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A. Rindi: GAS BREMSSTRAHLUNG FROM ELECTRON STORAGE RINGS.

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Abstract.

In high energy electron storage rings, tha radiative interaction of the electrons with the residual gas in the ring constitutes an important source of energetic gamma rays. We introduce the typical expressions for the high energy bremsstrahlung. Then, we calculate the gamma ray spectrum, total emission and dose rate for the case of the 1.5 GeV electron storage ring ADONE of the LNF of Frascati. The calculated values are compared with experimental measurements.

1. - Introduction - Storage rings.

Storage rings consist essentially of a doughnut-shaped vacuum chamber between the poles of bending and focussing magnets. Charged particles (electrons, positrons, protons, antiprotons), preaccelerated to a given energy, are injected into the ring: the function of the ring is to keep them circulating as long a possible at a fixed energy.

In many storage rings, then, the magnets provide a magnetic field constant in time and there are only one or two accelerating cavities to compensate for the energy losses of the particles by radiation and by the particle interactions between themselves and with molecules of the residual gas in the ring. Some storage rings, however, work for a part of the cycle as an accelerator, increase the energy of the injected particles up to a given value and then keep the particles circulating at that energy.

By storing the particles one can progressively increase the number of particles circulating in the ring and so the beam density increases up to very large values: densities up to 10^{14} particles can easily be achieved providing beam current equivalent to several A.

A particle and its antiparticle can be stored circulating in opposite directions in the same ring.

For increasing as long as possible the lifetime of the particles in the ring (at least a few hours) a very high vacuum has to be mantained in the ring: 10^{-10} Torr is a typical pressure.

The diameter of the ring is set by the energy and type of the stored particles. Several storage rings with diameters ranging from a few meters up to several hundred meters are in operation at high energy physics laboratories around the word. For instance, the LEP project, presently under study at the CERN in Geneva, foresees an electron storage ring of about 10 Km diameter where some 6 mA of electrons at about 120 GeV will be stored. Storage rings are used at nuclear research centers for studying the interactions of subnuclear particles amongst themselves.

In the last few years electron storage rings have found very useful applications in biology, in solid state physics, in material research and in industry as generators of the socalled "synchrotron radiation" which is a very intense and collimated radiation of energy ranging between that of the visible light up to a few tens of keV, produced by the bending of the electron path in a magnetic field. Its use is presently blooming.

At the INFN Laboratory of Frascati, where electron-positron collisions were first studied with a small storage ring in 1961, there is presently in operation an electron storage ring of 1.5 GeV, of some 30 m diameter, which is used for nuclear physics research as well as a synchrotron radiation facility. Fig. 1 shows a view of this facility.

From an health physics point of view, the main radiation exposure sources in a storage ring, once the particles have been injected inside, are:

a) The stored beam may accidentally deviate from his circular trajectory (e. g. for a bending magnet failure), leave the ring and interact with solid machine parts outside the ring. Also, when its intensity becomes too low for experimental use, the beam is "killed" by introducing a thick target in its trajectory. Given the high beam intensity and energy, this produces penetrating and intense electromagnetic showers.
One can localize the accidental source of exposure by forcing, when it is possible, the beam to be lost only in some fixed areas in the ring. However, this is a potentially high source of radiation and it is the reason why storage rings are built underground or completely surrounded by thick shielding.

b) The synchrotron radiation lines channel outside the ring very intense low energy radiation beams. Given the low energy of the radiation, the protection around the lines may be achieved with thin shields and traditional safety interlocking measures.

c) The beam interacting with the residual gas in the ring produces bremsstrahlung radiation all around the ring. Even though, given the high vacuum in the ring, the number of residual gas molecules is low (at pressure of 10^{-10} Torr there are some 3.5×10^{6} molecules cm^{-3} left) this may still represent a non negligible source of radiation, at least for electrons, that have a high bremsstrahlung cross section, because of the high intensity of the stored beams.
At synchrotron radiation facilities where beams are channeled outside the ring, the bremsstrahlung radiation, that is generated in a continuous spectrum up to the energy of the primary beam, may represent a non negligible radiation hazard.

