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Fueling experiments using neutral beam injection in the GAMMA 10 tandem mirror

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Abstract

Recent results of fueling experiments in the GAMMA 10 tandem mirror using neutral beam injection are described. Neutral beam injectors (NBI) have been installed at the anchor-cells and central-cell for this purpose. Both anchor and central NBs are injected into a standard ICRF-heated hot-ion-mode plasmas and the increase of the electron line-density by 27% in the ‘central-cell and 110% in the east anchor-cell is observed. Hα line-emission measured near the beam line of NBI indicates the enhancement of the neutrals in the periphery region of the beam line, which suggests the influx of cold gas from the ion source of NBI and the increase of hydrogen recycling due to the beam injection. An analysis of neutral particle transport using the DEGAS simulation code is developed to be able to calculate the spatial profile of neutral density in non-axisymmetric region. Detailed measurements of Hα line-emission from the central-cell to the east anchor-cell show the increase of particle source rate due to NBI and the obtained value occupies the total ionization rate by 29%.

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1. Introduction

It is an important subject to increase the plasma density in the main plasma region in order to establish high-β plasma production in the tandem mirror devices. GAMMA 10 is an effectively axisymmetrized minimum-B anchored tandem mirror with thermal barrier at both end-mirrors [1]. Several years ago a research started using a plasma production mode (hot ion mode) in which hot ions are generated in the central-cell with ion cyclotron range of frequency (ICRF) waves [2]. After attaining the doubled density due to potential confinement, the main objective of the GAMMA 10 experiment has been focused on the potential confinement in high-density tandem mirror plasmas [3,4].

In GAMMA 10, several gas puffers have been installed at various positions on the GAMMA 10 vacuum chamber for plasma production and sustainment. Recently plasma-heating systems by using high harmonic frequency wave and neutral beam injection were installed at the anchor and the central-cells to obtain higher density. By using these plasma heating systems, the plasma density of 4×10^{12} cm^{-3} have been achieved in the central-cell. In this paper, the first results of the

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fueling experiments using neutral beam injection are reported and the detail of particle source in the GAMMA 10 plasma is discussed based on the results of the Hα measurements and the neutral transport simulation.

2. Experimental apparatus

2.1. The GAMMA 10 device

Fig. 1 shows the schematic view of the GAMMA 10 tandem mirror together with heating and diagnostic systems related to the fueling experiments. The vacuum vessel of GAMMA 10 consists of a central-cell, anchor-cells, plug/barrier-cells and end-cells axially aligned and anchor neutral beam injector (NBI) tanks and beam dump tanks on sides. The length of the central-cell is 6 m and both ends of the central-cell are connected to the anchor-cells through the mirror throat regions. Plasma is initiated by two plasma guns at both ends, and then the main plasma is started up with ICRF waves together with gas puffing. One of the ICRF waves (RF1: 9.9 MHz)) is used for MHD stabilization of the whole plasma at the anchor-cell. Another wave (RF2: 6.3 MHz) is used for heating the central-cell ions by using a pair of the double half-turn antennas. In addition to these ICRF systems, newly applied wave with high harmonic frequency (RF3: 36–76 MHz) is excited with the west side of the same antenna of RF2 and used for plasma production [4]. The length of the plug/barrier cell is 2.5 m and the intensity of the magnetic field is 0.5 T at the mid-plane. Escaping particles along the magnetic field lines are confined by the plug potential produced with ECH by using gyrotrons installed in both plug/barrier cells.

2.2. NBI system in GAMMA 10

In the central-cell, as shown in Fig. 1, hydrogen neutral beam of 25 kV and 30 A (NBIc) is injected perpendicularly at 123 cm off the mid-plane. Another neutral beam with 25 kV and 60 A (NBIa) is injected toward the mid-plane of each anchor-cell at an injection angle of 82° to the magnetic axis. Maximum beam duration of all injectors are 0.1 s. Liquid He cooled cryo-pumping with the pumping speed of 4×10^5 l/s has been installed in each anchor injection tank for differential pumping on the anchor beam line [5]. For the beam dump of the central NBI system, a new surface pumping system using carbon materials is used [6,7]. Arrays of Hα line-emission detectors are installed at several locations from the mid-plane of the central-cell to the anchor-cell in order to evaluate the particle source density around these regions. An analysis of neutral particle transport using the DEGAS simulation code [8,9] is developed from two-dimensional configuration into a three-d simulation so as to be able to calculate the spatial profile of neutral density in non-axisymmetric region, such as anchor-cell.

