# Compton Gamma-Sources: Beam Dynamics and Performance

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# Goal

- Comparative analysis of Compton–based sources of polarized gammas
- Study on a Compton-ring structure with a longitudinal low-beta insertion

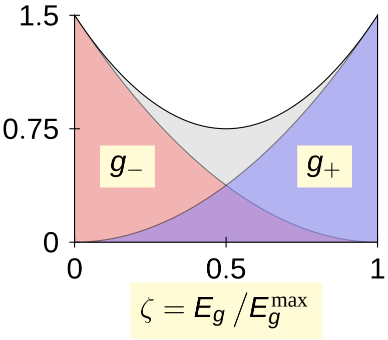
## Reference gamma sources based on linacs

- ILC undulator source: 150 GeV
- Reference Compton linac: 1.3 GeV

# Outline

1. Compton Sources: Advantages and Limits
    - Electron Beam Current
    - Statistics of Recoils
    - Balance of Energy in Compton Posipols
2. Longitudinal Low–Beta Scheme
3. Summary and Outlook
    - Choice of Photon Energy

# Polarization and Yield



## Advantages of Compton gamma sources:

- High energy of gammas (20. . . 30 MeV for Compton vs 10 MeV for undulator)
- Low deflection parameter → only fundamental harmonics.
- Collimation of gammas before a conversion target.

More positrons at higher polarization rate; lower power load in the conversion target.

# General Requirement

## Positron beam equals to electron beam

For the undulator source:

$$N_{\text{electrons}} = N_{\text{positrons}} = N^{\text{emitters}}_{\text{electrons}} \times C(\mathrm{e}^- \to \gamma) \times C(\gamma \to \mathrm{e}^+)$$

For ILC undulator source $N_{\text{electrons}} = N^{\text{emitters}}_{\text{electrons}}$:

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$$300 \times \frac{1}{200} = 1.5 \qquad (50\,\%\ \text{overhead})$$

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# General Requirement: Compton

Average current of positrons equals to electrons'.

Compton sources require accumulation of positrons.
Average current:

$$\mathrm{I}_{\text{positrons}} = \mathrm{I}_{\text{electrons}} = 45\,\mu\mathrm{A}$$

$$\mathrm{I}^{\text{emitters}}_{\text{electrons}} = \frac{\mathrm{I}_{\text{positrons}}}{C(\mathrm{e}^- \to \gamma)C(\gamma \to \mathrm{e}^+)D}$$

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# Laser Pulse Parameters

## Electron → gamma conversion

| parameter / model | ILC/YAG | CLIC | ERL |
|---|---|---|---|
| Laser pulse energy (J) | 17.76 | 0.592 | 6.0 |
| Laser pulse radius ($\mu$m) | 5 | 5 | 5 |
| Laser pulse length (mm) | 0.9 | 0.9 | 0.24 |
| Crossing angle (deg) | 8 | 8 | 8 |
| Max yield (1/e/J) | 0.18 | 0.18 | 2.27 |
| Reduction factor, simul | 0.21 | 0.16 | 0.091 |
| Conversion /J | 0.04 | 0.03 | 0.2 |
| Total Conv | 0.67 | 0.017 | 1.24 |

# Beam Current Limits in Compton Sources

## Min current and duty factor

| parameter / model | ILC/YAG | CLIC | ERL |
|---|---|---|---|
| Total $e^-$ →gamma conv | 0.67 | 0.017 | 1.24 |
| Gamma→$e^+$ conv | 0.01 | 0.01 | 0.01 |
| Min current×$D$ (A) | 0.0067 | 0.265 | 0.0036 |
| Nominal current (A) | 3.0 | 15.6 | 0.026 |
| Min duty factor | $2.2 \times 10^{-3}$ | $1.7 \times 10^{-2}$ | 0.14 |

## Summary on 'Beam Current – Duty Factor'

- All considered sources fit the requirements
- The ring–based sources allow much more manoeuvre with the temporal shape of the beam and the laser power

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# Steady Operation of Source

