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COMPTON SCATTERING OF LASER LIGHT; TECHNIQUES AND RESULTS

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COMPTON SCATTERING OF LASER LIGHT; TECHNIQUES AND RESULTS

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(Presented by G. Matone)

In 1963 R.H. Milburn(1) and F.R. Arutyunian(2) pointed out that backward Compton scattering of an intense polarized laser beam by high energy electrons would produce useful yields of nearly monoenergetic and polarized photons.

Over the past 18 years there have been several attempts to produce γ-ray beams by laser backscattering. At the Lebedev Institute, 1.78 eV light from a ruby laser was used with 600 MeV electrons to produce 7 MeV γ-rays(3). At the Harvard-MIT Synchrotron the same laser line was later used with a 6 GeV electrons to produce 400 MeV γ-rays(4). Both of these early attempts produced extremely low fluxes and could not be used for either nuclear or particle physics research. The first experiment to actually use laser-backscattered photons as a beam in a physics measurement was conducted at SLAC(5). Here, a massive hydrogen bubble chamber, acting as both target and detector, compensated for the very low fluxes ($300\ s^{-1}$) of 5 GeV γ-rays that were produced.

To achieve flux levels in the γ-ray beam that are useful for nuclear physics research, very high electron currents are required - of the order of one Ampere. Because of the enormous power levels implied by such a relativistic electron beam (1 GeV x Ampere=1000 MWatts), these currents can only be achieved in storage rings where the same circulating electron makes$\sim 10^6$ contributions to the charge passing a fixed point in one second. As a further constraint on the ring, a straight electron-laser interaction region, in which the angular divergence of the stored beam is small is required to achieve high luminosity, the γ-ray flux being directly proportional to the length of this region.

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In order to briefly summarize the mechanics of this beam production, one has to imagine to have a photon impinging upon an electron in the electron rest frame (ERF). In this system, the Compton scattering cross section is described by the usual Klein-Nishina formula which gives rise to a bean-like shape distribution for the θ-angle of the scattering photon as described in Fig. 1a.

In the laboratory system, the Lorentz-transformation squeezes this distribution down to an extremely narrow cone along the initial electron direction with a semi-aperture angle of the order of $1/\gamma$. (See Fig. 1b). Moreover this process is a two body process and consequently there is a fixed relationship between the energy of the produced photon and its emission angle: in particular the maximum energy is obtained exactly along the initial electron direction (backward scattering) and is given by $E_\gamma^{max} \simeq 4\omega\,\gamma^2$ where ω is the laser photon energy. (See Fig. 2).

From these two facts it can be easily understood that with a suitable collimation placed along the electron beam direction one can select narrow energy bands preserving at the same time substantially high counting rates. With simple kinematical calculations the energy resolution obtainable by collimation comes out to be

$$\frac{\Delta E_\gamma}{E_\gamma} \simeq (\gamma\,\Delta\,\theta)^2$$

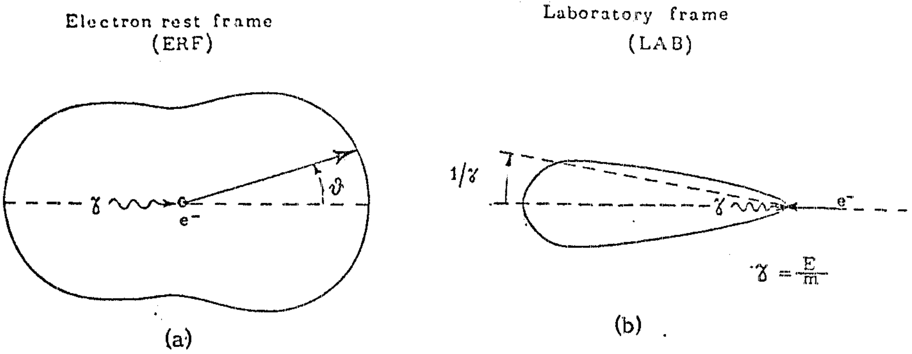

FIG. 1 - Profiles of the angular distributions of the scattered photons in the ERF (a) and in the Lab. system (b).

