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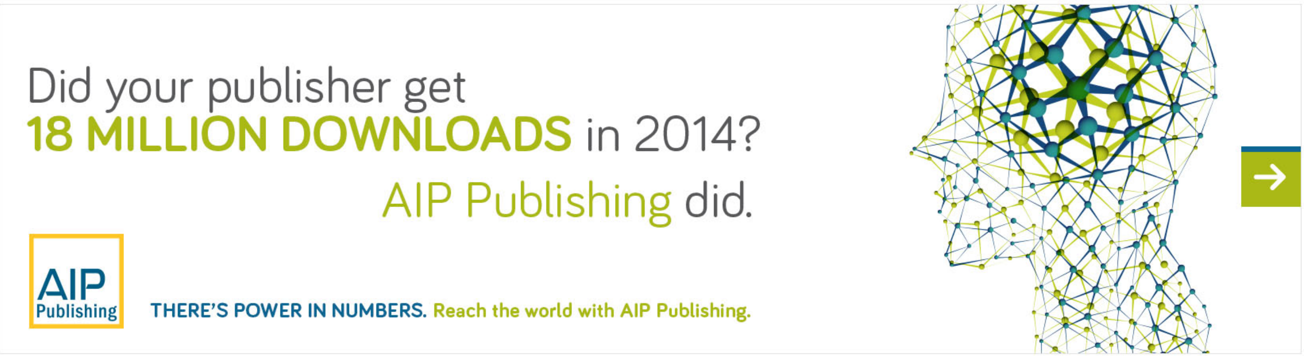

Microwave experiments on Prairie View Rotamak

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A 6 kW/2.45 GHz microwave system has been added on Prairie View Rotamak, and a series of experiments with microwave heating in both O-mode and X-mode configurations have been performed. Effective ionization of hydrogen in the two configurations is observed when filling pressure of the hydrogen gas is under $p_f = 0.1$ Pa. Clear oscillations in plasma current I_p and magnetic field B_R are excited when microwaves are injected into plasma in the X-mode configuration. The higher the injected microwave power, the sooner the emergence of the magnetic oscillations in B_R, which implies the microwave may have decreased the elongation of the plasma. In the experiments, the efficiency of the current drive mechanism due to the injected microwave is about 0.2 kA/kW. © *2015 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4921129]

Rotamak is a compact torus configuration having the feature that the toroidal plasma current is driven by means of an externally applied rotating magnetic field (RMF). This plasma current is kept in equilibrium by an externally applied "vertical" field. If the plasma current is large enough, the "vertical" field is reversed on the symmetry axis, resulting in a typical field-reversed configuration (FRC). When a steady toroidal magnetic field is added, the Rotamak is able to operate as a typical spherical tokamak (ST). The Rotamak scheme retains the basic advantages of the general compact tours concept, such as FRC and ST, with further offering a quasi-static formation scheme and the promise of steady-state operation. For this, and other reasons, the Rotamak has attracted much attention, and significant progress has been made in experimental and theoretical studies.[1–3]

Electromagnetic waves are widely used in fusion plasma experiments to heat plasma via electron cyclotron resonance heating (ECRH) or drive plasma current via electron cyclotron current driving (ECCD).[4,5] However, typical electromagnetic waves in the electron cyclotron range of frequencies (ECRF) are not effective in plasma confinement devices with low magnetic field, low temperature and high density ($\omega_{ce} \ll \omega_{pe}$, where ω_{pe}, ω_{ce} are, respectively, the electron plasma and electron cyclotron frequencies). The plasma is optically thin for the incident microwave and the energy transfer at the fundamental resonance becomes inefficient.[6] A special kind of electron cyclotron wave is the electron Bernstein wave (EBW), which is a short wavelength electrostatic wave in a magnetized plasma. EBW does propagate in this kind of plasma, which has the potential for providing localized, highly efficient heating or current drive.[7,8] The potential of using the EBW for heating such plasmas was recognized in the theoretical work and experiments. The effectiveness of both the obliquely launched ordinary mode (O-mode) and perpendicularly launched extraordinary mode (X-mode) electromagnetic waves has been clearly demonstrated.[9,10]

Microwaves have been used previously on the Rotamak-E II device as a pre-ionization system.[11] Recently, a 6 kW microwave system was added on Prairie View Rotamak to study mainly the ECRH and ECCD effects of microwave on the Rotamak plasma, with $\omega_{ce} < 2\pi f < \omega_{pe}$, where f is the microwave frequency. Electron Bernstein waves are expected to be excited in the Rotamak plasma through electromagnetic wave mode conversion. A series of microwave experiments in both O-mode and X-mode configurations have been performed on Prairie View Rotamak for modes FRC and ST, respectively.

