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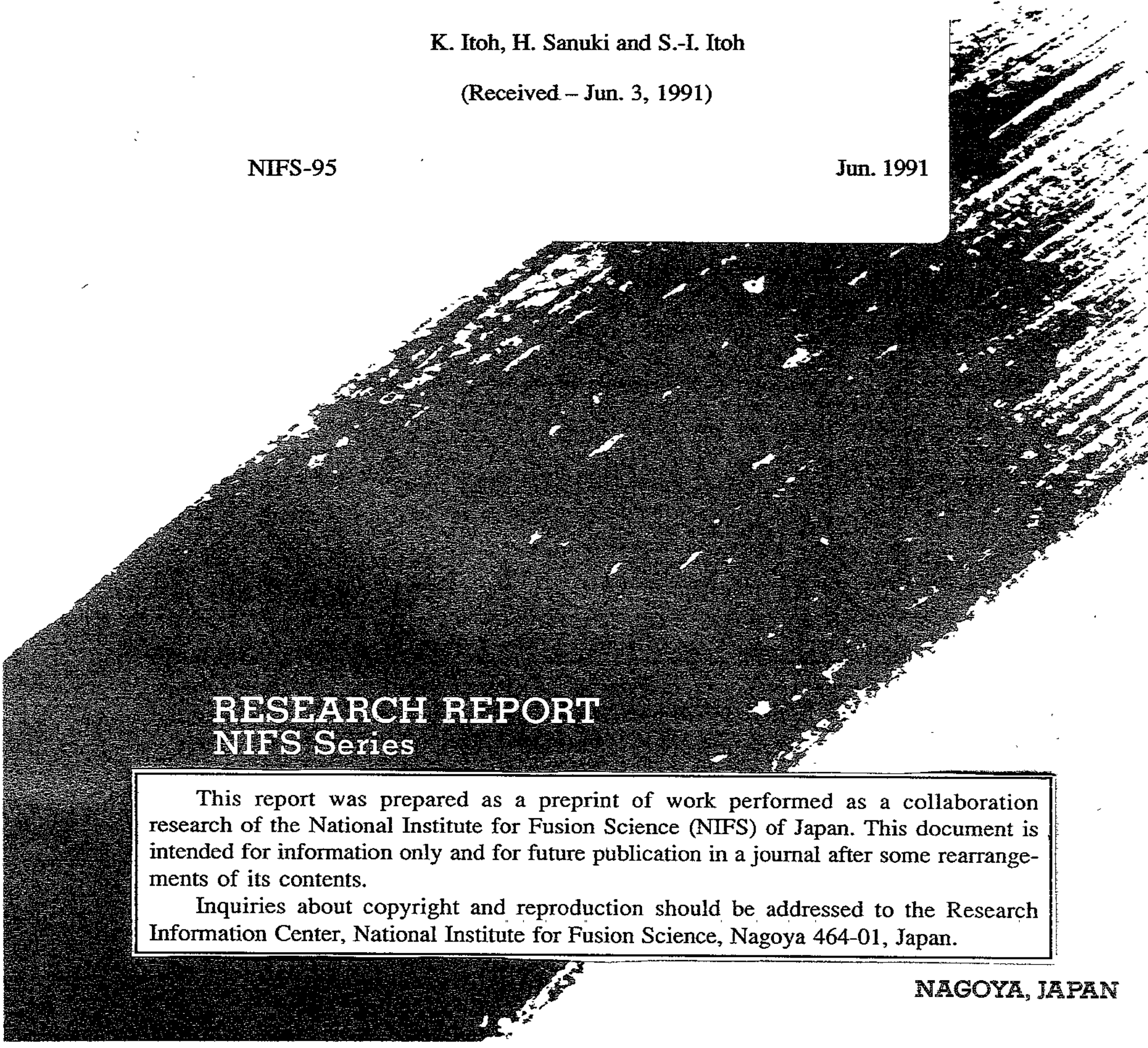

RESEARCH REPORT
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Influence of Fast Ion Loss on Radial Electric Field in Wendelstein VII-A Stellarator

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Abstract

Theoretical model is developed to determine the radial electric field and the fast ion loss simultaneously in stellarators, and is applied to the Wendelstein WII-A stellarator. The predicted value of the radial electric field is more closer to experiments than the purely neoclassical calculation. The loss rate, which is determined simultaneously, is in the range of experimental observations.

