



CLIC Accelerator Project: status and plans

Philip Burrows

*John Adams Institute, Oxford University
and CERN*

*On behalf of the CLIC Collaborations
Thanks to all colleagues for materials*

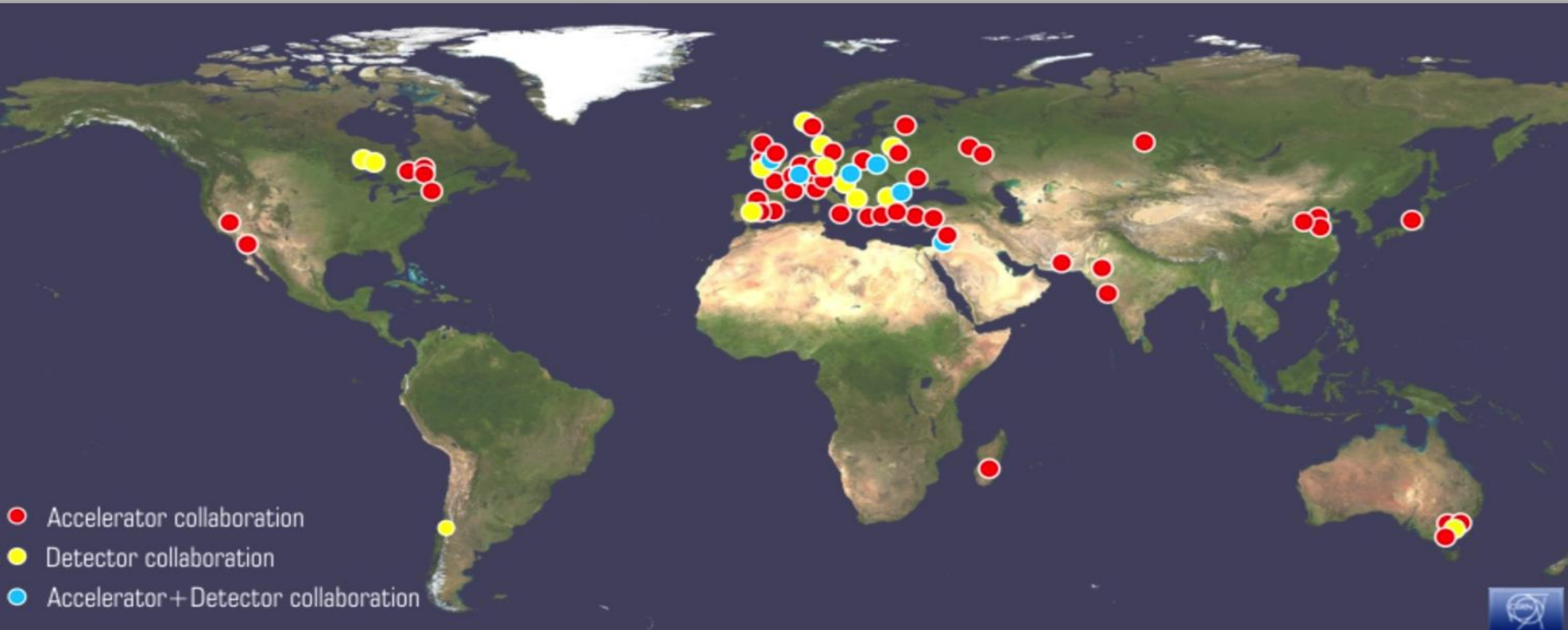


CLIC Collaborations

<http://clic.cern/>

CLIC accelerator collaboration
53 institutes from 31 countries

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





CLIC workshop January 2019



215 participants



Outline

- **Reminder of inputs to European Strategy Update**
- **Brief overview of CLIC**
- **Project staging + updated run model**
- **Power**
- **Cost**
- **Schedule**
- **Next steps**

Apologies for skipping many results + details



CLIC European Strategy Inputs



The Compact Linear e⁺e⁻ Collider (CLIC): Accelerator and Detector

Input to the European Particle Physics Strategy Update on behalf of the CLIC and CLICdp Collaborations

18 December 2018

Christophe J. Roth^{1,2}

Editors: P. N. Burrows^{3,4}, N. Capdevila Cabré^{5,6}, L. Jones⁷, M. Pospelov⁸, A. Sotnikov^{9,10}, J. Stenlund¹¹, S. Tashiro¹², A. Weiler¹³

¹CERN, Accelerator; ²University of Glasgow, United Kingdom; ³University of Oxford, United Kingdom

Abstract

The Compact Linear Collider (CLIC) is a 1.5 TeV multi-stage beam-driven linear e⁺e⁻ collider under development by international collaborations hosted by CERN. This document provides an overview of the design, technology and implementation status of the CLIC accelerator and the detector. For an optimal exploitation of its physics potential, CLIC is foreseen to be built and operated in stages, at centre-of-mass energies of 380 GeV, 1.5 TeV and 3 TeV, in a six-stage strategy between 1.5 km and 25 km. CLIC, as a two-beam acceleration scheme, is a high-current, high-luminosity, high-energy, high-precision machine, in which several outstanding high-priority LHC accelerator technologies are presented via a high-current driver based on the first stage, an alternating-field linear electron gun, in operation since 2010 and under development, and the single-bunch two-beam acceleration principle. CLIC might also demonstrate alternative, radical technologies, such as positronium and superconducting proton-injector stages. CLIC is a unique machine, which has led to an increased energy efficiency and reduced power consumption of around 70% for the 1.5 TeV stage, together with a reduced cost estimate of approximately 8 billion CHF. The detector concept, which matches the physics performance requirements and the CLIC operational conditions, has been studied using advanced software tools for simulation and reconstruction. Significant progress has been made on detector technology developments for the tracking and calorimetry systems. The construction of the final CLIC energy stage could start as early as 2026 and be completed by 2036. CLIC, as a linear collider, has the potential to address high-energy physics questions, which cannot be investigated by other machines, such as the LHC, and to provide unique insights into the Standard Model physics, through direct searches and via a broad set of precision measurements in Standard Model processes, particularly in the Higgs and top-quark sectors.



The Compact Linear e⁺e⁻ Collider (CLIC): Physics Potential

Input to the European Particle Physics Strategy Update on behalf of the CLIC and CLICdp Collaborations

18 December 2018

Christophe J. Roth^{1,2}

Editors: M. Franzoso^{3,4}, F. Roca⁵, J. Schwan⁶, A. Weiler⁷

¹CERN, Geneva, Switzerland; ²University of Bonn, Bonn, Germany; ³FNPI, Science of Future On-line, Bonn, Italy; ⁴University of Bonn, Bonn, Italy; ⁵CEP, EPFL, Lausanne, Switzerland

Abstract


The Compact Linear Collider (CLIC) is a proposed e⁺e⁻ collider at the 1.5 TeV scale whose physics potential originates from high-precision measurements in electron-positron annihilation at physics beyond the Standard Model. This document summarizes the physics potential of CLIC, centered in direct studies, using hard hadronic production of the CLIC detector. CLIC covers one order of magnitude of centre-of-mass energies from 380 GeV to 3 TeV, giving access to large cross-sections for a variety of NP processes, many of them for the first time in e⁺e⁻ collisions or for the first time at all. The high collision energy combined with the large luminosity enables the observation of the e⁺e⁻ annihilation through the measurement of the production of final state particles, such as the Higgs boson and the photon, with unprecedented precision. CLIC might also discover indirect effects of very heavy new physics by probing the parameters of the Standard Model Effective Field Theory with an unprecedented level of precision. The direct and indirect reach of CLIC is physics beyond the Standard Model significantly exceeds that of the LHC. This includes new particles allowed by challenging new candidate theories. With the physics programme CLIC will discover where our knowledge relating to the open questions of particle physics.




THE COMPACT LINEAR COLLIDER (CLIC) 2018 SUMMARY REPORT




CERN-2018-005-M




THE CLIC POTENTIAL FOR NEW PHYSICS




CERN-2018-009-M



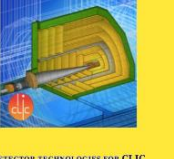
The Compact Linear Collider (CLIC) Project Implementation Plan



CERN-2018-010-M



DETECTOR TECHNOLOGIES FOR CLIC

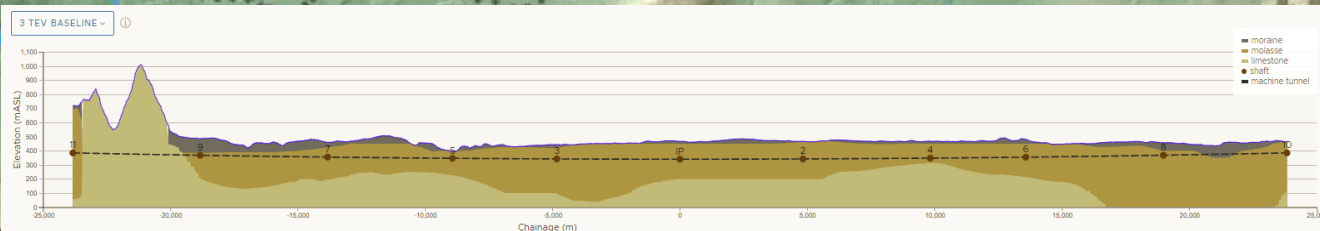
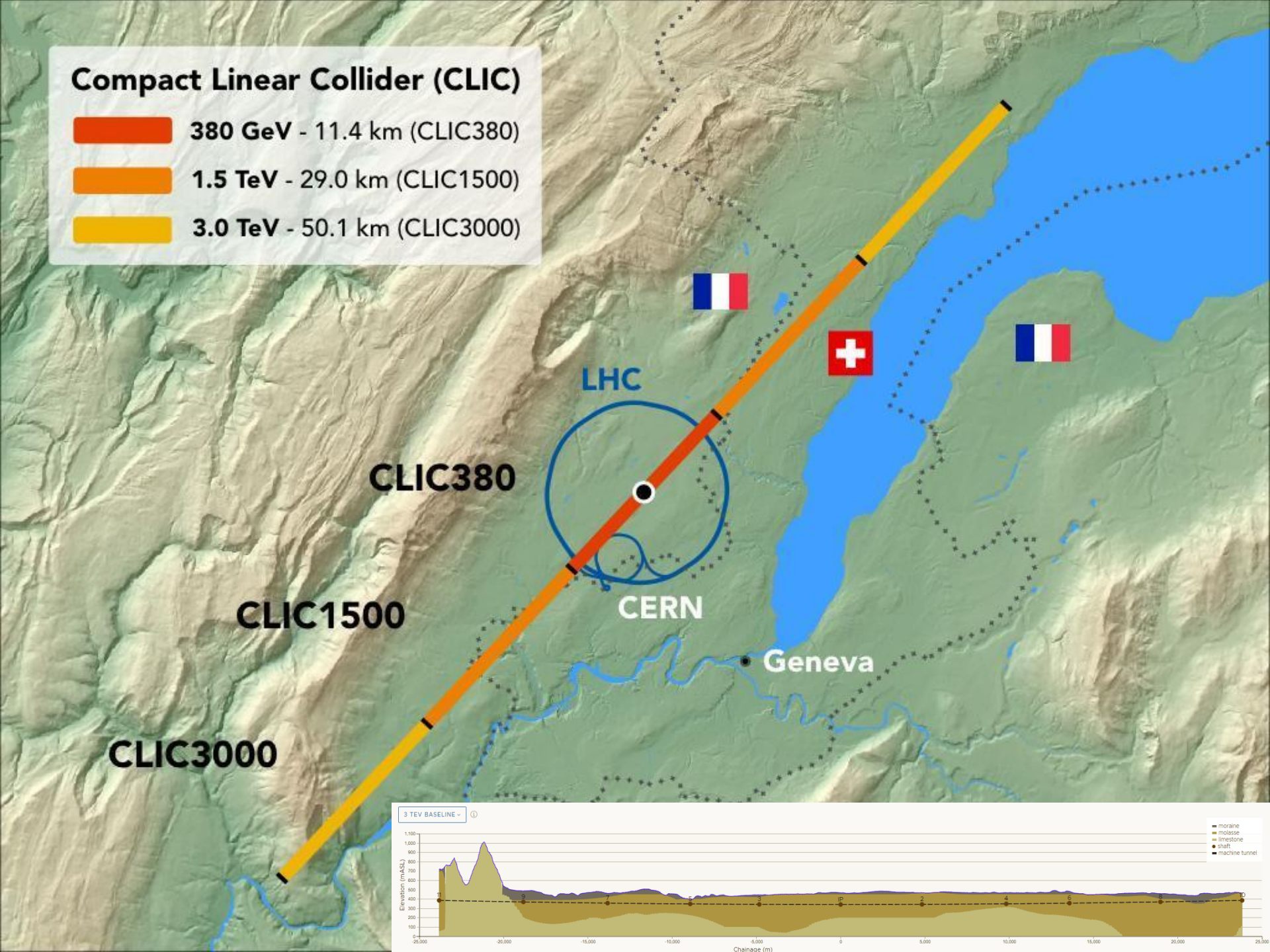


