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K. Adati, R. Kumazawa, H. Fujita, T. Oda, K. Kadota, K. Takiyama, M. Hamamoto, T. Ohgo, T. Watanabe, T. Aoki, J. Fujita, S. Hidekuma, T. Kawamoto, H. Masumoto, K. Nishimura, S. Okamura, T. Sato, H.R. Garner and A.M. Howald

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RESEARCH REPORT

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POTENTIAL FORMATION IN AN RF-PLUGGED AXISYMMETRIC MIRROR-CUSP DEVICE

K. ADATI, R. KUMAZAWA, H. FUJITA, T. ODA[†], K. KADOTA,
K. TAKIYAMA[†], M. HAMAMOTO[††], T. OHGO[*], T. WATANABE[**],
T. AOKI, J. FUJITA, S. HIDEKUMA, T. KAWAMOTO, H. MASUMOTO,
K. NISHIMURA, S. OKAMURA, T. SATO

Institute of Plasma Physics, Nagoya University
Chikusa-ku, Nagoya 464, Japan

H.R. GARNER, A.M. HOWALD

General Atomics
San Diego, California 92138, the United State of America

† Dep. of Appl. Phys. and Chem., Hiroshima Univ., Higashihiroshima 724.

†† Dep. of Engineering, Oita Univ., Oita 870-11

* Phys. Dep., Fukuoka Univ. of Education, Munakata 811-41

** Inst. for Fusion Theory, Hiroshima Univ., Hiroshima 730.

Further communication about this report is to be sent to the Research Information Center, Institute of Plasma Physics, Nagoya University, Nagoya 464-01, Japan

POTENTIAL FORMATION IN AN RF-PLUGGED AXISYMMETRIC MIRROR-CUSP DEVICE.

Abstract

Two experiments are described: 1) the first measurements of enhanced RF electric field at the RF plug section and resulting formation of the RF plug potential, 2) the mechanism of the plasma potential formation in the central section.

1. INTRODUCTION

The RFC-XX-M device (Fig. 1) has a linear, axisymmetric MHD stable configuration which is simple mirror field (central section) terminated by spindle cusp fields with radio-frequency (RF) plugging. Two line cusps are plugged by RF plug potential (ponderomotive potential) produced by RF fields in the ion cyclotron frequency range. In previous experiments [1], an empirical scaling for the RF plug potential up to 1 kV and MHD stability condition in a cusp-anchored mirror plasma were obtained. Also the negative potential mode was discovered with ICRF power only.

The distance between the field-nulls of the two spindle cusps is 3 m. The magnetic field strength in this experiment is 1.26 T at the line cusp, 0.21 T at the central mirror midplane, and 0.58 T at the mirror throat. A rotating type-III antenna is located in the mirror throat for plasma production and is driven by two 0.4 MW RF oscillators (f = 7 MHz). For RF plugging, a pair of ring electrodes is installed in each line cusp and connected to a 1 MW oscillator (f = 24.5 MHz). Typical plasma parameters at the mirror midplane are as follows: $n = 2.4 \times 10^{12}$ cm^{-3}, T_i = 100 eV with high energy component of 550 eV, T_e = 30 - 140 eV.

2. RF PLUG POTENTIAL FORMATION

A parametric survey [1] of RF plug potential showed that the RF plug potential was enhanced when RF frequency corresponds to the eigenfrequency of n = 1 mode of the ion Bernstein wave, where n is the mode number in the direction across the sheet plasma in the line cusp. For the plasma parameters of RFC-XX-M, only n = 1 mode can be excited whereas the various mode numbers (n = 0,1,2,) are possible for the eigenmode in the calculation. In order to confirm the existence of the eigenmode, we measured the electric field in the sheet plasma directly [2] by using combined technique of beam probe and laser-induced fluorescence, in which the forbidden fluorescence due to the Stark effect was observed. The optical detection system is movable in the direction across the sheet plasma in order to observe spatial distribution of the fluorescences.

