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Two-dimensional diagnostics of edge and divertor region of toroidal helical plasmas using a lithium beam probe

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Abstract

A two-dimensional neutral lithium beam probe has been designed and installed on the Compact Helical System (CHS) to study the edge and separatrix region of $l = 2$ helical divertor configuration. A 10–20 keV beam with equivalent neutral beam current of 0.1 mA is injected. Light emission from the injected beam by electron impact excitation (LiI/670.8 nm) is collected by an eight-channel detector system using optical band-pass filters and Avalanche Photodiodes. The injection beam line is mechanically tilted to cover the area two-dimensionally. The total system has been calibrated by injecting the beam into the helium-gas-filled CHS vacuum chamber. Detailed measurements of two-dimensional structure of edge and divertor region are expected to contribute to studies of helical divertor concept and to improve understanding of the role of edge plasmas on core confinement as well.

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Keywords: LiBP; Two-dimensional diagnostics; Divertor region; CHS

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1. Introduction

It has been recognized that plasma properties in the edge region of magnetic confinement devices have a key role in determining the global plasma confinement. Understanding and controlling edge plasmas are also important from the point of view of the divertor design for fusion reactors. In non-axisymmetric helical devices, edge magnetic configurations intrinsically include ergodic layer and magnetic island structures. A heliotron type device like the Large Helical Device (LHD) or the Compact Helical System (CHS) has a toroidally continuous natural divertor similar to the double-null X point structure in tokamaks. However the magnetic lines of force in this region have a chaotic behavior, forming an ergodic region. The separatrix is not as clear as that in tokamaks.

Recently a sharp pedestal in electron temperature profile is observed in LHD, suggesting edge thermal transport barrier formation [1]. The role of the ergodic layer such as the screening of impurities and fueling neutral particles has been discussed, but no clear physical picture has been obtained. It is important to measure the plasma distribution and its parameters in this layer. Measurement of plasma density in the separatrix region is also important from the diagnostic point of view. The core plasma density profile is often determined by Abel inversion of multi-channel interferometers. In the case of a heliotron type device, the chord inevitably passes the separatrix region. Ambiguity of the electron density in this region affects the accuracy of core density profile determination. In order to study plasma structures in the separatrix region as well as the ergodic layer in helical magnetic configuration, a two-dimensional diagnostic is essential.

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A lithium beam probing (LiBP) is one of the best techniques for the measurement of edge plasma density profile [2], which utilizes the emission of the injected neutral lithium beam by electron impact excitation. It can probe plasmas from the edge to the core crossing the last closed flux surface without perturbation or contamination to the plasma. It has been used in many magnetic confinement devices such as ASDEX [3], NBT-1M [4], TEXTOR [5], WVII-AS [6], JET [7] and more recently LHD [8]. But all those measurements are in one dimension along the fixed beam line. Similar one-dimensional measurements have also been carried out in CHS before [9].

Recently a new LiBP system has been designed and installed on CHS, which can measure the two-dimensional plasma structure in the edge plasma region, including the separatrix. In this paper, a detailed description of this new diagnostic system is presented.

The CHS is a heliotron/torsatron device that has a major radius of 1.0 m and minor radius of 0.2 m. The pole number and the toroidal periodic number of the helical field coils are $l = 2$ and $m = 8$, respectively. The magnetic configuration in the edge region of the CHS is calculated [10]. The thickness of the ergodic layer in the CHS differs depending on the position of the magnetic axis. Thus, a variety of edge magnetic field configuration can be realized by shifting the magnetic axis in CHS, which is an advantage for the present study.

2. Diagnostic system

2.1. Beam injector

The new 2D-LiBP system has been installed on the CHS. The Li-beam injector is located on the top of the torus as shown in Fig. 1. The injector consists of an ion gun with a thermionic Li source (6 mm diameter), a Pierce extractor and cylindrical lens. The beam energy is in the range from 10 to 20 keV with an equivalent neutral beam current of about 0.1 mA. Fig. 2 shows a typical beam intensity of our ion gun as a function of accelerating voltage. Here, beam current is measured by Faraday cup. The ion beam is neutralized in the Cs neutralizing cell. A metal plate detector is located just below the neutralizer to monitor the ion beam or neutral beam current. The neutralizing efficiency of the Cs cell is measured as a function of the cell temperature as shown in Fig. 3. The data were taken at the tests and before it is installed on CHS. The ion beam is almost neutralized at about 180 °C, which is chosen as the normal operational condition. In order to eliminate the effect of stray magnetic field on beam trajectory before being neutralized, the ion gun is covered with a magnetic shield. The beam energy is selected so that it offers both an adequate spatial resolution and beam penetration. The spatial

