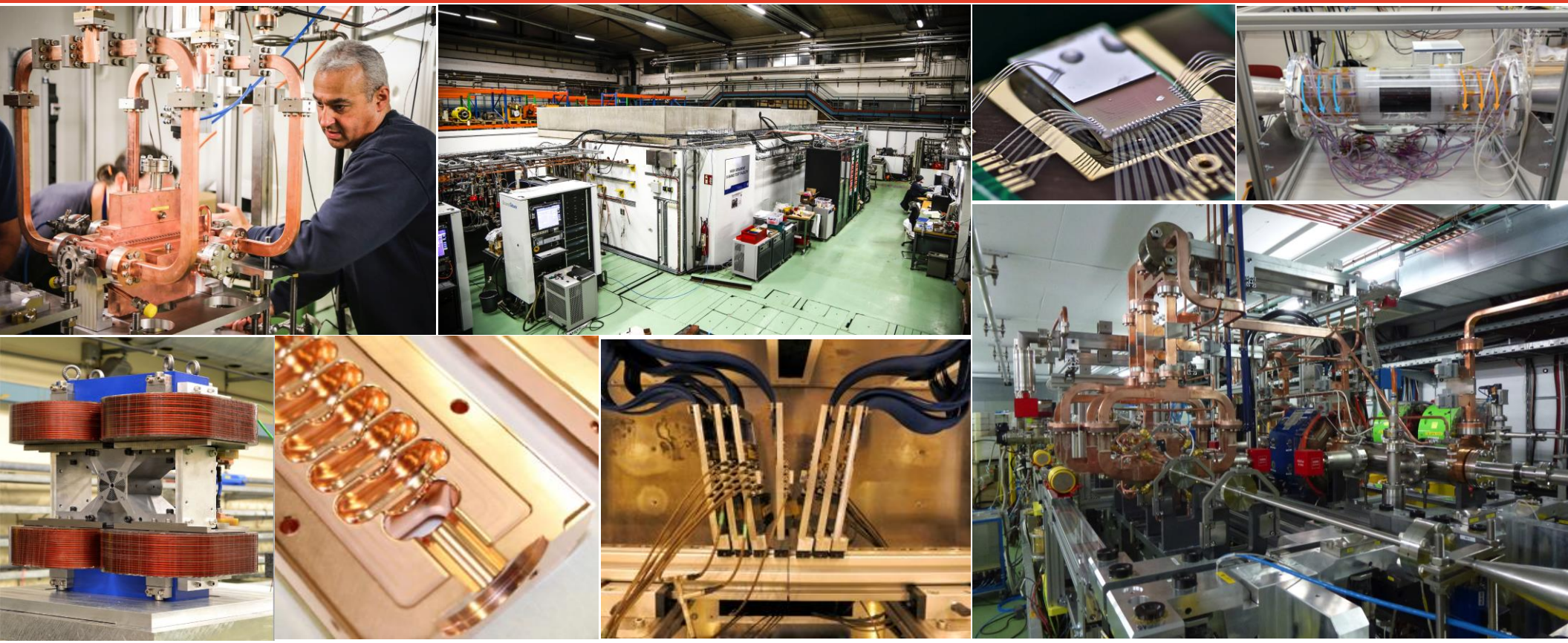
CLIC Status: The Compact Linear Collider



8th International Conference on New Frontiers in Physics, Crete

Andrea Latina, CERN

on behalf of the CLIC and CLICdp Collaborations

CLIC Status: The Compact Linear Collider

- Project overview
- Physics reach
- Accelerator challenges
- Outlook

Compact Linear Collider
e^+e^- collisions up to 3TeV
http://clic.cern/

8th International Conference on New Frontiers in Physics, Crete

Andrea Latina, CERN
on behalf of the CLIC and CLICdp Collaborations

Collaborations

http://clic.cern/

- CLIC accelerator design and development
- (Construction and operation of CTF3)

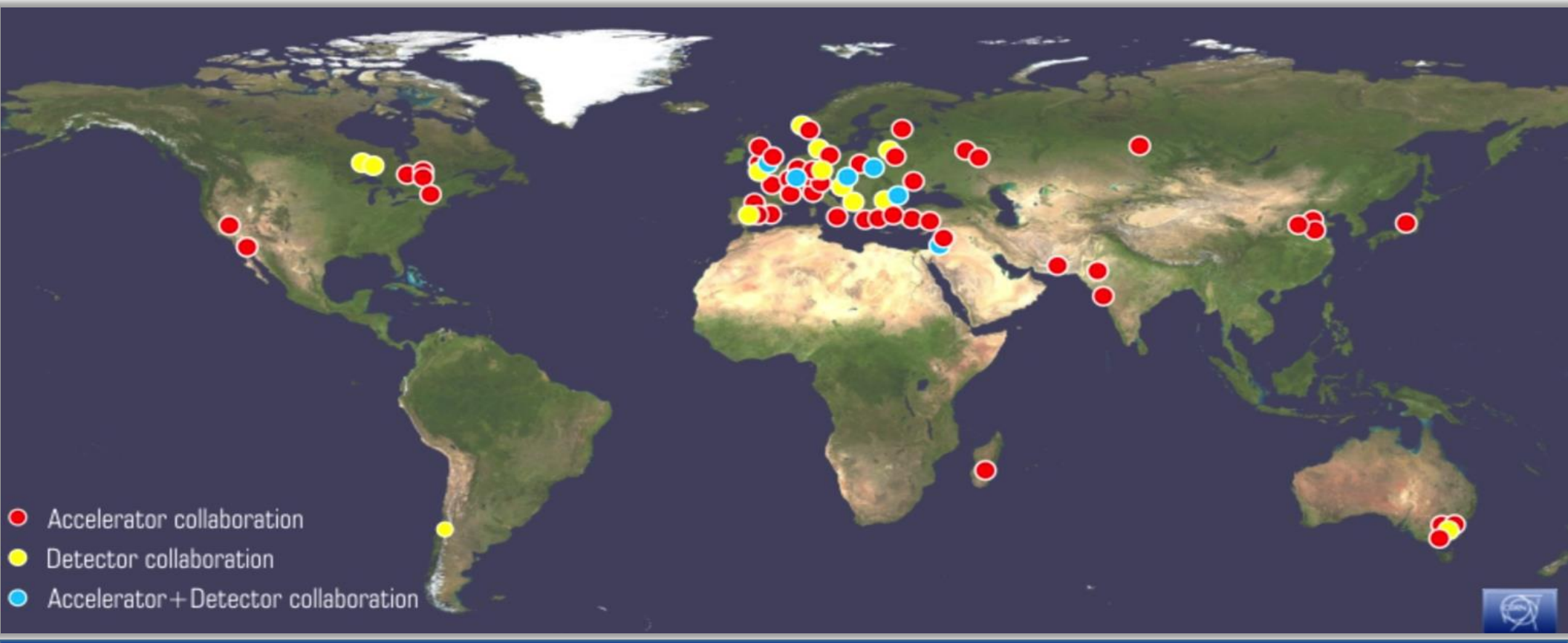
CLIC accelerator collaboration

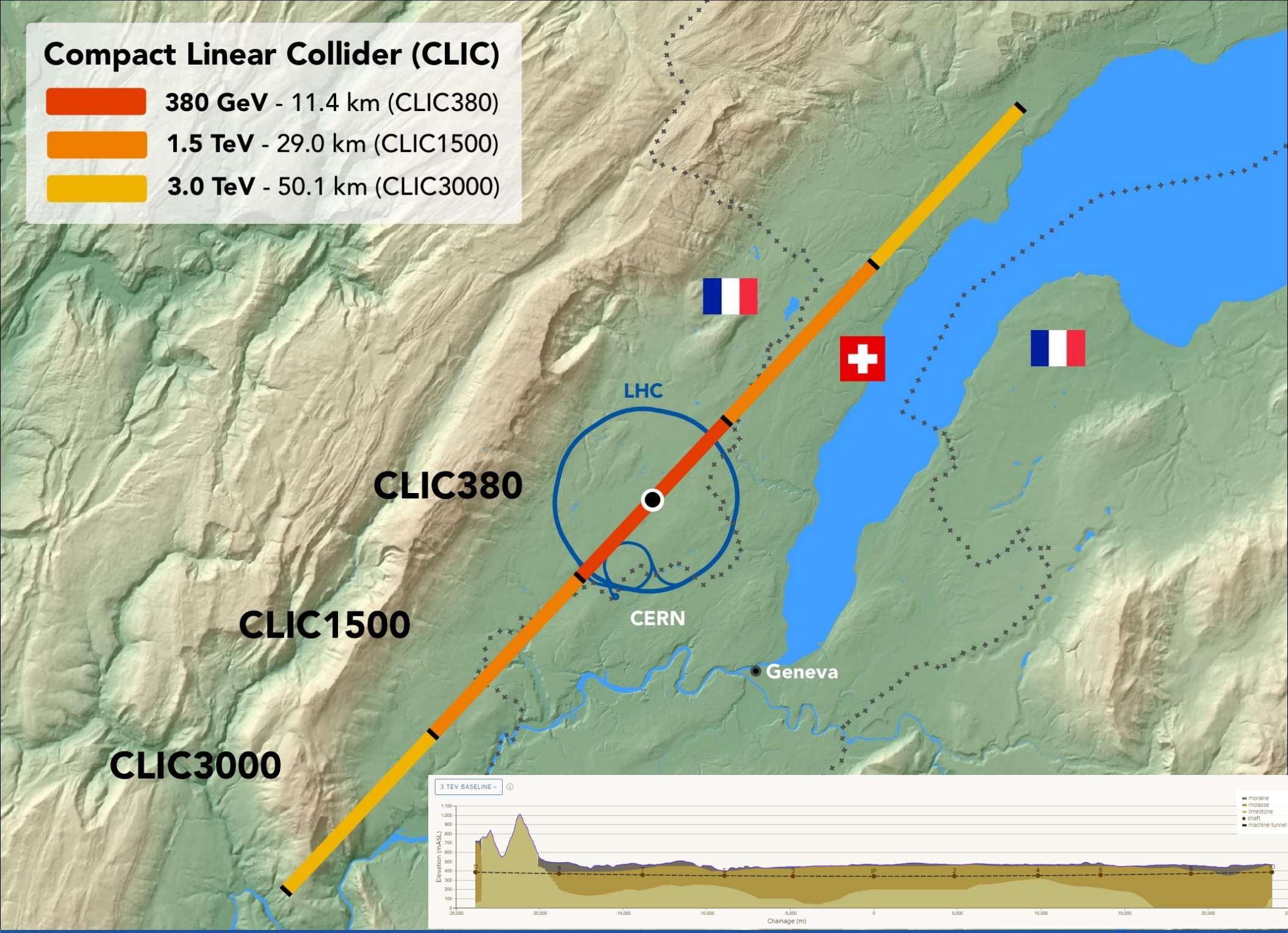
~60 institutes from **28 countries**

- CLIC physics prospects & simulation studies
- Detector optimization + R&D for CLIC

CLIC detector and physics (CLICdp)

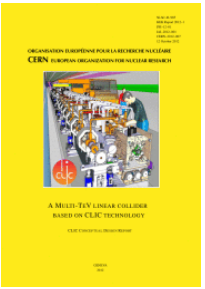
30 institutes from **18 countries**

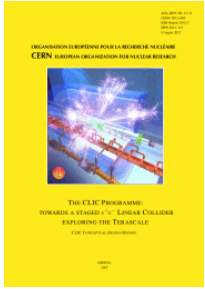



Compact Linear Collider (CLIC)
380 GeV - 11.4 km (CLIC380)
1.5 TeV - 29.0 km (CLIC1500)
3.0 TeV - 50.1 km (CLIC3000)
LHC
CLIC380
CLIC1500
CLIC3000
CERN
Geneva
3 TEV BASELINE
Elevation (mASL)
Chainage (m)
moraine
molasse
limestone
shaft
machine tunnel

CLIC parameters

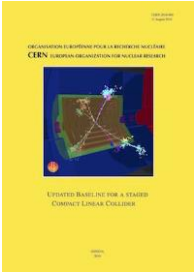
Parameter	Symbol	Unit	Stage 1	Stage 2	Stage 3
Centre-of-mass energy	$\sqrt{s}$	GeV	380	1500	3000
Repetition frequency	f_{rep}	Hz	50	50	50
Number of bunches per train	n_b		352	312	312
Bunch separation	Δt	ns	0.5	0.5	0.5
Pulse length	τ_{RF}	ns	244	244	244
Accelerating gradient	G	MV/m	72	72/100	72/100
Total luminosity	$\mathscr{L}$	10^{34} cm^{-2}s^{-1}	1.5	3.7	5.9
Luminosity above 99% of $\sqrt{s}$	$\mathscr{L}_{0.01}$	10^{34} cm^{-2}s^{-1}	0.9	1.4	2
Main tunnel length		km	11.4	29.0	50.1
Number of particles per bunch	N	10^9	5.2	3.7	3.7
Bunch length	σ_z	µm	70	44	44
IP beam size	σ_x/σ_y	nm	149/2.9	$\sim$ 60/1.5	$\sim$ 40/1
Normalised emittance (end of linac)	$\varepsilon_x/\varepsilon_y$	nm	920/20	660/20	660/20
Normalised emittance (at IP)	$\varepsilon_x/\varepsilon_y$	nm	950/30	—	—





CDR 2012

https://cds.cern.ch/record/1500095
https://cds.cern.ch/record/1425915
https://cds.cern.ch/record/1475225

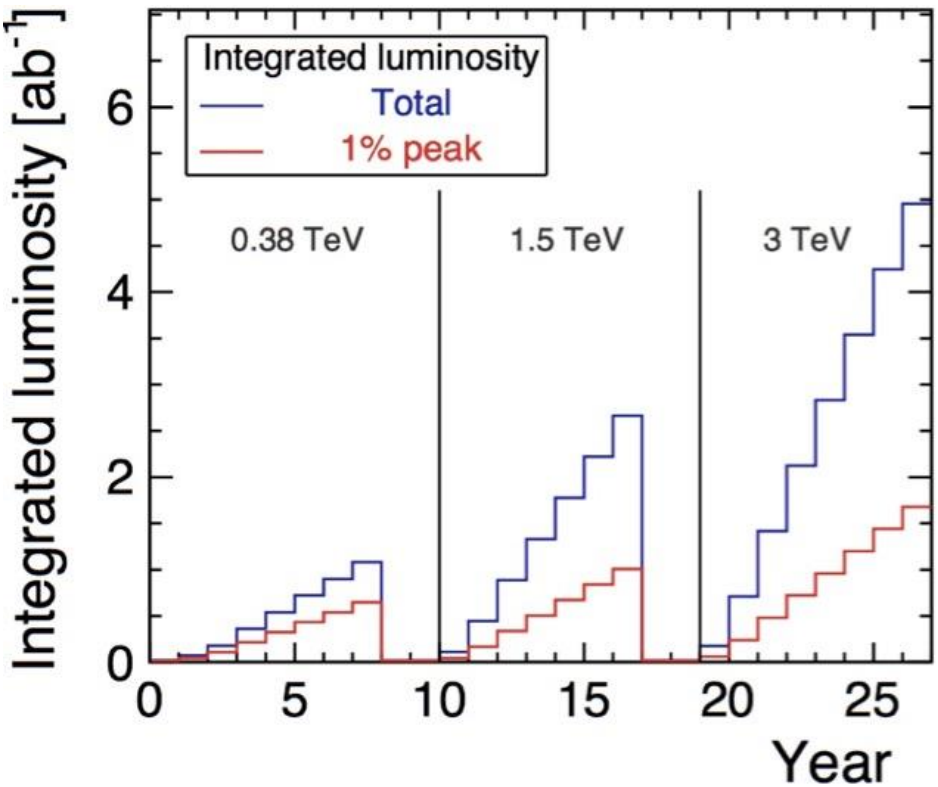


Updated Staging Baseline 2016

http://dx.doi.org/10.5170/CERN-2016-004

Project Implementation Plan 2018

Updated CLIC Staging



Stage	$\sqrt{s}$ [TeV]	$\mathscr{L}_{\text{int}}$ [ab^{-1}]	increased from
1	0.38 (and 0.35)	1.0	0.5+0.1ab^{-1}
2	1.5	2.5	1.5ab^{-1}
3	3.0	5.0	3ab^{-1}

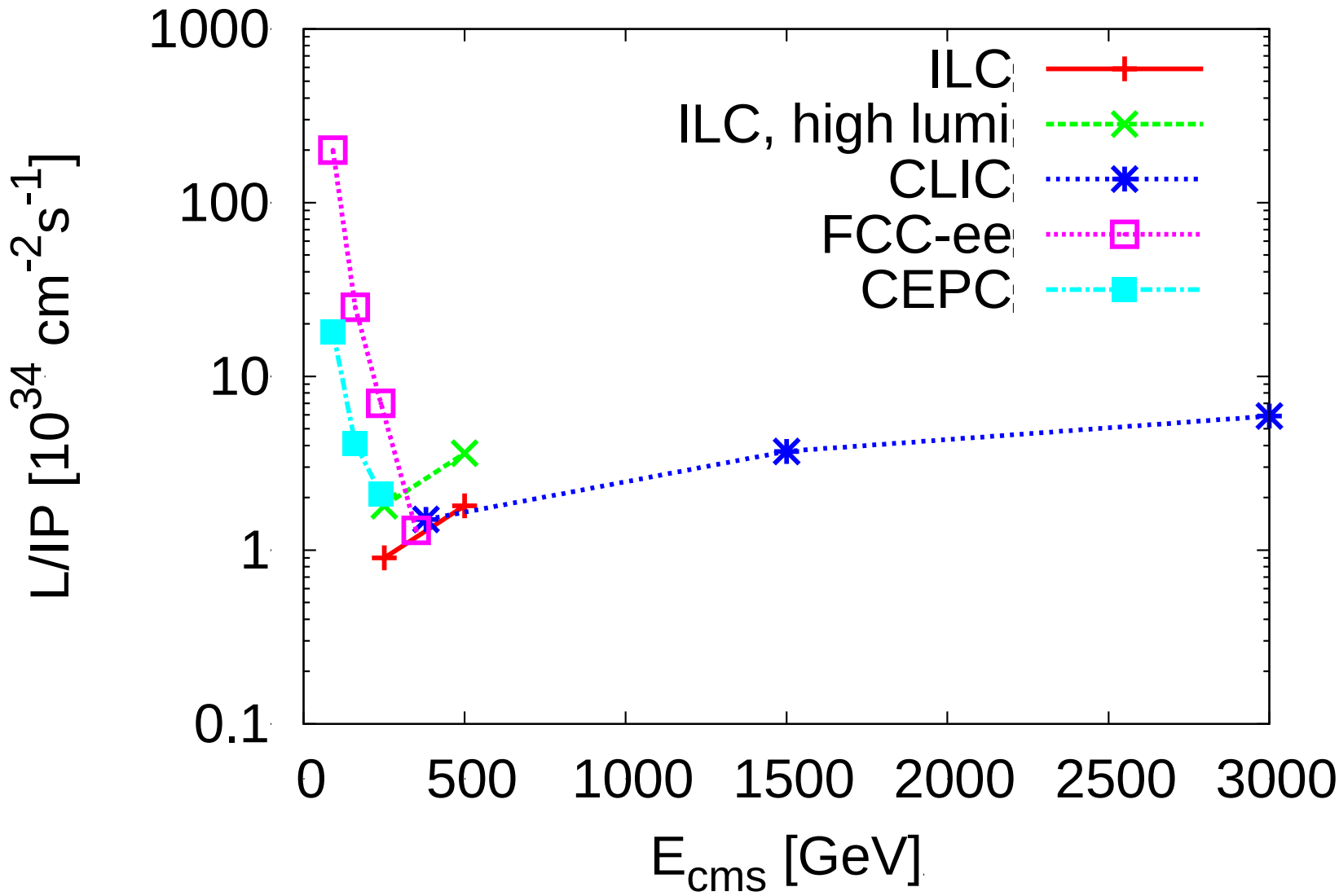
Electron polarisation enhances Higgs production at high-energy stages and provides additional observables

Baseline polarisation scenario adopted:
electron beam (–80%, +80%) polarised in ratio (50:50) at √s=380GeV ; (80:20) at √s=1.5 and 3TeV

γγ collider using laser scattering also possible
Upgrades using novel accelerator techniques also possible

Staging and live-time assumptions following guidelines consistent with other future projects:
Machine Parameters and Projected Luminosity Performance of Proposed Future Colliders at CERN
arXiv:1810.13022, Bordry et al.

