Status report from the CLIC Test Facility 3
Two-Beam Test Stand
US High Gradient Research Collaboration Workshop 2011, SLAC, CA, USA

Erik Adli, University of Oslo, Norway
For the CLIC/CTF3 collaboration
February 9, 2011
OUTLINE

• Introduction to CTF3 and TBTS

• TBTS structures

• Main results

• Details on how we achieved these results

• Future plans for CLIC Two-Beam Acceleration

• Conclusions
The Compact Linear Collider (CLIC)

- The Compact Linear Collider (CLIC): study for a Multi-TeV linear collider, with design parameters of 3 TeV COM and luminosity of $2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
- Main linac uses normal-conducting accelerating structures with an accelerating gradient of 100 MV/m (loaded)
- The large number of structures leads to a small rf break down rate criterion ($10^{-7}$ per structure per pulse), and the charge required to reach the luminosity goals must be distributed within short rf pulses (240 ns)
- **CLIC two-beam acceleration scheme**: high-power short rf pulses for main linacs are extracted from a compressed high-intensity 100 A e⁻ drive beam. Allows for good machine efficiency.

*New collaboration web-side: http://clic-study.org/*
CLIC drive beam scheme versus CLIC Test Facility 3

Drive Beam Accelerator
- efficient acceleration in fully loaded linac

Combiner Ring × 4
- pulse compression & frequency multiplication

Drive Beam Decelerator Section (2 × 24 in total)

Delay Loop × 2
- gap creation, pulse compression & frequency multiplication

RF Transverse Deflectors

Combiner Ring × 3
- pulse compression & frequency multiplication

Drive beam time structure - initial
- 240 ns
- 140 µs train length - 24 × 24 sub-pulses
- 4.2 A - 2.4 GeV - 60 cm between bunches

Drive beam time structure - final
- 240 ns
- 24 pulses - 101 A - 2.5 cm between bunches
- 5.8 µs
CLIC Test Facility 3 (CTF3) at CERN

CLIC Test Facility 3: designed to test key concept of the CLIC two-beam scheme. Main parts:

- **Drive Beam generation**: acceleration in a fully loaded linac with > 95% efficiency and bunch frequency multiplication by a factor $x \times 2 \times 4$ (from 1.5 GHz to 12 GHz)
- **Two-Beam Acceleration experiment (described in this talk)**
- Deceleration experiment, TBL (not described here)
- Instrumentation tests (not described here)
Two-Beam Test Stand (TBTS)

TBTS = two beams + structures + instrumentation

Subjects of study include:
1. acceleration and deceleration
2. effect of higher order modes, study of transverse kicks and wake field monitors
3. Rf breakdown studies, in the presence of beam
4. timing of the two beams
5. full system behavior; from component prototypes to two-beam acceleration unit prototype; Cross talk between drive and probe beam

Drive Beam (up to 28A, 150 MeV, 12 GHz, 140 ns @ 12 GHz)

Probe Beam (up to 1A, 180 MeV, 1.5 GHz, 150 ns)

R. Ruber, Uppsala University
TBTS accelerating structure: TD24

TD24: Tapered, wave-guide damped 24 cell structure with $v_g/c = 1.8$. 40 MW yields $\sim 100$ MV/m.

Bonded at 1000 deg (design for brazed)

<table>
<thead>
<tr>
<th></th>
<th>120°/cell</th>
<th>comments</th>
</tr>
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<tbody>
<tr>
<td>$f$ [GHz]</td>
<td>11.995</td>
<td></td>
</tr>
<tr>
<td>$S_{12}$</td>
<td>0.6542</td>
<td></td>
</tr>
<tr>
<td>$T_1$ [ns]</td>
<td>64.55</td>
<td></td>
</tr>
<tr>
<td>$Q^{Cu}$</td>
<td>5732</td>
<td></td>
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Gradient averaged over all cells

<p>| | | |</p>
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<tbody>
<tr>
<td>$V_{26}$ [V]@P_{in} = 1 W</td>
<td>3340</td>
<td>2 matching +24 regular cells $L_{acc} = 227.7$ mm,</td>
</tr>
<tr>
<td>$G_{26}$ [V/m]@P_{in} = 1 W</td>
<td>14661</td>
<td></td>
</tr>
<tr>
<td>$P_{in}$ [MW]@&lt;$G_{26}$=100MV/m&gt;</td>
<td>46.5</td>
<td></td>
</tr>
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Gradient averaged over regular cells only