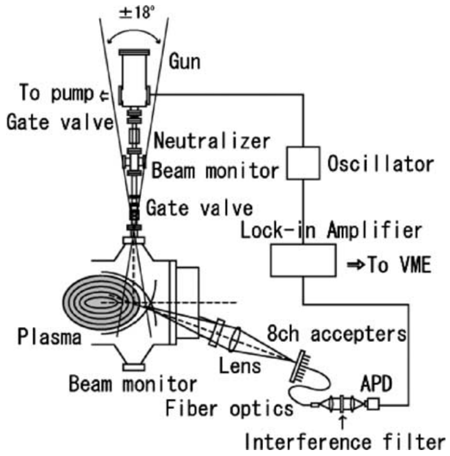

Fig. 1. Li-beam injector and optical system.

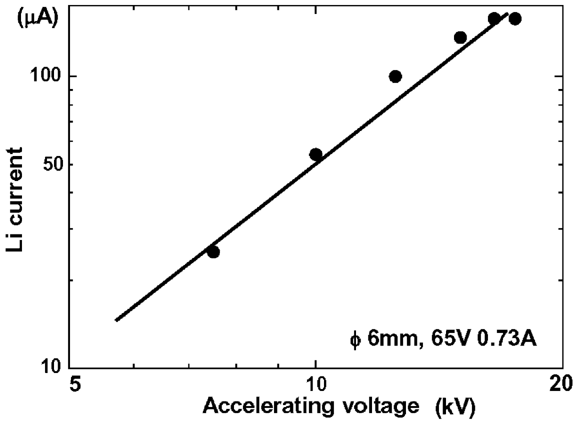

Fig. 2. Beam intensity for the ion gun with 6 mm diameter source as a function of the accelerating voltage (accelerate voltage: 7.5–17.5 kV).

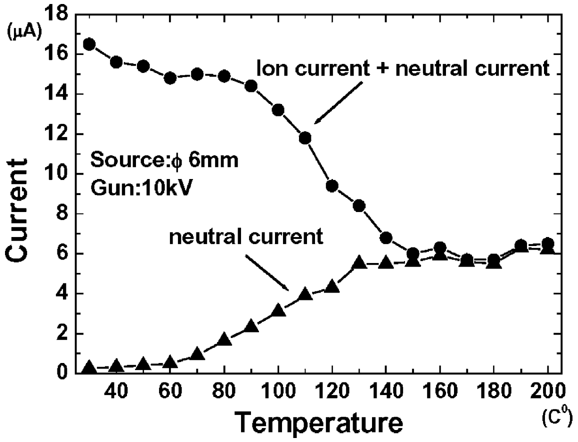

Fig. 3. Neutralizing efficiency of the Cs cell.

resolution is basically determined by the life time of the excited state (~27 ns). For the 10 keV beam the spatial resolution is less than 1 cm and beam penetration is expected to be about 2×10^{14} cm^{-2} of line integrated density. Higher energy beams have been used in several devices to get better penetration for high density plasmas. But in this case, the spatial resolution becomes worse. The neutral beam diameter is about 20 mm in the CHS vacuum chamber, which is about 2.5 m from the ion gun.

2.2. Optical system

The light collection optics, which detect the light emission from the lithium beam, is located on the side port of the torus. The optical system consists of a condenser lens, optical fibers, optical interference filters and Avalanche Photodiodes (APD) detectors. The light collection lens has a diameter of 100 mm and F-number is 6. The length of the optical fiber, which is made from fiber-glass reinforced plastic, is 15 m. Seven fibers (diameter of 1 mm) are packed into a bundle fiber with a diameter of 3 mm for each channel. The transmission efficiency is about 60% at 670.8 nm. The optical interference filter has a bandwidth of 0.5 nm and the peak transmission is about 65%. Twenty-four couplers for optical fibers are prepared on the light collection lens corresponding to 24 observation points along the beam with 8 mm spacing. Eight-channel optical fibers can select eight observation points by using eight couplers among those. This system is necessary to cope with the different plasma position depending on the position of the magnetic axis.

