TWO-BEAM LINEAR COLLIDERS SPECIAL ISSUES

R. Corsini for the CLIC/CTF3 Collaboration
Two Beam Linear Colliders – Special Issues

Talk outline

- Introduction - CLIC
- The Two-Beam Acceleration concept
  - Motivation and Initial Evolution of the Concept
  - The CLIC TBA
- Experimental results in CTF3
  - Past results
  - Present status
- Outlook

TWO-BEAM LINEAR COLLIDERS SPECIAL ISSUES

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Aim of the CLIC study:

- Develop technology for e-\textit{/}e+ linear collider with the requirements:
  - $E_{CM}$ should cover range from ILC to LHC maximum reach and beyond $\Rightarrow E_{CM} = 0.5-3$ TeV,
  - $L > \text{few } 10^{34} \text{ cm}^2$ with acceptable background and energy spread
  - Design compatible with maximum length $\sim 50$ km
  - Affordable
  - Total power consumption $< 500$ MW

Physics motivation:


Present goal:

Demonstrate all key feasibility issues and document in a CDR by 2010

Complementary approach to ILC

The CLIC/ILC collaboration is preparing together the future evaluation of the two technologies by the Linear Collider community made up of CLIC & ILC experts
Two Beam Linear Colliders – Special Issues

The CTF3 – CLIC world wide collaboration

28 institutes involving 18 funding agencies from 16 countries

Ankara University (Turkey)
BINP (Russia)
CERN
CIEMAT (Spain)
Cockcroft Institute (UK)
Gazi Universities (Turkey)
IRFU/Saclay (France)
Helsinki Institute of Physics (Finland)
IAP (Russia)
IAP NASU (Ukraine)
Instituto de Fisica Corpuscular (Spain)
INFN / LNF (Italy)
J.Adams Institute, (UK)
JINR (Russia)
JLAB (USA)
Karlsruhe University (Germany)
KEK (Japan)
LAL/Orsay (France)
LAPP/ESIA (France)
NCP (Pakistan)
North-West. Univ. Illinois (USA)
Oslo University (Norway)
PSI (Switzerland)
Polytech. University of Catalonia (Spain)
RRCAT-Indore (India)
Royal Holloway, Univ. London, (UK)
SLAC (USA)
Uppsala University (Sweden)
The CLIC way to a multi-TeV linear collider - Basic features

• High acceleration gradient (100 MV/m)

  ✓ “Compact” collider - overall length @ 3 TeV < 50 km

  ✓ Normal conducting accelerating structures

  ✓ High acceleration frequency (12 GHz)

• Two-Beam Acceleration Scheme

  ✓ Cost effective, reliable, efficient

  ✓ Simple tunnel, no active elements

  ✓ Modular, easy energy upgrade in stages

Drive beam - 100 A, 240 ns from 2.4 GeV to 240 MeV

Main beam – 1 A, 160 ns from 9 GeV to 1.5 TeV
The CLIC Two-Beam Accelerator
Two Beam Linear Colliders – Special Issues

CLIC schematic layout @ 3 TeV
CLIC RF power source

CLIC schematic layout @ 3 TeV
Why a Two-Beam scheme?

Luminosity scales as **wall-plug-to-beam efficiency**. Need to obtain at the same time **high-gradient acceleration** and **efficient energy transfer**.

- The use of **high-frequency RF** maximizes the **electric field** in the RF cavities for a given **stored energy**.
- However, **standard RF sources** scale unfavourably to high frequencies, both in for **maximum delivered power** and **efficiency**.
- A way to overcome such a drawback is to use **standard low-frequency RF sources** to accelerate the **drive beam** and use it to **produce RF power at high frequency**.
- The drive beam is therefore used for **intermediate energy storage**.
A. Sessler, 1982

- RF frequency 30 GHz
- Drive beam acceleration by induction cells
- RF power extraction by FEL
- Re-acceleration

W. Schnell, 1986

- RF frequency from 6 GHz to 30 GHz
- Drive beam acceleration by super-conducting cavities
- RF power extraction by resonant structures (PETS)
- Re-acceleration
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Relativistic Klystron TBA LBL/LBNL

- RF frequency ~ 30 GHz
- Drive beam acceleration by induction cells
- RF power extraction by resonant structures
- Re-acceleration

HD-TBA Extraction Section.

![Illustration of an rf extraction structure.]

