CLIC Accelerator Status

Philip Burrows

John Adams Institute, Oxford University

and CERN

On behalf of the CLIC Collaborations

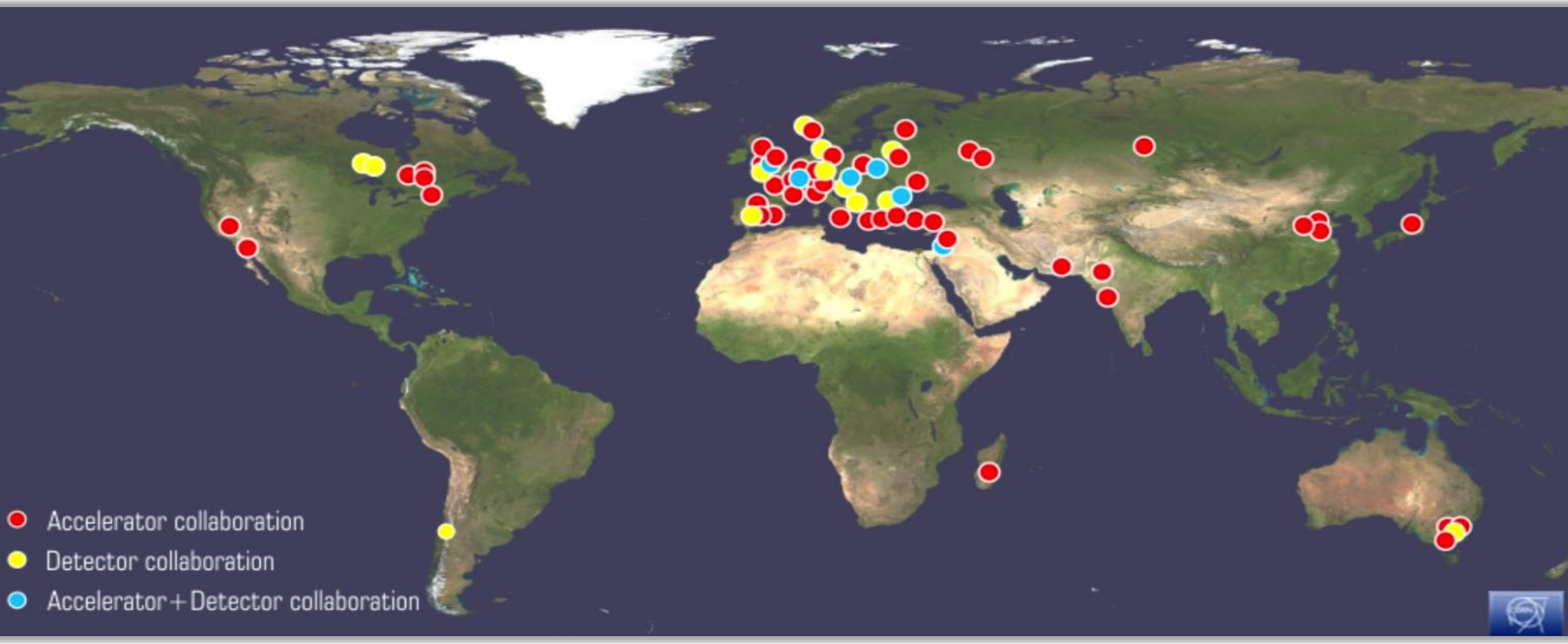
Thanks to all colleagues for materials

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

Apologies for skipping many results + details

CLIC European Strategy Inputs

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, arXiv:1903.08655)
- **The CLIC potential for new physics** (CERN-2018-009-M, arXiv:1812.02093)
- **Detector technologies for CLIC** (submitted to CERN Reports Editorial Board, EDMS)

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)

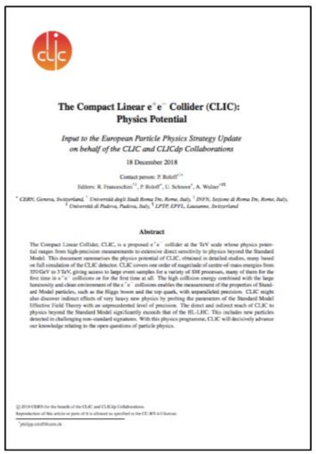
CLIC European Strategy Inputs


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

Abstract


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

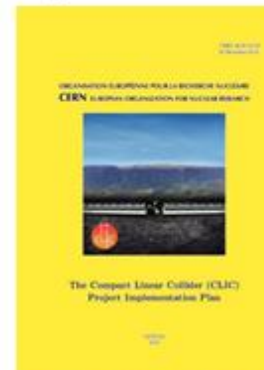
Abstract

CERN-2018-005-M

http://dx.doi.org/10.23731/CYRM-2018-002

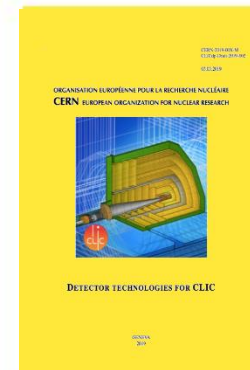
CERN-2018-009-M

http://dx.doi.org/10.23731/CYRM-2018-003



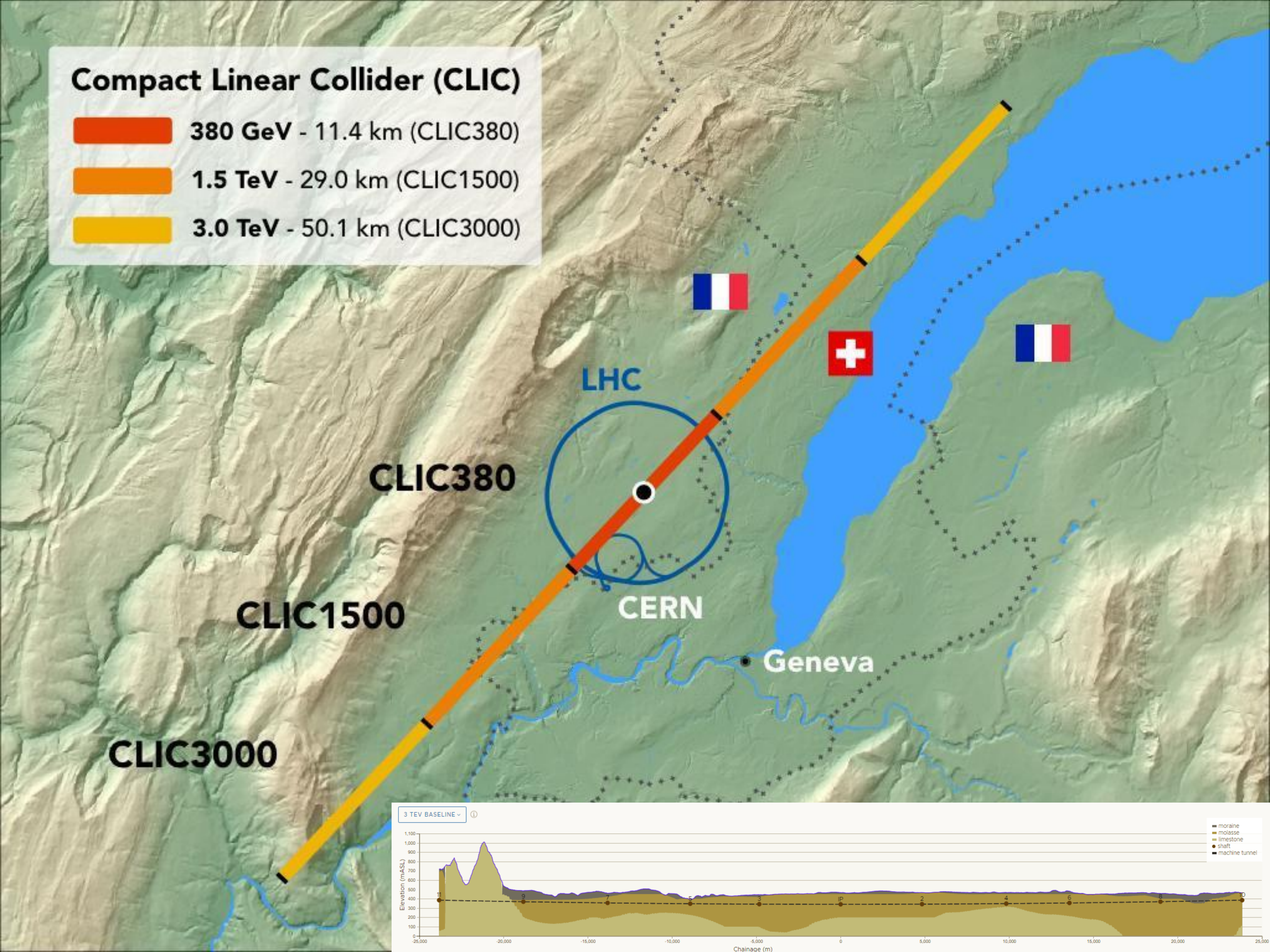
CERN-2018-010-M

http://dx.doi.org/10.23731/CYRM-2018-004



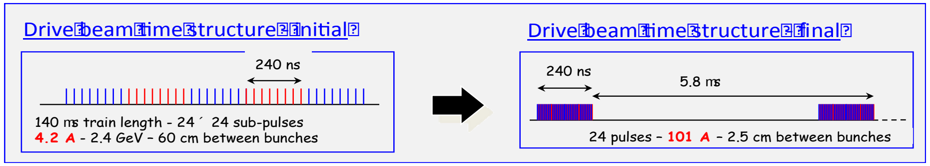
Submitted to CREB

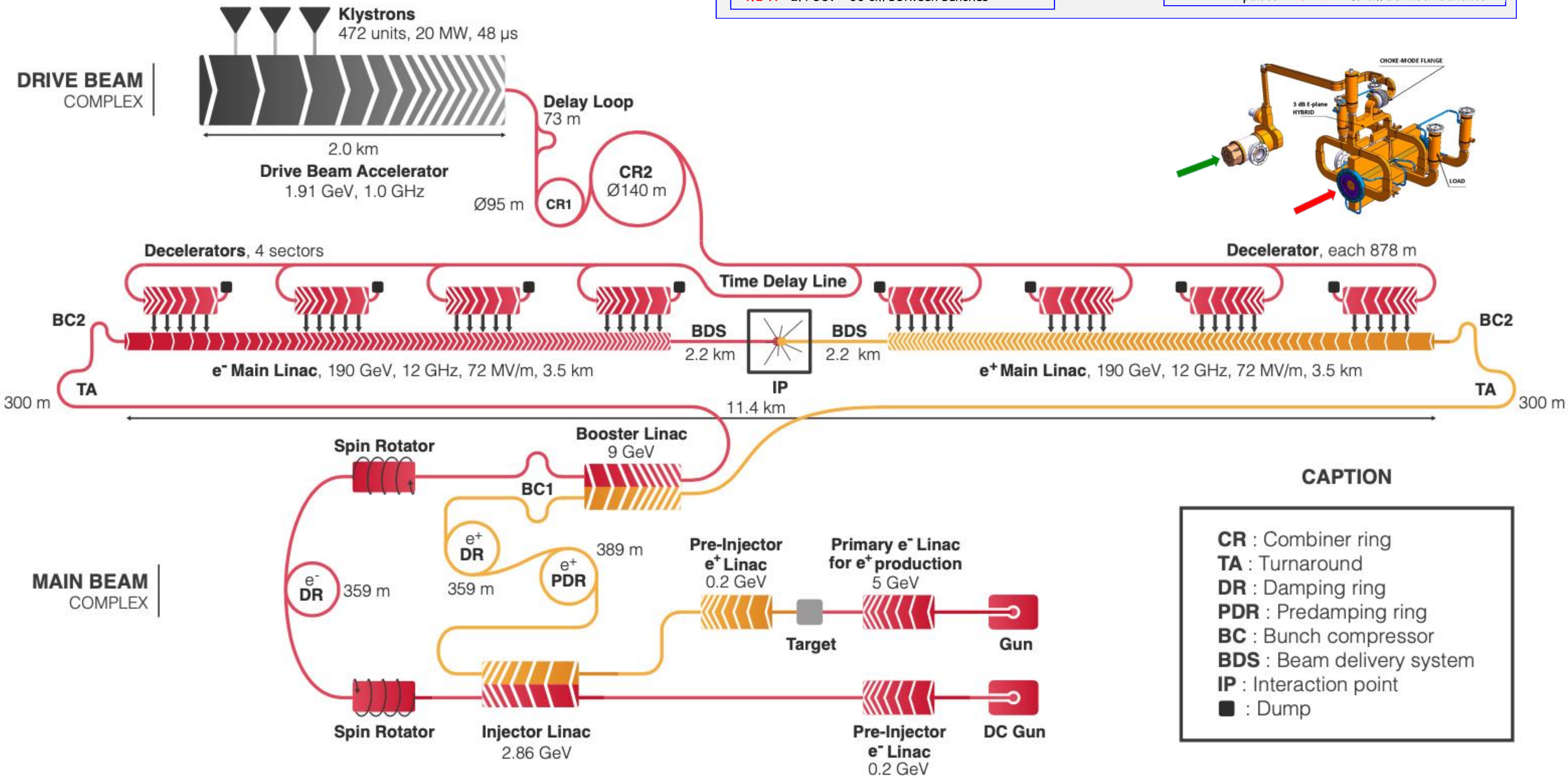
http://clic.cern/european-strategy



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
moraine
molasse
limestone
shaft
machine tunnel
Elevation (mASL)
Chainage (m)

