Measurement of Transmission and Neutralization Efficiency of KSTAR NBI-2

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1. Introduction

Neutral Beam Injection (NBI) plays a significant role in achieving high-performance scenarios in Korea Superconducting Tokamak Advanced Research (KSTAR) [1,2,3]. As shown in Fig. 1, there are two beam systems, the horizontally arranged NBI-1 and the vertically arranged NBI-2. The NBI-2 consists of one on-axis ion source (2A) and two off-axis ion sources (2B and 2C) for off-axis current drives and has been actively used with device commissioning since the 2020 KSTAR campaign [4].

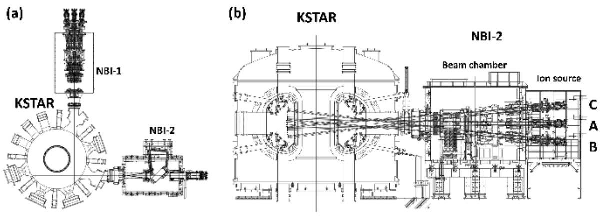

Fig. 1. (a) A cross-sectional view of the KSTAR NBI system. (b) A longitudinal view of the NBI-2 system.

It is necessary to know the essential beam characteristics for stable and reliable utilization of the NBI-2 system. The transmission efficiency is an important parameter that can be used for beam alignment to minimize beam loss. We also need to investigate the neutralization efficiency to select an appropriate neutralizer gas flow rate and maximize the beam power. These are the most fundamental parameters to avoid damage to the beam system and increase the performance of the beam, and they can be obtained through calorimetric analysis. Since the KSTAR NBI-2 system was constructed, the transmission and neutralization efficiency was measured for the first time. In this work, a simple calorimetric method in the KSTAR NBI-2 system will be introduced, and the transmission and neutralization efficiency results will be discussed.

2. Calorimetric method for efficiency calculation

In the KSTAR NBI-2 system, several scrappers and protective covers are prepared to prevent the beam from damaging the beam chamber, and each component consists of a cooling system. Therefore, the cooling water flow rate and temperature are continuously measured, and calorimetric analysis is possible. Fig. 2 shows the elements for which monitoring is performed in the NBI-2 system. Through the power calculated from each component, the transmission efficiency of Eq.1 and the neutralization efficiency of Eq.2 can be obtained.

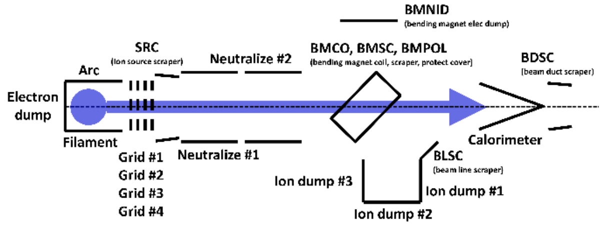

Fig. 2. Components of the KSTAR NBI-2 system where the calorimetric analysis is performed.

$$\eta_{trans} = \frac{Q_{BMNID} + \sum Q_{ID} + Q_{BLSC} + Q_{CMC}}{V_{G1} I_{G1}} \quad (1)$$

$$\eta_{neut} = \frac{Q_{BLSC} + Q_{CMC}}{Q_{BMNID} + \sum Q_{ID} + Q_{BLSC} + Q_{CMC}} \quad (2)$$

When the beam injection length is too short, the errors in calorimetric analysis increase. To check the minimum required injection length, the calculated beam power according to the beam injection length was investigated in Fig. 3. The beam power is saturated with injection length increase, and 1 second or more is sufficient for calorimetric analysis. The actual measurements were performed with a shot of 10 seconds or more to increase the calorimetric analysis's reliability further.

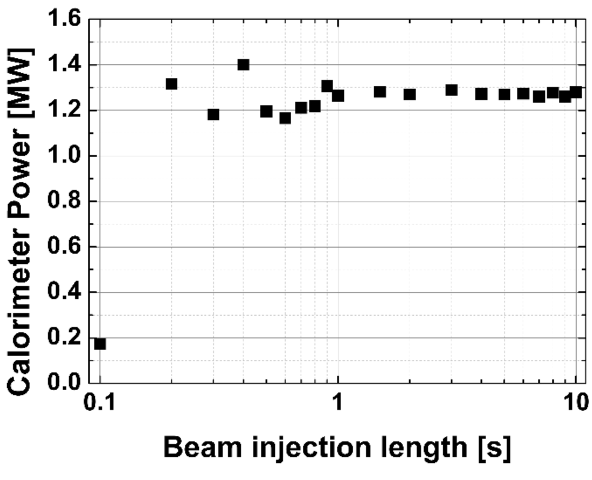

Fig. 3. The calorimeter power changes according to the beam injection length. If the injection length increases, the variation of the power decreases.

