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.

In a fusion reactor, high-Z materials will be used as plasma facing components and, thus, high-Z impurity transport is a concern. Since the changes of core plasma profile by the ITB would cause changes of impurity transport, transport of the tungsten impurities is analyzed for a tokamak reactor, using an impurity model in the toroidal transport analysis linkage (TOTAL) code. The result shows that the impurities decrease in the ITB formation region and that the outward flux of total impurity density is observed there.

It is advantageous in Stellarator/Heliotron (S/H) systems that plasmas can be produced by external heating power without loop voltage. Recently, plasma production by NBI was successfully demonstrated with assistance of 2.45GHz-5kW microwaves in Heliotron J. The necessary conditions for successful microwave-assisted NBI plasma start-up are investigated on the number of neutral particles (gas pressure), electron heating (microwave power), and the number of high-energy ions (NB power). The result shows that higher microwave power is required at lower magnetic field strength.

Tungsten will be used as an armor material of the first wall/blanket and divertor in a fusion reactor. Tungsten coatings on reduced-activation ferritic/martensitic steel F82H substrate by Vacuum Plasma Spray (VPS) have been produced, and high heat flux experiments are carried out to investigate thermo-mechanical properties at high temperature. The results indicate that the VPS-W coated F82H has high potential of these coating as plasma-facing armor under thermal loading of the first wall.

To improve plasma performance in the present and future experiments in the LHD, efficient fueling/pumping control should be emphasized. In FY2011 the closed helical divertor with the cryo-sorption pumping system was installed at 6 toroidal sections. For improvement of the pumping system, heat load on it is investigated for the modified configurations. The result shows that installation of buffer plates made of carbon, on the surface of which many grooves are scratched, is effective to reduce the heat load without serious degradation of the pumping efficiency. The spheromak-type compact toroid (CT) injector of SPICA (SPheromak Injector using Conical Accelerator) has been developed for advanced fueling in the LHD. Using the CT injection technique, production of an extremely super-high speed neutral particle flow (NPF) is investigated as a new approach to effective fueling, and a high-speed NPF comparable to an accelerated CT has been successfully produced. A Monte-Carlo simulation study on the neutralization of CT plasma has also progressed.

Development of heating systems is quite important to 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. Therefore, development of the high-energy neutral beam injection (NBI) technology is intensively carried out.

The NBI system in the LHD consists of three negative-ion-based NB injectors and two positive-ion-based ones. In the 15th campaign the total injection power was 15.7MW and 11.2MW in three negative-NB injectors and in two positive-NB injectors, respectively. The NBI system has greatly contributed to the extension of the LHD plasma parameter regime as a main heating system, and 7keV of the ion temperature was achieved by the NBI heating in the 15th campaign. Improvement of the LHD-NBI performance is continued. In the negative ion source, a cusp magnetic configuration of the arc chamber of the source was modified to produce higher negative ion current, and the arc efficiency for the negative ion current is increased by about 10%.

For development of the negative-NBI system in the ITER and DEMO, including further improvement of the LHD-NBI system, the negative-ion-related physics research is 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. To clarify the formation and transport mechanisms of H^- ions in such plasmas containing high-density H^- ions, a multi-diagnostic system has been installed. The H^- ion density measured with cavity ring-down spectroscopy (CRDS) is decreased during the H^- ion extraction, and the decrement of H^- ion density is compensated with electrons, which is confirmed from the change of the negative saturation current at a Langmuir probe. It is considered that electrons in the upstream plasma region flow into the extraction region to hold the charge neutrality. The H^- ion density is changed against the bias voltage which is applied between the arc chamber and the PG, and the decrement of H^- ion density during the extraction is also influenced by the bias voltage. The plasma potential would be related to these observations. For the precise measurement of the electron density in the extraction region, where relatively strong magnetic field exists for suppression of the electron extraction, a surface wave probe (SWP) technique based on the resonant spectroscopy is applied. As a result, it is observed that the electron density is reduced by applying the bias voltage while the H^- ion density is almost constant.

Modeling study for optimization of the negative hydrogen ion extraction is applied to the ion-ion plasma. A 2D3V PIC (Particle-in Cell) model has been developed to analyze the potential structure in the extraction region self-consistently with the charged particle dynamics. The results give the physical mechanisms for the ion-ion plasma with poor electrons in the extraction region, and show that the H^- emitting surface, i.e., the plasma meniscus for such ion-ion plasma is possibly located relatively far from the extraction hole and the PG surface.

