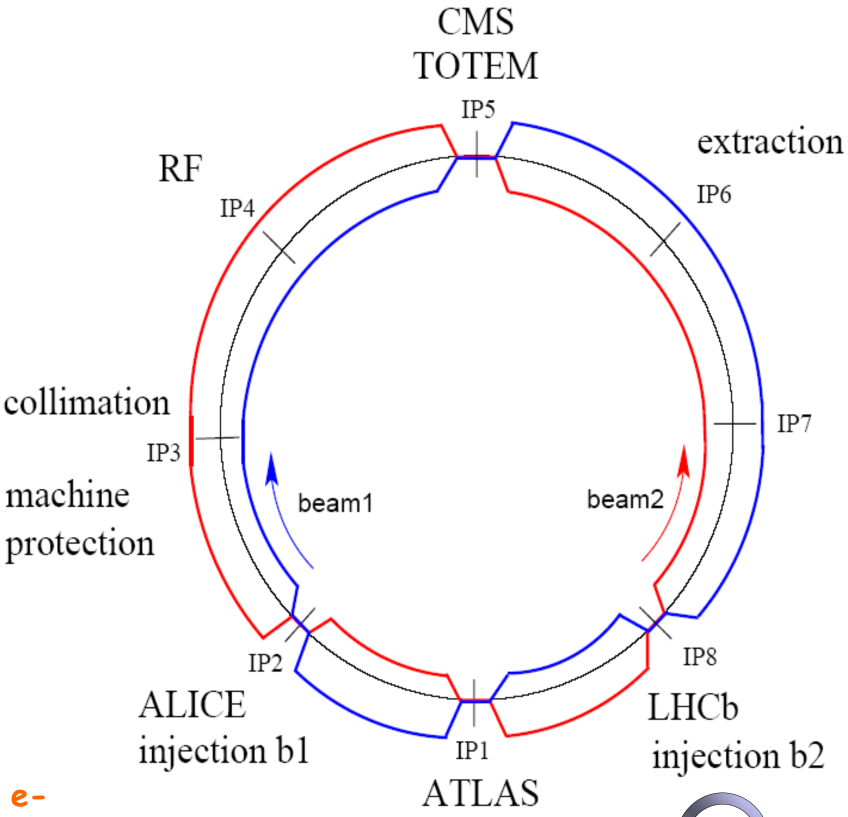
Summary

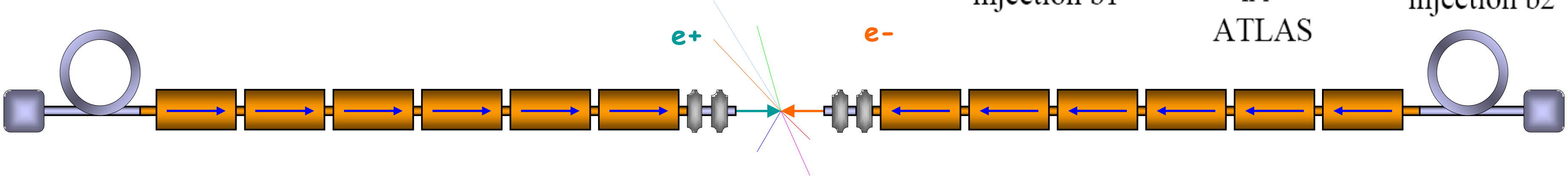
Circular versus linear colliders

We **lose two advantages of circular colliders** by going linear :
1) Each cavity accelerates each bunch only once
2) Each bunch only collide once

"Gedanken-experiment" LHC:
- Rf acceleration of ~10 MV/turn
- L = 10^{34} cm^{-2}s^{-1} realized by bunch crossing frequency of 40 MHz and 10^{11} particles per bunch

➔ corresponding to **1 TW beam power**





Linear collider: retain sufficiently high total acceleration voltage (centre of mass energy of ~TeV) and total collisions (luminosity ~10^{34}/cm^{2}/s) – while limiting the **total power consumption to a few 100 MW**

Reaching small beam sizes

Luminosity requirements push beam size requirements at the interaction-point down to 1 nm.

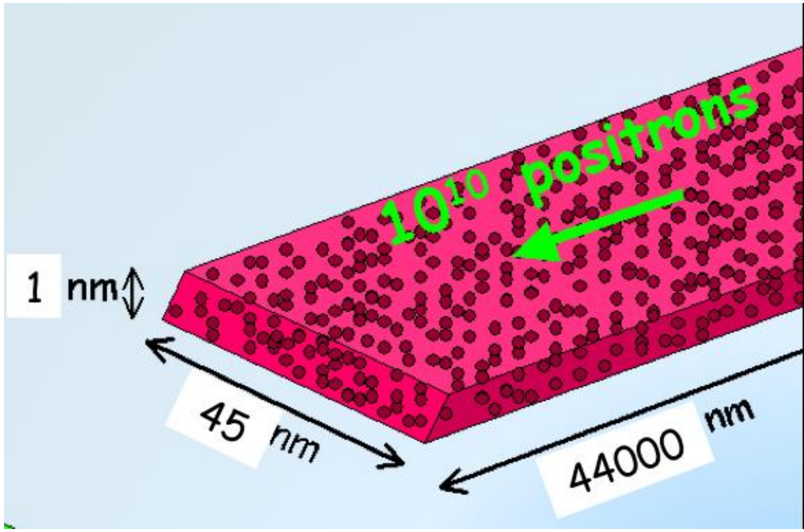
Beam size is give by :

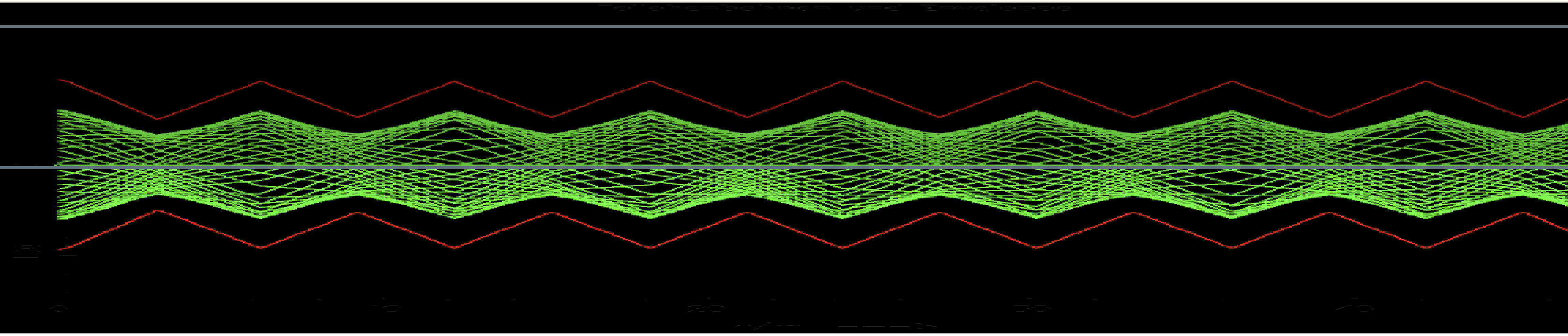
$$s(s)=\sqrt{e_{rms}b(s)}$$

Lattice

Beam quality: **emittance**

CLIC paramaters 2008





Summary challenges

Energy reach

$$E_{cm} = 2F_{fill}\, L_{linac}\, G_{RF}$$

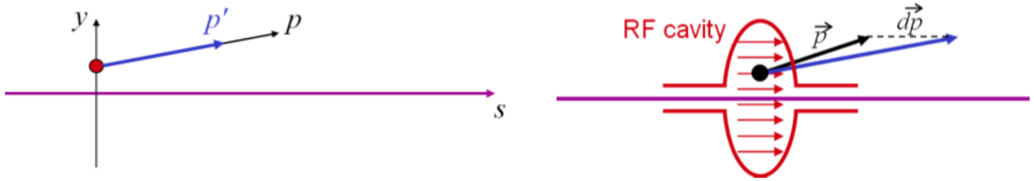
- Typical accelerator gradient ~10 MV/m -> ~100 km site for 1 TeV collisions
- Structures: **large accelerating gradient** with low breakdown rate

Luminosity

$$L = \frac{n_b N^2 f_{rep}}{4\pi\sigma_x^*\sigma_y^*} \times H_D \propto \frac{\eta_{beam}^{AC}\, P_{AC}}{\varepsilon_y^{1/2}}\, \frac{\delta_{BS}^{1/2}}{E_{cm}}$$

- Beam acceleration: ~10 **MW of beam power with high gradient and efficiency**
--- compare to "1 TW" LHC type beam: reduce beam sizes by a factor ~10^5

- **Generation of ~10 nm vertical emittances by radiation damping (damping rings):**



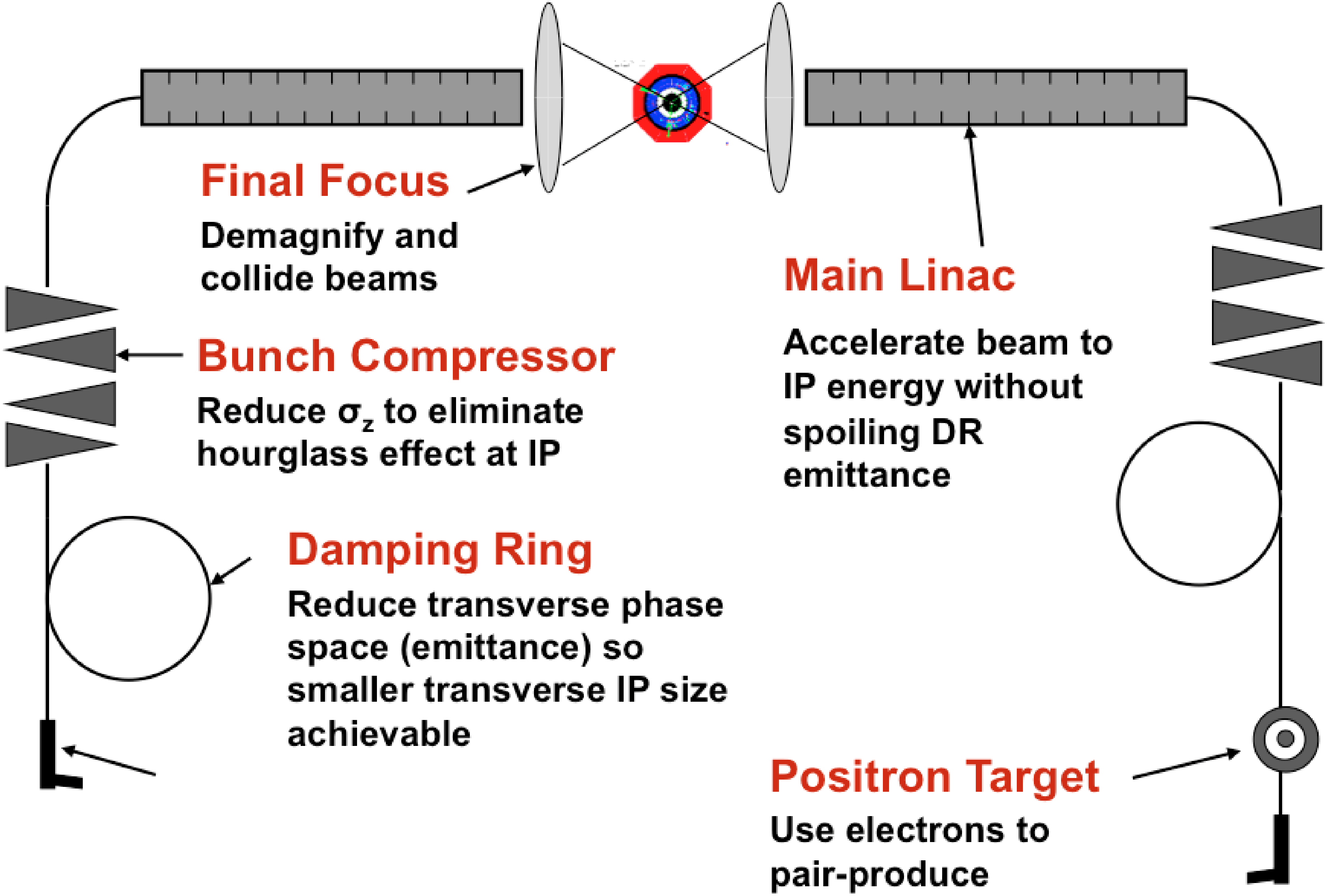
- **Preservation of ultra small emittances through main linacs :**

Precise static alignement, **beam-based alignment** plus advanced feedback and feed-forwards. **Stability of nanometer range**.

- **Chromaticity corrected final focus with beta function on the order of 100 um :**

Very strong final doublet magnets, and sextupoles to compensate chromatic aberrations. **Stability of sub-nanometer range**.

Linear collider conceptual scheme



Final Focus

Demagnify and collide beams

Main Linac

Accelerate beam to IP energy without spoiling DR emittance

Bunch Compressor

Reduce σ_z to eliminate hourglass effect at IP

Damping Ring

Reduce transverse phase space (emittance) so smaller transverse IP size achievable

Positron Target

Use electrons to pair-produce positrons

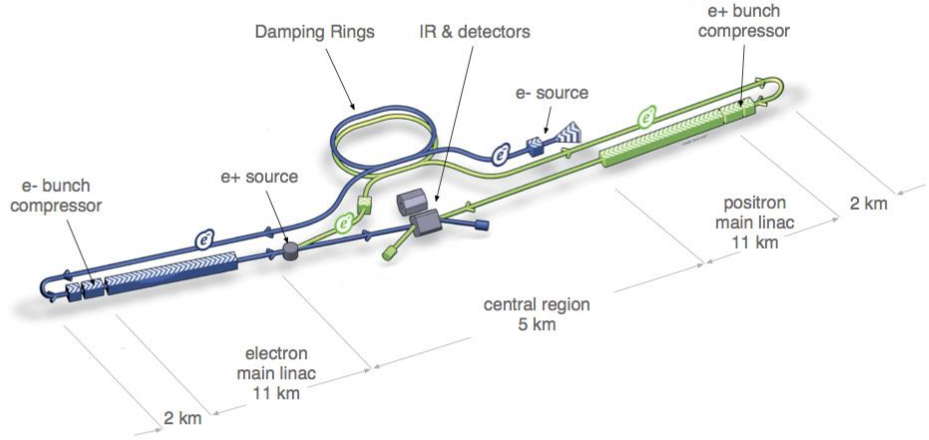
From B. Barish, ILC school 2012

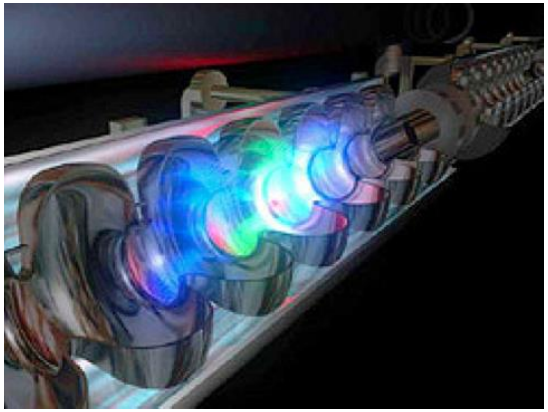
Linear Collider Projects

The International Linear Collider, **ILC**

Main linac technology: super conducting rf 1.3 GHz SW cavities, **31.5 MV/m**

Nominal design for $\mathbf{E_{CM} = 0.5\ TeV}$ (250 GeV to 1 TeV)

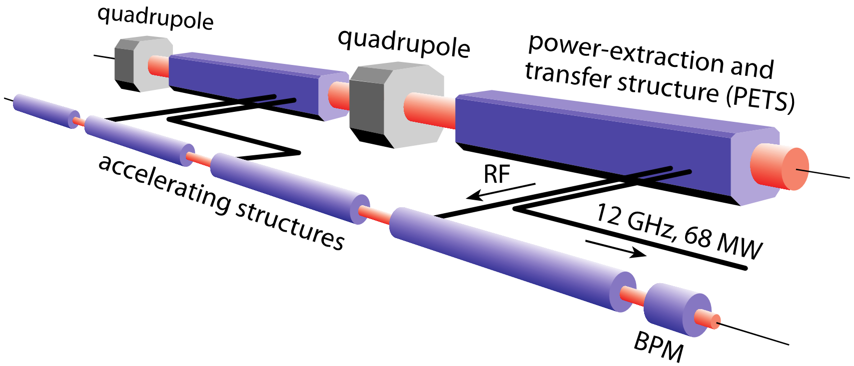


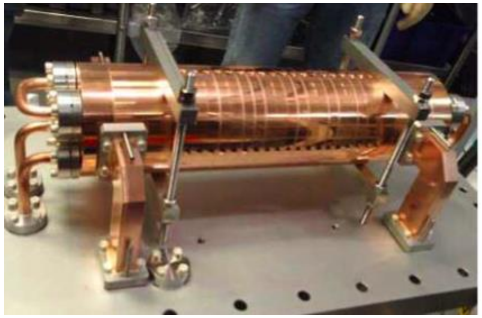


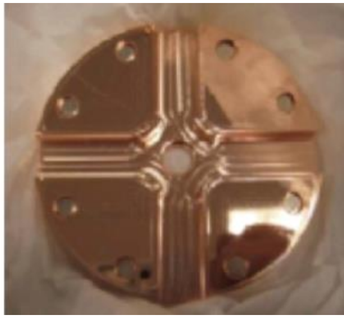
The Compact Linear Collider, **CLIC**

Main linac technology: normal conducting Cu rf 12 Ghz TW cavities, **100 MV/m**

Nominal design for $\mathbf{E_{CM} = 3\ TeV}$ (375 GeV to 3 TeV)







ILC

ILC main linac:1.3 GHz GHz super conducting Nb SW

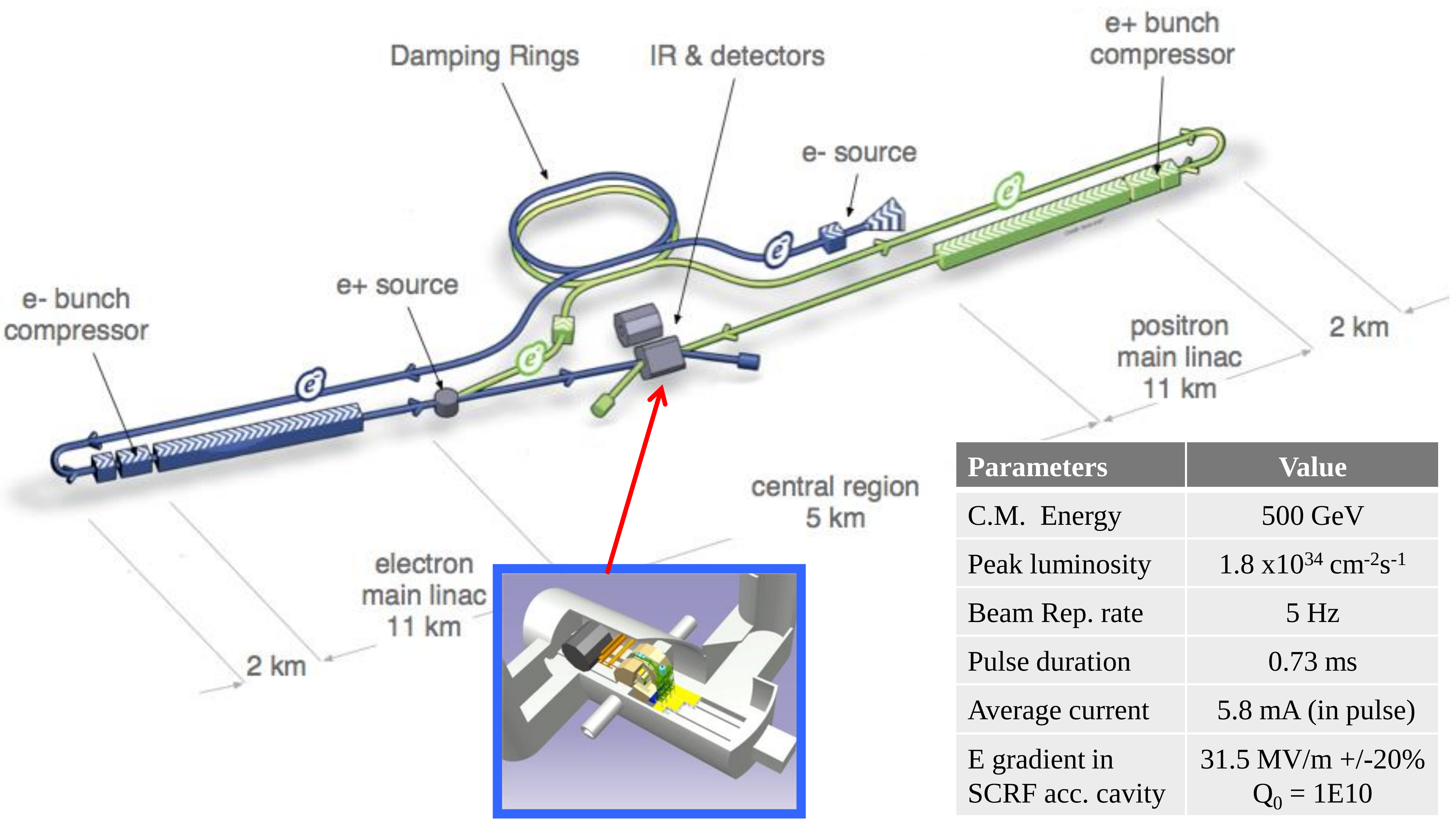
The ILC 9-cell cavity

- **31.5 MV/m average gradient**
- Gradient mainly **limited by superconductivity constraints**
- Allows for low rf frequency (1.3 GHz), long pulses while maintaining **high power efficiency**
- Low frequency rf **looser component tolerances,** lower wake fields

