CLIC polarized e+ source based on laser Compton scattering

Frank Zimmermann
CLIC Meeting, 16. December 2005

Thanks to Eugene Bulyak,
Masao Kuriki, Klaus Moenig,
Tsunehiko Omori, Junji Urakawa,
Alessandro Variola
outline

- introduction
- ILC scheme
- differences ILC - CLIC
- CLIC scheme
- Compton ring dynamics
- laser system
- optical cavities
- ATF R&D
- LAL studies
- stacking in DR or pre-DR
- Compton Workshop 2006
Introduction

- polarized e+ source based on laser Compton scattering for the ILC was proposed at Snowmass 2005

- experimental tests at the ATF have demonstrated the production of $10^4$ polarized e+ per bunch with 77 +/- 10% polarization

- stacking in the damping ring is a new feature proposed for the ILC
References


A proposal of a polarized e+ source based on laser Compton scattering for the ILC was presented at Snowmass 2005; the same scheme can be adapted to CLIC

“POSIPOL collaboration”
**ILC source**

- either YAG or CO2 laser (→ differing parameters)
- 1.3 or 4.1 GeV linac injecting into 1.3 or 4.1 GeV Compton storage ring with 280 (or 2x280) bunches and C=277 (649) m

- ILC Compton ring contains 30 coupled optical cavities with laser-beam interaction points producing 1.36 (1.8)x10^{10} polarized photons per bunch and turn
- after conversion on a target with yield 1.4% this results in 1.9 (2.4) x10^{8} polarized e+
- 100 (50) turns in Compton ring result in 10x2800 bunches of polarized e+ which are accelerated in a 5 GV pulsed s.c. linac operating at 100 Hz
- bunches are stacked 10 times in each bucket of the DR and the whole process is repeated ten times with a time separation of 10 ms for damping
- after 90 ms accumulation is completed; the damping ring stores e+ bunches for 100 further ms before extraction
ILC polarized positron source w. CO2 laser

30 CO2 Laser Pulse Stacking Cavities
210 mJ in each cavity, 8 degree crossing to e- beam (collisions in 50 turns + 9.9 msec cooling)x100 Hz
Ne+ = 2.4 x 10^8/bunch
280 bunches x 2
4.1 GeV e^- Linac (low Q)
Compton Ring
4.1 GeV e^- Storage Ring
C = 649 m (2.2μs / turn)
280 bunches x 2
Ne^- = 6.2 x 10^10/bunch
Ne+/Ne^- = 1.4%
gamma
Ng = 1.8 x 10^10 /turn/bunch (23-29 MeV)
5 GeV e^+ Linac
Super Conducting
100 Hz

5 GeV e^+ Main Damping Ring
(1) 5 turns of Compton Ring makes 2800 bunches (280 x 2 x 5).
50 turns of Compton Ring (110 μs) makes 10 times of stacking in each bucket in DR. Population reaches
Ne+ = 2.4 x 10^9/bunch.
Then 9.9 msec wait for damping.
(2) repeat this 10 times
Ne+ = 2.4 x 10^10/bunch
takes 100 m sec
C = 3247 m

(3) after stacking, DR has 100 m sec.
Then DR damp positrons and send them to Main Linac
Ne+ = 2.0 x 10^10/bunch
2800 bunches
ILC polarized positron source w. YAG laser

30 YAG Laser Pulse Stacking Cavities
600 mJ in each cavity, 8 degree crossing to e- beam
(collisions in 100 turns + 9.9 msec cooling) x100 Hz

1.3 GeV e- Linac
(low Q)

1.3 GeV e- Storage Ring
C = 277 m (0.9μs / turn)
280 bunches
Ne- = 6.2 x 10^{10} / bunch

Compton Ring
gamma

Ne+ = 1.9 x 10^8/bunch
280 bunches

5 GeV e+ Linac
Super Conducting
100 Hz

5 GeV e+ Main Damping Ring
(1) 10 turns of Compton Ring
makes 2800 bunches (280 x 10).
100 turns of Compton Ring (90 μs)
makes 10 times of stacking in each bucket in DR. Population reaches
Ne+ = 1.9 x 10^9 / bunch.
Then 9.9 msec wait for damping.
(2) repeat this 10 times
Ne+ = 1.9 x 10^{10} / bunch
takes 100 m sec
C = 2767 m

(3) after stacking,
DR has 100 m sec.
Then DR damp positrons and send them
to Main Linac
Ne+ = 1.6 x 10^{10} / bunch
2800 bunches
Schematic of one Compton IP for ILC

Phase Scan

Compton Scattering in every 357MHz

Scattered Gamma beam

Laser Repetition rate: 357MHz laser pulses

Electron repetition rate: 357MHz Electron bunches

schematic of one Compton IP for ILC

J. Urakawa
schematic view of multi-IP chamber for ILC

Laser

electron beam

Multi-Compton chamber system

J. Urakawa
Compton-based e+ source for CLIC

why?

