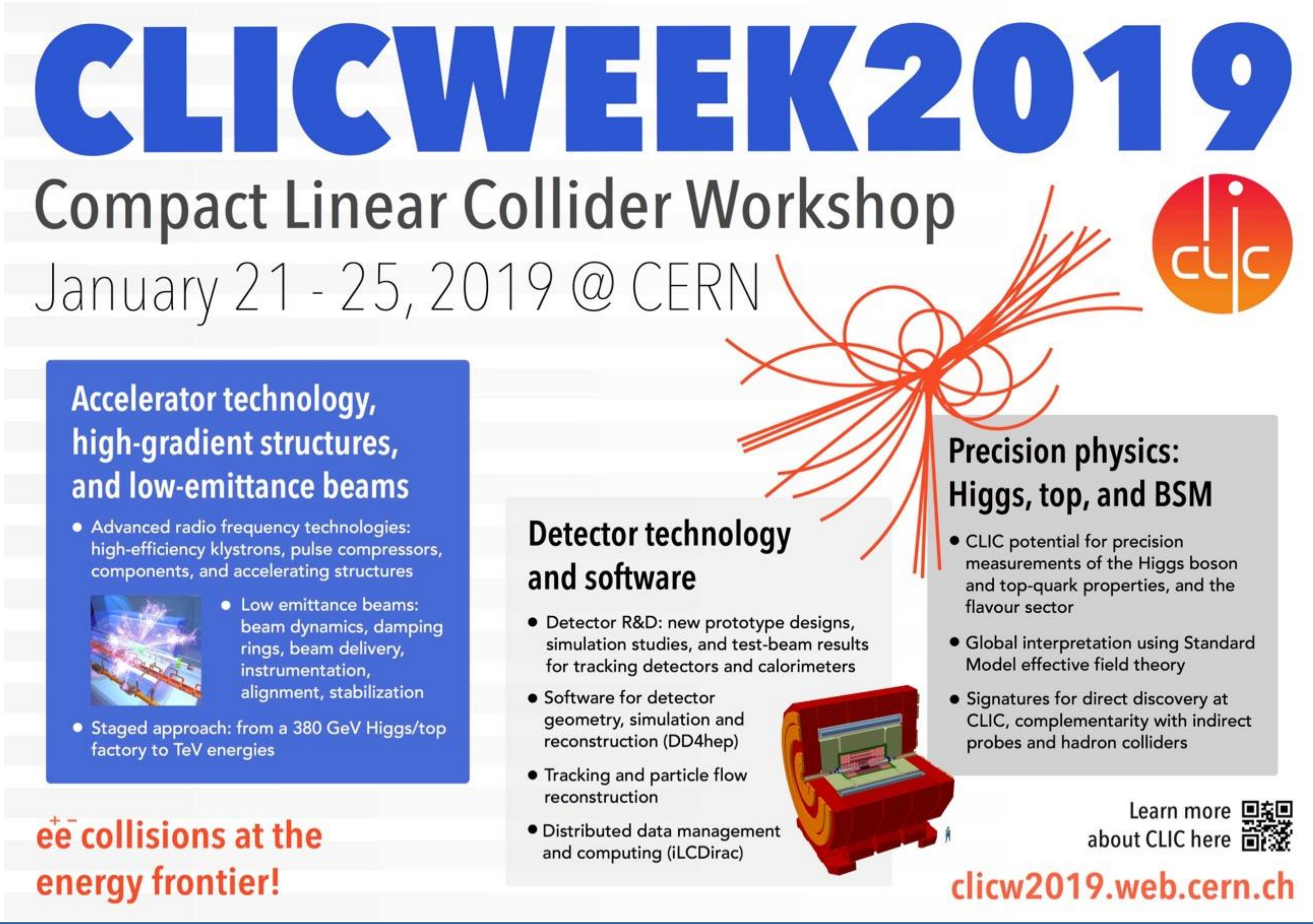
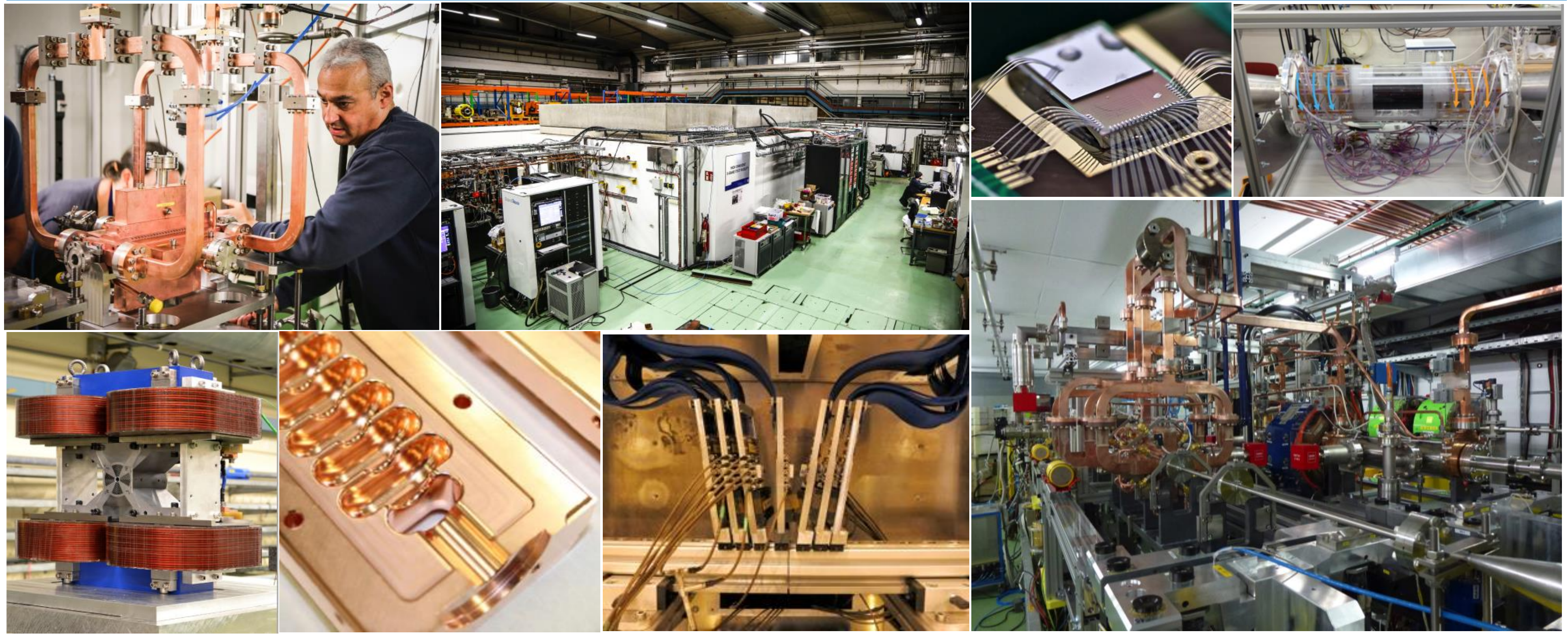

CLICWEEK2019
Compact Linear Collider Workshop
January 21 - 25, 2019 @ CERN
Accelerator technology, high-gradient structures, and low-emittance beams
• Advanced radio frequency technologies: high-efficiency klystrons, pulse compressors, components, and accelerating structures
• Low emittance beams: beam dynamics, damping rings, beam delivery, instrumentation, alignment, stabilization
• Staged approach: from a 380 GeV Higgs/top factory to TeV energies
Detector technology and software
• Detector R&D: new prototype designs, simulation studies, and test-beam results for tracking detectors and calorimeters
• Software for detector geometry, simulation and reconstruction (DD4hep)
• Tracking and particle flow reconstruction
• Distributed data management and computing (iLCDirac)
Precision physics: Higgs, top, and BSM
• CLIC potential for precision measurements of the Higgs boson and top-quark properties, and the flavour sector
• Global interpretation using Standard Model effective field theory
• Signatures for direct discovery at CLIC, complementary with indirect probes and hadron colliders
e^+e^- collisions at the energy frontier!
Learn more about CLIC here
clicw2019.web.cern.ch

The CLIC accelerator studies



The CLIC workshop 2019

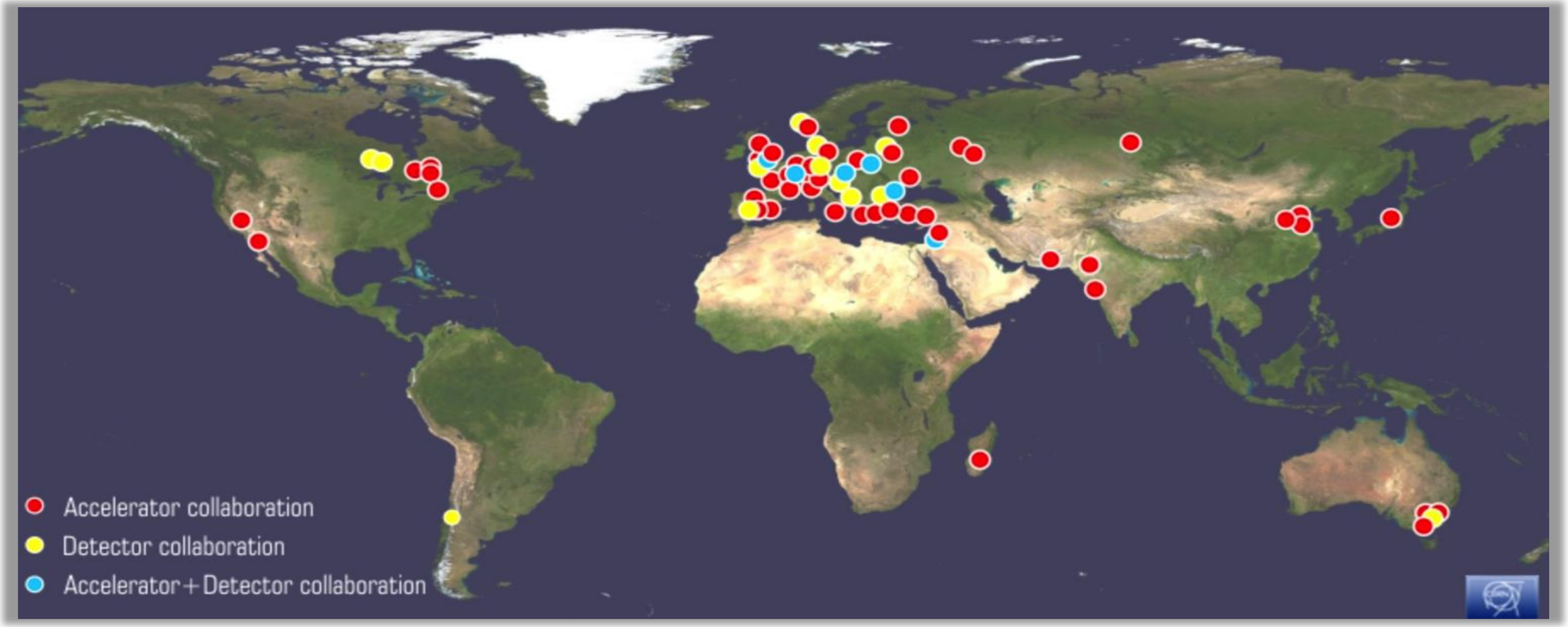
Steinar Stapnes on behalf of the CLIC accelerator collaboration

Collaborations

http://clic.cern/

CLIC accelerator collaboration
53 institutes from 31 countries

CLIC detector and physics (CLICdp)
30 institutes from 18 countries



For CLICdp see the following talks

CLIC input to the European Strategy for Particle Physics Update 2018-2020

Formal European Strategy submissions

- **The Compact Linear e+e- Collider (CLIC): Accelerator and Detector** (arXiv:1812.07987)
- **The Compact Linear e+e- Collider (CLIC): Physics Potential** (arXiv:1812.07986)

Yellow Reports

- **CLIC 2018 Summary Report** (CERN-2018-005-M, arXiv:1812.06018)
- **CLIC Project Implementation Plan** (CERN-2018-010-M)
- **The CLIC potential for new physics** (CERN-2018-009-M)
- **Detector technologies for CLIC** [In collaboration review]

