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DAΦNE GAMMA-RAY FACTORY

D. Alesini, S. Guiducci, C. Milardi, A. Variola, M. Zobov (INFN/LNF, Frascati, Rome, Italy);
I. Chaikovska, F. Zomer (LAL, Orsay, France)

Abstract

Gamma ray sources with high flux and spectral densities are the main requirements for new nuclear physics experiments to be performed in several worldwide laboratories with dedicated facilities. The paper is focalized on a proposal of experiment on γ photons production using Compton collisions between the DAΦNE electron beam and a high average power laser pulse, amplified in a Fabry-Pérot optical resonator. The calculations show that the resulting γ beam source has extremely interesting properties in terms of spectral density, energy spread and γ flux comparable (and even better) with the last generation γ sources. The energy of the γ beam depends on the adopted laser wavelength and can be tuned changing the energy of the electron ring. In particular we have analyzed the case of a γ factory tunable in the 2-9 MeV range. The main parameters of this new facility are presented and the perturbation on the transverse and longitudinal electron beam dynamics is discussed. A preliminary accelerator layout to allow experiments with the γ beam is presented with a first design of the accelerator optics.

INTRODUCTION

Many projects worldwide, based on Compton back-scattering between electron bunches and counter propagating laser pulses, are aimed to generate γ photons with high flux and high spectral densities [1-5].

For this purpose it is necessary both to increase the number of electron-photon collisions and to control the electron and laser beam qualities. In normal conducting photo-injectors [6] the maximum repetition rate of the collisions cannot exceed few kHz and also the bunch charge cannot overcome few hundred of pC to preserve good beam quality. On the other hand, due to the very good beam emittance, it is possible to strongly focalize the beam at the interaction point (IP). Then colliding lasers with a high energy per pulse and low repetition rate are required [3-4]. High flux and high spectral densities can be also obtained using storage ring and high rep. rate laser. The aim of the proposal [7] presented in this paper is to create such a source using the DAΦNE stored electron beam colliding with a laser beam amplified in a Fabry-Perot Cavity (FPC) similar to the one designed and fabricated at LAL Orsay, and used in the ATF experiment [8].

DAΦNE is an e+e- collider operating at the energy of Φ-resonance (1.02 GeV c.m.) [9]. Few machine parameters [10,11], are summarized in Table I. As discussed in the paper, the extremely high current storable in the electron ring and the achievable beam emittance, allow reaching excellent γ-beam qualities comparable (and even better) with those of the new generation sources. Moreover, with a proper choice of the machine parameters, the interval between two consecutive collisions of an electron with a photon can be much longer than the damping time of the machine and the beam dynamics is completely dominated by the dynamics of the electron ring without the laser.

Table I: DAΦNE Parameters

Energy	E [MeV]	510
Machine length	L [m]	97.6
Max. stored current	I_{MAX} [A]	2.5 (e- ring)
RF frequency	f_{RF} [MHz]	368.67
Max RF voltage	V_{RF_MAX}[kV]	250
Harmonic number	h_N	120
Min.bunch spacing	T_B[ns]	2.7 (=1/f_{RF})
Hor. emittance	ε_x [mm mrad]	0.250
Coupling	$coupl=\varepsilon_y/\varepsilon_x$ [%]	<0.5
Bunch length	σ_t [ps]	40-60
Energy spread	ΔE/E [%]	0.04-0.06
Long. Damp. time	τ_{damp} [ms]	17

COLLISION SCHEME AND RESULTS

Compton sources can be considered as electron-photon colliders. For a generic γ-source there are four important quantities that characterize the source: the total number of scattered photons per second over the 4π solid angle, the rms source bandwidth (BW), the number of photons per second in the bandwidth and the spectral density. These quantities can be calculated with simple formulas that can be found in [4,7,12-15].

A simple sketch of the interaction region is given in Fig. 1.

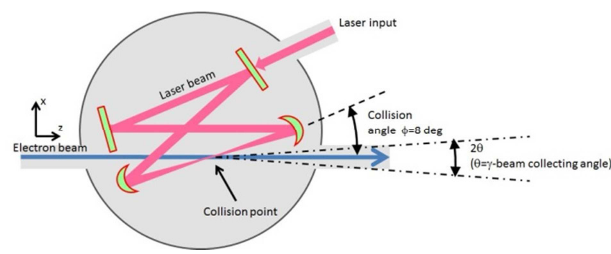

Figure 1: Simple sketch of the interaction region.

