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BNL 32361
Conf-8210115--1

BNL--32361
DE83 006275

The Brookhaven Medium Energy Gamma Ray Project

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Within the next year we hope to begin the construction of a facility that would provide intense beams of monochromatic and polarized photons with energies in the range of several hundreds of MeV. These γ rays will be produced by Compton backscattering laser light from the electrons circulating in the 2.5-3.0 GeV 'X-RAY' storage ring of the National Synchrotron Light Source (NSLS) at Brookhaven National Laboratory. Gamma rays up to 80 MeV in energy are produced by this mechanism at the LADON facility at Frascati.[1] However, the techniques that will be used at Brookhaven to produce monoenergetic polarized γ-ray beams are fundamentally different than those employed at Frascati. In this paper we summarize the essential aspects and phases of development of the BNL facility.

I. PRODUCTION MECHANISM

The scattering process is shown schematically in Fig. 1 (with angles greatly magnified). The laser photon and the electron approach each other at some small relative angle ϕ. After backscattering, the γ ray emerges at a small angle θ relative to the electron beam direction. In the frame in which the electron is initially at rest, the laser photon is boosted up in energy by a factor of about 2γ. At the same time, any angular divergences in the initial laser beam (represented by ϕ) are collapsed. In this frame the photon, now an x-ray, Compton scatters from the stationary electron. After backscattering, the x-ray is boosted up in energy by another factor of about 2γ when viewed in the laboratory. At the same time, the angular spread of the outgoing γ ray again experiences a collapse in transforming to the laboratory. The dependence of the final γ-ray energy upon angle comes chiefly from the Compton scattering process itself. Because of the sequential angular compressions from the Lorentz transformations, the final γ-ray energy is completely unaffected by the initial finite divergences that contribute to ϕ. To an excellent approximation, the γ-ray energy is given by

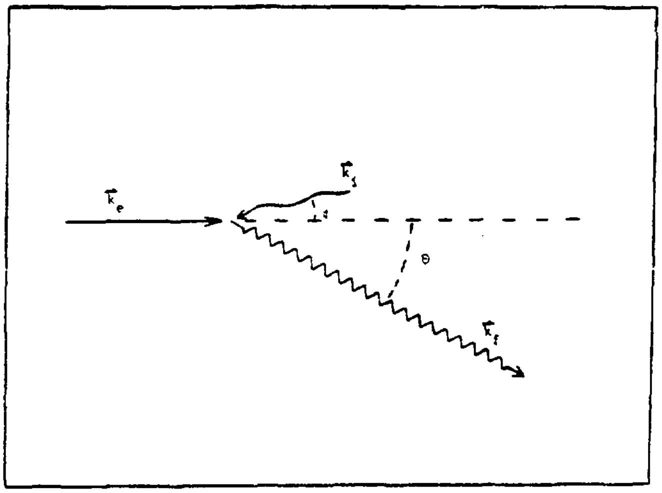

Fig. 1

$$E = \frac{4\gamma^2 \varepsilon_\ell}{1 + \frac{4\gamma\varepsilon_\ell}{mc^2} + \theta^2\gamma^2} \qquad (1)$$

where ε_ℓ is the energy of a laser photon and γmc^2 is the electron beam energy. The highest energy γ rays are traveling at $\theta=0^\circ$ relative to the electron direction. The resolution of this γ ray beam could thus be determined by collimation. However, in any practical situation the scattering angle cannot be defined to better than the electron beam divergence (θ_e), and thus for electrons with energy resolution ΔE_e, the resolution attainable with a collimator (whose half-angle is θ_c) is

$$\frac{\Delta E_\gamma}{E_\gamma} \simeq \left[\left(\frac{2\Delta E_e}{E_e}\right)^2 + (\gamma\Delta\theta)^4\right]^{1/2},$$

where (2)