- either ILC or CLIC could be realized depending on physics case and cost

- CLIC differs from ILC in beam parameters, damping ring, bunch spacing, and repetition rate → some aspects of e+ source become easier

- recommendation by Yokoya san to use a polarized e+ source at CLIC and not at ILC

for simplicity consider only YAG laser case, since it puts less demand on injection linac and Compton ring
four main differences between ILC and CLIC

- beam structure: CLIC has a smaller bunch charge (about 10x less) and less bunches per pulse (about 20x less) → relaxed laser parameters

- bunch spacing in DR: 0.533 ns instead of 2.8 ns → layout of optical cavities more challenging → multiple pulses stored in one cavity?

- damping ring; CLIC damping ring needs to produce beam with extremely small emittance, limited dynamic aperture; → pre-damping ring is required; we can use and optimize pre-damping ring for stacking polarized e+ from Compton source

- CLIC repetition rate is 150 Hz instead of 5 Hz for ILC
## CLIC and ILC Damping Ring Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>CLIC</th>
<th>ILC (OTW/PPA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>2.424 GeV</td>
<td>5 GeV</td>
</tr>
<tr>
<td>Circumference</td>
<td>360 m</td>
<td>3230 m (or &gt;)</td>
</tr>
<tr>
<td>Bunch population</td>
<td>$2.56 \times 10^9$</td>
<td>$2 \times 10^{10}$</td>
</tr>
<tr>
<td>Bunches/train</td>
<td>110</td>
<td>280</td>
</tr>
<tr>
<td>Intertrain gap</td>
<td>flexible</td>
<td>80 missing bunches</td>
</tr>
<tr>
<td># trains/pulse</td>
<td>2</td>
<td>10</td>
</tr>
<tr>
<td>Bunch spacing</td>
<td>0.533 ns</td>
<td>3.077 ns</td>
</tr>
<tr>
<td>Hor. norm. emittance</td>
<td>600 nm</td>
<td>3 $\mu$m (?)</td>
</tr>
<tr>
<td>RF frequency</td>
<td>$\sim 1.875$ GHz</td>
<td>650 MHz</td>
</tr>
<tr>
<td>Vert. norm. emittance</td>
<td>5-10 nm</td>
<td>$\sim 10$ nm (?)</td>
</tr>
<tr>
<td>RMS bunch length</td>
<td>1.54 mm</td>
<td>6 mm</td>
</tr>
<tr>
<td>RMS energy spread</td>
<td>0.126%</td>
<td>0.14%</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>150 Hz</td>
<td>5 Hz</td>
</tr>
</tbody>
</table>
as a consequence of these differences, we expect that we can significantly reduce the number of laser cavities in the CLIC Compton ring, ideally to one (a case which was already demonstrated at ATF)

this may considerably simplify design of Compton ring, laser hardware, and operation
schematic of total system for CLIC

1 YAG Laser Pulse
Stacking Cavity, 590 mJ

Compton ring
1.3 GeV storage ring,
C=42 m, 140 ns/turn
2x110 bunches
Nb=6.2x10^{10}