RK-TBA Test Accelerator
Two Beam Linear Colliders – Special Issues

Relativistic Klystron TBA LBL/LBNL

- RF frequency ~ 30 GHz
- Drive beam acceleration by induction cells
- RF power extraction by resonant structures
- Re-acceleration

Main issues

- Huge drive beam current, low energy
- Drive Beam transverse and longitudinal stability
- Cost of induction units
- Repetition rate
- Active elements in tunnel
Two-beam experiments at Argonne Wakefield Accelerator

- Wakefield acceleration in dielectric, iris loaded and photonic band gap structures
- Collinear two-beams
- Generation of high power cm wavelength RF
- Beam-driven plasma-based techniques

RF frequency: 1.3 GHz
Photoinjector: 1½ cell, Mg photocathode
Charge per bunch: 1 to 100 nC
Bunch length: 14 ps FWHM
Maximum energy: 14 MeV
Length: ~7 meters

Being upgraded

M. Conde - WE6RFP055
The CLIC RF power source can be described as a "black box", combining very long RF pulses, and transforming them in many short pulses, with higher power and with higher frequency.

- 650 Klystrons
  - low frequency
  - high efficiency

- Power stored in electron beam

- Power extracted from beam in resonant structures

- 140000 Accelerating Structures
  - high frequency
  - high gradient

Long RF Pulses $P_0, n_0, \tau_0$

Electron beam manipulation

Short RF Pulses

\[ P_A = P_0 \times N_1 \]
\[ \tau_A = \frac{\tau_0}{N_2} \]
\[ \nu_A = \nu_0 \times N_3 \]
Full beam-loading acceleration in TW sections

"short" structure - low Ohmic losses
Full beam-loading acceleration in TW sections

High current beam

“short” structure - low Ohmic losses

most of RF power (≥ 95%) to the beam
Full beam-loading acceleration in TW sections

\[ G_{\text{acc}} \]

- unloaded
- loaded

\[ L_{\text{struct}} \]

\[ E_{\text{beam}} \]

\[ E_0 \]

\[ \approx \frac{E_0}{2} \]

\[ t_{\text{fill}} \]

- steady state

Time resolved beam energy spectrum measurement in CTF3

\[ \Delta P/P (\%) \]

- Transient
- Steady state

Time (ns)
Beam combination/separation by transverse RF deflectors
Counter flow distribution

Instead of using a single drive beam pulse for the whole main linac, several ($N_b = 24$) short ones are used. Each one feed a 900 m long sector of TBA.

Counter propagation from central complex

DLDS-like system

Counter-flow distribution allows to power different sectors of the main linac with different time bins of a single long electron pulse. The distance between pulses is $2L_b = 2L_{\text{main}}N_b$. The initial drive beam pulse length is equal to $2L_{\text{main}} = 140 \mu s/c$. 
Counter flow distribution

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The distance between pulses is $2L_0 = 2L_{\text{main}}/N_0$. The initial drive beam pulse length is equal to $2L_{\text{main}} = 140 \mu s/c$. 
Use of drive beam in Plasma Wakefield Accelerator

Concept for multi-stage PWFA Linear Collider (collinear two-beam accelerator)

A. Seryi - WE6PFP079
Two Beam Linear Colliders – Special Issues

Drive Beam Accelerator
efficient acceleration in fully loaded linac

Combinder ring × 4
pulse compression & frequency multiplication

Combinder ring × 3
pulse compression & frequency multiplication

Delay loop × 2
gap creation, pulse compression & frequency multiplication

Transverse RF Defectors

CLIC RF power source
C. Biscari - WE6PFP076

Drive Beam Decelarator Sector (24 in total)

Power Extraction

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

Drive beam time structure - final
5.8 μs
24 pulses - 100 A - 2.6 cm between bunches
Phase coding

How to “code” the sub-pulses

Sub-Harmonic
Bunching $\nu_0 / 2$

Acceleraion $\nu_0$

Deflection $\nu_0 / 2$

180° phase switch

Gap creation & first multiplication $\times 2$

$$L_{\text{delay}} = n \lambda_g = c T_{\text{sub-pulse}}$$

Combination scheme

Delay Loop

odd buckets

RF deflector

even buckets
RF injection in combiner ring

- Injection line
- Septum
- 1st deflector
- 2nd deflector
- Local inner orbits
RF injection in combiner ring

\[ C_{ring} = (n + \frac{1}{4}) \lambda \]
CTF3 preliminary phase (2001-2002)

A first ring combination test was performed in 2002, at low current and short pulse, in the CERN Electron-Positron Accumulator (EPA), properly modified.
CTF3 preliminary phase (2001-2002)

- Beam structure in linac – 4 pulses
- Beam structure after combination (factor 4)