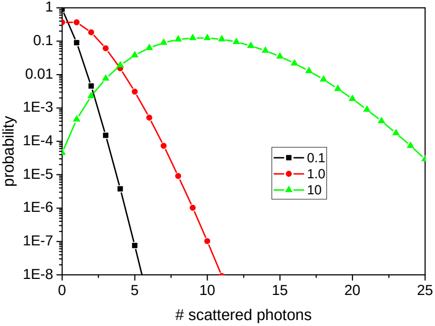
**Balance must be keeping:**

- Energy
- Number of electrons
- Entropy

Electron-to-laser photon collisions produce entropy

# Statistics of Scattering

## Recoil spectrum for single IP pass with $x$ average scattered photons



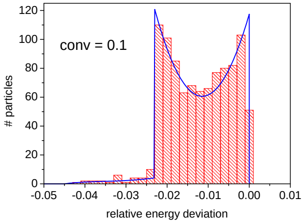
### Probability of Scattering $n$ Photons

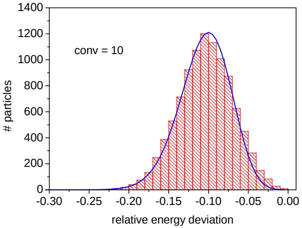
$$P(x,n) = \frac{x^n \exp(-x)}{\Gamma(1+n)}$$

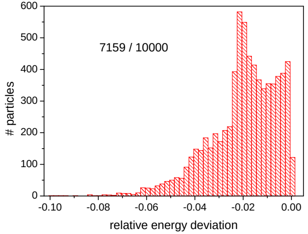
### Fraction of Noninteracted Electrons

$$P(x,0) = \exp(-x)$$

# Recoiled Spectra. Analytics and Simulations







## Widths of Spectrum

- $x \ll 1$ $\Delta E_e \approx E_\gamma^{\max}$
- $x \approx 1$ specific spectrum
- $x \gg 1$ $\Delta E_e \approx \sqrt{x} \times \langle E_\gamma \rangle$

# Energy Spread is Main Drawback

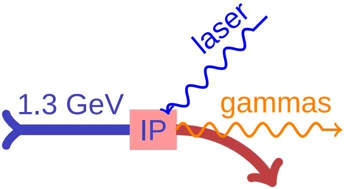
**Linac** (undulator) Increase of the energy spread by
$\Delta E_e \approx \sqrt{x} \times \langle E_\gamma \rangle = 170\,\mathrm{MeV}$
(if scattered gammas are uncorrelated)

**Ring** The ring must comprise spread up to
$\frac{\Delta E_e}{E_e} \approx \sqrt{\frac{7E_{\mathrm{laser}}\gamma}{10E_0}} \approx 6\,\%$

**ERL** Recovery of the energy from
a beam with the large spread
should be a challenging problem.

# Entropy and Power Consumption: Compton Linac

## The system initiated Compton POSIPOLs (T.Omori *et al* 2003)

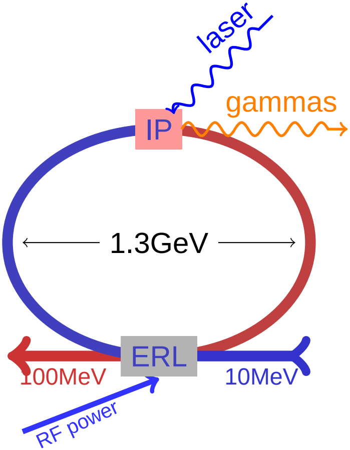


### Energy losses

- Linac's beam current $\mathrm{I}_{\mathrm{e}^-}^{\mathrm{emit}} = \frac{\mathrm{I}_{\mathrm{e}^+}}{C(\mathrm{e}\to\gamma)\times C(\gamma\to\mathrm{e}^+)} = \frac{45\times10^{-6}}{1.24\times0.01} \approx 3.6\,\mathrm{mA}$
- The beam power $3.6\,\mathrm{mA} \times 1.3\,\mathrm{GeV} = 4.7\,\mathrm{MW}$

# Entropy and Power Consumption: ERL

A. Variola, 2006

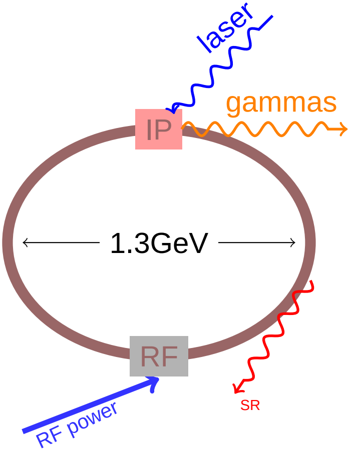


## Energy losses

- Emission of gammas: $P_\gamma = \frac{\mathrm{I}_{\mathrm{pos}} \langle E_\gamma \rangle}{C(\gamma \rightarrow \mathrm{e}^+)} = 67.5\,\mathrm{kW}$.
- Synchrotron radiation $P_{\mathrm{synch}} = \mathrm{I}\Delta E_s = 0.03 \times 87.5 = 2.6\,\mathrm{kW}$.
- Beam losses: $P_{\mathrm{beam}} = \mathrm{I}E_b = D \times 2 \ldots 3\,\mathrm{MW}$.

