CPC(HEP & NP), 2011, **35**(1): 104–108 **Chinese Physics C** Vol. 35, No. 1, Jan., 2011

Design and analysis of the tunnel connecting the beamcorridor and the spectrum hall of the CSNS

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Abstract: There is a tunnel connecting the beamcorridor and the target station in the spectrum hall in the CSNS project. The length of the tunnel is about 20 m. The shielding design of the tunnel is very significant for the persons working in the spectrum hall because the tunnel is not covered by soil for shielding. In order to reduce the dose rate at the exit of the cable ducts, we use the ISIS construction, which is designed with four turnings, as a reference for the tunnel design. The thickness of the shielding is obtained by a simulation with the Monte Carlo Code FLUKA. The result is compared with the data obtained with Moyer Mode and the reliability of the simulation is proved. This paper provides the basis for the design of the tunnel.

Key words: CSNS, dose rate, optimization, cable duct, shielding, FLUKA

PACS: 29.27.Th, 29.25.Dz **DOI:** 10.1088/1674-1137/35/1/022

1 Introduction

The China Spallation Neutron Source (CSNS) is an accelerator-based high-power project to be constructed in China. The complex is based on an H^- linear accelerator, a rapid cycling proton synchrotron accelerating the beam to 1.6 GeV, a solid tungsten target station, and five initial instruments for spallation neutron applications [1].

There is a tunnel connecting the beamcorridor and the target station in the spectrum hall in the CSNS project. In the tunnel there exists a beam transport line. Beam loss will occur when the particles are running in the transport line. The lost particles hit the tube wall, a process that can be treated in the same way as a beam hitting a target and producing lots of neutrons and gamma rays. This tunnel is aboveground without soil covering for shielding. Moreover, quite a few cables ought to be spotted through the tunnel, which means several cable ducts are needed. In order to avoid the escape of the neutrons and gamma rays produced in the tunnel, the ducts cannot be rectilinear. So the structure of the ducts is complex and important.

In this paper the following problems are discussed:

1) The design of the structure of the tunnel;

2) The theoretical analysis with a semi-empirical formula;

3) The analysis of the FLUKA program [2, 3] result;

4) The optimization of the shielding design and the equivalent dose at the thick shield surface.

2 Calculation model

2.1 The structure of the tunnel

The design of the CSNS is based on ISIS, which is the world's most successful pulsed spallation neutron source up to now [4]. The thickness of the composite shielding of ISIS is 150 cm mild steel clad on the outer surface with 75 cm ordinary Poland concrete. However, the particle energy of ISIS is 800 MeV and the routine beam loss is 1 W/m for 200 days per year, while the particle energy of CSNS is 1.6 GeV. So, the parameters of the tunnel should be amended to meet the standard of CSNS.

The structure of the tunnel is shown in Fig. 1.

As shown in Fig. 1, the pipe (which is parallel to the z axis) is at the spot x=120 cm and y=0 cm. A simulation shows that the result will not be affected by the thickness of the pipe if the latter is varied between 1 cm and 7 cm. So the inside and the outside diameters of the pipe are chosen as 10 cm and 11 cm, respectively. The thickness of the steel and the concrete are tentatively taken to be the same as at ISIS

