Study on CYCIAE-100 radiation field and residual radioactivity

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Abstract The accelerators should be properly designed to make the radiation field produced by beam loss satisfy the dose limits. The radiation field for high intensity H^- cyclotron includes prompt radiation and residual radiation field. The induced radioactivity in accelerator components is the dominant source of occupational radiation exposure if the accelerator is well shielded. The source of radiation is the beam loss when cyclotron is operating. In this paper, the radiation field for CYCIAE-100 is calculated using Monte Carlo method and the radioactive contamination near stripping foil is studied. A method to reduce the dose equivalent rate of maintenance staff is also given.

Key words cyclotron, beam loss, radiation field, Monte Carlo

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1 Beam loss for CYCIAE-100

Beam loss is the source of radiation field in accelerators. For H^- cyclotrons, the beam losses caused by magnetic stripping and residual gas stripping during acceleration are very important.

The outer-shell electron affinity of H^- is only 0.75 eV, therefore the strong rest-frame electric field produced by the magnetic field can strip H^- to neutral H^0[1]. The magnetic stripping mainly happens at high energy and it is the most important loss mechanism.

The electron loss section for H^- collisions with residual gas in vacuum tank is inversely proportional to the square of ion velocity[2], thus residual gas stripping dominants at low energy. A good vacuum is necessary to reduce the residual gas stripping loss.

For CYCIAE-100[3], the geometric model and the beam loss bombarding the inner wall of vacuum tank are shown in Fig. 1. The vacuum tank is made of aluminum alloy LF2 and the material of magnetic yoke is iron. In order to limit the magnetic stripping losses at higher energies, the hill field is limited to

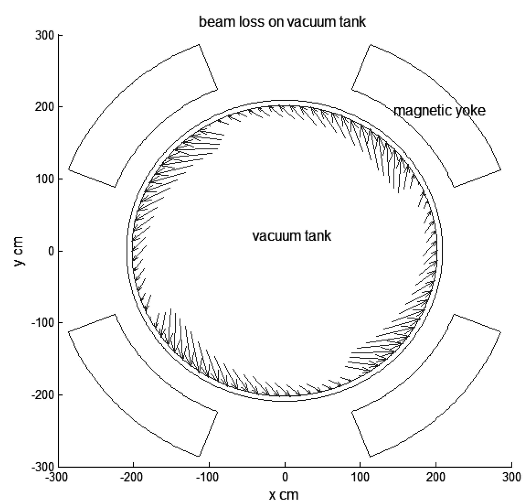

Fig. 1. The geometric model and the beam loss bombarding the inner wall of vacuum tank. The direction and magnitude of beam loss are displayed as arrows. It is assumed that the beam loss is uniform from $z = -0.5$ cm to 0.5 cm.

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1.32 T. The vacuum level is 2E-8 Torr according to the requirements of the beam loss portion by vacuum dissociation. The lost particles, whose distribution depends on the azimuth and the energy of lost beam, bombards the inner wall of vacuum tank with the direction and magnitude as displayed by the arrows. The total beam loss is about 1.62 μA.

2 The radiation field

For proton accelerators having energies higher than 10 MeV, neutrons are usually the dominant feature of the prompt radiation field that results from their interactions[4]. The prompt fields should be well shielded to reduce the occupational radiation exposure. However, considering the maintenance, accelerator designers and operators are more interested in the residual radiation level at some definite time after machine shut-down.

A multi-purpose Monte-Carlo code 'FLUKA' is adopted for the simulation of radiation field[5—6]. The build-up and decay of radioactive isotopes are treated with an exact analytical solution of the Bateman equations[6]. For serial decay chains, assuming that the concentrations of all the daughters are initially zero (i.e. , $n_i(0)=0$ for $i>1$), the concentration of the $i^{\rm th}$ radionuclide can be determined from[7]

$$n_i(t)=\lambda_1\lambda_2\cdots\lambda_{i-1}n_1(0)\sum_{j=1}^{i}e^{-\lambda_j t}/\prod_{\substack{k=1\\k\neq j}}^{i}(\lambda_k-\lambda_j), \quad (1)$$

where λ_i is the decay constant of the $i^{\rm th}$ radionuclide.

