Mo 08 Comparison of photometry measurement and numerical analysis for plasma density oscillation with doubled value of RF frequency in J-PARC RF ion source

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Abstract

Balmer alpha line intensity in J-PARC Radio Frequency (RF) negative hydrogen ion source has been measured by photometry measurement. The line intensity shows several interesting time characteristics in different phases; (1) 2 MHz (RF frequency) oscillation just after plasma ignition and (2) 4 MHz (doubled RF frequency) and 2MHz coupled oscillation in the steady-state. From the comparison between numerical analysis, it has been explained that electron acceleration in inductively coupled electromagnetic field takes place with 4 MHz frequency which results in the 4 MHz line intensity oscillation. From the understandings of the background physics, we can conclude that this fast photometry measurement is a good diagnosis tool to understand whether RF plasma is in E-mode or H-mode in general RF ion sources.

J-PARC RF ion source

The RFIS has cylindrical source chamber surrounded by 18 cusp magnets on sidewalls and 4 cusp magnets on the back-plate. A pair of rod-filter magnets is installed 16 mm distance from extraction aperture in order to prevent electrons temperature and density near the aperture. A three turns of RF antenna coil is inserted to the source chamber for power injection. Hydrogen gas (H_2) injection line and cesium (Cs) injector are also located on the back-plate. As an optical viewing port for Balmer line photometry in this study, we used same port for spectrometer in Fig.1. The optical port is located in angle of 16.46 degree from the ion source axis so that the line of sight pass through inner region of the RF antenna. More detailed explanation of J-PARC RFIS is summarized in Ref. [3].

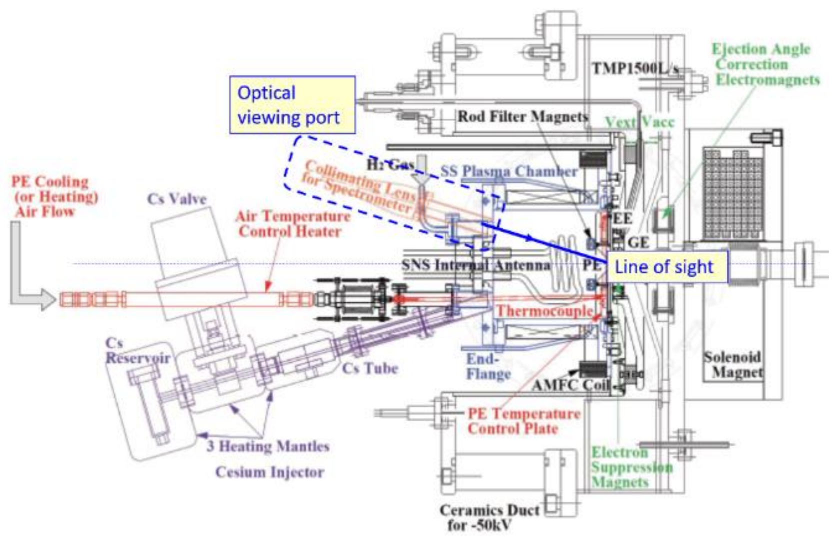

FIG. 1. Schematic drawing of J-PARC RFIS and optical viewing port.

Photometry measurement of Balmer line

In the present measurement, PMT (Hamamatsu; H10722-01MOD) is connected to the optical port via optical fiber as shown in Fig.2. A band pass filter for 656±5 nm is inserted just in front of PMT to observe Balmer alpha lines. Frequency range of trans. impedance amplifier is selected up to DC – 8 MHz for obtaining enough time resolution on line intensity measurement in J-PARC RFIS. Concept of the line intensity measurement is in reference to Ref. [4,5].

