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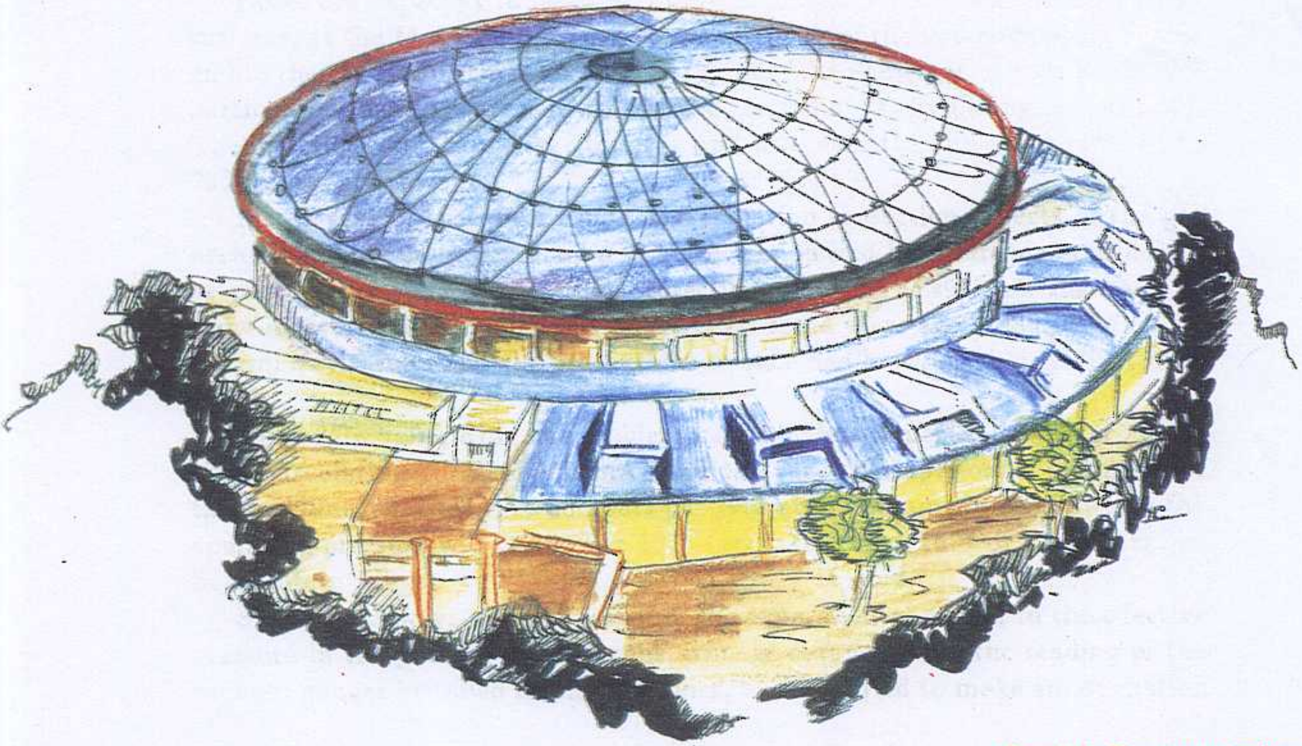

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Gas Bremsstrahlung Evaluation for the DAΦNE Project

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Abstract

Bremsstrahlung produced in the storage rings of the DAΦNE Project by the interactions of electrons and positrons with the residual gas in vacuum chambers has been studied using the FLUKA code. Photon spectra and quantitative estimates of fluence rate and tissue absorbed dose rate are given. On the basis of the obtained results the precautions to take are discussed.

1 Introduction

Bremsstrahlung produced by interactions of electrons and positrons with residual gas in the vacuum chambers of the Main Rings and Damping Ring could be potentially one of the main radiation protection problem of the DAΦNE Project.

Doses are expected to be particularly high, though limitedly to very small surfaces, at the Main Rings owing to the intensity of the two circulating beams and to their mean life time. In fact the target of the Project is to have $1.068 \cdot 10^{13}$ particles per beam, equivalent to $3 \cdot 10^{19}$ e^-/s and e^+/s circulating (about 5 A). The injection will take place "topping up" whenever the current is reduced to 25% of its initial value.

