To be submitted to
Nuclear Instr. & Meth.

ISTITUTO NAZIONALE DI FISICA NUCLEARE
Laboratori Nazionali di Frascati

LNF-86/5(P)
30 Gennaio 1986

M.Preger, B.Spataro, R.Bernabei, M.P.de Pascale and C.Schaerf:
MONOCHROMATIC AND POLARIZED TAGGED LADON GAMMA RAY BEAMS

Servizio Documentazione
dei Laboratori Nazionali di Frascati
Cas. Postale 13 - Frascati (Roma)

INFN - Laboratori Nazionali di Frascati
Servizio Documentazione

LNF-86/5(P)
30 Gennaio 1986

MONOCHROMATIC AND POLARIZED TAGGED LADON GAMMA RAY BEAMS

M. Preger, B. Spataro
INFN - Laboratori Nazionali di Frascati, Frascati, Italy

R. Bernabei, M.P. de Pascale and C. Schaerf
Dipartimento di Fisica dell'Università di Roma, and
INFN - Sezione di Roma, Roma, Italy

ABSTRACT

We discuss the production of monochromatic and polarized gamma ray beams by backward Compton scattering of Laser light against the high energy electrons circulating in a storage ring. The gamma ray energy resolution obtainable by photon collimation is compared to that obtainable by tagging the scattered electrons. A complete model of the tagged electron technique is developed in the linear theory of electron optics. The formulas are applied to the proposed 5 GeV European Synchrotron Radiation Facility (ESRP 27/3). The results appear very promising indicating an energy resolution better than 4 MeV at 780 MeV.

1.- INTRODUCTION

Monochromatic and polarized gamma ray beams have been produced by the scattering of Laser light against the high energy electrons circulating in a storage ring[(1)].

In this paper we wish to discuss the improvements which can be obtained in the performance of these beams by tagging the scattered electrons and with some changes in the optical properties of the stored electrons.

For head-on collisions[(1)] the energy of the scattered photons is given by:

$$k = 4\, k_1 \gamma^2 \frac{1}{1 + x + z} \tag{1}$$

and

$$k = E - E' \tag{2}$$

where:

k_1 is the initial photon energy;

k is the final photon energy;

E is the initial electron energy;

E' is the final electron energy;

m is the electron mass;

γ $= E/m >> 1$;

θ is the angle between the direction of the initial electron and that of the final photon: $<< 1$;

x $= (\gamma\theta)^2$;

z $= 4Ek_1/m^2 << 1$.

Therefore the maximum gamma-ray energy which can be obtained with this technique is:

$$k_M = 4\, k_1 \gamma^2 \frac{1}{1 + z} = E \frac{z}{1 + z} \, .$$

2.- COLLIMATED BEAM

Collimating the final photon beam within an angle $\Delta\theta$ the best energy resolution obtainable is approximately given by:

$$\frac{\Delta k}{k} \simeq (\gamma\Delta\theta)^2 \gtrsim (\gamma\sigma_x')^2 \gtrsim \gamma^2 \varepsilon_x/\beta_I \tag{3}$$

where:

σ_x' is the angular spread of the primary electron beam;

ε_x is the horizontal emittance of the electron beam;

β_I is the radial betatron wave-lenght of the storage ring in the electron-laser interaction region.

Formula (3) is valid only for $x << 1$ in which case it gives an indication of the Full Width at Half Maximum (FWHM) of the distribution. In the practical cases discussed later we have used a Monte Carlo calculation to obtain a better estimate of Δk.

3.- TAGGED BEAM

If the final electron is detected and its energy measured we have a tagged photon beam. In this case the energy of the scattered photons is determined not by their angle θ but by eq.(2).

The energy of the final electron can be determined using some components of the storage ring latice as a magnetic spectrometer and measuring the displacement from the main orbit of the final electron at a selected location in the storage ring.