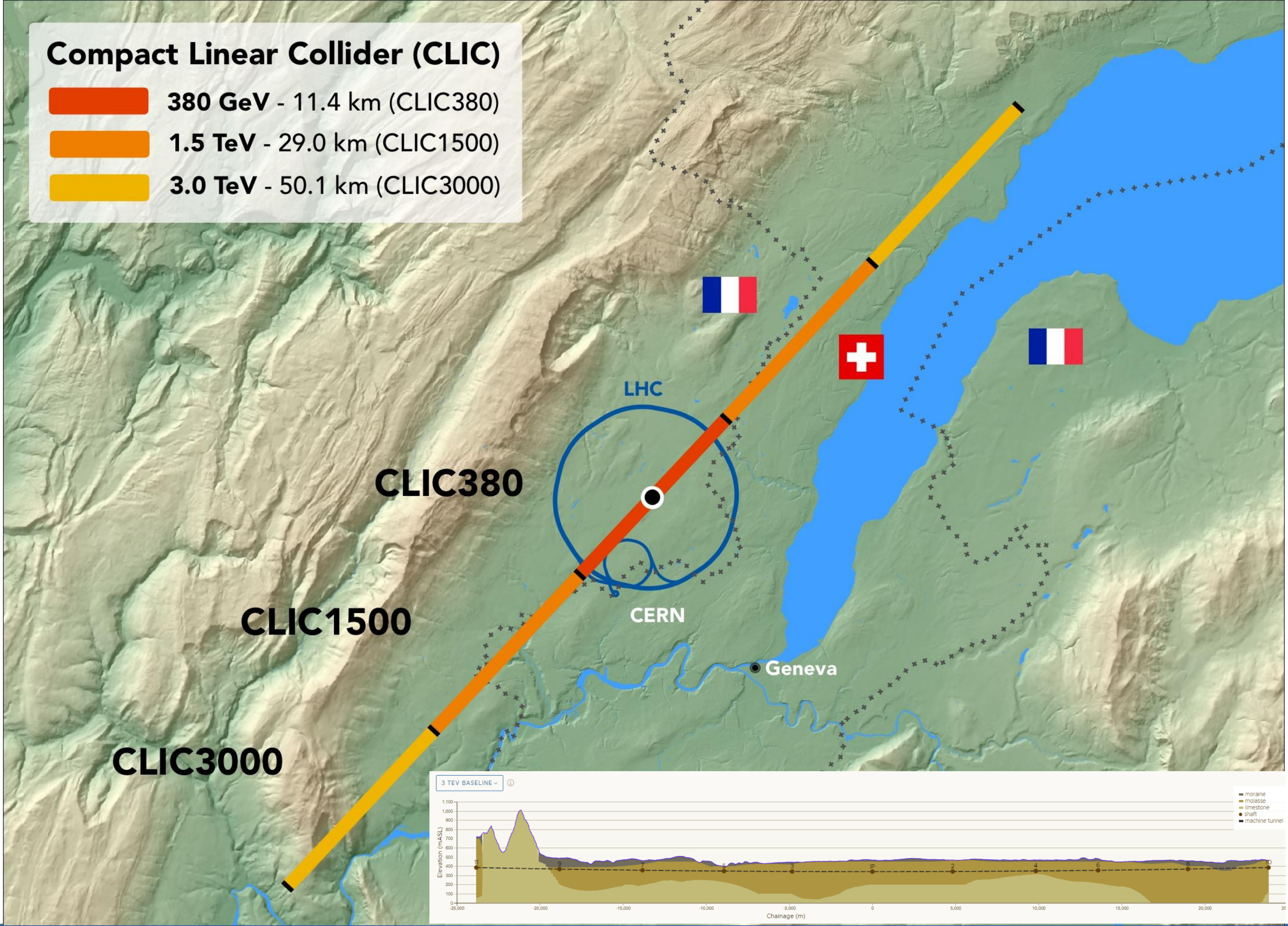
Journal publications

- **Top-quark physics at the CLIC electron-positron linear collider** [In journal review] (arXiv:1807.02441)
- **Higgs physics at the CLIC electron-positron linear collider** (Journal, arXiv:1608.07538)
  - Projections based on the analyses from this paper scaled to the latest assumptions on integrated luminosities can be found here: CDS, arXiv.

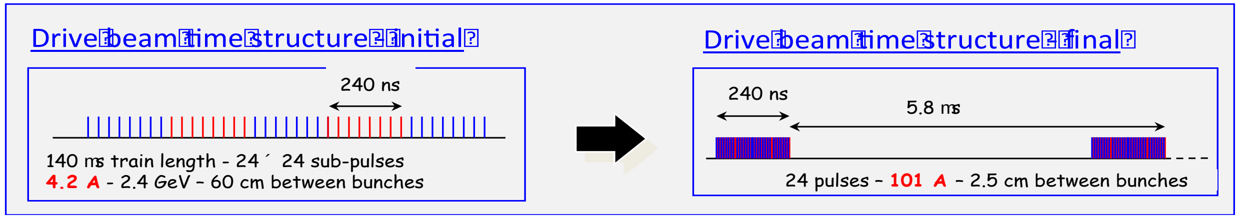
CLICdp notes

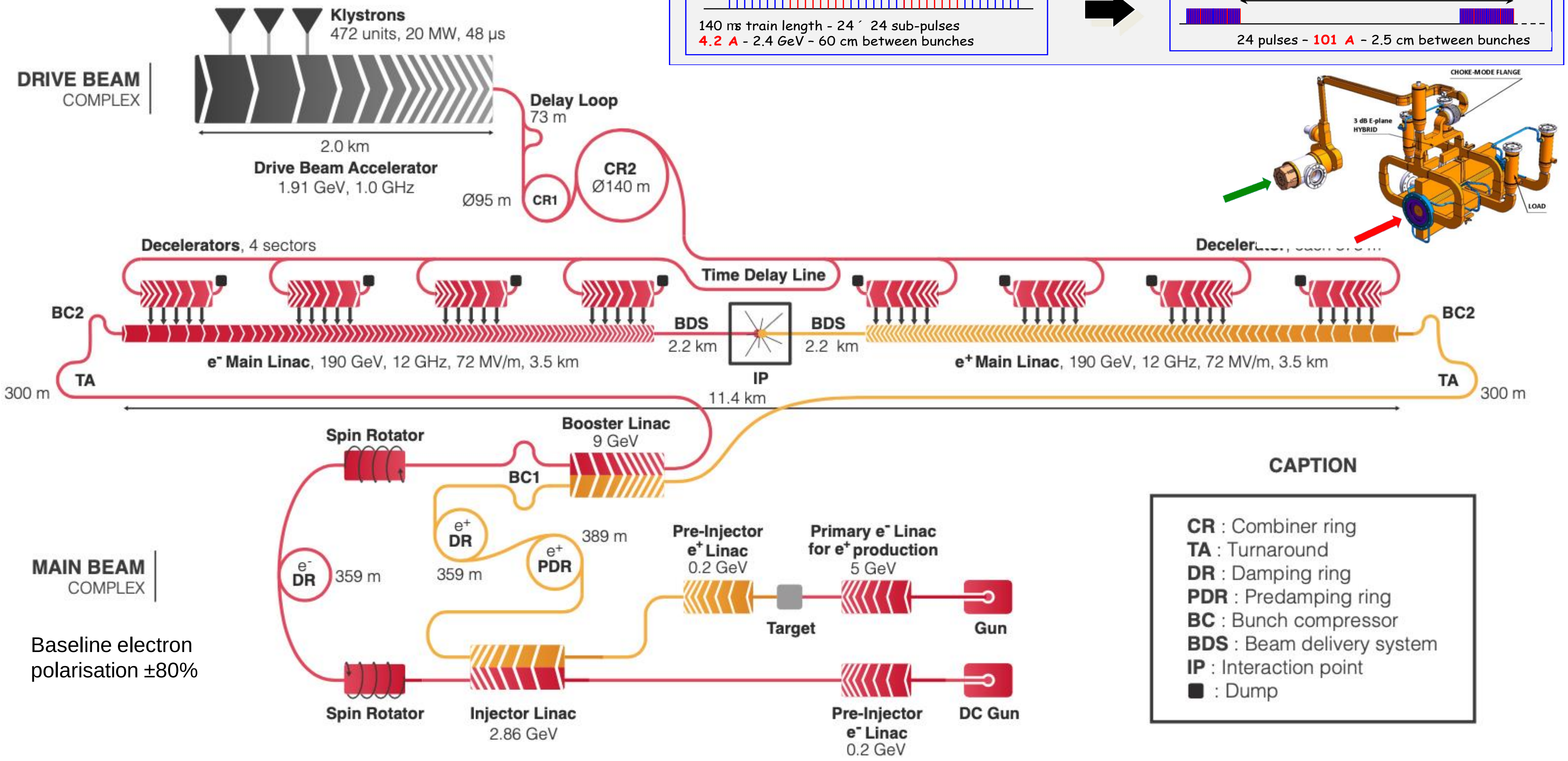
- **Updated CLIC luminosity staging baseline and Higgs coupling prospects** (CERN Document Server, arXiv:1812.01644)
- **CLICdet: The post-CDR CLIC detector model** (CERN Document Server)
- **A detector for CLIC: main parameters and performance** (CERN Document Server, arXiv:1812.07337)

Link: http://clic.cern/european-strategy


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

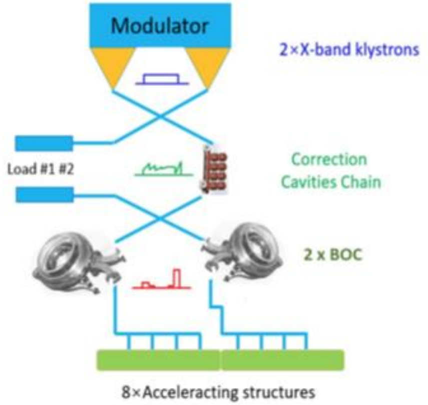
CLIC 380 GeV layout and power generation





Baseline electron polarisation ±80%

380 GeV klystron option

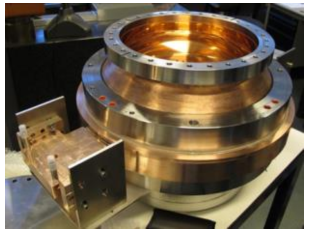


Replace drive-beam complex by local X-band RF power in tunnel
Larger tunnel, simpler module

