Final Results From the CLIC Test Facility (CTF3)

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For the CLIC Collaboration
CLIC in a nutshell

CLIC will be built in stages of increasing collision energy: starting from 380 GeV, then ~ 1-2 TeV, and up to a final energy of 3 TeV.

To limit the collider length, the accelerating gradient must be very high - CLIC aims at 100 MV/m, 20 times higher than the LHC.

CLIC is based on a two-beam acceleration scheme, in which a high current e- beam (the drive beam) is decelerated in special structures (PETS), and the generated RF power is used to accelerate the main beam.

The feasibility of CLIC has been demonstrated and documented in the CLIC Conceptual Design Report.
CLIC Timeline

2013 - 2019 Development Phase
Development of a Project Plan for a staged CLIC implementation in line with LHC results; technical developments with industry, performance studies for accelerator parts and systems, detector technology demonstrators

2020-2025 Preparation Phase
Finalisation of implementation parameters, preparation for industrial procurement, Drive Beam Facility and other system verifications, Technical Proposal of the experiment, site authorisation

2026 - 2034 Construction Phase
Construction of the first CLIC accelerator stage compatible with implementation of further stages; construction of the experiment; hardware commissioning

2019 - 2020 Decisions
Update of the European Strategy for Particle Physics; decision towards a next CERN project at the energy frontier (e.g. CLIC, FCC)

2025 Construction Start
Ready for construction; start of excavations

2035 First Beams
Getting ready for data taking by the time the LHC programme reaches completion
The CLIC study

[Diagram of the CLIC study with labels such as DRIVE BEAM INJECTOR, COMBINER RINGS, BYPASS TUNNEL, INTERACTION REGION, MAIN BEAM INJECTOR, DAMPING RINGS, DRIVE BEAM LOOPS, DRIVE BEAM DUMPS, TURN AROUND, e+ INJECTION DESCENT TUNNEL, e− INJECTION DESCENT TUNNEL, and text "CLIC SCHEMATIC (not to scale)".]
The CLIC study
What matters in a linear collider?

- Energy reach
  \[ E_{cm} \approx L_{\text{linac}} G_{\text{acc}} \]

- Luminosity

- Acceleration efficiency
- Generation of small emittance
- Conservation of small emittance
- Extremely small beam spot at IP

- High gradient
- X-band normal conducting

- CLIC specific Issues:
  - N.B.:
    \[ \sigma_{x,y} = \sqrt{\frac{\beta_{x,y} \epsilon_{x,y}}{\gamma}} \]

- Two-beam scheme
- Damping rings
- Wake-fields, alignment, stability
- Beam delivery system, stability
CLIC Test Facility (CTF3)
Two-beam scheme issues

Drive Beam Generation

- Full beam loading acceleration ✓
- High current stable acceleration ✓
- Bunch length control, isochronous beam lines ✓
- Phase coding ✓
- Combination with RF deflectors ✓
- Drive Beam stability (phase, charge, …) ✓

RF Power Production

- RF power level and pulse length (break-down limit) ✓
- Extraction efficiency, HOMs ✓
- Drive Beam deceleration (efficiency, transport, stability) ✓
- On-off mechanism (break-down protection) ✓
- RF pulse shape (beam loading compensation) ✓
# Two-beam scheme issues

## Drive Beam Generation
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## All covered in CTF3

## Two-Beam Acceleration
- Gradient, pulse length (break-down limit)
- Consistency with expectations
- Break-down kicks
- Test with full-fledged module
- Wake-field monitors

## RF Power Production
- RF power level and pulse length (break-down limit)
- Extraction efficiency, HOMs
- Drive Beam deceleration (efficiency, transport, stability)
- On-off mechanism (break-down protection)
- RF pulse shape (beam loading compensation)
CTF3 – the original mission

First beam – June 2003
CTF3 – the original mission

- High current, full beam-loading operation
- Bunch phase coding
- Linac
- Delay Loop
- Combiner Ring
- CALIFES Probe Beam Injector
- TBTS
- TBL
- CLEX