The Prairie View Rotamak is a rebuilt Rotamak based on the disassembled Flinders apparatus,[2] with plasma chamber, diagnostic tools, and control system upgrades. It focuses on the comparison of FRC and ST discharges with regard to the magnitude of driven plasma current, the study of active plasma shape control, and investigation of MHD instabilities and magnetic reconnection. A schematic of the Prairie View Rotamak is shown in Figure 1. The new chamber is a 0.8 m long/0.4 m diameter Pyrex glass vessel. The background vacuum in the chamber is maintained at 1.3×10^{-4} Pa. Working gas, which is Hydrogen, is continuously fed through the chamber at a pressure of $p_f \approx 2.7 \times 10^{-2}$ Pa. The RMF is produced by two pairs of coils, which are connected through a matching/tuning network to two 500 kHz/400 kW rf generators with a 90° phase shift between them.

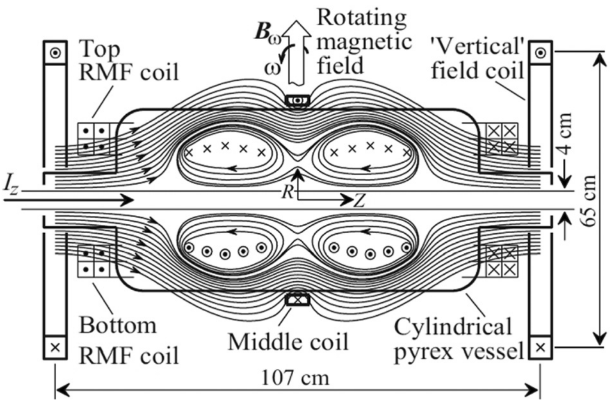


FIG. 1. The schematic of Prairie View Rotamak.

The equilibrium magnetic field system consists of two coils (vertical field coils) with diameter 0.65 m, separated by a distance of 1.07 m. In conducting microwave experiments, the microwave is injected into plasma through an upper right window. The setup of the microwave system in O-mode and X-mode configurations is shown in Figures 2(a) and 2(b), respectively.

The microwave generator is a complete self-contained microwave source. It is rated at a maximum 6 kW continuous power output and operates at the frequency 2.45 GHz ± 15 MHz. The generator uses a water-cooled magnetron to generate the microwave power from 1.5 kW to 6 kW. A 3-port circulator with water load protects the magnetron in the high-reflected power periods. Also, photoelectric arc detection is used to protect magnetron and waveguides.

A set of rectangular waveguides are used to transfer microwave to the plasma. In the waveguide system, two flexible waveguides with maximal insertion loss of 0.02 dB are used to couple with other waveguides. One E-bend corner-cut waveguide and one straight waveguide are used with maximal insertion loss of 0.20 dB. In addition, one 3-stub waveguide tuner is used for matching the plasma impedance. The total insertion loss of this waveguide system should be less than 6%. A vacuum sealed ceramics placed between the waveguides and the plasma chamber is used to enable high microwave power transmission and keep the high vacuum level in the Rotamak chamber. Copper meshes are used around the Rotamak chamber to prevent microwave from leaving the plasma chamber. The size of each mesh is about 0.2 m × 0.2 m and a thickness of about 0.5 mm, and the distance between any two meshes is less than 50 mm. Each mesh is composed of a grid of about 1.5 mm spacing, much smaller than the microwave wavelength ($\lambda_{2.45\text{GHz}} \approx 122$ mm). Connecting the meshes to each other would adversely affect the coupling between RMF and the plasma. In the experiments, the copper meshes are separated from each other to reduce this effect.

