The CLIC Electron and Positron Polarized Sources

Louis Rinolfi

for the CLIC* Study team

(*) CLIC = Compact Linear Collider
Acknowledgements

A. Brachmann¹, E. Bulyak², R. Chehab³, O. Dadoun⁴, S. Doebert⁵, W. Gai⁶, P. Gladkikh², T. Kamitani⁷, M. Kuriki⁸, W. Liu⁶, T. Maruyama¹, T. Omori⁷, M. Poelker⁹, J. Sheppard¹, J. Urakawa⁷, A. Variola⁴, A. Vivoli⁵, V. Yakimenko¹⁰, F. Zhou¹, F. Zimmermann⁵

¹, SLAC, California, USA
², NSC/KIPT, Kharkov, Ukraine
³, IPNL, Université Lyon-1, Lyon, France
⁴, LAL, Université Paris-Sud, Orsay
⁵, CERN, Geneva, Switzerland
⁶, ANL, Illinois, USA
⁷, KEK, Japan
⁸, Hiroshima University, Japan
⁹, JLAB, Virginia, USA
¹⁰, BNL, Upton, USA
General CLIC layout for 3 TeV

- **drive beam accelerator**: 2.38 GeV, 1.0 GHz
- **326 klystrons**: 33 MW, 139 μs
- **circumferences delay loop**: 72.4 m
  - CR1: 144.8 m
  - CR2: 434.3 m
- **decelerator**: 24 sectors of 876 m
- **TA radius**: 120 m
- **48.3 km**
- **4.8 km**
- **e⁻ main linac**: 12 GHz, 100 MV/m, 21.02 km
- **e⁺ main linac**: 12 GHz, 100 MV/m, 21.02 km
- **Booster linac**: 6.14 GeV
- **e⁻ injector**: 2.86 GeV
- **e⁺ injector**: 2.86 GeV
- **BDS**: beam delivery system
The CLIC Main Beams generation is focused on 3 studies to produce $e^+/e^-$ with the requested parameters at the entrance of the Pre-Damping Ring (PDR):

1) **Base Line configuration:**

   3 TeV (c.m.) - polarized electrons ($4.4\times10^9$ e$^-$/bunch) and unpolarized positrons ($6.4\times10^9$ e$^+$/bunch).

2) **Polarized positron configuration:**

   3 TeV (c.m.) - polarized $e^-$ and $e^+$ with same charge as above

3) **Double charge configuration:**

   500 GeV (c.m.) - polarized electrons ($8\times10^9$ e$^-$/bunch) and (un)polarized positrons ($12\times10^9$ e$^+$/bunch).
CLIC Main Beam Injector Complex in 2009

3 TeV
Base line configuration

unpolarized e⁺
polarized e⁻
Electron beam on the crystal:
- energy = 5 GeV
- beam spot size = 2.5 mm

- First target (1.4 mm) is a W crystal oriented along <111> axis where channeling process occurs
- Second target (10 mm) is W amorphous, 3 m downstream.

Simulations have shown that CLIC parameters are obtained with the present configuration and for unpolarized e⁺.

In this talk, we will briefly review only the generation of polarized e⁺.

CLIC Note to be published « Study of an hybrid source using channeling » by O. Dadoun (LAL) et al.
Generation of polarized electron
CLIC e⁻ beam time structure at 3 TeV

20 ms Repetition Rate (50 Hz)