Niobium is the material of choice to fabricate SCRF cavities:

- High critical temperature (T_c = 9.25K)
- High critical field ($H_c(0K) \cong$ 200mT)
- Chemically inert (surface covered by oxide layer)
  - Easily machined and deep drawn
  - Available as bulk and sheet material in any size

The International Linear Collider



Parameters	Value
C.M. Energy	500 GeV
Peak luminosity	1.8 x10^{34} $cm^{-2}s^{-1}$
Beam Rep. rate	5 Hz
Pulse duration	0.73 ms
Average current	5.8 mA (in pulse)
E gradient in SCRF acc. cavity	31.5 MV/m +/-20% Q_0 = 1E10

- **Designed for E_{CM} energy = 500 GeV, upgradeable to 1 TeV, Higgs Factory start-up option 250 GeV**

ILC status

ILC TDR finalized !

http://www.linearcollider.org/ILC/Publications/Technical-Design-Report

Volume 1 - Executive Summary

Download the pdf (9.5 MB)

Volume 2 - Physics

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Volume 3 - Accelerator

Part I:
R&D in the Technical Design Phase

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Volume 3 - Accelerator

Part II:
Baseline Design

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From Design to Reality

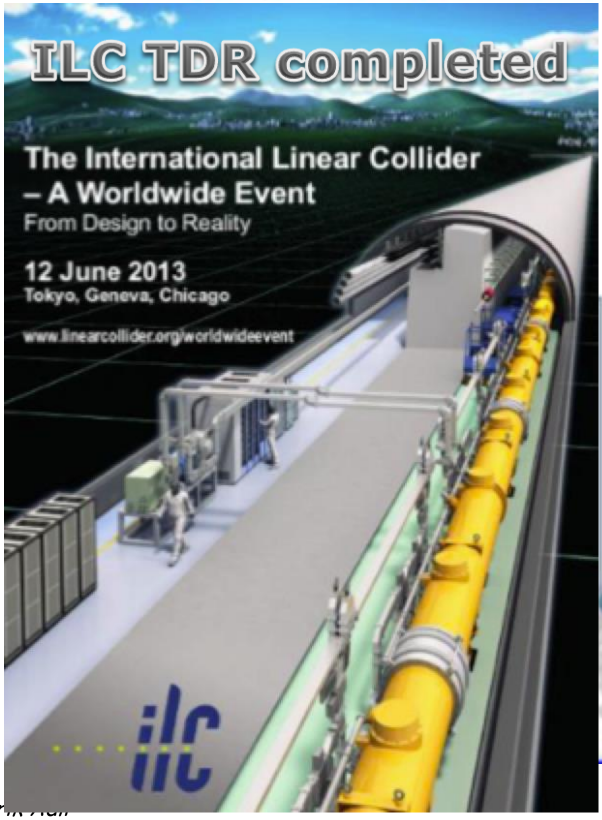
THE INTERNATIONAL LINEAR COLLIDER
FROM DESIGN TO REALITY

Download the pdf (5.5 MB)
Visit the web site

ILC: Japanese proposal

The Japanese scientific community has proposed **to host the ILC in Japan**, and commit to fund 50% of the material costs (**70% of an E_{cm} = 250 GeV first stage**), with construction to start as soon as feasible. Europe and USA positive, but financial level of support not yet clear.

- Japanese Mountainous Sites -

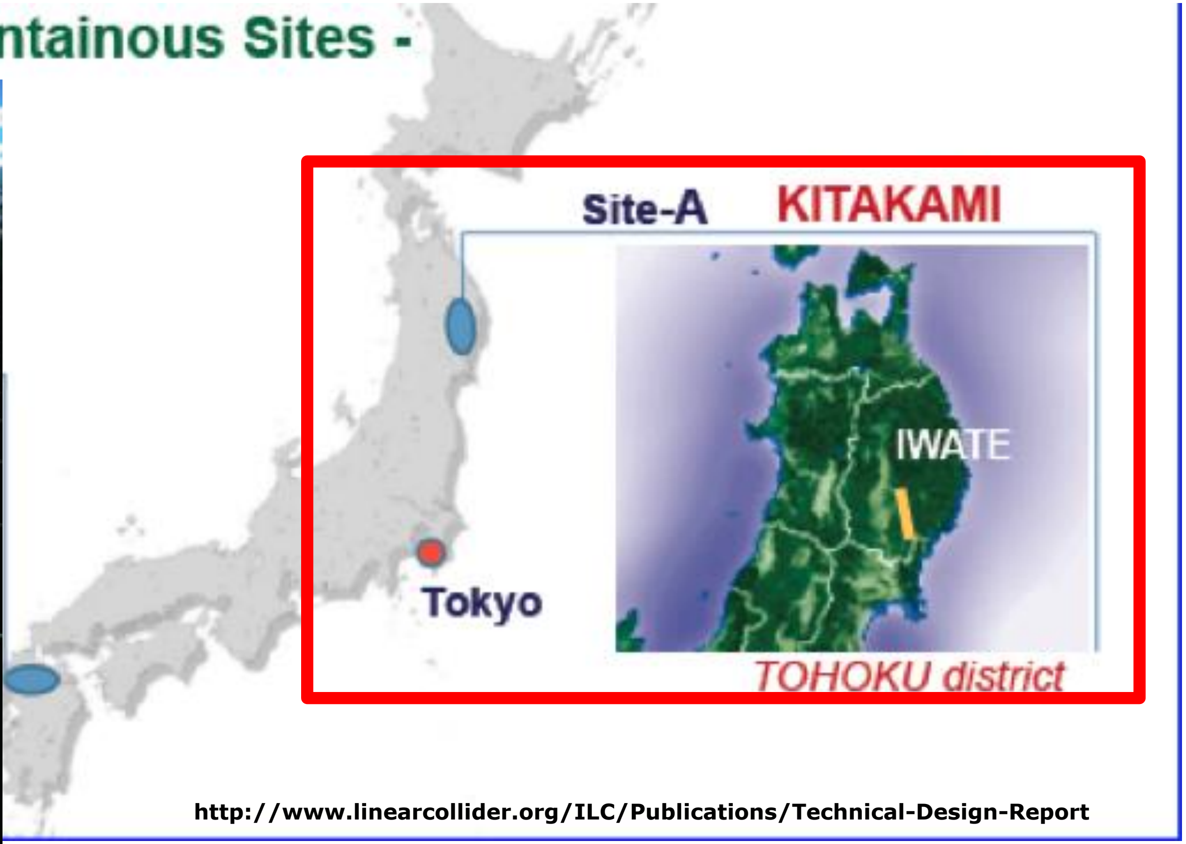


ILC TDR completed

The International Linear Collider
– A Worldwide Event
From Design to Reality

12 June 2013
Tokyo, Geneva, Chicago

www.linearcollider.org/worldwideevent



http://www.linearcollider.org/ILC/Publications/Technical-Design-Report

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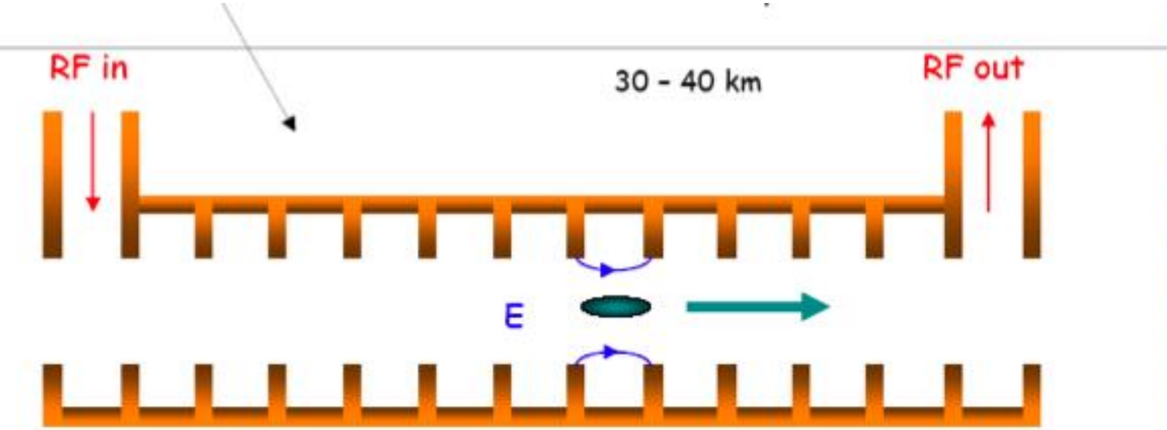
CLIC

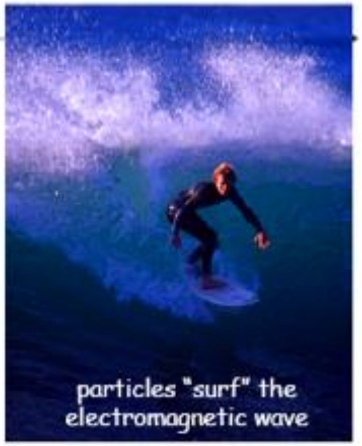
ILC

Summary

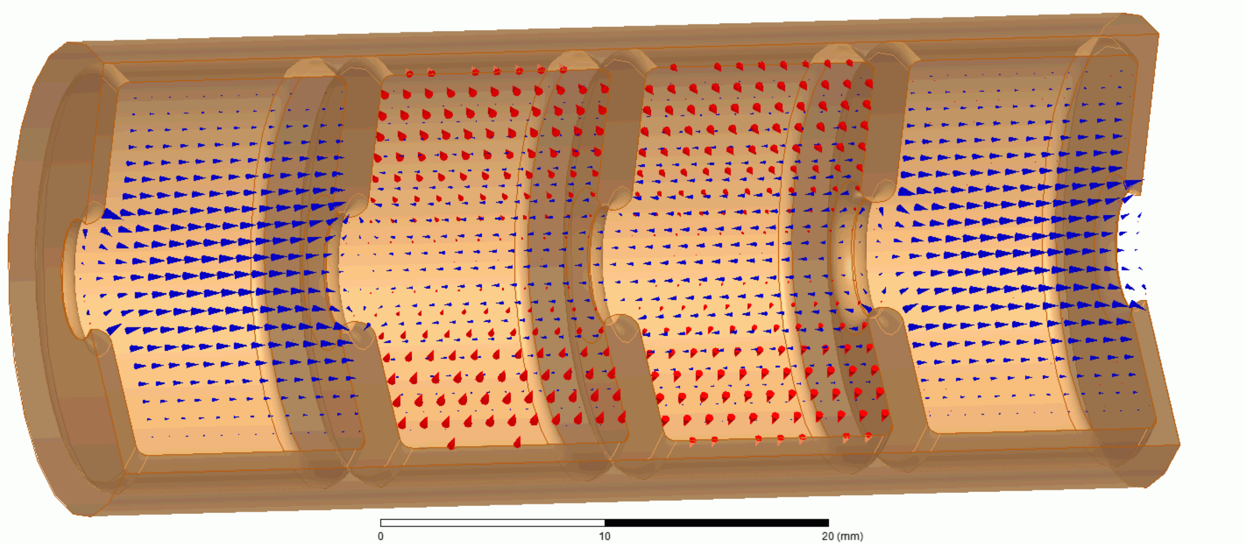
Electron linear accelerators

Electron linear accelerators: $v_{particle} = c$. Travelling wave coupled structures can be seen as a waveguide ($v_p > c$) "**disc-loaded**" with irises to reduces the phase velocity of a mode to $v_p = c$.





The main linac of the CLIC, 70% travelling wave structures



Animation by Rolf Wegner

High gradient limitations

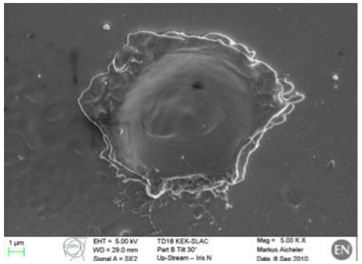
"Gradient"= effective **accelerating voltage / meter** [V/m]

* Field emission due to surface electric field

RF break downs

Break down rate (BDR) => Operation efficiency,

Local plasma triggered by field emission => Erosion of surface



Cu Surface after field break down

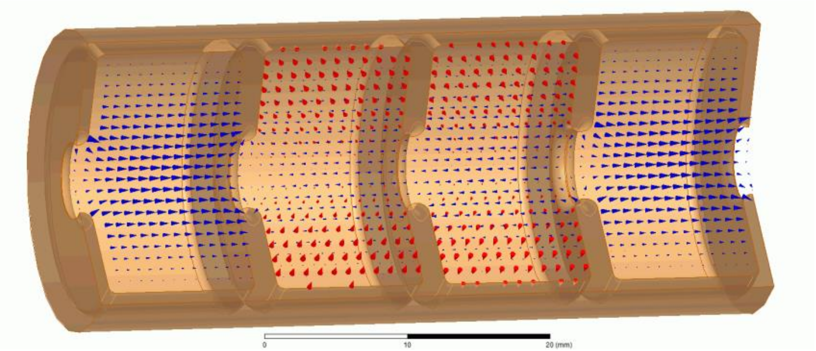
Break Down Rate = f(max field, rf pulse length, freq) ~ $\mathbf{E_{acc}^{30} t_p^{5}}$ (empirical)

* Surface magnetic field

Pulsed surface heating ΔT => material fatigue => cracks => limit length of rf pulse length

CLIC accelerating structure – pushes RF technology to the limits:

- **12 GHz** Copper
- **100 MV/m gradient** (loaded)
- **BDR** < 3 x 10^{-7}/pulse/m
- Rf pulse length: $\mathbf{t_p = 240}$ **ns**

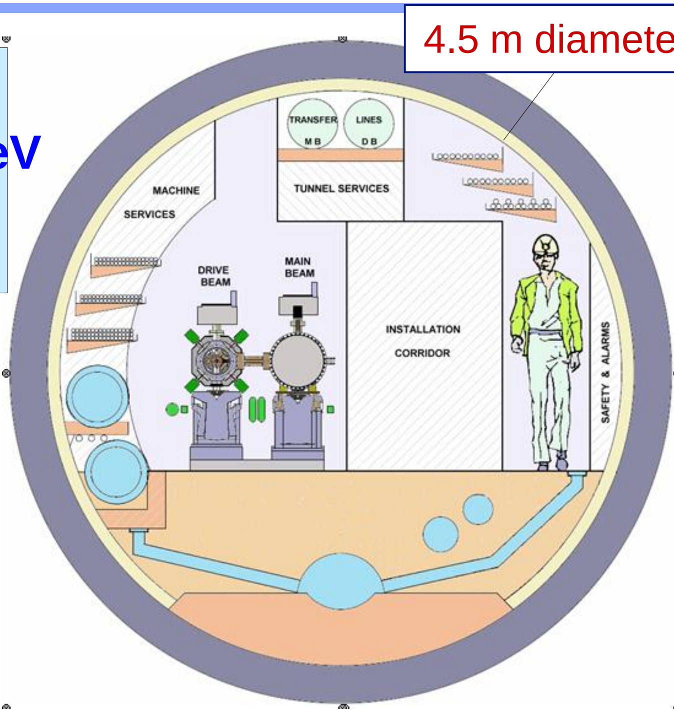


1 TeV collisions with 100 MV/m accelerating gradient yields a minimum of 10 km linacs.

Compact Linear Collider - CLIC

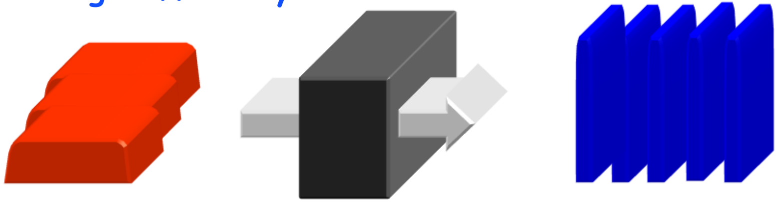
- **High acceleration gradient: > 100 MV/m**
  - **“Compact” collider: total length < 50 km at 3 teV**
  - **Normal conducting acceleration structures at high RF frequency (12 GHz)**

- **Novel Two-Beam Acceleration Scheme**
  - **Cost effective, reliable, efficient**
  - **Single tunnel, no active power components**
  - **Modular, staged energy upgrade**



CLIC TUNNEL CROSS-SECTION

Compact rf pulses: by e- compression



‘few’ Klystrons
Low frequency
High efficiency

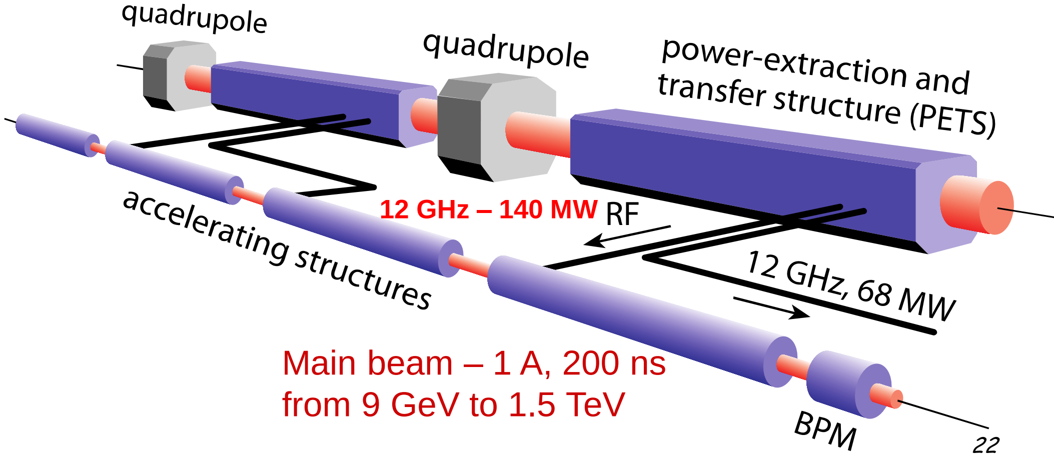
Accelerating Structures
High Frequency – High field
-> short pulses

