PRELIMINARY STUDY OF RADIATION FROM HEAVY-ION BEAMS AT J-PARC HADRON EXPERIMENTAL FACILITY

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Abstract

We are developing a future project to accelerate heavy-ion beams at J-PARC (J-PARC Heavy-Ion Project, J-PARC-HI) to create and study high-density nuclear matter, which should exist in the neutron star. In this project, we will build a new heavy-ion injector consisting of a linac and a booster ring, and accelerate heavy ions in the existing Rapid-Cycling Synchrotron (RCS) and Main Ring synchrotron (MR). The designed energy and the intensity are about 11 GeV per nucleon and 10^{11} Hz, respectively. We will transport slowly-extracted heavy-ion beams to J-PARC Hadron Experimental Facility through the primary proton beamline (high-P). In this work, we show the first attempt to study of the radiations with the heavy-ion beams at the present geometry of the high-P area, and the geometry with additional radiation shields for the designed high-intensity heavy-ion beams.

OVERVIEW OF J-PARC HEAVY-ION PROJECT

Goals

J-PARC Heavy-Ion Project (J-PARC-HI) [1] is aimed at studies of extremely high-density nuclear matter whose density is 5-10 times as high as the normal nuclear density. Such high-density matter is predicted to exist in the core of the neutron star, while also can be produced in heavy-ion collisions at the beam energy of several tens of GeV per nucleon in the laboratory system. By creating such dense matter, we will explore phase structures of the so-called QCD phase diagram. In the heavy-ion collisions of this energy, many strange quarks will be produced in each collision, where we search for new multi-strangeness particles/nuclei [2].

Acceleration scheme

In order to accelerate heavy-ion beams at J-PARC, we will build a heavy-ion injector consisting of a linac and a booster ring. In the injector, a heavy-ion beam (*i.e.* U) is accelerated to about 70 MeV per nucleon which has the same rigidity as 400 MeV proton. By adopting this rigidity, we can accelerate the heavy-ion beams using 3 GeV Rapid-Cycling Synchrotron (RCS) and Main Ring synchrotron at 30 GeV, to 11 GeV per nucleon without major modification of these synchrotrons. The designed beam intensity of heavy-ion beams is about 4×10^{10} per MR cycle, corresponding to about 10^{11} Hz.

Experimental plan

Heavy-ion beams are slowly extracted from MR to Hadron Experimental Facility through the primary proton beamline (high-P beamline), which will be completed in the end of 2019.

In the first stage of the heavy-ion collision experiment, we plan to use J-PARC E16 spectrometer [3, 4] which is located at the end of the high-P beamline.

In this work, we try to evaluate the radiations produced by heavy-ion beams in high-P beamline. The radiation sources are mainly the beamline window, the beam dump, the experimental target.

EVALUATION OF RADIATION AT J-PARC HADRON EXPERIMENTAL FACILITY

The beam dump and the radiation shields of the J-PARC Experimental Facility around the high-P beamline are designed for the maximum design proton rate of 0.5×10^{10} Hz, which corresponds to 1×10^{10} protons per spill of 2s in each MR cycle of 5.2s at the beam energy of 30 GeV. The maximum radiation limit for safety of at J-PARC is set to 25 μSv/h. In the following we evaluated the radiation with the actual beam rate (i.e. 0.5×10^{10} Hz), and multiplied the result by four to take account of the safety factor which is required by the J-PARC radiation safety section.

We use MARS version 15 (2019 version) installed in the KEKCC server for radiation simulation [5].

Radiation estimation for the proton beam

We first try to reproduce the radiation calculations for proton beams of 30 GeV and 0.5×10^{10} Hz with the current setup which were estimated by J-PARC Hadron Group (K. Aoki et al). The geometry of the beamline, target, the beam dump, and the radiation shields made of concrete and steel are shown in Figs. 1 and 2.

