Beam Dynamics and Technologies for Future Colliders

21 Feb 2018, 08:30 → 6 Mar 2018, 21:00 Europe/Zurich

Hotel Crowne Plaza (Zurich, Switzerland)

14:30 → 15:20 **Linear Collider Studies Overview**

Speaker: Dr. Steinar STAPNES (CERN)

Main sources: talks by Shin Michizono, Akira Yamamoto, Phil Allport – and my old slides from various talks also full of "extractions" from many LC colleagues
More information for most topics will be given in your lectures the next two weeks

Experimental Particle Physics

Accelerators

- Luminosity, energy, quantum numbers, physics goals

Detectors

- Efficiency, speed, granularity, resolution, physics goals

Trigger/DAQ

- Efficiency, compression, through-put, physics models

Offline analysis

- Signal and background, physics studies

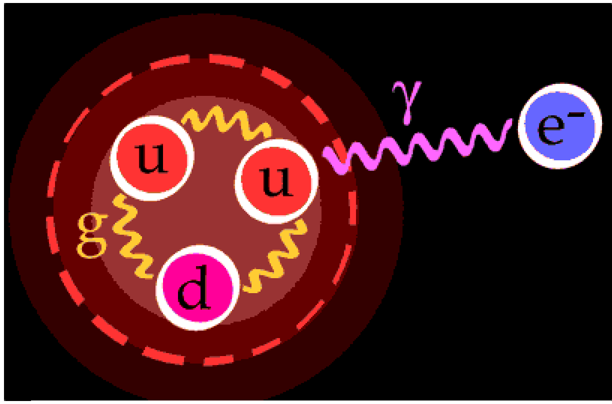
The primary factors for a successful experiment are the accelerator and detector trigger system, and losses there are not recoverable.

At all steps above simulations and real data are used

Particle type to accelerate

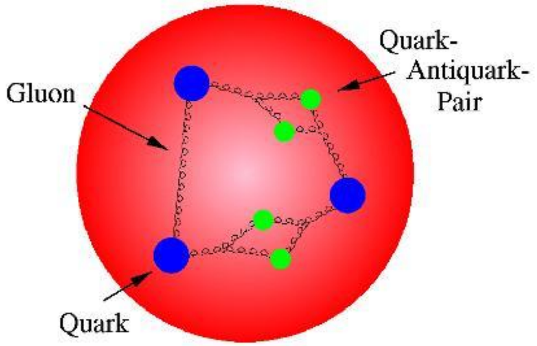
Not so many choices:

- Need stable charges particles: protons, electrons, (muons), ions – most used: electrons and protons
- Secondary beams: photons, pions, kaons, neutrons, neutrinos, …..



Proton collisions: compound particles

- Mix of quarks, anti-quarks and gluons: variety of processes
- Parton energy spread
- QCD processes large background sources

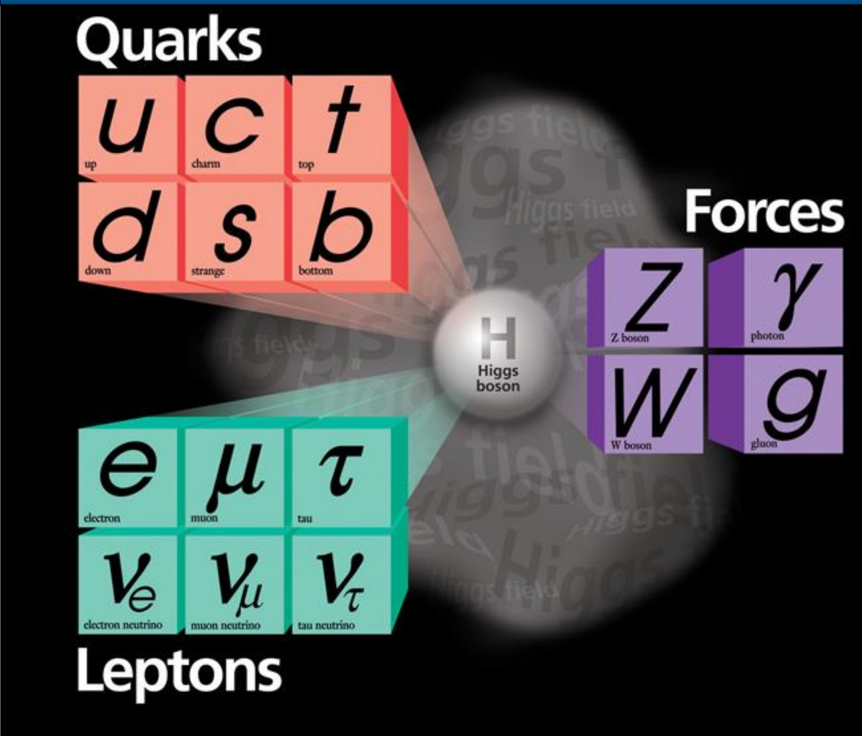


Electron/positron collisions: elementary particles

- Collision process known
- Well defined energy
- Background from other physics limited

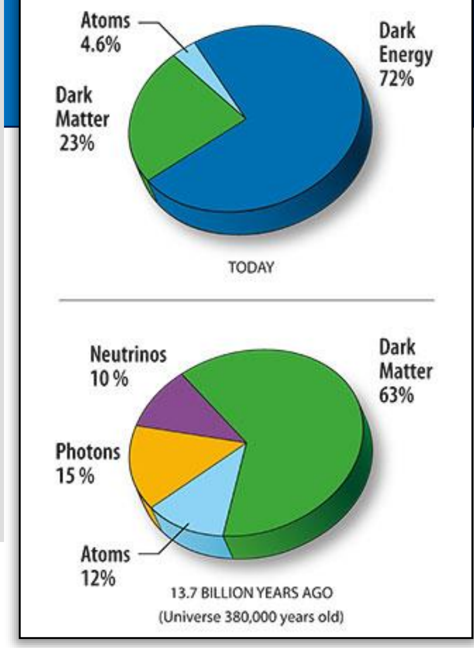
$$\frac{\text{proton mass}}{\text{electron mass}} \approx 2000$$

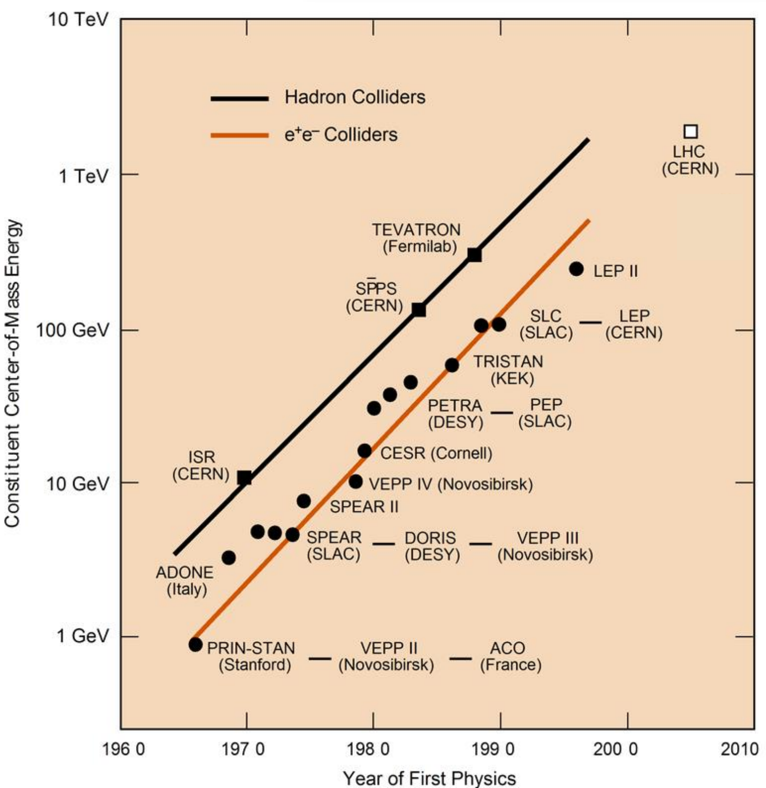
The landscape



"Unknowns":

- Flavour structure
- Matter-antimatter
- Why is the Higgs so light
- Neutrino sector
- Forces merging ?
- Gravity
- …





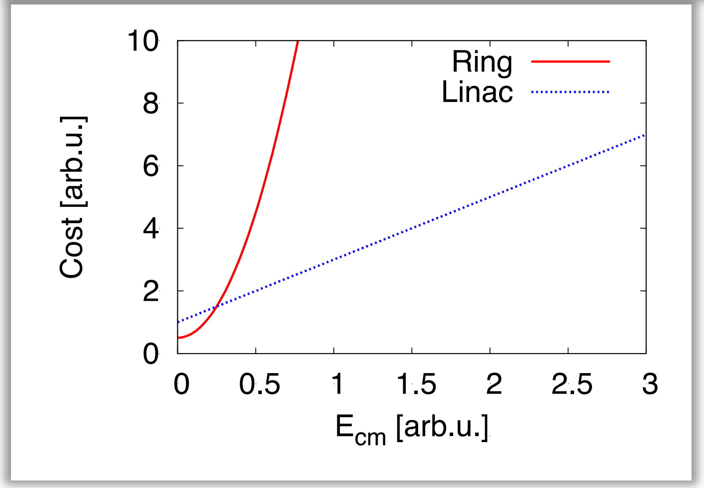
Limitations - synchrotron radiation

We want E_{cm} as high as possible for new particle accelerators
Circular colliders $\Rightarrow$ synchrotron radiation loss:

$$P_S = \frac{e^2 c}{6\pi\varepsilon_0} \frac{1}{(m_0 c^2)^4} \frac{E^4}{R^2}$$

For electrons a severe limitation, size and costs explode – go linear

Less of a problem with protons (size of ring driven by magnet technology but radiation losses also there becoming significant for the components)



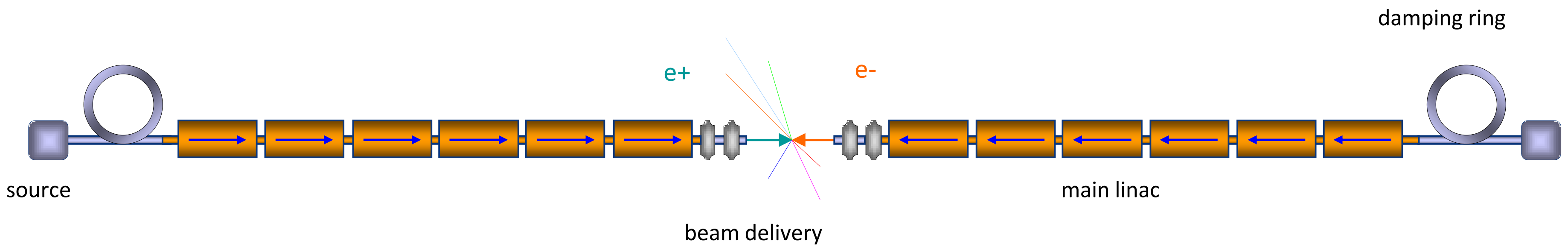
There are other reasons why linear colliders are pursued:

- Scalable (lengthen or shorten) and upgradable with new technology
- Very linked the main invest-area in accelerator construction – light-sources/FELs
- Affordable covering (most of) the Standard Model precision physics

Linear Collider (LC) studies – CLIC and ILC

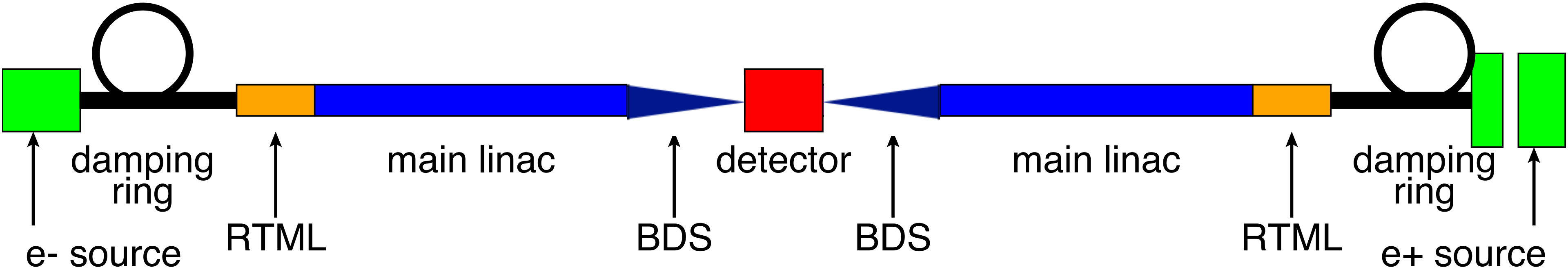
Outline:

- Generic elements and challenges of a Linear Colliders
- Focus on CLIC (380 GeV) and ILC (250 GeV) status
- Smaller Linear Accelerators for material characterization, medical applications , etc
- Key points



Generic Linear Collider

The key parameters: Energy and luminosity



The critical steps (in next slides):

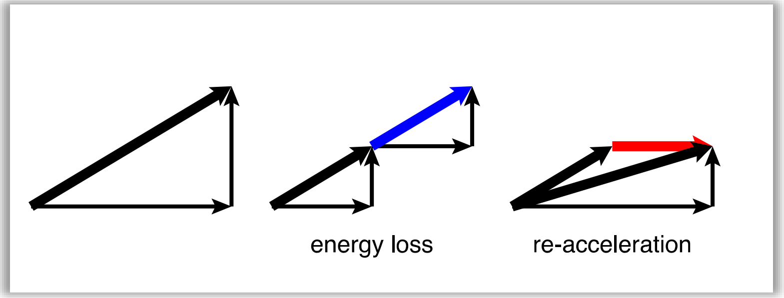
1) Create low emittance beams (sources, injector, damping rings, ring to main linac - RTML)
2) Acceleration in main linac (energy increase per length)
3) Supply energy as efficient as possible to beam (high power at 1, 1.3 and 12 GHz)
4) Nano-beams: Squeeze the beam (Beam Delivery System- BDS), i.e. reduce β

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

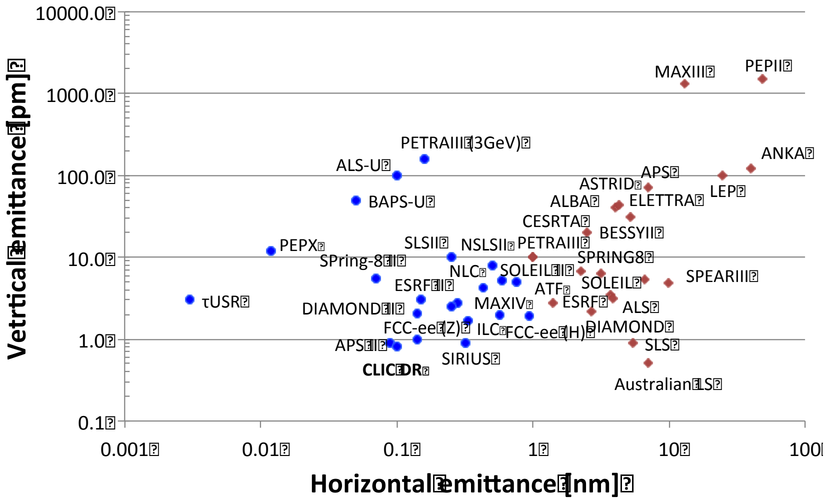
$$\sigma_{x,y} = \sqrt{\frac{\beta_{x,y}\epsilon_{x,y}}{\gamma}}$$

Damping ring, experience from light sources

The damping rings reduce the phase space (emittance $\varepsilon_{x,y}$) of the beam – wigglers to stimulate energy losses (SR)

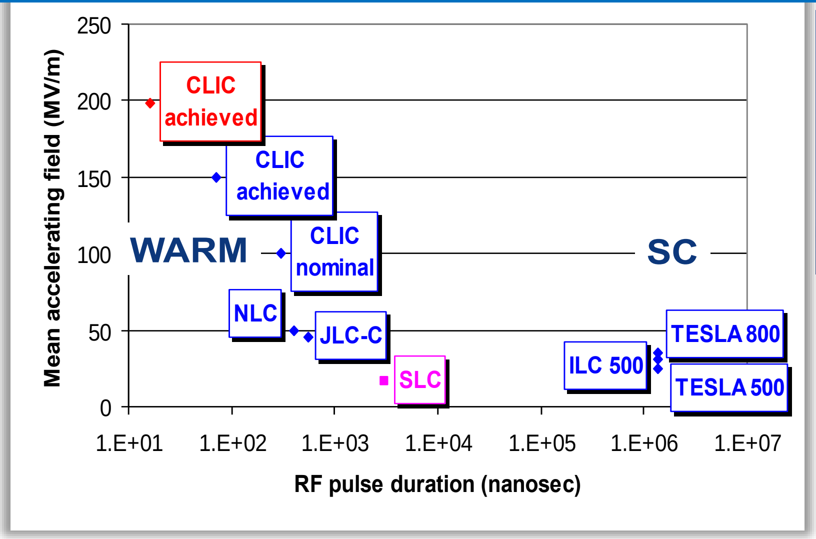


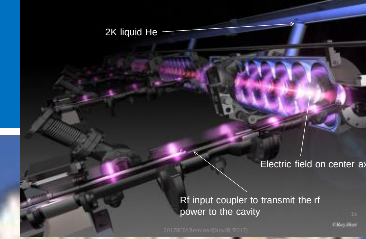
Light-sources need similar beams (picture: ALBA)



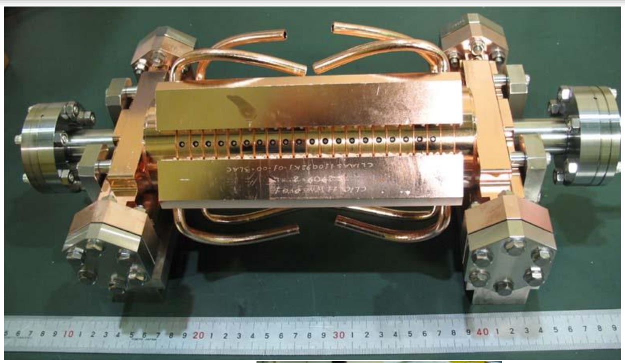
The RTML (ring-to-main linac transport) reduces the bunch length

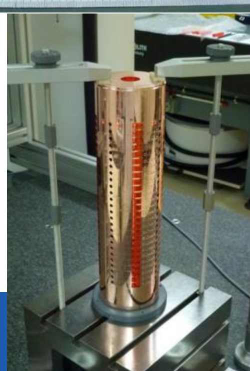
Maximize acceleration per meter





Below left: A high-gradient “warm” accelerating structure, 12 GHz for CLIC
Above: A superconducting 1.3 GHz Rf structure for ILC





Limitations by electrical and magnetic fields on surfaces, field emission and heating (key technology optimisation)

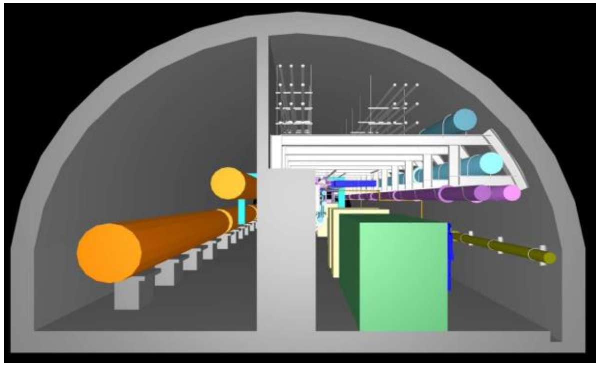
Different pulse lengths and bunch structure (ILC and CLIC):

Bunches per pulse	n_b	1312	312
Distance between bunches	Δz [mm]	554	0.5
Repetition rate	f_r [Hz]	5	50

… has ramifications for acc. size, beam dynamics , instrumentation, detectors, etc, ….

However, physics, cost, power, luminosities remarkably similar in the end (for similar collision energies)

RF power



Example: CLIC 20 MW L-band (1 GHz)
Multi-beam pulsed klystron.

20 MW, 50 Hz, 150 μsec
150 kW

180 kV

Modulator (η=0.9)
Energy storage
switch
HV transformer
150 kW + 88 kW

Cathode

RF circuit (η=0.7)

Solenoid 4 KW

Collector 60 KW

η_{Total} = 0.62

New/advanced technology

Lower (<60kV) voltage:
- 40 mini-cathodes
- No oil tank (cost)
- Shorter tube (cost)
- Faster switching (efficiency/cost)

Permanent Magnets:
- No power consumption
- Potential cost reduction

Vs. SC solenoid:
- More expensive solution

Depressed collector (η=0.5)

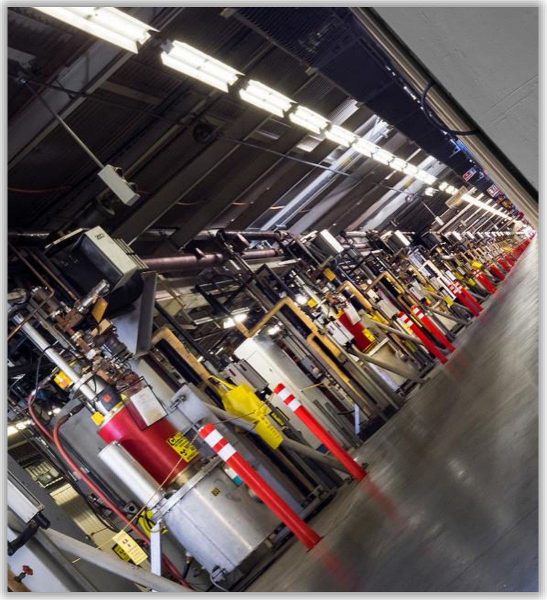
New klystron RF circuit (η=0.8)
(+) Reduced Collector dissipation (16 kW)

Gated mini-cathode:
- No switches (cost)
- Modulator efficiency ~1.0

(+) Improved stability

Power from grid:
~~290~~ 200 MW

η_{Total} = 0.9



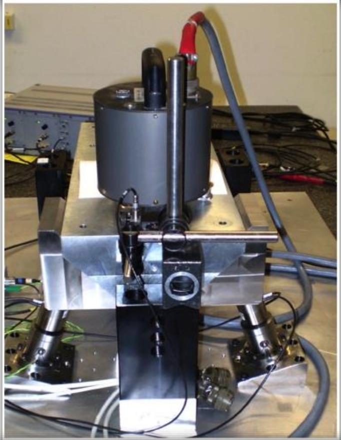
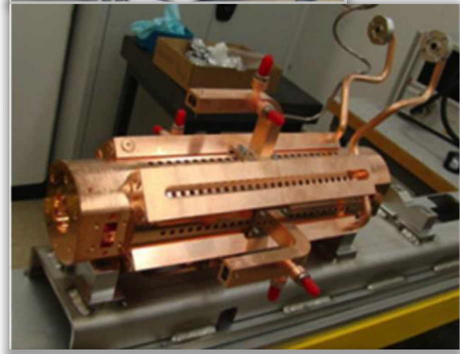
Nano-beams

Very small beams (example from ILC 500 GeV and CLIC 3 TeV)

Parameter	Symbol [unit]	ILC	CLIC
Centre of mass energy	E_{cm} [GeV]	500	3000
luminosity	L [$10^{34}cm^{-2}s^{-1}$]	1.8	6
Luminosity in peak	$L_{0.01}$ [$10^{34}cm^{-2}s^{-1}$]	1	2
Gradient	G [MV/m]	31.5	100
Particles per bunch	N [10^9]	20	3.72
Bunch length	σ_z [µm]	300	44
Collision beam size	$\sigma_{x,y}$ [nm/nm]	474/5.9	40/1
Vertical emittance	$\varepsilon_{x,y}$ [nm]	35	20
Bunches per pulse	n_b	1312	312
Distance between bunches	Δz [mm]	554	0.5
Repetition rate	f_r [Hz]	5	50

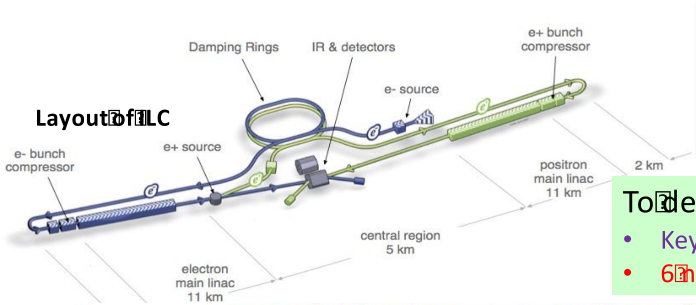
The CLIC strategy:

- Align components (10µm over 200m)
- Control/damp vibrations (from ground to accelerator)
- Measure beams well – allow to steer beam and optimize positions
- Algorithms for measurements, beam and component optimization, feedbacks
- Tests in small accelerators of equipment and algorithms (FACET at Stanford, ATF2 at KEK, CTF3, Light-sources)

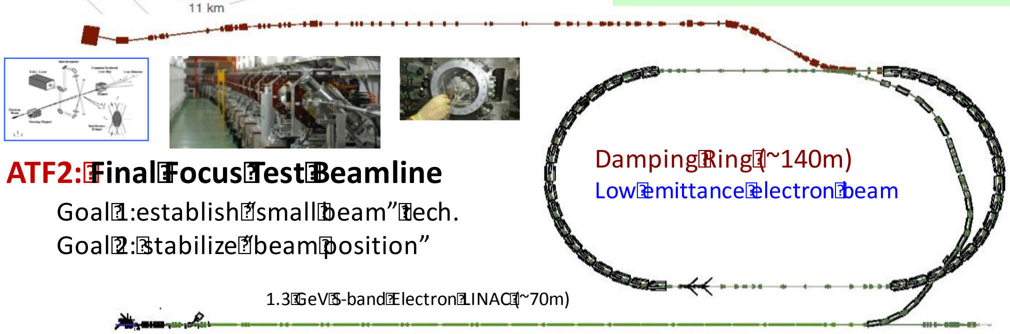

ATF/ATF2 Collaboration

Courtesy, N. Terunuma



To develop nano-beam tech.