156 ns, 312 micro-bunches

~ 100 ps

6x10^9 e⁻

0.5 ns

1.999 GHz
### Issues for the CLIC polarized e⁻ source

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>0.5 TeV</th>
<th>3 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number Electrons per microbunch</td>
<td>$N_e$</td>
<td>$10 \times 10^9$</td>
<td>$6 \times 10^9$</td>
</tr>
<tr>
<td>Number of microbunches</td>
<td>$n_b$</td>
<td>354</td>
<td>312</td>
</tr>
<tr>
<td>Width of microbunch</td>
<td>$t_b$</td>
<td>~ 100 ps</td>
<td>~ 100 ps</td>
</tr>
<tr>
<td>Time between microbunches</td>
<td>$\Delta t_b$</td>
<td>0.5002 ns</td>
<td>0.5002 ns</td>
</tr>
<tr>
<td>Microbunch rep rate</td>
<td>$f_b$</td>
<td>1999 MHz</td>
<td>1999 MHz</td>
</tr>
<tr>
<td>Width of macropulse</td>
<td>$T_B$</td>
<td>177 ns</td>
<td>156 ns</td>
</tr>
<tr>
<td>Macropulse repetition rate</td>
<td>$F_B$</td>
<td>50 Hz</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Charge per micropulse $(e \times N_e)$</td>
<td>$C_b$</td>
<td>1.6 nC</td>
<td>0.96 nC</td>
</tr>
<tr>
<td>Charge per macropulse $(C_b \times n_b)$</td>
<td>$C_B$</td>
<td>566 nC</td>
<td>300 nC</td>
</tr>
<tr>
<td>Average current from gun $(C_B \times F_B)$</td>
<td>$I_{ave}$</td>
<td>28 $\mu$A</td>
<td>15 $\mu$A</td>
</tr>
<tr>
<td>Average current in macropulse $(C_b / T_B)$</td>
<td>$I_B$</td>
<td>3.2 A</td>
<td>1.9 A</td>
</tr>
<tr>
<td>Duty Factor w/in macropulse $(t_b / \Delta t_b)$</td>
<td>$DF$</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Peak current of micropulse $(I_B / DF)$</td>
<td>$I_{peak}$</td>
<td>16 A</td>
<td>9.6 A</td>
</tr>
<tr>
<td>Current density $(I_{peak} / s)$ [spot size radius 1 cm]</td>
<td>$D$</td>
<td>5 A/cm²</td>
<td>3 A/cm²</td>
</tr>
</tbody>
</table>

One of the critical issues is the Surface charge limit => needs demonstration => depends on laser system
### ILC and CLIC $e^-$ sources

<table>
<thead>
<tr>
<th>Parameters</th>
<th>ILC</th>
<th>CLIC (0.5 TeV)</th>
<th>CLIC (3 TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrons/microbunch</td>
<td>$3 \times 10^{10}$</td>
<td>$1 \times 10^{10}$</td>
<td>$0.6 \times 10^{10}$</td>
</tr>
<tr>
<td>Charge / microbunch</td>
<td>4.8 nC</td>
<td>1.6 nC</td>
<td>1 nC</td>
</tr>
<tr>
<td>Number of microbunches</td>
<td>2625</td>
<td>354</td>
<td>312</td>
</tr>
<tr>
<td>Total charge per pulse</td>
<td>$79 \times 10^{12}$</td>
<td>$3.5 \times 10^{12}$</td>
<td>$1.9 \times 10^{12}$</td>
</tr>
<tr>
<td>Width of Microbunch</td>
<td>1 ns</td>
<td>~0.1 ns</td>
<td>~0.1 ns</td>
</tr>
<tr>
<td>Time between microbunches</td>
<td>360 ns</td>
<td>0.5002 ns</td>
<td>0.5002 ns</td>
</tr>
<tr>
<td>Width of Macropulse</td>
<td>~1 ms</td>
<td>177 ns</td>
<td>156 ns</td>
</tr>
<tr>
<td>Macropulse repetition rate</td>
<td>5 Hz</td>
<td>50 Hz</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Charge per macropulse</td>
<td>~12600 nC</td>
<td>566 nC</td>
<td>300 nC</td>
</tr>
<tr>
<td>Average current from gun</td>
<td>63 $\mu$A</td>
<td>28 $\mu$A</td>
<td>15 $\mu$A</td>
</tr>
<tr>
<td>Peak current of microbunch</td>
<td>4.8 A</td>
<td>16 A</td>
<td>9.6 A</td>
</tr>
<tr>
<td>Current density (1 cm radius)</td>
<td>1.5 A/cm$^2$</td>
<td>5 A/cm$^2$</td>
<td>3 A/cm$^2$</td>
</tr>
<tr>
<td>Polarization</td>
<td>&gt;80%</td>
<td>&gt;80%</td>
<td>&gt;80%</td>
</tr>
</tbody>
</table>
Superlattice GaAs: Layers of GaAs on GaAsP