In the case of the Main Rings, the radiation protection aspects of the gas bremsstrahlung emission along a straight section had been already considered, as part of the general radiation protection problems [Es92], on the basis of some measurements carried out at ADONE some years ago [Es86, Es87]. The preliminary results and the precautions to take had been previously illustrated [Es92].

At the Damping Ring the problem might be less important considering the lower circulating current (135 mA) and the very short period of operation of this machine, equivalent to 50 hours per year at maximum power. However the operating pressure will be 10^{-8} or 10^{-9} torr rather than 10^{-9} or 10^{-10} torr like in the Main Rings.

Since it is always very hard to link the experimental results to the effective pressure in the path of the electrons, usually different from the reading of the vacuum gauges installed on the machines, we have tried to make an estimation of the photon fluence and absorbed dose rates expected at DAΦNE by means of a Monte Carlo calculation performed by the FLUKA code [Fa93].

We have used the most recent version of the FLUKA code [Fe91, Fe92, Fe93a], which includes major modifications to the original one. In particular, the treatment of bremsstrahlung is completely new, as photon yield and spectra are now based on the tabulations of Seltzer and Berger [Se86] and the angular photon distributions are accurately described.

The calculations have been performed simulating the straight sections by air targets at atmospheric pressure. The results have been linearly scaled to the operating pressure of the machine. The details of the simulations can be found in a general paper dedicated to this subject [Fe93b].

We have shown that the fluence rate φ, expressed in photon/cm^{2}s, due to the bremsstrahlung emission in air by a current I (e-/s) of electrons or positrons of energy E (MeV) at a distance d (m) from the end of a straight section of length L (m) operating at a pressure p (torr) is given by:

$$\varphi = 1.9 \times 10^{-18} (\frac{E}{mc^2})^2 \frac{L}{d(L+d)} I \frac{p}{p_0} \qquad (1)$$

where mc^2=0.511 MeV and $p_0 = 10^{-9}$ torr.

Particle fluence is the fundamental quantity in radiation dosimetry. The knowledge of the fluence rate through eq. (1), joined to the radiation spectrum, allow to get any information for radiation protection purposes, including the absorbed dose itself.

In its turn, the tissue absorbed dose rate $\dot{D}$ (Gy/h) is given by:

$$\dot{D} = 2.5 \times 10^{-27} (\frac{E}{mc^2})^{2.67} \frac{L}{d(L+d)} I \frac{p}{p_0} \qquad (2)$$

We have shown that eq. (1) and (2) can be applied for distance d=20 cm over [Fe93b].

For the sake of simplicity, in this note, all the calculations have been made as if the residual gas was air. When it is different from air, the results of eq. (1) and (2) have to be multiplied for $(Z/Z_0)^2$, Z and Z_0 being the atomic numbers of residual gas and air respectively.

Eq. (2) is based on the conversion coefficients from fluence to tissue absorbed dose calculated by Rogers [Ro84], in the case of a broad parallel beam incident on a 30 cm semi-infinite tissue slab. Since the gas bremsstrahlung beam is confined to a very narrow cone, the absorbed doses evaluated by eq. (2) should be surely conservative. Moreover eq. (2) refers to ideal conditions seldom verified in practice, since it is very unlikely that no absorber is present between target and point of interest.

2 Main Rings

2.1 Dose rate estimate for the straight sections

The straight sections of the Main Rings are about 3.7 m to 14.4 m long. We have considered four of these straight sections 3.7, 5.6, 10 and 14.4 m long explicitly in our simulation by the FLUKA code.

Some results are shown in the fig. 1, 2 and 3, which refer to a 510 MeV circulating beam of 3.10^{19} e^-/s or e^+/s at a pressure of 10^{-9} torr.

Fig. 1 shows, as an example, the photon energy spectrum in the forward direction, in terms of fluence rate, in a location 1 m distant from the end of a straight section 3.7 m long. The radius of the scoring area was 0.05 cm.