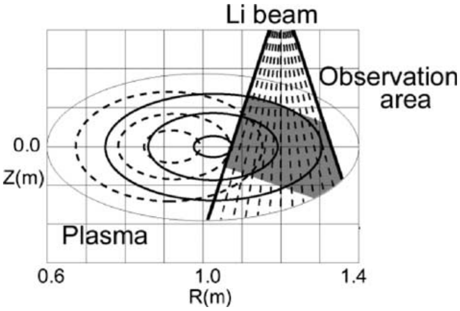

Fig. 4. The map of the observation area. The magnetic surfaces with broken lines are for $R_{ax} = 0.921$ m, and with solid lines for $R_{ax} = 0.995$ m.

2.3. Observation map

The injection beam line can be tilted in the major radius direction (±18° from vertical line) so that the edge ergodic layer around the separatrix can be observed two-dimensionally. Fig. 4 shows the map of the observation area. The shaded area indicates the possible sample volume location determined by the 24 optical couplers. When the beam line is tilted the light detected by the fixed lens system suffers a Doppler shift. For a beam energy of 10 keV, the Doppler shift is 0.0 nm (with $-18°$ beam tiling) to 0.72 nm (with $+18°$ beam tiling). The angle of the optical interference filter can be changed to tune to this wavelength.

2.4. Date acquisition and analysis

Since the signal to noise ratio for the present beam intensity (6 mm diameter source) is less than one ($S/N < 1$), the signal from APD detectors are introduced to phase sensitive detector with 4 kHz beam modulation. The time response is 3 ms at the moment. Fig. 5 shows sample signal from the plasma. The plasma is heated by ECH from $t = 20$ to 120 ms and additionally heated by NBI from $t = 100$ to 175 ms. The output signal are to be connected to an A/D converter module of VME standard.

In order to get electron density distribution along the beam, density profile reconstruction from the emission

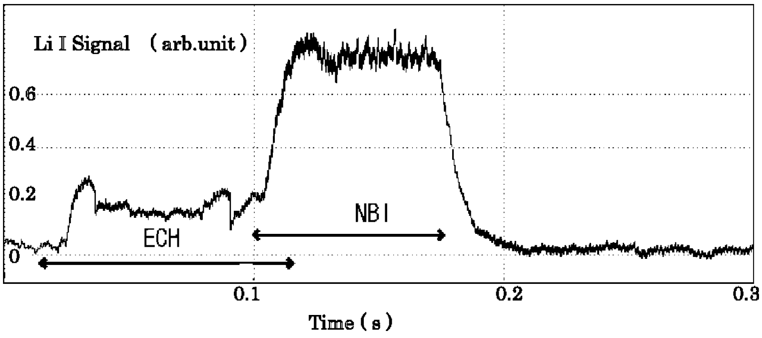

Fig. 5. The sample signals from the plasma. The plasma is heated by ECH from 20 to 120 ms in the discharge sequence. Additionally heated by NMI from 100 to 175 ms.

intensity profile is necessary. Two methods are used depending on the range of electron density. For those areas with low electron density and negligible beam attenuation, the intensity of Li–I emission signal is proportional to the electron density. The beam density and the sensitivity of the optical system are calibrated by injecting the Li beam into a fixed pressure target gas, where He gas is used. Since the excitation cross section for the Li atom in collision with He gas is known, the plasma electron density is directly obtained from the intensity of the Li–I emission. For the higher density region, beam attenuation becomes severe. Another density profile reconstruction algorithm is necessary, where multiple atomic process, such as ionization, charge transfer, deexcitation, are taken into account. Details on the density reconstruction algorithm are found elsewhere [9].

3. Summary

A new lithium neutral beam probe (LiBP) has been designed and installed on the CHS for two-dimensional measurements of the edge and separatrix region. A test signal from the plasma has been obtained using the phase sensitive detection method. Improved understanding for $l = 2$ helical divertor is expected.

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