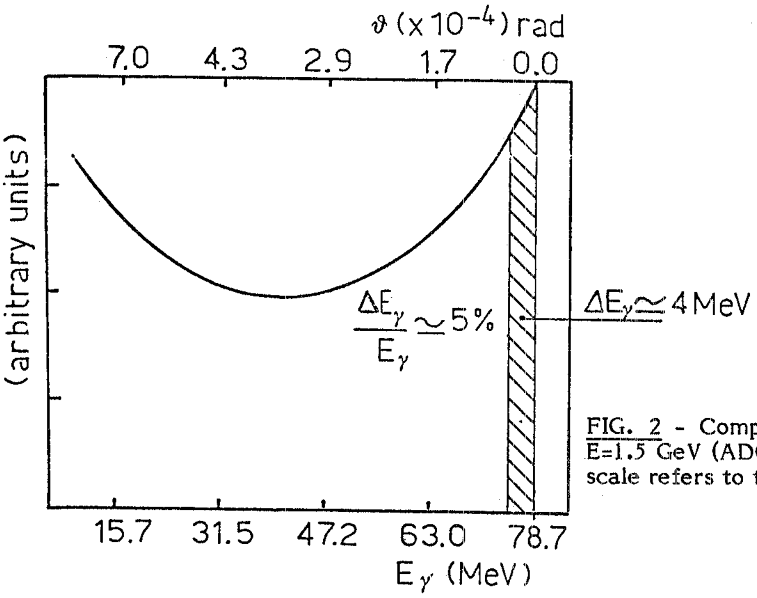

FIG. 2 - Compton energy spectrum in the Lab. for E=1.5 GeV (ADONE) and ω=2.41 eV (Argon). The top scale refers to the photon emission angle θ.

where $\Delta\theta$ is the semiaperture angle of the collimator. Finally, since the laser light is completely polarized, the produced beam has a polarization very close to unity. Of course all these considerations hold in the limit of zero spot sizes without any angular divergency.

In real life the geometrical characteristics of the two colliding beams modify quite substantially these expectations and a complete Montecarlo calculation(6) has to be performed for an exact comparison with the experimental results.

The first real γ-ray beam for nuclear physics research was developed at the 1.5 GeV ADONE storage ring at Frascati National Laboratories(7).

In the original design of this beam(8), a long laser cavity was proposed with the idea to provide an intracavity power up to 250 watt, but its realization would have encountered the following difficulties:

a) This long cavity should have been internally modulated, but there was no experience at all about the possibility of obtaining mode-locking with a cavity length that comes out to be 17.5 m.
b) The damage produced by synchrotron radiation on the end mirror forced to use either a metallic mirror with poor reflectivity or a dielectric mirror protected by a window made of a suitable material.
c) The alignement of such a long cavity on the electron beam line appeared very hard to be performed with the required high accuracy ($\sim 10^{-5}$ rad).

Due to these difficulties, we chose to temporarily abandon this original design and, in the first operation mode, a laser cavity-dumper, extensively described elsewhere(9), has been used. This technique produces light pulses 15 ns long at the Adone RF frequency of ~ 8.5 MHz. The maximum peak power does not exceed ~20W and consequently the average power is ~3W, corresponding to an energy of 0.3 μJ/pulse.

The general layout is sketched in Fig. 3. The experimental results obtained for the beam intensity, energy resolution and polarization can be summarized as follows:

1) a photon energy continuously adjustable between ~ 5 MeV and ~ 78 MeV, for an electron energy ranging from 0.37 GeV to 1.5 GeV;
2) a beam intensity between ~ 10^4 and ~ 10^5 photon/sec, depending on electron energy, electron current, laser power and photon energy resolution (see Fig. 4);
3) an energy resolution between ~1% and ~ 10% in the present working conditions of Adone (see Fig. 4);
4) an almost linear polarization ($\langle P \rangle \sim 1$);
5) a low background of photons of different energy;