The top plots of Figs. 3 and 4 show the resulting total dose equivalent (DET) (μSv/h). At all the evaluation points, DET is less than the maximum limit of 25 μSv/h. The result

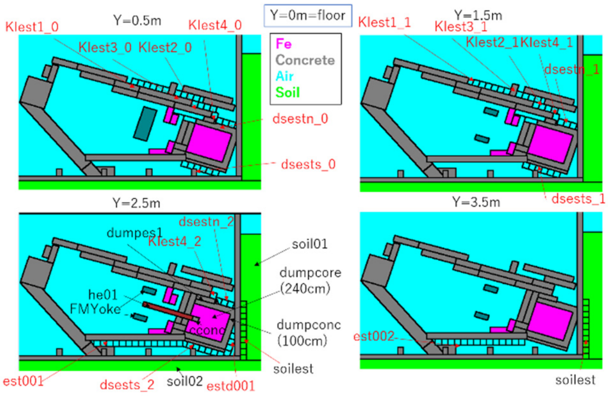

Figure 1: The current geometry of the high-P beamline area at 0.5 – 3.5 m above from the floor level.

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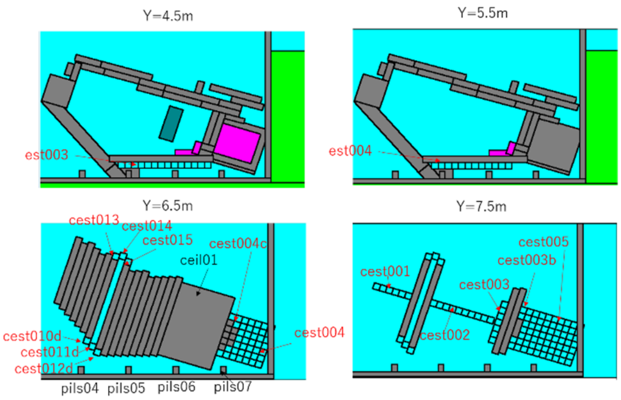

Figure 2: The current geometry of the high-P beamline area at 4.5 – 7.5 m above from the floor level.

is also consistent with the previous calculation by Aoki within ±10%.

Radiation estimation for the U beam with the current geometry

Next, we evaluated the radiation for U beams of 11 GeV per nucleon with the current setup. Suppose the radiation is proportional to the beam power, we can estimate the equivalent beam rate to be as follows;

$$R_U = R_p \frac{E_U}{E_p}\frac{A_U}{A_p}$$

where $E_U = 11$ GeV and $E_p = 30$ GeV are the kinetic beam energies per nucleon, and $A_U=238$ and $A_p=1$ are the atomic numbers for U and p, respectively. Then, the equivalent U beam rate is $R_U = 0.6\text{x}10^8$ Hz, corresponding to $R_p = 0.5\text{x}10^{10}$ Hz. We simulated the radiation at this rate of U beam with MARS and the resulting total dose equivalent at each evaluation point in Figs. 1 and 2 was obtained as shown in Figs. 3 and 4 (middle rows). The result is very similar for the proton with the same power (top rows of Figs. 3 and 4) as expected. From this result, we conclude the transport of U beams at $0.6\text{x}10^8$ Hz is possible.

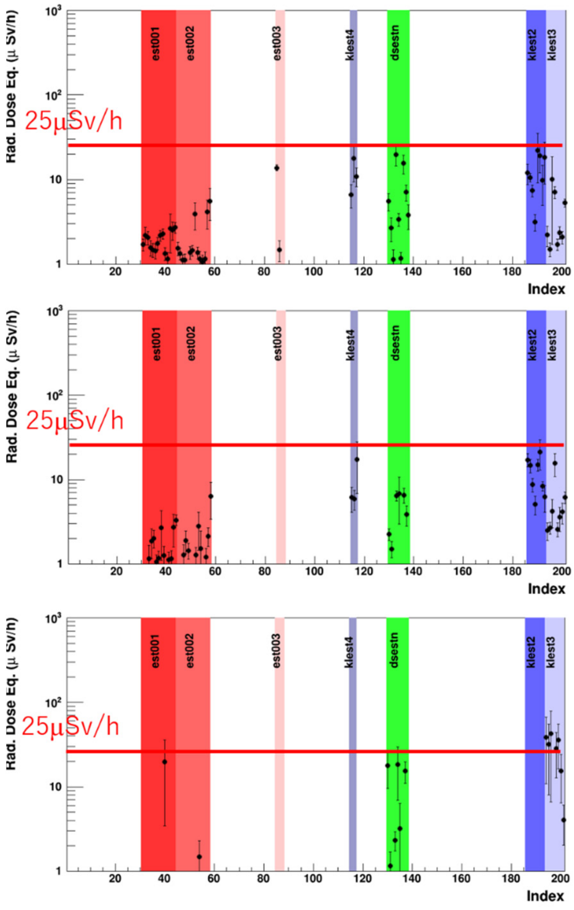

Figure 3: Total dose equivalent (μSv/h) at each radiation evaluation point at the height below 5 m from the floor level for the proton beams (above), for the heavy-ion beams with the same beam power as the proton beams (middle), and the heavy-ion beams with the designed beam power with additional shields (below).