Since, in the DAΦNE ring, the coupling can be small (typically <1%) we have considered, at the IP, the case of a flat electron beam and a round laser beam with equal vertical dimensions. It is easy to demonstrate [7] that, to have an equal contribution of the electron beam emittance to the γ final energy spread in both horizontal and vertical planes, the ratio of the β-functions β_y/β_x at the IP has to be equal to the machine coupling. The results of the calculations are given in Fig. 2-3 where few important γ-source parameters have been plotted as a function of the

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laser spot size. For the rms bandwidth calculation we have assumed that the main contribution to the energy spread is due to the collection angle and e$^-$ beam parameters. We have considered the case of 1.5 A in 60 equally spaced bunches that is compatible with the best performances of the machine in the last SIDDARTHA run [10] and 2.5% of coupling. The emittance has been considered to be 40% of its present value. As shown in [7,16] this value can be achieved in DAΦNE with a proper optics design. For the laser we have considered the case of λ_L=1µm with a collision angle of 8 degrees and a collisions repetition frequency of 184 MHz (f_{RF}/2). All these parameters are compatible with those of the FPC used in ATF [17]. The results show the extremely good quality of the source both in term of flux and in term of SPD. The best results have been summarized in Table II for two cases of 1% and 2.5% of coupling.

Table II: DAΦNE γ Source Parameters

Parameter	Case 1	Case 2
e$^-$ stored current [A]	1.5	
number of bunches	60	
e$^-$ emittance [mm*mrad]	0.100	
coupling @ IP [%]	2.5	1
e$^-$/laser pulse length [ps]	50/20	
e$^-$ σ_y (=laser) @ IP [µm]	40.0	30.0
e$^-$ hor. dim. @ IP [µm]	1600.0	3000.0
e$^-$ vert. β_y @ IP [m]	0.6	0.9
e$^-$ hor. β_x @ IP [m]	25.6	90
laser stored power [kW]	36.8	
Laser energy per pulse [µJ]	200.0	
laser wavelength [µm]	1.0	
Max. γ energy [MeV]	4.94	
total γ flux [ph/s]	$0.96{\cdot}10^{12}$	$0.75{\cdot}10^{12}$
γ energy spread [%]	0.57	0.21
γ flux in the BW [ph/s]	$5.8{\cdot}10^9$	$1.7\cdot10^9$
SPD [ph/s/eV]	81533	64158
Max. collecting angle [µrad]	63	39

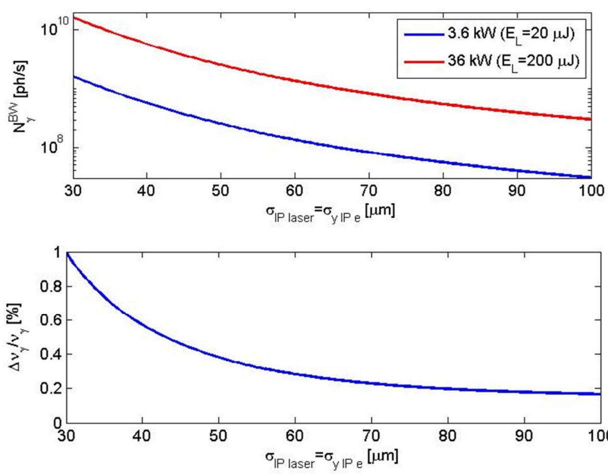

Figure 2: γ flux in the BW (top) and rms BW (bottom).

The energy of the γ beam can be changed by varying the energy of the laser, the energy of the electron beam or in another configuration the incidence angle. In order to avoid a strong reduction of the beam lifetime, it is important to maintain the maximum energy of the γ photons within the energy acceptance of the ring. The maximum energy of the γ beam as a function of the electron beam energy for λ_L equal to 10, 1 and 0.5 µm are given in Fig. 4. In the same figure it is also reported the required energy acceptance. The energy up to 700 MeV can be, in principle, reached in the DAΦNE electron ring by increasing the magnetic elements strength. Typical DAΦNE energy acceptances are below 1.5% (unless considering very high RF voltages and/or very low momentum compaction factors). As clear from Fig. 4, this fact forces the wavelength of the collision laser to $\lambda_L \geq 1\mu m$. The resulting energy of the γ photons can be then tuned reasonably in the range 2-9 MeV.

