ISSN 0469-4732

INSTITUTE OF PLASMA PHYSICS

NAGOYA UNIVERSITY

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(Received – July 3, 1986)

IPPJ- 784 July 1986

RESEARCH REPORT

NAGOYA, JAPAN

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Abstract

RFC-XX-M is an MHD stable and axisymmetric mirror-cusp device with radio frequency (rf) plugging. The plasma is produced by ion cyclotron resonant heating (ICRH) with gas puffing at the central mirror. The total ion energy confinement time including axial loss, electron drag and charge exchange is improved by a factor of three by the rf plugging and reaches 1 ms. The energy confinement time due to the axial particle loss is estimated to be 7.5 ms from a detailed analysis of ion energy loss channels. An rf plugging potential (ψ) is measured from the energy analysis of the escaping ions. It is determined that ψ is proportional to the square of an applied rf voltage and the maximum value reaches 250 V. This value agrees with a plugging potential deduced from the Pastukhov formula within a factor of 2.

Introduction

Many confinement schemes have been investigated for a thermonuclear fusion reactor. The open ended confinement scheme is one of the important approaches. In this scheme, the most critical point is axial confinement by end plugging. There are many methods for end plugging.[1-4]

Rf plugging has been studied in a series of experiments at the Institute of Plasma Physics, Nagoya University.[5-8] In this method, ions are confined axially by plugging potentials that are formed by rf fields in the ion cyclotron frequency range. This plugging method is characterized by the removal of impurities due to the preferential plugging.[5] RFC-XX-M has a completely axisymmetric magnetic field, so there is no resonant radial diffusion induced by non-axisymmetric magnetic fields.[9,10]

This letter reports the improvement of the energy confinement time by rf plugging and the empirical scaling relation of the rf plugging potential.

Experimental Setup

A schematic drawing of RFC-XX-M with its diagnostics is shown in Fig. 1. The central cell is a simple mirror whose ends are connected to two cusps which provide MHD stability. The distance between the two field-null points is 3 m. The magnetic field strength is 2.1 T at the line cusps and 3.9 T at the point cusp in full operation. At the central mirror, the magnetic field strength is 0.35 T at the mid-plane and 0.97 T at the throat, thus the mirror ratio is 2.8. A rotating type-III antenna[11] is installed at the mirror throat. This antenna is excited by two 400 kW rf oscillators ($\omega/2\pi$ = 7 MHz). For rf plugging, a pair of ring electrodes whose separaton is 3 cm is installed in each line cusp and excited by a 1 MW rf oscillator at an applied frequency, $f_L = \omega_L/2\pi$ =24.5 MHz.

The plasma studied here is produced in the following time sequence. First the initial target plasma is injected externally or produced by electron cyclotron resonant heating (ECRH, 2.45 GHz, 1 kW) near the field null region. The rotating type-III antenna is excited with left hand rotating excitation near the ion cyclotron frequency and hydrogen gas is puffed from a gas box at the throat just after the target plasma is turned off. The parameters of the plasma, which builds up to a steady state that lasts 10 - 20 ms, are as follows: the electron density on the axis at the mid-plane is $n_{e0} = 5.5 \times 10^{12} cm^{-3}$; the ion temperature on the axis is T_{i0} = 100 - 600 eV; the electron temperature on the axis is T_{e0} = 10 - 40 eV; the constant hydrogen gas puffing rate is 10 torr·ℓ/sec; and the ratio of the ICRH frequency to the local ion cyclotron frequency under the antenna is $\omega/\omega_{ci} = 0.63$. The cusp at the external plasma source side is called the LS cusp and the other cusp is called the LB cusp, as shown in Fig. 1.

Experimental Results and Discussion

The spatial profiles of plasma parameters as measured for one case of constant ICRH power are shown in Fig. 2. The radial profile of the density at the mirror mid-plane (z=0) is obtained by an electrostatic probe and Thomson laser scattering after calibrating by the line density (10^{14} cm^{-2}) measured by a 70 GHz microwave interferometer. The plasma is limited by a metal limiter. The electron temperature as measured by Thomson scattering is almost constant radially. A radial ion temperature profile is obtained by a fast neutral particle analyzer (FNA) after an Abel transformation considering the radial profiles of the ion density and an atomic hydrogen density which is measured by laser fluorescence spectroscopy at the H_α transition.[12] The electron temperature is 6 % of the ion temperature on the axis (T_{i0}). The electron densities are measured at two other axial positions, which are the off mid-plane (z = 42 cm) and the mirror throat (z = 76 cm). The density at the throat is half that at the mid-plane. The radial density profiles measured at three different positions are similar as functions of magnetic flux.

