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発表論文の要旨

Title　Development of a Large RF-Driven Hydrogen Negative Ion Source

In the next step fusion experimental devices such as ITER(International Thermonuclear Experimental Reactor), long pulse or continuous D-D/D-T burning experiments are proposed. In the second phase LHD(Large Helical Device) experiments, long pulse D-D experiments are also planned. A neutral beam injection (NBI) system in these devices should be operated continuously without maintenance for a long period, because the accessibility to the device is extremely restricted due to its radio-activation. The neutral beam injection energy in these devices is more than several hundreds keV. The neutralization efficiency of positive hydrogen ions is reduced to less than 20 % for such a high beam energy, while that of hydrogen negative ions is as high as 60 %. Thus, the negative ion beams should be utilized in these NBI systems. An rf-driven ion source is prospective for the long lifetime operation, because it has no erosive electrode like a filament that limits a lifetime of the ion source. The rf-driven positive ion source for the NBI system has been developed and generated high density plasmas by the inductively coupled discharge. There are two methods in the inductively coupled rf discharge. One is winding an induction coil antenna outside the plasma generator, and the other is immersing an induction coil antenna into the plasma generator. Since in the former method the plasma generator must be made of dielectric materials like quartz, it is difficult to enlarge the plasma generator due to its brittleness. On the other hand, it is easy to enlarge the plasma generator in the latter method since the plasma generator can be made of metal. Moreover, the plasma confinement can be improved by providing the cusp magnetic field on the inner surface of the metal plasma generator. A small rf-driven negative ion source with an immersed induction coil antenna has been developed and an intense negative ion beam has been extracted. However, this ion source is much smaller than that required for the future NBI system. Therefore, it is important to develop a large rf-driven negative ion source applicable to the NBI system and to investigate its characteristics.

In this thesis, the results of research and development of a large rf-driven hydrogen negative ion source, which is applicable to the future NBI systems, are described. The large rf-driven hydrogen negative ion source with an immersed induction coil antenna has been constructed, and the characteristics of the generated rf plasma were investigated. The optimization of the negative ion production was also performed in the pure-volume operation and a negative hydrogen ions were extracted. The enhancement of the negative ion production efficiency was confirmed in the cesium-seeded operation. For a long lifetime operation the antenna shielding materials and shielding method were also developed.

The rf-driven hydrogen negative ion source consists of an rf plasma generator and an accelerator. The plasma generator is made of stain less steel, the dimensions of which are 30 cm x 30 cm in cross section and 20 cm in depth. A cusp magnetic field for the plasma confinement is generated by permanent magnets around the plasma generator. A strong magnetic filter field, which is important for the negative ion production, is also generated in front of the plasma electrode by permanent magnets. The electron temperature in front of the plasma electrode should be about 1 eV in order to produce the negative ions efficiently and to avoid the negative ion destruction. The magnetic filter field separates the low electron temperature region(extraction region) from the discharge region (driver region). The maximum filter field strength is 100 G on the axis and the line-integrated filter field strength is 1030 Gcm. In order to generate the plasma efficiently by the inductive rf discharge, an induction coil antenna of rectangular shape of 20 cm x 20 cm is immersed into the plasma generator. In order to couple an rf power inductively, the antenna is shielded with a dielectric material.

The accelerator is composed of a plasma electrode, an extraction electrode and a grounded electrode. The extraction electrode and the grounded electrode are inlaid with the permanent magnet rows in the vicinity to the beam aperture for suppression of the electrons included in the negative ion beam. The extraction electrode and the grounded electrode were electrically connected to the ground potential in the experiments, and the applied maximum extraction voltage was 8.6 kV. The negative ions were extracted from a single aperture of 13 mm in diameter on the plasma electrode. The negative ion current was measured by a calorimeter located 17 cm downstream from the plasma electrode.

An rf power supply system is composed of an rf signal generator, an rf amplifier, a directional coupler, a matching circuit and a DC isolation transformer. The frequency is 2 MHz. The maximum rf output power is 30 kW and the pulse duration is 1 sec with a duty factor of 1/30. The forward and the reflected rf power are measured at the directional coupler, and the difference between the forward and reflected rf powers is defined as the rf power.