Keywords: Wendelstein VII-A, Stellarator, Fast Ion Loss,
Losscone, Radial Electric Field, Neoclassical Transport

The important roles of the radial electric field in stellarators (helical systems) has been widely known. Motivation for the analysis on the radial electric field was first given to assure the improved absolute trapping of particles[1)] (i.e., reduction of the loss cone), and then as a result of this, the reduction of neoclassical thermal transport[2)] was another strong drive for the investigations. Experiments in Wendelstein-VIIA (W-VIIA) has shown that, even though the anomalous transport prevails, the reduced loss was observed in NBI heated discharges in which the radial electric field was piled up as well[3,4)]. The causality between them has not been confirmed yet, but the recent observations and modelling on H-mode in tokamaks[5-7)] encourages the study of the radial electric field associated with the energetic particle loss.

The poloidal gyroradius of fast ions generated by the NBI in W-VIIA stellarator is compatible with the minor radius, and the trapping (and hence the plasma heating) is very difficult without the help of radial electric filed. The influence of the observed radial electric field on the orbit was studied, and the potential difference of about 1keV is enough to confine this energetic particles[8)]. The selfconsistent analysis, which determines the loss of energetic particle and electric field simultaneously, has not been performed, although the importance of the research of this kind was recognized.

In this article, we present a simple analytic theory for the equation to determine the loss boundary of energetic particle. Using the obtained formula, the radial electric field is determined by the procedure in which loss cone current is balanced with the neoclassical current. This analysis gives the radial profile and loss rate of fast ions simultaneously. We find the potential difference of the order of 1keV and the loss rate of fast orbit of about 30%, which is in the range of experimental observations. Dependence on the injection energy is also discussed. Higher injection energy increases the radial electric field for fixed plasma parameters.

The WVII-A stellarator[3)] has the very high aspect ratio, $a/R=1/20$, and medium rotational transform, $\iota = 1/3 \sim 1/2$. (a is the minor radius and R is the major radius). The poloidal gyroradius ρ_p of the deuteron ion with the injection energy of W_b=28keV reaches about 40cm (at B_T=2.5T) exceeding the minor radius of a=10cm. Substantial part of the injection power is carried by the particles with the energy of $W_b/2$ or $W_b/3$, but almost all of them enter the loss cone in the absence of radial electric field.

In the limit where the poloidal motion of particles is dominated by the E×B rotation, not by the parallel motion, the location in the poloidal cross section is dictated by the equation[9,10)]

$$[rW/eBR]\cos\theta - \Phi/B = \text{constant} \qquad (1)$$

where r is the minor radius, e is elementary charge, θ is the poloidal angle, and Φ is the static potential which is the function of r.

We define the loss cone by the condition that the particles starting from r=r, θ=0 (or θ=π) reaches to r=b at some poloidal angle. (b > a). The loss cone boundary r_* is defined by the condition that particles generated at the radius $r>r_*$ enter the loss cone and those bone in the region $r<r_*$ do not. We are interested in the case that the static potential is a monotonous function of the minor radius. [Note that we need not to assume that Φ is parabolic.] Substituting (b, 0) and (r_*, π) in the left hand side of Eq.(1), we have the relation by which the loss cone boundary is determined as

$$[\Phi(b) - \Phi(r_*)]e/W = (b+r_*)/R. \tag{2}$$

From this relation, we see the lower boundary for the potential barrier, which is necessary to confine some part of generated fast ions as

$$e[\Phi(b) - \Phi(0)] > (b/R)W \tag{3}$$

In the region $r>r_*$, there exists the radial current associated with the loss cone loss. We have derived in a previous article$^{11)}$ that

