MONTE-CARLO SIMULATION OF SYNCHROTRON RADIATION IN THE DESIGN OF CEPC VACUUM CHAMBER

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Abstract

The circular electron positron collider (CEPC) has been proposed by IHEP. Two 120GeV beams circulate around the 54km accelerator rings, which produce intense synchrotron radiation with photon energies up to a few of mega-electron volts. It is very important to analysis the source of synchrotron radiation. Two techniques of designing vacuum chamber which are contained Al covered by Pb and totally by Cu are put forward to protect sensitive machine components. A Monte-Carlo program called MCNP has been used to calculate dose rate, heat and energy spectrum of synchrotron radiation in the tunnel in former two designing cases. The results including dose rate, heat and energy spectrum which performed in various components of the CEPC are shown in this article.

INTRODUCTION

Synchrotron radiation (SR) is a kind of electromagnetic radiation which is released by charged particles, when the speed of particles is close to the speed of light (v ≈ c), while particles are moving in the magnetic field along the arc track. In CEPC, 120GeV electrons and positrons pass through the dipole magnets and focusing (quadrupole) magnets, which are always accompanied by the emission of SR. The spectrum of SR extends from the region of visible light through the energy range of ordinary diagnostic X-rays (hundreds of kilo-electron volts) up to ten mega-electron volts in the vacuum chamber. By calculation, the power of SR emitted per unit length is huge, which is up to 1KW/m. Hence, SR can bring about very high radiation dose rates in many components of accelerator and Air of the tunnel, which will induce the problems of heating of the vacuum chamber, radiation damage to machine elements, formation of ozone and nitrogen oxides in the air, further lead to corrosion of machine components and act [1],[2]. At present, two methods of designing vacuum chamber are proposed, there are including manufactured by Aluminum material [3],[4] and covered by lead shield, or fabricated totally by copper. Therefore, it is essential to confirm relevant parameters of these two choices, such as energy deposition, energy spectrum in every part of the tunnel, which could be used to calculate heat quantity, dose rate, the amount of harmful gases.

ANALYSIS OF SYNCHROTRON RADIATION SOURCE

In the accelerator, the spectrum of SR depends on the charge, the mass and energy of the particle and the bending radius. When determining the effects of SR, there are two important parameters including: the radiated power per unit beam path and the critical energy. The power of the synchrotron radiation emitted by the electrons and positrons per unit length is given by the simple expression:

$$P(W/m) = 14.08\frac{E(GeV)^4 I(mA)}{\rho(m)^2} \quad (1)$$

With P, the synchrotron power loss is in W/m;
E, the energy of electrons and positrons is in GeV;
I, the current of the circulating particles is in mA;
ρ, is the bending radius in meter.

The critical energy of synchrotron spectrum divides the emitting radiation power in two halves, which is defined by the following expression:

$$E_c(keV) = 2.218\frac{E(GeV)^3}{\rho(m)} \quad (2)$$

With E_C, the critical energy is in keV.

The energy spectrum of synchrotron radiation can be calculated by the following formula:

$$S\left(\frac{\omega}{\omega_c}\right) = \frac{9\sqrt{3}}{8\pi}\frac{\omega}{\omega_c}\int_{\omega/\omega_c}^{\infty} K_{5/3}(\eta) \quad (3)$$

With ω, the angular frequency of the synchrotron radiation photon in rad/s;
ω_c, the angular frequency of the critical energy photon in rad/s;
S, the relative share of spectrum in different frequency separation;
K, Bessel function.

992 blocks of magnets will be equipped in the main ring of CEPC, the bending angle would be given in this condition. Meanwhile, synchrotron radiation itself distributes as a solid degree, and the half angle of light cone is 1/γ, which is focused by 85% power of synchrotron radiation, γ can be expressed as:

$$\gamma = \frac{E_e}{mc^2} = 1957E_e(GeV) \quad (4)$$

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Table 1: Designing and Calculating Parameters of Synchrotron Radiation

Parameters of synchrotron radiation			values
Beam energy	E	GeV	120
Beam current	I	mA	16.60
Bending radius	ρ	m	6094
Power per unit length	P	W/m	1305.06
Critical energy	E_c	keV	628.93
Bending angle	θ	mrad	3.1669
Solid degree	φ	µrad	4.2582

According to formula 3, if photon energy is lower than 200keV, the following expression could be satisfied the energy spectrum.

$$S\left(\frac{\omega}{\omega_c}\right) = 1.333\left(\frac{\omega}{\omega_c}\right)^{1/3} \quad (5)$$

Though integration of the above formula and calculation of formula 3, it is only a small share of photons number in low energy area to compare with the total number of photons. And, these photons contribute a little of total heat and dose due to their energy. Although, the number of photons decreases with energy reduction when photon energy is lower than 200keV, we do a hypothesis that the number of these photons only contributes to heat in the vacuum chamber, the 1305.06M/m power of synchrotron radiation is totally contributed by the energy higher than 200keV for heat and dose in the air as shown in Figure 1. In this situation, calculation of heat and dose which are harmful to equipment would be conservative.