If $k \ll E$ then:

$$E' \simeq E$$

and the linear theory of electron optics yields (see ref.(2) and Appendix A, with $d = A_{13}$):

$$\sigma_k = E \frac{\sigma_T}{d} \tag{4}$$

and

$$\sigma_T^2 = \varepsilon_x \beta_T + \eta_T^2 \sigma_p^2 \tag{5}$$

where:

- σ_T is the total radial spread of the beam at the position of the tagging detector;
- η_T (sometimes indicated as Ψ) is the radial dispersion of the electrons as a function of their energy at the position of the tagging detector;
- σ_p is the fractional energy spread of the electrons in the storage ring;
- β_T is the betatron wave-lenght at the position of the tagging detector;
- d is the dispersion of the storage ring lattice (A_{13} or A_{16} of the transport matrix) from the interaction region to the tagging detector.

We have assumed that the radial position of the final electron can be measured with an accuracy much better than σ_T, and therefore the contribution of the finite size of the detectors can be neglected.

The best energy resolution is obtained at the location where σ_T/d is minimum. For most storage rings, and especially for those of higher energy, this quantity can be made of the order of 10^{-3}. To decrease it further special tricks must be devised.

One such trick is to find a way to circumvent the limit imposed by σ_p. Since this is the intrinsic energy spread of the circulating beam the only way to improve the monochromaticity of the incident electrons is to dispers them radially according to their energy and to impinge the laser beam only on a fraction of them.

Assuming that the rms radius of the Laser beam can be made substantially smaller than σ_{BI}, then the energy resolution of the incident electrons can be assumed to be:

$$\sigma_p' = \sigma_{BI}/\eta_I = \sqrt{\varepsilon_x \beta_I}/\eta_I \tag{6}$$

where some quantities have already been defined and:

σ_{BI} is the contribution of the betatron oscillations to the horizontal rms dimension of the beam;

β_I and η_I are the quantities already defined now calculated in the interaction region.

4.- SOME PRACTICAL CASES

ADONE

The Frascati 1.5 GeV storage ring has been the first one to be used for the production of monochromatic and polarized gamma ray beams by inverse Compton scattering. Despite its non optimal design[(3)] for this application the results have been quite encouraging and have stimulated further activity in this field[(4)]. Each of the twelve identical lattice elements consists of a (n=1/2) bending magnet with a quadrupole doublet on each side. This produces a symmetrical configuration of the type OFODOBODOFO. The electron-laser interaction region is located in a straight section (2.58 m long) between consecutive lattice elements.

Some typical parameters of the Adone storage ring and of the Ladon project are summarized in Table I.

Since the intrinsic energy resolution of the primary beam ($E \cdot \sigma_p$ = 0.86 MeV) is smaller than the result obtained from eq.(6)(ΔE = 1.07 MeV) nothing can be gained by the dispersion of the primary beam. On the other side the gamma-ray energy resolution that in principle can be obtained with tagging presents a substantial improvement over the results now available with the collimated beam in operation.

The most critical decision is to select the position of the tagging detector. The scattered electrons have transfered to the photon a small but non negligible fraction of their energy:

$$(E - E')/E = k/E \ .$$

Therefore they drift away from the main orbit till they hit the inside of the vacuum chamber which is 95 mm away. For this a large dispersion to improve the energy resolution must be compatible with the requirement of detecting the drifting electrons before they have reached the vacuum chamber wall. This occurs in the focusing quadrupole after the first bending magnet. A first set of detectors will be pla

Table I - LADON project : storage ring Adone

Electron energy	E	= 1.5 GeV					
Electron energy spread	σ_p	= 0.58×10^{-3}					
Horizontal emittance	ε_x	= 0.24×10^{-6} m·rad					
Argon-ion laser wave-length	λ	= 512 nm					
Initial photon energy	k_1	= 2.45 eV					
Recoil parameter	z	= 0.056					
Final photon energy	k_M	= 80 MeV					
		Interaction region			Tagging region		
					Pos. A	Pos. B	Pos. C
Betatron wave-length	β_x	= 9			6.46	6.46	4.03 m
Angular spread	σ'_x	= $1.6\text{x}10^{-4}$ rad					
Radial spread	σ_x	= 1.84			1.55	1.55	1.20 mm
Radial energy dispersion	η_x	= 2.0 m					
Initial el. en. res. (eq.6)	σ'_p	= $0.72\text{x}10^{-3}$					
Dispersion from I to T	d	= 0			1.53	3.33	2.54 m
		Collimation				Tagging	
		eq.(3)	M.C.	exp.		eq. (5)	
Photon energy res. FWHM	Δk	= 7.7	8.0	9.0	3.9	1.6	1.7 MeV
Max. tagged photon en.	k_M	=	80		80	43	57 MeV