9.8x10^6 pol. e+/turn/bunch

γ (23–29 MeV)
6.9x10^8 /turn/bunch

2.4 GeV linac
150 Hz

2.424 GeV Accumulator Ring
400 turns of Compton ring makes
220 bunches with 4x10^9 e+/bunch;
then 6.1 ms for damping

after stacking and damping,
extract beam and inject into
damping ring, 220 bunches
<table>
<thead>
<tr>
<th>parameter</th>
<th>CLIC</th>
<th>ILC</th>
</tr>
</thead>
<tbody>
<tr>
<td>energy</td>
<td>1.3 GeV</td>
<td>1.3 GeV</td>
</tr>
<tr>
<td>circumference</td>
<td>42 m</td>
<td>277 m</td>
</tr>
<tr>
<td>rf frequency</td>
<td>1.875 GHz</td>
<td>650 MHz</td>
</tr>
<tr>
<td>bunch spacing</td>
<td>0.16 m</td>
<td>0.923 m</td>
</tr>
<tr>
<td># bunches stored</td>
<td>220</td>
<td>280</td>
</tr>
<tr>
<td>bunch population</td>
<td>6.2x10^{10}</td>
<td>6.2x10^{10}</td>
</tr>
<tr>
<td>#optical cavities</td>
<td>1</td>
<td>30</td>
</tr>
<tr>
<td>photons/bunch/turn</td>
<td>2.8x10^{9}</td>
<td>5.8x10^{10}</td>
</tr>
<tr>
<td>photons 23.2 MeV-29 MeV</td>
<td>6.9x10^{8}</td>
<td>1.36x10^{10}</td>
</tr>
<tr>
<td>pol. e+ /bunch/turn</td>
<td>9.8x10^{6}</td>
<td>1.9x10^{8}</td>
</tr>
<tr>
<td>#injections/bunch</td>
<td>400</td>
<td>100</td>
</tr>
<tr>
<td>total # e+/pulse</td>
<td>5.6x10^{11}</td>
<td>5.3x10^{13}</td>
</tr>
<tr>
<td>total # e+/second</td>
<td>8.4x10^{13}</td>
<td>2.7x10^{14}</td>
</tr>
</tbody>
</table>
tentative YAG laser parameters for CLIC & ILC

<table>
<thead>
<tr>
<th>parameter</th>
<th>CLIC</th>
<th>ILC</th>
</tr>
</thead>
<tbody>
<tr>
<td>laser pulse duration</td>
<td>57 μs</td>
<td>90 μs</td>
</tr>
<tr>
<td>rest between Compton cycles</td>
<td>6.1 ms</td>
<td>9.9 ms</td>
</tr>
</tbody>
</table>
Tentative Compton IP parameters for CLIC

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>e- bunch length at C-IP</td>
<td>5 mm?</td>
</tr>
<tr>
<td>e- rms hor./vert. beam size</td>
<td>25, 5 μm</td>
</tr>
<tr>
<td>e- beam energy</td>
<td>1.3 GeV</td>
</tr>
<tr>
<td>e- bunch charge</td>
<td>10 nC</td>
</tr>
<tr>
<td>Laser photon energy</td>
<td>1.164 eV</td>
</tr>
<tr>
<td>RMS laser radius</td>
<td>5 μm</td>
</tr>
<tr>
<td>RMS laser pulse width</td>
<td>0.9 mm</td>
</tr>
<tr>
<td>Laser pulse energy</td>
<td>592 mJ</td>
</tr>
<tr>
<td>No. of laser cavities</td>
<td>1</td>
</tr>
<tr>
<td>Crossangle</td>
<td>~10 degrees</td>
</tr>
<tr>
<td>Photons in cavity pulse</td>
<td>3.2x10^{18}</td>
</tr>
<tr>
<td>Polarized γs per bunch &amp; turn</td>
<td>6.9x10^{8}</td>
</tr>
<tr>
<td>Positron yield e+/γ</td>
<td>0.014</td>
</tr>
</tbody>
</table>
Compton parameters
\( x = 0.023, \ E_{\gamma, \text{max}} = 30 \ \text{MeV} \)

\[
\sigma_c \approx \sigma_T = \frac{8\pi}{3} r_e^2
\]

→ laser-photon scattering probability
  in 1 collision < 10\(^{-8}\)
→ pulse depletion from scattering negligible

\[
\xi^2 = \frac{2n_\gamma r_e^2 \lambda}{\alpha} \approx 0.02 << 1
\]

→ nonlinear Compton effect not important
CLIC Compton ring dynamics and e+ yield

simulation of CLIC Compton ring dynamics and e+ yield was performed by E. Bulyak with code modeling longitudinal dynamics with nonlinear momentum compaction; Eugene considered Compton ring with circumference 42 m, rf frequency 1.875 GHz, and 1 YAG laser cavity with 590 mJ; all other parameters were taken as for ILC nonlinear lattice

e+yield per Compton-ring laser-bunch collision:
e+yield/bunch = (bunch population) x (gamma yield) x (energy collimation) x (positron yield)
e+yield/bunch = 6.2x10^{10} x 4.4645x10^{-2} x 0.248 x 1/70 = 9.8x10^6