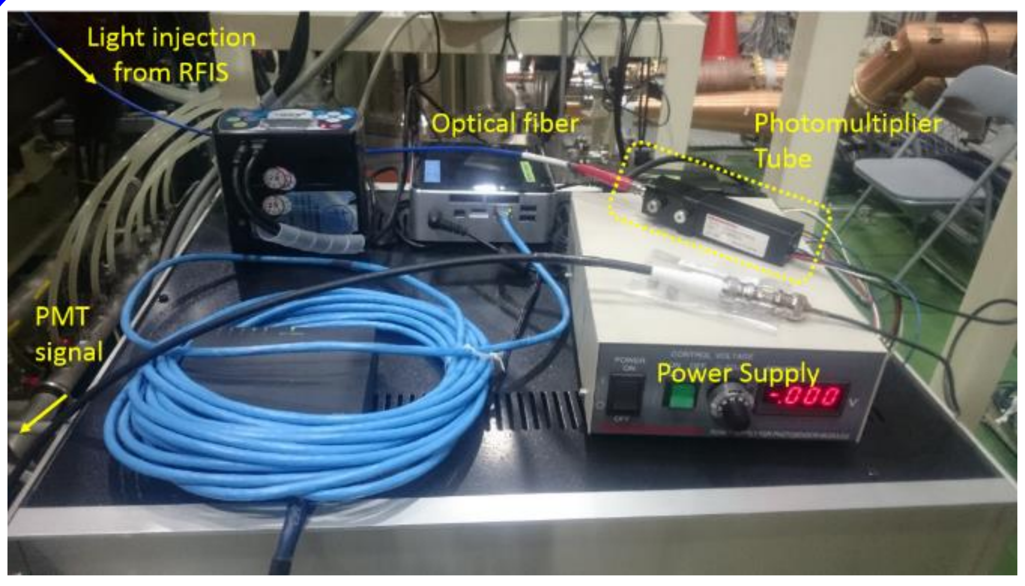

FIG.2 Balmer line photometry measurement system.