Long RF Pulses
P_0 , τ_0

Electron beam manipulation : Power compression, Frequency multiplication

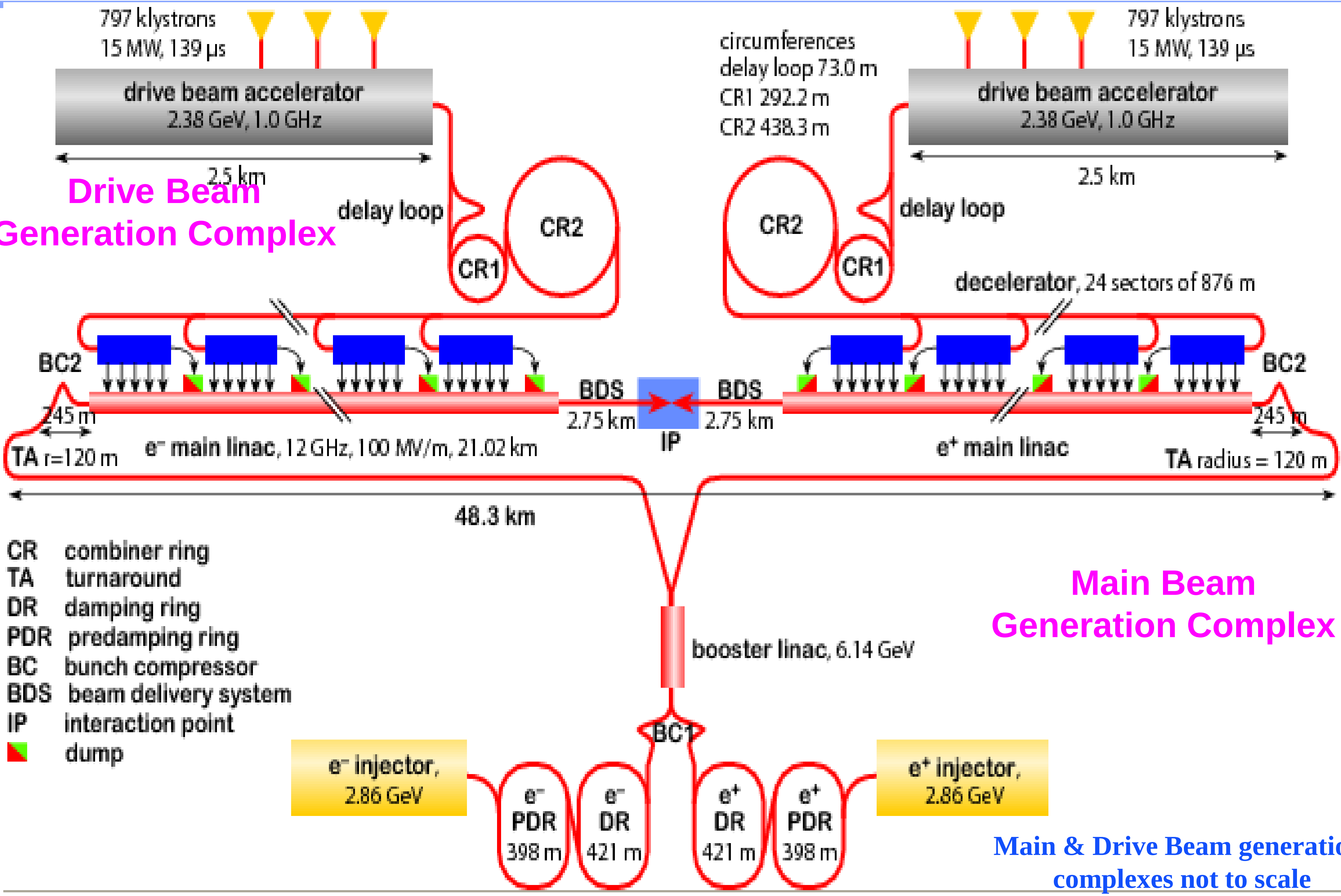
Short RF Pulses
$P_A = P_0 \times N$
$\tau_A = \tau_0 / N$

Drive beam - 100 A, 240 ns
from 2.4 GeV to 240 MeV



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

CLIC layout 3 TeV



CR	combiner ring
TA	turnaround
DR	damping ring
PDR	predamping ring
BC	bunch compressor
BDS	beam delivery system
IP	interaction point
🟥	dump

Drive Beam Generation Complex

Main Beam Generation Complex

Main & Drive Beam generation complexes not to scale

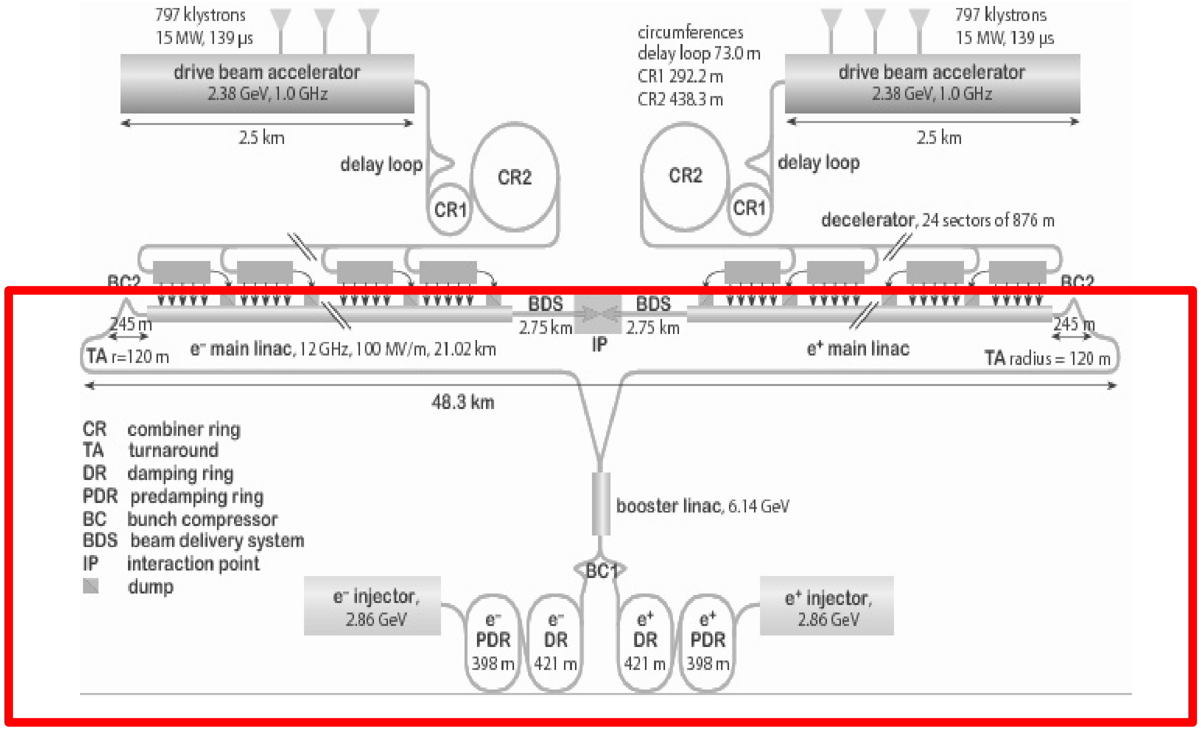
The CLIC collaboration

CLIC multi-lateral collaboration
48 Institutes from 25 countries

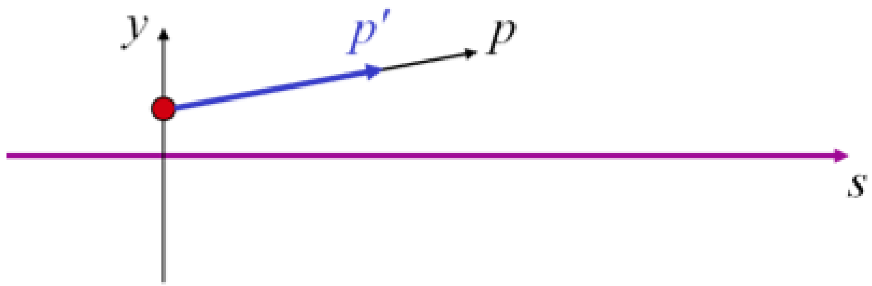
ACAS (Australia)
Aarhus University (Denmark)
Ankara University (Turkey)
Argonne National Laboratory (USA)
Athens University (Greece)
BINP (Russia)
CERN
CIEMAT (Spain)
Cockcroft Institute (UK)
ETHZurich (Switzerland)
FNAL (USA)
Gazi Universities (Turkey)
Helsinki Institute of Physics (Finland)
IAP (Russia)
IAP NASU (Ukraine)
IHEP (China)
INFN / LNF (Italy)
Instituto de Fisica Corpuscular (Spain)
IRFU / Saclay (France)
Jefferson Lab (USA)
John Adams Institute/Oxford (UK)
John Adams Institute/RHUL (UK)
JINR (Russia)
Karlsruhe University (Germany)
KEK (Japan)
LAL / Orsay (France)
LAPP / ESIA (France)
NIKHEF/Amsterdam (Netherland)
NCP (Pakistan)
North-West. Univ. Illinois (USA)
Patras University (Greece)
Polytech. University of Catalonia (Spain)
PSI (Switzerland)
RAL (UK)
RRCAT / Indore (India)
SLAC (USA)
Thrace University (Greece)
Tsinghua University (China)
University of Oslo (Norway)
Uppsala University (Sweden)
UCSC SCIPP (USA)

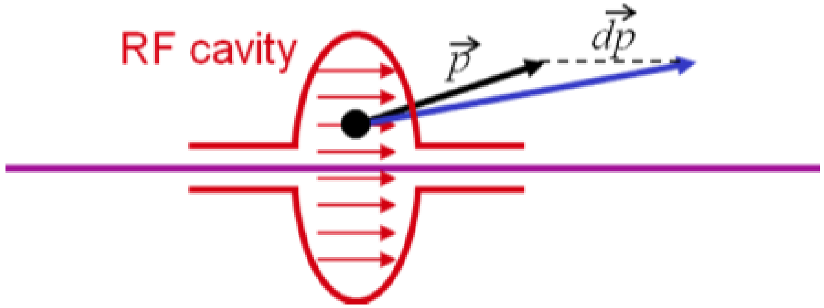
Walk-through of the CLIC main beam

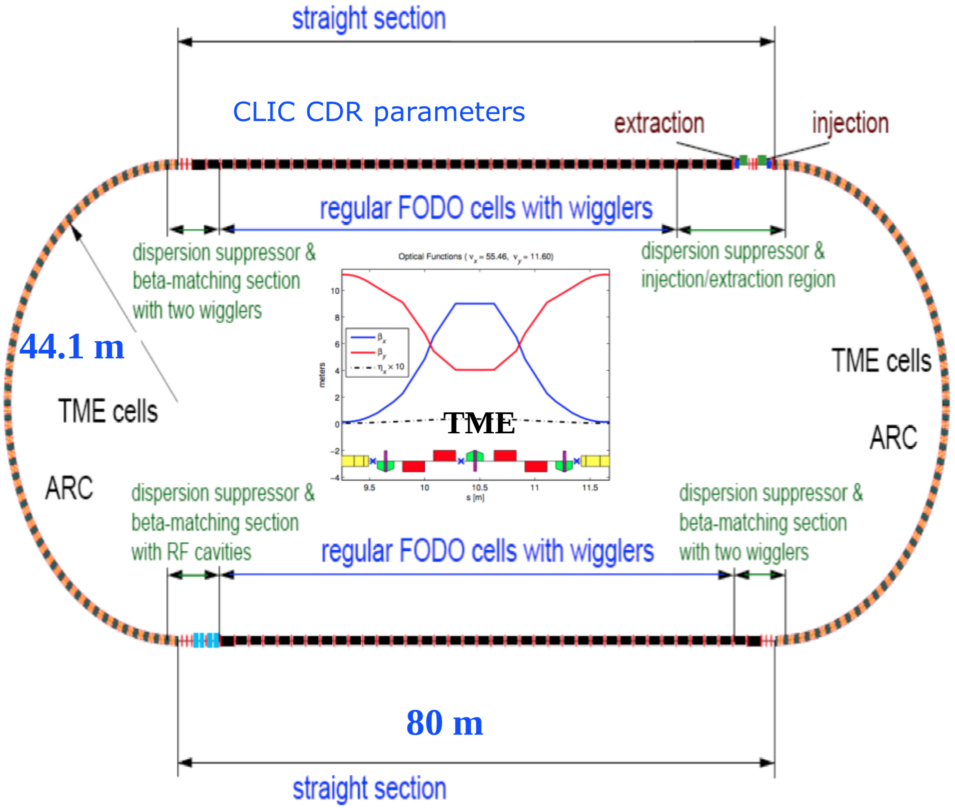
Corresponding to the "generic linear collider"



Damping rings: ultra low emittance







Very challenging CLIC requirements, **5 nm vertical emittance** at **50 Hz**

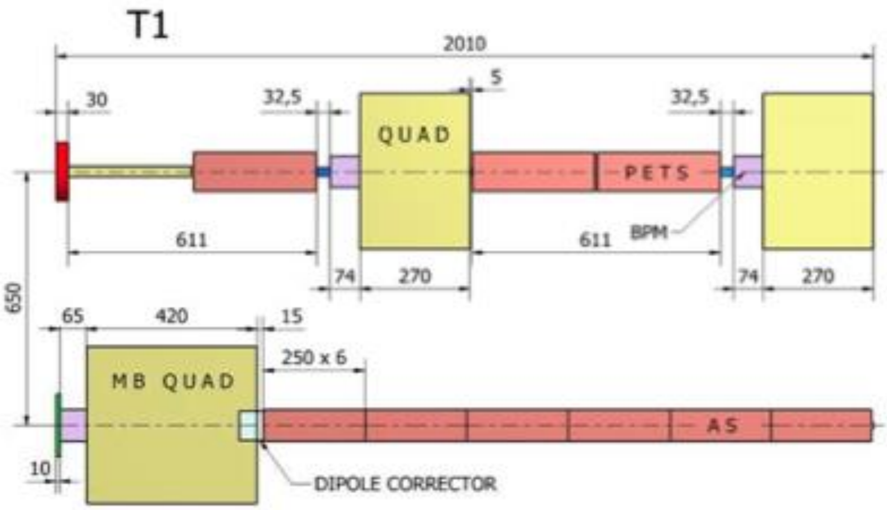
- Can be reached by radiation damping, for a very well aligned machine. Emittance targets comparable or more demanding than existing and planned synchrotron light sources
- Time to damp: a few ms damping time -> two-stage damping, **pre-damping rings required**
- Beam intensity in regime where **intra-beam scattering** becomes significant
- All of CLIC pulse (156 ns) fits inside the ring

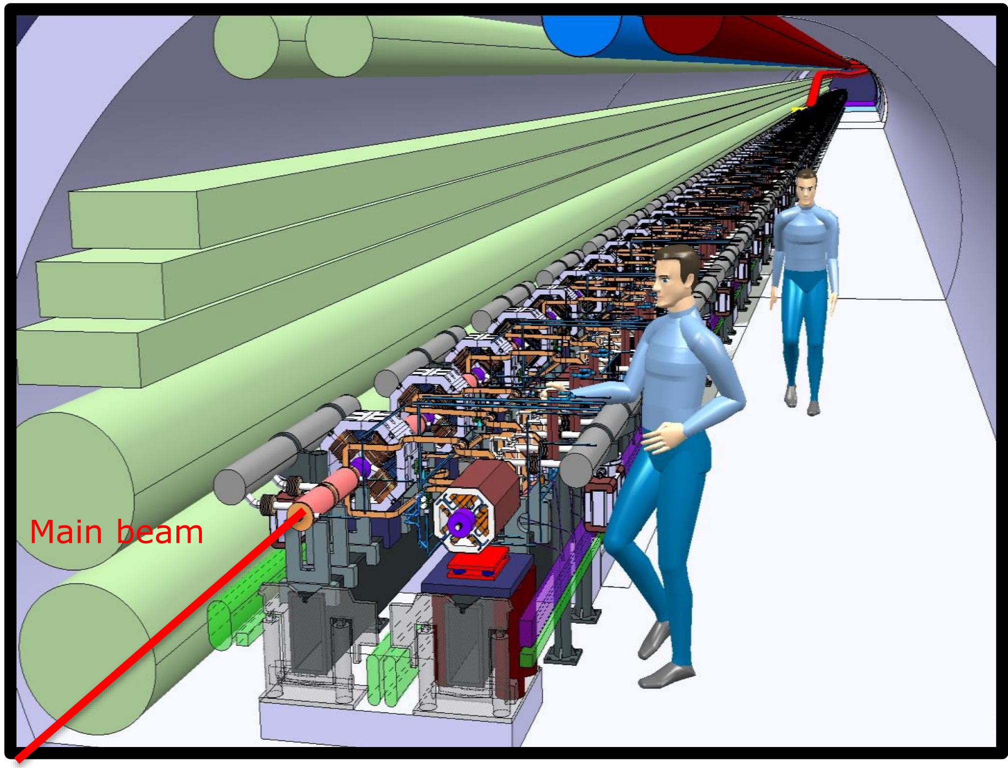
The CLIC main linac

Require **emittance preservation over 21 km of linac** $\Delta\varepsilon_{y,N} <= 10$ nm. Beam passes through **77,000** 100 MV/m accelerating structures and **2000** quadrupoles per linac.

Main sources of emittance growth:

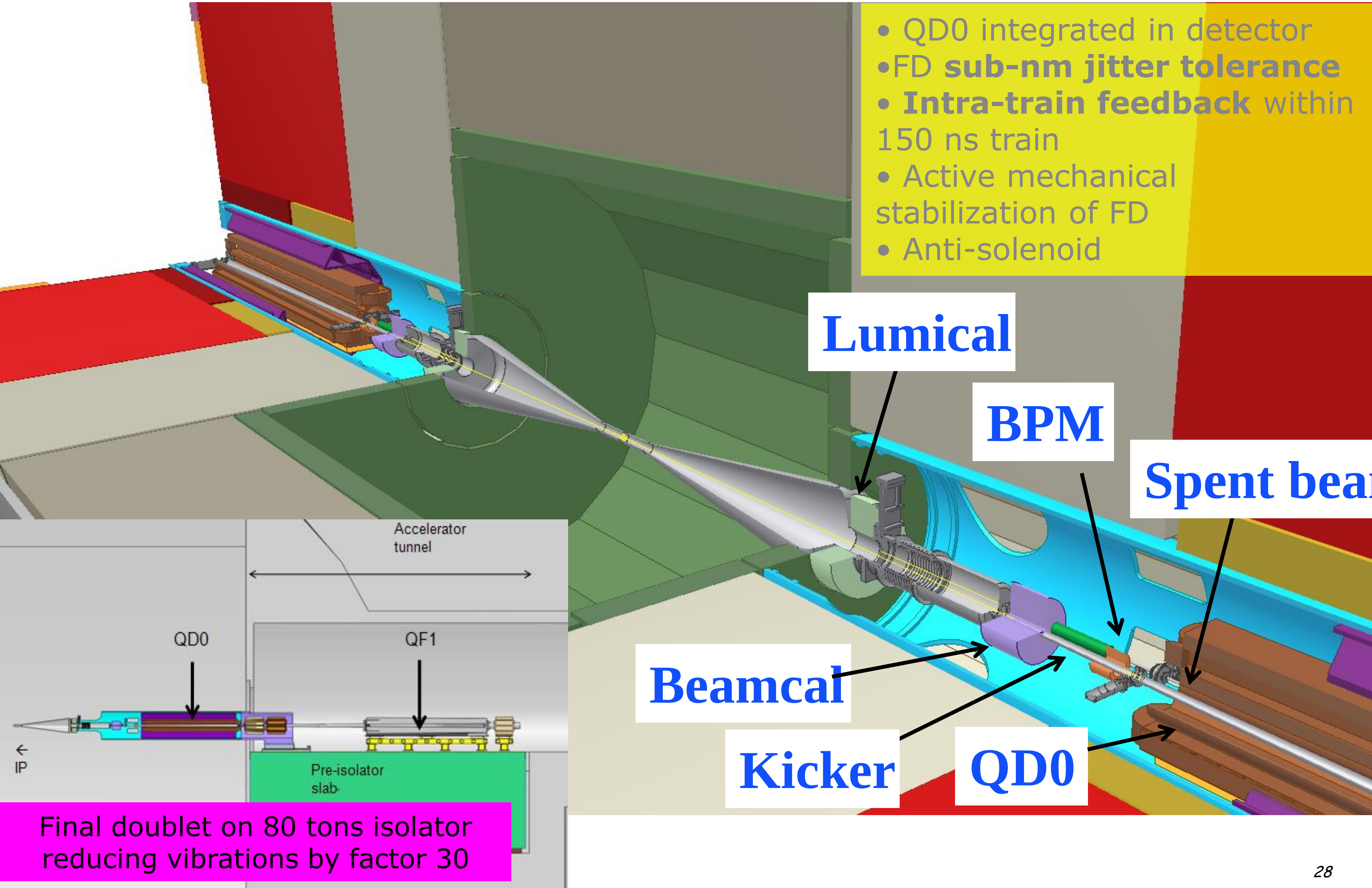
- **Wake fields**
- **Component misalignment**