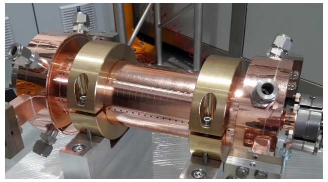
Modulator

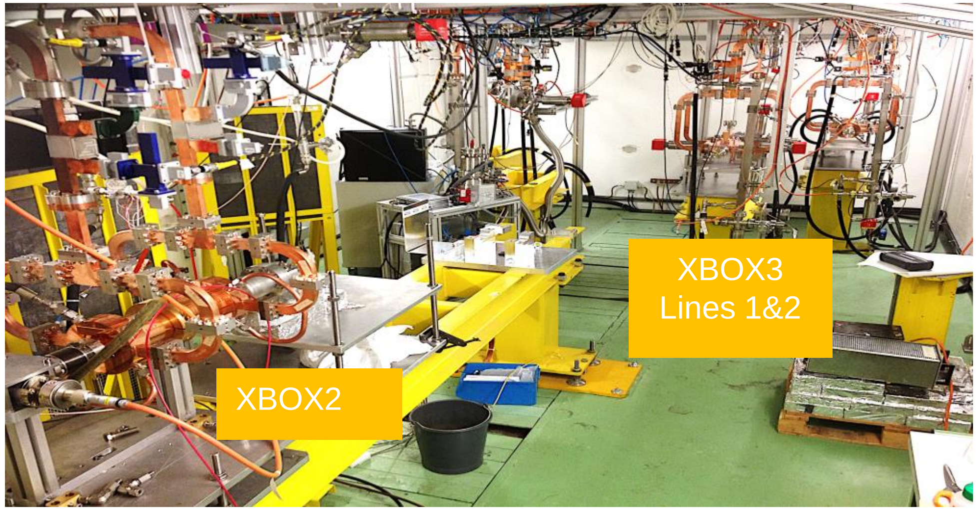
Klystron

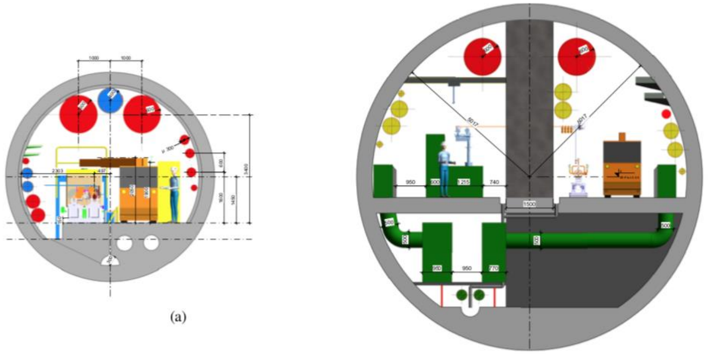
Pulse compressor



Accelerating structures

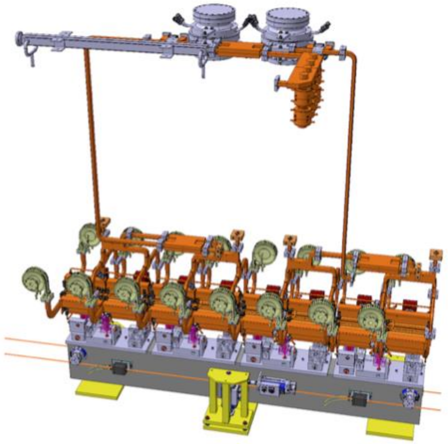






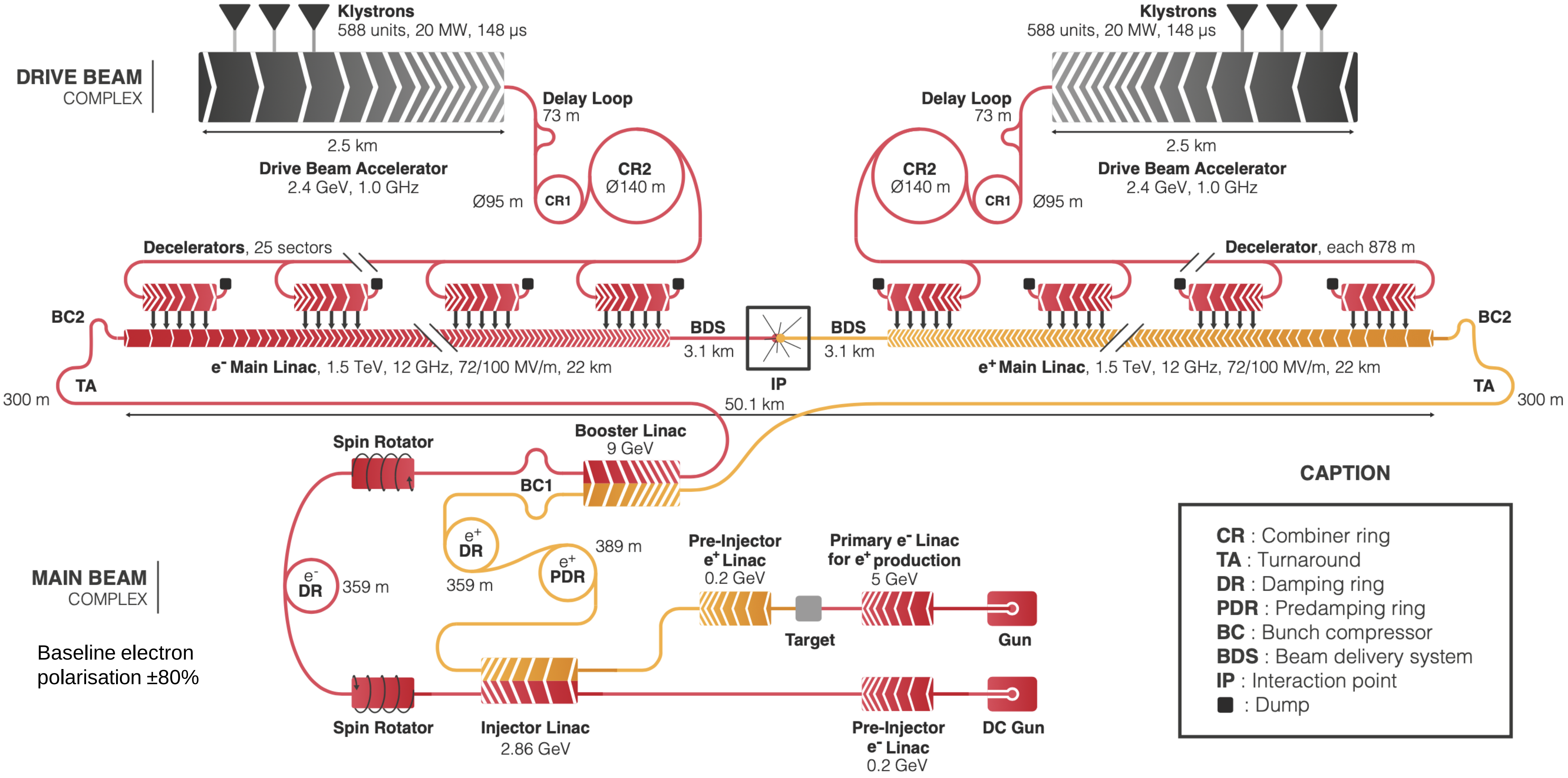
(a)

(b)



Assembled X-band systems in continues operation at CERN

CLIC layout – 3TeV



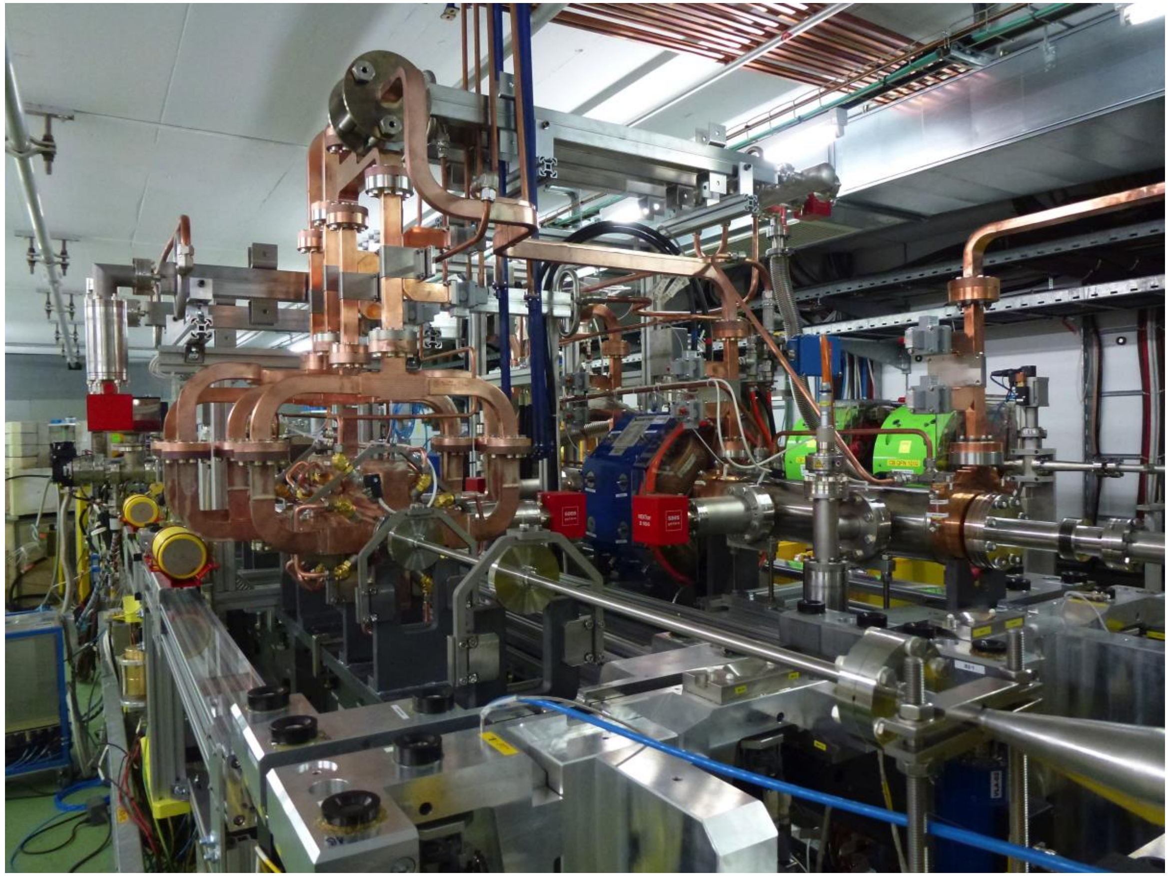
Baseline electron polarisation ±80%

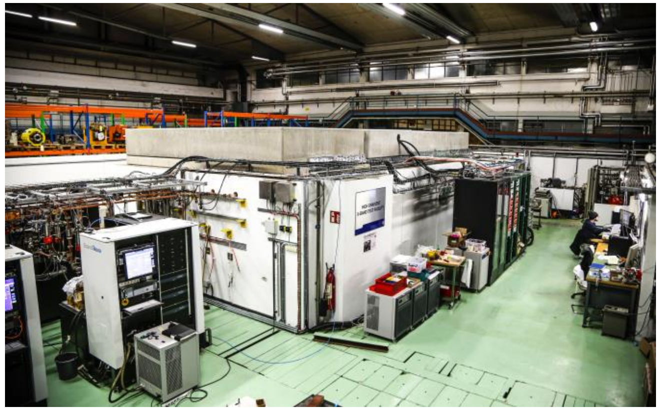
CLIC parameters

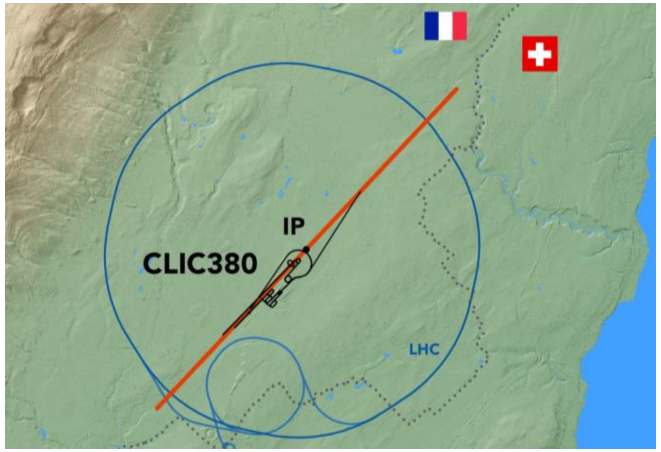
Parameter	Symbol	Unit	Stage 1	Stage 2	Stage 3
Centre-of-mass energy	$\sqrt{s}$	GeV	380	1500	3000
Repetition frequency	f_{rep}	Hz	50	50	50
Number of bunches per train	n_b		352	312	312
Bunch separation	Δt	ns	0.5	0.5	0.5
Pulse length	τ_{RF}	ns	244	244	244
Accelerating gradient	G	MV/m	72	72/100	72/100
Total 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
Total integrated luminosity per year	$\mathscr{L}_{\text{int}}$	fb^{-1}	180	444	708
Main linac 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	900/20	660/20	660/20
Final RMS energy spread		%	0.35	0.35	0.35
Crossing angle (at IP)		mrad	16.5	20	20

CLIC main achievements

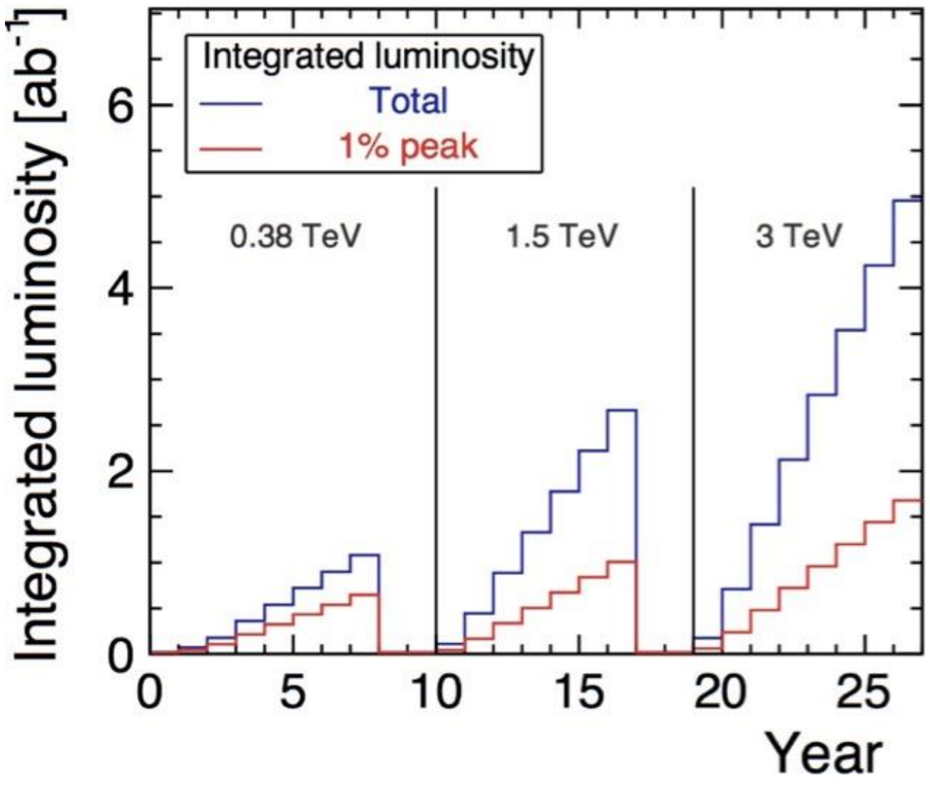
Key technologies have been demonstrated
CLIC is now a mature project ready for implementation







Updated CLIC Staging



Stage	$\sqrt{s}$ [TeV]	$\mathscr{L}_{int}$ [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

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.

Accelerator challenges

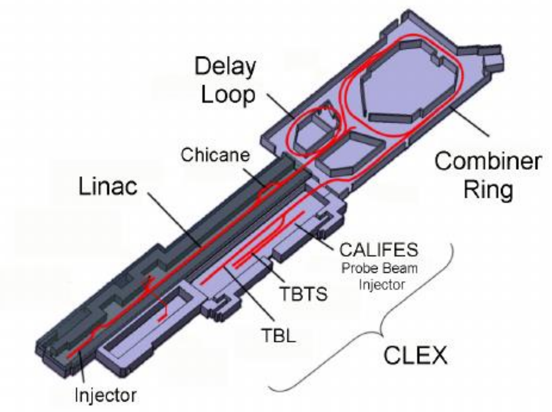
Four challenges:

High-current drive beam bunched at 12 GHz

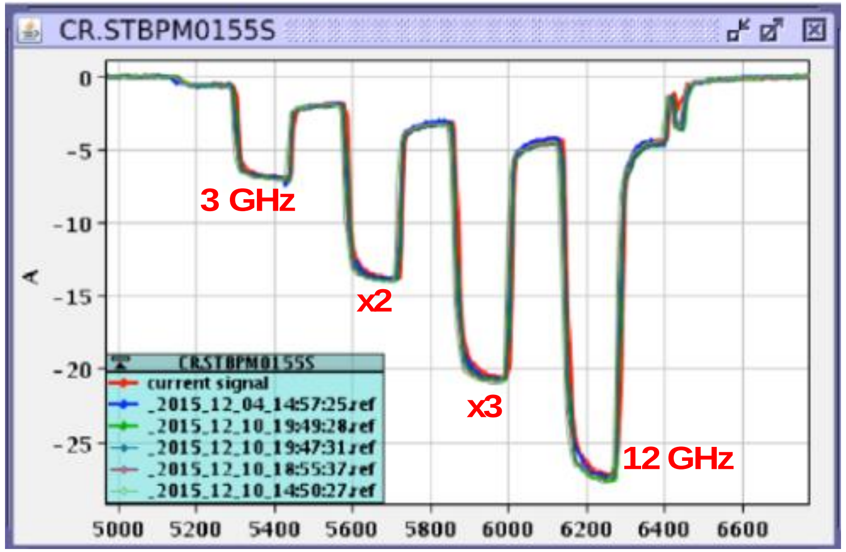
Power transfer + main-beam acceleration

~100 MV/m gradient in main-beam cavities

Alignment & stability



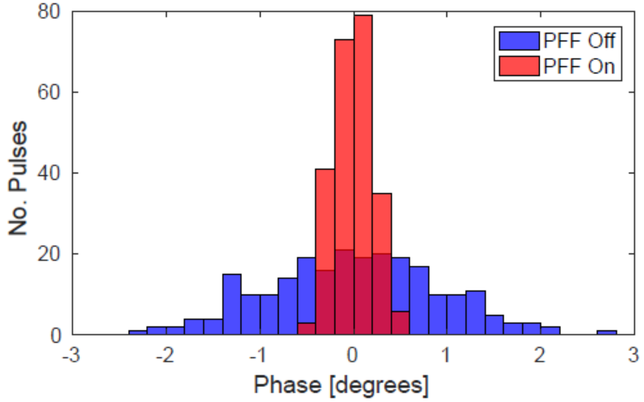
Drive beam quality:
Produced high-current drive beam bunched at 12GHz



