ISTITUTO NAZIONALE DI FISICA NUCLEARE
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GAS BREMSSTRAHLUNG PRODUCTION IN THE ADONE STORAGE RING

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GAS BREMSSTRAHLUNG PRODUCTION IN THE ADONE STORAGE RING

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1. INTRODUCTION

Bremsstrahlung on residual gas is one of the main cause of beam-loss in a storage ring and may represent in some circumstances a radiation hazard.

Orbiting electrons strike gas molecules or ions, so producing a "thin target" bremsstrahlung spectrum of photons extended up to the energy of the primary beam. The "spent" electrons are then energy analysed in the subsequent magnetic element. According to their energy they hit the vacuum pipe within the next dipole or quadrupole.

The radiation pattern produced by this mechanism was analysed in detail in ref.1, where the following components were identified:

- a narrow "jet" of bremsstrahlung X-rays is emitted in line with every straight section, produced by electrons moving in straight lines;

- a horizontal "fan" of bremsstrahlung X-rays is emitted from every dipole produced by turning electrons;

- a "spray" of electromagnetic radiation emanates from each dipole towards ring centre, caused by those spent electrons hitting the vacuum pipe within the dipole;

- a broad field of electromagnetic radiation is found along every straight section.

It is important to realize that, although interactions with residual gas take place all around the ring, it is mainly in the straight sections that a radiation problem could arise. The reason is that in each interaction, bremsstrahlung is produced in a narrow cone around the same direction, and each contribution adds up to form a "hot spot" of dose somewhere at the end of the straight section.

At synchrotron radiation facilities where beams are channeled outside the ring, the gas bremsstrahlung radiation may be transmitted along the pipes.

This could cause a relevant radiation hazard particularly in case of an accident in which the pressure on the vacuum chamber would suddenly be increased. The maximum credible accident could be assumed as due to some failure letting the storage ring or a part of it up to atmospheric pressure.

Several calculations have been performed in order to evaluate the doses produced by gas bremsstrahlung, whether in usual working conditions (2,3,4,5) or in case of accident (1,2,6). Particularly in this last case, the various estimates not always are in good agreement.

As regards the experimental results, only few data are still available (1,4,5,7). Likely the most extensive investigation into this matter has been carried out for Aladdin design study (1) , but even these results are not completely exhaustive.

In order to make clear the radiation protection aspects of this problem, we resumed the study of gas bremsstrahlung in the Adone storage ring. We have been induced to do it also for the gamma ray dose rates measured in some locations along the pipe of our wiggler synchrotron radiation beam.

2. CALCULATIONS

Let us consider a straight section of lenght L and calculate the tissue absorbed dose in a point P (fig. 1).

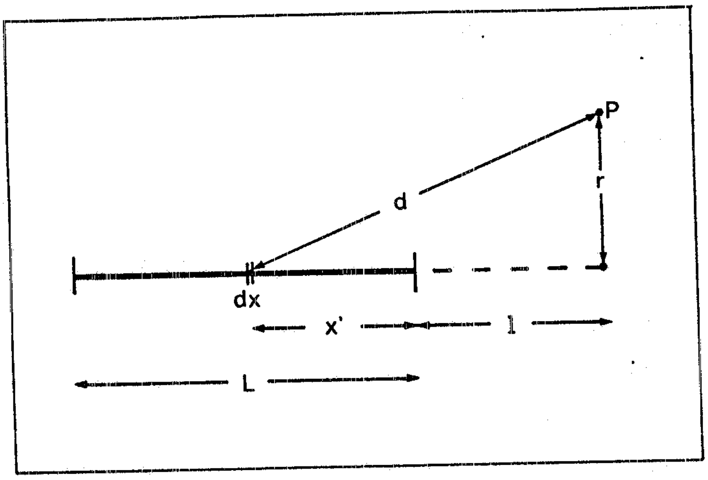

Fig. 1

If N_{st} is the number of stored electrons, the number N_{e-} of electrons crossing the straight section per unit of time is given by:

$$N_{e-} = \frac{N_{st} \times c}{C} \qquad 1.$$

where c is the velocity of the light and C the circumference of the ring.

