Plasma Surface Interaction in a Cs Loaded Negative Hydrogen Ion Source

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A future fusion reactor must warrant a reasonably long lifetime because of the expensive raw material prices and high initial construction costs. Plasma-surface interactions can determine the fusion reactor lifetime including direct plasma contact against the vessel wall and the divertor that pumps out fusion produced He gas from the confined plasma. Meanwhile, additional components attached to the fusion reactor may have shorter lifetimes. Auxiliary heating devices deliver high power density energy flux to the fusion plasma and can determine the overall fusion plant lifetime due to the large power loadings during their operations. A neutral beam heating system generates an intense beam plasma that interacts with the accelerator grid electrodes. The high energy beams from the ion source and the back streaming positive ions from the beam produced plasma erode accelerator grids and the armor tile in the ion source. Besides, low energy plasma-ion source wall interaction may result in inefficient source operation increasing the loss to produce good quality beams. The paper summarizes how plasma-wall interactions are correlated to the lifetime of a neutral beam injection system for a future nuclear reactor power plant.

1. Failure modes of neutral beam injection system

The ITER [1] being developed to demonstrate the production of energy through nuclear fusion reaction will equip two neutral beam lines to heat up the plasma confined in magnetic field produced by super conducting coils. The structure of an electrostatic accelerator of the injection system resembles the one of an ion engine for space propulsion [2]; ions are electrostatically extracted, focused and accelerated from the source plasma. Two main components: grids and a neutralizer, determine the lifetime of an ion engine. The final energy of the accelerator for the ITER neutral beam injection system reaches 1 MeV, and the hydrogen isotope ions do not sputter out accelerator grids but penetrate deep into the structure components. The hydrogen isotopes accumulated in the component damage (for example, increase the brittleness) the accelerator components to cause mechanical failures.

Another concern is the Cs introduced into the negative ion source for the neutral beam injection system. Because of the high efficiency to produce intense neutralized beam, negative ions of hydrogen isotopes are accelerated up to 1 MeV final energy [3]. Introduction of Cs into the ion source discharge enables extraction of high current density negative hydrogen isotope ions while keeping the electron current coextracted with negative ion current small enough to protect the extraction electrode from overheating. A stable ion source operation should require a small amount of Cs, but a continuous long-term operation can accumulate Cs into the ion source [4] causing Cs atoms to leak out from the source to migrate into the accelerator system. The retention of Cs in the downstream region can cause back streaming of Cs^+ ions toward the ion source extraction grid and the end plate for sputtering the surface of these components. Also, the accumulation of Cs inside the ion source alters the source discharge characteristics to reduce the efficiency of producing negative ions. These processes of plasma-surface interactions affecting the lifetime of a neutral beam heating system are investigated.

2. Grid erosion by hydrogen isotope ion beams

Energy as high as 1 MeV deeply implants hydrogen isotope ions to structure components of neutral beam injection system. Irradiation of a high-energy hydrogen isotope ion beam onto an accelerator electrode forms the surface layer with high concentrations of hydrogen isotopes which should exhibit larger energy absorption than pure material. A normally incident beam creates a hydrogen isotope retention layer deep inside the material from the surface. However, the ions striking the surface with the glancing incident angle can form the layer of high hydrogen isotope retention near the surface. Thus, the sputtering erosion around the beam passing holes of the accelerator grids will be severely influenced by the retention of hydrogen isotopes. Due to the direct momentum transfer to an identical mass particle retained inside the heavy element, erosion rate increases for an injection of an ion at an oblique angle. Further enhancement of sputtering erosion of accelerator/extraction grids may become possible as the sputtered grid materials are ionized and/or charge-exchanged in the accelerator. Incident ions of the same mass with the target material will result the self-sputtering of the grid element to rapidly erode the accelerator structure [5].

3. Cs accumulation in the ion source

P Injection of Cs into the ion source from a high temperature oven through a heated transfer tube realizes a stable control of Cs amount recycled during the ion source operation. The end nozzle directs the Cs flux to cover the source wall [6] so that neutral Cs will not directly escape from the ion source through a high transparency extraction grid system. Ion source discharge takes Cs on the wall to the plasma and transports Cs to the plasma grid to realize low work function condition of the grid to increase negative ion to electron density ratio. Leakage of Cs toward the accelerator from the ion source is diminished because the extraction potential repels the positive Cs^+ ions from the extraction hole region. However, neutral Cs atoms can escape out through extraction holes when the discharge is turned off. Meanwhile, emissions of the filament material in an arc discharge source [7] and material sputtering in an RF discharge source can cover the ion source wall with the Cs buried under the deposition layer. Therefore, additional Cs supply is indispensable for the continuous operation of a negative ion source. The Cs accumulated on the accelerator can trigger a voltage breakdown harmful to the beam injector power supply. Stored Cs inside the ion source can change the particle recycling during the ion source discharge to destabilize the operation.

4. Numerical simulation by ACAT

A computer simulation code ACAT (Atomic Collision in Amorphous Target) has been utilized to investigate the particle-material interactions in plasma devices. The code assumes a simple binary collision process but does not guarantee enough accuracy at lower energy. Both beam erosions [5] and Cs accumulations [8] have been discussed based on the simulation using ACAT. However, additional data are needed to predict lifetime of ion source/accelerator components for long-term usage. For example, binding energy against the particle emission due to sputtering must be different depending upon the precise surface structure. The wall surface is covered with materials emitted from ion source internal components. The surface nanostructure can also cause difference in surface migration speed of adsorbed atoms. Thermal diffusion constants for atoms and defects in electrode materials should influence the response of the solid target upon injection of particles at various energy. The range of validity to use ACAT for lifetime assessment of a neutral beam heating system and the necessary data compilation to improve accuracy in predictions are discussed.

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References

[1] G. Seriani *et al*. IEEE Trans. Plasma Sci. 51, 927(2023).

[2] Funaki, *et al.* 48th AIAA/ASME/SAE/ASEE Joint Propulsion Conf./Exh. AIAA 2012-3797(2012).

[3] S. Spagnolo *et al*. Fusion Engg. Design, 166, 112265(2021).

[4] R.S. Hemsworth and D. Boilson, AIP Conf. Proc. 1869, 060001(2017).

[5] M. Wada, T. Kenmotsu, K. Ikeda, M. Kisaki, H. Nakano, K. Tsumori, AIP Conf. Proc. 2373 080001(2021).

[6] M. Yoshida *et al*. Rev. Sci. Instrum. 91, 033313(2020).

[7] Y. Oka *et al*. Rev. Sci. Instrum. 71, 1379(2000).

[8] M. Wada, T. Kenmotsu, M. Sasao. AIP Conf. Proc. 1655, 0200010(2015).