In the case of the other straight sections investigated, the spectra have resulted practically superimposed to that of fig. 1.

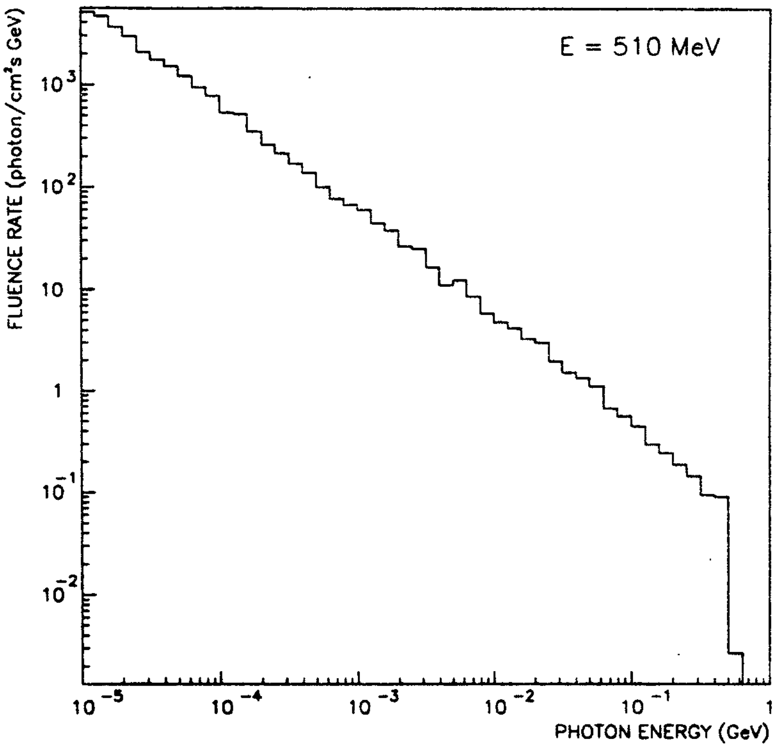

FIG. 1 – Photon energy spectrum in a location 1 m distant from the end of straight section 3.7 m long operating at pressure of 10^{-9} torr, in the case of a 510 MeV circulating beam of 3.10^{19} e–/s.

Fig. 2 and 3 show the fluence rate and the absorbed dose rate respectively as a function of L/d(L+d), in the case of the four straight sections considered.

For greater convenience the values of these two quantities at various distances (d) from the end of the straight sections, according to eq. (1) and (2), are shown in tab. I and tab. II respectively.