The energy dE irradiated by N_{e-} electrons in a thickness dx of the straight section is:

$$dE = E_o \frac{dx}{X_o} N_{e-} \qquad 2.$$

where E_o is the electron energy and X_o the radiation length in the residual gas.

Then the number $dN\gamma$ of equivalent quanta emitted per unit of time in dx is:

$$dN\gamma = \frac{dE}{E_o} = \frac{dx}{X_o} N_{e-} \qquad 3.$$

The elementary equivalent quanta flux density $d\varphi$ in the point P at a given distance d from dx will be:

$$d\varphi = \frac{N_{st}\, c}{X_o\, C} \quad \frac{dx}{2\pi(1-\cos\gamma)\quad (x+\ell)^2+r^2} \qquad 4.$$

if $r \leqslant (x+\ell)\gamma$, or $d\varphi = 0$ if $r > (x+\ell)\gamma$, where $\gamma = \frac{mc^{2}}{E^2}$ is the characteristic angle of emission of the photons and the emittance of the electron beam, as well as its dimensions, have been disregarded.

The total photon flux density in P will be:

$$\varphi = \frac{N_{st}\, c}{2\pi(1-\cos\gamma)\, X_o\, C} \int_a^L \frac{dx}{(x^2+\ell)^2+r^2} \qquad 5.$$

where $a = o$ if $\frac{r}{\gamma} \leqslant \ell$ and $a = \frac{r}{\gamma} - \ell$ if $\frac{r}{\gamma} > \ell$.

Assuming a conversion coefficient f from photon flux density to tissue absorbed dose rate, we obtain:

$$\dot{D} = \frac{fN_{st}\, c}{2\pi\,(1-\cos\gamma)\, X_o\, C\, r} \left(\mathrm{arctg}\,\frac{L+\ell}{r} - \mathrm{arctg}\,\frac{\ell}{r}\right) \qquad 6.$$

if $\frac{r}{\gamma} \leqslant \ell$;

$$\dot{D} = \frac{fN_{st}\, c}{2\pi\,(1-\cos\gamma)\, X_o\, C\, r} \left(\mathrm{arctg}\,\frac{L+\ell}{r} - \mathrm{arctg}\,\frac{1}{r}\right) \qquad 7.$$

if $\frac{r}{\gamma} > \ell$;

In a point aligned with the straight section (r=o) at distance ℓ from its effective end, eq. 6 gives approximatively:

$$\dot{D} = \frac{fN_{st}\, c}{\pi\gamma^2\, X_o\, C} \quad \frac{L}{\ell(L+\ell)} \qquad 8.$$

and in the points where $L \gg \ell$ eq. 8 becomes:

$$\dot{D} = \frac{fN_{st}\, c}{\pi\gamma^2\, X_o\, C\ell} \qquad 9.$$

The absorbed dose relative to a finite period of exposure T, while the stored current decreases from i_o to i, will be:

$$D = \dot{D}_o \int_o^T e^{-t/\tau} dt = \dot{D}_o \quad (1-e^{-T/\tau}) = \dot{D}_o \tau \frac{\Delta i}{i_o} \qquad 10.$$

if $\dot{D}_o$ is the dose rate corresponding to the initial current i_o, evaluated by eq. 6,7,8,9,τ the mean life of the stored beam and $\Delta i = i - i_o$ the current lost during T.

3. BREMSSTRAHLUNG MEASUREMENTS

Bremsstrahlung measurements have been carried out at Adone storage ring exposing a matrix of 66 TLD 700 (0.32 x 0.32 x 0.075 cm) at the end of the pipe of the Lela experiment, i.e. at about 9 m from the effective end of the straight section n. 11. In one case the exposure has been performed in the same time also at about 1.5 m from the effective end of the straight section n. 8. TLD's were shielded from synchrotron radiation eventually coming from the final part of the former dipole by minimum 12 mm of stainless steel.