In the following we shall briefly review the theory of bremsstrah

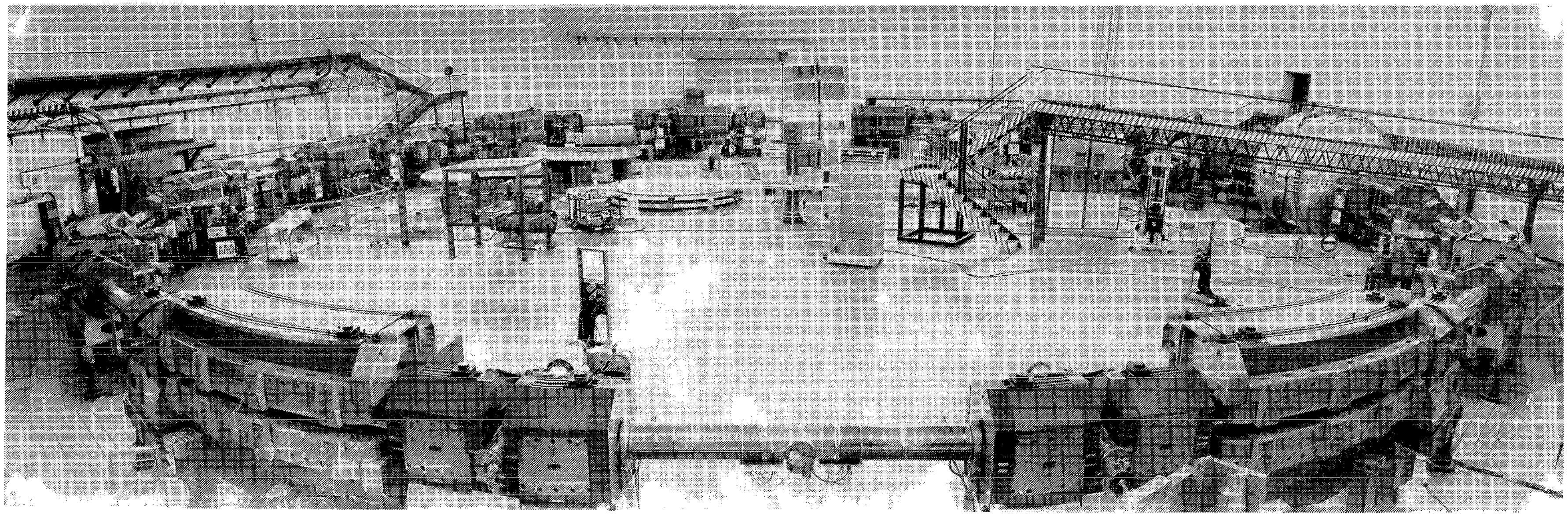

FIG. 1 - A view of the storage ring ADONE.

lung production from high energy electron-gas interaction, we will apply it to the storage ring case and finally show the results of experimental measurement at the ADONE ring in Frascati.

2. - High energy electron bremsstrahlung - Generalities.

Bremsstrahlung radiation is produced when a charged particle loses energy by deceleration in the electric field of an atom (radiative collision). It consists of gamma rays in a continuous energy spectrum ranging from zero to the initial energy of the colliding particle. Because the energy emitted by bremsstrahlung is inversely proportional to the square of the mass of the particle, the energy emitted by particles heavier than the electron becomes negligible compared to that by other energy loss processes. On the contrary, for high energy electrons it becomes the predominant mode of energy loss.