$$\Gamma_{lc} = [P(r)-P(r_*)]/4\pi^2 RrW_b \tag{4}$$

where the suffix lc indicates the loss cone, and P(r) is the injection power across the minor radius r. We solve the equation

$$\Gamma_{NC}{}^{e} = \Gamma_{NC}{}^{i} + \Gamma_{lc} \tag{5}$$

to determine the radial electric field profile $E_r(r)$. The expression of the neoclassical transport we employ here is quoted from Ref.[12]. It is noted that the solution of Eq.(5), $E_r(r)$, is a functional of the parameter r_*, because the loss cone current Eq.(4) depends on the choice of r_*. We have the equation (2), which r_* must satisfy. Thus we can determine the radial electric field and the loss rate simultaneously.

Numerical example is obtained. Figure 1 shows the sample distributions of density and temperatures. The profiles are assumed as, simulating results in Ref.[4],

$$n(\rho) = (n(0)-n_s)\frac{(1-\rho^{\alpha_2})}{\gamma}[1-(1-\gamma)(1-\rho^{\alpha_2})^{\beta_2-1}]+n_s, \tag{6}$$

$$T_e(\rho) = (T_e(0)-T_{es})(1-\rho^{\alpha_3})^{\beta_3}+T_{es}, \tag{7}$$

and

$$T_i(\rho) = (T_i(0)-T_{is})(1-\rho^{\alpha_4})^{\beta_4}+T_{is}, \tag{8}$$

where ρ is the normalized minor radius $\rho=r/a$, and the indices (α_k, β_k) are constant (k=2-4). The coefficient γ is introduced to fit even the hollow profile, and is given as $\gamma= 1-\beta_2{}^{-1}[1-\rho_m{}^{\alpha_2}]^{(1-\beta_2)}$. ρ_m is the minor radius corresponding to the maximum density. n_s and T_s represents the values at plasma edge. The injection power is taken to be 1.2MW.

In order to obtain a physics insight of the problem, we choose a uniform model for the birth profile. This simplification allows us to use

$$[P(a) - P(r_*)]/P(a) = (a-r_*)/a. \tag{9}$$

This assumption is not essential, and one can use more correct form of P(r) if necessary.] The following calculations were done by taking b=a. This is the upper bound of the loss cone, but gives a suitable measure because the wall plasma distance is much smaller than the poloidal gyroradius of fast ions.

Figure 2 shows the dependence of each current component on E_r at ρ=0.8. Solid line indicates the electron current, which has weak dependence on E_r. The dashed lines indicate Γ^i in the absence of beams, the case of r_*/a =0.7 and 0.5, respectively. This graph shows that the influence of the ion orbit loss is large, so that the self consistent determination is inevitable. We also plot the line of 10 times of $\Gamma_{NC}{}^i$ for the reference. We see that $\partial\Gamma_{NC}/\partial E_r$ is large for ions compared to electrons, and the absolute value of $\Gamma_{NC}{}^e$ is small. The enhancement by the factor 10 to the neoclassical estimation does not give a noticeable difference in the solution of Eq.(5).

By determining the loss boundary self-consistently, we have the radial profile of the electric field in Fig.3. We take W_b as 14keV. (This is because the power partition between W_b, $W_b/2$, and $W_b/3$ particles is 4:3:3. The value $W_b/2$ is chosen as an average.) The loss boundary is calculated as

$$r_* = 0.67\ a$$

for this case. The radial profile in the region of $r<2a/3$ is determine by the neoclassical process. The enhancement of radial electric field is found in the peripheral region, which is effective in confining the 2/3 of the injected fast ions. This loss boundary yields that the loss rate of fast ions comes to 1/3. This value is in a range of experimental observations[13).]

Figure 4 illustrates the dependence on the injection energy. As the injection energy increases, the loss boundary invades into the plasma axis, and the loss rate increases. The potential difference between the plasma surface and the loss boundary r_*, $\Phi(a)-\Phi(r_*)$, increases, which is necessary to confine fast ions. The radial electric field at fixed point (say $r=0.8a$) increases as well.

