KOMAC Ion Beam Capability for Nuclear Material Study

Han-Sung Kim*, Hyeok-Jung Kwon, Seung-hyun Lee, Jeong-Jeung Dang, Dong-Hwan Kim, Sang-Pil Yun
Korea Multi-purpose Accelerator Complex, Korea Atomic Energy Research Institute, Gyeongju 38180, South Korea
**Corresponding author: kimhs@kaeri.re.kr*

1. Introduction

Study on the nuclear material is a major part in research and development of next-generation advanced nuclear systems such as a molten-salt reactor (MSR), a sodium fast reactor (SFR) and a thermonuclear fusion reactor. Especially, various types of radiation damage on material induced by high-energy neutron should be taken into consideration for the development of advanced nuclear systems because the anticipated neutron energy and dose of such systems are much higher than those of the operating nuclear power plants. Estimated temperature-dpa requirements for various reactor concepts are shown in Fig. 1 [1].

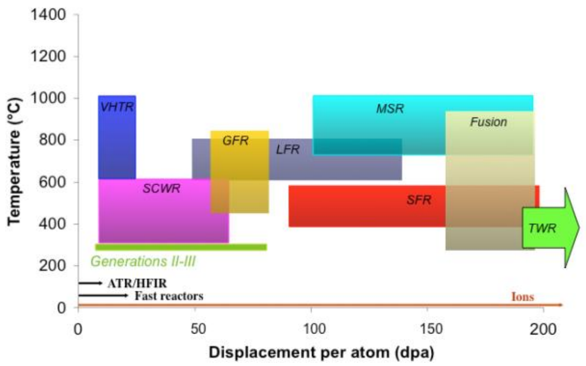

Fig. 1. Estimated temperature and dpa requirements for various advanced nuclear system.

Material study using neutrons from a research reactor is a most relevant and direct way, but it also has many difficulties such as long irradiation period spanning from months to years, high level of specimen activation and high cost for the neutron experiments.

On the contrary, material tests using ion beams instead of neutron can be an alternative with benefits including short irradiation time (~several days), low activation level after irradiation, and capability of in-situ experiments with well-controlled test parameters such as irradiation dose, dose rate and temperature. Table 1 compares the material test based on ion beam technologies with using test reactor [2].

2. Emulating Neutron Irradiation Effect with Ion

2.1 Radiation Induced Segregation

Figure 2 shows comparison of grain boundary segregation of Cr, Ni and Si in commercial purity 316 stainless steel following irradiation with either proton or neutron to similar dpa, along with comparison of elemental enrichment or depletion in grain boundary region from the bulk composition as a result of neutron and proton irradiation [3]. It shows that segregation effect induced by proton irradiation is very similar to that by neutron irradiation with equivalent dpa.

Table 1: Comparison between ion beam and test reactor.

Parameter	Ion beam	Test reactor
Dose	>500 dpa	10-20 max
Dose rate	100-1000 times reactor rates	Few times reactor rate
Energy	controllable	Neutron spectrum
Temperature	Better than 10℃	Several 10s of ℃
Activation	Low to none	High
In-situ test	TEM, RS, GC, etc	Challenging
Cost	Relatively low	Very high
Simultaneity	Corrosion, SCC, creep, diffusion	Doable but difficult
Sample thickness	A few nm to um	bulk

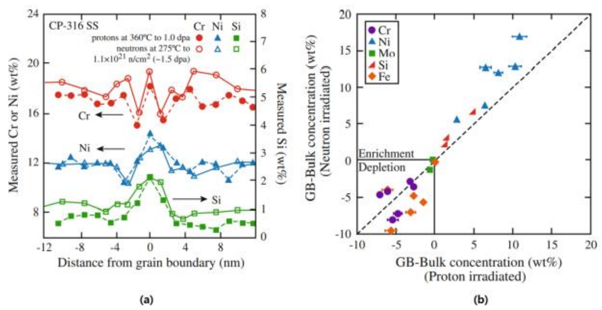

Fig. 2. Comparison of radiation induced segregation.

2.2 Radiation Hardening

Radiation hardening effect on 304 stainless steel is compared in Fig. 3 for similar dose of proton and neutron [3]. Yield strength change due to neutron irradiation as a function of dose level is quite similar to proton irradiation case at an elevated temperature.

2.3 Microstructure

Microstructures such as line dislocation, dislocation loops, precipitates in matrix and voids were observed after proton irradiation and neutron irradiation as shown in Fig. 4 [4]. It shows similarity of equivalent dpa proton irradiation to the neutron irradiation.