$$\Delta\theta = \left[\theta_e^2 + \theta_c^2\right]^{1/2}.$$

The cross sections for γ-ray production by laser backscattering are compressed into a narrow region about $\theta_{lab} = 0^\circ$ by the Lorentz transformations. The extent of this compression increases roughly as the square of the electron energy. This is evident in Fig. 2 where the dependence of the lab cross section upon angle is plotted for 3.0 eV laser light incident upon 0.7 GeV electrons (dashed curve) and upon 2.5 GeV electrons (solid curve). The dependence of the backscattered γ-ray energy, determined from Eq. (1), is also shown with its scale on the right (dot-dashed and open-circled curves, respectively). As can be seen from this energy variation with angle, the technique used at Frascati of collimating the γ rays to the minimum divergence of the electrons in the interaction straight section produces a fairly monoenergetic beam, provided the electron energy is moderately low. At high energies this technique is no longer attractive. For example, if γ rays produced by backscattering against the 2.5 GeV electrons of the NSLS X-RAY ring are collimated to this minimum divergence angle (4×10^{-5} radians, indicated by the dashed

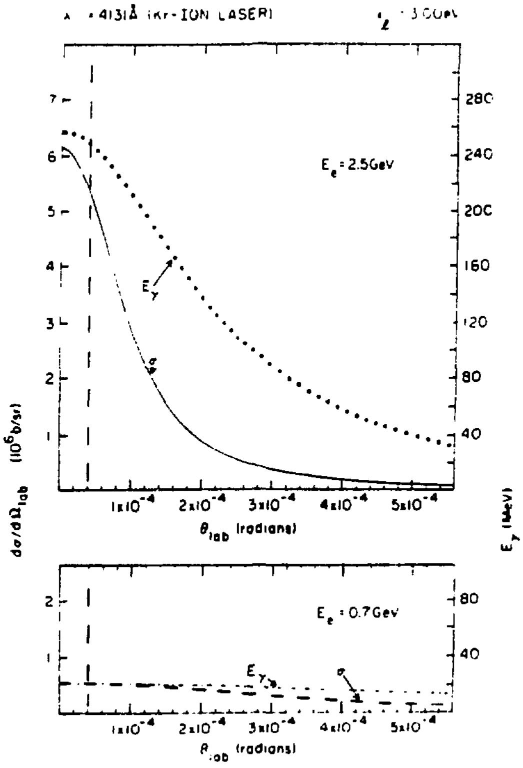

Fig. 2

vertical line in Fig. 2), the energy variation in the transmitted photon beam is about 3.5%. It is doubtful that this situation can be significantly improved. This divergence in the NSLS X-RAY ring straight section is already about a factor of 3 smaller than that of the ADONE ring at Frascati.

II. TAGGING

The total γ-ray spectrum produced by 3.0 eV laser light incident upon 2.5 GeV electrons is plotted in Fig. 3. (This is effectively the solid curve of Fig. 2, per unit solid angle, plotted against the open-circled curve of Fig. 2.) All of the γ rays capable of producing nuclear reactions are contained within 10^{-3} radians of the electron beam direction. The angle of the scattered electron that gave up $(E_e - E_{e'})$ of its energy to produce the high-energy γ ray is just $E_\gamma \theta_\gamma \times (E_e - E_\gamma)^{-1}$. Thus, for the spectrum of Fig. 3, the cone of scattered electrons is collapsed a factor of 10 smaller than the already narrow γ-ray cone. The storage-ring dipole magnet immediately following the straight interaction section momentum analyzes these scattered electrons. The γ-ray spectrum of Fig. 3 extends down to zero energy, and the corresponding scattered electrons become indistinguishable from the primary beam. However, all of the electrons associated with a high energy portion of the full backscattered spectrum can easily be separated from the primary beam and transported to a focal plane of the dipole magnet. The energy of the γ ray reaching the nuclear target is then defined by the position of its tagging electron on this focal plane. Septum magnets located after the storage-ring dipole improve the effective dynamic range and resolution of this tagging procedure. Our design for the electron-tagging spectrometer is discussed in detail in the contribution by C.E. Thorn to this conference. The photon energy resolution determined by this tagging spectrometer will be about 2.7 MeV for all γ-ray energies. Because of the extremely small divergence of the scattered electrons, the tagging efficiency is 100% within the dynamic range of the spectrometer, $E_\gamma > 175$ MeV. (If necessary, this limit can be lowered, but this requires a dedicated operation of the storage ring.) Thus, the energy of almost all γ rays and, in particular, all of the highest energy γ rays reaching the nuclear target is known. This is very different from tagged-Bremsstrahlung beams which are always accompanied by very large numbers of untagged γ rays of unknown energy.