ced between the quadrupoles of the doublet which follows this magnet (Position A in Fig. 1) where σ_k = 1.65 MeV and:

$$\Delta k = 3.9 \text{ MeV} \qquad \text{(FWHM at Position A).}$$

The photons scattered at a small angle receive a smaller energy according to eq.(1), and smaller will be the energy lost by the scattering electrons. Position B has been selected to optimize the resolution of this low energy gamma-rays. It is located between the quadrupoles after the second bending magnet where the dispersion d is close to a maximum. Only the electrons which have lost less than 43 MeV can reach this position but here the resolution is improved by a factor 2 to a value of:

$$\Delta k = 1.6 \text{ MeV} \qquad \text{(FWHM at Position B).}$$

A better compromise between energy resolution and acceptance is obtained at the exit of the second bending magnet (Position C). Here the maximum gamma-ray ener-

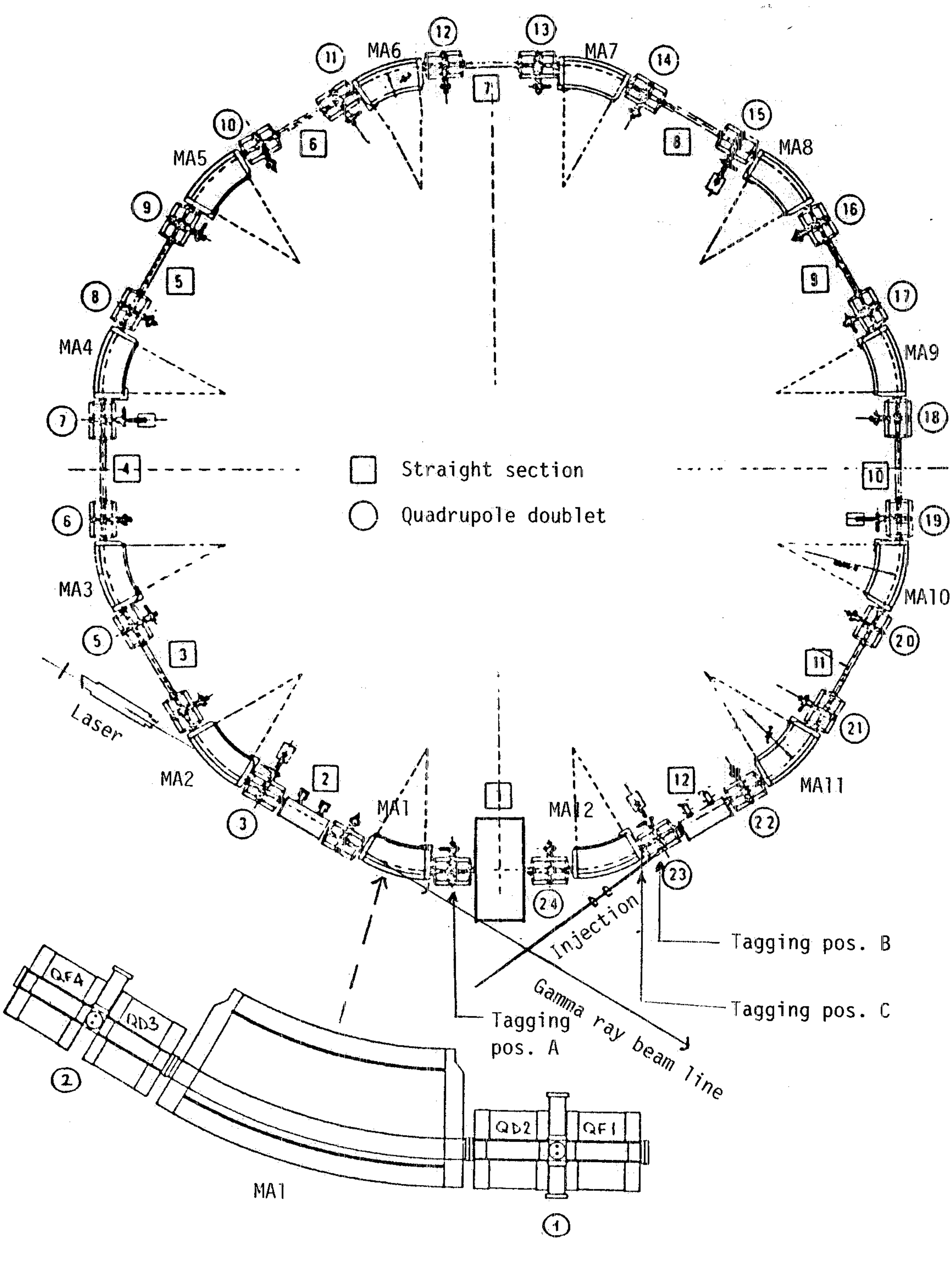


FIG. 1 - A schematic representation of the layout of the Adone storage ring with an indication of the electron-Laser interaction region, the direction of the gamma ray beam and positions A,B and C of the tagging detectors.

gy which can be tagged (at E_0 = 1500 MeV) is 57 MeV and the energy resolution is:

Δk = 1.7 MeV (FWHM at Position C).

Alternatively in Position C with a lower electron energy we obtain:

E_0 = 970 MeV; k_M = 36 MeV; σ_x = 0.777 mm;

d = 2.54 m; $\sigma_x/d = 0.306\times10^{-3}$; Δk = 0.7 MeV.

ESRF

The 5 GeV storage ring of the European Synchrotron Radiation Facility appears a very promising tool for the production of tagged Ladon beams[5]. Its essential parameters are indicated in Table II. The present design, ESRP-27/3[6], consists of 32 periods composed of a long straight section followed by a short one. The long straight sections are dispersion free and can be of two different types:

U) Undulator sections with 6 m free length, high β_x, and therefore large beam dimensions and small angular divergences;

W) Wiggler sections with 3 m free length, low β_x, and therefore small beam size but large angular divergences.

The shorter straight section have a small dispersion of the order of 0.5 m, and will be indicated by D.

In Fig. 2, taken from ref.(6), we have represented 1/16 of the machine composed of two half Undulator sections, two Dispersive sections and one Wiggler section. Therefore we have three possible choices of set-up:

D/2-W: the interaction region is located in a Dispersive section followed by a Wiggler section;

D/2-U: the interaction region is located in a Dispersive section followed by an Undulator section;