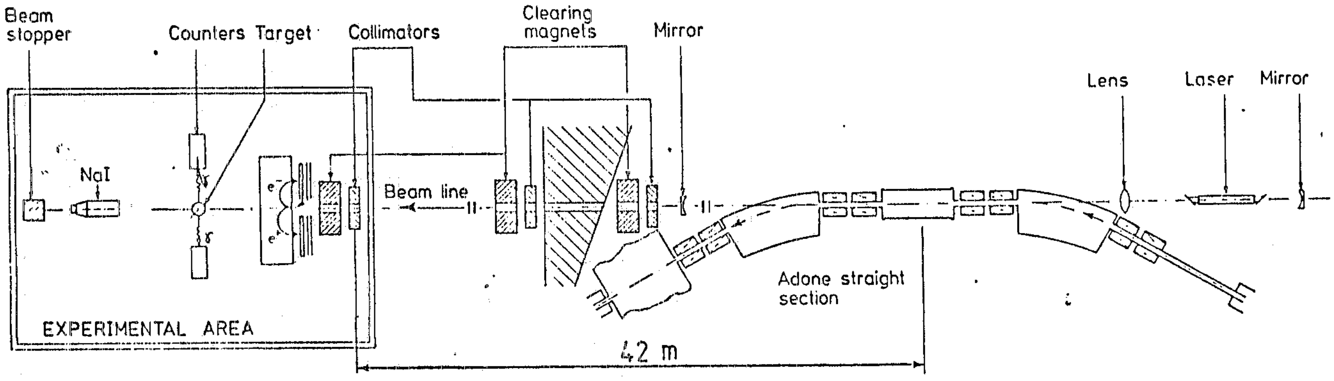

FIG. 3 - Overall view of the experimental set-up.

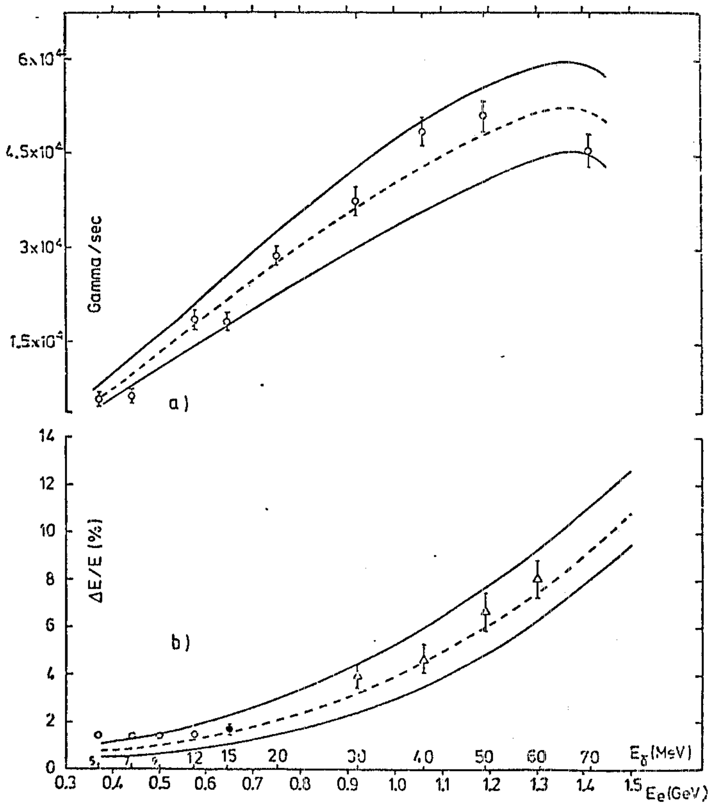

FIG. 4 - a) Photon flux, I=75 mA, laser pulse=20 W x 15 ns, $\Delta\Omega = 2.25 \times 10^{-8}$ sr; b) fractional energy resolution (full-width half-maximum). I=50 mA, $\Delta\Omega = 2{,}5 \times 10^{-8}$ sr. The dashed lines have been obtained via Montecarlo calsulation with the best estimates of the electron beam parameters. In these graphs the solid lines delimit the uncertainty we have in the knowledge of these parameters. o Ge(Li) detector; △ magnetic pair spectrometer; ● resonant scattering in ^{12}C.