Under the optimum condition where the frequency corresponds to the eigenfrequency, the measured electric field strength in the midplane of the sheet plasma increases almost linearly with the applied RF voltage V_{LB}, and is enhanced by about 2.5 times with respect to the vacuum field. The spatial distribution for the RF electric field in the direction across the sheet plasma was also measured under the optimum condition with V_{LB} = 4 kV as shown in Fig. 2(a). From this figure, we can see that one peak exists at the midplane of the sheet plasma and another peak is in the right-hand side. Unfortunately, the left-hand part could not be fully measured because the width of the laser light was set to be 10 mm in order to avoid the stray light of laser scattered from the surfaces of the RF electrodes. Figure 2(a) suggests that the electric field profile consists of a central peak and a pair of symmetric side peaks.

Numerical calculations carried out for this experimental condition show that the eigenmode of the ion Bernstein wave is found to be n = 1 mode, and the RF electric field of this mode has three peaks as shown in Fig. 2(b).

Thus the electric field profile obtained experimentally is in agreement with the theoretical one.

Since the ion Larmor radii are almost equal to the plasma thickness of the sheet plasma, ions feel the whole electric field profile which is equivalent to the electric field averaged in the direction across the plasma sheet. By using the averaged electric field in Fig. 2(a), the RF plug potenital is calculated to be 450 V which agrees with the value measured with a multi-grid energy analyzer. This plug potential gives the parallel confinement time of 500 ms for bulk ions with 100 eV according to the Pastukhov furmula.

3. PLASMA POTENTIAL FORMATION

Because of ion confinement by the RF plug potential it is expected that plasma potential in the central section will rise to a positive value which acts to confine electrons so as to equate ion and electron losses. Clarifying the mechanism of the potential formation [3] in the confinement region is very important for the understanding of plasma confinement in relation to non-ambipolar radial transport. When RF plugging is applied to both line cusps, the multi-grid energy analyzers placed at line cusp ends give Φ_{LS} and Φ_{LB} which are superpositions of RF plug potential Ψ_{LS} and Ψ_{LB} on the plasma potential ϕ_M, respectively, as illustrated in Fig. 1(c). The plasma potential ϕ_M is measured with the heavy ion beam probe system installed at the mirror midplane. Subtracting ϕ_M from Φ_{LS} and Φ_{LB}, we obtain the RF plug potential Ψ_{LS} and Ψ_{LB}.

In Fig. 3(a), Φ_{LS}, Φ_{LB} and ϕ_M measured under the optimum condition (ω/ω_{ci} = 1.4 and $\omega_{pi}^2/\omega_{ci}^2$ = 46) are plotted with solid curves against the plugging RF voltage. Without RF plugging, Φ_{LS}, Φ_{LB} and ϕ_M are almost equal at 220 V. As the pluggig RF voltage increases, Φ_{LS}, Φ_{LB} and ϕ_M increase to 1100 V, 840 V and 550 V, respectively. The RF plug potentials are therefore

$\Psi_{LS} = \Phi_{LS} - \phi_M = 550$ V and $\Psi_{LB} = \Phi_{LB} - \phi_M = 290$ V for $V_{LS} = 5.2$ kV and $V_{LB} = 4.0$ kV. For the non-optimum condition where $\omega/\omega_{ci} = 0.89$ and $\omega_{pi}^2/\omega_{ci}^2 = 25$, Φ_{LS} and Φ_{LB} increase only about 100 V as V_{LS} and V_{LB} increase to 5.1 kV and 3.9 kV, respectively. ϕ_M increases also slightly.