Bunch spacing:
- Total length: 1.3 ms
- Peak Beam Current: 0.3 A

Pulse Length: 6.6 ns

Bunch spacing:
- Factor 4

Beam Peak Current: 1.2 A
CTF3 preliminary phase (2001-2002)

Beam structure in linac – 4 pulses

streak camera measurement

6.6 ns 420 ns Bunch spacing 333 ps

total length 1.3 ms - Peak Beam Current 0.3 A
CTF3 preliminary phase (2001-2002)

Transition through zero momentum compaction optics - $\alpha \leq 10^{-4}$

streak camera measurement
CTF3 preliminary phase (2001-2002)

Transition through zero momentum compaction optics - $\alpha \leq 10^{-4}$

streak camera measurement

$\Delta p / p$

$x$
RF injection in combiner ring in CTF3 preliminary phase (2001-2002)

Streak camera images of the beam, showing the bunch combination process.
RF injection in combiner ring in CTF3 preliminary phase (2001-2002)

Streak camera images of the beam, showing the bunch combination process.
RF injection in combiner ring in CTF3 preliminary phase (2001-2002)

Streak camera images of the beam, showing the bunch combination process
RF injection in combiner ring in CTF3 preliminary phase (2001-2002)

Streak camera images of the beam, showing the bunch combination process.
The CLIC Test Facility CTF3

is a small scale version of the CLIC drive beam complex
Two Beam Linear Colliders – Special Issues

- Provide RF power to test accelerating structures and components
- Full beam-loading accelerator operation
- Electron beam recombination by RF injection at high current
- Safe and stable beam deceleration and power extraction
- Two-beam acceleration scheme

Structures
- Structure materials
- Drive Beam generation
- PETS on-off
- DB decelerator
- CLIC sub-unit
Drive Beam linac – high current, full beam loading operation

Measured RF-to-beam efficiency
95.3 %

Theory
96% (~ 4 % ohmic losses)
Fast phase switch from SHB system (CTF3)

3 TW Sub-harmonic bunchers, each fed by a wide-band TWT

\[ 8.5 \times 666 \text{ ps} = 5.7 \text{ ns} \]
Delay Loop – beam current multiplication x 2, hole creation

Beam current measured:

before DL

in DL

after DL

Delay Loop

RF deflector
Combiner Ring

Fast vertical beam instability in CTF3 solved by new deflectors with strong damping of the vertical deflecting mode and larger hor./vert. detuning

Old RF deflectors

D. Alesini - WE1PBC04

New RF deflectors (INFN-Frascati)
Built-in Aluminium – very fast conditioning to nominal power (1 day)
Without the losses from the fast vertical beam instability (plus improved optics control and tuning tools) it is now possible to circulate the 3 A beam with very small losses for hundreds of turns.

Combiner Ring

Bunch re-combination of a 3 A beam with factor four current increase had been demonstrated – 12 A reached.

(DL still by-passed, and limited by RF pulse length)
Learning in CTF3: procedures, measurements etc..

CTF3 is a test facility, we assume its main goal is to provide a convincing demonstration of the CLIC technology. BUT possibly even more important is use it to

- Identify potential problems
Learning in CTF3: procedures, measurements etc..

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- Develop measurement devices & methods

Path length variation as a function of wiggler field
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- Identify potential problems
- Develop measurement devices & methods
- Develop beam tuning procedures
- Test feedback & stabilization techniques
- Benchmark simulations
Two Beam Linear Colliders – Special Issues

Transfer lines and CLEX

Most of the hardware has now been installed!

V.C. Sahni - TH1GR104

A. Faus-Golfe - TH5RF054
Transfer lines and CLEX

Most of the hardware has now been installed!

V.C. Sahni - TH1GR104

C. Simon - TH5RFP024

A. Faus-Golfe - TH5RFP054
First power production from 12 GHz PETS
First power production from 12 GHz PETS

I. Syratchev - WE3RAC02

Re-circulation
CTF3 Status

Progress possible through successful collaboration between 28 international institutes

Technical programme is on track

- CTF3 on schedule
  - full beam loading
  - bunch phase coding and Delay Loop operation
  - First results on recombination in Combiner Ring

- All machine components installed - apart from TBL
Next Steps in CTF3

- TBL drive beam deceleration studies (string of up to 16 PETS)
- Study of two-beam issues
  - RF breakdown kicks experiment
  - Beam loading compensation of probe beam
- Photo-injector option full implementation
- Phase stability measurements & feed-forward tests
- CTF3 upgraded to X-band power production & testing facility
  2012 +
- Full-fledged CLIC modules beam tests in CLEX
- Instrumentation development for LC – Instrumentation Test Beamline
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Phase stability measurements & feed-forward

0.2 degrees phase stability @ 12 GHz required for CLIC drive beam for 2% luminosity loss
Phase stability measurements & feed-forward

- Phase & energy measurement
- Fast feed-forward kicker in final compression line
Two-beam modules in TBTS

- Module design and integration have to be studied for different configurations.
- Integration of the systems in terms of space reservation has been done. Detailed design started for the main systems, such vacuum, cooling, alignment, stabilisation ...
- Important aspects for cost and basic parameters provided for other areas of the study.