The rf plasma was produced efficiently by matching the output impedance of the rf power supply with the plasma impedance using the matching circuit. In order to investigate the coupling characteristics of rf power to the plasma produced by the inductive discharge, the rf power flow in the plasma generator was measured calorimetrically, and the supplied rf power to the antenna was calculated with the antenna voltage and the current including their phase difference. By estimating the equivalent plasma resistance, it is found that the coupling efficiency is improved as the rf power increases. The plasma production efficiency was compared for a 1-turn antenna and a 4-turn antenna by measuring the ion saturation current density. Since the 4-turn antenna has a larger surface area than the 1-turn antenna, there is a larger plasma loss area for the 4-turn antenna. As a result, a higher plasma density was obtained in the case of the 1-

turn antenna.

The plasma parameters were measured by a Langmuir probe. The electron temperature in the extraction region is high compared with that in the filament-arc type sources. In the filament-arc type ion source, it has been reported that the electron temperature in the extraction region decreases as the filter field strength increases. In this rf-driven ion source we investigated the dependence of the electron temperature in the extraction region on the magnetic filter field strength. It is found that in the rf-driven negative ion source a much stronger filter field is required to reduce the electron temperature in the extraction region to about 1eV compared with the filament-arc type negative ion source. The required filter field strength is about twice that in the filament-arc type ion source.

At 28 kW of an input rf power, the electron density and the ion saturation current density reach 1.5×10^{12} cm^{-3} and 300 mA/cm^2, respectively. The electron temperature and the plasma potential are not sensitive to the input rf power, and they are 4 eV and 19 V, respectively. The behavior of the plasma parameters in the extraction region indicate nearly the same tendency as those in the driver region. The electron temperature is about 1/3 of that in the driver region, as well as the electron density and the ion saturation current density. The plasma potential is 5 V lower than that in the driver region.

Hydrogen negative ions were extracted in the pure-volume production mode. The negative ion current was measured by the calorimeter with a collector of 6cm in diameter. The negative ion current increases as the input rf power increases, and reaches 5.5 mA at 15 kW of an input rf power and 8.6 kV of an extraction voltage. This ion current corresponds to a current density of 4.1 mA/cm^2. The current density normalized by the rf power density in the plasma generator is 5.0 $(mA/cm^2)/(W/cm^3)$. Taking the loss power in the rf transmission line into account, the negative ion production efficiency in the rf-driven ion source is superior to that in the filament-arc type ion sources. The bias voltage was applied to the plasma electrode against the plasma generator for reduction of the electrons extracted together with the negative ions. The negative ion current is kept high and the extraction current is suppressed enough by the optimum bias voltage. The optimum bias voltage is higher than that in the filament-arc type ion sources, due to the high plasma potential in the extraction region in the rf-driven ion source. Difference between the optimum bias voltage and the plasma potential is a few volts.

A cesium seeding has been reported to result in the improvement of the negative ion production efficiency and the reduction of the operational gas pressure in the filament-arc type ion sources. The cesium seeding effects were investigated in the rf-driven negative ion source. Since it was necessary to raise the temperature of plasma electrode to about 250 ℃ with a sheath heater to observe the cesium effects, a molybdenum plasma electrode was used. The results showed the similar effects to the filament-arc type ion sources, that is, the optimum operational gas pressure was reduced from 12 mTorr to 11 mTorr, and the negative ion current was increased from about 4mA to 5.3 mA at the same input rf power. The optimum bias voltage was reduced from 17 V to 11 V, which was not observed in the filament-arc type sources. This is ascribed to the reduction of the plasma potential in the extraction region by the cesium seeding in the rf-driven ion source.

From an engineering point of view, it is important to choose or develop a durable antenna shielding material to extend the lifetime of rf-driven ion source. We have tested four kinds of antenna shielding materials; quartz sock (cloth of quartz fibre), porcelain enamel, quartz tube and ceramic tube. The durability tests were performed under the operational conditions of 27 kW of an input rf power and 1 sec of a pulsed discharge in every 90 sec. After number of shots, the quartz sock and the porcelain enamel were burned out or damaged by abnormal discharges, while the quartz tube and the ceramic tube had no damage. This result is explained by their thermal characteristics. The melting point of the porcelain enamel (silicic glass) is 800 ℃ whereas these of the quartz tube and the ceramic tube (99 % Al_2O_3) are 1600 ℃ and 2030 ℃, respectively. The heat conductivity of the quartz sock is extremely low, while the quartz tube and the ceramic tube can be cooled by blowing the inside of the tube. There is no observation of the sputtering on the tube surfaces, and the tube surfaces are coated thinly with the plasma generator materials. Thus, the quartz tube and the ceramic tube have no problem as the antenna shielding materials for the present operational conditions. Although the further endurance test is required at a higher power in a continuous operation, the quartz is promising for he long lifetime operation.