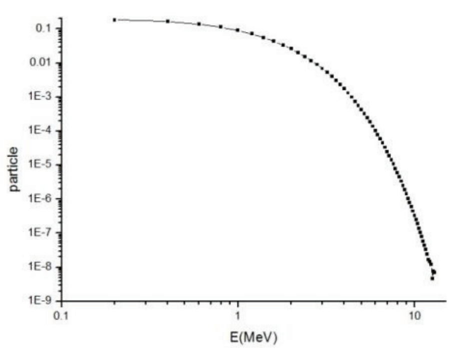

Figure 1: The photon spectrum of synchrotron radiation.

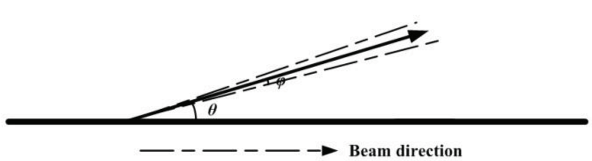

Figure 2: The direction of synchrotron radiation.

The photon spectrum of synchrotron radiation is calculated by formula 3. From energy spectrum and power, we could obtain the total number of photons in different energies. The average energy of photons is 0.9466MeV from the photon spectrum, and total number of photons is 8.62×1015S^{-1}m^{-1}. Due to previous hypothesis, power of the photons energy lower than 200keV is less than 40W/m which could be calculated by integration of average energy and total photon counting.In every point of beam direction, conical light of synchrotron radiation emits along a certain angle as shown in Figure 2.

MONTE-CARLO SIMULATION

In Monte-Carlo simulation, the tunnel and vacuum chamber of CEPC are regarded as straight sections, because the bending radius is larger than the distance which photons pass though vacuum chamber. As we know, the vacuum chamber may be manufactured by aluminum (Al), lead (Pb) or copper (Cu), it is necessary to acquaint shielding effective of these three kinds of materials. In Figure 3, the mass attenuation coefficients of Cu are between Al's and Pb's, so the vacuum chamber fabricated by Cu could instead of Al and Pb. In the real situation, the expression of $e^{-\mu x}$ is not suitable to calculate flux, spectrum or even dose.

Therefore, A Monte-Carlo program called MCNP is used to study the influence of synchrotron radiation for CEPC main ring, which could be directly used to calculate the energy deposition in the various regions, and use to determine the photon spectrum streaming out from vacuum chamber. The vacuum chamber is composed by a few millimeters of Al covered by 3 or 8mm of Pb or totally by a few millimeters of Cu, while the photons of synchrotron radiation hits the vacuum chamber at a grazing angle of 3.1669mrad, the photon energy streaming into tunnel is rather small, concentrating on hardening of the spectrum.

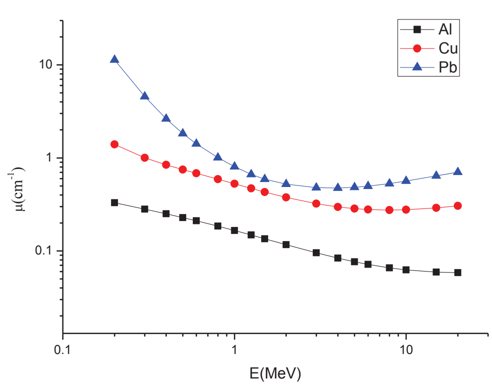

Figure 3: Mass attenuation coefficients of Al, Pb and Cu.

The geometric model is established by MCNP program. The cross section of vacuum chamber is shown in Figure 4, the picture "a" shows chamber is made of Al and Pb, the left and the right ends of the chamber is covered by 8mm Pb, the picture "b" shows chamber is totally manufactured by Cu, the size is as same as the left one. It