6) a time microstructure similar to that of the electrons in the storage ring: pulses as short as few ns separated by 117 ns.

Nuclear physics research with this beam has already started with the measurement of the asymmetry parameter in the deuteron photodisintegration as a function of the photon energy. Data on this subject have been already published(10,11).

Now, since the practical feasibility of the Ladon project has been experimentally proved, we are going to a definite set-up of the experiment to reach the projected laser power and the expected gamma ray intensity.

A way for increasing the laser power is to go back to the idea to built a very long laser cavity such as to include the Adone straight section where the electron-photon collisions take place(12). Moreover, by locking the longitudinal modes, laser pulses with a much higher power can be expected. When the longitudinal modes of the laser cavity are forced to mantain a fixed phase relationship with one another, the laser is said to be mode locked. In this condition the amplitudes of the modes add constructively at a particular time. This has the effect of converting the continuous beam inside the laser cavity to short intense pulses of light bouncing back and forth between the mirrors.

How this mode-locking can be obtained by simply using an amplitude modulator, can be easily understood as follows.

An amplitude modulation with frequency Ω of a monochromatic wave of frequency ω has the effect to transfer some fraction of the energy from the central line to two lateral sidebands of frequency $(\Omega+\omega)$ and $(\Omega-\omega)$, whose phases are determined by that of the original wave.

In a laser, if $\Omega = c/2L$, the lateral sideband of each mode overlaps entirely to the adjacent mode and the resulting electromagnetic field will have an intermediate phase between those of the original mode and of the sideband respectively. Consequently at each passage of the light through the modulator the phase between two adjacent modes will get closer and closer and finally a fixed relationship between all the modes takes over.

The general theoretical treatment of this phenomenon has been given by Harris and Mc Duff several years ago(13), starting from the self-consistency equations of Lamb(14), which describe the effect of an arbitrary optical polarizability upon the electric field of a high-Q optical resonator. The amplitude modulation introduces an extra oscillating contribution in the expression of the polarizability of the medium and two equations for the amplitude and phase of the electric field can be derived.

In our case, the numerical solution of these equations reproduces reasonably well the energy and shape of the pulses and the behaviour of their width as function of the modulation depth.

In Fig. 5 a typical calculated light pulse is shown.

The acoustooptic modulator we have built, works in the Raman-Nath regime with standing waves in crystalline quartz. The crystal is excited by an RF voltage at a frequency equal to its piezoelectric resonance. The interaction between a standing acoustic wave and the light beam produces a set of diffracted beams around the central axis, each one being modulated at a frequency double than the acoustic wave.

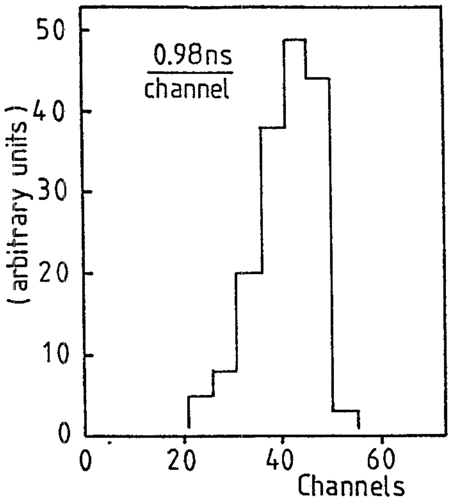

FIG. 5 - Typical light pulse as calculated by solving the self consistency equations of Lamb.