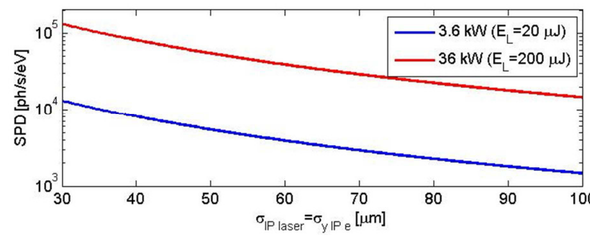

Figure 3: Spectral density.

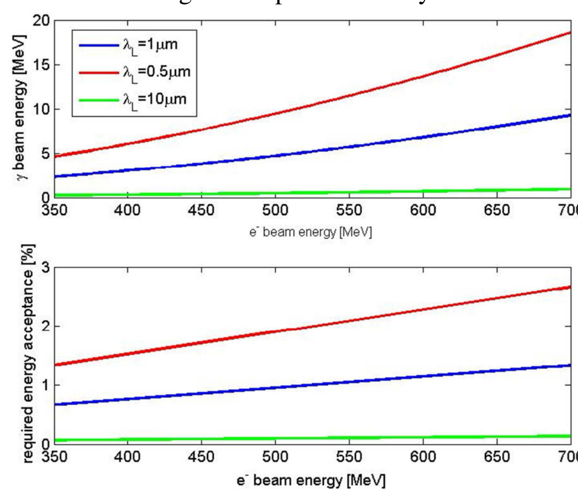

Figure 4: Maximum energy of the γ beam (top); required energy acceptance (bottom).

ELECTRON BEAM DYNAMICS

The electrons colliding with photons emit γ rays with energies proportional to the square of the electron energy and with a typical average spectrum [18-19]. This causes a radiation damping but also a quantum excitation of the beam energy since the γs are stochastically emitted in quantum. Moreover, the γ rays are emitted at different angles and there is a typical correlation between the energy and the angle [18-19]. The final transverse emittance and energy spread are due to the balance between these effects and those due to the synchrotron light emission in the ring [21]. Looking at the machine parameters given in Table II it is straightforward to recognize that the average interval between two

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consecutive collisions of an electron with a photon is much longer than the damping time of the machine and, as a consequence, the beam dynamics is completely dominated by the dynamics of the electron ring without the laser. This intuitive conclusion is more rigorously confirmed by following a theoretical approach or Monte Carlo simulations that we performed using the tracking code CAIN [7,20]. This code also validated the theoretical calculations. Some results are given in Fig. 5-6 for the parameters reported in Table II-case 1 [7].

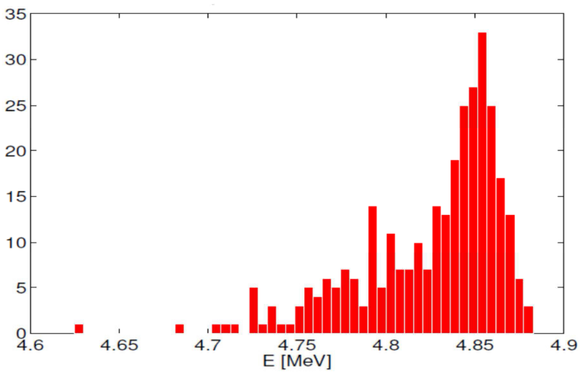

Figure 5: γ spectrum after collimation collimation.

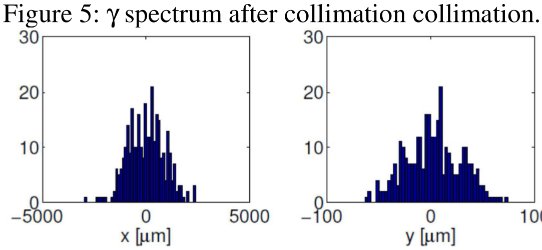

Figure 6: γ rays spatial distribution after collimation.