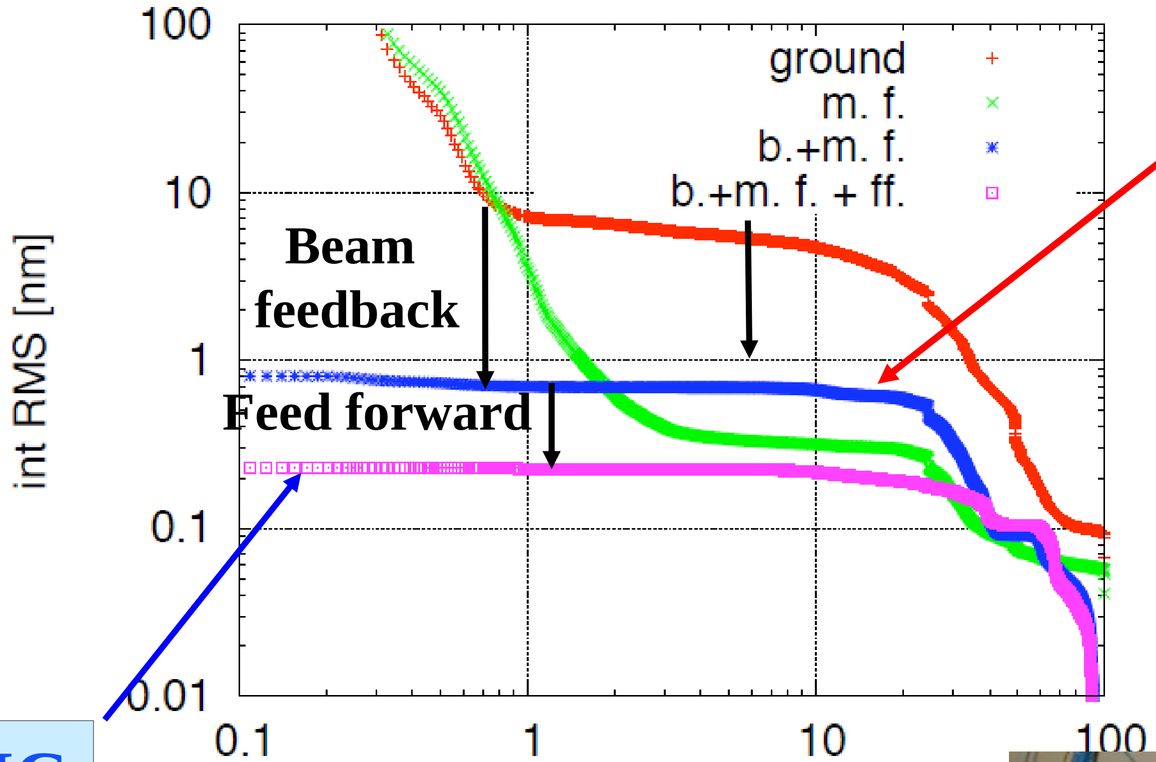
Machine-detector Interface

- QD0 integrated in detector
- FD **sub-nm jitter tolerance**
- **Intra-train feedback** within 150 ns train
- Active mechanical stabilization of FD
- Anti-solenoid



Final doublet on 80 tons isolator reducing vibrations by factor 30

Final doublet stabilization



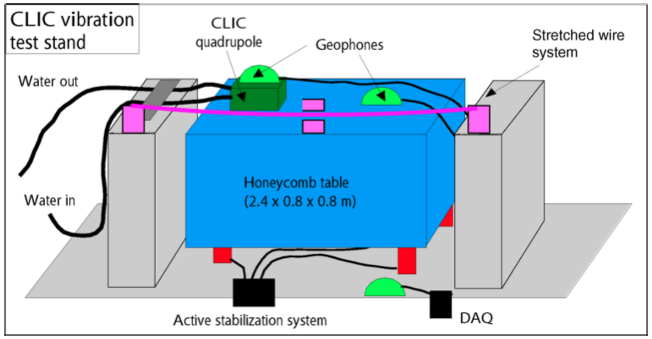
Beam feedback

Mechanical feedback

Feed forward

CLIC target

Sub-nm stability has been demonstrated experimentally :

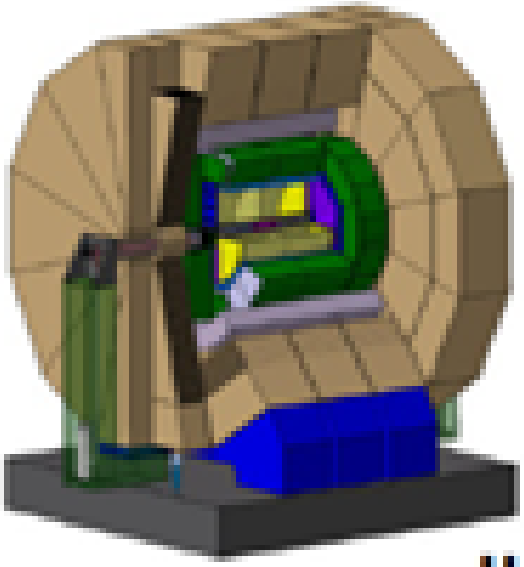


Detectors

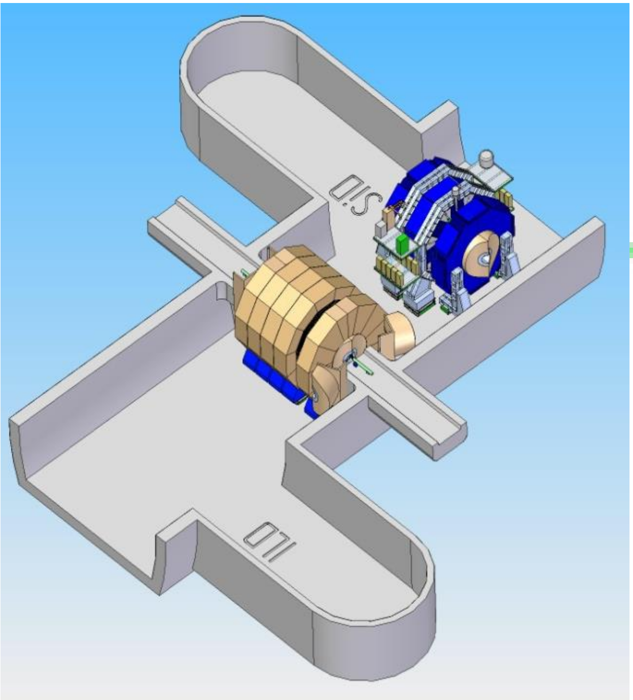
http://www.cern.ch/lcd

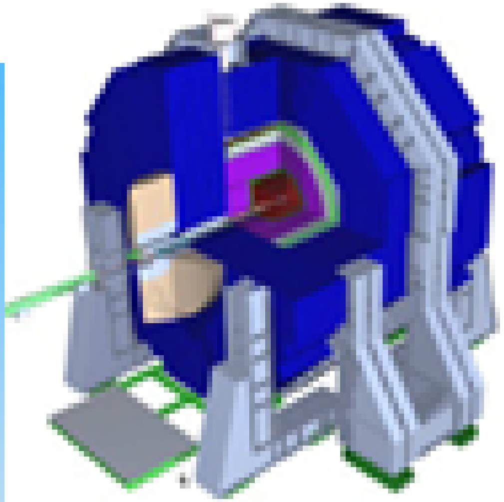
Push-pull concept: two detectors

CLIC detector concepts based on validated ILC detectors



ILD





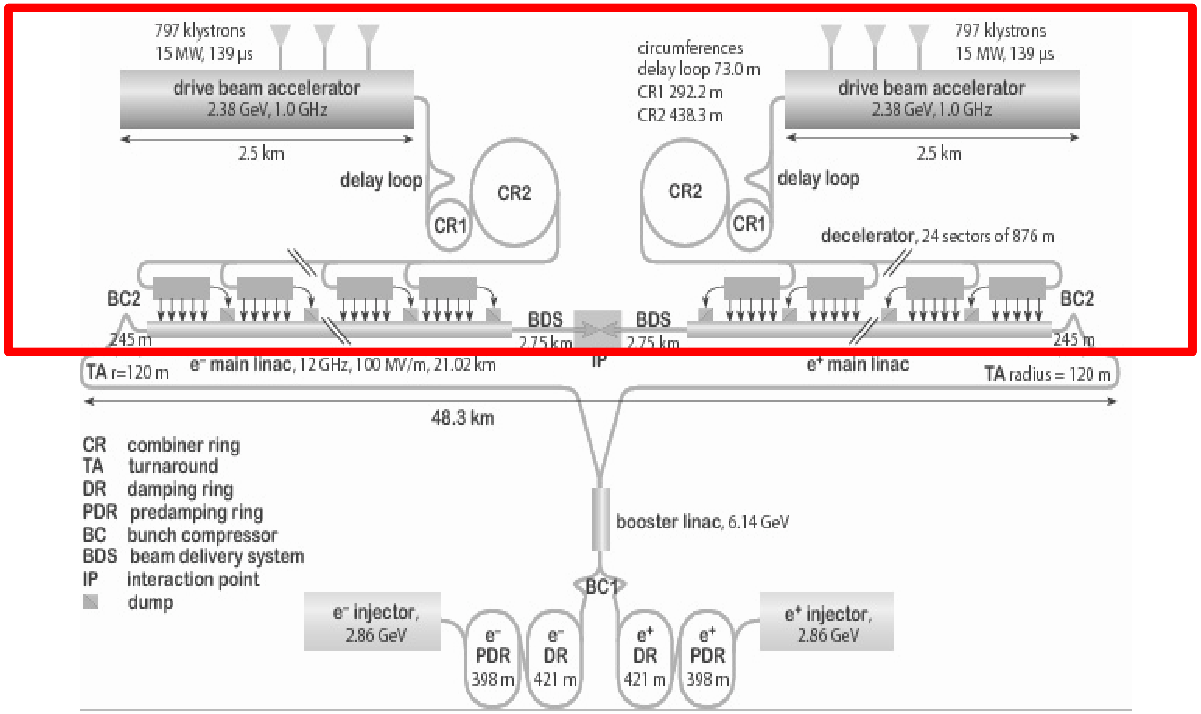
SiD

Specific CLIC challenges issues:

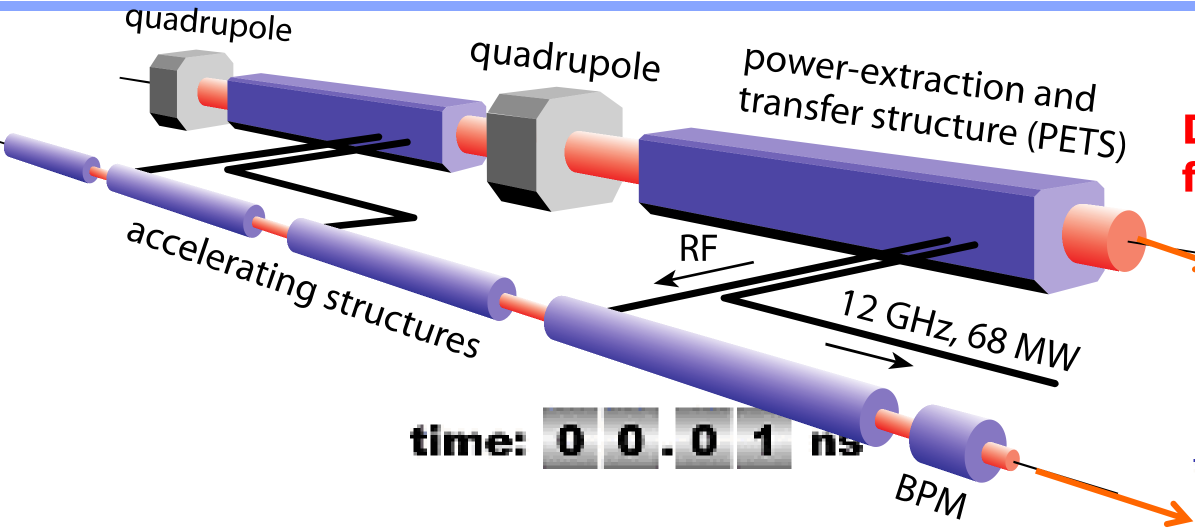
- **interval between bunches: 369 ns vs 0.5 ns**
- **Multi-TeV operation (beam-beam background)**

The CLIC drive beam rf power source

Unique for the CLIC two-beam acceleration scheme



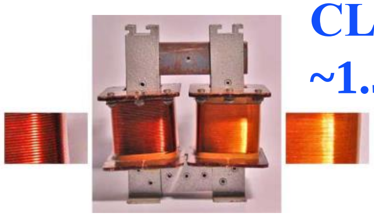
The CLIC Two-Beam scheme

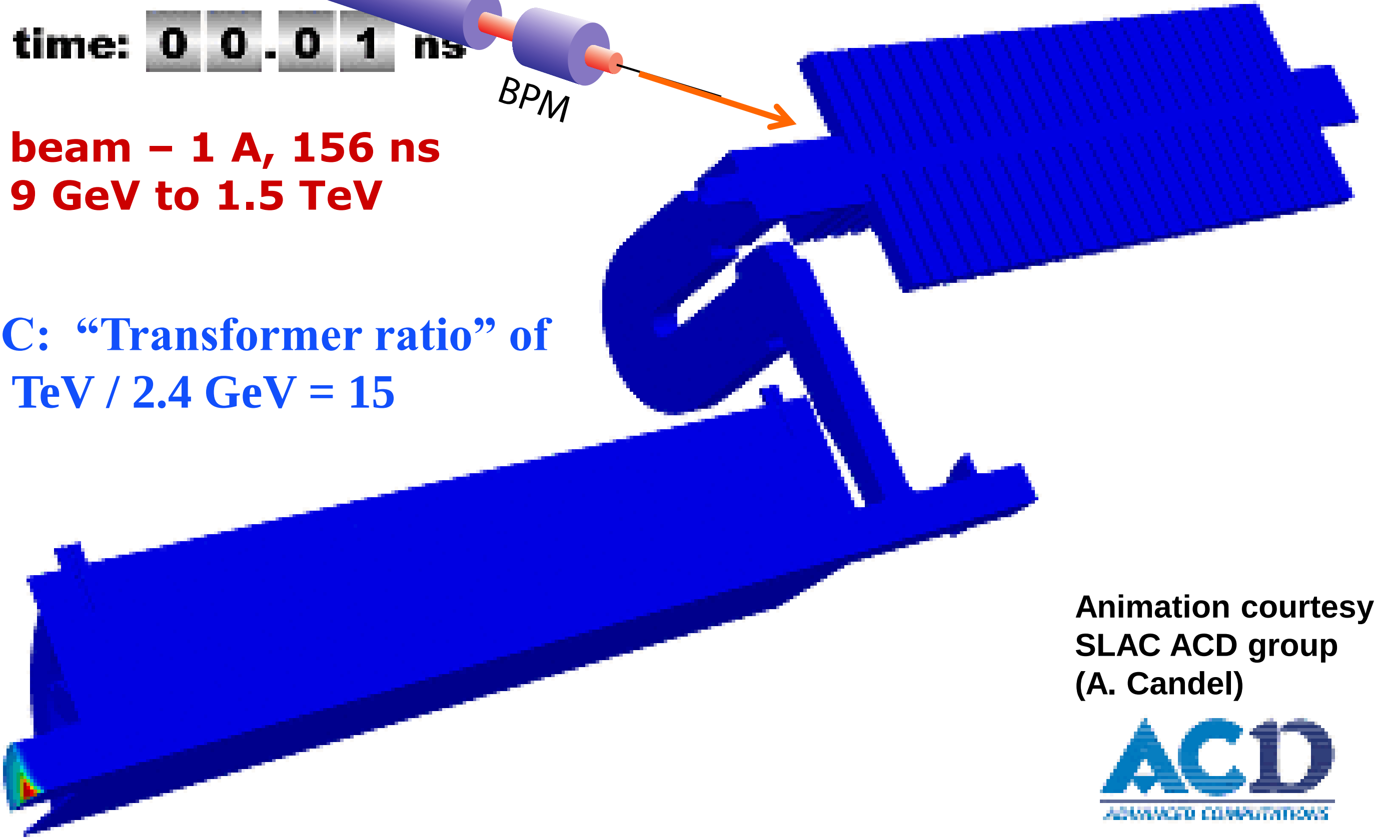


Drive beam - 101 A, 240 ns
from 2.4 GeV to 240 MeV

Main beam – 1 A, 156 ns
from 9 GeV to 1.5 TeV

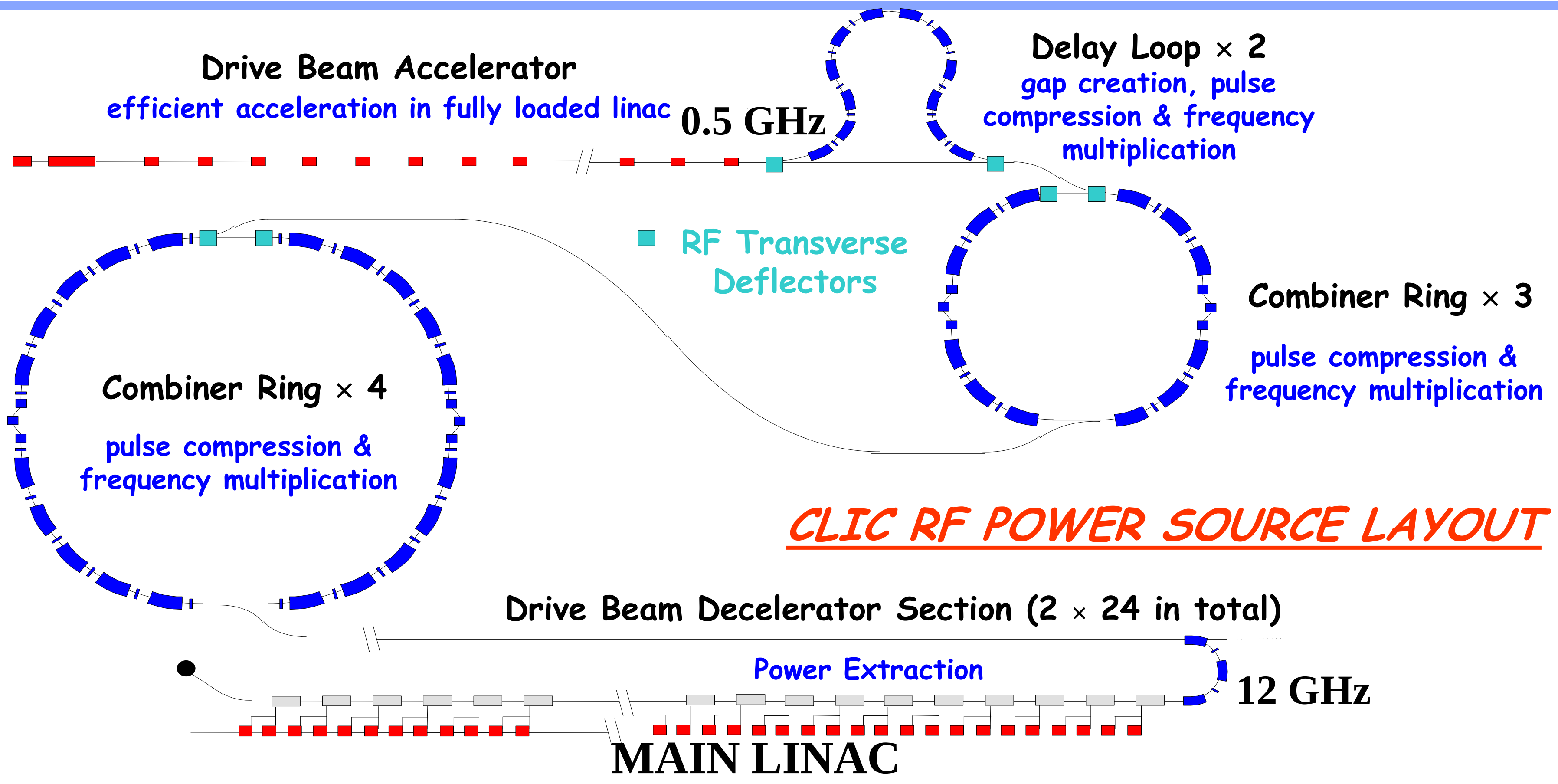
CLIC: “Transformer ratio” of
~1.5 TeV / 2.4 GeV = 15





Animation courtesy
SLAC ACD group
(A. Candel)