CLIC Compton ring can operate in steady state without losses; no cooling interval is required and e+ train length limited only by the length of the laser pulse; average photon production efficiency is rather high, namely ~64% of maximum theoretical (=initial) value for pointlike bunch matched to laser
Compton-ring particle phase-space distribution after 80, 240 and 400 turns; blue vertical lines indicate the rms laser splash size; the initial distribution of 200 test particles was pointlike; total duration of laser pulse is 400 turns
simulated photon yield as a function of turn number for continuous interaction with the laser over 400 turns
simulated *rms bunch length as a function of turn number* for continuous interaction with the laser over 400 turns
many ideas & simulations for Compton rings especially for difficult ILC conditions
- rf phase manipulation
- low & nonlinear momentum compaction
- wigglers
- pulsed momentum compaction lattice
- lattice design
- Compton simulation
Compton ring longitudinal dynamics for ILC
(with 30 laser-beam IPs)

circulating e- having interacted with laser avoid further interaction due to energy loss and synchrotron motion
→ train much shorter than synchrotron period enhances $\gamma$ rate
→ pulsed mode of operation
→ initial bunch position is chosen so that trajectory tangent is parallel to $p$ axis
→ zero quadratic and proper 3rd order momentum compaction can reduce trajectory curvature at the initial bunch point
→ periodical transport to optimal position
→ rf phase manipulation (RFPM)

E. Bulyak & P. Gladkikh
rf phase manipulation

rf phase manipulation scheme for ILC
RFPM enhances $\gamma$ intensity by factor 4; yield then equals 0.4 x theoretical maximum [YAG laser case] (CLIC: 0.64 w/o RFPM!)

E. Bulyak & P. Gladkikh
Compton ring lattice design

(for ILC, CO₂ laser)

E. Bulyak & P. Gladkikh

pulsed quadrupoles switched on just before laser system → pulsed α_c
schematic of laser system for CLIC or ILC

laser oscillator → solid state amplifier → stacking cavity

- **170 nJ**
- **10 ps FW**
- **117 MHz**
- **20 W**

- **600 µJ**, gain 3500, ATF: \(10^4\) (ATF rf gun)
- **CPMA**

- **600 mJ**, factor 1000 enhancement, ATF: 300 (pulsed laser wire)
- ATF: 1000 (cw laser wire), e.g., 16 pulses in 1.3-m cavity

*J. Urakawa*
*KEK scheme*
schematic of optical cavity

beam pipe with “small” hole

cavity length $l \sim d/\phi$

d $\sim 25$ mm, $\phi \sim 10^\circ$ $\rightarrow$ $l \sim 28$ cm

(3-4 pulses)

J. Urakawa
KEK/ATF scheme
cavity configurations

unstable 2 mirror configuration

stable 2 mirror configuration
larger spot size in the center

stable 4 mirror configuration (LAL) with small spot size

A. Variola
LAL scheme
laser frequency multiplication

1\textsuperscript{st} laser bunch injected

\[ \text{laser mode-lock period} \]

\text{fraction of laser mode-lock period} \approx 0.533 \text{ ns}

n\textsuperscript{th} laser bunch injected
another method for short bunch spacing

laser pulse 1

laser pulse 2

higher collision frequency with independent laser pulses in several larger optical cavities

Compton e- beam

A. Variola, LAL
Past Compton source R&D at ATF

Efficient propagation of the polarization from laser photons to positrons through Compton scattering and electron-positron pair creation

T. Omori\textsuperscript{1}, M. Fukuda\textsuperscript{2}, T. Hirose\textsuperscript{3}, Y. Kurihara\textsuperscript{1}, R. Kuroda\textsuperscript{3,4}, M. Nomura\textsuperscript{2}, A. Ohashi\textsuperscript{5}, T. Okugi\textsuperscript{1}, K. Sakaue\textsuperscript{3}, T. Saito\textsuperscript{3}, J. Urakawa\textsuperscript{1}, M. Washio\textsuperscript{3}, I. Yamazaki\textsuperscript{3}

