(4) Physics and Engineering of LHD Torus and Heating Systems

For a future upgrade of the LHD and consequent physics and engineering toward a fusion reactor, research and development related to the LHD torus and heating systems have been performed mainly under the NIFS collaboration programs.

To improve the particle control with the closed helical divertor installed in the LHD, a new type of cryosorption pump was proposed for enhancement of the pumping efficiency, in which no water-cooled blinds are needed for shielding liquid-nitrogen-cooled components. The pumping efficiency was calculated by a three-dimensional neutral particle transport simulation code (EIRENE), and the results show that the pumping efficiency in the proposed pump is higher than that in the original pump by more than a factor of two.

Tungsten is potential candidate for an armor of the first wall and the divertor plate of the fusion reactor because of its low erosion yield and good thermal properties. Thus, joint materials with tungsten and cooling channel will be used as the divertor plate. Mockups have been fabricated by jointing W rods on oxygen-free high thermal conductivity Cu block with a cooling tube using non defective bonding, and high heat loading experiments have been carried out under active cooling condition. The results show that temperatures at the W surface and the Cu part closely follow the changing heat load and that the temperatures increase monotonically with increasing the heat flux.

To understand the dynamics of in-depth migration and retention of hydrogen isotopes in Carbon Fiber Composites (CFCs) used as plasma facing materials, a dedicated experimental setup coupling an ECR ion source to the Saclay nuclear microprobe (CEA, France) was developed to expose CFC NB31 samples to deuterium implantation, and then to perform in situ μ-NRA analysis for 3D deuterium profiles. When deuterium concentration at the surface was homogeneous and fluence-independent, the in-bulk deuterium was concentrated in the porosities and increases in quantity with the incident fluence up to very large depth (500 μm). For interpreting the measurements, a model was built based on a Monte Carlo method and calculated the propagation of D atoms in a network of pores.

Effects of the helical field application on tokamak plasmas and effects of the plasma current on compact stellarator configuration have been investigated with the TOKASTAR-2, a small toroidal device, in which plasma confinement with tokamak, stellarator, and tokamak-stellarator hybrid configurations is possible. The plasma current has been increased to above 1kA with installation of new coils, and optimization of the tokamak plasma equilibrium control was performed. After that, tokamak plasmas were successfully obtained. Progress has been made in the operation of tokamak plasmas and stellarator plasmas in the TOKASTAR-2, which will extend to the study on tokamak-stellarator hybrid configurations.

Development of heating systems is inevitable for fusion relevant devices, such as ITER and DEMO, as well as the LHD experiments. Plasma heating and control by injecting high-energy neutral hydrogen/deuterium beams are most prospective to realize the burning fusion plasmas. The LHD is equipped with the neutral beam injection (NBI) system as a main heating system, which consists of three negative-ion-based NB injectors and two positive-ion-based ones. High-power and stable operation was achieved in the NBI system during the 17th campaign, and the total injection powers of 15MW and 12MW were available in negative-NB and positive-NB injectors, respectively. The high-power NBI heating has further extended the LHD plasma parameter regime, and the ion temperature was raised to 8.1keV in the 17th campaign

The negative-ion-related physics research has been carried out together with the technology developments. Investigation on the ionic plasmas, which consist of mainly positive and negative ions with quite low electrons, has progressed. The ionic plasmas are observed near the plasma grid (PG) in a cesium-seeded negative ion source for the NB injector, and their properties were measured with various diagnostics. For the negative ion density measurement, the cavity ring-down (CRD) system was used. With the combined measurement of a Langmuir probe and the CRD system, behavior of the electrons and the positive and negative ions was investigated for responding to the bias voltage, which is applied to the PG with respect to the arc chamber. The results suggest that the bias voltage affect to positive ions not to electrons magnetized with relatively strong magnetic field in the vicinity of plasma grid.

It was observed that the H^- density near the PG was reduced at the H^- extraction. The Hα emission caused by the mutual neutralization process becomes dominant in the ionic plasmas, and, thus, should be correlated with the H^- density near the PG. Correlation between the H^- density and the Hα emission intensity in the extraction region was investigated by comparison of the reduction amount at the H^- extraction. The results confirm linear correlation of the reduction amounts between the H^- density and the Hα emission intensity by way of mutual neutralization process in the ionic plasmas.

The electron density near the PG surface was measured with the surface wave probe (SWP), which is not influenced by the magnetic field existing in the extraction region. Response of the electron density to the bias voltage was investigated with and without the Cs seeding. In the pure-volume plasma the electron density significantly decreased with increasing the bias voltage. In the Cs-seeded plasma, the electron density near the PG became lower than that in the pure-volume plasma, and dependence on the bias voltage was weak.

