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R. Malvano, C. Mancini and C. Schaerf: SOME CONSIDERATIONS ON THE POSSIBILITY OF OBTAINING A QUASI-MONOCHROMATIC POLARIZED PHOTON BEAM FROM LASER-ELECTRON SCATTERING IN THE STORAGE RING ADONE. -

(Nota interna: n. 372)

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INTRODUCTION -

In this paper we discuss the possibility of using the electron beam of the Adone storage ring as a source of an intermediate energy photon beam. This beam can be obtained from the Compton scattering of coherent light on the high energy electrons circulating in the storage ring. Elastic scattering of light on very high energy electrons has been the subject of many theoretical papers and of some experimental work[(1)]. The high average intensity of the Adone storage ring togheter with the present availability of continuously operating, high power, gas lasers suggested a new approach to the old problem of producing a quasi monochromatic gamma ray beam, usefull for experiments in nuclear physics.

The Adone storage ring consists of 12 equal magnetic sections formed of bending magnets and quadrupoles[(2)]. Between two consecutive bending magnets there are straight section which are 6 meters long. We can use any of this straight sections as an interaction region

(x) - Istituto Nazionale di Fisica Nucleare, Sezione di Genova.

between the circulating electrons and our laser beam. An Argon gas laser appears to-day as the most suitable source of light for this experiment. At a laser energy of 2.56 eV (4880 Å) and an electron energy of 1.5 GeV it is possible to produce photon with energies up to 83 MeV.

Photons in this energy region are particularly interesting for the study of the electromagnetic interactions in nuclei. The cross sections for photo-disintegration are very sensitive to the correlations between nucleons in nuclear matter. Unfortunately the amount of experimental informations is severely limited by the energy spectrum of available gamma ray beams. This is especially a serious problem for very light nuclei where carefull measurements of the photo-disintegration cross sections at a known gamma ray energy would yield precious information for the construction of a consistent set of ground state wave functions.

COMPTON SCATTERING ON FAST MOVING ELECTRONS -

We summarize here the more relevant results in this field. We are only concerned with the results on the interaction of a light photon and a fast moving electron. The energy ω_2 of the scattered photon is given by:

$$\omega_2 = \omega_1 \frac{1 - \beta_1 \cos\theta_1}{1 - \beta_1 \cos\theta_2 + \frac{\omega_1}{\varepsilon_1}(1-\cos\theta)}$$

For head on collision $\theta_1 = \pi$ and for $\beta_1 \approx 1$, $\theta_2 = 0$, we have:

$$\omega_{2max} = \frac{2\omega_1}{\frac{1}{2}\left(\frac{m}{\varepsilon_1}\right)^2 + \frac{2\omega_1}{\varepsilon_1}}$$

where:

- ω_1 energy of the incident photon;
- ε_1 energy of the incident electron;
- ω_2 = K energy of the scattered photon
- m electron mass;
- β_1 electron velocity in units of c;
- θ_1 angle between the direction of the incident electron and the incident photon;
- θ_2 angle between the direction of the incident electron and the scattered photon.

θ angle between the direction of the incident and the scattered photon. All energies are expressed in MeV.

The results of the numerical computations for some typical values of the parameters are indicated in figures 1 and 2.

The total cross section is very close to the classical Thompson formula:

$$\sigma_T = \frac{8}{3}\pi r_o^2 = 0.665 \cdot 10^{-24}\ cm^2 = 0.665 \text{ barns}$$

The differential cross section in the laboratory is given by

$$\frac{d\sigma}{d\Omega} = \frac{2 r_o^2}{m^2 x_1^2}\left[4\left(\frac{1}{x_1} + \frac{1}{x_2}\right)^2 - 4\left(\frac{1}{x_1} + \frac{1}{x_2}\right) - \left(\frac{x_1}{x_2} + \frac{x_2}{x_1}\right)\right]\omega_2^2$$

where:

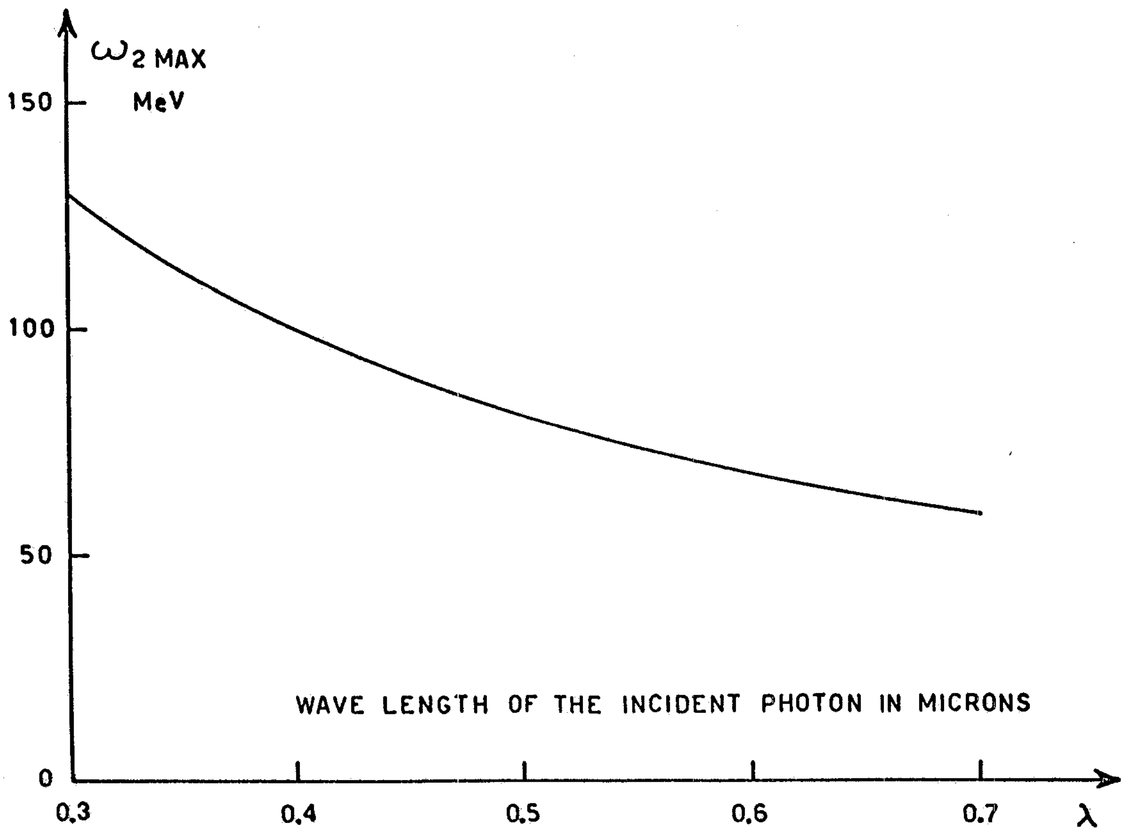
$$x_1 = -\frac{4\omega_1 \mathcal{E}_1}{m^2}$$

$$x_2 = \frac{2\omega_2}{m^2}\left\{\left[2\mathcal{E}_1 - \mathcal{E}_1\left(\frac{m}{\mathcal{E}_1}\right)^2\right]\text{sen}^2\frac{\theta}{2} + \frac{1}{2}\mathcal{E}_1\left(\frac{m}{\mathcal{E}_1}\right)^2\right\}$$

$$\omega_2 = \frac{2\omega_1}{\frac{2\omega_1}{\mathcal{E}_1} + \frac{1}{2}\left(\frac{m}{\mathcal{E}_1}\right)^2 + 2\left\{1 + \frac{1}{2}\left(\frac{m}{\mathcal{E}_1}\right)^2 - \frac{\omega_1}{\mathcal{E}_1}\right\}\text{sen}^2\frac{\theta}{2}}$$