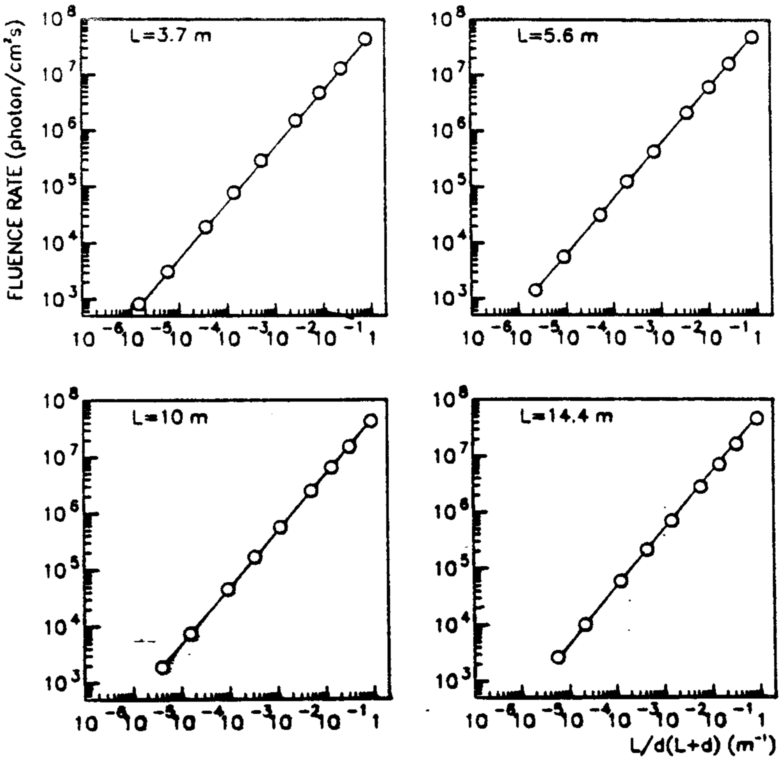

FIG. 2 – Photon fluence rate as function of L/d(L+ d) for some typical straight sections of the Main Rings operating at a pressure of 10^{-9} torr, in the case of 510 MeV circulating beam of 3.10^{19} e–/s.

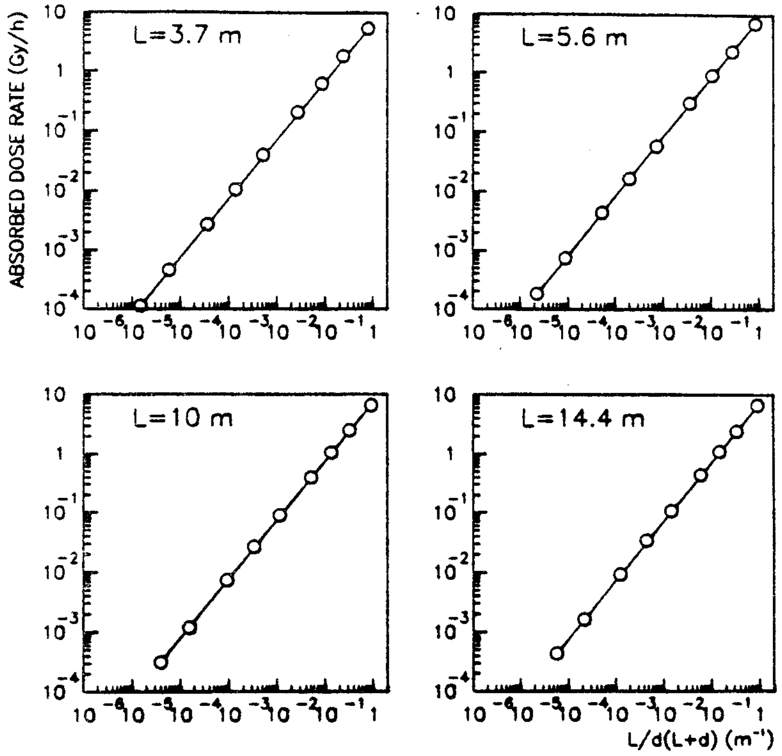

FIG. 3 – Tissue absorbed dose rate as a function of L/d(L+ d) for some typical straight sections of the Main Rings operating at a pressure of 10^{-9} torr, in the case of a 510 MeV circulating beam of 3.10^{19} e⁻/s.

Tab. I Fluence rate (photon/cm^{2}s), corresponding to the maximum current circulating in the Main Rings, as a function of the length of the straight section L and of the distance d from its end at a pressure of 10^{-9} torr.

d (m)	L=3.7 m	L=5.6	L=10 m	L=14.4 m
1.00E+00	4.48E+07	4.83E+07	5.18E+07	5.33E+07
2.50E+00	1.36E+07	1.58E+07	1.82E+07	1.94E+07
5.00E+00	4.85E+06	6.02E+06	7.59E+06	8.46E+06
1.00E+01	1.54E+06	2.04E+06	2.85E+06	3.36E+06
2.50E+01	2.94E+05	4.17E+05	6.51E+05	8.33E+05
5.00E+01	7.85E+04	1.15E+05	1.90E+05	2.55E+05
1.00E+02	2.03E+04	3.02E+04	5.18E+04	7.17E+04
2.50E+02	3.32E+03	4.99E+03	8.76E+03	1.24E+04
5.00E+02	8.37E+02	1.26E+03	2.23E+03	3.19E+03