The CLIC Two-Beam scheme



Drive Beam Accelerator

efficient acceleration in fully loaded linac

0.5 GHz

Delay Loop × 2

gap creation, pulse compression & frequency multiplication

RF Transverse Deflectors

Combiner Ring × 3

pulse compression & frequency multiplication

Combiner Ring × 4

pulse compression & frequency multiplication

CLIC RF POWER SOURCE LAYOUT

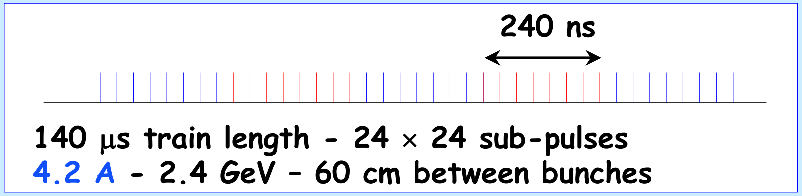
Drive Beam Decelerator Section (2 × 24 in total)

Power Extraction

12 GHz

MAIN LINAC

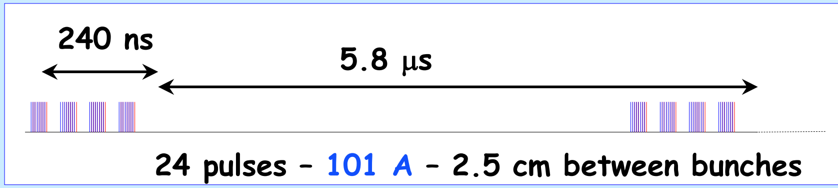
Drive beam time structure - initial



140 μs train length - 24 × 24 sub-pulses

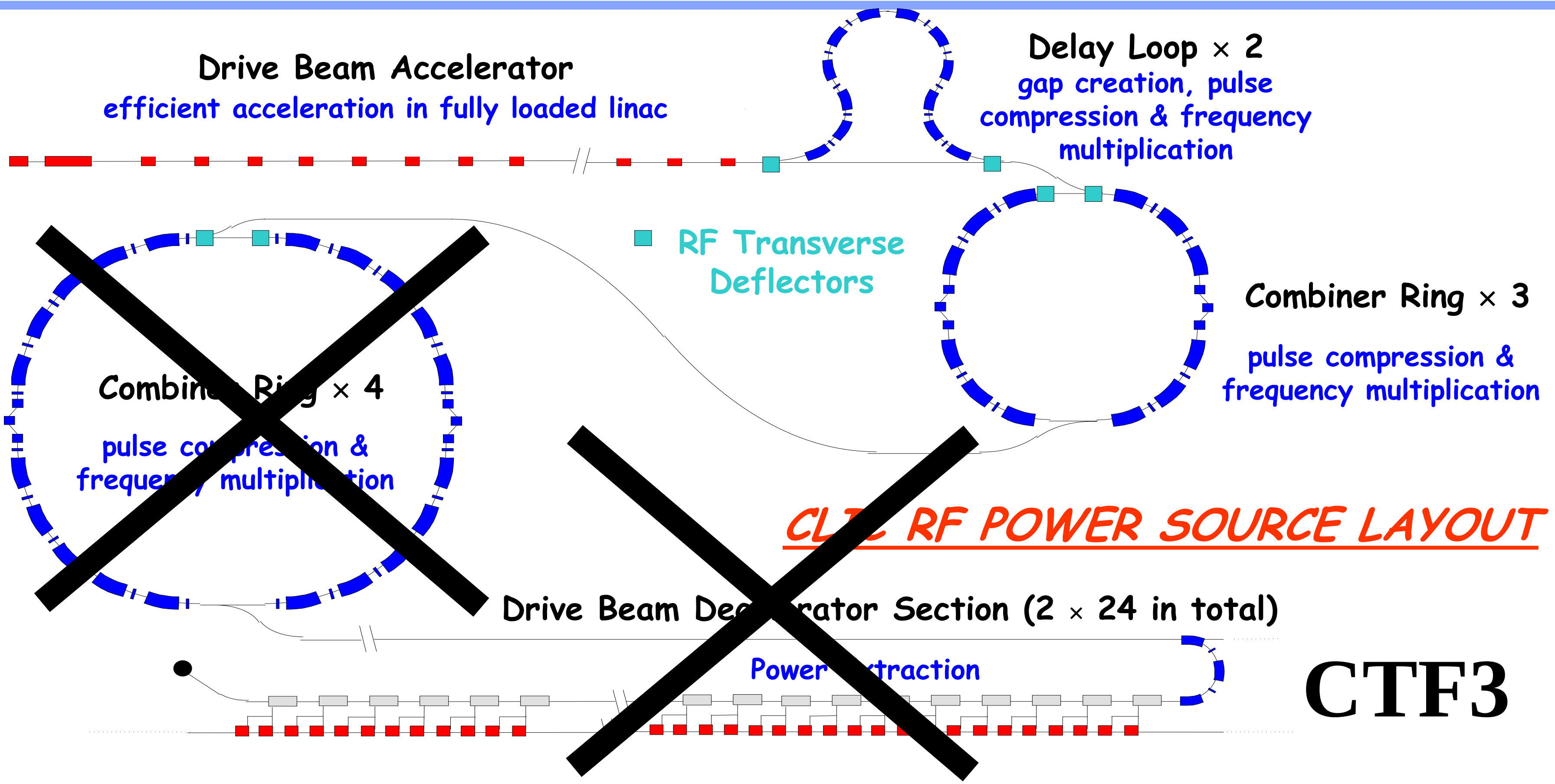
4.2 A - 2.4 GeV – 60 cm between bunches

Drive beam time structure - final



24 pulses – 101 A – 2.5 cm between bunches

The CLIC Test Facility 3



Drive Beam Accelerator
efficient acceleration in fully loaded linac

Delay Loop × 2
gap creation, pulse compression & frequency multiplication

RF Transverse Deflectors

Combiner Ring × 3
pulse compression & frequency multiplication

~~**Combiner Ring × 4**~~
~~pulse compression & frequency multiplication~~

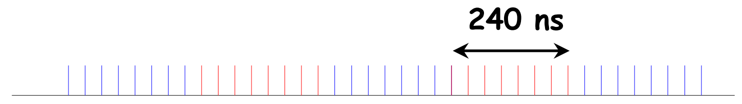
~~*CLIC RF POWER SOURCE LAYOUT*~~

~~**Drive Beam Decelerator Section (2 × 24 in total)**~~

~~Power Extraction~~

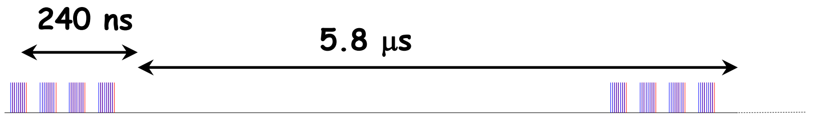
CTF3

Drive beam time structure - initial



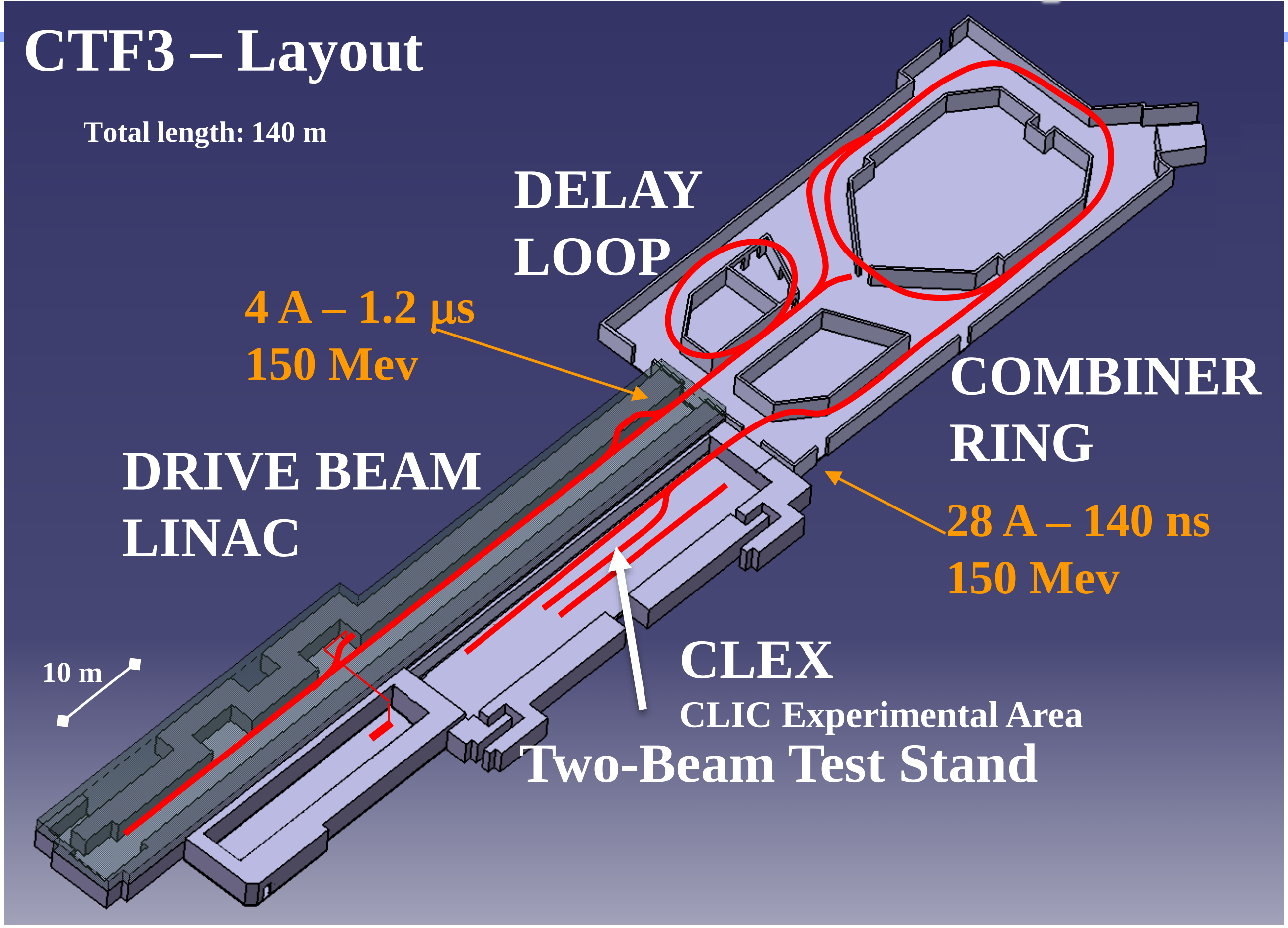
140 µs train length - 24 × 24 sub-pulses
4.2 A - 2.4 GeV – 60 cm between bunches

Drive beam time structure - final



24 pulses – 101 A – 2.5 cm between bunches

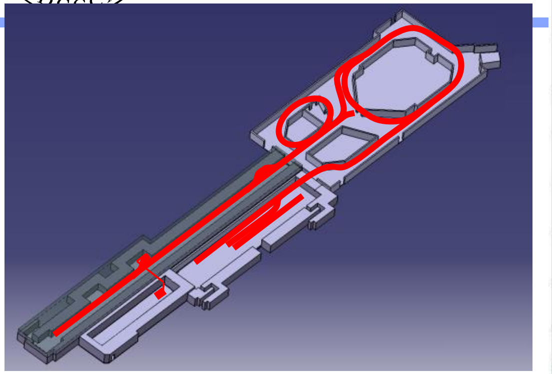
The CLIC Test Facility 3 at CERN

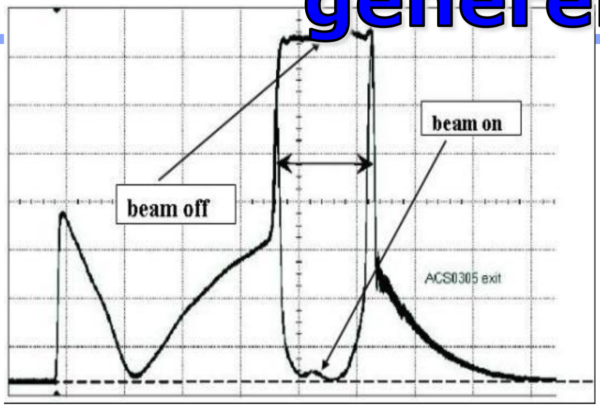


CLIC Test Facility 3 : designed to test key concept of the two-beam scheme. Main parts :

- ***Drive Beam generation*: acceleration in a fully loaded linac with 95 % efficiency and bunch frequency multiplication by a factor x 2 x 4 (from 1.5 GHz to 12 GHz)**
- ***Two-Beam Acceleration* experiment – reach nominal CLIC gradient and pulse length**
- ***Deceleration* experiment – heavy deceleration of intense electron beam (>50 %)**
- **Instrumentation tests**

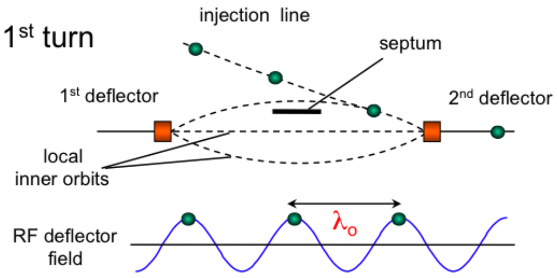
Milestones: drive beam genereration



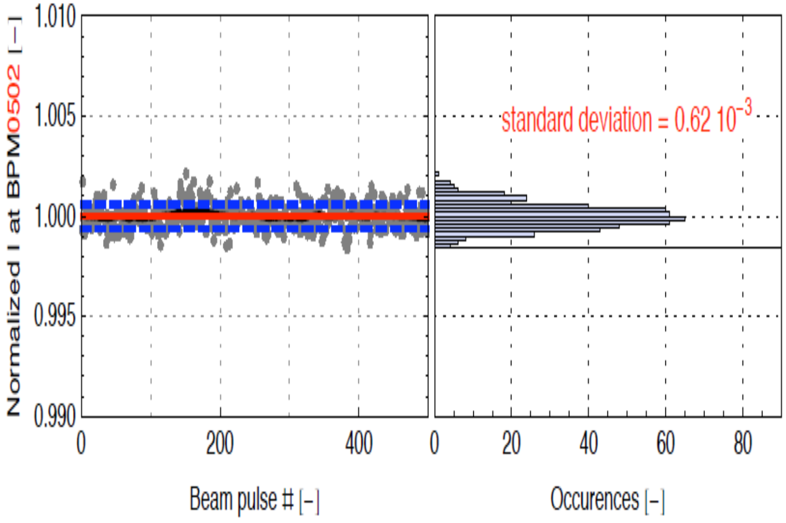


1.2 us drive beam pulse

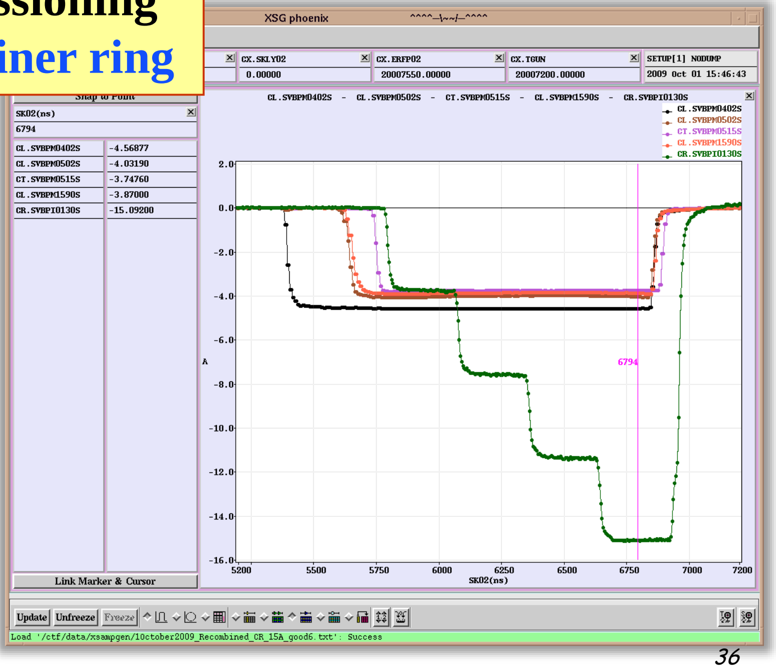
Fully loaded acceleration RF to beam transfer: 95.3 % measured. No issues found with transverse wakes in structures. Operation is routinely with full loading



Drive beam current stability at the end of the fully loaded linac : better than CLIC specification: 0.75 10^{-3}



Full commissioning of x 4 combiner ring



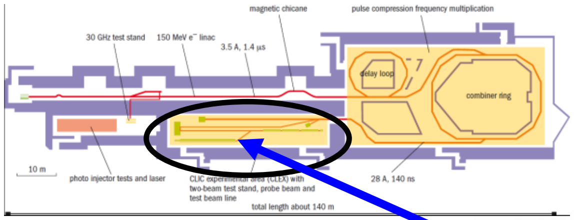
CX.SKLY02	CX.ERFP02	CX.TGUN	SETUP[1] NODUMP
0.00000	20007550.00000	20007200.00000	2009 Oct 01 15:46:43

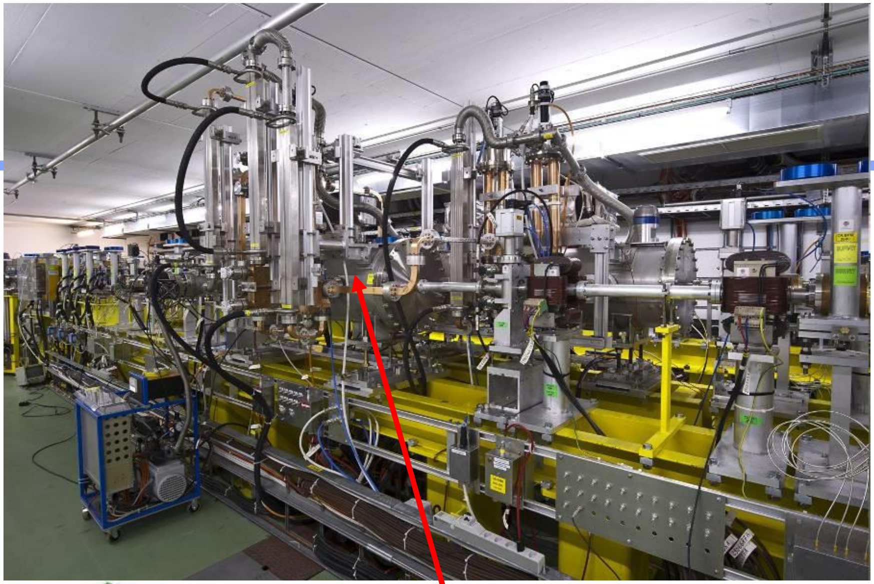
SK02(ns)
6794

CL.SVBPM0402S	-4.56877
CL.SVBPM0502S	-4.03190
CT.SVBPM0515S	-3.74760
CL.SVBPM1590S	-3.87000
CR.SVBPI0130S	-15.09200

```
Load '/ctf/data/xsampgen/1october2009_Recombined_CR_15A_good6.txt': Success
```

