Estimation on the Maximal Yield and Polarization in Positron Sources

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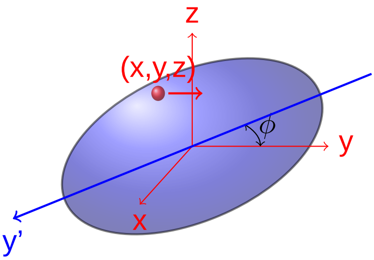
Abstract
goals

- To estimate the maximal yield and polarization in Compton based positron sources
- To compare performance of Compton and undulator sources
- To review ideas of enhancement the performance

Outline

Interaction of Electron with Laser Pulse

Pulse 3D Gaussian (σ_r, σ_y)



yield / electron turn

$$Y = \frac{N_{\mathrm{las}}\sigma_{\mathrm{C}}}{2\pi\sigma_r\sqrt{\sigma_r^2 + \sigma_y^2 \tan^2\phi/2}} \times \exp\left[-\frac{(x + y\tan\phi/2)^2}{2(\sigma_r^2 + \sigma_y^2\tan^2\phi/2)} - \frac{z^2}{2\sigma_r^2}\right]$$

$\sigma_{r,y}$ are rms dimensions of the laser pulse
x, y, z deviations of an electron from ideal matching

Maximal Yield

Exact matching $x = y = z = 0$

Second factor equals to unity — max yield/electron/turn

Simulations, max conversion factor

	CLIC/YAG	ILC/YAG	/CO2	undul
Fconv	0.11	3.2	2.1	$\approx$ 300
e–ph interact	singular	plural	plural	multiple
Egamma (MeV)	30	30	30	$\approx$ 20

Longitudinal Steady State

- Partial energy spread in a bunch is independent of the lattice and RF

$$s_c^2 \equiv \frac{\sigma_E^2}{\gamma^2 E_0^2} = \frac{7}{10}\frac{\gamma E_{\mathrm{las}}}{E_0}$$

- Total spread (synchrotron radiation + Compton)

$$s^2 = \frac{s_{sr}^2 (\Delta E)_{sr} + s_c^2 (\Delta E)_c}{(\Delta E)_{sr} + (\Delta E)_c}$$

Subscribed sr natural quantities (laser turned off)
Subscribed c partial Compton quantities (naturals = 0)
(ΔE) energy losses per turn

partial Compton spreads

CO2 ring 3.58 %, YAG ring 6.37 %, undulator 0.5 %

Steady–State Emittances

- Partial transverse emittance dependent on betatron function at IP

$$\epsilon_c = \frac{3\beta_{\rm ip}}{10}\frac{E_{\rm las}}{\gamma E_0} \approx 2.7\times 10^{-10}\,\beta_{\rm ip}$$

for YAG rings ($E_{\rm las} = 1.164\,$eV, $E_{\rm beam} = 1.3\,$GeV)

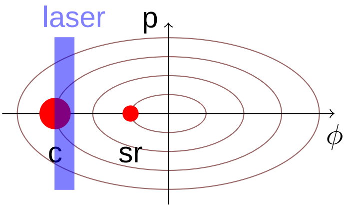
- Total emittance (synchrotron radiation + Compton)

$$\epsilon = \frac{\epsilon_{sr}(\Delta E)_{sr} + \epsilon_c(\Delta E)_c}{(\Delta E)_{sr} + (\Delta E)_c}$$

behaves similar to the squared energy spread

Pulsed Mode of Operation

non–head–on electron–laser collisions



stationary operation

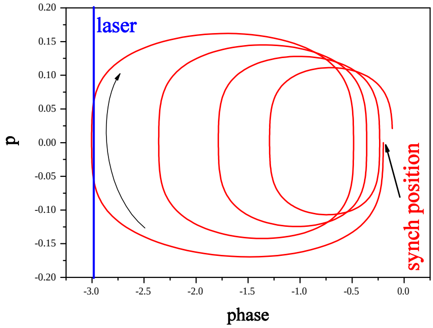
Compton ring gamma sources with plural conversion (ILC/CO2 and ILC/YAG) unable to operate in steady state:

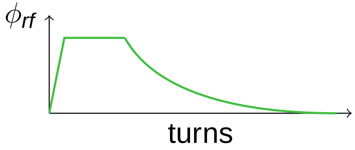
- Synchronous phase with laser on offsets by more than laser pulse length
- Plural scattering causes severe quantum losses

CLIC Compton ring in principle can afford steady state

Pulsed Mode of Operation

phase manipulation scheme

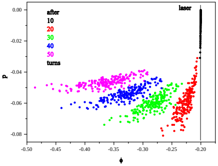




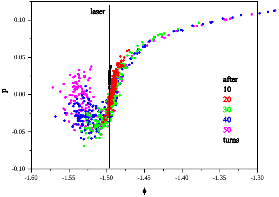
rf phase manipulation

- fast advance in RF phase
- 'shelf' to provide interaction with laser
- slow adiabatic return into initial position

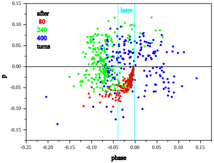
Pulsed Mode of Operation
simulation



ILC CO2 ring, no RFPM



ILC CO2 ring, RFPM



CLIC YAG ring, no RFPM

yield per cycle

ilc	co2	yag	clic/yag
rfpm	on	on	off
turns	50	100	2546
N gms	30	60	45–100

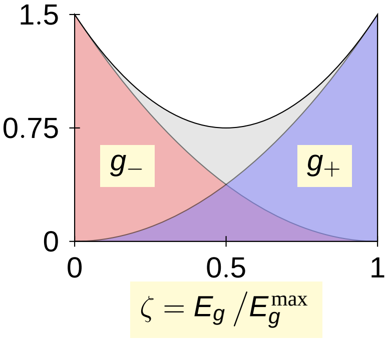
Summary of Electron Bunch Kinetics

feasibility of Compton sources

- Yield over the working cycle reached $0.2 \ldots 0.4$ of maximum
- Transverse emittances heated up or cooled down depending on Compton to natural emittance ratio
- Energy spread in the bunches increased up to a few %%
- Phase manipulation enhanced yield by $3 \ldots 5$ times
- Deviation of the energy in RFPM mode exceeded 10 %

Remark: The single pass of bunch through undulator increased spread by 0.12 %. Transverse dimensions were not affected

Gammas Spectrum and Polarization



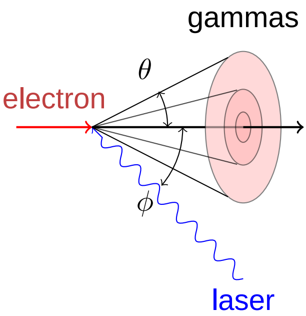
Definition of polarization

$$\mathcal{P} = \frac{N^{(+)} - N^{(-)}}{N^{(+)} + N^{(-)}}$$

- High energy gammas, g_+, mostly polarized positively
- low energy ones, g_-, negatively
- Energy spectra are the same for all sources
- Total polarization is zero

Spatial Shape of Gamma Beam

Mono-Energetic Electrons, Parallel Trajectories



Relative energy of gammas ζ scattering angle θ correlation

Collimator opening angles (micro rad)

	YAG 1.3	CO2 4.1	undul 150	GeV
ζ				
0.8	200	66	1.7	POSIPOL
0.5	400	124	3.4	min reas
0.2	800	250	6.8	clearing

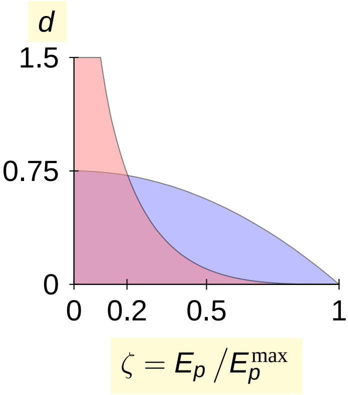
Assumptions

Semi-quantity approximations of actual dependencies allow to get analytical formulas appropriate for the bird's-eye view:

- Gammas traversing the target do not change the polarization
- Polarization of a positron equals to gamma's
- The cross section of pair production is independent of the energy of the gamma
- Energy of the positrons is distributed uniformly within the interval from mc^2 to $E_{\mathrm{gamma}} - mc^2$
- The only losses of the positron energy in the target are the ionization ones

Positron Spectra from Thin Target

Full Gamma Spectrum



Two positron ensembles produced in the converter body

Positively polarized (desirable) $n_p^{(+)}$

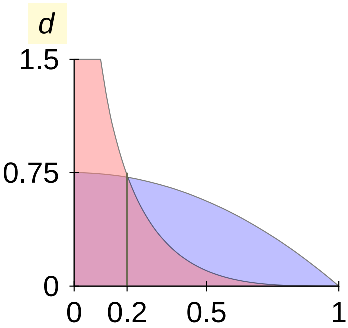
Negatively polarized (background) $n_p^{(-)}$

Normalization of positrons to unity (full gamma spectrum produces unity of positrons)

Zero total polarization $N_p^{(+)} = N_p^{(-)}$

Positron Spectra from Thin Target

Energy Selection of Positrons (post-selection) [A.Mikhailichenko]

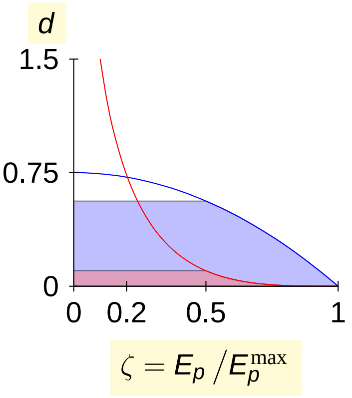


$\zeta = E_p / E_p^{\max}$

- Positively polarized positrons possess higher energy
- Discarding of low-energy positrons $\Rightarrow$ polarization
- Limit of selection 0.2 of maximal energy
  $\Rightarrow$ 0.46 of positrons remained at polarization 0.53

Positron Spectra from Thin Target

energy selection of gammas (pre-selection) [J.Urakawa]

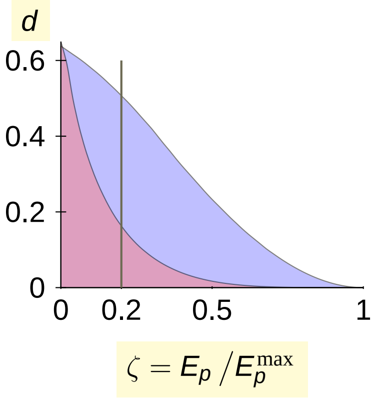


- Discarding of low-energy gammas
  $\Rightarrow$ lesser positrons produced
- Minimal gammas energy of one-half of maximal
  $\Rightarrow$ 0.5 of positrons produced at polarization 0.75

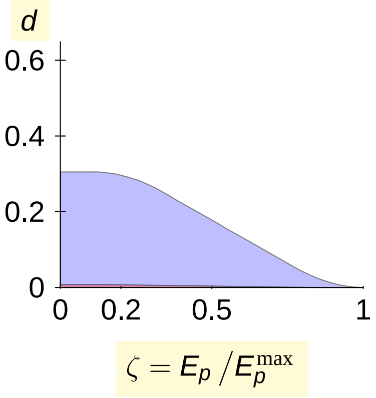
Positron Spectra from Thick Target

full and preselected gamma spectra, $b = 0.67$

full gamma spectrum



preselected from 0.77



Positron Yield from Target

analytical results

Energy of positrons attenuating due to ionization losses,
b the energy loss from maximal over the target thickness

yield and polarization

b	pre min	post min	yield	polariz
0.001	0	0.2	0.46	0.53
0.001	0.77	0.035	0.26	0.95
0.67	0	0.2	0.17	0.75
0.67	0.77	0.035	0.16	0.96
0.67	0.77	0.2	0.11	0.96