CERN-2019-001

<http://clic.cern/european-strategy>

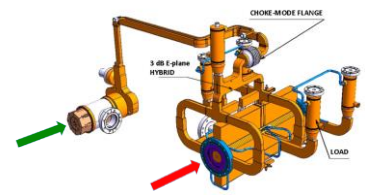
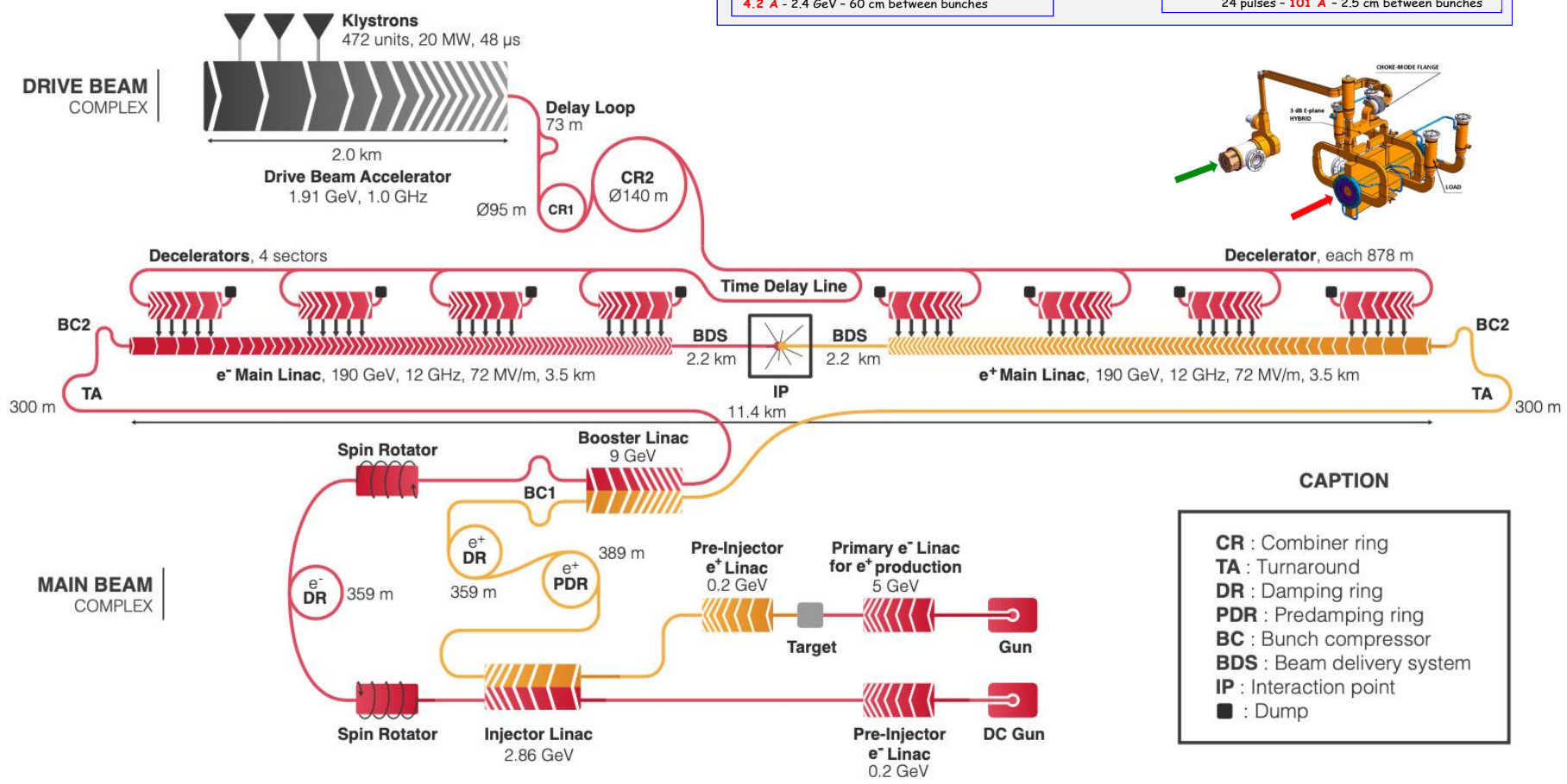
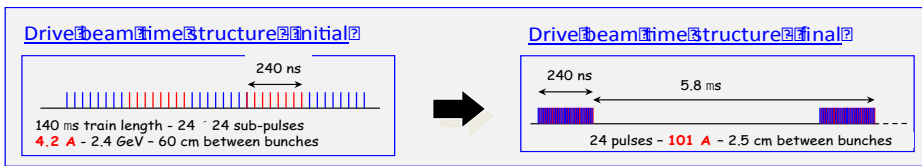
Compact Linear Collider (CLIC)

- 380 GeV - 11.4 km (CLIC380)**
- 1.5 TeV - 29.0 km (CLIC1500)**
- 3.0 TeV - 50.1 km (CLIC3000)**





CLIC 380 GeV layout

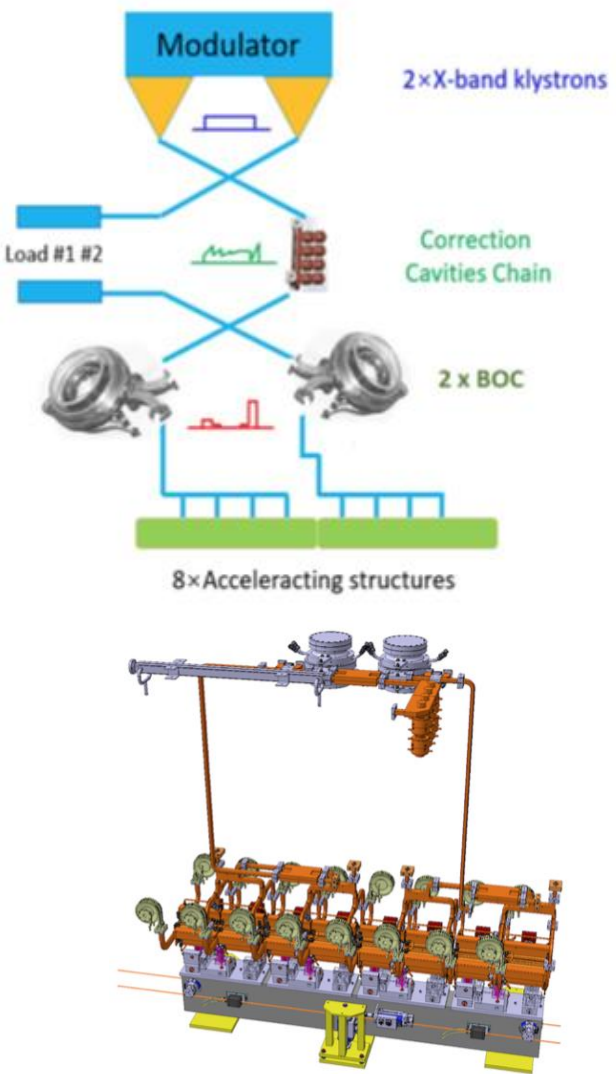


CAPTION

- CR : Combiner ring
- TA : Turnaround
- DR : Damping ring
- PDR : Predamping ring
- BC : Bunch compressor
- BDS : Beam delivery system
- IP : Interaction point
- : Dump

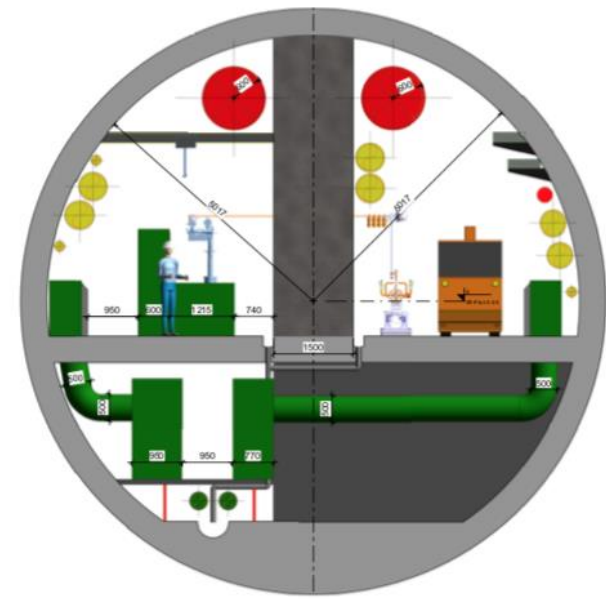
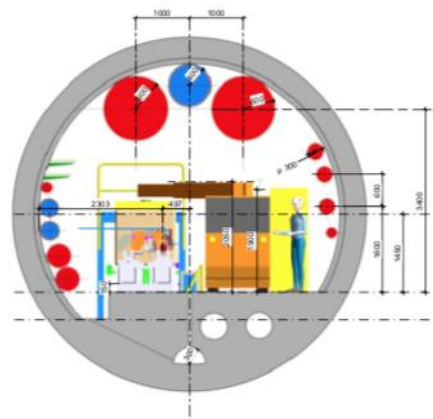
Baseline electron polarisation $\pm 80\%$