# Entropy and Power Consumption: Ring

X–ray: Z.Huang, R.Ruth 1998, Gammas: S.Araki *et al* 2005



## Energy losses

- Emission of gammas – the same $P_\gamma = 67.5\,\text{kW}$.
- Significant synchrotron losses:
  - Circulating current up to a few Amperes;
  - Radiation cooling requires wigglers;

  $P_{\text{synch}} = \mathrm{I}_{\mathrm{e}^-} \Delta E_s = 0.1 \ldots 0.5\,\text{MW}$.
- Beam losses: negligible.

# Problems of Compton Sources

## ERL and Ring most promising

### ERL

- Bunch parameters determined by injector
- Required rather high beam current (for ERL)
- High power losses (with the beam)
- Effective energy recuperation

### Ring

- Bunch parameters determined by the ring
- Required moderate beam current (for rings)
- Moderate power losses (with SR)
- Large energy spread in transverse dynamics

# POSIPOL 2006 lines up options for ILC and CLIC

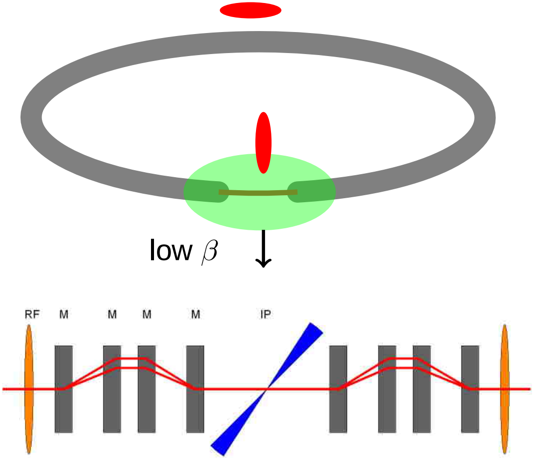
Louis Rinolfi, CERN, POSIPOL chair

**CERN Courier, 9 vol.46 (2006)**

. . . For the Compton scheme, the main recommendations were the publication of the design of a Compton ring with a chicane and with optimization of the energy of the Compton photons, . . .

# Ring: A Method to Reduce Spread

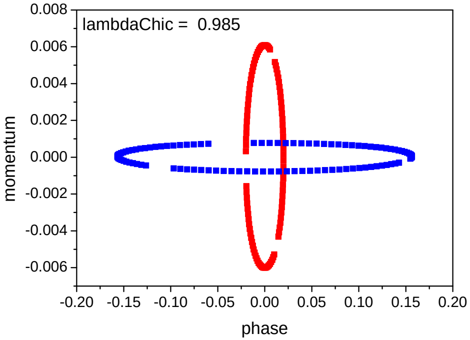
## Longitudinal Low-$\beta$ Insertion (Junji Urakawa, 2006)



### Idea: Strong Focusing

- Emittance (not spread) is conserved.
- Balance 'heating–cooling' at IP determines the spread.
- Chicane+RF transforms the emittance.
- RF+chicane restores the emittance.

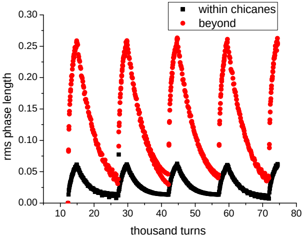
# Longitudinal Low-$\beta$

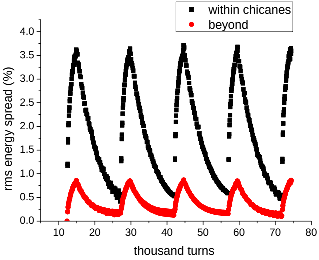


## Results – It Works

- Negative phase slip beyond LLBS: More energetic particles circulating faster.
- High rf–voltage necessary.