At first the measurement of the total ion energy confinement time is carried out without the rf plugging. Since the ion temperature is much higher than the electron temperature, a diamagnetic loop signal obtained at the mid-plane mainly shows the stored ion energy. An rf power modulation method is adopted to measure the ion energy confinement time in the presence of the rf field. The ion energy confinement time can be deduced from the measured decay time (τ_{EM}) of the diamagnetic loop signal when the input ICRH power is modulated by 10 ~ 15 %. By changing the ICRH power (50 ~ 200 kW) the dependence of τ_{EM} on T_{i0} is obtained as shown in Fig. 3. The energy confinement time increases with T_{i0} at constant electron density on the axis at the mid-plane, ($n_{e0} \simeq 5.5 \times 10^{12}$ cm^{-3}) and the same gas puffing rate. For example, τ_{EM} is 0.61 ms in the case of T_{i0} = 610 eV and T_{e0} = 32 eV. In this figure, the dependence of the electron temperature on the axis (T_{e0}) on T_{i0} is also shown. T_{e0} is proportional to T_{i0}.

The ion energy confinement time due to various loss channels can be evaluated by adopting some reasonable assumptions and considering the experimental results. The ion and electron temperatures are assumed to be constant along a magnetic field line because their confinement times are much longer than their transit times. A spatial profile of the electron density is approximated to have a following form (-100 cm $< z <$ 100 cm),

$$n_e(r,z) = n_{e0} g\left(r\cdot\left(\frac{B(z)}{B(0)}\right)^{1/2}\right)\cdot\left(1 + C\cdot\exp\left(-\left(\frac{D}{L_m}z\right)^2\right)\right)/2,$$

where B(0) and B(z) are the axial magnetic field strength at the mid-plane and at any axial position, respectively, g is a function of the radial position at the mid-plane as shown in Fig. 2 and L_m is the half distance between the throats, 100 cm. From the experimental results, C is determined to be 1 and D is 4.

The spatial distribution of the atomic hydrogen density in a plasma is calculated from a penetration code, in which the atomic hydrogen density drops due to ionization and charge exchange while penetrating into the plasma. When this code is applied to the experimental condition of reference 12, the calculated radial profile agrees with the experimental results, which show that the atomic hydrogen density on the axis is one-third that at the plasma boundary (n_{ab}) when the line density is 10^{14} cm^{-2}, T_{i0} = 300 eV and T_{e0} = 18 eV. For the present experiment, the spatial distribution of the atomic hydrogen is calculated by this code (as shown by dashed line in Fig. 2) with the assumption that n_{ab} = 10^{10} cm^{-3}, which turns out to be consistent with the experimental results.

Particle losses by ion-ion scattering, electron drag loss and charge exchange are considered to be the most dominant ion energy loss channels in this experiment. Particle and thermal diffusions across the magnetic field are thought to be negligibly small. The energy confinement time for the above mentioned three loss channels can be determined by averaging the local value over the plasma volume. The energy confinement time based on the particle loss (τ_{EP}) is calculated according to the Sivukhin formula[13] as shown in Fig. 3. This confinement time is about 3 τ_{EM}. The electron drag time, τ_D is proportional to $T_{e0}^{3/2}$ and since $T_{e0} \propto T_{i0}$ from the experimental result, $\tau_D \propto T_{i0}^{3/2}$ as shown in Fig. 3, where τ_D is almost 2 τ_{EM}. The charge exchange loss time (τ_{CX}) has a slight dependence on T_{i0} and decreases a little with T_{i0} from 3 ms to 2 ms, which is longer than τ_{EM}. It is noted that the main loss channel is the electron drag loss in this experiment. The total ion energy confinement time can be deduced from $1/\tau_E = 1/\tau_{EP} + 1/\tau_D + 1/\tau_{CX}$ and can be compared with the experimental results (τ_{EM}). The solid line shows the calculated τ_E which agrees with τ_{EM}. The change in slope of this line at T_{i0} = 600 eV, detaching from the scaling of $\tau_{EM} \propto T_{i0}^{3/2}$, is due to the increasing importance of charge exchange. The charge exchange loss will not be negligibly small for higher ion temperature, $T_{i0} > 1$ keV.

A plugging experiment is carried out to improve the energy confinement time of the plasma whose loss channels are well known. Since the non-adiabatic region near the magnetic field null point is not large, the plasma produced at the central mirror escapes mainly through the line cusp along the magnetic field lines. The point cusp loss is only a few percent of the line cusp loss. Therefore, the rf plugging is only applied to both line cusps at the frequency ratio of $\omega_L/\omega_{ci}^L = 1.1$.

As shown in Fig. 4(a), the stored energy is increased by about 30 % by LB cusp plugging 2 ms after plasma production. The LS cusp is plugged 2 ms after the LB plugging, thus both line cusps are plugged at this time. The energy confinement time (τ_{EM}) reaches 1.0 ms for the plasma, T_{i0} = 600 eV and T_{e0} = 46 eV when both line cusps are plugged. Figure 4(b) shows the dependence of τ_{EM} on V_{LS} for the case of V_{LB} = 4.3 kV, where V_{LS} and V_{LB} are the applied rf voltages to the LS and the LB plugging electrodes. The value of τ_{EM} is improved by a factor of three when V_{LS} = 5.5 kV and V_{LB} = 4.3 kV in comparison with no rf plugging.