Received 15 March 2010

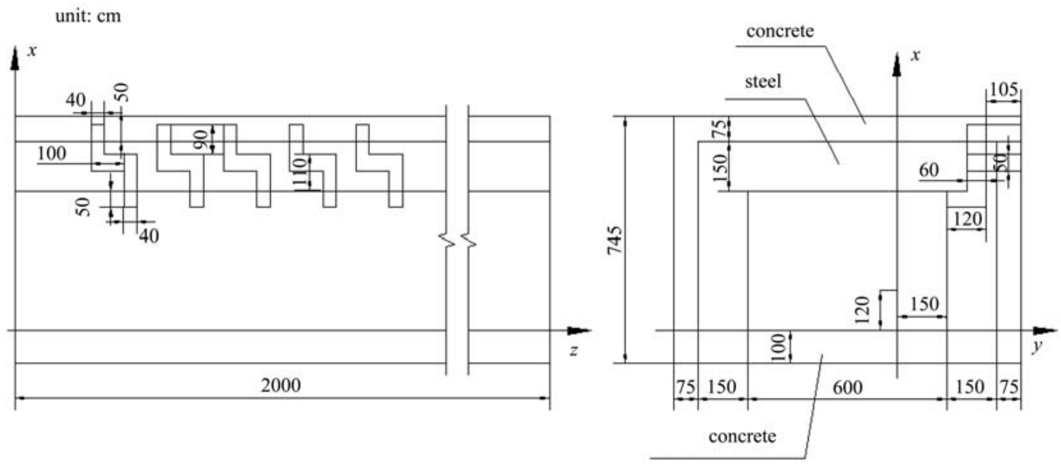

Fig. 1. The structure of the tunnel.

and then the optimization of the thickness should be obtained from the simulation. In addition, there is a 100 cm thick concrete layer serving as underground shielding.

Several cable ducts ought to exist in the shielding because lots of cables need to pass through the shielding wall. In order to prevent the many high energetic particles which are produced in the tunnel from escaping along the cable ducts, the latter are designed as crooked structures instead of rectilinear ones. So the structure of the passages is complex. Figs. 1 and 2 show the structure.

There are four knees in the structure of the passages. They go into the steel shielding first and then turn upwards. After that, the passages become horizontal for a short distance and then turn upwards again until they reach the concrete shielding. Finally they go straight out of the wall in this shielding. The parameters are depicted in Fig. 1.

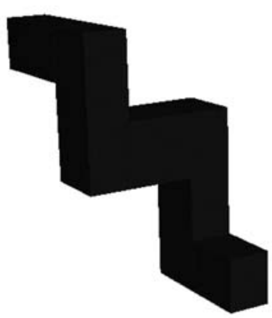

Fig. 2. The structure of the cable ducts.

2.2 The process of the simulation with the program FLUKA

The length of the tunnel in the simulation is 20 m, the thickness of the steel shielding is 150 cm and that of the concrete shielding is 75 cm. There is a 100 cm concrete shielding underground as well. The pipe is parallel to the z axis at the spot x=120 cm and y=0 and the beam goes, as a default, into the positive direction of the z axis. The beam loss is 1 W/m. The parameters of the cable ducts are shown in Fig. 1.

In the first calculation, we did not use the option of variance reduction. As a result, the statistics error was unacceptable and the computing time too long. Another problem was that the binning division by the USRBIN command was so big that the chromatic graph of the dose rate was very coarse. Then the binning division was made smaller and the option of variance reduction was adopted. The steel shielding was divided into 15 layers (10 cm per layer) and the concrete was divided into 4 layers (10 cm per layer) [5]. A multiplying weight was set to each layer. Then the result of the calculation in which 700000 particles were simulated was obtained after about four days, reducing the statistics error to a value lower than 10%.

Next the beam loss was considered. The used model assumed that the beam hit a fixed steel target in the pipe in order to simulate the beam loss in the original calculation. However, the actual situation can be interpreted as a well-distributed loss instead as a point loss. So the SOURCE command was used to call a user-written source file. In the file, there are among the particles sampled to hit the pipe wall some that propagate even along the pipe and the angle between the direction of the sampled particles and the pipe is 10 radians. This angle is so small and the tunnel is so short that the following situation may occur: the particles may pass the tunnel already but still do not hit the pipe wall. There are two methods to solve the problem. One is to assume that the pipe is a stuffed steel stick. The result will not be affected by this because the Russian Roulette Method is used. The program will sample the position and the direction of the particles. The other method is to set another thin pipe inside but adjacent to the original one. Then the particles will be sampled in the new pipe. In this way, the particles will hit the original pipe wall easily in a short distance. In the simulation, the latter method is adopted.

The elemental compositions and densities of the materials are shown in Table 1.

2.3 Analytical method

While the particles are running in the beam pipe line, beam loss occurs. The lost protons hit the pipe. This can be considered as a process where the beam hits a target. The main problem of radiation protection for the heavy ion accelerator is caused by secondary neutrons, which are produced by the bombardment of the thick target by heavy ions. The secondary neutrons have the following characteristics:

1) Promptness. When the accelerator is shut down, secondary neutrons will not be emitted immediately.