Current in combiner ring

28A

Drive beam arrival time stabilised to CLIC specification of 50fs



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

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

Accelerator challenges

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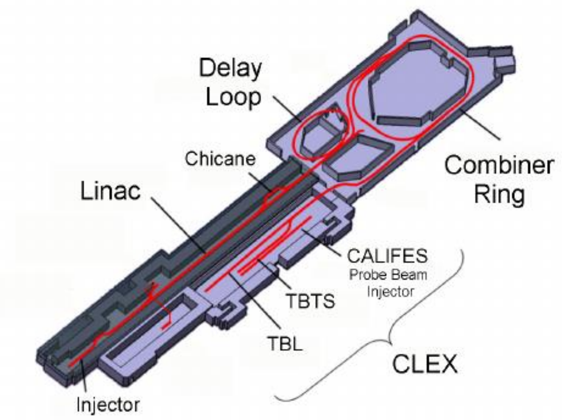
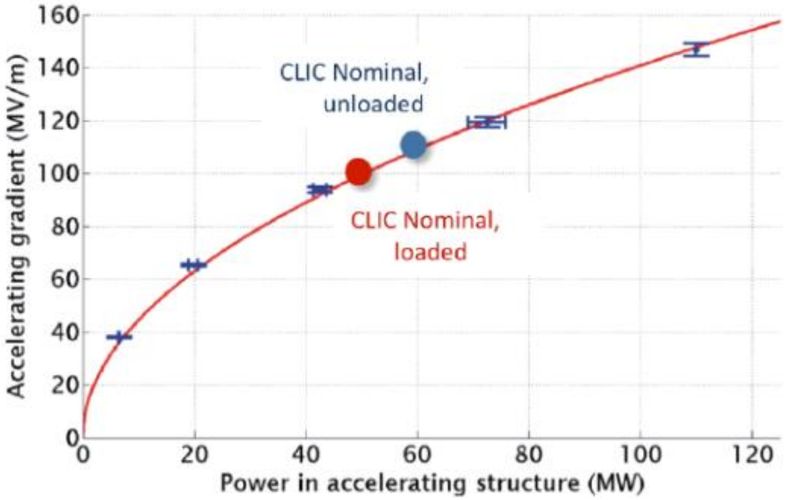
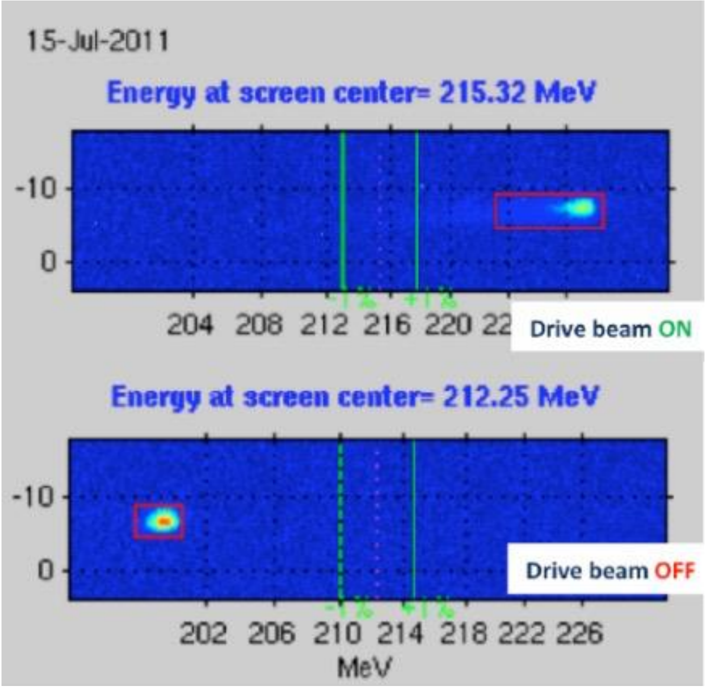


Demonstrated 2-beam acceleration



31MeV = 145MV/m



Accelerator challenges

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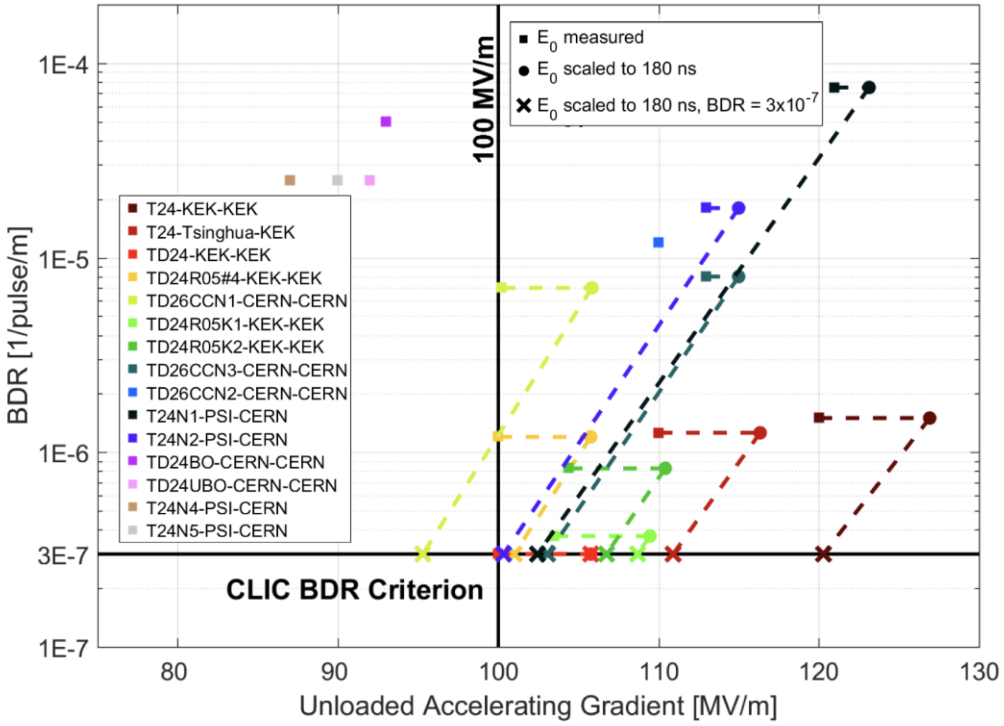
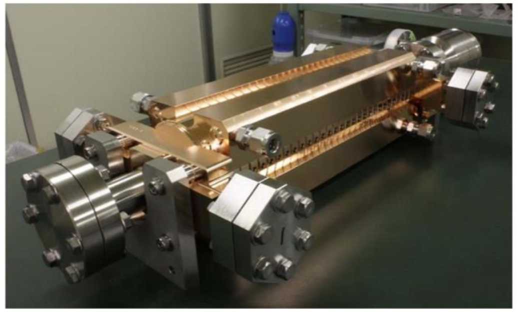
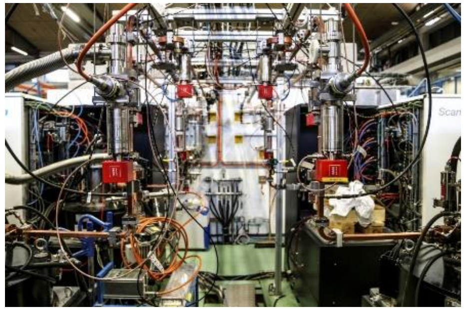
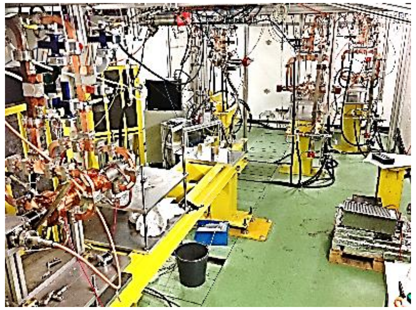
X-band performance: achieved 100MV/m gradient in main-beam RF cavities









Accelerator challenges

Four challenges:

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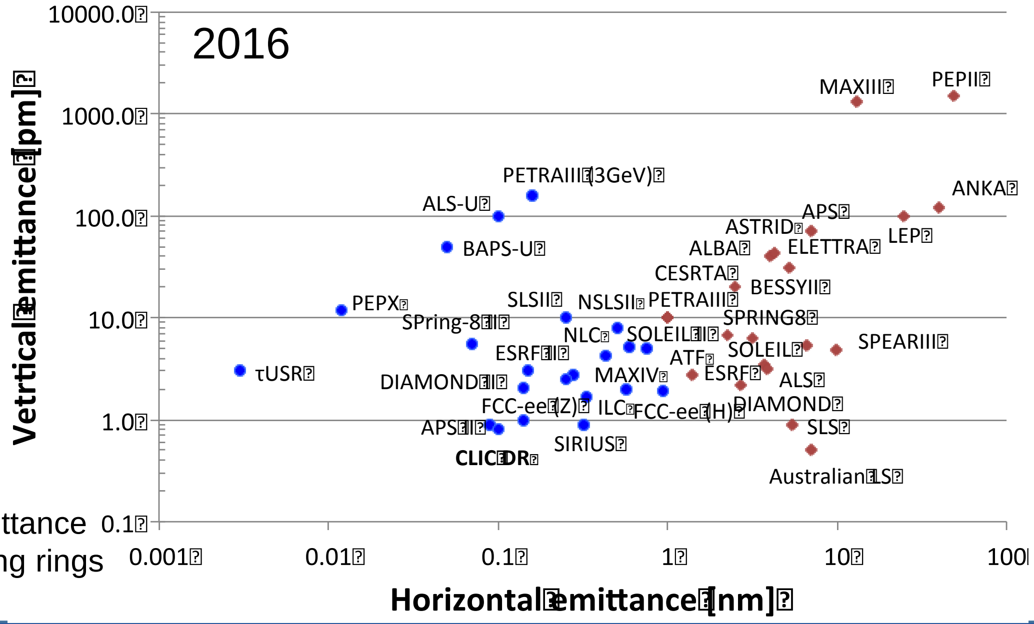
~100 MV/m gradient in main-beam cavities

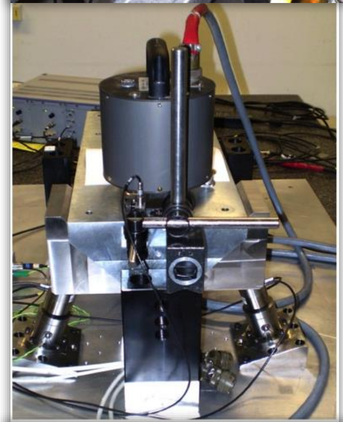
Alignment & stability

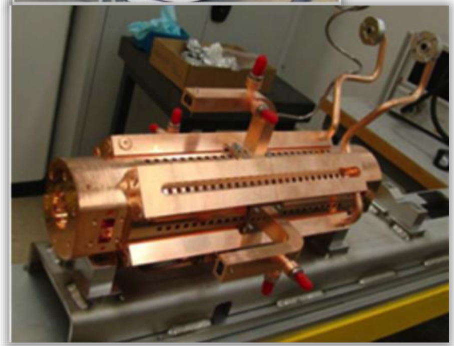
The CLIC strategy for nano-beams:

- 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)