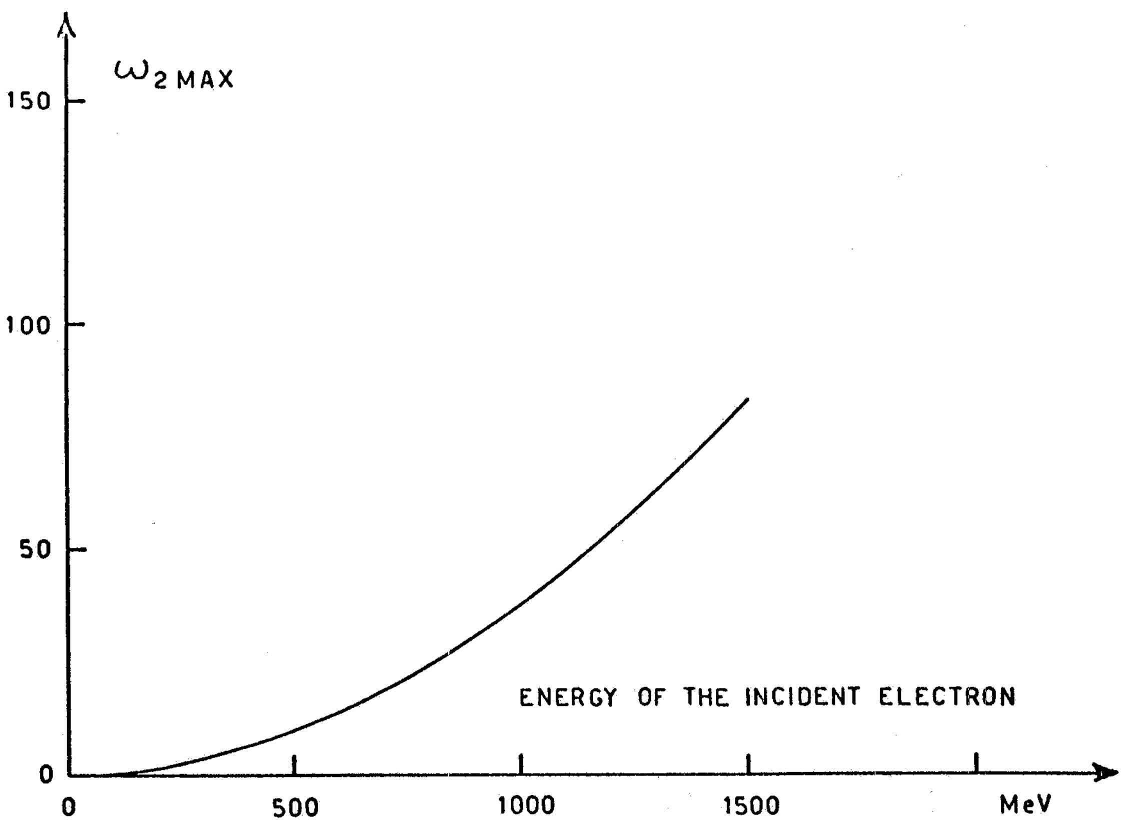
The differential photon spectrum is given by:

$$\frac{d\sigma}{dy} = \omega_{2max}\frac{\pi r_o^2}{2}\frac{m^2}{\omega_1\mathcal{E}_1^2}\left\{\frac{m^4}{4\omega_1^2\mathcal{E}_1^2}\left(\frac{Y}{\frac{\mathcal{E}_1}{\omega_{2max}} - Y}\right)^2 - \frac{m^2}{\omega_1\mathcal{E}_1}\left(\frac{Y}{\frac{\mathcal{E}_1}{\omega_{2max}} - Y}\right) + \frac{\frac{\mathcal{E}_1}{\omega_{2max}} - Y}{\frac{\mathcal{E}_1}{\omega_{2max}}} + \frac{\frac{\mathcal{E}_1}{\omega_{2max}}}{\frac{\mathcal{E}_1}{\omega_{2max}} - Y}\right\}$$



$\omega_{2\,MAX}$
MeV
150
100
50
0
WAVE LENGTH OF THE INCIDENT PHOTON IN MICRONS
0,3
0,4
0,5
0,6
0,7
λ

FIG. 1



$\omega_{2\,MAX}$
150
100
50
0
ENERGY OF THE INCIDENT ELECTRON
0
500
1000
1500
MeV

FIG. 2

where:

$Y = \omega_2 / \omega_{2max}$.

