SUPERCONDUCTING DETECTOR MAGNET WORKSHOP

12–14 Sept 2022
CERN
Europe/Zurich timezone

CLIC:
The Compact Linear Collider, Detector and Magnet

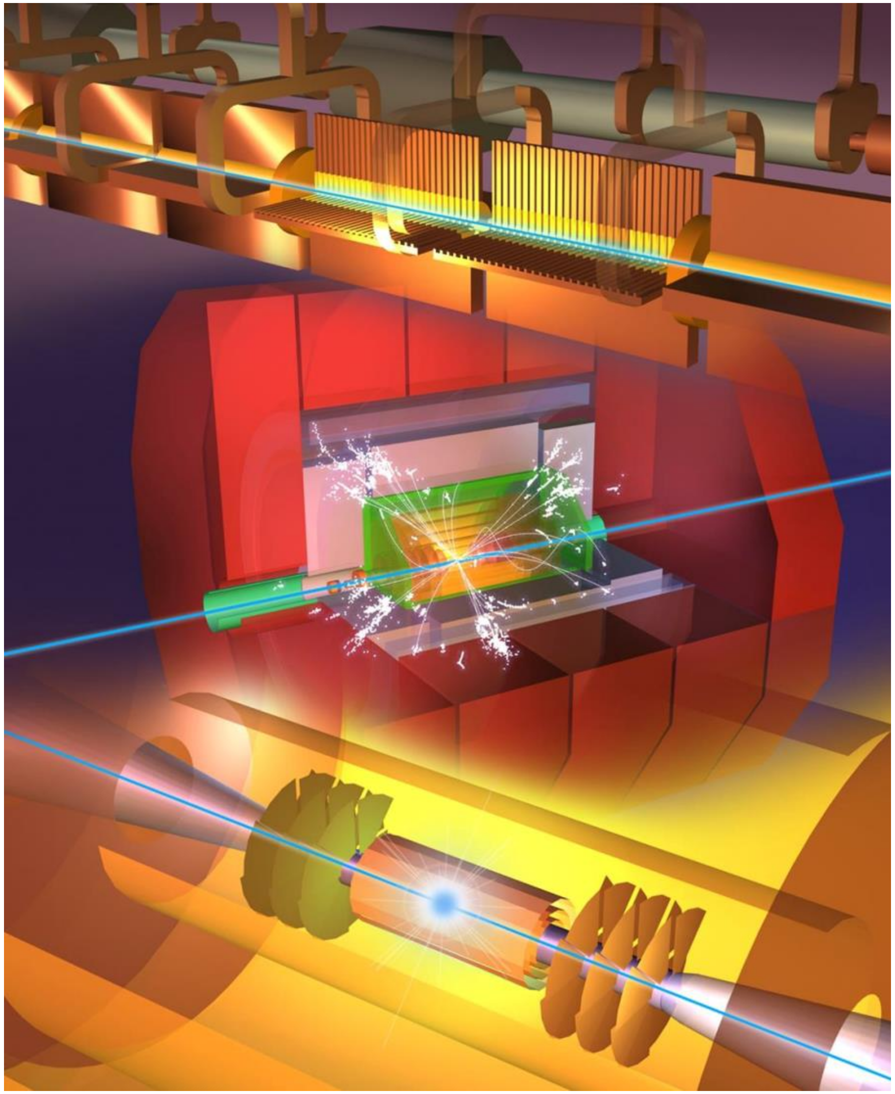
Benoit CURÉ, CERN

On behalf of the CLICdp collaboration

The Compact Linear Collider, Detector and Magnet

Outline

- The CLIC Collaboration
- CLIC physics context
- The CLIC accelerator: overview
- The detector for CLIC
- The CLIC detector magnet
- Summary



CLIC collaboration

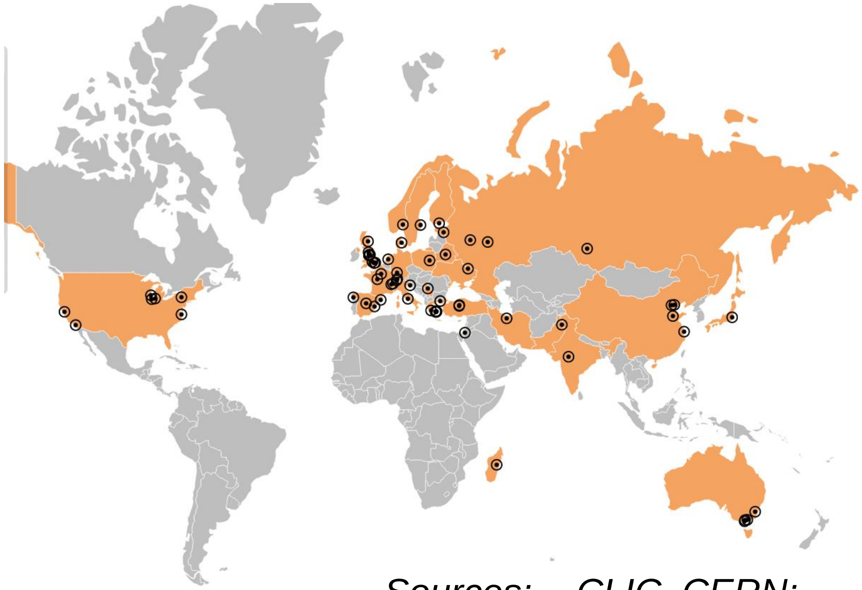
CLIC/CTF3 accelerator collaboration

~70 institutes from **~30 countries**

http://clic-study.web.cern.ch/

CLIC accelerator studies:

- CLIC accelerator design and development
- Construction and operation of CLIC Test Facility



Sources: CLIC, CERN; clic.cern; clicdp.web.cern.ch

CLIC detector and physics (CLICdp)

30 institutes from **18 countries**

http://clicdp.web.cern.ch/

Focus of CLIC-specific studies on:

- Physics prospects and simulation studies
- Detector optimisation + R&D for CLIC

CLIC physics context

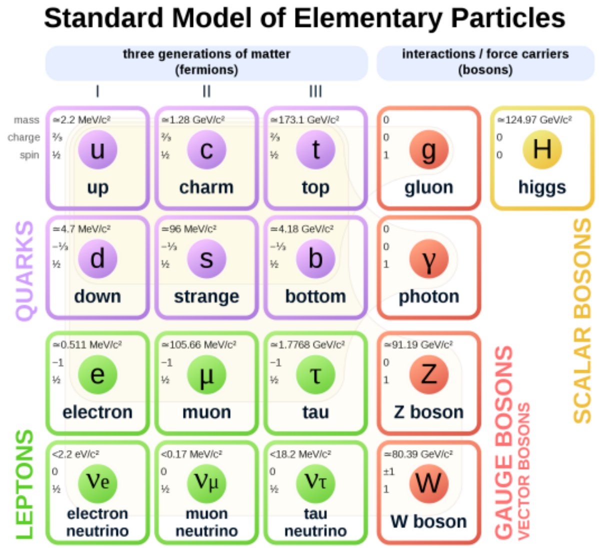
CLIC provides energy-frontier capability for electron-positron collisions, for precision exploration of potential new physics that may emerge from LHC

- The Standard Model of particle physics has been extremely successful (including prediction of the Higgs boson discovered at the Large Hadron Collider)

- However, it does not explain observations of:

  - Dark Matter
  - The baryon-antibaryon asymmetry
  - Light neutrino masses and mixing

- No guaranteed regime where new physics will emerge



→ Exploration of new territory motivates ambitious future colliders

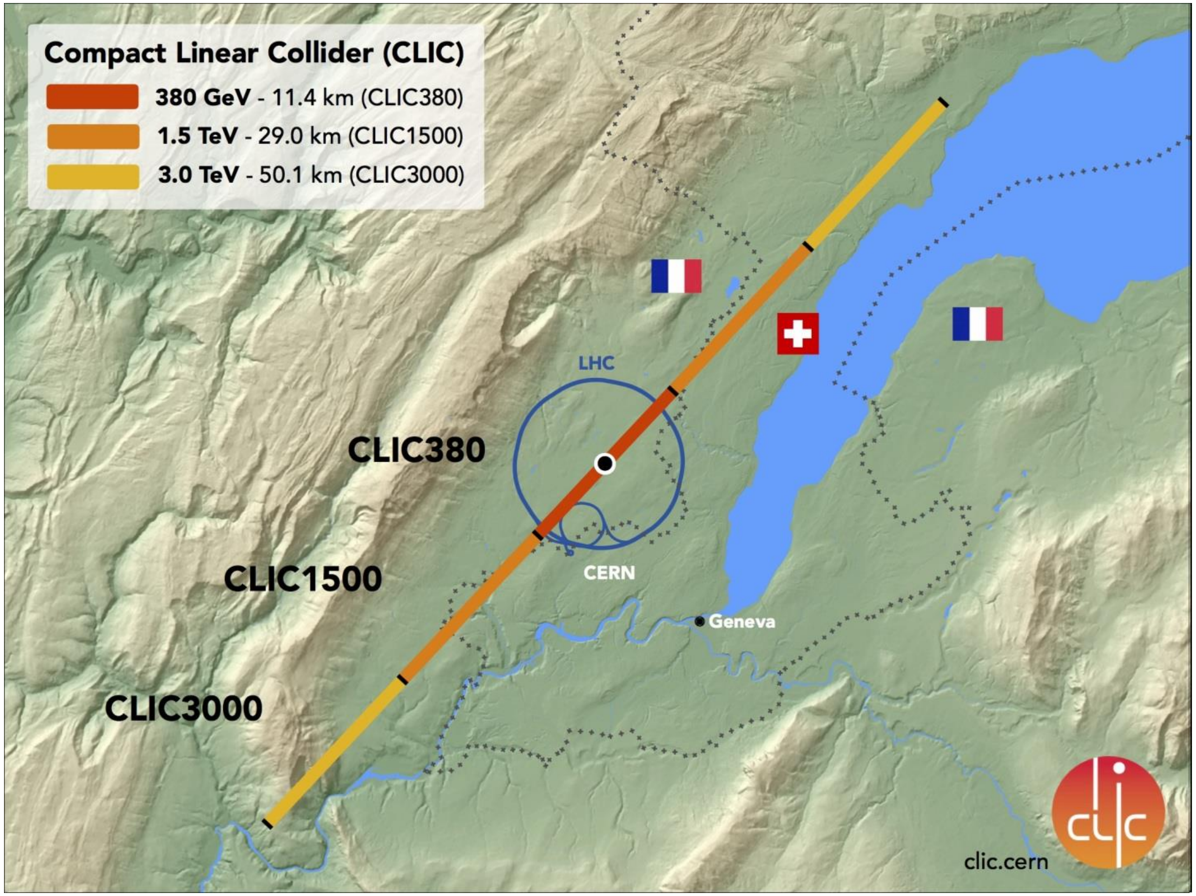
Philipp Roloff, CLIC 2019

CLIC accelerator: overview

- **The Compact Linear Collider (CLIC)** is a proposed accelerator that is being designed as an addition to CERN's accelerator complex.
- Its objective is to **collide electrons and positrons** (antielectrons) head-on at energies of up to several tera-electronvolts (10^{12}eV or TeV).
- For an optimal exploitation of its physics potential, CLIC is intended to **be built and operated in three stages**, at collision energies of **380 GeV, 1.5 TeV and 3 TeV** respectively, for a site length ranging from 11 to 50 km
- **Accelerator optimisation, technical developments and system tests** have resulted in significant progress in recent years including a reduced cost and an increased energy efficiency.