3. Experimental results

High-density plasma production experiments using both NBIc and NBIa are carried out in standard ICRF-heated hot-ion-mode plasmas. The time behavior of the

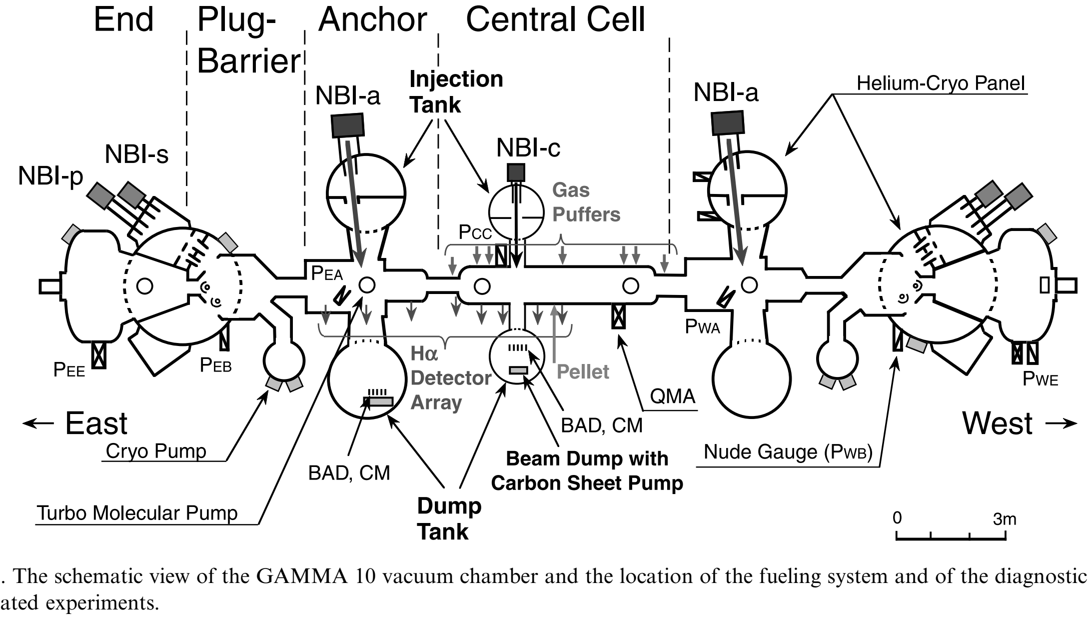

Fig. 1. The schematic view of the GAMMA 10 vacuum chamber and the location of the fueling system and of the diagnostic system for related experiments.

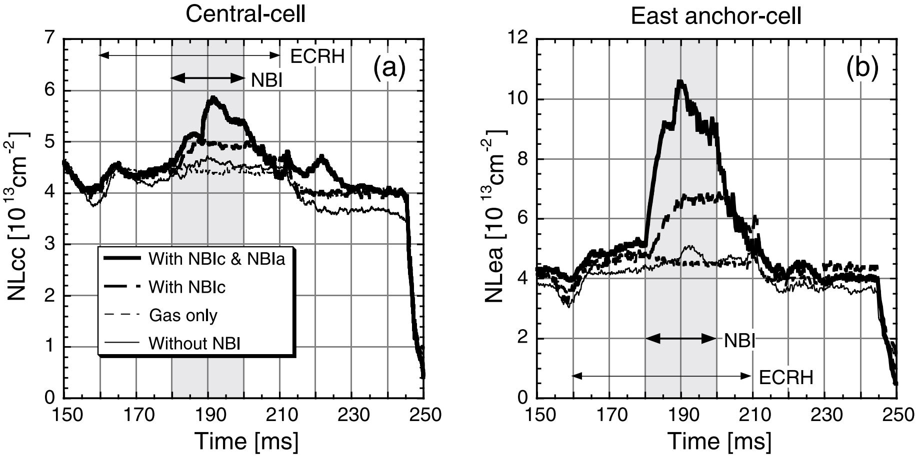

Fig. 2. Temporal behavior in the line-density measured at the east anchor-cell and the central-cell.