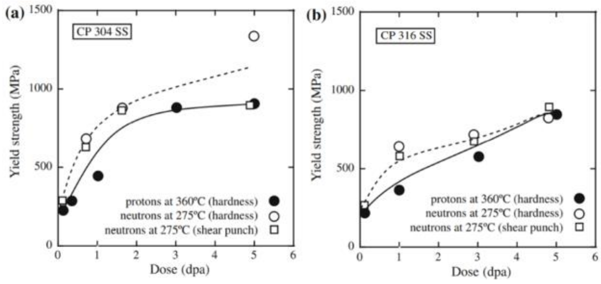

Fig. 3. Comparison of radiation hardening effect.

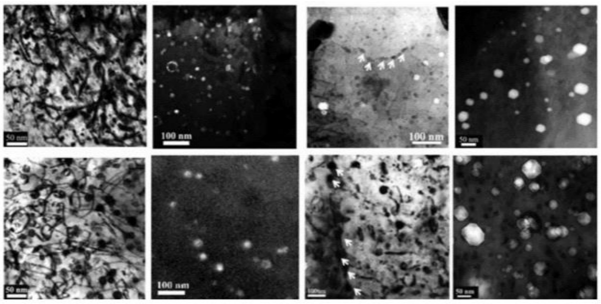

Fig. 4. Comparison of irradiation microstructure in HT9 following Fe^{2+} irradiation (460℃, 188 dpa, top images) and following reactor irradiation in FFTF (443℃, 155 dpa, bottom images)

3. Ion Beam Facilities around World

Around world, there are several ion beam facilities performing nuclear material study. Among them, a few leading facilities are summarized in Table 2 [5-7]. In addition to the conventional ion beam irradiation experiments, in-situ tests with TEM are gaining attention along with dual or triple-beam irradiation capability. Main device for ion beam irradiation in those facilities is several MV grade tandem accelerator.

Table 2. Representative ion beam facilities

MIBL (USA)	DuET (Japan)	JANNuS (France)
400 keV ES 1.7 MV tandem 3 MV tandem	1 MV ES 1.7 MV tandem	2 MV tandem 2.5 MV tandem 3 MV tandem
TEM in-situ	-	TEM in-situ

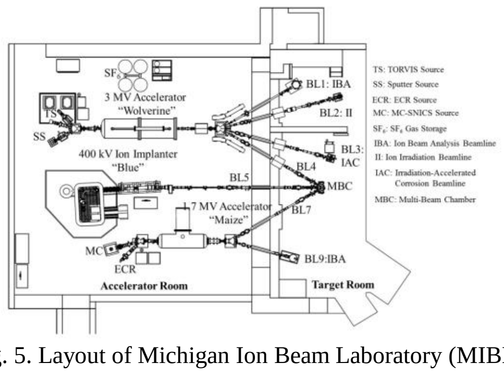

Fig. 5. Layout of Michigan Ion Beam Laboratory (MIBL).

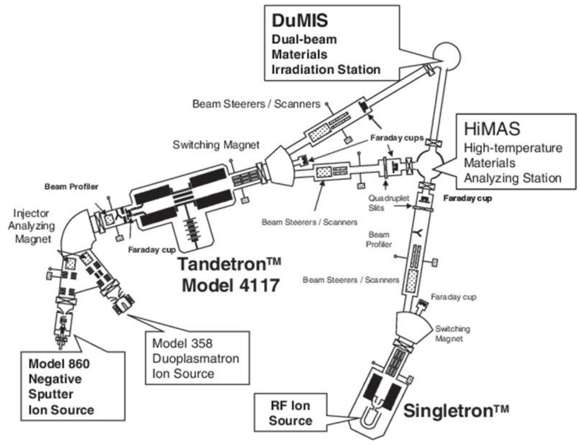

Fig. 6. Layout of Dual-beam Facility for Energy Science and Technology (DuET).

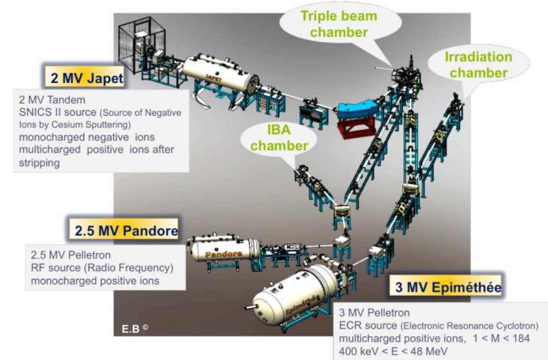

Fig. 7. Layout of Joint Accelerators for Nanoscience and Nuclear Simulation (JANNus).

