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Feasibility Study for NITE SiC/SiC as the Target Material for Pions/Muons Production at High-Power Proton Accelerator Facilities

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The feasibility study for Nano-Infiltration and Transient Eutectic phase process SiC/SiC (NITE SiC/SiC)NITE SiC/SiC as a potential novel target material for pions/muons production at high-power proton accelerators facilities is in progress. Compared with graphite that is the principal target material for pions/muons production, higher transport efficiency and higher oxidation resistance can be expected. However, the residual radiation dose of NITE SiC/SiC is 400 times higher than that of graphite a year after the irradiation. To validate the simulation, the residual radionuclides of the irradiated samples have been analyzed by gamma-ray spectroscopy. To understand the thermal shock behavior, NITE-SiC/SiC was included in the HRMT35 experiment at CERN's HiRadMat facility. In these studies, NITE SiC/SiC is proved to be a promising material for pions/muons production with the higher transport efficiency and the oxidation resistance, though the maintenance scenario has to be carefully designed due to higher residual radiation dose. The thermal shock resistance and proton-irradiation resistance of NITE SiC/SiC will be confirmed to be applied for the pions/muons production.

KEYWORDS: target material, pion, muon, silicon carbide, composite material, beam optics

1. Introduction

Intensity of the proton accelerator facility is increasing in order to obtain more intense pions and/or muons (hereafter, pions/muons) to make further discoveries in the new fields of fundamental physics and material science. The pions/muons are produced through collisions between the high-energy proton and nuclei of the target material. The high intense proton irradiation leads to a high thermal load and radiation damage to the target material. Consequently, the requirement for the target material is getting more and more demanding. Polycrystalline graphite is principal candidate for production of pions/muons under high-intense proton beam irradiation in different facilities all over the world, such as J-PARC [1, 2], Rutherford Appleton Laboratory [3], Paul Scherrer Institute [4], Fermilab [5], CERN [6] and others. Graphite shows an extremely high performance for these applications due to its thermal, mechanical, and other properties. Furthermore, the residual radiation dose of graphite after proton irradiation is lower than that of high-Z material.

However, graphite is easily oxidized at high temperature [7]. If air is unexpectedly introduced into the primary beamline during the high-power beam operation, the rapid oxidation of the graphite target and the consequent mass loss could be detrimental to safe operation. The presence of graphite oxidation contaminants complicates these recovery procedures. Moreover, the transport efficiency of pions/muons to secondary beamlines depends on the density of the target material. In general, denser material is preferable to have a point wise source for secondary beam transport. Therefore, to replace the graphite, it is important to develop the material that is denser while keeping excellent mechanical and thermal properties as well as more resistant to oxidation. Now, we started to investigate new target material with higher performance. Silicon carbide (SiC) is an excellent candidate because it satisfies the characteristic mentioned above in addition to good heat resistance and high mechanical strength. However, monolithic SiC cannot be used as structural material under a pulsed heating cycle, because it is of a brittle nature. To avoid brittleness the investigation of Nano-Infiltration and Transient Eutectic phase process SiC/SiC (NITE SiC/SiC) composite material was started. NITE SiC/SiC has been developed for the fusion and fission reactor applications at Organization of Advanced Sustainability Initiative for Energy System/Materials (OASIS), Muroran Institute of Technology [8]. Figure 1 shows a picture of a specimen of NITE SiC/SiC for the irradiation test at HiRadMat of CERN [9] described in session 2.4. The width, the height, and the depth of the samples were 78 mm, 34 mm, and 20 mm, respectively.

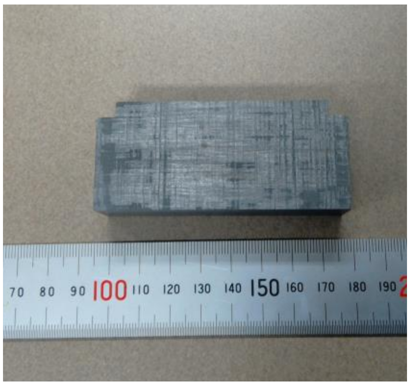

Fig. 1. A picture of a specimen of NITE SiC/SiC for the irradiation test at HiRadMat of CERN

2. Evaluation of NITE SiC/SiC as the target material

2.1 Transport efficiency by the targets made of NITE SiC/SiC

In general, the density of the target material should be higher, because the reduced spatial volume of the source is beneficial to more efficient transport. The density of NITE SiC/SiC is ranging between 2.8-3.2 g/cc, while one of graphite is 1.82 g/cc. The quality and the number of the pions/muons, used for the aimed experiments, depend on the process of pions/muons production, the fraction of the pions/muons that escapes from the target material, and the transport efficiency through the secondary beam line.