From these results the improved τ_{EP} can be calculated to be 7.5 ms if the three above mentioned ion energy losses are dominant during rf pluggings. The value of τ_{EP} without rf plugging is 1.5 ms for T_{i0} = 600 eV as obtained from Fig. 3, so τ_{EP} with rf plugging is improved by a factor of 5. The uncertainty in the calculated τ_{EP} can be estimated from the uncertainties of T_{e0} and n_{ab}, which are both about 10 %. Thus τ_{EP} ranges from 5 ms to 15 ms. In addition the enhancement factor of the particle confinement can be deduced to be 5 times from the fact that the loss flux from the line cusp decreases by 80 % when the rf plugging is applied.

This increase in the energy confinement time is due to the presence of an rf plugging potential. This plugging potential is calculated to be 400 V from the measured axial energy confinement time, τ_{EP} = 7.5 ms and the Pastukhov formula[14]. On the other hand, the rf plugging potential, ψ, is directly measured by multi-grid energy analyzers (MGA) located at both line cusps to certify its existence in the other series of experiments. The schematic profile of the plasma potential and rf plugging potential along a magnetic line of force are shown in Fig. 5, where ϕ and ϕ_p indicate the plasma potential at the central mirror region and the rf plugging region, respectively. As ψ is superposed on ϕ_p, the potential measured by the MGA on the LS side becomes $\Phi_{LS} = \psi + \phi_p$. On the other hand, ϕ is measured by the MGA on the LB side as Φ_{LB}. The rf plugging potential is regarded as the difference between Φ_{LB} and Φ_{LS}. Assuming the electrons have a Boltzmann distribution, ϕ_p is smaller than ϕ by a few times the electron temeprature. Therefore ψ obtained from this method is measured to be smaller than the real value. Ion energy spectra with and without rf plugging are also shown in Fig. 5, where Φ_{LS} increases remarkably with the rf plugging.

Figure 6(a) shows the dependence of ψ on V_{LS} in the case of $\omega_L/\omega_{ci}^L = 1.2$. The value of ψ is proportional to the square of V_{LS} and reaches 200 V at V_{LS} = 2 kV. The rf plugging potentials are also measured for various values of ω_L/ω_{ci}^L in the case of constant applied rf voltage as shown in Fig. 6(b). It is clear from this figure that there exists an rf plugging potential only in the range of $\omega_L/\omega_{ci}^L > 1$, which is consistent with the theoretical calculation that an ion-Bernstein wave (IBW) eigenmode can be excited in this condition.[15]

The rf field in the plasma, E_p, is estimated from the rf plugging potential by using the ponderomotive potential equation for a single particle. The value of E_p is calculated to be 1.8 kV/cm and 4.3 kV/cm for the cases of $\omega_L/\omega_{ci}^L = 1.1$ and 1.4, respectively. In these cases, as the applied rf field in the vacuum, E_{rf}, is 2 kV/cm, E_p is larger than E_{rf}. This fact also suggests the existence of the eigenmode of IBW.

Summary

1) The characteristics of the ion energy confinement are well understood for the plasma produced by ICRH at the central mirror of RFC-XX-M. The loss due to the electron drag is the main loss. Charge exchange loss becomes non-negligible in the higher ion temperature range.
2) The total ion energy confinement time is improved by a factor of 3 and reaches 1 ms with rf pluggings at both line cusps.
3) The energy confinement time based on axial particle loss during rf plugging is estimated to be 7.5 ms and the enhancement factor is 5, which agrees with the fact that the end loss is suppressed by 80 %.
4) The rf plugging potential is obtained directly by energy analysis of the ions lost from the open ends. A plugging potential, ψ, is formed only for $\omega_L/\omega_{ci}^L > 1$, and is proportional to the square of the applied rf field, which agrees with the theoretical calculation. The maximum value of ψ reaches 250 V, which agrees with a plugging potential deduced from the Pastukhov formula within a factor of 2.

Acknowledgements

The authors would like to acknowledge Prof. T. Watanabe for useful discussions. We also wish to express thanks to Dr. A.M. Howald and Dr. B.J. Leikind, GA Technologies Inc. for stimulating discussions and to Prof. S. Tanahashi, Mr. M. Mugishima and Mr. T. Nakagawa for the operation of the flywheel generator.

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Figure Captions

Fig. 1 Schematic drawing of RFC-XX-M with diagnostics.

Fig. 2 The radial profiles of plasma properties at the mid-plane. The electron density (n_e) and the atomic hydrogen density (n_a) are normalized to the electron density on the axis (n_{e0}) and the atomic hydrogen density at the plasma boundary (n_{ab}), respectively. The ion temperature (T_i) and the electron temperature (T_e) are normalized to the ion temperature on the axis (T_{i0}).