CLIC accelerator: overview

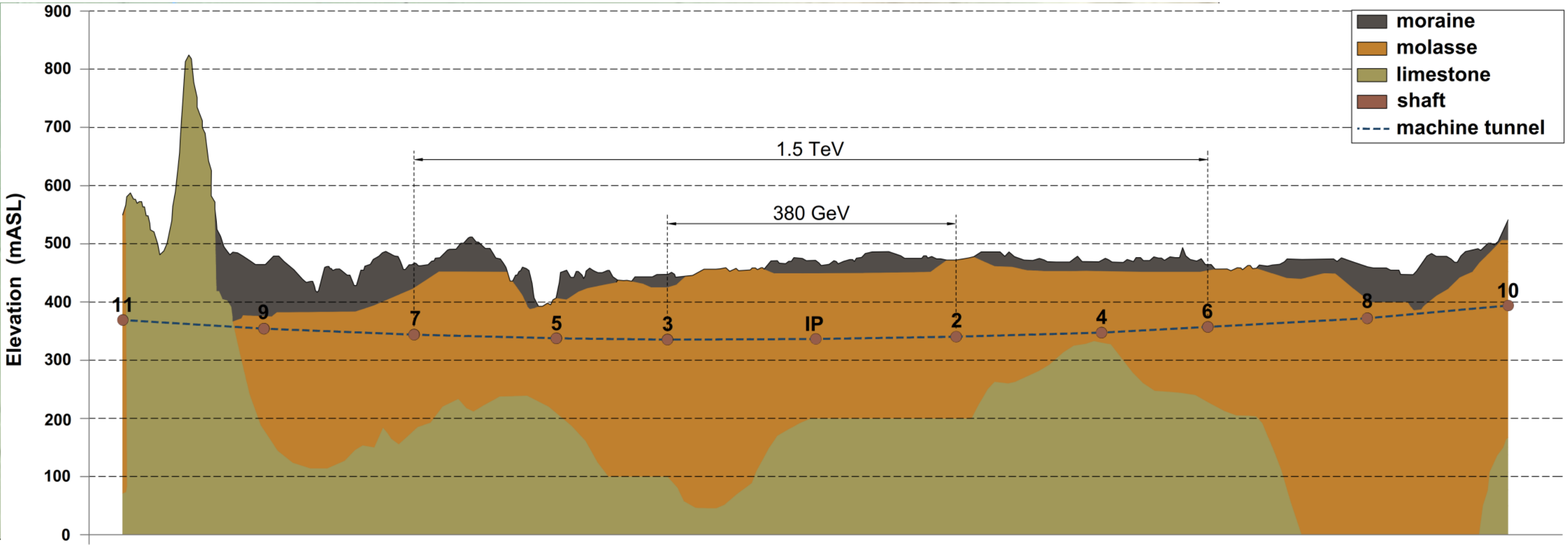
- Optimized design w.r.t. cost and power for a staged approach to reach multi-TeV scales.
- 3 stages:



CLIC accelerator: overview

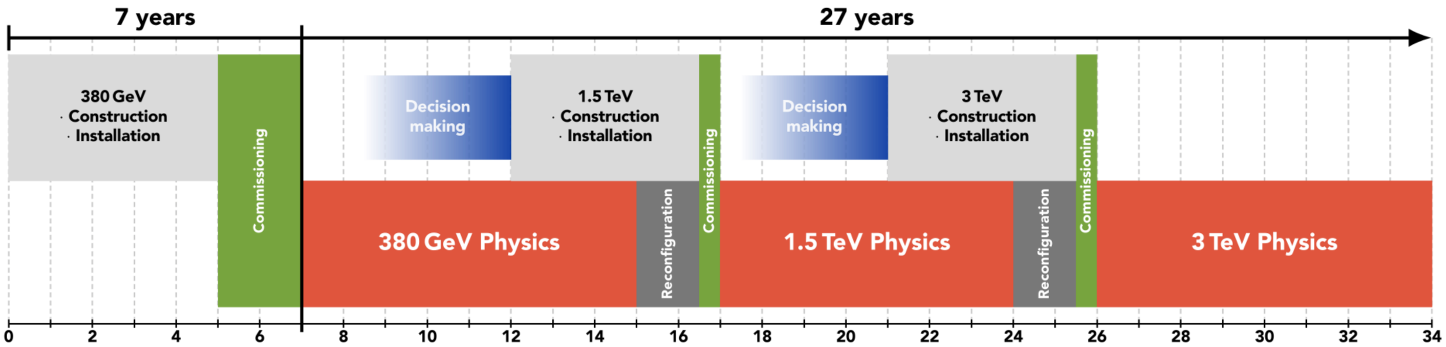
The underground tunnel

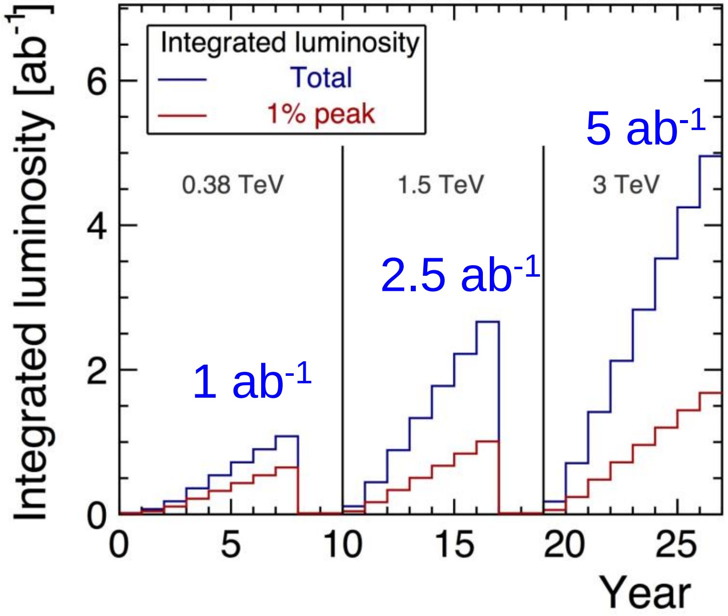
Depth: -100m / -150m



CLIC accelerator: overview

Staging scenario adapting appropriately to LHC + other physics findings





Number of particle collision events per attobarn (= 10^{-42} cm^2) of target cross-section

380 GeV:

- Optimised for precision SM Higgs and top physics

1.5 TeV, 3 TeV:

- Best sensitivity for new physics searches,
- Rare Higgs processes and decays

A. Robson, P. Roloff, Updated CLIC luminosity staging baseline and Higgs coupling prospects, 2018

CLIC accelerator: overview

CLIC Technology : 2-beam acceleration scheme

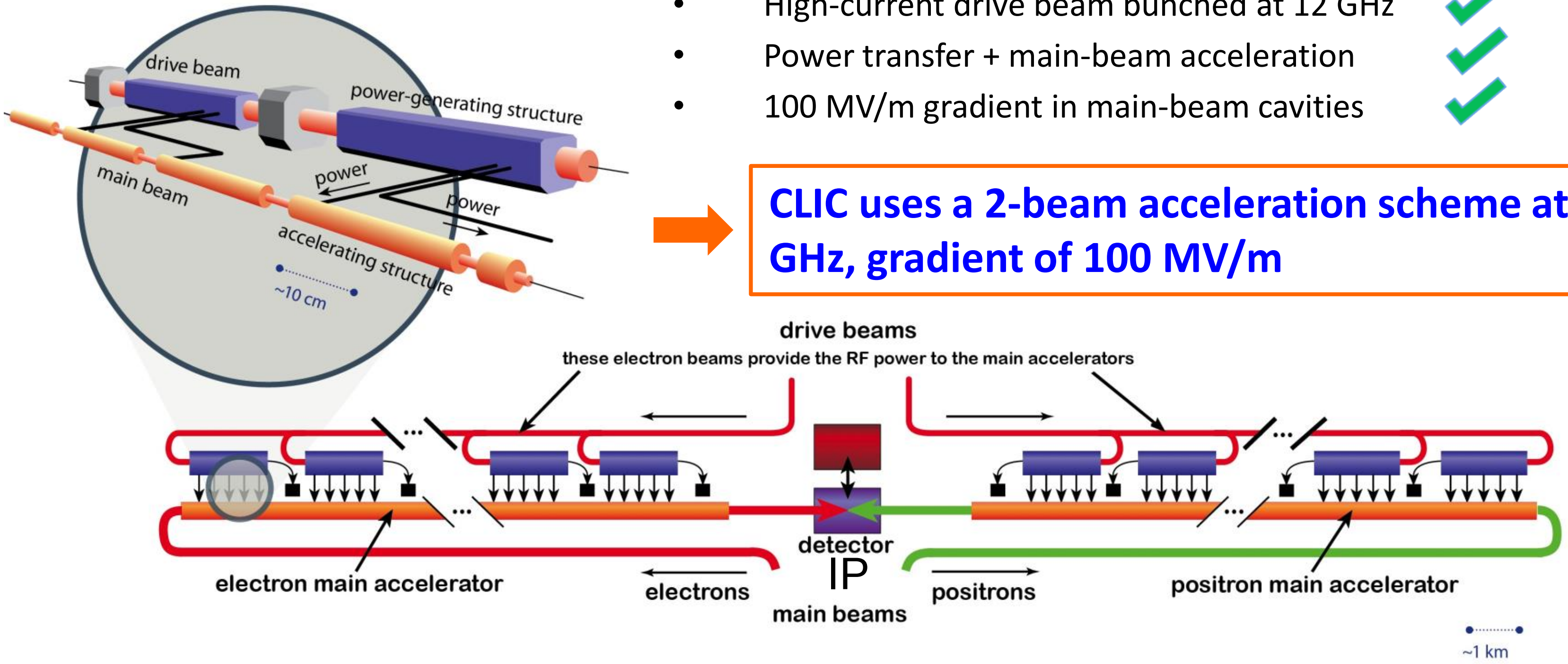
A high intensity "drive beam" is decelerated to produce the **radiofrequency power** needed to accelerate the electrons and positrons of **the "main beam".**

High centre-of-mass energy requires high-gradient acceleration

- High gradients feasible in **normal conducting structures** with high RF frequency (12 GHz)
- Initial transfer from wall plug to beam (klystron) is efficient at lower frequency (~1 GHz)
- To keep power low, apply RF power only at the time when the beam is there.

Key technical challenges for CLIC :	**solved**
• High-current drive beam bunched at 12 GHz	✓
• Power transfer + main-beam acceleration	✓
• 100 MV/m gradient in main-beam cavities	✓

CLIC uses a 2-beam acceleration scheme at 12 GHz, gradient of 100 MV/m

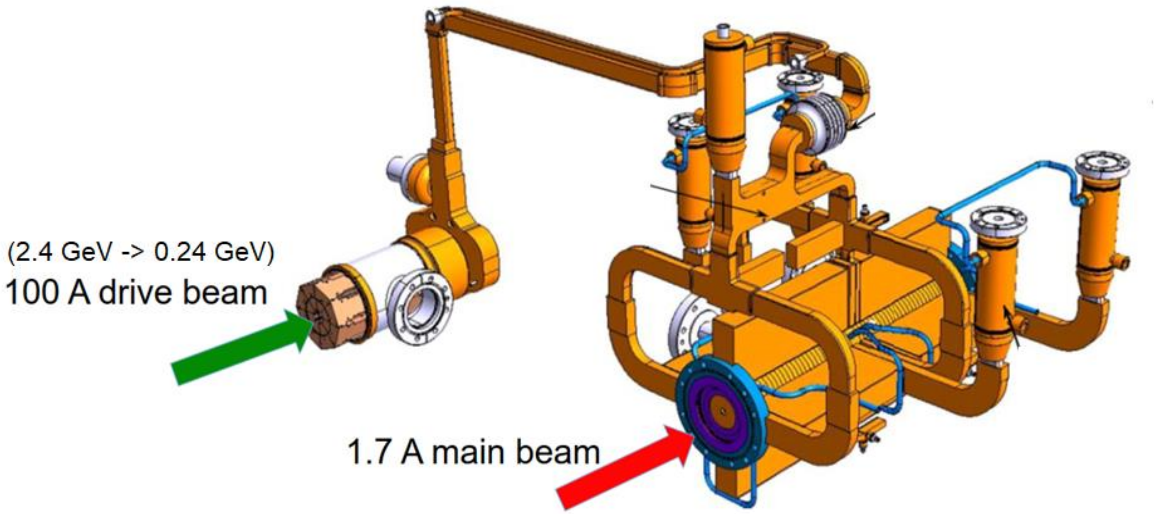


CLIC accelerator: overview

CLIC 2-beam acceleration scheme

- The short and intense electron pulses of the "**drive beam**" are produced by **interleaving bunches** in a delay loop and two combiner rings.
- The "**main beams**" have their independent "guns", pre-accelerating and damping rings followed by a long transfer line to beginning of their respective linear accelerator.
- **Synchronization** of the arrival time of "drive beam" and "main beam" bunches is crucial.