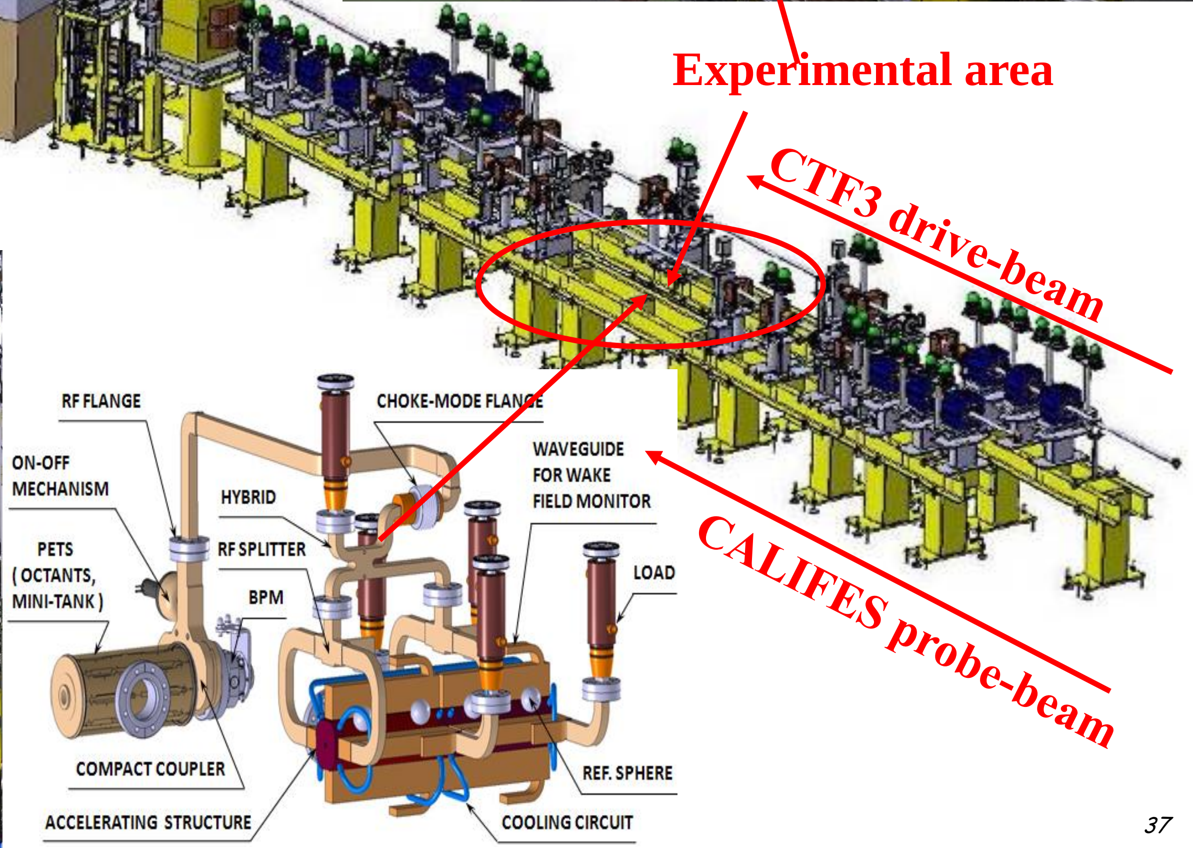
The Two-Beam Test Stand





Spectrometers
and beam dumps

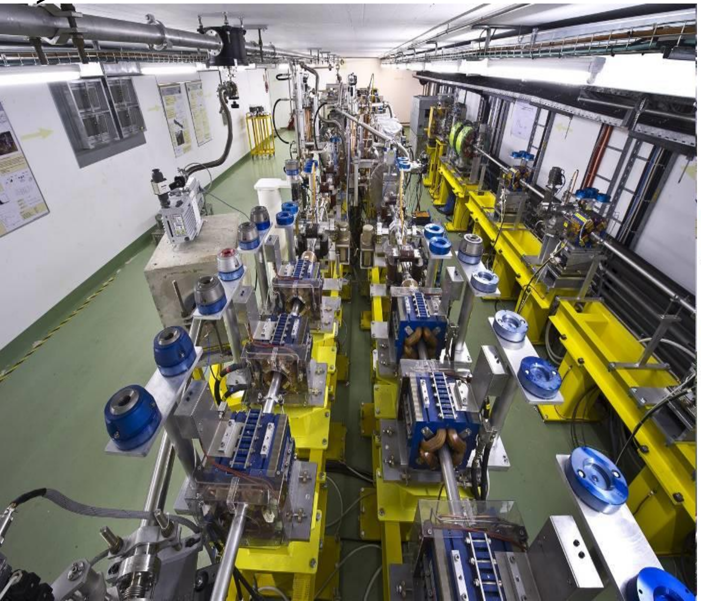
All hardware installed
Beam in both lines up to end
Commissioning with beam:
PETS 2009,
Two Beam Acceleration 2010->



Experimental area

CTF3 drive-beam

CALIFES probe-beam

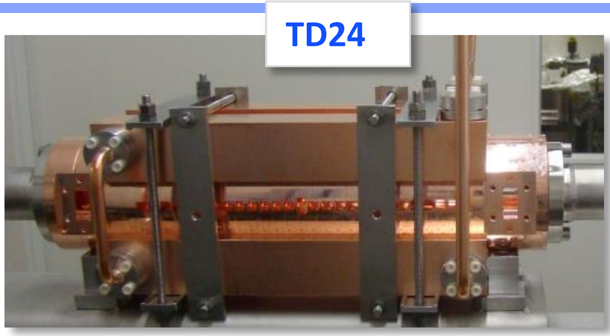


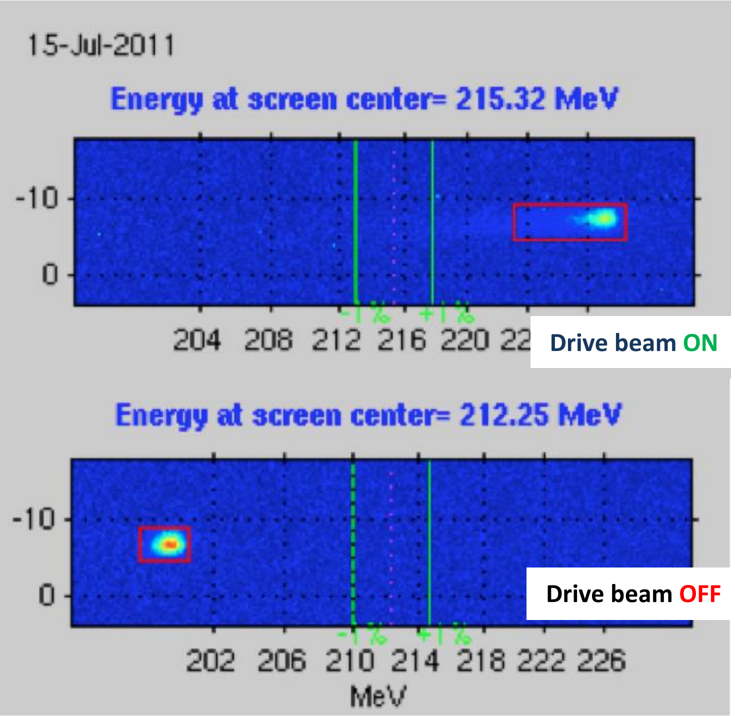
Two-beam Acceleration

Two-Beam Acceleration demonstration in TBTS

Up to 145 MV/m measured gradient

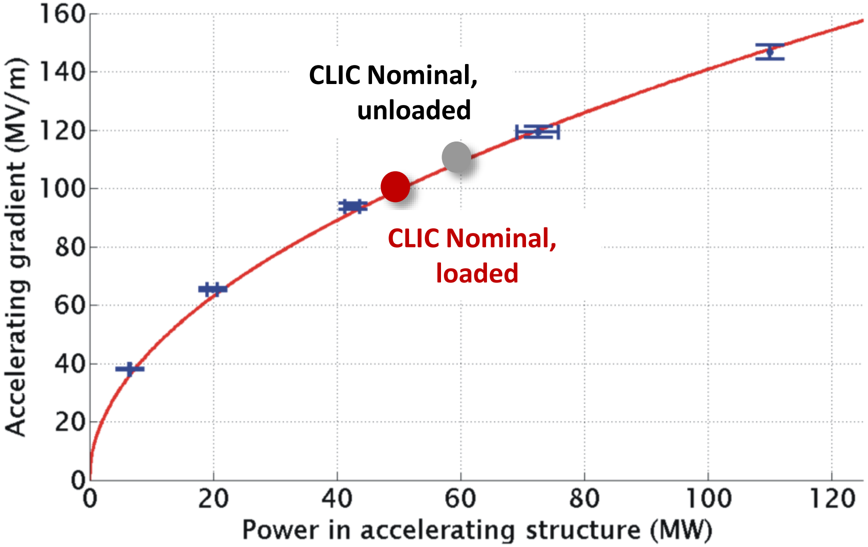
Good agreement with expectations (power vs. gradient)





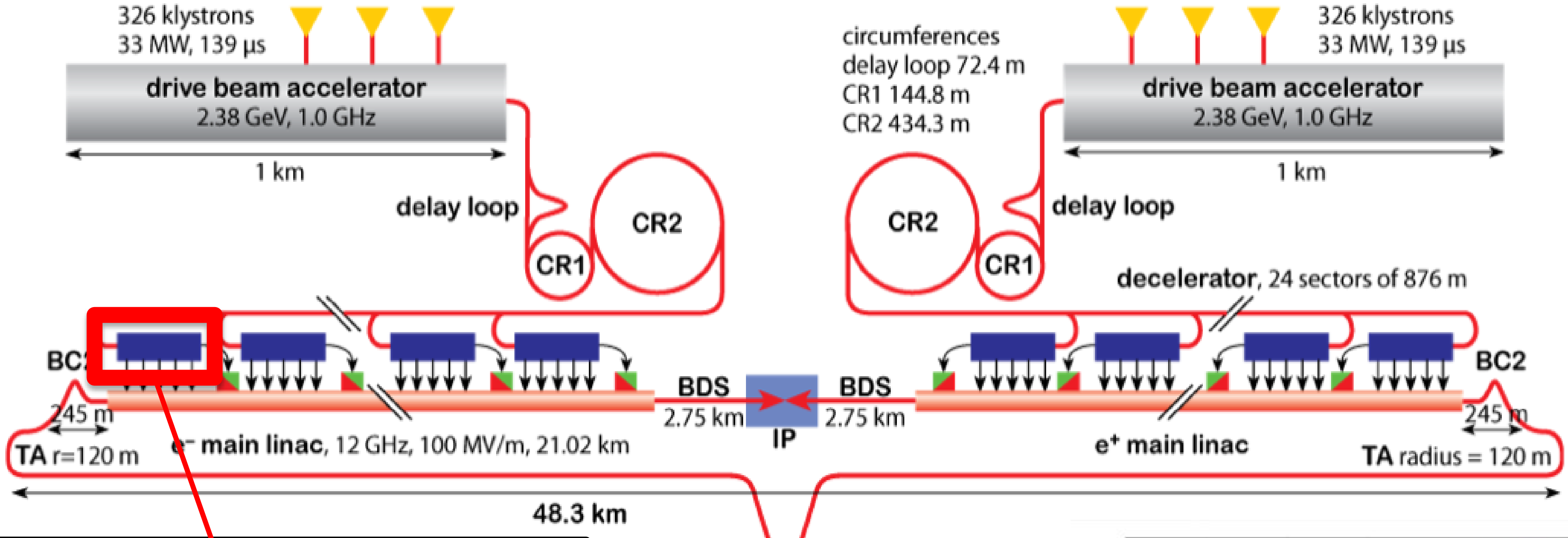
Maximum stable probe beam acceleration measured: 31 MeV

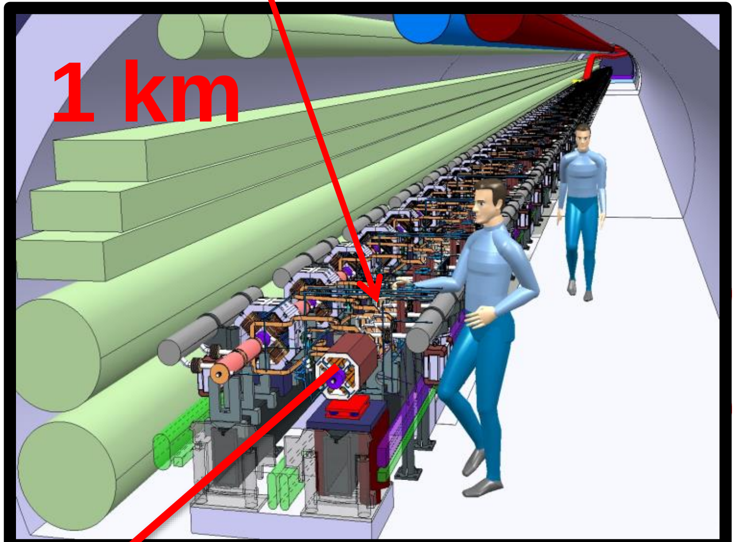
⇒ Corresponding to a gradient of 145 MV/m

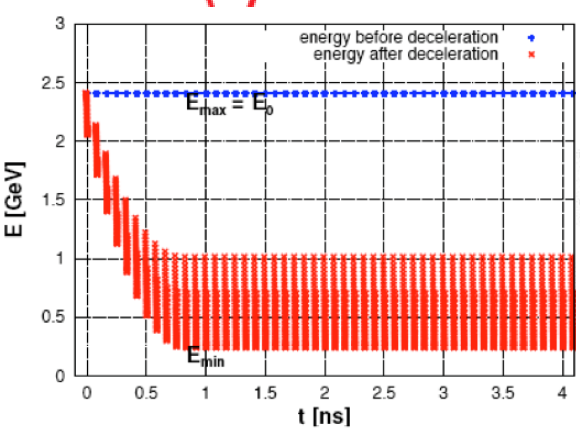


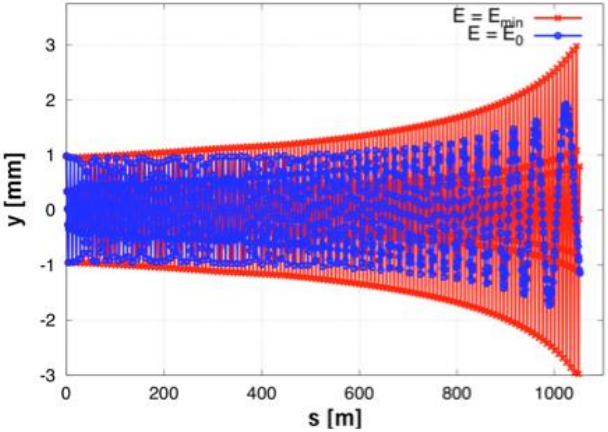
The CLIC decelerator

Decelerator: Transports the 101A, 2.4 GeV CLIC Drive Beam,extracting more than 80% of the energy





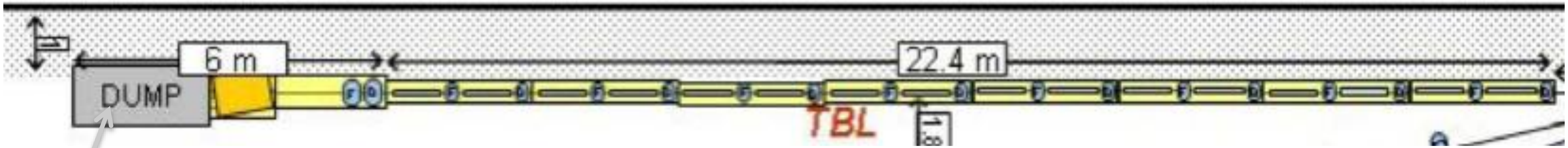




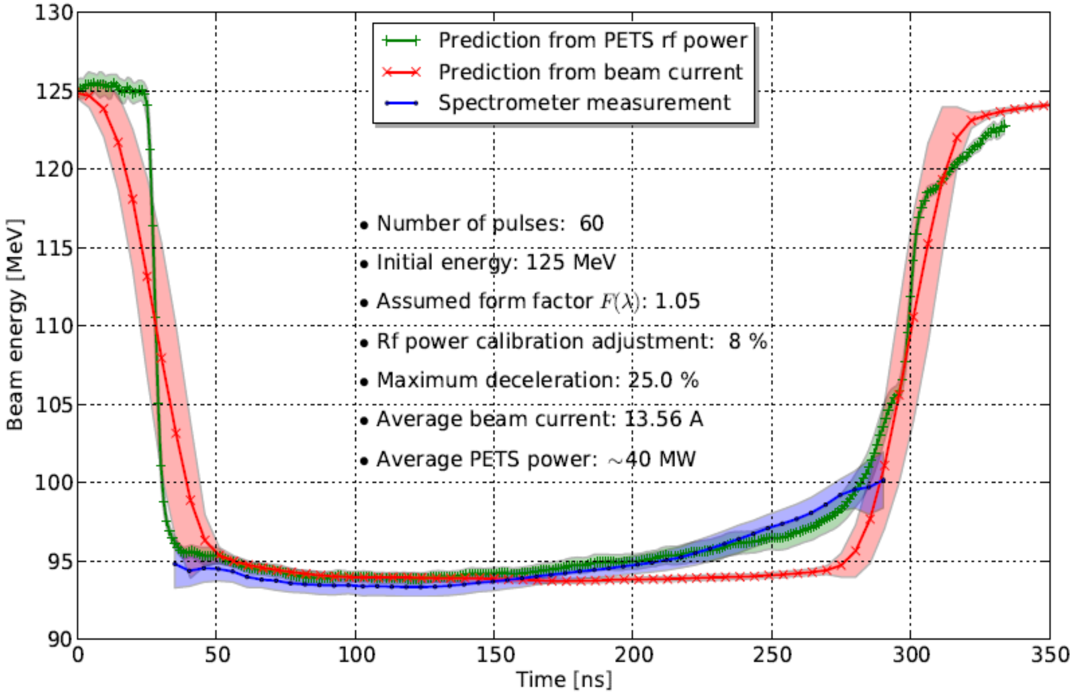
The drive beam is decelerated to 10% energy. The high energy transient must be equally well transported to the end of each 1 km decelerator.

Decelerator Test Beam Line

Test Beam Line: Transport of the 28A, 150 MeV CTF3 Drive Beam, while extracting more than 50% of the energy using 16 PETS, each producing CLIC level rf power, with small loss level.

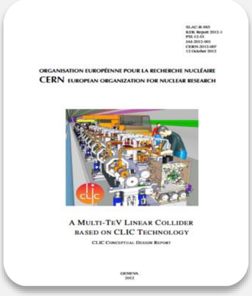


Current status: 13 out of max. 16 PETS installed demonstarting > 35% drive beam deceleration. Correlation beam parameter versus rf power production and deceleration carefully studied and shows very good agreement.



CLIC Status

- **Conceptual Design Report completed** (2012) and **proof of principle of the two-beam scheme demonstrated**
- 2012-2018: technical design, CTF3 system tests, application of X-band technology, cost and power optim., staging and scope of project with continuous input from LHC



SLAC-R-985
KEK Report 2012-1
PSI-12-01
JAI-2012-001
CERN-2012-007
12 October 2012

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

A MULTI-TEV LINEAR COLLIDER
BASED ON CLIC TECHNOLOGY
CLIC CONCEPTUAL DESIGN REPORT

GENEVA
2012

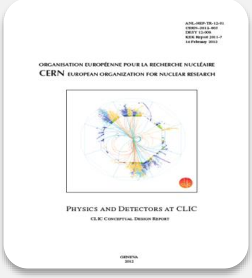
Vol 1: The CLIC accelerator and site facilities

- CLIC concept with exploration over multi-TeV energy range up to 3 TeV

- Feasibility study of CLIC parameters optimized at 3 TeV (most demanding)

- Consider also 500 GeV, and intermediate energy range

- https://edms.cern.ch/document/1234244/



ANL-HEP-TR-12-01
CERN-2012-003
DESY 12-008
KEK Report 2011-7
14 February 2012

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

PHYSICS AND DETECTORS AT CLIC
CLIC CONCEPTUAL DESIGN REPORT

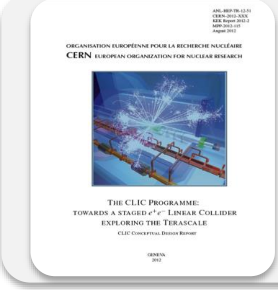
GENEVA
2012

Vol 2: Physics and detectors at CLIC

- Physics at a multi-TeV CLIC machine can be measured with high precision, despite challenging background conditions

- External review procedure in October 2011

- http://arxiv.org/pdf/1202.5940v1



ANL-HEP-TR-12-51
CERN-2012-XXX
KEK Report 2012-2
MPP-2012-115
August 2012

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

THE CLIC PROGRAMME:
TOWARDS A STAGED e^+e^- LINEAR COLLIDER
EXPLORING THE TERASCALE
CLIC CONCEPTUAL DESIGN REPORT

GENEVA
2012

Vol 3: "CLIC study summary"

- Summary and available for the European Strategy process, including possible implementation stages for a CLIC machine as well as costing and cost-drives

- Proposing objectives and work plan of post CDR phase (2012-16)

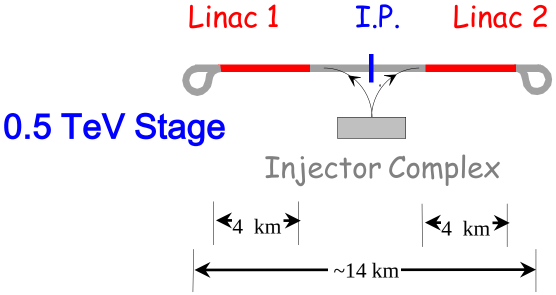
- http://arxiv.org/pdf/1209.2543v1

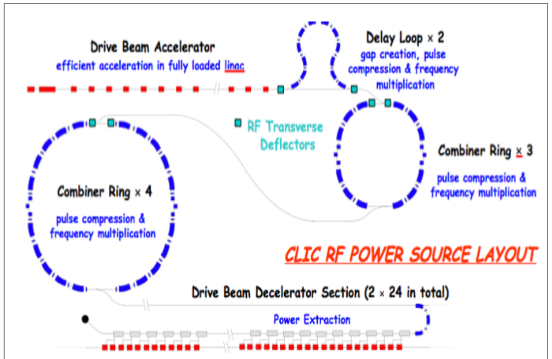
CLIC Energy Stages

CLIC two-beam scheme : energy staging is straight-forward.

