The Condition of γ-ray Emission by Electrons Interacting with the Wall in Medium Energy Electron Storage Rings

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Abstract

The condition of γ-ray emission is reported on medium energy electron storage rings. The electrons interact with the wall during injection and after being scattered by residual gas molecules or by mutual Coulomb interaction while circulating in the ring. It is shown that the location where heavy interaction occurs can be determined from the injection condition and the design condition of the electron orbit. The angle, by which the electrons impinge on the wall, is usually about 1° or less to the surface. The γ-ray emitted to the side of building walls in this case can be effectively shielded by the material located along the beam ducts. An important point is that, in shallow impinge of electrons, convergent γ- ray emission occurs in the back scattering direction of electrons. By installing additional shielding materials for this convergent emission, the thickness of building shielding walls can be effectively alleviated.

I. INTRODUCTION

Synchrotron radiation emitted from medium energy electron storage rings is a candidate to be used for lithography to produce future large scale integrated circuits. Since the machine is to be used in the industrial community, the cost effectiveness becomes an important issue. This is also the case for the building structure to shield γ-ray and the accompanied neutrons. This paper analyses the process, in which the electrons interact with the wall, and tries to propose an effective way to shield γ-ray.

It is well-known that the γ-ray is convergently emitted in the direction of electron path way and that the accompanied neutron emission, in contrast, is rather isotropic. It has been shown that the γ-ray is self-shielded by the target and its emission tends to be isotropic when electrons collide on the target in grazing incidences [1]. This is considered to be a key to effectively reduce the thickness of the building shielding wall. This paper is organized as follows. In Sec. 2, electron-wall interaction in beam ducts is analyzed, showing that the electrons impinge on the wall in very shallow angles and that the location, where severe interaction occurs, can well be identified depending on magnet lattice structures and on electron scattering mechanisms. Sec. 3 describes the γ-ray emission for far grazing incidence of electrons. Sec. 4 discusses how to put additional shielding materials to alleviate the thickness of building shielding walls, which is followed by conclusions in Sec. 5.

II. ELECTRON-WALL INTERACTION

In usual multi-turn injection, the electron orbit is rather slowly retrieved to the original position to try to keep the injected amount highest. The electrons inevitably interact with the inflector wall in this method [2]. The incident angle (measured from the wall surface) in this case is given by [3]

$$x_i' = A_i \gamma_{xi} , \quad (1)$$

$$A_i = (x_{inj} - x_o)^2/\beta_{xi} , \quad (2)$$

$$\gamma_{xi} = (1+\alpha^2_{xi})/\beta_{xi} , \quad (3)$$

$$\alpha_{xi} = -\beta'_{xi}/2 , \quad (4)$$

where the subscript i denotes the inflector location, x_{inj} is the horizontal displacement of the injection point, x_o is the retrieving orbit center, and β_x is the horizontal betatron function. Suppose x_{inj} = 0.045 m, x_o = 0 to make the value of x'_i maximum, β_{xi} = 5 m, and β'_{xi} = 4, the x'_i obtained is 0.02 rad (1.1°). It should be pointed out that during injection the electrons interact with the wall mainly at the inflector location, once the closed orbit distortion is corrected.

Initial large orbit oscillation of injected beams is reduced by radiation damping. The electrons, thereafter, impinge on the wall surface only when they receive large scattering either by interaction with residual gas molecules or by mutual Coulomb interaction. First, in elastic scattering with residual gas molecules, the betatron oscillation itself is increased. Since the duct size is usually smaller in the vertical direction, the interaction occurs when the vertical oscillation, given by the following equation, is beyond the wall position.

$$y = \theta_s^2 \beta_y \beta_{ys} , \quad (5)$$

where θ_s is the scattering angle, β_y is the vertical betatron function at the interaction point, and β_{ys} is the one where the scattering takes place. After averaging with respect to the elastic scattering throughout the ring, the value of θ_s, which is necessary for electrons to hit the wall, is given by

$$\theta_{sw} = A_y / \beta_y \beta_y \quad (6)$$

where A_y is the duct half height, and β_y is the value averaged along the beam orbit. According to the equation of Moeller scattering [4], the dependency of the total cross-section in elastic scattering is given as

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$$\sigma_c \propto 1/\theta^2_{sw} \propto \beta_y\beta_y/A^2, \quad (7)$$

showing that the probability of electron–wall interaction in this case is almost linear to the value of β_y in each position. After analyzing the beam trajectory in phase space, the following incident angle is obtained as the most typical value.

$$y'_w = \alpha_y\sqrt{\varepsilon_y/\beta_y}, \quad (8)$$

$$\alpha_y = -\beta'_y/2, \quad (9)$$

$$\varepsilon_y = A_y^2/\beta_y. \quad (10)$$

Taking A_y = 2 cm, β_y = 8 m, and β'_y = 7 as an example, the value of y'_w is 0.0087 rad (0.52°). General trends are that the larger θ_s, which is of smaller probability, gives the larger y'_w because the electron–wall interaction occurs in the smaller β_y.