Modular system:

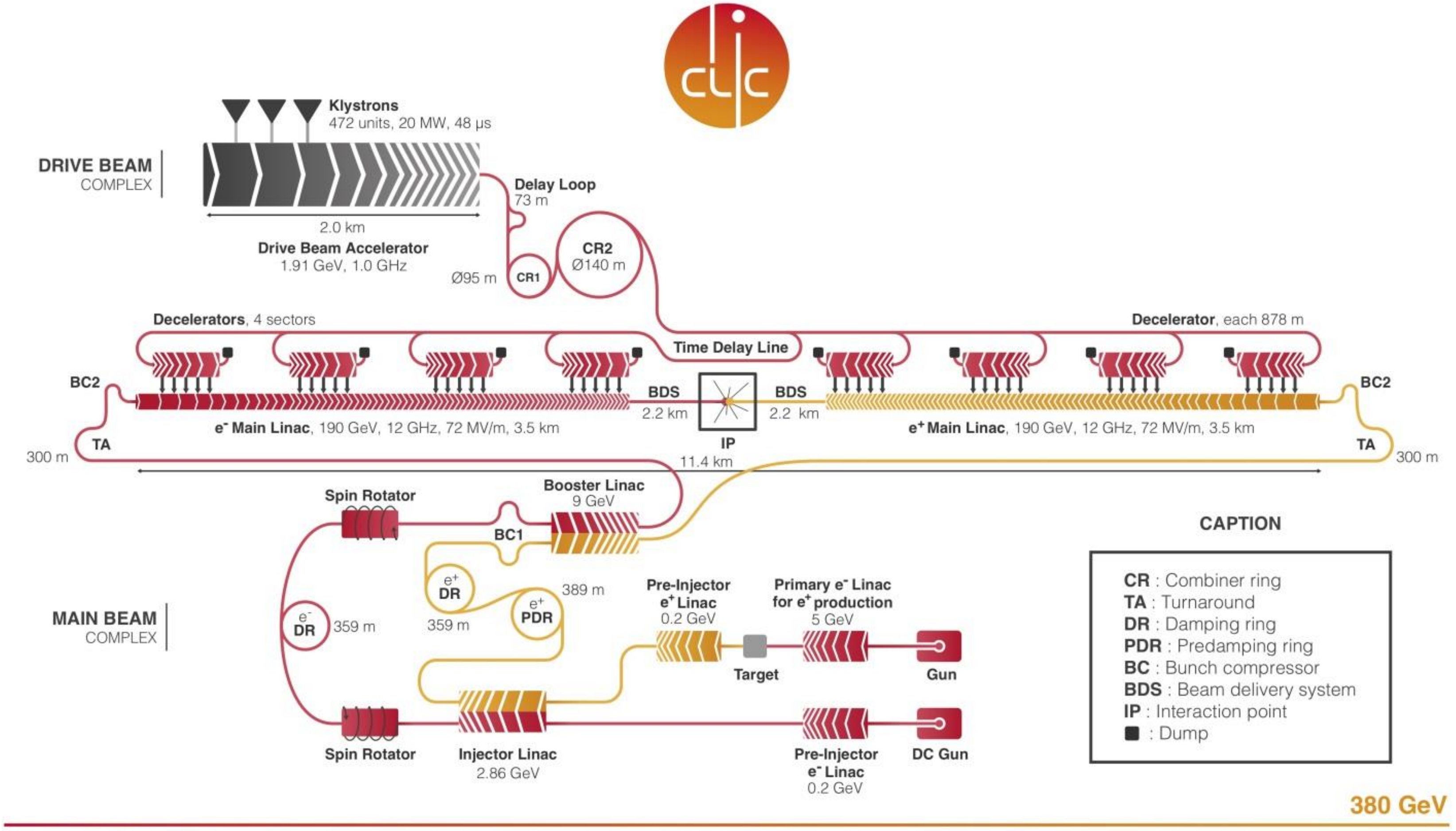


Drive Beam supplies RF power
- 12 GHz bunch structure
- low energy (2.4 GeV - 240 MeV)
- high current (100A)

Main beam for physics
- high energy (9 GeV – 1.5 TeV)
- current 1.7 A

CLIC accelerator: overview

First stage:



CAPTION

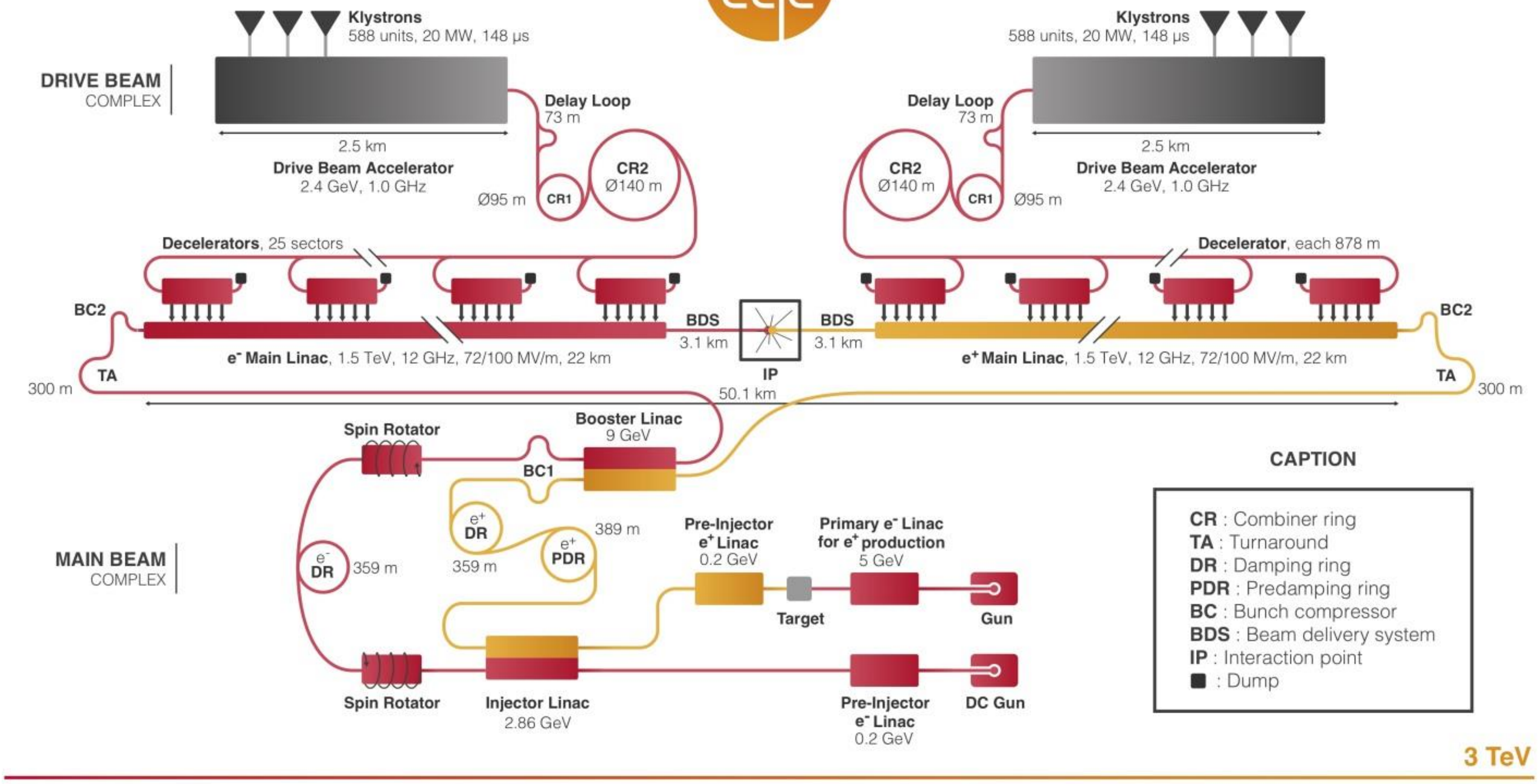
CR : Combiner ring
TA : Turnaround
DR : Damping ring
PDR : Predamping ring
BC : Bunch compressor
BDS : Beam delivery system
IP : Interaction point
■ : Dump

CLIC - Scheme of the Compact Linear Collider (CLIC)

CLIC accelerator: overview

Next stages:

- re-use systems / components
- Add linac and drive pulse length
- at 3 TeV, add 2nd drive beam



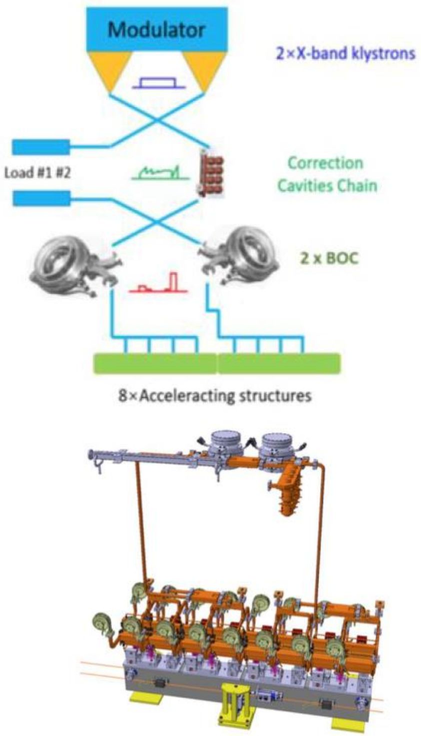
CLIC - Scheme of the Compact Linear Collider (CLIC)

CLIC accelerator: overview

Several paths of development aiming at saving power and energy have been identified and are under investigation.

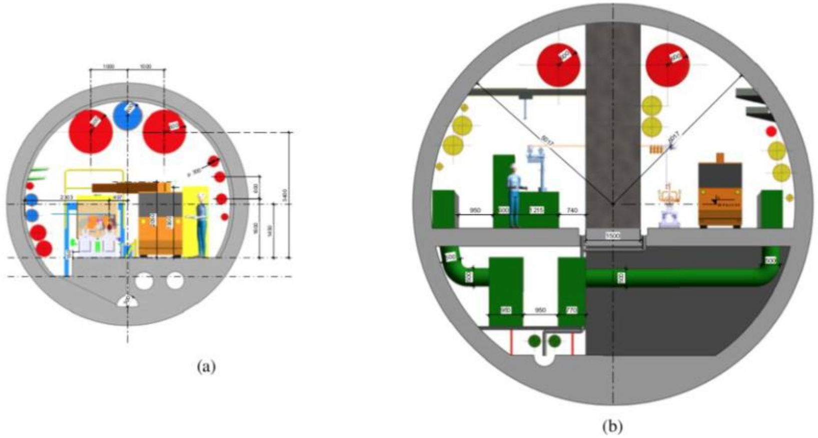
An alternative to the CLIC drive beam scheme : the main linac power is produced using X-band klystrons.

380 GeV klystron option



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

Simpler module, larger tunnel **(inner diameter from 5.6 m to 10 m)**



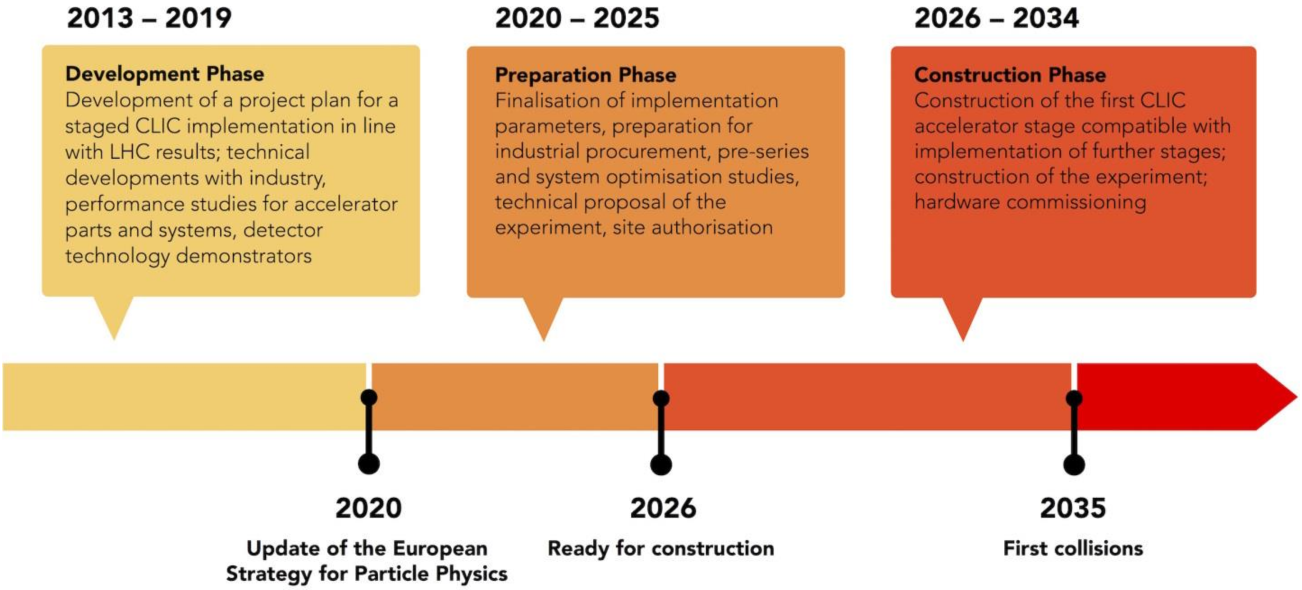
(a)

(b)

Philipp Burrows, ICHEP 2020, CLIC Status and plans

CLIC accelerator: overview

Initial plans revised according to European Committee for Future Accelerator roadmap, **with continuation of R&D studies, optimization and design**.