First beam – June 2003

4 A, 1.4us 120 MeV
CTF3 – the original mission

Operation of isochronous lines and rings

Beam recombination and current multiplication by RF deflectors

First beam – June 2003

Linac

Chicane

Delay Loop

Combiner Ring

CALIFES
Probe Beam Injector

TBTS

TBL

CTF3 – the original mission

30 A, 140 ns
120 MeV

R. Corsini – Final Results From the CLIC Test Facility, CTF3
CTF3 – the original mission

First beam – June 2003

30 A, 140 ns
60 MeV

CALIFES
Probe Beam Injector

TBTS

TBL

CLEX

12 GHz power generation by drive beam deceleration
High-gradient two-beam acceleration
CTF3 in 2015-2016

Dogleg Beam loading experiment

Last beam – December 2016
CTF3 in 2015-2016

Phase feed-forward experiment

Linac

Combiner Ring

CALIFES
Probe Beam Injector

TBTS

TBL

CT

DL

TL1

CR

Incor

injector

Last beam – December 2016
CTF3 in 2015-2016

Diagnostics R&D using CALIFES

Last beam – December 2016
CTF3 in 2015-2016

Delay Loop

Chicane

Combiner Ring

Linac

TBTS

TBL

CAL Prob In

TBL deceleration

Last beam – December 2016

Two Beam Module, Wake-field monitors...
Drive Beam Generation

Full beam loading acceleration

95.3% RF to beam efficiency
Stable high current acceleration
Factor 8 current & frequency multiplication

RF pulse at structure input
RF pulse at output

RF in
No RF to load

High beam current
“short” structure – low Ohmic losses

Most RF power to beam

Factor 8 combination
Drive Beam Generation

Beam recombination
- Fast bunch phase switch in SHB system
- Operation of isochronous rings and beam lines

![OTR light after the Delay Loop](image)

![Graphs showing non-isochronous and isochronous measurements](image)
**Drive Beam Stability**

**Tests in CTF3**
- Emittance $\varepsilon_x, \varepsilon_y \leq 150 \mu m$
- Transverse jitter $\leq 0.3 \sigma$
- Current stability $1 \times 10^{-3}$
- Phase stability $0.2^\circ @ 12\,GHz$

**Verified in CTF3**
- $1$ to $3 \times 10^{-3}$
- $< 0.2^\circ$

**CLIC Drive Beam requirements**
- Emittance $\varepsilon_x, \varepsilon_y \leq 100 \mu m$
- $\leq 0.1 \sigma$
- Current stability $0.75 \times 10^{-3}$
- Phase stability $0.035^\circ$
- RF power stability $0.2\%$
- RF phase stability $0.05^\circ$
- Current stability $0.21\%$
- $0.035^\circ$
- $0.2 \times 10^{-3}$

**Feed-forward tests in CTF3**
- $\sim 1^\circ @ 12\,GHz$
Drive Beam Stability

Pulse charge stability at end of the linac better than CLIC requirements

Charge stability – Factor 8

Repeatability and long term current stability greatly improved in final years.

Many feedback loops operational, for temperature, RF phase and power and gun current.
Drive Beam Stability

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General lesson from CTF3 (and SLC): Diagnostics, tuning procedures and feedbacks are vital

Repeatability and long term current stability greatly improved in final years.

Many feedback loops operational, for temperature, RF phase and power and gun current.
Power production in the Two-Beam Test Stand

PETS operated routinely above 200 MW peak RF power providing reliably pulses ~ 100 MW to accelerating structure. About twice the power needed to demonstrate 100 MV/m acceleration in a two-beam experiment with the nominal CLIC structure.
Demonstration of PETS on-off mechanism

- Feasibility issue
- Switch off power from individual PETS to accelerating structure in case of breakdown
- Reduce substantially power in PETS, to cope with PETS breakdowns
- PETS on-off principle fully tested
- Conditioned at high power (135 MW - nominal) by recirculation
- System routinely used in CTF3 for power enhancement and tuning
Two-Beam Acceleration demonstration in TBTS

Up to 145 MV/m measured gradient

Good agreement with expectations (power vs. gradient)

Maximum stable probe beam acceleration measured: 31 MeV

⇒ Corresponding to a gradient of 145 MV/m
Two-Beam Module Experimental Program 2015-2016

CLIC two-beam module tests

- Power production, stability + control of RF profile
- RF phase/amplitude drifts along TBL, PETS switching at full power
- Two-beam acceleration, power transfer & phasing, breakdown detection and effects of breakdowns...
- Alignment tests, with and w/o beam, including Wake-Field Monitors and main beam prototype BPMs

- Aim: gather all possible information, to feed back into next generation Two-Beam Module design