The differential photon spectrum and the differential photon energy spectrum are given in fig. 3 for some typical values of the pa

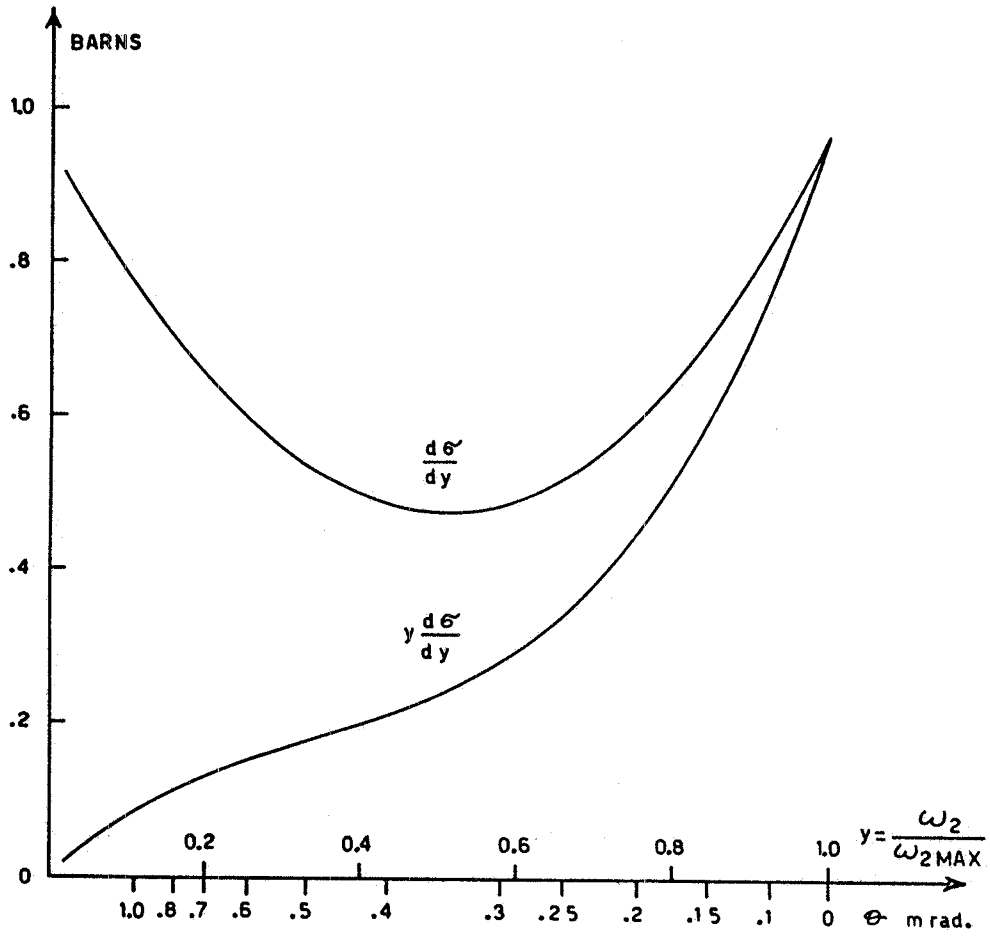


FIG. 3

rameters. On the same figure we have indicated in the abscissae also the angle at which photons of a given energy are scattered.

It is now clear from this figure that it is possible to obtain a quasi-monochromatic photon spectrum with a very narrow collimation of the scattered photons. This seems to be feasible taking into account the very small angular divergence of the electron beam. For the electrons circulating in Adone seems to be reasonable to assume an angular divergence of the order of 10^{-4} radiants. Assuming that we can actually utilize a collimator which accepts only particles within an angle of 10^{-4} rad the line width of our photon beam turns out to be of the order of 10%. Under this hypothesis the differential photon energy spectrum is given in fig. 4 (solid line).