The graphite target at MUon Science Innovative muon beam Channel (MuSIC) [10] of the Research Center for Nuclear Physics of Osaka University (RCNP, Osaka) is located in the capture solenoid magnet composed of the super conducting magnets. The maximum energy and the maximum current of the proton beam are 392 MeV and 1.1 μA, respectively. The length of the graphite target is 200 mm. Even if the graphite target is replaced with the SiC target with the optimizations of diameter and location, the number of pions/muons transported to the experimental area decreases by 10 percent in the Monte-Carlo simulation, PHITS [11]. On the contrary, when the graphite target is replaced with the SiC target in the COMET target [12] of the J-PARC, whose concept is similar to that of MuSIC, the number of pions/muons transported to the experimental area increases by 30 percent due to higher 8 GeV energy of the proton beam.

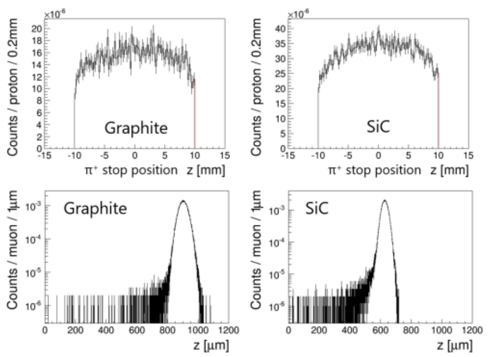

Fig. 2. Comparison of the graphite and the SiC targets at MLF, whose thicknesses are 20 mm. The upper figures are pions-stop-positions inside the targets when 3 GeV protons are irradiated. Ranges of surface muons (4 MeV) in graphite and SiC are shown in the bottom figures.

In the case of Materials and Life Science Experimental Facility (MLF) of J-PARC, pulsed muon beams are produced by using 3 GeV protons from the RCS. The muon production target is made of graphite and its thickness is 20 mm. If the SiC target of the same thickness is used, the number of pions that stop near the target surfaces increase about two times as expected due to the increase of nucleon density. The upper two figures of Figure 2 shows pions-stop-position distributions inside the graphite and SiC targets when the 3 GeV proton beam is injected. The simulation was performed using GEANT4.10.3.p02 with a hadronic model of INCLXX_ABLA. Muons produced from the stopped pions have to escape from the inside of the target, therefore muon range inside the target is another important parameter for muon production efficiency and was also simulated using GEANT4. The result is shown in the bottom of Fig. 2. The range of surface muons (4 MeV) inside the SiC target is 1.4 times shorter than that of the graphite target, and as a result, the surface muon production of the SiC target is 1.4 times more efficient.

DeeMe [13] is also an experimental search for muon-electron conversion at MLF. The signal electrons from the muon-electron conversion in muonic atoms formed in the muon production target are captured and transported to the spectrometer by the secondary beam line. Because the conversion takes place inside the target on the proton beamline, the efficiency strongly depends on the atomic number of the target material. In this case, the efficiency of SiC is 6 times higher than that of the graphite target when thickness of both targets is same [14].

2.2 Oxidation resistance of NITE SiC/SiC

SiC exhibits two types of oxidation behavior: active and passive oxidation at high temperature, depending on oxygen partial pressure. At low partial pressure, active oxidation that leads to some mass loss by gaseous SiO formation is observed and no protective film is formed. On the other hand, passive oxidation characterized by mass gain and oxide film formation is observed at high oxygen partial pressure. The silicon dioxide film protects the surface of SiC, and thus results in excellent oxidation resistance at high temperature [15]. Because NITE SiC/SiC is composed of reinforcement fibers, matrix and pyrolytic carbon (PyC) as fiber/matrix interphase, the oxidation behavior is different from that of pure SiC. Since the performance of NITE SiC/SiC is concerned to degrade due to the oxidation of PyC interphase, it is necessary to protect the PyC interphase. Therefore, the oxidation behavior of NITE SiC/SiC with CVD (Chemical Vapour Deposition) -SiC coating was studied, and its high performance was confirmed [16].