Two-beam acceleration in TBM thoroughly tested

Verified again power production/energy gain vs. expectations

Operated at nominal CLIC gradient and pulse length, ~ 100 MV/m and 240 ns

Experiment on control of RF profile (beam loading compensation) done
TBM – accelerating gradient in 2016

- Energy gain: 74.1 MeV
- Califes Energy: 199.4 MeV
- Accel. Grad. = 110 MV/m
- Beam Energy [MeV]
- Bunch length: 4 ps FWHM
- Califes energy spread: 2.5 MeV
TBM – wake-fields effect

Low charge

High charge

Beam position vs. DHG0385 current

Beam at the centre of the ACS

Beam position on MTV790 for various girder positions

slope: -0.081 mrad/mm
TBM – wake-fields effect

- Low charge: 85.3 kV/nC/mm/m
- High charge: 85.5 kV/nC/mm/m

Beam at the centre of the ACS

- Wake (girder movers) 85.3 kV/nC/mm/m
- Wake (corrector scan) 85.5 kV/nC/mm/m

slop: -0.061 mrad/mm
14 Power Extraction & Transfer Structures (PETS) installed and running from 2015

Full beam transport to end-of-line spectrometer, stable beam

Power produced (90 MW/PETS) fully consistent with drive beam current (24 A) and measured deceleration.
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Drive beam phase feed-forward

Goal:
Stabilize drive beam phase to the CLIC requirement
0.2° @ 12 GHz (50 fs)

DB feed-forward results, 2015

Phase Along the Pulse

REAL Feedforward Results

SIMULATED Feedforward Results

FF Off (std 0.74±0.06°, corr 0.93±0.04)
FF On (std 0.28±0.02°, corr 0.19±0.12)

Simulated FF (std 0.27±0.02°, corr 0.06±0.12)
Drive beam phase feed-forward

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to the CLIC requirement
0.2° @ 12 GHz (50 fs)

DB feed-forward results, 2015

Drive-beam phase feed-forward tests in 2016

From about 1° to 0.2° @ 12 GHz, or 50 fs
Beam loading changes the field distribution for the same average gradient

How is the break-down rate affected?
 Beam Loading Experiment

- A BDR reduction by beam loading up to an order of magnitude was measured.
- BDR seems dominated by the peak gradient, confirmed by the measured distribution inside the structure, which follows roughly the gradient profile.
- Possibility to further optimise the CLIC structure by targeting a flat gradient along the structure during the operation with beam.

Figure 5: Breakdown cell distribution along the TD26CC structure for unloaded (blue), loaded (red) and anti-loaded (green) case.
CTF3 Exp. Program 2015-2016 – Instrumentation Tests

Beam day x experiments with CALIFES in 2015

Wake-Field Monitors
- 4 um resolution
- Studies of DB noise
- Confirmed by new version

Drive Beam BPM
- Confirm 2.5 um resolution
- Rad hardness

Optical Fiber Beam Loss
Monitors in TBL
- Localization of losses below 2 m (2015)
- Multi-loss location case

Main beam BPM prototypes
- Sub-micron resolution measured
- Time resolution (50 nm) OK
Wake Field Monitors

Wake field monitors precisely determine the beam position with respect to the electrical center of an accelerating structure.

In CLIC, WFM signals will be used to center the beam in the structure and minimize transverse wake-fields.

Requirement: 4.5 um resolution.
CLIC Test Facility (CTF3)  
† 2016
CERN Linear Electron Accelerator for Research (CLEAR)

🌟 2017
The CLEAR\(^1\) facility at CERN

CTF3 ended operation in December 2016

However, the probe beam injector CALIFES will become the focus of a new multi-purpose facility, CLEAR

CLEAR, among other activities, will continue some CLIC related studies on high-gradient and diagnostics

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The CLEAR (CERN Linear Electron Accelerator for Research) proposal

The CLEAR\(^1\) facility at CERN

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CONCLUSIONS

• CTF3 has addressed and solved the CLIC issues related to drive beam generation, power production and two-beam acceleration.

• CTF3 successfully completed its planned experimental program in December 2016 as planned, and stopped operation.

• The experience gathered in CTF3 is now being documented, in view of the update of the European Strategy in 2019.

• The approval of the CLEAR program gives the opportunity to maintain local testing capability at CERN for CLIC instrumentation and high-gradient structure testing with beam, alongside with other non-CLIC activities.
The CLIC Test Facility has been the collective effort of a large collaboration over more than a decade.

Many thanks to all individuals who participated over this period to the conception, design, construction, commissioning and operation of CTF3!