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Suppression of ionization instability in a magnetohydrodynamic plasma by coupling with a radio-frequency electromagnetic field

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We describe the suppression of ionization instability and the control of a magnetohydrodynamic electrical power-generating plasma by coupling with a radio-frequency (rf) electromagnetic field. The rf heating stabilizes the unstable plasma behavior and homogenizes the nonuniform plasma structure, whereby the power-generating performance is significantly improved. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1926410]

Recently, closed-cycle magnetohydrodynamic (CCMHD) energy conversion[1] has been revived and has been the focus of great attention with respect to perceived space needs, such as multimegawatt space power installations.[2,3] The CCMHD electrical power generator has several advantages, that is, virtually no upper limits to the temperature it can tolerate, rapid response, and the ability to achieve high thermal efficiency and power density,[4] which lead to a reduction of the system specific mass. Despite such great advantages, the MHD generator is still subject to unstable nonequilibrium plasma behavior due to ionization instability. Physically, ionization instability occurs when the local increase in the joule heating rate of electrons exceeds the rate at which generated heat can be transferred by collision, radiation, and conduction. The growing ionization instability causes instability and inhomogeneity in the nonequilibrium plasma. Complete plasma stabilization under a wide range of operating conditions could be difficult[5–8] even with full seed ionization; that is, a state in which seeded atoms are fully ionized without the ionization of inert gas atoms, whereby the plasma becomes stable against infinitesimal perturbations.[9]

We have proposed a combined scheme of dynamic plasma stabilization with electromagnetic fields and static plasma stabilization with a fully ionized seed concept. Here, we employ a homogeneous application of an inductively coupled radio-frequency (rf) electromagnetic field in space and time to control the unstable plasma in a disk-shaped Hall MHD generator. The results of feasibility studies by multidimensional numerical simulations[10,11] and shock-tube-driven power-generation experiments[12] have indicated the superiority of the present rf power-assisted technique over previous methods.[13–16] In this Letter, we describe the suppression of the instability and inhomogeneity in the ionization–unstable plasma by coupling with the rf field and the resulting improvement of the power-generating performance.

Figure 1 shows back wall and cross-sectional views of the present disk generator consisting of an upstream supersonic nozzle (from first to second anodes, which are electrically shorted) and a downstream MHD power-generating channel (from the second anode to the cathode, which are loaded by 0.2 Ω).[5] A shock tube supplies a high-enthalpy cesium-seeded helium gas flow of a total pressure of 0.10±0.005 MPa and a total temperature of 2100±50 K. Thermal input to the generator is 3.2±0.2 MW. A Helmholtz magnet supplies a pulsed field (3.0 T; 6-ms duration). Spectroscopic measurements are performed at the radii of 100 mm (upstream window) and 145 mm (downstream window). The electron temperature and the electron and cesium ion number densities are estimated from the cesium ion recombination continuum intensity $\epsilon_{(\lambda)}$, which is divided into a number-density-dependent component and a temperature-dependent component, $\epsilon_{(\lambda)}=n_e n_{Cs^+} f(\lambda, T_e)$, where n_e, n_{Cs^+}, λ, and T_e denote the electron number density, cesium ion number density, wavelength (406.0 and 490.0 nm), and electron temperature, respectively.[6,10,17] A high-speed camera (6000 frames per second with an exposure time of 0.8μ) visualizes

