Development status of 30 MeV cyclotron-based neutron source in Korea

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Abstract. KAERI has developed plasma heating systems and fusion engineering technologies such as blanket first wall and breeding blanket for nuclear fusion reactor development, as well as nuclear data production. Based on these technologies, we have successfully developed various ion sources-based D-D compact neutron generators and are developing a 30 MeV cyclotron-based neutron source for on-site neutron radiography service. Final construction and phase-1 licensing have been completed, and preliminary tests have demonstrated neutron yield of a 1.6×10^{12} n/s at 30 MeV and 0.01 mA. Under these conditions, neuron images were acquired at a resolution of 0.3 mm with an exposure time of 5 minutes.

1 Introduction

Nuclear fusion is considered to be a next-generation clean and sustainable energy due to its inherent safety and abundant fuel resource. In this context, ITER has been built to resolve the scientific and technological issues that remained for the ignition at Cadarache in France since 2006, and Korea has joined this international project and contributed to its construction in parallel with the understanding of plasma physics through domestic KSTAR (Korea Super Conducting Tokamak Advanced Research) operation. Also, Korea has been developing a fusion energy roadmap to support engineering R&D, including materials, blankets, system engineering, licensing, codes and standards centered on fusion neutron source (FNS) promoting the development of fusion demonstration reactors and fusion reactors by refining the fusion energy roadmap. Various neutron sources are currently being considered, including a 40 MeV linear accelerator-based neutron source, an assembly of cyclotron-based neutron sources, a spherical tokamak-based neutron source, and so on [1].

As an organization that researches fusion energy with a focus on nuclear energy, the Nuclear Physics and Applied Research Division at KAERI is responsible for engineering research on plasma heating systems, and breeding blankets and plasma-facing components for nuclear fusion reactor development, as well as nuclear data production. We are promoting the development of neutron sources using our technologies, research utilization, and further industrial utilization. Following the success of the D-D compact neutron generator, the development of a 30 MeV cyclotron-based neutron source is imminent. In the present paper, we will briefly introduce the status of the division and the technologies behind it, followed by a brief overview of the development status and results of the 30 MeV cyclotron-based neutron source.

2 KAERI activities for fusion and basic technologies for CANS

KAERI, especially for Fusion Nuclear Engineering Development Division has long experience on fusion plasmas through KT-1 development and KT-2 planning since 1983. After that, we participated in the KSTAR and ITER projects in various fields, as shown in Fig.1.

In KSTAR construction and operation, we developed the tokamak heating and current drive devices such as ion cyclotron range of frequency (ICRF) and neutral beam (NB) since 1996. They are successfully providing KSTAR heating power at

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present; NB contributed to the achievement of long-pulse stable H-mode during 40 sec at KSTAR [2-9], and ICRF heating and current drive system has been developed to provide 2 MW power for KSTAR high beta long pulse operation [10, 11]. In participating in ITER construction and preparing for the operation, KAERI developed the ITER blanket first wall (BFW) as a plasma facing component (PFC) and test blanket module (TBM) as a breeding blanket for the fusion reactor. For PFCs' development, we constructed a KAERI heat load test facility using an electron beam system (KoHLT-EB) to evaluate the fabrication technologies required for the ITER BFW and DEMO FW, in which joining technologies of Be/CuCrZr, CuCrZr/SS, W/CuCrZr, W/FMS(Ferritic martensitic steel) were developed [12-19]. For breeding blanket development, KAERI has developed a helium-cooled ceramic reflector (HCCR) test blanket module (TBM) to be tested in ITER for developing the fusion breeding blanket. Through the conceptual design review (CDR), its design integrity was demonstrated at the conceptual design level at various loads in 2016 [20-23].
From these experiences and technologies of the KSTAR heating system and ITER PFC/blanket developments, we started to develop the neutron generators using the accumulated ion source, and target and its cooling technologies, as shown in Fig. 2. We developed 10^7 to 10^{10} n/s neutron sources with D-D reaction and the results are summarized in Table 1. For industrial and defense applications such as materials analysis, explosive material detection, nuclear weapon detection, and so on, we are collaborating with the military, industry, and government. And also a startup company, "Q-beam Solution" has recently founded and successfully funded to date.
To sequentially produce and utilize neutrons with higher yields, we have established a roadmap for neutron sources development and their application, as shown in Fig. 3, and started to develop compact accelerator-based neutron sources (CANSs) using the existing cyclotron for neutron radiography and other applications. Further neutron sources are considered to be developed for fusion research with a heavy ion accelerator (KAHIF) for fusion and fission materials' supporting R&D [1].