A first thorough theoretical study of the energy loss of an electron by radiative collision has been presented by Bethe and Heitler (Be 34) ; it has since been perfected by different authors and more updated treatments can be found in (He 54) or (Se 65). There is not, as yet, a fully comprehensive theory of bremsstrahlung. However several pratical formulas to be used for different electron energies and materials are in (Se 53), (Ro 52), (Ka 72), (ICRU 78) and especially in (Ko 59). We limit ourselves here to some considerations useful for introducing the expressions to be used for very high energy electrons in storage rings.

a) The electric field of the nucleus as well as that of the atomic electrons contribute to the bremsstrahlung. While for high Z materials and for low energy electrons the effect of atomic electrons is negligible compared to that of the nucleus, for our case we shall take it into account.

b) The field of atomic electrons, on the other hand, may act as a "screen" to the field of the nucleus, as seen from the incoming electrons. This screening effect increases with the energy of the interacting electron and with decreasing the Z of the material. It cannot, then, be disregarded in the present case. The effect of screening is related to the value of the so-called "screening parameter"

$$\gamma = 100 \frac{\mu k}{E_o (E_o - k) Z^{1/3}} \qquad (1)$$

In Table 1 are listed the symbols and constants that are used in the text.

TABLE 1

Symbols and constants used in the text

μ	= rest mass of the electron = 0.511 MeV
r_e	= classical electron radius = 2.82×10^{-13} cm
N_o	= Avogadro number = 6.022×10^{23}
E_o	= total energy of the incoming electron
T_o	= kinetic energy of the incoming electron
E_o	= $T_o + \mu$
E	= total energy of the electron after collision
k	= total energy of the bremsstrahlung gamma
E_o	= E + k
α	= k/E_o = total energy of the bremsstrahlung gamma in unit E_o
Z	= atomic number of the gas

When $\gamma \gg 1$, the screening can be neglected and for $\gamma \ll 1$ we have complete screening. As we will see in the following, in our particular case of bremsstrahlung from very high energy electrons in gas, γ becomes not negligible only for values of $k > 0.98\ E_o$ so that we can use the expressions for complete screening.
Fig. 2 shows, for a given E_o and Z, the variation of γ as a function of k.

c) The Born approximation used for deriving the following expressions is valid for elements with $Z/137 \ll 1$. Under these assumptions, the formuals to be used are the following.
The probability or the cross section for an electron of total energy

E_o to produce a gamma of energy between k and k+dk when passing by an atom of atomic number Z is :

$$\Phi_k dk = C\ Z(Z+1) \frac{dk}{k}\ f(E, E_o, Z) \quad (cm^2) \tag{2}$$

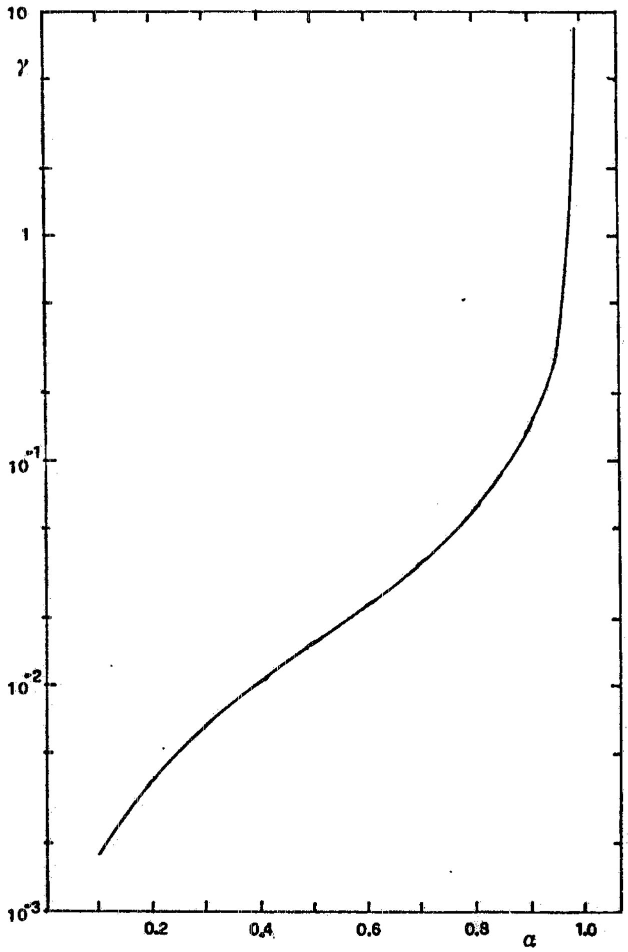

FIG. 2 - The screening parameter γ as a function of the ratio α of the energy of the photons to the energy of the electrons. It has been plotted for E_o = 1500 MeV and Z = 10.