<p>| | | |</p>
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</thead>
<tbody>
<tr>
<td>$V_{24}$ [V]@P_{in} = 1 W</td>
<td>3078</td>
<td>24 regular cells only $L_{acc} = 200.0$ mm,</td>
</tr>
<tr>
<td>$G_{24}$ [V/m]@P_{in} = 1 W</td>
<td>15390</td>
<td></td>
</tr>
<tr>
<td>$P_{in}$ [MW]@&lt;$G_{24}$=100MV/m&gt;</td>
<td>42.2</td>
<td></td>
</tr>
</tbody>
</table>

A. Grudiev, RF design and parameters of 12 GHz TD24_vg1.8_disk
https://edms.cern.ch/document/1070498/1
TBTS power extraction structure (PETS)

TBTS PETS has CLIC-design where a 0.23 m PETS with 100A gives 135 MW power. TBTS x4 longer (1m) to compensate for x4 lower CTF3 drive beam current. In addition, field recirculation (resonant loop) is added for increased power production:

Max. 28 A

TBTS PETS tank with power splitter and phase shifter
December 14, 2010:

Probe beam accelerated by 23 MV in a TD24 accelerating structure, corresponding to 106 MV/m, in a reproducible way.

Meas. PETS power input to structure ~ 80 MW (~200 MW in the resonant loop)

Drive beam: 12.5 A, 113 MV, 12 GHz in CLEX (1.5 GHz beam combined factor 8), 140 ns pulse length

Probes beam: 0.08 A, 173 MV, 1.5 GHz, 8 ns pulse length
Progress in drive beam generation

Drive Beam Optimization for RF power production

- Bunch length
- Combination phase
- Phase variation along the pulse
- All affecting power production efficiency (form factor F)

Example: bunch phase errors due to LIPS pulse compressors in linac.

Example before optimization: ~20% reduction in power due to combination dephasing

Needs careful tuning (and in 2010 we had new operation point (E, I) due to missing klystron.

Example 12 GHz RF phase

Example after optimization: ~1% reduction

Erik Adli, Reidar Lillestøl, Sep 2010
Difficulties reaching nominal gradient, Fall 2010

First two-beam accelerations attempts (black curves) : noticed factors up to x 3-4 more power than estimated for a given measured acceleration! Part of the problem was calibration issues (~ 100 dB attenuation, in couplers, cables, fixed and variable attenuators). But we could not reach CLIC gradient with available input power, (even with recirculation, for a long time.

Power measured at structure input

Power measured at structure output, renormalized using known attenuation
Correlated deceleration and power measurements, applying a simple two-parameter model of PETS with recirculation $(g, \phi)$.

Shows good reconstruction, and help identify calibration issues (here: 1 dB out of 100 dB attenuation).

**Model ident. with phase scans.**
Measurement of resonant frequency of TD24

“Pinging” structure with short probe beam (10 ns << t_fill), mixing with known signal and checking difference signal:

Mixing with signal of 11.994 MHz

Mixing with signal of 12.009 MHz

Measurements indicated that resonant frequency was 10-15 MHz higher than nominal.

S. Doebert, December 1, 2010
The peak 106 MV/m gradient was achieved only after heating the accelerating frequency, by attaching heated water of 60 deg to accelerating structure cooling loop. This is estimated to lower the resonance frequency by 6 MHz.
Shutdown measurements: structure detuning confirmed

- 10 MHz structure detuning after Two-Beam Tests confirmed in shutdown measurements (Jan 2011)
- Possible cause: deformation/squashing when clamping the cooling circuit onto the structure.

Jiaru Shi, January, 2011
Reconstruction of voltage from rf input

For detailed energy budgets we need to take into account the TBTS non-flat rf pulse shape (due to rf recirculation), the operating conditions, using a model of the accelerating structure taking into account the detuning.

The TD24 accelerating structure has a fill time of 65 ns. The time synchronization between probe beam and rf was performed by moving the time slot window of the laser pulse picker (by steps of about 10 ns or less) and probe beam klystron by steps of 52 ns. Scanning the two knobs until peak acceleration is measured.

Oleksiy Kononenko, Feb 2011
Two-Beam Acceleration Test - History

July 2010: first TBA

November 2010: pushed PETS power production

Temperature control + cross-calibration problem

December 2010: compensated for detuning:
CLIC TBA gradient target reached!

