QUASI-MONOENERGETIC PHOTON SOURCE BASED ON ELECTRON-POSITRON IN-FLIGHT ANNIHILATION*

A. Afanasev#, Hampton University, Hampton, VA and Muons, Inc., Batavia, IL, USA
R. Abrams, C. Ankenbrandt, K. Beard, R. Johnson, T. Roberts, C. Yoshikawa, Muons, Inc.
M. Popovic, Fermilab, Batavia, IL, USA

Abstract

We study electron-positron in-flight annihilation as a potential source of quasi-monoenergetic photon (or gamma-ray) beams. A high-intensity tunable-energy (1.5-15 MeV) gamma source has many potential uses in medical, industrial and security applications. Several electron-positron collision geometries are considered: a) head-on; b) collinear; and c) positron beam incident on a fixed electron target. We analyze advantages of each of the geometries in order to optimize parameters of the generated gamma-ray beams.

INTRODUCTION

High-intensity tunable photon beams have important applications that range from medical use to homeland security. We are interested in photon sources whose energies can be tuned from about 1.5 MeV to 15 MeV, with intensities reaching 10^{12} γ/s. Depending on the application, either a broad-band source or a narrow-band source is acceptable. In a broad-band configuration, we allow energy spread of the photon beam to be a few MeV. On the other hand, for a narrow-band configuration, which is most useful for detection of photo-nuclear spectroscopic response, only the MeV photons within about 20 eV range are relevant for corresponding applications.

The most common method of producing high-intensity photon beams of MeV photons is based on bremsstrahlung of energetic electrons passing through a high-Z target. This method, however, has two disadvantages. First, the resulting spectrum of photons is too broad, and the photon flux is enhanced at lower energies (as $1/E_\gamma$), resulting in high irradiation dose of the interrogated targets and surrounding areas, and high backgrounds in gamma detectors. The second disadvantage is that the bremsstrahlung spectrum is suppressed toward its high-energy endpoint. Therefore in order to produce high fluxes of photons with energies, for example, up to 10 MeV, in practice one needs to exceed this limit, leading to unwanted effects such as photoactivation of scanned targets. Let us consider positron annihilation as an alternative method for development of a high-intensity photon source.

ANNIHILATING POSITRONS FOR GAMMA-RAY PRODUCTION

Electron-positron in-flight annihilation was used as a source of quasi-monochromatic gamma-rays starting in the 1960s in SLAC, LLNL and Saclay. The positrons were produced by an electron beam on a high-Z target (tungsten), then pass through accelerating RF structures and then annihilate in a low-Z annihilation target (e.g., LiH or Be) to produce gamma-ray beams. However, for lower energies <30MeV bremsstrahlung, multiple scattering and ionization in the annihilation target significantly distort the monochromatic feature of the gamma-ray spectrum.

Let us consider several different geometries for electron-positron annihilation and characterize properties of the resulting gamma-ray spectra.

The differential cross section for annihilation, $e^+ + e^- \rightarrow 2\gamma$ is determined in terms of standard Mandelstam invariants *s, t,* and *u* as

$$\frac{d\sigma}{d(-t)} = 8\pi r_e^2 \frac{m^2}{s(s-4m^2)} \left\{ \frac{1}{4}\left(\frac{u-m^2}{t-m^2} + \frac{t-m^2}{u-m^2}\right) - \left(\frac{m^2}{t-m^2} + \frac{m^2}{u-m^2}\right)^2 - \left(\frac{m^2}{t-m^2} + \frac{m^2}{u-m^2}\right) \right\}, \qquad (1)$$

where r_e is the classical electron radius. Defining energies and momenta of the initial electron (positron) as $E_{e(p)}$ and $p_{e(p)}$, the energy of the produced gamma-quantum is in one-to-one correspondence to its emission angle θ:

$$E_\gamma = \frac{m^2 + E_p E_e - p_p p_e}{E_p + E_e - (p_p + p_e)\cos\theta}\ . \qquad (2)$$

Here we assume that initial particles move along the *z*-axis. Depending on the relative signs of the colliding particle momenta, the maximum (or minimum) of the produced photon energy corresponds to θ=0 or 180°. In a special case of same-magnitude opposite-sign momenta, the produced photons are mono-energetic with an energy equal to the incoming beam energy, $E_\gamma = E_p = E_e$.