Figure 2 shows the contour lines for prompt radiation fields. It is about 0.5 Sv/h at radius of 300 cm without yoke and 11.6 mSv/h due to the shielding of yoke. This result is used for the design of local shielding.

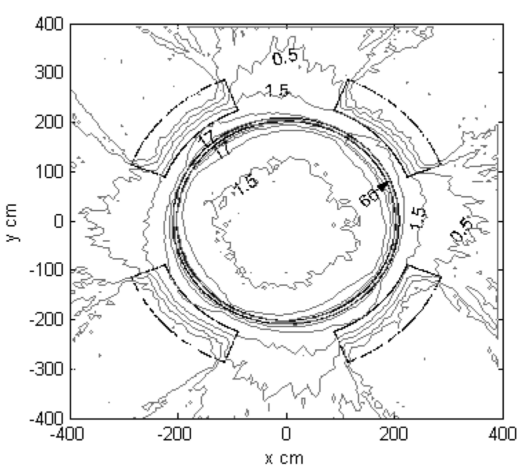

Fig. 2. The contour lines for prompt radiation fields (unit: Sv/h).

The residual dose equivalent rate as function of cooling time for different distances from the accelerator centre and different azimuth angle is shown in Fig. 3. After a cooling time of 20 hours, it has a value of about 36 mSv/h at R of 200 cm and θ of 45^o. The residual dose equivalent rate at θ of 45^o is higher than θ of 0^o since the beam loss is more concentrated there.

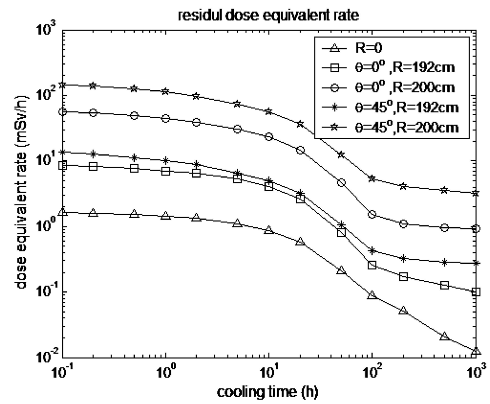

Fig. 3. The residual dose equivalent rate as a function of cooling time after 10 days of operation. R is the distance from the accelerator center and θ is the azimuth angle.

3 The radioactive contamination

A thin foil is adopted to extract beam by stripping in the cyclotron. Because of the thermal effect of the deposited energy by the passing beam, the temperature of the foil will be very high. There may exist radioactive contamination near the stripping foil since the evaporation of radioactive species produced in the foil. For residual radiation considerations, Be7 is the most important radionuclide produced in carbon foils.

If we bombard a target for a time t_i and then let it decay for a time t_c, then the specific activity after the cooling time will be

$$A(t_c)=N\sigma\phi\{1-\exp(-\lambda t_i)\}\{\exp(-\lambda t_c)\}, \quad (2)$$

where N is the number density of target atoms, σ is the cross section for the production of radionuclide, ϕ is the flux density of the incident particles and λ is the decay constant.

Radioactive contamination is produced when the foil gets hot enough to evaporate carbon and carries Be7 along with it. The maximum temperature of the stripping foil of CYCIAE-100 is about 1000 K in the case of uniform distribution for 150 ug/cm^2 carbon foil, which is well below the evaporation point. Therefore, no evaporation will be observed and the radioactive contamination near the stripping foil is not a problem.

4 Method to reduce residual radiation

To reduce the residual dose which is critical for the machine maintenance, an absorber liner attached to the inner wall of vacuum tank is designed.