Fig. 2 shows typical distributions of the doses so measured at two

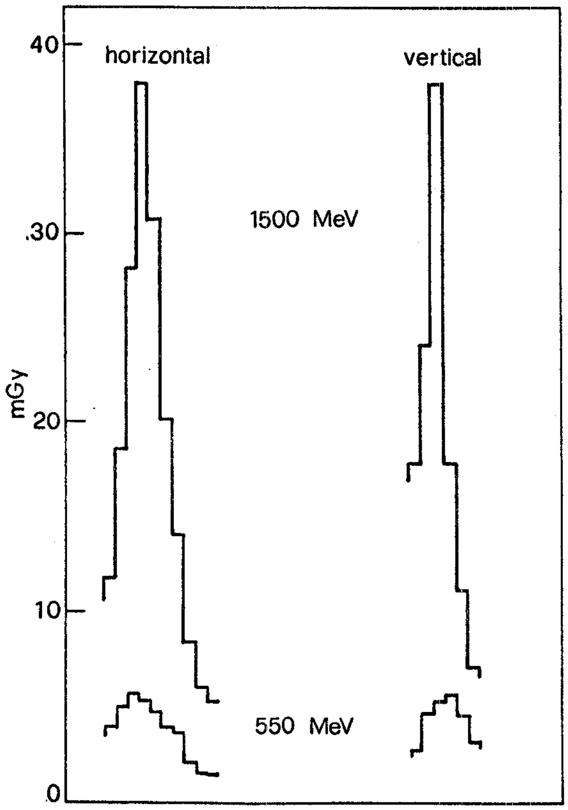

Fig. 2 - Horizontal and vertical dosimeter reading distributions for two different energies of the stored beam (E = 1500 MeV, Δi= 20.3 mA, τ=1.7h, p = $5.2.10^{-9}$ mbar; E = 550 MeV,Δi = 6.8 mA,τ=5.8 h, p = $4.5.10^{-9}$ mbar).

different energies. Each space in the histograms represents a single chip. The maximum value D measured should be due to the jet bremsstrahlung. The beam spot appears to be elliptical and the surface, calculated assuming the length of the semi-axis at 1/2 from peak value, depends on the energy as shown in fig. 3.

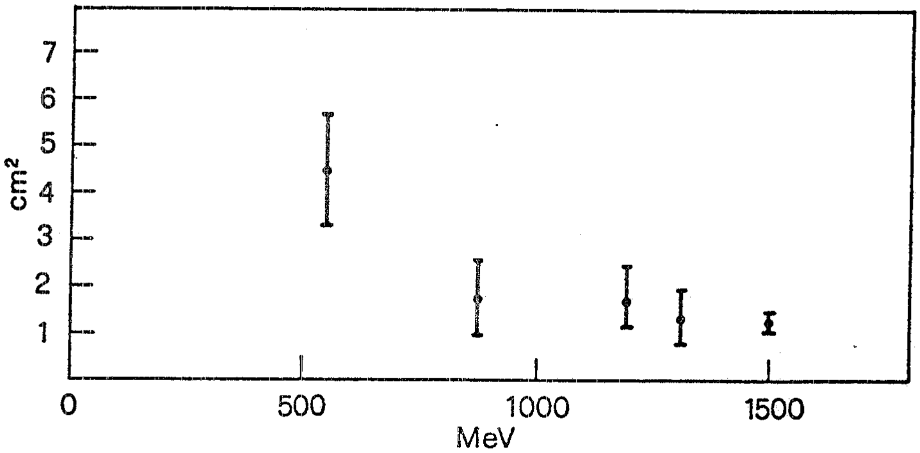

FIG. 3 - Surface of the jet bremsstrahlung spot vs electron energy.

Of course the surface of the spot depends also on the distance from the ring. At 1.5 m from the straight section n. 8, it was about 0.21 cm^2 in the case of a beam of 1.5 GeV.

A summary of the results of the measurements in various experimental conditions is given in Table I, where d represents the distance from the effective end of the considered straight section.

Table I - Bremsstrahlung measurements in various experimental conditions.

Energy (MeV)	d (m)	Run	$\dot{D}$ (μGy h^{-1}mA^{-1})	D (μGy mA^{-1})
1500	9	Lela	430	5000
1500	9	LDS	94	1000
1500	9	LDS	157	1870
1500	9	FIMA	280	4460
1500	9	LDS	230	1430
885	9	LADON	110	2800
550	9	LELA	23	820
1500	1.5	FIMA	1930	31460

The values of $\dot{D}$ were normalized at a pressure of $0.75.10^{-9}$ mbar (10^{-9} torr). Due to the vacuum meter system installed in Adone, the accuracy on the determination of the pressure was not better than a factor of 2. The experiment in run is also quoted in Table I (third column) because some important parameters of the machine (for instance the current of the quadrupoles) change with it. That partially explains some of the differences found in the various experimental conditions being the electron energy equal.