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

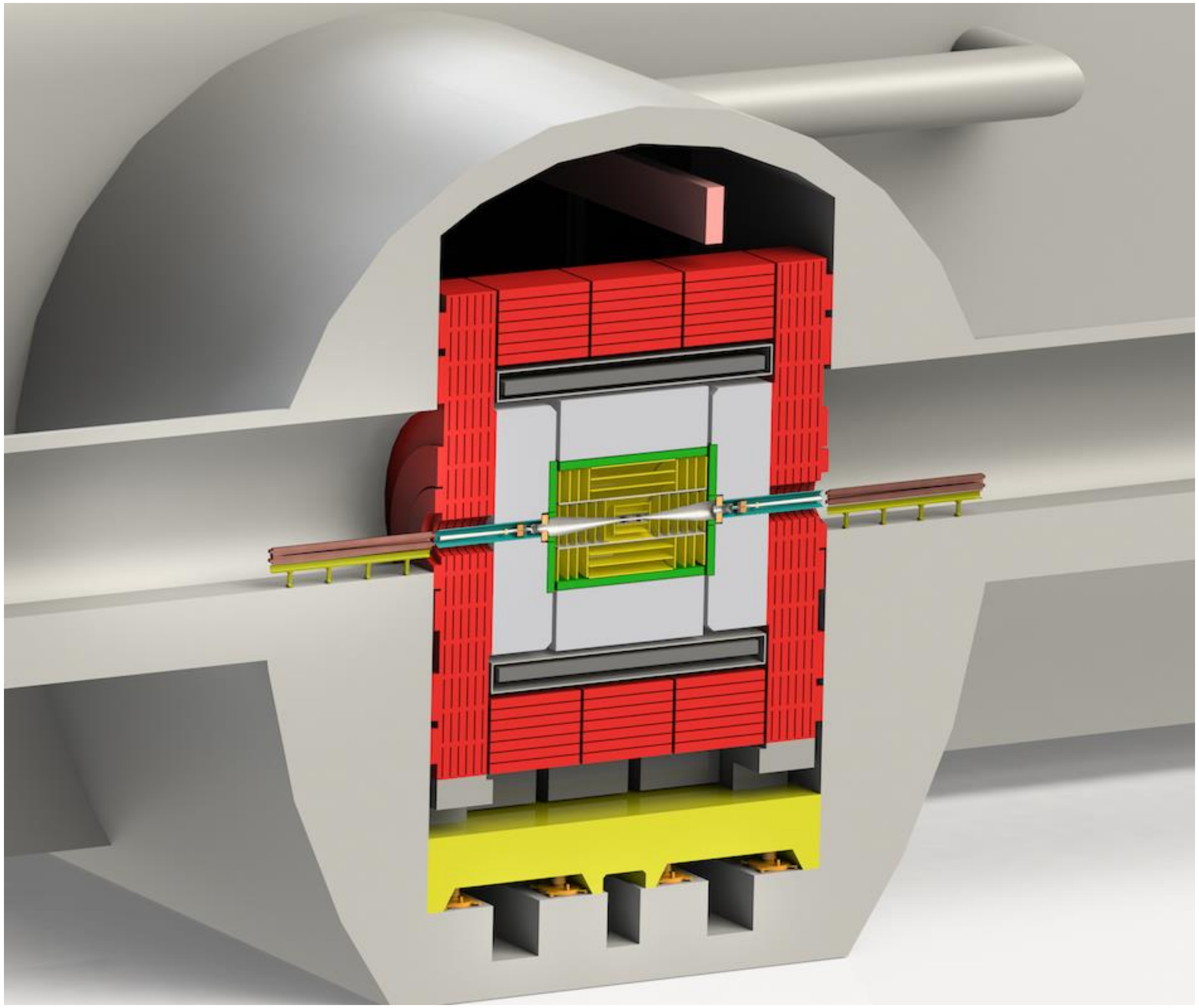
Construction Phase
Construction of the first CLIC accelerator stage compatible with implementation of further stages; construction of the experiment; hardware commissioning

2020
Update of the European Strategy for Particle Physics

2026
Ready for construction

2035
First collisions

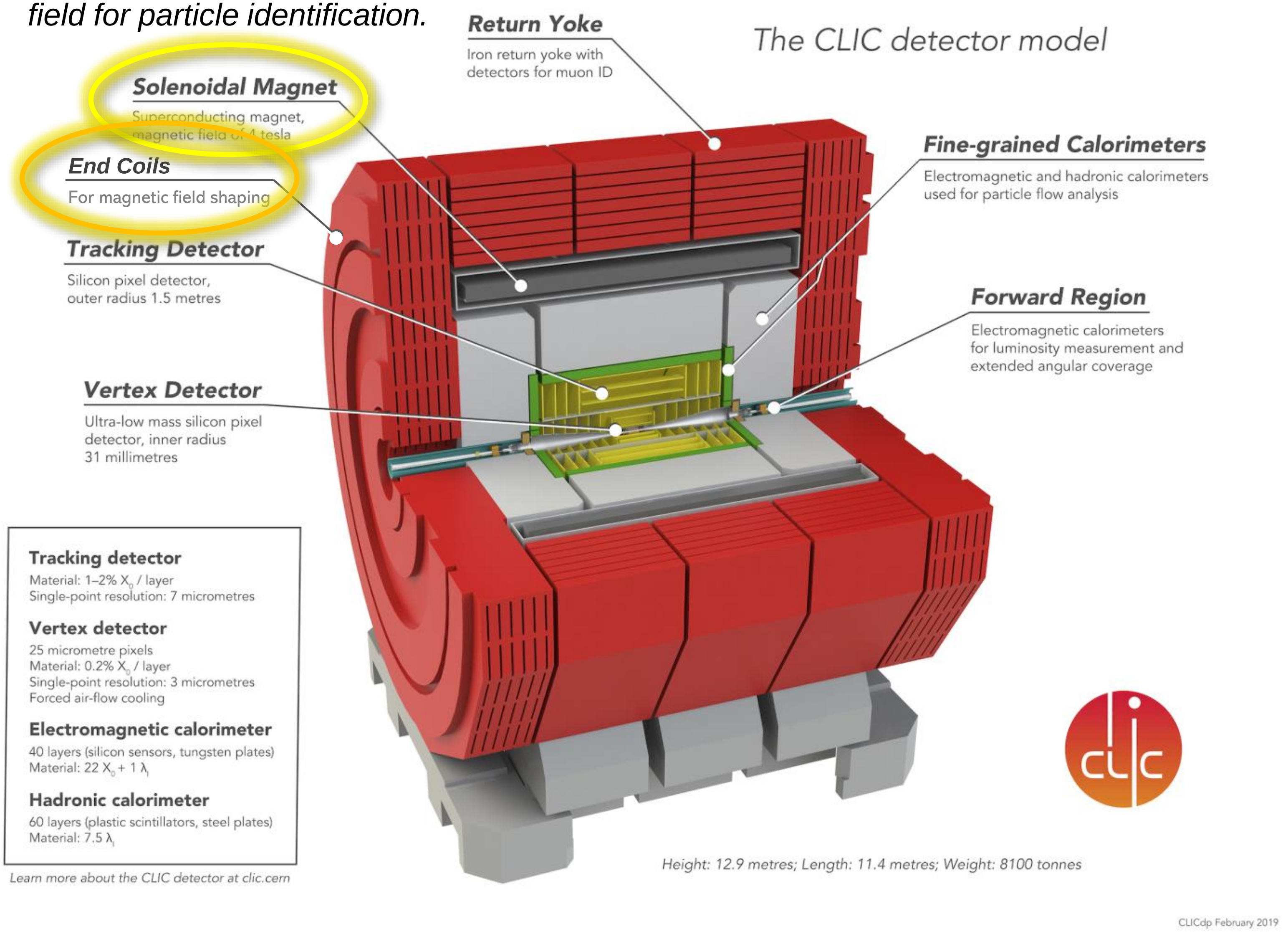
CLIC detector



The CLIC detector at the Interaction Point

CLIC detector

Magnet provides background field for particle identification.



The CLIC detector model

Return Yoke
Iron return yoke with detectors for muon ID

Solenoidal Magnet
Superconducting magnet, magnetic field of 4 tesla

End Coils
For magnetic field shaping

Tracking Detector
Silicon pixel detector, outer radius 1.5 metres

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

Fine-grained Calorimeters
Electromagnetic and hadronic calorimeters used for particle flow analysis

Forward Region
Electromagnetic calorimeters for luminosity measurement and extended angular coverage

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

Learn more about the CLIC detector at clic.cern

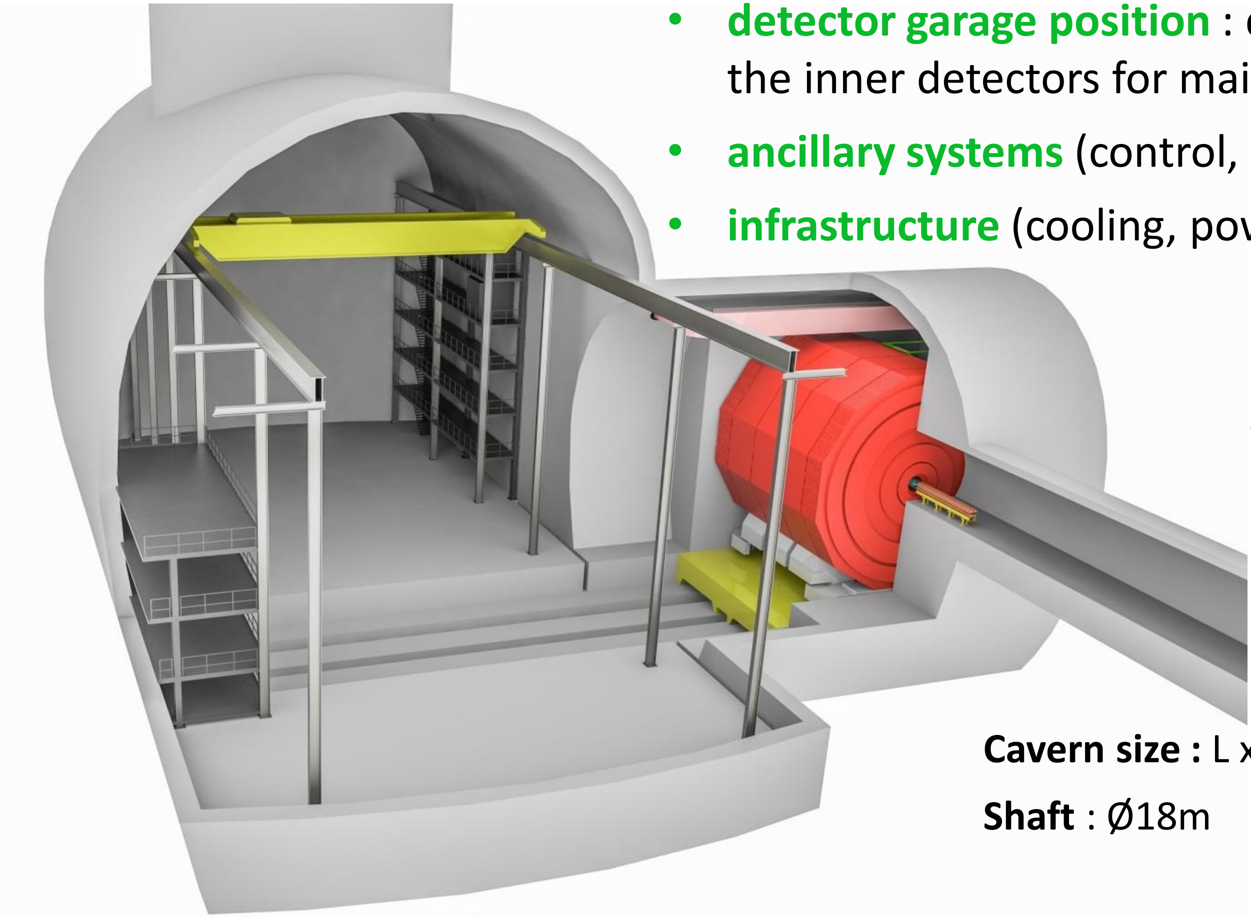
Height: 12.9 metres; Length: 11.4 metres; Weight: 8100 tonnes

CLICdp February 2019

CLIC detector

Experimental underground cavern :

- Main cavern for detector access and maintenance
- Alcove for detector at accelerator IP
- detector garage position : detector opening to access the inner detectors for maintenance and upgrades.
- ancillary systems (control, safety, etc.),
- infrastructure (cooling, power, HVAC, DAQ, etc.).