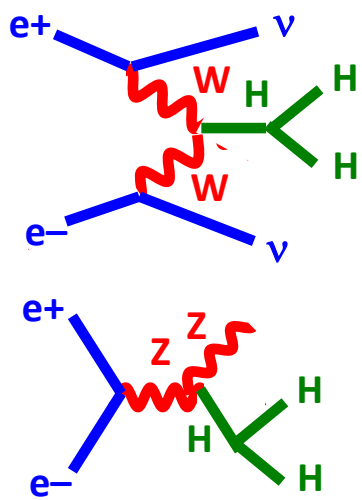
Linear vs Circular Colliders

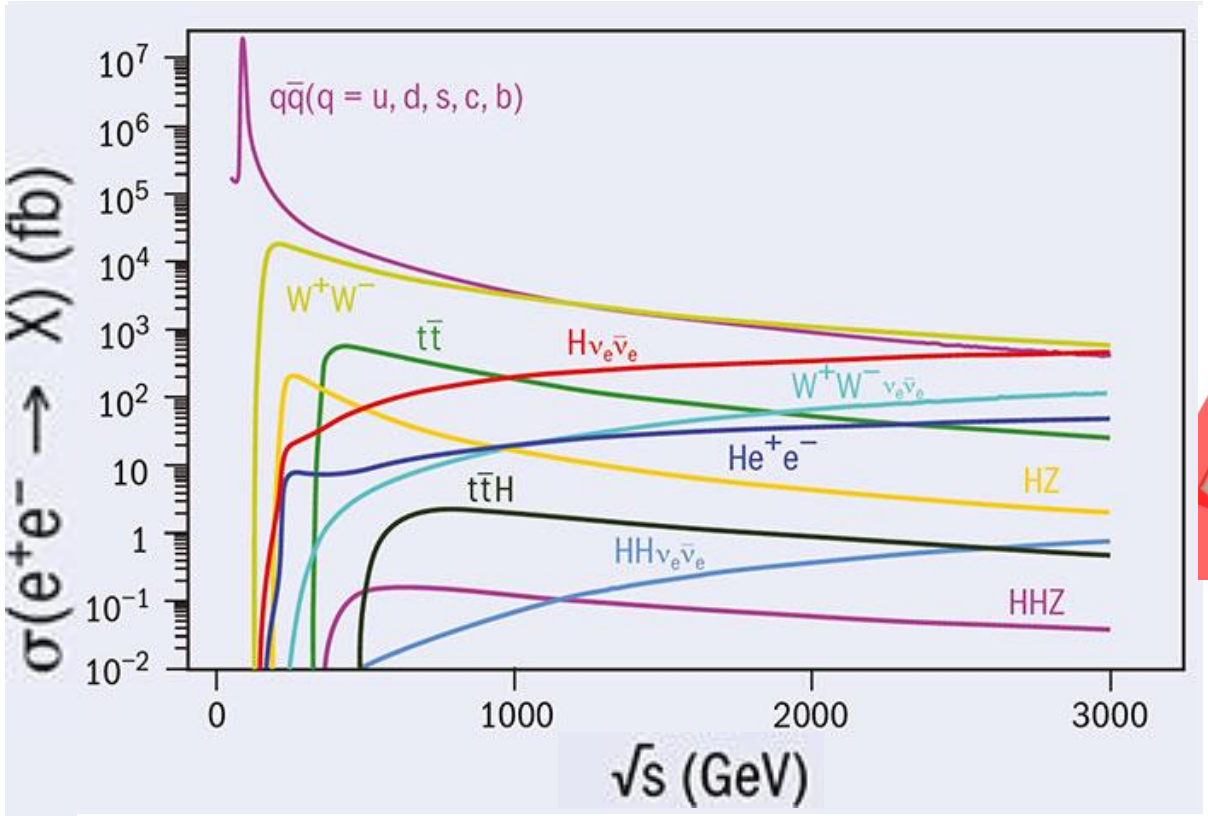


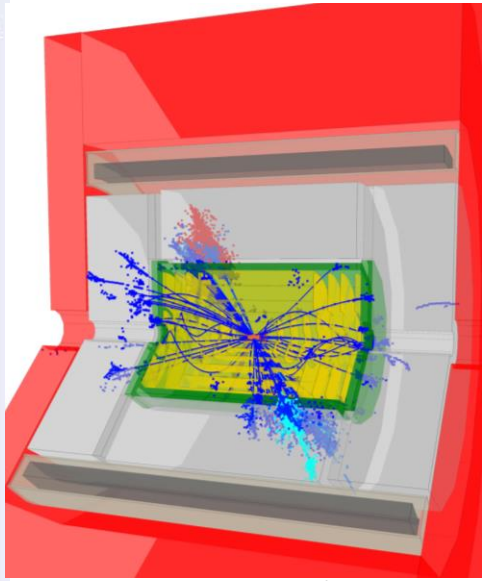
$$\Delta E \propto \left(\frac{E}{m}\right)^4 \frac{1}{R}$$

CLIC Physics

◆ Precision Higgs







tt at $\sqrt{s}$=3TeV

◆ Precision top

◆ Beyond Standard Model

Issues not addressed by SM:
- origin of the weak scale interactions
- dark matter
- origin of matter/antimatter asymmetry

Many new studies focused on discovery prospects at CLIC
Exploring the physics landscape as broadly as possible

New!

Yellow Report in preparation

The CLIC Potential for New Physics

Higgs coupling sensitivity

Full GEANT-based simulation studies including beam backgrounds of many channels at all 3 stages –> global fit including correlations;

$\sigma(ZH) \sim g^2_{HZZ}$

$\sigma(ZH) \times BR(H \to VV/ff) \sim g^2_{HZZ} g^2_{HVV/Hff} / \Gamma_H$

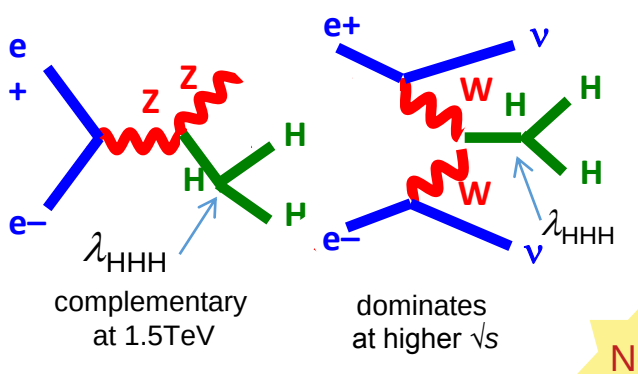
$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to VV/ff) \sim g^2_{HWW} g^2_{HVV/Hff} / \Gamma_H$

Precision $\lesssim$1% for most couplings

c/b/W/Z/g couplings significantly more precise than HL-LHC even after 380GeV stage

Γ_H is extracted with 4.7 – 2.5% precision

Higgs self-coupling requires high energy

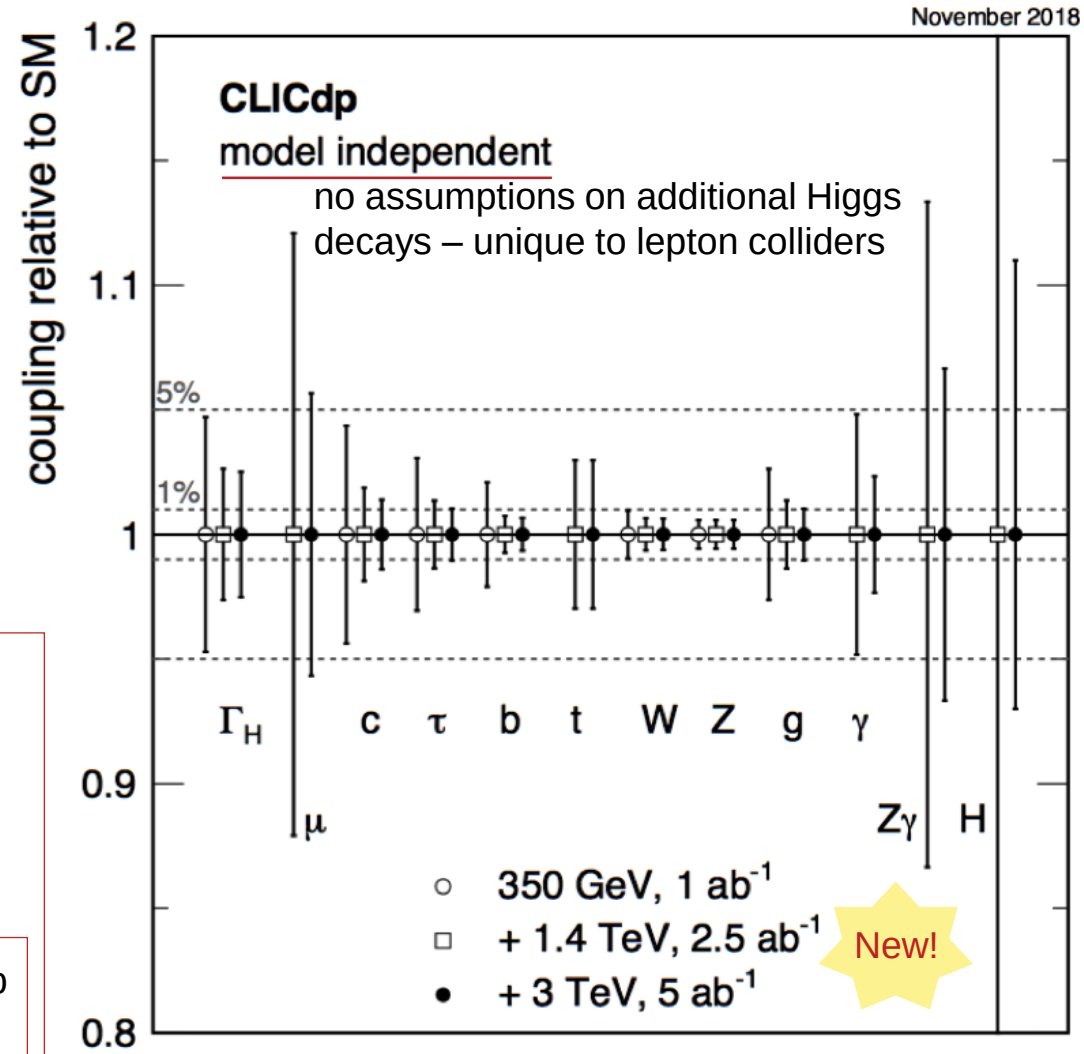


Using *M*(HH) differential distribution:

$\Delta\lambda/\lambda = {}^{+11\%}_{-7\%}$

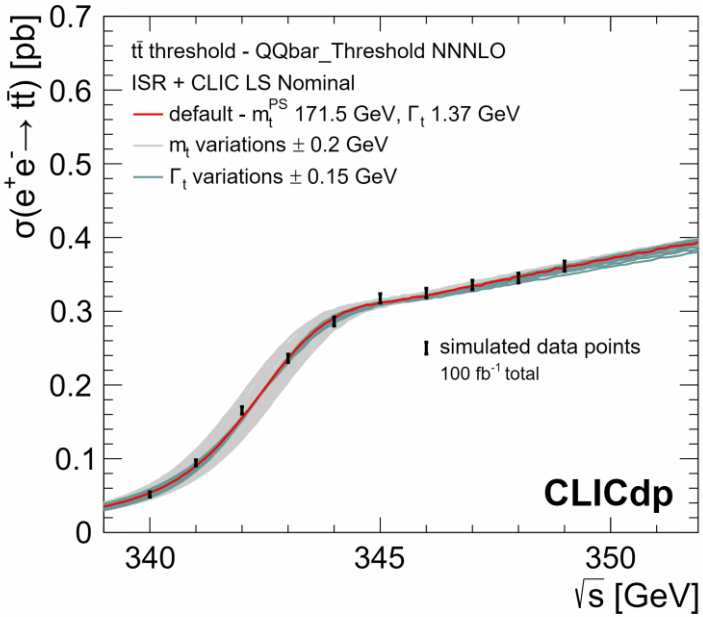
New!

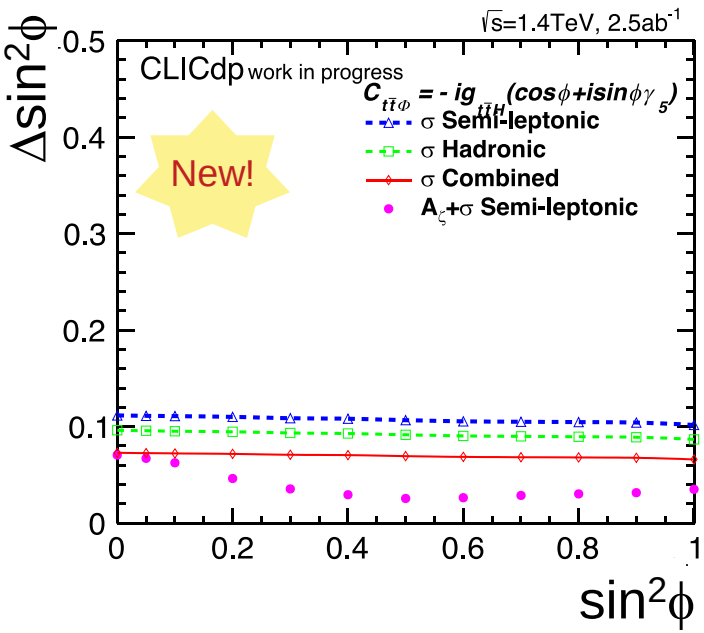
Each energy stage contributes significantly



Based on Eur. Phys. J. C 77 475 (2017) updated to new luminosity scenario

Top physics





- Intending threshold scan around 350 GeV (10 points, ~1 year) as well as main initial-stage baseline √s=380GeV
- sensitive to top mass, width and couplings
- observe 1S 'bound state', Δm_t ~ 50 MeV

