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Taladon: a polarized and tagged gamma ray beam

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We present the first measurements of the gamma-ray beam energy resolution obtained with a new tagging system for the Ladon facility on the storage ring Adone at Frascati. A resolution of the order of 3% in the energy region of 30–80 MeV is obtained in accordance with predictions.

1. Introduction

Backward Compton scattering of laser light against the high energy electrons circulating in a storage ring has produced polarized high energy gamma ray beams with an intensity useful for elementary particles and nuclear physics experiments [1–3]. The photon energy can be defined by a severe collimation of the gamma rays or by tagging of the scattered electron and a measurement of its energy. A collimated beam has been in operation at Frascati for several years and has been used in a variety of experiments at photon energies between 20 and 80 MeV (Ladon project). Unfortunately the gamma ray energy resolution decreases with increasing energy. Already at energies of several tens of MeV tagging is able to produce a better energy resolution than collimation. Tagging remains the only real possibility when the angular divergence of the electron beam becomes comparable with γ^{-1} ($\sigma_x' \geq m/E$), which is generally true at Adone for electron energies greater then 1 GeV.

In this note we report the first measurements of the gamma ray beam energy resolution obtained at the Ladon project on the storage ring Adone at Frascati.

2. Tagging

Two types of tagging have been built: internal and external. In internal tagging the scattered electrons are momentum analyzed by the dipole magnets and quadrupoles of the storage ring. The tagging counters measure the displacement of these electrons from the equilibrium orbit and, to cover an adequate range of photons energies, should be placed very close to it. Therefore they must be removed during injection and for two other reasons: to protect them from the radiation damage of uncaptured stray electrons and to make the entire cross section of the vacuum chamber available for the injected electrons.

In external tagging the scattered electrons are removed from the machine lattice with the help of an auxiliary magnetic field located after the first dipole, and are momentum analyzed by an external magnetic spectrometer. The auxiliary magnet must be trimmed very carefully to produce a field of less than 1 G at the main orbit in order not to disturb the circulating electrons.

The calculated gamma ray energy resolution of both systems can approach the limit imposed by the electron beam emittance and energy spread and therefore they are comparable from this point of view. This is very important in photonuclear reactions where the possibil-

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ity to discriminate different processes, leaving the final nucleus in the ground or in the excited states, depends on the energy resolution of the gamma ray beam and the experimental apparatus.

The main differences of the two systems are:

1) Internal tagging is less expensive to build and operate because it does not require new magnets and does not increase the volume of the vacuum chamber by an appreciable amount.

2) Since a detector can be located closer to the main orbit than a magnetic field can, internal tagging permits a lower limit on the minimum gamma ray energy that can be tagged and therefore yields, ceteris paribus, a higher intensity of usable gamma rays.

3) In internal tagging the detectors must have a high spatial resolution ($\delta x < 1$ mm) and, in terms of presently available technologies, must be microstrip solid state silicon detectors (μSD) or scintillating optical fibers. The μSDs being very close to the beam suffer from radiation damage and must be replaced periodically.

4) In external tagging the detectors do not need a very high spatial resolution ($\delta x \approx 5$–10 mm) and can be located at a reasonable distance from the ring in a heavily shielded and radiation-safe location, possibly accessible even when the ring is in operation.

The energy resolution, σ_k, of an internally tagged Ladon beam has been derived by Preger [4] in the linear approximation. Starting from:

$$k = E - E' + k_1 \approx E - E'$$

and

$$\sigma_k^2 = \sigma_E^2 + \sigma_{E'}^2,$$

where σ_E and $\sigma_{E'}$ are correlated if we work in a dispersive section, we have:

$$\sigma_k = E \sigma_{xT}/d,$$

where

$$\sigma_{xT}^2 = \varepsilon_x \beta_{xT} + \eta_T^2 \sigma_p^2,$$

and

k	is the energy of the scattered gamma ray [MeV];
E	is the energy of the incoming electron [MeV];
E'	is the energy of the scattered electron [MeV];
d	is the energy dispersion of the magnetic components of the ring lattice from the interaction region to the tagging detectors (A_{13} in many matrix notations) [m];
ε_x	is the horizontal emittance of the stored beam [m r];
σ_P	is the fractional energy spread of the stored beam;
β_{xT}	is the horizontal betatron wavelength at the position of the tagging detectors [m];
η_T	is the energy dispersion at the position of the tagging detectors [m];