where

$$f(E, E_o, Z) = \left\{ \left[1 + \left(\frac{E}{E_o}\right)^2 - \frac{2}{3}\frac{E}{E_o} \right] \ln(183\, Z^{-\frac{1}{3}}) + \frac{1}{9}\frac{E}{E_o} \right\} \tag{3}$$

$$C = \frac{4 r_e^2}{137} = 2.32 \times 10^{-27} \quad (cm^2) . \tag{4}$$

Note that (2) is not exact because it diverges for $k \to 0$. In addition, for $k \to E_o$, i.e. for $E \to 0$, it has to tend to zero because an electron cannot radiate more energy than its kinetic energy. By considering Φ_k k, i.e. the intensity of the bremsstrahlung as a function of k or of k/E_o as in Fig. 3 the divergence disappears and one can see that the intensity is roughly constant all over the spectrum.

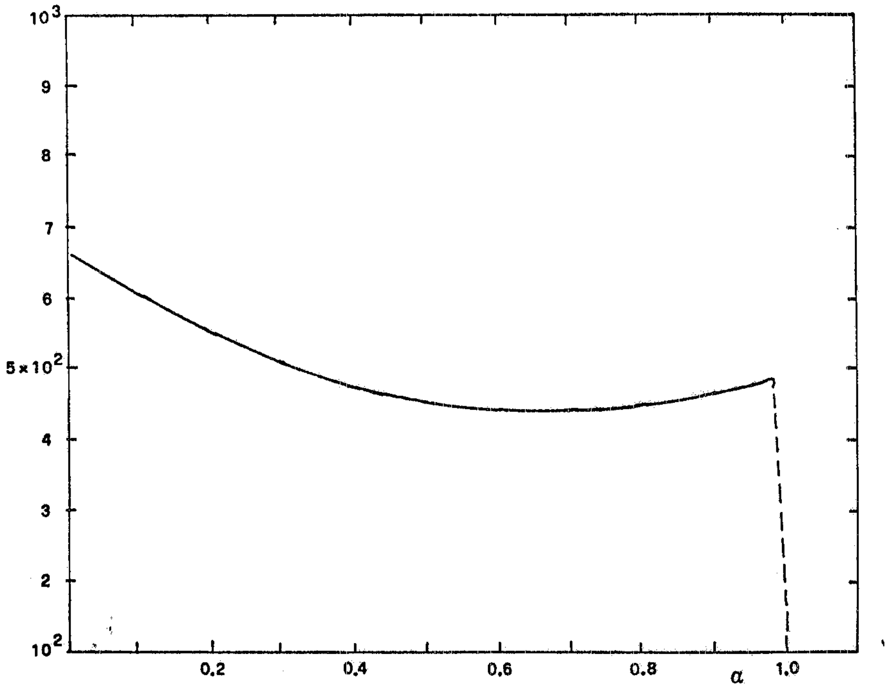

FIG. 3 - The general shape of the intensity distribution of gas bremsstrahlung as a function of the energy of the photon relative to the primary electron energy (expression (13)).

By reducing the screening effect, as it is the case for high k, the second discrepancy is corrected.
However, for our case of high energy electrons and low Z material, the (2) is valid for all the energy range but very small ragions around k = 0 and $k = E_o$.