- FCNC decays
- CP properties of ttH
- cross-section and A_{FB}

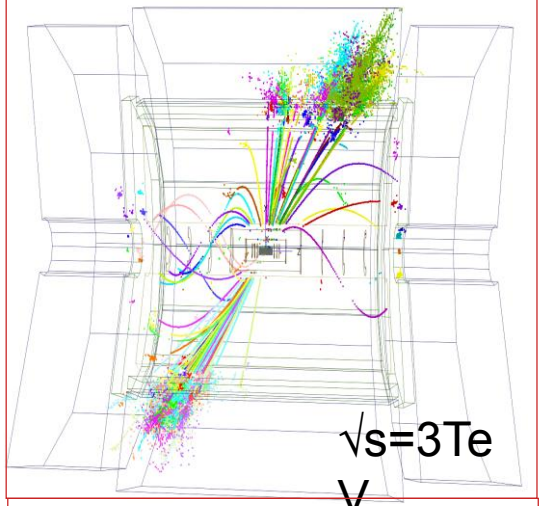
-> resolved, semi-resolved, boosted

- couplings to Z and γ
- EFT interpretation

–> initial and high-energy stages are very complementary

Polarisation provides new observables

First study of boosted top production in e^+e^-



$e^+e^- \to t\bar{t} \to q\bar{q}q\bar{q}b\bar{b}$

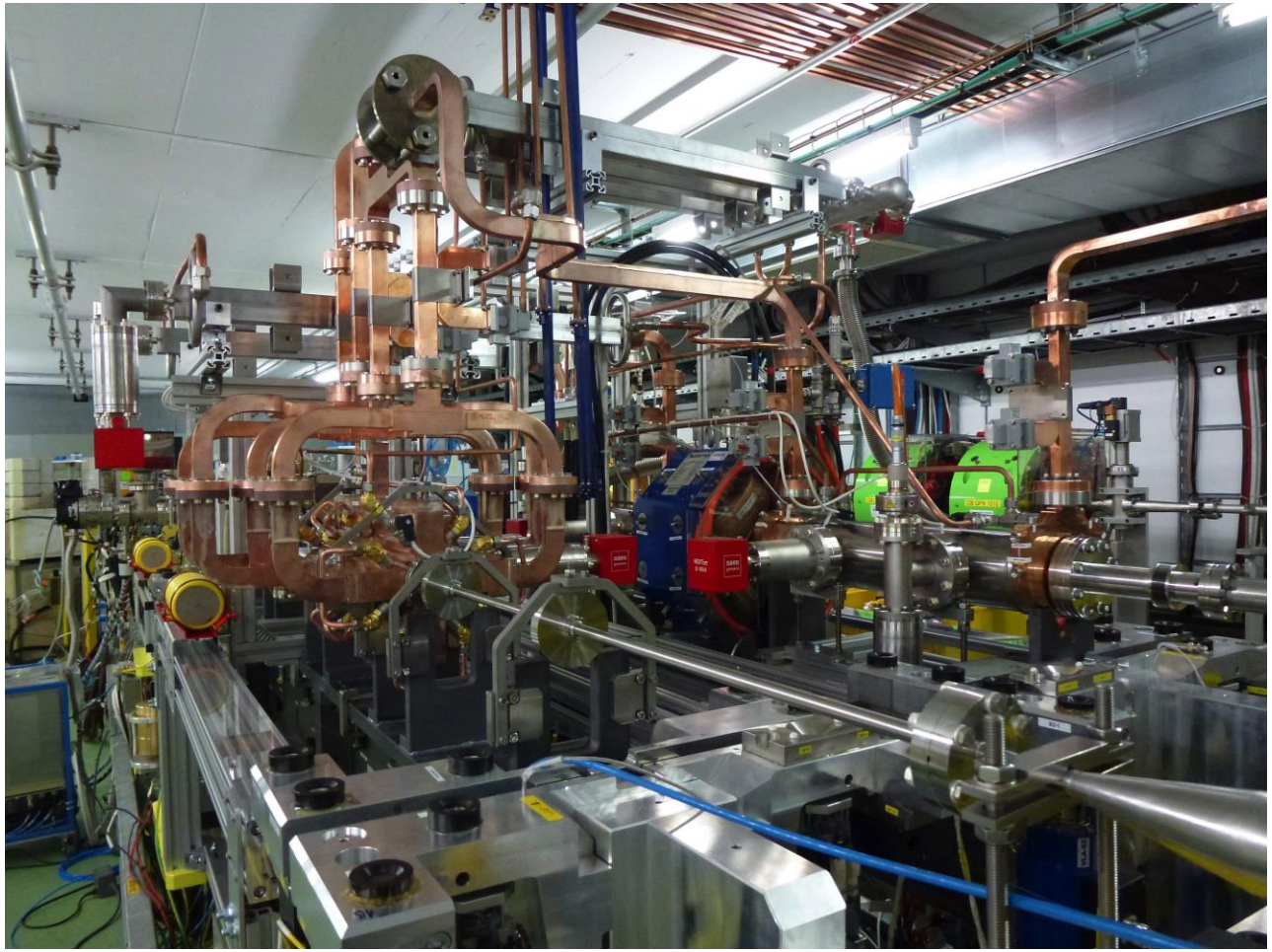
Hadronic decays of high-energy top quarks do not lead to 3 separated jets –> identify substructure

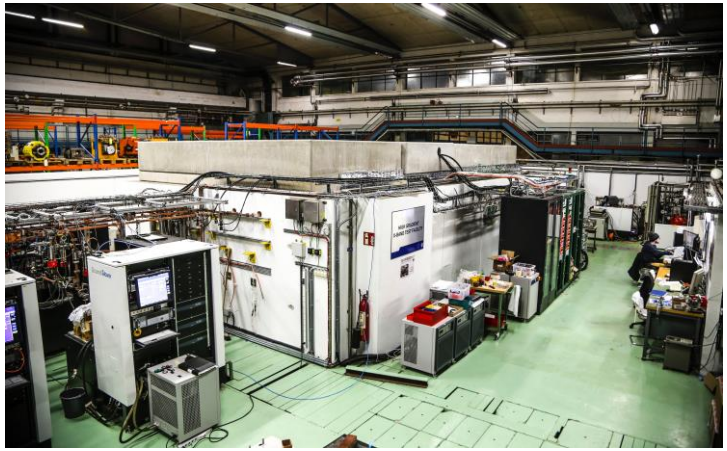
arXiv 1807.02441: Top-quark physics at the CLIC electron–positron linear collider

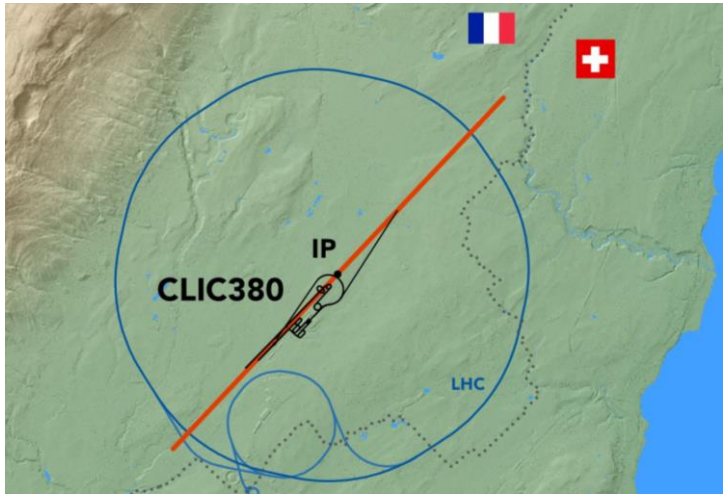
in journal review

CLIC challenges

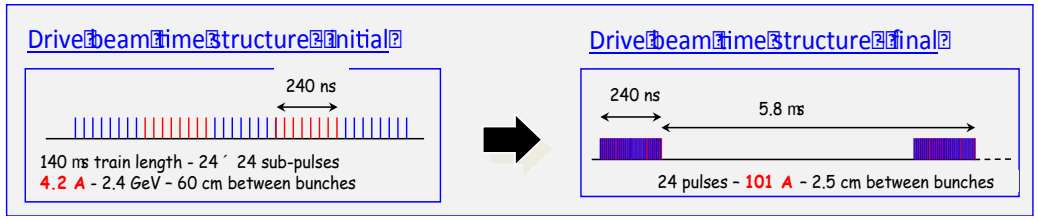
- Key technologies have been demonstrated
- CLIC is now a mature project, ready to be built

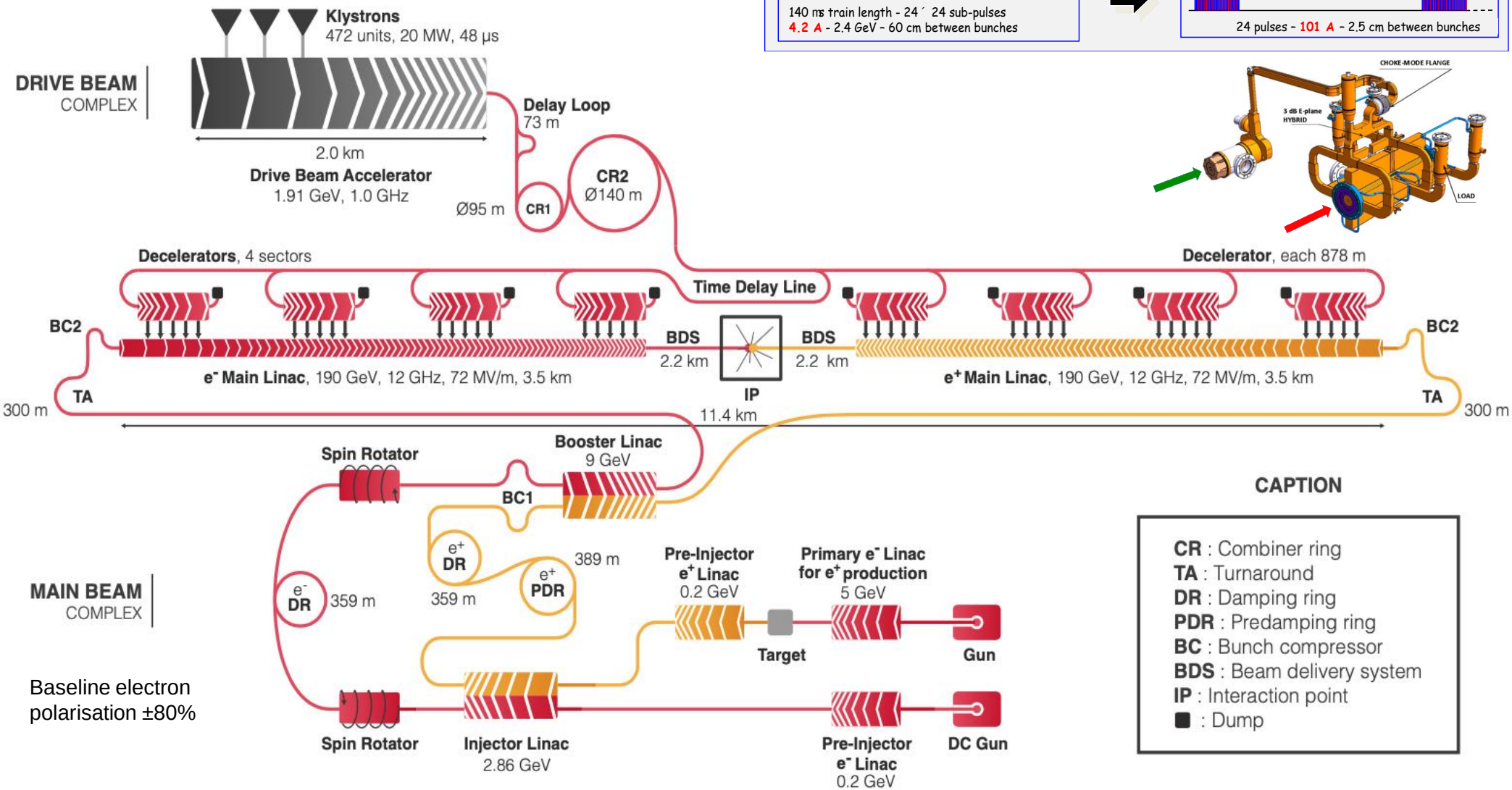






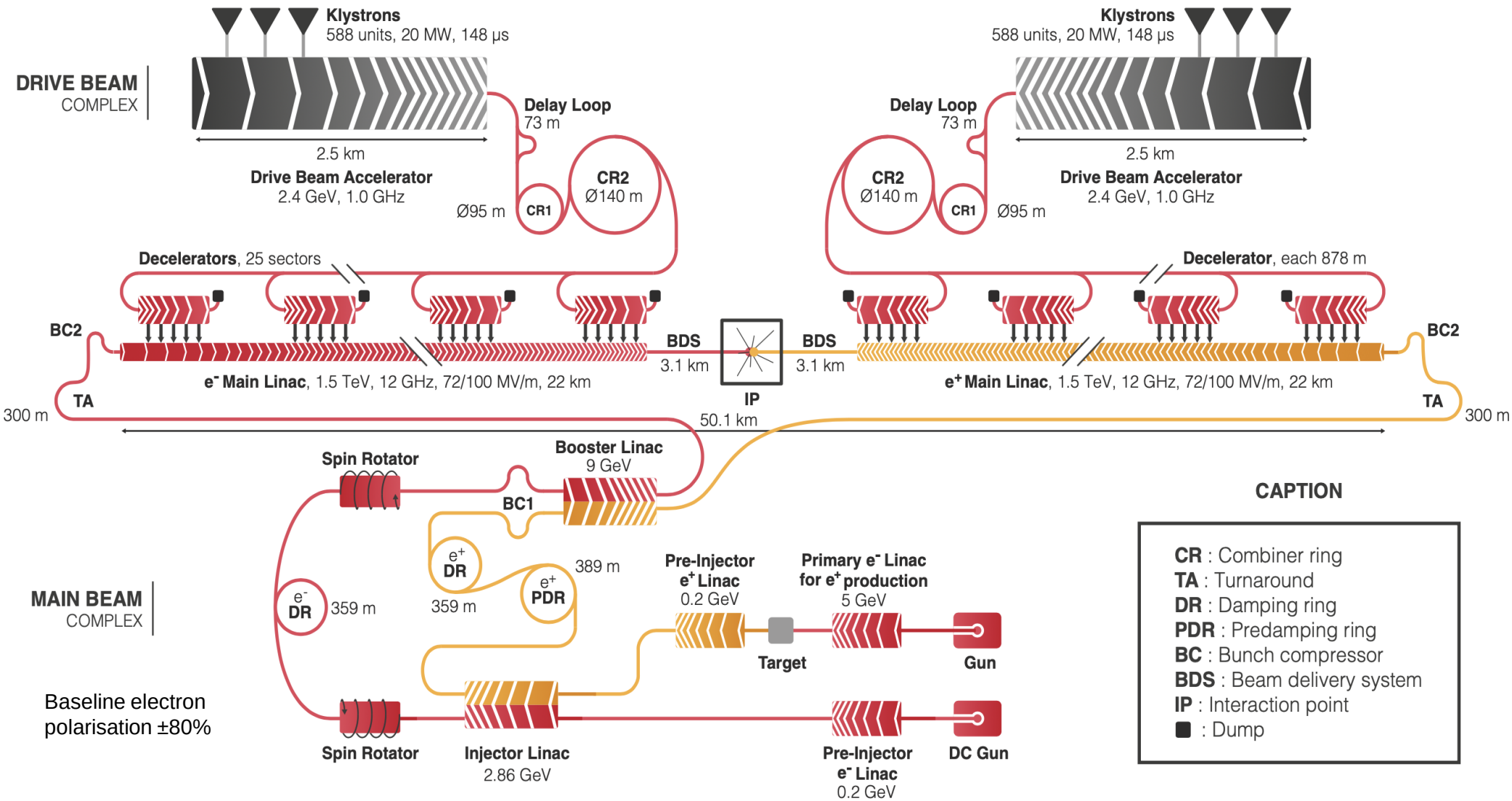
CLIC layout – 380 GeV





Baseline electron polarisation ±80%

CLIC layout – 3 TeV

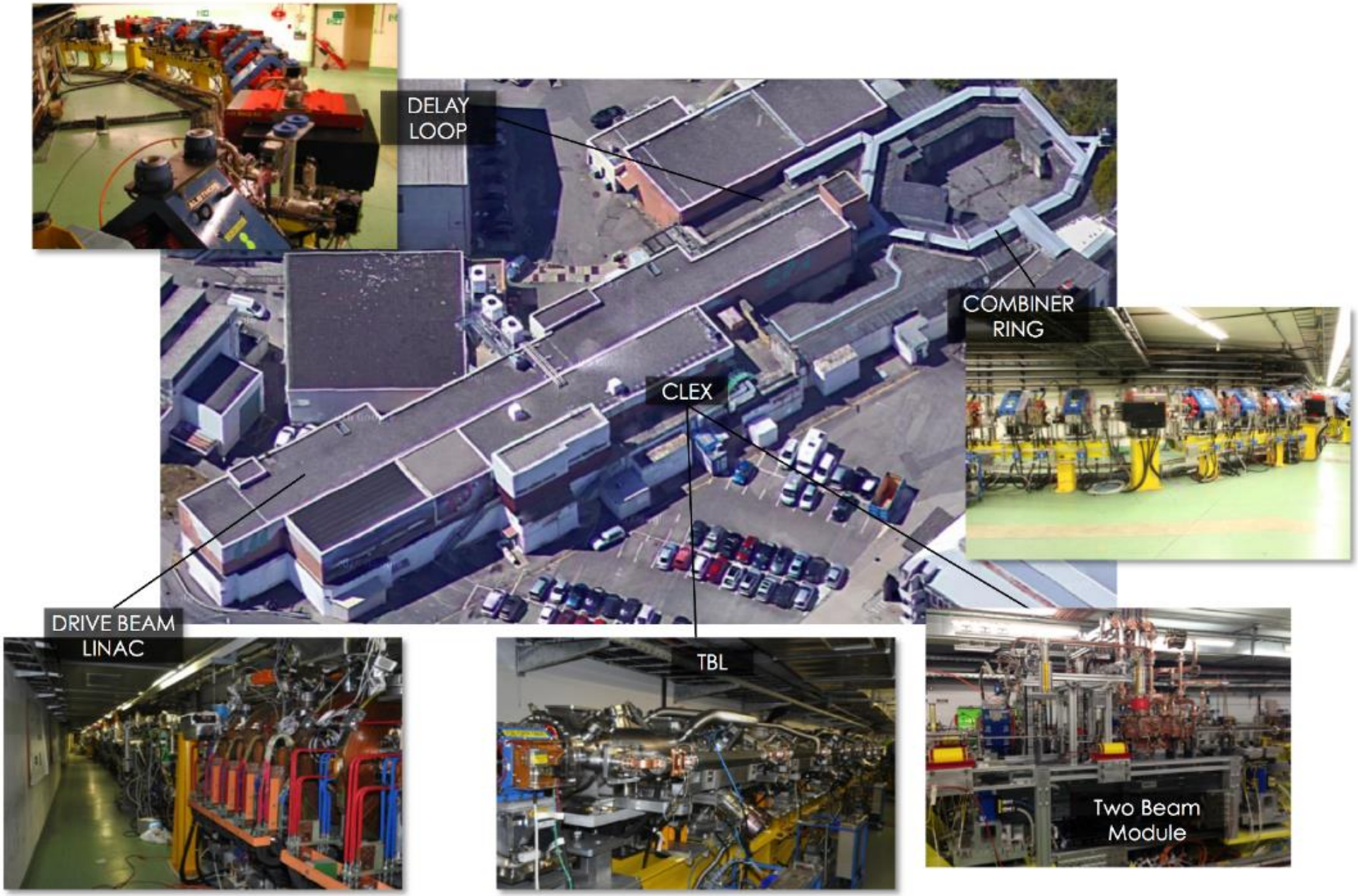


Baseline electron polarisation ±80%

Key accelerator challenges

- High-current drive beam bunched at 12 GHz
- Power transfer + main-beam acceleration
- 100 MV/m gradient in main-beam cavities
- Produce, transport, and collide low-emittance beams
- System integration, alignment and stability, engineering, cost, power …

