Correlation between discharged current and neutron production rate for various ion /electron convergences in spherical inertial electrostatic confinement plasmas

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The SIEC fusion system has intrinsic potential for earlier practical use of fusion energy as a compact and economical neutron/proton source, and the studies to improve the system performance are now in progress.

With increasing current ⇨ increment in fuel-ion density

With increasing voltage ⇨ increment in fusion cross section

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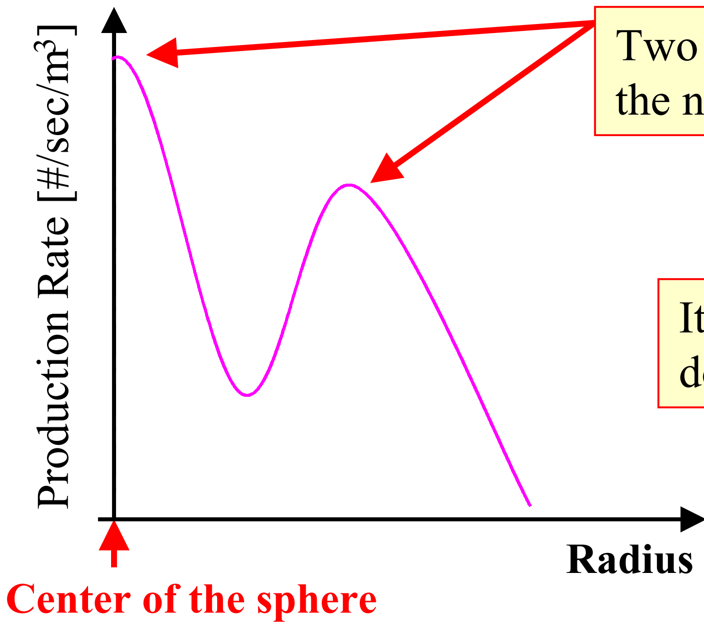
Cathode grid overheating

How can we more efficiently improve the device performance without overheating ?

Phenomena occurring in SIEC devices

(1) ***Double radial peak*** in neutron production rate



Two peaks appear in radial profile of the neutron/proton production rate.

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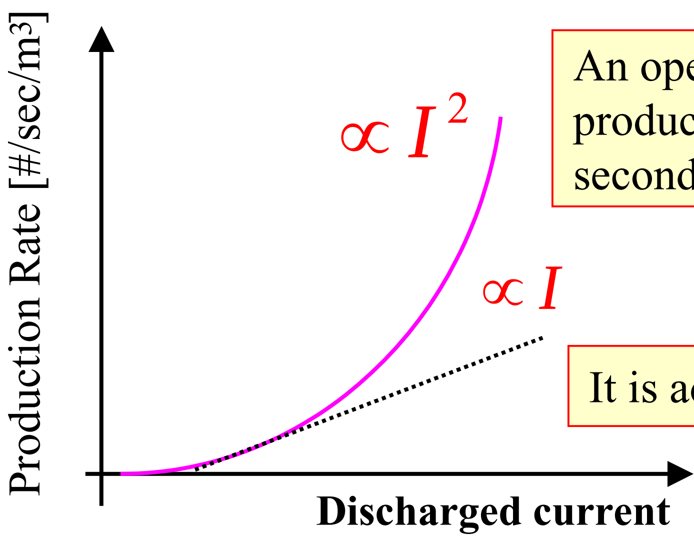
It suggests the formation of the double potential well.

(2) ***I²-scaling*** of neutron production rate



An operation mode in which neutron production rate increases in proportion to second power of the discharged current.

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It is advantageous to the device scaling.

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In order to efficiently improve the device performance, it is important to ***consistently*** understand the phenomena occurring in the SIEC plasmas.