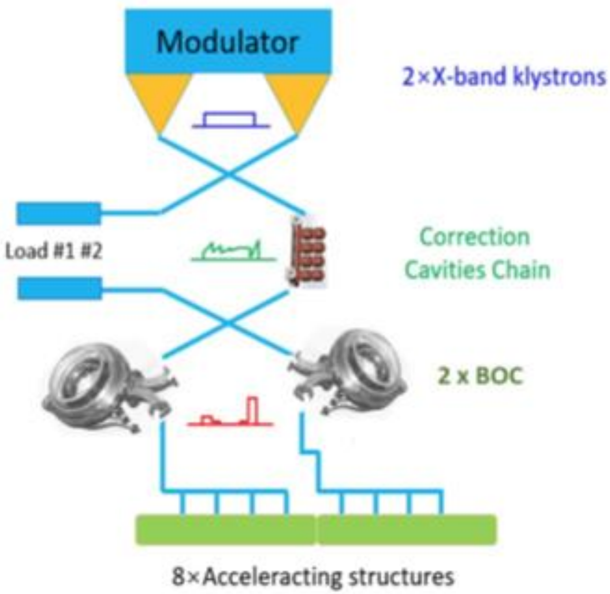
CLIC 380 GeV layout

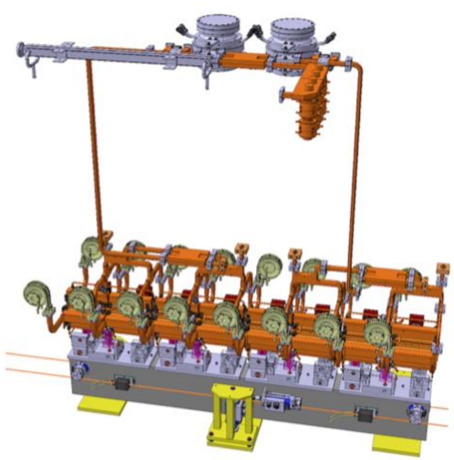




Baseline electron polarisation ±80%

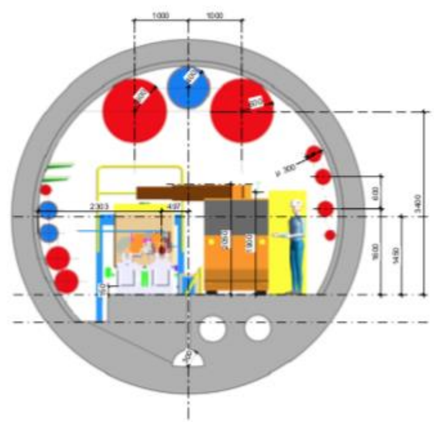
380 GeV klystron option





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

Simpler module, larger tunnel



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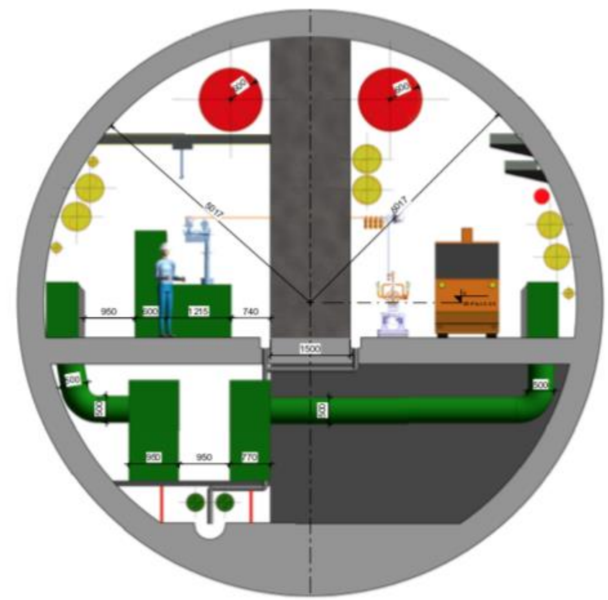


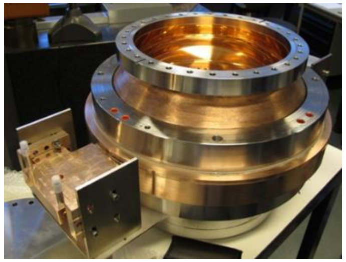
(b)