CLIC Test Facility (CTF3)



Accelerator challenges

Key challenges:

High-current drive beam bunched at 12 GHz

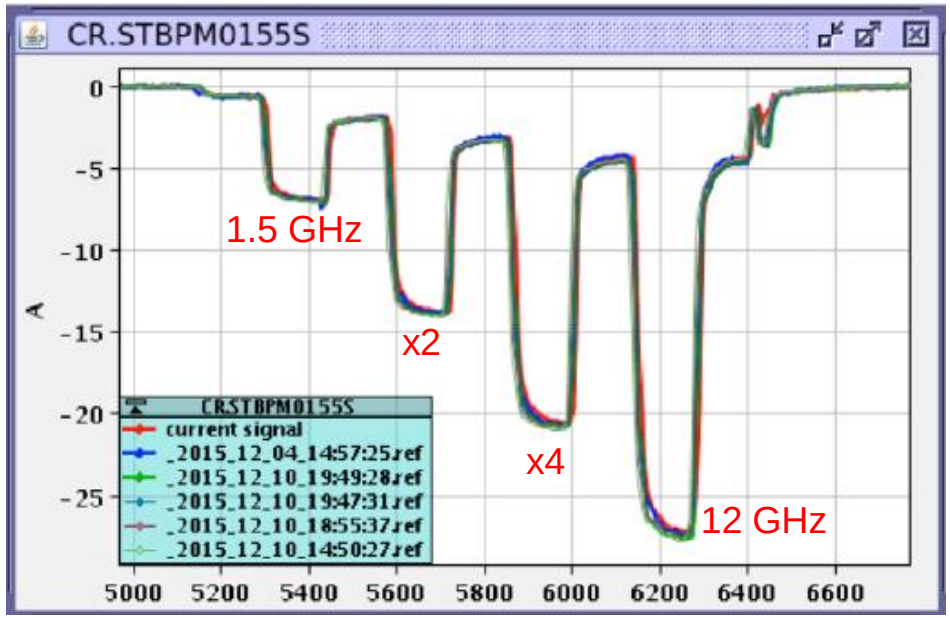
Power transfer + main-beam acceleration

~100 MV/m gradient in main-beam cavities

Low emittance generation

Alignment & stability

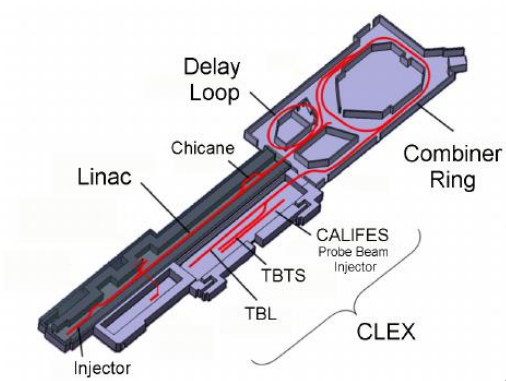
Drive beam quality:
Produced high-current drive beam bunched at 12GHz



Current in combiner ring

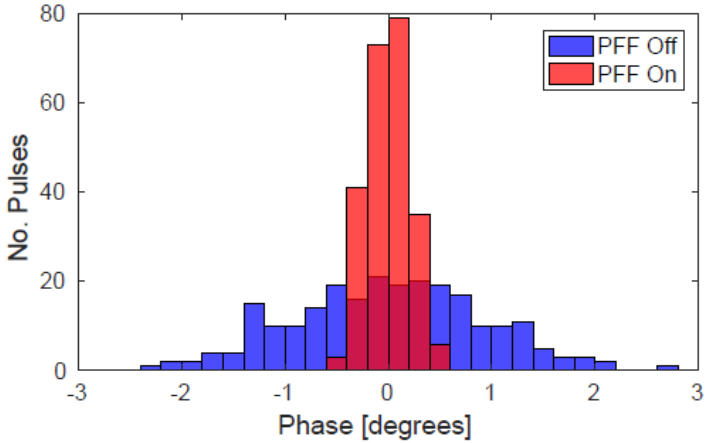
28A

Drive beam arrival time stabilised to CLIC specification of 50 fs:



Examples of measurements from CLIC Test Facility, CTF3, at CERN.

CTF3 now the 'CERN Linear Electron Accelerator for Research' facility, CLEAR



Accelerator challenges

Demonstrated 2-beam acceleration

Key challenges:

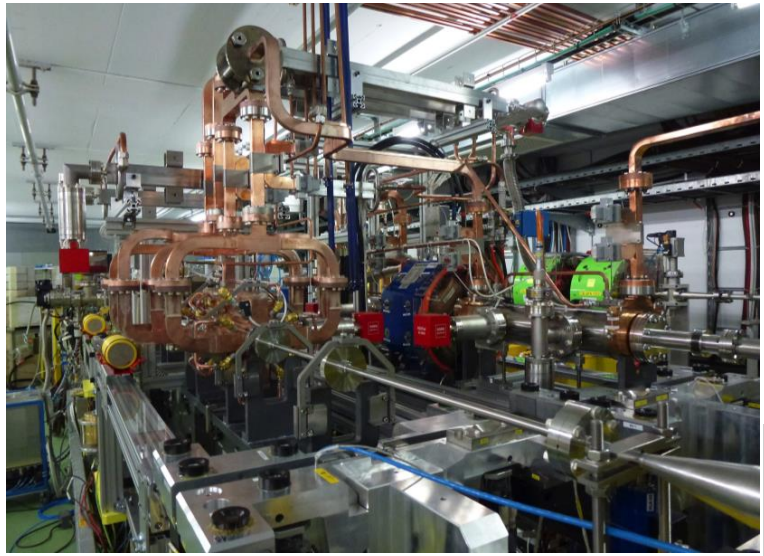
High-current drive beam bunched at 12 GHz

Power transfer + main-beam acceleration

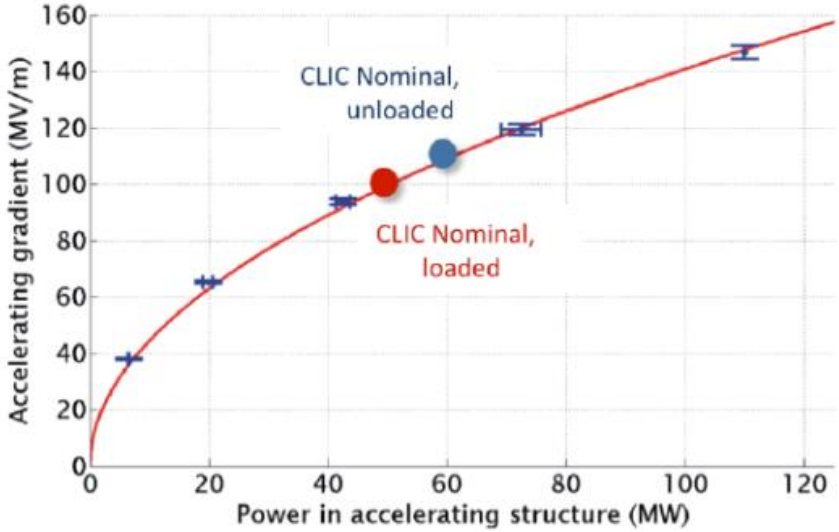
~100 MV/m gradient in main-beam cavities

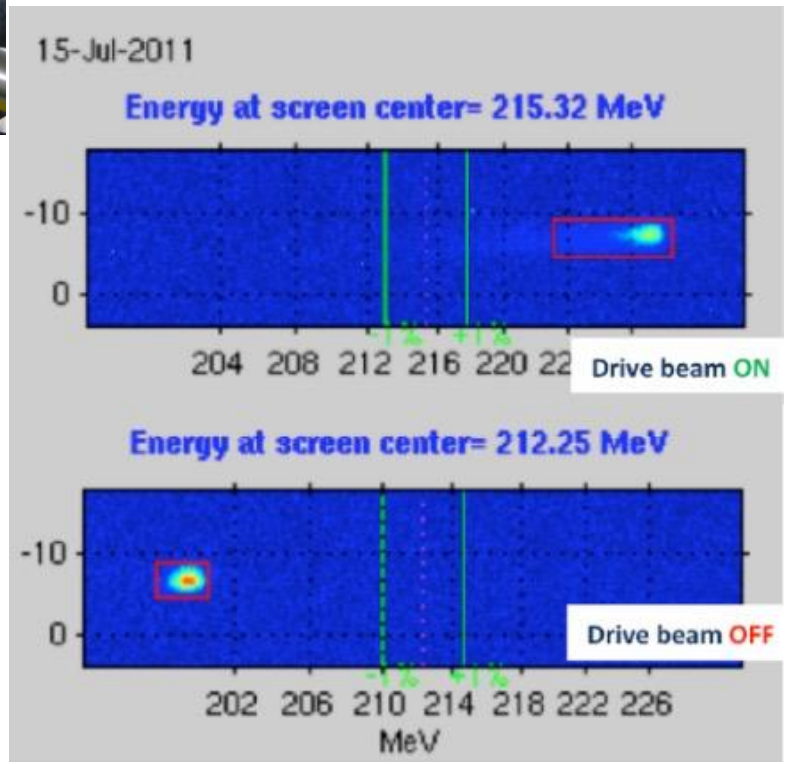
Low emittance generation

Alignment & stability



31MeV = 145MV/m





Accelerator challenges

X-band performance: achieved 100MV/m gradient in main-beam RF cavities

Key challenges:

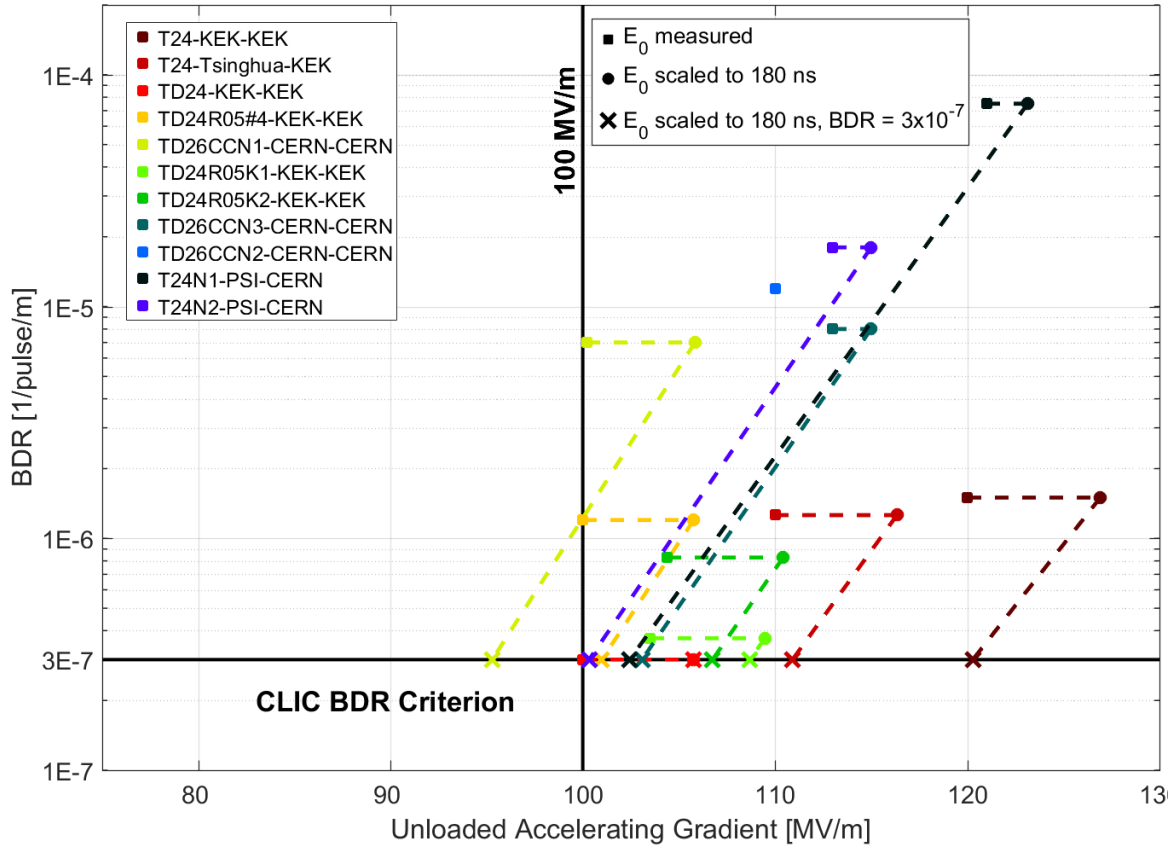
High-current drive beam bunched at 12 GHz

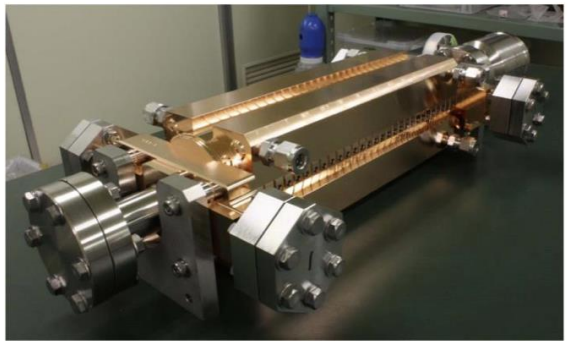
Power transfer + main-beam acceleration

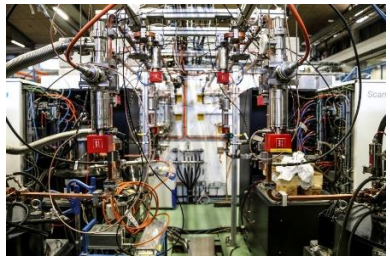
~100 MV/m gradient in main-beam cavities

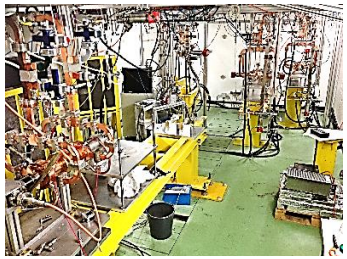
Low emittance generation

Alignment & Stability









Accelerator challenges

Nano-beams

Key challenges:

High-current drive beam bunched at 12 GHz

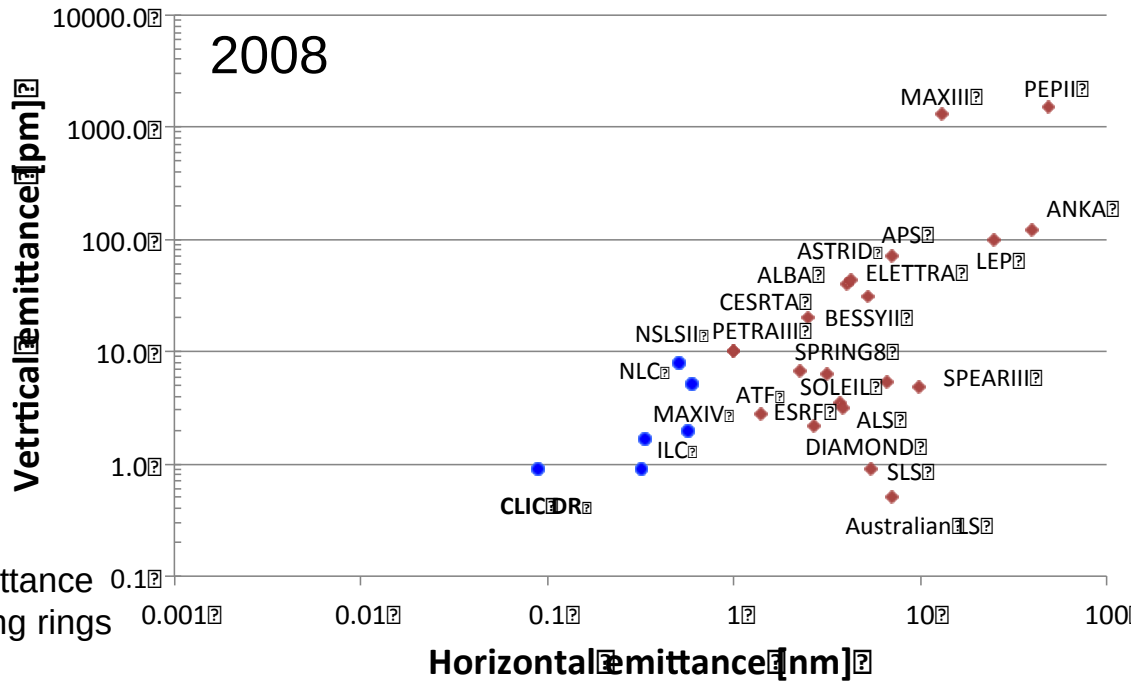
Power transfer + main-beam acceleration

~100 MV/m gradient in main-beam cavities

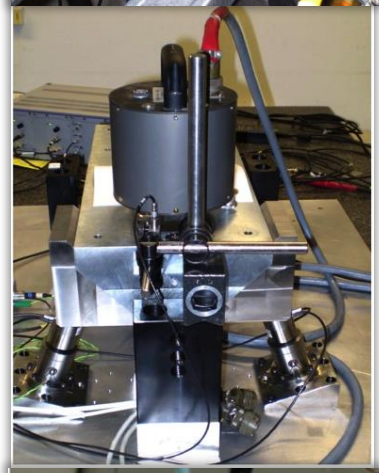
Low emittance generation

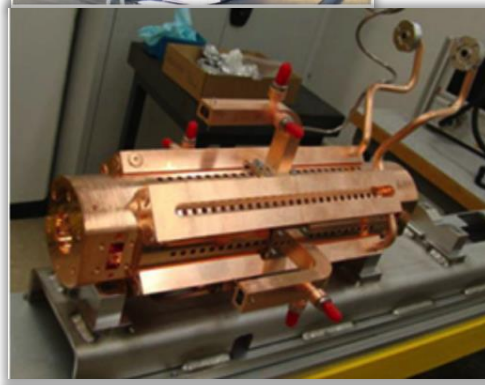
The CLIC strategy:

- 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 existing accelerators of equipment and algorithms (FACET at Stanford, ATF2 at KEK, CTF3, Light-sources)



CLIC emittance at damping rings





Accelerator challenges

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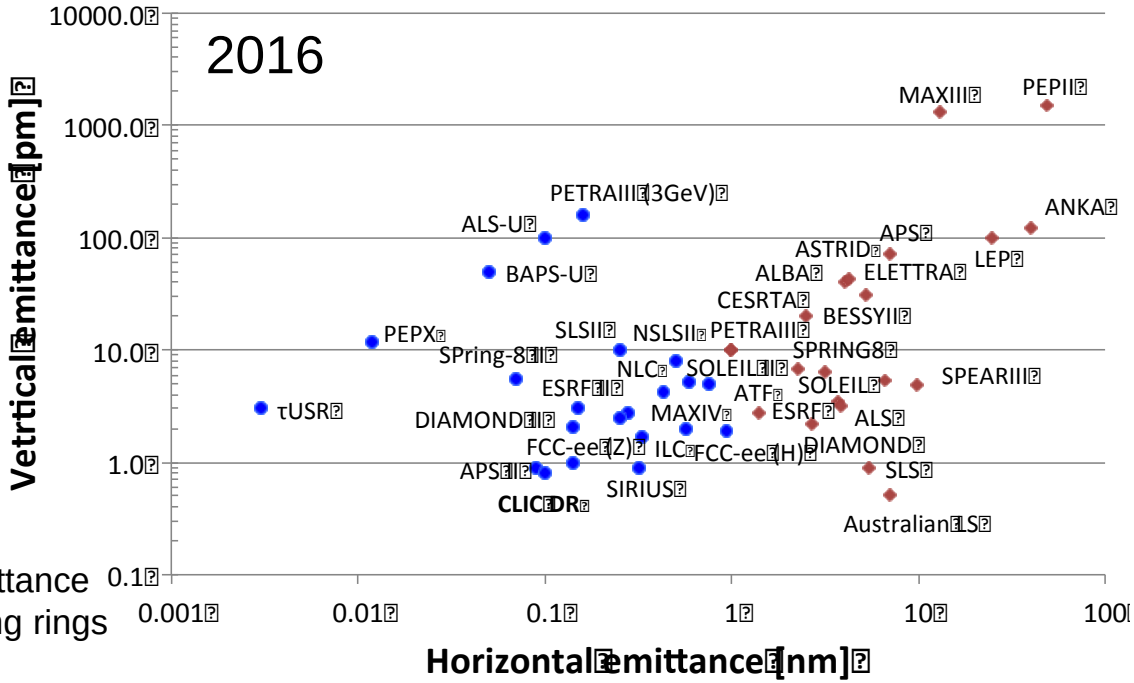
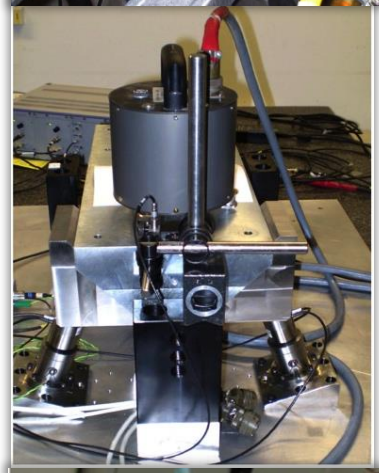
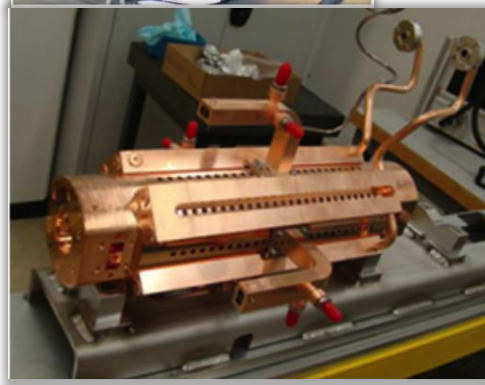
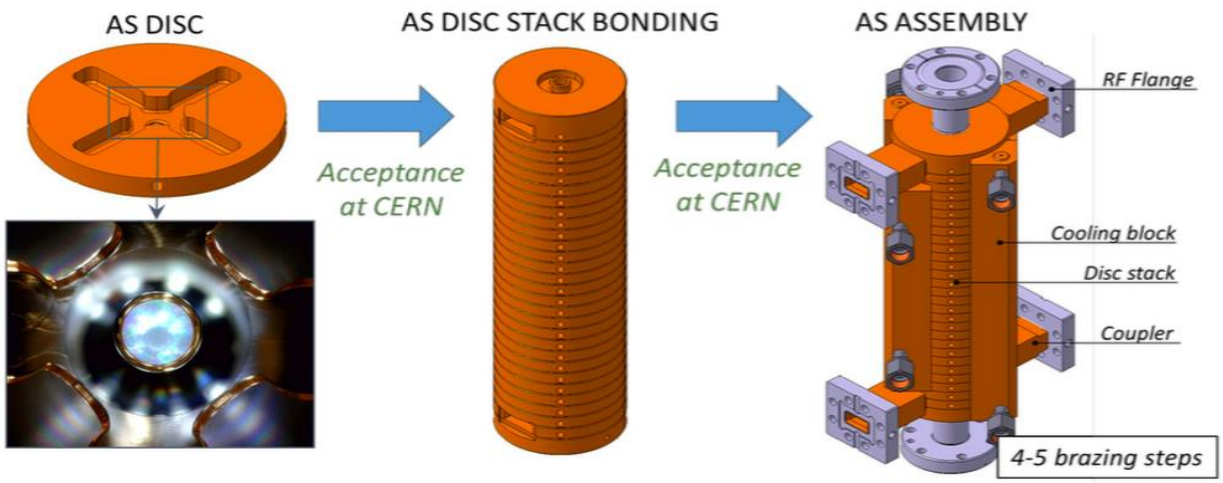


CLIC emittance at damping rings





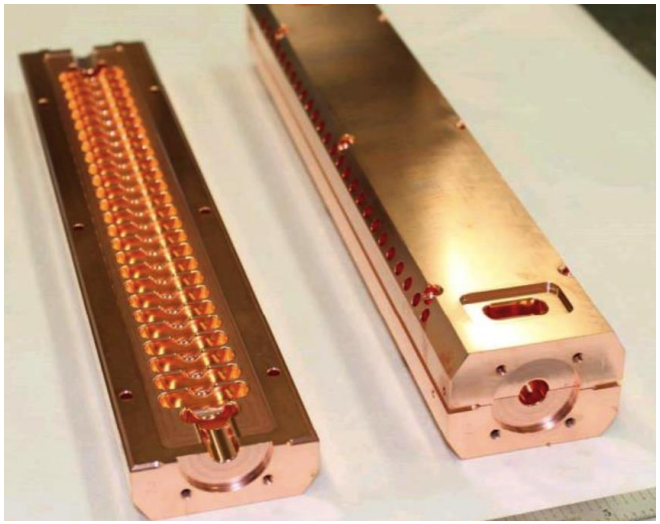
Towards industrialisation



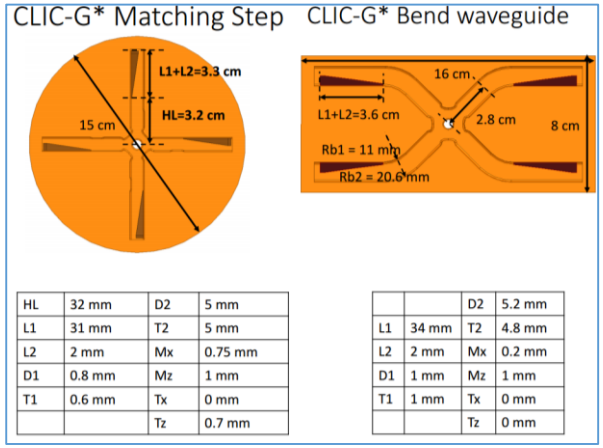
Investigating paths to industrialisation

Baseline manufacturing technique:
- bonding and brazing

Alternatives:
- brazing as for SwissFEL
- machining halves



Target is structures that are low-cost & easy-to-manufacture

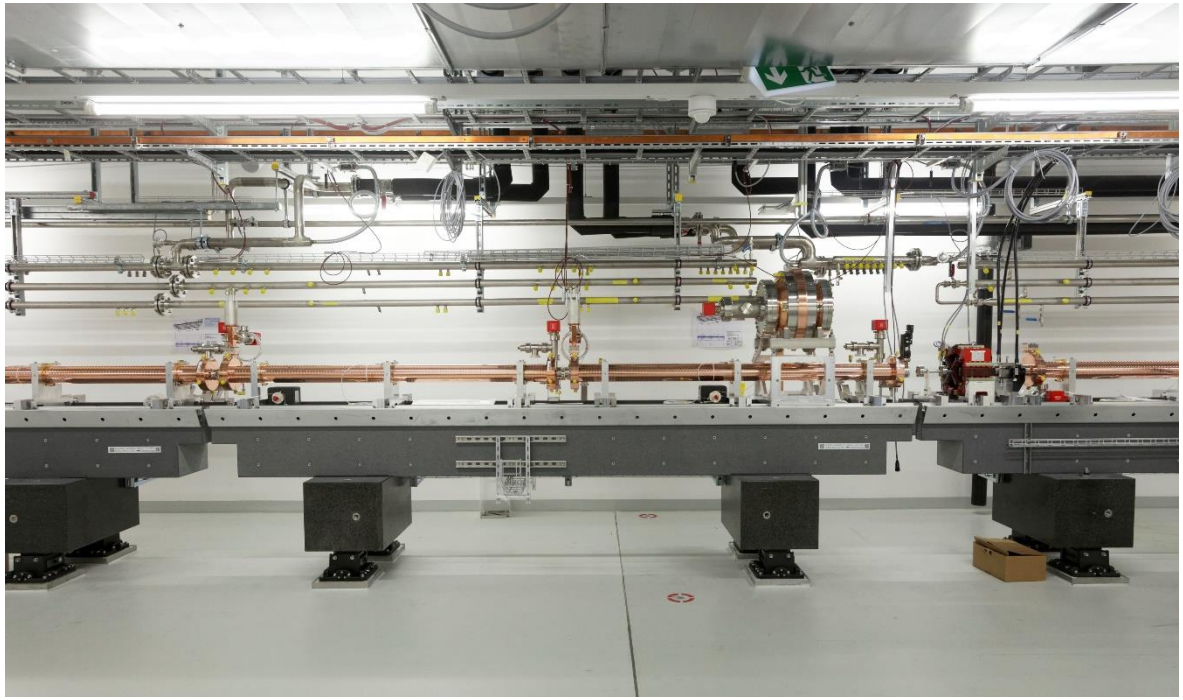


HL	32 mm	D2	5 mm
L1	31 mm	T2	5 mm
L2	2 mm	Mx	0.75 mm
D1	0.8 mm	Mz	1 mm
T1	0.6 mm	Tx	0 mm
		Tz	0.7 mm

		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

SwissFEL – C-band linac

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



X-band

EuPRAXIA@SPARC_LAB

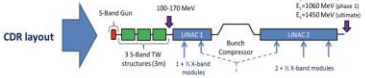
EuPRAXIA@SPARC_LAB CDR Review Committee Meeting
27-28 November 2018 INFN Frascati

A. Gallo: X-band RF Linac technology

X-BAND LINAC DESIGN

WP1: particle driven plasma acceleration
WP2: laser driven plasma acceleration
WP3: no plasma acceleration, only RF

X-Band LINAC parameters				
L_i [m]	16			
	WP1	WP2	WP3	Ultimate
E_f [MeV]	100	170	170	170
E_{inj} [MeV]	450	380	890	1280
<G> [MV/m]	20(L1)-36(L2)	20(L1)-27(L2)	57	80
E_i [MeV]	550	550	1060	1450



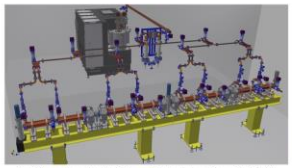
Design under revision (2 RF modules in both linac #1 and #2). Work is well advanced.

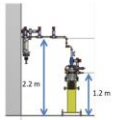
13

EuPRAXIA@SPARC_LAB CDR Review Committee Meeting
27-28 November 2018 INFN Frascati

A. Gallo: X-band RF Linac technology

RF MODULE LAYOUT





Preliminary layout of the **RF module** (collaboration with CERN): **8 structures, 1 SLED, 1 or 2 Klystrons** per module.

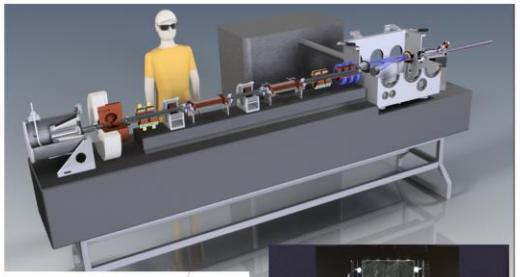
WR-90 total length [mm]	3758
WC-50 circular wg length [mm]	3674
WR-90 loss [dB]	-0.368
WC-50 loss [dB]	-0.0456
total loss [dB]	-0.414
total loss [%]	-9.09

Estimated **waveguide attenuation** (including circular waveguide): **10%**

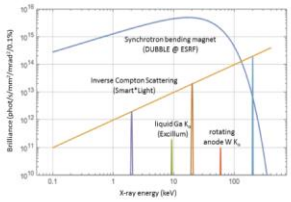
15

Inverse Compton Scattering Source – Smart*Light

Compact, highly monochromatic X-ray source.
Complementary to X-ray tube and synchrotron light source.
Applications in cultural heritage, material science, medical, etc.

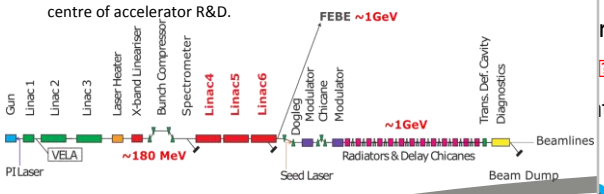


Brilliance



Upgrade proposal: XARA

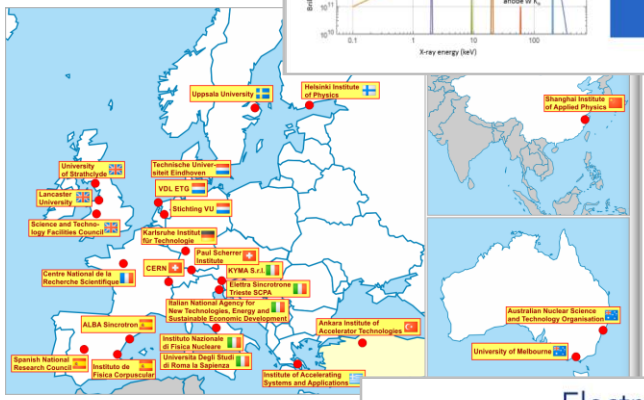
- X-band Accelerator for Research and Applications
- The 4th CLARA linac is replaced by an X-band accelerating section to reach 1 GeV
- Novel FEL technology
- An EUV/soft x-ray FEL facility for ultra fast chemistry and biology, and a centre of accelerator R&D.