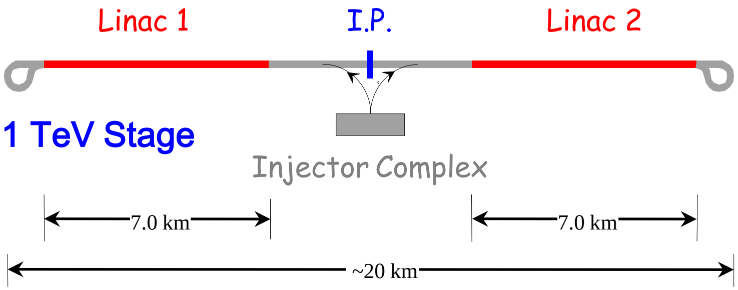
Lower energy machines can run most of the time during the construction of the next stage.

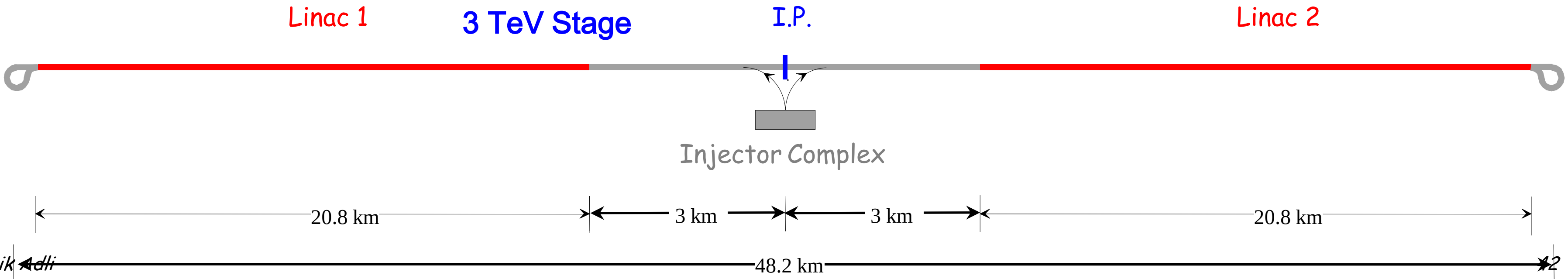
Physics results will determine the energies of the stages.



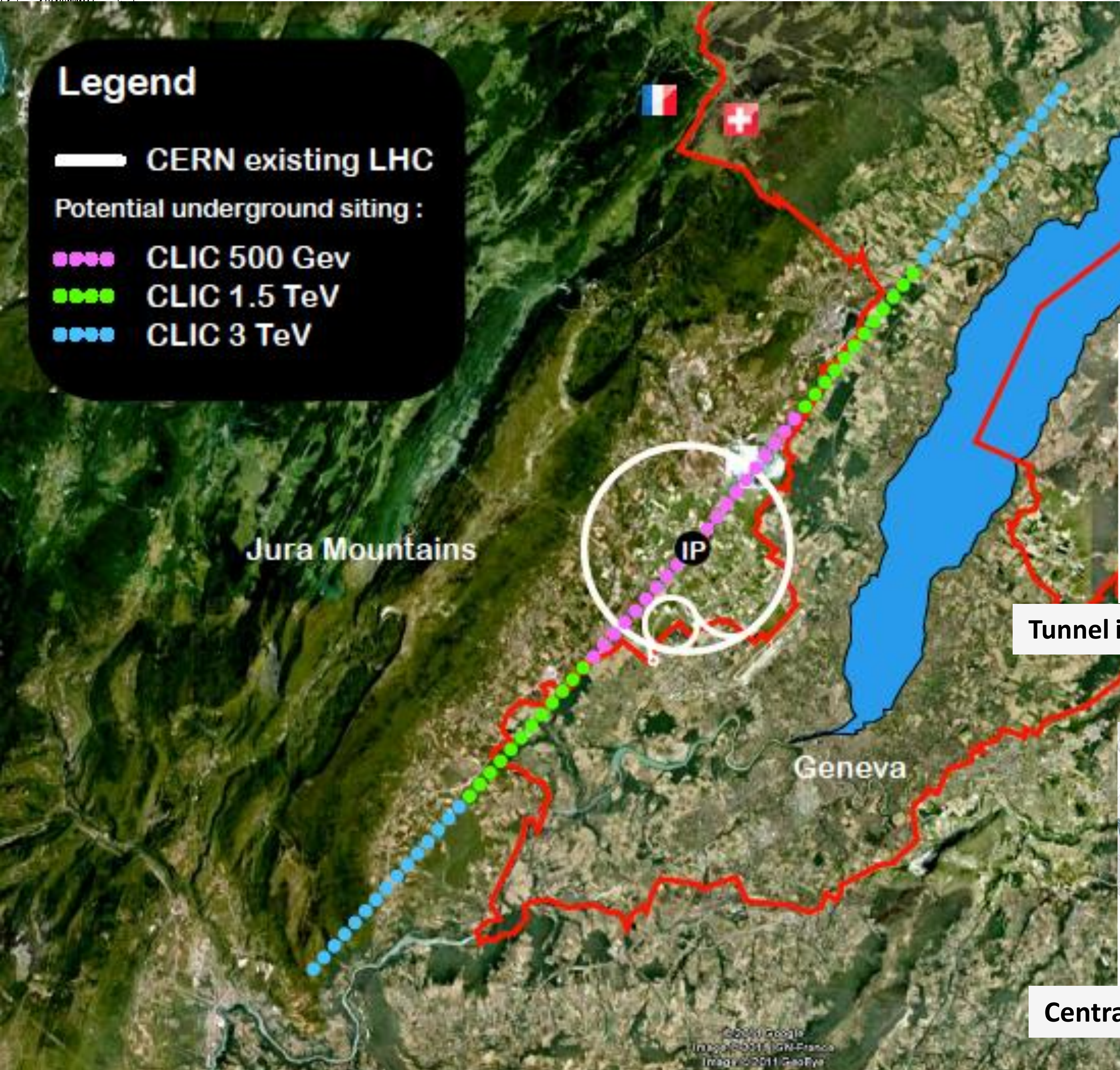


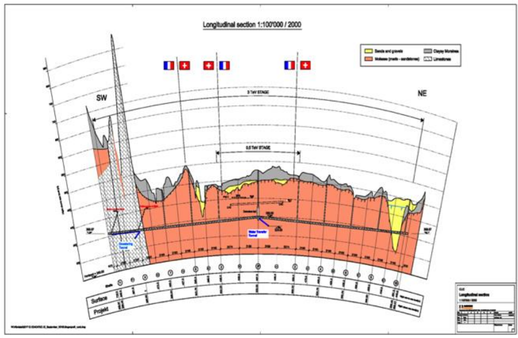
The drive beam complex will stay the same for all stages.



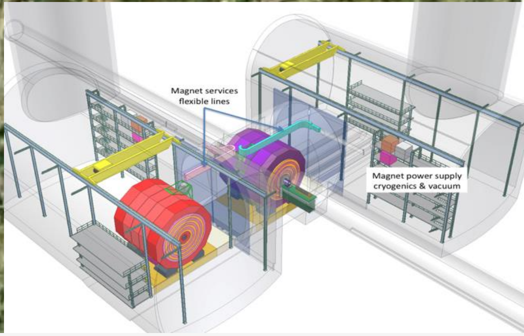


CLIC site near CERN





Tunnel implementations (laser straight)



Central MDI & Interaction Region

Conclusions

Exciting time in the linear collider world!

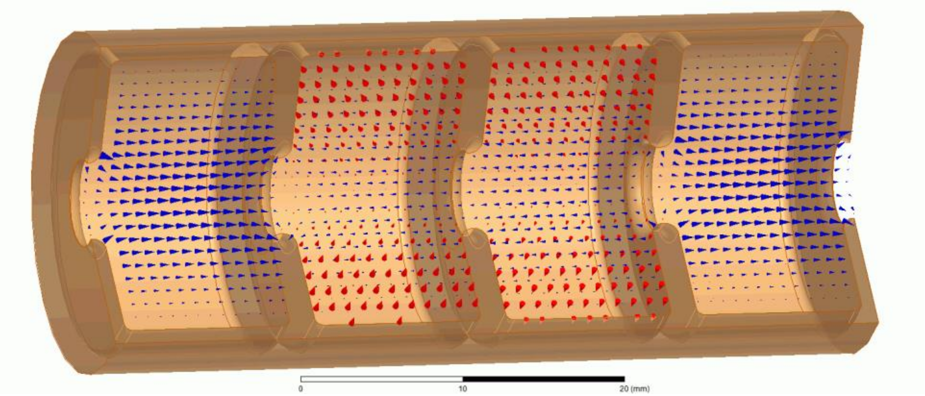
ILC is basically ready for construction and a Japanese site has been proposed

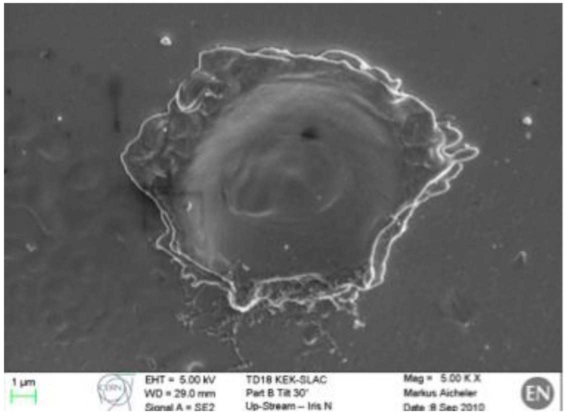
CLIC, as **a Multi-TeV e+ e- option,** is in an thriving R&D phase as the CLIC high gradient X-band technology is becoming mature and now being considered for other accelerator application

LHC results will guide what kind of machine is needed. In the **next few years** the future of linear colliders should be more clear.

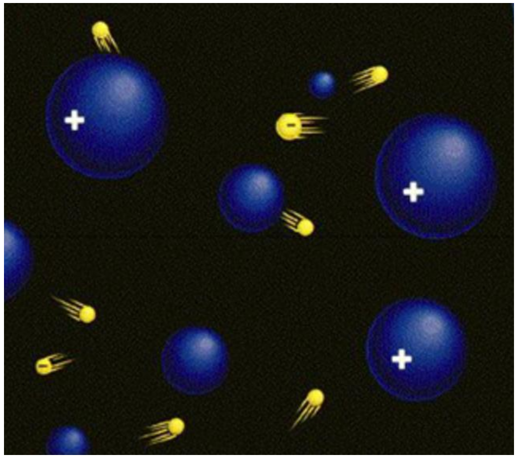
Teaser: plasma acceleration

Recap: if you push the field to hard inside metallic structure, the field will eventually break down, creating electric discharges. Field cannot be sustained. Structures may be damaged. Current limit for accelerating structure (CLIC): ~100 MV/m electric field. Some factor higher for dielectric structures.



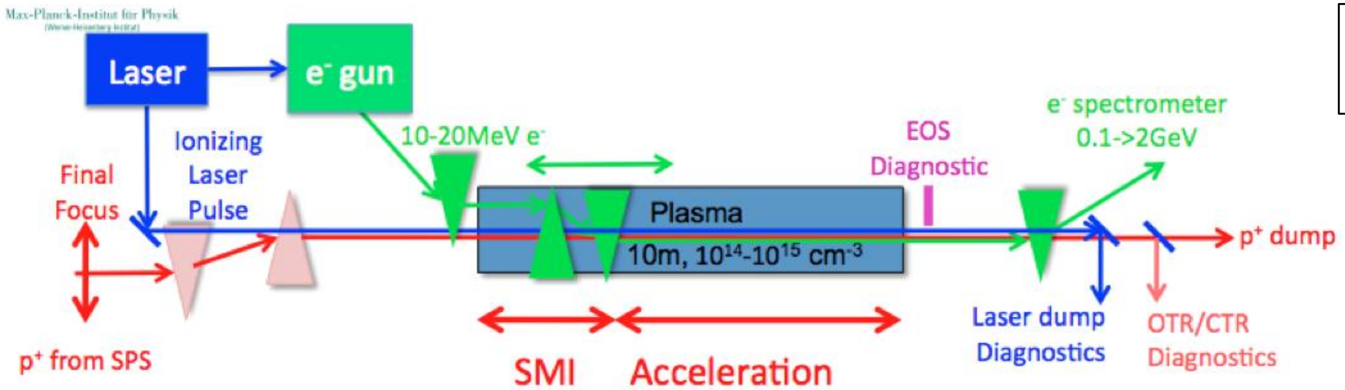


A plasma: collection of free positive and negative charges (ions and electrons). Material is already broken down. A plasma can therefore sustain very high fields.

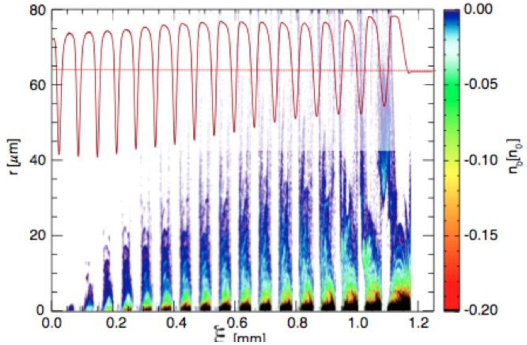


The AWAKE experiment at CERN

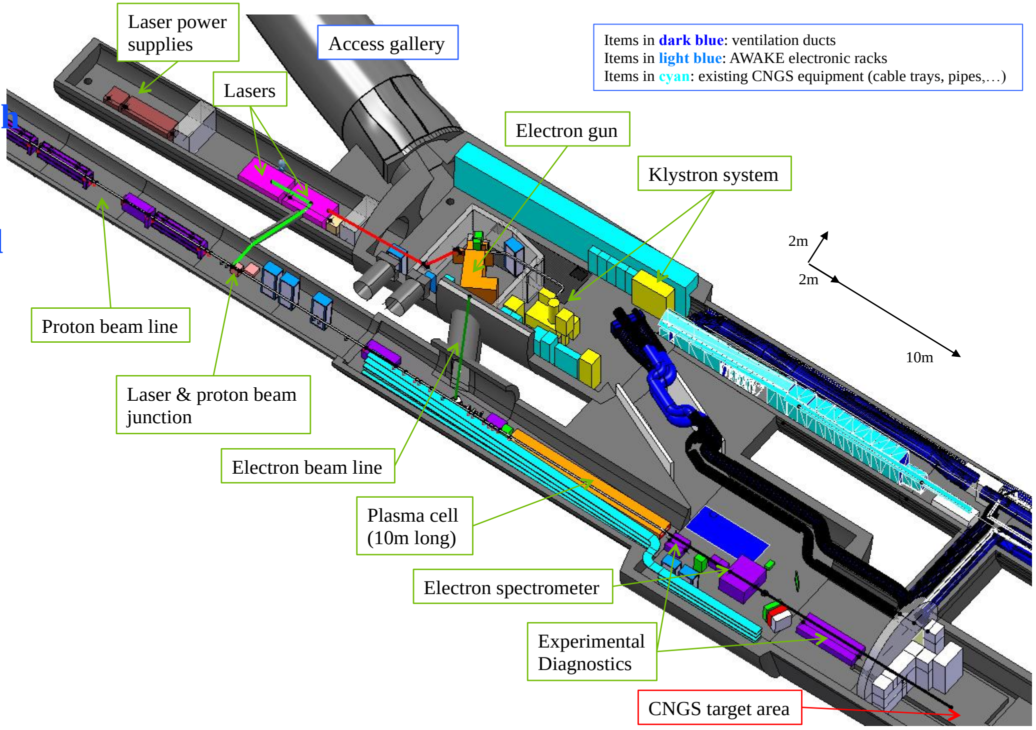
Talk for another day



AWAKE: "A Proton Driven Plasma Wakefield Acceleration Experiment at CERN". Idea: use CERN proton bunches with kJ energies as a PWFA driver. A 400 GeV SPS bunch is sent into a plasma source, in which it drives self-modulated wake fields with accelerating fields of about 1 GV/m over 10 meters. An e- bunch will sample the wake. Global collaboration with MPI as lead experiment partner. First beam: 2016.



The low-density long beam will self-modulated and generate intense wake fields.



Acknowledgements

- In addition to CLIC CDR and ILC TDR material, I have borrowed slides from the linear collider community; Frank Tecker, Barry Barish, Nick Walker, Alex Chao and many others

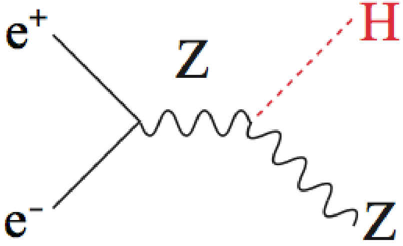
- I enjoyed useful discussions with Marc Ross, Jean-Pierre Delahaye and Steinar Stapnes while preparing this talk

EXTRA

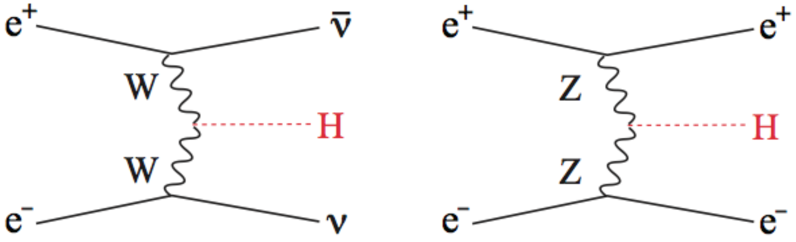
Luminosity requirements

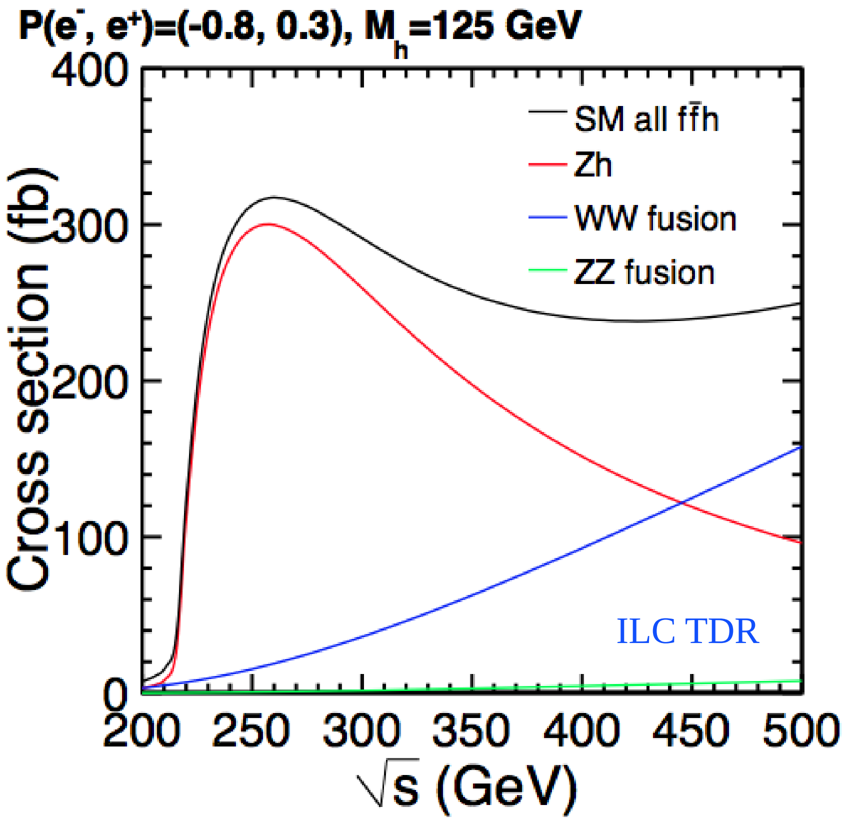
Example: Higgs production at an e^+e^- collider