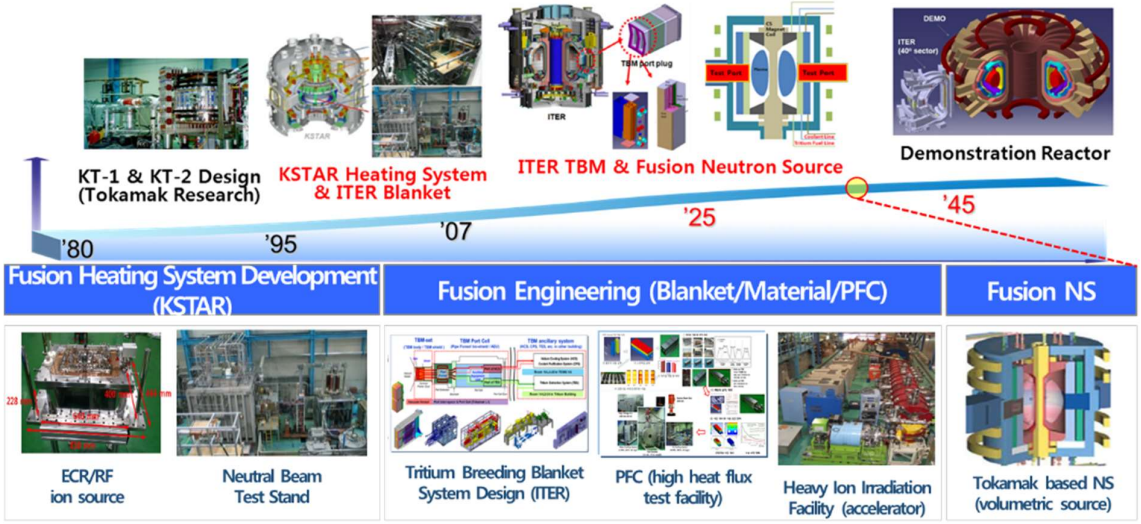

Fig. 1 National roadmap for fusion energy and related R&Ds at KAERI.

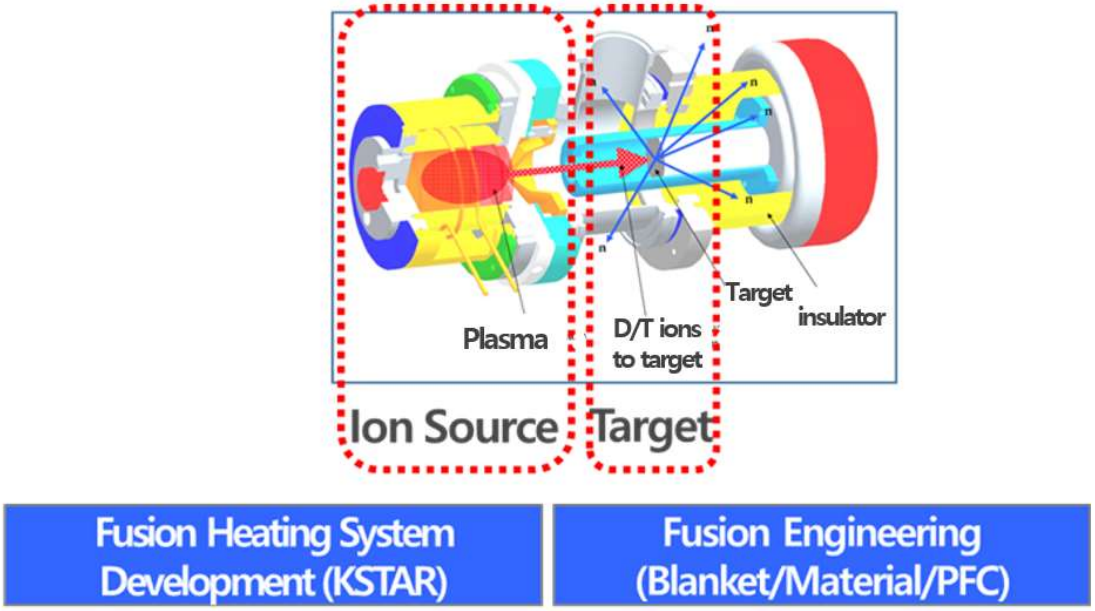

Fig. 2 Schematic of the developed DD generator based on the experiences and technologies of the KSTAR and ITER projects.

