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Diagnostic approach to the isotope effects
質量比・同位体効果の解明に向けた計測

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Based on the isotope effects observed for the confinement improvement of magnetically confined toroidal plasmas, diagnostic approach to investigate the contribution of recycling is discussed. For the purpose, recent high dynamic range Balmar-α spectroscopy to measure the radial density distribution of hydrogen from the edge to core regions is presented. Measurements necessary to evaluate the local density ratio of the isotopes in a hydrogen-deuterium mixture discharge are also considered.

1. Isotope effects on magnetically confined toroidal plasmas

A plasma is a typical complexity system composed of astronomical number of interacting ions, electrons and atoms together with electric and magnetic fields. A traditional reductionism approach may be hard to be applied to understand its nature. However, it is not disorder but universalistic phenomena sometimes appear in it. One example is the confinement improvement by the L-H transition of toroidal plasmas [1]. However, all the phenomena have not been clarified such as the isotope effects on the confinement improvement.

In tokamak plasmas, several isotope effects caused by increase in the atomic mass number have been reported such as reduction of the threshold power for the H-mode transition, improvement of the confinement saturation, increase in the energy confinement time, increase in the stored energy in the pedestal region and reduction of the edge localized mode (ELM) frequency [2-6]. These phenomena, however, are inconsistent with the prediction by the gyro-Bohm scheme.

With the Large Helical Device (LHD) in National Institute for Fusion Science (NIFS), deuterium discharge experiments are scheduled to start from 2016. Based on the experience with tokamak plasmas, further improvement in the plasma performance by the isotope effects and realization of the LHD target plasma parameters are expected. At the same time, since the isotope effects are thought to be universalistic phenomena in toroidal plasmas and have been open question for comprehensive understanding of the plasma physics, the LHD experiments are expected to contribute to this issue from a scientific point of view.

2. Isotope effects on recycling

It is known that the recycling from the edge affects on the plasma confinement. For example, low recycling has been realized by adoption of low Z element as the material of plasma facing walls, and the enhancement of the energy confinement and the reduction of the ELM have been observed [7,8]. In LHD, low recycling has been realized by the wall-conditioning using the ion cyclotron range of frequency (ICRF) heating discharge, and a high ion temperature plasma exceeding 7 keV has been generated [9].

The relation between the recycling and the H-mode performance was analyzed with a theoretical model about 20 years ago [10]. In the paper, a possible mechanism of the isotope effects was also discussed; since the speed of heavier isotope atoms is slower, the number of the atoms penetrating into the plasma decrease, and then the energy and momentum loss of ions by charge exchange collisions will decrease.

3. Quantitative measurement of the recycling

Recently, it becomes possible to measure hydrogen atomic density distribution from the edge to core regions by high dynamic range Balmar-α spectroscopy [11]. Its principle is rather simple; since the velocities of a hydrogen atom and a proton are exchanged by a charge exchange collision, the velocity distribution of the atoms reflects the proton temperature where the charge exchange collisions take place. From the observed Doppler-broadened Balmar-α spectrum, especially its wings, with the information of the radial distribution of the proton temperature, the radial distribution of the hydrogen atomic density can be deduced.

For LHD plasmas, the radial distributions of the electron temperature and density are quantitatively measured by the Thompson scattering method [12] and that of the proton temperature is measured by the charge exchange spectroscopy with NBI [13]. With these data and the cross sections of electron impact excitations and ionizations, proton impact excitations and ionizations, and charge exchange collisions, the hydrogen transport from the edge to core regions can be also simulated [14].

4. Toward unified comprehension of the isotope effects

From the radial distribution of hydrogen (deuterium) atomic density, the NBI heating loss, especially in the core region, and momentum loss, especially in the pedestal region, of the bulk plasma may be deduced.

However, as was written in section 1, unified comprehension is indispensable because simple linear summation of the contributions of elementally processes is not applicable. For the purpose, a unified model to simulate the overall plasma with the input of all the measurement results including the radial distributions of impurities and Z_{eff} should be necessary because the contribution of carbon impurities have been investigated in the connection with the confinement improvement in LHD [15]. Feedback from the simulation to the measurement and repetitive improvement between the simulation and measurement may be also necessary. TASK3D, the integrated transport analysis suite, should play a key role in this activity [16].

5. Issues to overcome in measurement of the recycling isotope effects

There are still not a few problems on the precision measurement of the radial distribution of hydrogen atomic density. For example, contribution of proton impact excitations to the wings of the Balmar-α spectrum becomes larger than that of electron impact excitation when the proton temperature exceeds 5 keV. Such situation will be realized in high ion temperature plasmas with the ion internal transport barrier (ITB), in which the isotope effects are expected to appear. In the analysis of the Balmar-α spectrum, the contribution of the proton excitations should be included. Furthermore, the spatial distributions of the plasma parameters, especially the ion temperature, in the scrape-off layers (SOLs) is demanded because their accuracy is indispensable for the quantitative estimation of hydrogen atom flux into the confined region.

In the actual situation, a hydrogen-deuterium mixture discharge will be generated in LHD. Therefore, local density measurements for both the hydrogen and deuterium ions and those for both the hydrogen and deuterium atoms may be necessary. Regarding the local density ratio measurement of hydrogen and deuterium ions, the charge exchange spectroscopy with NBI is expected be applicable. On the other hand, the high dynamic range Balmar-α spectroscopy cannot be fully applicable to the local density ratio measurement of hydrogen and deuterium atoms because, in addition to the very small wavelength shift of the Balmar-α spectra between hydrogen and deuterium atoms, theoretical treatment of velocity change caused by an elastic collision between a hydrogen ion and a deuterium atom, or between a hydrogen atom and a deuterium ion, in the spectral profile analysis is not trivial.

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