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

To improve plasma performance in the present and future experiments in the LHD, efficient pumping control should be emphasized. Before the 16th campaign the closed helical divertor with the cryo-sorption pumping system was installed at 6 toroidal sections, and the pumping experiments were carried out at one section. For improvement of the pumping system design, properties of the pumping speed of the cryo-sorption pump are analyzed. The simulation was performed in a three-dimensional grid model for the pumping system, using a three-dimensional neutral particle transport code (EIRENE). The results prove that the pumping speed strongly depends on both the conductance of the pumping system and the absorption ratio of the charcoal panel.

Tungsten is a potential candidate for armor of the first wall and the divertor plate in a fusion reactor because of its low erosion yield and good thermal properties. Tungsten coatings on reduced-activation ferritic/martensitic steel F82H substrate by Vacuum Plasma Spray (VPS) have been produced, and high-heat flux experiments were carried out to evaluate their possibility as the plasma-facing armor. Also, quantitative analyses about temperature profiles and thermal stress were performed using FEM.

Development of heating systems is quite important 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 neutral beam injection (NBI) system is a main heating system in the LHD, which consists of three negative-ion-based NB injectors and two positive-ion-based NB injectors. During the 16th campaign the total injection powers of 14MW and 12MW were available in three negative-NB injectors and in two positive-NB injectors, respectively. The high-power NBI heating has greatly extended the LHD plasma parameter regime, and in the 16th campaign the ion temperature was successfully raised to 7.3keV by the NBI heating.

The negative-ion-related physics research has been carried out together with the technology developments. The ion-ion plasmas, which consist of mainly positive and negative ions with quite low electrons, have been observed near the plasma grid (PG) in a cesium-seeded negative ion source. It was observed that the H^- density near the PG was reduced at the H^- extraction. The $H\alpha$ emission is correlated with the H^- density near the PG, and the two-dimensional image of the reduction of the $H\alpha$ emission at the extraction was directly observed in a view parallel to the PG surface. This result clearly indicates that the motion of extracted negative ions generated on the PG surface is widely distributed in the extraction region.

To clarify the formation and transport mechanisms of H^- ions in such plasmas containing high-density H^- ions, the H^- ion density has been measured with cavity ring-down spectroscopy (CRDS). The movable CRDS system was developed, in which the laser path and the cavity mirrors are moved in the parallel direction to the PG surface. The H^- density measured along a line of sight containing mainly the extraction apertures was lower than that containing mainly the metal surface between the apertures. That directly indicates that the H^- is produced on the cesium-covered PG surface. On the other hand, during the H^- ion extraction the decrement of H^- ions is compensated with electrons, which is confirmed with a Langmuir probe measurement. In order to investigate the electron diffusion, the electron flow was measured in the extraction region with a directional Langmuir probe. Polar distributions of the electron saturation current were obtained at a fixed distance from the PG surface, and the electrons are suggested to enter to the extraction region along the linkage magnetic field.

For further improvement of the beam power and the pulse length, reduction of the heat load on the acceleration grids and the beamline components is strongly required. Since the heat load is mainly caused by the secondary particles produced in the accelerator, the simulation study on the secondary particles has been carried out for a multi-aperture accelerator. The influence of non-uniformity in the magnetic field on the trajectories of the H^- ions and the secondary particles was investigated. The result indicates that the secondary electrons are more likely to be intercepted by the grounded grid due to the stronger magnetic field.

Modeling study for optimization of the negative hydrogen ion extraction has been applied to the ion-ion plasma. A 2D3V PIC (Particle-in Cell) model has been developed to analyze the plasma density profile in the extraction region self-consistently with the charged particle dynamics. The simulation result indicates that during the beam extraction the electrons compensate the decrement of the H^- density due to the beam extraction, which supports the qualitative explanation of the experimental results.

The voltage holding capability of large-sized multi-aperture grids has been studied for giant negative ion sources developed for negative-NBI systems in LHD, JT-60SA, and ITER. The voltage degradation due to the beam acceleration has been investigated, and the related charged particle flow in the acceleration gap was analyzed using the experimental results on the JT-60 ion source.

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 or continuous operation, it is requisite to develop RF-driven H^- sources. A compact RF-driven H^- ion source by using a FET-switching inverter power supply as an RF source has been developed. High-density plasmas of $10^{19}cm^{-3}$ at the driver region and more than $10^{18}cm^{-3}$ at the expansion region have been produced. Long-pulse operation for 100sec was demonstrated. A small amount of cesium vapor was injected, and the cesium effect was investigated with the cesium line emission measurement. The H^- ion density near the plasma grid was measured with the CRD technique, and the H^- ion to electron ratio was investigated in the Cs seeding.