100 nm
14 pairs

No strain relaxation
QE ~ 1%
Pol ~ 85%
@ 780 nm

Photocathodes for ILC and CLIC

First successful superlattice by KEK/Nagoya group.

Large band-gap photocathode gave a high current. First GaAs-GaAsP photocathode with superlattice structure, strain, modulation doping by KEK/Nagoya group.

Developments at JLAB by M. Poelker group.

“Lifetime Measurements of High Polarization Strained Superlattice Gallium Arsenide at Beam Current > 1 mA Using a New 100 kV Load Lock Photogun”, J. Grames et al., Particle Accelerator Conference, Albuquerque, NM, June 25-29, 2007

Developments at SLAC by J. Sheppard group.
cw laser parameters for $e^-$ source

$$E_L = \frac{hc}{q} \frac{Q}{\lambda \times QE}$$

$$E_L(J) = 1.24 \times 10^{-6} \frac{Q(nC)}{\lambda(nm) \times QE}$$

$\lambda \approx 775 - 780$ nm for GaAs photocathodes

$QE \approx 0.2 \%$ (KEK, Nagoya, JLAB, SLAC)

$\eta \approx 70\%$ for the bunching system

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Units</th>
<th>CLIC 500 GeV</th>
<th>CLIC 3 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser energy on photocathode ($E_L$)</td>
<td>J</td>
<td>453x10^{-6}</td>
<td>240x10^{-6}</td>
</tr>
<tr>
<td>Laser energy based on bunching efficiency ($E_B = E_L/\eta$)</td>
<td>J</td>
<td>647x10^{-6}</td>
<td>343x10^{-6}</td>
</tr>
<tr>
<td>Peak power ($P_p = E_B / T_B$)</td>
<td>W</td>
<td>3654</td>
<td>2197</td>
</tr>
<tr>
<td>Average power ($P_a = E_B \times F_B$)</td>
<td>W</td>
<td>0.032</td>
<td>0.017</td>
</tr>
<tr>
<td>Repetition frequency ($F_B$)</td>
<td>Hz</td>
<td>50</td>
<td>50</td>
</tr>
</tbody>
</table>
$\lambda \approx 775 - 780$ nm for GaAs photocathodes

$\text{QE} \approx 0.2 \%$

$\eta \approx 90\%$

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Units</th>
<th>CLIC 500 GeV</th>
<th>CLIC 3 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Micropulse repetition frequency ($f_p$)</td>
<td>MHz</td>
<td>2000</td>
<td>2000</td>
</tr>
<tr>
<td>Micropulse length ($t_p$)</td>
<td>ns</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Micropulse laser energy on cathode ($E_B = E_L / \eta$)</td>
<td>J</td>
<td>$1.4 \times 10^{-6}$</td>
<td>$0.9 \times 10^{-6}$</td>
</tr>
<tr>
<td>Micropulse peak power ($P_p = E_B / t_p$)</td>
<td>W</td>
<td>14000</td>
<td>9000</td>
</tr>
<tr>
<td>Macropulse laser energy on cathode ($E_m = E_B \times n_b$)</td>
<td>J</td>
<td>$496 \times 10^{-6}$</td>
<td>$280 \times 10^{-6}$</td>
</tr>
<tr>
<td>Macropulse peak power ($P_m = E_m / T_B$)</td>
<td>W</td>
<td>2800</td>
<td>1800</td>
</tr>
<tr>
<td>Macropulse average power ($P_a = E_m \times F_B$)</td>
<td>W</td>
<td>0.024</td>
<td>0.014</td>
</tr>
<tr>
<td>Repetition frequency ($F_B$)</td>
<td>Hz</td>
<td>50</td>
<td>50</td>
</tr>
</tbody>
</table>
Polarized $e^-$ produced at SLAC