Analysis Model

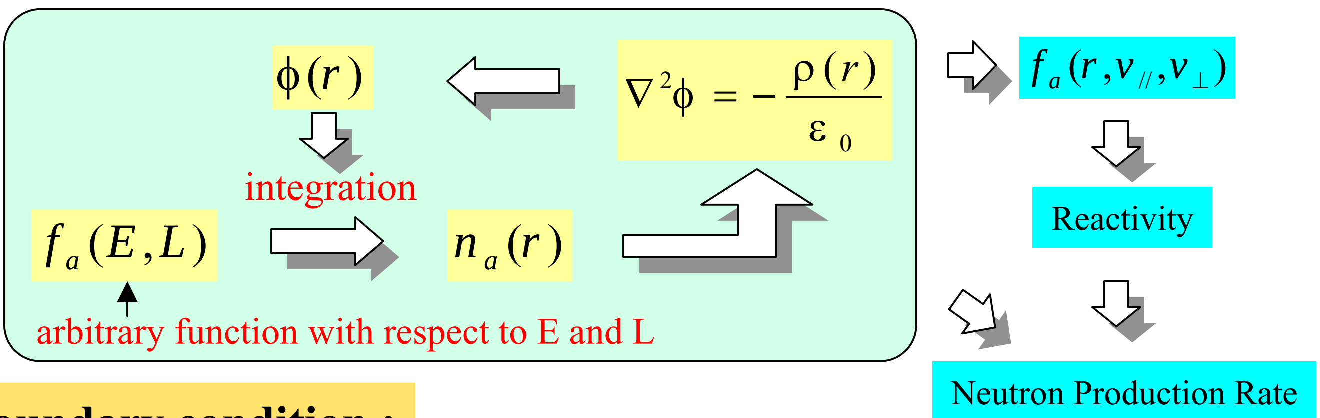
Assumption : weak collisional system

$$\begin{cases} E = 1/2mv^2 + q\phi \\ L = mrv_{\perp} \end{cases} \Rightarrow f_a(E,L) = c_a \exp\left[-\left(\frac{E-\xi_a|q\phi_0|}{\alpha q\phi_0}\right)^2 - \left(\frac{L}{\beta_a L_0}\right)^2\right]$$

$$\begin{cases} \phi_0 \text{ : external voltage} \\ L_0 = r_{cat}\sqrt{2m_a q\phi_0} \end{cases}$$

The deuterons are confined keeping the quantities E and L almost constant.

Poisson equation



Boundary condition :

Inside area of the spherical cathode is considered.

- external voltage at the cathode ϕ_0
- Ion and electron densities at the cathode $n_a^{cat} \longleftarrow I_{meas}$

Following Thorson's treatment, cathode density is related to the measured current:

$$n_{\mathrm{i}}^{cat} = \frac{1}{1-\gamma^2}\frac{1}{1+\delta}\frac{I_{meas}}{4\pi r_{cat}^2\sqrt{2e\phi_0/m_{\mathrm{D}}}\,e}$$

$$n_{\mathrm{e}}^{cat} = \frac{\kappa\delta}{1+\delta}\frac{I_{meas}}{4\pi r_{cat}^2\sqrt{2e\phi_e/m_{\mathrm{e}}}\,e}$$

- transparency factor of inner grid : γ
- number of secondary electrons emitted from the grid due to ion impact : δ
- secondary electrons kinetic energy emitted from the cathode : ϕ_e
- fraction of secondary electrons drawn inside the cathode : κ

Calculations

By using the developed model, ***correlation between discharged current and neutron production rate*** have been investigated for various ion/electron convergences.

(1) When both ion and electron have almost the same convergence

$$\beta_D \approx \beta_e$$

(2) When electron has slightly higher convergence than ion

$$\beta_D \geq \beta_e$$

(3) When electron has much higher convergence than ion

$$\beta_D >> \beta_e$$

It is shown when electron has higher convergence and total (i.e. kinetic plus potential) energy compared with ion, the neutron production rate can increase proportional to more than a power of the discharged current, even if the neutron production is sustained mainly by the fusion reactions between beam (deuteron) and background (deuterium) gas.

