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論文内容の要旨

Summary of thesis contents

Neutral beam injection (NBI) is an effective method for plasma heating and current drive for a fusion device. In a neutral beam injector, charged particles are produced in the ion source, accelerated, neutralized and injected into the plasmas confined in the fusion device. Having the advantages of high neutralization efficiency, negative-ion-based Neutral Beam Injector (N-NBI) has been intensively developed to inject the beam with sufficient penetration length in the fusion plasmas. As the source of negative ions, the negative ion source determines the performance of the N-NBI system. Comparing to positive ion sources, negative ion sources have some differences, which are (1) the negative ones involve strong magnetic field to magnetize electrons in the source, (2) the source plasma consists of electrons, positive and negative ions, and (3) a part of electrons are extracted together with negative ions. In order to understand the mechanisms of electron and positive ion flow during beam extraction and the extraction of H^- ions in Cs-seeded plasma for the improvement of the present negative hydrogen ion source, investigation on charged particle dynamics of the negative-ion-rich plasma has been conducted. In this research, Langmuir probe, cavity ring-down, photodetachment, and four-pin directional Langmuir probe have been utilized for the experiments on the negative hydrogen ion source to investigate the characteristics of the negative-ion-rich plasma and the charged particle flows.

In Chapter 1 of this thesis, the worldwide energy issue and the importance of the development of magnetic confinement fusion was introduced. A neutral beam injector can inject high energy particles into a fusion device to heat the core plasma and drive plasma current. Having the advantages of high neutralization efficiency and low beam divergence angle, the N-NBI system is a preferable choice. The basis of negative hydrogen ion source has been introduced in this Chapter. In a negative hydrogen ion source, negative ions (H^-) are produced by two mechanisms: (1) volume production and (2) surface production. In a practical negative ion source, Cs vapor is seeded and H^- ions are mainly produced by the mechanism of surface production. At National Institute for Fusion Science (NIFS), remarkable results have been achieved. The injection energy reached 190 keV and the total injection power was kept more than 15 MW. Research on improvements of the negative ion source is still necessary. In the R&D Negative Hydrogen Ion Source (NIFS-RNIS), negative-ion-rich plasma, of which electron density is one to two orders lower than that of H^- ion, has been observed in the beam extraction region. During beam extraction, H^- ion density decreases due to the extraction and electrons flow to the extraction region together with positive ions. Consequently, negative-ion-rich plasma is contaminated with electrons and the co-extracted electron current is increased. The co-extracted electrons are filtered from the beam and absorbed onto the extraction grid. Increment of co-extracted electron current carries more heat load to the extraction grid and causes damages in high power and long pulse beam acceleration. Understanding of the mechanisms of the electron and positive ion flow in the extraction region and H^- extraction is required for the improvement of the negative hydrogen ion source.

In Chapter 2, the negative ion source RNIS utilized for the experiments was introduced and described, as well as the diagnostic methods. This ion source is divided into a driver region and an extraction region by a transversal magnetic field named filter field. Plasma is generated by filament-arc

discharge and confined in the multi-cusp magnetic field. Diagnostic tools including Langmuir probe, cavity ring-down and photodetachment technique have been applied to the experiments. Langmuir probe provided basic plasma parameters, for example, plasma potential V_s, electron density n_e, electron temperature T_e and so on. Although line-averaged H^- ion density has been accurately obtained by cavity ring-down, H^- ion density at a specific point is necessary for this research. For this purpose, photodetachment technique has been applied to the experiments. H^- ion density n_{H-} is proportional to the photodetachment current and a coefficient is required to evaluate n_{H-}. In the conventional photodetachment method for electron-rich plasma, the coefficient is determined by the ratio of photodetachment current to electron saturation current of the probe. However, this method is not available in negative-ion-rich plasma. Then a new method based on the combination of cavity ring-down and photodetachment has been developed to determine the coefficient for the estimation of n_{H-}. This is the first time that n_{H-} at a specific point is measured in a Cs-seeded negative ion source. In principle, this new method has no limitation of plasma condition.