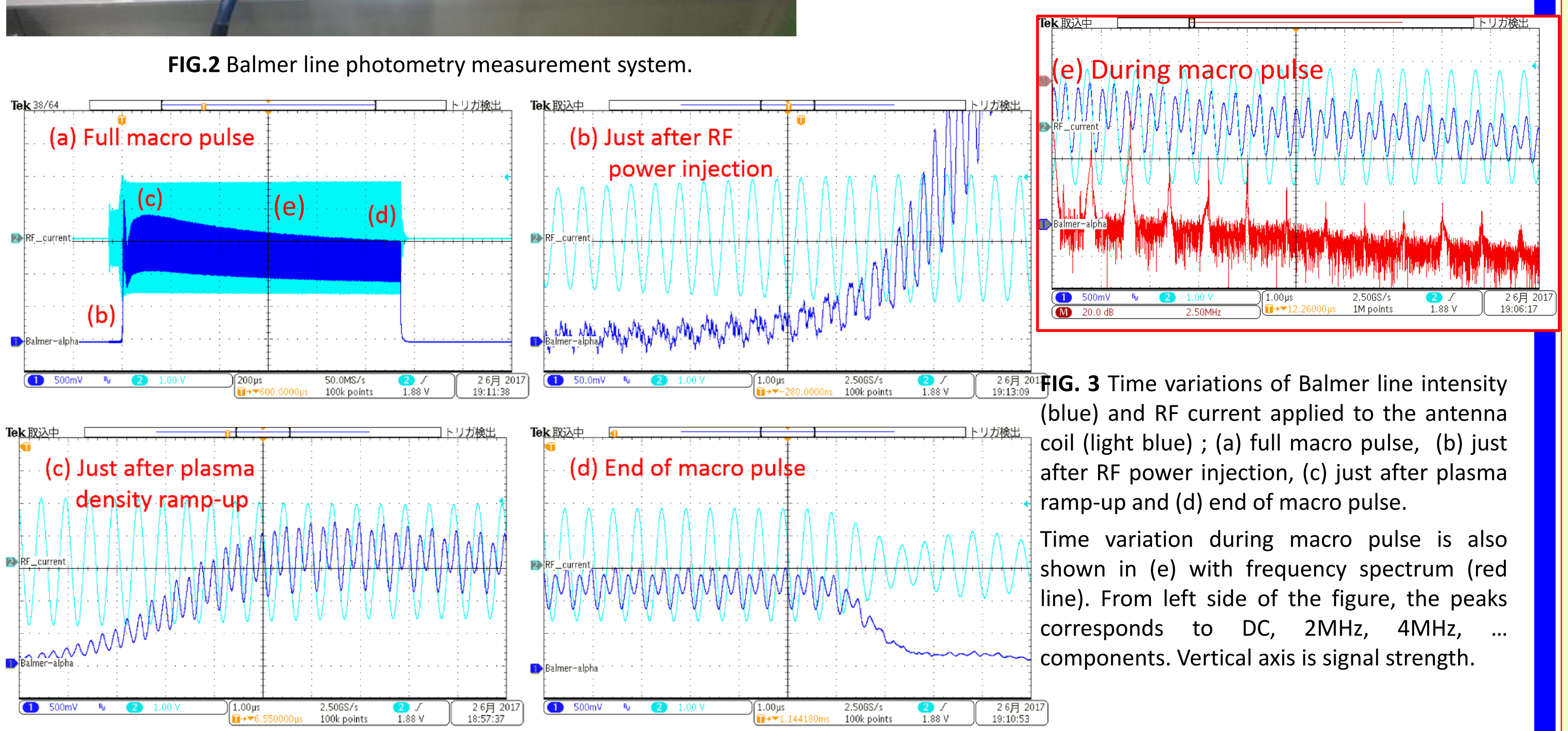

FIG. 3 Time variations of Balmer line intensity (blue) and RF current applied to the antenna coil (light blue) ; (a) full macro pulse, (b) just after RF power injection, (c) just after plasma ramp-up and (d) end of macro pulse.

Time variation during macro pulse is also shown in (e) with frequency spectrum (red line). From left side of the figure, the peaks corresponds to DC, 2MHz, 4MHz, … components. Vertical axis is signal strength.

Frequency of Balmer line oscillation in different RF plasma states

The line intensity signal in phase is relatively lower compared to that in the steady-state by a factor of around 30 which corresponds to ramp-up of plasma density. In the phase just after RF power injection (Fig.3 (b)), frequency of the line intensity oscillation is initially same as that of RF current which oscillates with RF frequency 2 MHz. However, in later half of Fig.3 (b), a peak of 2 MHz line intensity splits and 4 MHz-like intensity oscillation appears. After plasma ramp-up, oscillation of line intensity with a coupling of 2 MHz and 4 MHz frequencies takes place until end of the macro pulse(Fig.3 (c) and (d)).

The frequency of Balmer line time structure is measured by spectrum analyzer (Tektronix RSA5103B Real-Time Signal Analyzer). As shown in FIG. 5, frequency component of 2MHz takes place from plasma ignition phase (count 0 – 400 ; 70 μs after RF power injection) to the steady-state phase (count 2400 ; 120 μs after RF power injection). On the other hand, the doubled RF frequency (4 MHz) component start to increase at the moment plasma ramp-up takes place. In the steady-state plasma, the 4 MHz component signal is around 15 dB (a factor of 5 - 6) higher than that of 2MHz component.

