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Numerical Validation and Experimental Demonstration of Beam Trajectory and Hot Spots in the KSTAR NB-2

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1. Introduction

A neutral beam injection has been adopted as an effective means for a plasma heating in a number of fusion experiments [1,2]. The KSTAR has been equipped with two systems of the neutral beam injection [3]. Each device generates an ion beam of 18 MW from three ion sources and injects a neutral beam of 6 MW into a tokamak considering beam transmission and neutralization efficiencies [3]. In practice, the realistic trajectory of the neutral beam could be different from the desired one of the neutral beam. There are two main reasons. First, a non-neutralized beam is affected by the KSTAR stray field. Second, there is an alignment error of the ion source. These make the expected beam transmission efficiency worse, and thus more heat flux is generated on beamline components. Multiphysics simulation is very useful to deal with the problem. In the previous work, we modeled the dipole electromagnet and the particle release from the ion source based on finite element framework COMSOL Multiphysics. The trajectory of the non-neutralized beam was traced from the ion source to dipole magnet to ion dump, and the heat load was evaluated on the ion dump. However, focused grids of the ion source were not considered in the work while the technique was applied to the KSTAR NB-2 to focus the neutral beam at tokamak. In this paper, we improve the model by considering focused grids. Simulation results expect a twin hot spot on the ion beam dump and calorimeter, not a single hot spot. We verify the simulation results through the temperature monitoring of beamline components during the 2022 KSTAR campaign.

2. Methods and Results

This section shows methods used to model focused grids of the ion source and experimental setups to validate the model. The neutral beam injection system usually consists of the ion source, neutralizer, bending magnet, calorimeter, etc. A deuterium ion is generated by the arc discharge in the bucket chamber with filaments and the multi-cusp magnetic field, and the ion is then accelerated by the electric field in accelerating grids. The ion beam is neutralized colliding with a neutral gas in the neutralizer. The neutralization efficiency is about 53% in the KSTAR. The neutralized beam is injected into the tokamak through the neutral beam injection port. Before the plasma experiment, a local conditioning should be performed, and thus we can evaluate the beam power and beam trajectory using the calorimeter. Meanwhile, the non-neutralized beam is deflected to the ion dump by the magnetic field generated from the bending magnet. This is because the non-neutralized beam can damage beamline components by the KSTAR stray field.

2.1 Numerical Validation

Particle trajectories are simulated in the domain including the exit grid of the ion source, bending magnet, ion dump and calorimeter. The problem can be described by the Newton's second law. This can be numerically solved by the generalized-alpha method [4]. COMSOL Multiphysics is employed with the workstation equipped with Intel Xeon processor 3.7GHz and 512GB ECC memory. Focused grids are composed of 280 apertures vertically and horizontally focused at 10 m and 12 m from the exit grid, respectively. Herein, the particle beam is assumed to be release from the exit grid in a cone shape whose angle is equal to the beam divergence of 1°. The beam energy is 70 keV. The distance between the exit grid and bending magnet is 3.80 m, and the distance between the exit grid and calorimeter is 5.24 m.

Fig. 1 shows simulation results about the heat flux distribution by the non-neutralized beam on the ion dump surface. The maximum heat load is 9.75 MW/m^2. The heat load is distributed in a trapezoidal shape due to the vertical component of the Lorentz force on the non-neutralized beam passing through the dipole magnet. The farther the distance from the bending magnet is, the larger the vertical beam expansion is. It is noted that red circles indicate the twin hot spot on the dump surface. The twin hot spot can be explained with the fact that the distance between the exit grid and bending magnet is less than focusing lengths of focused grids. The distribution of the heat flux by the neutralized beam on the V-shaped calorimeter is shown in Fig. 2. The maximum heat load is 12.1 MW/m^2. It is easy to show the twin hot spot on the calorimeter surface. As in the case of the ion beam dump, this is caused by the distance between the exit grid and calorimeter smaller than focusing lengths.