In fig. 4 the experimental data for d = 9 m are compared with the results of the calculations. The curve has been drawn on the basis of the eq. 8.

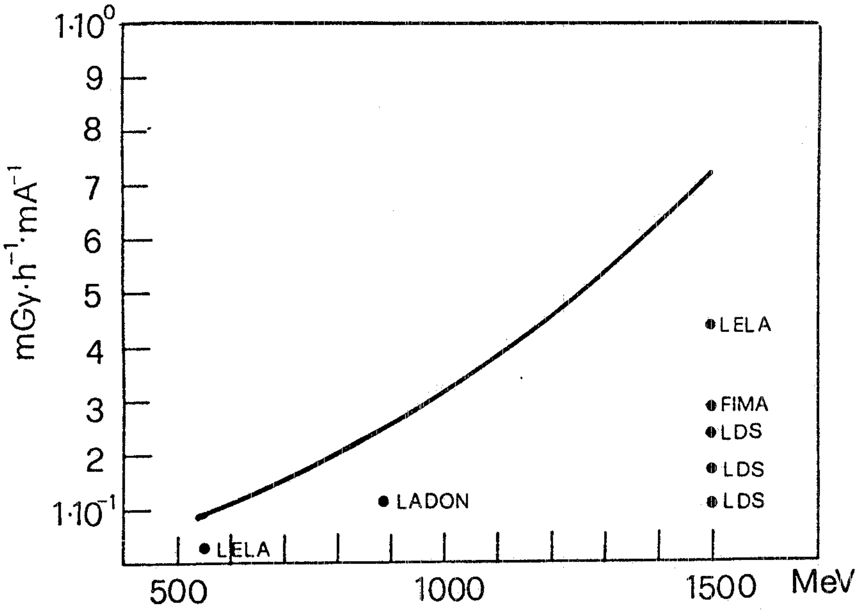

FIG. 4 - Comparison of experimental data with the results of calculation. All the data are normalized at a pressure of $0.75.10^{-9}$ mbar.

The agreement is rather good, if one considers that the dose rates calculated by eq. 8 refers to the maximum of the depth dose curve in tissue, while during measurements TLD's were shielded by more than 12 mm of stainless steel. Some differences can be also explained by the crude approximations introduced in the calculations and in the choice of the numerical values of some parameters, particularly the radiation length in the residual gas. Moreover, some differences are still due to the oscillations of the stored beam, which getting larger the beam spot decrease the doses.

Within the limits of accuracy of this experiment, dose and dose-rates seem to scale approximatively with the square of the energy, as expected.

Comparing the results of the two measurements performed at different distance in the same time, the dependence on the geometry expected from eq. 8 is also confirmed. In fact experimental doses scale of about a factor 7, while the ratio expected is 6.9.

4. IMPLICATIONS FOR WORST POSSIBLE ACCIDENT.

The results of these measurements can be usefully exploited in order to obtain informations about absorbed doses in normal working conditions and in case of accident. This has been done beginning with the data of the last column of Table I and the results are shown in Table II. As concerns the energy of 1500 MeV the highest dose measured has been conservatively considered.

Table II - Doses per unit current lost in normal working conditions and in accidental conditions.

Energy (MeV)	D (μGy mA^{-1})	D' (mGy mA^{-1})	D* (Gy m^2 mA^{-1})
1500	5000	85	11.5
885	2800	47	6.4
550	820	14	1.9

The data in the second column represent the doses at about 9 m from the storage ring in the case of 1 mA beam loss uniformly distributed along the ring. Multiplying these doses by the ratio of the Adone circumference to the length of the straight section one obtains the values of D', i.e. the doses that would be measured at 9 m from the ring in the case of 1 mA beam-loss occurring uniformely in the considered straigth section. This corresponds to an accident, in which the pressure on the vacuum chamber of that straigth section would suddenly be increased to atmospheric pressure.