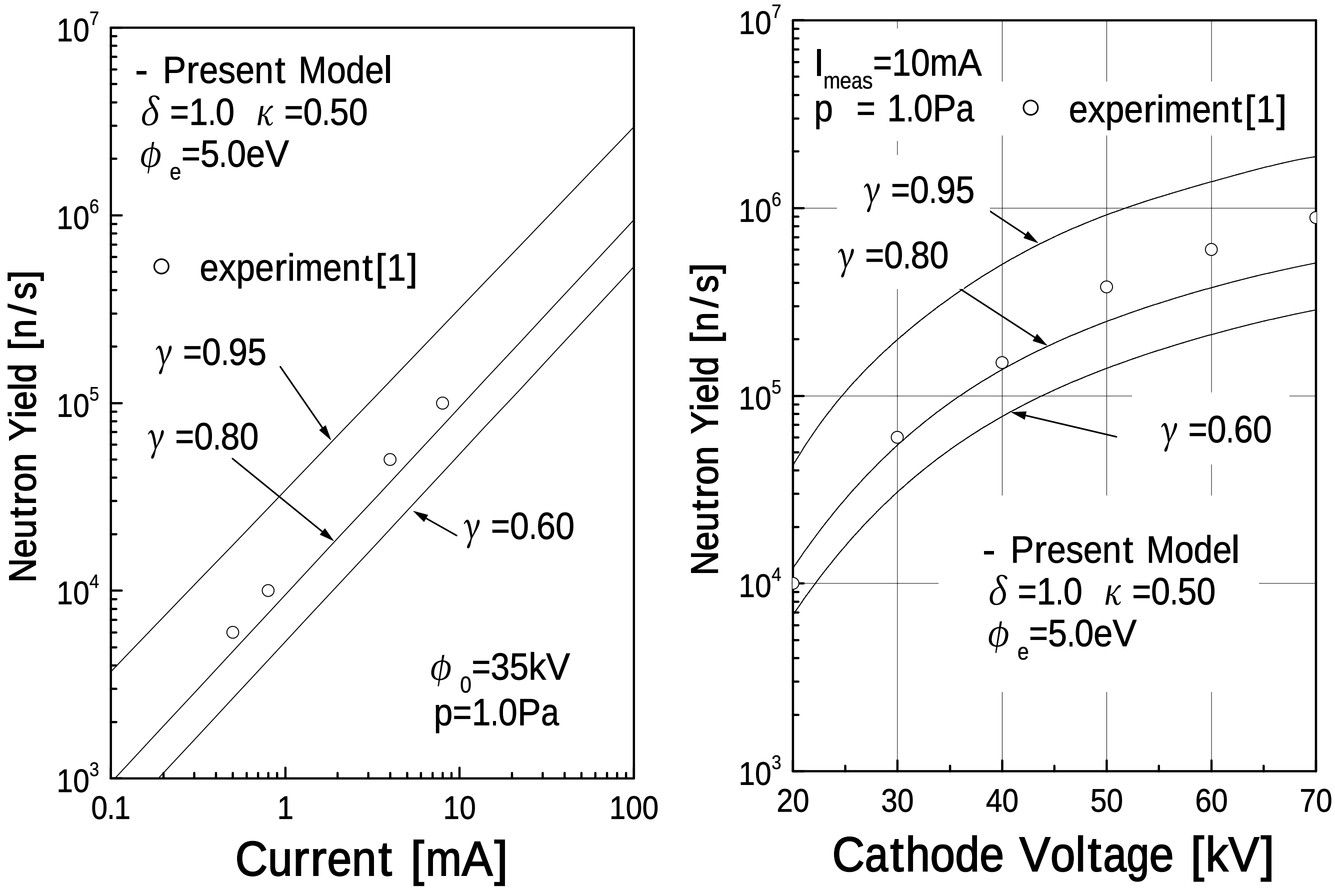
$$f_a(E,L) = c_a \exp\left[-\left(\frac{E - \xi_a |q\phi_0|}{\alpha q \phi_0} \right)^2 - \left(\frac{L}{\beta_a L_0} \right)^2 \right]$$