In the RFC-XX-M device, most of the plasma is confined in the adiabatic confinement region which is illustrated by hatch in Fig. 1(a). This particle confinement can be discussed by the generalized Pastukhov formula. By setting the ion confinement time equals to the electron confinement time, the ambipolar potential in the central section, ϕ_A, can be evaluated. As is clear from Fig. 3(a), Ψ_{LS} is larger than Ψ_{LB}, because of the difference of V_{LS} and V_{LB}. This means that the ion confinement is limited by the RF plug potential on the LB side which is lower than that on the LS side. Therefore, substituting the quantities measured at the LB line cusp and the central mirror midplane into equations of the particle confinement time for ions and electrons, we obtain ϕ_A for a wide range of plasma parameters including the case of no RF plugging. These values of ϕ_A are compared with ϕ_M measured with the heavy ion beam probe system for the corresponding shots in Fig. 3(b). All the points are in agreement with the solid line which shows the measured plasma potential is equal to the ambipolar potential which develops to equate ion loss and electron loss along the magnetic lines of force, and strong non-ambipolar radial loss is not driven as expected in a completely axisymmetric magnetic field configuration.

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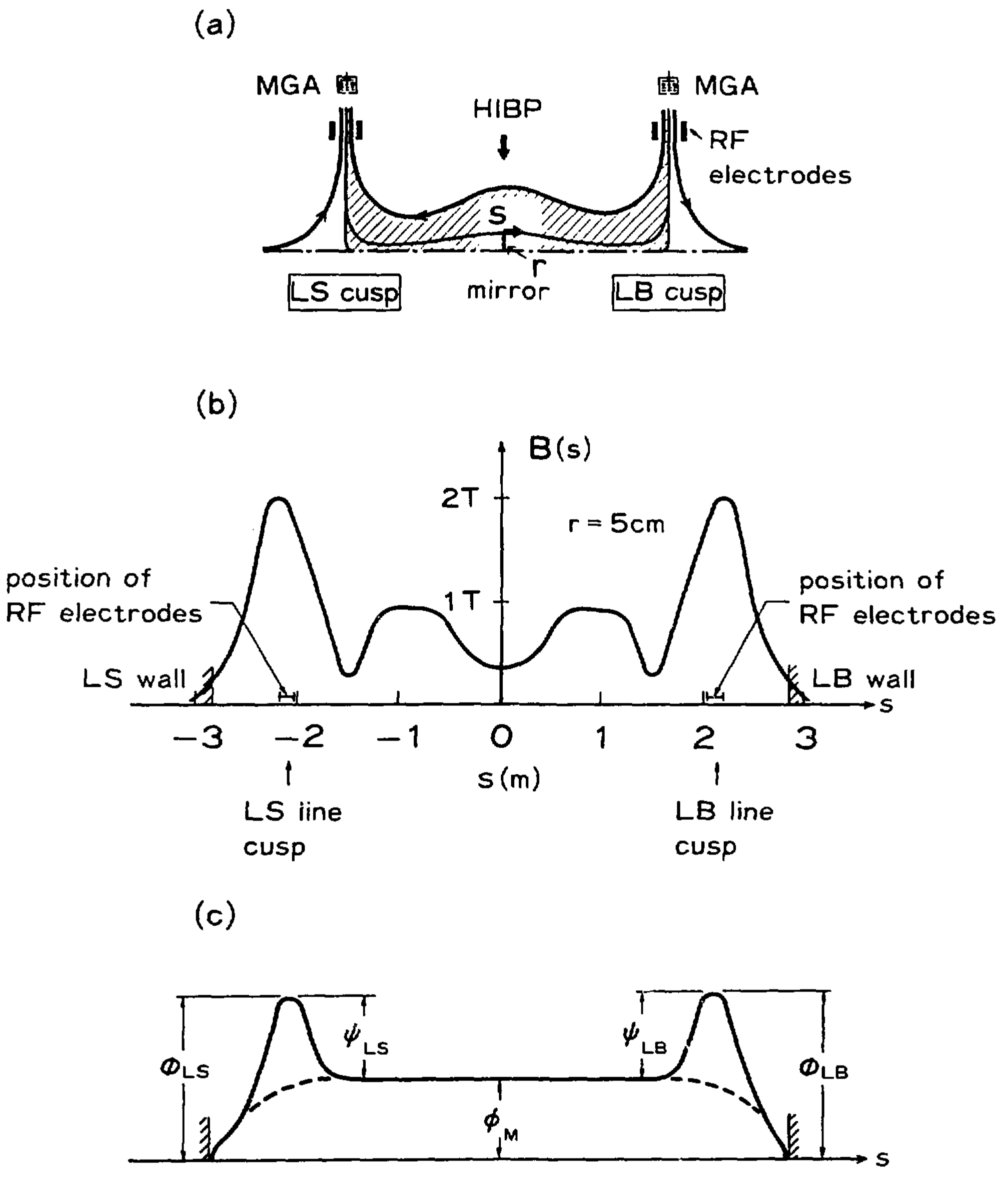