Fig. 3 The ion energy confinement times and the electron temperature (T_{e0}) versus the ion temeprature on the axis (T_{i0}). The open circles indicate the total ion energy confinement time (τ_{EM}) without rf plugging. The values of τ_{EM} before and during rf plugging are also plotted. Calculated values of τ_D, τ_{cx} and τ_{EP} are also shown as solid lines.

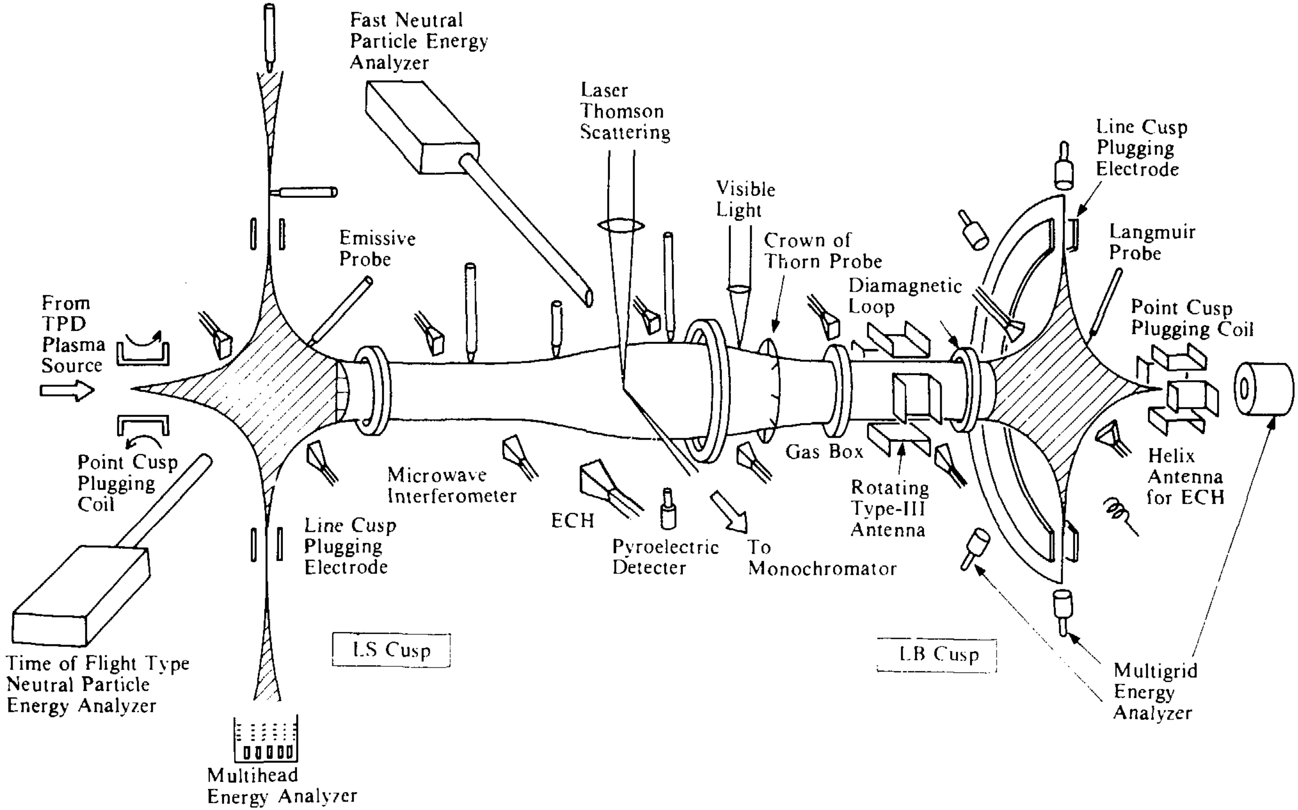
Fig. 4(a) Time evolutions of the diamagnetic signal, ICRH power, plugging voltage of the LS line cusp (V_{LS}) and plugging voltage of the LB line cusp (V_{LB}).

(b) Dependence of τ_{EM} on V_{LS} in the case of V_{LB} = 4.3 kV. τ_{EM} without rf plugging is also plotted.

Fig. 5 Schematic profile of the plasma potential and rf plugging potential along a magnetic field line. The energy spectra of axially escaping ions measured by the multi-grid energy analyzers with and without rf plugging are also shown.

Fig. 6(a) The rf plugging potential (ψ) versus the plugging voltage of LS line cusp (V_{LS}), where ω^L/ω^L_{ci} = 1.2.