CLIC emittance at damping rings





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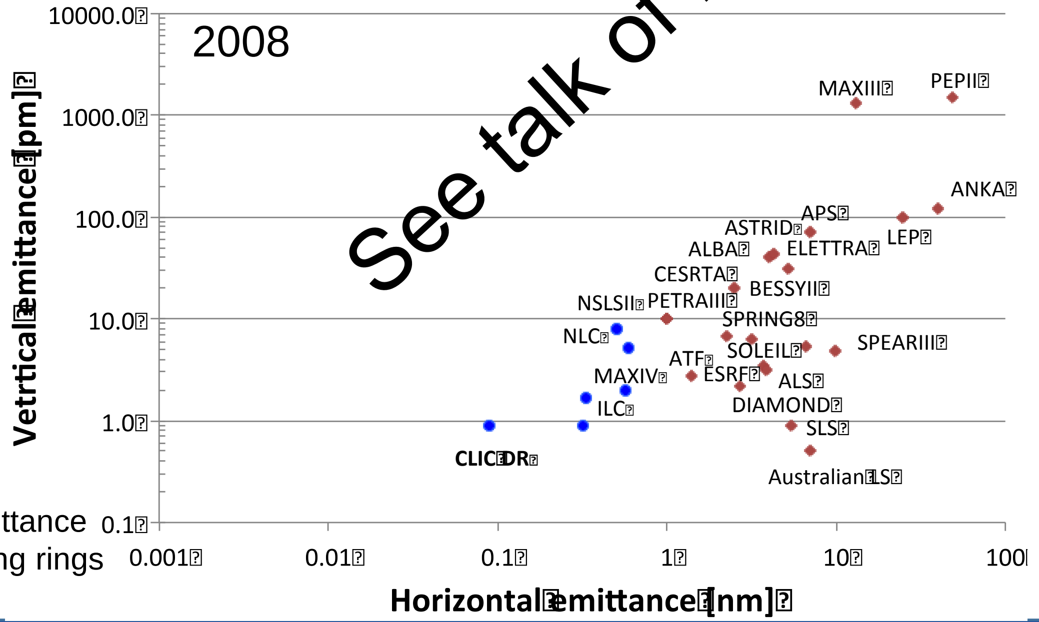
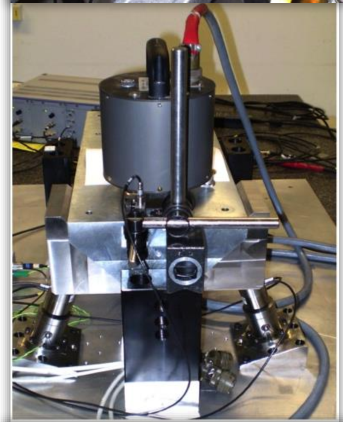
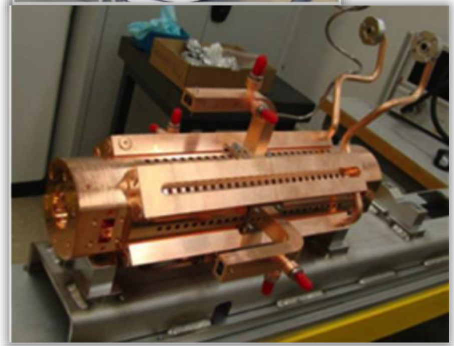
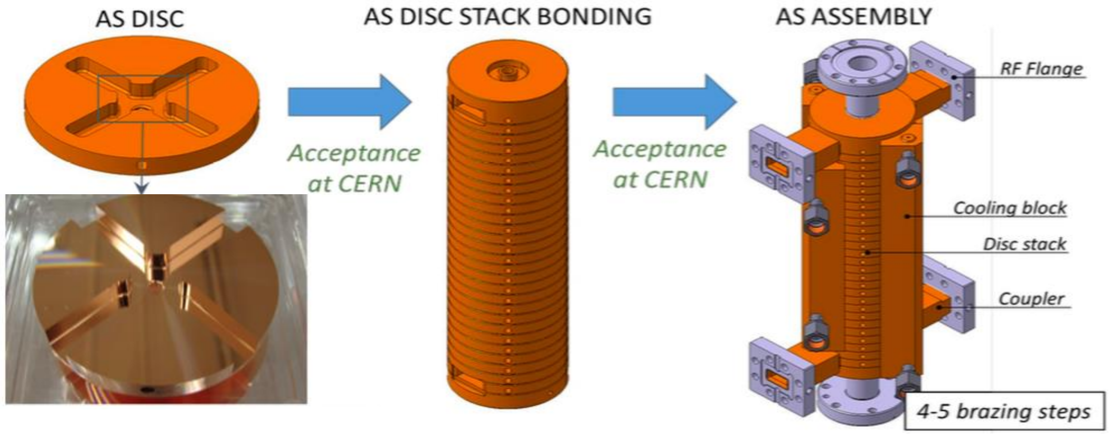
See talk of Daniel Schulte

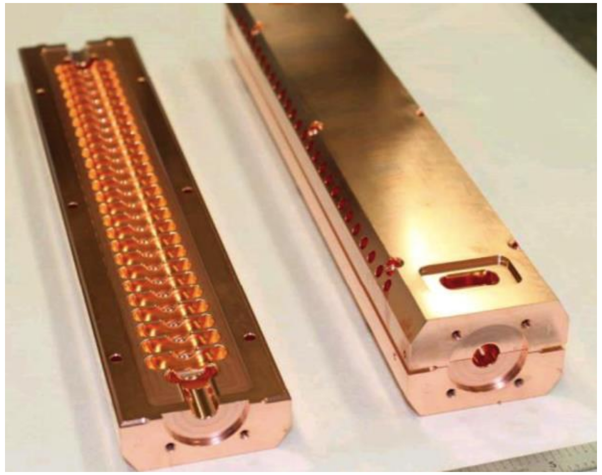


CLIC emittance at damping rings


Industrialisation





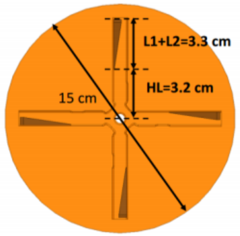
Investigating paths to industrialisation

Baseline manufacturing technique:
  bonding and brazing

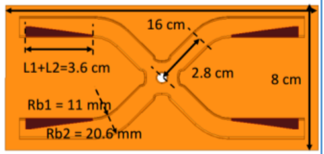
Alternatives:
  brazing as for SwissFEL also for disks
  machining halves

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

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

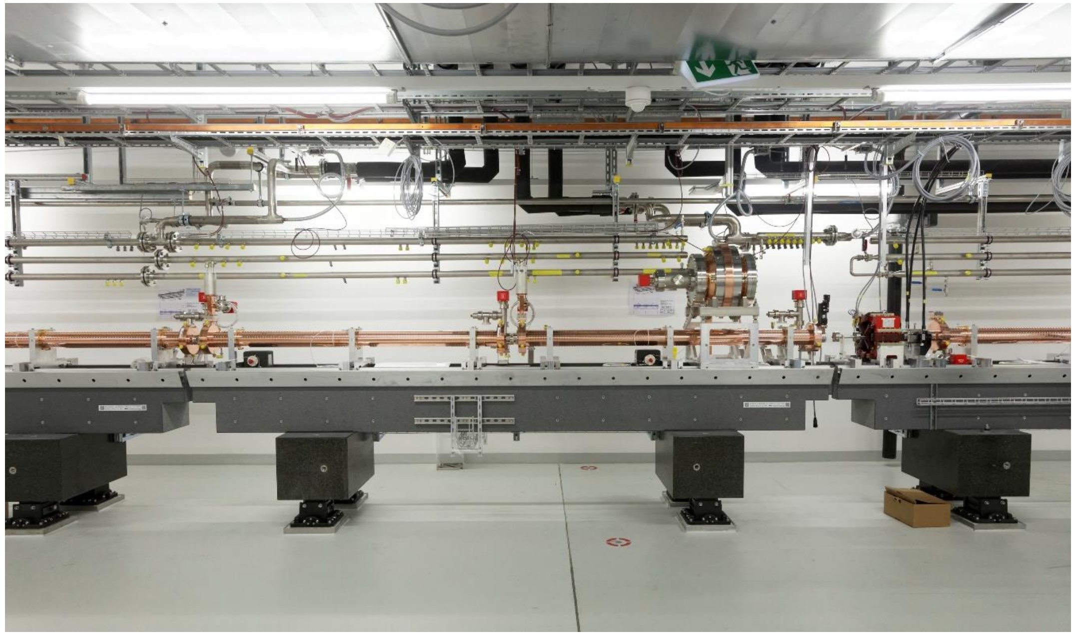
X-band technology base

- X-band activities and studies in institutes and industry (intensity linked to resources, publications …)
- Similar maps possible to draw for Asian and US activities (and for other technologies than X-band)
- X-band used as part of machines (linearizers, deflectors) or as main RF

See talk of Walter Wuensch

SwissFEL – C-band linac

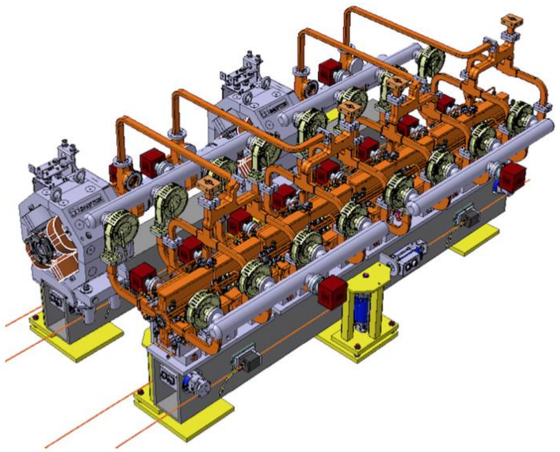
- 104 x 2m-long C-band structures
  (beam → 6 GeV @ 100 Hz)
- Similar **µ**m-level tolerances
- Length ~ 800 CLIC structures
- Being commissioned

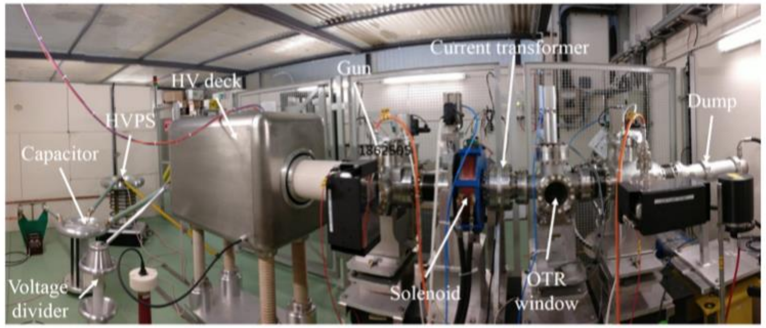


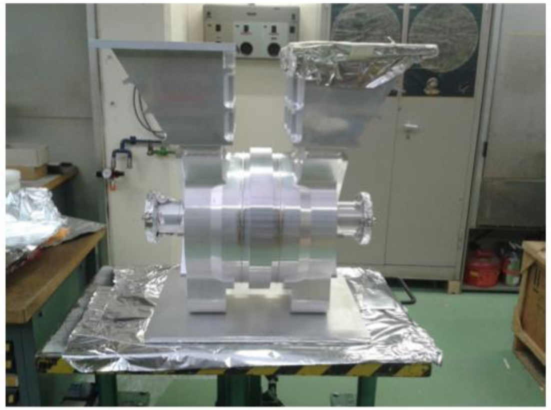
Technical developments - I

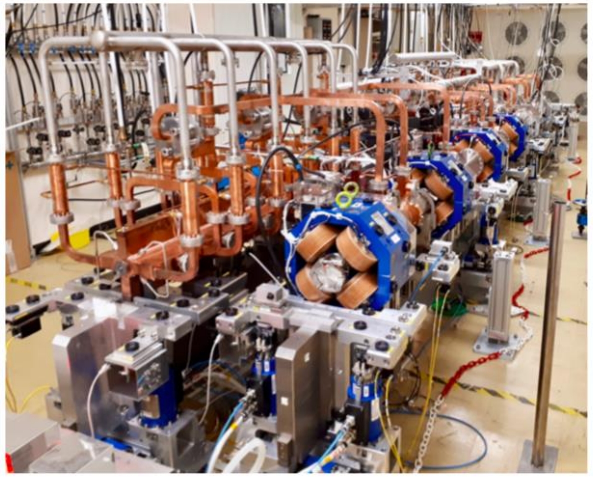
Sources and Injectors

The Klystron and Drive-Beam Modules

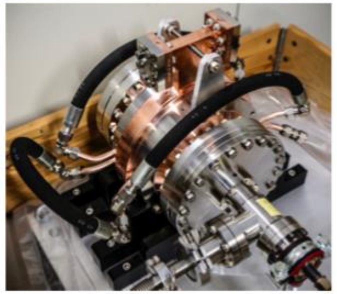


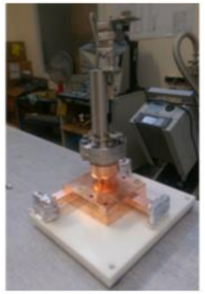


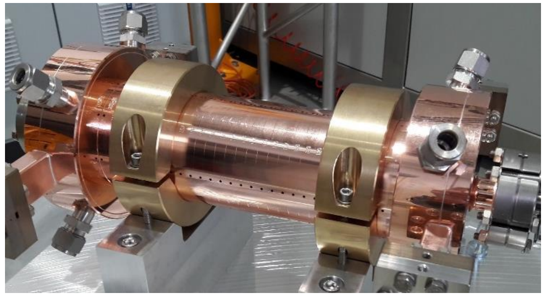




Technical developments - II



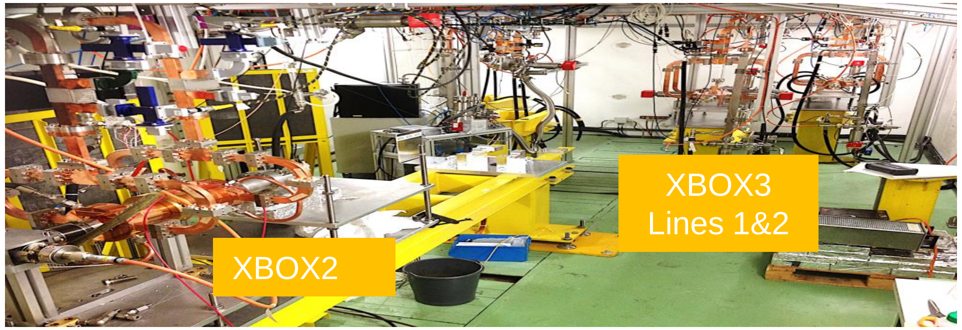


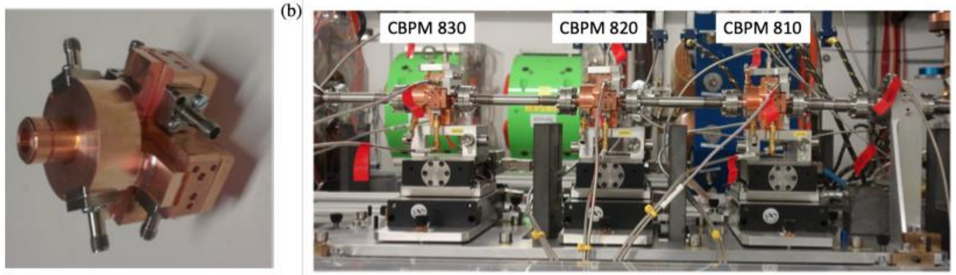
Pulse Compression System for the Klystron-Based Option