- Key for the luminosity
- 6 nm beam at IP (ILC)



ATF2: Final Focus Test Beamline

Goal 1: establish "small beam" tech.
Goal 2: stabilize "beam position"

A. Yamamoto, 171106

Nano-beams

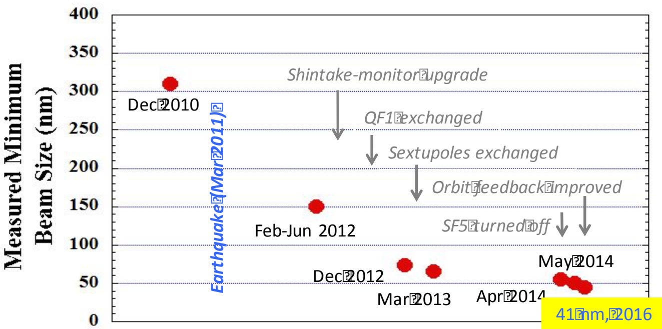
Progress in FF Beam Size and Stability at ATF2

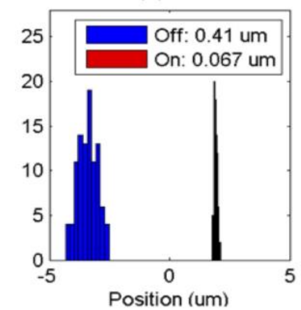
Goal 1:
Establish the ILC final focus method with same optics and comparable beamline tolerances

- ATF2 Goal: **37** nm → ILC **6** nm
  - Achieved **41** nm (2016)

Goal 2:
Develop a few nm position stabilization for the ILC collision by feedback

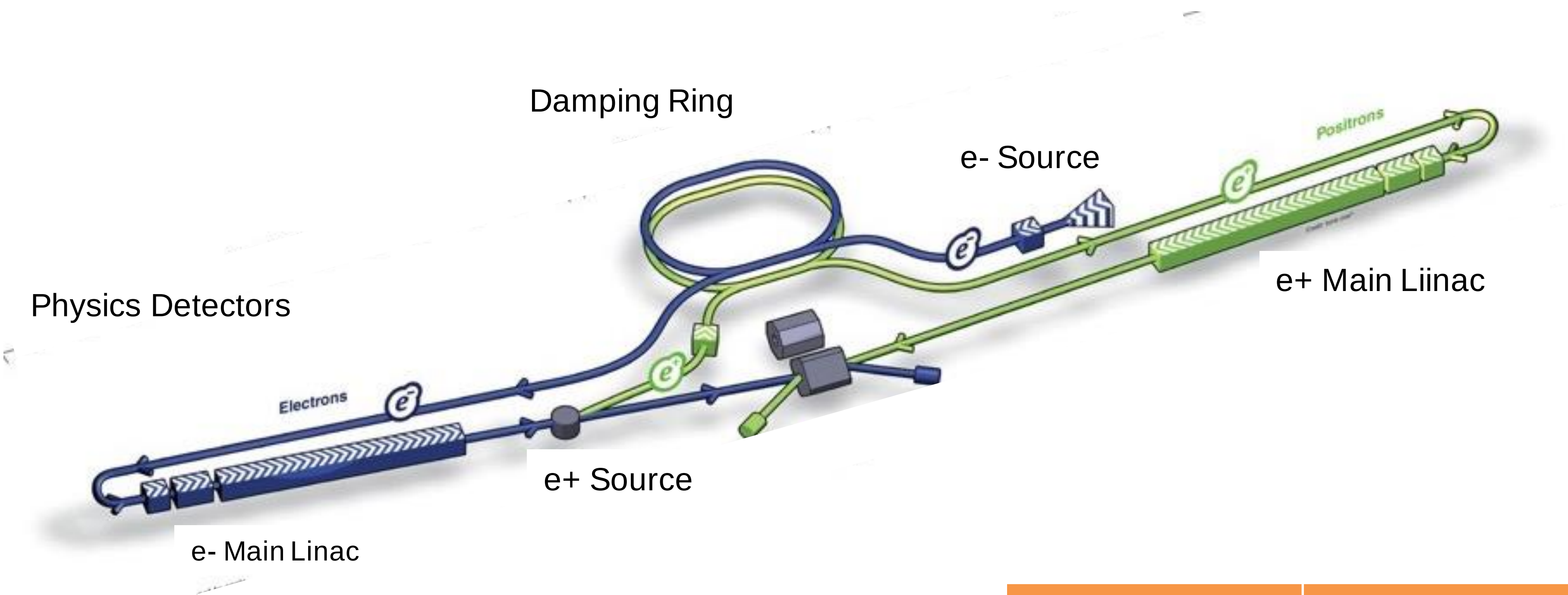
- **FB latency 133 nsec achieved**
  (target: < 300 nsec)
- **positon jitter at IP: 410 → 67 nm (2015)**
  (limited by the BPM resolution)

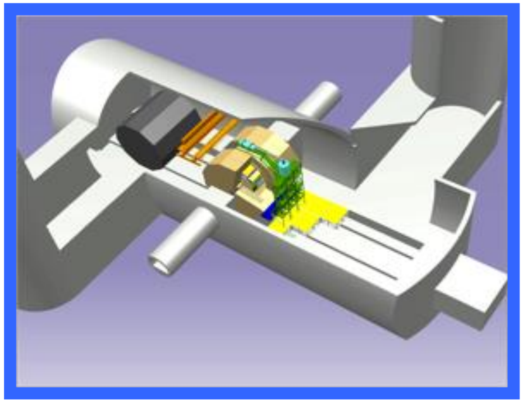




ILC Candidate Location: Kitakami, Tohoku

ILC Layout

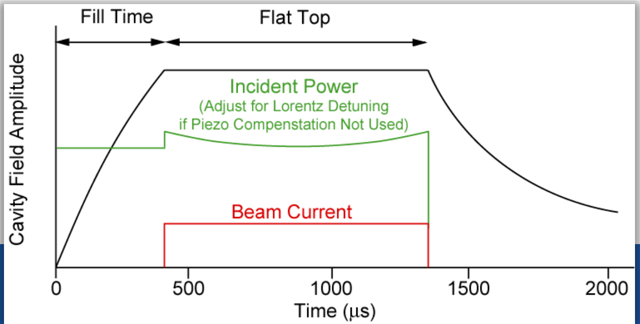




Parameters	Value
C.M. Energy	500 GeV
Peak luminosity	$1.8 \times 10^{34}\ cm^{-2}s^{-1}$
Beam Rep. rate	5 Hz
Pulse duration	0.73 ms
Average current	5.8 mA (in pulse)
E gradient in SCRF acc. cavity	31.5 MV/m +/-20% Q_0 = 1E10

ILC: SCRF

- Ultra-high Q_0 (10^{10})
  - Almost zero power (heat) in cavity walls (in SC RF the main efficiency issues related to fill factors and cryogenics)
  - Standing wave cavities with low peak power requirements
  - Long beam pulse (~1 ms) - favorable for feed-backs within the pulse train
- Low impedance
  - beam generates low “wakefields”
  - relatively large structures (1.3 GHz)

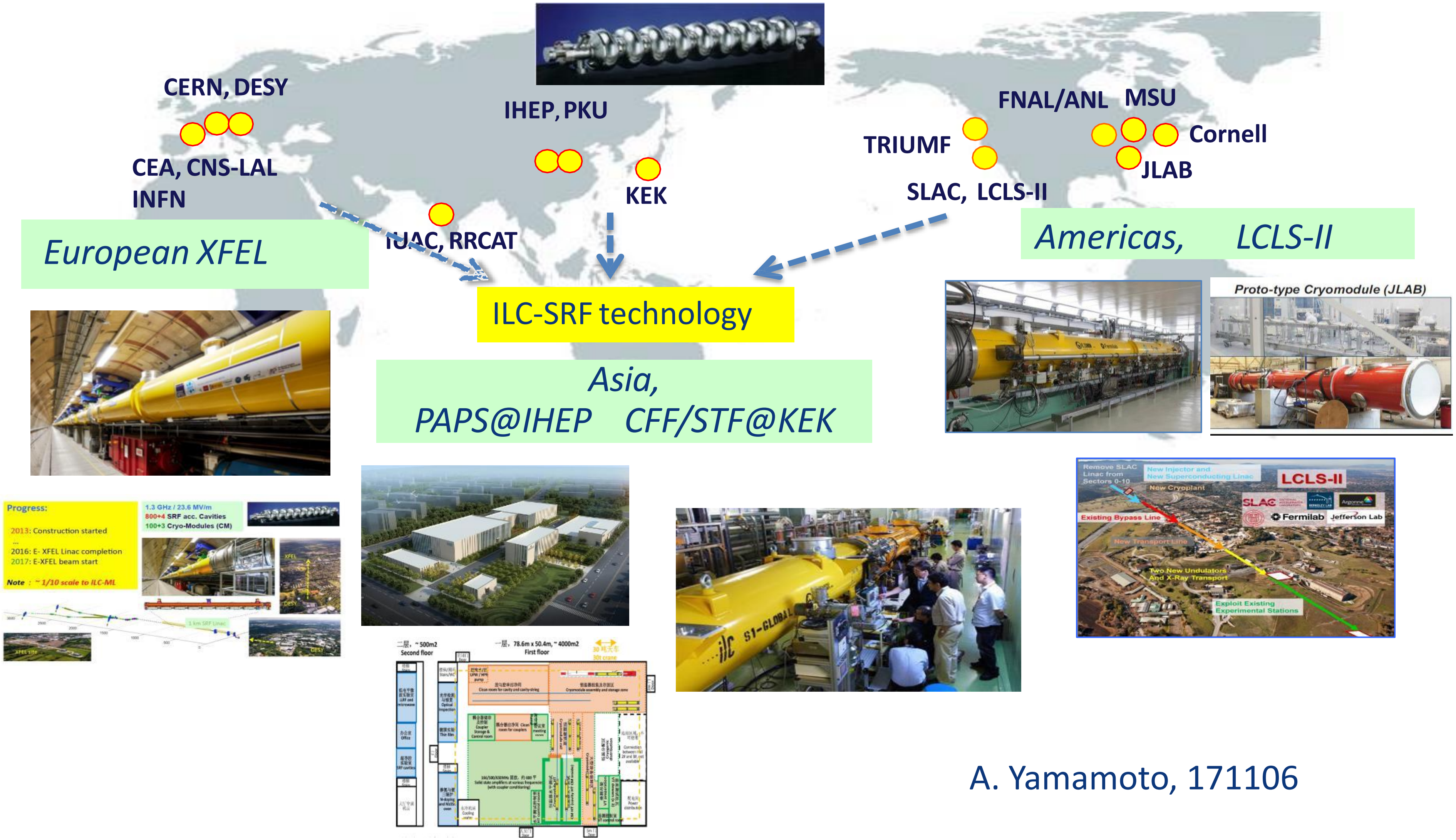


SCRF Accelerators Advances … 2010 ~

Courtesy, H. Padamsee

Project	Notes	# cavities
CEBAF-JLAB (US)	Upgrade 6.5 GeV => 12 GeV electrons	80
XFEL-Hamburg (EU)	18 GeV electrons – for Xray Free Electron Laser – Pulsed)	840
LCLS-II – SLAC (US)	4 GeV electrons –CW XFEL (Xray Free Electron Laser)	300
SPIRAL-II (France)	30 MeV, 5 mA protons -> Heavy Ion	28
FRIB – MSU 8US)	500 kW, heavy ion beams for nuclear astrophys	340
ESS (Sweden)	1 – 2 GeV, 5 MW Neutron Source ESS - pulsed	150
PIP-II–Fermilab (US)	High Intensity Proton Linac for Neutrino Beams	115
ADS- (China, India)	R&D for accelerator drive system	> 200
Globally Int. Effort		> 2000

Worldwide SRF Collaboration



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The E-XEL

European XFEL, SRF Linac Completed

Courtesy, H. Weise

Progress:

2013: Construction started

…

2016: E- XFEL Linac completion

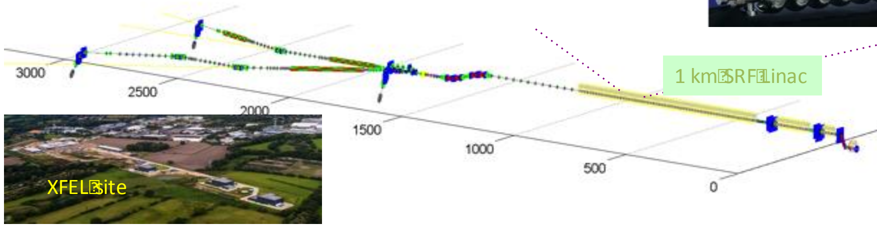
2017: E-XFEL beam start

1.3 GHz / 23.6 MV/m

800+4 SRF acc. Cavities

100+3 Cryo-Modules (CM)

: ~1/10 scale to ILC-ML



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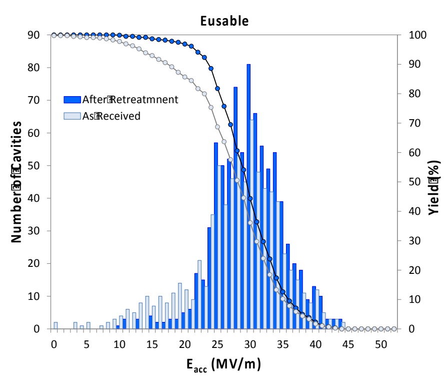
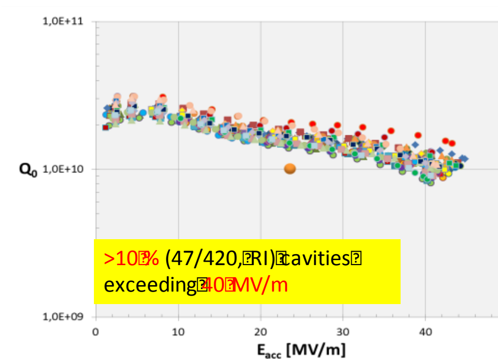
Courtesy, D. Reschke , N. Walker, C. Pagani

European XFEL: SRF Cavity Performance



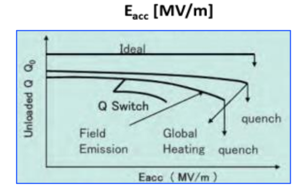


After Retreatment:

E-usable: 29.8 ± 5.1 [MV/m]

(RI): E usable 31.2 ± 5.2 [MV/m]), w/ 2nd EP

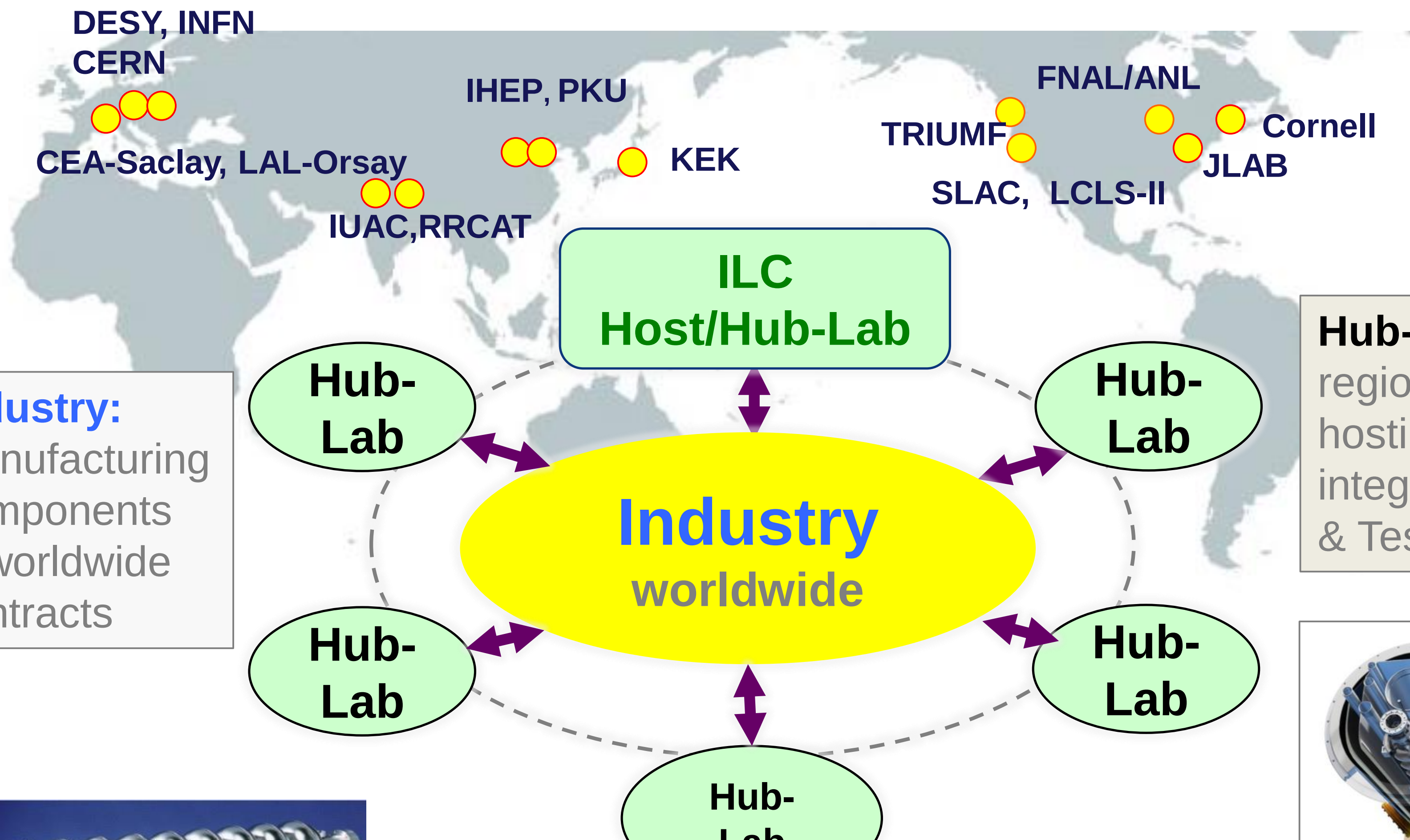
(EZ): E usable 28.6 ± 4.8 [MV/m]) w/ BCP (instead of 2nd EP)



ILC Parameters demonstrated

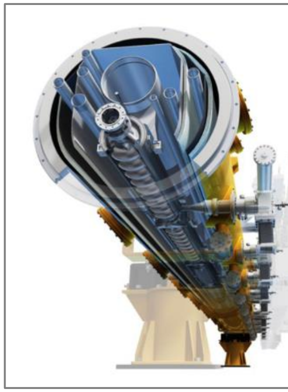
Characteristics	Parameter	Unit	Demonstrated
Nano-bam:			
ATF-FF equiv. beam size (y) ILC-FF beam size (y)	37 (reaching **41**) 5.9 (correspond. **7**)	nm nm	KEK-ATF
SRF:			
Average accelerating gradient	**31.5 (±20%)**	MV/m	DESY, FNAL, JLab, Cornell, KEK,
Cavity Q_0	**10^{10}**		
(Cavity qualification gradient	**35 (±20%)**	MV/m)	
Beam current	**5.8**	mA	DESY-FLASH), KEK-STF
Number of bunches per pulse	**1312**		DESY
Charge per bunch	3.2	nC	
Bunch spacing	554	ns	
Beam pulse length	**730**	ms	DESY, KEK
RF pulse length (incl. fill time)	**1.65**	ms	DESY, KEK, FNAL
Efficiency (RF→beam)	0.44		
Pulse repetition rate	**5**	Hz	DESY, KEK

ILC SC RF global integration model



Industry: manufacturing components w/worldwide contracts

Hub-lab: regionally hosting integration & Test



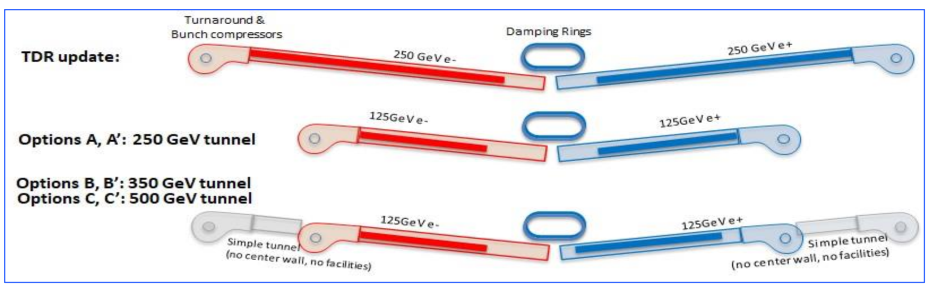
ILC since the TDR in 2012-13: Technical focus and changes

Site specific studies

Technical developments for most accelerator systems - high Q improvements for example

E-XFEL at DESY successfully constructed and put into operation – a key technology demonstration

Options for ILC Staging at 250GeV



Options	Gradient [MV/m]	E_{CM} [GeV]	Total E_{CM} Margin	n	Space margin	Reserved tunnel	Total tunnel
TDR update	31.5	500	2%	10	1,473 m	0 m	33.5 km
Option A		250	6%	6	583 m	0 m	20.5 km
Option B				6&8		3,238 m	27 km
Option C				6&10		6,477 m	33.5 km
Option A'	35			6	1,049 m	0 m	20.5 km
Option B'				6&8		3,238 m	27 km
Option C'				6&10		6,477 m	33.5 km

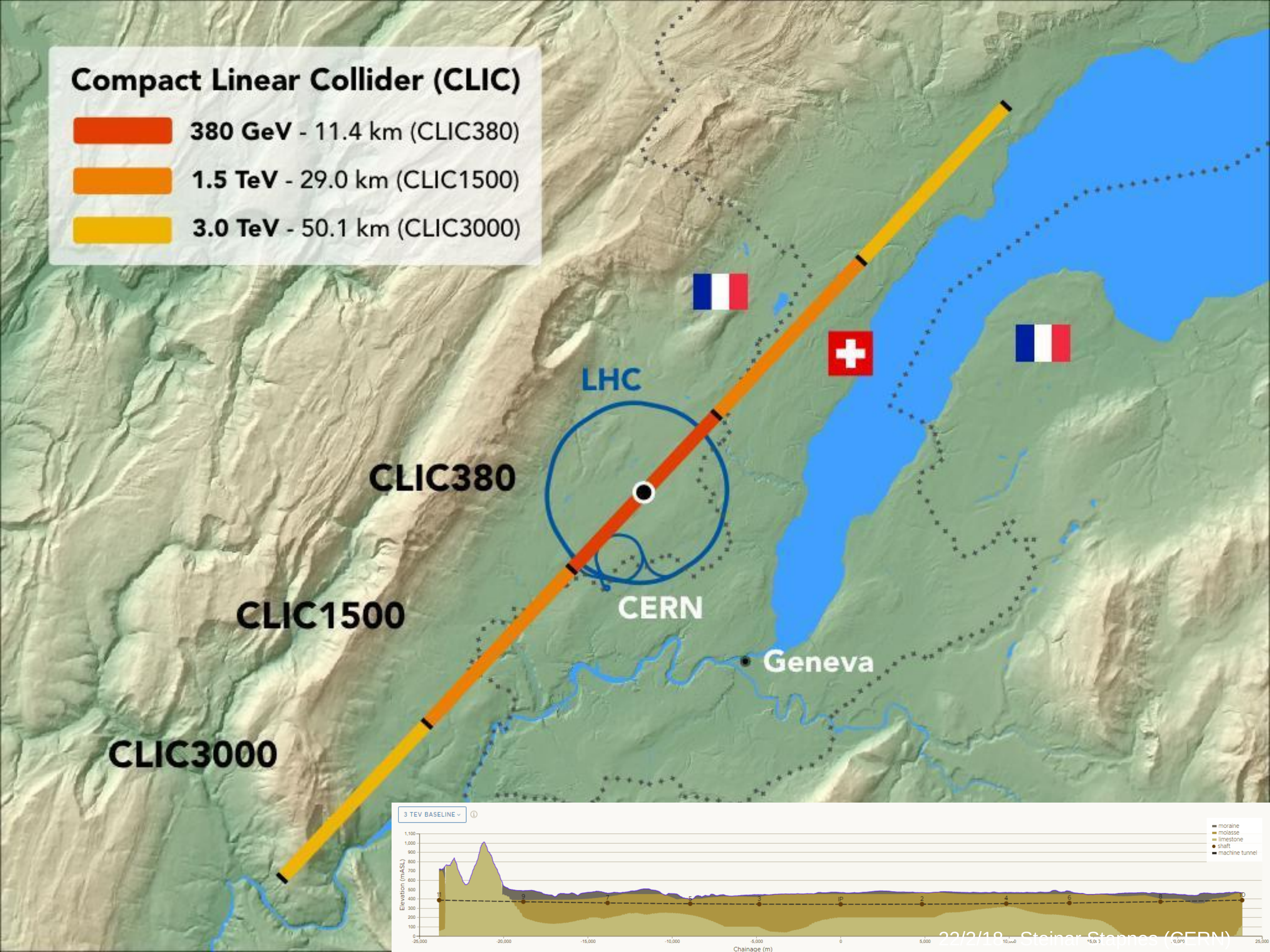
Recent proposal to start with an initial energy of 250 GeV (physics impact report) – key issues:

- Higgs precision depends significantly on HiLumi performance and theory assumptions (link)
- Below ttbar threshold
- Reduced search capabilities

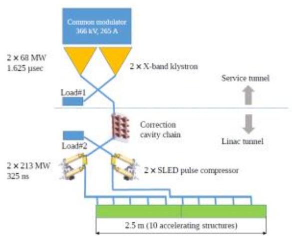
Nevertheless, provides impressive precision, and remains upgradable.