depth about 100 m

Cavern size : L x l x H = 62 x 31 x 33 m

Shaft : Ø18m

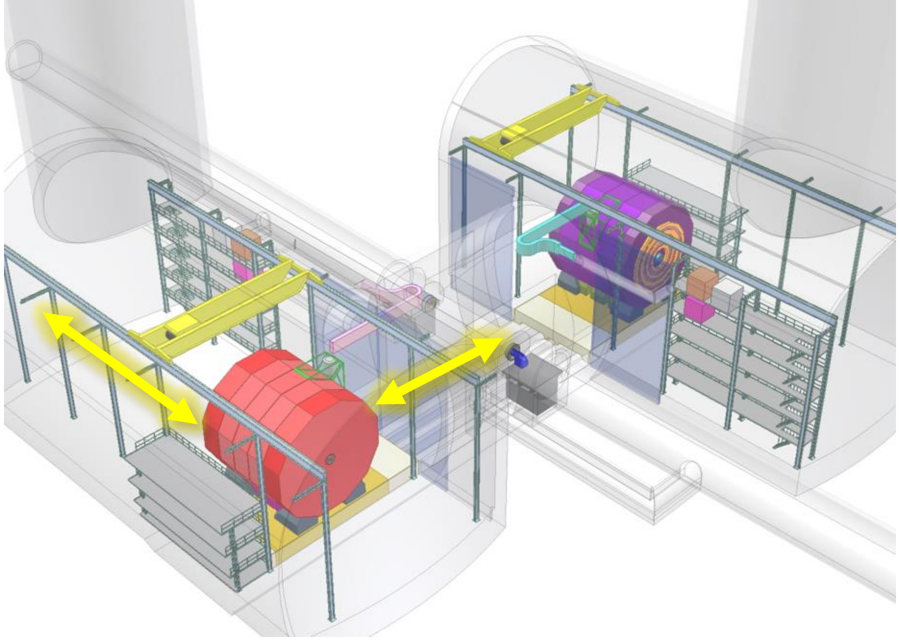
CLIC detector

Experimental underground cavern :

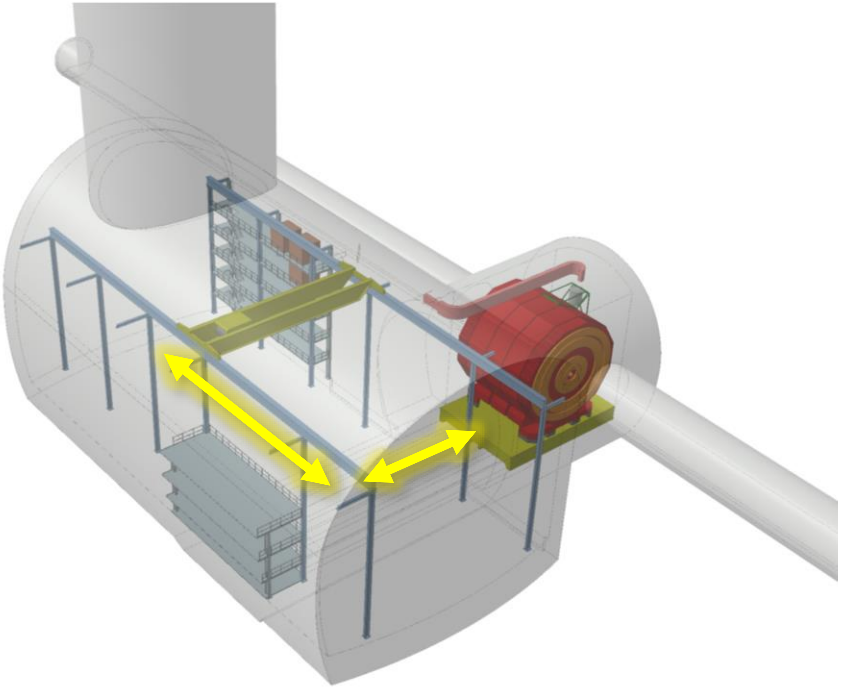
Original plan was with 2 different detectors sharing the same IP and a push-pull system with a mobile platform for each detector.

In latest design with one detector only: plateform kept for the detector move from IP to garage position.

Original plan



Latest cavern layout



CLIC detector

Technological Challenges addressed for Detector Magnet in Push-Pull configuration (*A. Gaddi, CERN*):

Avoid Magnets' services disconnection to keep magnet cold during Push-Pull with:

- Flexibles fore vacuum pumping lines,
- Flexibles cryogenics lines (*similar to ATLAS end-cap toroid*)
- Max acceleration during push-pull at 0.05g.

Flexibles superconducting powering lines

- A permanent connection of the solenoid power supply to the coil current leads would save time and avoid risks associated with connection & disconnection.
- Superconducting lines provide a gain on space and voltage drop wrt resistive lines
- *Similar to MgB_2 superconducting links developed at CERN for HL-LHC.*

Prototypes of the multi-cables HTS powering line (courtesy A. Ballarino)

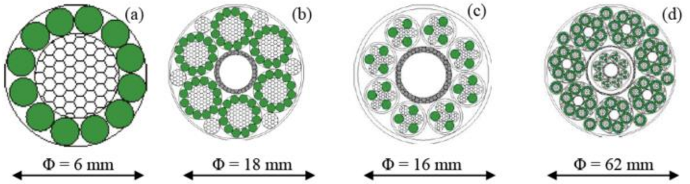


Figure 1. Layout of: 3 kA cable (a), 14 kA cable (b), group of 8 × 0.6 kA cables (c), configuration of 7 × 14 kA, 7 × 3 kA and 8 × 0.6 kA cables (d). The MgB_2 is shown solid, the copper is shown hatched.

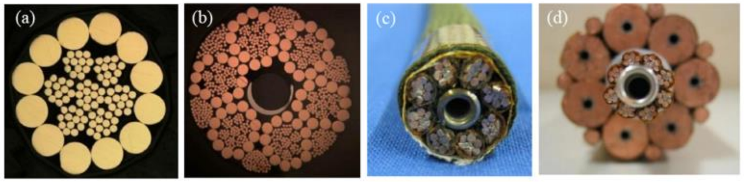


Figure 2. Mock-up of: 3 kA cable (a), 14 kA cable (b), group of 8 × 0.6 kA cables (c), configuration of 7 × 14 kA, 7 × 3 kA and 8 × 0.6 kA cables (d). The external diameter of each assembly is reported in Figure 1.

Amalia Ballarino, 2014, Supercond. Sci. Technol.

Superconducting links developed for HL-LHC upgrade

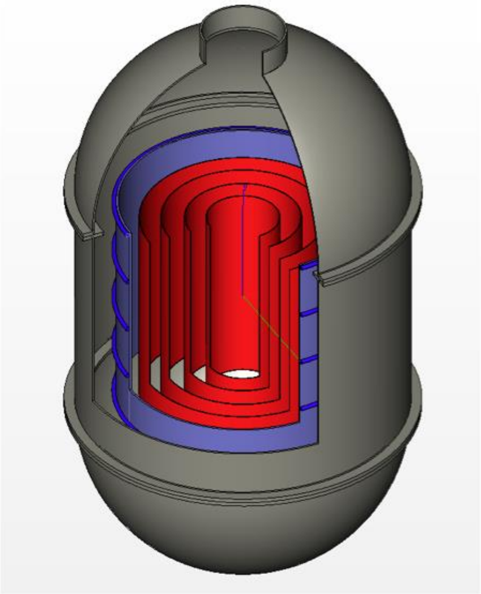
CLIC detector

Technological Challenges addressed for Detector Magnet in Push-Pull configuration (*A. Gaddi, CERN*):

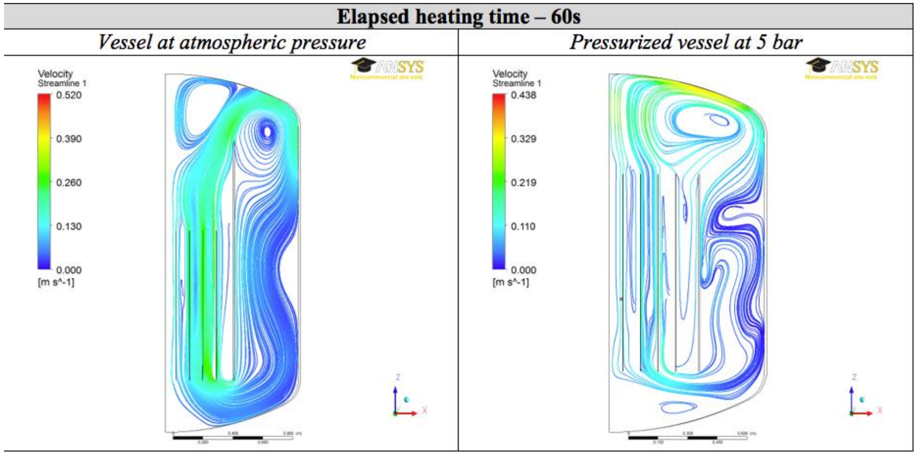
On-board compact dump resistor to safely discharge the magnet energy.

Main characteristics of the compact dump resistor

Water pressure (bar abs)	Water volume (m^3)	Enthalpy (15–100°C) (kJ/kg)	Total energy (MJ)	Peak power (MW)
1.0	3.6	355	1.28	12



3D model of a compact passive water cooled dump resistor

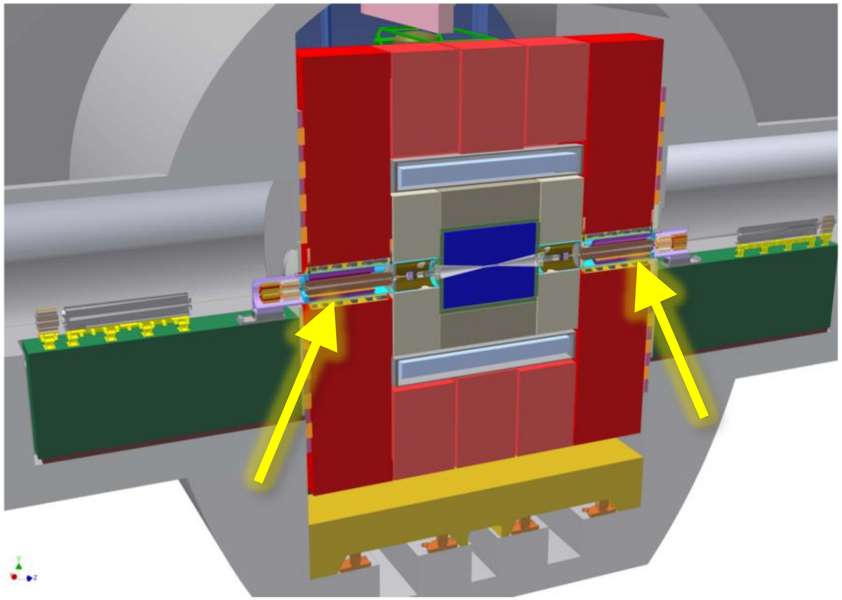


Thermo-fluid dynamic simulation of the compact water cooled dump resistor

CLIC detector

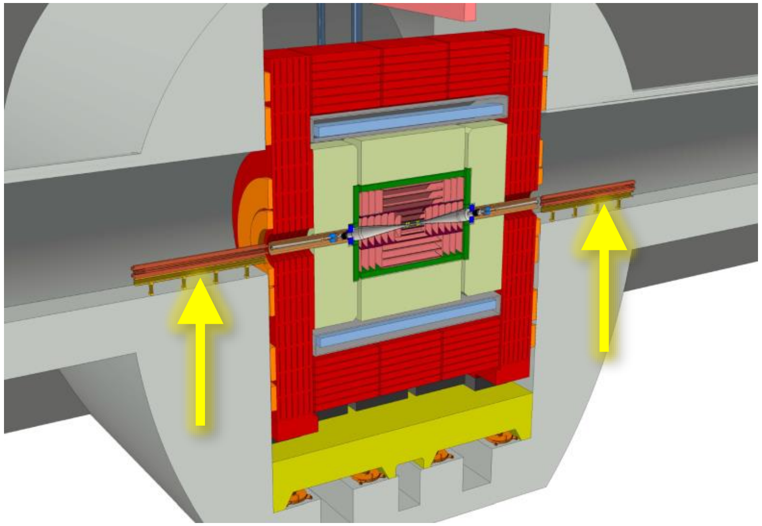
Machine-Detector Interface: position of quadrupole QD0 needed for final beam focusing

Initial layout : QD0 inside detector L*=3.5m



- Special support of QD0 inside the detector,
- Pre-insulator system against vibration (δr < 0.1nm),
- Complex access with reduced space for intervention,
- Anti-solenoid to shield against main solenoidal field.