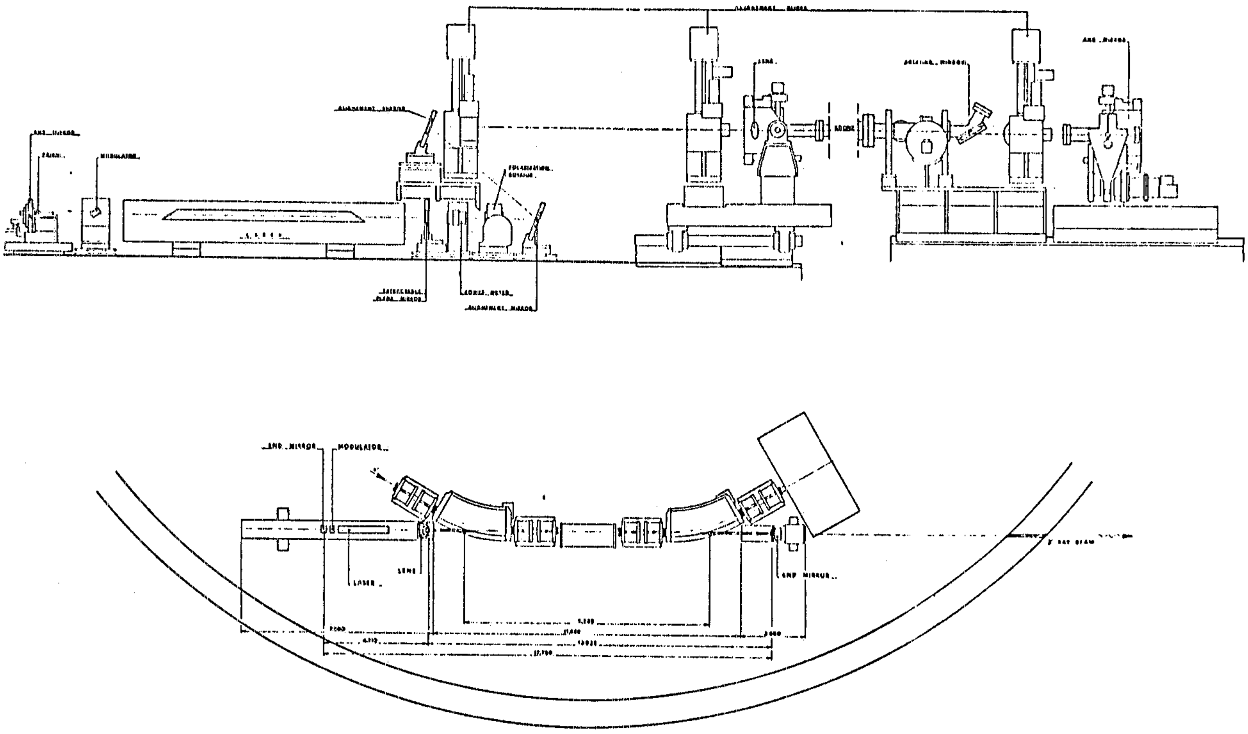

FIG. 6 - Arrangement of the laser cavity on the straight section.

To avoid any change of polarization, the crystal is cut in such a way that the light impinges at the Brewster angle and travels along the y- axis with the polarization lying parallel to the z(optical axis) - direction. The RF-voltage is applied along the x-direction and is derived from the ADONE RF-system through a phase-locking loop amplifier, which divides the frequency by two while conserving the phase. Both the RF amplitude and the temperature of the modulator are stabilized to achieve a constant modulation efficiency.

Fig. 6 shows a general lay-out of the laser cavity together with some details of its final arrangement on the machine. The total length is 17.5 m in order to match exactly the Adone RF-frequency with one pulse oscillating back and forth between the two terminal mirrors. The Adone vacuum system is isolated by a lens and a quartz window at the Brewster angle, placed on two optical benches at each side of the straight section. The first bench supports the laser tube, the modulator and the steering system for the alignement of the laser beam on the electron central trajectory; the second one hosts the final mirror. Since the polarization of the laser light must be changed continuosly, the Brewster angle window has been mounted in such a way to be able to rotate without breaking the Adone's vacuum(15).

All the optical elements of the system are remotely controlled via Camac by a PDP-11/04 mini-computer that performs automatically the whole procedure for the maximization of the light power inside the cavity and for the alignment of the beam. The mirror holders are equipped with DC-motors and position transducers able to achieve a precision on the angular setting of a few μ-rad. Three pairs of slides(16) intercept the beam and provide measurements of its profile and central point. The position of these slides is read by absolute photoelectric encoders with an accuracy of 1 μm over a range of some centimeters. Using the two alignement mirrors the beam can be positioned on the required direction with a precision of 10^{-5} rad.