electron line-density measured at the east anchor-cell (NLea) and the central-cell (NLcc) is shown in Fig. 2. In this figure, a number of cases in the operation of NBI are represented. Simultaneous injection of both anchor and central NBs provides the increase of the electron line-density by 27% in the central-cell and 110% in the east anchor-cell. Only the gas injection from NBI, on the other hand, causes no increase in the line-density on both cells and this is similar to the case without NBI. From these observations, it is confirmed that high-energy neutral beam injection has a significant effect on the density increase.

Fig. 3 shows the time evolution of Hα line-intensity measured near the beam line of NBIc divided by the line-density of central-cell measured at the same time. As shown in the figure, the intensity of line-emission increases just after the onset of NBI and keeps the higher level during injection. Although this increase rapidly returns after turning off the beam injection, it should be noted that there is another component that causes the continuous increase during and after NBI. This is ascribed to the down streaming gas flowing into the plasma in the central-cell due to insufficient differential pumping in the NBI tank. In the gas-injection case (narrow dashed line in the figure), continuously increasing Hα signal is observed and the decrease of diamagnetism is observed in the central-cell. This suggests that the improvement in capability of differential pumping in the NBI tank of the central-cell may enhance the heating efficiency of NBIc.

Radial profiles of hydrogen neutral density obtained from the results of neutral transport simulation performed by the DEGAS code are shown in Fig. 4. In this simulation, the particle source from NBI is considered in addition to the gas puffer at the mirror throat region and recycling source near the mid-plane of the central-cell. It is found that the neutral density near the beam line ($z = -140$ cm) increases by more than 2 due to the beam injection. The density in the location away from the

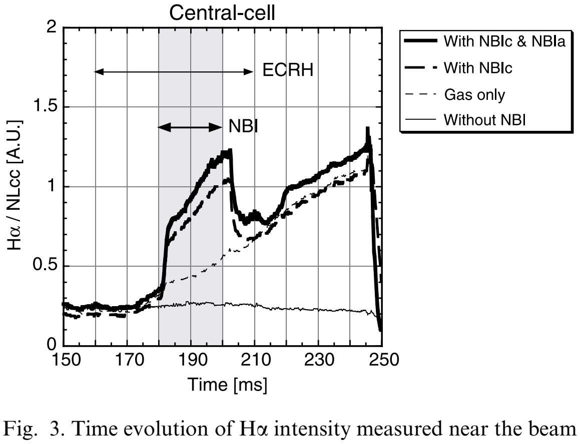

Fig. 3. Time evolution of Hα intensity measured near the beam line of the central-cell.

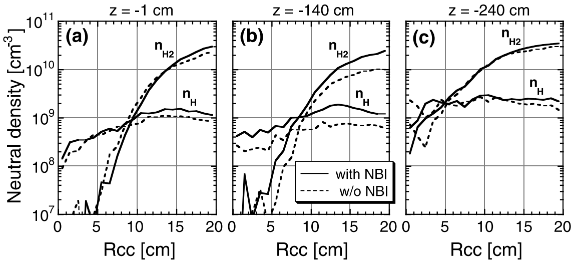

Fig. 4. Radial profile of hydrogen neutral particle density at various locations in the central-cell. Solid lines show the results in the case with NBI and dashed lines represent those in the case without injecting both neutral beam and cold gas from the ion source.

beam line by more than 1 m ($z = -1$ cm, $z = -240$ cm) does not increase so much due to NBI. This implies that the increasing area of neutrals due to NBI is localized around the injection port, which suggests the influx of cold gas from the ion source of NBI and the increase of hydrogen recycling due to the beam injection.