380 GeV klystron option



Replace drive-beam complex by local X-band RF power in tunnel

Simpler module, larger tunnel





X-band RF test infrastructure

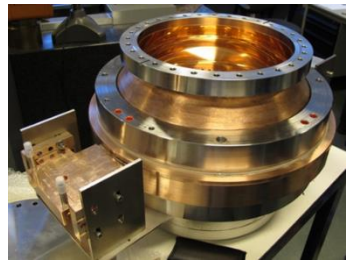
Modulator



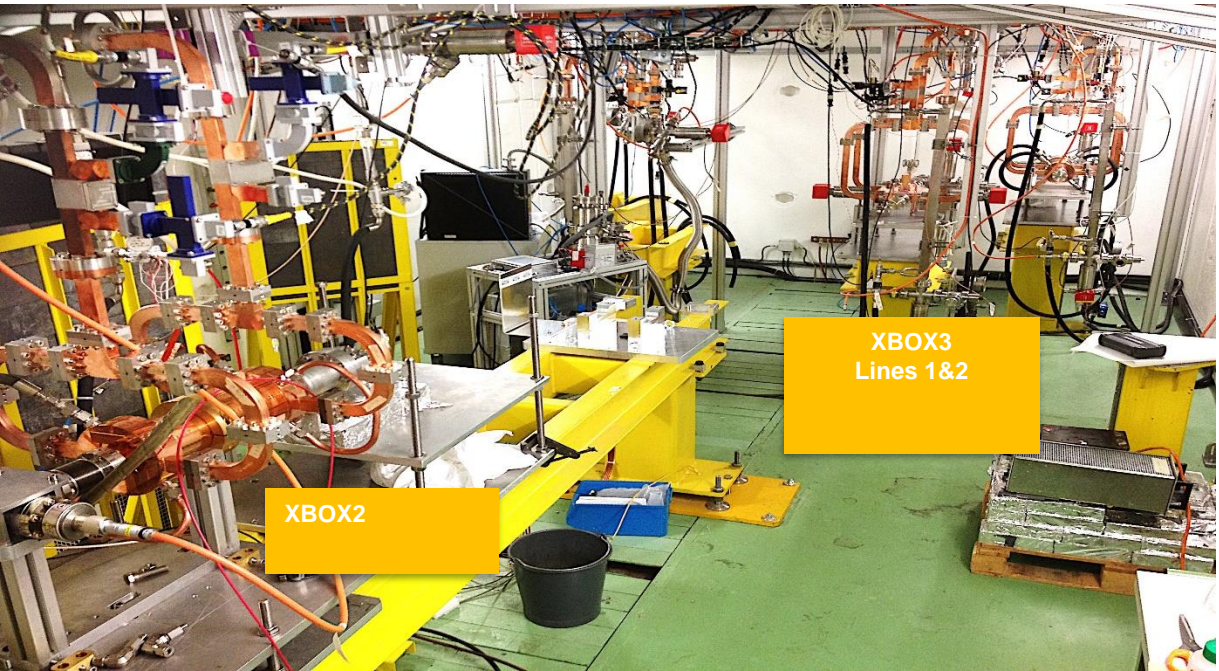
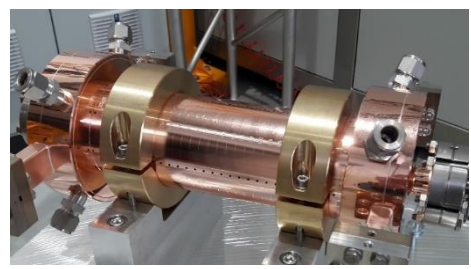
Klystron



Pulse compressor



Accelerating structures



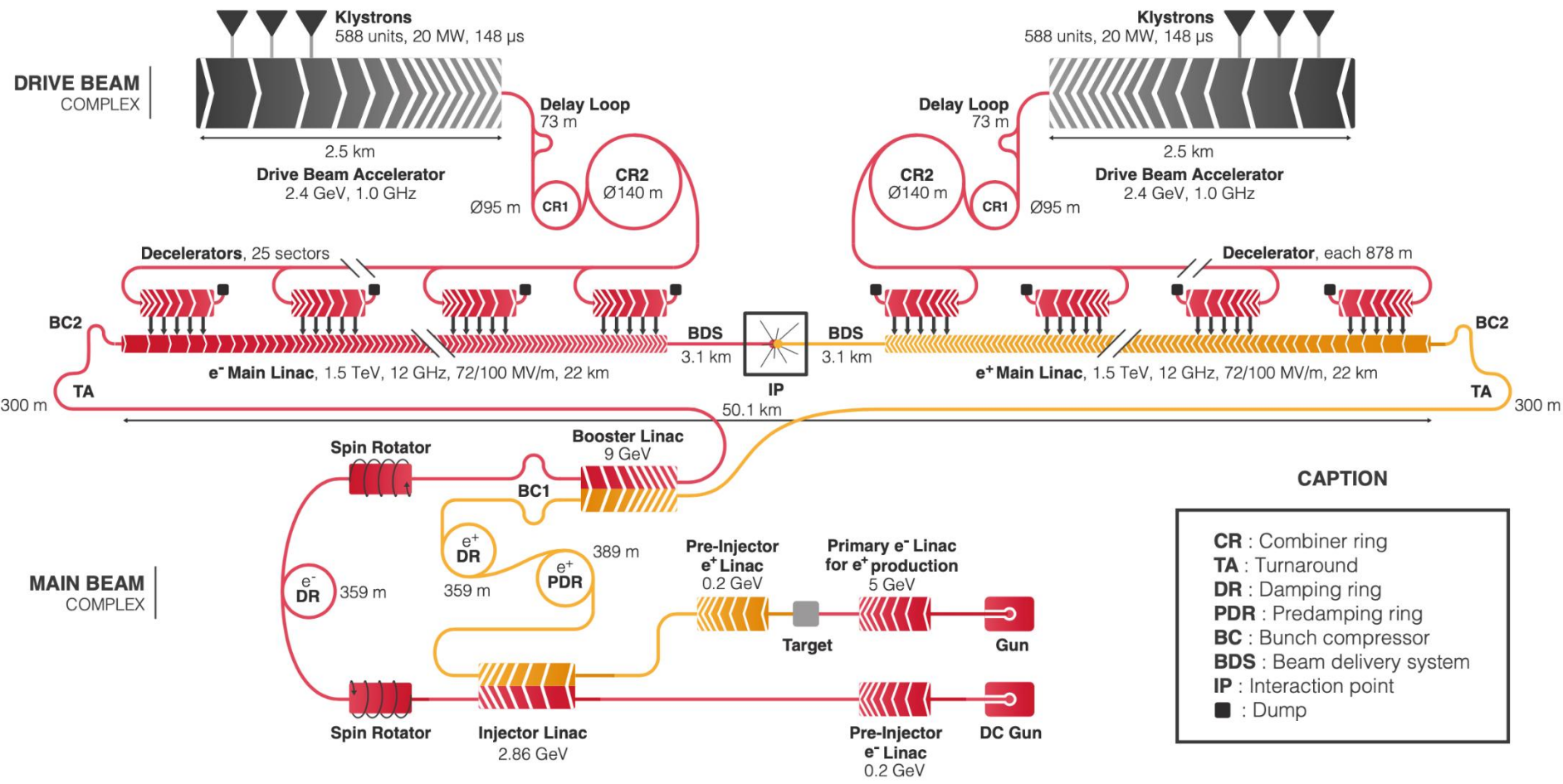
XBOX3
Lines 1&2

XBOX2

Assembled X-band systems in continuous operation at CERN



CLIC 3 TeV layout



CAPTION

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	\mathcal{L}	$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$	1.5	3.7	5.9
Luminosity above 99% of \sqrt{s}	$\mathcal{L}_{0.01}$	$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$	0.9	1.4	2
Total integrated luminosity per year	\mathcal{L}_{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 detector

Mature CLICdet detector model; performance extensively validated:

Return Yoke

Iron return yoke with detectors for muon ID

Solenoidal Magnet

Superconducting magnet at 4 Tesla

Fine-grained Calorimeters

Electromagnetic and hadronic calorimeters used for particle flow analysis

Tracking Detector

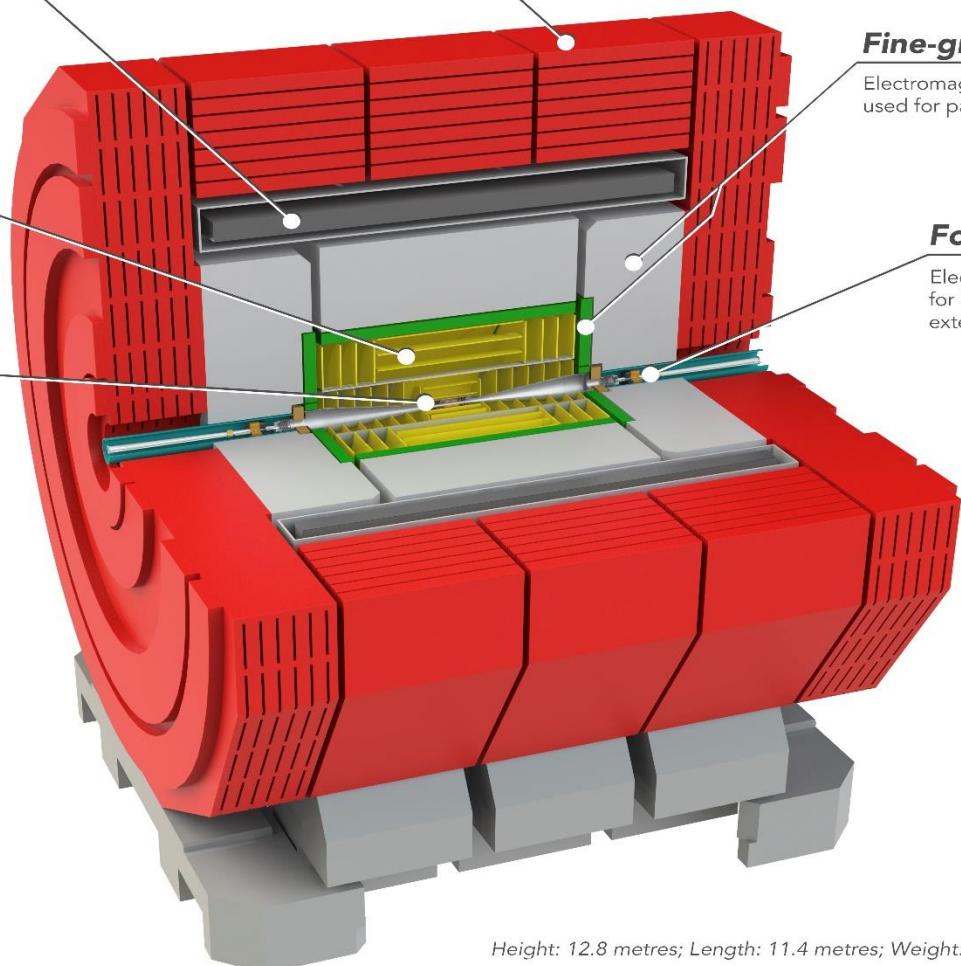
Silicon pixel detector, outer radius 1.5 metres