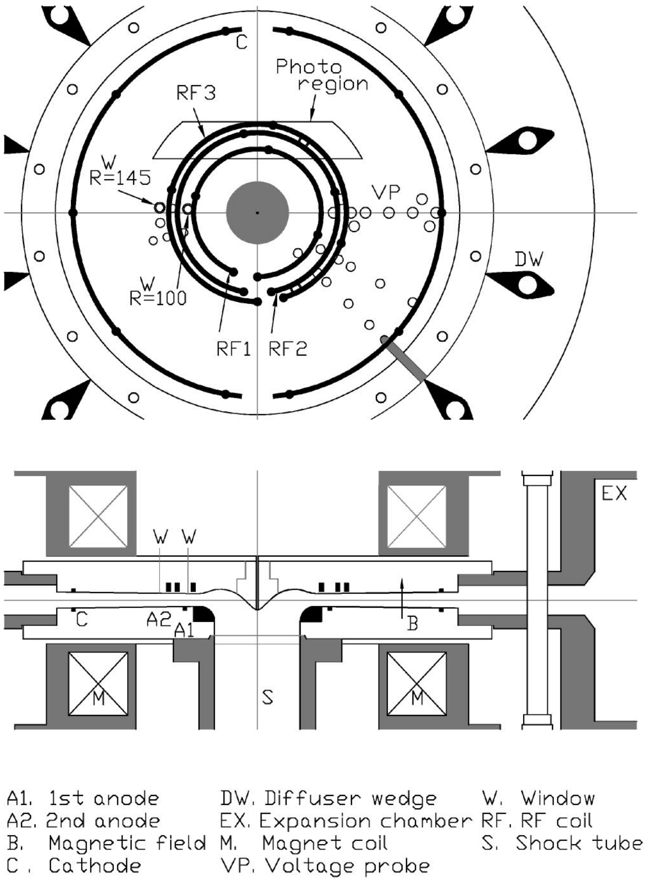

FIG. 1. Back wall and cross-sectional views of disk generator.

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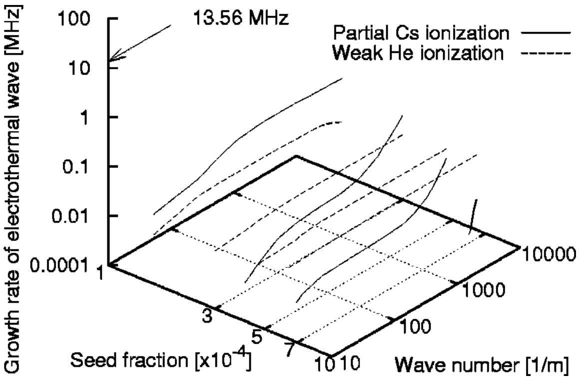

FIG. 2. Rate of electrothermal wave growth due to partial cesium ionization and weak helium ionization for typical wave numbers and seed fractions. The excitation frequency of the rf field, 13.56 MHz, is also indicated.

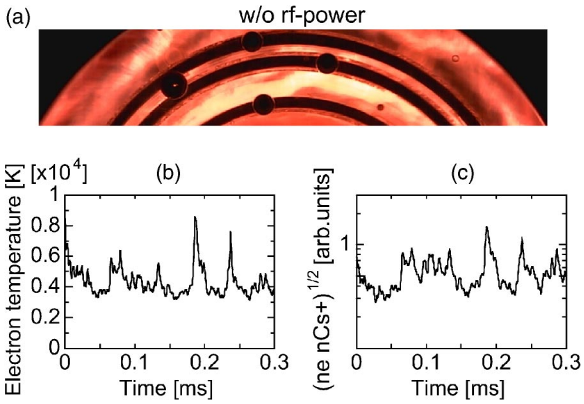

FIG. 3. The rf power is not applied. (a) A photograph of the plasma and time variations of (b) the electron temperature and (c) the function of electron and cesium ion number densities. The seed fraction is 13×10^{-4}.

plasma structures from the back wall. Three rf inductive coupling coils, RF1, RF2, and RF3 (6-mm-wide copper rings), are embedded in the back wall.[12] The rf inductive coupling technique is considered to be one of the best ways to generate and control an azimuthally uniform plasma in the disk generator. The rf electromagnetic field (the excitation frequency is 13.56 MHz and the net power supplied to the plasma is 5.2±0.1 kW) is applied through the outermost coil (RF3). A detailed examination is necessary to quantify a threshold rf power needed to effect the plasma, which is an important aspect for our planned future work.

A linear perturbation analysis[18] is performed to clarify the relationship between the growth rate of ionization instability and the excitation frequency of the present rf field (details of the calculation procedures and conditions are described in Refs. 6 and 18, respectively). Figure 2 shows the growth rates of an electrothermal wave due to partial cesium ionization and weak helium ionization, which is one of the most serious instabilities that deteriorate the generator performance, for representative wave numbers and seed fractions. The dynamic plasma stabilization is effective only when the frequency of the additional oscillation is much greater than the instability growth rate. Figure 2 confirms that the excitation frequency of 13.56 MHz is sufficiently higher than the electrothermal wave growth rates of 1 kHz to 1 MHz. The skin depth is comparable to the height of the generator channel under the present rf field and plasma conditions; therefore, it is negligible. The strength of the rf electric field at the radius of 129 mm (RF3 position) and at the center of the channel height is approximately 180 V/m, which is weaker by one order of magnitude than that of a steady self-excited tangential electric field.