2.3 Residual radiation dose and radionuclides of NITE SiC/SiC

The target material is radio-activated by proton irradiation. In the case of NITE SiC/SiC, the isotope of sodium, ^{22}Na, whose half-life is 2.6 years, leads to high residual radiation dose. The residual radiation dose of pure SiC or NITE SiC/SiC is 400 times higher than that of graphite a year after proton irradiation. The handling of the irradiated NITE SiC/SiC must be carefully considered for the actual operation. To validate the evaluation through the Monte-Carlo simulation, a 392-MeV proton irradiation test of NITE SiC/SiC was conducted at the N0 beamline of RCNP, Osaka, on July 11 and 12, 2017 (E494 experiment). So far, since graphite is the most popular material for a pions/muons production target, IG-430U of TOYO TANSO Co. LTD [17] was irradiated as reference material. NITE SiC/SiC includes some additives such as aluminum, yttrium and so on. Pure SiC, manufactured by CVD, was also irradiated to investigate the effect of the additives. The beam energy, the current, the duration time, and the beam diameter are 392 MeV, 500 nA, 30-210 min. and about 4 mm, which was measured by fluorescent profile monitor, respectively. The diameter and the thickness of the samples were 10 mm and 0.75 mm, respectively. The maximal temperatures of NITE SiC/SiC and CVD-SiC during the irradiation was estimated to be 610 K and that of the graphite was 510 K.

The residual radiation dose was sufficiently low that, one day after the irradiation, the samples could be handled manually at Radio Isotope (RI) Building in RCNP. The production of the radionuclides was anticipated through the Monte-Carlo code, PHITS. Actually-obtained radionuclides by the irradiation were measured by the gamma-ray spectroscopy using the high-purity germanium calibrated with a standard ^{22}Na source. The measured values of the induced activity of ^{22}Na generated in NITE SiC/SiC and CVD-SiC were both 1.8 kBq, and the calculated results using PHITS were 4.4 kBq. The difference between the experimental value and the calculated value is considered to be the fluctuation of the proton beam current, the measurement error, and the error of the nuclear reaction model used for the PHITS calculation. The experiment and the calculation agree with the factor, and it was confirmed that PHITS can accurately evaluate the radiation induced by proton irradiation of 392 MeV.

2.4 Thermal shock resistance of NITE SiC/SiC

Highly-cyclic and volumetric heating with extremely short-time width is induced by high-energy and pulsed proton beam. The temperature of the beam spot increases and the volume is constrained by the surroundings at low temperature. Consequently, the compressive-to-tensile stress causes the propagation of the displacement. The wave propagation could severely damage the target material. At first, the mechanical properties of a pressure-less sintering SiC, SC-1000 of Kyocera Co. LTD [18] as typical monolithic SiC material are compared with those of IG-430U to simplify the discussion, because the mechanical properties of NITE SiC/SiC depend on the structure and the orientation of the composing fabric. The Young's modulus of SiC is 440 GPa and that of IG-430U is 11 GPa: SiC has 40-times larger Young's modulus than that of the graphite. The heat generated on SiC by the proton beam is 1.8 times higher than that on graphite according to higher density. Because thermal stress is proportional to temperature difference and Young's modulus, the approximately 72-times stronger thermal stress on SiC will take place than that in the case of graphite. The bending strength of SiC is 450 MPa, and that of the graphite is 59 MPa: SiC has 7.5 times larger strength than graphite. This means SiC has almost 10-times larger risk than graphite in terms of thermal shock [19].

