RADIATION SHIELDING DESIGN FOR MEDICAL CYCLOTRON

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Abstract

With the increasing applications of cyclotrons in health care, a number of cyclotrons ranging from several MeVs to hundreds MeVs have used for radio diagnostic and radiation therapy. A 14 MeV PET cyclotron, CYCIAE-14, has been installed in a shielding building for tests at China Institute of Atomic Energy (CIAE) that can be used for FDG production. In the mean time, the development of a 230MeV cyclotron, CYCIAE-230, which can be used for proton therapy, is in progress at the same laboratory. In terms of the cyclotron application in factories and hospitals, an appropriate radiation shielding design is of critical importance.

This paper will give an introduction to the radiation shielding design for CYCIAE-14 and CYCIAE-230 respectively. The neutron source of different cyclotrons has been estimated to define the thickness of the total shielding, and the concrete is selected as the main shielding material. The typical layout for the application of the two machines is presented in this paper which can be applied in factories and hospitals as well.

Introduction

Medical cyclotron can be used for the radio diagnostic and radiation therapy. Positron Emission Tomography (PET) as a kind of radio diagnostic can be used in hospital. And 18F-fluorodeoxyglucose (FDG) is a widely used radio-pharmaceuticals for PET. Proton therapy as a cancer treatment is used in many hospital or institute in Europe, South Africa, and the USA [4].

Several kinds of medical cyclotron were developed at China Institute of Atomic Energy (CIAE). A 14MeV cyclotron, CYCIAE-14, was designed and built at CIAE which can be used for the production of FDG with an intense beam (up to 100 μA). In addition this kind of PET cyclotron can be used as a neutron source for boron neutron capture therapy (BNCT)[3]. In the mean time, the development of a 230 MeV/1μA cyclotron, CYCIAE-230, which can be used for proton therapy.

Efficient radiation shielding is very important for safe operation of modern hospital-based Medical Cyclotrons and Radiation Medicine Centre (RMC) for both producing large activities of short-lived radioisotopes and proton therapy [1][2][4].

This paper discusses the shielding design for CYCIAE-14 and CYCIAE-230.

Calculation Methode

The shielding calculations for CYCIAE-14 and CYCIAE-230 use the exponential dose attenuation:

$$\mathrm{H}\left(E_p,\theta,d(\theta)\right)=\frac{\mathrm{H}_0\left(E_p,\theta\right)}{r^2}e^{-\frac{d(\theta)}{\lambda(\theta)}} \qquad (1)$$

Where E_p is the proton beam energy, r is the distance from the target to the measuring point and d(θ) is the effective shielding thickness (i.e., the length of shielding material that is being traversed). $H_0(E_p,\theta)$ is the angle dependent source terms. And λ(θ) is attenuation lengths in shielding material [5].

Source Term Assessment

The shielding walls of CYCIAE-14 and CYCIAE-230 were determined by source term. Source term is generated from the proton beam hits the target or beam losses on the other accelerator components. For the proton accelerator, only neutron is considered for the shielding wall, because photon is much easier to shield than neutron and dose rate contributions outside the shielding wall from other secondary particles can be negligible [5].

For CYCIAE-14, only 1.4 kW FDG target is considered as source term, because most of power losses in this target. The composition of FDG target is 95% $H_2{}^{18}O$ and 5% $H_2{}^{16}O$. The $H_0(Ep,\theta)$ is calculated by MCNP shows in table1.

For CYCIAE-230, source term is treated as 250 MeV proton beam hit thick iron or copper target in cyclotron vault and beam line area. For the gantry room, tissue target is also considered. The evaluated beam losses in cyclotron components and device are listed in table 3.

Table 1: Source Terms of FDG Target

Angle bin	$H_0(10^{-15}$ Sv.m^2/p)	$H_0(E_p,\theta)$ (Sv.m^2/μA)
0-15	0.019	1.18E-04
15-30	0.017	1.08E-04
30-45	0.015	9.59E-05
45-60	0.014	8.68E-05
60-75	0.012	7.74E-05
75-90	0.011	7.05E-05
90-105	0.010	6.45E-05
105-120	0.0096	6.01E-05
120-135	0.0089	5.57E-05
135-150	0.0083	5.16E-05
150-165	0.0079	4.93E-05
165-180	0.0077	4.80E-05

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Table 2: Source Terms of CYCIAE-230 [4-6]

Angle bin	Iron H_0 (10^{-15} Sv.m^2/p)	Copper H_0 (10^{-15} Sv.m^2/p)	Tissue H_0 (10^{-15} Sv.m^2/p)
0-10	9.0	7.0	7.4
10-20	7.5	5.6	5.4
20-30	6.8	4.7	3.5
30-40	3.9	3.5	3.3
40-50	3.3	2.5	2.0
50-60	2.5	1.8	1.2
60-70	2.0	1.1	0.71
70-80	0.81	0.71	0.41
80-90	0.62	0.57	0.25

Table 3: Beam Loss Estimate of CYCIAE-230

location	Beam loss	rate	material
Cyclotron vault	100nA/250MeV	10%	Iron
ESS	1 μ A/250MeV	100%	Iron Copper
Beam line	1nA/250MeV	0.1%	Iron
Bending magnet	20nA/250MeV	2%	Iron
Experiment room	10nA/250MeV	1%	Iron Copper
Gantry room	1nA/250MeV	0.1%	Iron Copper Tissue

Estimation of Shielding Thickness

The shielding material uses 2.3 g/cm^3 ordinary concrete in CYCIAE-14 and CYCIAE-230. The attenuation lengths in ordinary concrete for CYCIAE-14 are calculated with MCNP. For all directions, $\lambda(\theta)$ is 24.2 g/cm^2 and the half value thickness is 7.31 cm. The does rate limit outside the shielding wall is 1 μ Sv/h. Therefore the thickness of shielding wall is 1.78 m at 0 degree, 1.73 m at 90 degree and 1.68 m at 180 degree. For the roof shielding, dose rate limit is 10 μ Sv/h. Therefore the roof is 1.48 m thick.