Integrating the differential cross section with respect to *t*, and accounting for identical photons in the final state, we obtain a total cross section for electron-positron annihilation as a function of Mandelstam *s*, where $\tau = s/m^2$

$$\sigma_{annih} = \frac{2\pi r_e^2}{\tau^2(\tau-4)}\left[(\tau^2 + 4\tau - 8)\log\frac{\sqrt{\tau}+\sqrt{\tau-4}}{\sqrt{\tau}-\sqrt{\tau-4}} - (\tau+4)\sqrt{\tau(\tau-4)}\ \right]. \qquad (3)$$

Defining the relative velocity as

$$v_{rel} = \frac{\sqrt{(p_+p_-)^2 - m^4}}{p_+p_-} = \frac{\sqrt{\tau(\tau-4)}}{\tau-2},$$

we obtain in the non-relativistic limit $\tau \rightarrow 4$:

$$\sigma_{annih} = \frac{\pi r_e^2}{\sqrt{\tau-4}} = \frac{\pi r_e^2}{v_{rel}}$$

In an ultra-relativistic limit $\tau \rightarrow \infty$ the cross section reads

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[#] andrei.a@cox.net

$\sigma_{annih} = 2\pi r_e^2 \frac{\log\tau}{\tau}$.

To evaluate the photon energy spectrum and angular distribution in the lab, we need the Jacobians,

$$dt = \left(\frac{dt}{dE_\gamma}\right) dE_\gamma,\ \frac{dt}{dE_\gamma} = 2\frac{(E_p p_e - E_e p_p)}{(p_e + p_p)},$$
$$dt = \left(\frac{dt}{d\cos\theta}\right) d\cos\theta, \qquad (4)$$
$$\frac{dt}{d\cos\theta} = 2\frac{(E_p p_e - E_e p_p)(E_e E_p - p_e p_p + m^2)}{[E_p + E_e - (p_p + p_e)\cos\theta]^2}.$$

Let us compare energy spectra of annihilation photons in three different set-ups:

(A) Collinear beams with close energies;
(B) Opposite-direction electron and positron beams;
(C) A positron beam incident on fixed-target electrons.

The spectra are obtained from Eqs.(1-4),

$$\frac{d\sigma}{dE_\gamma} = \frac{d\sigma}{dt}\left(\frac{dt}{dE_\gamma}\right).$$

In the following, we use beam energies relevant to applications of interest.

A. Collinear Beams

Choosing E_p=5.5 MeV and E_e=4.5 MeV for the co-moving beam energies, the range of photon energies is limited to 0.03MeV<E_γ<9.97 MeV. Total annihilation cross section is σ=25.0x10^{-25}cm^2. In this collinear kinematics, gammas within the allowed energy interval are produced with (almost) equal probability. This is due to the small relative momentum of the colliding beams. Energy vs. angle dependence for emitted photons shows that higher-energy photons are emitted in the forward direction. For the chosen beam energies, collimating the produced gammas by an angle 0.084 rad would select gammas with the energies above 6 MeV, which is about 40% of the total number of annihilation gammas.

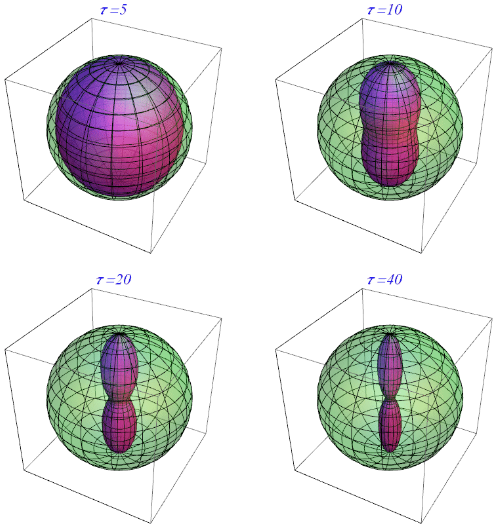

Figure 1: Angular distributions of annihilation gammas from equal-energy head-on electron-positron collisions for different c.m. energies (τ), with the colliding beams pointing along the vertical direction. The quantity $\boldsymbol{v_{rel}\frac{d\sigma}{d\Omega}(\theta,\phi)}$ is shown in the plots (inner surface). The outer surface (a sphere) corresponds to the non-relativistic limit $\boldsymbol{\tau \to 4}$.