(1) When both ion and electron have almost the same convergence

D(d,n)^{3}He Neutron Production Rate

$\beta_D = \beta_e = 0.1$

transparency factor of inner grid : γ

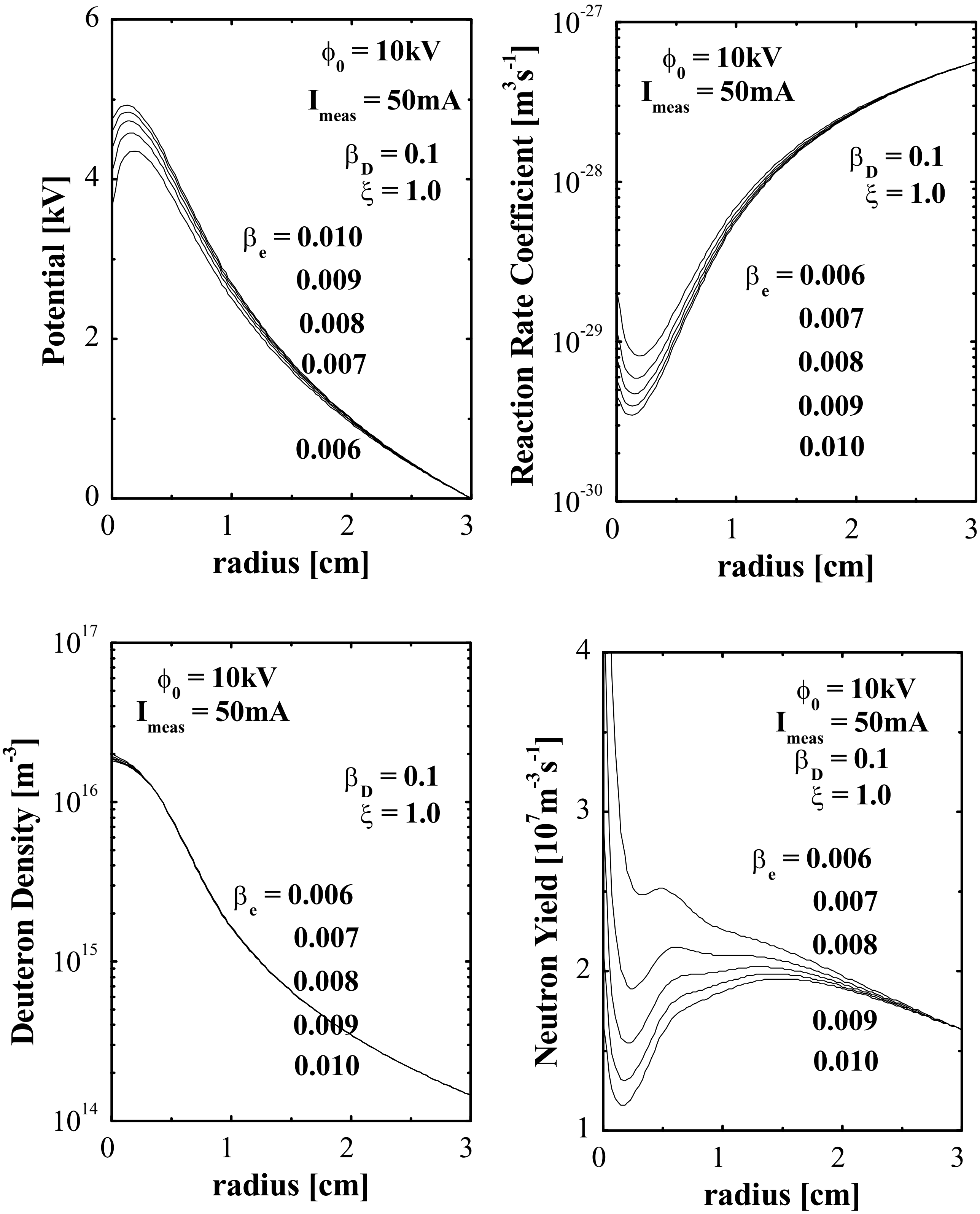


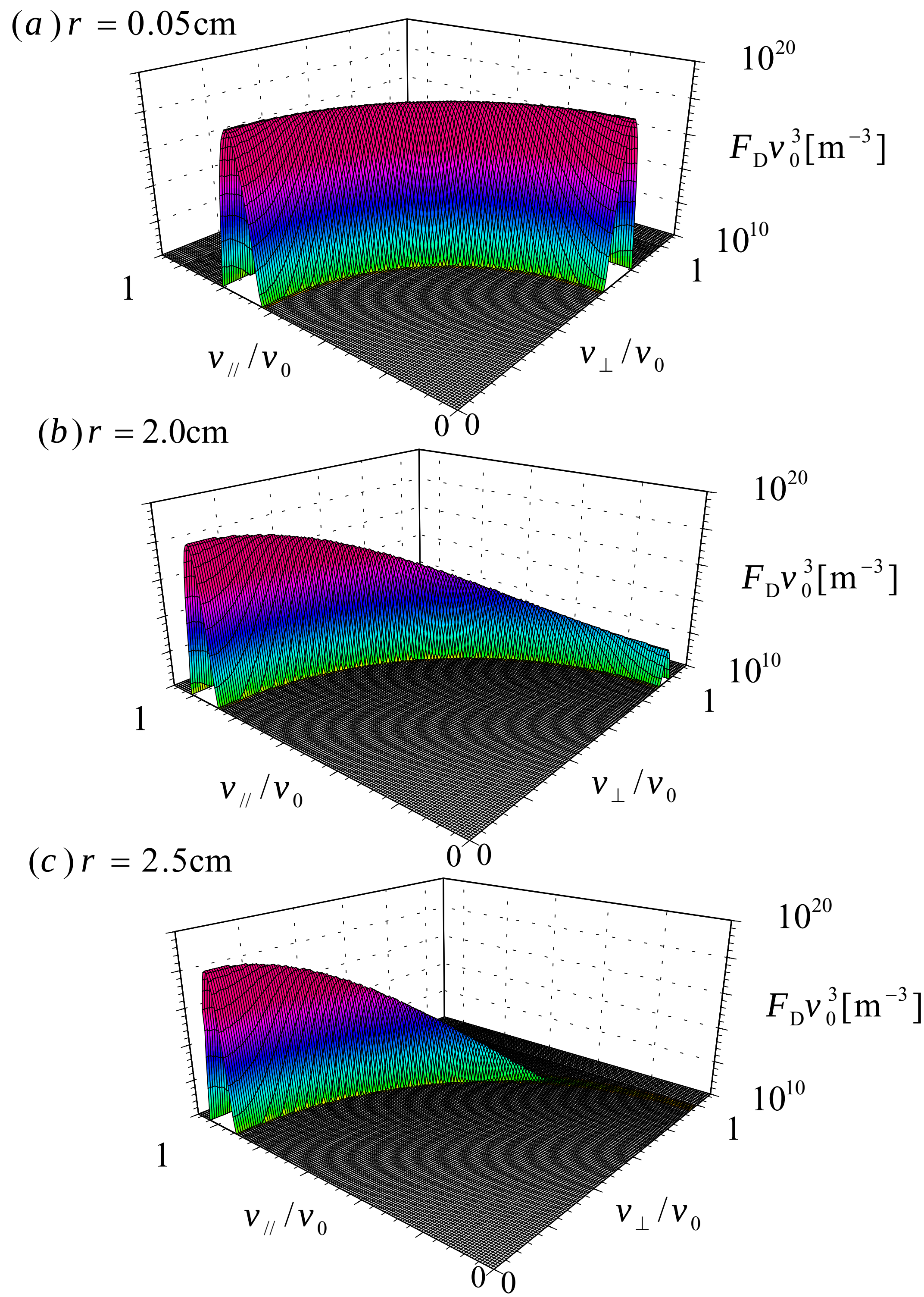
[1] G.H.Miley, et al., Fusion Technol., 19 (1991) 840.