For an advanced and future plasma source for the NBI, a helicon plasma source is attractive because of flexible operation of the external parameters. Also, it is meaningful to develop a small plasma source with a low magnetic field operation. A high-density and small-diameter helicon plasma source was developed. In the case of 2cm-inner diameter tube with a magnetic field of 0.057T, a high-density of close to $10^{13}cm^{-3}$ was successfully produced with Ar gas. In the case of 1-cm inner diameter tube, a high-density plasma was also obtained.

A multi-antenna type RF-driven ion source has been developed. A new multi-antenna unit with the Faraday shield is tested to efficiently couple near rf fields to the plasmas, and the relation between the plasma density profile and the antenna structure was investigated.

The H^- extraction mechanism has been investigated using a simple beam extraction system with three electrodes, and the H^- extraction probability was discussed related to the H^- destruction at the extraction electrode.

A negative-ion beam probe system has been proposed as a new scheme to diagnose the beam profiles of high intensity positive ion beams, such as the IFMIF deuteron beams. To solve the difficulty to measure the negative ion beam attenuation, a new probe beam diagnostic system, which is based on measurement of the negative ion beam profile by using deflection of the beam orbit due to scattering with the positive ions, was designed.

Electron cyclotron resonance heating (ECRH) is widely utilized in the LHD experiments, especially for electron heating and current drive experiments. In FY2012, one 1 MW-class 154GHz gyrotron, developed under the collaboration between NIFS and Univ. of Tsukuba, was operational, and the total injected power of ECRH into the LHD exceeded 4.6MW including the three 1MW-class 77GHz gyrotrons. That contributed to achieve 13.5keV of the electron temperature at $n_e=1x10^{19}m^{-3}$. The high-power and long-pulse millimeter-wave transmission components have been developed with high reliability. Several transmission components for 154GHz gyrotron, such as the power monitor, the miter bend polarizers, the arc detector/temperature monitor mount, and the quasi-optical mirrors, were developed and installed on the LHD, taking care of the smallness of the sub-waveguide components and the accompanied fabrication tolerance due to the shorter wavelength. The transmission mode analyses using the series of burn patterns in a corrugated waveguide were further developed to minimize errors in the measured and the calculated burn patterns.

To evaluate the position and the profile of a high-power (MW level) millimeter wave propagation even in the evacuated corrugated waveguide, a real-time beam-position monitor (BPM) has been developed, in which a two-dimensional array of Peltier devices is installed and aligned on the atmospheric side of a thin miter-bend reflector. A transient analysis of the variation of the Peltier device voltage was carried out.

To actively control the ECR heating location according to the order of plasma response time, the ECH mirror control system for the 1.5L-port of LHD was improved. For the first step, an AC servo motor was used instead of the present ultrasonic motor. As the next step, a feedback function for the active control was designed.

A high-power sub-THz gyrotron is required for application to the CTS diagnostics. The developed sub-THz gyrotron was approaching 100kW at 389GHz in second harmonic (SH) oscillation. However, mode competition with fundamental harmonic (FH) modes has prevented achievement of much higher power. Then, development of an FH mode sub-THz gyrotron has been tried, and the maximum oscillation power was achieved to over 200 kW.

Bloch waves were studied on rectangularly corrugated cylindrical waveguides in millimeter and sub-millimeter wave region. K-band and G-band corrugations were designed to examine Bloch waves. The dispersion curves of G-band corrugation were discussed, and the Bloch waves were examined based on a cavity resonance method. G-band corrugations were also fabricated, and the corrugation parameters were measured. The Bloch waves were excited by the electron beams as a different method by the wire-disk antennas.

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 technologies, a workshop was held. The main themes were development of klystrons and gyrotrons and their application. There were 2 topical lectures and 3 research reports, and 21 participants discussed the wave technology and its application.

For the ICRF heating experiment in the 17th campaign of LHD, a pair of Field-Aligned-Impedance-Transformer (FAIT) antennas was developed. The antennas, in which the Faraday shield is aligned to the magnetic field lines and the current strap is perpendicular to them, were designed as high-power injection, and there is impedance transformer in the transmission line for reduction of the electric field. The maximum power of 1.6MW/antenna is expected for a typical short-pulse plasma discharge. For steady-state operation, copper is used for several parts suffering high heat-load, and the estimated maximum steady-state power is 1.2 MW.

Ion cyclotron range of frequency (ICRF) heating is prospective for future fusion devices. To strengthen the development action of the technology for high power and reliable ICRF heating, a workshop was held on "Development and reactor application of ICRF heating device". 7 topics were presented and discussed by around 20 participants.

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

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