4. Discussion

A three-dimensional neutral transport simulation by using the DEGAS code has been started in order to estimate the detailed distribution of the particle source rate from the central mid-plane to the anchor-cell. Fig. 5

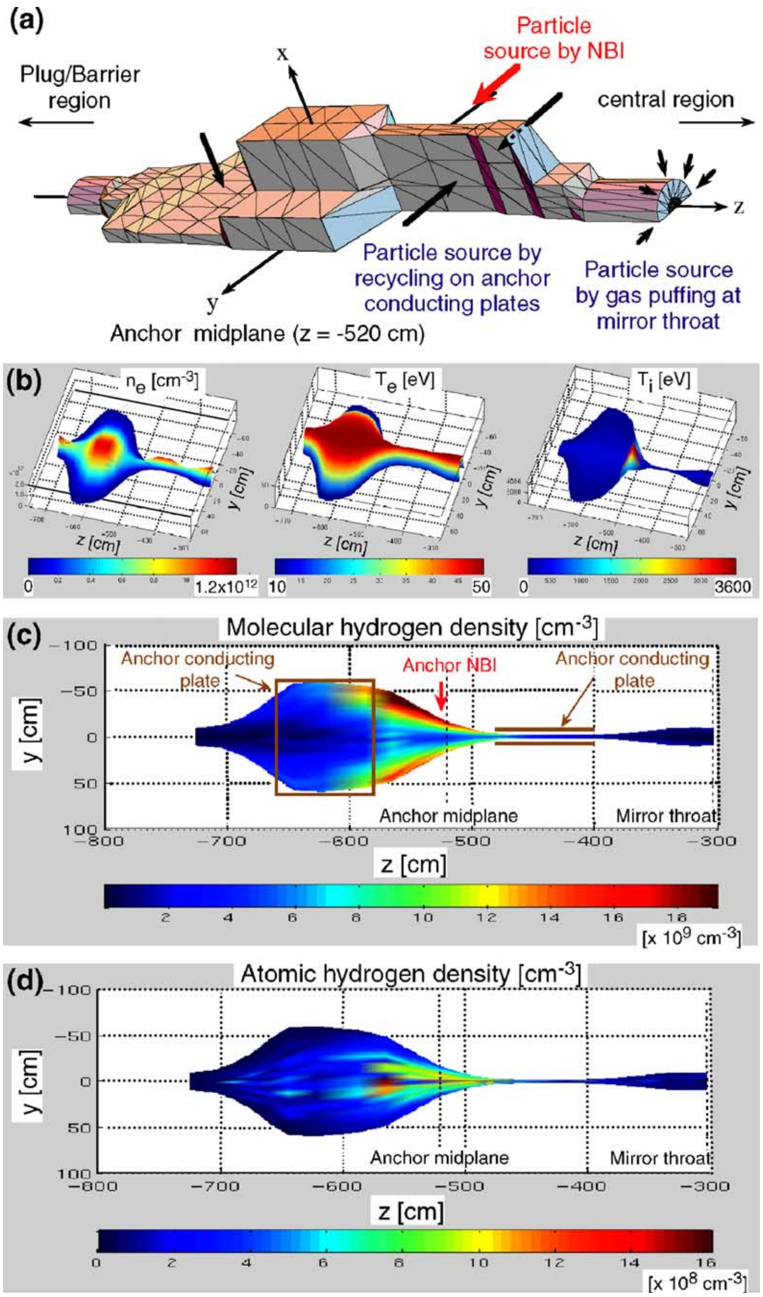

Fig. 5. Simulation results, a mesh model of the GAMMA 10 anchor-cell and input plasma parameters, used in the 3D-DEGAS code. (a) Structure of wall surface, (b) spatial profiles of ne, Te and Ti on y–z plane used for DEGAS, (c) cross-sectional view of surface plot in molecular hydrogen density on y–z plane, (d) cross-sectional view of surface plot in atomic hydrogen density on y–z plane.