Science & Technology Facilities Council | UK Research and Innovation

...design study for a ...
...and low-cost XFEL.
...wissFEL performance at ...
...ost, to bring XFELs to ...
...nd regional facilities.
...advances in:
...rs
...linac technology
...tors

Compact



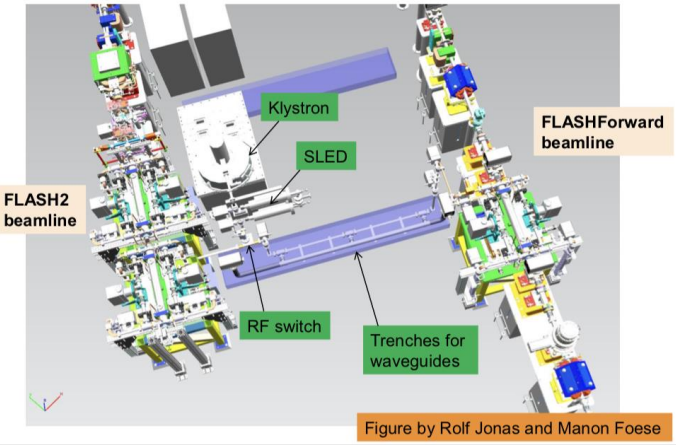


Figure by Rolf Jonas and Manon Foese

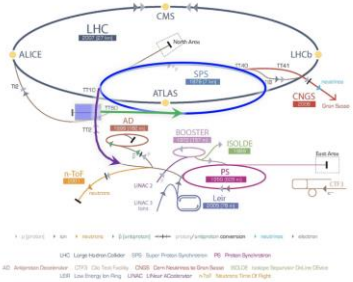
CLIC week | W. Wuensch, CERN

Elements in existing linacs (DESY, PSI)

Electrons at CERN, overview

Accelerator implementation at CERN of LDMX type of beam

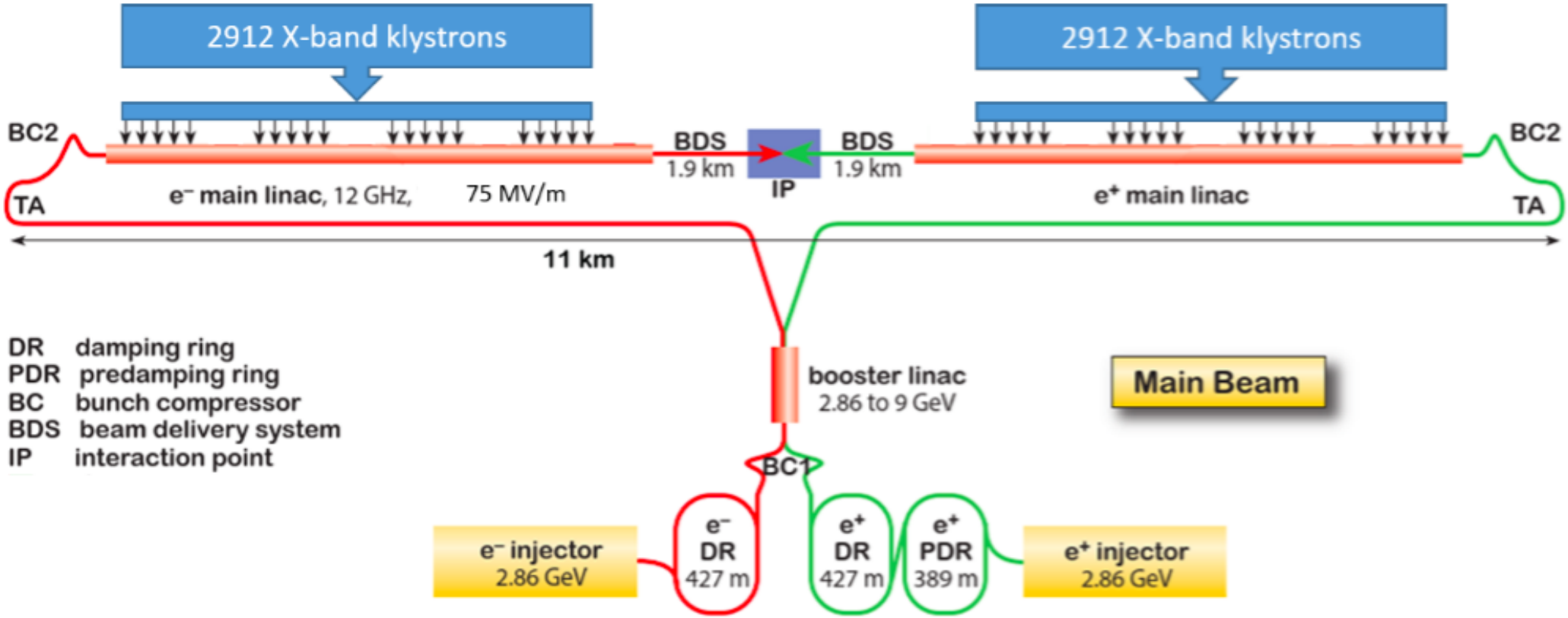
- X-band based 70m LINAC to ~3.5 GeV in TT4-5
- Fill the SPS in 1-2s (bunches 5ns apart) via TT60
- Accelerate to ~16 GeV in the SPS
- Slow extraction to experiment in 10s as part of the SPS super-cycle
- Experiment(s) considered by bringing beam back on Meyrin site using TT10



Beyond LDMX type of beam, other physics experiments considered (for example heavy photon searches)

Acc. R&D interests (see later): Overlaps with CLIC next phase (klystron based), future ring studies, FEL linac modules, e-beams for plasma, medical/irradiation/detector-tests/training, impedance measurements, instrumentation, positrons and damping ring R&D

380 GeV Klystron option



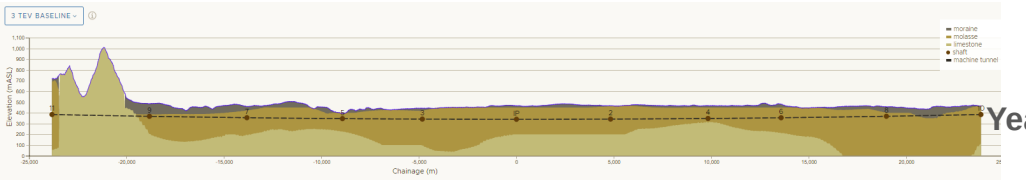
Schedule

Updated schedule:
Construction + commissioning: 7 years

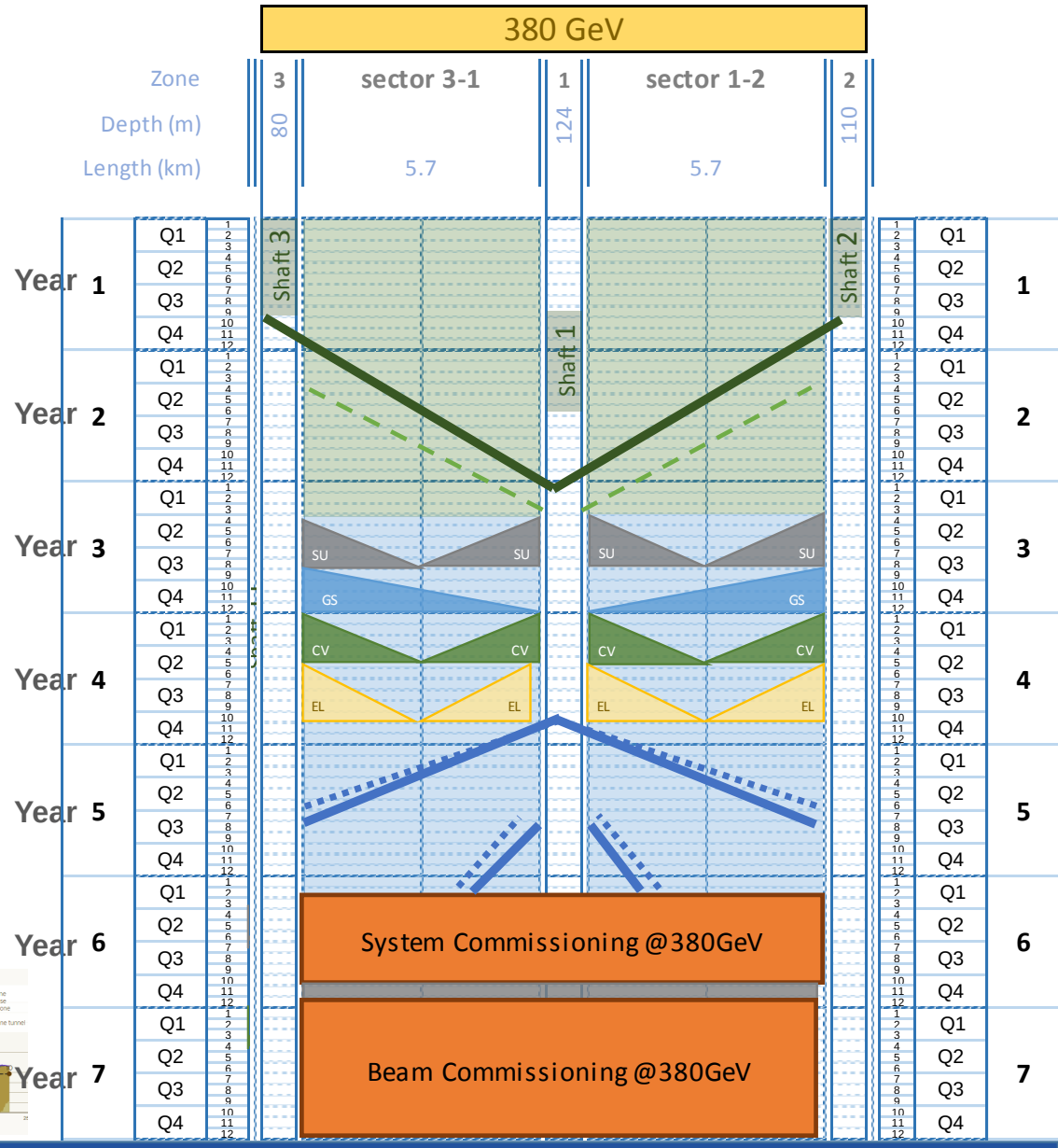
Civil Eng.
- Tunnel excavation TBM Good rock
- Inner lining

Infrastr. + Machine Inst.
- Survey works
- General services installation
- CV Installation works
- Electrical installation and cabling
- Machine transport
- Machine Installation

- Commissioning period
- Physics

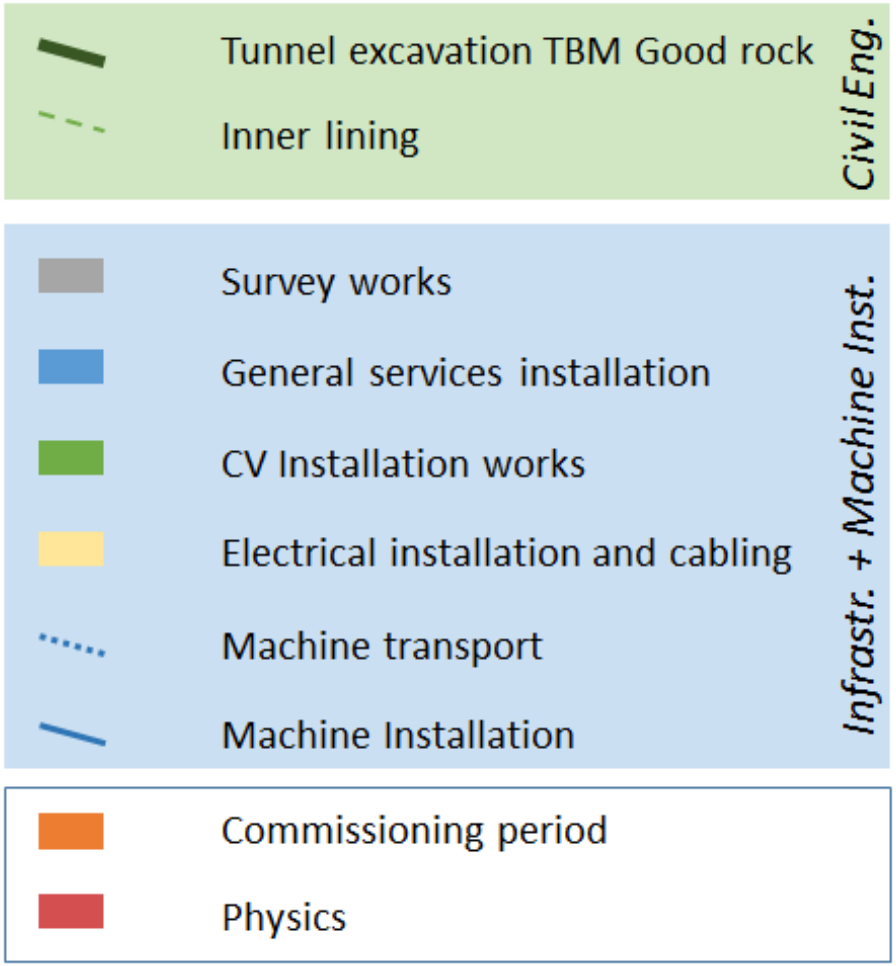


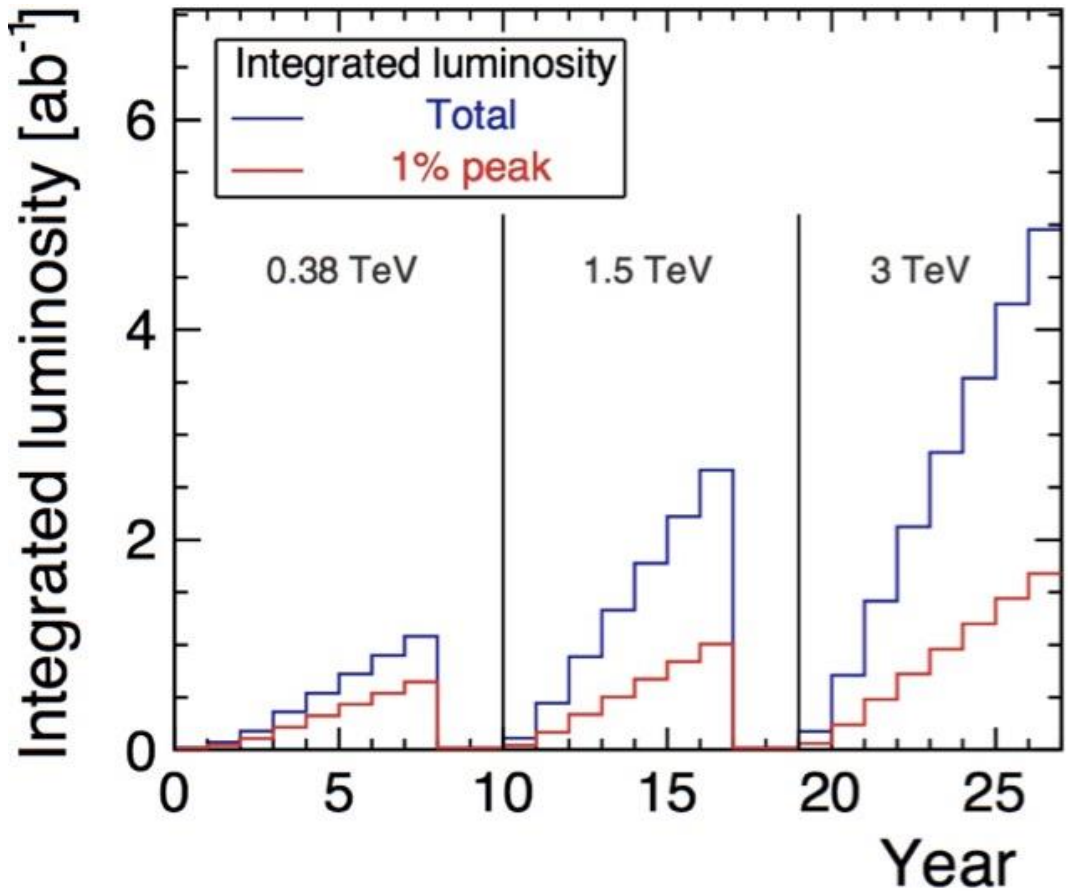
CLIC 11km tunnel option - 380GeV - Drive Beam Option

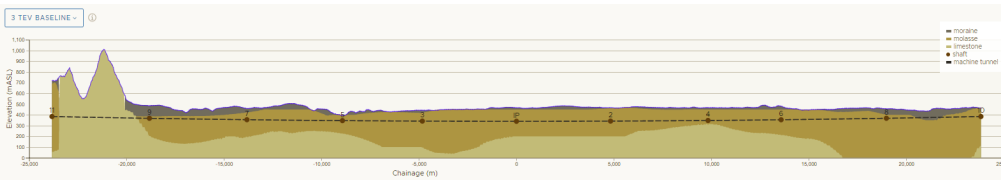


Schedule

Updated schedule:
Construction + commissioning: 7 years, followed by 25–30 year physics programme



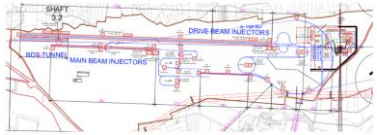


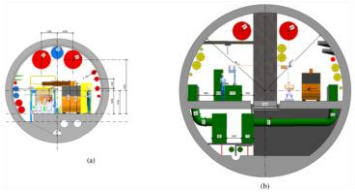


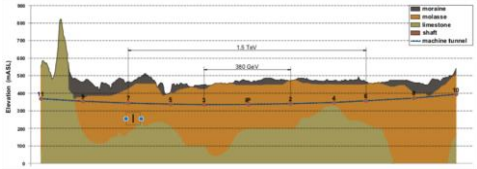
Civil Engineering and Infrastructure Studies

Important effort within:
- Civil engineering
- Electrical systems
- Cooling and ventilation
- Transport, logistics and installation
- Safety, access and radiation protection systems

Crucial for cost/power/schedule

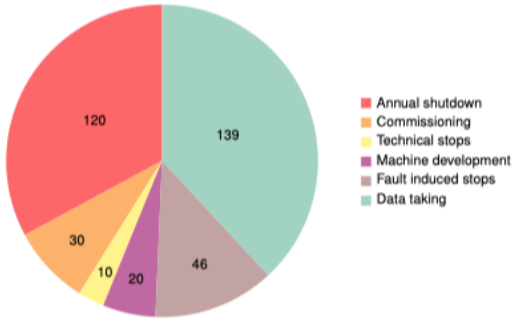


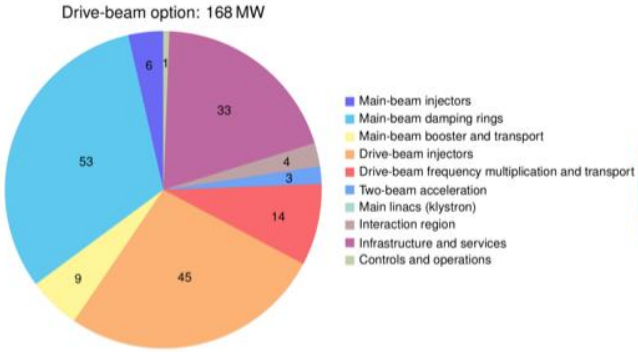


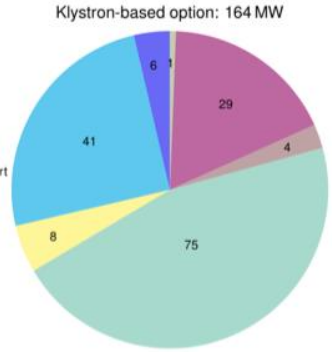


Power Estimates

Collision Energy [GeV]	Running [MW]	Standby [MW]	Off [MW]
380	168	25	9
1500	364	38	13
3000	589	46	17



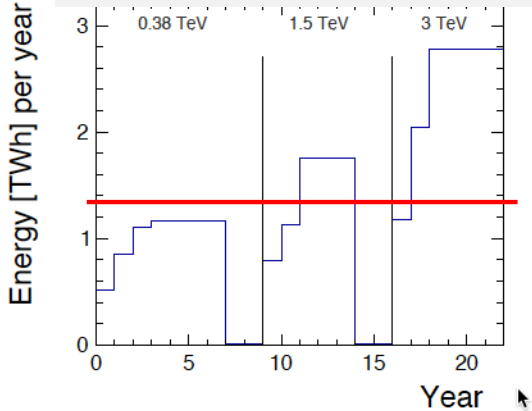




Power estimate bottom up (concentrating on 380 GeV systems)
- Very large reductions since CDR, better estimates of nominal settings, much more optimised drivebeam complex and more efficient klystrons, injectors more optimisation, etc

