22Cp07

大電流イオンビーム輸送における空間電荷中和システムの開発
Development of Space-Charge Neutralization System for High-Current Ion Beam Transport

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In the fields of nuclear fusion and medical, there is a need for a stable supply of high-energy, high-current CW (Continuous Wave) ion beams. To obtain high-energy, high-current ion beams, an ion source capable of producing high-current beams and a low-energy beam transport system (LEBT) that injects the ion beams into a back-end accelerator such as a radio frequency quadrupole (RFQ) are required. The injector (ion source + LEBT) is required to generate and transport a low-divergence beam to satisfy the acceptance of the back-end accelerator in order to achieve low loss and stable supply of high-current ion beams. Hitachi has developed an injector capable of producing a 40 mA H+ beam with a single-hole CW for BNCT. Therefore, to satisfy the demand for even higher current in the field of nuclear fusion, we are aiming to develop a 100 mA class injector with a single-hole CW.

Hitachi has adopted a microwave ion source that can generate a large volume of uniform plasma and is easy to maintain. In order to extract a high current beam of over 100 mA from the ion source, the diameter of the extraction hole has been increased to 12 mm and the extraction voltage to 50 kV. In addition, by developing an ion source equipped with a magnetic path, the leakage magnetic field to the beam extraction area was reduced. Stable beam production was achieved by suppressing the inter-electrode discharge caused by plasma generation. The ion source developed by Hitachi has a maximum current of 200 mA for the H+ beam and can stabilize CW beam of more than 100 mA within 5 minutes of plasma ignition, enabling discharge-free operation for more than 2 hours.

For high-current ion beams exceeding 100 mA, the effect of beam divergence due to space-charge effects during low-energy transport becomes noticeable. Therefore, space-charge neutralization by neutralizer injection is necessary to suppress the space-charge effect in LEBT. However, neutralizer injection involves a trade-off between space-charge neutralization and beam losses associated with ion beam neutralization. In order to achieve low divergence beam transport that meets the acceptance requirements of the back-end accelerator while minimizing beam losses, a space-charge neutralization system is required according to the beam conditions and other factors.

To develop a space-charge neutralization system, it is necessary to establish a reproducible evaluation system that can be used for LEBT system design and adjustment. Since it is difficult to accurately calculate the reaction process between ion beams and neutralizers due to computational complexity, a space-charge neutralization model based on experiments is developed. We believe that this will enable beam transport calculations that include the neutralization process in a realistic calculation time. In this study, a space-charge neutralization model was developed based on experimental data such as beam distribution with respect to injection neutralizer volume. By combining this model with existing beam transport and molecular flow simulations, beam transport calculations with high experimental reproducibility will be realized.

We measured the beam distribution for different injection volume and positions of neutralizer injection, Kr gas, using an H+ beam with a source extraction hole diameter of 5 mm, an extraction voltage of 50 kV, and an extraction current of 36 mA. Here, the beam current is reduced to account for the heat load on the detector, but the current density is equivalent to 125 mA beam current with a 12 mm extraction hole. The space charge neutralization rate relative to neutralizer injection volume was evaluated by comparing the relative change in beam distribution with respect to the neutralizer injection volume and the relative change in beam distribution with respect to the space charge neutralization rate in the simulation. Based on these results, a model was developed to calculate the space-charge neutralization rate with respect to the neutralizer injection volume.

In order to calculate the beam transportation considering the space charge neutralization, the charge neutralization ratio for each spatial position is calculated by the developed model based on the neutralizer distribution evaluated by the molecular flow simulation "MolFlow". Then, the beam simulation software "Warp" is used to calculate the beam trajectory for each evaluation system based on the above space charge neutralization ratio. For different beam conditions and neutralizer types, calculations can be performed by model transformations based on cross-section data.

In the future, we will evaluate the experimental reproducibility of the developed orbit calculation system considering space-charge neutralization by comparing beam emittance for beam energy and neutralizer species conditions between experiments and calculations.