TDR costs of ~8 BILCU for 500 GeV (ILCU = 2012 US$ estimate used in the TDR) can be reduced by up to ~40%

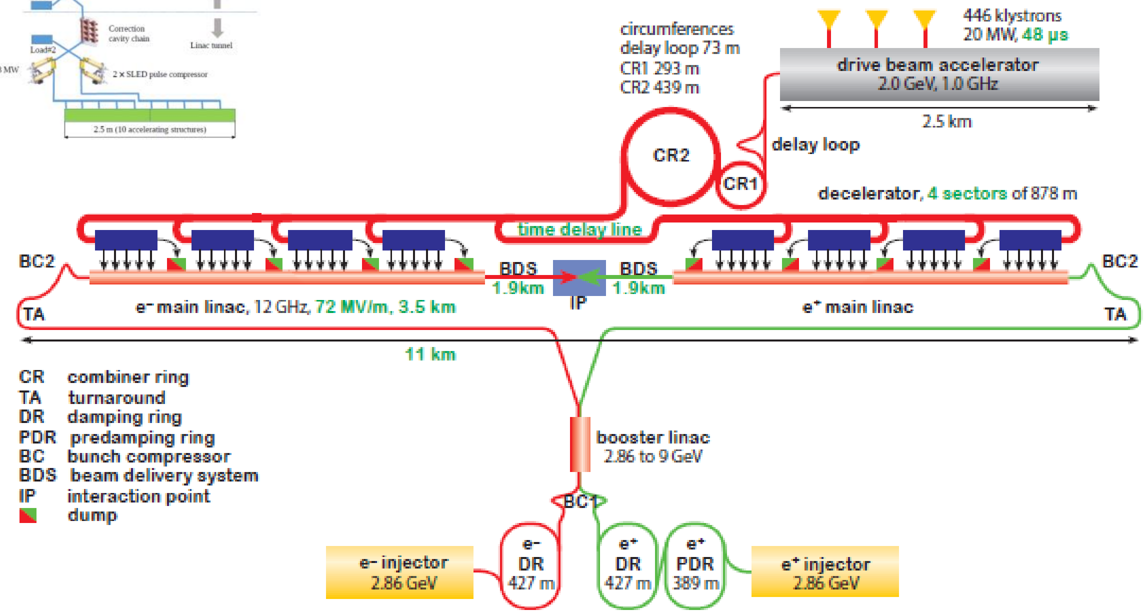
Status and Prospect for ILC

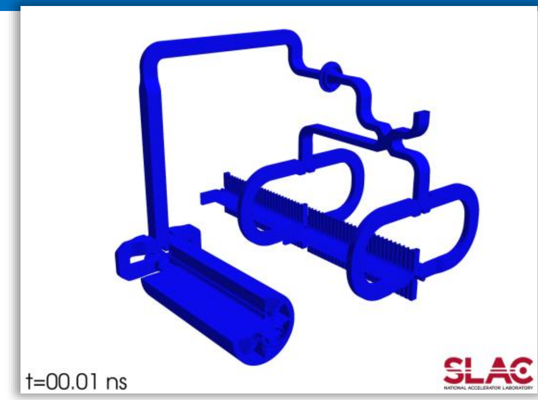

Compact Linear Collider (CLIC)
380 GeV - 11.4 km (CLIC380)
1.5 TeV - 29.0 km (CLIC1500)
3.0 TeV - 50.1 km (CLIC3000)
LHC
CLIC380
CLIC1500
CLIC3000
CERN
Geneva
3 TEV BASELINE
moraine
molasse
limestone
shaft
machine tunnel
Elevation (mASL)
Chainage (m)

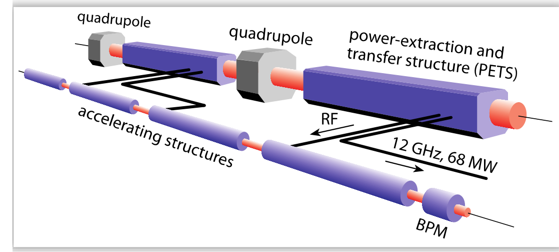
CLIC layout, power generation



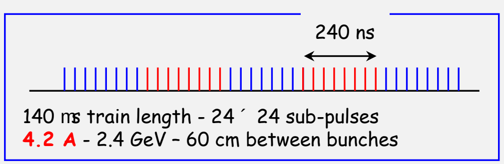
Drive-beam (low energy, high intensity, long pulses) created by klystrons



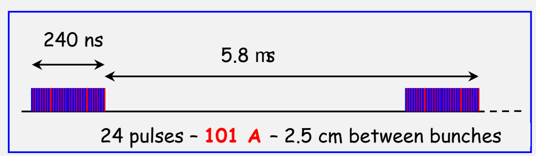




Drive beam time structure - initial



Drive beam time structure - final



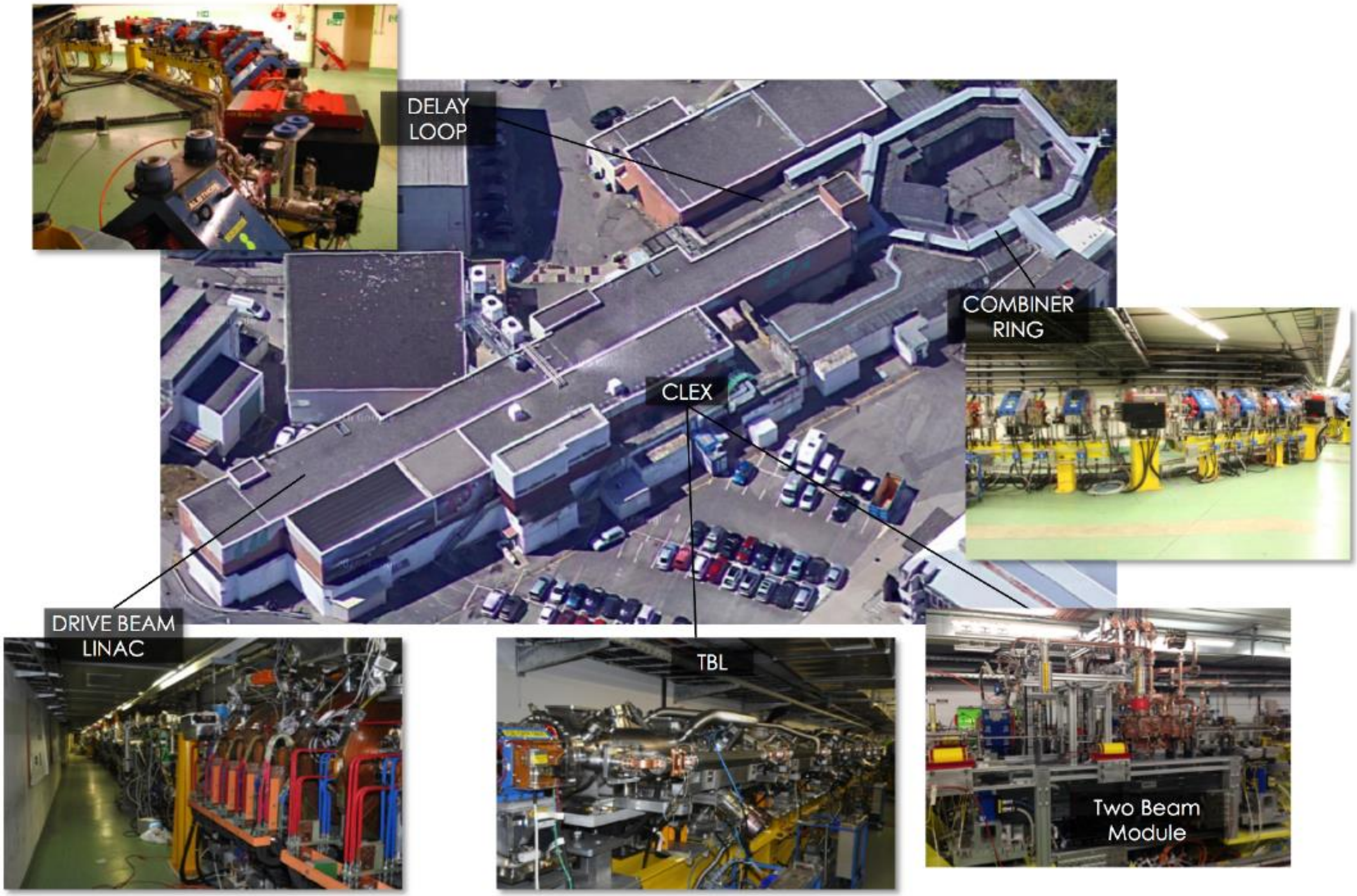
First stage energy ~ 380 GeV

Parameter'	Unit'	380'GeV'	3'TeV'
Centre&of&mass,energy,	TeV,	0.38,	3,
Total,luminosity,	10^{34}cm$^{\&2}$s$^{\&1}$,	1.5,	5.9,
Luminosity,above,99%,of,√s,	10^{34}cm$^{\&2}$s$^{\&1}$,	0.9,	2.0,
RepeEEon,frequency,	Hz,	50,	50,
Number,of,bunches,per,train,		352,	312,
Bunch,separaEon,	ns,	0.5,	0.5,
AcceleraEon,gradient,	MV/m,	72,	100,
Site,length,	km,	11,	50,

Let us look at three challenges:

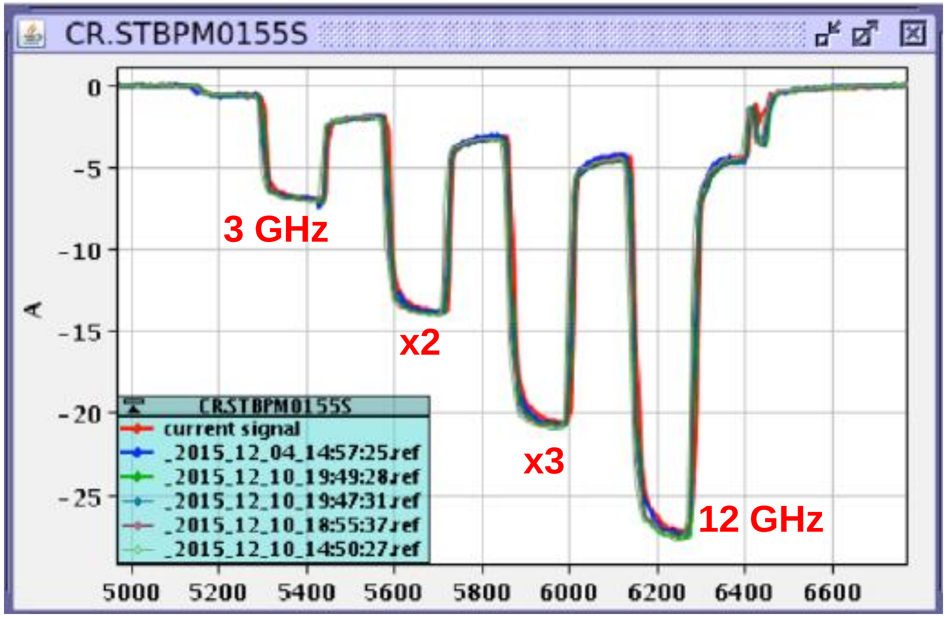
- High-current drive beam bunched at 12 GHz
- Power transfer + main-beam acceleration
- ~100 MV/m gradient in main-beam cavities

CLIC Test Facility (CTF3)