Further savings possible, main target damping ring RF
Will look also more closely at 1.5 and 3 TeV numbers next

CERN energy consumption
2012: 1.35 TWh



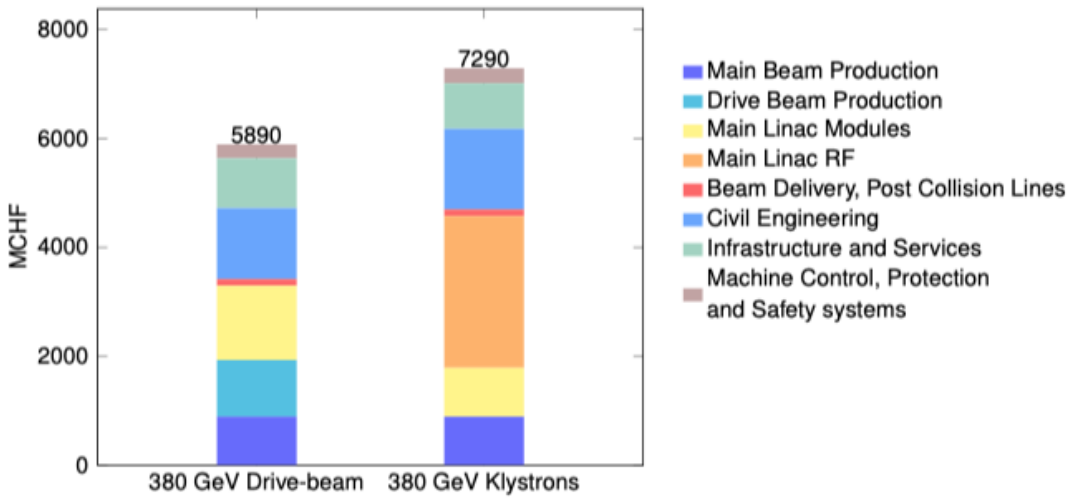
From running model and power estimates at various states – the energy consumption can be estimated

CERN is currently consuming ~1.2 TWh yearly (~90% in accelerators)

Cost - I

Machine has been re-costed bottom-up in 2017-18

- Methods and costings validated at review on 7 November – similar to LHC, ILC, CLIC CDR
- Technical uncertainty and commercial uncertainty estimated



Domain	Sub-Domain	Cost [MCHF] Drive-Beam	Cost [MCHF] Klystron
Main Beam Production	Injectors	175	175
	Damping Rings	309	309
	Beam Transport	409	409
Drive Beam Production	Injectors	584	—
	Frequency Multiplication	379	—
	Beam Transport	76	—
Main Linac Modules	Main Linac Modules	1329	895
	Post decelerators	37	—
Main Linac RF	Main Linac Xband RF	—	2788
Beam Delivery and Post Collision Lines	Beam Delivery Systems	52	52
	Final focus, Exp. Area	22	22
	Post-collision lines/dumps	47	47
Civil Engineering	Civil Engineering	1300	1479
Infrastructure and Services	Electrical distribution	243	243
	Survey and Alignment	194	147
	Cooling and ventilation	443	410
	Transport / installation	38	36
Machine Control, Protection and Safety systems	Safety system	72	114
	Machine Control Infrastructure	146	131
	Machine Protection	14	8
	Access Safety & Control System	23	23
Total (rounded)		**5890**	**7290**

CLIC 380 GeV Drive-Beam based: 5890^{+1470}_{-1270} MCHF;

CLIC 380 GeV Klystron based: 7290^{+1800}_{-1540} MCHF.

Cost - II

Other cost estimates:

Construction:
- From 380 GeV to 1.5 TeV, add 5.1 BCHF (drive-beam RF upgrade and lengthening of ML)
- From 1.5 TeV to 3 TeV, add 7.3 BCHF (second drive-beam complex and lengthening of ML)
- Labour estimate: ~11500 FTE for the 380 GeV construction

Operation:
- 116 MCHF (see assumptions in box below)
- Energy costs

– 1% for accelerator hardware parts (e.g. modules).
– 3% for the RF systems, taking the limited lifetime of these parts into account.
– 5% for cooling, ventilation and electrical infrastructures etc. (includes contract labour and consumables)

These replacement/operation costs represent 116 MCHF per year.

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

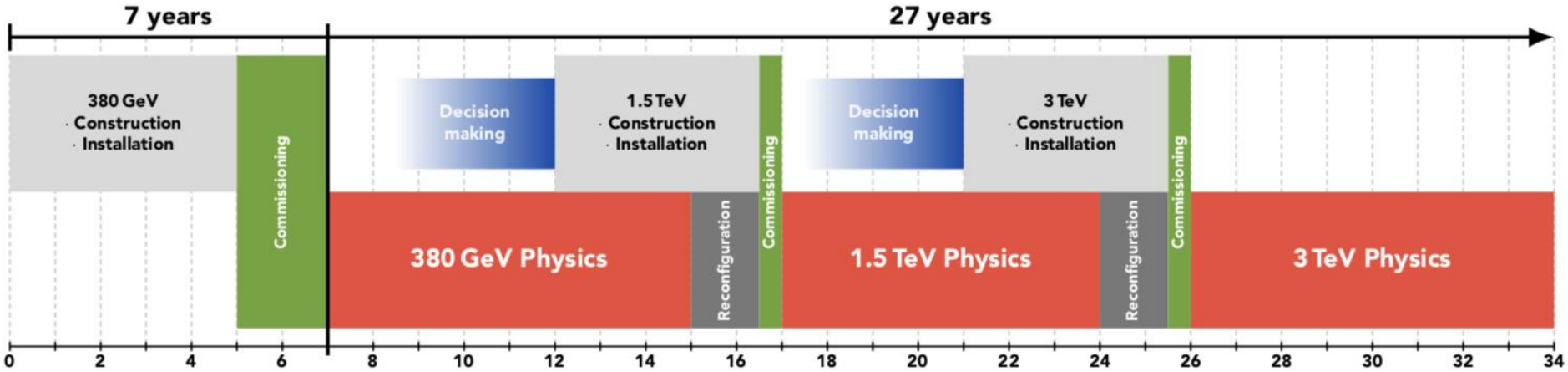
Update of the European Strategy for Particle Physics; decision towards a next CERN project at the energy frontier (e.g. CLIC, FCC)

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

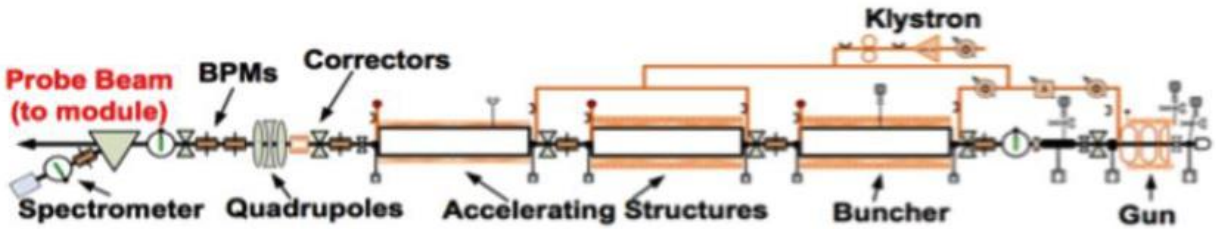


Looong term future - NAT

- Working group for use of Novel Acceleration Technologies (NAT) – plasma with various drivers, dielectrics, etc (short chapter in Project Implementation Plan document)
  - Physics and accelerator parameters (luminosity in particular)
  - Consider status of various studies
  - Key challenges beam-quality, positrons, energy efficiency for suitable luminosities
- Possible re-use of tunnel/infrastructure/drive-beams/injectors etc interesting for a LC infrastructure
- The fact the actual effective ML might remain short (and hence possibly “cheap” and inter-changeable in a limited time) makes this long term perspective worth considering
- Have not found any “constrains/guidance” from these very long term “hopes” that would impact the design of CLIC stages 1-3
  - CLIC is laser-straight and with a “reasonable” crossing angle likely to compatible with higher beam energies and the bunch separations needed for these technologies

CLEAR

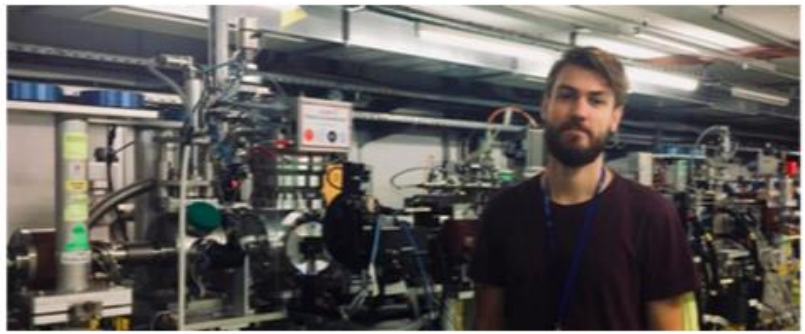
CERN Linear Electron Accelerator for Research



CALIFES beamline

80–220 MeV electrons
Bunch charge 0.01–1.5 nC

CLEAR started with beam in August 2017



Main activities:

CLIC & high-gradient X-band

Instrumentation R&D

VESPER irradiation test station
- Electronic components for space applications (with ESA)
- Medical applications (VHEE)
- Electronic components for accelerators and detectors

Novel techniques: plasma focusing and acceleration, THz radiation, dielectric structures

Open to proposals for user experiments

Linear Collider Community Meeting

8-9 April 2019
SwissTech Convention Center, Lausanne
Europe/Zurich timezone

Search...

- Overview
- Program Committee
- Timetable
- Participant List
- Registration
- Payment information
- Venue and access
- Visa Information
- Accommodation
- Lausanne Tourism

LC Community Meeting 19
LC19-LOC@cern.ch

The meeting has three main objectives:

- Initiate the formation of a strategy for future linear collider activities.
- Discuss how to present the case for linear colliders at the Open Symposium in Granada.
- Address the future organisation of the international linear collider activities beyond LCC.

In addition to the input provided by CLIC and ILC to the European Strategy process, the decision of Japan concerning hosting the ILC is expected to be known at the time of the meeting.

The meeting will be open. It will start Monday 8.4 at 11:00 and conclude Tuesday 9.4 at 16:00.

The meeting is arranged on the initiative of LCB/IFCA and is supported by ECFA. CERN and EPFL act as local organisers.
The venue is the SwissTech convention centre at the EPFL campus: https://www.stcc.ch/fr/

Juan Fuster (ECFA LC physics&detector study)
Steinar Stapnes (LC/CERN)
Tatsuya Nakada (LCB and EPFL)

Starts 8 Apr 2019, 09:00
Ends 9 Apr 2019, 16:00
Europe/Zurich

SwissTech Convention Center, Lausanne
SwissTech Convention Center, Lausanne
https://www.stcc.ch/fr

Juan Fuster Verdú
Steinar Stapnes
Tatsuya Nakada

There are no materials yet.

LC strategy discussed ahead of Granada.
See summary (at link), extract below:

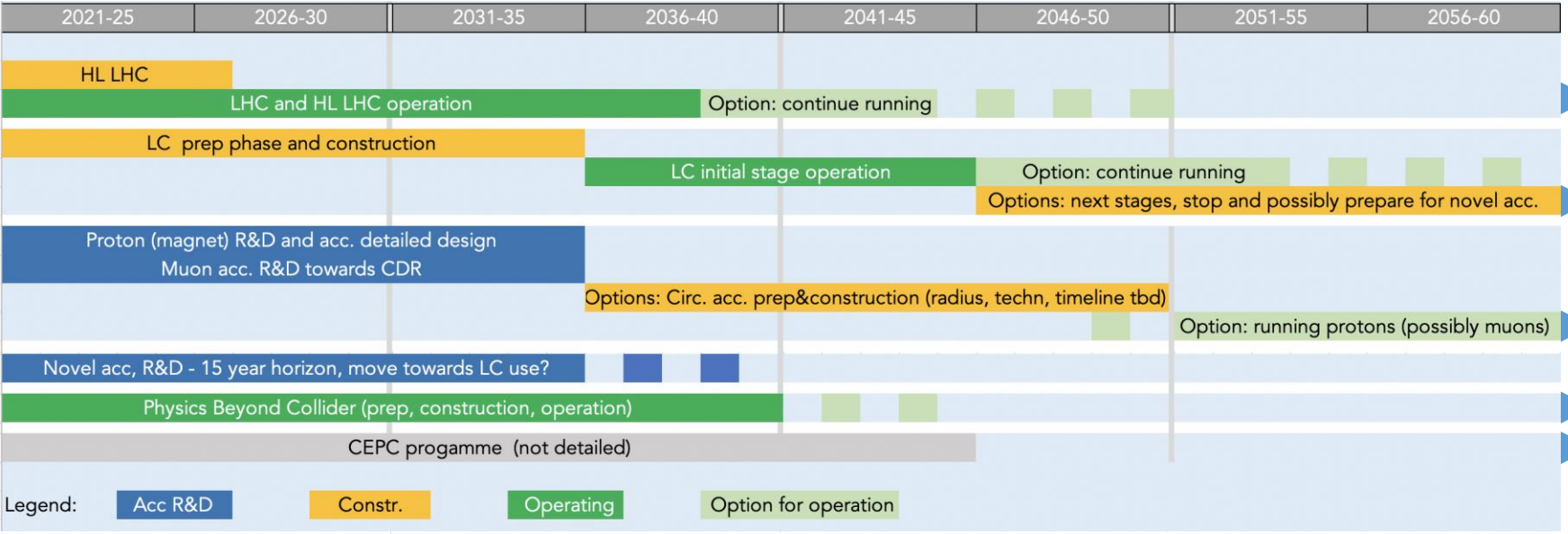
Conclusions from the Linear Collider meeting in Lausanne April 2019.

The highest scientific priority in particle physics is to uncover phenomena that establish new physics addressing the shortcomings of the Standard Model (SM). Precision studies in e+e- collisions of the properties of the Higgs boson including its self-interaction, of the top quark, and of other processes, can elucidate the underlying dynamics of electroweak symmetry breaking and “point the way” to new physics Beyond the Standard Model (BSM). Direct searches for new phenomena that are difficult to observe in hadronic interactions can also be pursued. All of these studies could address fundamental questions such as the origin of mass and of the matter-antimatter asymmetry, and the nature of dark matter.

The most cost effective, fast, and versatile approach is construction of a linear e+e- collider (LC) facility starting from an initial energy and luminosity optimised for the targeted measurements. Such a facility will also provide physics guidance for future accelerators beyond the initial LC. The facility should provide the foundation for a long-term e+e- physics programme and hence be upgradable in the future with the same, improved, or new technologies to much higher energies, allowing improved precision and reach for SM and BSM physics. The LC should be pursued for construction start-up in about 5 years, aiming for operation by ~2035.

During the ESPP process important conclusions will be drawn concerning future projects and studies, which are crucial for a timely construction start-up of a LC project. This is a unique opportunity to move ahead quickly towards constructing a LC that fulfils the goals described above. Europe and CERN should play leading roles in this endeavour, wherever the LC is realised.

A linear collider as part of an overall strategy



HL LHC until ~2038

LC const. "ready", affordable, provide opportunities for long term e+e- data

Acc. R&D opening for proton (possibly muon) colliders by/before 2050 – no 100 km constrain or wait for tunnel access (limited by R&D and funding)
PBC programme
CEPC development will unfold

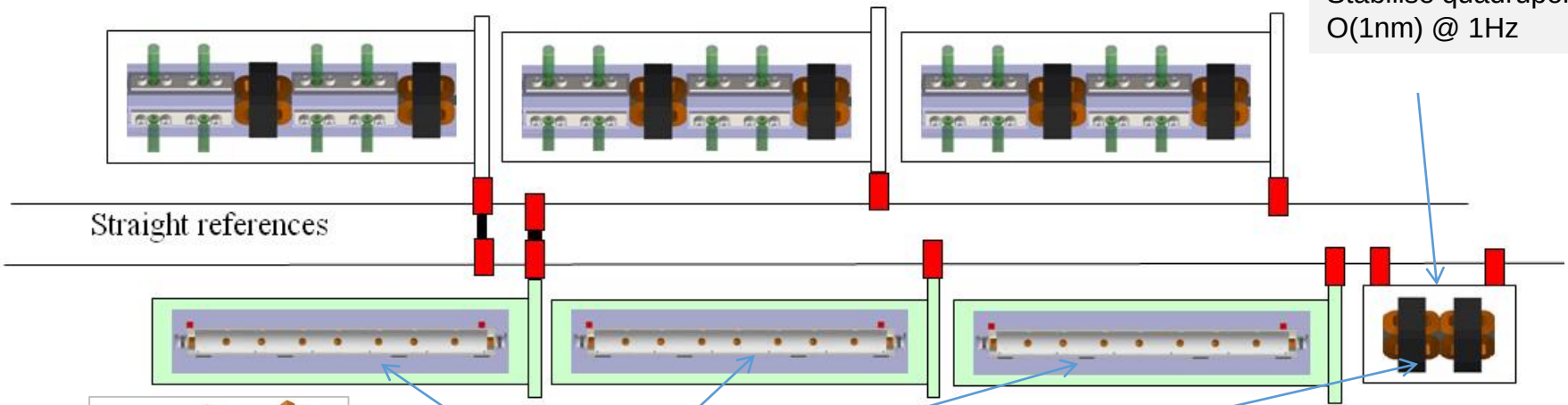
Summary

- CLIC is now a mature project, ready for implementation
- The main accelerator technologies have been demonstrated
- The cost and implementation time are similar to LHC
- The physics case is broad and profound, and being further developed
- The detector concept and detector technologies R&D are advanced
- The full project status has been presented in a series of Yellow Reports and other publications: **http://clic.cern/european-strategy**