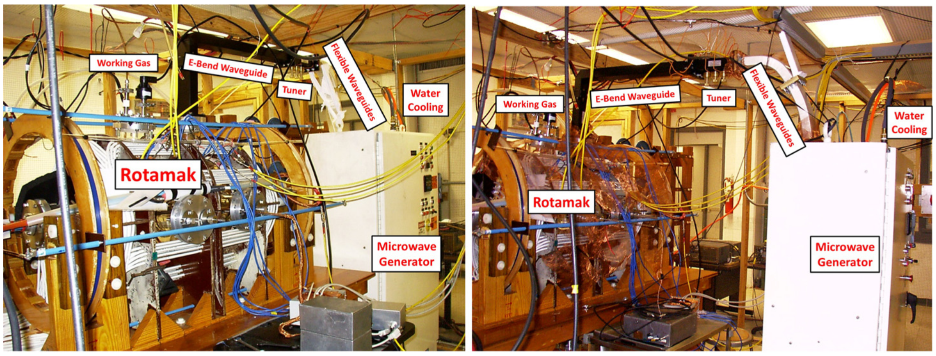
The dominant mode of the waveguide is TE_{10}. By adjusting the 3-stub tuner, the reflected microwave power can be decreased to 10% during the microwave experiments. Our experiments have been operated for both the O-mode and X-mode configuration. In the experiments, the plasma current is measured with a Rogowski coil, while the plasma temperature and density are measured with a double floating Langmuir probe. An array of 32 Mirnov coils installed on the outside chamber surface is used to observe magnetic instabilities during the experiments.

A series of microwave experiments in both O-mode and X-mode configurations have been performed on Prairie View Rotamak. In the O-mode configuration, effective ionization of hydrogen has been observed when the filling pressure of the hydrogen gas is under $p_f = 0.1$ Pa. However, we cannot drive plasma current by RMF when the filling pressure of the hydrogen gas is under $p_f = 0.1$ Pa. Apart ionization, the plasma does not seem to respond to the injected 2.45 GHz microwaves in the O-mode configuration.

The density of the Rotamak plasma is high. The cut-off density of the X-mode is higher than the O-mode, thus the X-mode can be absorbed more effectively in the Prairie View Rotamak. Concerning power absorption of the X-mode microwave in the experiments, two scenarios are possible: direct absorption of X-mode microwave or direct coupling of the X-mode to the EBW and subsequent absorption of the EBW. In the X-mode configuration, effective ionization of hydrogen can also be observed when the filling pressure of the hydrogen gas is under $p_f = 0.1$ Pa. Also, clear oscillations of the plasma current I_p and magnetic field B_R are excited when the microwaves are injected into the plasma in the X-mode configuration. Figure 3 shows four typical discharges with injected microwave power $P_{MW} = 0$, 1, 2, and 3 kW, respectively. These four shots are performed with the same discharge parameters except for the injected microwave power. Because the microwave power is relatively low compared to the typical power of the RMF generators, no obvious change in the plasma temperature and density is observed in the experiments. But clear oscillations of the plasma current I_p and magnetic field B_R are excited when microwaves are injected into the plasma.

Shot 1 is a reference discharge without input microwave power. The plasma current is about $I_p \approx 1.3$ kA, with plasma density $n_e \approx 5 \times 10^{17}$ m^{-3} and temperature $T_e \approx 11.5$ eV. There are no obvious magnetic instabilities in this discharge condition. When microwaves are injected into plasma, clear oscillations in plasma current I_p and magnetic field B_R are excited, which can be seen in shots 2, 3, and 4.

Microwaves are injected into plasma during the entire discharge period, and oscillations in plasma current exist during the entire discharge period. The time-frequency spectra of the oscillations from plasma current signal in shot 1 and shot 2 are shown in Figures 4(a) and 4(b), respectively.



(a) (b)

FIG. 2. Setup of the microwave system in (a) O-mode and (b) X-mode configurations.