ε_x and σ_P are general machine parameters while β_{xT} and η_T depend on the location of the tagging detectors, and d depends on the locations of the interaction region and the tagging detectors. In most storage rings there are only one or, at most, two types of straight sections, and therefore the possible choices for the location of the interaction region are one or two. For this reason the way to optimize the gamma ray energy resolution is to choose the location of the tagging counters in the position (characterized by the curved coordinate s) where the values of $\beta_{xT}(s)$, $\sigma_P(s)$ and $d(s)$ give a minimum for the quantity:

$$(\varepsilon_x \beta_{xT} + \eta_T^2 \sigma_P^2)/d^2.$$

In machines of modern design with a Chasman–Green lattice there is a dispersion-free straight section where $\eta_T = 0$ and therefore we only have to find the location where β_{xT}/d^2 is minimal.

In older machines like Adone the magnetic structure did allow a large choice since it has only one type of straight section and also limited possibilities for the position of the tagging counters. Its basic cell (1/12 of the storage ring) consists of one dipole with two quadrupoles on each side, as indicated in fig. 1. The best compromise appeared to be the one indicated as position A, with the counters squeezed between the first two quadrupoles in the straight section following the interaction region. Locating the counters further away might have improved the energy resolution but would have reduced the maximum energy of tagged gamma rays because the electrons which have radiated a gamma ray with the maximum energy and polarization, would strike the walls of the vacuum chamber before reaching the counters.

With the accepted values of the Adone parameters: $E = 1500$ MeV; $k = 78$ meV; $E' = 1422$ MeV; $d = 1.41$ m; $\varepsilon_x = 2.4 \times 10^{-7}$ m r; $\sigma_P = 10^{-3}$; $\beta_{xT} = 6.46$ m and $\eta_T = 1.55$ m, the calculated value of the energy resolution is:

$$\sigma_k = 17 \text{ MeV (rms)},$$

or

$$\Delta k = 4 \text{ MeV (FWHM)},$$

and

$$\Delta k/k = 5\%.$$

It is interesting to note that the value of σ_k is very close to the energy spread of the primary beam:

$$1.7 = \sigma_k \approx \sigma_E = E\sigma_P = 1500 \times 10^{-3} = 1.5 \text{ MeV (rms)}.$$

The numerical results obtained for Adone [4] have been repeated recently using a Monte Carlo simulation. We followed the trajectories of the scattered electrons in the storage ring magnetic lattice from the interaction to the tagging region. These results have also allowed the identification of 0.65 mm as the maximum pitch (separation) of the tagging counters which does not appreciably affect the energy resolution.

3. Detectors

The tagging counters consist of a silicon solid-state microstrip detector built by Micron Semiconductor (UK) on a silicon wafer 0.3 mm thick and composed of 96 vertical strips with a pitch of 0.65 mm. They were backed by a fast plastic scintillator viewed by a photomultiplier. The signal of the microstrips at the exit of the amplifiers (LABEN preamplifiers model 5311 followed by LABEN amplifiers model 5185) is about 30 mV, very close to the measured noise level of 15 ± 5 mV. To reduce the background the μSD discriminators which follow the amplifiers are strobed by a fast pulse produced by the signal in the plastic scintillator. This pulse, strobed by an OR of the microstrip discriminators, is also used for fast timing between the tagged electrons and the gamma ray reaction products. In this way a timing resolution of the order of 1 ns (FWHM) has been achieved.