- number of secondary electrons emitted from the grid due to ion impact : $\delta = 1$
- secondary electron energy emitted from the cathode : $\phi_e = 5\mathrm{eV}$
- fraction of secondary electrons drawn inside the cathode : $\kappa = 0.5$

(2) When electron has slightly higher convergence than ion

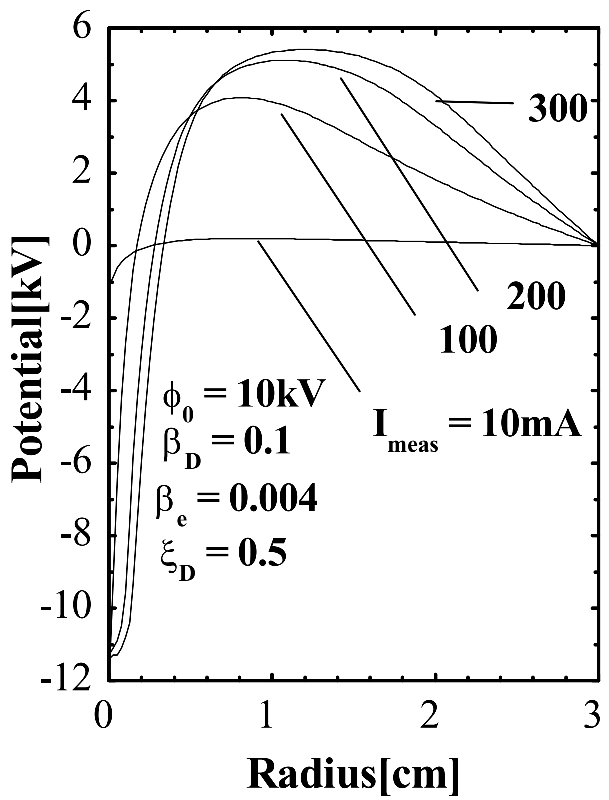
$$\beta_D = 0.1, \beta_e = 0.01$$

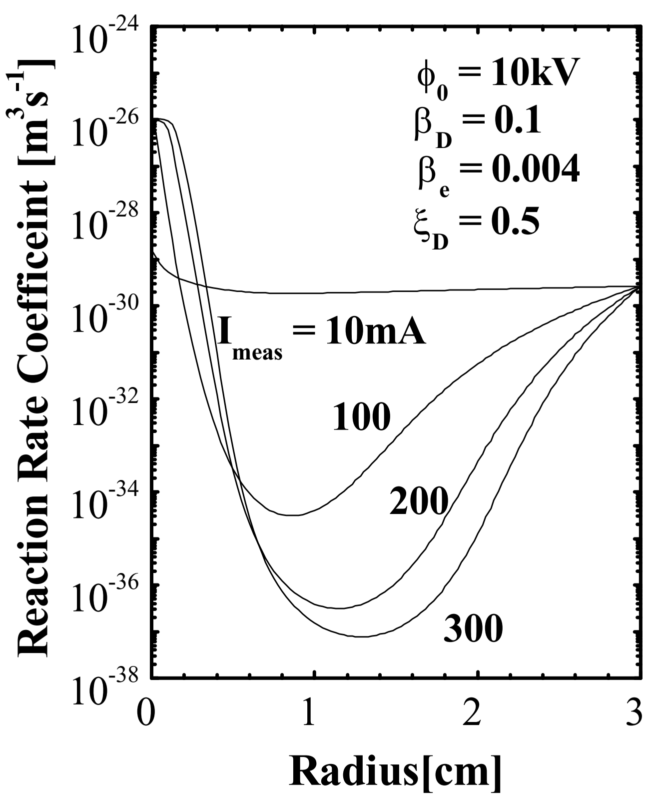


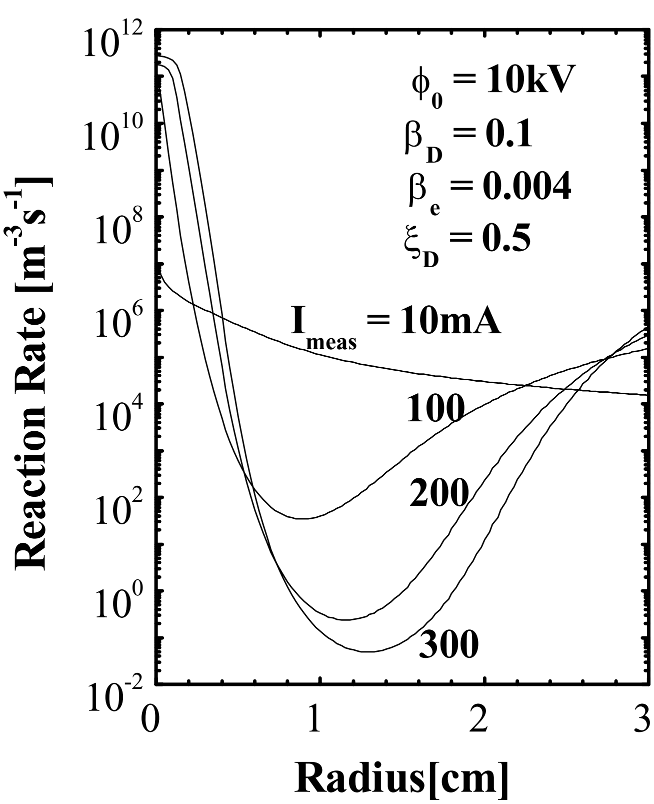

(a) r = 0.05cm
10^20
F_D v_0^3 [m^-3]
10^10
1
v_// / v_0
1
v_⊥ / v_0
0 0
(b) r = 2.0cm
10^20
F_D v_0^3 [m^-3]
10^10
1
v_// / v_0
1
v_⊥ / v_0
0 0
(c) r = 2.5cm
10^20
F_D v_0^3 [m^-3]
10^10
1
v_// / v_0
1
v_⊥ / v_0
0 0