Forward Region

Electromagnetic calorimeters for luminosity measurement and extended angular coverage

Vertex Detector

Ultra-low mass silicon pixel detector, inner radius 31 millimetres

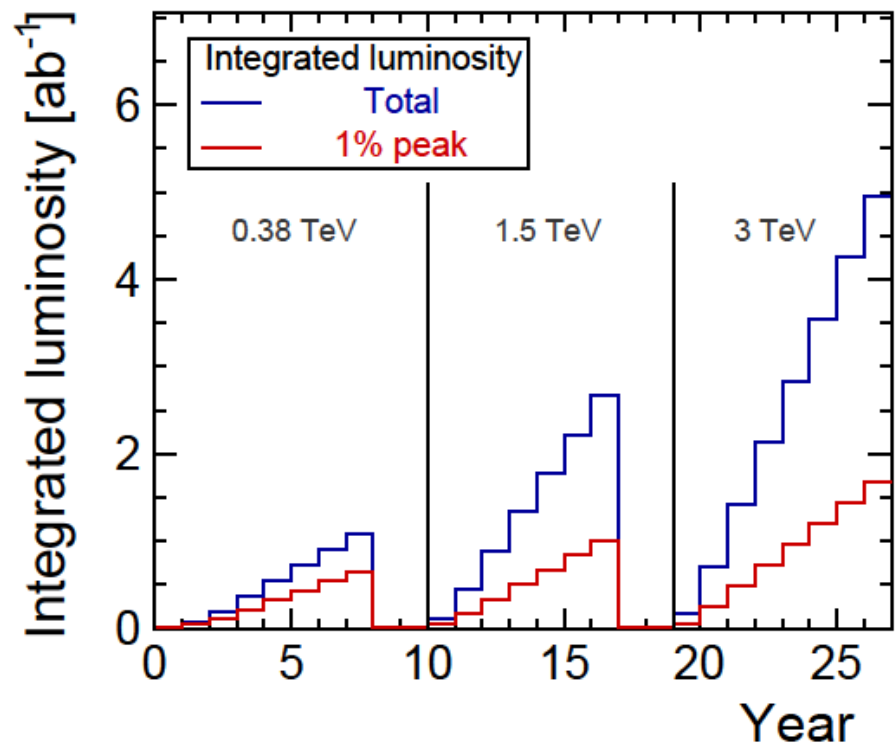


Tracking detector
Material: 1–2% X_0 / layer
Single-point resolution: 7 micrometres
Vertex detector
25 micrometre pixels
Material: 0.2% X_0 / layer
Single-point resolution: 3 micrometres
Forced air-flow cooling
Electromagnetic calorimeter
40 layers (silicon sensors, tungsten plates)
Material: 22 X_0 + 1 λ_i
Hadronic calorimeter
60 layers (plastic scintillators, steel plates)
Material: 7.5 λ_i



Height: 12.8 metres; Length: 11.4 metres; Weight: 8100 tonnes

Luminosity staging baseline



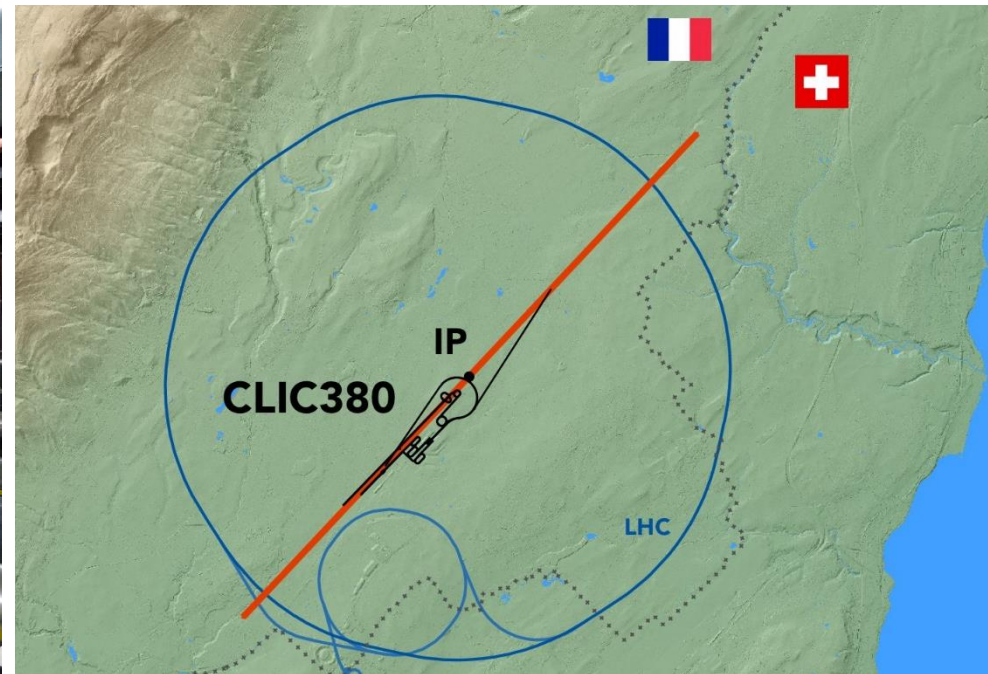
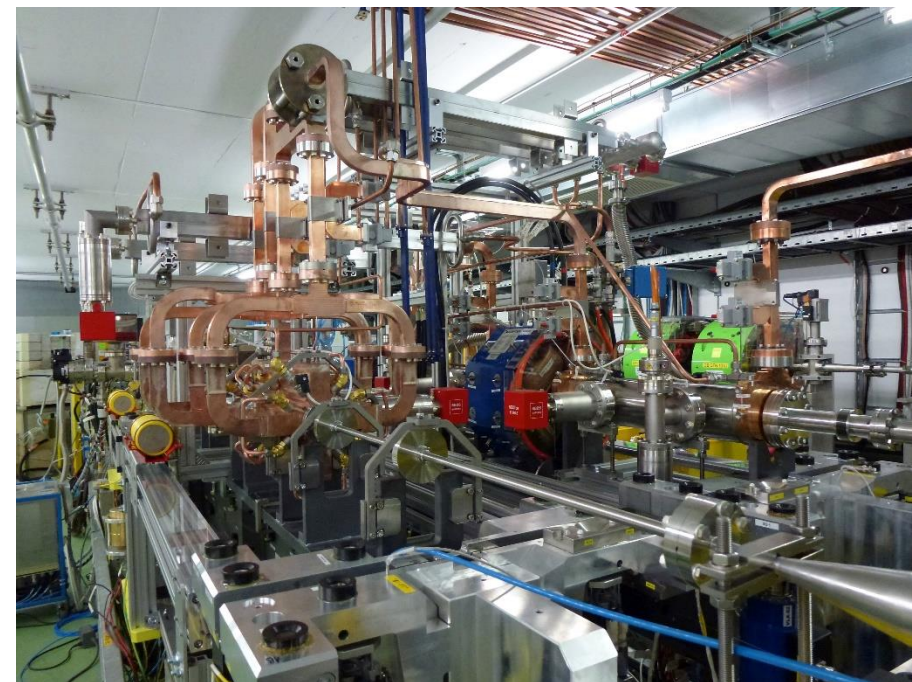
Stage	\sqrt{s} [TeV]	\mathcal{L}_{int} [ab ⁻¹]
1	0.38 (and 0.35)	1.0
2	1.5	2.5
3	3.0	5.0

Baseline polarisation scenario adopted:
 electron beam (−80%, +80%) polarised in ratio
 (50:50) at $\sqrt{s}=380\text{GeV}$; (80:20) at $\sqrt{s}=1.5$ 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](https://arxiv.org/abs/1810.13022), Bordry et al.

Status

Key technologies have been demonstrated
CLIC is now a mature project ready to move towards implementation
(see later for timeline)



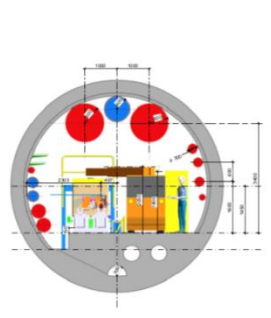
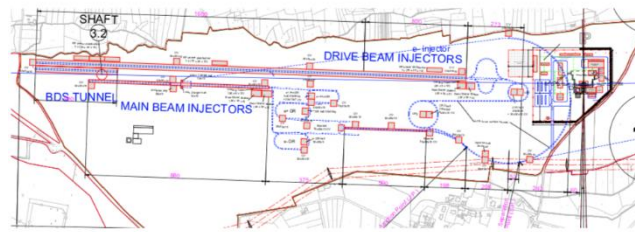
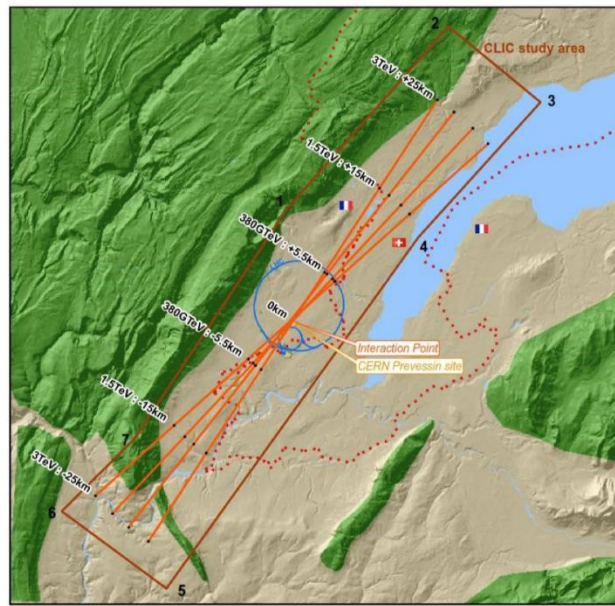


