A GAMMA-RAY BEAM LINE FOR NUCLEAR PHYSICS AND APPLICATIONS AT THE SPANISH SYNCHROTRON ALBA

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Abstract

We present here the concept of the proposed gamma-ray beam line for the ALBA synchrotron light source to be built near Barcelona. The gamma-rays are produced by Compton backscattering of laser light from the ring electrons. Without affecting the machine performance it will be possible to produce high intensity beams with energies up to 500 MeV. The beam is focused naturally and is easily polarized. The beam energy can be defined by collimation at the lower energies and by internal tagging at high energies. Such gamma-ray beams can be used to study photo-nuclear processes of interest in basic nuclear physics, ranging from nuclear structure at low energies to sub-nucleonic degrees of freedom at high energies, and astrophysics. At the same time it can be used to obtain nuclear data relevant to the fields of dosimetry, radiation shielding and radiation therapy. Other applications are the non-destructive inspection of objects and their elemental analysis.

Introduction

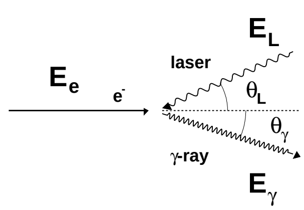
The construction of a third generation synchrotron light source in Spain has been recently approved and will start soon at the Laboratorio de Luz Sincrotrón (LLS) in the vicinity of Barcelona. The machine, named ALBA, will provide radiation in the energy range up to soft X-rays for research in fields such as biology, materials science, chemistry, pharmacology, etc. However it is possible, and desirable for both scientific and resource optimization reasons, to extend the energy of the radiation into the range of intermediate energy γ-rays (500 MeV). The generation of such energies is possible through the process of Compton scattering of laser photons from the highly energetic electrons circulating in the synchrotron ring. It is an alternative method to the generation of γ-rays through the electron bremsstrahlung process and has specific advantages. The characteristics of the γ-ray beam (energy, intensity, etc.) depend on the parameters of the colliding electron and laser beams and will be explored in the next section. The availability of γ-rays, say from a few MeV up to some 500 MeV, expands the range of research fields of LLS into basic and applied nuclear physics. Some examples of these applications will also be presented. Currently a proposal to build a γ-ray beam line at ALBA is being prepared by a collaboration between several national groups.

Gamma-ray beam characterization

Compton scattering on energetic electrons

Back in 1963, it was pointed out ([1], [2]) the possibility to produce an energetic and highly polarized gamma-ray beam through Compton scattering of polarized laser light with the electrons accelerated in a high energy machine. The first installation for experiments was build at Frascati [3] and presently, installations of this type exist at several places (see [4] for references).

The kinematics of the collision is described by the modified Compton formula [5]:



$$E_\gamma = \frac{(1+\beta_e cos\theta_L)E_L}{1-\beta_e cos\theta_\gamma + \frac{E_L}{E_e}\left[1+cos(\theta_\gamma+\theta_L)\right]} \quad (1)$$

Here E_e, E_L and E_γ, are respectively the electron, laser photon and γ-ray energies, β_e the electron velocity in units of c, and θ_γ (θ_L) the angle of the outgoing (incoming) photon with respect to the incident electron direction, not necessarily in the same plane. For fixed E_e and E_L, the maximum possible γ-ray energy is obtained for the backscattered photon ($\theta_\gamma = 0°$) in a head-on collision ($\theta_L = 0°$). In Fig. 1 we represent the maximum γ-ray energy obtainable for $E_e = 3$ GeV (the nominal energy of ALBA) as a function of laser wave-length. All γ-ray energies are possible between the minimum E_L and the maximum. Due to the relativistic "boost" the scattered gamma rays are strongly forward focused, thus forming a beam, as can be deduced from Fig. 2, which shows the angle θ_γ as a function of $z = E_\gamma/E_\gamma^{\max}$, the energy of the gamma-ray normalized to the maximum energy. We see that the top 90 % range of γ energies is contained within a cone of angle 0.55 mrad. This figure and the following, has been calculated for $E_e = 3.0$ GeV and $E_L = 1.17$ eV (Nd:YAG laser), but will change little over the range of energies of practical high power lasers when the universal variable z is used.