Table 1. The compositions and density of the materials.

	element	fraction(%)	density/(g/cm^3)
air	N	75.56	
	O	23.16	1.225×10^{-3}
	Ar	1.28	
concrete	H	1.00	
	C	0.10	
	O	52.91	
	Na	1.60	
	Mg	0.2	2.53
	Al	3.39	
	Si	33.70	
	Ca	4.40	
	Fe	1.40	
	K	1.30	
soil	C	0.85	
	N	0.10	
	O	42.77	
	Na	0.42	
	Mg	0.44	
	Al	6.76	
	Si	33.80	1.90
	K	1.99	
	Ca	1.91	
	Ti	0.87	
	Mn	0.20	
	Fe	8.14	
	H	1.75	
Fe	Fe	100.00	7.874

2) The secondary neutrons are obviously divided into two components: the high-energy neutrons from the nuclear cascade process and the low energy neutrons from evaporation processes. The high energy neutrons are strongly peaked in the forward direction while the low energy neutrons are more isotropic.

3) A significant number of neutrons is emitted with energies higher than the incident energy per nucleon and a few of them can even reach about twice this energy.

4) The yields of the secondary neutrons obviously increase with the projectile energy per nucleon. For constant incident energy per nucleon, the yields increase with the incident particle atomic mass. On the other hand, the effect of the atomic mass of the target is not very important [6].

It is a complicated process to get the dose rate on the surface of the shielding exactly with the analytical method. Fortunately, however, a semi-empirical formula can be used and the accuracy is considered to be acceptable.

For an incident energy of more than 1 GeV, the Moyer Model can be used [7]. The analytical formula is the following,

$$H=H_0\left(\frac{E_\mathrm{p}}{E_0}\right)^m\cdot r^{-2}\cdot\exp(-\beta\theta)\exp\left(-\frac{d}{\lambda}\csc\theta\right)(\mathrm{Sv/s}).$$

Here, r is the distance to the source (m), d is the thickness of the shielding (g/cm^2), E_p is the energy of the proton (GeV), $H_0(E_\mathrm{p})$ is the equivalent dose at a point 1 m away from the target without shielding (Sv·m^2/proton), E_0 1 GeV, m 0.8±0.10, θ is the angle between the beam direction and the line that connects the source point and the calculating point (radian), β 2.3±0.2 radian^{-1}, λ is the attenuation length of the protons in the material, H_0 $(2.84\pm0.14)\times10^{-13}$ Sv·m^2·proton^{-1}.

The dose rate at each point can be calculated by the Moyer Model. In order to prove the reliability of the simulation, a comparison of the analytical results with the simulated ones is made. This will be elaborated explicitly below.

3 Results and discussion

3.1 The comparison of the results obtained by the two methods

In order to prove the reliability of the simulation, the analytical method (Moyer Mode) is used to compare with the results obtained from the simulation with FLUKA. For x=120 cm (in the plain containing the pipe), a comparison of the two methods (from y=150 cm to y=375 cm) is made.

The Moyer Mode mentioned in section 2.3 is suitable for the situation of point losses, which is the process that the beam hits a target. However, the error will be unacceptable if the Moyer Mode is used in the situation where the beam loss is equal along the pipe. In that case, the Moyer integral should be used. Another way is simpler, as follows. Divide the pipe into many parts that can be considered as many points and then calculate the effect of the different points to the aimed spot. The sum of these dose rates is the analytical result of the spot.

Here, the region from 0 to π is divided into 1000 parts. These small angles are put into the Moyer Mode. Then the sum of these results is considered to be the result of the analytical method.

The comparison of these results from the two methods is shown in Table 2. They agree well with each other.