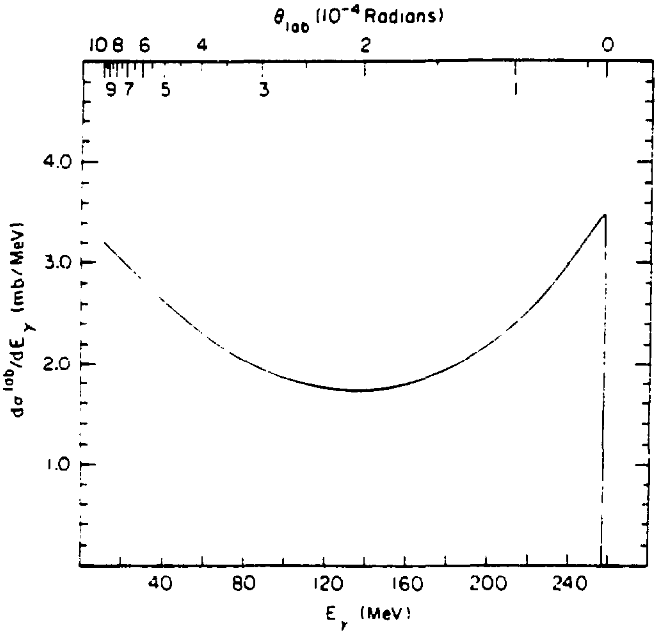

Fig. 3

There are several advantages to tagging the backscattered γ ray beam: (1) The photon collimator can be large enough to accept most of the Compton scattering cross section. This results in a high total γ-ray flux. (2) Data from experiments may be accumulated over a large range of γ ray energies without changing the energy of the electron beam in the storage ring. Thus, γ-ray production can operate as simply another passive user and does not require dedicated use of the ring. (3) The resolution attainable with tagging is significantly better than what can be achieved by collimation at these high energies. (4) The tagged γ-ray beam is much less sensitive to the tune of the storage ring, to small changes in electron beam phase space and position, and is almost completely insensitive to the electron divergence.

There remains a single limitation on the flux of tagged γ-rays. The tagging that follows laser backscattering is 100% efficient so that if two γ rays, in the energy range defined by the collimator and above the minimum acceptance of the tagging spectrometer (175 MeV), are produced within a single electron pulse, then two counters on the tagging focal plane will fire. Any resulting nuclear event must be discarded since the energy of the incident photon that caused this event is ambiguous. For the NSLS X-RAY ring, this maximum tagged photon flux will be about 2×10^7 sec^{-1}.

III. POLARIZATION

Because of the small spin-flip amplitude in backward Compton scattering, the γ ray beam retains most of the polarization of the incident laser light. The parallel component of the cross section is compared to the total (parallel + perpendicular) in Fig. 4, assuming a circular collimator and a linearly polarized laser beam. The ratio of these two, the polarization, is shown at the bottom of the figure.