The cross section can be expressed as a function of $\alpha = k/E_o$ as:

$$\Phi_k dk = C\, Z\,(Z+1)\, \frac{dk}{k} \left[\left(\frac{4}{3} - \frac{4}{3} \quad + \quad ^{2}\right) \ln\left(183\, Z^{-\frac{1}{3}}\right) + \frac{1}{9}(1 - \alpha) \right] \; (cm^2) \quad (5)$$

When the electron crosses a thickness of dx cm of a material containing N atoms cm^{-3}, the number of gammas with energy between k and k+dk emitted is given by

$$N_k \, dk\, dx = N \Phi_k \, dk\, dx \quad . \tag{6}$$

The total energy emitted by an electron in traversing a thickness dx (cm) is calculated by integrating (6), multiplied by k, between 0 and $k_{max} = E_o - \mu \approx E_o$. Its expression is :

$$dE_o = C N Z(Z+1) E_o \left[\ln(183 Z^{-\frac{1}{3}}) + \frac{1}{18} \right] dx \qquad (MeV). \tag{7}$$

This total energy can be expressed as function of the radiation lenght Xo (cm) as

$$dE_o = \frac{E_o}{X_o} dx \qquad (MeV) . \tag{8}$$

The angular distribution of bremsstrahlung is a rather complicated expression. For high energy electrons, the average angle of emission of gamma is about

$$\theta_o = \frac{\mu}{E_o} \tag{9}$$

independent of the energy of the gamma.

For $E_o \gg \mu$, as it is our case, the gammas are emitted practically fully forward.

3. - Gas bremsstrahlung from high energy electron storage rings.

In an electron storage ring, electrons are forced to circulate at a speed very close to c in a ring which often includes some straight sections.

The current in the ring is often expressed in Ampere (A) or in circulating electrons (B). Then the real current I (in $e^- s^{-1}$) is given by

$$I = 6.24 \times 10^{18} \, A \qquad or \qquad 3 \times 10^{10} \frac{B}{L} \qquad (e^- s^{-1}) \tag{10}$$

where L is the total lenght of the ring (in cm). Sometime it is given the so called machine natural frequency ν (s^{-1}), then $I = B\nu$.

The ring is kept at a high vacuum as possible for reducing the number of interactions of the electrons with the residual gas and than increasing the lifetime of the stored beam. The number of atoms per cm^3 of residual gas in the ring at a temperature of 18^oC and at a pressure p (Torr) is given by

$$N = 3.77 \times 10^{16} p \qquad (cm^{-3}) . \qquad (11)$$

By combining (2), (6) and (11) we obtain the number of gammas of energy between k and k+dk emitted per second by bremsstrahlung per cm of path by a current of I electrons s^{-1} of total energy E_o circulating in a ring at a pressure p

$$F_k dk = 8.75 \times 10^{-11} Z(Z+1) p I \frac{dk}{k} f(E, E_o, Z) \qquad (cm^{-1}s^{-1}) \qquad (12)$$

where $f(E, E_o, Z)$ and the other symbols have the known meaning.

In Fig. 3 we have plotted the expression

$$Z(Z+1) \left[(\alpha^2 - \frac{4}{3}\alpha + \frac{4}{3}) \ln (183 Z^{-\frac{1}{3}}) + \frac{1}{9}(1-\alpha) \right] \qquad (13)$$

for $Z = 10$ as a function of $\alpha = k/E_o$. This shows the shape of the intensity distribution of the gas bremsstrahlung valid for any electron energy.

The total energy emitted per cm of path and per second will be given from (7)

$$dE_o = 8.75 \times 10^{-11} Z(Z+1) p I E_o \left[\ln(183 Z^{-\frac{1}{3}}) + \frac{1}{18} \right] \quad (MeV\, cm^{-1}s^{-1}) \qquad (14)$$

or from (8)

$$dE_o = \frac{E_o I}{X_o} \qquad (MeV\, cm^{-1}s^{-1}) \qquad (15)$$

where X_o is the radiation lenght for the residual gas.

4. - The ADONE case.