The laser used is a Coherent Radiation model CR-18, whose characteristics specify an output power of 8 watt on the green line (5145 Å) corresponding to an internal power of $\sim$70 watt with a 12% transmittivity mirror. In the CW operation mode on the 17.5 m long cavity, an internal power of 60 watt has been obtained, as expected by taking into account the total losses of the cavity and the characteristics of the active medium. Particularly significant is the role played by the homogeneous-broadening of the holes burnt in the gain curve evaluated to be $\sim$30 MHz, much greater than $c/2L = 8.5$ MHz. It can be shown that in practice this effect keeps the stored power almost constant for cavity lengths above 3 m.

In the mode-locking operation the average power in the cavity decreases down to 35 W according to the additional losses introduced by the modulation and to the effect of the lifetime of the upper level (7 ns) much shorter than the repetition period(17). The energy per pulse comes out to be $\sim$ 4 μJ (200 watt x 20 ns), which is substantially ten times as much as that of the cavity-dumper in the old set-up.

Since the light spot size in the interaction region has been reduced, we estimate an extra gain factor of $\sim$ 1.7 in the intensity of the produced photon beam. According to this, a final intensity of $\sim 10^6$ γ/sec at high energy can be foreseen in this new stage of the Ladon photon beam.

At this point any further development of this technique goes toward higher energy machines and possibly free electron lasers. The first step along this line will be the X-ray machine at the Brookhaven National laboratories where a joint FNL/ROME/BNL proposal has been already presented. Details of this new project are reported at this Conference by A. Sandorfi and C. Thorn.

Another important topic to be discussed at this conference is the LEP case. On this subject a dedicated workshop has been organized at CERN in 1980 to explore any possible impact that LEP could have for the intermediate energy nuclear physics(18).

Backward Compton scattering at LEP would be very appealing for the very wide energy tunability one can have: with a CO_2 laser crossing the electron beam at angle different from 180°, photons from hundreds MeV up to several GeV can be produced. On the other hand the designed value for the electron angular divergency much greather than $1/\gamma$, is sufficient to kill the monochromaticity almost completely. A typical example is given in Fig.

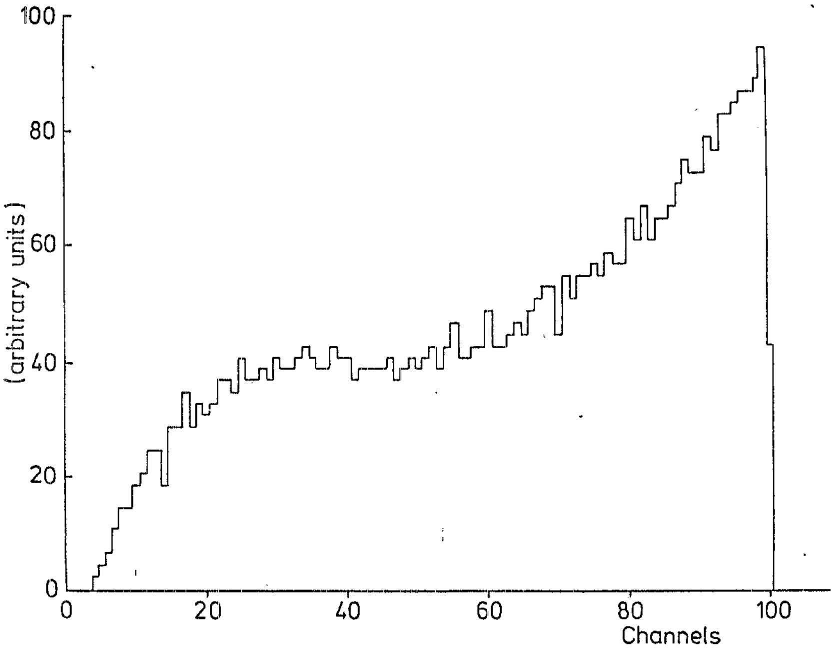

FIG. 7 - Energy spectrum obtainable at LEP (50 GeV) with a CO_2 laser crossing the electron beam at 42°. The right edge cut corresponds to an energy of 600 MeV. The electron angular divergency is that of LEP-I (30.6 km) $\sigma'_x=2 \times 10^{-5}$ rad and the collimation angle is $\pi(\sigma'_x)^2$.

