For a future upgrade of the LHD and consequent physics and engineering contribution to a fusion reactor, research and development related to the LHD torus and heating systems has been executed.

High-Z impurity transport is a concern for fusion reactors, and the toroidal transport analysis linkage (TOTAL) code was applied to the high-Z impurity transport analysis. The result shows that forming an internal transport barrier (ITB) for the electron density can prevent the high-Z impurity accumulation. Plasma production by NBI was successfully demonstrated with assistance of 2.45GHz-5kW microwaves in Heliotron J. Applicability of the 2.45GHz microwave-assisted NBI plasma start-up to the LHD was investigated.

Dust generation in the fusion device and its ejection to the confined plasma are potential problems for the impurity accumulations and the tritium retentions. Silica (SiO_2) aerogel was tested to detect the accelerated dust particles and their trajectories, and the incident dust particles, which were trapped into the aerogel and remained after the vacuum vent, were investigated by exposure of the aerogels to the LHD plasmas. Tungsten will be used as an armor material of the first wall/blanket in a demo fusion reactor. The mechanical properties of tungsten were investigated by tensile tests to examine the material behavior under loading of stress at high temperature of 550^{o}C.

A direct electric power generation by a thermionic energy converter (TEC) on a divertor plate is proposed. An influence of the magnetic field on the power generation efficiency by the TEC was investigated with a 2D Particle-In-Cell (PIC) simulation code. The power generation with a TEC test module was demonstrated in the divertor plasma environment in NAGDIS-II.

Efficient fueling/pumping control is emphasized since it has potential to improve plasma performance in the present and future experiments in the LHD. For the closed helical divertor system to be installed in FY2011, a design of the cryo-sorption pumping system is carried out, and the heat loads on the adsorption panels cooled by 20K-He gas and the LN_2-cooled chevron shield were numerically investigated. A compact toroid (CT) fueler of SPICA (SPheromak Injector using Conical Accelerator), which is characterized by neutral particle injection with extremely super-high speed flow, has been developed for the LHD. Performance of the CT acceleration and ejection was investigated on the single-stage SPICA. A CT plasma was injected into the neutralizer cell filled with hydrogen gas, and the neutralization process was investigated including a Monte-Carlo simulation.

Plasma heating and control by injecting high-energy neutral hydrogen/deuterium beams into the magnetically confined plasma is most prospective to realize the burning fusion plasmas. Therefore, development of the high-energy neutral beam injection (NBI) technology is quite important to fusion relevant devices, such as ITER and DEMO, as well as the LHD experiments.

The LHD is equipped with high-power NBI systems as a main heating method. In FY2010 a positive-NBI was upgraded as the 5th injector and successfully started its operation. The operation of the LHD-NBI system in the 14th campaign is summarized, and the total injection power was 15.7MW and 11.8MW in three negative-NB injectors and two positive-NB injectors, respectively, which contributed to the achievement of 6.5keV of the ion temperature. The upgrade of the positive-NB injector was carried out so as to optimize the hydrogen beam injection at 45keV-6MW, and the employed positive ion sources were tested also at 60keV for future modification.

For further improvement of the negative-NBI system in the LHD, including development of that for the ITER and DEMO, the negative-ion-related physics research was carried out together with the technology developments. The most interesting topic is that ion-ion plasmas were confirmed in a cesium-seeded negative ion source. In the negative ion extraction region of the arc plasma, the electron saturation current of a Langmuir probe is gradually decreased with the cesium seeding, and the absolute values of electron and ion saturation currents approaches almost the same by sufficient Cs supply. That indicates that the plasma consists of only positive and negative ions there. Such ion-ion plasmas were investigated with a time-resolved Langmuir probe, and it was observed that the negative saturation current exceeds the positive one at the negative-ion beam extraction while the difference between negative and positive saturation currents is almost zero before the beam extraction. Electrons should flow into the extraction region when the negative ions are extracted from the ion-ion plasma. The negative ion density in the extraction region was directly measured with cavity ring-down spectroscopy (CRDS). The negative ion density profile along the beam axis was measured, and it was observed that the negative ion density is gradually decreased toward the extraction boundary. A reduction of the negative ion density was also confirmed at the beam extraction with CRDS, and the similar tendency was observed in H_α/H_β measurement by optical emission spectroscopy (OES). A linear correlation between the H_α/H_β by OES and the H^- density by CRDS was confirmed, and, thus, the H_α/H_β measurement by OES can be applied to estimation of the H^- density through the calibration with CRDS. On the other hand, the electron density in the extraction region was directly measured with millimeter-wave interferometer of 39GHz. The electron density is decreased according to an increase in the H^- density measured by CRDS as the cesium is seeded. Electron density measurement by a surface wave probe, which is not influenced by the magnetic field, was also tried.

Integrated modeling study for the negative hydrogen ion production, extraction and acceleration is carried out to optimize large negative ion sources for the next-step NBI system. The LHD-NBI negative ion source was modeled, and the negative ion extraction from the ion-ion plasma was also investigated.