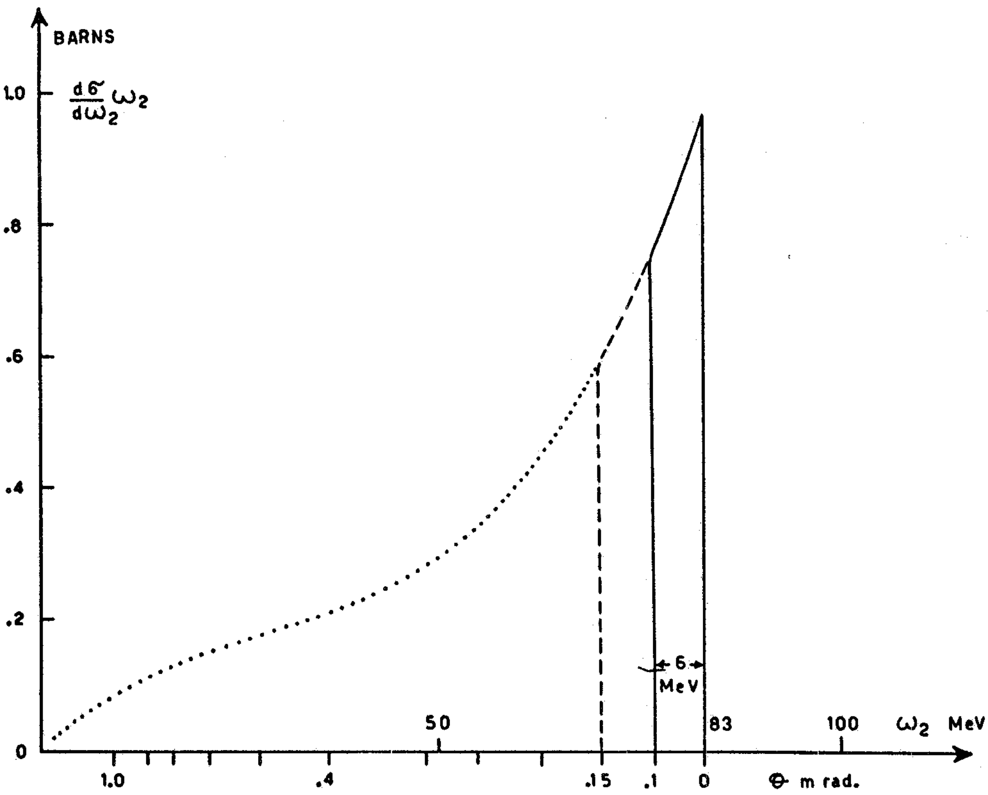


FIG. 4

PHOTON YIELD -

The number of scattered photons per second per unit solid angle is given by:

$$\frac{d\dot{n}}{d\Omega} = \frac{d\sigma}{d\Omega} c \int \rho_e \rho_\gamma dV \qquad (1)$$

where:

$\frac{d\sigma}{d\Omega}$ is the differential cross section in the laboratory in cm^2/ster,

c is the velocity of light in cm/sec,

ρ_e and ρ_γ are respectively the densities of electrons and photons expressed in number of particles per cubic centimeters,

dV is the integration variable in cm^3,

and the integral has to be extended over the region where the two beams are simoultaneously present.

If we assume that the beams have a constant density in the volumes V_e and V_γ and that one of this two volumes is completely contained in the other (e.g. $V_\gamma \subset V_e$) then we can write:

(2) $$\frac{d\dot{n}}{d\Omega} = \frac{d\sigma}{d\Omega} c\, n_e n_\gamma S' l$$

where n_e and n_γ are the average particles densities, l is the lenght of the interaction region and S' is the smaller of the cross sections of the two beams.