In order to estimate absorbed dose at another location, at a given distance d(m) from the storage ring, the values of D' must be multiplied by

$$(L+9)9/(L+d)d \ .$$

From the value D measured by TLD's we can determine a point source term D* given by:

$$D^* = \frac{\ell(\ell+L)}{L}\, c\, D \qquad 11.$$

whose values, shown in the last column of Table II, represent the doses at 1 m from a point of the straight section where the beam had completely lost.

Beginning with the results of the calculations, the values of D' and D* would increase of a factor which can be inferred from fig. 4.

As concerns the comparison with the data quoted in literature our results seem more closed to the estimations made at BNL (2) rather than to those of other authors (1,6).

5. SHIELDING CONSIDERATIONS

The attenuation of the "jets" in copper and lead absorbers was also studied by means of matrices of TLD 100 (0.32 x 0.32 x 0.075 cm). Unfortunately, due to space limitations, the front area of the absorbers was only 7x7 cm. The results are shown in fig. 5.

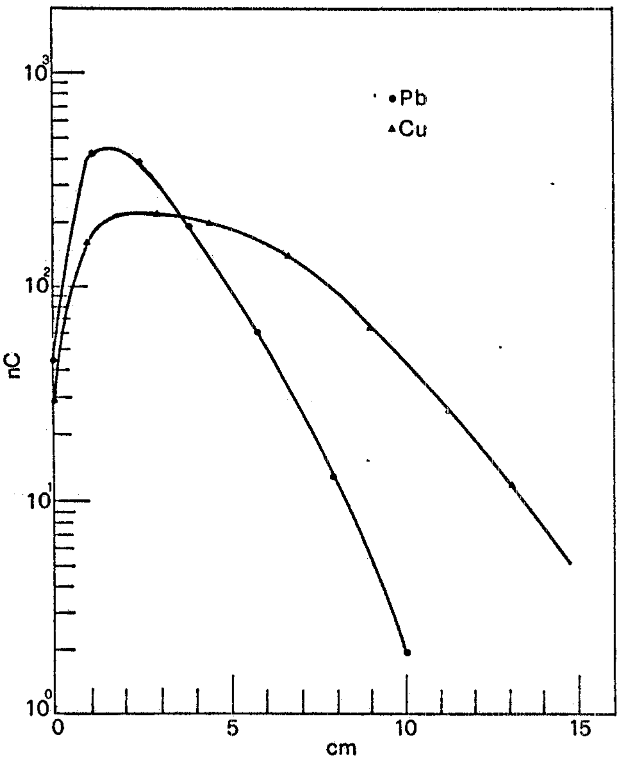

FIG. 5 - Attenuation of bremsstrahlung jets in lead and copper.

A buildup is seen which peaks at about 1.5 cm (2.6 r.l.) in lead and at about 3 cm (2 r.l.) in copper. During these measurements the jets went out from the pipe crossing about 12 mm of stainless steel corresponding to an additional 0.65 r.l.. The buildup factor is about 11 in lead and 7.7 in copper. The peaking is followed by approximatively esponential attenuation characterized by tenth-value layers of about 53.3 g cm^{-2}, in good agreement with the results generally found in literature (8). However in the case of lead the slope quickly changes to less than 30 gcm^{-2}, probably due to an effect of the small sizes of the absorber used in this experiment.

On the basis of the doses shown in Table II we can verify the efficacy of the shield installed at the end of a synchrotron radiation channel (at least 20 cm of lead) in direct view with a straight section.

In the normal working conditions, assuming three fill (100 mA-1500 MeV) each day, 200 days per year, the dose at a distance of about 30 m will be 38 Gy/year. A lead 20 cm thick introduces an attenuation of about 10^{-3}, taking into account the buildup and considering prudently a TVL of 5 cm (8). So the dose per year will be reduced at about 38 mGy/year and the dose 2 m far away the absorber at about 0.25 mGy/year(9).

In the case of a catastrophic beam loss in a point of a straight section, the dose at the end of the synchrotron radiation channel would be about 1.27 Gy. Behind a lead absorber 20 cm thick this dose will be reduced at 1.27 mGy and at 2 m from the absorber at 8.6.10^{-2} mGy.

Of course, gas bremsstrahlung will be a hazard whenever the beam pipe diameter reduces in size or in presence of some obstructions. For this reason lead wall 5 cm thick had been installed all along the wiggler pipe near the working area.

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