3. Transmission and neutralization efficiency

For three ion sources of the NBI-2 system, the transmission efficiency was measured for beam energy that has been commissioned, and the results are shown in Fig. 4.

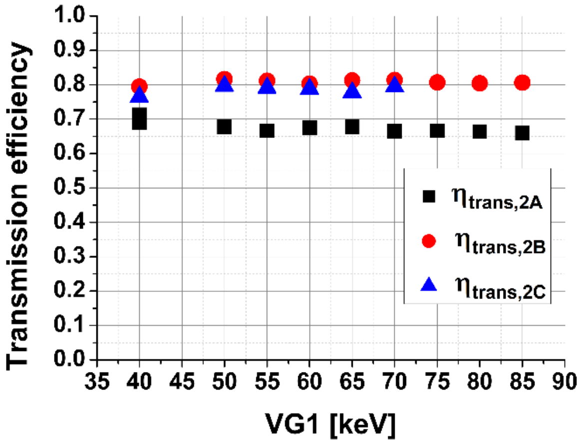

Fig. 4. Results of the NBI-2 transmission efficiency of the 2022 KSTAR campaign.

For 2B and 2C, the transmission efficiency reaches up to 0.8, which is the design target of the NBI-2 system. In addition, it is not affected by beam energy because the beam injection was carried with the same optimum perveance and divergence. What is noteworthy in this measurement is that 2A has significantly lower transmission efficiency than 2B and 2C. This means that in the case of 2A, unlike the design target, there is an alignment issue.

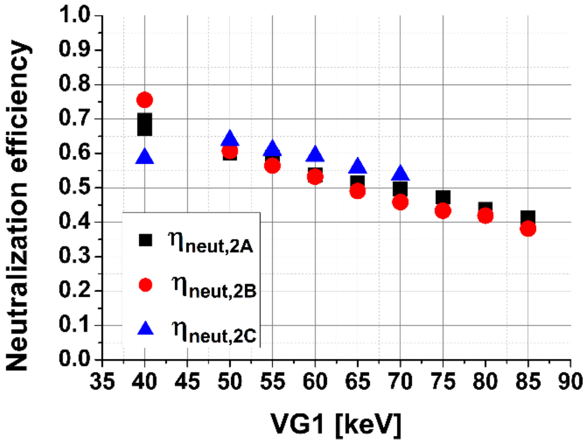

Fig. 5. Results of the NBI-2 neutralization efficiency of the 2022 KSTAR campaign.

Theoretically, the neutralization efficiency decreases as the beam energy increases [5]. The same trend can be seen in the NBI-2 neutralization efficiency measurement results in Fig. 5. However, all ion sources have lower values than the theoretical neutralization efficiency. The current neutralizer gas flow rate is lower than the optimum value. To approach the theoretical neutralization efficiency and find the optimum value, scanning experiments were performed.

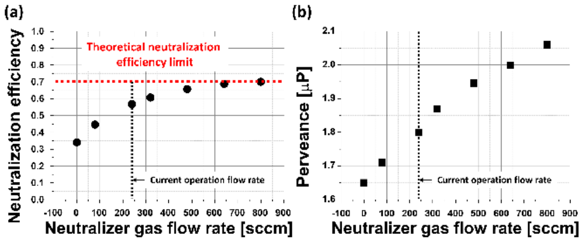

Fig. 6. (a) Neutralization efficiency according to the neutralizer gas flow rate. (b) Perveance according to the neutralizer gas flow rate (NBI-2B, 60 keV).

Naturally, high neutralization efficiency can be obtained at a high gas injection, as shown in Fig. 6. The theoretical neutralization efficiency at 60 keV beam injection is 0.7. We achieved the theoretical neutralization efficiency by increasing the gas flow rate. However, as the neutralization efficiency increases, the pressure of the ion source increases, which causes changes in beam optics and beam faults. Therefore, it is necessary to balance the neutralizer and ion source flow rates.

4. Summary and discussion

In this work, we measured the transmission and neutralization efficiency of the NBI-2. In the case of the 2A source, the transmission efficiency is smaller than that of 2B and 2C. Therefore, the beam alignment work for 2A is required to achieve the design value of 0.8. In the 2023 KSTAR campaign, the flow rate of the ion source and the neutralizer will be balanced to find operating conditions with maximum neutralization efficiency under the optimum perveance. Based on this calorimetric calculation method, we are preparing the transmission and neutralization efficiency monitoring tool as shot by shot.

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