7 where not even the width of the distribution can easily be defined.

On top of this difficulty, the time structure of the machine forces to have photon bursts 2 nsec wide every 25 μ sec corresponding to a duty-factor of 4×10^{-5}. Consequently the photon intensity can not be much greater than some $10^5 \gamma$/sec and thus any experimental exploiting appears to be very hard. In a way similar to that realized at SLAC, the only practical possibility is the bubble chamber technique in connection with high energy physics: this idea has been already discussed in some details in Ref. (18,19).

The most interesting aspect in the LEP case lies in the low energy photon beam obtainable with the synchrotron radiation. The intensity involved here is really very high: one has to think that the total power emitted around the ring at LEP amounts for ~20 Mwatts at $E = 90$ GeV. The crytical energies of the spectra obtained from the normal bending magnet are 0.098 MeV and 0.44 MeV at E=51.5 GeV and 85 GeV respectively. Higher values can be obtained with wigglers: using for example the Daresbury superconducting magnet operating at 3.4 Tesla and 4.0 Tesla, the two crytical energies can be increased up to 6.0 MeV and 19.2 MeV. The spectra for these two cases are reported in Fig. 8: clearly the intensities are remarkably high but, once again, the lack of any monochromaticity, sensibly reduces the possibilities offered by these beams. Energy spectra similar to those obtainable by backward Compton scattering but in the region below 10 MeV can be obtained with plane and helical unodulators which provide linear and circular polarization respectively.

Contrary to the previous synchrotron radiation spectra or even the bremsstrahlung the sharp right edge cuts of these spectra better qualify the beams obtained with unodulators.

All these possibilities have been discussed extensively during the CERN meeting and interesting suggestions have been presented like the monochromatization via positron annihilation or Bragg diffraction in bent crystals. As a final conclusion a possible photon facility for nuclear physics at LEP has been designed in the following way.

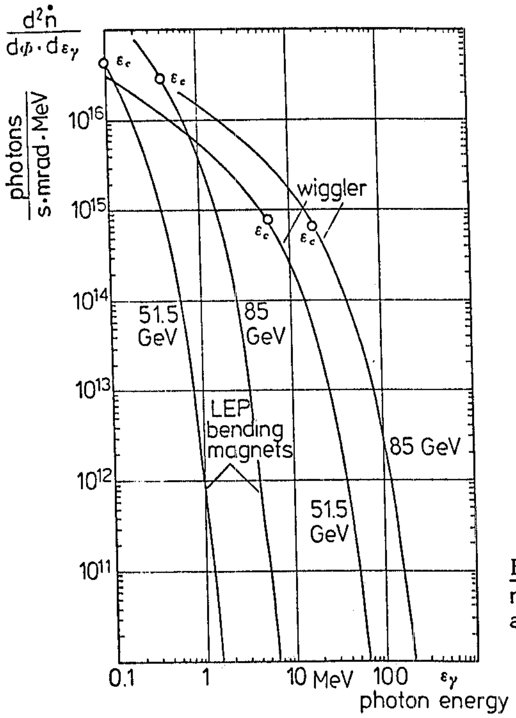

FIG. 8 - Energy spectra obtainable at LEP with the normal bending magnet and with a wiggler at E=51.5 GeV and E=85 GeV.

The machine LEP has two free straight sections on each side of the interaction regions. Their lengths are 7.9 m and 9.6 m and their distance from the interaction point are 350 m and 390 m. These sections might be suitable for the installation of wiggler magnets and undulators according to the layout of photon beam lines indicated in Fig. 9.