X-band RF test infrastructure

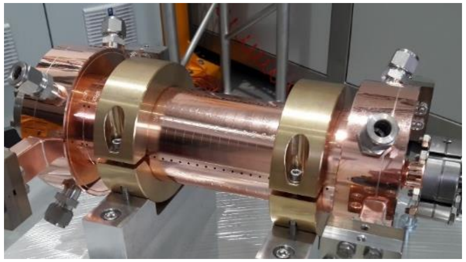
Modulator

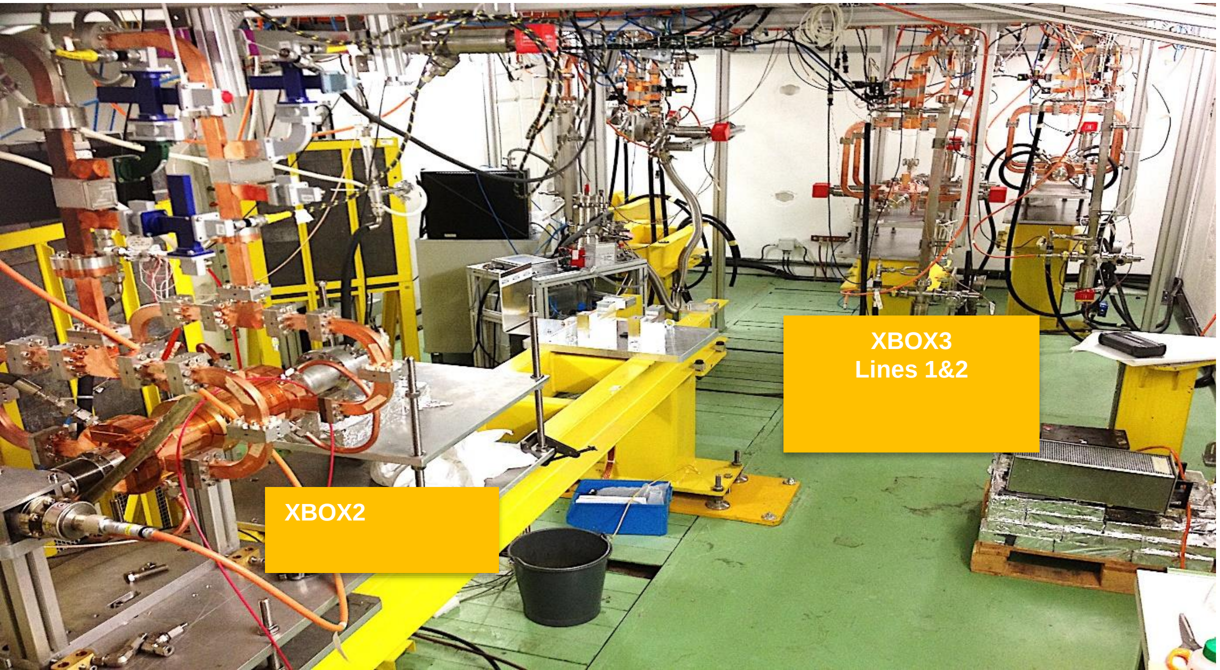
Klystron

Pulse compressor



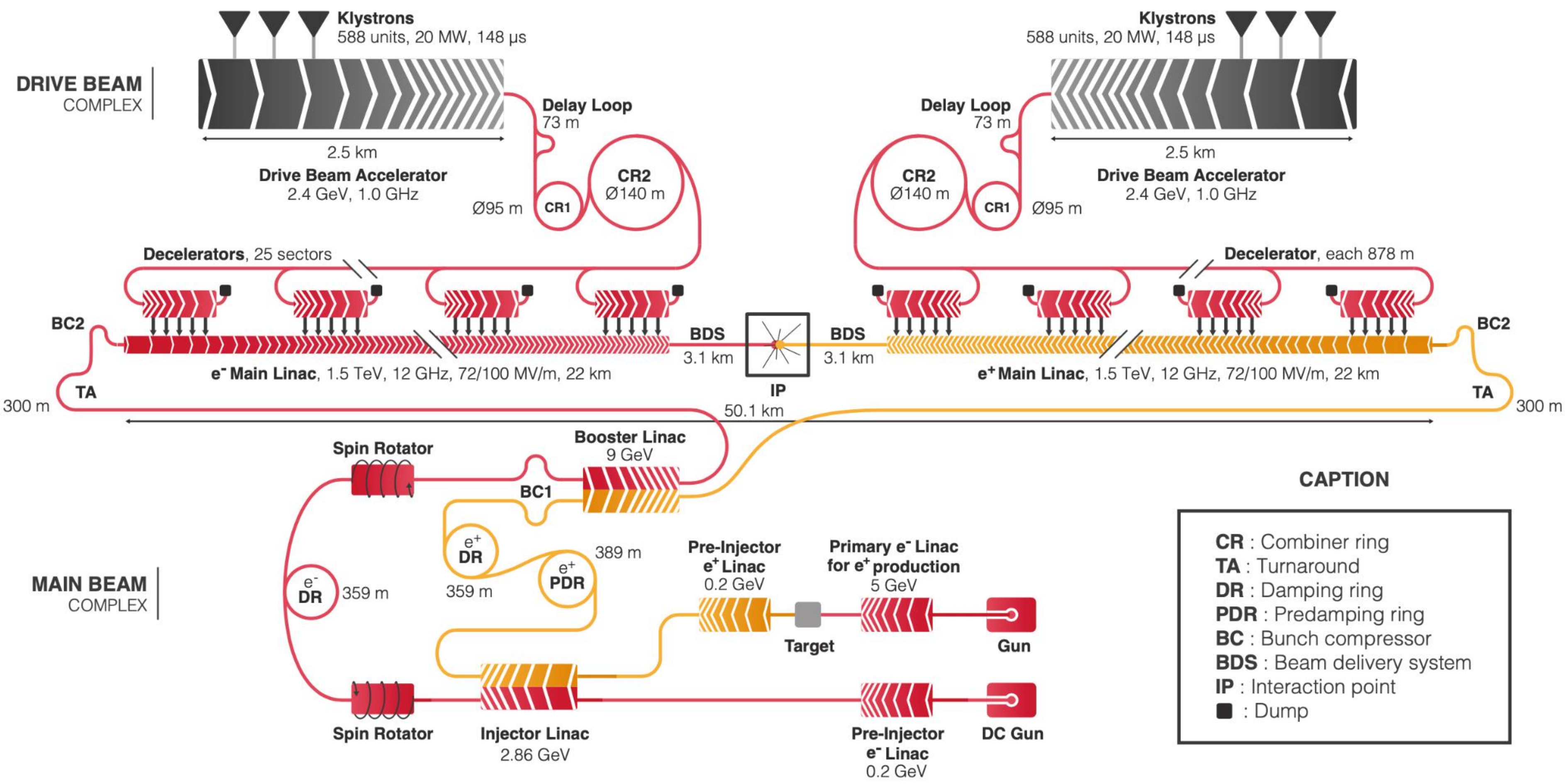
Accelerating structures





Assembled X-band systems in continuous operation at CERN

CLIC 3 TeV layout



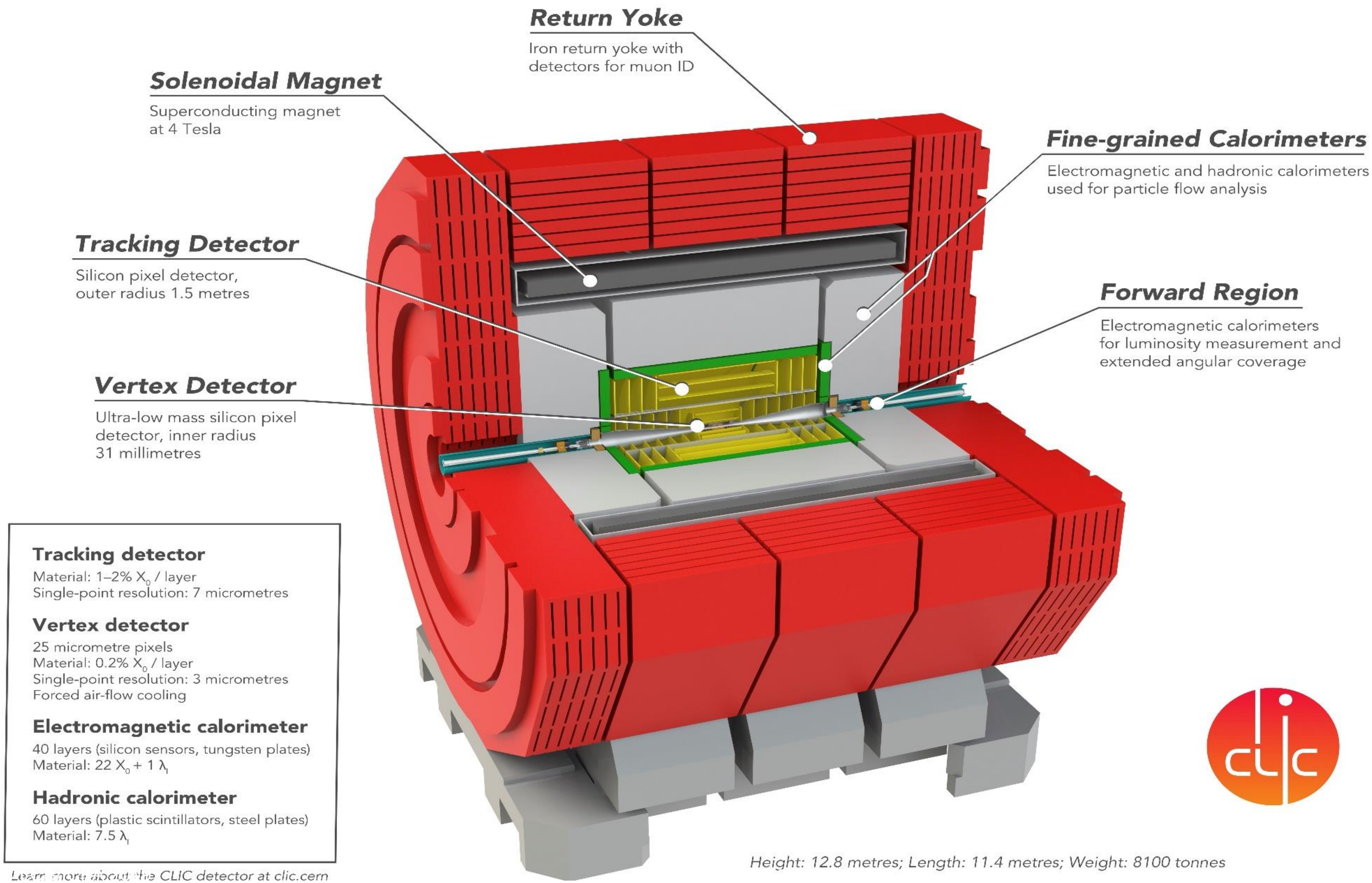
Baseline electron polarisation ±80%

CLIC parameters

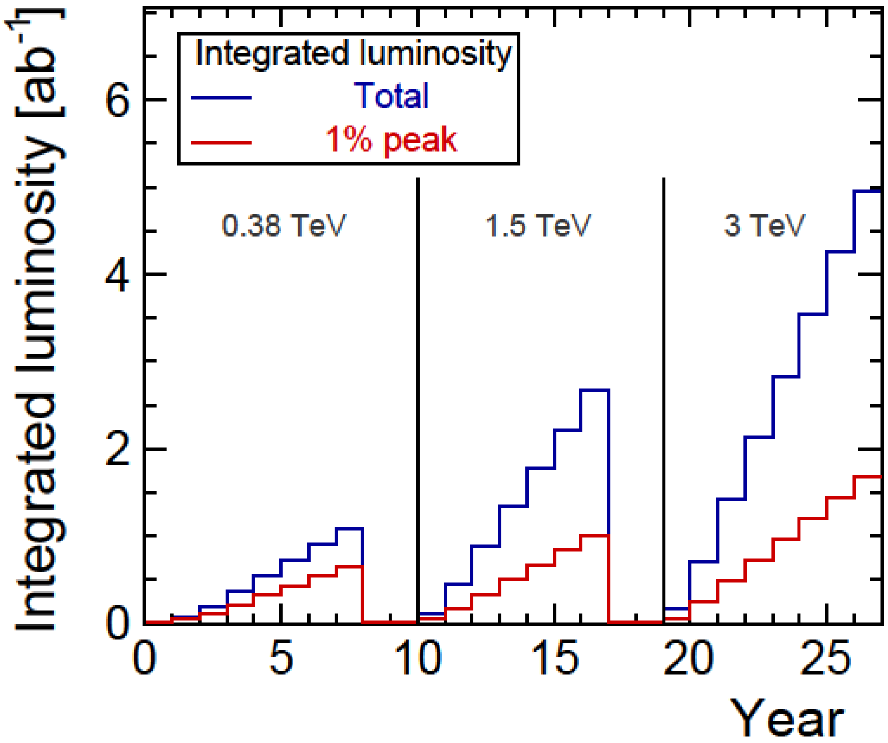
Parameter	Symbol	Unit	Stage 1	Stage 2	Stage 3
Centre-of-mass energy	$\sqrt{s}$	GeV	380	1500	3000
Repetition frequency	f_{rep}	Hz	50	50	50
Number of bunches per train	n_b		352	312	312
Bunch separation	Δt	ns	0.5	0.5	0.5
Pulse length	τ_{RF}	ns	244	244	244
Accelerating gradient	G	MV/m	72	72/100	72/100
Total 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	$\mathscr{L}_{\mathrm{int}}$	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)	ϵ_x/ϵ_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:



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 √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

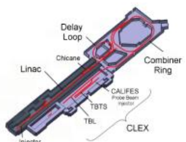
Four challenges:

High-current drive beam bunched at 12 GHz

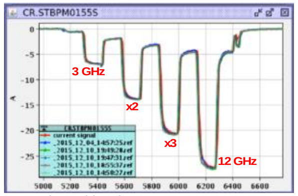
Power transfer + main-beam acceleration

~100 MV/m gradient in main-beam cavities

Alignment & stability



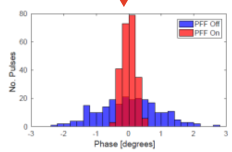
Drive beam quality:
Produced high-current drive beam bunched at 12GHz



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

Four challenges:

High-current drive beam bunched at 12 GHz

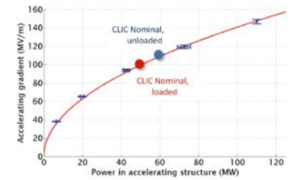
Power transfer + main-beam acceleration

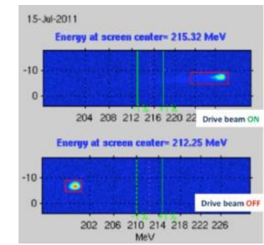
~100 MV/m gradient in main-beam cavities

Alignment & stability

Demonstrated 2-beam acceleration

31MeV = 145MV/m





Accelerator challenges

Four challenges:

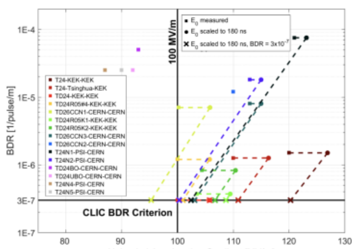
High-current drive beam bunched at 12 GHz

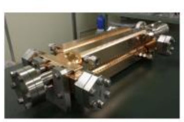
Power transfer + main-beam acceleration

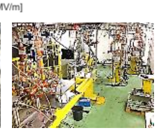
~100 MV/m gradient in main-beam cavities

Alignment & stability

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







Accelerator challenges

Four challenges:

High-current drive beam bunched at 12 GHz

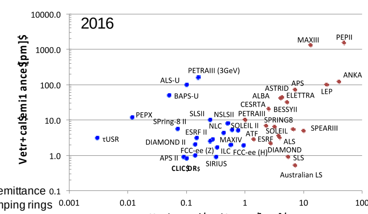
Power transfer + main-beam acceleration

~100 MV/m gradient in main-beam cavities

Alignment & stability

The CLIC strategy for nano-beams:

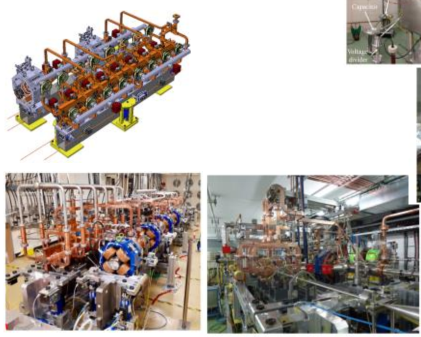
- Align components (10µm over 200m)
- Control/damp vibrations (from ground to accelerator)
- Measure beams well
  – allow to steer beam and optimize positions
- Algorithms for measurements, beam and component optimization, feedbacks
- Tests in small accelerators of equipment and algorithms (FACET at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



CLIC emittance at damping rings

Technical developments - I

Sources and Injectors
The Klystron and Drive-Beam Modules

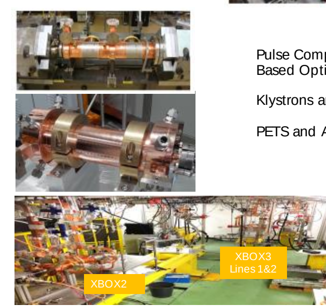


Technical developments - II

Pulse Compression System for the Klystron-Based Option

Klystrons and Modulators

PETS and Accelerating Structures

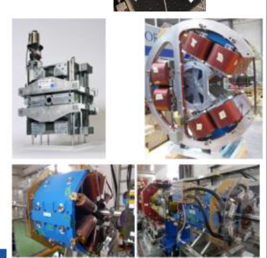


Technical developments - III

Beam Instrumentation

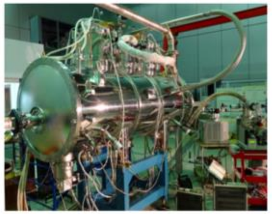
Survey and Alignment
Ground Motion
Stabilisation

Normal Conducting Electro-Magnets and Permanent Magnets



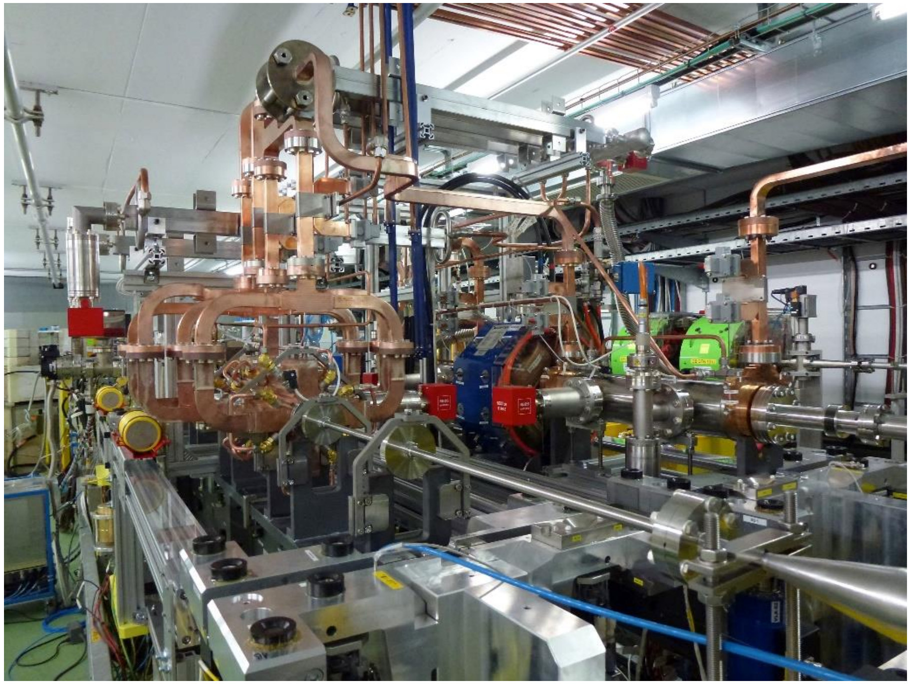
Technical developments - IV

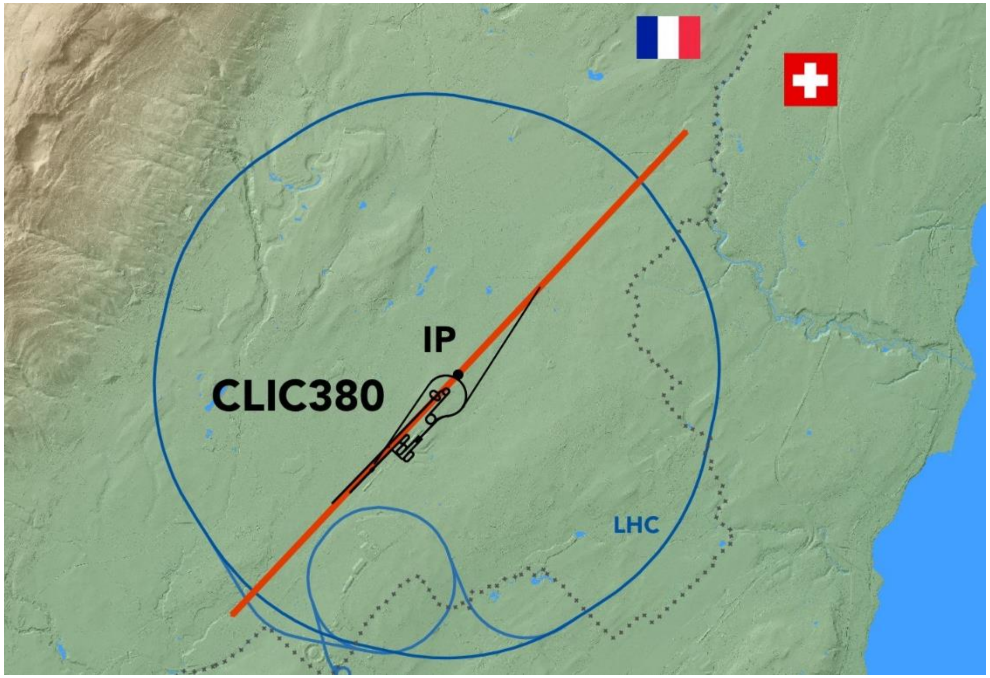
Super-Conducting Damping Wiggler
Vacuum
Beam transfer
Controls
Fine Time Generation and Distribution
Machine Protection
Beam Interception Devices