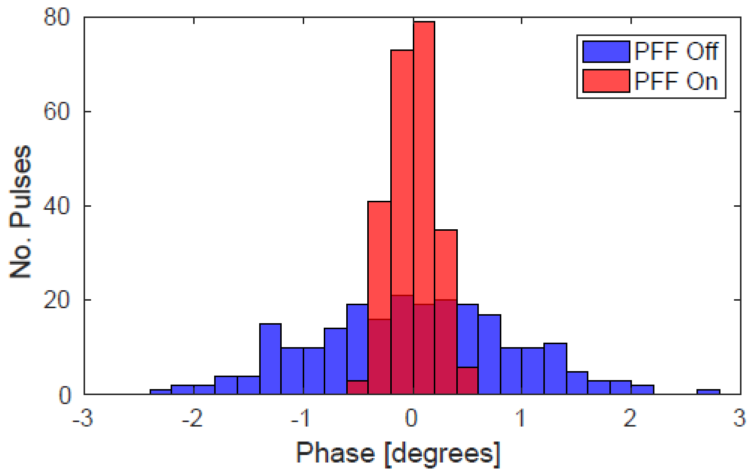
Status

- **Produced high-current drive beam bunched at 12 GHz**



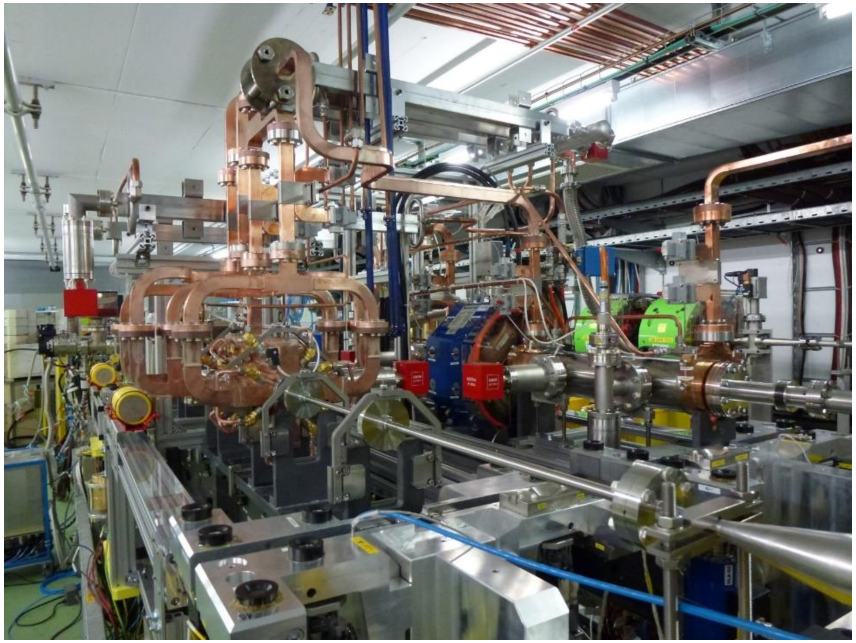
28A

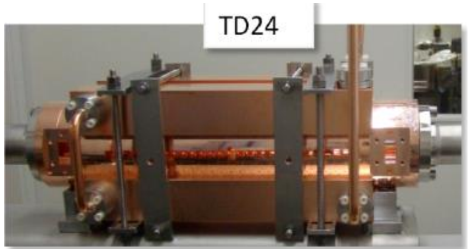
Arrival time stabilised to 50 fs



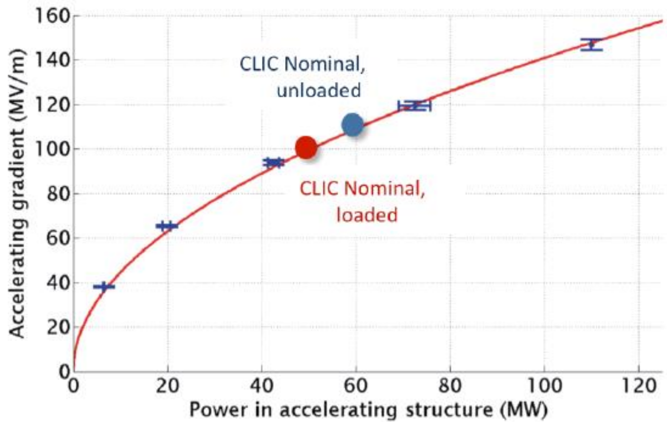
Status

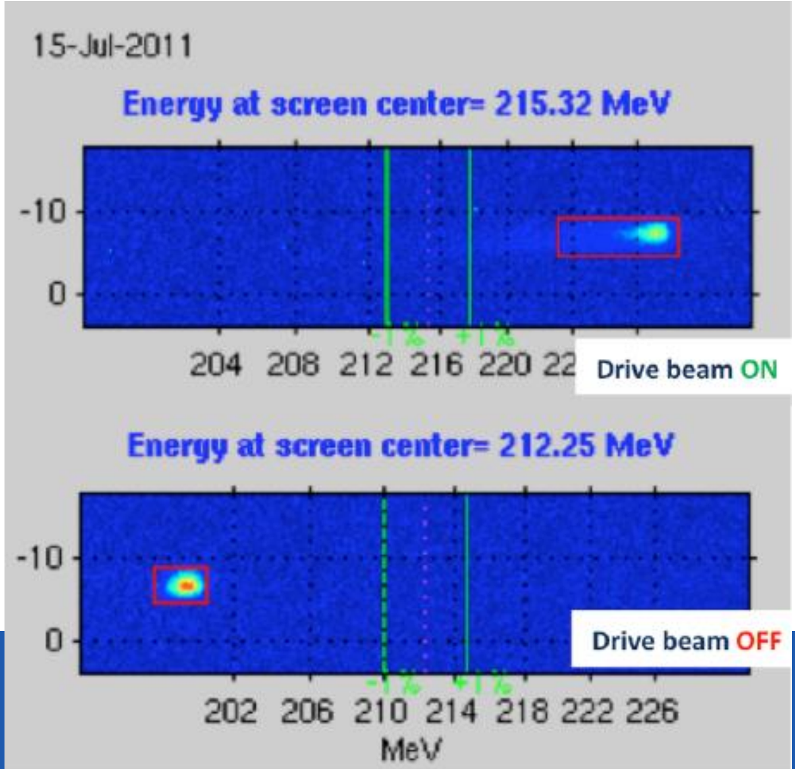
- **Demonstrated two-beam acceleration**





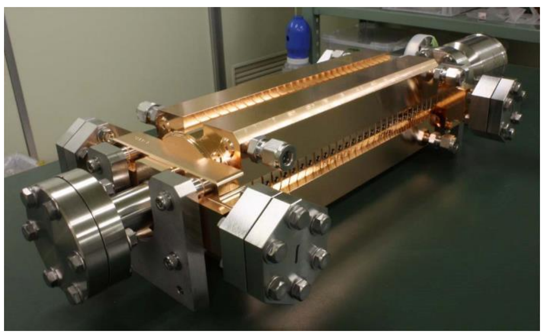
31 MeV = 145 MV/m

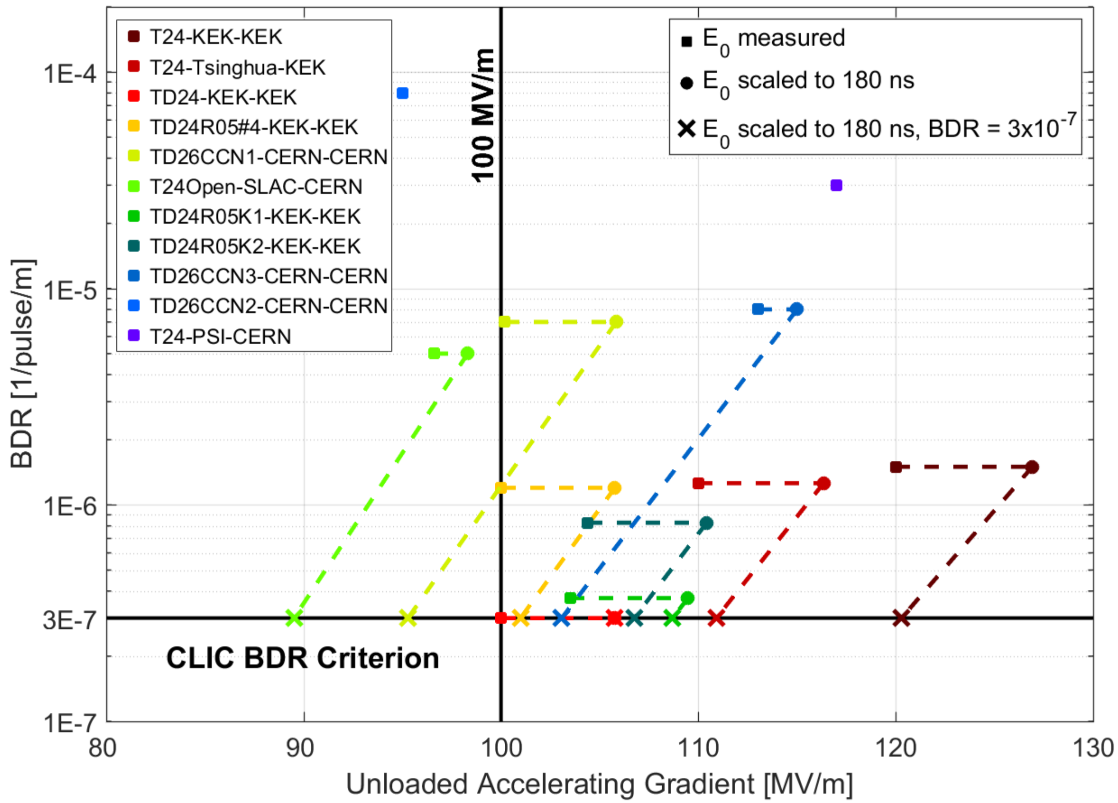


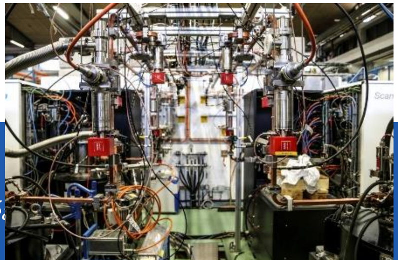


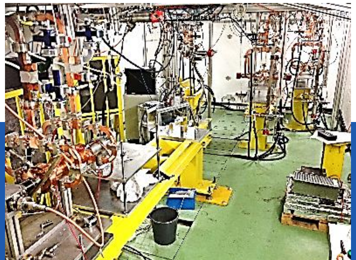
Status

- Achieved 100 MV/m gradient in main-beam RF cavities



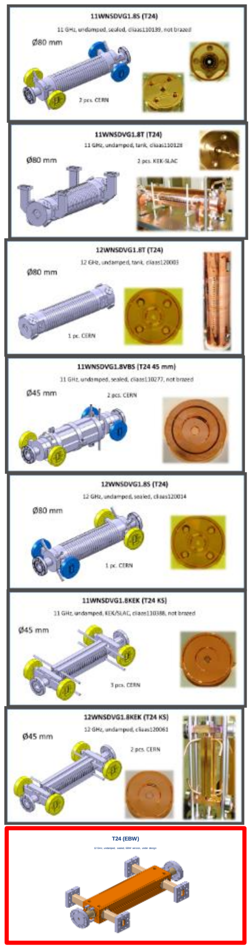


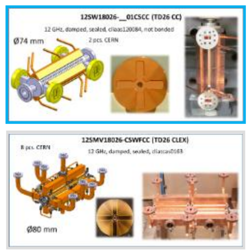




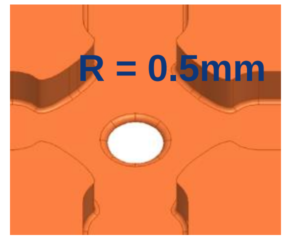
Acc. Structures TD24&26 – new baseline optimised and alternatives for manufacturing and cost

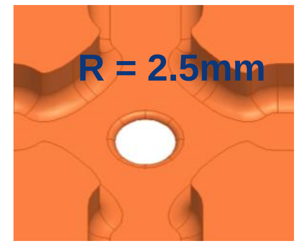
Baseline: Machines disks, damping structures, bonding steps





3 TeV structure CLIC G* (optimised)



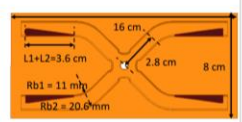


SwissFEL Assembly (brazing)

Rectangular (manufacturing)