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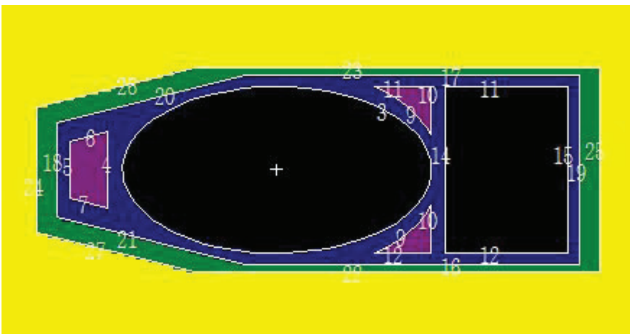
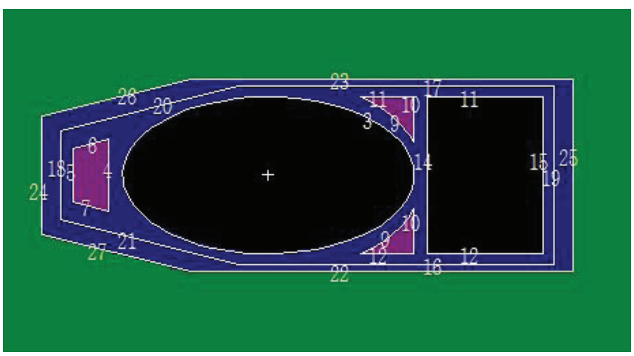
is hard to describe the whole chamber as the arc structure, fortunately the radius of curvature of main ring is up to 6000m, the chamber seems as a straight line in tens of meters distance. Hence, the vacuum chamber is designed as 80 meters long as long as the photon source. If the cross section is regarded as XY plane consistent with the Descartes coordinate system, Z axis is along our sight direction perpendicular to the XY plane, the origin is in the center of the ellipse. Then, the direction of photon could be considered in the XZ plane, with the Z axis direction of 3.1669mrad.



(a)



(b)

Figure 4: The cross section of vacuum chamber (a: Al&Pb, b: Cu).

In the input file of MCNP, the 80 meters long tunnel is divided into eight sections, any section is 10 meters long, what is aimed to record energy deposition and spectrum accurately. In the source description, it is a linear source of 80 meters long, and every point on the linear source emits cone light at a certain angle with the linear source. Spectrum is given by discrete points as shown in Figure 1. F6 card is used to record energy deposition of an equivalent photon. F4 card is used to record energy spectrum of photons. The energy deposition of air is in a radius of 2.25m of the tunnel center.

Table 2: Energy Deposition of an Equivalent Photon (in MeV/g), Dose Rate (Gy/h) and Heat (W/m) in Different Areas

Al&Pb			
Materials	Energy Deposition (MeV/g)	Dose rate (Gy/h)	Heat (W/m)
Left H_2O	4.0×10^{-8}	1.5888×10^{4}	------
RightH_2O	1.2×10^{-7}	4.7664×10^{4}	------
Al	5.3×10^{-7}	2.1052×10^{5}	7.092×10^{2}
Pb	7.5×10^{-8}	2.9790×10^{4}	2.990×10^{2}
Air	3.5×10^{-10}	1.3902×10^{2}	------
Cu			
Materials	Energy deposition (MeV/g)	Dose rate (Gy/h)	Heat (W/m)
Left H_2O	2.4×10^{-8}	9.5328×10^{3}	------
RightH_2O	5.0×10^{-8}	1.986×10^{4}	------
Inner Cu	2.18×10^{-7}	8.6594×10^{4}	9.673×10^{2}
Outer Cu	1.9×10^{-8}	7.5468×10^{3}	8.43×10^{1}
Air	2.9×10^{-10}	1.1519×10^{2}	------

Energy deposition of an equivalent photon, dose rate and power in different areas are given in Table 2. In this model, there is only a vacuum chamber in the tunnel without magnets and other components, so the dose rate in the air is large. Most of the power is converted into heat deposited in the metal.

The spectrum of photons in the air (Al&Pb, Cu) is shown in Figure 5, which is recorded by F4 card. Energy of most of photons is between 100keV and 300keV, the vertical axis represents the flux of photons produced by an equivalent photon. The flux out of Cu is obviously lower than Al&Pb's.

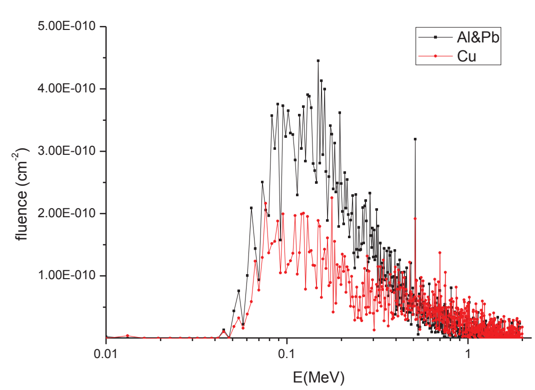


Figure 5: The spectrum of photons in the air (Al&Pb, Cu).

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CONCLUSIONS

In this study, we use MCNP program to simulate synchrotron radiation problems of vacuum chamber in the accelerator tunnel. MCNP is a useful tool to solve the problems of synchrotron radiation. Though the calculation, it is obviously to obtain the energy deposition of an equivalent photon, which could be used to calculate deposition of heat in the vacuum chamber. Meanwhile, the spectrum of photons in each component could get from simulation. In order to obtain a more adequate result, the physics model which is including a lot of physical entities should be more realistic.

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