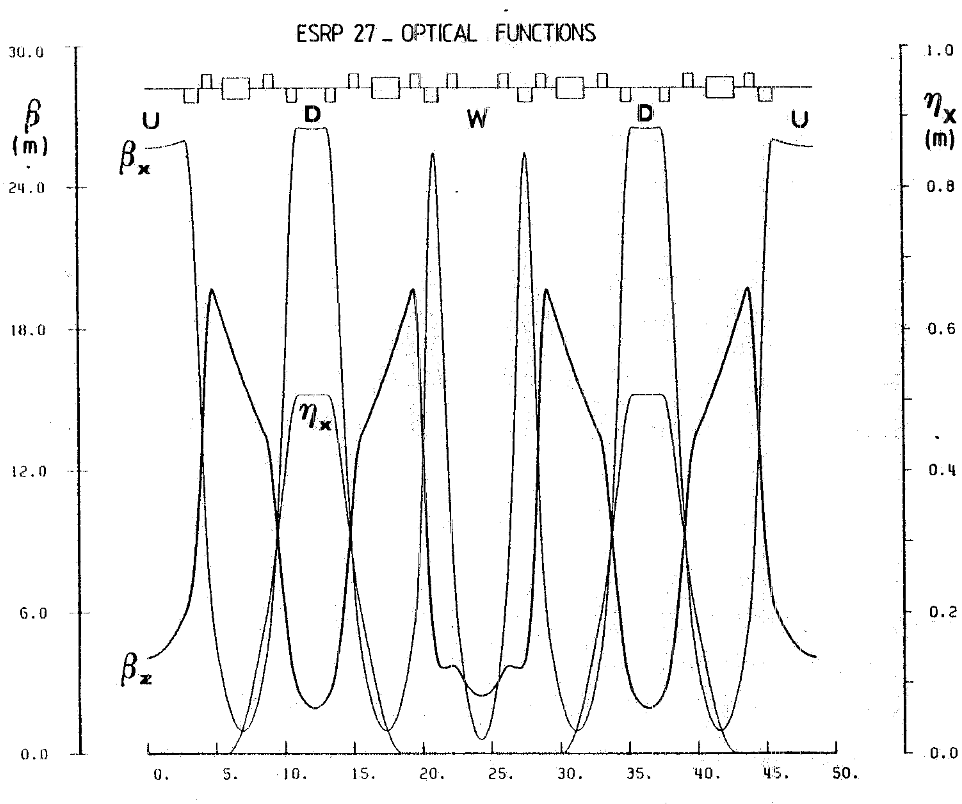
U/2-D: the interaction region is located in an Undulator section followed by a Dispersive section.

Since we will find that the tagging detector should be located in the straight section after the first bending magnet it is not important which is the section after the second bending magnet. Moreover since the quadrupoles before the first bending magnet do not contribute to the dispersion of the system, the W/2-D set-up gives the same results of the U/2-D, and it is not important in which position of the straight section the electron-Laser interaction takes place, since for all positions of the same straight section we have the same value from eq.(4).

In the last column of Table III we have indicated the best theoretical values of the energy resolution (FWHM in MeV) which can be obtained at a selected location

Table II - TALADON project
European Synchrotron Radiation Facility - Main parameters

Electron energy		$E = 5$ GeV	
Electron energy spread		$\sigma_p = 9.5 \times 10^{-4}$	
Initial photon energy		$k_1 = 2.45$ eV	
Recoil parameter		$z = 0.188$	
Final photon energy		$k_M = 780$ MeV	
	ESRP	27/3	27/3 Mod
Horizontal emittance		$\varepsilon_x = 7.2 \times 10^{-9}$	15.2×10^{-9} m·rad



$\beta_{x,\ z}$: horizontal, vertical betatron functions

η_x : dispersion function

FIG. 2 - Representation of the lattice of 1/16 of the ring ESRP-27/3. Optical functions.

Table III - TALADON project - ESRP
Gamma ray energy resolution

1 Set-up	2 Position	3 Component	4 L m	5 d m	6 σ_T mm	7 σ_T/d 10^{-4}	8 ΔX mm	9 Δk FWHM MeV
$\frac{D}{2}$ - W	51	1	8.2	0.35	0.36	10.2	5.4	12
	71	1	11.4	0.12	0.10	8.6	6.7	10
$\frac{D}{2}$ - U	51	1	8.2	0.33	0.33	10.2	5.1	12
	104	1	17.4	0.19	0.16	8.7	7.5	10
$\frac{U}{2}$ - D	58	1	9.6	0.32	0.42	12.9	5.1	15
$\varepsilon_x = 1.57 \times 10^{-8}$ mrad								
$\frac{A}{2}$ - D' - $\frac{U}{2}$	70	1	11.6	0.33	0.80	23.9	5.2	28.0
	100	1	16.6	0.55	0.18	3.3	8.6	3.9
	107	4	17.6	0.65	0.13	2.0	10.1	2.3
	114	1	18.6	0.79	0.20	2.5	12.3	3.0
$\frac{D'}{2}$ - A - $\frac{D'}{2}$	52	1	8.2	0.33	0.71	21.8	5.1	26.0
	97	1	16.3	0.88	0.68	7.7	13.6	9.0