Tab. II Tissue absorbed dose rate (Gy/h), corresponding to the maximum current circulating in the Main Rings, as a function of the length of the straight section L and of the distance d from its end at a pressure of 10^{-9} torr.

d (m)	L=3.7 m	L=5.6	L=10 m	L=14.4 m
1.00E+00	5.97E+00	6.43E+00	6.89E+00	7.09E+00
2.50E+00	1.81E+00	2.10E+00	2.42E+00	2.58E+00
5.00E+00	6.45E-01	8.01E-01	1.01E+00	1.12E+00
1.00E+01	2.05E-01	2.72E-01	3.79E-01	4.47E-01
2.50E+01	3.91E-02	5.55E-02	8.66E-02	1.11E-01
5.00E+01	1.04E-02	1.53E-02	2.53E-02	3.39E-02
1.00E+02	2.70E-03	4.02E-03	6.89E-03	9.54E-03
2.50E+02	4.42E-04	6.64E-04	1.17E-03	1.65E-03
5.00E+02	1.11E-04	1.68E-04	2.97E-04	4.24E-04

Of course fluence and absorbed dose rates will be ten times lower if the operating pressure in the Main Rings is 10^{-10} torr.

The shield suggested, 20 cm of lead at the end of each straight section [Es92], in addition to the structural wall of the building housing the machine, 1 m of concrete thick, seems completely adequate. In fact, the attenuation introduced by the lead will be at least a factor 10^3 on the basis of measurements carried out at ADONE at 1.5 GeV [Es86] or a factor about 10^4, according to the results of calculations performed by the Monte Carlo code EGS4 at 500 MeV [Tr90]. The absorbed dose rate at a distance of 10 m from the end of the longest straight section would be $4.5 \cdot 10^{-4}$ Gy/h or $4.5 \cdot 10^{-5}$ Gy/h, according to which of the two above mentioned attenuation factors is considered. The concrete wall of the building will introduce in addition a further attenuation factor of 100 at least [IAEA79].

With the shields suggested, the dose rates should be still acceptable if the pressure in the vacuum chamber is a factor 10 or 100 worse than expected.

2.2 Dose rate estimate for the bending magnets

In the case of a bending magnet the arc length which contributes to the gas bremsstrahlung is the magnetic length. The absorbed dose rate $\dot{D}_{bm}$ can be approximately estimated from the results obtained by eq. (2), considering a straight section of length equivalent to the magnetic length and taking into account the different surfaces over which the photons emitted are spread:

$$\dot{D}_{bm} = \dot{D}_{ss}\frac{L_{bm}}{L_{ss}}\frac{L_{ss}+d}{L_{bm}+d}\frac{S_{ss}}{S_{bm}} \tag{3}$$

where $\dot{D}_{ss}$ is the absorbed dose rate at a distance d from the end of a straight section L_{ss} long, L_{bm} the magnetic length, S_{ss} and S_{bm} the surfaces where the photons emitted can be considered spread in the two cases.

At a distance of 10 m from the end of a straight section some meter long, the gas bremsstrahlung spot covers a surface S_{ss} approximately circular of radius R equal to about 1 cm [Fe93b]. The surface S_{bm} can be in turn approximated to an ellipse (or to a rectangle) of semiaxes R and $(d+\varrho)\alpha/2$, where ϱ and α are the radius and the opening angle of the bending magnet respectively. Therefore eq. (3) becomes:

$$\dot{D}_{bm} = \dot{D}_{ss}\frac{L_{bm}}{L_{ss}}\frac{L_{ss}+d}{L_{bm}+d}\frac{2R}{\alpha(d+\varrho)} \tag{4}$$

Calculations have been done in the case of some representative magnets of the Main Rings, the parameters of which have been deduced from [Bi92, Bi93]. The results, in terms of tissue absorbed dose rates at a distance of 10 m, are given in tab III.

Tab. III Tissue absorbed dose rate, corresponding to the maximum current circulating in the Main Rings, at a distance 10 m from some representative magnets (pressure: 10^{-9} torr).