We apply the previous expressions to the case of the storage ring of the LNF of Frascati, ADONE.

A precise calculation of (12) in a gas mixture requires its evaluation for every value of Z in the mixture, i. e. for every component of the residual gas. Table II shows a typical composition of the residual gas in our storage ring for a pressure of about 10^{-9} Torr. From that, one calculates an average value of Z of about 10 to be used in (12).

Other typical parameters of the storage ring are :

$p = 10^{-9}$ Torr ,

$I = 100$ mA =

$= 6.24 \times 10^{17}$ e s^{-1} ,

$E_o = 1500$ MeV .

TABLE 2

Component	Percent by volume
H	4.7
H_2	9.4
C	7.5
N	1.5
CH_4	4.8
OH	3.7
H_2O	9.7
CO	49.5
Ar	5.4
CO_2	3.8

From (12) we derive the equation for the intensity spectrum of gammas emitted by a straight section of 600 cm

$$F_k = \frac{3.6 \times 10^3}{k} \left\{ \left[\left(\frac{k}{1500}\right)^2 - \frac{4}{3}\frac{k}{1500} + \frac{4}{3} \right] 4.44 + \frac{1}{9}\left(1 - \frac{k}{1500}\right) \right\} \quad (s^{-1}) \tag{16}$$

or

$$F_k = \frac{2.4}{\alpha} \left[\left(\alpha^2 - \frac{4}{3}\alpha + \frac{4}{3}\right) 4.44 + \frac{1}{9}(1 - \alpha) \right] \quad (s^{-1}) \tag{17}$$

where $\alpha = \frac{k}{1500}$.

Experimental measurements of the gas bremsstrahlung spectrum at ADONE have been performed by Dehne et al. (De 74). In Fig. 4 we compare an intensity spectrum measured for an electron energy of 1 GeV and the calculations from (12) : we have plotted the intensity spectrum $F_k k$ as a function of α, have used arbitrary units in the ordinate, and have normalized the experimental and theoretical curves at the plateau ($\alpha \approx 0.75$). The figure shows a very good

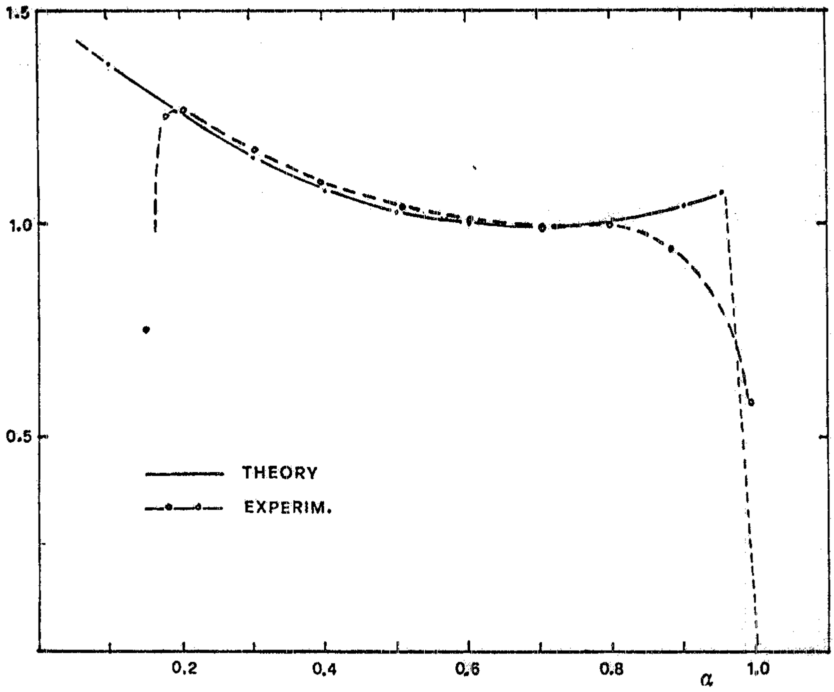

FIG. 4 - Comparison of theoretical and experimental intensity distributions.