Column	Name	Description
1	Set-up	indicates the position of the interaction region and the successive sections up to the location of the tagging detector;
2	Position	indicates the position of the tagging detector in the computer code we have used;
3	Component	indicates the magnetic component of the storage ring lattice at the selected location: 1 means a drift space and 4 a bending magnet;
4	L	is the distance in meters from the center of the interaction region to the selected position;
5	d	is the dispersion in meters calculated from the interaction region to the tagging detector;
6	σ_T	is the total radial spread of the beam at the position of the tagging detector;
7	σ_T/d	is the gamma ray energy resolution as a fraction of the electron energy given by eq.(4);
8	Δx	is the maximum displacement from the main orbit of the scattered electrons before they reach the tagging detector;
9	Δk	is the gamma ray energy resolution (Full Width at Half Maximum) in MeV.

along the storage ring for a maximum gamma ray energy k_M = 780 MeV with a machine energy E_o = 5 GeV. The result is interesting and indicates that placing the interaction region in a Dispersive section gives better results then placing it in an Undulator or Wiggler section.

Encouraged by this outcome we have proceeded to study if a suitable modification of the machine in the form of an insertion could produce a better energy resolution. The insertion studied by one of us(7) and indicated by A will require a modification of a long straight section and the two adjoining Dispersive sections (D') with a small increase in the average dispersion of the machine and therefore in its horizontal emittance from $\varepsilon_x = 7.29 \times 10^{-9}$ to $\varepsilon_x = 1.57 \times 10^{-8}$.

The results with this configuration (ESRP-27/3 Mod) are indicated in the last part of Table III with the name A/2-D'-U/2. The best energy resolution (2.3 MeV) is obtained by placing the interaction region in the modified A section and the tagging detector inside the second bending magnet at the end of the Undulator section (code name position 107). This however is technically very difficult and therefore we have considered also positions 100 and 114 which are located in regions with no magnetic fields just before and after the bending magnet. In particular position 100 appears very interesting since the scattered electrons arrive there at a distance of 8.6 cm from the main orbit and therefore we can detect them if we are able to modify only two quadrupoles and 5 meters of vacuum chamber.

At position 100 the energy resolution is 3.9 MeV (FWHM) at 780 MeV. Quite an exciting result and an improvement of almost a factor of three over the unmodified machine. This figure can be reduced to 3.5 MeV if we shoot the Laser beam on only a fraction of our electrons. A further improvement not needed once we reach this level.

The alternative to use the modified Dispersive section as the interaction region (D'/2-A-D'/2) does not present any interest as is indicated in the last two lines of the Table III.

This calculations clearly indicate that the proposed 5 GeV ESRF machine appears a very exciting tool for the production of high resolution, fully polarized, monochromatic gamma ray beams in the energy range of 1 GeV. The energy of 780 MeV corresponds to a reduced wave length ($\lambdabar = \lambda/2\pi$) of 0.25 fm. A spatial resolution which should allow to investigate the sub-nucleonic degrees of freedom of nuclei.

It is also important to note that while the result obtainable with the present design (Δk = 10 MeV) are already very interesting, very exciting results (Δk = 2-4 MeV) are in sight with some changes in the present version.

It may be useful to remind that the predicted results are obtained in the linear approximation, while the maximum electron energy loss is $\sim$15% and the distance from the central orbit ranges up to $\sim$ 9 cm. It will be important, when the actual field distribution in quadrupoles and bending magnets will be known, to check the calculations with tracking programs, which take into account all these effects.

We conclude by stressing that this application of the new machine and the interesting physics which can become available should be kept in mind when the final design of the storage ring is decided in order to optimize its the performance also for this application.