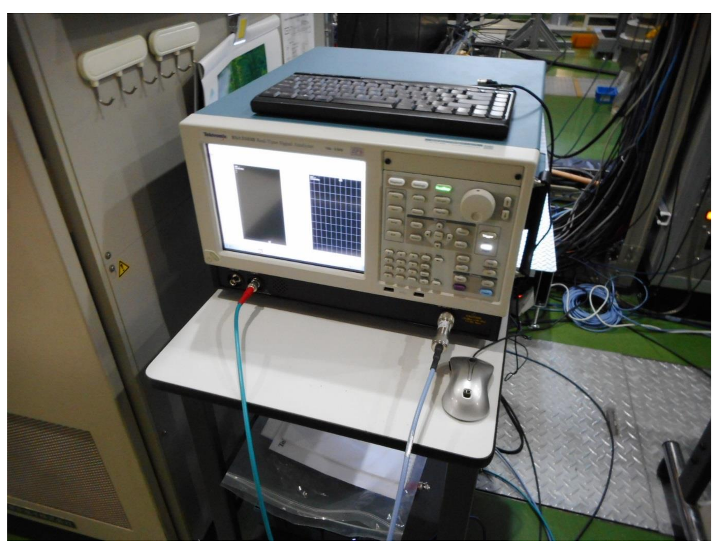

FIG.4 Spectrum analyzer.

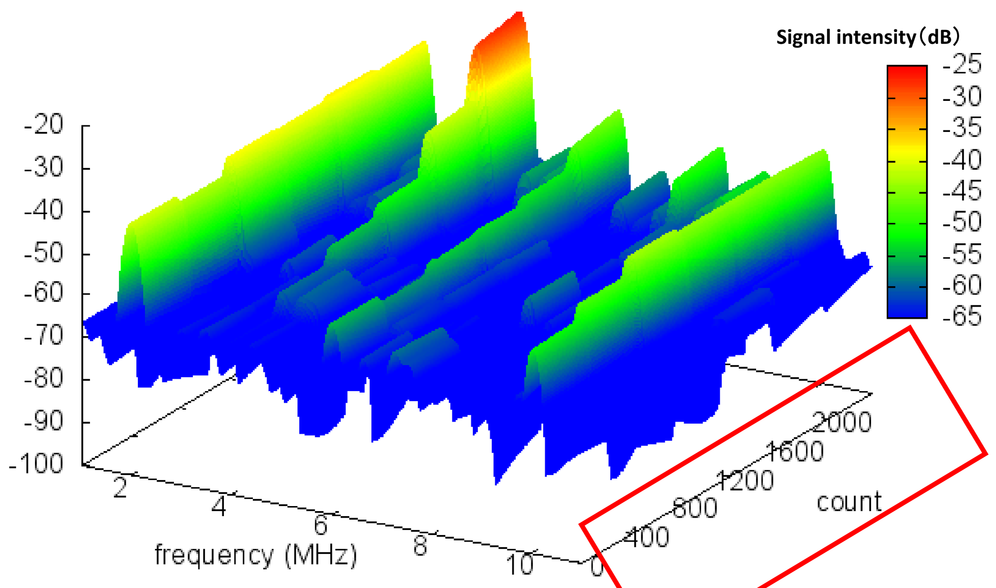

FIG. 5 Balmer line signal strength for 2MHz, 4MHz, 6MHz, 8MHz and 10 MHz frequency spectrum.
(1) 0 – 400 count: 70 μs after RF power injection, (2) 400 – 800 count: 95 μs after RF power injection,
(3) 800 – 1200 count: 110 μs after RF power injection, (4) 1200 – 1600 count: 112 μs after RF power injection,
(5) 1600 – 2000 count: 113 μs after RF power injection, (6) 2000 – 2400 count: 120 μs after RF power injection.
Plasma ramp-up was observed around 112 – 113 μs after RF power injection.

Summary

Time variation of Balmer alpha line intensity in J-PARC RFIS was measured by photometry measurement. The line intensity shows 2 MHz (RF frequency) oscillation just after RF power injection and coupling of 4 MHz (doubled RF frequency) and 2MHz oscillations in the steady-state. From the comparison with numerical analysis, it has been explained that electron acceleration in capacitively coupled (E-mode) RF plasma results in 2 MHz density oscillation and the inductively coupled (H-mode) electromagnetic field produces electron density ramp-up in 4 MHz frequency oscillation. From these comparisons, we can apply this photometry measurement for diagnosis of RFIS to judge whether plasma is in E-mode or H-mode during the long run operation. Also, in R&D of general RF ion sources, this measurement can be a diagnosis to understand directly whether H-mode RF plasma is obtained without extracting beam from IS and with lower R&D cost.