The R&D activities of the negative-ion-related technology are carried out in the NIFS collaboration program for the next-step negative-NBI system as well as the LHD-NBI system. Heat load on electrodes of a negative ion source should be reduced for a long pulse operation. To analyze and test the heat load on electrodes in a long pulse or continuous operation, an RF ion source which extracts the same current density as the large source has been developed. The developed RF-driven hydrogen plasma source employs an FET-based RF power supply with a frequency of 0.3-0.5MHz. The negative ions were extracted with the cesium seeding, and the extracted current density was $10mA/cm^2$ at an initial try.

For an efficient large RF-driven ion source needed in a future NBI system, a helicon plasma source with a large diameter of 40-74 cm and a short axial length down to 5.5 cm is developed, and high-density plasmas of 10^{12}-$10^{13}cm^{-3}$ were produced. A multi-antenna type of large-area RF ion source has also been developed, which is characterized by all-metal antennas installed inside the plasma chamber with a Faraday screen. The antenna was modified to increase the RF inductive field at the plasma edge. The ion current density increased more than few tens of times due to improvement of the coupling of the antenna fields to the plasma, and reached $8A/cm^2$.

To investigate the plasma potential effect to the negative ion extraction probability, a secondary filament is inserted in the extraction area for control of the plasma potential by supplying the additional electrons. It was confirmed that the local H^- extraction probability was enhanced as a function of the plasma potential although the extracted total H^- beam current was decreased by the electron supply.

A negative-ion beam probe system is proposed as a new scheme to diagnose the beam profiles of high intensity positive ion beams, such as the IFMIF deuteron beams of 40MeV-125mA. For the probe beam source, an H^- ion source was designed and assembled, and the H^- beam profile was measured at a small test bench.

A beam neutralization alpha particle measurement system using an energetic He^0 beam is proposed for ITER, and intense and high-energy helium negative ions are required for the system. To form a He^- beam through the two-step electron capture process in alkali vapor, a He^+ bucket source, equipped with a strongly focused grid system, has been developed. The emittance of the extracted 301 merging He^+ beamlets was measured, and no phase mixing in the merging beamlets was observed.

Electron cyclotron resonance heating (ECH) is widely utilized in the LHD experiments, especially for electron heating and current drive experiments. Presently, three 77GHz gyrotrons are operational for the plasma experiments with each output power of over 1MW, and the total injected power into the LHD exceeded 3.7MW in FY2010, which contributed to achieve 20keV of the electron temperature. The anode voltage of the 77GHz gyrotrons can be flexibly controlled using the preset waveform. By applying the anode voltage stepwise, the electrical efficiency was improved, and, as a result, 1.8MW of the output power was stationary obtained for 1s. For reliable long-distance transmission of the ECH microwave, a real-time beam-position monitor (BPM) was developed, which can measure the position of high power (megawatt level) millimeter wave propagating even in the evacuated corrugated waveguide. Two-dimensional Peltier device arrays are installed and aligned on the atmospheric side of a thin miter-bend reflector. A high power test was performed using a 82.7GHz microwave with the power of about 200kW for 100ms every 30s, and it was confirmed that a position of the highest voltage change of the Peltier device coincides with the peak temperature position. In order to accommodate high power of the order of 1MW and long-pulse or CW transmission with high reliability, an evacuated corrugated waveguide system and corresponding components are developed. A new power monitor including its miter bend block for a 60.3-mm inner diameter waveguide system were designed and fabricated for a 170GHz system. To optimize coupling of the gyrotron output to the corrugated waveguide system, a special phase retrieval technique was developed, in which burn patterns of the waveguide ends were taken by adding a 1-m waveguide one by one.

Presently, millimeter wave and Tera-Hertz wave oscillators and the related components have been progressively developed, and applied to material and medical sciences. To encourage the development of these technologies, a workshop was held under keywords of "high power millimeter and Tera-Hertz wave source using an intense electron beam". 22 participants discussed the millimeter wave technology in the workshop.

Ion cyclotron range of frequency (ICRF) heating has contributed to the long-pulse and steady-state LHD experiments. In FY2010 a toroidal phasing antenna, a hand-shake form type antenna (a HAS antenna), was designed and installed in the LHD. In the antenna design, the RF-field around the antenna was calculated using a three dimensional electromagnetic solver "HFSS" in order to reduce local hot spots which are caused by the RF sheath loading and the RF absorption at a plasma edge. In the LHD experiments using the toroidal phasing antenna, it was confirmed that the heating efficiency with the reverse-phase (~90%) was higher than that with the in-phase (~80%), and that a decrement in the local hot spots was achieved with the reverse-phase.

An advanced complex-conjugate impedance antenna system for the ICRF heating were proposed to alleviate the reflected RF power in such transitions as that of ELMy H-L mode due to a large change in the plasma resistance. The numerical calculation showed that the reflected RF power fraction could be drastically reduced to 1% while it would be 27% with a conventional conjugate antenna system. It was also experimentally confirmed that the maximum reflected RF power fraction was 1%.

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

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