New calibration + effective power increase
Two-Beam experiments compared to rf tests

Breakdown rate at 100 MV/m (unloaded) accelerating gradient and scaled to 180 ns pulse length

TD24 – CLIC nominal being tested with beam in CTF3 two-beam test stand.
Two-Beam-Test Stand: plans for 2011

Continue Two-Beam Acceleration experiments:
• Will attempt to re-tune and re-install TD24 [back up solution: install an available T24]
• Without detuning, nominal 100 MV/m should be easily reached with CLIC pulse length (x 4 combination) -> will allow for better break down rate estimates [but not more than few $10^5$ pulses, personal estimate]
• Full study of power, deceleration and acceleration budgets

Other TBTS activities:
• PETS On/Off mechanism
• Kick measurements
• Break down measurements in accelerating structure and PETS (next slide)

Additional CTF3 activities:
• Further drive beam generation optimization and stabilization
• Multi-PETS deceleration experiments (Test Beam Line), up to 8 PETS in 2011
• Photo injector tests (PHIN)

In addition at SLAC/KEK/CERN:
• High power structure tests, including TD24 (see next talks)
• CERN: on-line this year with 12 GHz Klystron Test Stand (~ summer 2011?)
Planned kick and break down measurements

- Measurements of beam kick due to HOM and RF break downs both on the drive beam and on the probe beam
  (10 μm BPMs resolution for 10 mrad angular resolution)

already in 2009 for the drive beam without considering incoming energy variation
(CTF3-Note-098)

- better understanding of the breakdown process with:
  - indirect RF measurements (reflection during breakdowns);
  - direct measurements of emitted electrons and ions (flashbox).
CTF3+ : first update plans (2012)

• First upgrade of CTF3 two-beam acceleration test: **adding one full CLIC-type module**, in addition to TBTS.

  ![Diagram of CLEX and TBTS PETS](image)

  **CLEX - one two-beam module (2012)**

  **TBTS PETS**

• Realistic beam **tests of a module** with all relevant components in CLEX.
• Next step after this: 3 CLIC modules chained together
• Then: N CLIC modules
Conclusions

• 2010: a year of very good progress for CTF3, despite a 4 months start-up delay due to a fire
  • Demonstrated the CLIC gradient of 100 MV/m in a reproducible way
  • Hard work and clever ideas (heating station...) allowed to reach the target despite a significant ~10 MHz structure detuning
  • Optimized and increased stability of CTF3 drive beam generation by flattening beam phase and adding current and phase feedbacks
  • Better precision of power production and deceleration measurements

• 2011: a lot of interesting work to be done, including
  • Stable Two-Beam Acceleration with a non-detuned structure
  • Understanding transverse effects observed in accelerating structure
  • PETS on/off
  • Break down rate measurements in two-beam acceleration
  • TBTS kick measurements and break down experiments

• 2012+: program to upgrade TBTS to a full-fledged CLIC TBA demo (3+ modules)
Extras
Example of TBTS signal pulse to pulse jitter, and along the pulse signals

- Taken from measurements day for characterization of power and deceleration (machine optimized for stability, x 4 combination)
- My opinion: beam transport and stability this day good day quite good with respect to year (but cannot say whether it was one of the best)

(Nov 26, 2010)

Shown: 1) current just after PETS, 2) H position just before spectrometer, 3) power in PETS loop:
- quite nice and flat current top of over > 200 ns
- many % pulse to pulse jitter
- dispersion not under control
- significant losses from ring to TBTS
Second upgrade of CTF3 two-beam acceleration tests: adding two more CLIC-type modules

Clear goal: realistic beam tests of different modules (type 0 and type 1) + interconnections.
Optics: aperture limitations now start to become more challenging
Power: drive beam limitations, \((25/100)^2 \approx 1/16\) is still a challenge
## CTF3 achievements summary