In Chapter 3, the basic characteristics of the RNIS have been investigated by the diagnostics tools introduced in Chapter 2. The negative ion source requires long Cs-conditioning time because of the complicated and slow Cs expansion. After seeding Cs into the plasma, the plasma potential V_s decreases due to the emission of H^- ions from the plasma-grid surface. The density of surface-produced H^- ions increases comparable to electron density n_e, which decreases as increasing n_{H-} during Cs-seeding. The electron density n_e is sensitive to the bias voltage applied to the plasma grid with respect to the plasma chamber, and n_e decreases at higher bias voltage. n_{H-} in the extraction region is lower at higher bias voltage of the plasma grid. It is necessary to apply low bias voltage to the plasma grid to obtain high H^- beam current with the premise of avoiding damage on the extraction grid. Hydrogen pressure also influences the plasma in the extraction region. In this experiments, n_{H-} decreases at high pressure due to the mutual neutralization with positive ions. Therefore, extraction and acceleration currents decrease at higher pressure. Low operational gas pressure is beneficial to the negative ion source, because the stripping loss of H^- ions due to collisions with neutral molecules and atoms is reduced. However, the discharge is unstable in extremely low gas pressure, because the plasma of the ion source is sustained by electrons impact ionization and the mean free paths of electrons are larger at lower pressure. In addition, electron percentage in the source plasma increases with respect to H^- percentage in low gas pressure. Consequently, 0.2 to 0.4 Pa of hydrogen pressure is a proper choice for the operation of the negative ion source.

In the negative hydrogen ion source for NBI, an electron deflection magnetic field (EDM field) is introduced in the extraction gap to filter the co-extracted electrons. This EDM field forms a loop field by partially penetrating into the extraction region. The result of plasma profile measured with a Langmuir probe indicates that the boundary of the EDM field is at ~10 mm apart from plasma grid. Electrons near the plasma grid are magnetized with the EDM field and trapped into the cusp region of the field.

The plasma response to extraction field has been investigated by scanning the measurement position of the Langmuir probe and photodetachment probe perpendicular to the plasma grid. By comparing the profiles of the probe saturation current and n_{H-} before and during beam extraction, the profile of the plasma response to the extraction region has been obtained. The results show that the maximum n_e increase and n_{H^-} decrement caused by the beam extraction is at ~20 mm apart from the plasma grid. The linear extrapolation of the profiles suggests the boundary of the extraction region and driver region of the ion source is at ~40 mm apart from the plasma grid. Although the maximum response is initially expected close to the extraction aperture, the experimental results show that the peak position of the plasma response is located far from the plasma grid. Charged particle flow measurements are required to understand this unexpected phenomenon.

In Chapter 4, flows of electrons and positive ions have been investigated by a four-pin directional Langmuir probe. The flow direction has been determined by the periodic distribution of the probe saturation current by rotating the directional Langmuir probe. The flow speed has been determined by the difference of probe saturation currents at upstream and downstream positions. The movement of electrons and positive ions are ambipolar. Flow changes of electron and positive ion have been observed by subtracting the two-dimensional flow patterns before and during beam extraction. By considering the flow pattern before beam extraction as a background and the transition of flow occurs is in a finite time, the change of the flow velocity is regarded as the flux increments of electrons and positive ions induced by beam extraction. The flux increments are from lower to upper side and trapped into the cusp region of the EDM field. The channel of the flux increments is at ~20 mm apart from the plasma grid and this region is the transition region of the filter field and the EDM field. Therefore, the probe located in this region can detect the maximum plasma response to the extraction field.

In Chapter 5, the four-pin directional Langmuir probe with photodetachmen has been utilized to the experiments to investigated H^- flow for the understanding of the extraction mechanism and the unexpected position of the maximum H^- ion density reduction. Flow velocity has been estimated using the recovery speed of the H^- ion in the photodetachment region at upstream and downstream probe tips. Meanwhile, temperature of H^- ions has been obtained. The result indicates that in the extraction region, temperature of H^- ions is ~0.12 eV which is consistent with the result of saturated cavity ring-down measurement. The two-dimensional flow pattern of H^- ions suggests that H^- ions come from the direction of the plasma grid and flow to the extraction region. During beam extraction, H^- flow turns to the aperture direction at ~20 mm apart from the plasma grid. Therefore, the maximum reduction of n_{H^-} can be detected near this position. In the extraction region, the Larmor radius of H^- ion is ~10 mm. Note that the boundary of the EDM field is at ~10 mm apart from the plasma grid. These two dimensions elucidate the existence of stagnation point of the H^- ions located at ~20 mm apart from the plasma grid.

In conclusion, it becomes clear that H^- ions undergo following sequence from production to extraction by applying extraction field: (1) H^- ions come from the direction of the metal part of the plasma grid, (2) once flow towards the plasma in the extraction region, (3) turn at the stagnation point located at ~20 mm apart from the plasma grid (4) move to the aperture of the plasma grid. The behavior of the H^- flow is affected by the EDM field and filter field. The region of the stagnation point corresponds to the transition region of the filter field and the EDM field. In this region, the extraction-induced additional electron and positive-ion fluxes increase and the stagnation point appears. Consequently, the maximum plasma response to the extraction field is far from the plasma grid. In addition, the H^- ion temperature is estimated to be ~ 0.12 eV. This is one of the evidences that negative hydrogen ion beam has a low beam divergence angle. In the NIFS-RNIS, H^- ions are not extracted directed from the surface of the plasma grid but mainly from the region near the aperture of the plasma grid.