(b) The rf plugging potential (ψ) versus the frequency ratio, ω^L/ω^L_{ci}, where V_{LS} = 4 kV.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Laser Thomson Scattering
Visible Light
Crown of Thorn Probe
Line Cusp Plugging Electrode
Langmuir Probe
Diamagnetic Loop
Point Cusp Plugging Coil
Emissive Probe
From TPD Plasma Source
Point Cusp Plugging Coil
Microwave Interferometer
ECH
Pyroelectric Detecter
To Monochromator
Gas Box
Rotating Type-III Antenna
Helix Antenna for ECH
Line Cusp Plugging Electrode
LS Cusp
LB Cusp
Time of Flight Type Neutral Particle Energy Analyzer
Multihead Energy Analyzer
Multigrid Energy Analyzer

Fig.1

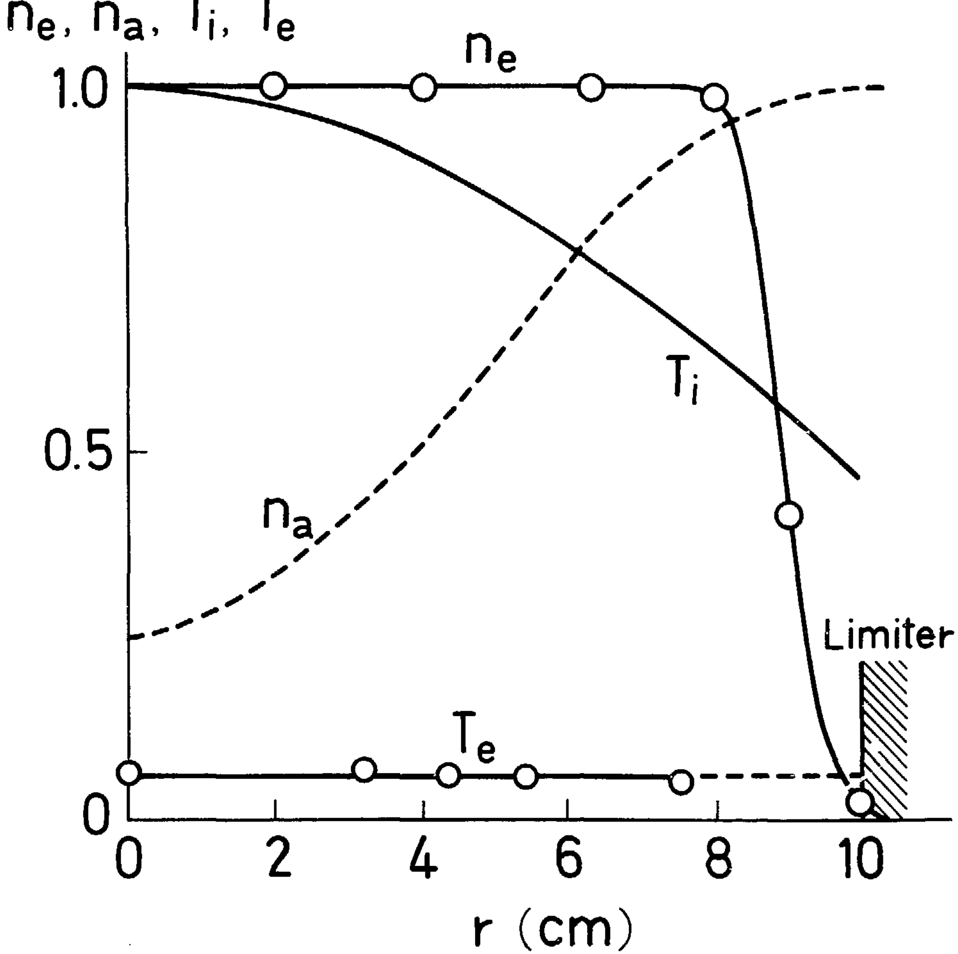


Fig. 2

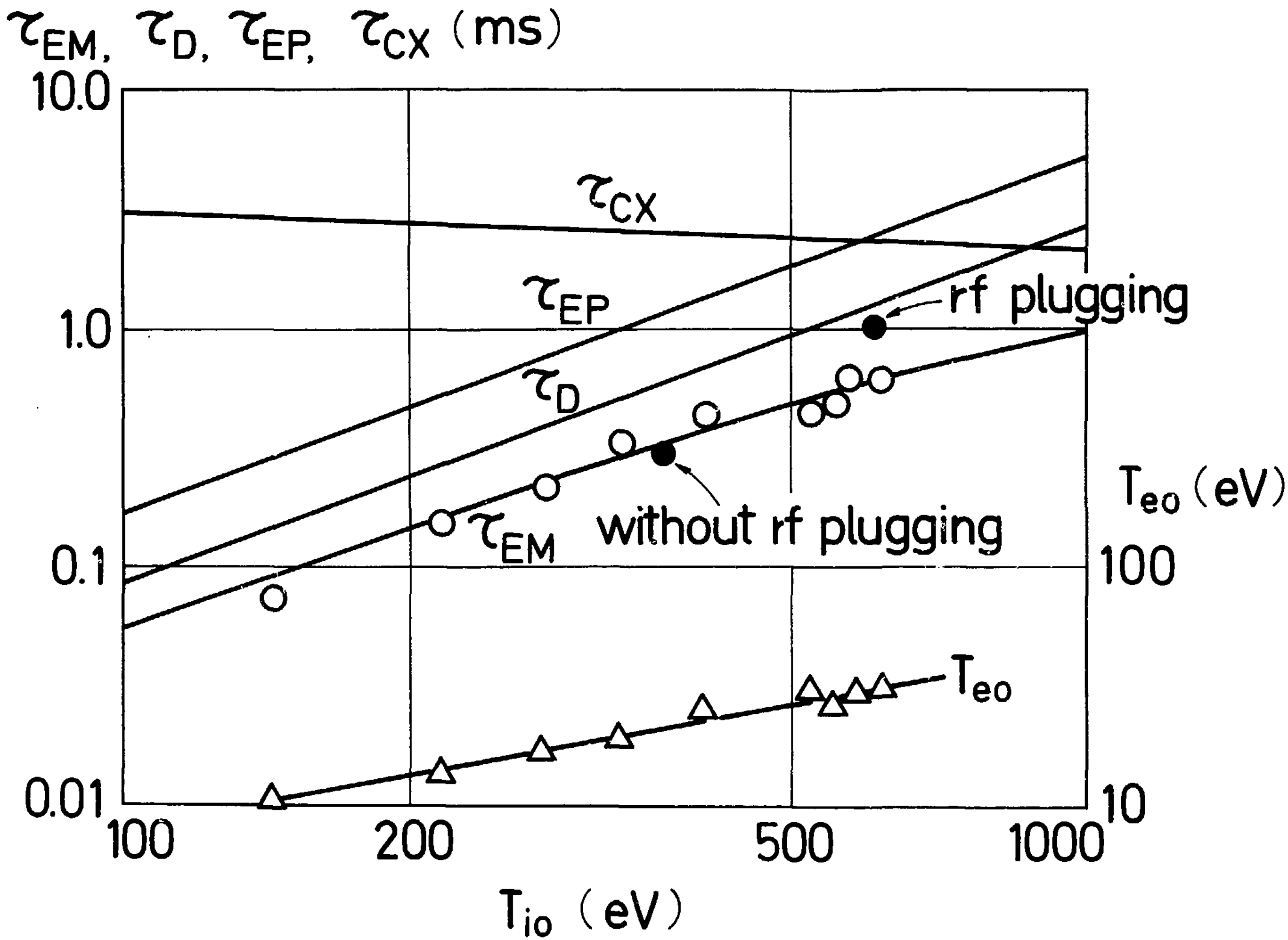

τEM, τD, τEP, τCX (ms)
10.0
1.0
0.1
0.01
τCX
τEP
τD
τEM
rf plugging
without rf plugging
Teo (eV)
100
10
Teo
100
200
500
1000
Tio (eV)