Table 2. Comparison of the results from the Moyer Mode and the simulation.

distance to the pipe/m	analytical results(A)/ (μSv/h)	data from simulation(S)/ (μSv/h)	the ratio (A/S)
1.578	1.51E6	1.09E6	0.72
1.692	9.87E5	3.80E5	0.39
1.806	6.45E5	1.59E5	0.25
1.920	3.59E5	7.20E4	0.20
2.034	2.02E5	3.43E4	0.17
2.148	1.15E5	1.70E4	0.15
2.262	6.18E4	8.60E3	0.14
2.376	3.35E4	4.45E3	0.13
2.490	1.89E4	2.34E3	0.12
2.604	9.93E3	1.25E3	0.13
2.718	5.19E3	6.73E2	0.13
2.832	2.65E3	3.66E2	0.14
2.946	1.09E3	2.01E2	0.19
3.060	3.27E2	1.32E2	0.40
3.174	1.02E2	1.01E2	0.99
3.288	4.60E1	7.75E1	1.69
3.402	1.56E1	5.98E1	3.84
3.516	1.12E1	4.62E1	4.13
3.630	7.95E0	3.58E1	4.50
3.744	5.07E0	2.78E1	5.48
3.858	4.83E0	2.16E1	4.48

3.2 The simulation results

Close attention is paid to the dose rate near the outer surface. The distribution of the dose rate is shown in Fig. 3. It is easy to see that the total dose rate on the plane which contains the pipe out of the shielding is larger than anywhere else. The dose rate value is larger than 10 μSv/h, which is much higher than the limiting design value of CSNS (2.5 μSv/h). In addition, the dose rate at the exit of the ducts is also higher than 10 μSv/h.

The shielding effect is shown in Fig. 4. This figure shows the variation in the dose rate with the x-coordinates for 630 cm$\leqslant z \leqslant$670 cm. The curves from the top to the bottom correspond to y=150 cm, 300 cm and 375 cm, respectively. The dashed line corresponds to 2.5 μSv/h.

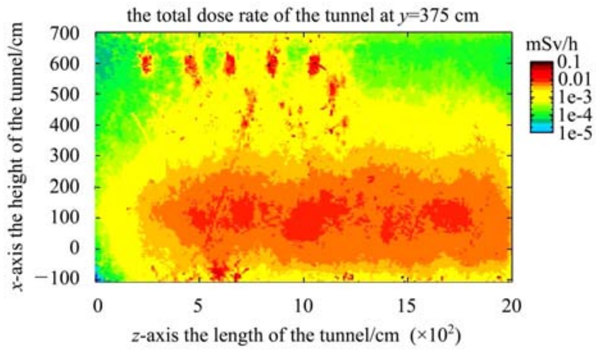

Fig. 3. (color online) The total dose rate at y=375 cm.

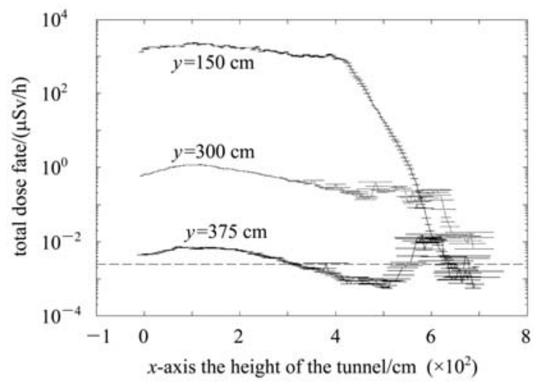

Fig. 4. The shielding effects.

In order to observe the attenuation of the total dose equivalent rate through the ducts, all the information is provided in Fig. 5. In this figure, the y-axis represents the total dose equivalent rate, the unit of which is mSv/h. The x-axis is along the length of the ducts. However, the coordinate axis will change at the spots of the duct-knees. In the first leg of the ducts, which consist of the first ten data in the figure, the abscissa means the interval between y=150 cm and y=270 cm. In the following second leg of the ducts, including the 11th data to the 51st data, the abscissa changes into the interval from x=370 cm to x=540 cm. So are the left legs. The abscissae are z (from 370 cm to 230 cm), x (from 480 cm to 620 cm) and y (from 210 cm to 375 cm) successively. As a result, it is difficult and unnecessary to denote the coordinate of the abscissa clearly. We just express them with the data number. This omission will not prevent us from getting the attenuation effect of the ducts. In the figure we can see that the dose equivalent rate will attenuate almost one order at the spot of the knees. In each leg, the attenuation trend is easily seen. So it is safe to say that the dose equivalent rate will attenuate less than the standard of the design value of 2.5 μSv/h as the 5th leg extends, which means that thickening the concrete shielding layer will help meet the dose rate criterion.