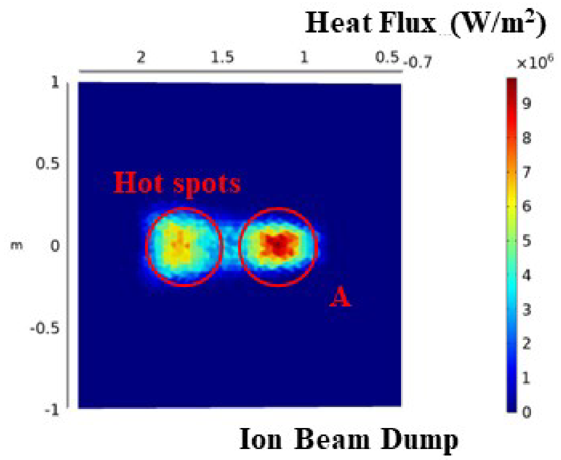

Fig. 1. Heat flux distribution by the non-neutralized beam on the ion dump surface. Hot spots are indicated by red circles. One of three ion sources is considered (NBI-A).

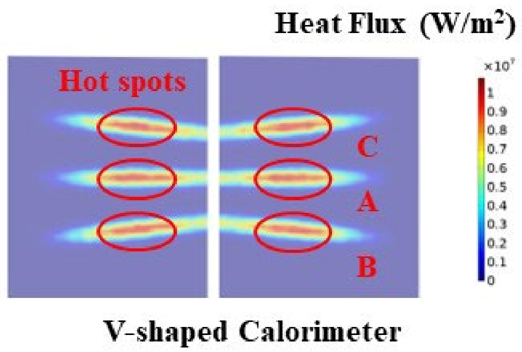

Fig. 2. Heat flux distribution by the neutralized beam on the V-shaped calorimeter. Hot spots are indicated by red circles. All three ion sources are considered (NBI-A, B and C).

2.2 Experimental Demonstration

The temperature of beamline components of the neutral beam injection system was monitored during the 2022 KSTAR campaign. Herein, the temperature data obtained from the local conditioning of the neutral beam injection is analyzed. The V-shaped calorimeter was fabricated with a water cooled device, i.e., the HyperVapotron [5], to endure the high heat load. Each side of the V-shaped calorimeter has a total of 45 thermocouples. Because the front face of the calorimeter is in the extreme environment, temperature sensors should be mounted at the back face of the calorimeter.

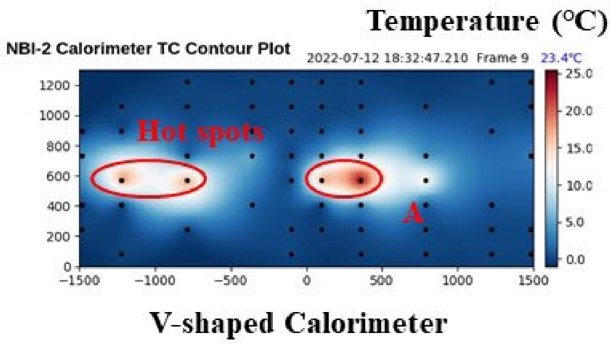

Fig. 3. Interpolated temperature data using a radial basis function. Block dots represent temperature sensors. One of three ion sources is considered (NBI-A).

Fig. 3 shows the interpolated temperature data using a radial basis function. Black dots represent thermocouples attached to the calorimeter, but failed sensors are omitted. In this experiment, one of three ion sources, NBI-A, was operated with the beam energy of 70 keV and the beam duration of 10 s. It is easy to observe that the twin hot spot on the calorimeter surface, as in Fig. 2. Compared with simulation results in the calorimeter, experimental results show that the trajectory of the neutral beam deviates from the center to the left. Because there is no the KSTAR stray field in the local conditioning, this deviation of the neutral beam results from the alignment error of the ion source. The insufficient number of temperature sensors brings about an uncertain information in the region of the left hot spot.

3. Conclusions

The previous computational model for the KSTAR NB-2 is upgraded by considering focused grids of the ion source. We compare simulation results about the twin hot spot on the V-shaped calorimeter with experimental data obtained from the temperature monitoring of the calorimeter during the 2022 KSTAR campaign. This experimental demonstration can verify the improved NB-2 model. An assumption of a single hot spot will lead to an incorrect estimation of the beam trajectory because focused grids actually result in the twin hot spot on beamline components. To consider focused grids will make the accurate evaluation of the heat flux on NB-2 beamline components. More importantly, the twin hot spot will be the indispensable information when we align ion sources with aiming units. Therefore, the numerical validation and experimental demonstration of the twin hot spot is of significant importance in the KSTAR NB-2.

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