4. KOMAC Ion Beam Facilities

At KOMAC (Korea Multipurpose Accelerator Complex), we have several ion beam accelerators which can be used for nuclear material study. A 1.7 MV tandem accelerator and 1 MV single-ended electrostatic accelerator are under operational and 1 MeV/n RFQ based accelerator is under development. In addition to them, 3 MV tandem accelerator is under test. Figure 8 shows tentative layout of 1 MeV/n RFQ based accelerator and 1.7 MV tandem accelerator for dual beam irradiation. By using 1 MeV/n RFQ and 1.7 MV tandem, we can irradiate He beam up to 4 MeV and Fe beam up to 5 MeV simultaneously. Table 3 summarizes the KOMAC ion beam facilities.

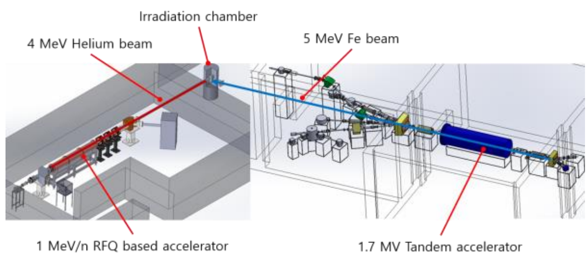

Fig. 8. Tentative layout of KOMAC dual beam irradiation facility.

Table 3. Summary of KOMAC Ion beam facilities.

1.7 MV Tandem	1 MV Single-End	1 MeV/n RFQ	3 MV Tandem
H, He, Fe, Cl, etc	Proton	A/q <2.5 (D, He, Ar)	From H to Au
P 3.4 MeV Fe 5.1 MeV	1 MeV	He 4 MeV	P 6 MeV Fe 9 MeV
Operational	Operational	Development	Test

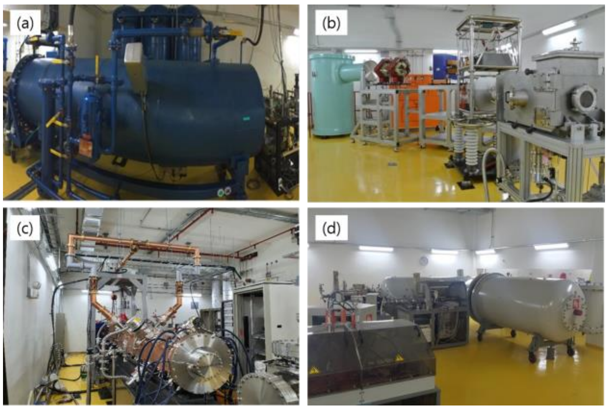

Fig. 9. KOMAC ion beam facilities (a) 1.7 MV tandem, (b) 1 MV single-end, (c) 1 MeV/n RFQ, (d) 3 MV tandem.

For the case of 5 MeV Fe beam irradiation on the stainless steel by using 1.7 MV tandem accelerator, Fe ion range and dpa were estimated by using SRIM code [8]. The results are shown in Fig. 10. Range was about 1.4 um and dpa level of 16 were expected when the ion beam fluence was about 1.0E16 ions/cm^2.

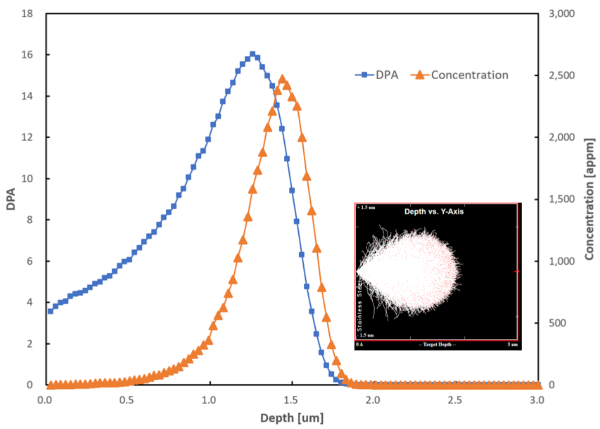

Fig. 10. Range and dpa estimation for the case of 5 MeV Fe beam on the stainless steel.

5. Conclusions

Ion beam technology is a promising alternative to the neutron irradiation experiments for studying nuclear material. It provides data on the effects of irradiation under very specific conditions of temperature, radiation dose and dose rate as well as benefits of low activation level. It allows rapid achievement of material damage level not accessible by neutron irradiation in test reactors due to cost and time constraints. At KOMAC (Korea Multipurpose Accelerator Complex), we have several ion beam accelerators which can be used for nuclear material study. By configuring the existing accelerators along with development of irradiation chamber to provide sample environment, various researches on the nuclear material for advanced nuclear system are expected to be performed at KOMAC in near future.

ACKNOWLEDGEMENT

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