The other way of interaction with residual gas molecules is Bremstrahlung radiation induced by nuclear atoms and direct interaction with the molecule orbital electrons. In these two processes as well as in mutual Coulomb interaction, the electrons loose the energy beyond the aperture of rf acceleration. After circulating numerous times in the ring, they reach the energy in which the electron orbit displacement is beyond the wall position. It is evident that the electron–wall interaction of this kind occurs near the place where the momentum dispersion function η is maximum. The typical incident angle in this case is given by

$$x'_w \simeq \eta'_w A_x/\eta_{max}, \quad (11)$$

where A_x is the horizontal duct half size, and the subscript w means the typical position near the maximum η. Taking A_x = 5 cm, η'_w = 1.5, and η_{max} = 4 m as an example, the value of x'_w is 0.019 (1.1°).

The numerical examples stated in this section are what we think most probable for each case. These values may be increased mainly depending on the magnet lattice structures. We would further state that this increase is within a factor of 2 in the kind of the machines related to this study.

III. γ–RAY EMISSION

Electromagnetic interaction process between electrons and wall materials for very shallow incidence of electrons was simulated by using the Monte Carlo computer code EGS4 written by Nelson et al. [5]. Fig. 1 shows the angular dependence of the γ–ray emission for the electron energy of 1 GeV and the incident angle Ψ_i of 1°. To show the dependence, the angle Ψ_e was counted in the direction in which the γ–ray goes through the target. Since the target is the duct wall in real cases, this direction is hereafter called a wall side. When the target thickness d is 2 mm, the line–of–sight electron path length, d/sin Ψ_i, is 11.4 cm. This indicates that the incident electrons still have an energy of several 10 MeV when they come out of the wall. The γ–ray emission, therefore, has a peak in the direction of incident electrons. When the d is

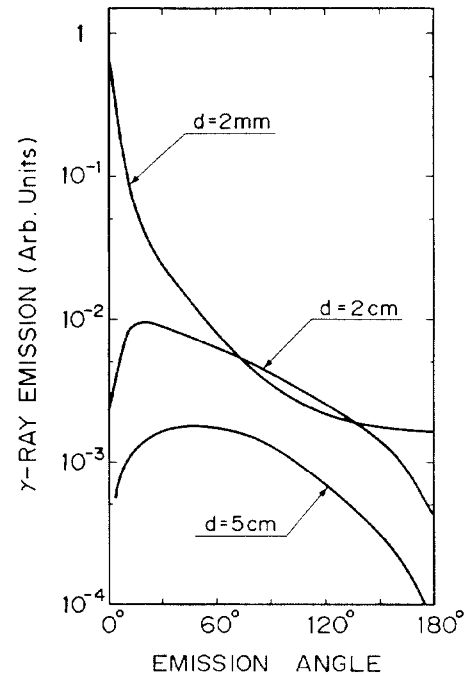


Fig. 1 Angular dependence of the γ–ray emission for the electron energy of 1 GeV, the incident angle of 1°, and different target thicknesses (d). The emission is the mean value inside the emission angle.

increased to 2 cm, the incident electrons are completely stopped in the forward direction. The γ–ray produced near the entrance region is effectively shielded, which results in disappearance of the convergent emission. The scattered electrons, by the way, yield slightly higher γ–ray emission near Ψ_e = 90°, compared with the case for d = 2 mm. By increasing the d to 5 cm, the γ–ray emission becomes much less than the d = 2 mm case throughout the emission angle.

The convergent γ–ray emission always exists in the electron backscattering direction, which is hereafter called a vacuum side. Fig. 2 compares the angular dependence of the γ–ray emission of the vacuum side in d = 5 cm with the one of the wall side in d = 2 mm. The electron energy and the incident angle are the same as for Fig. 1. The γ–ray emission of the vacuum side is observable over Ψ_e = 1° in the figure. It has a peak near Ψ_e = 2.5°, the maximum value of which is about a forth of the emission in d = 2 mm and $\Psi_e \sim 0°$. Although the vacuum side emission becomes slightly larger than the wall side one for d = 2 mm over Ψ_e = 10°, these two curves behave quite similarly in the region $\Psi_e > 2.5°$, indicating that the shielding effect for the released γ–ray is accidently comparable between these two cases.