Laser-aided spectroscopic diagnostics was applied to investigations on the production processes and the extraction mechanisms of the negative hydrogen ions in the cesium-seeded negative hydrogen ion source. This research activity was started with investigating the behaviors of atomic hydrogen and cesium vapor, and detection of the laser absorption signal in the Balmer-line of atomic hydrogen was tried. The frequency-modulated absorption spectroscopy was employed, and from the Doppler-broadening of the absorption line profile the temperature of atomic hydrogen was estimated at around 3,000 K. The temperature of atomic hydrogen was observed to be insensitive to the arc-discharge power.

Voltage holding capability of high-energy accelerators is one of the critical issues in giant negative ion sources for fusion research. In order to understand and predict the voltage holding capability with the beam acceleration, the breakdown properties has been investigated by comparing the ion sources for LHD, JT-60SA and the MeV accelerator for ITER R&D. The effect of the multiple acceleration stages on the voltage degradation due to the beam acceleration was firstly pointed out by the comparison of ion sources with the different number of the acceleration stage.

Integrated modeling study for optimization of the negative-hydrogen ion production, extraction and acceleration has been performed to the ionic plasma. To investigate the formation mechanism of plasma meniscus in the ionic plasma, the developed 2D3V PIC (Particle-in Cell) model was improved to the 3D model from the 2D one, and quantitatively more reasonable agreement with the experiments has been obtained by the 3D model in a relatively simplified geometry with one extraction aperture.

For the next-step negative-NBI system, the R&D activities of the negative-ion-related technology have been carried out. For a long-pulse and long-life operation, it is required to develop RF-driven H^- sources. The compact RF-driven H^- ion source, which utilizes a FET-switching inverter power supply as an RF source, has already been developed with a 70mm-inner diameter and 175mm-long ceramic tube as an RF-driver plasma region. It was upgraded to a large-scaled ion source with a 230mm inner diameter ceramic tube, and high-density plasmas over $10^{19}m^{-3}$ were obtained in the driver region.

For an advanced and future plasma source for the NBI, a helicon plasma source is attractive because of flexible operation with high stability, high plasma density and high ionization. To develop and characterize a very small diameter and high-density helicon plasma source with a relatively low magnetic field operation, the Small Helicon Device (SHD) was developed and tested. In the smallest diameter down to 0.5cm, the electron density of 10^{17}-$10^{19}m^{-3}$ was successfully produced with Ar gas.

To study a role of the magnetic field on the H^- extraction and the co-extracted electron suppression, the H^- extraction probability was estimated with two kinds of photodetachment methods using a small ion source, and the results were discussed with a PIC calculation.

Electron cyclotron resonance heating (ECRH) is widely utilized in the LHD experiments, especially for electron heating and current drive experiments. In FY2013, with simultaneous operation of the three 77GHz and one 154GHz 1MW-gyrotrons, the total injected power of ECRH into LHD exceeded 4.6MW. For the high-temperature steady-state plasma confinement experiments in LHD, development of the high-power and long-pulse millimeter-wave transmission components is inevitable, and the evacuated corrugated waveguide system has already been developed, as well as the general design and the fabrication method of miter bend for the system. In addition, development of a new type of power/polarization monitor was started from the necessity to monitor and control the polarization state of the injected power for optimization of the heating efficiency in LHD.

To precisely align a propagating millimeter-wave beam to a transmission line to avoid mode conversion to the other higher-order modes, a real-time beam-position and profile monitor (BPM) has been developed. It was improved to obtain higher spatial resolution, and the method for the mode content analysis was considered.

Bloch waves were studied on rectangularly corrugated cylindrical waveguides in millimeter and sub-millimeter wave region. The corrugation is formed on the inner wall of waveguide or the outer wall of inner cylinder of coaxial waveguide, and the Bloch waves are generated on the inner corrugation as a cylindrical surface-wave and on the outer corrugation as the TM modes. The K-, G- and Y-band corrugations were designed to examine Bloch waves. Applying a cavity resonance method, the K-band corrugation of inner cylinder was excited by a wire-disk antennas, and the dispersion curves of Bloch wave on the inner corrugation were obtained for the G- and Y-band corrugations.

Recently, microwave, millimeter wave and Tera-Hertz wave oscillators and some components have been progressively developed, and applied to plasma, material and medical sciences. To promote the exchange of the state-of-the-art information on the related research and technologies, a workshop was held. The main themes were research and development of klystrons and gyrotrons, and new ideas and application of high-power vacuum tubes to the research fields other than nuclear fusion. There were 7 research reports, and 22 participants discussed the wave technology and its application.

For the ICRF heating experiments in LHD, a pair of Field-Aligned-Impedance-Transformer (FAIT) antennas were installed in the 17th campaign. These were utilized in the long-pulse experiments, and a steady-state plasma with the density over $1x10^{19}m^{-3}$ was sustained for about 48min. by 1.2MW of the heating power of ICRF and ECRH.

Ion cyclotron range of frequency (ICRF) heating is prospective for heating of the core ions in future fusion devices like ITER. To enhance the ICRF heating technology, a workshop was held on "Development and reactor application of ICRF heating device". 9 topics were presented and discussed by 28 participants.

It should be noted that universities outside NIFS make major contribution to these studies presented here.

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