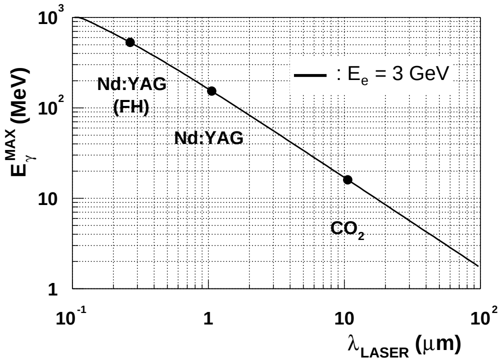


Figure 1: Maximum γ-ray energy as a function of laser photon energy

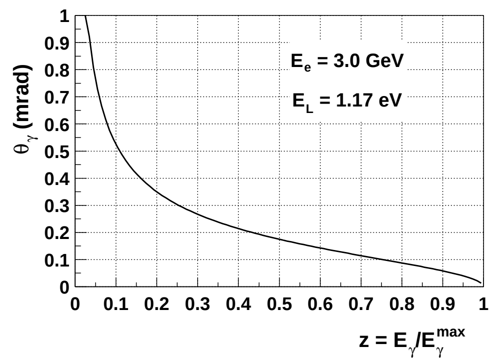


Figure 2: γ-ray energy as a function of scattering angle

The gamma-ray energy spectrum can be obtained through the proper integration of the differential cross section angular distribution. The expression can be written as follows [6]:

$$\frac{d\sigma_C}{dz} = \frac{1}{2(1+x)} C_{00} = \frac{1}{2(1+x)} \left[1 - y + \frac{1}{1-y} - \frac{4y}{x(1-y)} + \frac{4y^2}{x^2(1-y)^2} \right] \tag{2}$$

where $x = 4E_e E_L / m_e^2 c^4$, $y = E_\gamma / E_e$. Again, $d\sigma_C/dz$ does not vary much with E_e and E_L, and we represent in Fig. 3 the normalized (by σ_C) values. The distribution has a saddle shape, with the maxima at the energy extremes being twice that in the middle. The total cross section is a slowly varying function of electron and laser energies, and has a value of approximately $\sigma_C = 0.6$ b.

If the laser beam is polarized, either linearly or circularly, the polarization is transferred to the backward scattered gamma. For fully polarized laser photons the degree of linear P_γ^L or circular P_γ^C polarization of the scattered γ-ray is given by [6]:

$$P_\gamma^L = \frac{1}{C_{00}} \frac{2y^2}{x^2(1-y)^2} \quad (3)\ , \qquad P_\gamma^C = -\frac{1}{C_{00}} \left(\frac{2y}{x(1-y)} - 1 \right) \left(1 - y + \frac{1}{1-y} \right) \quad (4)$$

In Fig. 4 we represent the degree of polarization of the γ-ray as a function of $z = E_\gamma / E_\gamma^{\max}$. We observe that the sign of the circular polarization is inverted for the backscattered photon. We also observe that the degree of polarization decreases with decreasing energy. Polarizations in excess of 80 % are obtained for the top 30 % energy range.

Characteristics of the installation

The accelerator parameters from the original design [7] of the synchrotron at LLS are presently being reconsidered [8], with the purpose of achieving a unique performance in terms of the light source luminosity. The exact characteristics of the γ-ray beam will depend on the final machine parameters but its main characteristics can already be estimated. We will use for this purpose the parameters from one of the synchrotron lattice structures under consideration (of the so called QBA type) which are summarized in Table 1.