To minimize the interference with the storage ring

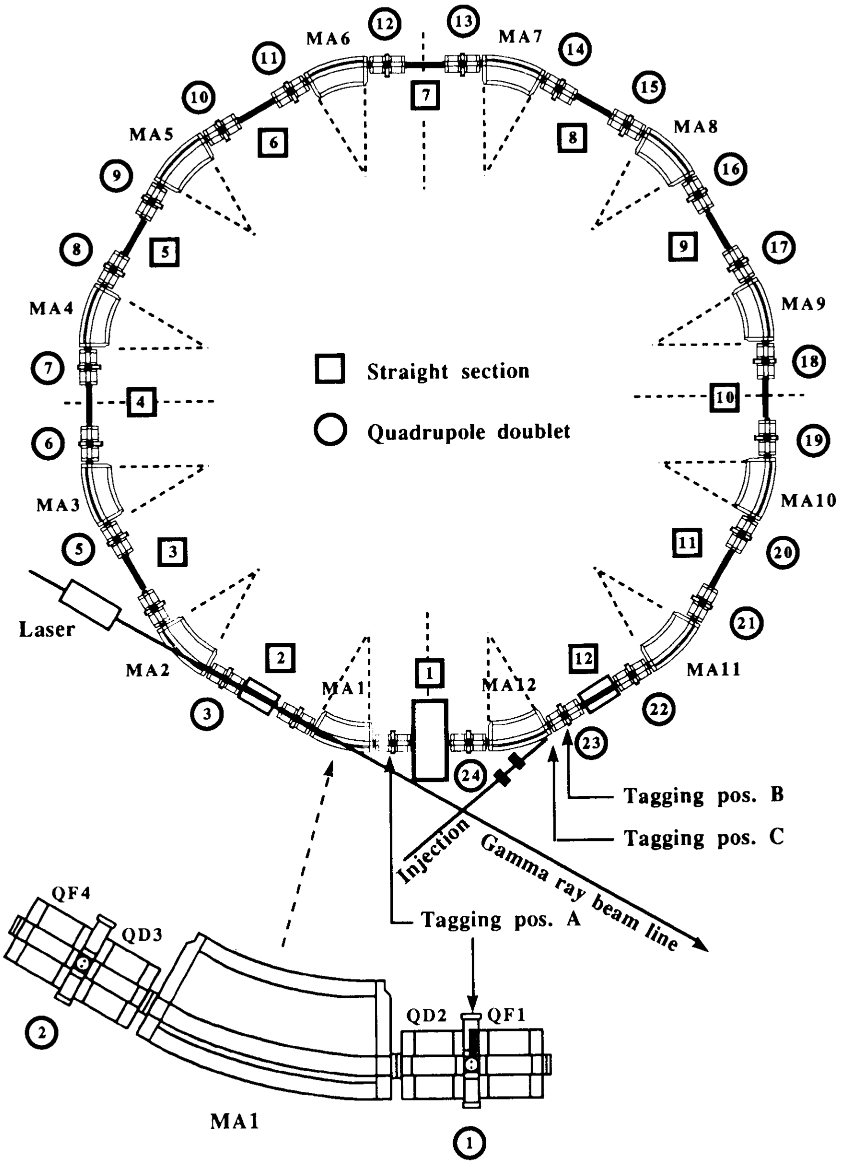

Fig. 1. A schematic representation of the layout of the Adone storage ring with an indication of the electron–laser interaction region, the position (A) of the tagging counters and the direction of the gamma ray beam.

high vacuum system, the microstrips, their preamplifiers and the scintillation counter are placed in a stainless steel sleeve shaped box, open to air on one side. This box can be moved into the accelerator vacuum chamber through a stainless steel bellows. In front of the microstrips the box has a thin window for the passage of the scattered electrons.

A remote control, interlocked with the ring safety system, can displace the steel box (and the counters inside it) vertically by 100 mm IN and OUT of the ring plane. When the box is IN the detectors are positioned in the storage ring symmetry plane at a distance of 17 mm from the equilibrium orbit. In this position the detectors tag all the electrons which have lost more than 1.1% of their energy. The energy of the scattered gamma ray is equal to the energy lost by the electron and it is therefore proportional to the electron's distance from the main orbit. It is a linear function of the microstrip number.

With the box OUT the entire cross section of the vacuum chamber is free and the counters are above the symmetry plane in a position shielded by the iron and the copper coils of the quadrupoles. Only in this position the operator is enabled to inject electrons into the ring.

This arrangement has the added advantage that the microstrips and their electronics can be extracted and replaced without interfering with the storage ring vacuum system.