# Longitudinal Low-$\beta$: Simulation CLIC–20

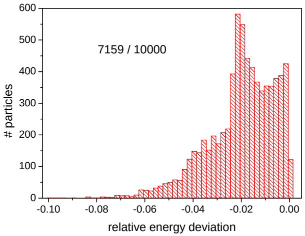


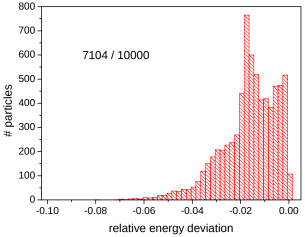


### Parameters

- Beam energy 1.06 GeV
- Max energy of gammas 20 MeV
- RF frequency 1.875 GHz
- RF voltage 150 MV
- Chicane $\lambda = 0.98$
  - magnet length 1.3 m
  - gap length 1.2 m
  - field strength 1 T
- Laser pulse energy 0.6 J

# ERL Gammas’ Energy 30 MeV vs. 20 MeV





## ERL Recoil Spectra

30 1.30 GeV, Recoil 26 ± 18 MeV

20 1.06 GeV, Recoil 17 ± 12 MeV

Recoils shrink quadratically

# Ring Gammas' Energy 30 MeV vs. 20 MeV

## CLIC YAG Rings

| | | |
|---|---|---|
| Beam energy (GeV) | 1.06 | 1.301 |
| Max gammas energy (MeV) | 20 | 30 |
| Cycle (turns) | 2546/14888 | 2546/14888 |
| Max $C(\mathrm{e}^- \to \gamma)$ /pass | 0.1 | 0.1 |
| Yield (gammas/cycle) | 112 | 85 |
| Particle losses /cycle | 0 | 1.5 % |

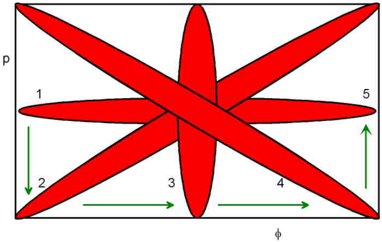
# Summary.

## Compton sources

### Compton gamma sources

- Advantages:
  - High polarization of positrons attainable ($\gtrsim 90\,\%$).
  - Moderate power density at the positron converter.
  - Independent of the main linac operation.
- Issues to be studied:
  - Large energy spread and affect upon transverse motion.
  - Choice of an optimal energy of gammas (compromise between gamma- and positron conversion).
- It seems reasonable to study ERL and Ring Compton sources in parallel

# Phase Transformation in Chicanes



## Parameter

$$\lambda = \eta_c U = \frac{4eV_{\mathrm{rf}}F_{\mathrm{rf}}R_0}{cE_e}$$
$$\times \left[ \frac{dR_0\left(dD + R_0^2 - d^2\right)\sqrt{1-(d/R_0)^2}}{\left(R_0^2 - d^2\right)^2} \right.$$
$$\left. + \arcsin\frac{d}{R_0} \right] \lesssim 1$$

# Positron Yield

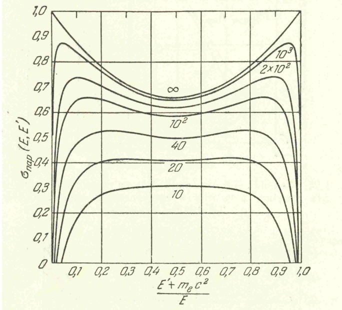
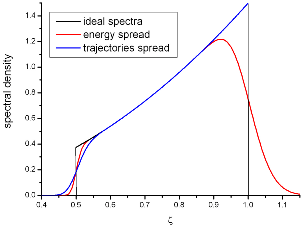


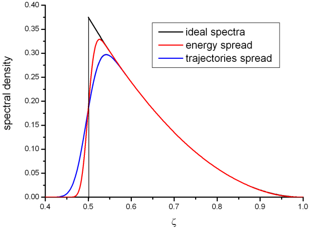
Рис. 1.23. Дифференциальное сечение образования пар в свинце в зависимости от энергии частиц пары для различных энергий налетающих γ-квантов в естественных единицах.

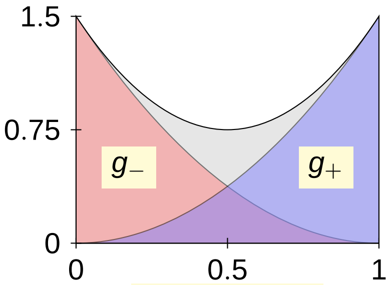
## Positron production cross section

- Preselection efficiency increases with decreasing the positron collection threshold

# Preselection and Polarization







$$\zeta = E_g \big/ E_g^{\max}$$

Angular and energy spreads will decrease the yield of positrons but not polarization