Status

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





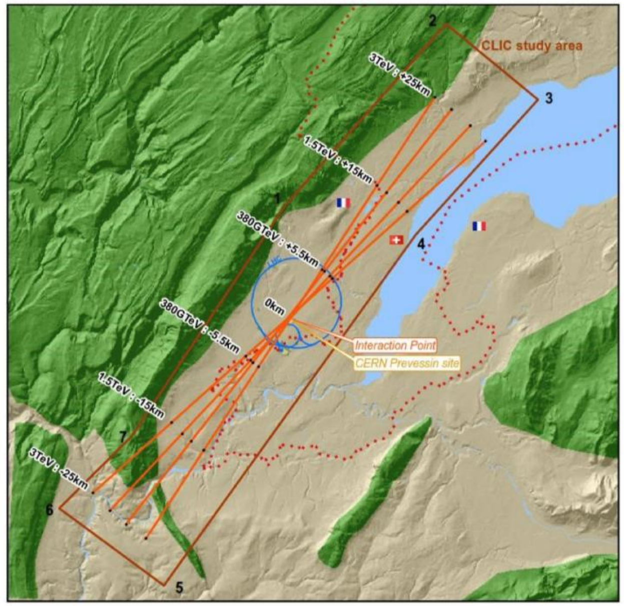
LINEAR COLLIDER COLLABORATION

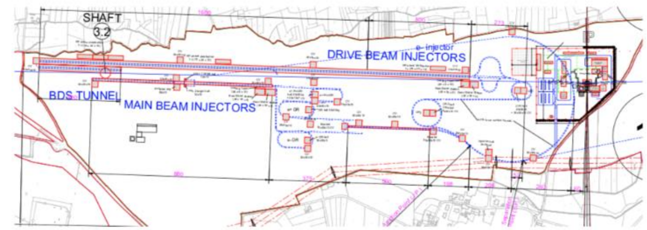
Civil Engineering and Infrastructure Studies

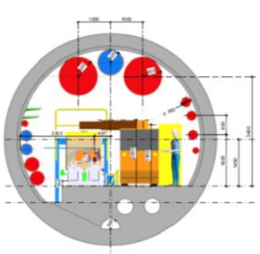
Important effort within:

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

Crucial for cost/power/schedule







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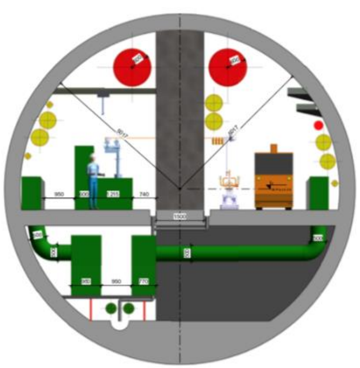

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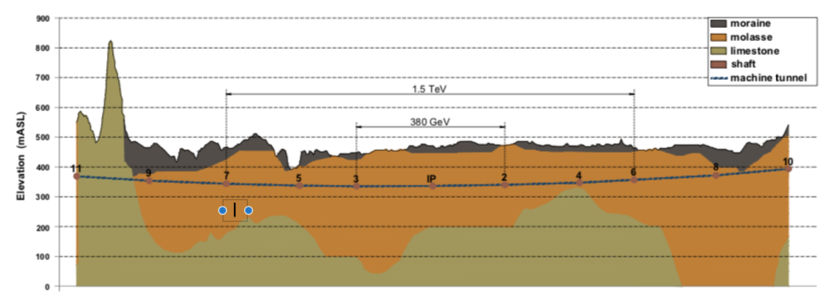
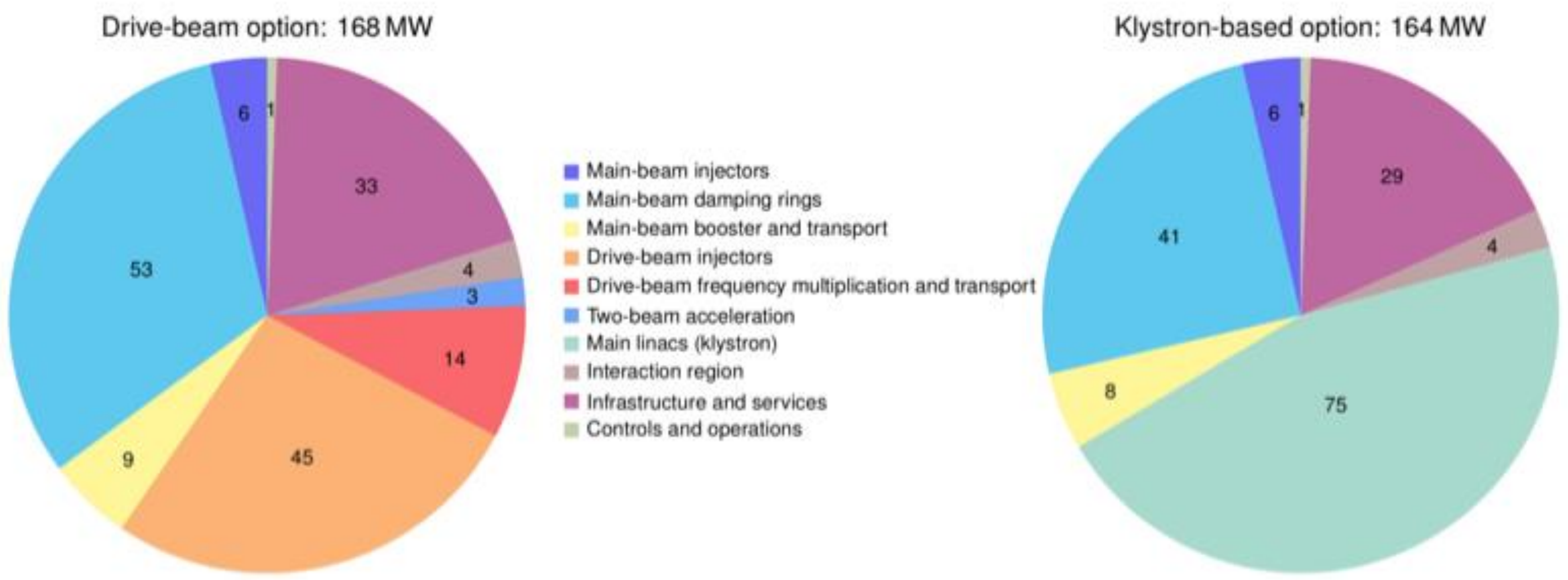


Power

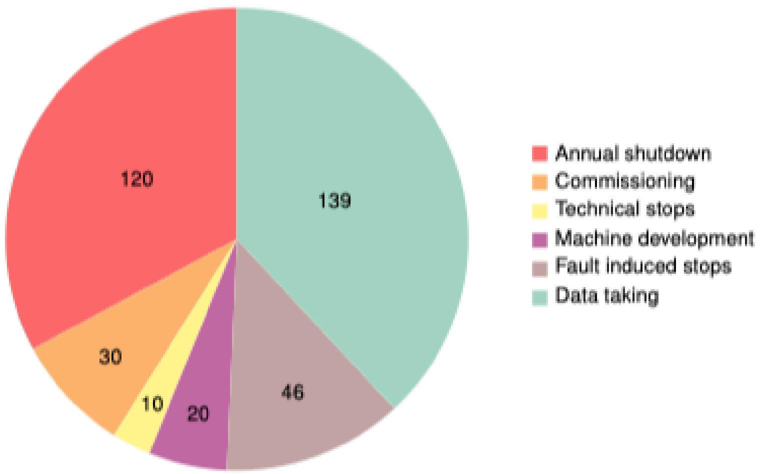
Power estimate bottom up (concentrating on 380 GeV systems)

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



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

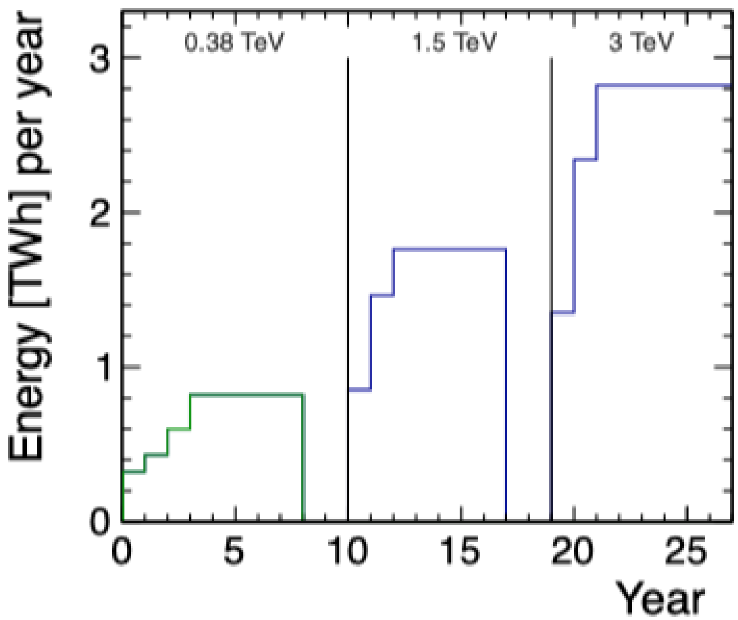
Energy



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

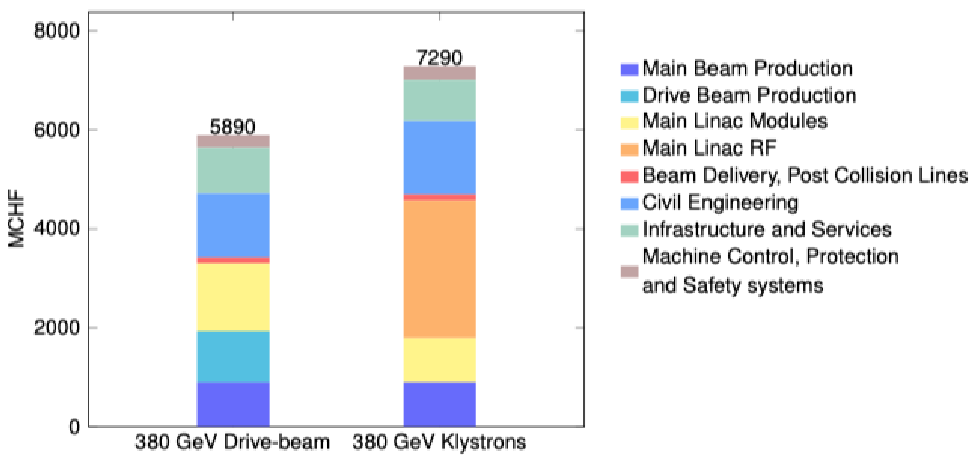
From running model and power estimates at various states – the energy consumption can be estimated

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



Cost – 380 GeV stage

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.

LINEAR COLLIDER COLLABORATION

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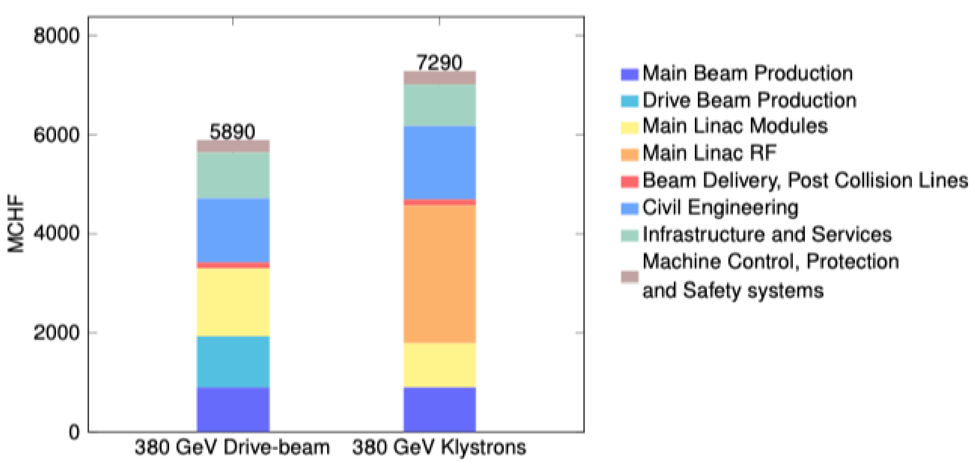