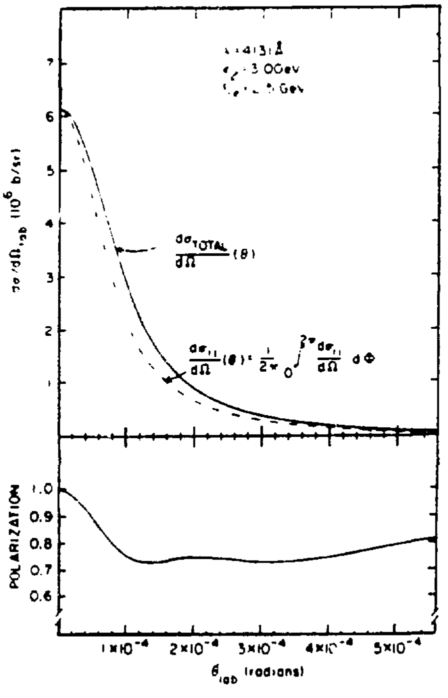

Fig. 4

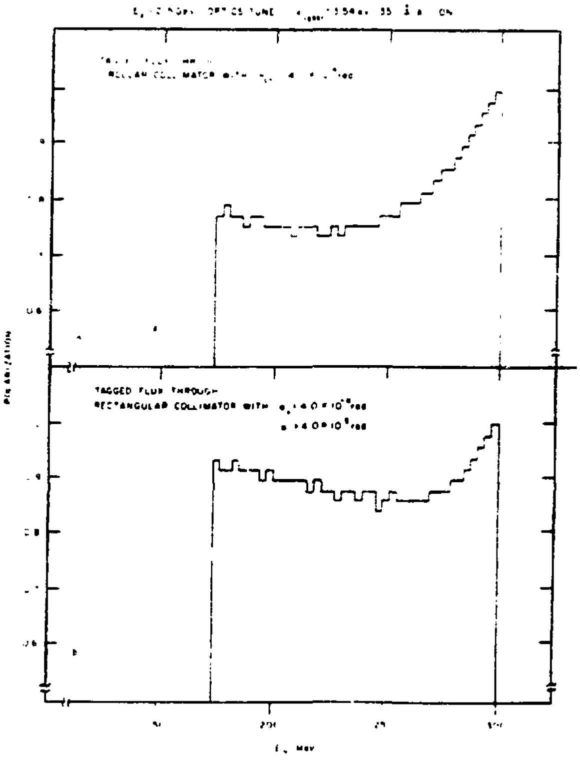

Fig. 5

At all angles, and hence all γ-ray energies, the polarization is greater than about 75%. However, even this level can be greatly improved. The contamination of the beam with γ rays polarized perpendicular to the electric vector of the laser light $\vec{P}_\ell$ comes from scattering into azimuthal angles near o or π, relative to $\vec{P}_\ell$. If a rectangular γ-ray collimator is used that is narrow in the direction of $\vec{P}_\ell$, the polarization of the transmitted flux can be dramatically increased. This is illustrated in Fig. 5. Here the results of Monte Carlo calculations are plotted for a circular (a) and a rectangular (b) collimator. (In (b), $\alpha_\perp$ and $\alpha_\parallel$ are the half angles subtended by the collimator in planes perpendicular and parallel to $\vec{P}_\ell$, respectively.) The calculations include the effects of the variation of the electron beam size and angular divergence along the interaction region. The rectangular collimator of Fig. 5(b) reduces the transmitted flux by a factor of about 2.5, but increases the polarization to greater than 90%.

IV. EXPECTED γ-RAY FLUX LEVELS

For an electron-laser interaction length L_L, an energy ε_L per laser photon and a peak laser power P_L during the light pulse, and a stored electron current of I_e, the expected γ-ray flux is

$$Y\,(\mathrm{sec}^{-1}) = \frac{(2.60)\, I_e(\mathrm{amps})\, P_L(\mathrm{Watts})\, \sigma(\mathrm{mb})\, L_L(\mathrm{cm})}{\varepsilon_L(\mathrm{eV})\; A(\mathrm{cm}^2)} \quad , \qquad (3.1)$$

where σ is the laboratory cross section for backscattering, integrated over the γ-ray beam defining collimator, and A is the effective area of overlap of the laser and electron beams. If the electron beam has a Gaussian distribution in space characterized by half-widths σ_x and σ_y, and if the cylindrical laser beam has a Gaussian power distribution which falls off radially with half-width σ_L, then

$$A = 2\pi \sqrt{\sigma_L^{\,2} + \sigma_x^{\,2}} \cdot \sqrt{\sigma_L^{\,2} + \sigma_y^{\,2}} \ . \qquad (3.2)$$

The NSLS X-RAY ring is designed for operation at I_e=0.5 amps with an extremely small beam size—σ_x=0.4 mm and σ_y=0.07 mm in the straight sections. This leads to a very high flux with only modest laser powers. In particular, it will not be necessary to stretch the laser cavity to include the interaction region as is now done in the LADON-II facility at Frascati. A laser external to the storage ring is sufficient to produce 2×10^7 tagged photons per second. Furthermore, because the resolution is defined by tagging and not by collimation, there is no reason to pulse the laser to avoid regions of large electron divergence near quadrupoles. Thus, the γ ray production at the NSLS X-RAY ring will not be hampered by many of the technical problems encountered at Frascati.