Figure 3 shows (a) a photograph of the plasma, and time variations of (b) the electron temperature and (c) the function of electron and cesium ion number densities $(n_e \cdot n_{Cs^+})^{1/2}$ upstream, which were obtained without the rf power under a seed fraction of 13×10^{-4}. In the case that free electrons are provided only from singly ionized cesium ions, $(n_e \cdot n_{Cs^+})^{1/2}$ is proportional to the electron number density. It is seen from Fig. 3(a) that the plasma is inhomogeneous and is associated with distorted layerlike luminosities. The concentration and distribution of the luminosity is influenced by the temperature and density profile in the plasma. We can observe, in Figs. 3(b) and 3(c), that the density changes in close correlation with the electron temperature. In the fluctuating unstable plasma, the low "background" electron temperature of 3000–3500 K and low background density results in the weak brightness. In these dark regions, the seeded cesium atoms are partially ionized. In contrast, high temperature and density (the peak electron temperatures reach 6000 and 8500 K) lead to the high-luminosity layers. The present ionization instability is originally caused by partial seed ionization due to the low electron temperature. We can identify the electrothermal wave from six wavelike peaks in the temporal temperature and density behavior [Figs. 3(b) and 3(c)]. The measured characteristic frequency of electrothermal wave propagation is 20–25 kHz, which is related to the time-periodic interval required for the high-luminosity wavelengths to pass through the optical window. Since the distance between the neighboring luminous layers is approximately 20 mm, the propagation velocity is estimated to be approximately 400–500 m/s, which is low compared with the gas velocity of approximately 3000 m/s at a local Mach number of 1.

Figure 4 shows the noteworthy effects of rf power assistance on the improvement of the plasma structure and the plasma behavior. Due to the additional rf heating, the plasma is homogenized and the ionization instability is suppressed. The plasma structure becomes symmetric in the azimuthal direction and is accompanied by stationary luminosities (radially expanding trails). The temporal temperature and density behaviors are relatively stable; the electron temperature is only slightly pretreated in a narrow range from 3900 to

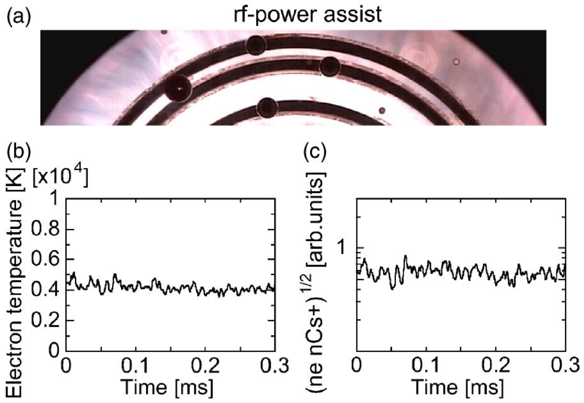

FIG. 4. The rf power is applied. (a) A photograph of the plasma and time variations of (b) the electron temperature and (c) the function of the electron and cesium ion number densities. The seed fraction is 13×10^{-4}.

5200 K. The decline of the electron temperature due to rf heating seems to be inconsistent with the concept of the superimposition of additional heating on self-excited joule heating. However, this is the core of the present paper. The slight but prominent enhancement of the background electron temperature from 3000 to 3900 K prevents the growth of electrothermal waves. The "effective" electrical conductivity or Hall parameter that was reduced by the plasma nonuniformity could be recovered through rf power stabilization and homogenization. This effect directly contributes to the energy conversion efficiency. The enthalpy extraction ratio [(power output)/(thermal input)] is improved from 5.7% (Fig. 3 case) to 7.9% (Fig. 4 case).

In summary, we overcame ionization instability of the MHD electrical power-generating plasma by coupling with an rf electromagnetic field. The rf heating suppressed the ionization instability in the plasma behavior and homogenized the nonuniformity of the plasma structure. As a result, the power-generating performance was significantly improved. The increment of the enthalpy extraction ratio of around 2% was significantly greater than the fraction of the net rf power, that is, 0.16%, to the thermal input.

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