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NIFS-R&Dイオン源での統合的負イオンプラズマ計測
Comprehensive diagnostic study of negative-ion-rich plasmas in NIFS-R&D negative ion source

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Hydrogen/deuterium negative ion (H^-/D^-) source has been developed and applied for neutral beam injector (NBI) to obtain high power beam of the energy range above 100 keV [1]. Negative-ion-based neutral beam injector (NBI) systems are scheduled to be adopted and considered for the reactor level fusion machines such as ITER and DEMO [2,3]. In order to enhance the H^-/D^- current, tiny amount of caesium (Cs) vapor is seeded in this type of negative ion source. Seeded Cs lowers the work function on the surface of so-called plasma grid (PG), which separates the ion source into negative-ion generator and acceleration region, and H^-/D^- is produced on the PG surface. At the same time, co-extracted electron current reduces as H^-/D^- increases.

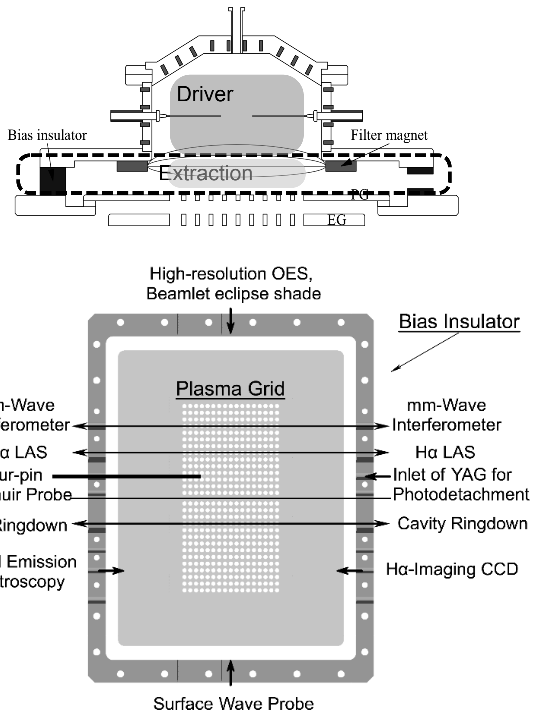

Fig. 1. Cross section of NIFS-R&D negative ion source on short side (upper) and alignment of multiple diagnostic modules (lower) in a view on the top of upper figure. Notice that the scale of lower figure is compressed in lower one.

In order to obtain higher and stable H^- current density, production and extraction mechanisms of H^- was necessary to understand. For this reason, measurement of the plasmas at beam extraction region has started with use of multiply combined diagnostics. The alignment of the diagnostic modules is indicated in Fig. 1. Outer size of the measured region is 700 (H) x 350 (W) x 35 (D) mm. Some of the modules are two- dimensionally movable and can measure the spatial distributions of densities and potential in the extraction region.

In the negative ion source, tiny amount of caesium (Cs) is seeded in the plasma chamber to enhance the H^- production by lowering the work function on so-called plasma grid (PG), which separates the plasma chamber and beam accelerator. Electron density in the extraction region decreases by seeding Cs, and the plasma consists of only hydrogen positive and negative ions finally [4]. Shielding feature of electrostatic field in this H^- rich plasma is different from "normal" electron-positive ion plasmas as shown in Fig. 2.

Potential slopes do not change in the "normal"

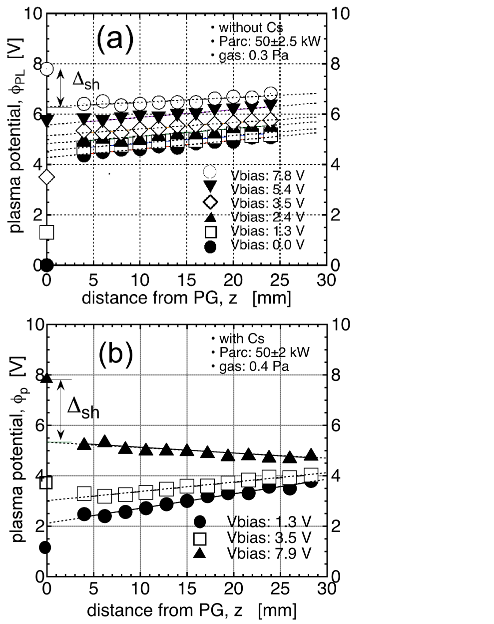

Fig. 2. Spatial distributions of plasma potentials obtained with Langmuir single probe (a) in hydrogen plasma without Cs and (b) in Cs-seeded plasma. Plots marks indicates difference of the bias voltage and the probe tip scanned in the direction normal to the plane of PG surface toward driver region.