Revised layout: QD0 inside tunnel L*=6m



- **Reduced yoke** (end-cap and barrel),
- **No pre-insulator** required,
- **Easier access** for intervention,
- **Stray field zeroed** near QD0 by end-coils,
- Gain in **detector detection range (acceptance).**

F. Plassard et.al., CLIC Workshop 2018

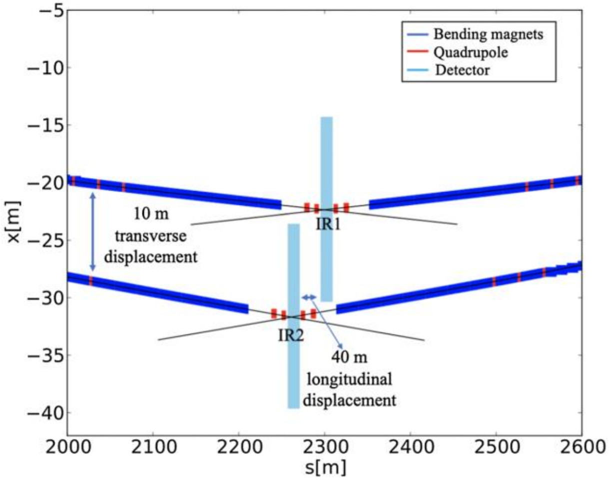
CLIC detector

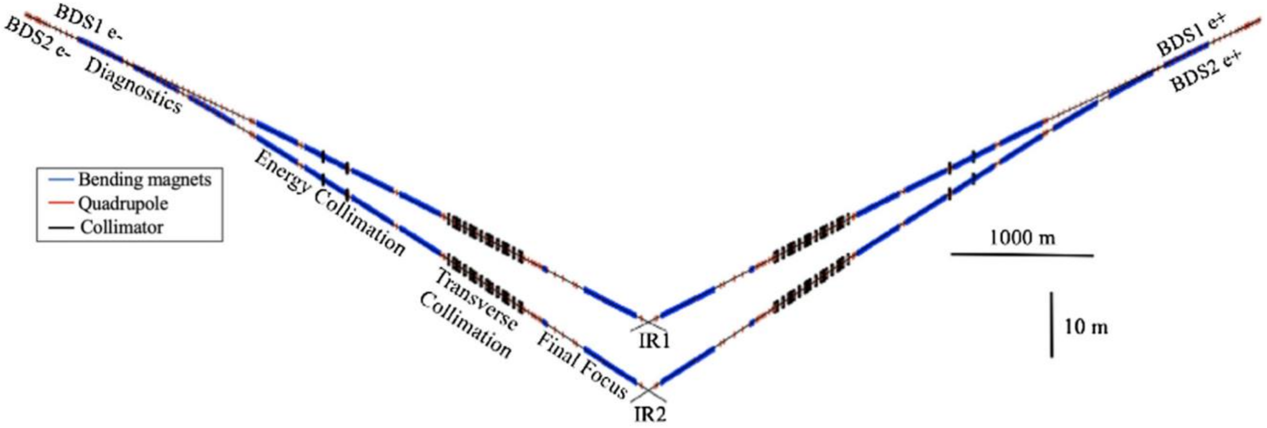
Recent works on a Dual Beam Delivery System :

Study of luminosity performance with 2 interaction regions (2 detectors) with different crossing angles.

Vera Cilento et.al.,
Dual beam delivery system serving two interaction regions for the Compact Linear Collider,
PHYSICAL REVIEW ACCELERATORS AND BEAMS 24, 071001 (2021)

Top view of interaction regions

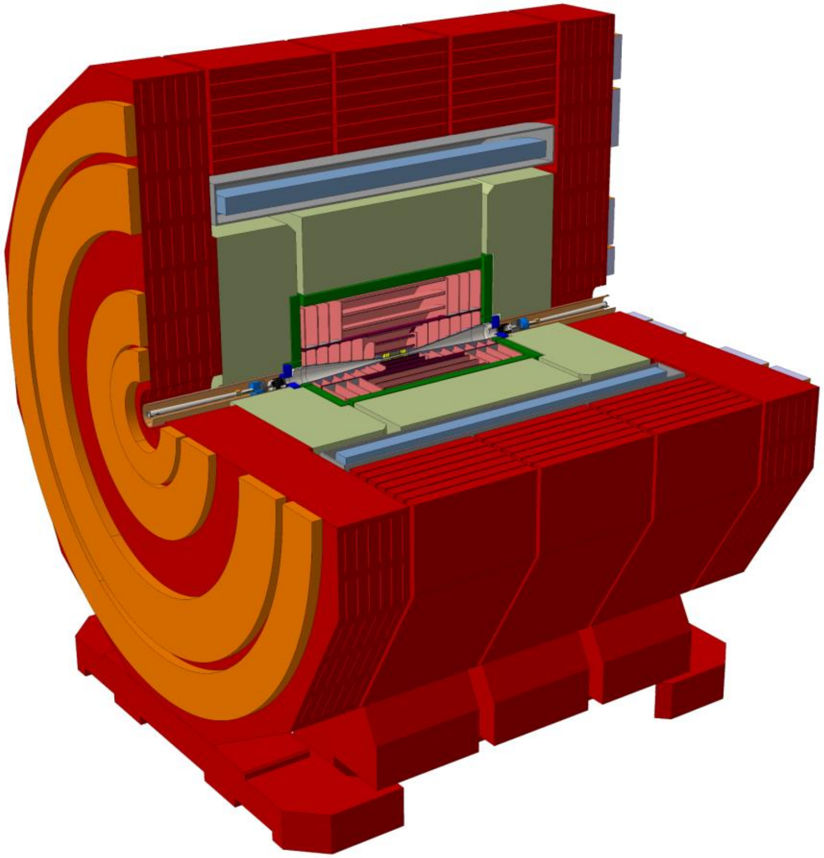




Layout of the new dual CLIC 3 TeV BDS system for two IRs.

CLIC detector magnet

The Conceptual Design



Reference: N. Alipour et al., *CLICdet: The post-CDR CLIC detector model,* CLICdp-Note-2017-001 (revised 05 April 2019), CERN 2017-03-01.-42. *https://cds.cern.ch/record/2254048*

CLIC detector magnet

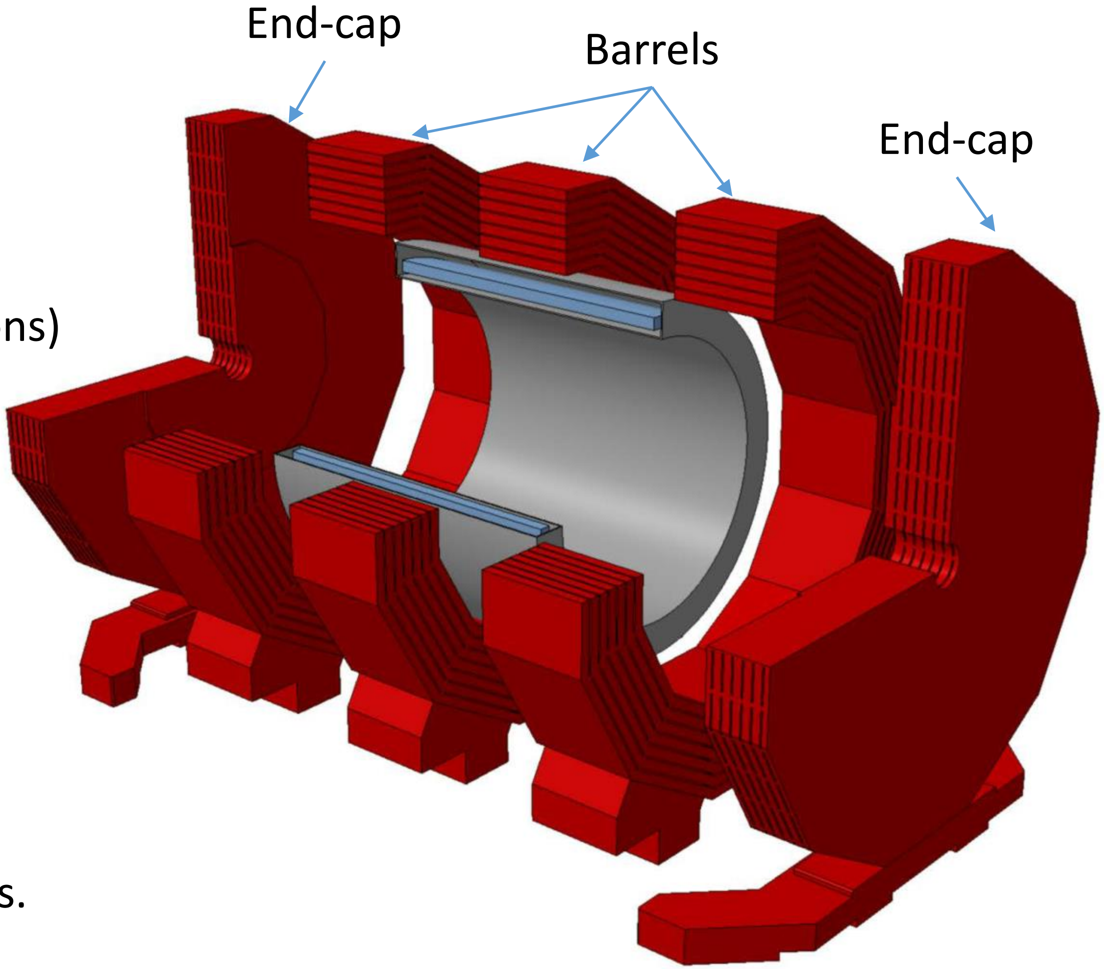
The magnet and its iron yoke

- One superconducting solenoid
- 2x4 end coils
- 3 iron barrels
- 2 end cap iron disks

Total weight: **8100 tons** (iron: 6400 tons)

Dimensions

- External diameter : **12.9m**
- Total length: **11.4m**
- Coil vactank bore radius: **3.5m**
- Coil vactank length: **8.3m**



Detector opening/closing:
airpad + hydraulic jack systems.

End coils are attached to the end caps.

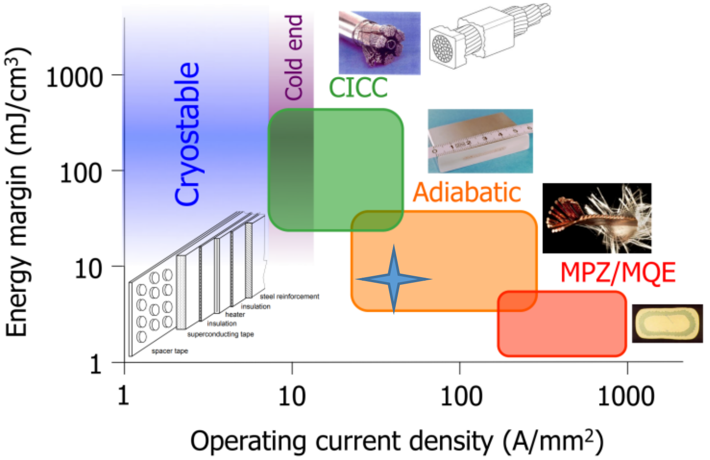
SC solenoid in a stainless steel vacuum tank fixed to the central barrel.
Vacuum volume for thermal insulation at 1e-6 mbar.

CLIC detector magnet

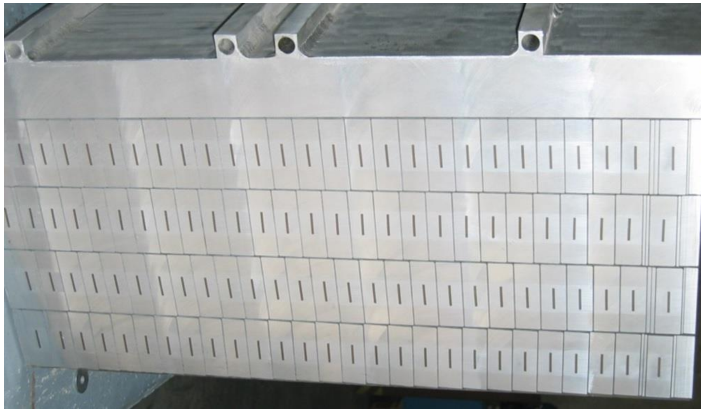
The superconducting solenoid – conceptual design

- **4-T solenoid** that follows **same concept and manufacturing methods as the CMS magnet:** aluminium stabilized conductor (*thermal and electrical conductivity, bonding SC/stab, indirect cooling,* ***enthalpy stabilisation***).
- **Conductor:**
  NbTi/Cu Rutherford cable cooled at 4.2K,
  Reinforced aluminium stabilized superconductor.
- **Winding:**
  External aluminium mandrel (50mm-thick),
  Modular coil (3 modules),
  4 layers of conductor, inner winding technique,
  Insulation with fiberglass reinforced epoxy,
  Vacuum impregnated,
  Indirectly cooled in thermosiphon mode,
  Module/layer electrical joints in low field region.

Superconductor Stability CAS. 2013. L. Bottura



Section of the CMS coil prototype manufactured at Ansaldo



CLIC detector magnet

The superconducting solenoid – conceptual design

Field at IP	4	T
Inductance	**11.9**	H
Nominal current	20	kA
Stored energy	**2.4**	GJ
Average Energy density	**13**	kJ/kg
Number of layers	**4**	
NbTi/Cu Rutherford cable	32	strands
Conductor cross section	**82.85 x 20.31**	mm
Coil inner radius (length)	3.65 (7.8)	m

- Inductance and
- number of layers

kept at "acceptable levels"

Large conductor cross section

- Weight of conductor in winding = **167 tons** (total length about **37 km**)
- Weight of cold mass = **201 tons**
- Coil module (x3): **68 tons**, L = 2.6m, $\varnothing_{\text{external}}$ **= 8.2m**

→ at the limit of road transport capacities to CERN.

CLIC detector magnet

The superconducting solenoid – conceptual design

Large magnetic forces on the coil:

- 64 bar inner pressure,
- axial compression 21 000 tons.

