Author's response to the reviewer's comments on "Copper Neutron Target Design and Installation in KOMAC"

Dear Editor and Reviewer:
Thank you very much for your valuable comments and suggestions to improve the quality of the paper. According to editor and review's comments, the overall revision of the paper including the description of the source, discussion on the measure electron energy probability functions with simple modeling has been performed to enhance the conclusion of this paper.
Below, we included our responses/answers to your comments in blue. Also, we have revised/updated the paper (Marked Manuscript), in which we colored the modifications in red.

REFEREE REPORT(S):
Referee: 1

COMMENTS TO THE AUTHOR(S)

1. In this study, neutron energy spectrum on the ground was considered. Neutron induced soft error of the semiconductor occurs mainly at a flight altitude of 10-20 km. Is it necessary to consider the energy distributions of the atmospheric neutrons at the ground and flight altitude?

It is indeed true that soft error by cosmic ray-induced neutron usually occurs at much higher altitude, but in this research the requirement for this design is specifically for reproducing ground level atmospheric neutron. I added a line in method and result part to clarify the purpose of this research.

2. In the calculation of Geant4, it would be good to clarify which model was used to calculate the transport of high energy protons and neutrons. (Or whether you used a library process)

Physics model used for the entire process is QGSP_BIC model. I added a line in the introduction describing physics model I used throughout the simulation.

Copper Neutron Target Design and Installation in KOMAC

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1. Introduction

A copper target to provide fast neutron utilizing 100 MeV proton beam is designed and installed in this research. Simulation with Geant4 using QGSP_BIC physics model is conducted to evaluate target material candidates in respect to similarity of generated neutron with the cosmic-ray induced atmospheric neutron. Target geometry and thermal analysis is determined subsequently so that the target is able to stop 100 MeV proton inside its water cooling channel for prevention of hydrogen blistering inside the target body. Target thermal analysis is conducted with the same geometry to verify that the configuration is able to afford proton beam energy deposition up to 2 kW. Finally, the designed target is manufactured and installed at the end of beam line in 100 MeV proton accelerator in KOMAC, preparing for its neutron characterization in near future.

2. Methods and Results

2.1 Target Material Analysis

The neutron target aims to produce an atmospheric neutron-like spectrum with a sufficient flux at the irradiation station. It must be used for soft error assessment on semiconductor devices by neutron irradiation from cosmic-ray-induced neutrons at ground level. It, therefore, must generate a continuous distribution of energy from 1 MeV to 100 MeV similar to the atmospheric neutrons.

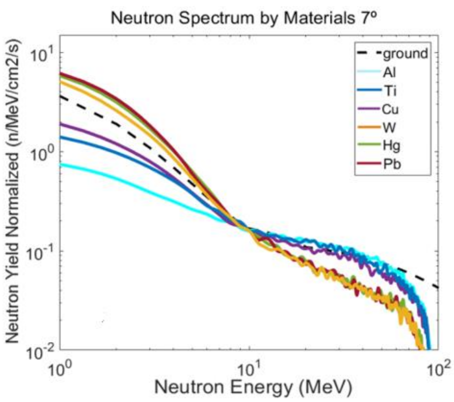

Figure 1. Neutron spectrum generated by different materials compared with atmospheric neutron at ground level.

Fig. 1 illustrates the comparison between the neutron energy spectra calculated for various target materials irradiated by the 100 MeV proton beam and the JEDEC reference spectrum at New York, measured and formulated by JEDEC [1]. All neutron spectra are normalized to the neutron yields at 10 MeV neutron energy. Evaluation of comparison is conducted by a new parameter defined by:

$$\sigma = \sqrt{a\sum_{i=1}^{10}(x_i-\bar{x}_i)^2 + \; b\sum_{i=10}^{100}(x_i-\bar{x}_i)^2} \quad ,(1)$$

where x_i and $\bar{x}_i$ are the differential neutron yield of the i_{th} energy bin for each target material and the atmospheric neutron flux at the i_{th} energy bin, respectively. The weighting factors a and b are 0.1 and 0.9 according to the energy-dependent contribution to the occurrence of soft errors [2, 3]. The result is listed table 1 below, signifying that copper is the most suitable material for imitating atmospheric neutron for soft error assessment.