POSSIBLE IMPLEMENTATION

A sketch of a possible collider implementation is shown in Fig. 7 with the experimental hall located near the present Cryogenics hall. The FPC can be placed in the first interaction region. As pointed out in the previous sections, the calculations we have done are referred to the case of the FPC already realized by the LAL Orsay Laboratory and successfully tested [17]. The picture of the cavity is given in Fig. 8. Few modifications have to be implemented but there are enough margins for them [7].

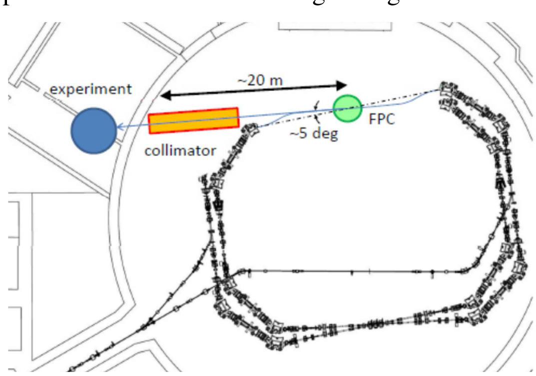

Figure 7: Possible implementation of the γ factory.

A preliminary lattice for the DAΦNE γ factory has been also elaborated [16]. The DAΦNE lattice has enough flexibility to vary the emittance in the range between 0.28 and 0.045 mm·mrad. In this approach the DAΦNE layout has been modified to insert a dogleg section necessary for the extraction of the γ beam. The easiest way to achieve this, is to install two magnets in the interaction region straight section with an angle of 5 degrees and to modify the bending angle of the nearest dipoles. This layout allows to easily extract the γ beam line from the ring vacuum chamber. As Interaction Region for the γ factory, it is possible to use either the center of the straight section (between the dogleg dipoles) or the 2.5 m long straight section adjacent to the "Short" arc. The optical functions in half of the ring are shown in Fig. 9, the other half ring being symmetric.

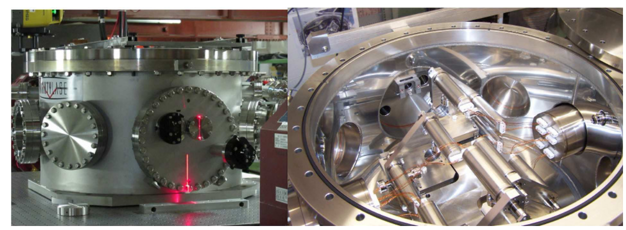

Figure 8: Pictures of the LAL Orsay FPC.

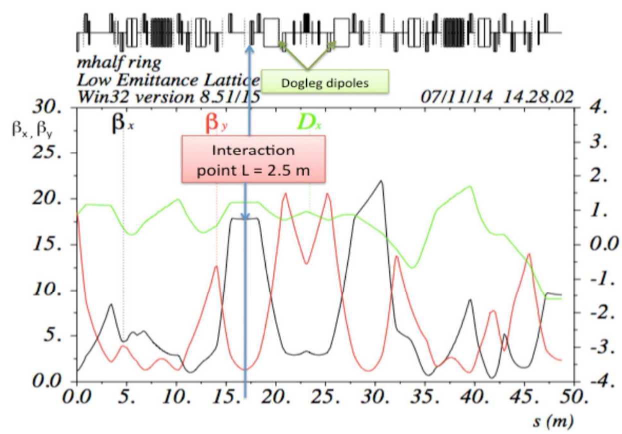

Figure 9: Lattice optical functions for half ring.

CONCLUSIONS

Preliminary studies show that tunable γ photons beams can be generated in DAΦNE using Compton collisions. The photons energy can be tuned in the 2-9 MeV range. The calculations have shown that the resulting γ beam source has extremely competitive properties in terms of spectral density, energy spread and γ flux. The main parameters of this new facility are feasible. For this experiment there is the possibility to use (with few feasible modifications) the FPC designed and fabricated by the LAL Orsay Laboratory and already tested at ATF. Besides, preliminary DAΦNE layout and low emittance optics have been elaborated.

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