Civil Engineering and Infrastructure Studies

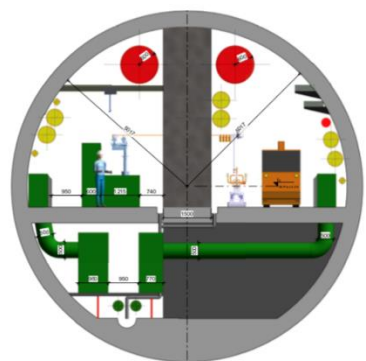
Important effort within:

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

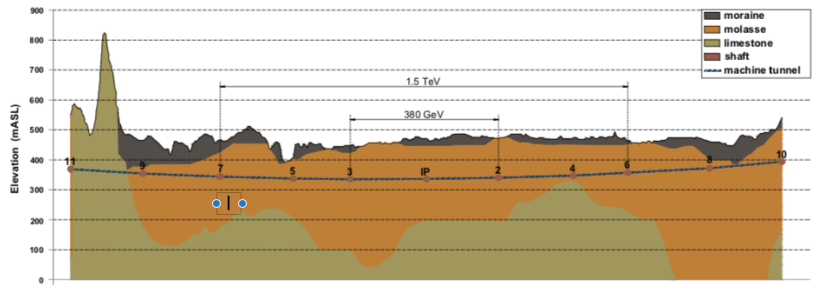
Crucial for cost/power/schedule



(a)



(b)

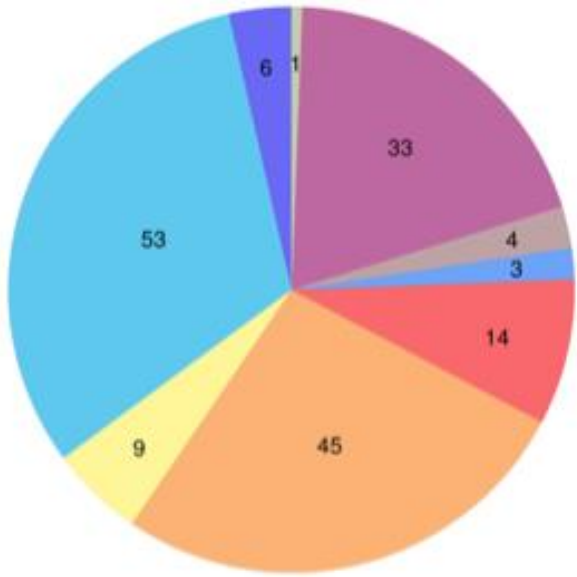


Power

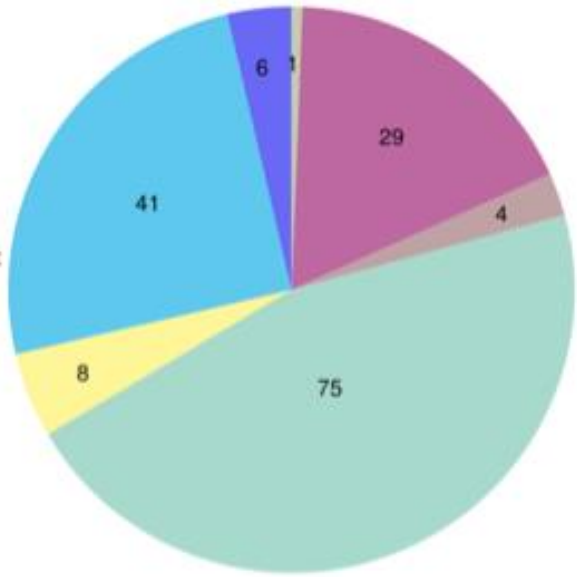
Power estimate bottom up (concentrating on 380 GeV systems)

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

Drive-beam option: 168 MW



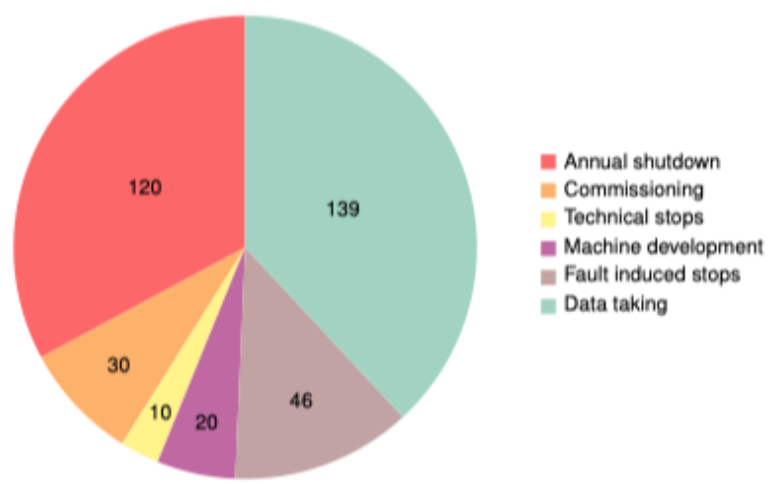
Klystron-based option: 164 MW



- Main-beam injectors
- Main-beam damping rings
- Main-beam booster and transport
- Drive-beam injectors
- Drive-beam frequency multiplication and transport
- Two-beam acceleration
- Main linacs (klystron)
- Interaction region
- Infrastructure and services
- Controls and operations

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

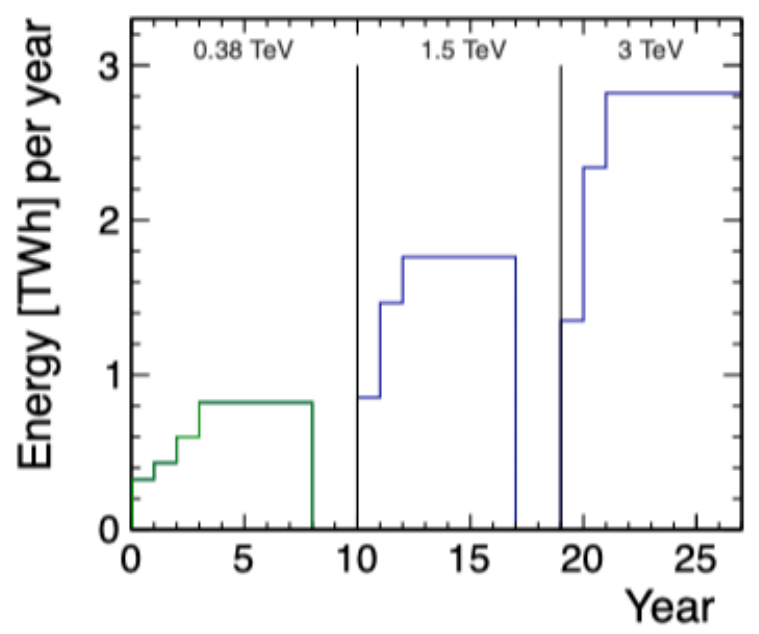
Energy



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)

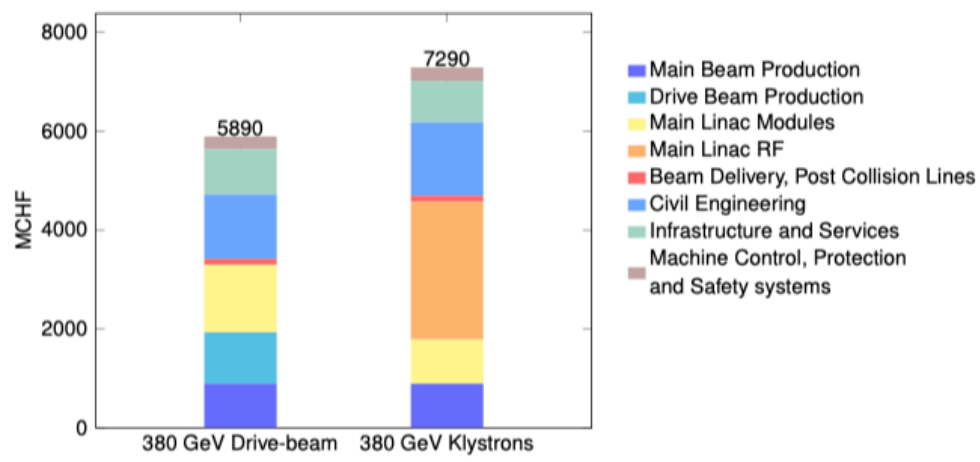




Cost – 380 GeV stage

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

- Methods and costings validated at review on 7 November 2018 – similar to LHC, ILC, CLIC CDR
- Technical uncertainty and commercial uncertainty estimated



Domain	Sub-Domain	Cost [MCHF]	
		Drive-Beam	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
	Electrical distribution	243	243
Infrastructure and Services	Survey and Alignment	194	147
	Cooling and ventilation	443	410
	Transport / installation	38	36
	Safety system	72	114
Machine Control, Protection and Safety systems	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;