### Drive beam generation

<table>
<thead>
<tr>
<th>System</th>
<th>Item</th>
<th>Feasibility Issue</th>
<th>Unit</th>
<th>Nominal</th>
<th>Achieved</th>
<th>How</th>
<th>Feasibility</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two Beam Acceleration</td>
<td>Fully loaded accel effic</td>
<td>%</td>
<td>97</td>
<td>95</td>
<td>CTF3</td>
<td></td>
<td></td>
<td>Novel scheme fully demonstrated in CTF3 in spite of lower current since beam dynamics more sensitive than nominal due to lower energy (250MeV/20A)</td>
</tr>
<tr>
<td></td>
<td>Freq Current multipl</td>
<td>-</td>
<td>2*3</td>
<td>2*4</td>
<td>CTF3</td>
<td></td>
<td></td>
<td>End of DBA. To be demonstrated for combined beam in 2011, achieved in CTF3, XFEL design</td>
</tr>
<tr>
<td></td>
<td>Combined beam current (12 GHz)</td>
<td>A</td>
<td>4.5*24-100</td>
<td>3.5*8-28</td>
<td>CTF3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Combined RF power</td>
<td>mW</td>
<td>150</td>
<td>130</td>
<td>TBTS/LAC</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Combined RF power</td>
<td>ns</td>
<td>170</td>
<td>170</td>
<td>TBTS/LAC</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Combined RF power</td>
<td>/m</td>
<td>&lt; 1*10^-7</td>
<td>&lt; 2.4*10^-7</td>
<td>TBTS/LAC</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Combined RF power</td>
<td>@50 Hz</td>
<td>-</td>
<td>-</td>
<td>CTF3/TBL</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Drive beam to RF efficiency</td>
<td>%</td>
<td>50</td>
<td>50</td>
<td>CTF3/TBL</td>
<td></td>
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<td>Drive beam to RF efficiency</td>
<td>%</td>
<td>50</td>
<td>50</td>
<td>CTF3/TBL</td>
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<tr>
<td></td>
<td>RF pulse shape control</td>
<td>%</td>
<td>&lt; 0.1%</td>
<td></td>
<td>CTF3/TBTS</td>
<td></td>
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</table>

### Two Beam Acceleration

<table>
<thead>
<tr>
<th>Structure Acc field</th>
<th>Structure Flat Top Pulse length</th>
<th>ns</th>
<th>100</th>
<th>100</th>
<th>CTF3 Test, Stand, Slac, Kek</th>
<th>2011</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structure Flat Top Pulse length</td>
<td>Structure Breakdown Rate</td>
<td>/m</td>
<td>170</td>
<td>170</td>
<td>CTF3 Test, Stand, Slac, Kek</td>
<td>2011</td>
</tr>
<tr>
<td>Structure Breakdown rate</td>
<td>RF to beam transfer efficiency</td>
<td>%</td>
<td>21</td>
<td>15</td>
<td>CTF3 Test, Stand, Slac, Kek</td>
<td>2011</td>
</tr>
</tbody>
</table>

### Power production and probe beam acceleration in Two Beam module

<table>
<thead>
<tr>
<th>Power production and probe beam acceleration in Two Beam module</th>
<th>MV/m</th>
<th>ns</th>
<th>100</th>
<th>170</th>
<th>CTF3</th>
<th>2011</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drive to main beam timing stability</td>
<td>MV/m</td>
<td>ns</td>
<td>100</td>
<td>170</td>
<td>CTF3</td>
<td>2011</td>
</tr>
<tr>
<td>Two Beam Acceleration</td>
<td></td>
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<td>Two Beam Acceleration</td>
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</table>

### Ultra low Emittance generation

| Ultra low Emittance generation | Emittance generation HV | nm | 300/12 | CTF3 | 2011 |
|                                | Emittance preserving | Blow up | 160/15 | CTF3 | 2011 |
|                                | Emittance preserving | Simulation & simulation | 160/15 | CTF3 | 2011 |

### Alignment

<table>
<thead>
<tr>
<th>Main Linac components</th>
<th>Microns</th>
<th>15</th>
<th>10 (princ)</th>
<th>CTF3</th>
<th>2011</th>
</tr>
</thead>
<tbody>
<tr>
<td>Final Doublet</td>
<td>Microns</td>
<td>2 to 8</td>
<td>CTF3</td>
<td>2011</td>
<td></td>
</tr>
<tr>
<td>Quad Linac</td>
<td>Microns</td>
<td>1.5</td>
<td>1.5</td>
<td>CTF3</td>
<td>2011</td>
</tr>
<tr>
<td>Final Doublet (assumed feedbacks)</td>
<td>Microns</td>
<td>0.2</td>
<td>0.13</td>
<td>CTF3</td>
<td>2011</td>
</tr>
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</table>

### Operation and Machine Protection System (MPS)

<table>
<thead>
<tr>
<th>MPS</th>
<th><a href="mailto:72MW@2.4GeV">72MW@2.4GeV</a></th>
<th>CTF3</th>
<th>2011</th>
</tr>
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<tbody>
<tr>
<td>main beam power of <a href="mailto:13MW@1.5TeV">13MW@1.5TeV</a></td>
<td>CTF3 simulations</td>
<td>2011</td>
<td></td>
</tr>
</tbody>
</table>

Report integrating LHC experience under preparation.
Reproducible CLIC target gradient shown

Gradients above CLIC target continuously reproducible.