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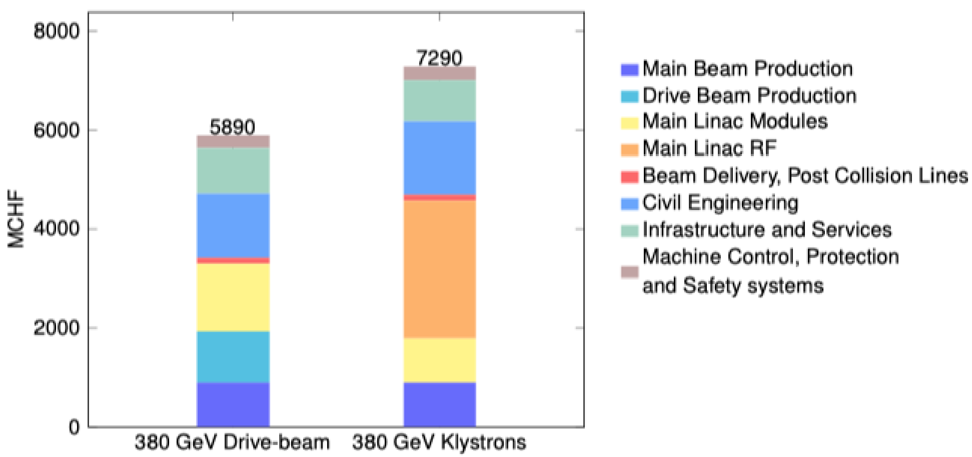


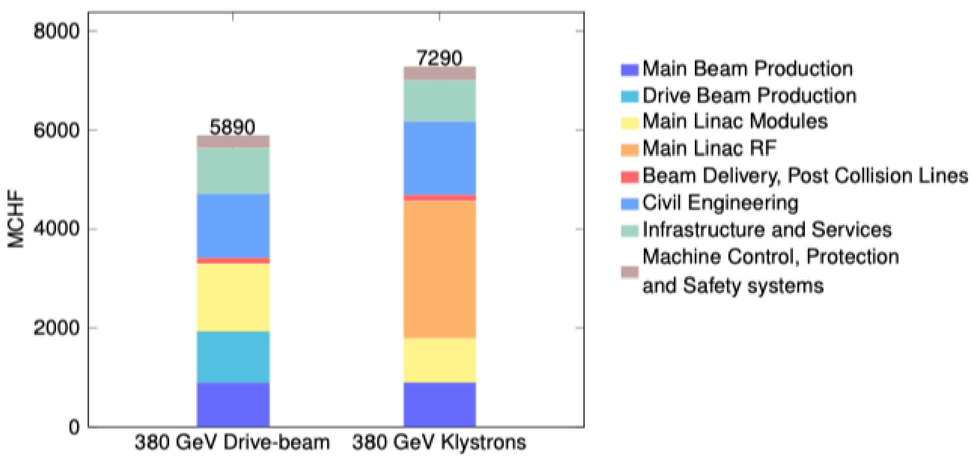
CLIC 380 GeV Drive-Beam based: 5890^{+1470}_{-1270} MCHF;

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

Cost – 380 GeV stage

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**

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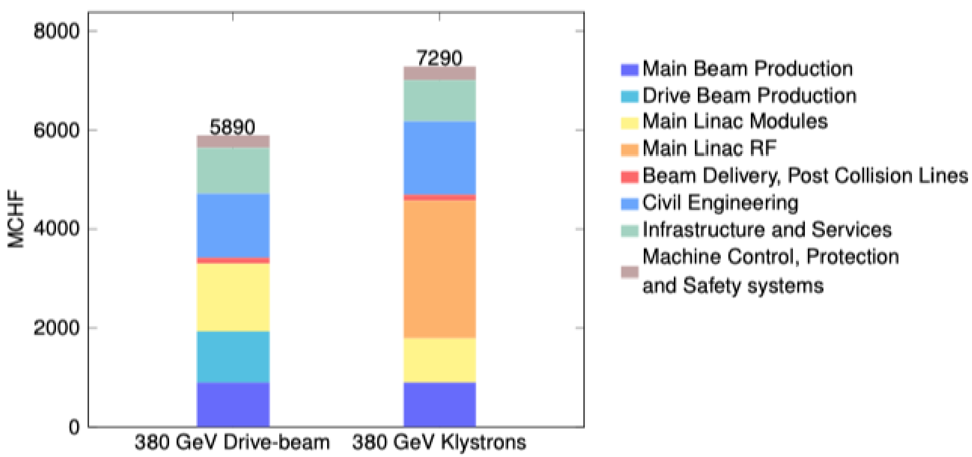

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CLIC 380 GeV Drive-Beam based: 5890^{+1470}_{-1270} MCHF;

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**

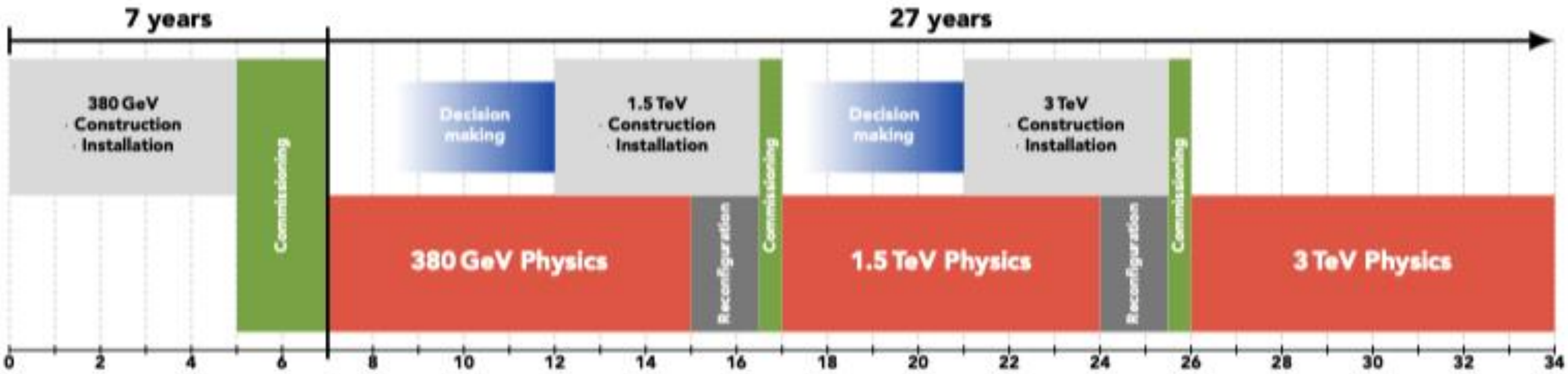
Operation:

- **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)

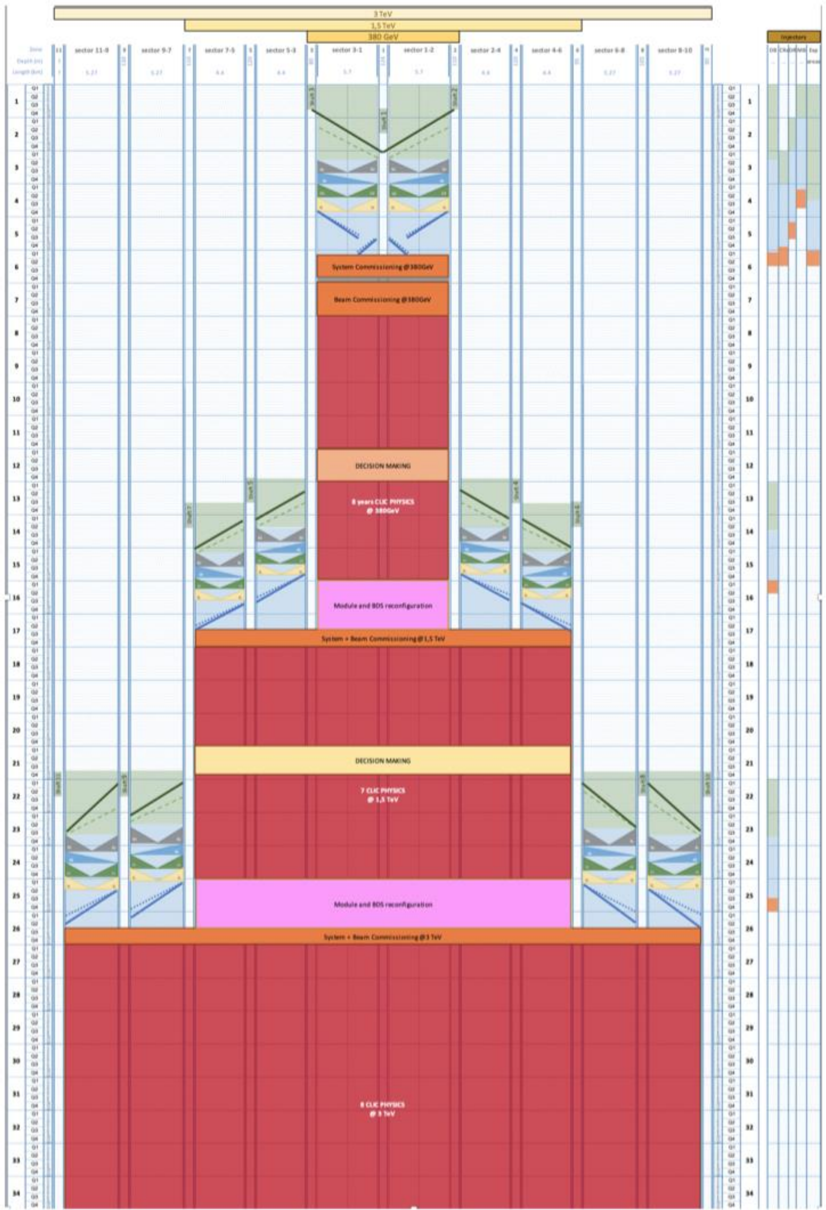
These replacement/operation costs represent 116 MCHF per year.

Schedule



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

Full project schedule



Longer-term outlook

- A LC infrastructure offers possibility to re-use tunnel/infrastructure, injectors, drive-beams, etc. for major energy upgrades with new technologies

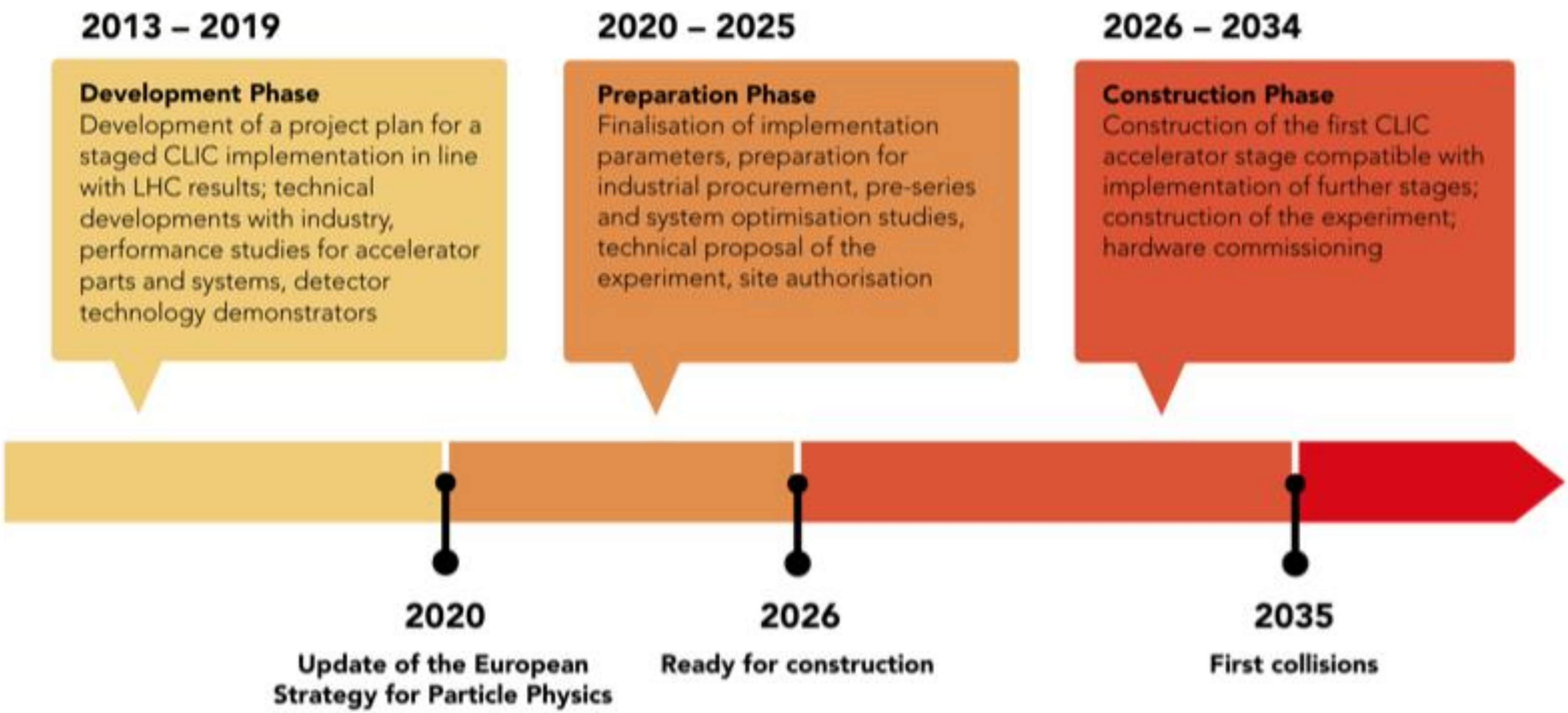
- CLIC is laser-straight and with a “reasonable” crossing angle likely to compatible with higher beam energies and the bunch separations needed for these technologies