Drive beam

Main beam

20780 modules (2 m long)
71450 power prod. structures PETS (drive beam)
143010 accelerating structures (main beam)
Two-beam modules in TBTS

- Module design and integration have to be studied for different configurations.
- Integration of the systems in terms of space reservation has been done. Detailed design started for the main systems, such vacuum, cooling, alignment, stabilisation ...
- Important aspects for cost and basic parameters provided for other areas of the study.
- Goal: build prototype → test with beam of a few modules in CTF3 from 2010

Drive beam

Main beam

- 20750 modules (2 m long)
- 71450 power prod. structures PETS (drive beam)
- 143010 accelerating structures (main beam)
Conclusions

- The CLIC TBA scheme, coupling high-gradient acceleration and efficiency, evolved during the years, as ideas and techniques were devised and tested.

- The scheme basics were virtually untouched in the last few years as the concept reached maturity.

- The CTF3 facility is the main tool to demonstrate the scheme feasibility. A number of issues were already addressed, such as isochronicity, full beam loading operation, bunch phase coding, path length control and the interleaving scheme.

- CTF3 commissioning is being completed and a full current combination test is expected in 2009.

- The next major step, to be completed by 2010, is the study of drive beam deceleration in a string of PETS in the TBL line, presently under installation.

- Future short term studies include an assessment of the drive beam stability, both in current and phase, and the identification of the main sources of jitter.

- In the longer term other experimental tests are under evaluation, including the construction and use of a series of full-fledged CLIC TBA modules and the implementation of a fast phase feed-back system to test the very tight phase stability requirements of the CLIC drive beam (0.2° at 12 GHz).
Performance vs reliability in CTF3

30 A demonstration

10-15 A Routine operation in TBTS for power production

Routine operation of CTF3 (albeit at a reduced current), with 12 GHz power production in the TBTS and later in a full TBL will provide a convincing demonstration of the CLIC RF power source concept
Two Beam Linear Colliders – Special Issues

Work Plan until 2010:

- Demonstrate feasibility of CLIC technology (R&D on critical feasibility issues)
- Design of a linear Collider based on CLIC technology  
  http://clic-study.web.cern.ch/CLIC-Study/Design.htm
- Estimation of its cost (capital investment & operation)
- CLIC Physics study and detector development  
  http://clic-meeting.web.cern.ch/clic-meeting/CLIC_Phys_Study_Website/default.htm

Conceptual Design Report to be published in 2010 including:
- Physics, Accelerator and Detectors
- Results of feasibility study
- Preliminary performance and cost estimation

R&D Issues classified in three categories:

- critical for feasibility  
  fully addressed by specific R&D to be completed before 2010 
  results in CDR
- critical for performance  
  being addressed now by specific R&D to be completed before 2015 
  first assessments in CDR 
  results in Technical Design Report (TDR) with consolidated performance & cost
- critical for cost
Tentative long-term CLIC scenario
Shortest, Success Oriented, Technically Limited Schedule

Technology evaluation and Physics assessment based on LHC results
for a possible decision on Linear Collider with staged construction starting with the lowest
energy required by Physics

|------------------------------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|      |
| R&D on Feasibility Issues    |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| Conceptual Design            |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| R&D on Performance and Cost issues |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| Technical design             |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| Engineering Optimisation & Industrialisation |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| Construction (in stages)     |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| Construction Detector        |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |

- Conceptual Design Report (CDR)
- Technical Design Report (TDR)
- Project approval?
- First Beam?
Photo-injector option full implementation

- Smaller transverse emittance
- Shorter bunches, no energy tails
- No satellites
- Lower current

Single bunch option will allow
- Check and correction of beam optics with high precision
- CSR measurements with high precision in DL, CR and TL2 bunch compressor
- a response of PETS and beam instrumentation
- ...

Possible integration of the photo injector

2.5 m

1.2 m
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<th>Parameter</th>
<th>Unit</th>
<th>CLIC nominal</th>
<th>Present state of the art</th>
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<th>Objective 2012</th>
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