4. Tagged spectrum

In our apparatus the gamma ray beam spectrum has been measured since the beginning with an electron–positron magnetic pair spectrometer installed in the experimental hall. The master trigger of the spectrometer consists of a quadrupole coincidence between two plastic counters on the electron side and two on the positron side. This coincidence triggers a wire chamber readout system which produces the information of the positions of the electron and the positron at the exit of the spectrometer. From these data the energy of the gamma rays is obtained with a resolution of the order of 3% in this energy range. This turns out to be much better than the one expected from our tagging system.

A fast coincidence between the master trigger of the pair spectrometer and the tagging counters provides the synchronization for a 96 channel input register which strobes in the signals of the microstrip discriminators. Since the efficiency of the tagging system is very close to one, for each gamma ray in the spectrometer at least one microstrip channel should have fired. The tagging input registers and the wire chamber readout system are in the same CAMAC crate under the same intelligent create controller (CES 2160 Firecracker). The crate controller and the on-line computer store on magnetic tape the information relative to the position of the electron and positron and six words, corresponding to 96 bits, to indicate which tagging channels have fired.

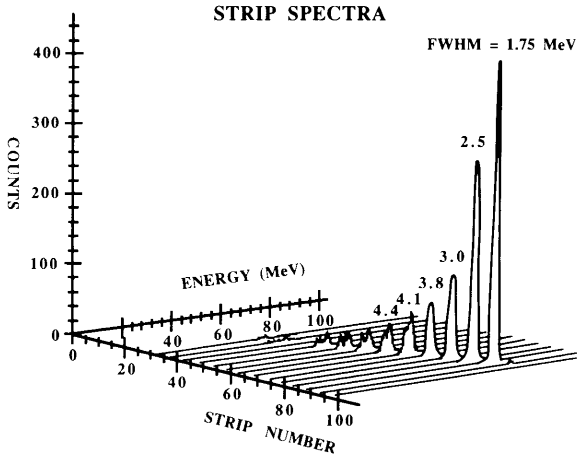

Fig. 2. Sample gamma ray spectra measured with the pair spectrometer in coincidence with the microstrip channels. Each spectrum corresponds to one microstrip.

If only one tagging channel has fired we have a correlation between the energy lost by the electron and that of the scattered gamma ray. Some gamma ray spectra, in coincidence with some selected channels of the tagging counter, are accumulated on-line by the computer and presented immediately for monitoring the experiment.

Off-line we calculate 96 gamma ray spectra, one for each tagging channel. Ambiguous events in which more than one channel is active are discarded. A representative sample of these spectra, one every five channels, is shown in fig. 2.

An interesting result is the narrow width of the peaks at the highest energies. This is due to the fact that in the experimental hall the beam passes through a collimator with a bore of 7.8 mm diameter which defines a half aperture angle at the source (the interaction region) of 9.3×10^{-5} rad.

The energy of the gamma ray as a function of the scattering angle is given by:

$$k = k_{\mathrm{Max}}\left[1 - (\gamma\theta)^2\right]$$

where γ is the electron energy in units of its rest mass ($= 2935$ in Adone) and θ is the angle between the direction of the incoming electron and that of the scattered photon. Therefore the gamma rays with the highest energy are emitted at a very small angle ($< 10^{-4}$ rad) from the direction of the incident electrons and only those electrons which have a small angular divergence can radiate a high energy photon which enters our very small collimator. In this way our apparatus