For the next-step negative-NBI system, the R&D activities of the negative-ion-related technology are 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 with a frequency of 0.3-0.5MHz 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 are produced. The H^- ions are extracted, and with adding a small amount of cesium vapor an increase in the H^- current are confirmed. The H^- ion density near the plasma grid is evaluated with the CRD technique. The volume-produced H^- density is measured at $1x10^{16}m^{-3}$ in the RF source plasma.

For an advanced and future plasma source in NBI, a helicon plasma source with the largest diameter of 74cm and short axial length down to 4.7cm has been developed. High-density of 10^{12}-$10^{13}cm^{-3}$ helicon plasmas are produced, and the plasma production efficiency is investigated on the axial length. A multi-antenna type RF-driven ion source has been modified to realize a close coupling configuration of the multi-antenna, which is characterized by all-metal antennas installed inside a vacuum vessel with a Faraday screen. As a result, the ion saturation current density increases with an increase in the RF power to $5.5A/cm^2$ at 157kW.

The effect of the plasma potential near the extraction hole on the negative ion extraction efficiency is investigated using a simple beam extraction system with three electrodes. It is observed that the plasma potential is varied by the extraction voltage applied to the plasma.

As a new scheme to diagnose the beam profiles of high intensity positive ion beams, such as the IFMIF deuteron beams of 40MeV-125mA, a negative-ion beam probe system has been proposed. To validate the capability of the system, an H^- ion source is designed, assembled and tested. An experimental setup is also prepared for proof-of-principle experiment of the H^- beam probe system.

In the LHD experiments electron cyclotron resonance heating (ECH) is widely utilized, especially for electron heating and current drive experiments. Due to the successful development and the simultaneous operation of the three 1MW-77GHz gyrotrons, the total injected power of ECRH into the LHD exceeded 3.7MW in FY2010, which contributed to achieve 20keV of the electron temperature. In order to accommodate high power of the order of 1MW and long-pulse or CW transmission with high reliability, the miter bend and the power monitor have been designed and fabricated for an evacuated corrugated waveguide with several inner diameters against the existing 3.5-inch waveguide transmission lines. In FY2011, a new power monitor including its miter bend block for 88.9 mm inner diameter waveguide system are designed and fabricated for the 154GHz gyrotron system which will be used in the 16th campaign. To minimize the transmission loss of the corrugated waveguide system, the modes inside the waveguide system are analyzed utilizing infrared images on the target planes. This method is applicable to infer the amount of miss alignment at the waveguide inlet. To precisely align a propagating millimeter-wave (mmw) beam to a transmission line, a real-time beam-position monitor (BPM) has been developed, which measures the intensity profile of a high power (MW level) mmw propagating in an evacuated corrugated waveguide without any disturbance. A two-dimensional array of Peltier devices is installed and aligned on the atmospheric side of a thin miter-bend reflector. 52 Peltier devices with 10mm-square size are aligned for higher spatial resolution, and this Peltier-device array will be installed in the high power transmission line of the LHD-ECH system.

For active control of the ECR heating location according to the order of plasma response time, a fast scanning antenna system has been developed. To improve the scanning speed of the final mirror of the antenna, an AC servo motor is used instead of the present ultrasonic motor, and 10 times faster antenna sweep speed is achieved. The 77GHz-ECH system is also utilized for collective Thomson scattering (CTS) measurement in the LHD. The CTS probe beam power is modulated in the measurement, and, however, the spurious mode radiations, which are superimposed on the measured CTS spectrum, harm the scattered signal. By adjusting the magnetic field strength in the 77GHz gyrotron operation, the spurious radiation is suppressed at 74.7GHz although the main mode power is decreased down to one third, which should be optimized.

A high power sub-terahertz gyrotron is required for application to CTS diagnostics. A second harmonic gyrotron of demountable type was fabricated and achieved the oscillation power of 50 kW at 350 GHz and about 40 kW at 390 GHz. In FY 2010 with a newly fabricated sealed-off type gyrotron a new power record of 62 kW at 388 GHz was obtained. For further upgrade, a new electron gun is designed, fabricated, and mounted on the gyrotron, and a higher power record of 83 kW at 388.9 GHz is achieved in FY2011.

In these days, millimeter wave and Tera-Hertz wave oscillators and some components have been progressively developed, and applied to material and medical sciences. To encourage the exchange of the state-of-the-art information on the related technologies, a workshop is held under keywords of ”high power millimeter and Tera-Hertz wave source using an intense electron beam”. There were 8 presentations, and 21 participants discussed the millimeter wave technology and its application in the workshop.

Ion cyclotron range of frequency (ICRF) heating is prospective for future fusion devices. To solve the ICRF heating issues, such as heating efficiency, power density, and arcing in the transmission line and antenna, a workshop was held for exchange of the information on the ICRF heating technology. 8 topics were presented and discussed by the participants.

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

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