Table 1 Developed neutron generators with various ion sources and neutron yield.

Development Status	**Complete (2018.12)**	**Complete (2018.12)**	**Complete (2020.10)**	**Complete (2022.12)**	**Complete (2023.10)**
Ion source	PIG	PIG	RF	ECR	ECR
Operation	Pulse	CW	Pulse	CW	CW
Beam Energy [keV]	100	100	100	50	200
Current [mA]	1	1	100	50	50
Target (reaction)	Be (Ti coated) D-D	Be (Ti coated) D-D	Be (Ti coated) D-D	Be (Ti coated) D-D	Be (Ti coated) D-D
Neutron Yield [n/s]	10^7	10^7	10^9	10^8~10^9	10^{10}
High voltage insulation	Vacuum	Vacuum	SF_6	Air	SF_6
Cooling at target	No cooling	Air	Water	Water	Water

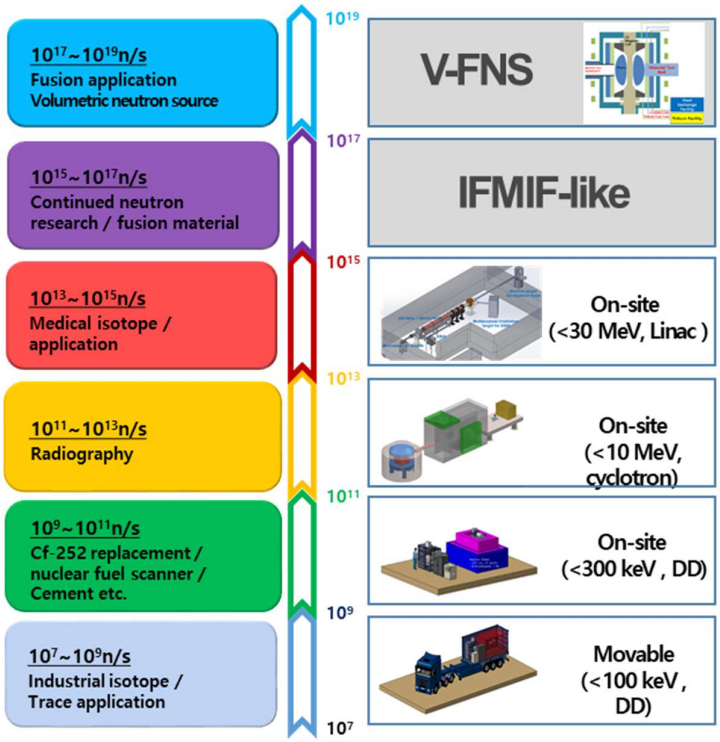

Fig. 3 Neutron sources development roadmap and their application plan.

3 Status of 30MeV Cyclotron-based CANS development

Due to the neutron characteristics of its interaction with low atomic material, it has been used as a non-destructive testing method for such as an explosive, ammunition, an aerospace compartment, etc., especially where X-ray imaging has limitations. So far, the research reactor, HANARO has provided the radiography (~10^{14} n/cm^2/s, 10^{18} n/s at reactor core), but the accessibility is decreasing due to the recently strengthened regulation and the limitation of the object size. The need for an on-site neutron source for radiography of industry and defense is increasing, therefore a new project was started in April 2020 to develop the neutron production over 10^{12} n/s considering the minimum neutron yield for radiography. The overall project scheme and concept of neutron source and radiography were introduced in Fig. 4. And it consists of the following Tasks;

(Task 1) Target-Moderator-Reflector-Shield (TMRS) system development.

(Task 2) On-site neutron radiography development and supply of stable proton beam. The well-established thermal neutron imaging technique will be used and compared with HANARO.

(Task 3) Comparison developed neutron radiography with X-ray ones with a company, in which more complex internal structure and feasibility/advantage of neutron image will be confirmed.

(Task 4) For produced neutron energy and spectrum, neutron flux will be measured at various locations in the laboratory including the specimen.