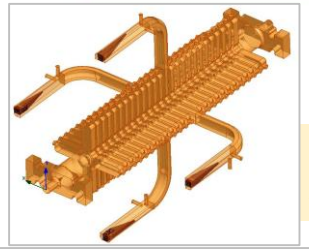
Thanks to all providing material - and more generally ALL contributors to the CLIC ESPP input/background documents , from which this material is drawn

Extra slides

Low emittance transport

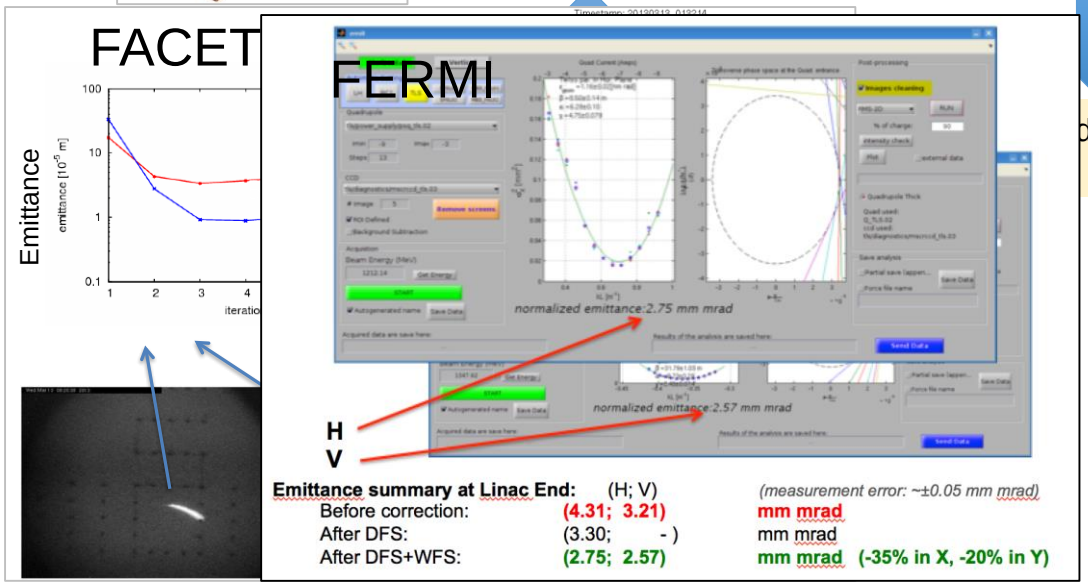


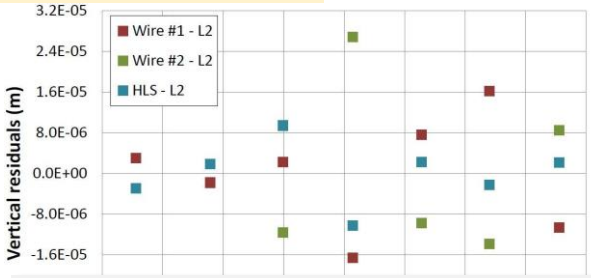
Stabilise quadrupole
O(1nm) @ 1Hz



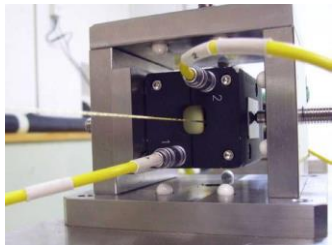
3) Use wake-field monitors
accuracy O(3.5μm) – CTF3

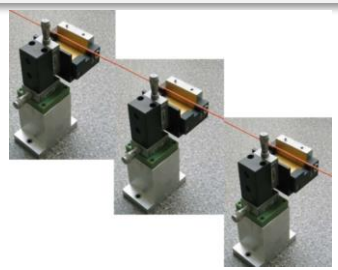
1) Pre-align BPMs+quads
accuracy O(10μm) over about 200m



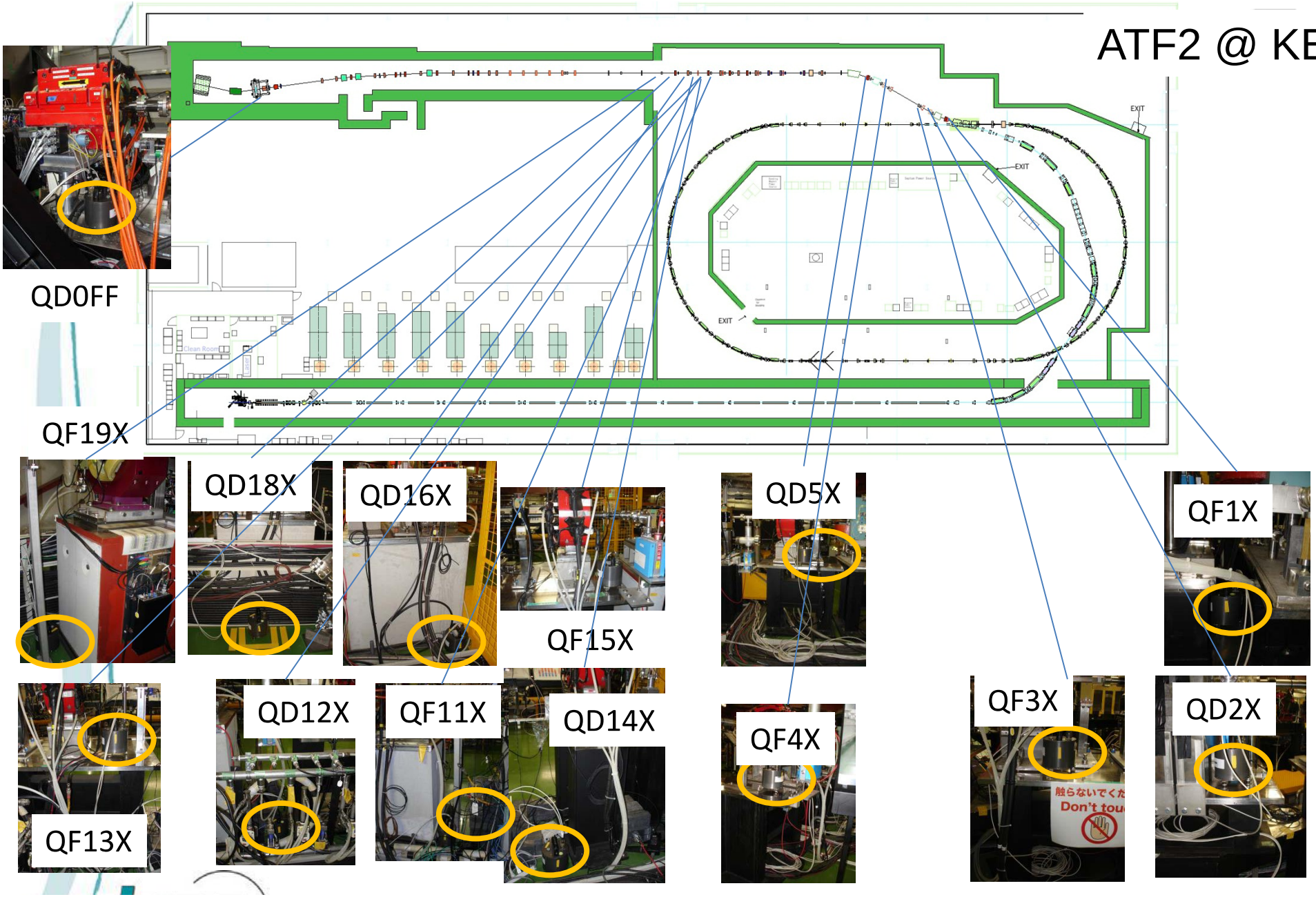


PACMAN, Marie Curie Action:
- vertical RMS error of 11μm
- i.e. accuracy is approx. 13.5μm





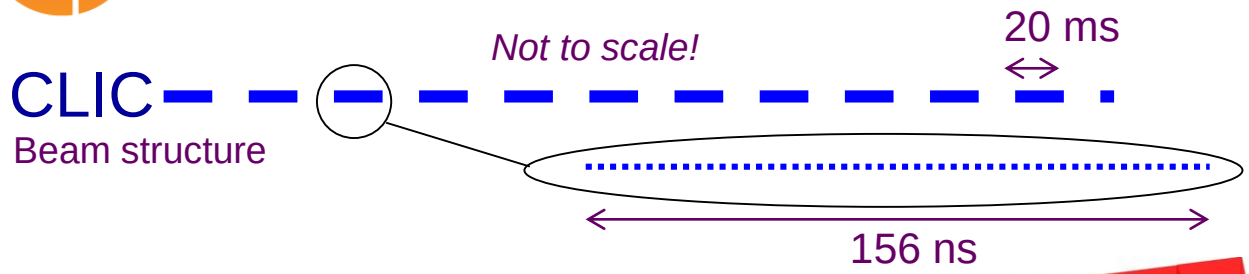
Final focus system



Next phase

Details	Purpose
Main linac modules	
Build ten prototype modules in qualified industries, two beam and klystron versions	Final technical design, qualify industry partners, verify performance
Accelerating structures	
Around 50 structures incl. for modules above	Industrialization, manufacturing and cost optimisation
Operating X-band test-stands, high efficiency RF	
X-band test-stands at CERN and collaborating institutes, cost optimized X-band RF	X-band component tests, validation and optimization, cost reduction and industrially available RF units
Technical components	
Magnets, instrumentation, alignment, stability, vacuum	Luminosity performance, costs and power, industrialization
Design&Parameters	
Beam dynamics studies, parameter optimization, costs, power	Luminosity performance, risk, costs and power reduction
Drivebeam studies	
Drivebeam front end optimisation and systemtests to around 20 MeV	Verification of the most critical parts of drivebeam concept, develop further the industrial capabilities for L-band RF systems

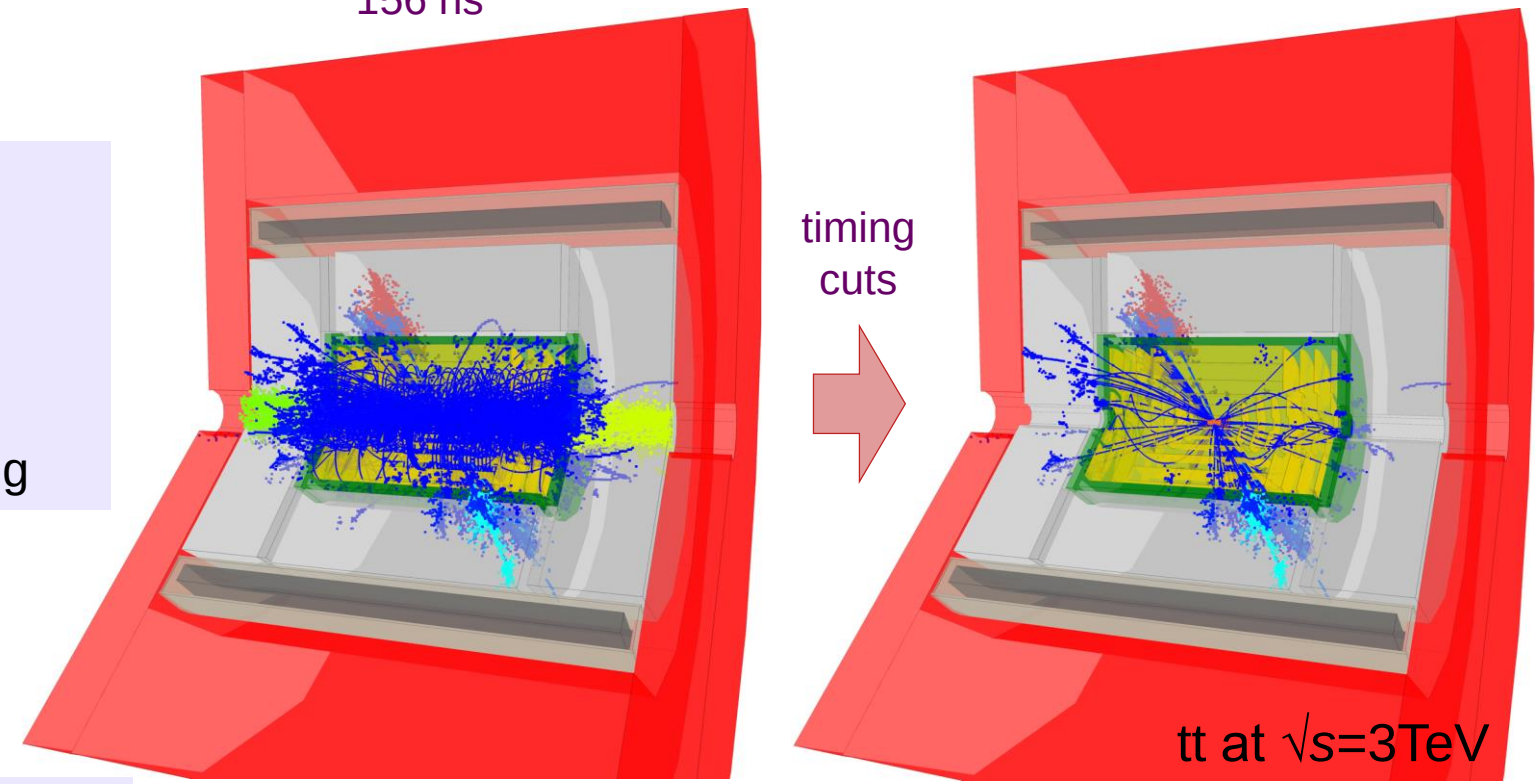
Collider environment



High bunch charge density
–> beam-related backgrounds
small effect at √s=380GeV
large effect at high energies

Precise timing required for beam background rejection

1ns in calorimetry,
5ns in vertexing/tracking



High precision:
- jet energy resolution
  –> fine-grained calorimetry
- momentum resolution
- impact parameter resolution

$\sigma(E)/(E) \sim 3.5\%$ for E>100GeV

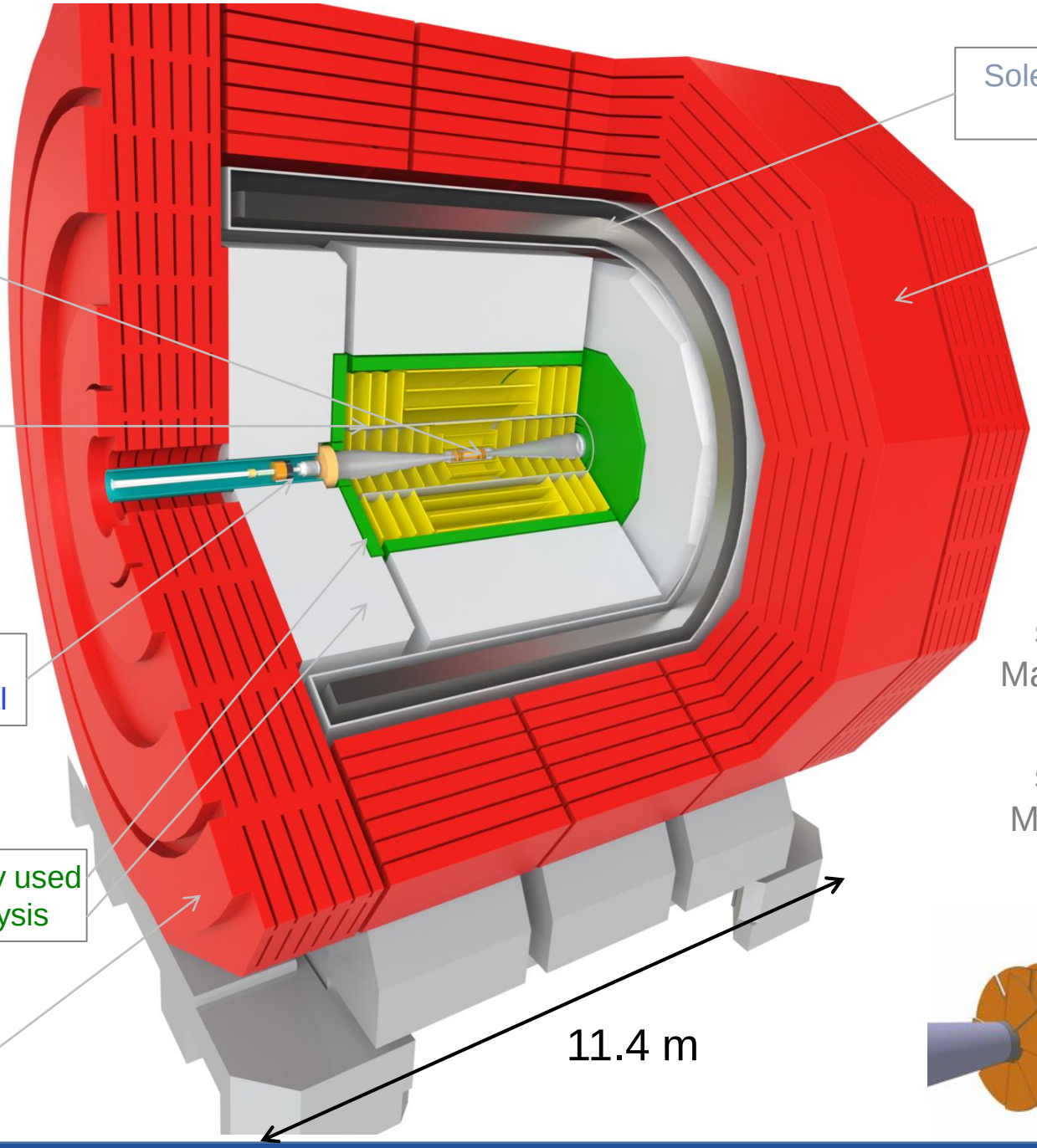
$\sigma(p_T)/p_T^2 \sim 2\times10^{-5}$ GeV^{-1}

$\sigma_{d0} \sim 5 \oplus 15/(p\,[\mathrm{GeV}]\sin^{3/2}\theta)$ μm

CALICE / FCAL

CLICdp vertexing/ tracking programme

CLICdet



Triggerless readout

Tracker
spatial resolution: 7μm
Material: 1–2% X_0 / layer

Vertex detector
spatial resolution: 3μm
Material: 0.2% X_0 / layer
–> forced air cooling