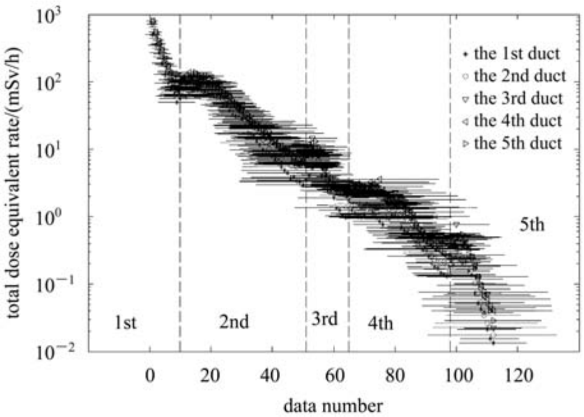

Fig. 5. The attenuation of the dose equivalent rate through the ducts.

3.3 The optimization of the shielding design

As was illustrated above, the concrete shielding is not enough to meet the standard of the design value, which is 2.5 μSv/h. So it ought to be thickened until it can fit the bill. Fig. 6 shows us how thick the concrete shielding should be if the principle that "the workers and public ought to be irradiated safely, reasonable, feasible, and as light as possible" is taken into consideration.

In this figure, the dashed line corresponds to 2.5 μSv/h. The curve is the average value for z between 119.25 cm and 127.95 cm, while x is 120 cm. The data and the figure show the result: for $y \leqslant 0$ the concrete should be more than 109 cm. For $y \geqslant 0$ the concrete shielding should never be less than 135 cm. In this situation, the dose rate at the exit of the passage will also be on average below 2.5 μSv/h. There may be some spots whose dose rate is slightly higher than the design value. However, because the exits of the ducts are 5.7 m far away from the ground, which is much more than the height of human beings, the concrete shielding is also safe enough to meet the request.

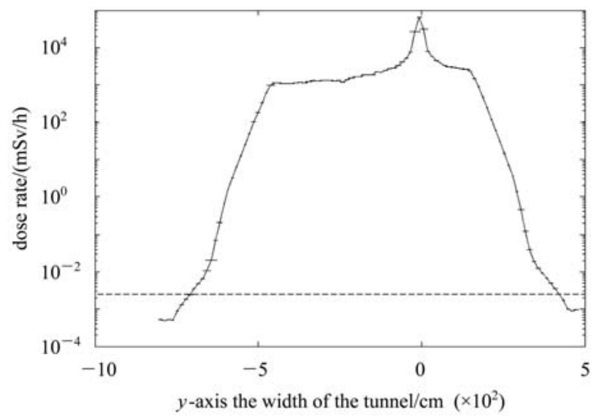

Fig. 6. The optimization of the shielding.

4 Conclusions

According to the comparison between the results obtained from the FLUKA simulation and the semi-empirical formula, the reliability of the simulation with FLUKA, analyzing the radioactive field, is testified. When designing the tunnel, the option of variance reduction can easily save computing time and achieve reliable results. The cable ducts are designed as a crooked structure with four knees in order to prevent the particles from being emitting out of the tunnel along the ducts. Besides the 1.5 m thick steel shielding, there should be another 75 cm thick concrete layer at the top and a 109 cm thick concrete layer at the side without the cable ducts and a 135 cm thick concrete shielding at the side with the ducts. In this situation, the design value of 2.5 μSv/h can be met effectively and economically.

References

1 WEI J, FANG S X, FENG J et al. China Spallation Neutron Source Design. in: Proceedings APAC 2007. Indore: Dr. Sahni V C, 2007. 310–314

2 Fasso A, Ferrari A, Ranft J et al. FLUKA: A Multi-Particle Transport Code. CERN-2005-10(2005), INFN/TC-05/11, SLAC-R-773

3 http://www.fluka.org

4 http://www.isis.stfc.ac.uk

5 Roesler S, LIU C, Rokni S H et al. Nuclear Instruments and Methods in Physics Research A, 2003, **503**: 606–616

6 SU You-Wu et al. High Energy Physics and Nuclear Physics, 2005, **29**(11): 1100–1103 (in Chinese)

7 Wade Patterson H, Thomas Ralph H. Accelerator health Physics. New York: Academic Press, 1973. 93–159