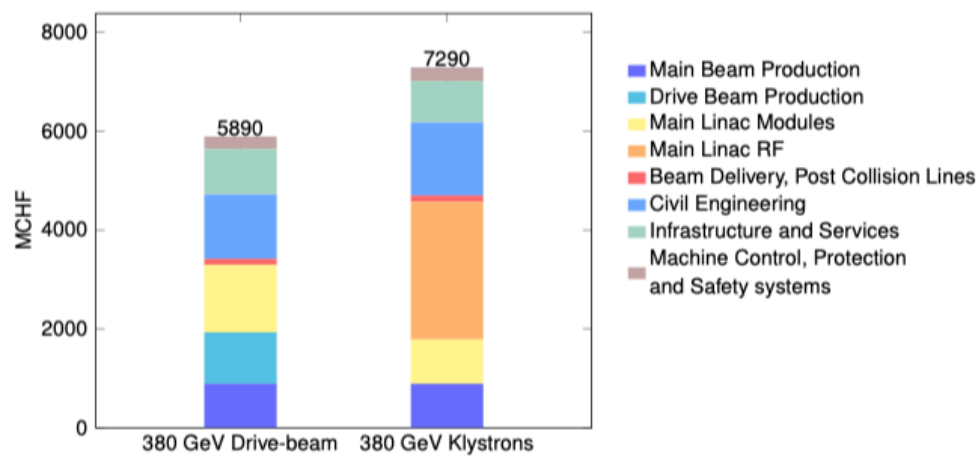
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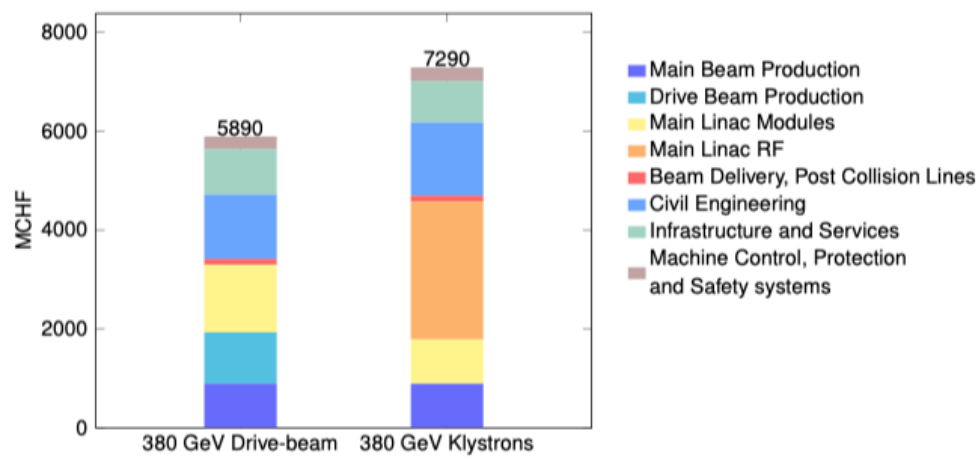
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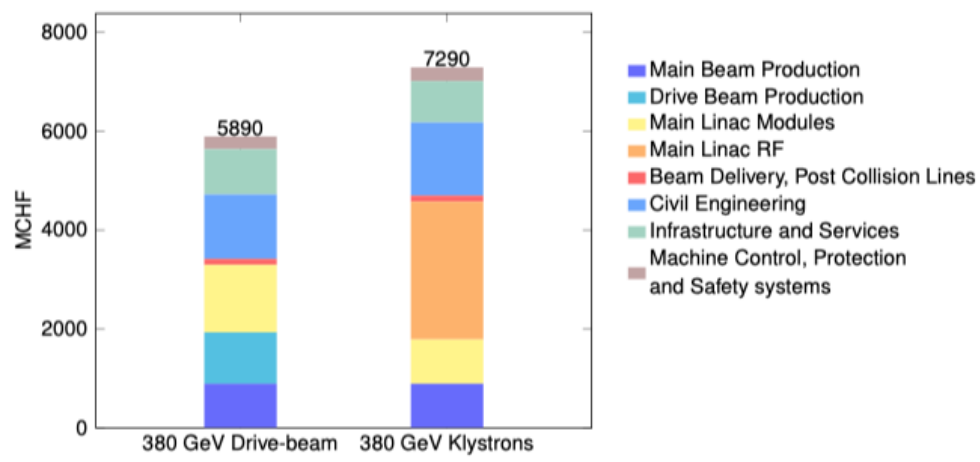
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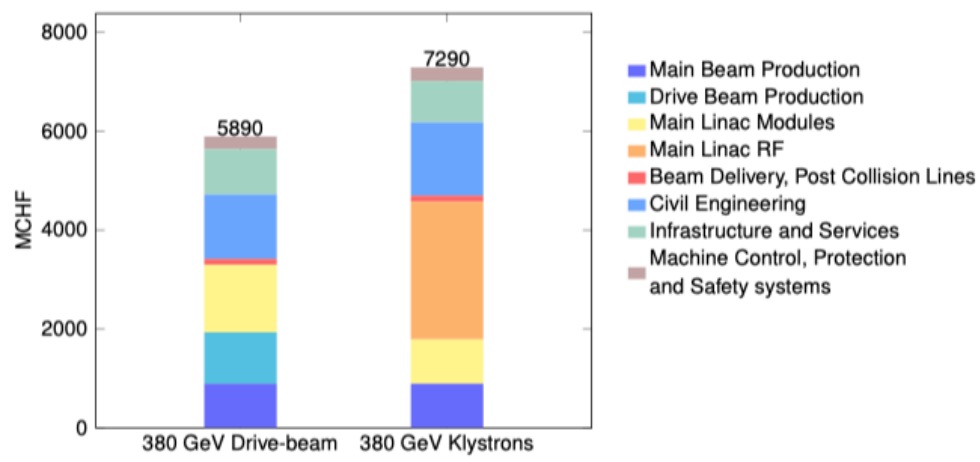
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CLIC 380 GeV Klystron based: 7290^{+1800}_{-1540} MCHF.



Costs - II

Other cost estimates:

Construction:

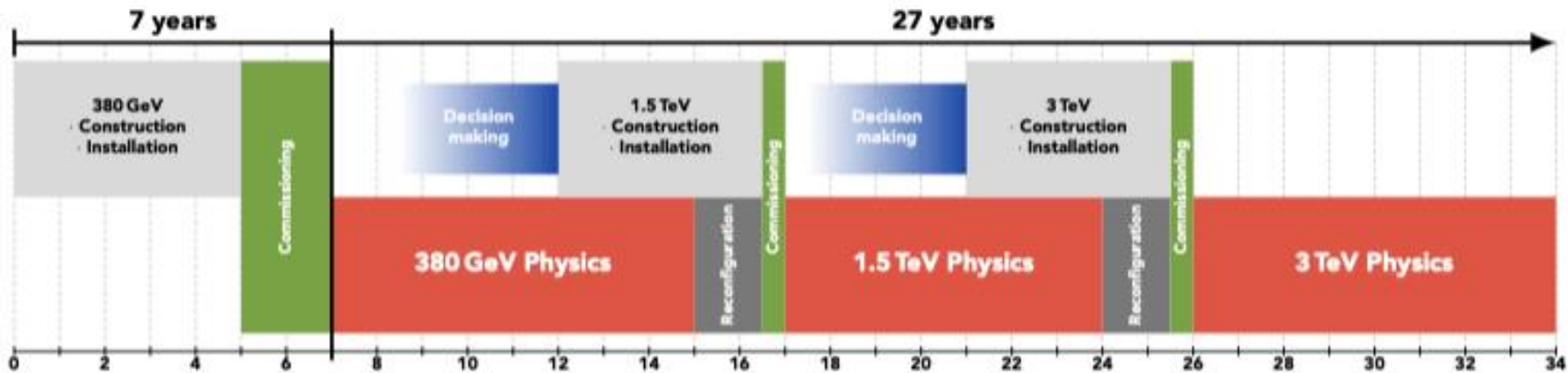
- From 380 GeV to 1.5 TeV, add 5.1 BCHF (drive-beam RF upgrade and lengthening of ML)
- From 1.5 TeV to 3 TeV, add 7.3 BCHF (second drive-beam complex and lengthening of ML)
- Labour estimate: ~11500 FTE for the 380 GeV construction

Operation:

- 116 MCHF (see 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



Construction + installation: 5 years
Commissioning: 2 years
380 GeV physics programme: 8 years
Additional energy stages: ...



Longer-term outlook

- **A LC infrastructure offers possibility to re-use tunnel/infrastructure, injectors, drive-beams, etc. for major energy upgrades with new technologies**
- **CLIC is laser-straight and with a “reasonable” crossing angle likely to be compatible with higher beam energies and the bunch separations needed for these technologies**
- **Working group for use of Novel Acceleration Technologies (NAT):
plasma wakefield, dielectrics ...**
- **The actual effective linac length might remain short (and hence possibly “cheap” and inter-changeable in a limited time)
→ long term perspective worth considering**
- **Short chapter in Project Implementation Plan**

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, pre-series and system optimisation studies, 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



2020

Update of the European Strategy for Particle Physics

2026

Ready for construction

2035

First collisions



Next phase 2020-25

Activities 2020-2025	Purpose
Design and parameters, final optimization and system verifications	Luminosity performance, risk, cost power reduction
Construction of pre-series of modules	Final technical design and industrial capabilities
Accelerator structures optimization and production of modules	Final design, industrial capabilities, conditioning
X-band test facilities inside and outside CERN	Needed for construction, further cost/power reduction
Final parameters and design of magnets, instrumentation, alignment, stability, vacuum systems	Luminosity performance, prepare for construction <i>tenders</i>
Drive beam front end optimization to ~20 MeV and system tests	Drivebeam most critical parts, production preparation
Detailed site design, impact studies, finalise infrastructure specifications	Final CE and infrastructure parameters, permits, tenders

X-band NCRF technology

Prototype components

Laboratory with commercial

- Accelerating structures
- pulse compressors
- alignment
- stabilization
- etc.

Full commercial supply

- X-band klystrons
- solid state modulators
- etc.

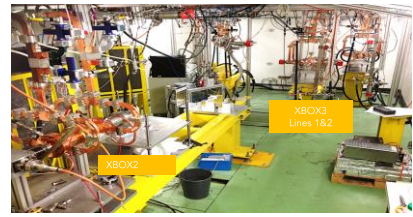
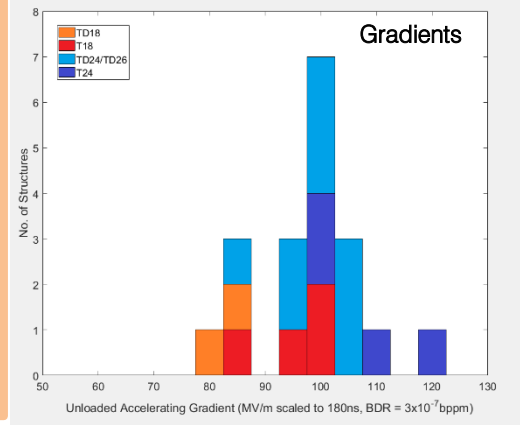
Normal-conducting, low-emittance GeV-range facilities

Operational

- SACLA
- SwissFEL

Systems and 100 MeV-range facilities

- XBoxes at CERN
- (NEXTF KEK)
- Test stand at Tsinghua
- Frascati
- NLCTA SLAC
- Linearizers at Electra, PSI, Shanghai and Daresbury
- Deflectors at SLAC, Shanghai, PSI and Trieste
- NLCTA
- Smart*Light
- FLASH



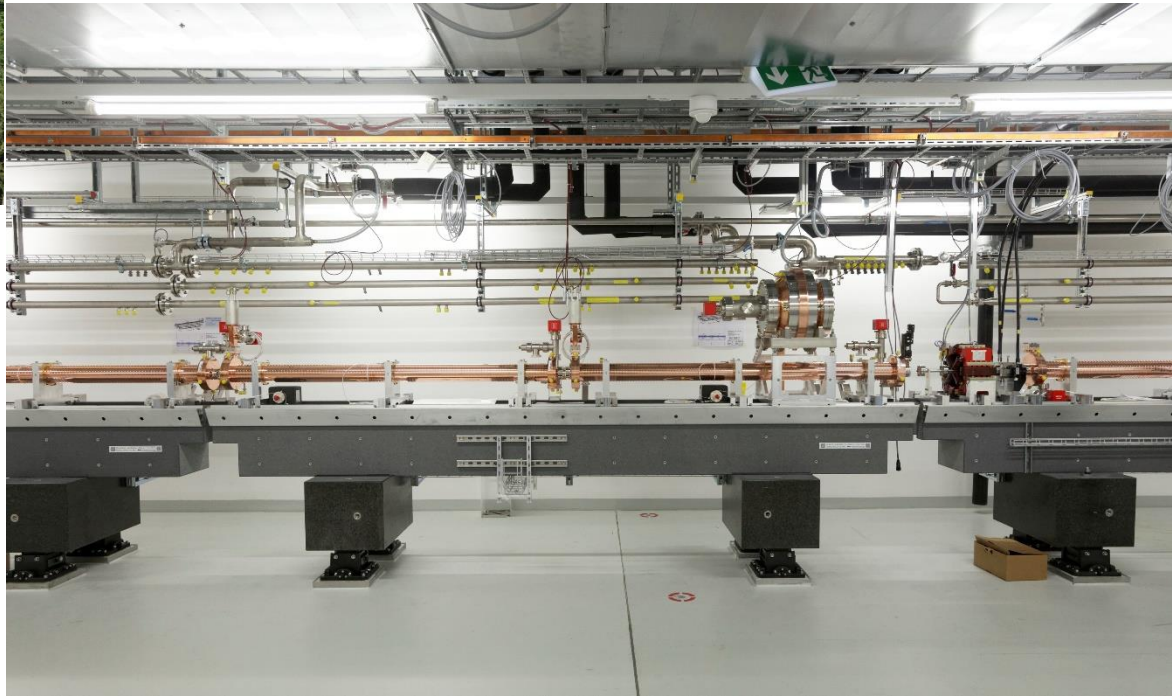
X-band GeV-range facilities

Planning:

- EU-Praxia
- eSPS
- CompactLight

SwissFEL

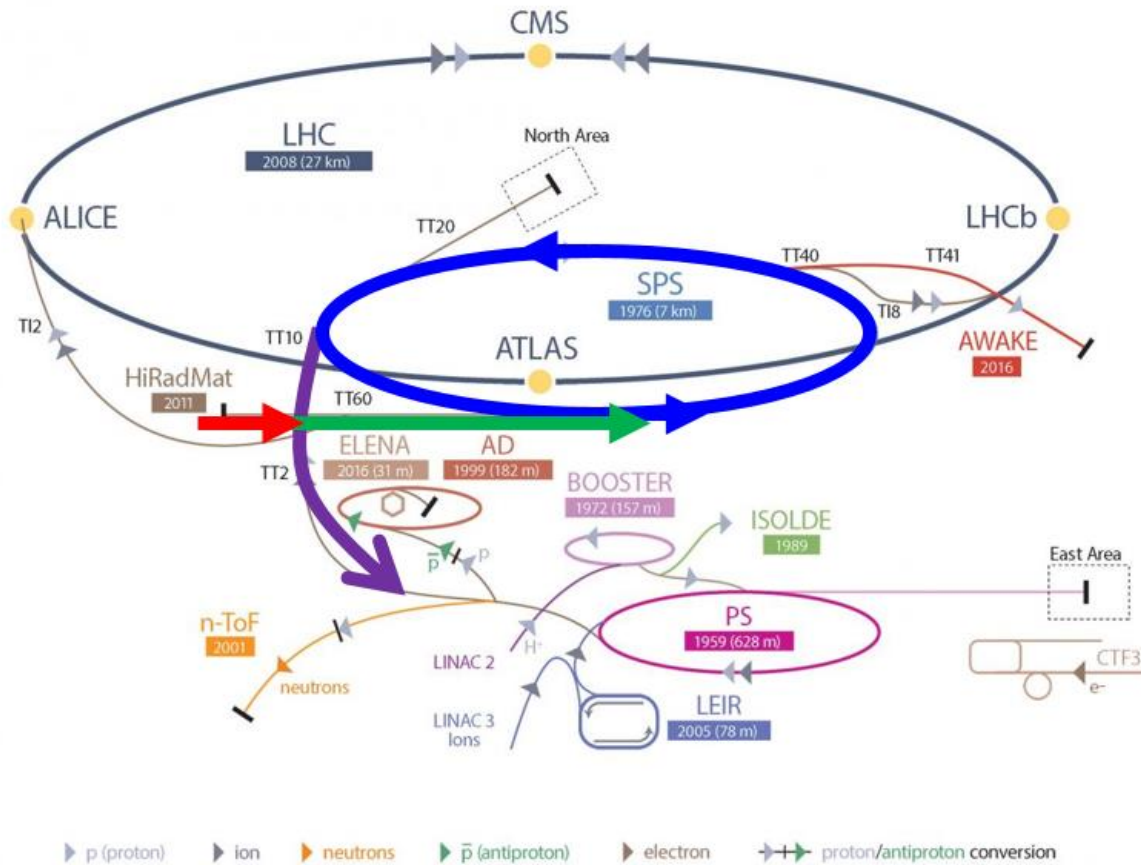
- 104 x 2m-long C-band structures (beam \rightarrow 6 GeV @ 100 Hz)
- Similar μm -level tolerances
- Length \sim 800 CLIC structures



eSPS proposal



CERN's Accelerator Complex



3.5 GeV Linac

Transfer to SPS

Acceleration to in SPS

Extraction



Summary

- **CLIC is now a mature project, ready for implementation**
- **Offers staged, flexible approach towards the energy frontier**
- **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>**
- **We are sharpening plans for preparation phase 2020-25**



Following Granada

- Looking at CLIC380 design margins:

'perfect' machine > DR

$$L = 4.3 \cdot 10^{34}$$

static imperfections only

$$L = 3 \cdot 10^{34}$$

margins for static imperfections

$$L = 1.9 \cdot 10^{34}$$

nominal luminosity goal

$$L = 1.5 \cdot 10^{34}$$

- Updating studies for running at Z-pole:

CLIC380 linacs run @ Z

$$L = 2.3 \cdot 10^{32}$$

linacs configured for Z running only $L = 3.6 \cdot 10^{33}$ (PRELIMINARY)

- Task force looking at doubling rep rate for CLIC380: 50 Hz \rightarrow 100 Hz

double the luminosity

PRELIMINARY indications: power + ~50 MW, cost + ~5%

- Updating concept for gamma-gamma collisions



**Thanks to all CLIC collaborators
for outstanding support**



Backup slides



Key technical challenges

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



CLIC Test Facility (CTF3)