References

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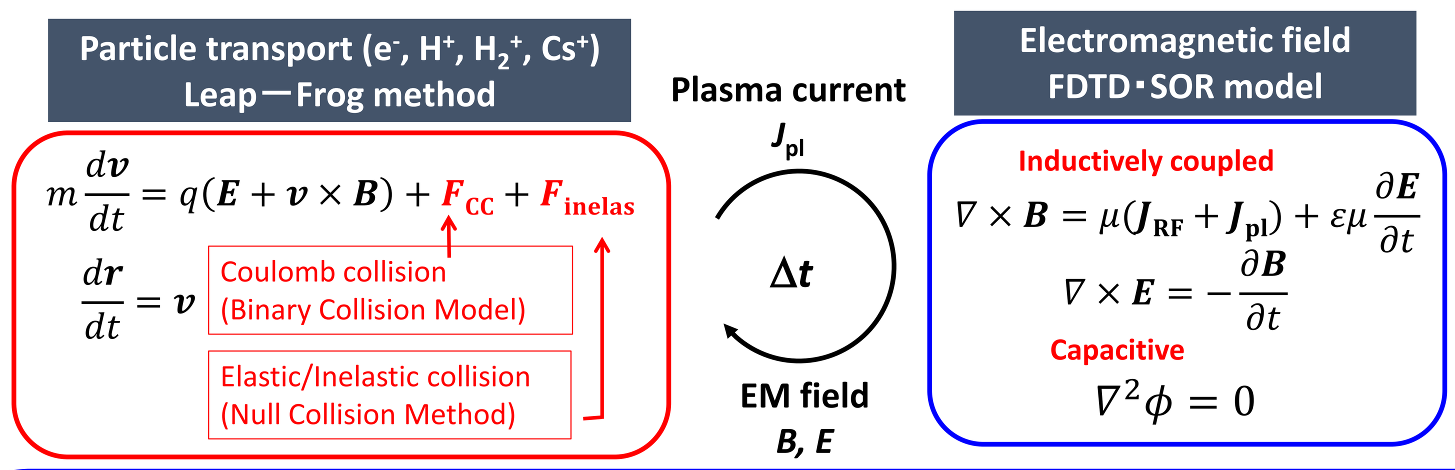
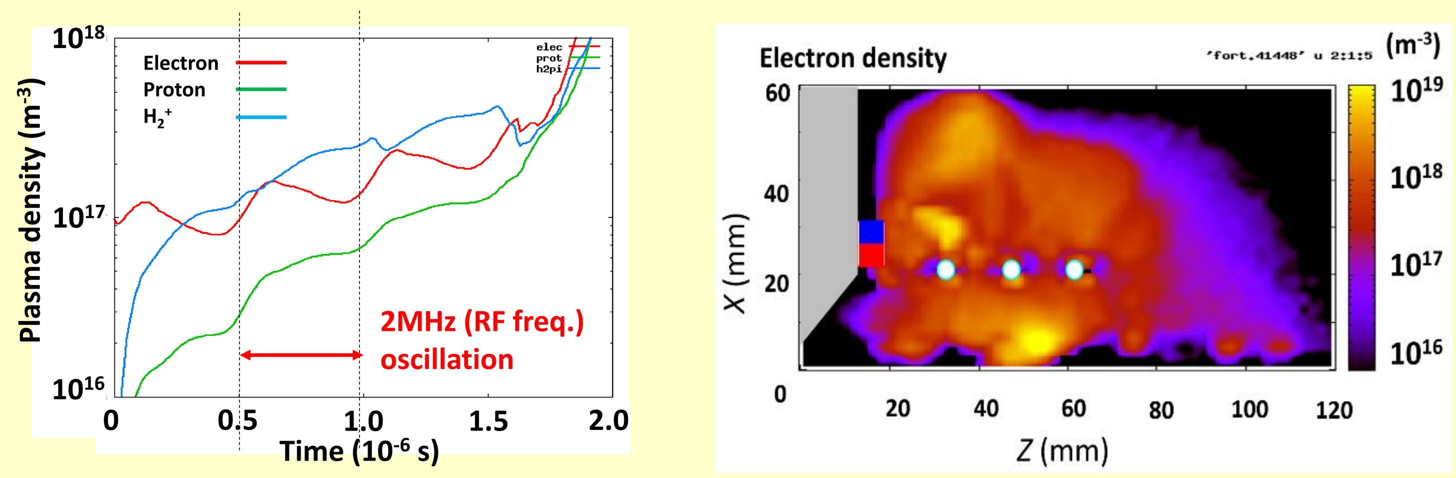
Numerical analysis of RF plasma