(3) When electron has much higher convergence than ion

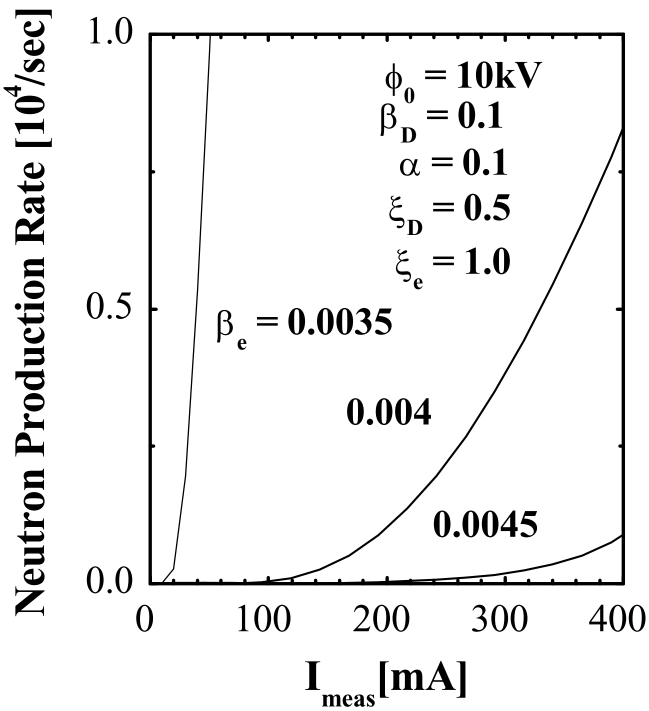
$\beta_D = 0.1, \beta_e = 0.004$



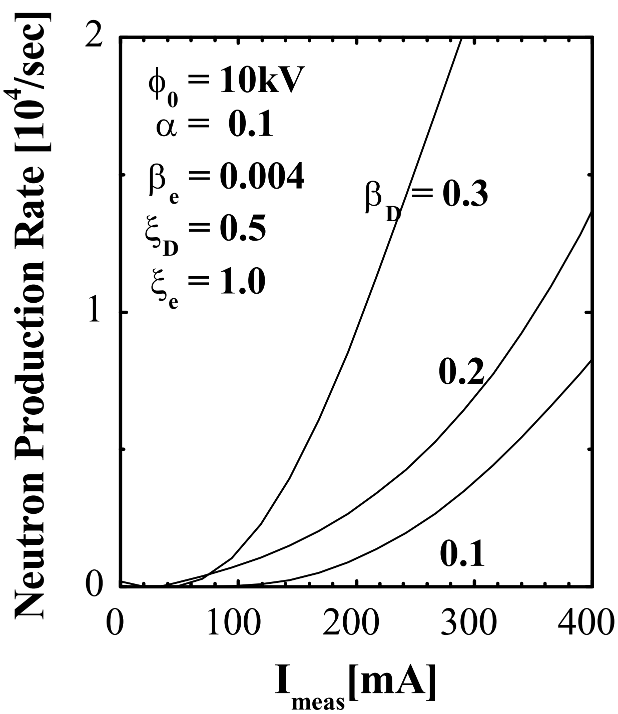




$\beta_D = 0.1, \beta_e = 0.004$



Neutron production rate for several β_e values as a function of the discharged current.



Neutron production rate for several β_D values as a function of the discharged current.

Discussion (1)

(1) Both ion and electron have almost the same convergence

$\beta_D = \beta_e = 0.1$

- The virtual cathode could not be seen.

(Owing to the increased potential, most neutron is produced near the cathode region.)

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- Total neutron production rate ***linearly increases*** proportional to a power of the discharged current.

(2) Electron has slightly higher convergence than ion

$\beta_e = 0.01$

- The virtual cathode begins to appear.

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- Neutron production gradually increase in center core region.

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- ***Double radial peak in neutron production rate*** can appear.

(3) Electron has much higher convergence than ion

$\beta_e = 0.004$

- The double potential well can be clearly formed.

(Most of the neutrons are produced in the center core region.)

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- The $D(d,n)^3He$ fusion cross section rapidly increases in proportion to more than a power of the relative speed between deuteron and background deuterium.