Since the extraction process occurs in the region near the plasma-grid aperture, the improvement of the negative hydrogen ion source is possible to be focused to this region. One of the improve method is to increase the EDM field, and then boundary of the EDM field becomes far from the plasma grid. For this purpose, the material of steering grid will be replaced from molybdenum to iron. More H^- ions will be extracted by increasing the magnetic region. Meanwhile, suppression of electrons near the plasma grid is then enhanced. Consequently, the increase of the extracted H^- ion current and decrease of electron component are possible. The performance of the negative ion source is expected to improve.

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博士論文の審査結果の要旨

Summary of the results of the doctoral thesis screening

中性粒子ビーム入射装置（NBI）は、熱核融合炉の実現に向けて、最も有力なプラズマ加熱装置である。NBIのイオン源には、入射ビームエネルギーが100 keV以上の場合、中性化効率における優位性から水素負イオン（H^-）が用いられる。このため、核融合研究を推進する各国の大学・研究所では、水素負イオン源の開発研究が精力的に行われている。H^-は、プラズマ電極表面で生成すると考えられているが、負イオン源の性能向上には、未だ解明されていないH^-の生成からビーム引き出しに至る輸送過程の理解が必要である。出願者は、独自に開発した測定手法を用いて、負イオン源内におけるH^-をはじめとする荷電粒子の、外部電場に対する応答と輸送過程の研究を行った。

第1章では、世界全体のエネルギー需要による核融合発電の必要性と、熱核融合炉に必要な負イオン型NBIの説明がなされ、負イオン源の分類と負イオン生成過程が記述されている。第2章では、研究に用いた水素負イオン源の構造と、本研究の主要計測法である静電プローブ法、光脱離プローブ法、そしてキャビティリングダウン法の測定原理の説明がなされている。続いて、出願者が光脱離プローブ法とキャビティリングダウン法を組み合わせて開発した負イオンプラズマ中での局所H^-密度の測定手法と、同手法による世界初となる測定結果が示されている。第3章では、負イオン源中にセシウムを添加した際の、電子プラズマから負イオンプラズマへの状態の変化が示されている。また、バイアス電圧や水素ガス圧の変化に対する負イオンプラズマのパラメータの変化について、計測データを基に、負イオンプラズマの基本特性を整理した結果が述べられている。さらに、ビームの引き出し前後の負イオンプラズマ内のH^-密度と電子密度の空間分布の変化から、荷電粒子密度の変化がプラズマ電極表面から約20 mmの領域でピークを持つことが示されている。第4章では、方向性プローブを用いて計測した、負イオン引出領域における電子と正イオンの二次元フロー分布が示されている。これらの測定結果から、電子と正イオンが、プラズマ生成部から両極性拡散をしていること、さらにビーム引き出し前後には、フロー変化に停留点が現れ、その位置が第3章で示されたビーム引き出し前後の、荷電粒子密度の変分分布のピーク位置と一致することが示されている。第5章では、光脱離方向性プローブを用いて得られたH^-の二次元フロー分布が示されている。その結果から、H^-の輸送過程は、これまで提唱されている「H^-が電極孔周辺の表面で生成され、プラズマ中を通過せずに直接引き出される」というモデルと異なることが明確になった。すなわちH^-は、プラズマ電極表面から一旦プラズマ生成部の方向に移動し、第3、4章で示された停留点を通過した後、方向を反転させてプラズマ電極のビーム引出孔へ向かうことが世界で初めて実験的に明らかになった。また、停留点の位置は、プラズマ電極近傍の磁場構造と強度によって決定されることが述べられている。さらにH^-の温度計測で得られた約0.1eVという値は、引き出されたビームの発散角の測定結果と矛盾しないことが示されている。第6章では、全体のまとめと本研究の今後のNBI用水素負イオン源開発への応用が述べられている。

本研究は、これまで系統的な測定が行われていないNBI用水素負イオン源プラズマ内の電子· 正イオン・H^-の輸送過程を、新たに開発した計測手法を用いて明らかにした。この成果は、今後のNBI用負イオン源開発に重要な指針を与え、核融合研究全体の発展へ多大

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な貢献をするものと期待される。以上のことから本審査委員会は、本論文が博士学位論文として十分な価値を有し、合格に値するものであると判定した。