First Observation of RF-Induced Visible Light Fluctuations

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(Received 30 March 2007 / Accepted 23 April 2007)

In order to detect rf modulation of visible light emitted from plasma, a high-speed photodiode measurement system was developed. The system is located outside the vacuum vessel of the TST-2 spherical tokamak and measures visible light emissions through a quartz window. A dedicated amplifier for the photodiode was made. Care was taken to reduce the rf pickup noise. The frequency spectrum of the light signal detected during high harmonic fast wave (HHFW) heating showed modulation by HHFW. This is the first measurement of visible light modulation induced by HHFW, and shows promise for measurement of the rf electric field in the plasma core.

Keywords: high harmonic fast wave, photodiode, density fluctuation, visible light modulation, spherical tokamak, TST-2

DOI: 10.1585/pfr.2.023

In spherical tokamaks, which can produce stable high-beta plasmas, the establishment of electron heating and current drive methods is important. One candidate for such a method is the high harmonic fast wave (HHFW). However, in HHFW heating, parametric decay instability can occur and deteriorate the power absorption efficiency [1]. Furthermore, multiple scattering by drift wave-type density fluctuations can occur and change the deposition profile [2]. These phenomena can be measured by rf pickup probes and electrostatic probes. In high temperature plasmas, however, such probes should be installed outside the plasma, and therefore they cannot measure the electric wave field inside the plasma. The oscillating rf electric field induces a radial $\boldsymbol{E} \times \boldsymbol{B}$ drift, and a density oscillation appears when the density has a radial gradient. Thus, radiation from the plasma, which is a function of density, is expected to reflect the density oscillation induced by HHFW. In the present paper, detection of the rf (21 MHz) modulation of visible light by high-speed photodiodes is proposed, and the results of the developed system are reported.

Here we describe a measurement system which consists of a photodiode, an amplifier, an rf amplifier, and a digitizer. The rise time of the photodiode should be short enough to measure the rf-modulated visible light emission. Furthermore, the capacitance of the photodiode should be small in order to prevent gain peaking in the signal amplification process. In this study, a silicon photodiode AXUVHS5 manufactured by International Radiation Detectors, Inc. was used. The photodiode's sensitive area, rise time, and capacitance are 1 mm^2, 700 ps, and 40 pF, respectively. In TST-2 (Tokyo Spherical Tokamak - 2) plasmas, the detected photoelectric current is estimated to be a few micro-amperes. For amplification of the modulated radiation, an operational amplifier with low bias current and fast response is required. In the present study, an OPA355 manufactured by Texas Instruments, Inc. with 3 pA of bias current and 200 MHz of gain bandwidth was used. The circuit diagram of the photodiode and the amplifier is shown in Fig. 1. In this amplifier, the photoelectric current is converted to a voltage signal by a resistor and the voltage signal is amplified by the OPA355. The photodiode and the dedicated amplifier were contained in an rf-shielded box

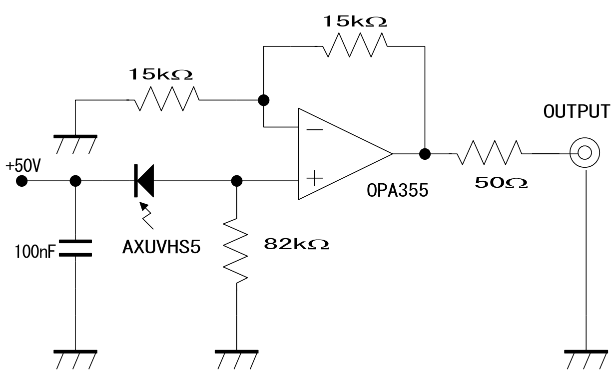

Fig. 1 Circuit diagram of the high-speed photodiode and the amplifier. The photoelectric current is converted to a voltage signal by a resistor. The voltage signal is amplified by an OPA355.

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and several measures for preventing rf pickup noise were taken, which reduced the noise by 40 dB compared with the first system which did not include any noise reduction efforts.

For verification of the fast response of the photodiode and the dedicated amplifier, a light pulse from a YAG laser was measured. The signal rose in 10 ns, confirming the fast response of the photodiode measurement system.

The output signal from the amplifier during a discharge is composed of large low frequency components and small rf components, which makes extracting the rf component from the acquired signal difficult. A commercially produced rf amplifier (28 dB gain and 0.01 to 500 MHz frequency range) was connected after the amplifier, and the output was fed to a fast oscilloscope and was digitized at a sampling rate of 1 Gsamples/sec.

The TST-2 is a spherical tokamak device [3] with a major radius, minor radius, aspect ratio, and toroidal field strength at the magnetic axis of 0.38 m, 0.25 m, 1.5, and 0.14 T, respectively. This device can routinely produce plasmas with an electron density of 10^{19} m^{-3} and a toroidal plasma current of around 80 kA.

For preventing rf pickup noise from the HHFW heating system, the photodiode system was installed outside a quartz vacuum window on the outboard side of the torus. The emitted light was detected after passing through a window. Wavelengths in the range of 200-1100 nm were determined by the transmissivity of the window on the short wavelength side, and by the sensitive range of the photodiode on the long wavelength side.