Higgs-strahlung dominates at low energies:



Vector boson fusion dominates at higher energies:



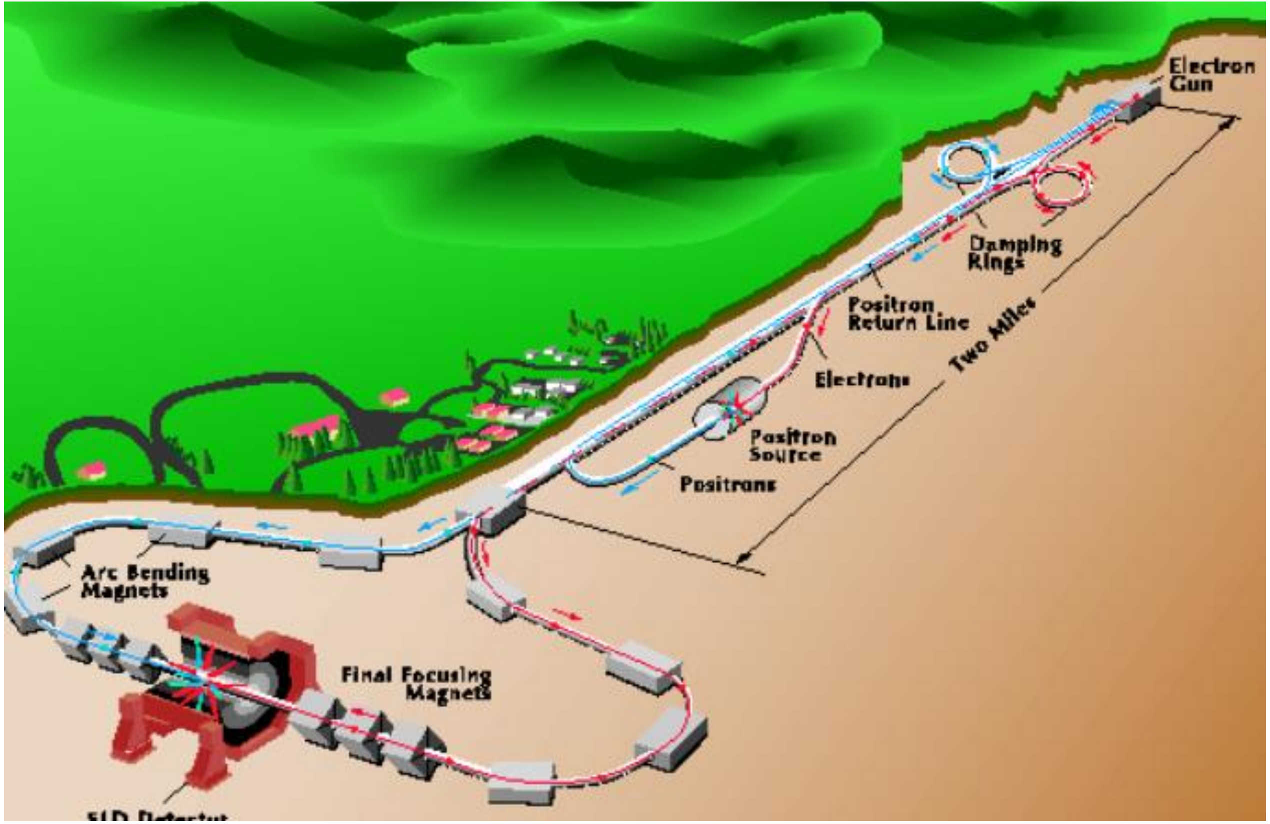


Higgs production order of 100 fb + requirement of 10,000-100,000 Higgs events for precision measurement for rare processes

➔ order of ab^{-1} integrated luminosity needed = L~10^{34}/cm^2/s over ~10 years (LHC level luminosities)

History: SLC

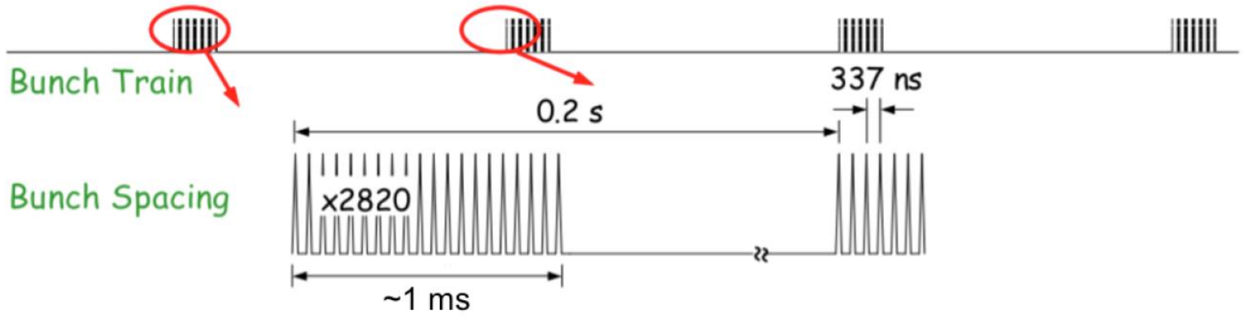
- Only one e+ e- collider have been in operation, **the Stanford Linear Collider** (SLC) from 1989 to 1998
- E_{cm} = 91 GeV (Z^0), gradient 17 MV/m, $L \sim 10^{30}/cm^2/s$, single bunch collisions at 120 Hz, $\sigma_x \sim 1.5$ um, $\sigma_y \sim 0.5$ um
- Very challenging to operate, but brought under control by hard work and careful accelerator physics studies, in particular ring and linac instabilities
- Valuable proof of principle and lessons learned



Luminosity versus power

Linear collider bunch structure: bunch trains collided with a given repetition rate :

Example:
ILC time
structure



Basic luminosity formula

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

n_b: # of bunches in train (2820)
N: particles per bunch
f_{rep}: train repetition rate (5 Hz)

Total beam power is calculated as

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

The energy transfer efficiency from the wall-plug into the beam is typically $\eta_{AC2beam} \lesssim 10\%$, which yields a wall-plug power of

$$P_{AC} = P_{beam}/\eta_{AC2beam}$$

P_{AC}: power required from the grid (wall plug)

The luminosity is thus related to power as

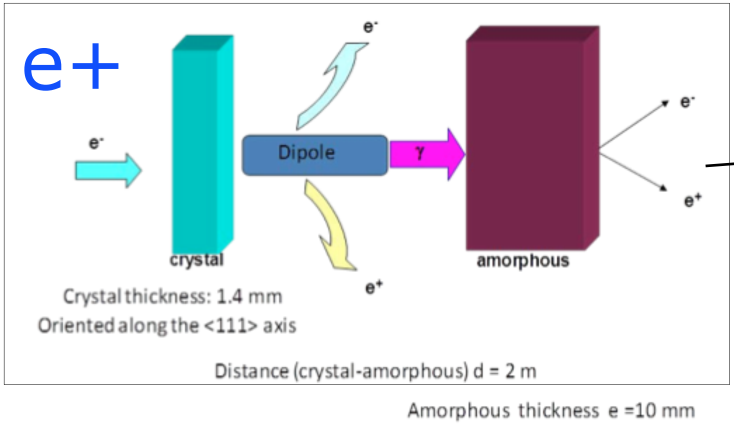
$$L = \frac{\eta_{AC2beam} P_{AC}}{E_{cm}} \frac{N}{4\pi\sigma_x\sigma_y}$$

$$\Rightarrow L/P_{AC} = \frac{\eta_{AC2beam}}{E_{cm}} \frac{N}{4\pi\sigma_x\sigma_y}$$

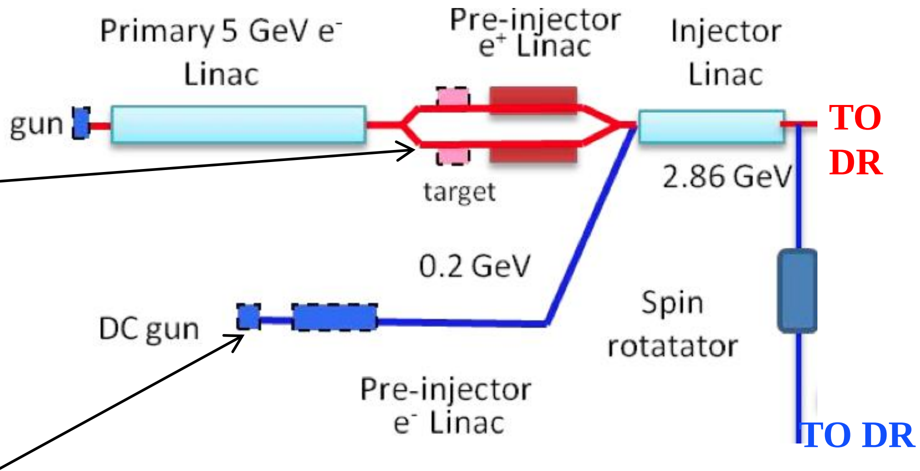
Luminosity per power is the key figure of merit for a linear collider

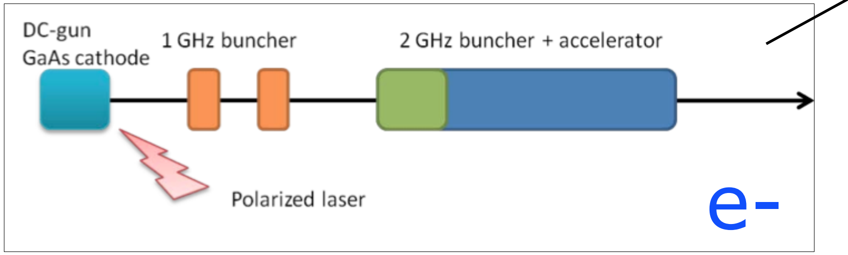
Main Beam: Injector Sources

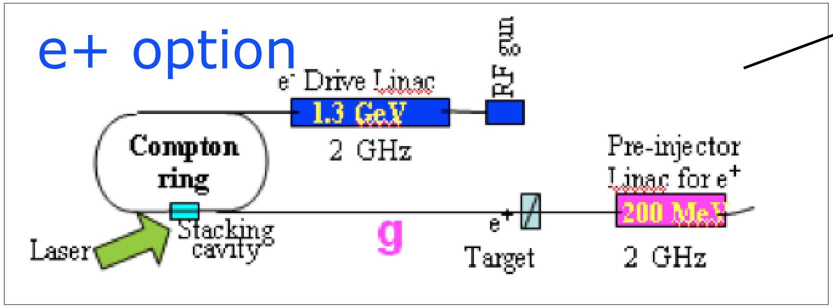
Injector charge of N = 4 x 10^9 electrons (polarized) and positrons (unpolarized) as baseline



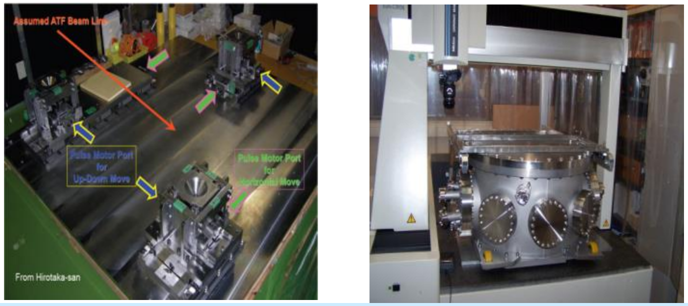
CLIC injector





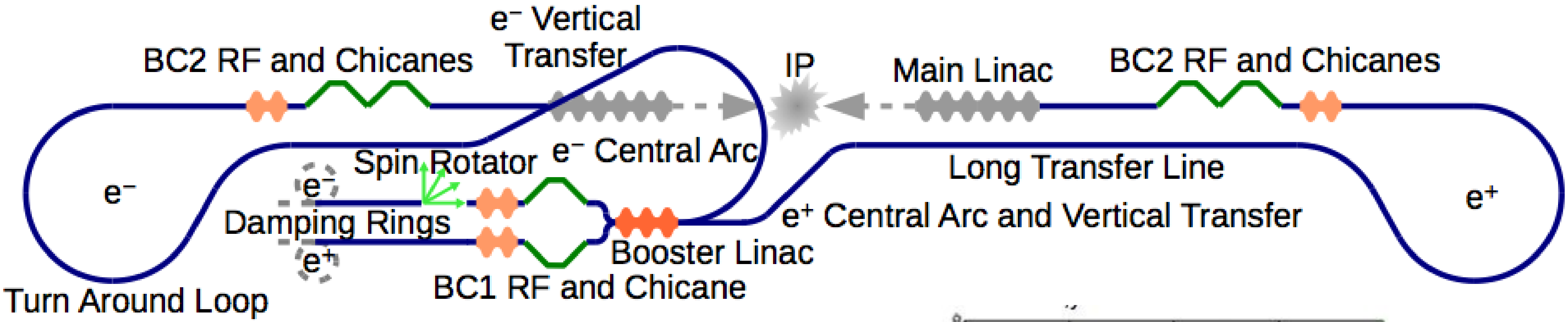


Option (R&D) for polarized e+:



Tests @ KEK of Optical cavity using Compton backscattering for ILC and CLIC polarized e⁺ (Collaboration CERN/LAL/KEK)

Rings to Main Linac



RTML not a simple transport line :

- Bunch compression (BC) needs to be done in two stages to keep energy spread small.

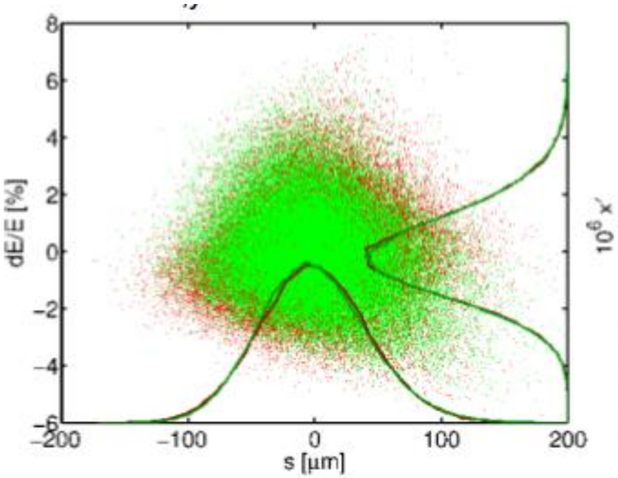
- **BC1 stage**: bunch length from 5 mm to 1.5 mm at 2.4 GeV

- **Booster linac** from 2.4 to 9 GeV

- Transfer line and turnaround loops

- BC2 stage: from 1.5 mm to 44 um

=> **max 5 nm vertical emittance growth is allowed**

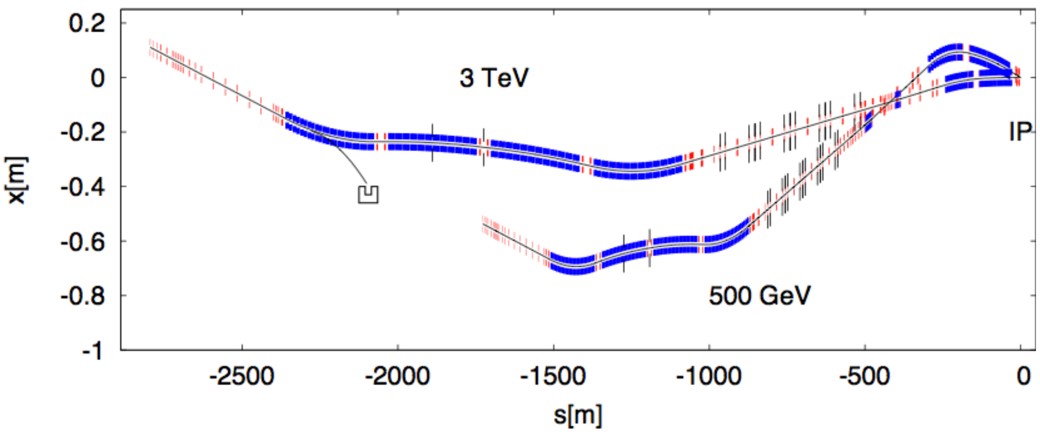


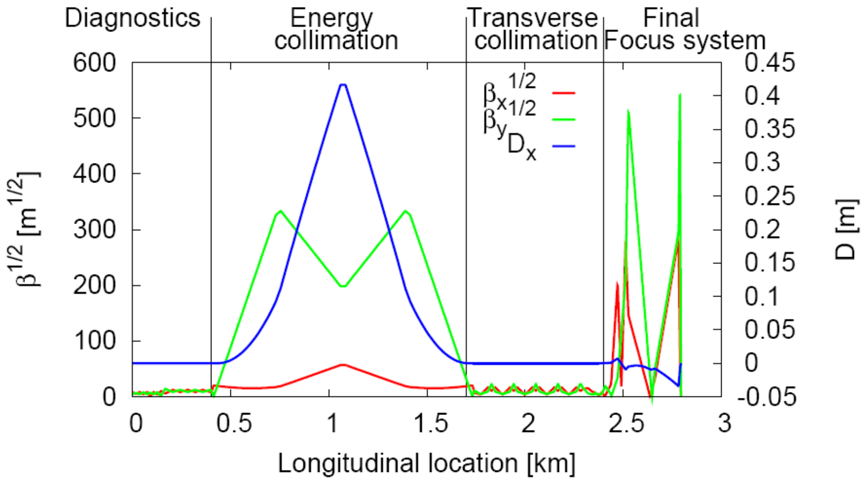
RTML final phase space simulated with ISR, CSR and wake fields effects included

Beam dynamics studies : full start to end simulations including **ISR, CSR, wake fields** and imperfections are required to demonstrate acceptable emittance growth.

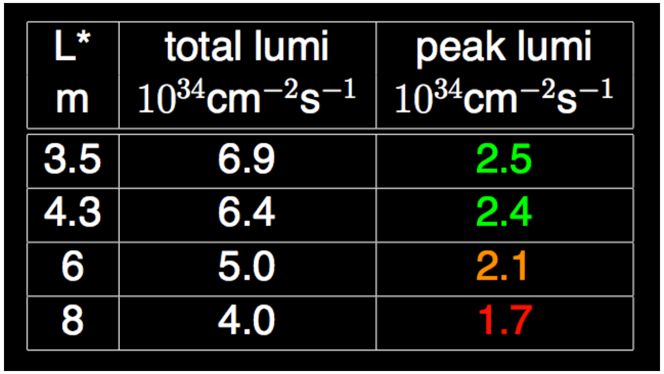
Beam Delivery System

CLIC BDS: focus to a bea**m spot of σ_x=40 nm** (β_x=10 mm), **σ_y=1 nm** (β_y=0.1 mm). Design uses local chromatic correction (proposed by P. Raimondi and A. Seryi). In addition, the BDS provides **final emittance measurement, matching and collimation**. BDS length depends on $E_{cm.}$

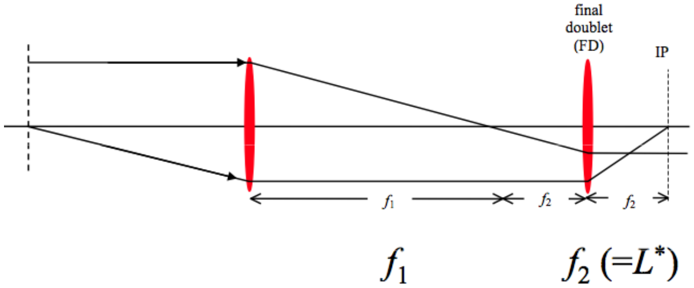




BDS layout for E_{cm} = 3 TeV and E_{cm} = 0.5 TeV



L* m	total lumi 10^{34}cm^{-2}s^{-1}	peak lumi 10^{34}cm^{-2}s^{-1}
3.5	6.9	2.5
4.3	6.4	2.4
6	5.0	2.1
8	4.0	1.7



Final double magnification:
m = f_1/f_2

Nominal L* = 3.5 m (QD0 inside detector)
Nominal crossing angle is 20 mrad (crab cavities required)

Challenge: Alignment and tuning with sextupoles.