For TMRS, the thickness of the Be target and the width of the water coolant were determined to be 5.5 mm and 4.5 mm, respectively, considering the maximum proton energy of 30 MeV and the depth of energy deposition to avoid blistering. To obtain the optimal neutron spectrum for radiography, high-density polyethylene (HDPE) moderators are used, varying in thickness from 5 cm to 30 cm, and the target-moderator assembly is designed and fabricated to be replaceable. The reflector and shield have a layered structure of HDPE, lead, and concrete mixed casemate combination as shown in Fig. 5, consisting of 48 cm of primary HDPE, 12 cm of lead, 25 cm of secondary HDPE, and 15 cm of concrete and steel shot casemate.

Proton beam irradiation tests were conducted in conjunction with the TMR fabrication to (1) confirm the proton beam stable withdrawal conditions (30 MeV, 0.1 mA) over 36 hours and (2) confirm proton beam transmittance of >90% on the Be target through beam optical alignment with replacing the larger Al window (before replacement, it was 75%). For neutron spectrum measurements, we developed a scintillator-based device (H3164/9111B series PMT with HDPE boner sphere) as shown in Fig. 6, and unfolded it with MCNP 6.2 calculations to evaluate neutron yield.

Initially using the Be target without HDPE moderators, neutron spectrum and yields were evaluated to be 2.6x10^{10} n/s and 1.6x10^{12} n/s at 1.2 μA and 10 μA (0.01 mA), respectively. Fig. 7 shows the measured and unfolded neutron spectrum at each current. Preliminary neutron images of the modulation transfer function (MTF) bar patterns were obtained at 30

MeV and 0.01 mA conditions, as shown in Fig. 8, with progressively more closely spaced bar patterns providing a more quantitative way to characterize the spatial resolution of the detector. Using this standard, the limiting resolution of this radiography is about 0.3 mm.