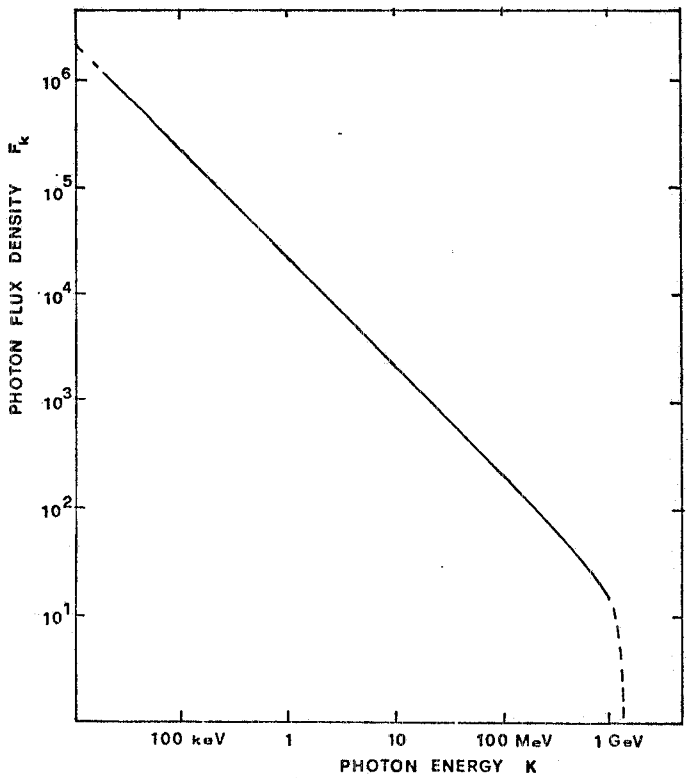

FIG. 5 - Differential gamma spectrum calculated for gas bremsstrahlung from the storage ring ADONE.

agreement : the discrepancies at high α are due to the poor resolution of the spectrometer used which also had an energy lower threshold at about 200 MeV ($\alpha \approx 0.2$).

In Fig. 5 is plotted the calculated differential gamma bremsstrahlung spectrum as emitted from a 600 cm straight section at ADONE for the given standard machine parameters as given by (16).

It shows that the bremsstrahlung gamma flux as a function of the gamma energy k follows a 1/k law for a large range of k.

The total energy emitted from the 600 cm of straight section is given by using (14)

$$E = 2.43 \times 10^{7} \ (\mathrm{MeV\, s^{-1}}) = 1.4 \times 10^{-2} \ (\mathrm{J\, h^{-1}}) \qquad (18)$$

Using the differential spectrum of Fig. 5, a calculation of dose rate has been performed by numerical integration, taking into account the emission angle given by (9). At a distance of 15 m from an amission point, a surface dose rate of 1.9×10^{-1} mGy h^{-1} per mA of accumulated beam is calculated.

Absorbed dose measurements have been performed at the end of a synchrotron radiation channel, tangent to the ring of ADONE. A beam of about 1 mA of electrons at 1.5 GeV was stored in the ring. TLD LiF dosemeters calibrated with Co 60 radiation were used.

In addition to the radiation from gas bremsstrahlung, at the end of the channel are present also synchrotron radiation as well as possible bremsstrahlung from other sources. In order to shield out the synchrotron radiation that is peaked at about 1 keV, a thickness of 0.5 mm of Cu was introduced before the TLD. An average value of 2×10^{-1} mGy h^{-1} per mA of beam was measured. If one introduces in the calculations a shielding of 0.5 mm of Cu, the calculated value is reduced to 4.2×10^{-2} mGy h^{-1} per mA. We feel that the experimental and calculated values are in good agreement, given the approximations in both the calculation and the measurement.

We conclude by warning that gas bremsstrahlung may become a very important radiation source at high intensity electron storage rings.

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