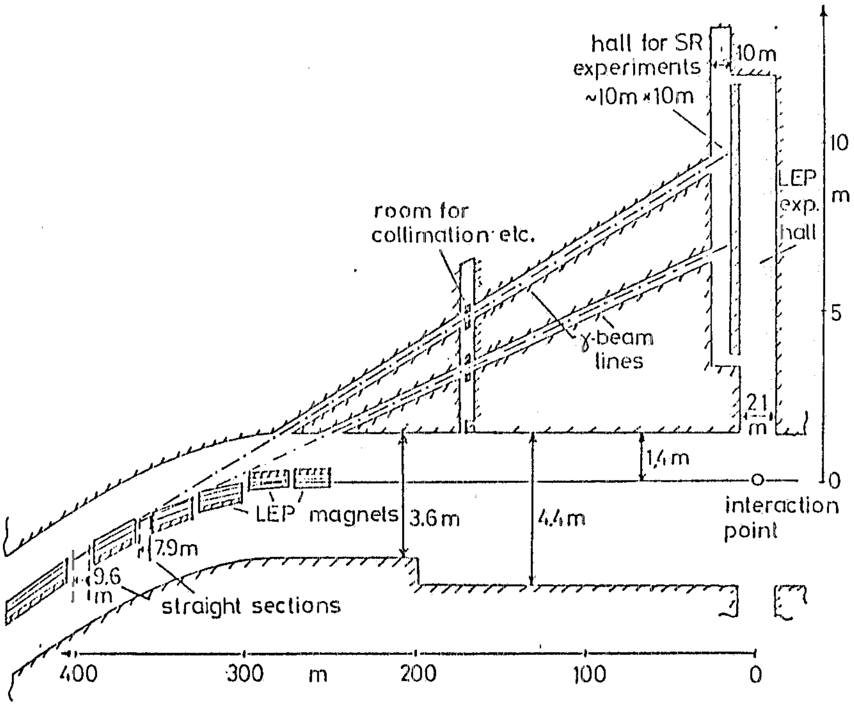

FIG. 9 - Possible lay-out of the photon beams originating at the two free straight sections. If necessary, a full size tunnel could be constructed between the experimental hall and the collimator room.

These lines extend all the way to the hall provided for high energy physics experiments. The exact sizes of these halls are still under study and the one shown in the figure is only an example. In the center of this hall the extended beam lines from the two straight sections would have a distance of 7.5 m and 10.2 m from the interaction point. The photon beam lines reach the tunnel wall at a distance of about 140 m from the source point. From there a couple of small diameter holes could extend the beam lines to a collimation room and from there to the nuclear physics experimental hall as indicated in Fig. 9. If the collimation room has to be accessible during operation or if more space is necessary, a full size tunnel could be constructed between the collimator room and the experimental hall. The layout shown in Fig. 9 represents only a possible example; different solutions might be desired for certain experiments.

In any case these two straight sections could host the different lines of research that have been individuated according to this possible skematic:

STRAIGHT SECTION A) -9.6 long for the wiggler + linac undulator

Experiments with wiggler

- photofission
- phtoabsorption measurements
- photon scattering using the Bragg diffraction in crystals
- monochromatization via positron annihilation will be foreseen only with LEP operating at 90 GeV.

Experiments with linear undulator

- Bragg diffraction for { low Dalbrück scattering
  nuclear resonance fluorescence

STRAIGHT SECTION B - 7.9 m long for the circular undulator

Experiments

- parity violations
- Bragg diffraction for { Compton on electrons
  Rayleigh scattering

It should be noted that with a suitable arrangement of the beam lines different experiments can run at the same time. For ex., the crystal set-up on line A) can be operated simultaneously with photoabsorption and photofission at the end of the channel.

The case of the laser backscattering must be further explored but would become particulary pressing if the measurement of the electron transverse polarization will be performed using circularly polarized light. Studies in this sense have been already developed at the Frascati National Laboratories by the LADON group and probably a 9.6 long straight section should be completely dedicated to it.

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