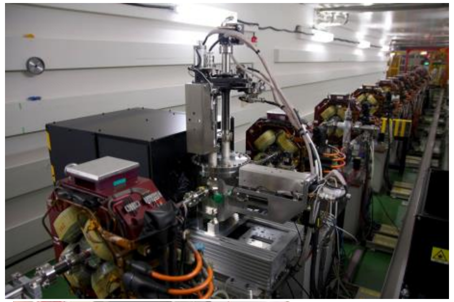
Klystrons and Modulators

PETS and Accelerating Structures




Technical developments - III

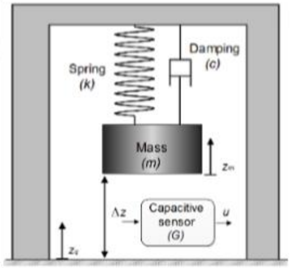


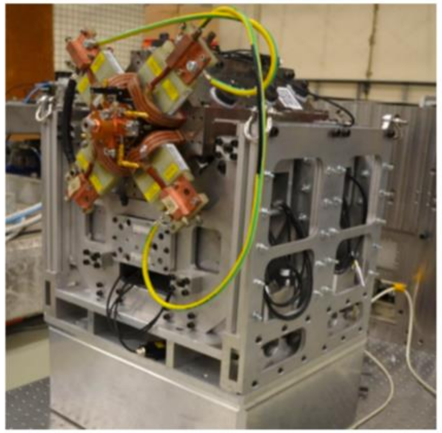


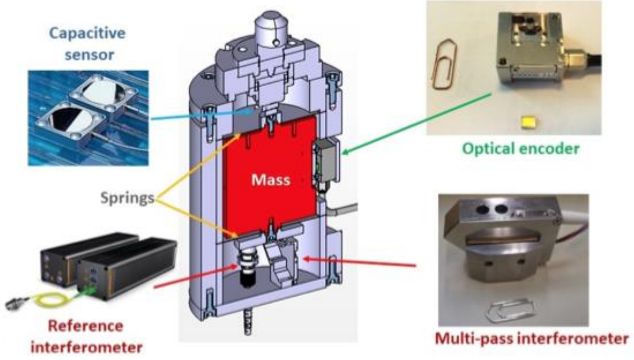
Beam Instrumentation

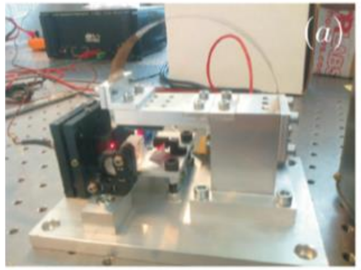
Survey and Alignment
Ground Motion
Stabilisation

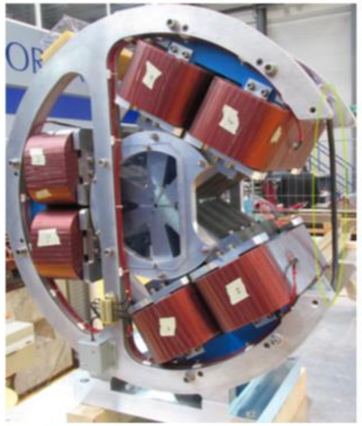
Normal Conducting Electro-Magnets and Permanent Magnets

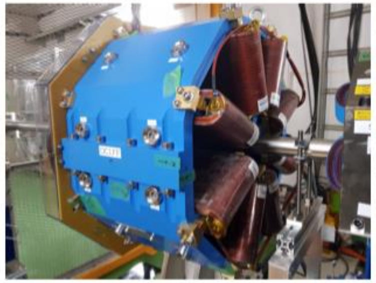


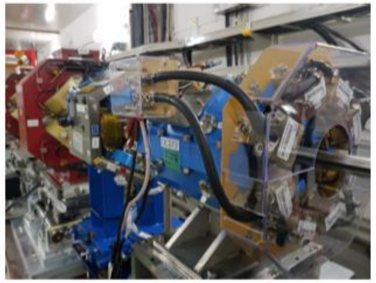






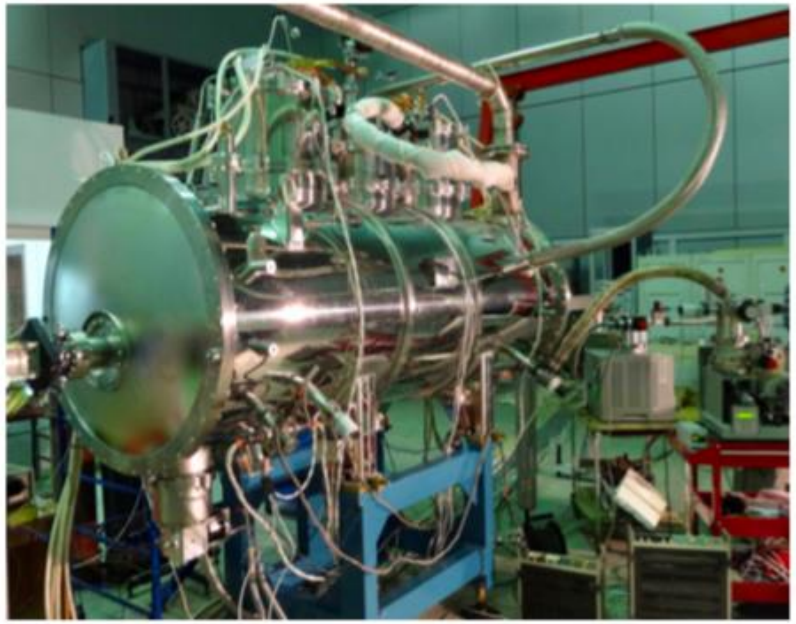


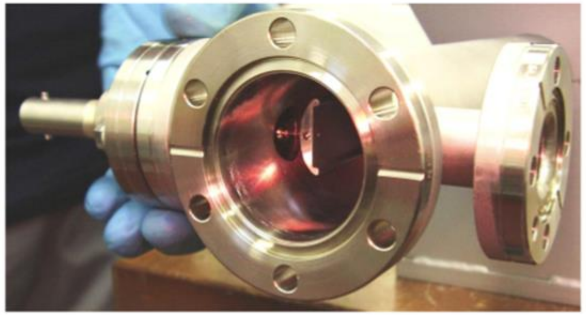




Technical developments - IV

Super-Conducting Damping Wiggler
Vacuum
Beam transfer
Controls
Fine Time Generation and Distribution
Machine Protection
Beam Interception Devices



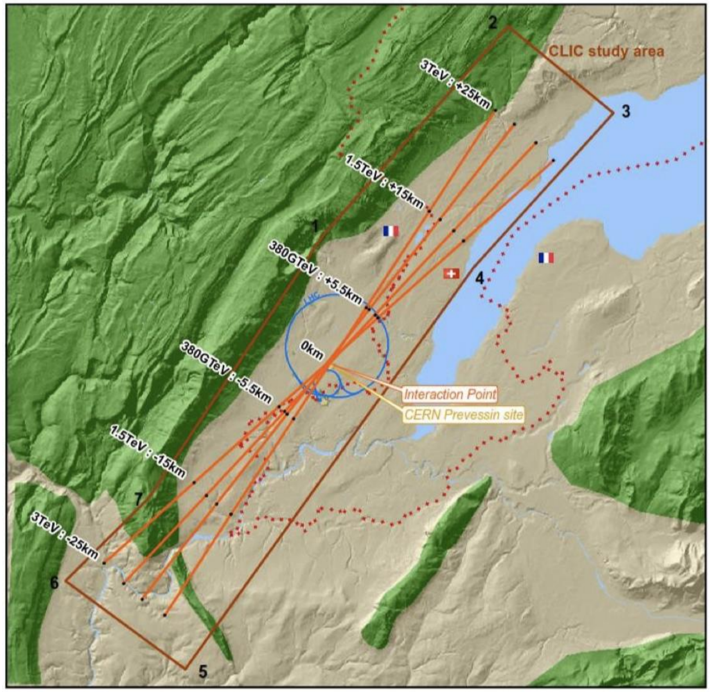


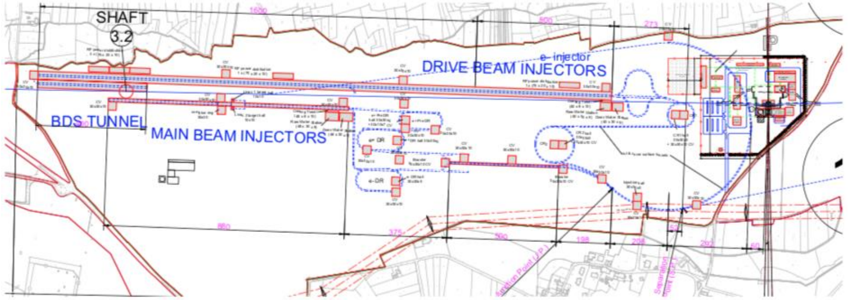
Civil Engineering and Infrastructure Studies

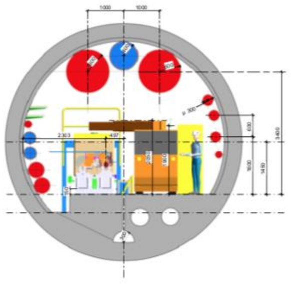
Important effort within:

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

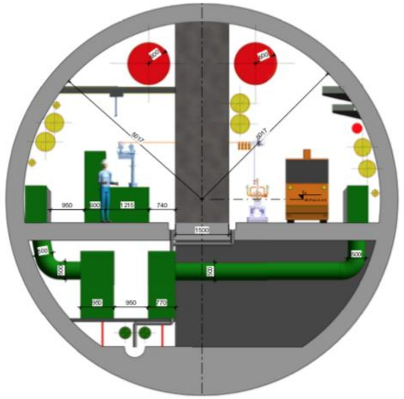
Crucial for cost/power/schedule







(a)



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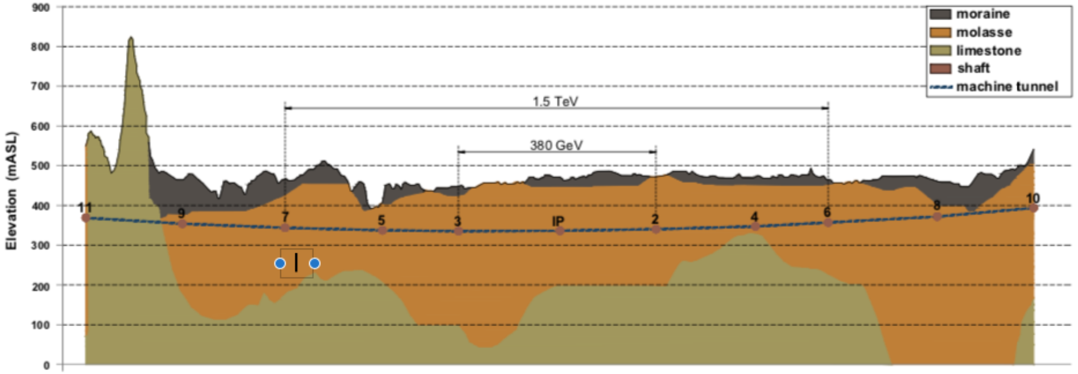
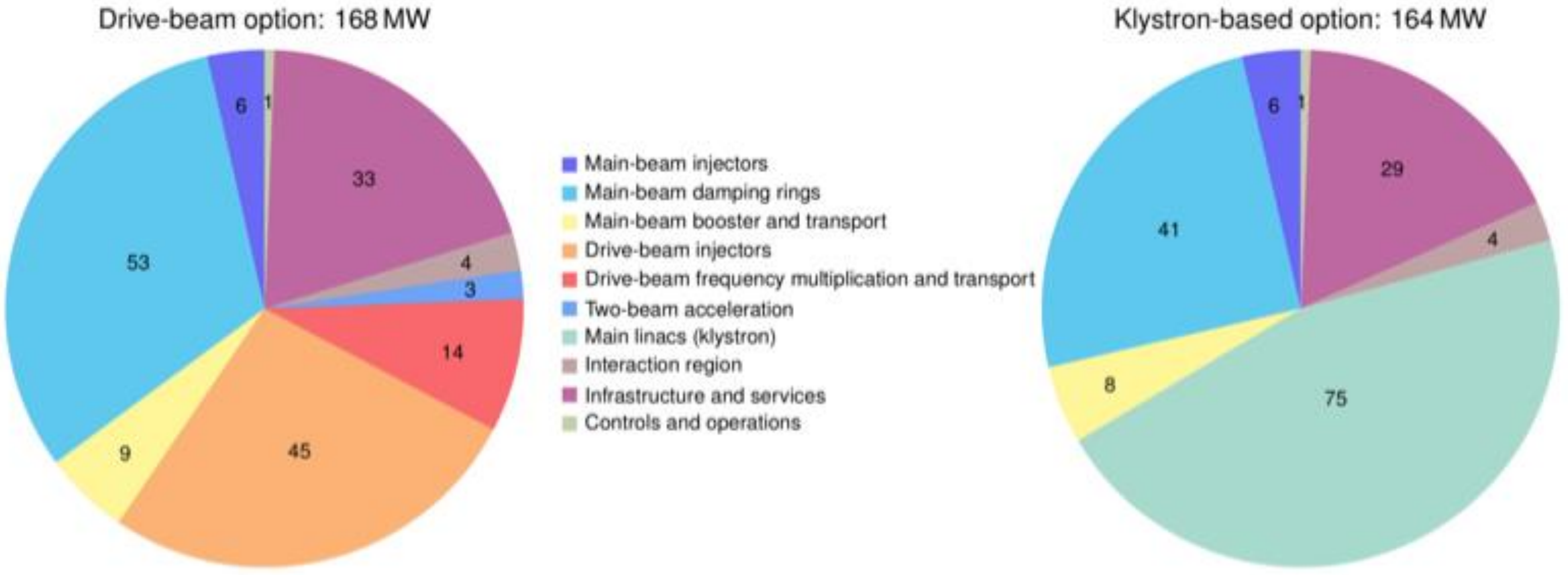