The number of γ rays backscattered through the beam-defining collimator depends not only upon the areas of the electron and laser beams, but also upon how these areas vary with position along the interaction region, and upon how the angular divergence of the electrons varies along the interaction length. The effects of these variations are not included in Eq. (3). We have performed Monte Carlo calculations to simulate these effects in a straight section of the X-RAY ring. The resulting fluxes are slightly less than a factor of 2 lower than would be predicted by Eq. (3).

V. PHASES OF DEVELOPMENT

In the first phase of our project, the CW light from an Ar-Ion laser external to the storage ring will be made to traverse the full length of the injection straight section of the X-RAY ring. With 3 watts of CW power in the UV at 3511 Å (ε_L=3.54 eV) and 0.5 amps of stored electron current, this will produce a tagged flux of γ rays on target between 175 MeV and 300 MeV of 1x10^7 $\sec^{-1}$. In this case, the total number of electrons removed from the beam will be 4.3x10^7 $\sec^{-1}$, which implies a lifetime of 13 hours for the 2x10^{12} stored electrons of the X-RAY ring. This is significantly longer than the expected lifetime of the ring due to other effects and will not seriously affect other users of the NSLS. The experimental area available in the existing NSLS building is just sufficient for test equipment and for a few simple (and compact) experiments. It is, however, far too restrictive for magnetic spectrometers and similar equipment necessary to detect the reaction products of medium-energy γ rays. The second phase of the project thus includes an extension to the existing building to provide target areas for the planned medium-energy physics program. The layout of the γ-ray production and experimental areas is shown in Fig. 6. During this phase we hope to