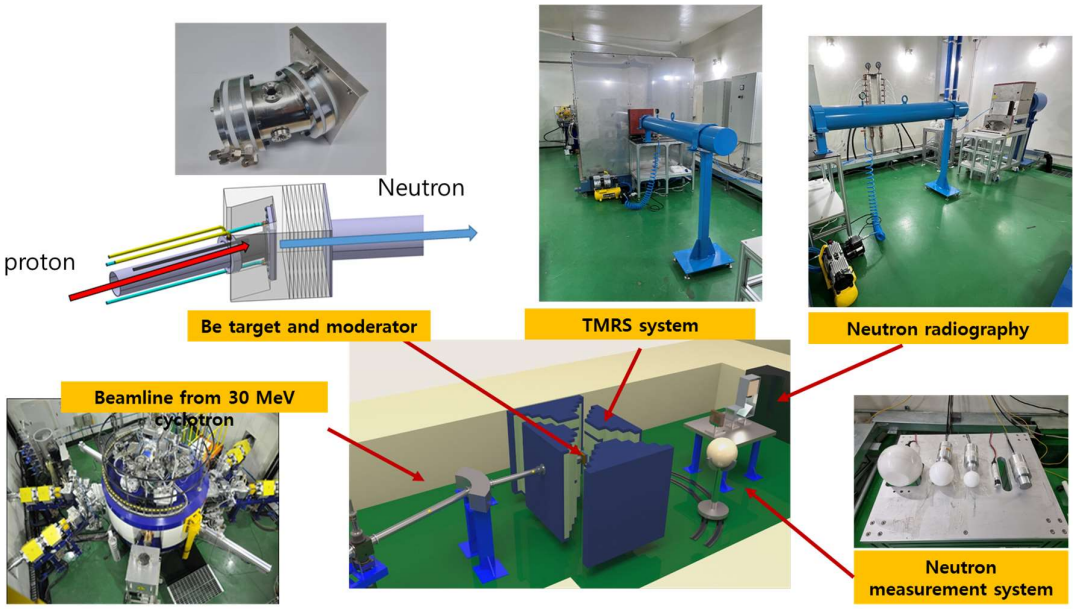

Fig. 4 Project scheme and concept of neutron source

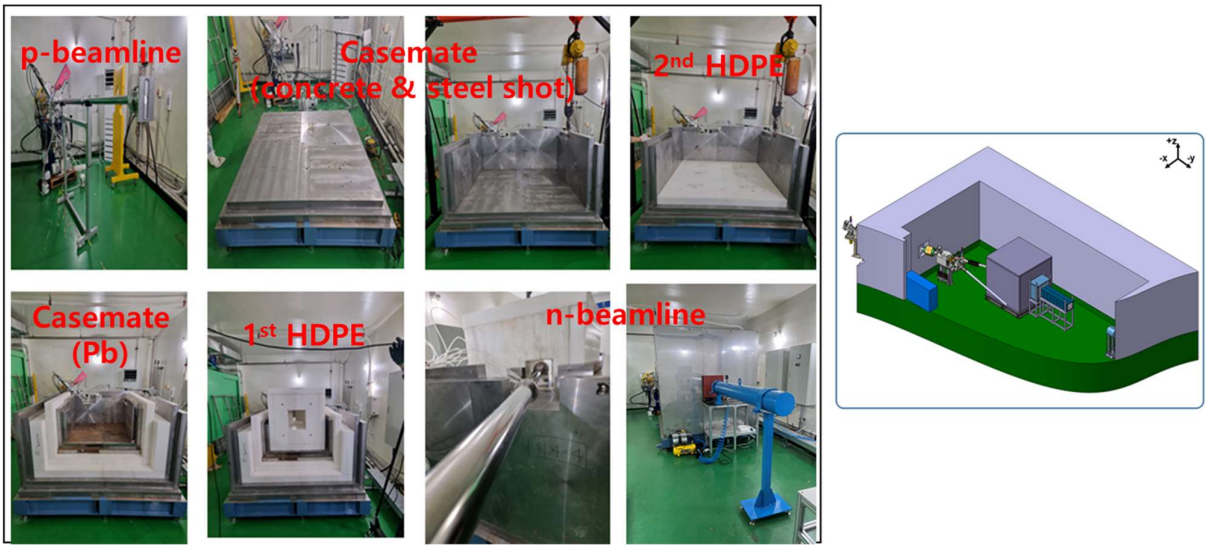

Fig. 5 Fabrication procedure of TMRS for neutron production

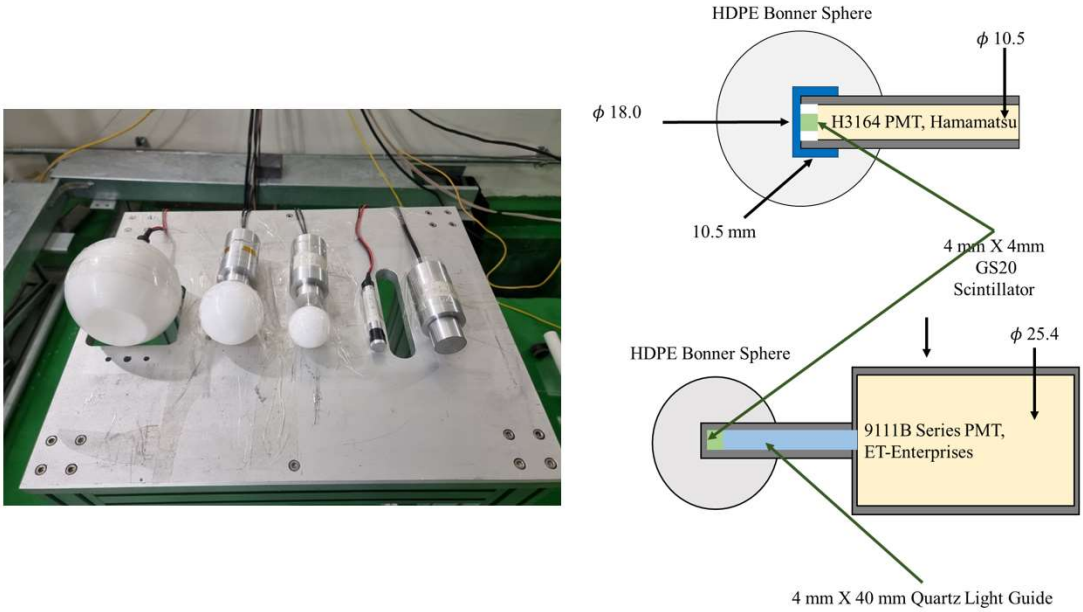

Fig. 6 Neutron measurement system and installation location, and its results

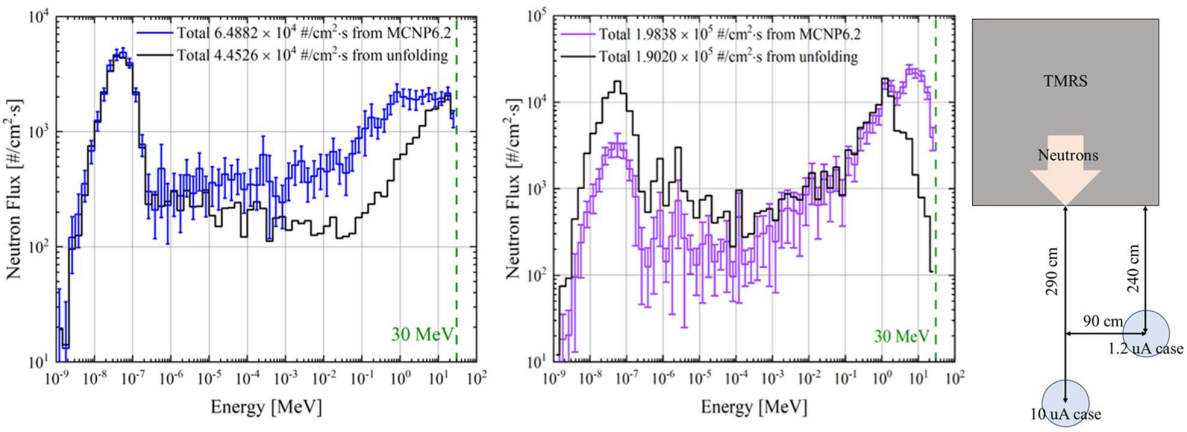

Fig. 7 Preliminary Neutron spectrum results of 1.2 μA (left) and 10 μA (center) at 30 MeV, and measurement position (right)

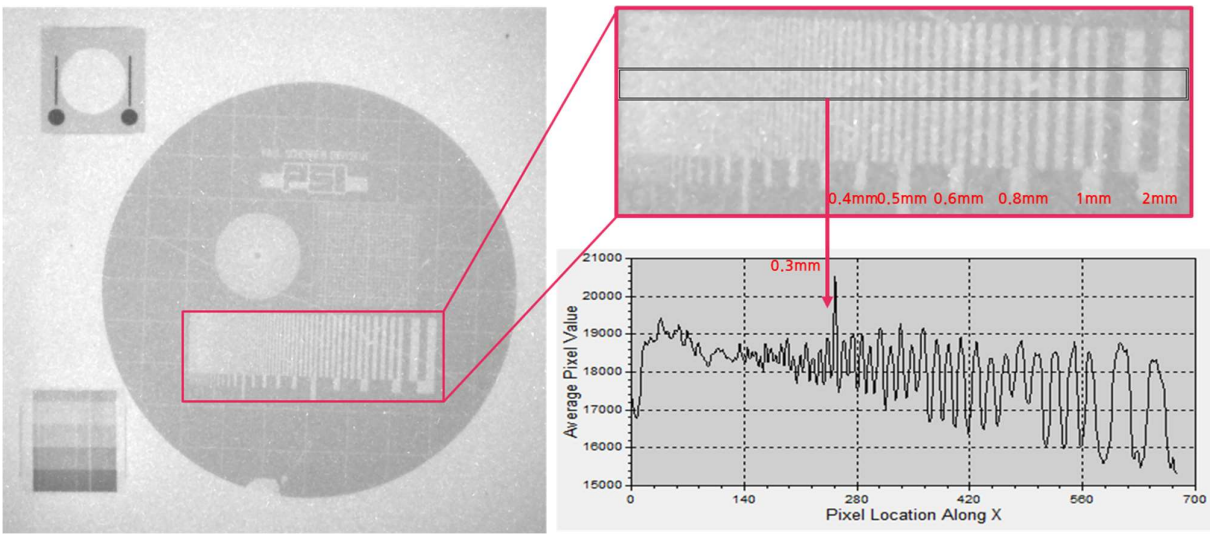

Fig. 8 Neutron image of the bar pattern to measure the MTF (left) and enlarged MTF bar and an intensity profile of the image (right).

4 Conclusions

KAERI has developed a variety of neutron generators and CANS according to the established neutron sources development plan, utilizing our over 40 years of research experience and technologies for fusion plasma heating and engineering. Recently, the 30 MeV cyclotron-based neutron source was developed starting in April 2020 and preliminary tests at 0.01 mA confirmed its performance of 1.6×10^{12} n/s neutron yield with a neutron imaging resolution of 0.3 mm. We will further confirm the neutron imaging by increasing the current which will enable industrial service.

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