From these experimental results it was concluded that the developed rf-driven hydrogen negative ion source has the performance that is required for a high power hydrogen negative ion source for fusion application, such as, the high plasma production efficiency, the high negative ion production efficiency, and the potential of a long pulse operation. The developed rf-driven ion source and the experimental results described in this thesis give a basis of the design of a long lifetime large rf-driven negative ion source required in the future fusion experimental devices.

論文の審査結果の要旨

本論文は、負イオン方式ＮＢＩ用として将来の長時間運転、保守簡素化のイオン源として期待されている高周波水素負イオン源の大型化の開発研究の結果を、技術的・工学的見地からまとめたものである。その内容は、１．高周波プラズマ源の特性研究、２．負イオン生成に最適な、プラズマを生成するプラズマ源の条件の研究、３．アンテナ材料の研究、4. 負イオン引き出し特性の研究、から成っている。

現在まで、小型の高周波水素負イオン源の開発研究は行われているが、大型の高周波負イオン源の開発研究はなされていない。大型高周波負イオン源として体積生成方式のタンデム型負イオン源を用い、独自に設計製作した整合回路によって放電に有効に高周波電力の供給をはかり、十分な密度のプラズマを生成し、高周波電力の流れの計測を行い、放電のモデルを考察し、負荷は抵抗性でありプラズマ密度の増大と共に電力効率が上昇することなどを確かめている。また、生成されたプラズマの諸量をラングミュアプローブで測定し、アンテナとプラズマとの結合、タンデム型負イオン源で重要なフィルター磁場と生成プラズマのパラメータの関係等、プラズマ諸量とプラズマ源動作条件との関係の詳細な実験を行った。その実験を解析し、タンデム方式大型高周波負イオン源でのプラズマ生成効率と負イオン生成に最適なプラズマ生成のプラズマ源の条件として、1）１ターンアンテナの方が4ターンアンテナよりプラズマ生成効率がよいこと、2）引き出し部での電子温度はフィルター磁場が強いほど低くなり、負イオン生成に有効な電子温度１ｅＶを得る有効フィルター磁場は１０３０Ｇ・ｃｍで、フィラメントによる直流放電型負イオン源より強いこと、3）イオン密度は引き出し面領囲（２０ｃｍ×２０ｃｍ）にわたり5％ 以下で一様で、大型負イオン源の条件を満足していること、等の結論を見いだしている。

アンテナの保護絶縁材料のテストを融点、加工性、経済性の異なるクオーツソック、ホーロー、石英管とセラミックについて行い、石英管とセラミックが高融点という観点から優れているが、総合的には石英が最適で、満足が得られるものであるとの結論を得た。

この研究で見いだした条件に従って最適化したプラズマ源で、単孔からの負イオン引き出し実験を行い、カロリメータで測定した負イオンビームの電流と高周波電力、動作ガス圧、プラズマグリッドへのバイアス電圧との関係等の特性は、直流放電方式負イオン源と定性的に同じで８．５ｋＶの引き出し電圧で５．５ｍＡ（電流密度４．１ｍＡ／ｃｍ^2）の水素負イオンを引き出している。これは単位体積当たりの高周波電力に対する負イオン電流密度として５．５ｍＡ／ｃｍ^2・Ｗ／ｃｍ^{3}となり、直流アーク方式負イオン源より高効率であることを示している。さらに高周波水素負イオン源でのセシウム添加による負イオン生成効率、動作ガス圧、引きだし特性の変化の初期実験を行い、直流放電方式と定性的には同じであることを確認し、大型化について高周波イオン源の原理的実証を行っている。

以上、本研究は大型高周波水素負イオン源での開発研究課題、1．必要なプラズマ密度・温度の一様なプラズマの生成、２．誘導型アンテナの高効率化と被覆材料と製作技術、３．タンデム型高周波水素負イオン源の最適化条件、４．負イオン 体積生成に対し、直流放電方式と同等又はそれ以上の負イオン引きだし特性、５．セシウム添加方式での放電特性と負イオン引きだし特性等に手法を見いだし、大型高周波水素負イオン源の設計指針に新しい知見を与えており、工学博士の論文として十分な内容を備えていると認め合格とした。