Fig.3

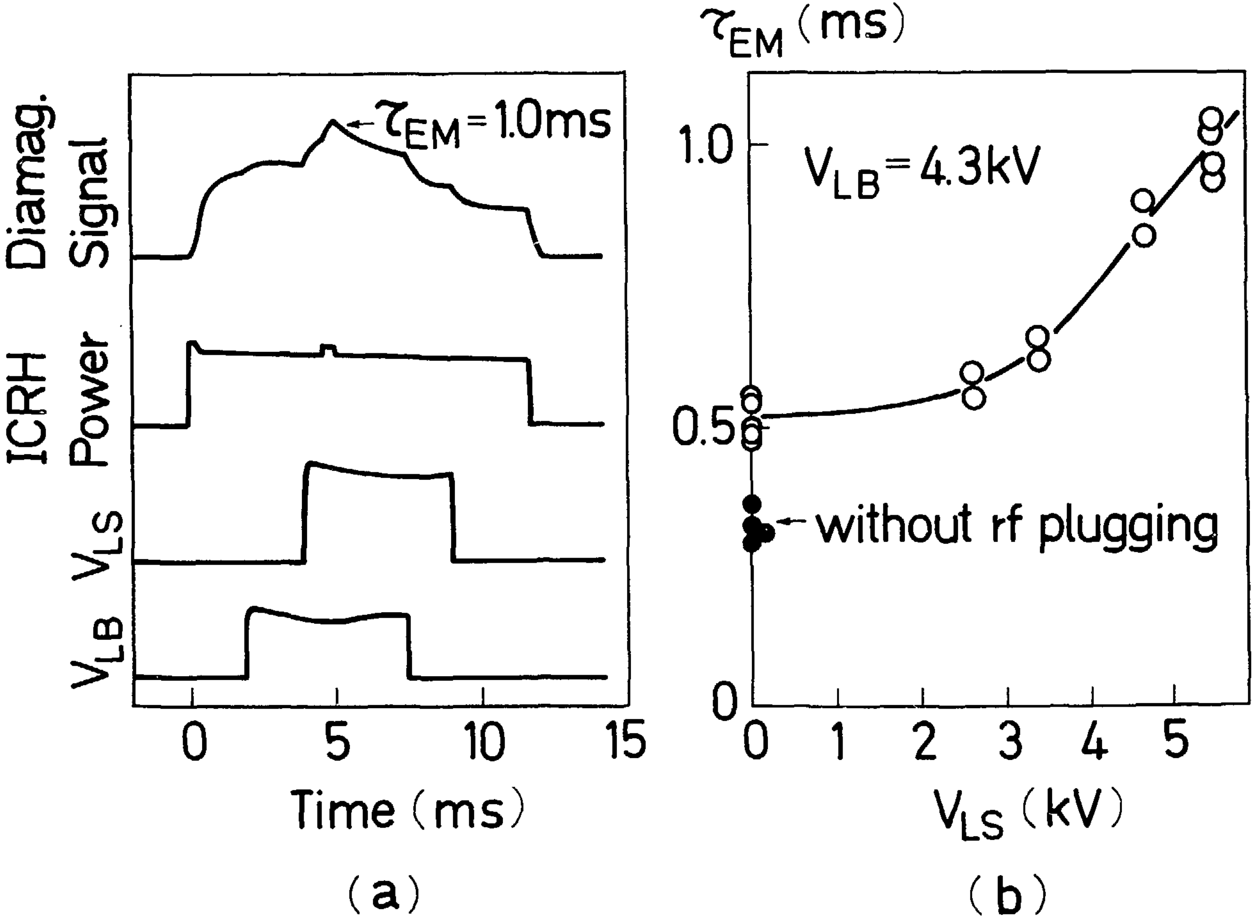
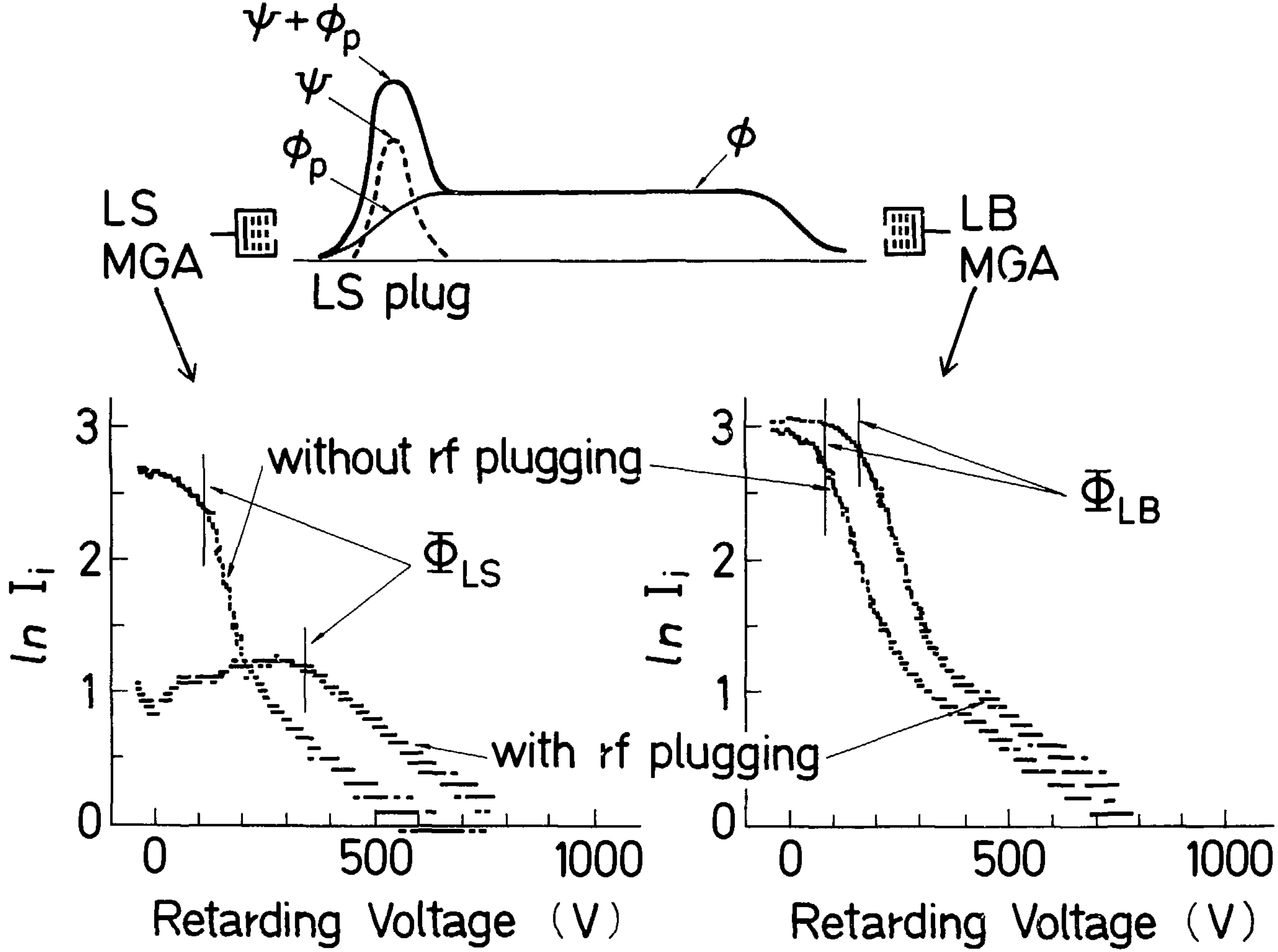