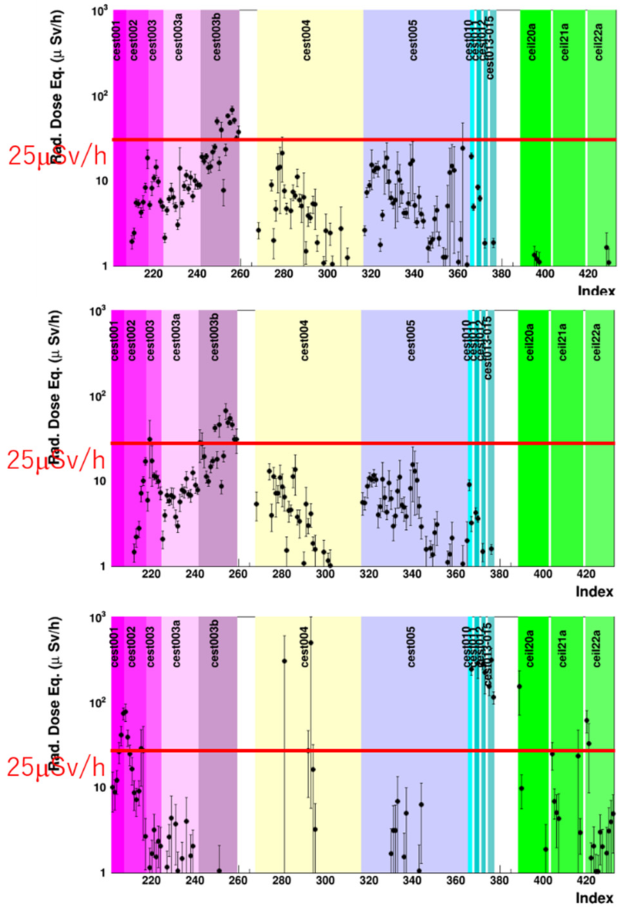

Figure 4: Total dose equivalent (μSv/h) at each radiation evaluation point at the height above 5 m from the floor level for the proton beams (above), for the heavy-ion beams with the same beam power as the proton beams (middle), and the heavy-ion beams with the designed beam power with additional shields (below).

Radiation suppression for the designed intensity U beam

Next, we use the designed U beam intensity of $0.5\text{x}10^{11}$ Hz with thicker beam dump and shields. In order to roughly estimate the required beam dump thickness, we performed Moyer model calculations [6] for shielding calculations.

Table 1: Estimation of dose equivalent at 90 degree using Moyer model. ΔE is the beam loss, L_{con}, L_{Fe}, L_{air} is the thickness of concrete, Fe and air in the beam dump. DEQ shows the dose equivalent from Moyer model. Note the beam rate in the table is the designed value scaled by four to be consistent with the radiation results in MARS.

Config.	E (GeV)	ΔE(kW)	Ion	L_{con}(m)	L_{Fe}(m)	L_{air}(m)	DEQ(μSv/h)@90^{o}	Beam rate(Hz)
1	30	0.1	p	1	2.4	5	1.21	2.1x10^{10}
2	11.1	0.1	U	1	2.4	5	1.21*	2.4x10^{8}
3	11.1	85	U	1	2.4	5	1.0x10^{3}*	2x10^{11}
4	11.1	85	U	1.5	3.9	5	0.99*	2x10^{11}

Table 1 shows the results. The beam dump of the current geometry (Configuration 1) for the 30 GeV proton beam at 2x10^{10} Hz consists of the steel of 2.4 m thick and the concrete of 1 m thick, which supress the dose equivalent to 1.2 μSv/h. In order to supress the dose equivalent to the similar level with the designed U beam rate of 0.5x10^{11} Hz, the beam dump should have the steel of 3.9 m thick and the concrete of 1.5 m thick.