Table 1. Calculated average variance from atmospheric spectrum by materials

Materials	Deviation 1–10 MeV	Deviation 10–100 MeV	Effective overall deviation
Al	3.31	0.191	1.061
Ti	2.46	0.204	0.801
Cu	1.91	0.221	0.638
W	1.65	0.405	0.649
Hg	2.64	0.386	0.911
Pb	3.05	0.395	1.035

2.2 Target Design

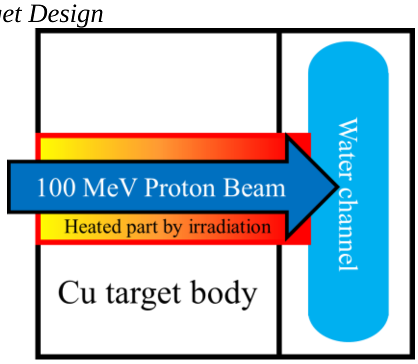

Figure 2. Simplified diagram of the target with cooling water channel.

Fig. 2 illustrates a simplified model of the target assembly consisting of the Cu target body and the cooling water channel attached to the backside of the target. The design is such that the 100 MeV proton beam should fully penetrate through the Cu target medium to stop in the middle of the cooling water. This concept allows an effective heat removal of 2 kW power of proton beam irradiation to the Cu target. It also ensures a longer target life expectancy by preventing probable blistering when the proton beam is fully stopped and remains inside the Cu target. The copper body and water channel thickness is determined to be 13 mm and 10 mm respectively with Geant4 calculation.

2.3 Target Thermal Analysis

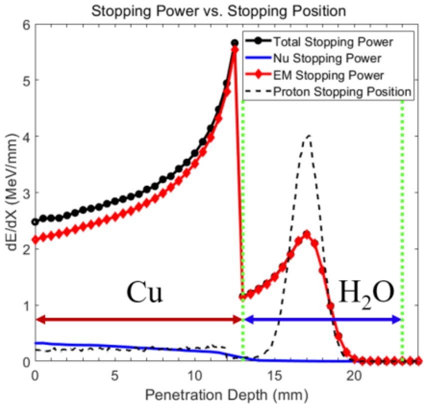

Figure 3. Stopping power characteristics of a 100 MeV proton beam impinging on the target assembly consisting of a 13-mm-thick Cu target body and 10-mm-thick cooling channel

As shown in fig. 3, energy deposition of proton impinging the target body is calculated and implemented in thermal analysis with ANSYS student. Energy deposition depending on the proton penetration depth is imitated by placing different heat volume sources inside the target body. The maximum temperature as a result of constant proton irradiation with 2 kW beam power is simulated and calculated with different water flow rate. It can be seen in fig. 4 that temperature rise of the target at its hottest spot is maintained under 60 degree at water flow rate of 7.5 LPM, which the KOMAC facility is able to provide.

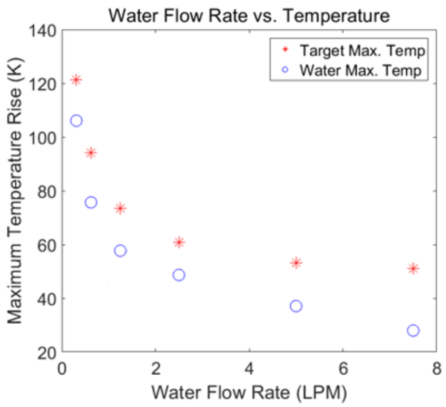

Figure 4. Temperature rise of the target at its maximum with different water flow rate.