The absorber liner is placed around the periphery of the cyclotron vacuum tank to absorb the lost particles in the form of H° by both the magnetic stripping and the residual gas collisions. It is removable so as to change to a new one if the radioactive species produced in it is too concentrated.

For aluminum, iron and copper absorption liner, Fig. 4 shows the dose equivalent rates as a function of bombardment time for cooling time of 1 day, 1 week and 1 month. Though the stopping ranges of proton in iron and copper are shorter, considering both the space limitation and the residual radiation, aluminum

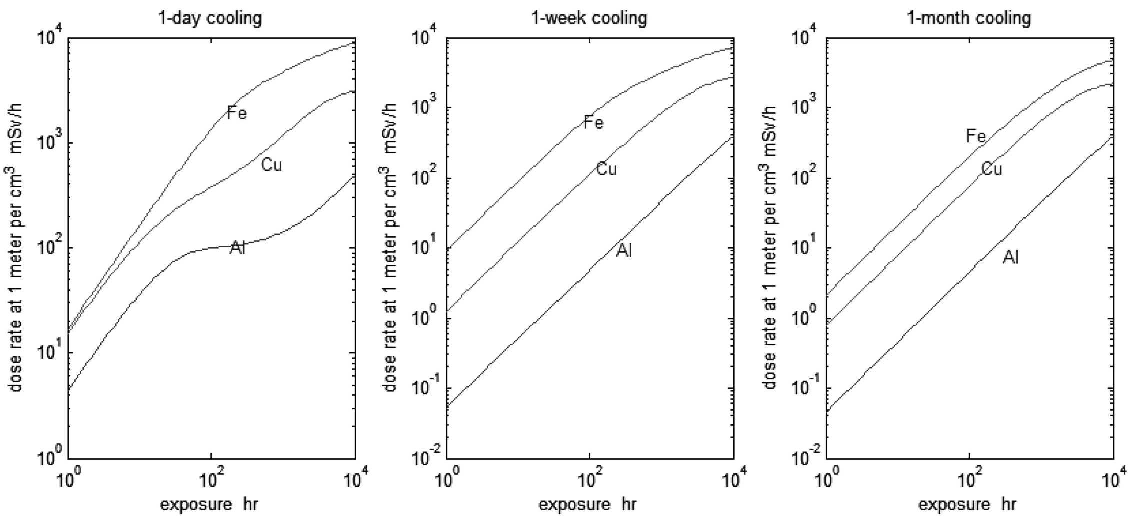

Fig. 4. The dose equivalent rates as a function of bombardment time for cooling time of 1 day, 1 week and 1 month.

is the best material. There are three main radioactive species produced in aluminum: Be7 with gamma energy of 0.5 MeV, yield of 10% and half-life of 54 days; Na22 with mean gamma energy of 2.2 MeV and half-life of 2.6 years; Na24 with gamma energy of 4.1 MeV and half-life of 15 hours.

Considering the incident angle of 45^o, an aluminum liner with the thickness of 26 mm and height of 40 mm is selected.

5 Conclusion

The beam loss for CYCIAE-100, namely magnetic stripping electron loss and residual gas collisions, will produce comparable radiation fields near the cyclotron. It leads to a prompt radiation field of about 0.5 Sv/h at radius of 300 cm without yoke and 11.6 mSv/h due to the shielding of yoke. The maximum of residual dose happens inside the vacuum tank. Considering both the contributions of vacuum tank wall and magnetic yoke, the induced residual field is about 10 mSv/h for a cooling time of 2 days at the radius of 200 cm. The effective dose rate doesn't exceed the reference levels, thus the design of magnet and vacuum system is reasonable. The radioactive contamination due to the evaporation of the stripping foil is not a problem for the maximum foil temperature of about 1000 K. A removable proton absorption liner in aluminum is designed to reduce the dose rate exposed to the maintenance staff.

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