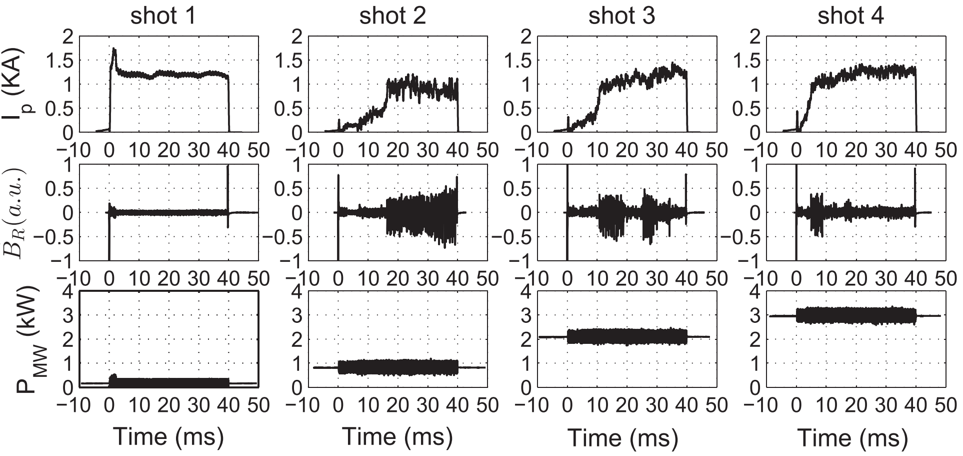


FIG. 3. Four typical discharges with injected microwave power $P_{MW} = 0\,\text{kW}$ in shot 1, $P_{MW} = 1\,\text{kW}$ in shot 2, $P_{MW} = 2\,\text{kW}$ in shot 3, and $P_{MW} = 3\,\text{kW}$ in shot 4.

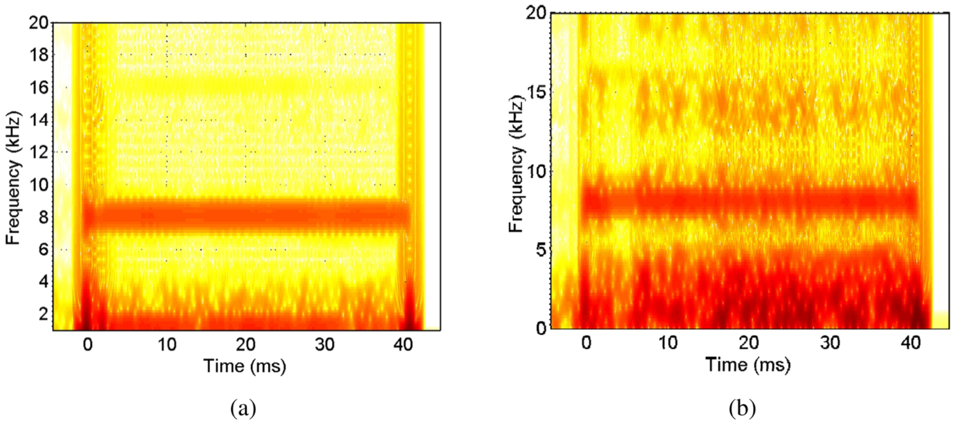
In the figures, the observed oscillation at 8 kHz is noise, which comes from the vertical field's power supply system. This noise can also be observed during shot 1. In comparison with shot 1 when no microwaves are injected into plasma, oscillations with a wide frequency range of 0–5 kHz can be observed when microwaves are injected into plasma. This implies that the oscillations in plasma current resulted from the injected microwaves.

Figure 5 shows the time evolution of I_p and B_R, along with the B_R spectra from the Mirnov coils during shot 2. Oscillations in magnetic field B_R have much wider frequency range below 20 kHz and only emerged after a few milliseconds during the discharges. The higher the injected microwave power, the sooner the emergence of the magnetic oscillations in B_R. Those magnetic oscillations are identified as n = 1 radial shift mode (the phase shift between two sets of Mirnov coils is π). According to theory, the radial shift mode is expected to become unstable at sufficiently small elongation $E < 0.7$ ($E = Z_S/R_S$, with Z_S and R_S the separatrix half-length in the axial direction and separatrix radius, respectively).[12] This implies that the injected microwave may have decreased the elongation of the plasma. When the microwave power is higher, it can decrease the elongation of the plasma sooner to the threshold value. Then the radial shift mode emerges. Usually excitation of radial shift mode results in plasma disruption within 1 ms.[13] But as seen from Figure 3, it is difficult to build a flat plasma current at the beginning of those discharges until the emergence of the magnetic oscillations in B_R. So, it implies the excitation of radial shift mode seems to favor the building of the flat plasma current in our microwave experiments. We will further study this phenomenon in our future work.

Comparing the flat top phase of plasma current in shots 2, 3, and 4, it shows plasma current $I_p \approx 0.9$, 1.1, and 1.3 kA when injected microwave power $P_{MW} \approx 1$, 2, and 3 kW, respectively. The plasma current in flat top phase is higher when the injected microwave power is larger. It seems the microwave system is operating as a plasma current driving mechanism rather than a plasma heating mechanism. The efficiency of current driving of the microwave system is about 0.2 kA/kW in our experiments.