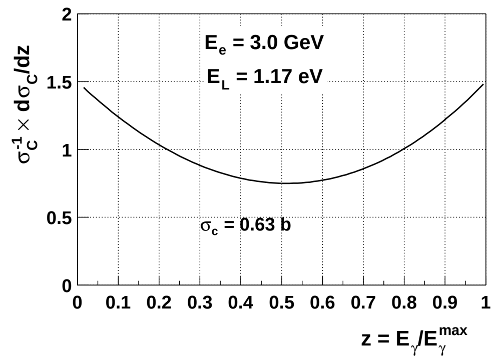


Figure 3: γ-ray relative intensity as a function of energy

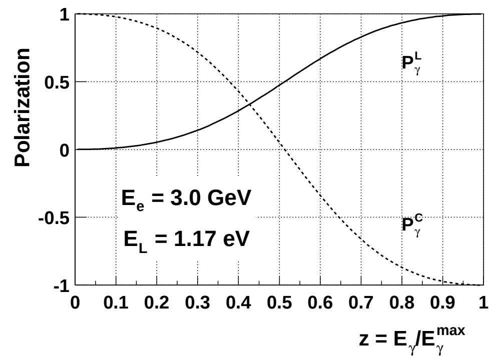


Figure 4: γ-ray polarization as a function of energy

Ring	
Intensity I_e	0.250 A
Energy E_e	3.0 GeV
Resolution σ_{E_e}/E_e	0.001
Horizontal emittance ϵ_x	5.0 nmrad
Vertical emittance ϵ_y	0.05 nmrad
Momentum acceptance $\Delta p/p_0$	0.015
Straight section	
Length L_{int}	5 m
Horizontal beam envelope σ_X	0.250 mm
Vertical beam envelope σ_Y	0.015 mm
Horizontal slope envelope $\sigma_{X'}$	0.020 mrad
Vertical slope envelope $\sigma_{Y'}$	0.004 mrad

Table 1: Electron ring parameters used in the calculations

The accelerator complex includes a 100 MeV linac, the booster which brings the energy up to the nominal value of 3.0 GeV, and the ring itself. The booster and the ring will share the same shielding tunnel. The ring is a four fold structure with a circumference length of about 255 m. Sixteen straight sections will be available for insertion devices. In the normal operation mode the ring is filled with about 1.4×10^{12} electrons grouped in bunches 20 ps long separated by 2 ns, which can be regarded as a continuous beam in practice. The nominal intensity of 250 mA will be maintained within $\sim$ 1 % by frequent re-fillings (topping-up mode). One of the straight sections, about 5 m long, between bending magnets could be used to produce the Compton scattered γ-rays. For this purpose a well focused and aligned laser beam will be injected into the vacuum chamber using an adequate mirror. The γ-ray beam obtained traverses the mirror and continues up to a measuring station which will be located some 20-30 m away.

The maximum γ-ray energies which can be obtained with some of the commercially available high power lasers are indicated in Fig. 1. With a CO_2 laser $E_\gamma^{\max}$ would be 16.0 MeV , with a Nd:YAG laser it would be 152.5 MeV, 290.3 MeV, 415.0 MeV and 529.3 MeV in the fundamental, second harmonic (SH), third harmonic (TH) and fourth harmonic (FH) modes respectively. The use of the higher harmonics allows one to obtain a high degree (> 80 %) of polarization in the energy range 200-530 MeV (see Fig. 4). For reasons that will be explained later, to cover the region of γ-ray energies from 15-150 MeV we are considering the use of a continuously tunable laser source, based on an optical parameter oscillator (OPO) [9] pumped by the Nd:YAG. In this case the polarization would be essentially 100 %.