APPENDIX A - ENERGY RESOLUTION OF TAGGED PHOTONS

The energy of the backscattered photon is:

$$K = E_1 - E_2 \tag{A1}$$

where E_1 and E_2 are the electron energies before and after the scattering. Normalizing all energies to the synchronous energy E_0 of the storage ring, we get:

$$k = K/E_0 \ , \qquad \varepsilon_1 = (E_1-E_0)/E_0 \ , \qquad \varepsilon_2 = (E_2-E_0)/E_0 \tag{A2}$$

and

$$k = \varepsilon_1 - \varepsilon_2 \ . \tag{A3}$$

If $k \ll 1$ the linear approximation for the beam transport along the storage ring can be used. If A_{jk} are the elements of the transport matrix from the interaction point to the detector position, the horizontal displacement of the electron at the detector is:

$$x_d = A_{11}x_i + A_{12}x_i' + A_{13}\varepsilon_2 \tag{A4}$$

where x_i and x_i' are the displacement and the angle of the electron trajectory at the interaction point. Separating the contributions of the betatron and synchrotron oscillations, and introducing the dispersion function η_i and its derivative η_i' at the interaction point, we get:

$$x_i = x_{i\beta} + \eta_i\varepsilon_1 \ , \qquad x_i' = x_{i\beta}' + \eta_i'\varepsilon_1 \tag{A5}$$

and substituting expressions (A5) and (A3) into eq.(A4)

$$x_d = A_{11}x_{i\beta} + A_{12}x_{i\beta}' + (A_{11}\eta_i + A_{12}\eta_i' + A_{13})\varepsilon_1 - A_{13}k \ . \tag{A6}$$

Since the dispersion function propagates as a betatron oscillation, the expression between parenthesis in (A6) is the dispersion function at the detector position η_T so that eq.(A6) can be solved with respect to the normalized photon energy:

$$k = -\frac{x_d}{A_{13}} + \frac{A_{11}x_{i\beta}+A_{12}x'_{i\beta}+\eta_T\varepsilon_1}{A_{13}} . \qquad (A7)$$

The expression $A_{11}X_i+A_{12}x'_i+\eta_T\varepsilon_1$ gives exactly the horizontal displacement at the detector of the electron, if the scattering of the laser photon would not have occurred, so that its r.m.s. distribution is nothing else than the horizontal beam width σ_T at the detector. Eq.(A7) can be written as:

$$k = -\frac{x_d \pm \sigma_T}{A_{13}} \qquad (A8)$$

with

$$\sigma_k = \frac{\sigma_T}{A_{13}} = \frac{\sqrt{\varepsilon_x\beta_d + \eta_T^2\sigma_p^2}}{A_{13}} . \qquad (A9)$$

REFERENCES

(1) L.Federici et al., Backward Compton scattering of Laser light against high energy electrons. The LADON photon beam at Frascati, Nuovo Cimento 59B, 247 (1980).

(2) M.Preger, Ottimizzazione della risoluzione energetica per un fascio di backscattering di luce Laser da un fascio di elettroni, Internal Memorandum LNF, No. G-66 (1985).

(3) F.Amman et al., ADONE, the Frascati electron positron storage ring, in Proc. of the Intern. Conf. on High Energy Accelerators, Frascati 1965, ed. by M.Grilli (CNEN, 1966), pag. 703.

(4) A.M.Sandorfi, M.J.LeVine, C.E.Thorn, G.Giordano, G.Matone and C.Schaerf, High energy gamma ray beam from Compton backscattered Laser light, IEEE Trans. on Nucl. Sci. NS-30, 4 (1983).

(5) L.Federici et al., The LADON photon beam with the ESRF-5 GeV machine, Lett. Nuovo Cimento 27, 339 (1980).

(6) B.Buras and S.Tazzari, Report of the ESRP, Second edition, c/o CERN, LEP Division (1985).

(7) M.Preger, Inserzione ad alta risoluzione energetica per il fascio gamma monocromatici sulla macchina europea per la luce di sincrotrone, Internal Memorandum LNF, No. G-56 (1985).