(Depth of the virtual cathode increases with increasing discharged current.)

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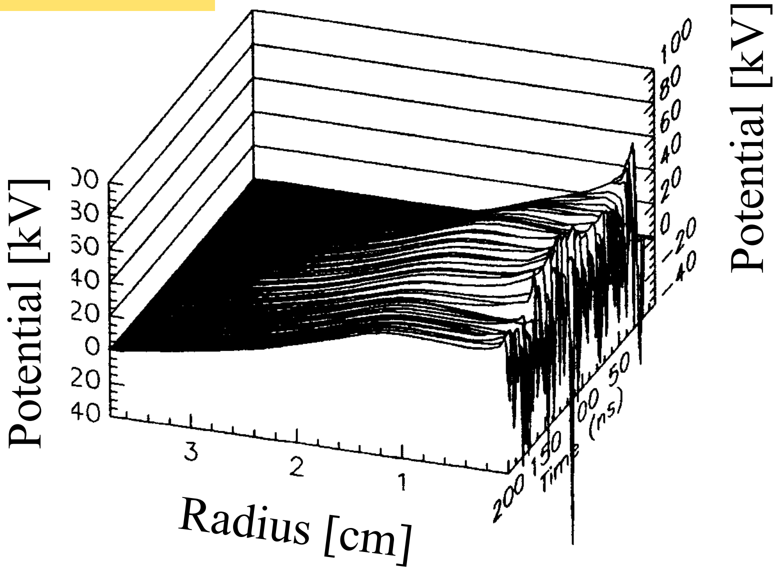
The total neutron production rate also increases ***proportional to more than a power of the discharged current***.

Discussion (2)

Convergence of electrons

PIC simulation



[Ohnishi M., et al., Nucl. Fusion, 37 (1997) 611.]

(The potential well is unstable and oscillates with a period much longer than the inverse ion plasma frequency.)

If electrons have higher convergence than ions in the unstable potential behavior.

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The total neutron production rate would increase ***proportional to more than a power of the discharged current,*** even if the neutron production is sustained mainly by the fusion reactions between beam (deuteron) and background (deuterium) gas.

Summary

By solving the Poisson equation for fixed ion and electron distribution functions, the correlation between ion/electron distribution function and the neutron production rate has been examined.

- The possible mechanism for I^2-scaling in neutron production rate has been presented.

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The study to examine the distribution function itself.

- Boltzmann-Fokker-Planck analysis