- 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

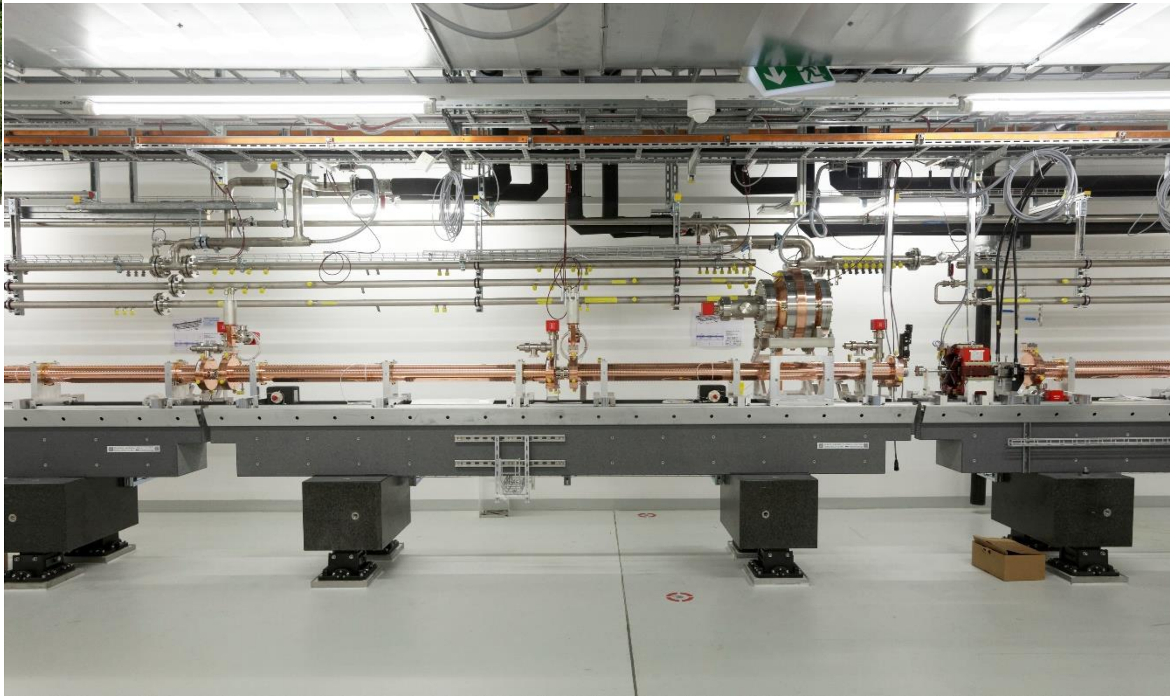


Next phase

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

SwissFEL

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



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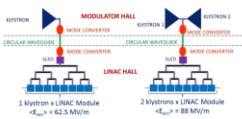
EuPRAXIA@SPARC_LAB CDR Review Committee Meeting
27-28 November 2018 INFN Frascati
A. Gallo: X-band RF Linac technology

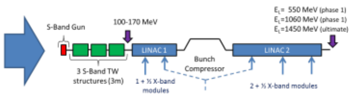
X-BAND LINAC DESIGN

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

X-Band LINAC parameters				
L_T [m]	16			
	WP1	WP2	**WP3**	Ultimate
E_0 [MeV]	100	170	**170**	170
E_{gain} [MeV]	450	380	**890**	1280
<G> [MV/m]	20(L1)-36(L2)	20(L1)-27(L2)	**57**	80
E_L [MeV]	550	550	**1060**	1450



CDR layout



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

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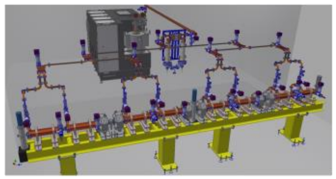
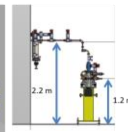
EuPRAXIA@SPARC_LAB CDR Review Committee Meeting
27-28 November 2018 INFN Frascati
A. Gallo: X-band RF Linac technology

RF MODULE LAYOUT





Preliminary layout of the **RF module** (collaboration with CERN):
4 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

15

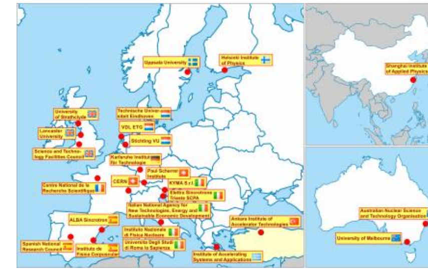
Compact

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

Target: SwissFEL performance at half the cost, to bring XFELs to national and regional facilities.

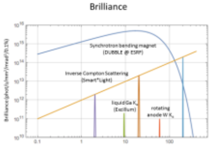
Based on advances in:

- Injectors
- X-band linac technology
- Undulators



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

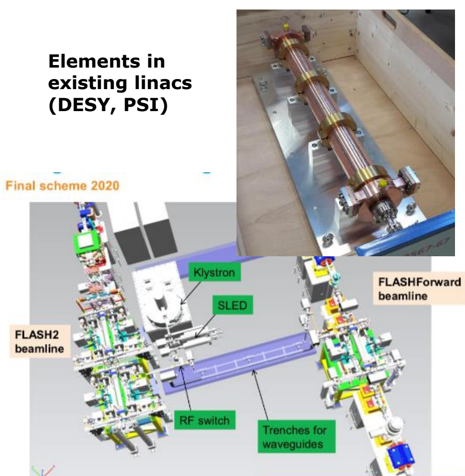
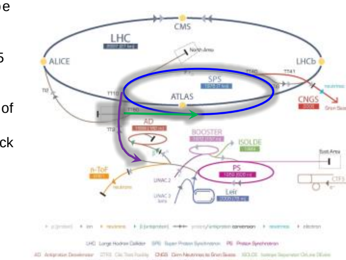


Figure by Rolf Jonas and Manon Foese

Electrons at CERN, overview

Accelerator implementation at CERN of LDMX type of beam

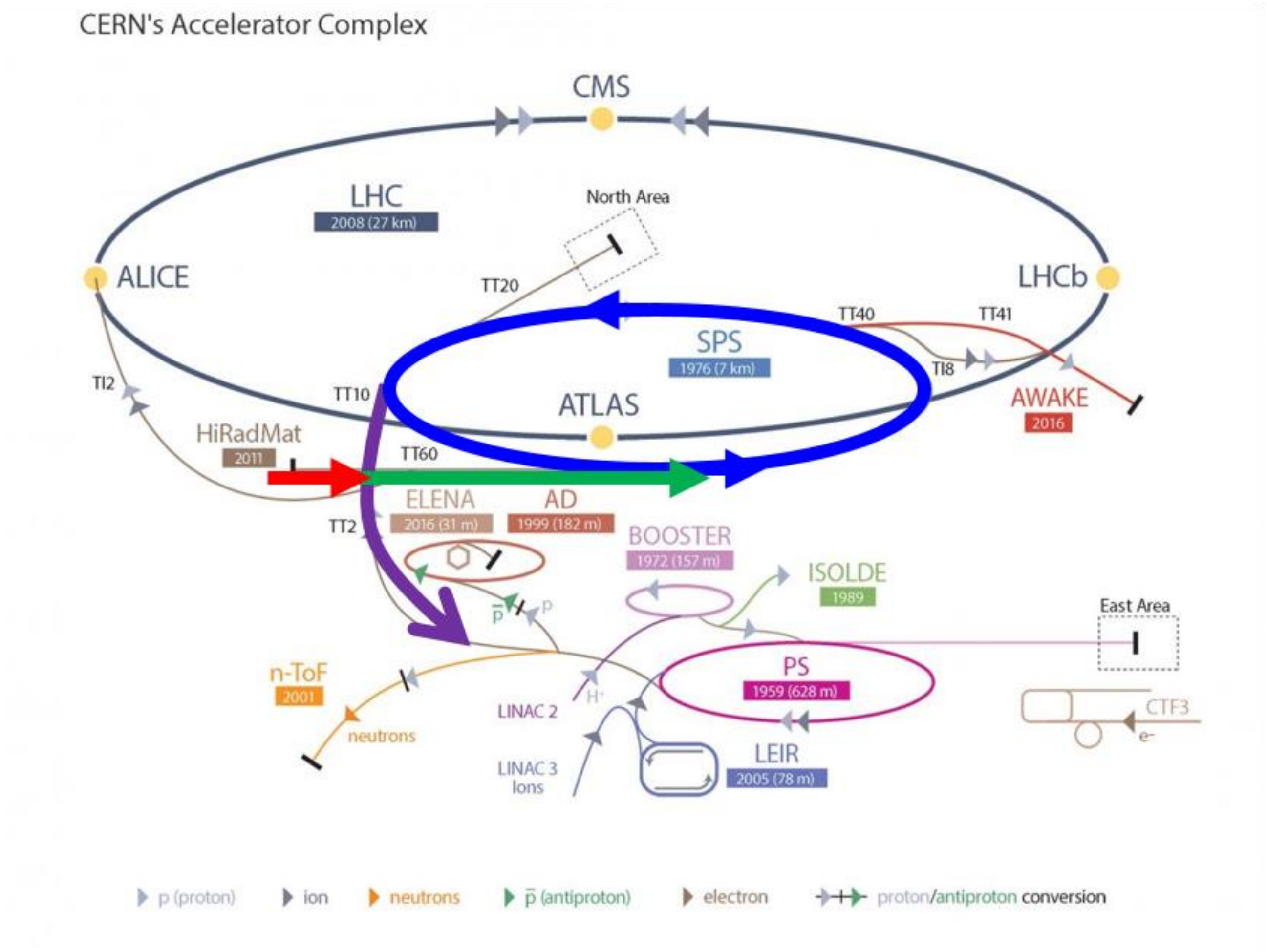
- X-band based 70m LINAC to ~3.5 GeV in TT4-5
- Fill the SPS in 1-2s (bunches 5ns apart) via TT60
- Accelerate to ~16 GeV in the SPS
- Slow extraction to experiment in 10s as part of the SPS super-cycle
- Experiment(s) considered by bringing beam back on Meyrin site using TT10



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

eSPS proposal



3.5GeV Linac

Transfer to SPS

Acceleration to in SPS

Extraction

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 CLIC collaborators for outstanding support