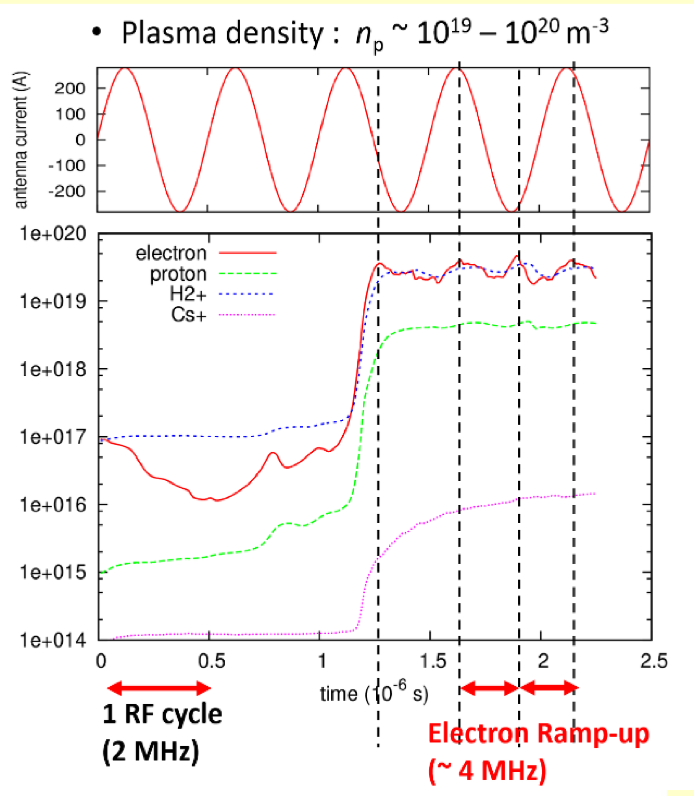
From comparisons between photometry results with numerical results as reported in Ref. [2], it has been explained that 2 MHz single frequency oscillation takes place in the E-mode phase where capacitively coupled electric field is dominant (Fig.4 and 5 in Ref. [2]). On the other hand, 4 MHz plasma oscillation in the steady-state (H-mode) RF plasma is seen in the present experiment (via Balmer line intensity) and in the numerical analysis. The reason explained in the simulation is that inductively coupled electric field accelerates electrons in azimuthal direction twice (+ and - directions) in 1 RF cycle (Fig.6 -8 in Ref. [2]). At these moments, electrons are accelerated and have enough energy for excitation of hydrogen atoms from principle number p = 1 to 3 which leads to the Balmer alpha line emission.



2MHz electron density oscillation in E-mode RF plasma



4MHz electron density oscillation in H-mode steady state RF plasma



Unlike in low density (10^{17} m^{-3}) E-mode phase, electron density shows 4 MHz temporal oscillation in high density (10^{19} m^{-3}) H-mode phase. Electron density (bottom left) and electric field in azimuthal direction (bottom right) at each phases in 1 RF cycle are plotted below. Electron density ramp-up takes place in phase (B) and (D) while strong electric field is produced in phase (A), (C) and (E) since electron acceleration takes place with $\pi/2$ phase difference from electric field oscillation for collisional plasma.