FIG. 1. (a) Magnetic lines of force of RFC-XX-M (shown the upper half). (b) Magnetic field porfile along an off-axis field line in full operation. (c) Potential profile along a magnetic field line.

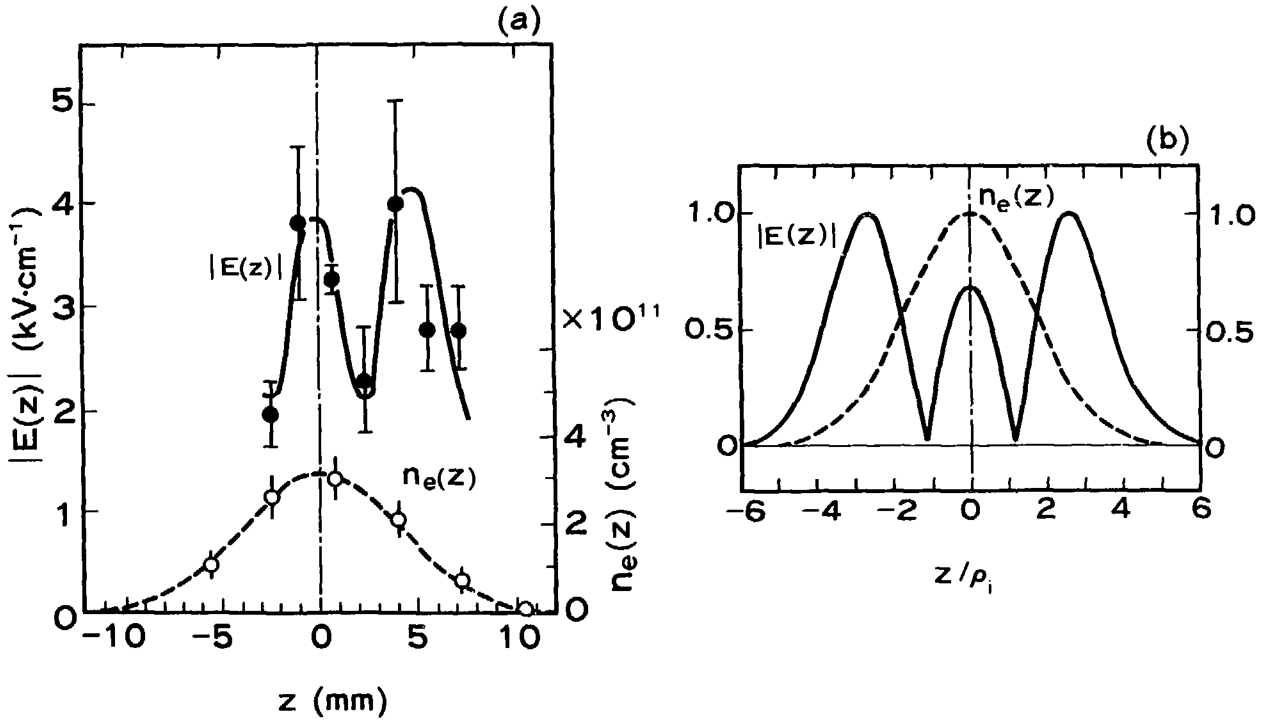
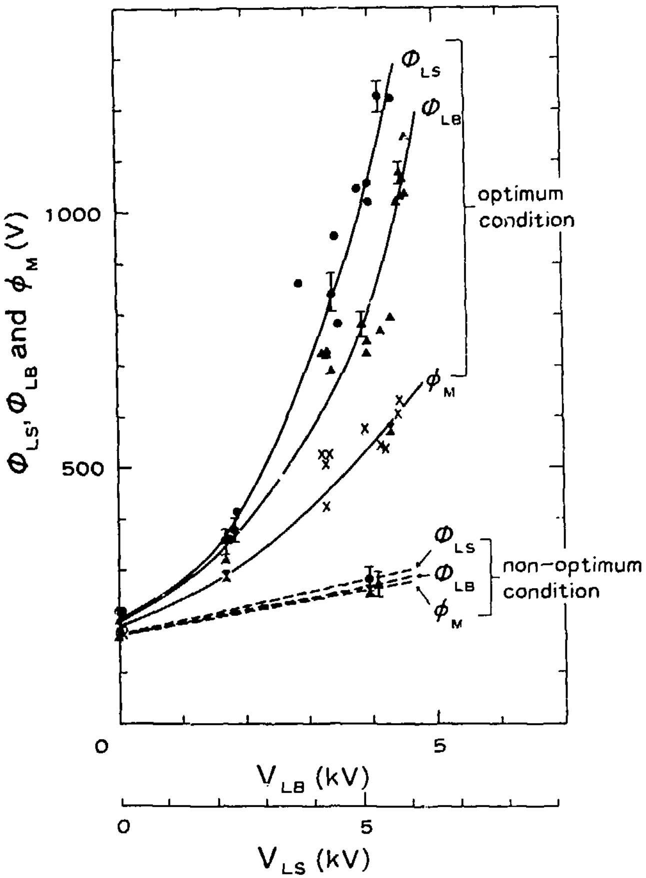