The intensity of the γ-ray beam depends on the overlap of the colliding electron and laser photon densities and on the Compton cross-section [6]:

$$I_\gamma = 2c\sigma_C \int n_e n_L dV \tag{5}$$

The electron density n_e is adequately represented by a transverse gaussian distribution in both X and Y directions with parameters σ_X and σ_Y constant along Z. The laser photon density n_L will be assumed to be that of a diffraction limited circular gaussian beam. In this case the RMS width has a minimum σ_0 at the centre of the interaction region and diverges with z [10]: $\sigma_L = \sigma_0\sqrt{1 + (\lambda z/\pi\sigma_0^2)^2}$. Using the parameters of Table 1 and assuming $\sigma_0 = 0.5$ mm for the laser beam, the intensity obtained is $I_\gamma = 4 - 5 \times 10^6 s^{-1}$ per Watt of laser power and wave lengths in the range $\lambda = 1 - 100\mu$m. I should be noticed that although the number of laser photons per Watt is proportional to the wavelength, this effect is counter balanced by the increase in the divergence of the laser beam. Nd:YAG laser devices with 100 W CW power are readily available, with conversion efficiencies of about 40 %, 30 % and 10 % for the second, third and fourth harmonics, which would provide beams of $10^7 - 10^8$ gamma rays per second. Still higher powers are available for CO_2 lasers, and intensities larger than $10^9 s^{-1}$ can be expected. In the case of the OPO source, powers of about 5 W are foreseen giving intensities in excess of $10^7 s^{-1}$.

One possible limit to the ultimately obtainable γ-ray intensity is the removal of electrons from the beam in the scattering process. Electrons which lose less than 45 MeV, equivalent to the ring acceptance $\Delta p/p_0$ (see Table 1), are kept in the ring in principle, except for multiple scattering effects for very high laser powers. For γ-rays above that energy, the electron will eventually hit the vacuum chamber and will be lost. In the topping-up mode electrons are replenished frequently to compensate for the usual losses of intensity in the ring. Assuming a refilling time period of 100 s and that the new source of losses should be limited to a fraction of one percent, will impose a limit of a few times 10^7 in the γ-ray intensity.

As was mentioned earlier the spectrum of γ-rays arriving at the measuring station is rather flat (see Fig. 3). Most of the measurements performed will require a determination of the γ-ray energy. There are two possible methods to define the energy: collimation and tagging.

The tagging technique requires the determination of the energy of the electron dispersed in the collision in coincidence with the γ-ray or its reaction products. Given the energies involved, it implies the use of magnetic analysis for the electron. For cost reasons it would be convenient to make use of the ring itself for this purpose. In the so called internal tagging one places a position sensitive counter at the exit of the next bending magnet after the laser-electron interaction region, to measure the electron energy loss. Si-microstrip detectors have been successfully employed for this purpose [11]. The energy resolution which could be obtained depends on the ring optics [12] (dispersion and magnification). Given the uncertainty in the ring parameters we can not evaluate at present the resolution which can be expected at ALBA. In a study made for the original ring design we have shown [13] that resolutions (FWHM) of the order of 4 MeV or 7 MeV (independent of γ-ray energy) could be obtained depending on the configuration. The tagging technique is another source of limitation for the achievable γ-ray intensity [14]. At high rates both pile-up signals in the tagger and random coincidences with the measuring detectors introduce spurious events which need to be corrected for. The maximum admissible rate depends on the time resolution and also on the type of experiment but is of the order of $10^7 - 10^8 s^{-1}$.