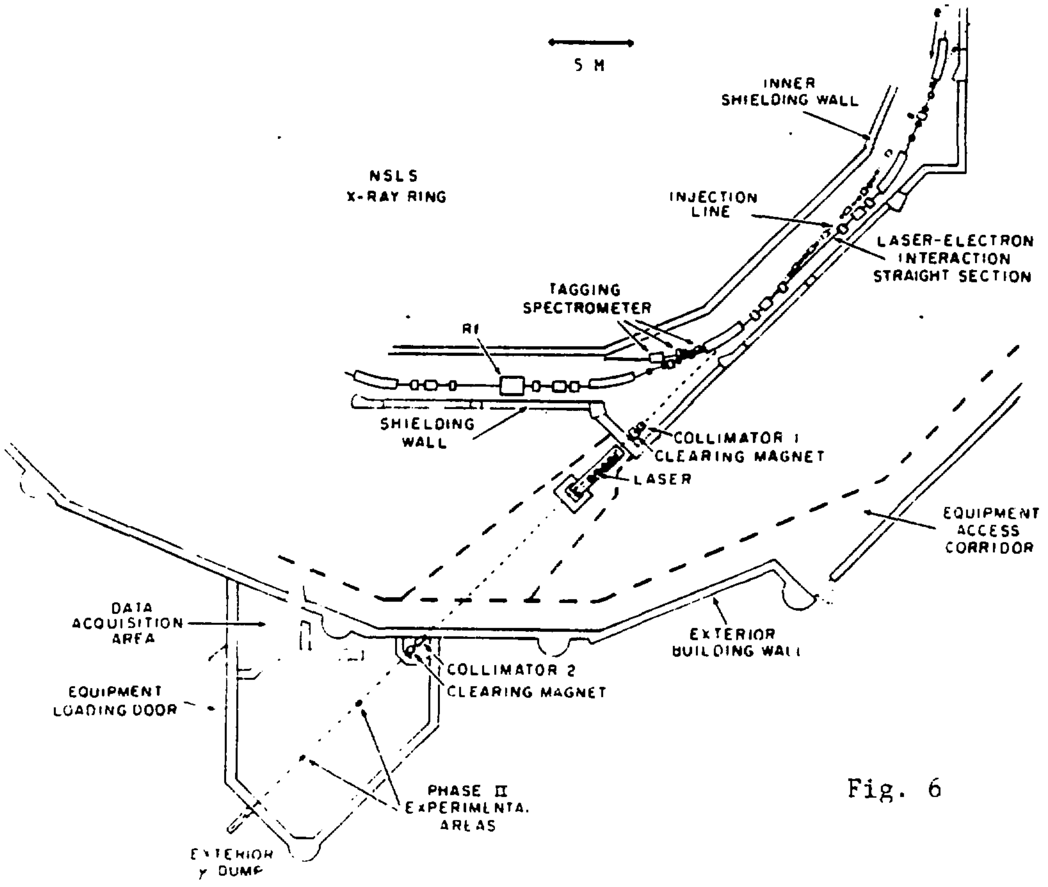

Fig. 6

install a >7 watt UV Argon laser which will bring the tagged flux on target up to 2×10^7 sec^{-1} between 175 MeV and 300 MeV. When the X-RAY ring achieves its expected 3 GeV operation, the maximum γ-ray energy will extend up to 420 MeV with this system.

The 300 MeV (420 MeV) limit on the γ-ray energy arises from a lower limit of 3500 Å on the wavelength of the laser light used for backscattering at 2.5 GeV (3 GeV). Lower wavelengths are commercially available by frequency-doubling Ion lasers or Ion-pumped Dye lasers. However, such devices can operate with high duty-cycles only at power levels that are about 10^3 times smaller than the Ar-Ion laser. The corresponding reductions in γ-ray flux would result in a beam of limited usefulness. The only way to decrease the laser wavelength, and thus increase the γ-ray energy, while maintaining a power level sufficient to produce a high γ-ray flux, is to use a Free Electron Laser (FEL). This is a device in which photons and electrons together traverse a periodically varying magnetic field. The presence of photons and electrons inside this undulating field stimulates the emission of more photons of the same wavelength.

The wavelength of the photons emerging from an FEL is related to the periodicity λ_o of the magnetic field in the undulator and to the energy of the electron beam γmc^2 by

$$\lambda = \frac{\lambda_o}{2\gamma^2}\,(1+K^2) \quad , \qquad (4)$$

where the parameter K is proportional to the r.m.s. magnetic field.

The construction of an FEL on a straight section of the $E_e \leq 700$ MeV VUV ring at the NSLS is presently nearing completion. The undulator is made up of permanent Rare-Earth-Cobalt magnets with a periodicity λ_o=6.5 cm. The undulator gap is adjustable, allowing K (Eq. 4) to vary from about 1.4 to 3.1. With these parameters, it should be possible to obtain wavelengths as low as 2000 Å with electron energies of 300 to 600 MeV in this storage ring.

One might imagine such an FEL mounted on the X-RAY ring with the resulting laser light arranged to backscatter from the 2.5 GeV electrons and produce ultra-high energy γ rays. However, the factor γ in Eq. (4) would then be 4900 and, since it is difficult to realize fields that would produce values of K much greater than about 3, FEL wavelengths in the 2000 Å - 3000 Å range could only be produced with a λ_o=1 meter periodicity undulator. Such an undulator would require 30 to 40 periods to obtain a gain comparable to the VUV-FEL. This length of straight section, free from optical elements, is certainly not available anywhere in the world. Furthermore, it would be virtually impossible to construct such an ~30 meter straight region, throughout which the electron beam area was small. The solution to this problem is unique to the NSLS at Brookhaven. Because of the proximity of the low-energy and high-energy storage rings, and because both rings can be run from the same Rf oscillator and thus synchronized in time, the light from the FEL on the VUV ring can be transported to the injection straight of the X-RAY ring and there, backscattered. The power levels at 2000 Å expected from the VUV-FEL would produce a total tagged γ-ray flux of 2×10^7 sec^{-1}, extending from 280 MeV up to about 500 MeV. When the X-RAY ring achieves 3 GeV operation, this tagged spectrum will be shifted up to almost 700 MeV. This coupling of the two NSLS storage rings is planned for the third phase of our project.

This work was supported by the U.S. Department of Energy under Contract No. DE-AC02-76CH00016.

1) L. Federici, *et al.*, Nuovo Cimento 59B, No. 2, 247 (1980).