2.4 Target Installation

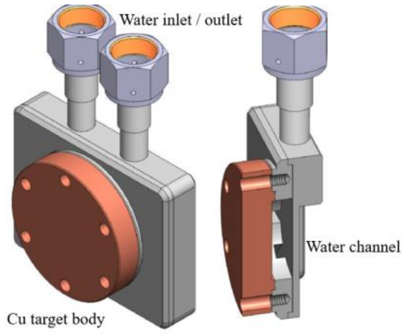

Figure 5. Drawings of Cu target body.

Fig. 5 illustrates a drawing done by ITS vac. The target follows the configurations and dimensions calculated above, and is attached to a linear guide so that it can be installed and removed remotely depending on its demand. Target body diameter and thickness are 60 mm and 13 mm respectively, and it is in direct contact with 10 mm thick water channel. Fig. 6 is the picture of the installation on a chamber located at the end of proton beam line.

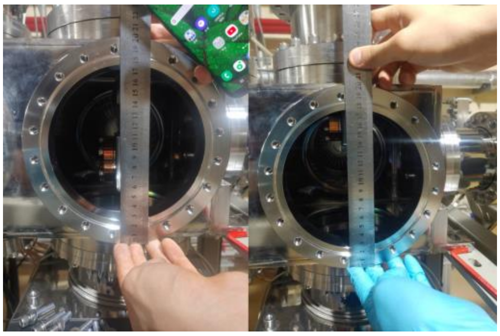

Figure 6. Picture of target installation inside a beam line chamber, when the target is in use (left) and removed (right)

3. Conclusions

We conducted a design and performance evaluation of the atmospheric-like neutron target for a 100 MeV proton beam at the KOMAC facility to prepare a beam service for the accelerated soft error assessment. Cu is chosen as the most atmospheric-like neutron-generating target material throughout the Geant4 Monte-Carlo simulation toolkit. The geometry for the target assembly is determined as a 13-mm-thick Cu body with a 10 mm water channel behind the target body to carry the proton outside the target to prevent hydrogen blistering. The target should deliver 1.07 × 10^7 neutrons/cm^2 at the irradiation station located at 5 m and 7º away from the target, which is equivalent to an acceleration factor of 2.24 × 10^9, providing atmospheric-like neutrons to semiconductor devices for soft error testing.

Acknowledgment

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REFERENCES

[1] M. S. Gordon, P. Goldhagen, K. P. Rodbell, T. H. Zabel, H. H. K. Tang, J. M. Clem, and P. Bailey, "Measurement of the flux and energy spectrum of cosmic-ray induced neutrons on the ground," IEEE Trans. Nucl. Sci. 51(6), pp. 3427-3434, 2004.
[2] J. Baggio, D. Lambert, V. Ferlet-Cavrois, P. Paillet, C. Marcandella, and O. Duhamel, "Single event upsets induced by 1–10 MeV neutrons in static-RAMs using mono-energetic sources," IEEE Trans. Nucl. Sci. 54(6), pp. 2149-2155, 2007.
[3] R. Baumann, The new JEDEC JESD89A test standard: how is it different than the old one and why should we use it? RADECS 2007, Deauville, France, 2007.
[4] Geant4: Reference Physics List. https://geant4.web.cern.ch/node/628.
[2] G. Folger, V.N. Ivanchenko, J.P. Wellisch, "The binary cascade," Eur. Phys. J. A21(3), pp. 407-417, 2004.
[3] P. Lee, "Design of the 100 MeV proton-beam target system for the pulsed neutron source at the KOMAC," J. Korean Phys. Soc. 73(8), pp. 1068-1072, 2018.
[4] Sang-Pil Yoon et al, "The Preliminary Design of the Neutron Production Target for the KOMAC Pulsed Neutron Source." Transactions of the KOrean Nuclear Society Spring Meeting, 2017.
[5] J. F. Ziegler, "Terrestrial cosmic rays," IBM J. Res. Develop. 40(1), pp. 19-39, 1996.