FIG. 2 (a) Electric field profile in the direction across the sheet plasma with the corresponding electron density profile. (b) Calculated profile of the eigenmode in the present experimental condition. ρ_i denotes the ion Larmor radius.



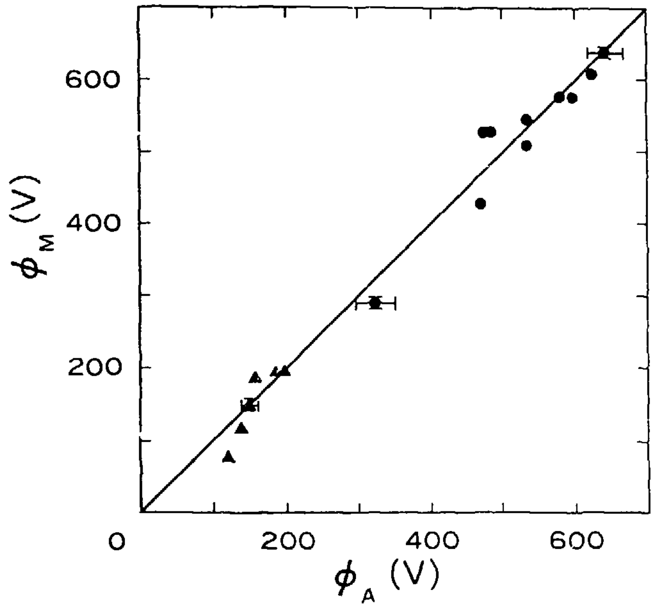


Fig. 3 (a) Measured potentials, Φ_{LS}, Φ_{LB} and ϕ_M versus the plugging RF voltage under the optimum condition and the non-optimum condition. (b) ϕ_M measured with a heavy ion beam probe system is compared with ϕ_A deduced from the generalized Pastukhov formula. The solid line shows $\phi_M = \phi_A$.