With 4 layers in the winding, the conductor reinforcement is necessary

→ 3 baseline options:

a/ CMS-like:

High purity aluminium stabilizer

+ Electron beam welded aluminum alloy bars

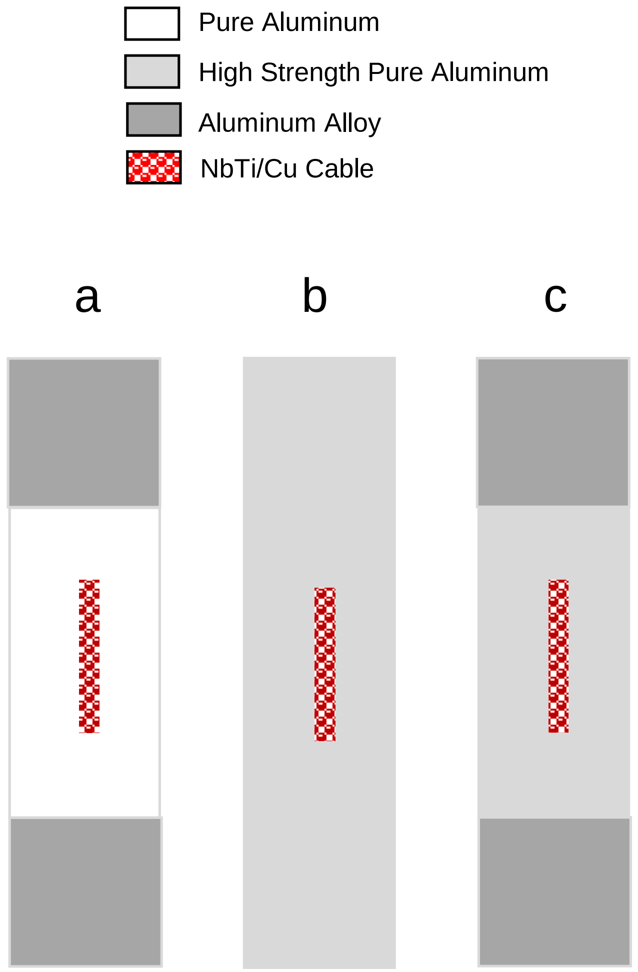
b/ ATLAS-CS like:

High strength stabilizer

+ Cold working for improved mechanical performances

c/ both a and b:

High strength stabilizer + cold work + EBW (Al alloy section may be smaller than in option a, keeping same total cross section)



CLIC detector magnet

The superconducting solenoid – conceptual design

Mechanical stress-strain for CLICdet

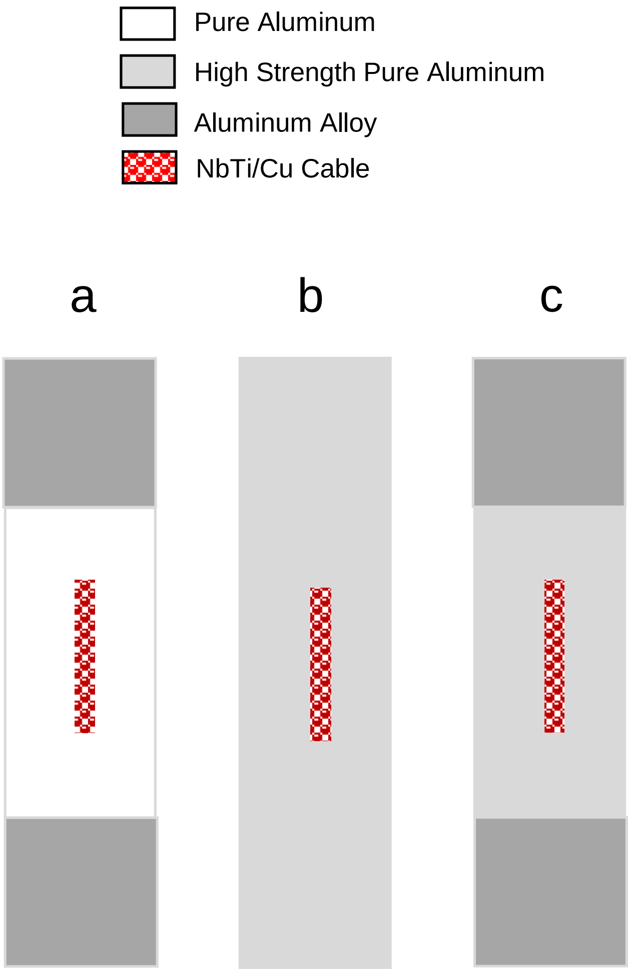
Option a compared to b and c:

Option a:

- Reinforcement in the elastic domain σ_{eq}**= 150 MPa**
- Pure aluminium at **0.15%** hoop strain in elasto-plastic domain (pure aluminum : yield strength ~ 30 MPa at 4K)

Options b & c:

- Entire conductor cross section works in elastic domain σ_{eq}**= 82 MPa**
- Hoop strain : **0.08%**

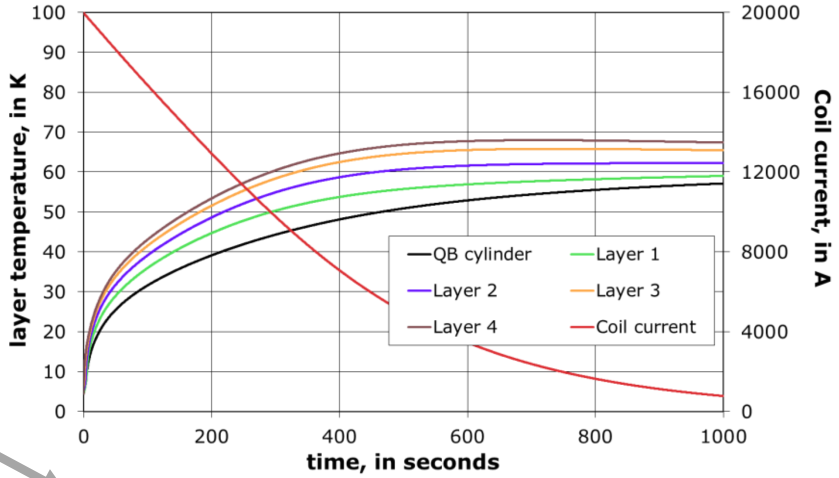


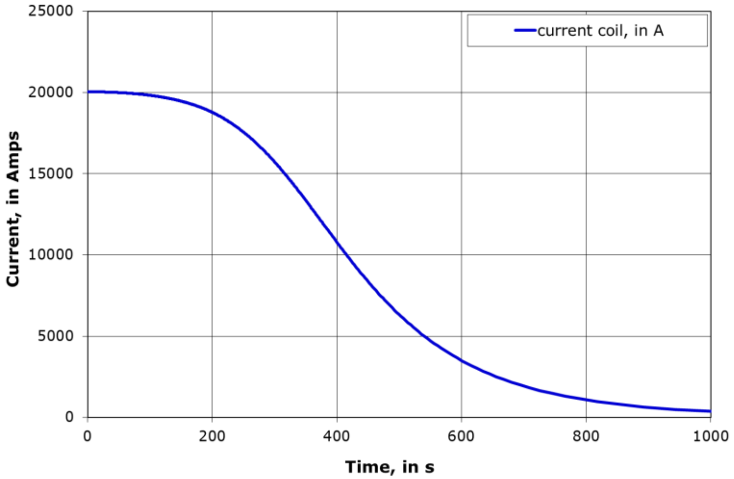
CLIC detector magnet

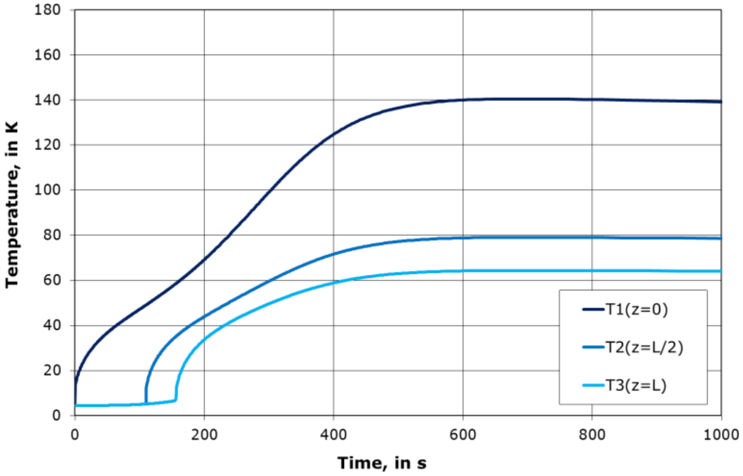
The superconducting solenoid – conceptual design

Quench protection

- Extraction of the energy on external dumping system (resistor)
- Quench back process: uniform heat release in the external mandrel (eddy currents): **T<70K**
- In case of **protection system failure**, the coil must be able to withstand the full energy release : average temperature below 100K (min-max: **65K-140K**)





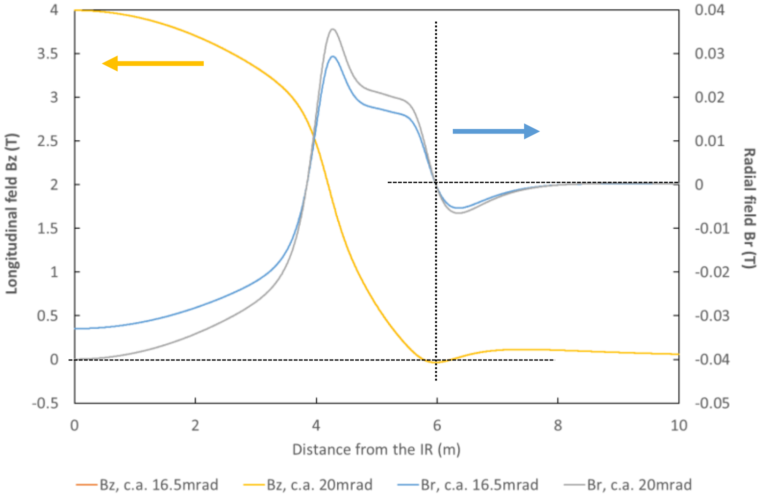


Figures correspond to the high strength stabilizer option b

CLIC detector magnet

The end coils

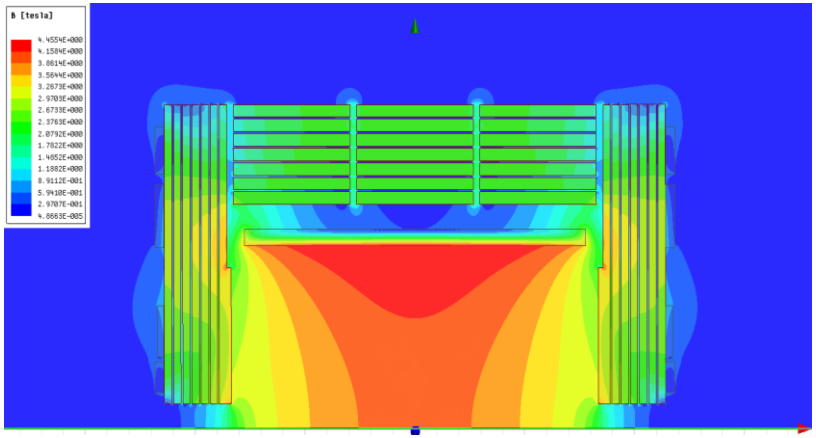
- limit the magnetic field in the machine detector interface region,
- limit the stray field outside the detector,
- contributes to reduce the amount of iron in the yoke (~ 2 000 tons).



The radial Br and the longitudinal Bz magnetic along the beam axis.

Conceptual design is considering as baseline the use of **resistive coils** (2MW per side) with water cooling.

Potential application for more sustainable solution such as High Temperature Superconductor.



Longitudinal fieldmap
(half of the coil is represented)

CLIC detector magnet

The superconducting solenoid

Plans for manufacturing and assembly of the magnet:
Use of proven (and available!!!) technologies.

The baseline is the CMS magnet and conductor manufacturing.