CLIC-G* Matching Step

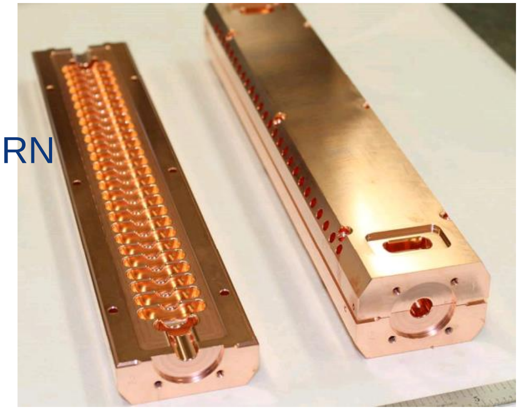
CLIC-G* Bend waveguide



HL	32 mm	D2	5 mm
L1	31 mm	T2	5 mm
L2	2 mm	Mx	0.75 mm
D1	0.8 mm	Mz	1 mm
T1	0.6 mm	Tx	0 mm
		Tz	0.7 mm

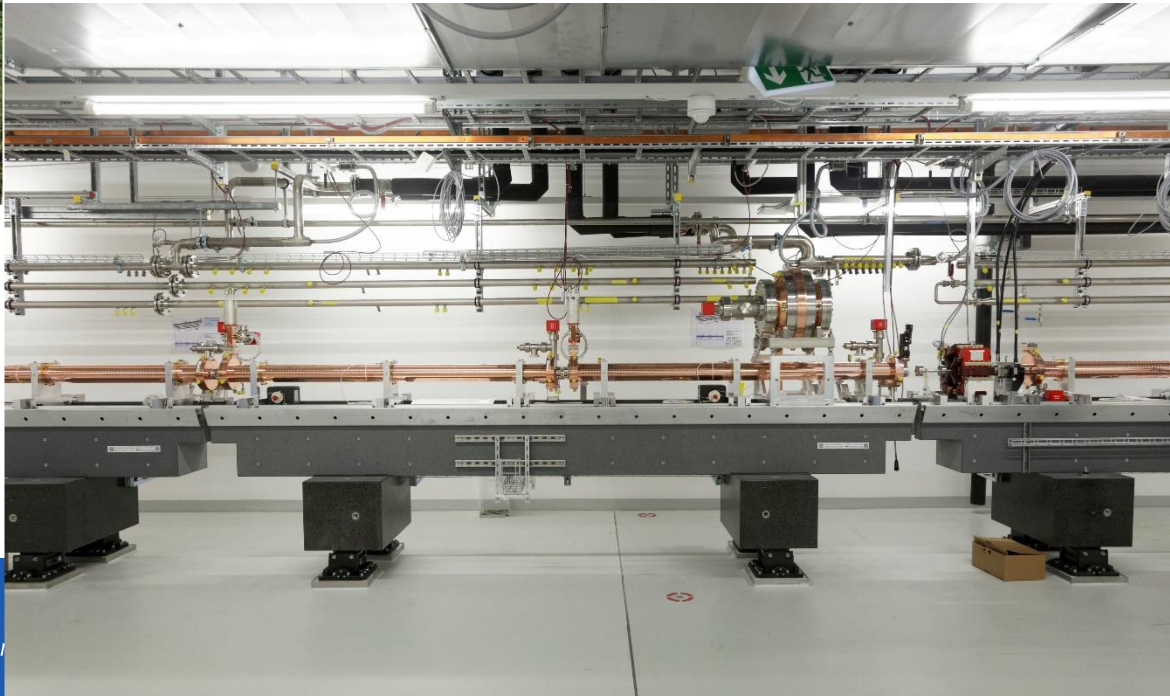
		D2	5.2 mm
L1	34 mm	T2	4.8 mm
L2	2 mm	Mx	0.2 mm
D1	1 mm	Mz	1 mm
T1	1 mm	Tx	0 mm
		Tz	0 mm

Halves: SLAC/CERN



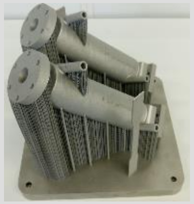
SwissFEL

- 104 x 2m-long C-band structures
  (beam → 6 GeV @ 100 Hz)
- Similar um-level tolerances
- Length ~ 800 CLIC structures



Industrial considerations
(example)

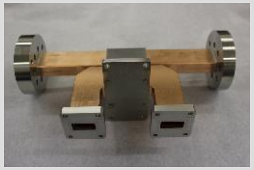
Bodycote (FR)
Reuter (DE)
TMD (UK)



SWISSto12 (CH)
3T RPD (UK)
Concept Laser (DE)
INITIAL (FR)
Protoshop (DE)

VDL (NL)
LT-Ultra (DE)
Yvon Boyer (FR)
DMP (ES)
Morikawa (JP)
KERN (DE))

Thermocompact (FR)
BACMI (FR)
Multivalent (NL)



CINEL (IT)
VDL (NL)
BACMI (FR)
CECOM(IT)
Reuter (DE)
Nihon (JP)
COMEB (IT)
Viztrotech (KR)

Thales (FR)
CPI(US)
Toshiba (JP)

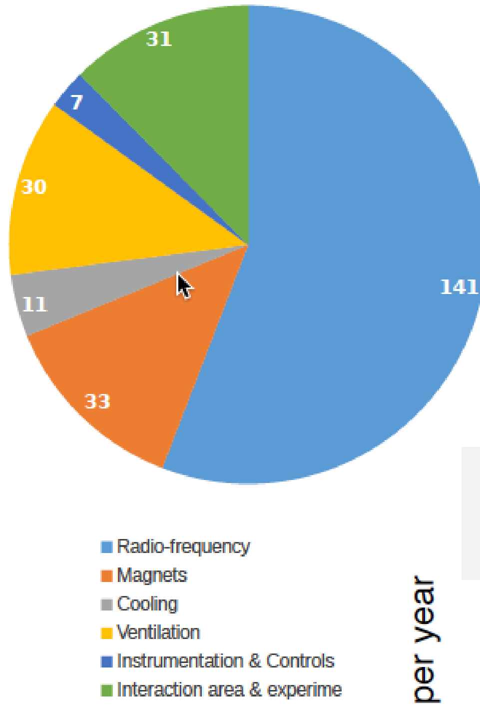
Scandinova (SE)
Jema (ES)
Picatron (CH)

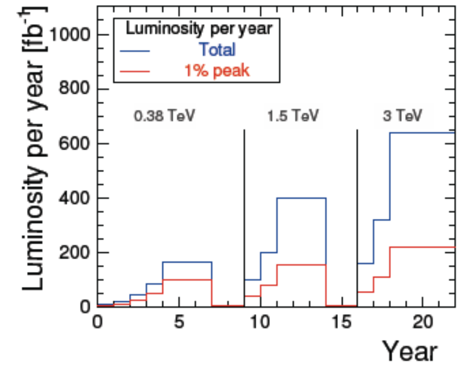
Compact Linear Collider

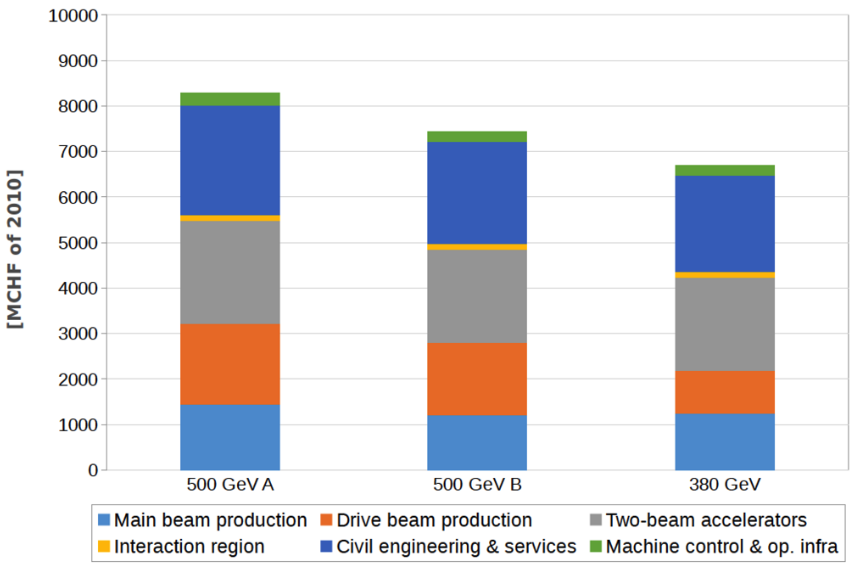
Cost and Power

Table 11: Value estimate of CLIC at 380 GeV centre-of-mass energy.

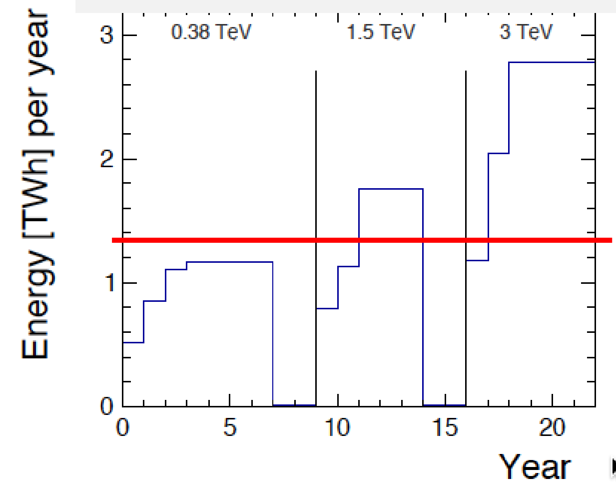
	Value [MCHF of December 2010]
Main beam production	1245
Drive beam production	974
Two-beam accelerators	2038
Interaction region	132
Civil engineering & services	2112
Accelerator control & operational infrastructure	216
Total	6690







CERN energy consumption 2012: 1.35 TWh



A cost of ~6 BCHF and power ~200 MW are “reasonable” values

→ Continue work on modules, RF and CE for costs; for power RF and magnets

CLIC roadmap

2013 - 2019 Development Phase

Development of a Project Plan for a staged CLIC implementation in line with LHC results; technical developments with industry, performance studies for accelerator parts and systems, detector technology demonstrators

2020 - 2025 Preparation Phase

Finalisation of implementation parameters, preparation for industrial procurement, Drive Beam Facility and other system verifications, Technical Proposal of the experiment, site authorisation

2026 - 2034 Construction Phase

Construction of the first CLIC accelerator stage compatible with implementation of further stages; construction of the experiment; hardware commissioning

2019 - 2020 Decisions

Update of the European Strategy for Particle Physics; decision towards a next CERN project at the energy frontier (e.g. CLIC, FCC)

2025 Construction Start

Ready for construction; start of excavations

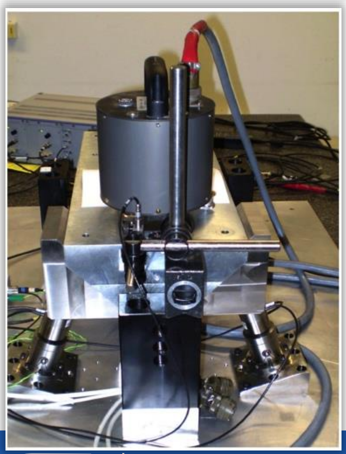
2035 First Beams

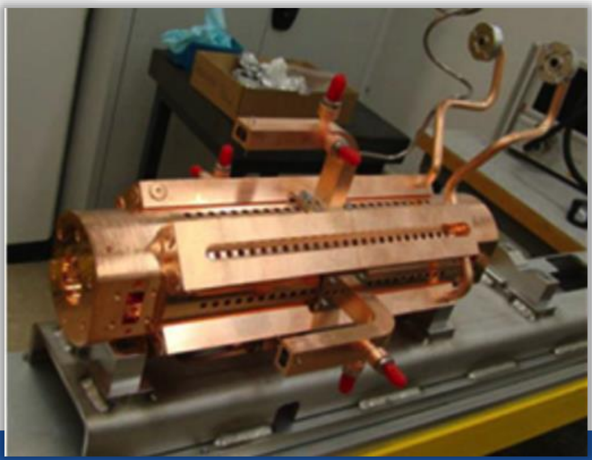
Getting ready for data taking by the time the LHC programme reaches completion

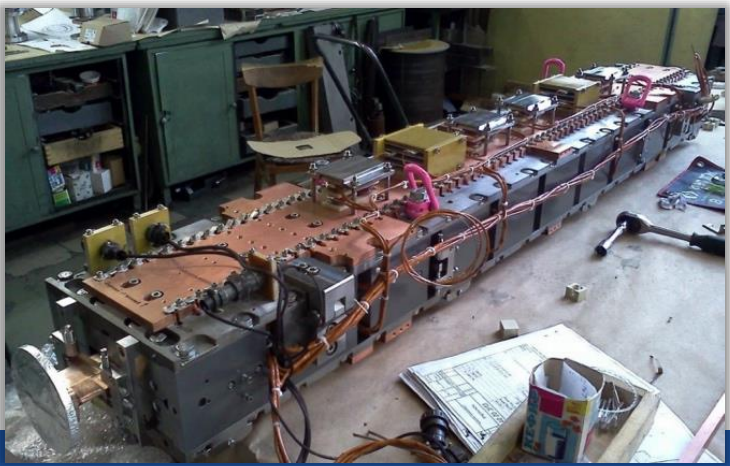
Technical activities – examples

Technical Developments are motivated by several possible reasons – and are now quite mature:

- Key components for system-tests (example magnets, instrumentation, modules)
- Critical for machine performance (example alignment, stabilization, damping ring studies)
- Aimed at cost or power reduction (example magnets, klystrons, modules)



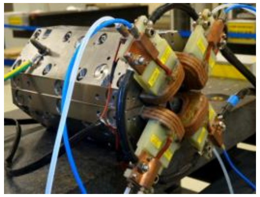




Information about some relevant suppliers and subcontractors participating to prototypes procurement for the CLIC Magnets R&D phase

Note: majority of coils and of other components manufacturing, magnet assembly, was done by CERN apart for the DBQ magnets (EM and PM versions).