In summary, a microwave power injection system has been added on Prairie View Rotamak. The water-cooled microwave generator is rated at a maximum 6 kW continuous power output and operates at a frequency of 2.45 GHz. The total insertion loss of the waveguide system is less than 6%. By adjusting a 3-stub tuner, the reflected microwave power can be decreased to 10% with copper meshes surrounding the Rotamak chamber. Depending on the direction of the waveguide system with respect to the Rotamak's vertical field, the microwave can be launched into the plasma in O-mode or X-mode configuration.

A series of microwave experiments have been performed in both O-mode and X-mode configurations. Effective ionization of hydrogen is observed when the filling pressure of the hydrogen gas is under $p_f = 0.1$ Pa in both O-mode and X-mode configurations. Oscillations in plasma current I_p and magnetic field B_R are excited when the



(a) (b)

FIG. 4. Time-frequency spectra of the oscillations from plasma current signal in shot 1 (a), and shot 2 (b).

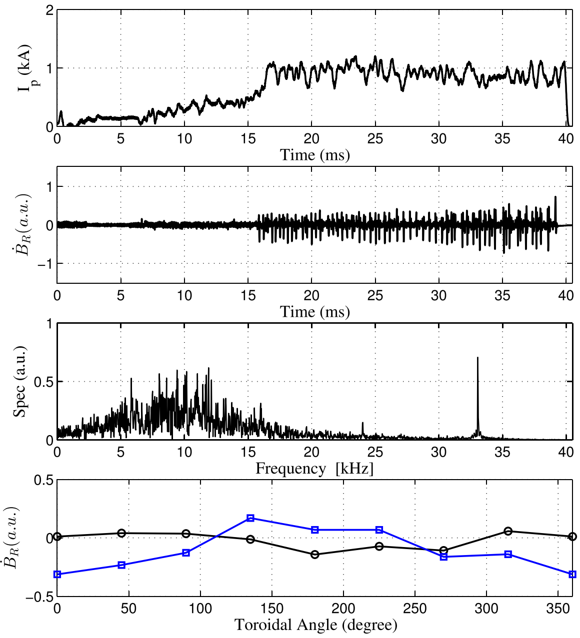


FIG. 5. Time evolution of I_p, B_R, spectra for B_R, and signals from two sets of Mirnov coils during shot 2.

microwave is injected into plasma in the X-mode configuration. The excited magnetic oscillations are identified as the n = 1 radial shift mode. The higher the injected microwave power, the sooner the emergence of the magnetic oscillations in B_R, which implies that the microwaves may have decreased the elongation of the plasma. The efficiency of the current drive mechanism due to the injected microwave is about 0.2 kA/kW in the microwave experiments.

In further work, an upgraded microwave generator with higher power will be considered to get larger plasma temperature increase.

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[1] I. R. Jones and W. N. Hugrass, J. Plasma Phys. **26**, 441 (1981).
[2] I. R. Jones, Phys. Plasmas **6**, 1950 (1999).
[3] T. S. Huang, Y. Petrov, and F. Zhong, Plasma Phys. Controlled Fusion **47**, 1517 (2005).
[4] M. Sato, O. Motojima, S. Sudo, T. Mutoh, H. Zushi, K. Kondo, S. Besshou, H. Kaneko, T. Mizuuchi, and K. Hanatani, Nucl. Fusion **23**, 1333 (1983).
[5] V. Erckmann and U. Gasparino, Plasma Phys. Controlled Fusion **36**, 1869 (1994).
[6] A. Kohn, G. Birkenmeier, E. Holzhauer, M. Ramisch, and U. Stroth, Plasma Phys. Controlled Fusion **52**, 035003 (2010).
[7] C. Forest, P. Chattopadhyay, R. Harvey, and A. Smirnov, Phys. Plasmas **7**, 1352 (2000).
[8] P. Chattopadhyay, J. Anderson, T. Biewer, D. Craig, C. Forest, R. Harvey, and A. Smirnov, Phys. Plasmas **9**, 752 (2002).
[9] H. Sugai, Phys. Rev. Lett. **47**, 1899 (1981).
[10] H. P. Laqua, Plasma Phys. Controlled Fusion **49**, R1 (2007).
[11] M. Kuhnapfel, A. Stampa, R. Tabersky, and H. Tuczek, Plasma Phys. Controlled Fusion **29**, 1501 (1987).
[12] E. Belova, S. Jardin, H. Ji, M. Yamada, and R. Kulsrud, Phys. Plasmas **8**, 1267 (2001).
[13] X. Yang, S. Houshmandyar, O. Dada, E. Reddic, and T. S. Huang, Rev. Sci. Instrum. **83**, 10E304 (2012).