Power

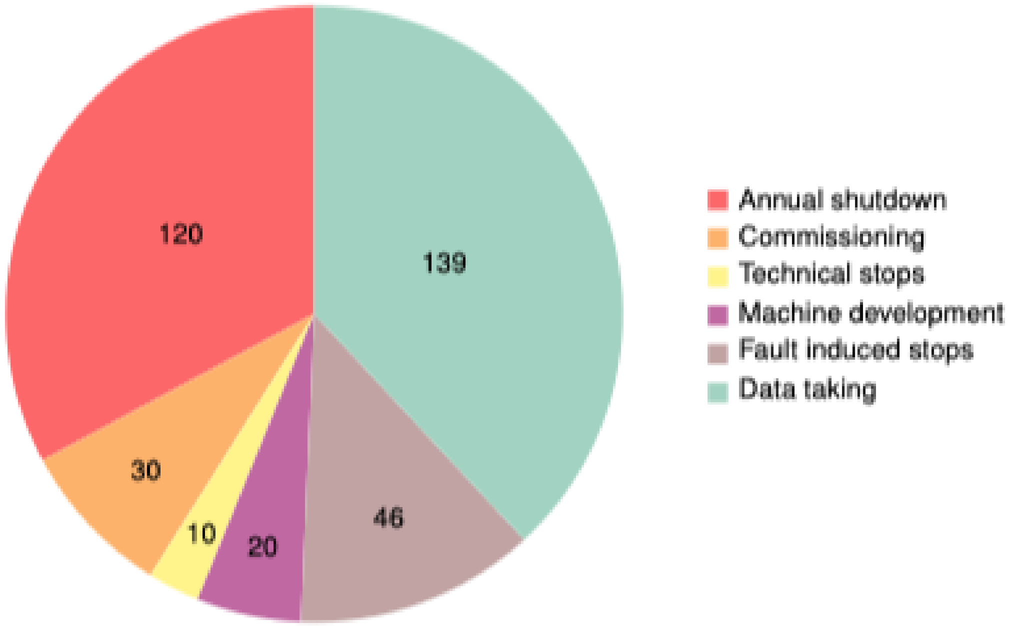


Power estimate bottom up (concentrating on 380 GeV systems)

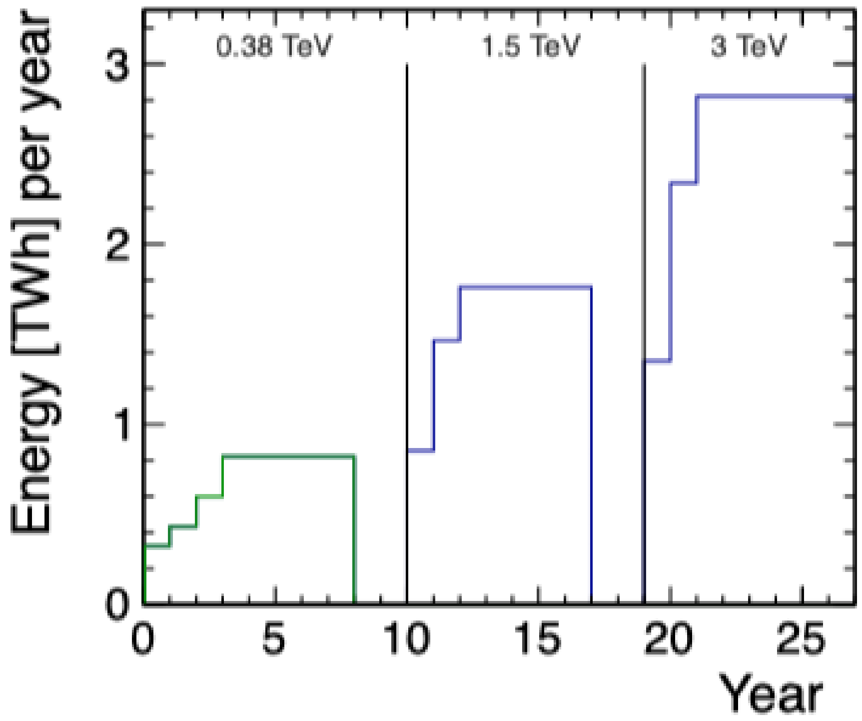
- Very large reductions since CDR, better estimates of nominal settings, much more optimised drivebeam complex and more efficient klystrons, injectors more optimisation, etc

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

Energy



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



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

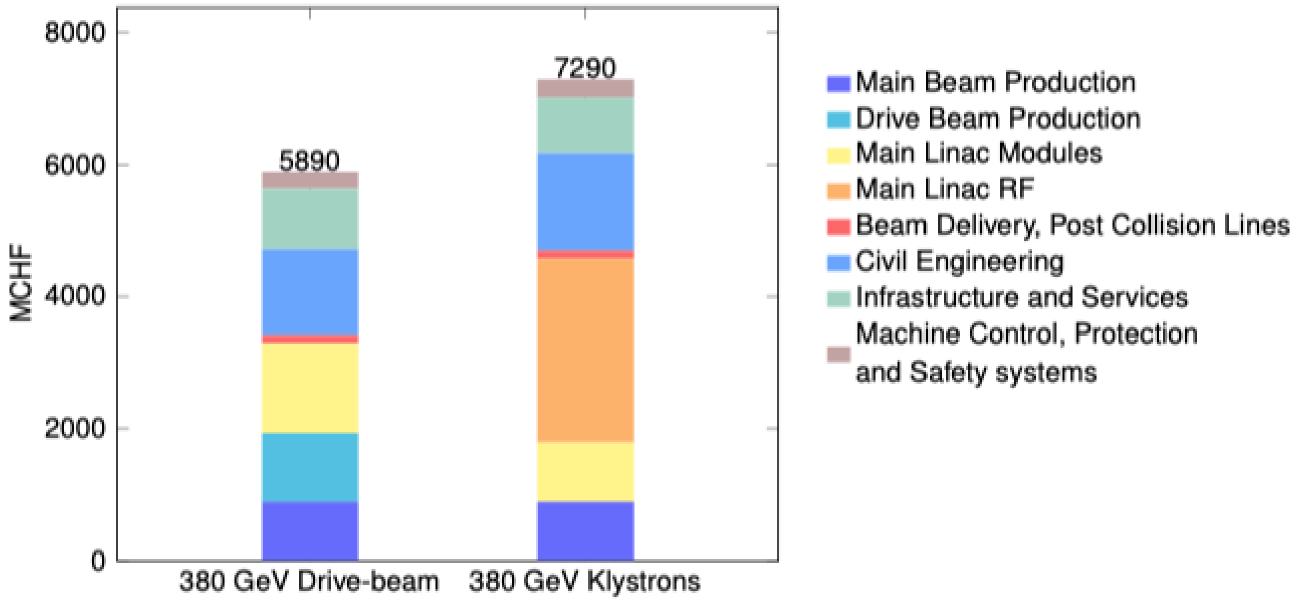
CERN is currently consuming ~1.2 TWh yearly (~90% in accelerators)

~

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

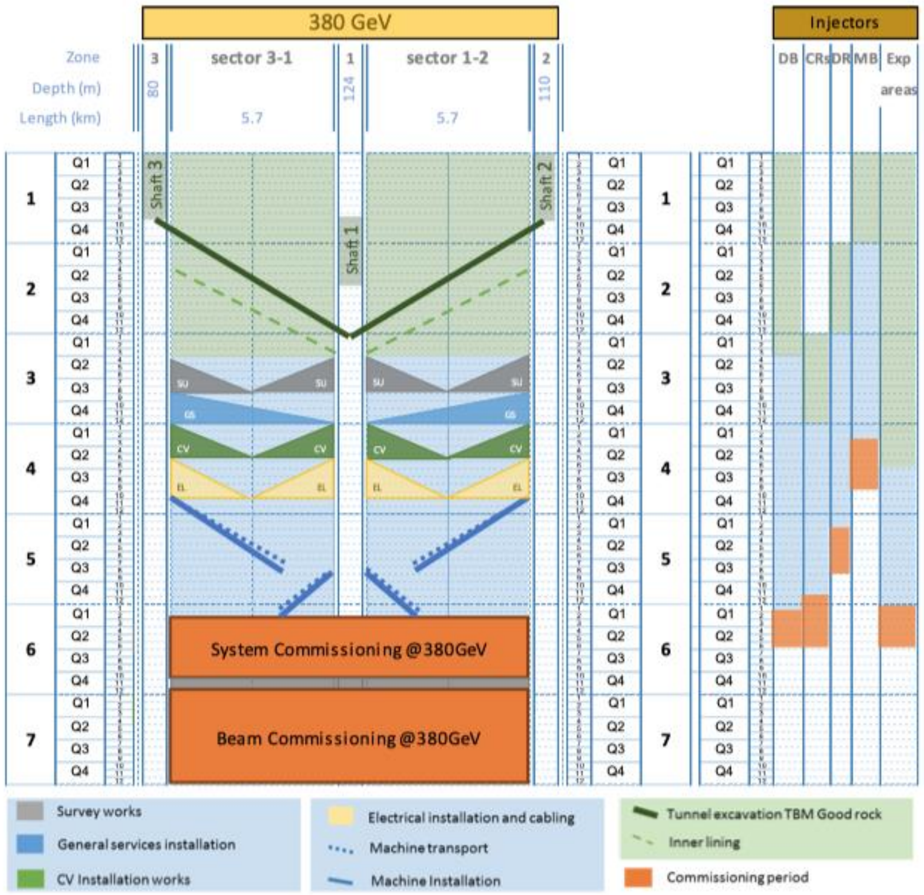
Operation:
- 116 MCHF (see assumptions in box below)
- Energy costs

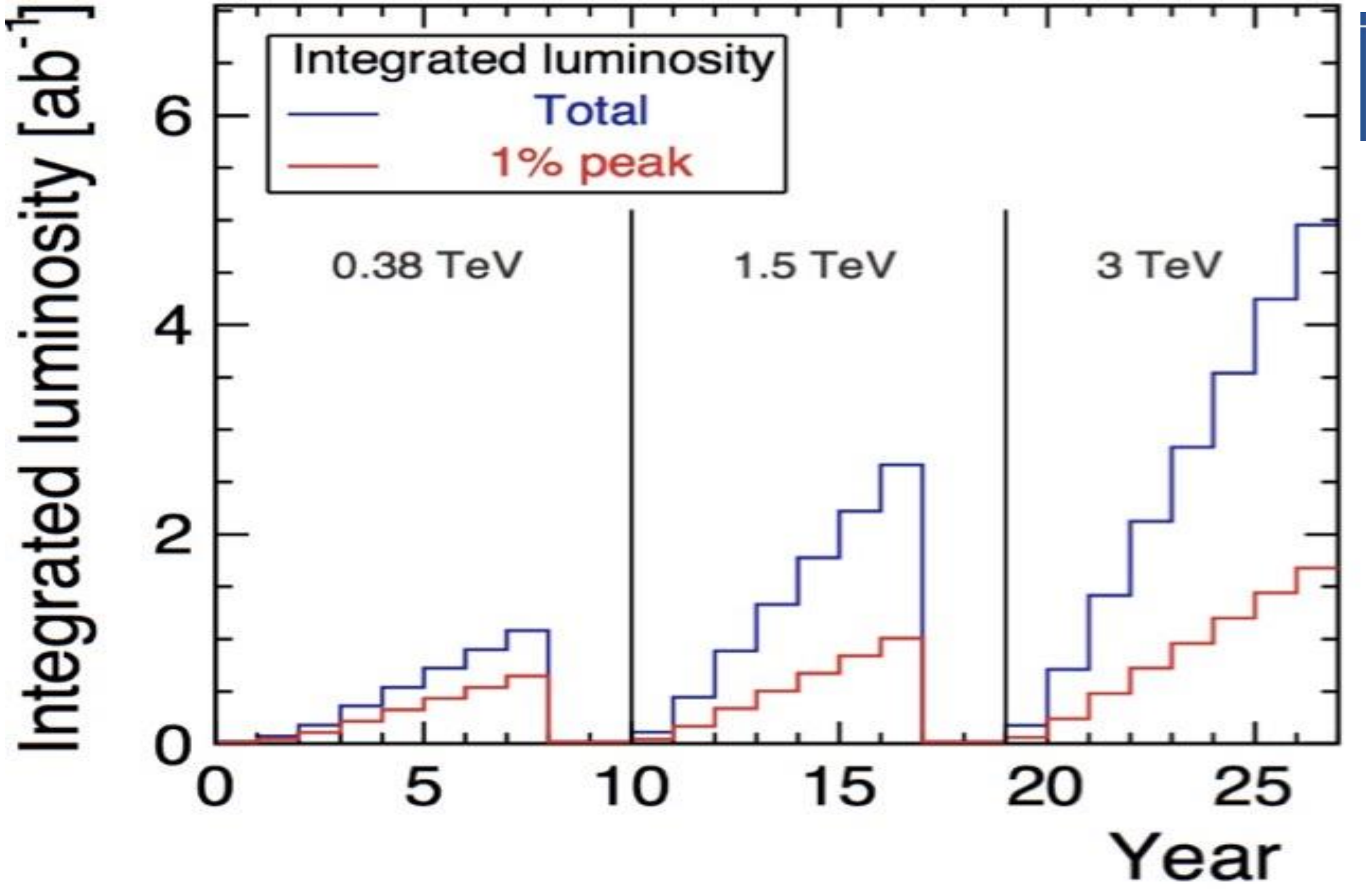
- 1% for accelerator hardware parts (e.g. modules).
- 3% for the RF systems, taking the limited lifetime of these parts into account.
- 5% for cooling, ventilation and electrical infrastructures etc. (includes contract labour and consumables)