IV. DISCUSSION

It was shown that the place, where electron impinge on the wall is highly localized, is injection sections and near the position with η_{max}. The scheme of local shielding for the latter is shown in Fig. 3. It is common in separated function lattices that the η_{max} is located in quadrapole magnets. To shield the wall side emission, additional shielding material is installed

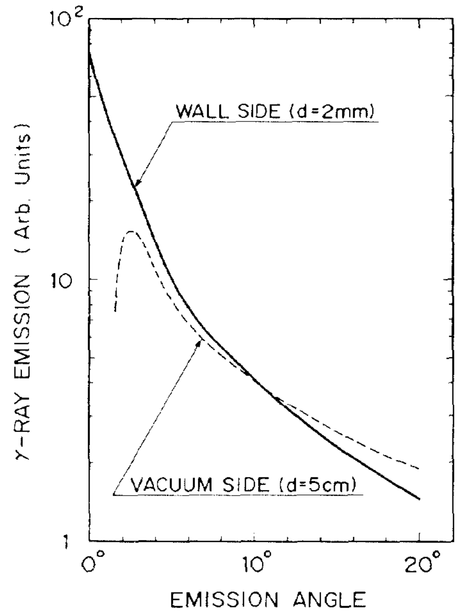


Fig. 2 Angular dependence of the γ-ray emission for the wall side in d=2 mm and for the vacuum side in d=5 cm.

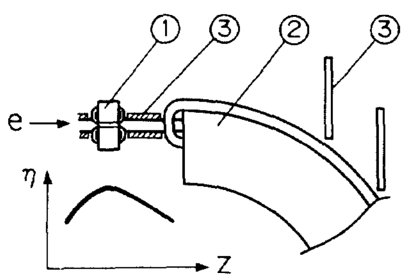
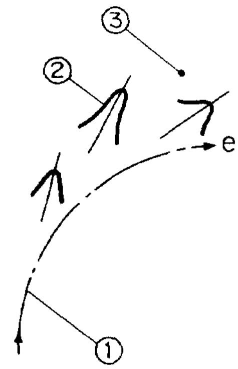


Fig. 3 Arrangement of local shielding for straight sections: 1 quadrapole magnet; 2 bending magnet and 3 shielding material.

along the beam duct. Special care was taken for the vacuum side emission, since the convergently emitted γ-ray can reach bending sections and go through the gap of magnet iron cores. Additional shielding blocks are installed in front of the straight section, the detailed arrangement of which should be determined depending on the neighboring hardware structures. As for the γ-ray emission from the injection sections, thin inflector walls give highly convergent emission which is something like the wall side emission for d = 2 mm plus the vacuum side emission. Local shielding should properly be designed considering these angular dependences.

The γ-ray emission in the bending sections is mainly attributed to the electrons elastically scattered by residual gas molecules. As was described in Sec. 2, the electron impinge in this case is in vertical direction. The γ-ray emitted on the wall side is therefore shielded by the magnet iron core. The important matter again is the vacuum side emission which can go through the iron core gap. The point, which is different from the case in the straight sections, is that the electron-wall interaction is distributed depending on the β_y value and that the γ-ray emission direction is correspondingly distributed, as is shown in Fig. 4. If one calculates the γ-ray absorption at any point near the bending magnet, the following equation may be

Fig. 4 γ-ray emission from bending sections: 1 electron orbit; 2 emitted γ-ray; and 3 estimation point.



applied for an order of estimation.

$$I_{ab} = I_c \, f_c \, f_v \, f_b \, f_i \,, \qquad (12)$$

where I_c is the reference value which is, in this case, the emission at $\Psi_e \sim 0°$ in d = 2 mm in Fig. 1, f_c denotes the fraction of all the stored electrons which impinges on the wall after elastic scattering with residual gas molecules, f_v is the mean ratio of the vacuum side emission with the reference emission, f_b is the fraction of the elastically scattered electrons whose γ-ray emission has a chance to project any estimation point near the bending magnet, and f_i denotes the averaging factor by integration with respect to projecting directions and lengths. Although the exact value of each f should be determined by detailed simulation analysis, we would suggest to use the following to draw a crude image: $f_c = 1/3$; $f_v = 1/2$; $f_b = 1/8$; and $f_i = 1/10$. These conditions give $I_{ab} = I_c/480$, indicating that almost no additional shielding is necessary for the related γ-ray emission.

V. CONCLUSIONS

The condition of γ-ray emission was studied on medium energy electron storage rings. It was shown that the location where heavy electron-wall interaction occurs can well be identified and that electron impinge takes place in shallow angles. Effective ways to shield the convergently emitted γ-ray were proposed on the basis of the angular dependences of the emission. It should be pointed out that the convergent emission is mainly attributed to electron-wall interaction in straight sections and that the emission from bending sections themselves is more or less divergent.

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