shows the input plasma parameters used for DEGAS and the simulation results together with the mesh model of the anchor minimum-B region adopted in the code. The calculation is carried out with the DEGAS ver.63 code, which are modified in order to take the dissociative-excitation processes of hydrogen molecules into consideration in the neutral transport processes. Due to the complicated structure in the cross section of the plasma in this region and existence of non-axisymmetric particle source, such as NBI, this simulation is indispensable for detailed analysis of particle balance. As shown in Fig. 5(b), electron density ($\sim 2 \times 10^{12}$ cm^{-3}) is measured at the anchor mid-plane with a microwave interferometer. The temperatures Te and Ti are estimated to be 50 eV and 3.5 keV from soft X-ray measurement and charge-exchange neutral particle analysis, respectively. Axial profiles of these data are given by interpolating the measured data between the central mirror throat and anchor mid-plane taking account of the shape of the magnetic flux tube. In this simulation, gas desorption from anchor conducting plates [10,11] installed closely to the edge plasmas in transition regions of anchor-cell is considered. In addition to this condition, a particle source due to NBIa is given artificially so as to reproduce the spatial profile of Hα line-emission. As shown in Fig. 5(c), molecular hydrogen density is enhanced near the beam injection side of the anchor mid-plane and the penetration of neutrals is observed in the edge region where the plasma thickness becomes thin. In contrast to the molecular density, atomic hydrogen density shown in Fig. 5(d) has a tendency to concentrate in the plasma core region. Although this mechanism is not clarified in detail, longer mean free path of Franck–Condon neutrals compared with the plasma thickness may play a significant rule on the formation of neutral density profile.

By accumulating the information of the neutral density obtained above and the data of plasma parameters, total particle source rate from the central-cell to the anchor-cell is evaluated. As shown in Fig. 6, axial profile of the particle source rate radially integrated up to Rcc = 20 cm is plotted in cases with NBI and without NBI. In the case with simultaneous injection of NBIc and NBIa, the increase of the source rate is calculated to be 21% and 38% in the central-cell and the anchor-cell, respectively. The total increase of the source rate is 29% due to NBI. The source-rate increase in the anchor-cell is smaller than that of the density shown in Fig. 2(b). This discrepancy is not quantitatively explained yet. However, there exists a trapping mechanism due to ion cyclotron resonance surface in this area, which may cause a density peaking near the anchor mid-plane. In this estimation, detailed three-dimensional data with respect to plasma parameters are needed as input parameters for the DEGAS simulation, and then a number of data is forced to be assumed for the input parameters.

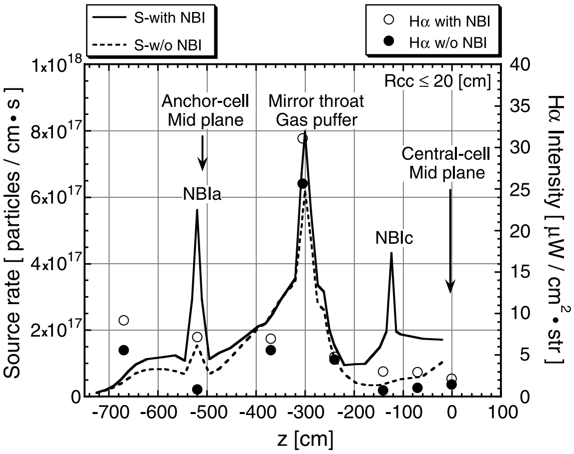

Fig. 6. Axial profile of the measured Hα intensity and of the calculated source rate integrated within Rcc = 20 cm. Solid line and open circles show the results in the case with NBI and dashed line and filled circles represent those in the case without injecting both neutral beam and cold gas from the ion source.

There also might be an insufficient optimization of the mesh geometry for modeling due to the limitation of computational resources. In spite of such circumstances, however, important information for fueling experiment will be deduced by using this evaluation method.

5. Conclusions

Both anchor and central NBs are injected, for the first time, into a standard ICRF-heated hot-ion-mode GAMMA 10 plasmas and the increase of the electron line-density by 27% in the central-cell and 110% in the east anchor-cell is observed. From the measurements of Hα line-emission near the beam line of the central-cell NBI, it is found that the increase of the neutral density localized near the injection port. A three-dimensional neutral transport simulation is successfully performed by applying the DEGAS ver.63 code in the non-axisymmetric anchor-cell. The total amount of source rate due to NBI in the main plasma production region can be estimated by using the measured results of Hα line-emission detector array together with the simulation.

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