DELAY LOOP



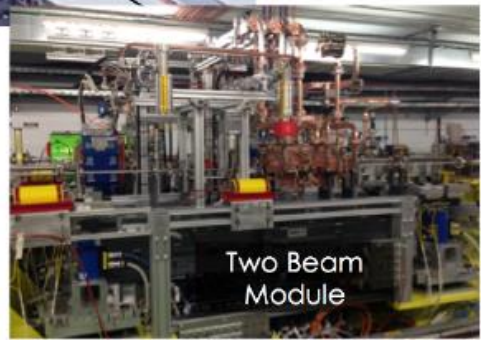
COMBINER RING

CLEX

DRIVE BEAM LINAC



TBL

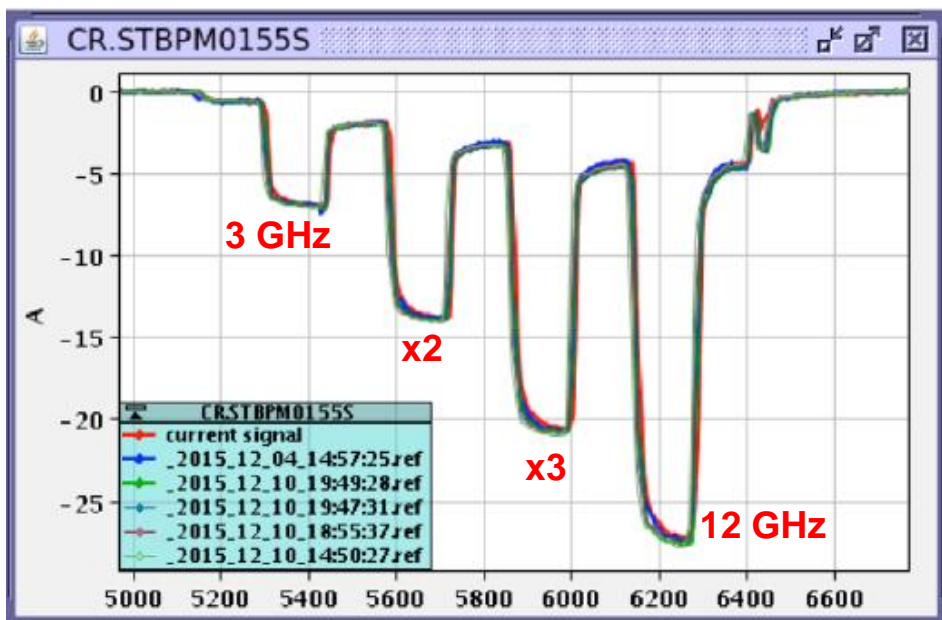


Two Beam Module



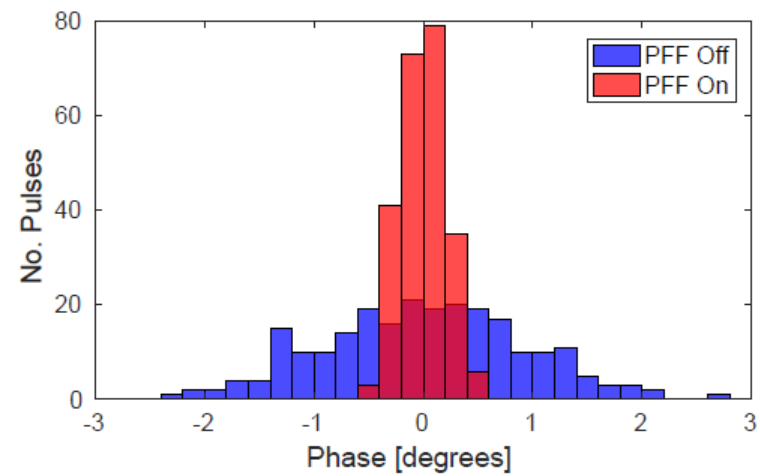
Status

- Produced high-current drive beam bunched at 12 GHz



Arrival time stabilised to 50 fs

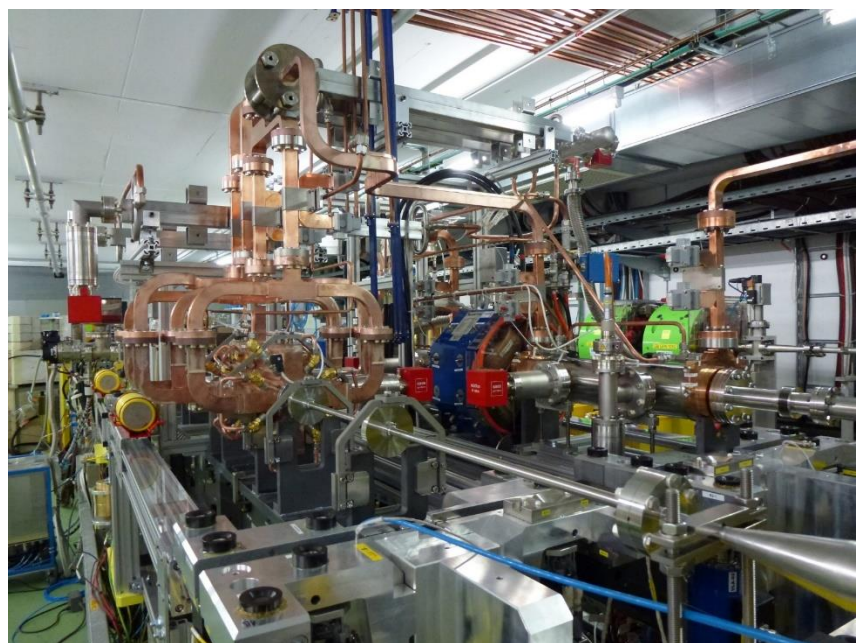
28A



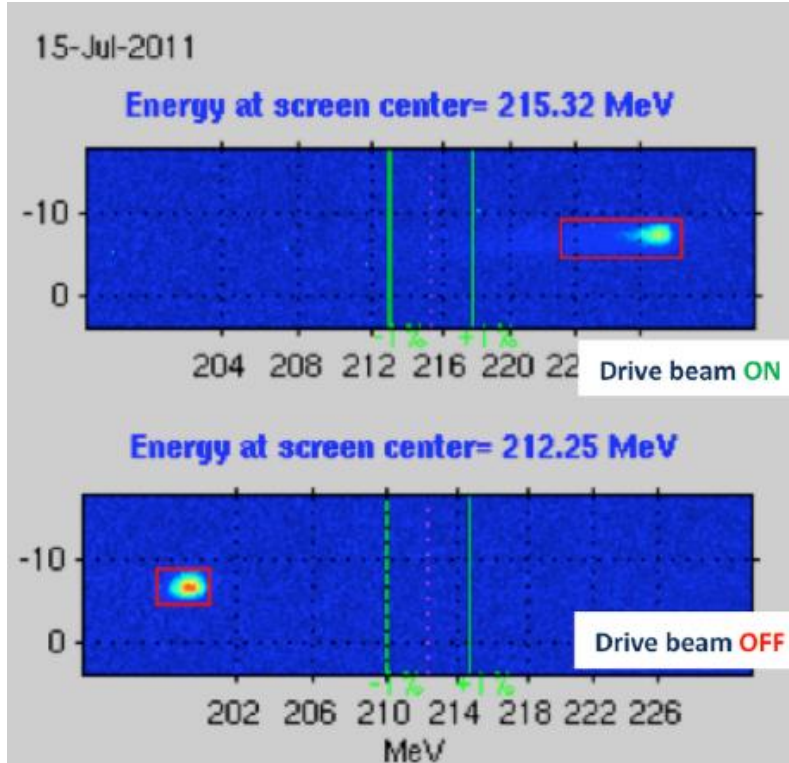
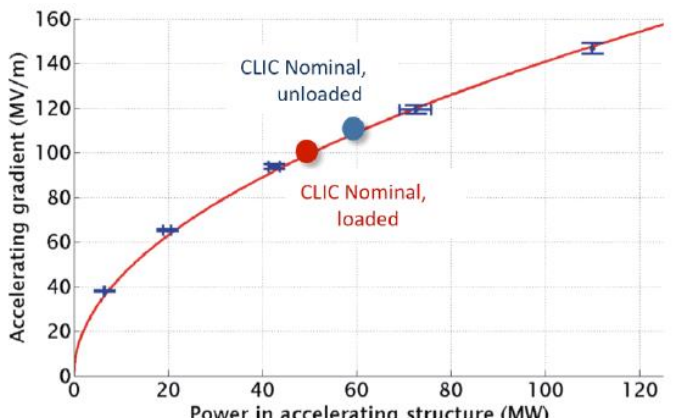


Status

- Demonstrated two-beam acceleration



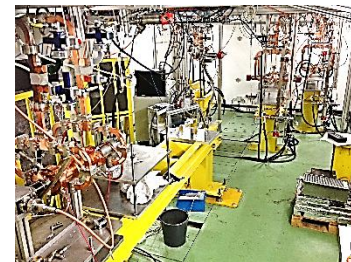
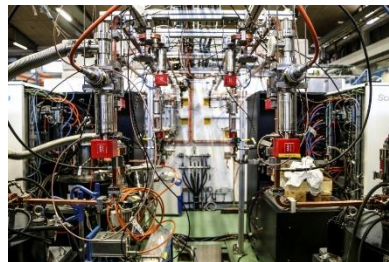
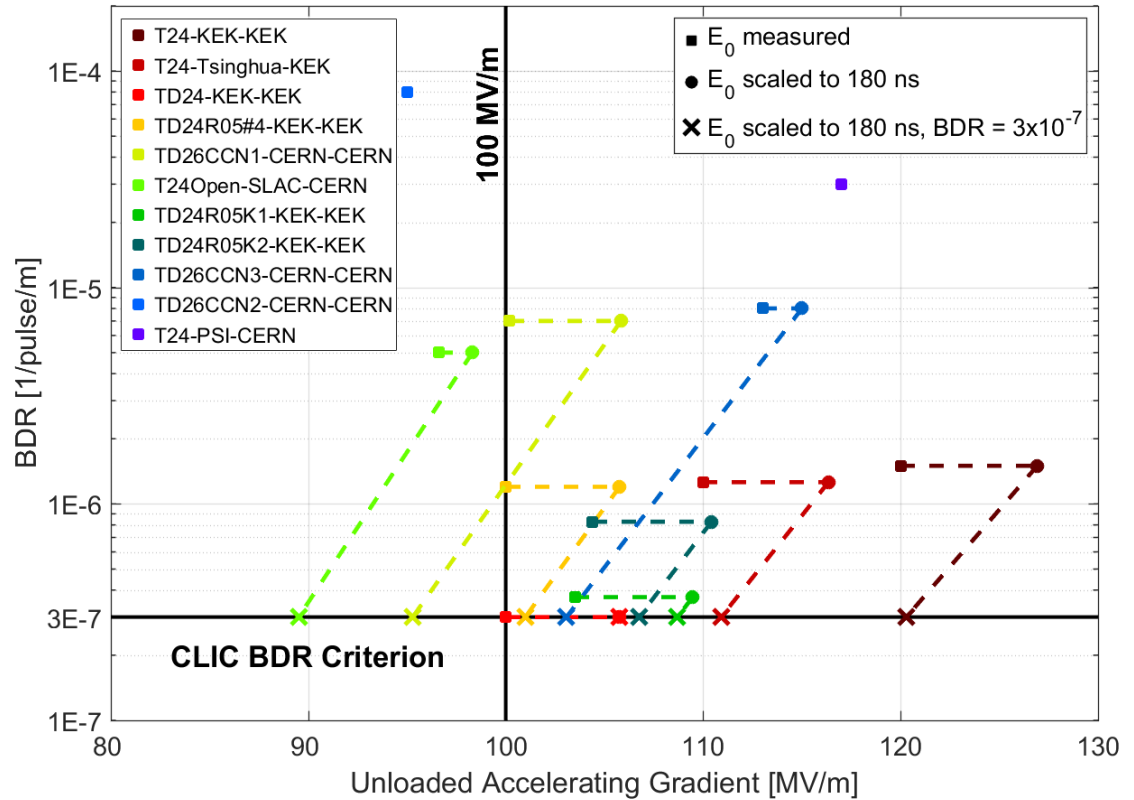
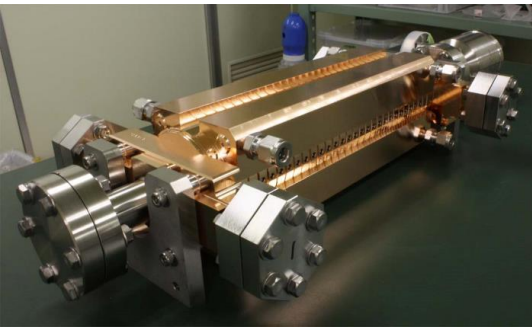
31 MeV = 145 MV/m








Status

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



Key technical challenges

- **High-current drive beam bunched at 12 GHz** 
 - **Power transfer + main-beam acceleration** 
 - **100 MV/m gradient in main-beam cavities** 
- **Industrialisation of 12 GHz RF/structure technologies**
- **Application to medium- and large-scale systems**

Updated CLIC luminosity model

First-stage construction period ends with one year of beam commissioning with the whole machine before Lumi starts

Luminosity ramp-up:

**380 GeV: 10%, 30%, 60% then nominal L
(same as ILC)**

1.5 TeV: 25%, 75% then nominal L

3 TeV: 25%, 75% then nominal L

Updated CLIC availability model

Task force study of LHC + modern light sources;

→ CLIC availability model common with FCCee

120 days winter shutdown (17 weeks)

30 days commissioning

20 days machine development

10 days technical stops

185 days physics @ 75% efficiency

→ 1.2 10^{7} s (c.f. ILC 1.6 10^{**7} s)**



EuPRAXIA@SPARC_LAB



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

A. Goffo, X-band RF Linac technology

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

A. Goffo, 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 [m]	WP1	WP2	WP3	Ultimate
E_{inj} [MeV]	300	270	120	270
E_{out} [MeV]	450	380	890	1280
γ [GeV/m]	200(11-36)(2)	200(11-27)(2)	57	80
E_{max} [MeV]	550	550	1060	1450

CDR layout

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

RF MODULE LAYOUT

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

Estimated waveguide attenuation (including circular waveguide): 10%

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



Compact



EU funded design study for a compact and low-cost FEL.

Target: SwissFEL performance at half the cost, bringing FELs to national and regional facilities.

Based on advances in:

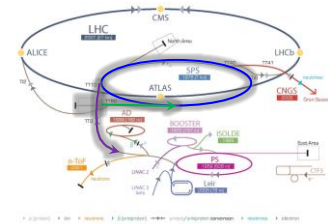
- Injectors
- X-band linac technology
- Undulators



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



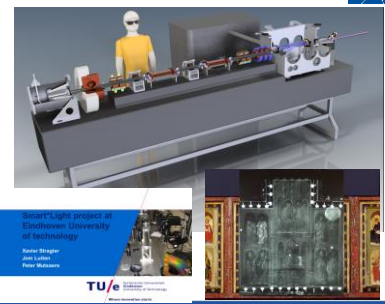
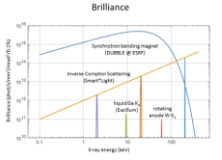
Beyond LDMX type of beam, other physics experiments considered (for example heavy photon searches)

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



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.



Elements in existing linacs (DESY, PSI)

Final scheme 2020

FLASH2 beamline

FLASH Forward beamline

Klystron

SLED

RF switch

Trenches for waveguides

Figure by Rolf Jonas and Manon Foesle



Full project schedule