Manufacturing outside CERN in industrial facilities of:

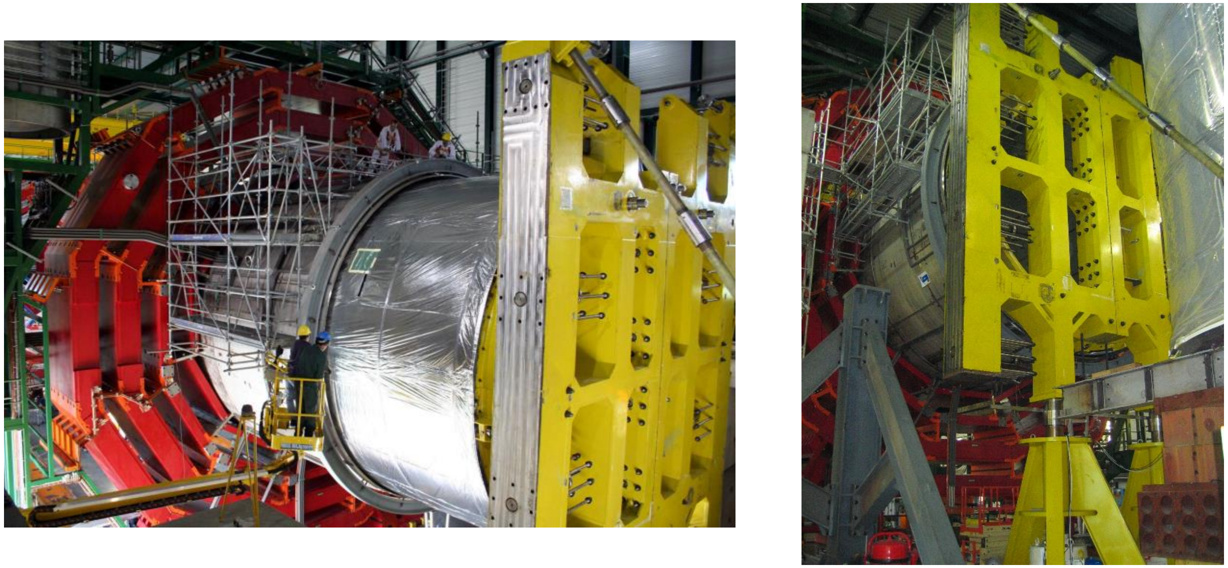
1. Conductor and components: strands, Rutherford cable, co-extrusion, reinforcement.
2. Module : mandrel + flanges, winding, vacuum impregnation.

Transport of modules to CERN.

Final assembly at CERN in a surface hall:

1. Coil assembled vertically stacking modules, with thermal shields, and final connections,
2. Swivelled horizontal for introduction and fixation into external vactank.

CLIC detector magnet



Credit: CMS, CERN

Summary

- **CLIC** – an excellent option for a future e^+e^- collider:
  380 GeV, upgrade stages of 1.5 TeV and 3 TeV

- great potential for precision physics beyond HL-LHC
  (studied in detail, using full simulation incl. backgrounds):
  < 1% accuracies on Higgs couplings already at the 1st stage

- New Physics - direct discovery in the TeV range, or indirect observation: 1% precision on top quark couplings to Z and γ ;
  Higgs self-coupling measured to 10% precision

Konrad Elsener,
SPS Annual Meeting, 2018

- **A large 4-T** detector superconducting magnet,

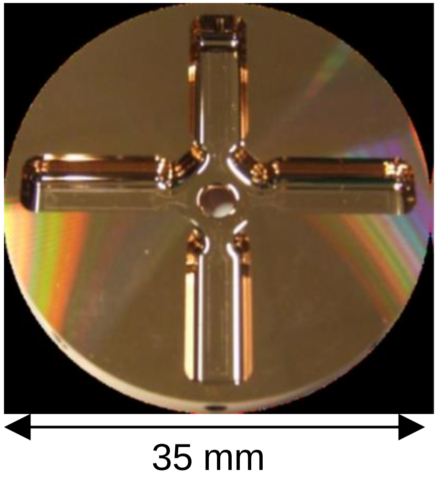
- A sturdy design based on **proven technologies with Al-stabilized NbTi/Cu SC**,

- **Potential application for latest developed technologies** on powering components with High Temperature Superconductor (end coils, current leads, superconducting links, power converter).

Spare slides

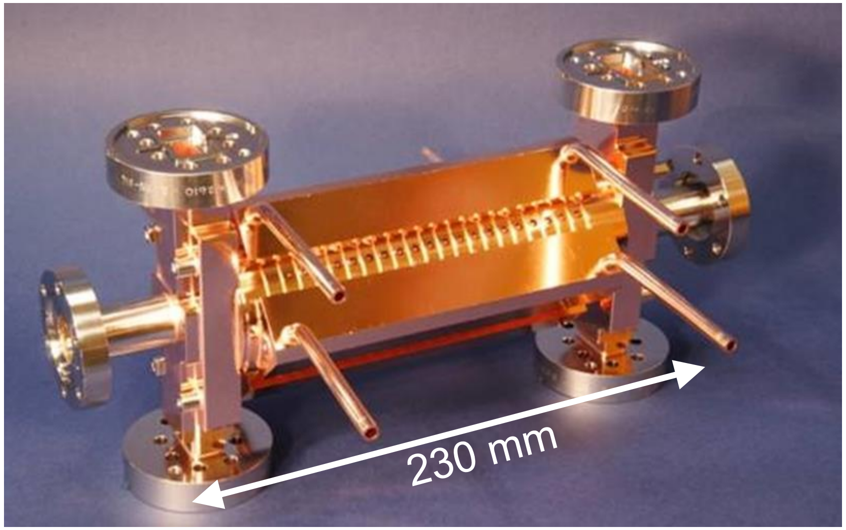
The CLIC accelerator: overview

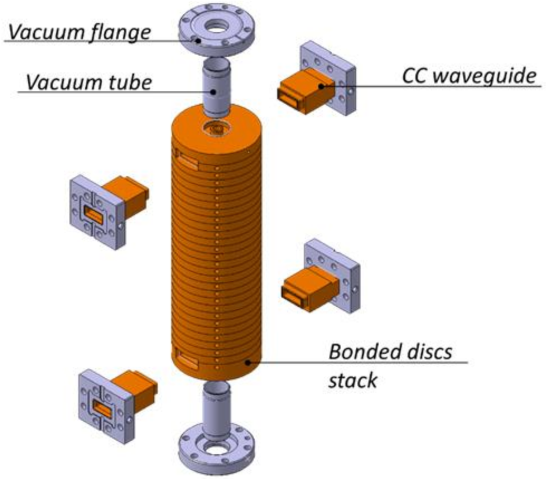
CLIC accelerating structure – normal cond. technology



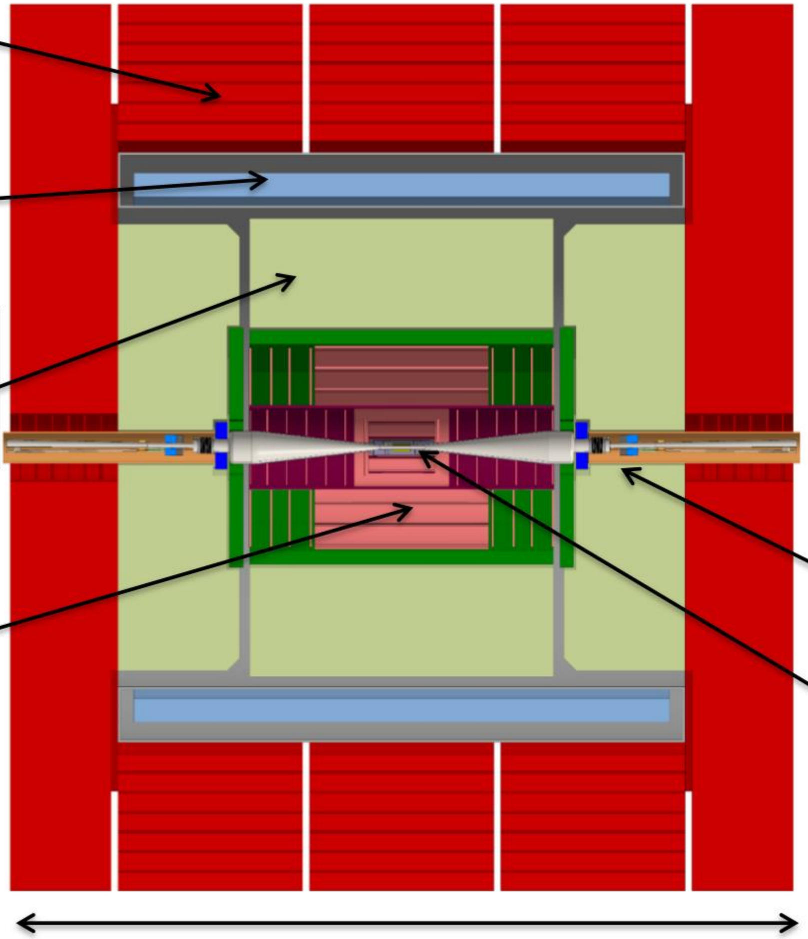
RF frequency 12 GHz;
244 ns pulses @ 50 Hz

	380 GeV	3TeV
Length [cm]	27	24
Gradient [MV/m]	72	100
Number of structures	20600	143000





CLIC detector



return yoke (Fe) with muon-ID detectors

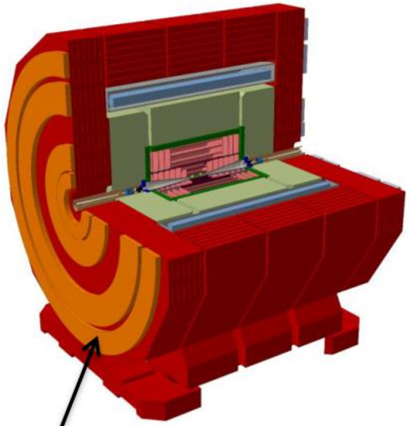
superconducting solenoid, 4 Tesla

fine grained (PFA) calorimetry, 1 + 7.5 Λ_i, Si-W ECAL, Sc-FE HCAL

silicon tracker, (large pixels / short strips)

Note: final beam focusing is outside the detector

11.4 m



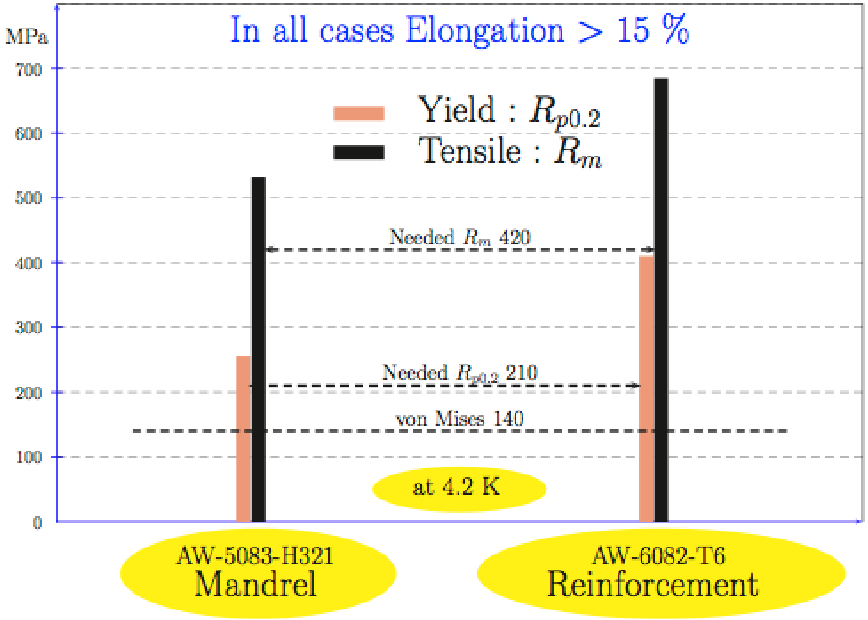
end-coils for field shaping

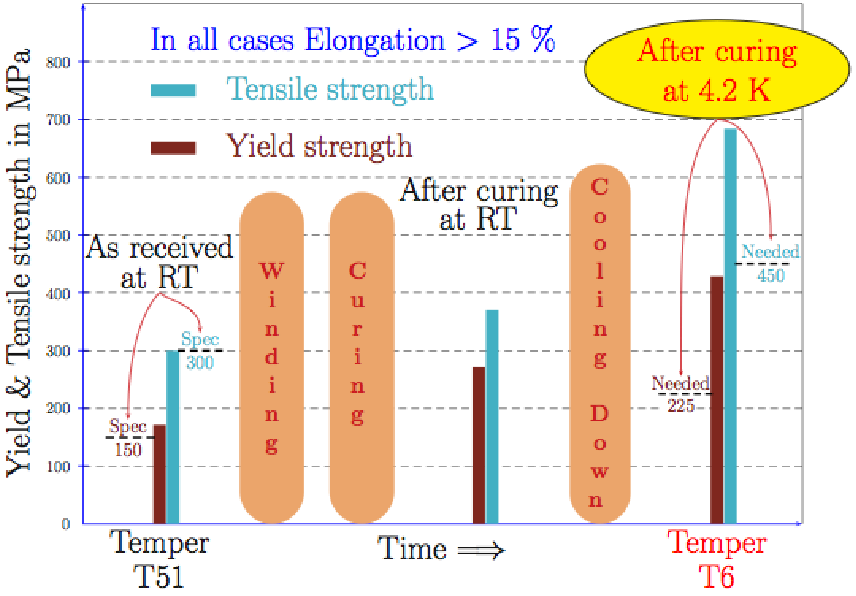
forward region with compact forward calorimeters

ultra low-mass vertex detector, ~25 µm pixels

CLIC detector magnet

- CMS reinforcement alloy: AA6082 chosen.
- Temper T6 obtained after coil curing cycle. Allowed winding with a not too stiff conductor.





A. Hervé, CLIC09 workshop