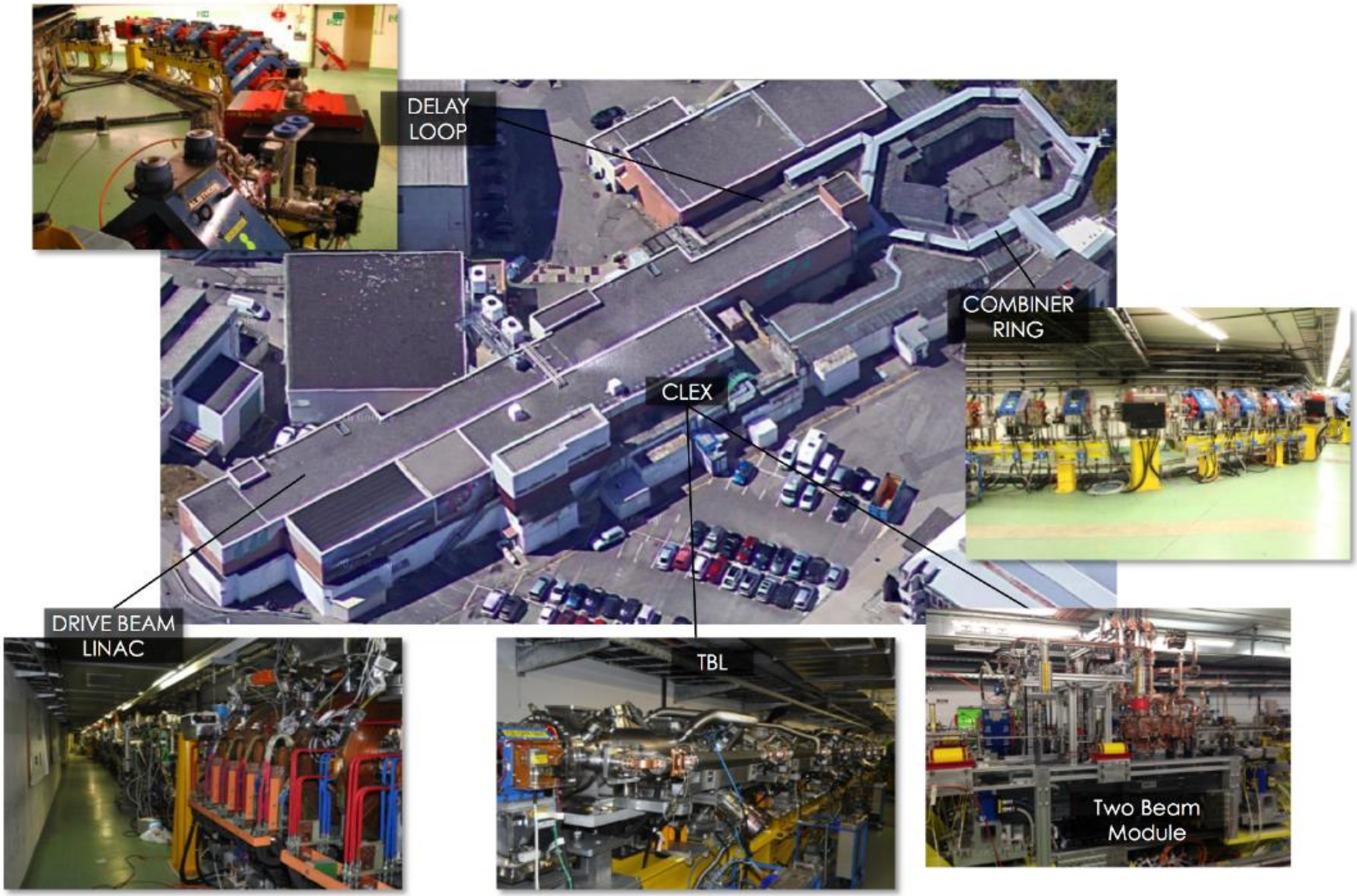
Backup slides

Key technical challenges

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

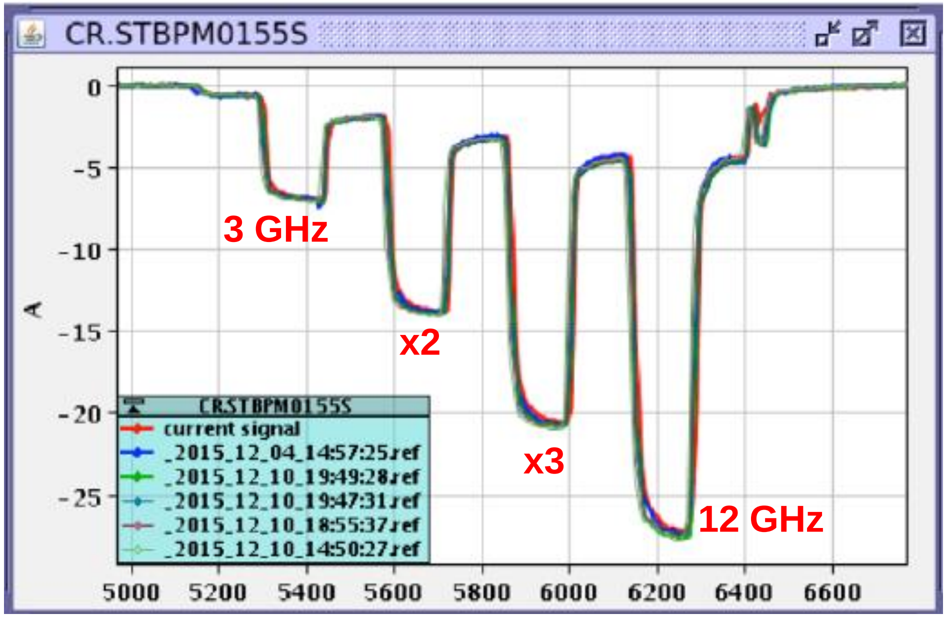
- Produce, transport + collide low-emittance beams
- System integration, engineering, cost, power …

CLIC Test Facility (CTF3)



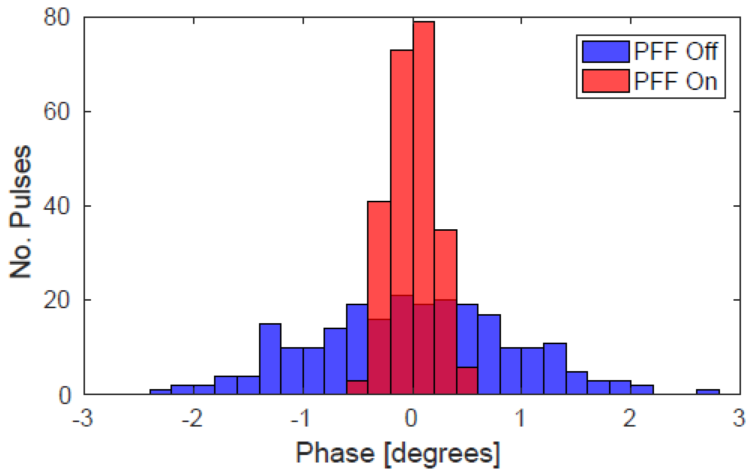
Status

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



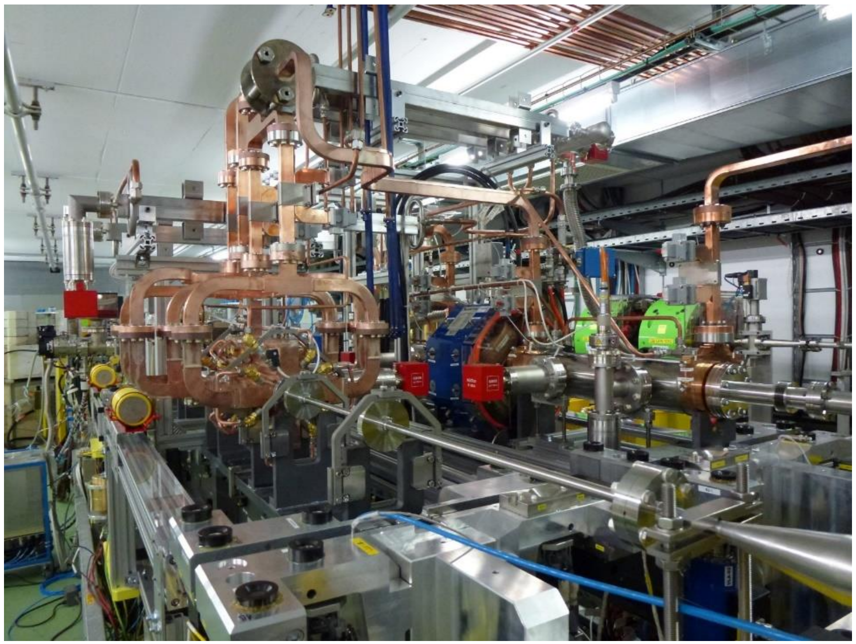
28A

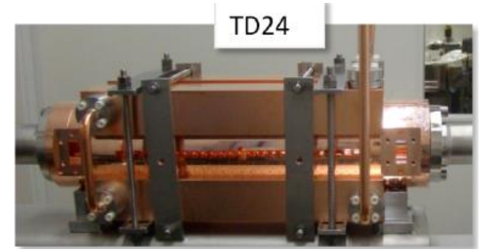
Arrival time stabilised to 50 fs



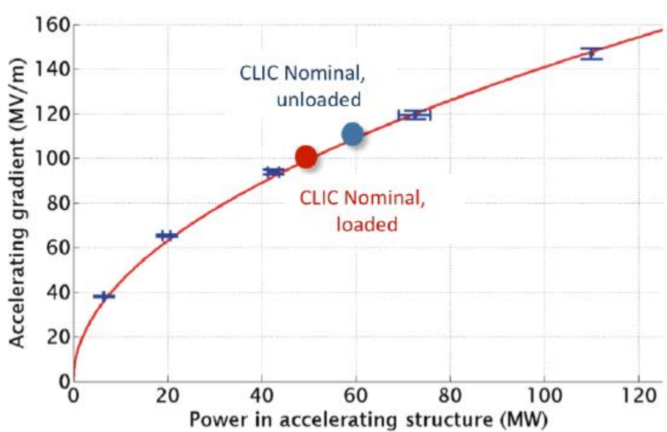
Status

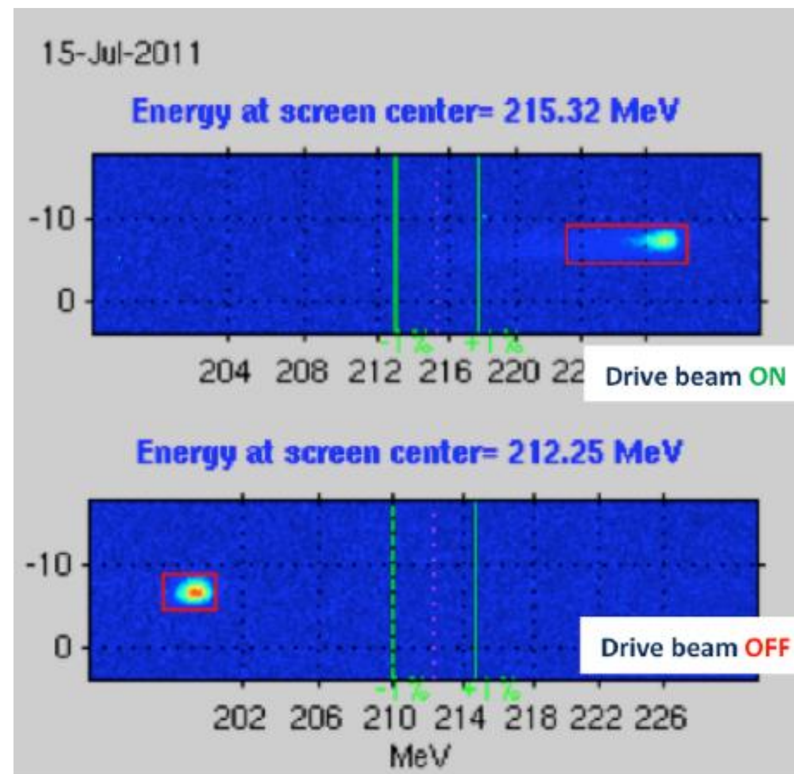
- **Demonstrated two-beam acceleration**





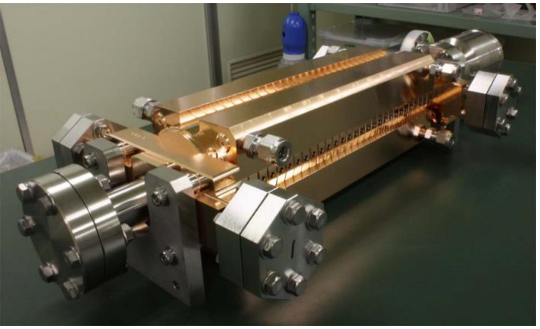
31 MeV = 145 MV/m

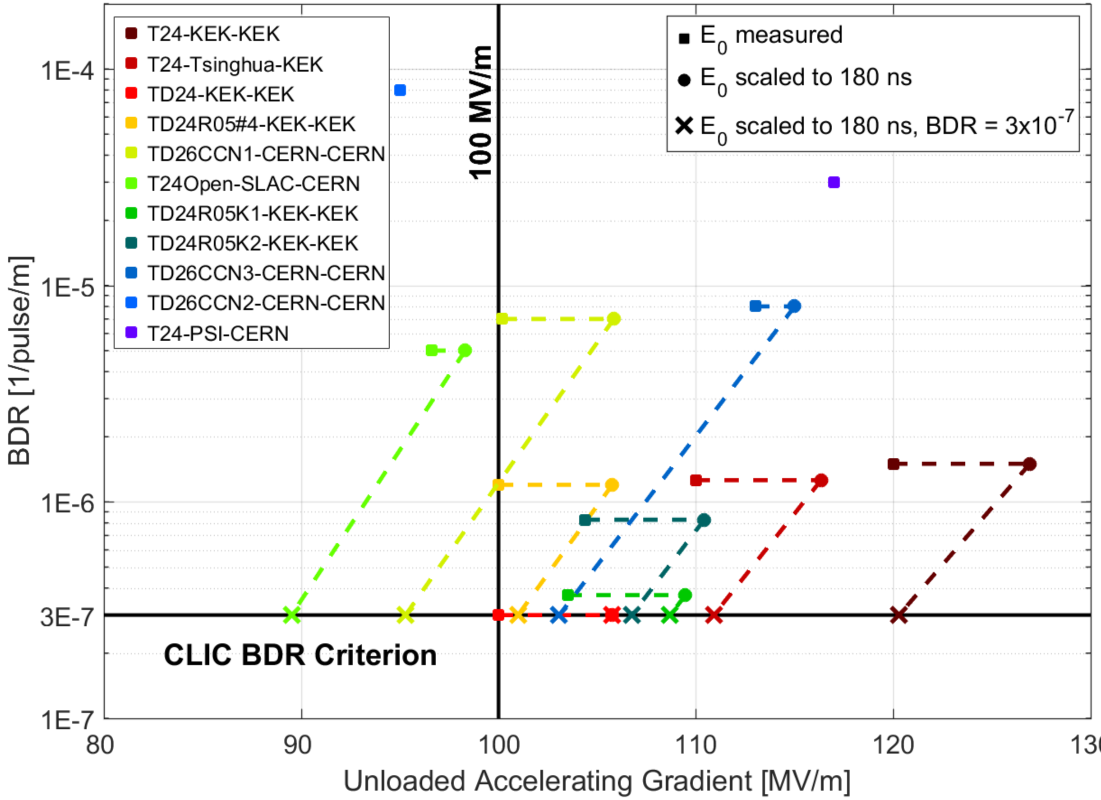


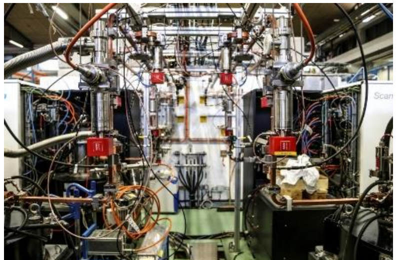


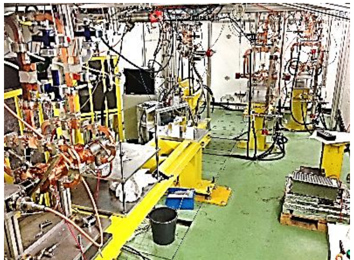
Status

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









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**
	→ 1.2 107 s** (c.f. ILC 1.6 10**7 s)