B. Electron-Positron Head-On Collision

If the initial particle momenta are equal and opposite in sign, the produced gammas are mono-energetic, carrying the same energy as the colliding particles. For non-equal energies of relativistic colliding beams, the gammas emerge with two distinct energies. The photon spectrum is isotropic for low energies, but it becomes highly anisotropic for relativistic collisions, being sharply peaked in the forward and backward directions with an opening angle of the order ~m_e/E_e. For high collision energies the total cross section decreases as $(\log\tau)/\tau$ but the *differential* section in forward and backward directions $d\sigma/d\Omega(\theta_\gamma=0^\circ,\ 180^\circ)=r_e^2/2$ remains constant, leading to sharp kinematic focusing at these angles (Fig.1).

C. A positron beam incident on fixed-target electrons

We choose the kinematic parameters as E_e=0.511MeV, E_p=9.5MeV. The gamma-rays from annihilation are produced in the energy range 0.25MeV<E_γ<9.77MeV with a total cross section σ=0.8x10^{-25} cm^2. The corresponding energy spectrum and angular distribution are shown in Fig.2.

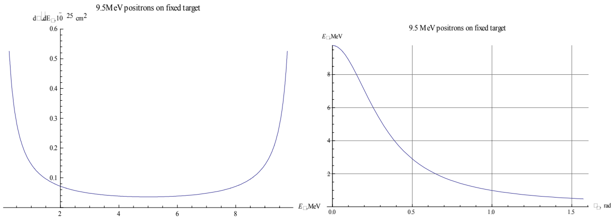

Figure 2: Energy spectrum and angular distribution for gammas produced in annihilation of 9.5MeV positrons with electrons at rest.

Rate Estimates

Let us estimate luminosity for (a) colliding beam and (b) fixed target set-up.

(a) Colliding Beams. For two bunches of relativistic particles colliding in a storage ring with frequency *f*, the luminosity is estimated according to the formula

$$L_{col} = f\frac{n_e n_p}{4\pi\sigma_x\sigma_y},$$

where n_e (n_p) is the number of electrons (positrons) per bunch, and σ_x (σ_y) are Gaussian transverse beam profiles. Assume the following parameters: $n_e = 10^{13}$; $n_p=10^{10}$; $\sigma_x = \sigma_y$= 0.1cm. The frequency of collisions is estimated based on circumference of the storage ring taken at 30m-long, i.e., f=c/length=10^7Hz. The (relativistic) luminosity is then: L=0.8x10^{31} cm^{-2} s^{-1}. It results in *total* rate of photon production for colliding beams, Rate=$L\cdot\sigma_\gamma$:

Rate=4.0x10^6 Hz (collinear, 5.5 MeVx4.5 MeV);
Rate=3.6x10^4 Hz (head-on, 9.5 MeVx9.5 MeV),
Rate=6.0x10^5 Hz (head-on, 1.73 MeVx1.73 MeV).

(b) Fixed-target. Luminosity is given by:

$$L=r_p\,\rho_e\,h,$$

where r_p is the number of incident positrons per unit time, ρ_e is the volume density of target electrons, and h is the target thickness. A bunch of 10^{10} positrons circulating in a storage ring with frequency 10^7 Hz yields $r_p=10^{17}$ positrons/s. For a 0.5mm-thick graphite target used for positron annihilation, we obtain

$$\rho_e \cdot h = 6.6\text{x}10^{23}\text{cm}^3\text{x}0.05\text{cm} = 3.3\text{x}10^{22}\text{electrons/cm}^2.$$

It results in the luminosity $L=3.3\text{x}10^{39}\text{cm}^{-2}\text{s}^{-1}$ and the rate of annihilation photons $\text{Rate}=L\cdot\sigma_\gamma=2.6\text{x}10^{14}$ Hz; or $2.6\text{x}10^7\gamma$ for a single bunch, using fixed-target kinematics from the above example.