For the average particles densities we have:

(3) $$n_e = N_e / S_e 2\pi R$$

where:

N_e = Number of electrons circulating in the storage ring, $2 \cdot 10^{11}$
S_e = Average cross section of the electron beam, $< 10^{-2}\ cm^2$
R = Average radius of the equilibrium orbit 1670 cm
and:

(4) $$n_\gamma = P/(h\nu) S_\gamma c\, e$$

where:
P = Power of the laser beam in watts,
$h\nu$ = photon energy in electron volts, 2. 8 eV
c = velocity of light,
S_γ = Average cross section of the laser beam, $10^{-2}\ cm^2$
e = electron charge in Coulomb.

From equations 2, 3 and 4 we obtain:

$$\frac{d\dot{n}}{d\omega_2} = P\left(\frac{d\sigma}{d\omega_2}\frac{1}{\sigma_T}\right)\frac{1}{2\pi R}\frac{\sigma_T N_e}{S\, e\, (h\nu)}$$

where S is the larger of the cross sections of the two beams ($\sim 10^{-2} cm^2$) and σ_T is the Thompson cross section previously given.

We have now:

$$\frac{d\dot{n}}{d\omega_2} = P \frac{d\sigma}{d\omega_2}\frac{1}{\sigma_T} A$$

with:

$$A = 1.58 \cdot 10^6\ \text{Watts}^{-1}\ \text{sec}^{-1}$$

PHOTON BEAM -

a) Duty cycle -

The electrons circulating in a storage ring are modulated by the radio frequency system in small bunches. In Adone the bunches have an approximate length in time of 1. 5 ns and are separated by 117 ns. For head on collision between relativistic electron and a photon, where the scattered photon moves in the direction of the incoming electron, the time structure of the scattered photon beam is the same of that of the electron beam. Therefore our photon beam will be made of short pulses 1. 5 ns long each 117 ns, with a duty cycle of approximately 1. 3%.

b) Polarization -

There has been a substantial amount of theoretical investigation on the polarization of such a photon beam(3). The results, in this energy region, indicate that if the laser beam is completely polarized then the photon beam emitted in the direction of the electrons will also be polarized. The change of polarization with the scattering angle being sharp, the degree of polarization of the photon beam depends very much on its collimation. With a collimation of 10^{-4} rad we can expect a polarization higher than 95%.

BACKGROUND -

The most obvious source of background is due to the Bremsstrahlung of the electrons on the molecules of the residual gas. The integrated energy spectrum of this photons is given by:

$$W_B = t\, n_e\, E_e\, a/e$$

where:

W_B is the radiated energy in MeV/sec,
t is the radiation lenght of a volume of gas six maters long,
n_e is the circulating electron current in Amperes,
e is the electron charge,
E_e is the energy of the electron beam in MeV,
a is the fraction of gamma rays accepted by our solid angle ($\Delta\Omega \approx \pi\theta^2 \approx 3 \,.\, 10^{-8}$ ster).

At a pressure of 10^{-9} Tor we have for nitrogen:

$$t = 3 \,.\, 10^{-14}$$

and therefore:

$$W_B = 3 \cdot 10^{-14}\, 10^{-1}\, 1.5 \cdot 10^{3}\, a/1.6 \cdot 10^{-19}$$

$$W_B = 3 \cdot 10 \cdot a \qquad \text{MeV/sec}$$

from fig. 4 of references (4):

$$a = \frac{8.6}{108.6} = 0.08$$

and finally we obtain

$$W_B = 3 \cdot 10^{6} \cdot 0.08 \sim 2.4 \cdot 10^{6}\, \frac{\text{MeV}}{\text{sec}}$$

This can be compared with the total energy in the photon beam obtained by compton scattering. For a laser power of 1 Watt and a photon collimation of 10^{-4} rad we have:

$$W_c \approx \left(\frac{1}{\sigma_T}\frac{d\sigma}{d\omega_2}\,\omega_2\right)\Delta\omega_2 PA = 2.1 \cdot 10^{7}\ \text{MeV/sec}$$

ACKNOWLEDGEMENTS -

It is a pleasure to thank Prof. F. T. Arecchi for many enlightening discussions on various aspects of modern laser technology.