There is a minimum γ-ray energy which can be tagged, related to the synchrotron ring dispersion at the position of the detector, and the distance of closest possible approach of the detector to the electron beam envelope. Given the uncertainty in the ring parameters we can only give a rough estimate of about 150 MeV for the minimum tagged energy. For energies below this limit the alternative method of collimation, which exploits the angle-energy relation of the scattered photons (see Fig. 2), can be used to define the γ-ray energy. Obviously, smaller opening angles procure better energy resolution at the cost of intensity, so a balance between the two must be reached for actual experiments. In addition, since the angular definition also depends on the directions of the colliding electron and photon and the position of their interaction, there is a minimum energy resolution which can be obtained depending on the electron and laser beam parameters and the collimation geometry. It is possible to obtain an estimate of the uncertainty in the γ-ray energy due to the uncertainty in the angles and energies, applying the error propagation formula to Eq. 1. It can be deduced in this way, that the collimation method gives too rough an energy resolution except when the collimator is placed at zero degrees. In this case a variation of the γ-ray energy requires a variation of the electron energy (not feasible at ALBA) or of the laser photon energy. As was mentioned earlier we plan to use an OPO source with wavelength range $\lambda = 1 - 12\mu$m to cover the energy range $E_\gamma = 15 - 150$ MeV. We are also considering the possibility of using a Free Electron Laser (FEL) to extend the collimated energy range to lower energies [15].

An accurate estimation of the resolution and intensity that could be obtained in this case requires the proper consideration of the possible variations of the parameters in Eq. 1. We have chosen the Monte Carlo method for this purpose. The electron and laser photon beam spatial distributions are modeled in the same way as was explained before. In addition one needs to model the momentum distributions. For electrons, they are adequately represented by gaussian distributions of the slopes in both X and Y directions with parameters $\sigma_{X'}$ and $\sigma_{Y'}$, constant along Z, and by a gaussian distribution in the energy with parameter σ_{E_e}. For laser photons we assume a well defined energy in a direction perpendicular to the laser wave-front, characterized by the radius [10]: $R_L = z\sqrt{1 + (\pi\sigma_0^2/\lambda z)^2}$. For each scattering event the differential angular Compton cross section is sampled to obtain the γ-ray momentum, and the energy of those traversing the collimator opening is accumulated.

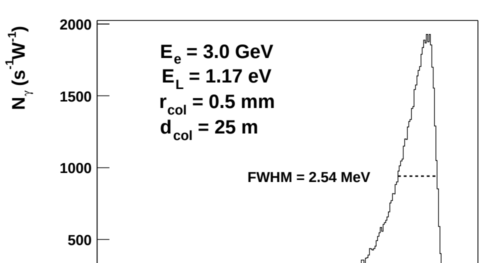


Figure 5: Collimated γ-ray energy distribution

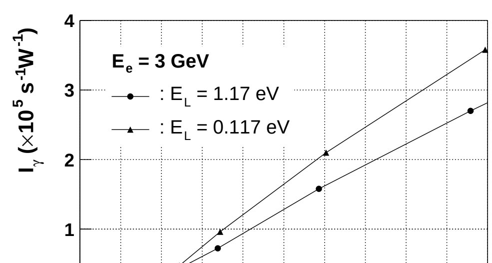


Figure 6: Collimated intensity and resolution

Fig. 5 shows the result of the Monte Carlo simulation for a laser photon energy $E_L = 1.17$ eV

(Nd:YAG laser) when a collimator of radius $r_{col} = 0.5$ mm is placed at $\theta_{col} = 0°$ and a distance $d_{col} = 25$ m from the centre of the 5 m long interaction region. As can be observed the energy distribution is characterized by a low energy tail coming from the distribution of angles, most of the effect being due to the horizontal divergence of the electron beam ($\sigma_{X'} = 20\mu$rad) in this case. The electron energy resolution has a small smearing effect. The FWHM resolution amounts to $\Delta E_\gamma/E_\gamma = 1.7$ % and the collimated intensity is $7.3 \times 10^4 s^{-1}$ per Watt of laser power (uncollimated intensity: $4.0 \times 10^6 s^{-1}$). The simulations were repeated for several collimator openings and laser photon energies. Fig. 5 shows the relation between γ-ray energy resolution and intensity for two different laser photon energies, for collimator radii: 0.25, 0.35, 0.50, 0.75 and 1.0 mm. The chosen laser photon energies $E_L = 1.17$ eV (Nd:YAG laser) and $E_L = 0.117$ eV (CO_2 laser) would provide γ-ray energies of $E_\gamma = 152$ MeV and $E_\gamma = 16$ MeV respectively. As can be observed, the relation intensity-resolution is approximately linear except when the intrinsic resolution limit is approached. For a given collimator radius the energy resolution is nearly independent of the laser photon energy. Given the foreseen 5 W power of the OPO source, intensities in excess of $10^5 s^{-1}$ can be expected for a beam collimated to an energy resolution $\Delta E_\gamma/E_\gamma = 1.5$ % in the energy range $15 - 150$ MeV.

