A recombining plasma is obtained in the case with a high electron density and a low electron temperature. Investigations of recombining plasmas are important in the nuclear fusion research since they are closely related to ‘plasma detachment’, which is considered to be a hopeful operation scenario of a nuclear fusion machine to avoid the excess heat flux to the divertor plate. We believe that recombining plasmas are also useful in plasma-aided material processing technologies because of their extremely low electron temperature.

In recombining plasmas, electronic excited states of atoms are produced not by electron impact excitation but by three-body recombination between electrons and ions. In this case, highly excited states (Rydberg states) are populated significantly, and the optical emission spectra are considerably different from those of usual ionizing plasmas. As is well known (and as will be shown below), in the case of a recombining hydrogen plasma, the optical emission spectrum is occupied by many lines corresponding to the Balmer series of atomic hydrogen at Rydberg states. In contrast, the optical emission spectrum from molecular hydrogen in a recombining plasma is seldom investigated. In this work, we measured the optical emission spectrum from molecular hydrogen in a recombining hydrogen plasma.

We used a linear machine with a uniform magnetic field along the cylindrical axis. An rf power source at 13.56 MHz was connected to a helical antenna wound around a glass tube with an inner diameter of 1.6 cm. The glass tube was attached to a vacuum chamber, which was evaluated using a turbomolecular pump. We used pure hydrogen gas for the discharge in this experiment. A high-density plasma was produced in the glass tube by the helicon mode, which was obtained at an rf power higher than 1.5 kW. By adjusting the gas pressure to be higher than 56 mTorr, we observed a recombining hydrogen plasma (a blue hydrogen plasma) in the downstream chamber. If the rf power was lower than 1.5 kW, the source was operated below the mode-jump threshold.
resulting in a low-density plasma. We used a spectrograph having a focal length of 50 cm for optical emission spectroscopy.

Figure 1(a) shows an optical emission spectrum observed from a recombining plasma, which was produced at an rf power of 2.5 kW and a gas pressure of 63 mTorr. The many lines shown in Fig. 1(a) are assigned as the Balmer series of atomic hydrogen. We detected optical emission intensities from Rydberg states having principal quantum numbers up to 18. The high populations of the Rydberg states indicate that electronic excited states of atomic hydrogen in this plasma are mainly produced by three-body recombination, and the plasma is surely a recombining plasma. After calibrating the absolute sensitivity of the spectrograph, we obtained a Saha-Boltzmann plot as shown in Fig. 1(b). The linearly-aligned data points indicate that the plasma is at the local thermal equilibrium state, and the electron density and the electron temperature were evaluated to be 3.2x10^{12} cm^{-3} and 0.1 eV, respectively, from the Saha-Boltzmann plot.

We shifted the grating of the spectrograph to the wavelength range corresponding to the Fulcher band of molecular hydrogen. Figure 2 shows an optical emission spectrum observed at an rf power of 1 kW (the low density mode). In this case, we observed a pink plasma, and it is sure that the plasma is a usual ionizing plasma. The electron temperature of this ionizing plasma is estimated to be 4 eV. The several lines shown in Fig. 2 are completely assigned as the transitions of the Fulcher band. The spectrum shown in Fig. 2 is rather normal one, and is frequently observed by many authors.

Figure 3 shows an optical emission spectrum observed from the same plasma as that shown in Fig. 1. It is clearly understood that spectrum shown in Fig. 3 is completely different from that shown in Fig. 2. A part of the many lines shown in Fig. 3 are assigned as the transition of the Fulcher band, but the intensities of the Fulcher-band lines shown in Fig. 3 were weaker than those shown in Fig. 2. In other words, the intensities of the Fulcher-band lines in the ionizing plasma at 1 kW were stronger than those in the recombining plasma at 2.5 kW. The other many lines included in Fig. 3 were assigned as the transitions of triplet and singlet bands of molecular hydrogen. It should be emphasized that the lines other than the Fulcher-band ones are never observed in ionizing plasmas.

From the fact that only the Fulcher-band lines are observed in ionizing plasmas, it is speculated that electron impact excitation from ground-state molecular hydrogen occurs to the d^3Π_u state selectively. This speculation is supported qualitatively by the analysis of the potential curve of molecular hydrogen. The unique spectrum shown in Fig. 3 is understood that there are no selective production processes of electronic excited states in recombining plasmas since they are mainly produced by recombination. The detailed investigation of the recombination processes for producing the electronic excited states of molecular hydrogen is an important research subject in the future.

![Fig. 2](image1.png)  ![Fig. 3](image2.png)

**Fig. 2** Optical emission spectrum observed from an ionizing hydrogen plasma.  
**Fig. 3** Optical emission spectrum observed from a recombining hydrogen plasma.