For the CYCIAE-230, the dose rate limit outside the shielding wall is 1 μ Sv/h and 10 μ Sv/h outside the roof. The attenuation lengths in ordinary concrete shows in table 4. All the shielding requirements for different source term show in table 5.

By the shielding requirements of two cyclotrons, the layouts of CYCIAE-14 and CYCIAE-230 which can be applied in factories or hospitals show in Figure 1 and Figure 2. For CYCIAE-14, shielding wall is 1.8m and roof is 1.5m. For CYCIAE-230 main shielding wall is 2m ordinary concrete. And local shielding should be used to meet the total shielding requirements.

Table 4: The Attenuation Lengths in Ordinary Concrete for CYCIAE-230[4-6]

Angle bin	Iron $\lambda(\theta)$ g/cm^2	Copper $\lambda(\theta)$ g/cm^2	Tissue $\lambda(\theta)$ g/cm^2
0-10	109	110	100
10-20	106	108	101
20-30	101	106	96.7
30-40	98.7	100	90.5
40-50	92.9	97	84.5
50-60	89	91	79.8
60-70	83.7	82	76.7
70-80	78.2	72	68.9
80-90	62.8	63	61.8

Table 5: Total Shielding Requirements for CYCIAE-230

location	Shielding thickness (m)	Roof (m)
Cyclotron vault	2.1	1.5
ESS	3.8	3.1
Beam line	2.0	1.4
Bending magnet	2.8	2.2
Experiment room	<5	1.5
Gantry room	<3.5	1.6

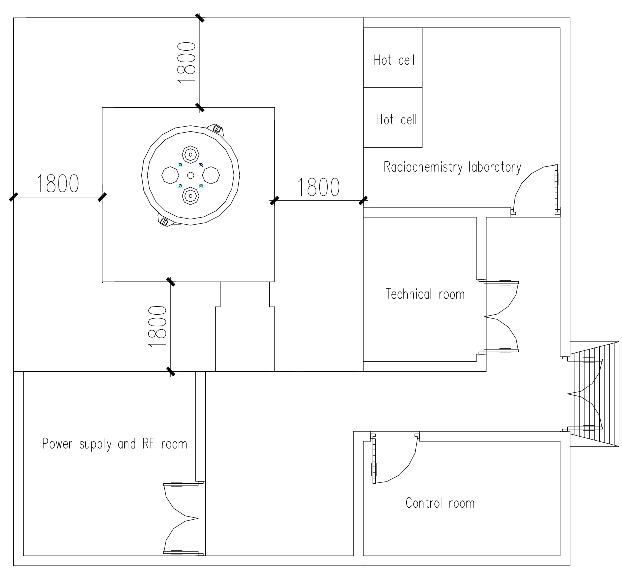

Figure 1: Layout of CYCIAE-14.

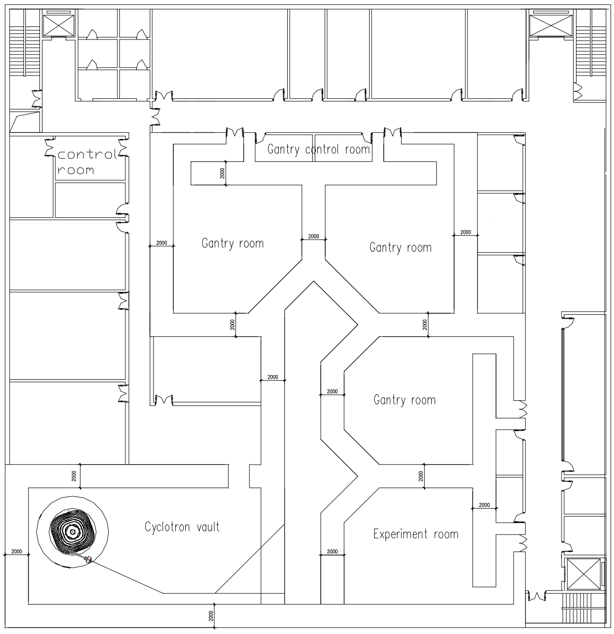

Figure 2: Layout of CYCIAE-230.

Summary and Discussion

The paper proves a preliminary shielding design for a PET cyclotron and a proton therapy cyclotron at CIAE. For the PET cyclotron vault, 1.8m ordinary concrete wall and 1.5m roof is applied at last. Shielding for CYCIAE-230 is more complex. The dose rate from different source term should be superposed and angle distribution can not be negligible. The shielding requirements can guide the layout design and Monte-Carlo computer code calculation is necessary in particular application. Specific local shielding should be used in particular area and cyclotron components such as experiment room and bending magnets.

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