1) **Main Beam Quadrupoles. 4 prototypes** procured: 3 Type1 (the shorter), 1 Type4 (the longer)



Relevant procurements:

- *Coils:* **TESLA** Engineering LTD, Storrington, West Sussex - UK
- *High Precision quadrants machining:*
- **DMP** 20850 Mendaro, Gipuzkoa - ES

2) **Drive Beam Quadrupoles** (EM version): **8 prototypes** procured:

Relevant manufacturers:

-*Complete manufacturing:*

Danfysik A/S 2630 Taastrup, DK

Rele

-*Des*

-*PM*

Hana

-*Hig*

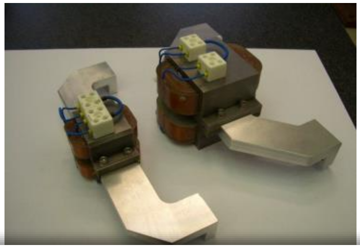
-**SEN**

-**TSV**

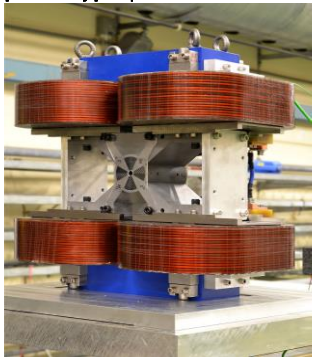
-**Mc**

3) **Drive Beam Quadrupoles** (PM version): **2 prototypes** procured by Daresbury Laboratory

4) **Main Beam Steering Dipoles**: **2 prototypes** procured



5) **Final Focus Quadrupole QD0**: **1 prototype** procured



Relevant manufacturers:

- *PM blocks, Permendur EDM machining:* **Vacuumschmelze** GmbH & Co. KG, Hanau - D

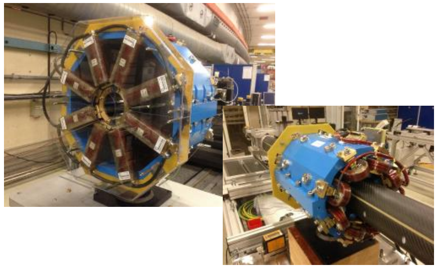
6) **Final Focus Sextupoles SD0:** *(**1 prototype** procurement **on-going**)*

Relevant manufacturers:

- *Permendur and PM blocks procurement:*

VDL Groep BV, Eindhoven - NL

7) **Octupoles for ATF** facility at KEK, Japan: **2 magnets** procured

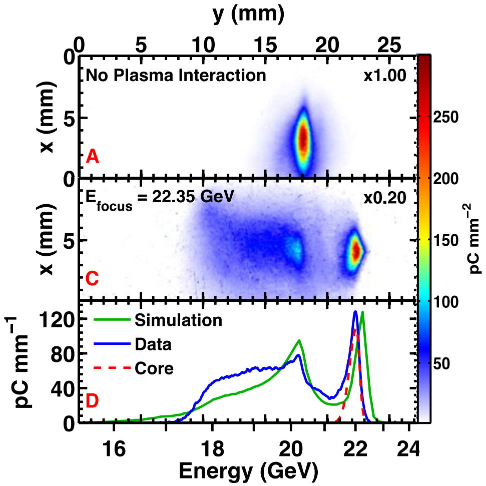


Relevant manufacturers:

- *Coils:* **S.E.F.** Sarl, Labège - F
- *Iron Yokes EDM Machining:*

Röttgers Værktøj A/S Odense - DK

Towards TeV beams with new technology ?



1.7 GeV energy gain in 30 cm of pre-ionized Li vapor plasma.

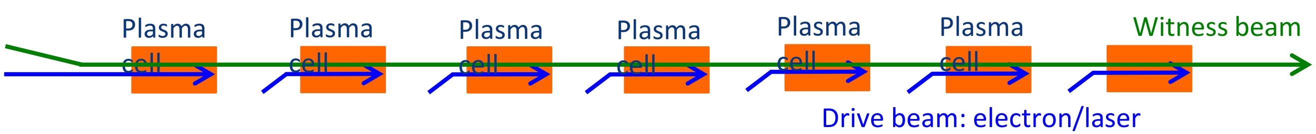
2% energy spread

Up to 30% wake-to-bunch energy transfer efficiency (mean 18%).

A possible witness beams:
Electrons: 10^{10} particles @ 1 TeV
~few kJ

Existing driver beams options :
Lasers: up to 40 J/pulse
Electron driver: up to 60 J/bunch
Proton driver: SPS 19 kJ/bunch, LHC 300 kJ/bunch

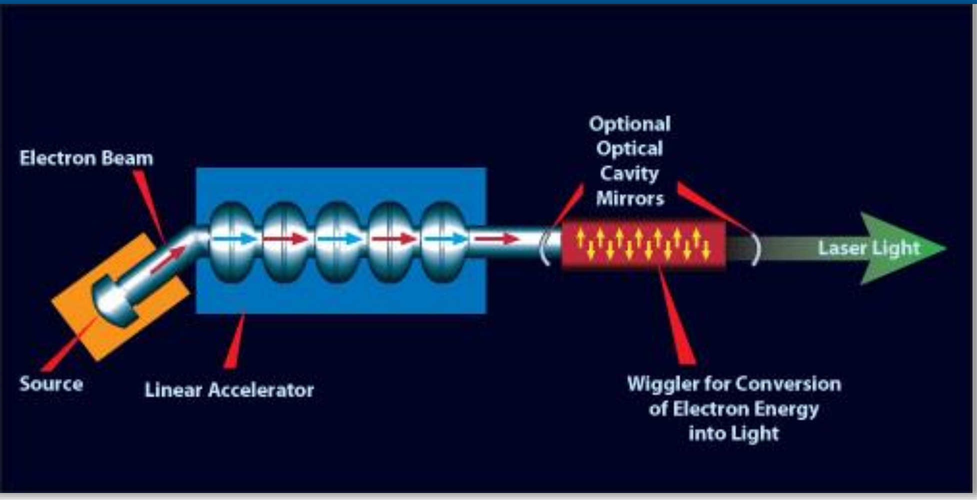
While GeV acceleration in plasmas has been demonstrated for with both lasers and electron beams, reaching TeV scales requires **staging** of many drivers and plasma cells. Challenging.

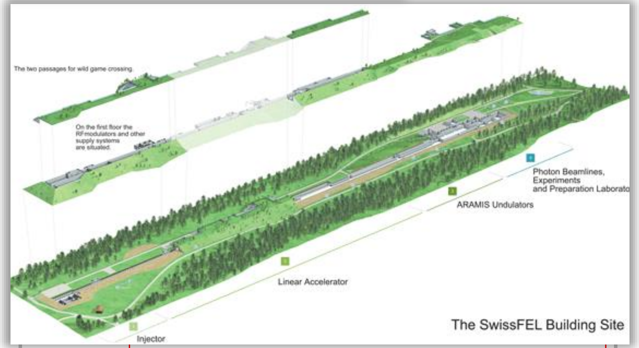


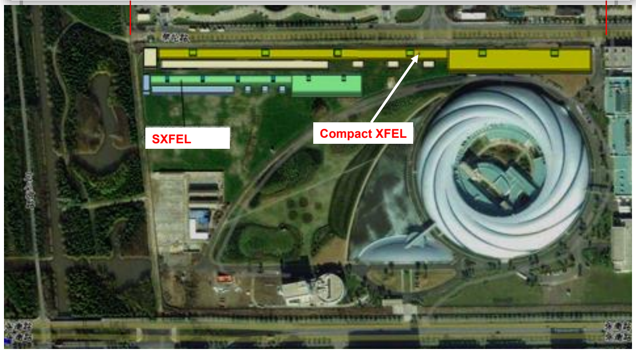
Current focus on "small scale" applications – for LCs a long way to go:
Electrons and Positrons, staging, energy efficiency, suitable beam-parameters and luminosity
However – disruptive technologies so (always) very important to pursue (and cost in this case likely less)

Mostly from E.Adli

Free electron lasers and Linear Colliders



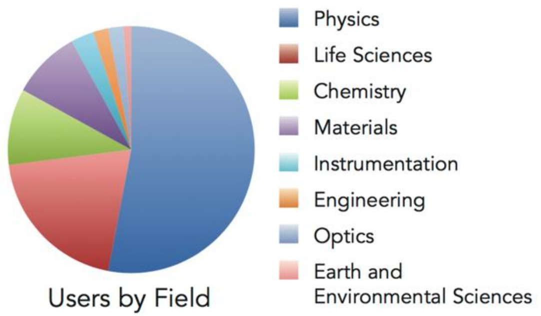




User community in many fields of science (LCLS 2013)

LCLS Facts

- 594 scientists conducted experiments in 2013
- 4,580 operating hours in 2013
- 277 publications since LCLS began in 2009
- 15 collaborators, on average, per experiment proposal
- 6 experimental stations



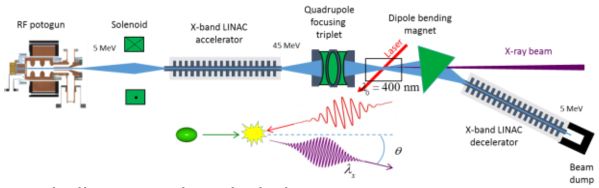
Users by Field

LCLS I and II, SACLA, E-XFEL, SwissFEL … many more (from soft to hard X-ray)

Ex. links LCs and FELs for CLIC(ILC shown already)

CERN	XBox-1 test stand	50 MW	Operational, connection to CLEAR planned
	Xbox-2 test stand	50 MW	Operational
	XBox-3 test stand	4x6 MW	Operational
Trieste	Linearizer for Fermi	50 MW	Operational
PSI	Linearizer for SwissFEL	50 MW	Operational
	Deflector for SwissFEL	50 MW	Design and procurement
DESY	Deflector for FLASHforward	6 MW	Design and procurement
	Deflector for FLASH2	6 MW	Design and procurement
	Deflector for Sinbad	tbd	Planning
Tsinghua	Deflector for Compton source	50 MW	Commissioning
	Linearizer for Compton source	6 MW	Planning
SINAP	Linearizer for soft X-ray FEL	6 MW	Operational
	Deflectors for soft X-ray FEL	3x50 MW	Procurement

Australia	Test stand	2x6 MW	Proposal submission
Eindhoven	Compact Compton source, 100 MeV	6 MW	Design and procurement
Valencia	S-band test stand	2x10 MW	Installation and commissioning
KEK	NEXTEF test stand	2x50 MW	Operational
SLAC	Design of high-efficiency X-band klystron	60 MW	In progress
Daresbury	Linearizer	6 MW	Design and procurement
	Deflector	tbd	Planning
	Accelerator	tbd	Planning
Frascati	XFEL,plasma accelerator, 1 GeV	4(8)x50 MW	CDR
	Test stand	50 MW	Design and procurement
Groningen	1.4 GEV XFEL Accelerator, 1.4 GeV	tbd	NL roadmap, CDR



Eindhoven University led
SMART*LIGHT Compton Source

Key points

Two linear collider projects are being pursued **(ILC and CLIC)** – with large collaborative effort.

- **Both are mature, have a clear physics case, are (each) affordable** – and it is likely one will be built.
- Within 1-2 year the landscape in Japan and Europe can be expected to be clearer.

The developments (design, technical developments, tests of single elements or systems, industrial (pre)-productions – and also civil engineering, conventional systems, power and cost optimizations, are done **by international teams/collaborations**, usually led a major lab with special interest in the project but with world-wide participation since the technology developments and knowledge are transferable to other and/or **local projects.**

Linear accelerator technology and development are currently strongly taking part outside particle physics – very beneficial in both directions and easy to show societal impact

Any linear collider facility is likely to host many future machines. It can be **extended** – and/or equipped with new technology in the future … but still a long way to go

Future accelerators in particle physics are today **cost and power limited** – don't scale energy unless you can scale down cost/GeV and maintain or increase luminosities