Magnet	l (m)	ϱ (m)	α (rad)	$\dot{D}_{bm}$ (μGy/h)
BENDING	1.21	1.40	0.86	167
BENDING	0.99	1.40	0.71	169
DHRTE01	0.76	1.46	0.52	180
SPTTE01	1.23	2.08	0.59	233

The radiation dose rates shown in tab. III are not sufficient enough to require some additional shielding to the concrete wall of the building housing the machine.

3 Damping Ring

3.1 Dose rate estimate for the straight sections

In the case of the Damping Ring the maximum circulating current will be about 135 mA and the operating pressure could be even 10^{-8} torr. The longest straight section of this machine is 3.5 m long. The absorbed dose rates obtained from eq. (2) as a function of the distance are summarized in tab. IV.

Tab. IV Tissue absorbed dose rate (Gy/h), corresponding to the maximum current circulating in the Damping Ring, as a function of the distance d from the end of a straight section 3.5 m long at a pressure of 10^{-8} torr.

d (m)	$\dot{D}(Gy/h)$
1.00E+00	1.63E+00
2.50E+00	4.90E-01
5.00E+00	1.73E-01
1.00E+01	5.44E-02
2.50E+01	1.03E-02
5.00E+01	2.75E-03
1.00E+02	7.10E-04
2.50E+02	1.16E-04
5.00E+02	2.92E-05

In the case of the Damping Ring the radiation emitted has to pass through the iron of the magnets (TVL=10.82 cm) along an effective path of about 19 cm. The attenuation introduced is about a factor 56. An additional factor 134 at least is due to the general shielding, 1 m of concrete thick (TVL=47 cm). The dose rate in a location at a distance of 10 m from the end of the straight section considered will be at most 7.2 μGy/h.

This figure could be accepted, taking into account the short time of operation of this machine and the very small size of the gas bremsstrahlung spot of which we are dealing with. Moreover at the end of the most part of the straight sections of the Damping Ring there will be a lead shield installed with the aim to attenuate the secondary radiation produced by the beam-losses during the injection. In case, lead shield may be added at the end of the other straight sections too, according to the destination of the surrounding areas. A lead shield 5 cm thick beside the magnets is sufficient to reduce the gas bremsstrahlung dose rate of an additional factor of ten.

3.2 Dose rate estimate for the bending magnets

The dose rates originated by interactions occurring in a bending magnet of the Damping Ring, are expected to be lower than in the case of the Main Rings, due to the minor current circulating in this machine and to the self-shielding in the magnets.

As an example, calculations have been carried out in the case of a bending magnet and of an injection septum, according to their parameters quoted in [Ma92]. The results obtained neglecting the self-shielding are shown in tab. V.

Tab. V Tissue absorbed dose rate, corresponding to the maximum current circulating in the Damping Ring, at a distance 10 m from some magnets (pressure: 10^{-8} torr).

Magnet	l (m)	ϱ (m)	α (rad)	$\dot{D}_{bm}$ (μGy/h)
BEND031	0.86	1.1	0.78	38.4
SPTTR01	1.23	2.08	0.59	64.5

The dose rates become completely negligible behind the general shielding of the building housing the machine.

4 Maximum credible accident

Many authors have attempted to determine the upper bound for possible accidents around a storage ring by estimating the gas bremsstrahlung dose due to an istantaneous vacuum loss [Bl80, Ry81, Th82, Sw85, Es86, Mo91]. All these evaluations are quite conservative and the large differences among the results probably denote poor reliability. According to these calculations, the increase of pressure should occurr in a short segment of the guide, a point in the border-line event, suddenly brought up to the atmospheric pressure.

Actually, in the case of a realistic accident, the pressure inside the ring should grow in a defined interval of time. The increase of pressure should propagate in the ring and the circulating beam should be destroyed right before the pressure reaches the atmospheric value.

Moreover our machine will have a set of sector valves with a response time of about 1 s. A vacuum loss could reasonably occur because of the rupture of a feedthrough, due to thermal expansion or material imperfection. Since the sublimation pumps would go on working at very high speed, the vacuum machine experts estimate that the pressure inside the Main Ring, in 1 s, could rise at the most a factor thousand (i.e. from 10^{-9} torr to 10^{-6} torr) [Ch93].