Preselected from 0.77 gamma beam produces 0.27 of all positrons

High Z Converter Target
[T. Omori]

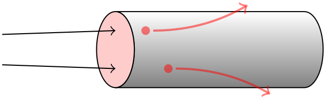
Basic idea. Calculations

- Positron production prop to thickness in r.l.
- Energy losses prop to thickness in (grams/sq cm) about 2 MeV /(gram/sq cm)
- Rad length (Al) = 25 (gram/sq cm)
- Rad length (W) = 6.3 (gram/sq cm)
- $b(\mathrm{Al}) \approx 4b(\mathrm{W})$

b	pre min	post min	yield	polariz
0.67	0	0.2	0.17	0.75
0.67/4	0	0.2	0.36	0.64
0.67	0.77	0.035	0.16	0.96
0.67/4	0.77	0.035	0.24	0.96

Rod target
[V.Lapko, N.Shul'ga 2006]

main idea



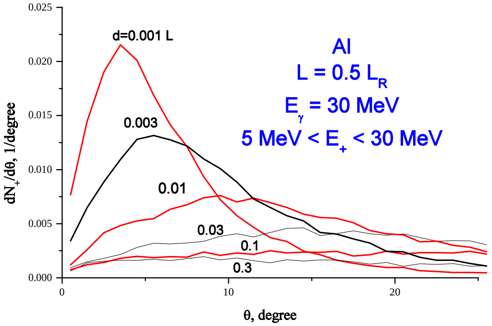
Shortening the positron path in target

- improves emittance
- reduces positron losses

Efficiency of the method in proportion to 'length/radius' ratio
The rod target produces 'natural collimation' of the gamma beam

Rod Target Simulations

[V.Lapko, N.Shul'ga 2006]

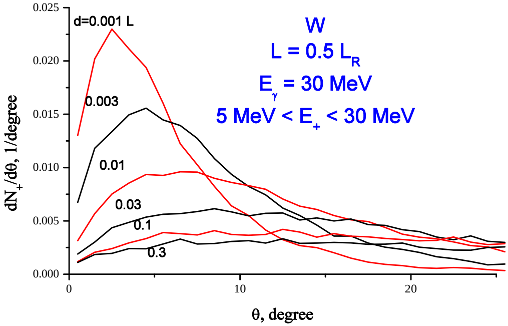


conditions simulated

- aluminum cylindrical rod
- uniform distribution of gammas at butt-end
- monoenergetic gamma beam

Rod Target Simulations

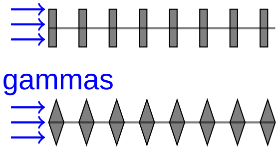
[V.Lapko, N.Shul'ga 2006]



conditions simulated

- tungsten cylindrical rod
- uniform distribution of gammas at butt-end
- monoenergetic gamma beam

Combination: High Z Rod Converter



bare idea

Increase length-to-radius ratio without increasing the length in units of rad.length

Summary. Yield and Polarization
upper limits

Factors in reversed order

- Positron yield (preselection 0.8) ≈ 0.16

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Summary. Yield and Polarization
upper limits

Factors in reversed order

- Positron yield (preselection 0.8) ≈ 0.16
- Pair production ($7/9$ per r.l.) ≈ 0.3
- Gamma production per electron-turn ≈ 0.6
- Total $0.16 \times 0.3 \times 0.6 \approx 0.03$
  or 33 electron–turns for a positron with polarization 90 %

Conclusions

Compton ring–based positron source

- Compton scheme feasible to produce required positron bunches
- Ring's acceptance should be high
- Efficiency of the ring increases with decreasing the linear momentum compaction factor
- RF phase manipulation in nonlinear lattice will enhance yield but requires rather large energy acceptance

Conclusions

collimation of the gamma beam

- Collimation of gamma beam realizable
  for moderate energy of electrons (some GeVs)
- Positron production scheme with collimated gamma beam provides higher polarization
  compared with the scheme of positron energy selection
- Positrons produced in such a way have wider energy spectra
- Heat load of targets lower in preselected scheme