\textsuperscript{1}KEK: High Energy Accelerator Research Organization, 1-1 Oho, Tsukuba, Ibaraki 305-0801 Japan
\textsuperscript{2}National Institute of Radiological Sciences, 4-9-1 Anakawa, Inage, Chiba-city, Chiba 263-8555, Japan
\textsuperscript{3}Advanced Research Institute for Science and Engineering, Waseda University, 3-4-1 Okubo, Shinjuku-ku, Tokyo 169-8555, Japan
\textsuperscript{4}National Institute of Advanced Industrial Science and Technology, 1-1-1 Umezono, Tsukuba, Ibaraki 305-8568 Japan
\textsuperscript{5}Department of Physics, Tokyo Metropolitan University, Minami-Ohsawa, Hachioji-shi, Tokyo 192-0397, Japan

Abstract

We demonstrated for the first time the production of highly polarized short-pulse positrons with a finite energy spread in accordance with a new scheme that consists of two-quantum processes, such as inverse Compton scattering and electron-positron pair creation. Using a circularly polarized laser beam of 532 nm scattered off a high-quality, 1.28 GeV electron beam, we obtained polarized positrons with an intensity of $10^4$ e\textsuperscript{+}/bunch. The magnitude of positron polarization was determined to be $73 \pm 15$(sta) \( \pm 19\text{(sys)}\%$ by means of a newly designed positron polarimeter.
Future Compton source R&D at ATF

Kharkov colleagues study 42-cm cavity for 2 pulses; such cavity will be installed at ATF in January 2006; new ATF laser system was ordered for March 2006

2 studies will be performed in 2006:
(1) stacking of multiple pulses in single cavity
(2) two coupled cavities with feedback control

J. Urakawa
Compton source studies at LAL (K. Moenig, A. Variola, F. Zomer)

different concept:

- laser operates in **continuous mode at 40-80 MHz**
  (1 μJ per pulse available now, assume 10 μJ is possible)
- consider **quality factor of optical cavity equal to 10^4 or 10^5**
  in continuous mode
- laser pulse energy of ~100 mJ in optical cavity
  or ~6 times less than in pulsed laser scheme;
- produce more e+ bunchlets to accumulate full charge
- use all 3 ILC damping rings for intermediate storage and accumulation during 150 ms
- then apply rf gymnastics to generate final bunches and store
  in 1 or 2 rings for 50–ms damping (Raimondi scheme)
- LAL feedback acts on laser (laser-cavity amplifier & frequency), - KEK feedback acts on optical cavity
OPTICAL CAVITY: feedback circuit

A trombone for a signal delay

Mode locked Laser

Laser Rep.rate feedback

357MHz

Signal Generator

Transmission

PZT voltage

PI circuit

DC

Shoulder feedback system (OFF: background)

By a phase detector, the signal is synchronized with Ring RF.

Feedback ON/OFF

J. Urakawa
KEK/ATF scheme
**e+ stacking**

**ILC scheme:**
10 turn injection into the same bucket of main DR (at different $\delta$);
followed by 10 ms damping,
this is repeated 10 times!

**CLIC:**
250-400 turn injection into the same bucket, no repetition

**CLIC uses**
pre-damping ring
optimized for e+ accumulation

**stacking in ILC – longitudinal phase space**
Proposal for a workshop on Compton-based polarized positron source

Place: CERN?
Time: End of April 2006?
Duration: 2 or 2.5 days
Initiative: LAL (A. Variola)
interested parties

KEK (Japan), IPN Lyon (France), LAL Orsay (France), INFN Frascati (Italy), CERN (Switzerland), BINP (Russia), NSC KIPT (Ukraine), DESY-Zeuthen (Germany), Waseda U., Kyoto U., NIRS, Hiroshima U., Sumitomo HI (all Japan), IHEP (China), IHEP (Russia), Munich U. (Germany), SLAC (USA), European laser industry (e.g., TimeBandwidth / Switzerland),…
addressing several open questions

- design & dynamics of Compton ring
- laser system
- optical cavities & feedback
- e+ production & capture system
- e+ stacking in accumulator or damping ring
- experimental program (KEK/ATF, LAL, Frascati, various light sources, ...)

it seems time to bring the dispersed community together to arrive at a consistent overall design
ELAN workshop?

- **focused topical workshop** to address critical issues, find solutions for this type of e+ source & **finalize** conceptual design
- **ELAN support** would help for travel
- in particular might allow travel **subsistence for a few Ukrainian and/or Russian colleagues**
- **ELAN steering group** suggested combination with mini-workshops on lasers for accelerators (G. Blair) & on advanced acceleration (B. Cros)
- **Louis Rinolfi** will co-organize the workshop
thank you

merry Christmas

& a happy 2006!