hydrogen plasma and sheath difference (Δ_{sh}), which is defined as the gap between the bias voltage applied at PG and extrapolated fitted line of potential distribution [5]. On the other hand, the potential distribution in Cs-seeded case changes the slopes and the sheath gap is shallower. Similar effect is seen by applying electrostatic field to extract beams from H^- rich plasma. Actually, Ha filtered CCD shows extracted H^- ions distribute widely over the extraction region [6]. Charge neutrality is conserved by positive ions and H^- before beam extraction, while electrons diffused from driver region to conserve the excess positive charge during H^- extraction [4].

In the case of H^- rich plasma, electric field in the plasma at extraction region is sensitive to applied external field. Magnetic field is relatively strong in this region and drifts of charged particles are expected. Thus, flows of charged particles are measured, and they are compared to their temperatures. Temperature of hydrogen atom is measured by means of high-resolution optical emission spectroscopy (HR-OES) [7] and Hα laser absorption spectroscopy (Hα LAS) [8]. The H^o temperatures in the cases of OES and Hα LAS are 0.5 – 1.0 eV and 0.3 eV, respectively. In the HR-OES, Hα can emit from neutralized hydrogen positive ions via following two reactions;

$$H_2^+ + e \rightarrow H(n=3) + H(n=1)$$

$$H^+ + H^- \rightarrow H(n=3) + H(n=1)$$

Here *n* indicates principal quantum number.
The Doppler shift changes with bias voltage, indeed. The largest difference of HR-OES and Hα LAS is direction of the sights, and it is necessary to flip their sights to confirm the difference.

Temperatures and flows of charged particles are measured with a 4-pin Langmuir probe shown in Fig. 3(a). The probe is movable in three direction of *x*, *y* and *z*, and rotatable around the probe axis parallel to the *x* direction. The probe tips are irradiated with Nd:YAG laser to apply photo-detachment technique [9] for the measurement of H^- density. Flow directions of positive ions are shown in Fig. 3(b) at three different distance of the measurement. Flow directions of electron are almost parallel to the ion flows due to ambipolar diffusion. Those flows of H^- are illustrated in (c) of the same figure. The H^- flows direct parallel to the magnetic field lines and to the opposite directions of the positive ion and electron. Considering the source regions of positive ion and electron defused on right hand side in the figure and H^- production on the surface of PG, the experimental result is consistent. The H^- flow velocity and temperatures are listed in Table 1. According to the experimental results, H^- temperature is about 0.1 eV, which is confirmed

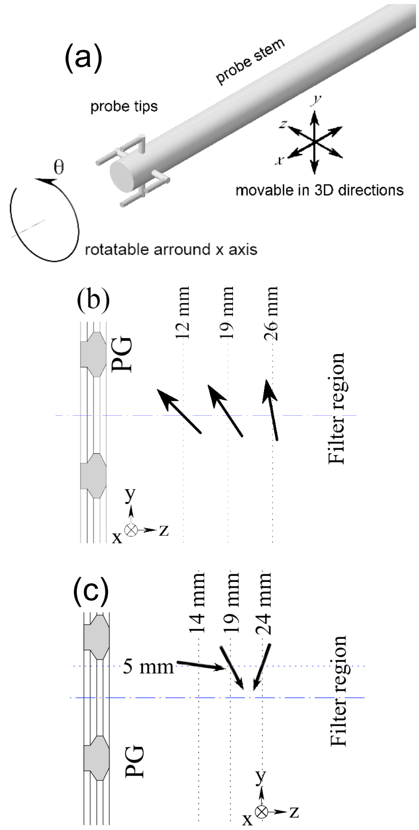

Fig. 3. (a) Structure of 4-pin Langmuir probe, (b) flow directions of positive ions at z of 12, 19 and 26 mm, and (c) that of H- flow direction at z of 14, 19 and 24 mm.

with saturated CRD measurement [10], and flow speed is 0.1 to 0.5 times of thermal velocity of H^-. This shows cold H- rich plasma is produced in the extaction region.

TABLE 1. H^- temperature (T_{H^-}) and flow velocities in y (v_y) and z directions (v_z).

	z=14 [mm]	z=19 [mm]	z=26 [mm]
Temperature	0.13 eV	0.10 eV	0.12 eV
v_y	-69 m/sec	-308 m/sec	-378 m/sec
v_z	477 m/sec	152 m/sec	-137 m/sec

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