We can see that the production rate of gammas is significantly higher for a fixed-target configuration. The resulting energy spectra of gammas are broadened at MeV level, and they contain a significant component from bremsstrahlung even for the lowest-Z targets, as shown in the simulation in Fig.3. Nevertheless, enhancement followed by a sharp cut-off of the annihilation spectrum near the high-energy endpoint provides an advantage over bremsstrahlung photon sources.

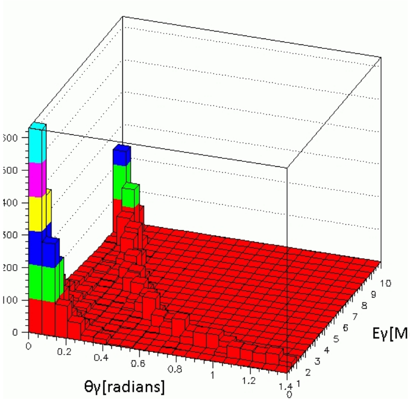

Figure 3: Energy vs angle distribution of gammas from a 9 MeV positron beam incident on a 1mg/cm^2-thick hydrogen target. Simulation performed with G4Beamline software package [3] based on GEANT4.

On the other hand, colliding electron-positron beams present an opportunity for selective production of gammas within a pre-set narrow energy band (δE_γ<1keV), provided that the colliding beams have sufficiently low emittance. As a result, lower total yields of gammas would be compensated by higher relative yields within a line-width of certain nuclear resonances.

While our work on a narrow-band gamma source is in progress, we present below a conceptual design of a compact and tunable wide-band source.

BASELINE SYSTEM DESIGN

The overall schematic for our strategy to produce a compact tunable intense beam of gammas is shown in Figure 4. It consists of an electron beam impinging on a high-Z target (tungsten) to pair-produce positrons and electrons. This target is followed by a dipole to create dispersion for the desired positrons and a wedge of low Z material to take advantage of the dispersion in order to mono-energize the beam of positrons. This beam of mono-energetic positrons would then be bent by a second dipole to separate the neutral and wrong signed particles created in the wedge from the desired positrons and direct them onto a low Z target to annihilate with electrons, producing a mono-energetic beam of gammas. The method for obtaining monochromatic positrons is described in more detail in Ref. [1] and optimization of the electron beam and W target is presented in Ref.[2]. The important feature of the system design is that an RF system is not required for re-acceleration of positrons.

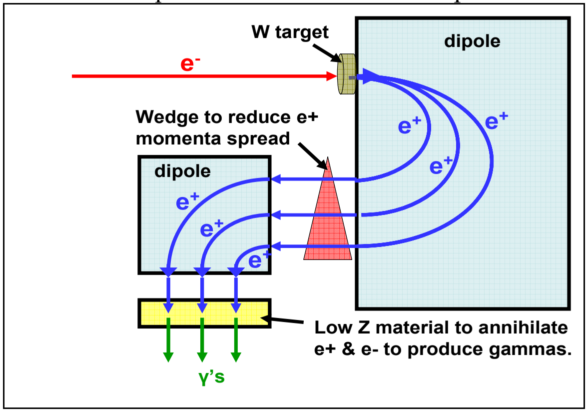

Figure 4: Overall layout for production of a beam of intense mono-energetic gammas. See Refs.[1-2] for additional details.

We focus our efforts on producing positrons in range of 2 MeV/c ≤ p(e+) ≤ 15 MeV/c. The optimal configuration is found to be a pencil beam of 75 MeV electrons on a large radius (≥ 14 mm) W target of length 4.4 mm. The positron production rate is 97.7% of that of a 100 MeV electron beam of the same power, with a ~6% lowering of dosage attributed to the background neutrons [2].

SUMMARY

We studied electron-positron annihilation as a potential high-intensity source of mono-energetic photon beams with tunable energies in the range of 1.5-15 MeV. We presented an optimized conceptual design for a positron source that comprises the front end of a compact tunable gamma source. The optimal configuration is a pencil beam of 75 MeV electrons incident on a tungsten target of length of several millimeters.

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