According to rf measurements, an input power several factors larger than expected required for this gradient.

(T. Persson, December 14, 2010)
TD24 (front) and PETS tank in CLEX Two-Beam Test Stand
Details for installed TD24 TBTS accelerating structure

Bonded at 1000 deg (design for brazed)

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Gradient averaged over all cells

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Gradient averaged over regular cells only

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- $P_{in}$ [MW]@<$G_{24}$=100MV/m>: 42.2

A. Grudiev, RF design and parameters of 12 GHz TD24_vg1.8_disk
https://edms.cern.ch/document/1070498/1

Measurement Condition

- Structure Name: TD24
- Measured by: Riccardo, Andrey, Jiaru
- Date: 29-Oct-2009
- Location: CERN
- VNA Model: Agilent E8364B
- Temperature: 23°C
- Designed frequency at $2\pi/3$: 11.994 GHz

- $\Delta f$ due to vacuum $\Rightarrow$ air: $-3.5$ MHz
- $22^\circ$C $\Rightarrow$ $23^\circ$C: $-0.2$ MHz
- w/o $\Rightarrow$ w/ wire: $-0.3$ MHz
  (total): $-4$ MHz

Expected $f$ under measurement condition (w/ wire, air, 23°C): 11990 MHz

- High-power temperature: 30°C
- $\Delta f$ due to air $\Rightarrow$ vacuum: $+3.5$ MHz
- $23^\circ$C $\Rightarrow$ $30^\circ$C: $-1.4$ MHz
- w/ $\Rightarrow$ w/o wire: $+0.3$ MHz
  (total): $+2.4$ MHz

Target $f$ under measurement condition (w/ wire, air, 23°C): 11991.6 MHz

"After tuning, the frequency of 2pi/3 mode at 30°C vacuum is now 11995.8 MHz"

J. Shi, 12WDSDvg1.8Cu No2 (TD24 No2 12GHz)
RF Measurement Results after tuning
https://edms.cern.ch/document/1051875/1
Typical Operation History

1200 x 3600 x 60 pulses:
TBTS beam tests will not try to mimic break down rate studies

Final Run at 230 ns: 94 hrs at 100 MV/m w BDR = 7.6e-5
60 hrs at 85 MV/m w BDR = 2.4e-6

C. Adolphsen
F. Wang
SLAC
Gradient at CLIC $4 \times 10^{-7}$ BDR and 180 ns pulse length

- T18 – strong tapering
  - Conditioning time [hr]: 1400
- T18 – strong tapering
  - Conditioning time [hr]: 3900
- T18 – strong tapering
  - Conditioning time [hr]: 280
- T18 – strong tapering (CERN built)
  - Conditioning time [hr]: 550
- TD18 – waveguide damping
  - Conditioning time [hr]: 1300
- TD18 – waveguide damping
  - Conditioning time [hr]: 3200
- T24 – high efficiency
  - Conditioning time [hr]: 600
- T24 – high efficiency
  - Conditioning time [hr]: 600

MV/m vs. Conditioning time [hr]
Characterization of PETS power with resonant field recirculation

Example pulses from phase-scan calcs for reconstructed power.

(E. Adli, December 8, 2010)
Sending long probe beam (~100 ns) with 11.994 MHz bunch spacing

Mixing with signal of 11.994 MHz

(S. Doebert, December 1, 2010)
Achieved current stability

- New heater power supply, better set-point, improved measurement procedures
  \[ \Delta I/I \sim 0.75 \times 10^{-3} \]
- Gun feed-back
  \[ \Delta I/I \sim 0.6 \times 10^{-3} \text{ (or lower...)} \]

Below CLIC DB specs!
Hardware upgrades, •
Feed-back systems

- Improvements in low-level and high-power RF
- Gun improvements (new heater power supply, ...)
- RF phase feedback – now fully operational
- RF temperature feedback for pulse compression

☞ reproducibility, stability

Feed-backs plus optics improvements...

Alexey Dubrovskiy