In summary, we have developed a selfconsistent analysis in determining the radial electric field and ion loss cone. Analysis was applied to the Wendelstein VII-A stellarator. The increased loss makes the radial electric field deeper, and the experimental observation is better reproduced in comparison with the neoclassical analysis. The loss rate of fast ions is evaluated as 1/3 which is in the range of experimental observations. If one takes into account the charge exchange loss effect by neutrals, the discrepancy seems become smaller14). The more precise experimental data would provide a test of the validity of the modelling.

The increased electric field can reduce the neoclassical thermal conduction. The neoclassical component of the ion heat flux, which is derived using $E_r(r)$, reduces from 2.7kW (E_r without fast ion loss effect) to 1.5kW (in the case of W_b=14keV) at ρ=0.75. This reduction, which amounts to 1.2kW, however, is smaller than the increment in the direct orbit loss (about 30% of the injected power). From the over all consideration on the energy balance, in this case, it is concluded that the enhanced fast ion loss is energetically not favourable. The role of this radial electric field on the anomalous transport is discussed in a separate article$^{14)}$.

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Figure Captions

Fig.1 Density (a) and temperature (b) profiles for the analysis. (α_2=5, β_2=7, α_3=7, β_3=7, α_4=8, β_4=42, ρ_m=0.)

Fig.2 Dependences of the current component on the radial electric field on the minor radius of ρ=0.8. Solid line is for electron component. Ion current by the neoclassical prediction (dotted line), that with the ion orbit loss (cases of $\rho_* = 0.5$ and 0.7; dashed lines) and that estimated by 10 times of neoclassical flux (dashed-dotted line) are shown. Circles indicate the solution of of the radial electric field. Injection energy is 14keV and the power is 1.2MW.

Fig.3 Radial profile of the radial electric field. Solid line is the selfconsistent solution for the electric field and fast ion loss. dotted line is for the neoclassical prediction. Solid circles indicate experimental results (quoted from Ref.[4]).

Fig.4 Dependence of the loss cone boundary (a) and electric field (b) on the injection energy. Injection power is kept 1.2MW. Solid line in (b) denotes the radial electric field at ρ=0.8 (dotted line shows the result of neoclassical calculation for the reference), and dashed line for the potential difference between the surface and loss cone boundary.