NITE-SiC/SiC is expected to resist thermal shock because of the pseudo ductility. However, the actual damage behavior must be confirmed because the pseudo ductility is essentially based on a complicated destructive process. HiRadMat facility at CERN has dedicated to the study of the impact of intense pulsed beams. On August 14 and 15, 2017, NITE-SiC/SiC was included in the HRMT-35 experiment that was including several graphite material with or without functional coating. The beam energy was 440 GeV. The beam radius was $\sigma_x=\sigma_y=0.3$ mm. The time width of one bunch was 25 ns. One bunch included 1.2×10^{11} protons. 288 bunches irradiated the target material for one position. After the irradiation test, slight damage with three stripe-lines, where the beam was irradiated, was observed on the surface through the visual test taken by the remote-controlled camera. After cooling of the residual radiation dose, further post-irradiation examination was conducted. The results will be reported soon.

3. Conclusion

The feasibility study for NITE SiC/SiC as the target material for pions/muons production is in progress. Compared with the graphite that is the principal target material for pions/muons production, higher transport efficiency can be expected in some cases. Moreover, NITE SiC/SiC has much higher oxidation resistance than graphite. However, the residual radiation dose of NITE SiC/SiC irradiated by high-energy proton is 400 times higher than that of graphite a year after the irradiation. To validate the simulation, the samples made of CVD-SiC, NITE SiC/SiC and the IG-430U were irradiated at RCNP, Osaka University. Then the residual radionuclides of the irradiated samples have been analyzed by gamma-ray spectroscopy using high-purity germanium detectors. To understand the effect of highly-cyclic and volumetric heating with extremely short-time width induced by high-energy and pulsed proton beam, NITE-SiC/SiC was included in the thermal impact testing facility, HiRadMat at CERN. Further post-irradiation examination will be reported soon.

In these studies, NITE SiC/SiC is proved to be a promising material for pions/muons production with the higher transport efficiency and the oxidation resistance, though the maintenance scenario has to be carefully designed due to higher residual radiation dose. The thermal shock resistance and proton-irradiation resistance of NITE SiC/SiC will be confirmed to be applied for the pions/muons production.

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References

[1] S. Makimura et al., Journal of Radioanalytical and Nuclear Chemistry, 305, 811-815, 10.1007/s10967-015-3949-0 (2015)
[2] T. Nakadaira et al., AIP Conference Proceedings 981, 290, 10.1063/1.2898964 (2008)
[3] G. H. Eaton, Zeitschrift fur Physik C - Particles and Fields 56, S232-S239 (1992)
[4] S. Kopp, Proceedings of 2005 Particle Accelerator Conference, Knoxville, Tennessee, 1-3, 10.1109/PAC.2005.1590344 (2005)
[5] G. Heidenreich, AIP Conference Proceedings 642, 122, 10.1063/1.1522602 (2002)
[6] K. Elsener, CERN-98-02; INFN-AE-98-05, 10.5170/CERN-1998-002M.
[7] Takahashi et al., Journal of Nuclear Science and Technology 31 12, 1275-1286, 10.1080/18811248.1994.9735290 (1994)
[8] A.Kohyama, et al., Ceramic Transactions, 256, 37-52, 2016
[9] https://acceleratingnews.web.cern.ch/article/hiradmat-testing-materials-under-high-radiation, accessed in May of 2019
[10] Y.Hino, et. al., Nucl. Phys. Proc. Suppl. 253-255 (2014) 206-207
[11] T. Sato *et al*., Particle and Heavy Ion Transport Code System PHITS, Version 2.52, J. Nucl. Sci. Technol. 50:9, (2013) 913-923
[12] http://comet.kek.jp/Documents_files/IPNS-Review-2014.pdf, accessed in May, 2019
[13] N. Teshima on behalf on behalf of the DeeMe Collaboration, Proceedings of Science, vol. 295 (NuFACT 2017) 109 (2018), 10.22323/1.295.0109
[14] Y. Nakatsugawa et al., Nuclear and Particle Physics Proceedings 273–275 1692–1698, 10.1016/j.nuclphysbps.2015.09.273, (2016)
[15] T. Narushima et al., Journal of the American Ceramic Society, 72 [8] 1386-90 (1989)
[16] Joon-Soo Park, et al., Ceramics International 44(14) 17319-17325 (2018)
[17] TOYO TANSO: http://www.toyotanso.co.jp/index_en, accessed in May, 2019
[18] KYOCERA: http://global.kyocera.com/fcworld, accessed in May, 2019
[19] S. Makimura et al., KEK MSL REPORT 2014, KEK Progress Report 2015-4, p7-8 (2015)