The total charge produced is a:

- factor 3 above the CLIC requirement for 0.5 TeV and a
- factor 5 above the CLIC requirements for 3 TeV

The measured polarization is 82%
Production of e⁻ pulse length of 156 ns

Laser working at 60 Hz

Measurements performed at 30 Hz up to $4.3 \times 10^{12}$ e⁻ per pulse

Measurements performed at 10 Hz at higher charge due to radiological limits in the Gun Test Facility

With this scheme, the peak current and the surface charge limit are reduced by a factor 5.

A. Brachmann, T. Maruyama, J. Sheppard, F. Zhou / SLAC
DC guns for polarized $e^-$ source

JLAB  100 kV electron gun  (courtesy from M. Poelker)

SLAC  120 kV electron gun  (courtesy from J. Sheppard)
CLIC bunching system simulations

DC-gun 2-GHz pre-bunchers accelerator

140kV 156ns Buncher

156ns DC beam (312 2-GHz RF periods) ⇒ 312 2-GHz microbunches

4 RF periods (2-GHz) of DC beam on cathode

4 2-GHz microbunches at injector exit
## Simulations for the CLIC e⁻ source

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Units</th>
<th>CLIC 3 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gun voltage</td>
<td>kV</td>
<td>140</td>
</tr>
<tr>
<td>Injector energy</td>
<td>MeV</td>
<td>20</td>
</tr>
<tr>
<td>Initial charge at the gun</td>
<td>nC</td>
<td>1</td>
</tr>
<tr>
<td>Capture efficiency</td>
<td>%</td>
<td>88</td>
</tr>
<tr>
<td>Initial bunch length at the cathode</td>
<td>ns</td>
<td>156</td>
</tr>
<tr>
<td>Final bunch length (FWHM)</td>
<td>ps</td>
<td>14</td>
</tr>
<tr>
<td>Energy spread (FWHM)</td>
<td>keV</td>
<td>100</td>
</tr>
<tr>
<td>Normalized rms emittance</td>
<td>mm.mrad</td>
<td>22</td>
</tr>
</tbody>
</table>

Very good results for CLIC parameters
**CLIC polarized e⁻ source challenges**

**Gun:**
- Reliable load locked gun
- High voltage 100 kV - 350 kV => No field emission
- Ultra-high vacuum requirements => range of $10^{-11}$ Torr
- Cathode/anode optics => challenge for uniform focusing properties

**Photocathode:**
- Production of the full current with space charge and surface charge limits
- High polarization: 80 % - 90% => Measurements and accuracy
- High Quantum Efficiency: 0.2 – 1 % => Photo-cathodes preparation techniques
- Long life time

**Laser:**
- Laser frequency: 2 GHz or cw
- Pulse length: 0.1 to 1 ns or 156 ns
- Pulse energy: ~ 1 mJ
Generation of polarized positron
### Flux of $e^+$

<table>
<thead>
<tr>
<th></th>
<th>SLC</th>
<th>CLIC</th>
<th>ILC</th>
<th>LHeC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^+/\text{bunch}$</td>
<td>$3.5 \times 10^{10}$</td>
<td>$0.64 \times 10^{10}$</td>
<td>$2 \times 10^{10}$</td>
<td>$1.5 \times 10^{10}$</td>
</tr>
<tr>
<td>Bunches / macropulse</td>
<td>1</td>
<td>312</td>
<td>2625</td>
<td>20833</td>
</tr>
<tr>
<td>Macropulse Rep. Rate.</td>
<td>120</td>
<td>50</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>$e^+/\text{second}$</td>
<td>$0.042 \times 10^{14}$</td>
<td>$1 \times 10^{14}$</td>
<td>$2.6 \times 10^{14}$</td>
<td>$31 \times 10^{14}$</td>
</tr>
</tbody>
</table>