The rf power for HHFW heating is generated by two generators, and is transmitted to two loop antennas inside the TST-2 vacuum vessel through coaxial transmission lines with DC breaks and capacitive tuners. The frequency is 21 MHz, and the maximum output power per generator was 200 kW. The dominant toroidal mode number is about 10 when the two antennas are driven out of phase.

Plasma was produced by 1.4 kW of 2.45 GHz electron cyclotron heating and 300 kW of Ohmic heating power. For the discharges used in this experiment, the maximum plasma current was 60 kA and the electron density was $\sim 0.5 \times 10^{19}$ m^{-3}. When the plasma current reached the maximum level, 150 kW of HHFW was injected for 1 ms. The signal of the high speed photodiode measurement system showed qualitatively a time evolution similar to that of the Hα line emission.

A typical power spectrum near the HHFW frequency is plotted in Fig. 2 by the thick curve. This spectrum contains not only the rf-induced modulated signal but also rf pickup noise. This noise can be evaluated by preventing light from entering the detector system by use of a blackout curtain. Such a spectrum taken during HHFW injection is shown in Fig. 2 by the thin curve. The difference between the two spectra is due to light emission from the plasma, and it can be attributed to rf effects in the plasma. While the latter has a sharp peak at 21 MHz, the former

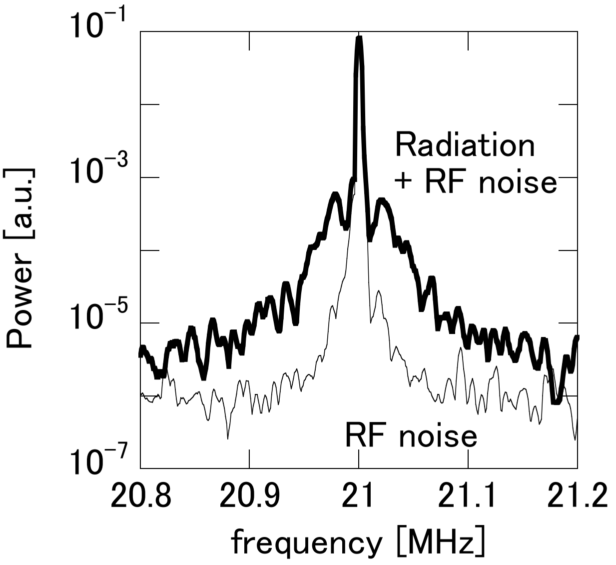

Fig. 2 Frequency spectra of signals detected by the high speed photodiode detector. The sum of the modulated visible light signal and rf pickup noise is plotted by the thick curve, and rf pickup noise is plotted by the thin curve. The difference between the two spectra is due to light emission from the plasma.

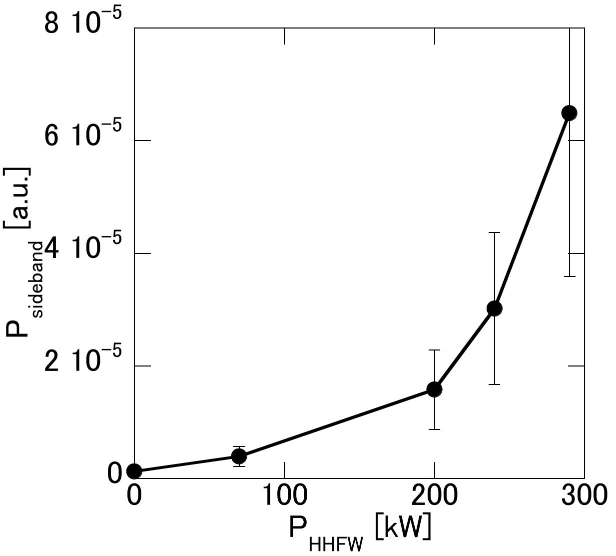

Fig. 3 Dependence of the lower sideband power on injected HHFW power.

shows a broadening of 21.00 ± 0.02 MHz which was not observed by rf pickup probes. The power at the injected frequency of 21.00 MHz varied shot by shot. Statistically, the power with light was larger than that without light (i.e., a noise component) by 50 %, which corresponds to the signal. The ratio of the 21.00 MHz signal component to the stationary component before rf injection is of the order of 0.01 %. The sidebands at 21.00 ± 0.02 MHz cause amplitude modulation at 20 kHz. Perturbations of the magnetic field at around the same frequency were observed using magnetic probes. It is noted that the amplitudes of the sidebands increased with HHFW injection power nonlinearly as shown in Fig. 3. The threshold power was not found. On the other hand, the frequency components of parametric instability around 21 ± 1.7 MHz, which have been observed by rf pickup coils and a microwave reflectometer in similar discharges [4], were not observed by the photodiode system.

In summary, for the purpose of measuring rf-induced density oscillation, a high speed photodiode measurement system was developed and installed on the TST-2. During HHFW injection, the rf components were successfully identified. This result shows promise for the application of fast visible light detection to the measurement of rf electric fields in the plasma core.

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