APPENDIX A -

Some considerations on the laser beam -

The output beam of an Argon laser working in the fundamental modes (TEM_{00q}) at a fixed frequency (4880 Å) has an angular divergence of the order of 10^{-3} rad and a maximum power output of the order of 1 Watt. Due to the lenght of the straight sections in the storage ring ($\sim$ 7 m) this angular divergence will produce a substantial decrease in the average photon density in the interaction region.

To obtain a substantial increase in the photon density we are planning to construct a resonant laser cavity which overlaps with the interaction region. In our opinion this can be easely obtained for an Argon laser with the configuration schematically indicated in fig. 5. The two mirrors system resembles a conventional confocal laser cavity. The radius of curvature of each mirror being equal the distance

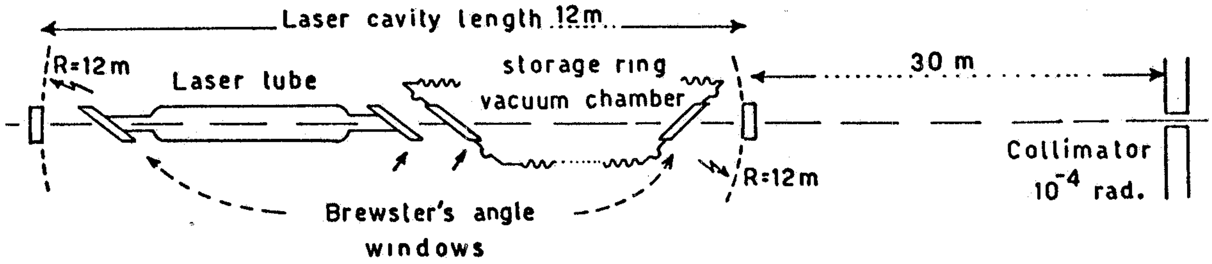


FIG. 5

between the mirrors. The reflectivity of each mirror being as high as possible. The active region is located near one of the mirrors and its lenght is short compared to the lenght of the entire cavity. Two Brewster windows separate the region were the gas is contained from the vacuum of the interaction region.

The spot size of a fundamental made can be indicated as the radius at which the energy density is 1/e the value it has on the laser optic axis.

In the center of confocal cavity this radius is given by[5]:

$$w_o = \sqrt{\frac{\lambda d}{2\pi}}$$

where:

d is the distance between the mirrors 12 m
λ is the wavelenght of the emitted light 4880 Å

and we obtain:

$$w_o = 0.95 \text{ mm}$$

On the surface of the mirrors the beam radius w_m is:

$$w_m = \sqrt{2}\ w_o = 1.35 \text{ mm}$$

This tecnique of using a resonant laser cavity has the further advantage that the photon flux inside the cavity can be much larger than the photon flux of the extracted laser beam. In this way it seems reasonable to obtain an increase in the photon flux of one or two orders of magniture.

REFERENCES -

(1) - F.R. Arutyunyan and V.A. Tumanyan, Phys. Letters 4, 177 (1963); Soviet Phys. Uspekhi 83, 339 (1964).
R.H. Milburn, Phys. Rev. Letters 10, 75 (1963);
Proc. of the Int. Symp. on Electron and Photon Interac. at High Energies, 8-10 june 1965, pg. 445.
C. Bemporad, R.H. Milburn, N. Tanaka and M. Fotino, Phys. Rev. 138B, 1546 (196).
Y.Y. Telnow, E.I. Filippov and M.N. Yakimenko, Phys. Letters 13, 344 (1964).
H. Krüger, Z. Physik 189, 302 (1966).
(2) - F. Amman et al., Notiziario CNEN 10, n. 3 (1964).
(3) - F.R. Arutyunyan and V.A. Tumanyan, Soviet Phys. Uspekhi 83, 339 (1964).
(4) - J.H. Hubbel, J. Appl. Phys. 30, 981 (1959).
(5) - G.D. Boyd and J.P. Gordon, B.S.T.J. 40, 489 (1961).