Diamag. Signal
ICRH Power
V_{LS}
V_{LB}
τ_{EM}=1.0ms
0
5
10
15
Time (ms)
(a)
τ_{EM} (ms)
1.0
0.5
0
V_{LB}=4.3kV
without rf plugging
0
1
2
3
4
5
V_{LS} (kV)
(b)

Fig.4



ψ+φp
ψ
φp
φ
LS MGA
LB MGA
LS plug
without rf plugging
ΦLS
ΦLB
with rf plugging
ln Ii
0
1
2
3
0
500
1000
Retarding Voltage (V)
Retarding Voltage (V)

Fig.5

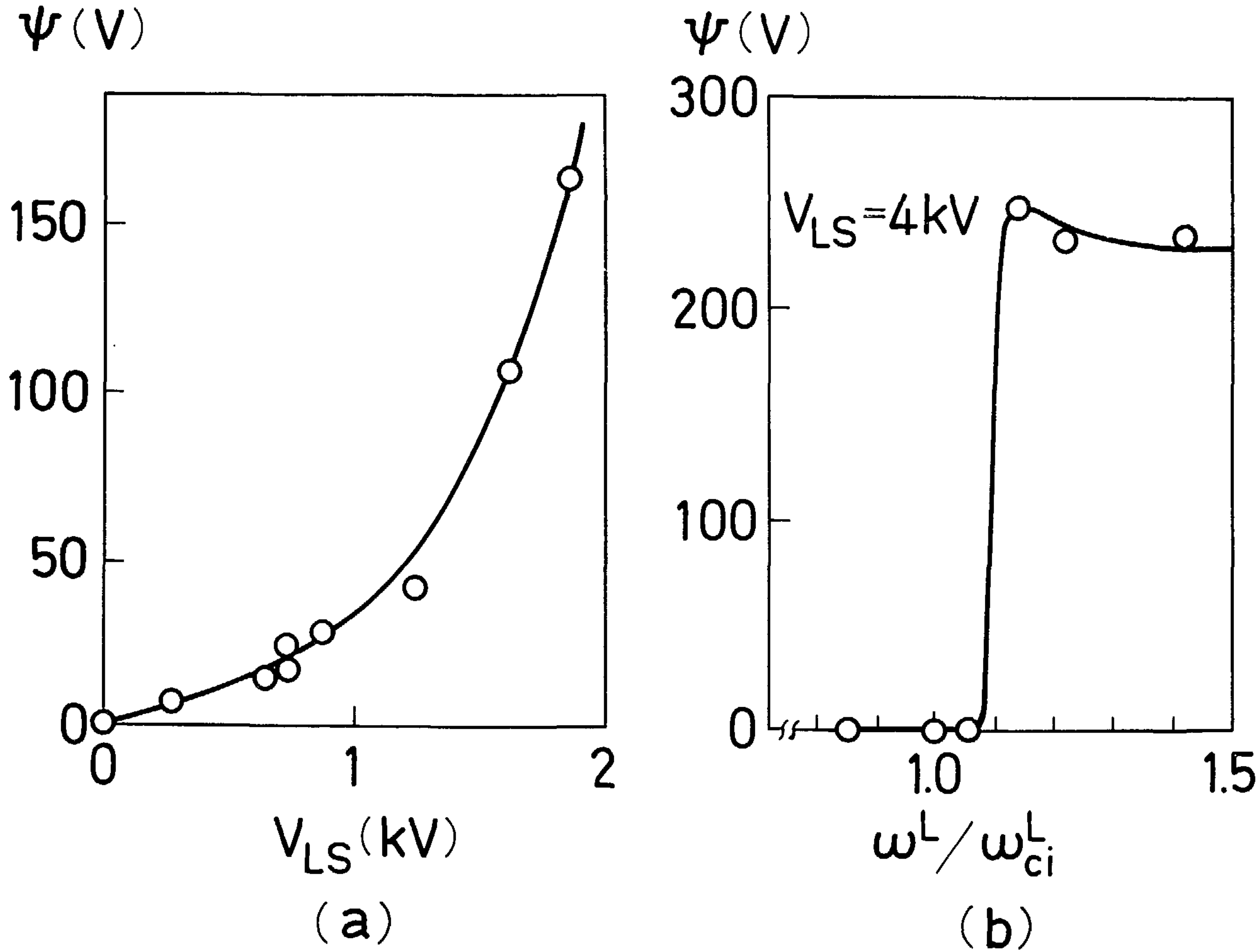


Fig.6