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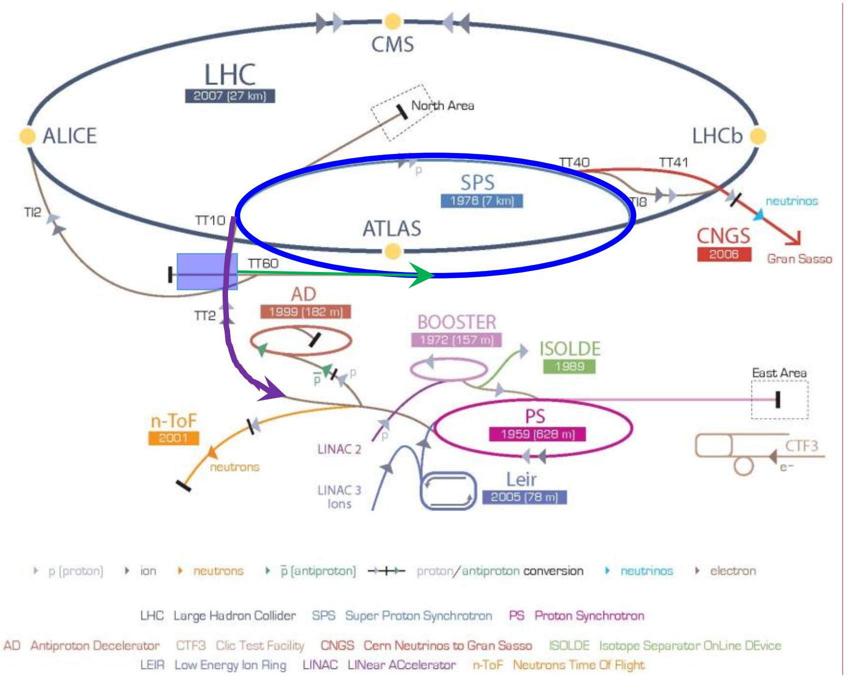

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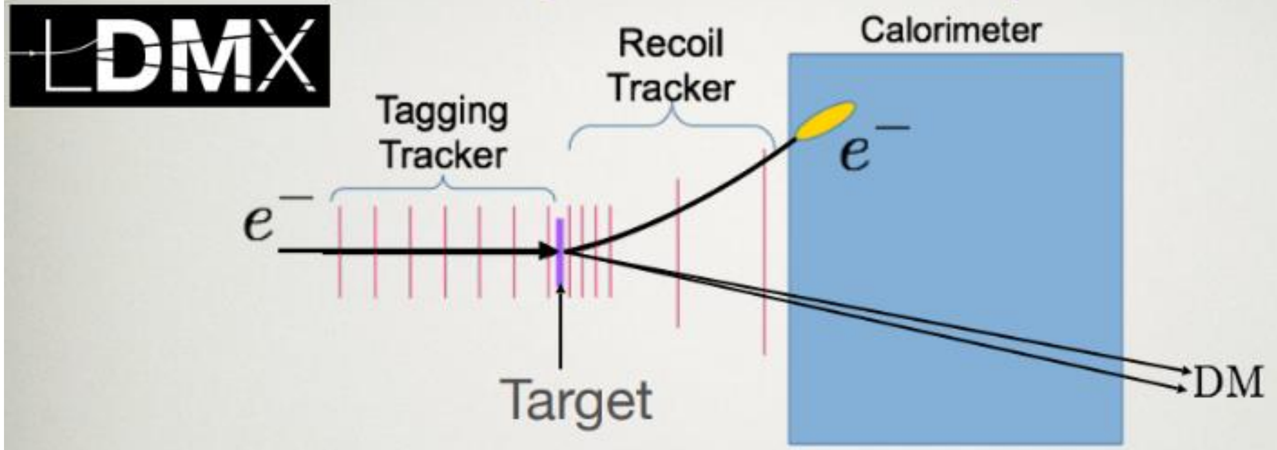
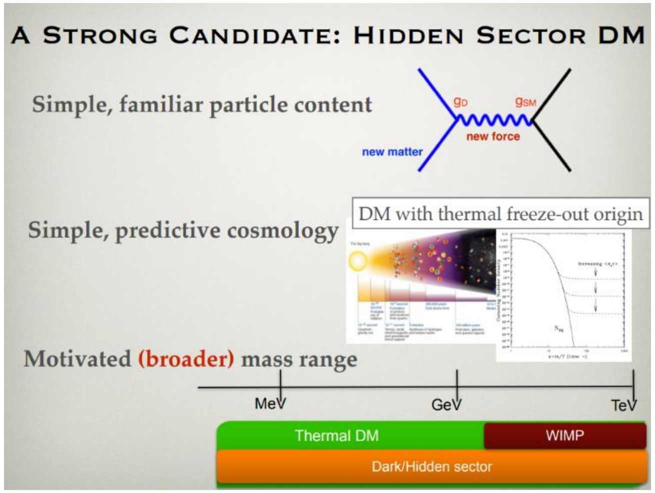
Physics with e-beams, LDMX

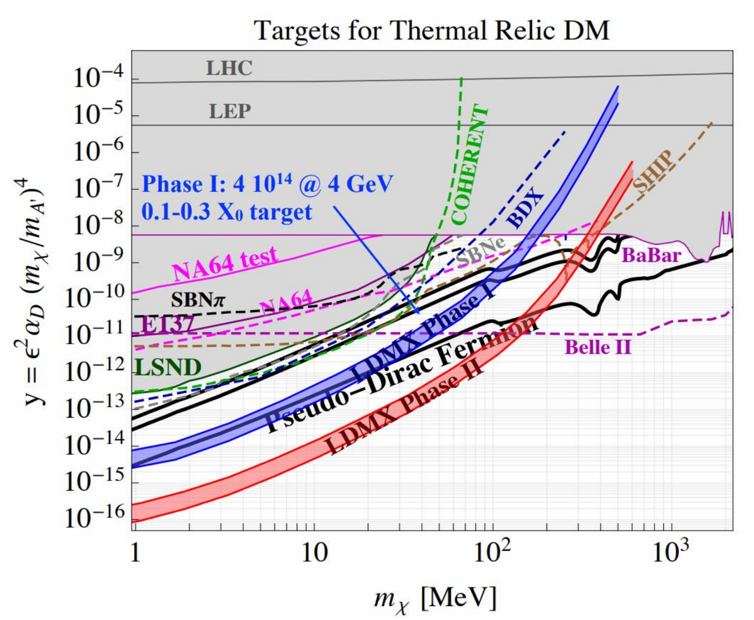
Basic Concept & Beam Requirements

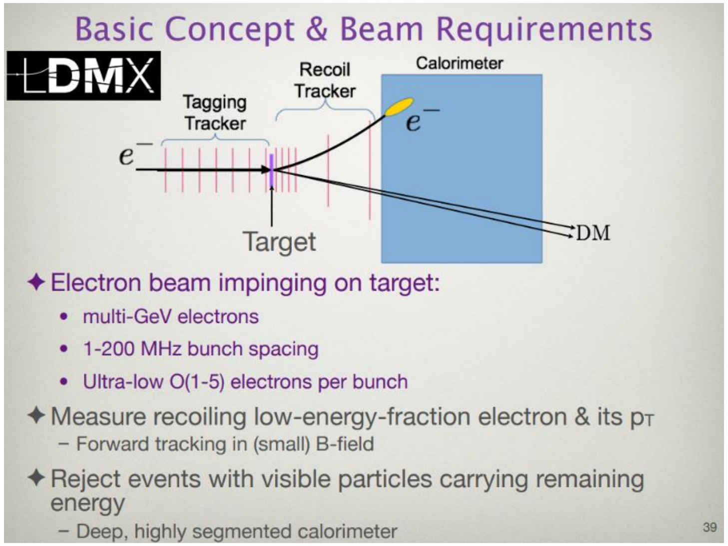


- Electron beam impinging on target:
  - multi-GeV electrons
  - 1-200 MHz bunch spacing
  - Ultra-low O(1-5) electrons per bunch
- Measure recoiling low-energy-fraction electron & its p_T
  - Forward tracking in (small) B-field
- Reject events with visible particles carrying remaining energy
  - Deep, highly segmented calorimeter

Physics with e-beams, LDMX





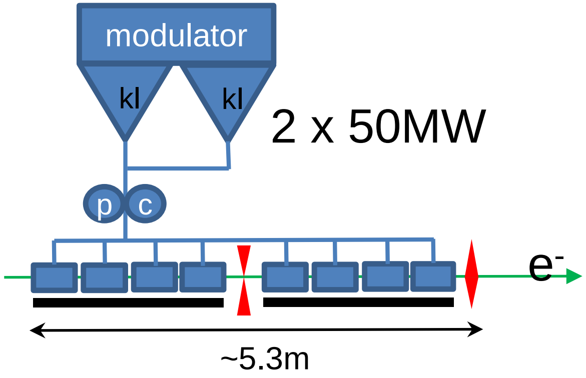


[1]Talk by P. Schuster
Exploring Hidden Sector Physics with an electron beam facility
Physics beyond collider annual workshop
November 21 2017, CERN
indico.cern.ch/event/644287/contributions/2762531/

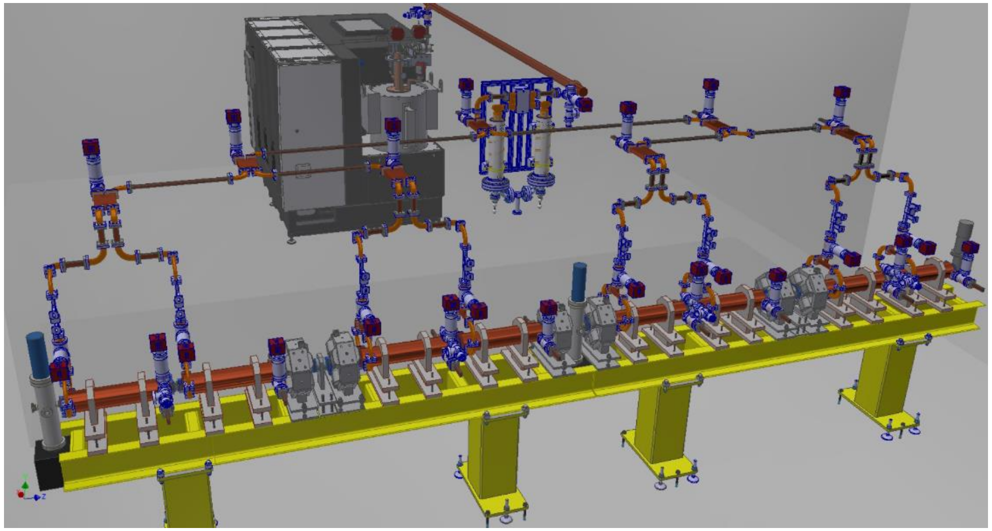
[2] See more about the physics and project in recent talk: T. Åkesson https://indico.lal.in2p3.fr/event/4884/

Linac parameters

- 0.1GeV S-band injector
- 3.4GeV X-band linac
  - High gradient CLIC technology
  - 13 RF units to get 3.4 GeV in ~70 m



Possible parameters	
Energy spread (uncorrelated*)	<1MeV
Bunch charge	52 pC
Bunch length	~5ps
Norm. trans emittance	~10um
N bunches in one train	40
Train length	200 ns
Rep. rate	50/100 Hz



RF design of the X-BAND linac for the EUPRAXIA@SPARC_LAB project
M. Diomede Et al., IPAC18

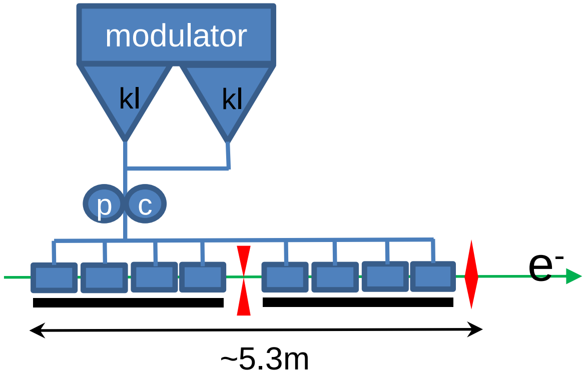
Linac components available

- Examples

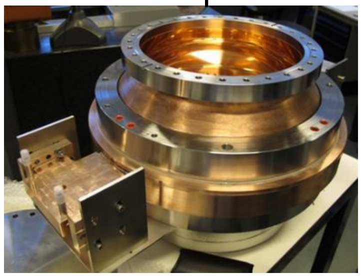
Klystron

Modulator

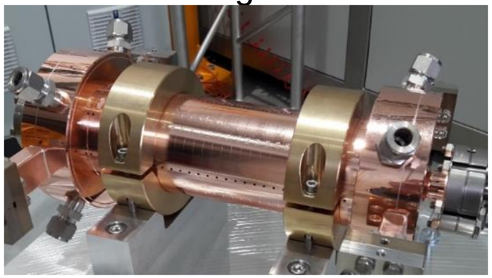
- One RF unit accelerates 200ns bunch train up to 264 MeV



Pulse compressor



Accelerating structure



EoI to SPSC: https://cds.cern.ch/record/2640784