Fig. 1

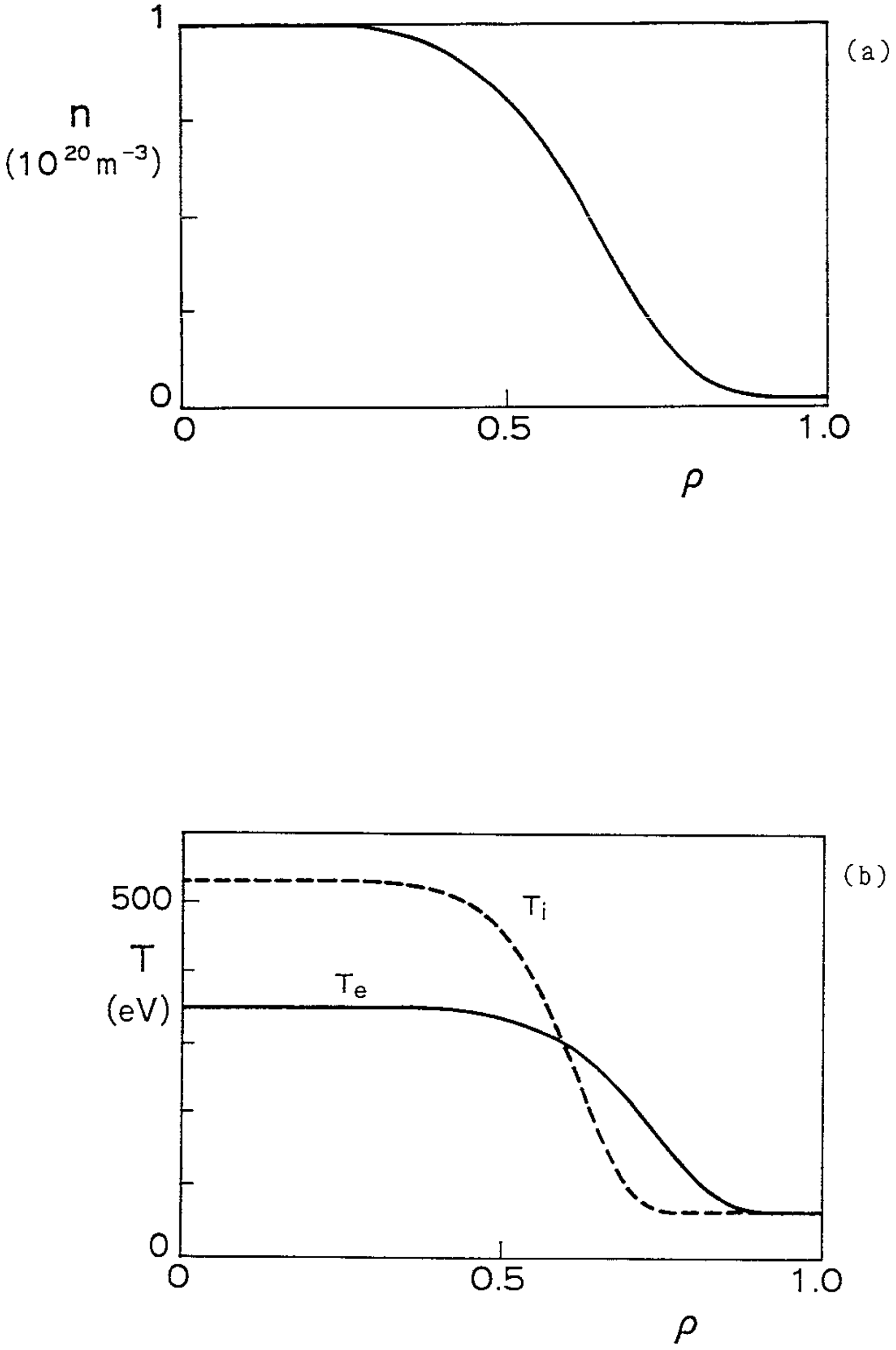


Fig. 2

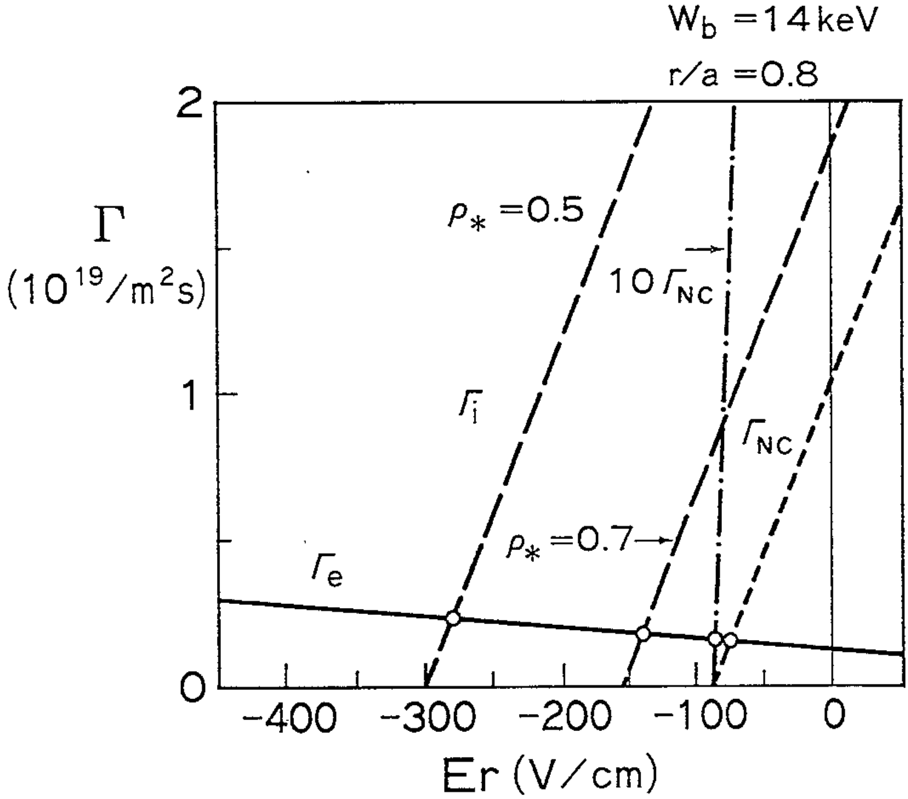

W_b =14 keV
r/a =0.8
Γ
(10^{19}/m^2s)
2
1
0
ρ_* =0.5
10 Γ_{NC}
Γ_i
Γ_{NC}
ρ_* =0.7
Γ_e
-400
-300
-200
-100
0
Er (V/cm)