Applications

The availability of intense highly polarized photon beams in the range of a few MeV to 500 MeV at LLS opens the possibility for a broad range of studies in basic or applied nuclear physics. We are currently working on the definition of an experimental programme and we will only give some general ideas here.

Studies in basic nuclear physics: Low energy and highly polarized gamma rays can be used to study the structure of bound nuclear states and to map the dipole electromagnetic strength, using the nuclear resonance fluorescence (NRF) technique. At higher energies the photon induced particle emission will give important information on the structure and damping of the collective Giant Dipole Resonance (GDR). Reactions of this type are also of interest in nuclear astrophysics, either directly since they are responsible for the nucleosynthesis of proton rich nuclei, or indirectly, for example to determine the cross section of the inverse capture reaction which is otherwise very difficult to measure in the laboratory, or to get information on neutrino induced reactions governed by similar operators. At still higher energies, reactions of the one or two nucleon emission type give important information on the short range correlations and meson exchange currents in nuclei. The elastic scattering of photons on nucleons will give information on their internal structure. On the other hand photon induced fission can be used to investigate the evolution of fission barriers and the viscosity of nuclear matter. The study of the production of pions near the threshold gives insight into the subnucleonic structure. Pionic atoms could be produced in order to study the relevant pion-nucleus interaction. Further up in energy, the Delta resonance will be excited and its interaction in the nuclear medium can be studied.

Nuclear data for applications: Besides the more basic interest, nuclear data is also relevant for fields like nuclear technology, therapy, dosimetry and radiation shielding. In this respect it will be important to fill in the missing information in the photo-nuclear data bases.

Industrial applications: Intense collimated beams of about 10 MeV would be an important tool for the non-destructive inspection of objects using radiographical techniques such as gammagraphy and Computerized Tomography (CT). White intense beams of up to about 10 MeV can be used for non destructive elemental analysis using the NRF technique.

Instrumentation: Photon beams of this type and quality can be used for precise calibration of specialized detectors such as dosimeters, gamma ray lenses, etc.

Conclusions

We have shown that it will be possible to produce at LLS, without affecting the synchrotron performance, γ-ray beams with intensities in excess of $10^7 s^{-1}$ and energies up to 500 MeV. For energies below 45 MeV much larger ($\times 10^2$) intensities would be possible. In the range of $15 - 150$ MeV collimation could be used to obtain a resolution of 1.5 % or better, essentially 100 % polarization and intensities larger than $10^5 s^{-1}$. Above these energies internal tagging can be used to obtain resolutions of the order of 5 MeV, a high degree (> 80 %) of polarization and intensities larger than $10^5 s^{-1}$ in a 5 MeV energy bin. If we compare such an installation with existing backscattering facilities [4], the LEGS facility [14] comes closer in the tagged energy range (110-450 MeV) and has an order of magnitude less intensity. In the energy range $E_\gamma < 220$ MeV, the HIGS facility [15], based on a dedicated synchrotron and using collimation, is foreseen to have comparable intensity at the higher end, and one order of magnitude larger intensity at the lower end of the range when completed. In comparison with a bremsstrahlung installation a backscattering installation would have a reduced low energy background and an easily changeable and potentially higher polarization degree. No backscattering installation covering the proposed energy range exists in Europe. At present a proposal is being prepared by several national groups. International collaboration would be welcome.

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