We can estimate the dose due to a vacuum loss, evaluating the number of traversals of a straight section made by the electrons during 1 s. A straight section of lenght L will be crossed c/L_{MR} times, for a time $t_1 = L/L_{MR}$, where c is the light velocity and L_{MR} the lenght of a ring.

Assuming conservatively, during the accident, the upper value of 10^{-6} torr for the pressure and the maximum circulating current, by eq.(2), the tissue absorbed dose at a distance of one meter from the end of a straight section 10 m long, would result about 1Gy.

Let us imagine an accidental circumstance consisting on a bad working of all the sector valves too. This event may occurr, but the probability is extremely low. Nevertheless we have also evaluated the dose in such a circumstance.

In order to describe the vacuum loss, for the sake of semplicity, we have assumed that the entry of air molecules creates a region of uniform pressure p whose volume increases along the ring at thermal velocity.

We have supposed that the electrons, passing through this region, lose energy only by bremsstrahlung in the air until the beam is completely destroyed. Therefore the electrons will cover a mean path S(p):

$$S(p) = -ln(1 - \frac{\Delta E_{max}}{E})X_0(p) \tag{5}$$

where X_o(p) is the radiation lenght at pressure p, ΔE_{max} the maximum energy loss allowed to an electron of energy E to remain in orbit.

The fraction ΔE_{max}/E is determined by the acceptance of RF cavities and in the case of the Main Rings should be equal to 2.2%.

According to the value of the pressure into the air region, we can consider two different situations: a) the pressure is so low that the electrons still make a very long path after the filling of the ring; b) the pressure is so high that the electrons cover the whole path S(p) within the time required to the filling, or the path made after is comparable to that one covered during the filling.

Case a) occurs at pressure values lower than 10^{-5} torr. The number of turns of the electrons is approximately equal to S(p)/L_{MR}. A straight section of lenght L will be crossed S(p)/L_{MR} times, during a time t given by:

$$t = \frac{L}{L_{MR}}[-ln(1 - \frac{\Delta E_{max}}{E})]\frac{X_0(atm)}{c}\frac{p_{atm}}{p} \qquad (6)$$

The tissue absorbed dose, in the same conditions previously considered, results equal to about 4 Gy. Such a dose would be received in different time depending on the vacuum pressure: about 20 s at 10^{-6} torr, about 2 s at 10^{-5} torr, etc.

Case b) occurs at pressure values above or equal to 10^{-5} torr. A straight section of lenght L will be crossed for a time Ln(p)/c, where n(p) is the number of turns corresponding to the path S(p) made by the electrons. We have evaluated n(p) taking into account that the fraction of path S(p), covered during the filling, is given by the multiple traversals of the air region whose volume increases with the time.

The absorbed dose results of about 4 Gy at 10^{-5} torr and it would increase up to several tens of Gy at higher pressures.

Since about 10 s are necessary to achieve a pressure of 10^{-5} torr and about 2 s is the time required to lose completely the beam at this pressure, we can assume that the duration of beam circulation can not be over 12 s. During this time, the pressure inside the guide should not exceed values of the order of 10^{-5} torr and according to the previous results the dose would be about 4 Gy.

This figure is at least two order of magnitude smaller than that obtained using the approach of the other authors.

At last, it should be noted that, assuming a beam life of 4 hours, during the normal operation, a dose of 4 Gy will be accumulated in the same location in about 0.62 h.

In case, higher doses could be accumulated during prolunged injections in the Main Rings in presence of a bad vacuum in the guide.

5 Conclusion

In conclusion the doses due to the gas bremsstrahlung from the DAΦNE Project can be easily reduced by suitable lead shield installed at end of each straight section.

No supplementary shielding is on the contrary required around the bending magnets.

Since dose rates unacceptable could occurr in the case the pressure rose unexpectedly, the injection is planned to be automatically prevented when the pressure in the vacuum chambers will exceed some fixed level.

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