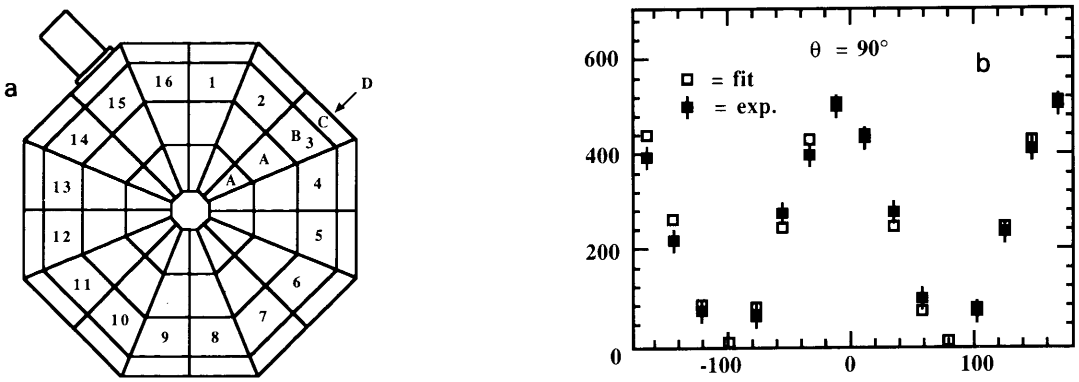

Fig. 3. (a) Layout of the Rome Crystal ball in the plane perpendicular to the direction of the gamma ray beam; (b) Azimuthal angular distribution of elastically scattered 15.1 MeV photons on ^{12}C.

selects a subset of electrons with a smaller angular divergence. The elements of the transport matrix of the Adone magnetic lattice from the interaction region to the tagging counters are:

$$a_{11} = (x \mid x_0) = 0.125 \ll 1, \quad a_{12} = (x \mid x_0') = 7.60 \text{ m},$$

$$a_{13} = (x \mid \delta) = 1.41 \text{ m}.$$

Therefore a small electron angle x_0' will produce a small beam size (Δx) at the tagger and an improved energy resolution:

$$\Delta x \approx a_{11}\,\Delta x_0 + a_{12}\,\Delta x_0' \approx a_{12}\,\Delta x_0' \approx 7.6 \times 9.3 \times 10^{-5}$$

$$\approx 7.1 \times 10^{-4} \text{ m},$$

and

$$\Delta k = E\,\Delta x / a_{13} = 1500 \times 7.1 \times 10^{-4} / 1.41 = 0.75 \text{ MeV}$$

$$\text{(half width)},$$

which is equivalent to a full width at half maximum (FWHM) of $\Delta k_{\text{th}} = 1.8$ MeV, a value in very good agreement with our result:

$$\Delta k_{\text{exp}} = 1.7 \pm 0.2 \text{ MeV},$$

which is obtained from the peak corresponding to microstrip number 85.

5. Gamma ray beam polarization

One of the most interesting features of the Compton backscattered gamma ray beams is their polarization. Since for very relativistic electrons helicity is a good quantum number, electrons cannot flip their spin during Compton scattering. Moreover for scattering in the backward direction there is also no transfer of orbital angular momentum from the electrons to the photons. Therefore gamma rays with energy close to the allowed maximum have the same polarization of the initial laser photons. This has the advantage of a gamma ray beam fully polarized over a rather broad energy range and whose polarization can be changed easily and rapidly, changing the polarization of the laser light. This is true for all directions of linear polarization and both the orientations of circular polarization. The degree of polarization can be easily calculated from theory for all gamma ray energies below the maximum.

However, measuring the polarization of a gamma ray requires a time consuming experiment usually not very precise since the analyzing power of most reactions is of the order of a few percent. Fortunately a good measurement can be performed at 15.1 MeV using the 1^+ level of carbon 12. This level can be reached from the ground state by photon absorption via a magnetic dipole transition with a large width. Therefore 15.1 MeV photons have a large cross section for elastic scattering on ^{12}C and this reaction is a perfect polarization analyzer, with unity analyzing power, since only the M1 multipole contributes to its transition.

Electrons of 635 MeV were used in Adone to produce a collimated Ladon beam with an energy of 15.1 MeV and a width (FWHM) of 1.5%. The beam impinged on a graphite target located in the center of the small NaI crystal ball. Fig. 3 shows the azimuthal distribution of elastically scattered photons at a polar angle of 90°. The experimental data clearly indicate a distribution of the form:

$$1 + \cos 2\phi,$$

as expected from the scattering of a fully polarized beam on a perfect polarization analyzer. In this way a check of the theory has been obtained at least at one gamma ray energy.

6. Conclusions

Internal tagging in a storage ring can produce tagged gamma ray beams with an energy resolution in agreement with Monte Carlo calculations and close to the energy spread of the primary beam. Collimation of the gamma rays can greatly improve this resolution but at the price of a reduced intensity. The polarization of forward scattered gamma rays is unity as predicted from the theoretical calculations.

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