We try to implement the beam dump in the high-P area, with also additional steel and concrete shields to suppress the dose equivalent to a few tenth μSv/h as shown in Figs. 5 and 6. In this configuration, we have not considered the real feasibility as the experimental area. Apparently the beam dump dimensions are too large to fit in the high-P area, and the space for the access routes to the KL (KL beamline area for KOTO experiment) and high-P experimental areas or exits are not enough. However, the radiation limit less than 25 μSv/h are cleared in most of the estimated reference points.

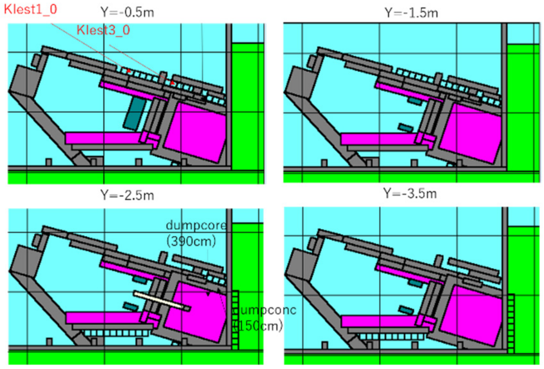

Figure 5: The geometry with the larger beam dump and additional Fe and concrete shields for the heavy-ion beams at 0.5 – 3.5 m above from the floor level.

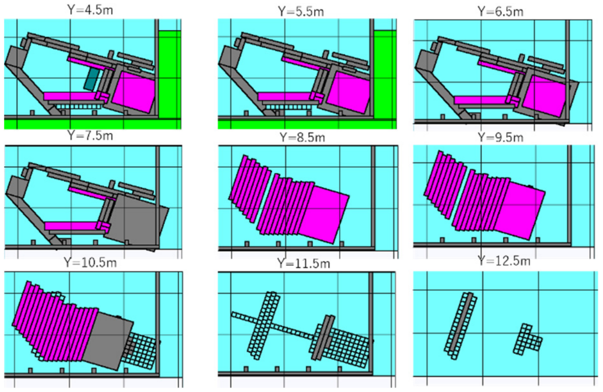

Figure 6: The geometry with the larger beam dump and additional Fe and concrete shields for the heavy-ion beams at 4.5 – 12.5 m above from the floor level.

By considering space limitation of high-P area, it is a little room to increase the shields. We could increase slightly the maximum HI beam rate from the power-equivalent 0.6x10^{8} Hz, for example, by access restriction control during the beam operations. However, it is more suitable to design a new beam dump and radiation shields for large J-PARC-HI spectrometer in the anticipated extended area and the extended high-P beam line of Hadron Experimental Facility. We further need to study carefully the various effects due to heavy-ion beams, for various isotopes due to heavy-ion collisions, effects of beam halo due to different beam parameters from the proton beam.

SUMMARY

In summary, we estimated the radiation level around the high-P beamline in J-PARC Hadron Experimental Facility with transportation of heavy-ion beams expected in J-PARC-HI. In the current geometry of the beam dump and radiation shields in the high-P area, the heavy-ion beams can be transported up to 0.6x10^{8} Hz. Suppression of the radiation level to the limit of 25 μSv/h is possible by increasing the size of the beam dump and adding more shields, but it is practically hard due to space limitations. We will further study in more detail actual limit of the beam intensity by adding shields which could fit in the high-P area. We also study beam transport of the heavy-ion beams and possible other effects on radiations.

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* Actually, DEQ is estimated with proton scaled with 238 (U atomic number).

REFERENCES

[1] H. Sako *et al.*, (J-PARC-HI Collaboration), J-PARC-HI Letter Of Intent, https://j-parc.jp/researcher/Hadron/en/pac_1607/pdf/LoI_2016-16.pdf

[2] H. Sako *et al.*, (J-PARC-HI Collaboration), Nucl. Phys. A982 (2019) 959-962.

[3] J-PARC E16 proposals, http://j-parc.jp/researcher/Hadron/en/pac_0606/pdf/p16-Yokkaichi_2.pdf

[4] https://j-parc.jp/researcher/Hadron/en/pac_1707/pdf/E16_2017-10.pdf

[5] N. Mokhov *et al.*, MARS simulation code, https://mars.fnal.gov/

[6] J. B. McCasling, W. P. Swanson, R. H. Thomas, Nucl. Instrum. Meth. A 256, 418-426 (1987).