Fig. 3

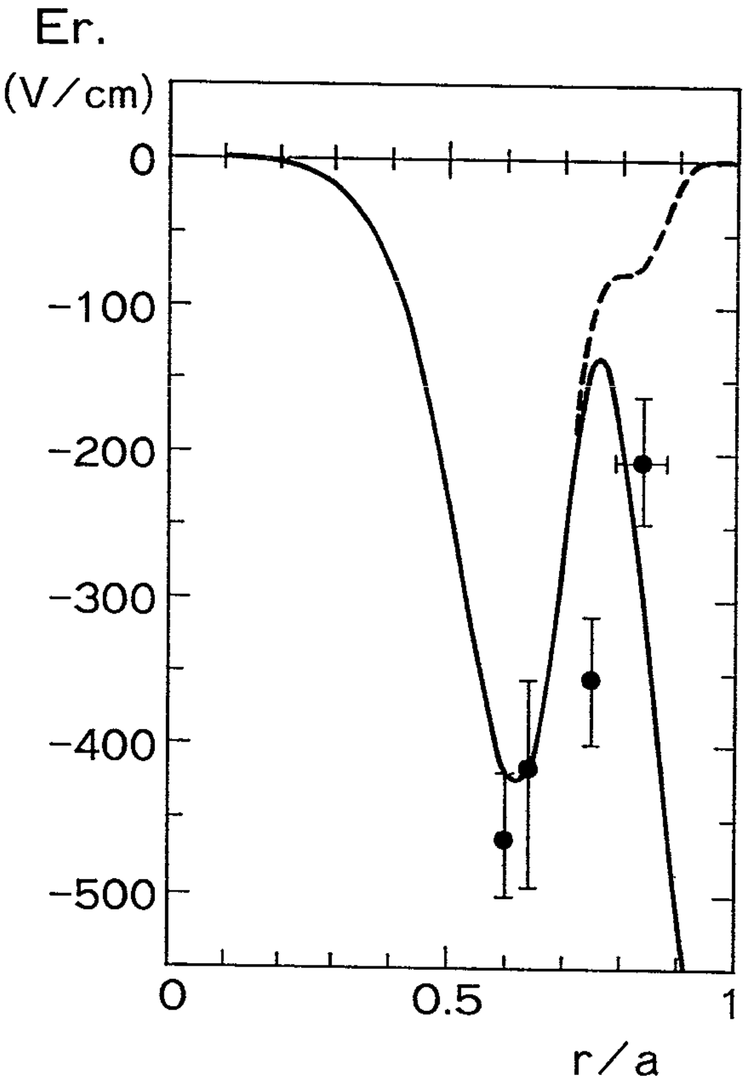
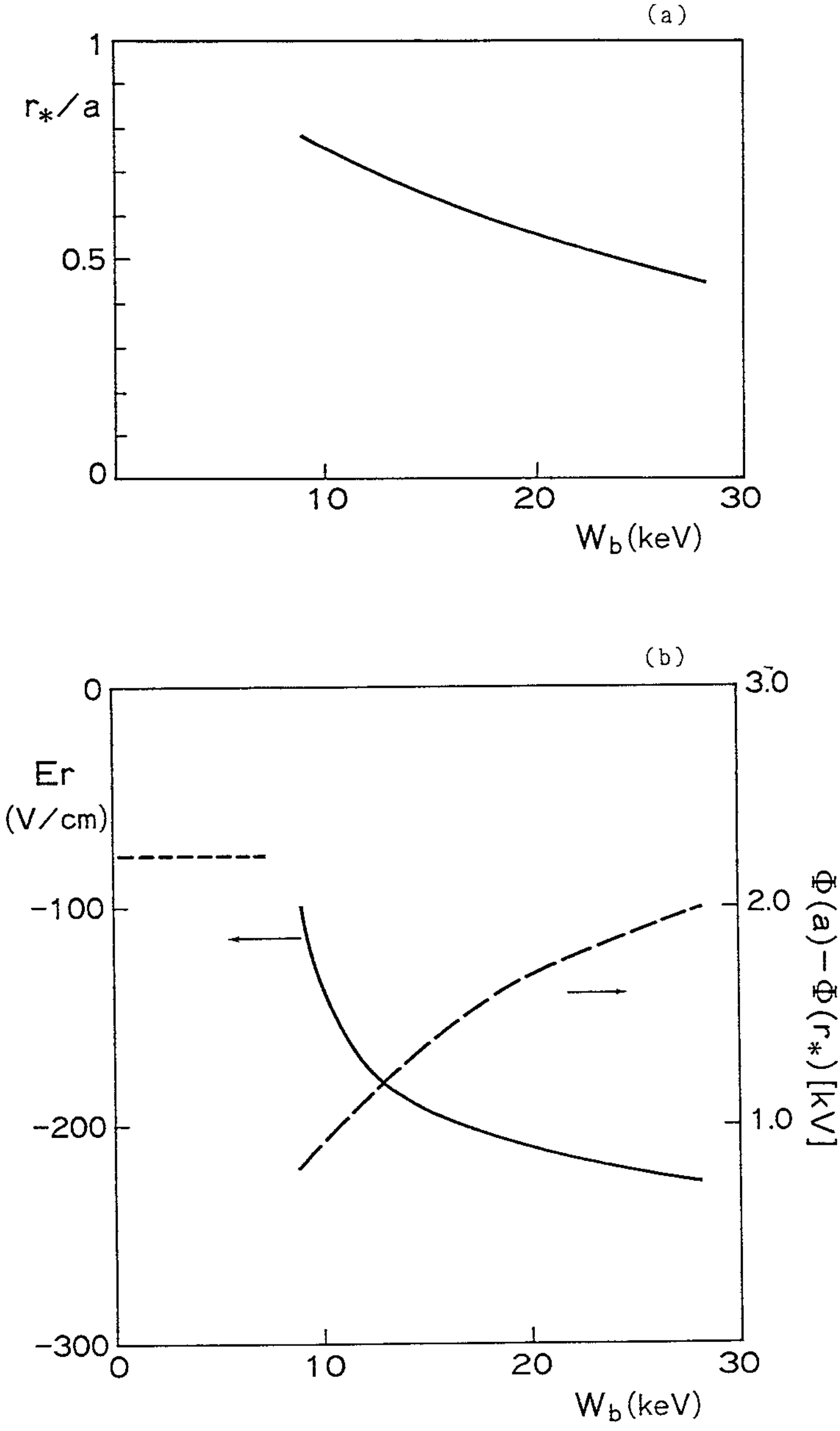


Fig. 4


(a)
1
r*/a
0.5
0
10
20
30
Wb(keV)
(b)
0
Er
(V/cm)
-100
-200
-300
0
10
20
30
Wb(keV)
3.0
2.0
1.0
Φ(a)-Φ(r*) [kV]

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