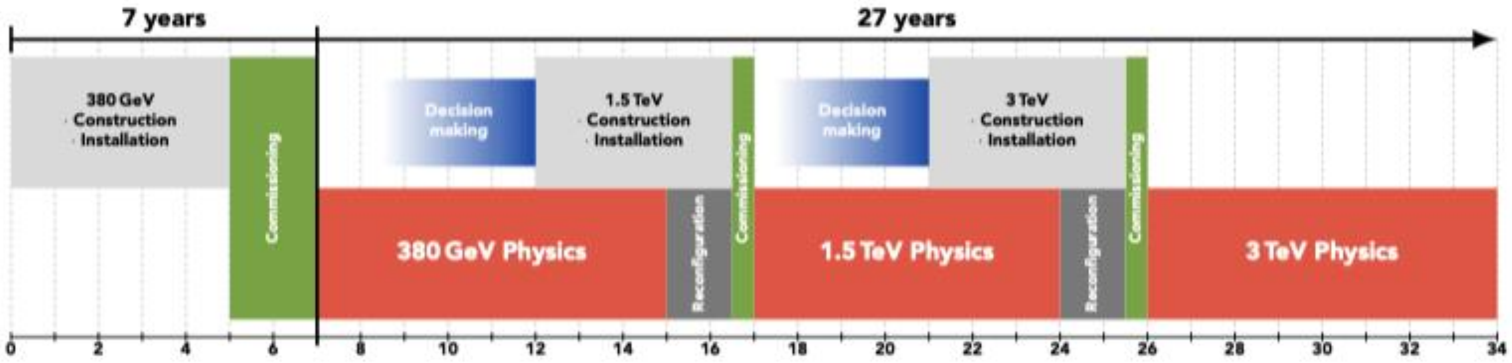
These replacement/operation costs represent 116 MCHF per year.

Schedule

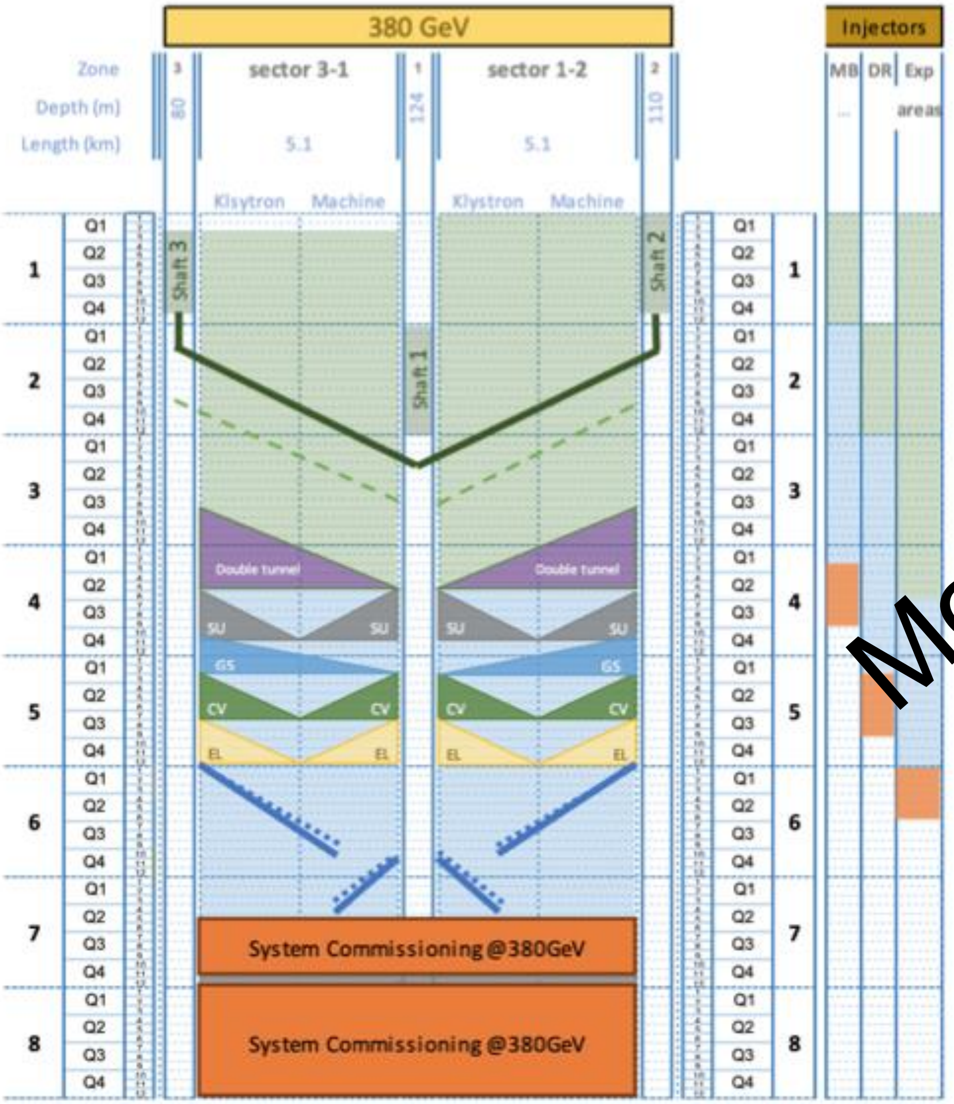
Updated schedule:
Construction + commissioning for 380 GeV: 7 yr
Full physics programme 27 yr



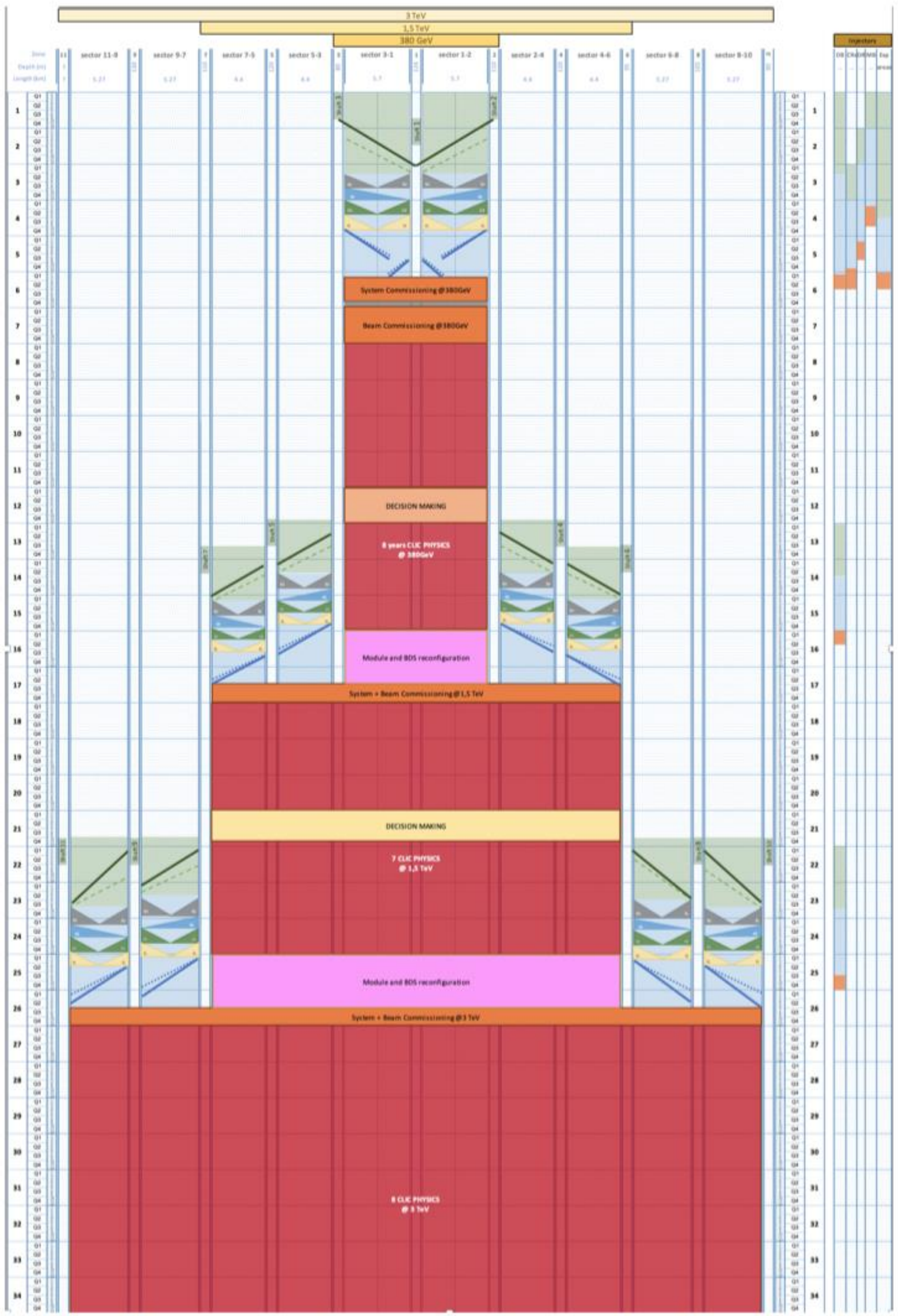




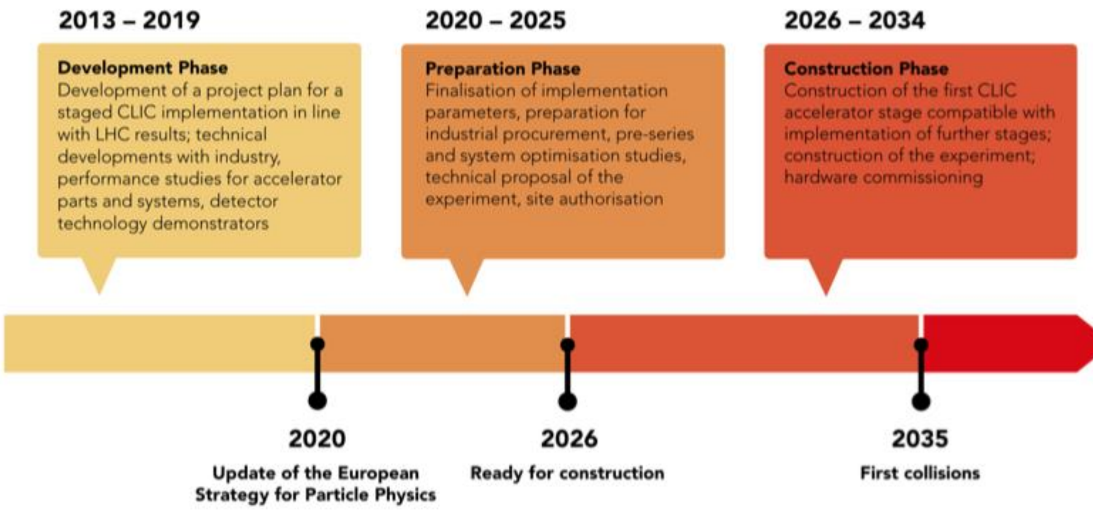
Klystron and overall schedules



More details



Next phase



Activities	Purpose
Design and parameters	
Beam dynamics studies, parameter optimisation, cost, power, system verifications in linacs and low emittance rings	Luminosity performance and reduction of risk, cost and power
Main Linac modules	
Construction of 10 prototype modules in qualified industries, Two-Beam and klystron versions, optimised design of the modules with their supporting infrastructure in the Main-Linac tunnel	Final technical design, qualification of industrial partners, production models, performance verification
Accelerating structures	
Production of ~ 50 accelerating structures, including structures for the modules above	Industrialisation, manufacturing and cost optimisation, conditioning studies in test-stands
Operating X-band test-stands, high efficiency RF studies	
Operation of X-band RF test-stands at CERN and in collaborating institutes for structure and component optimisation, further development of cost-optimised high efficiency klystrons	Building experience and capacity for X-band components and structure testing, validation and optimisation of these components, cost reduction and increased industrial availability of high efficiency RF units
Other technical components	
Magnets, instrumentation, alignment, stability, vacuum	Luminosity performance, costs and power, industrialisation
Drive beam studies	
Drive beam front end optimisation and system tests to $\sim 20\,\mathrm{MeV}$	Verification of the most critical parts of the drive beam concept, further development of industrial capabilities for L-band RF systems
Civil Engineering, siting, infrastructure	
Detailed site specific technical designs, site preparation, environmental impact study and corresponding procedures in preparation for construction	Preparation for civil engineering works, obtaining all needed permits, preparation of technical documentation, tenders and commercial documents

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

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 (see next talks)
- The detector concept and detector technologies R&D are advanced (also next talks)
- 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 project implementation plan documents, from which this material is drawn