*Note:* The flux of $e^+$ is multiplied by 24.
Two methods to produce polarized $e^+$

1) Helical undulator

- $e^-$ beam
- $E > 100$ GeV
- High energy
- $L > 100$ m
- Long undulator
- $E = 10 - 20$ MeV
- $e^+$

2) Compton with laser

- $e^-$ beam
- $E = 1 - 6$ GeV
- Low energy
- $E = 30 - 60$ MeV
- $e^+$

These two methods apply for High Energy Physics.

There are other possibilities which are not mentioned here (polarized $e^-$ on the target, …)
CLIC Undulator scheme

250 GeV

100 m long undulator with $K=0.7$, $\lambda u=1.5$cm without photon collimator is assumed
OMD is flux concentrator
Target is 0.4X0 Ti non-immersed target

$\gamma$ dump

W. Gai, W. Liu / ANL
N\gamma / N_{e^-} = 1 \text{ (demonstrated at BNL)}

N_{e^+} / N_{\gamma} = 0.02 \text{ (expected)}

i.e. \approx 50 \text{ gammas to generate } 1 \text{ e}^+

Data for CLIC:

N_{e^+} = 6.4 \times 10^9 / \text{bunch} \sim 1 \text{ nC}

N_{e^-} = 0.32 \times 10^{12} / \text{bunch} \sim 50 \text{ nC}

With 5 \text{ nC} / \text{e}^- \text{ bunch and 10 Compton IP's}

=> 1 \text{ nC} / \text{e}^+ \text{ bunch}
CLIC requires $4.4 \times 10^9$ e+/bunch.
CLIC Compton Ring

2.86 GeV

$e^+ \text{ DR}$

2.86 GeV

$e^+ \text{ PDR and Accumulator ring}$

420 turns makes 312 bunches with $4.2 \times 10^9$ $e^+/bunch$

$C = 47 \text{ m, 156 ns/turn, 312 bunches with } 6.2 \times 10^{10} \text{ e }^+/bunch$

$1 \text{ YAG Laser pulse}$

$\sim 10^9 \text{ photons/turn/bunch}$

$\sim 10^7 \text{ pol. } e^+/turn/bunch$

156 ns $\times 440 \text{ turns}$ => 70 $\mu$s pulse length for both linacs
Some challenges for the e+ source

1) Devices for Undulator scheme (Helical undulator, collimators, dumps, …)
2) Devices for Compton schemes (Optical cavities at IP, powerful laser systems, …)
3) Targets issues (Heat load dynamics, beam energy deposition, shock waves, breakdown limits, activation, ….)
4) Adiabatic Matching Device (AMD)
5) Capture and acceleration sections (Transport and collimation of large emittances)
6) Find out a maximum e+ yield (Trade off between yield, polarization and emittances)
7) Polarization issues (Analyze systematic errors of polarization measurements)
8) Efficient use of existing codes (EGS4, FLUKA, Geant4, PPS-Sim, …)
9) Integration issues for the target station (remote handling in radioactive area)
10) Radioactivity issues
11) ……..
Summary

- For polarized e\(^-\) and for the Base Line configuration at 3 TeV, they would be generated and accelerated close to the requested performance. However simulations, in parallel with an important R&D program, remain to be done to confirm the present studies.

- The 500 GeV configuration (double charge) is more challenging but seems doable.

- For polarized positrons, several big challenges remain to be investigated and demonstrated by simulations. Fortunately extensive studies are carried on, in collaboration with several institutes (mentioned in the Acknowledgements).

- The production of unpolarized e\(^+\) for the Base Line configuration is less challenging and seems doable.