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Modeling of the Transport of the Plasma and Neutrals in the Divertor Layer with 1D GARMIT Code

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Modeling of the Transport of the Plasma and Neutrals in the Divertor Layer with 1D GARMIT Code

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Abstract

A simple, one-dimensional model describing the transport of the plasma and neutral gas in the divertor layer and divertor of a tokamak has been developed for parametric studies of the divertor performance. The usual fluid equations along the magnetic field are employed for the plasma transport, while the two components of the neutral flow velocity, along and across the magnetic field, are treated in an one-dimensional fluid approach. Similar terms are added to the energy equations. Both components of neutral gas flow are taken into account in the energy transport with neutrals and the energy balance for the plasma allows for the impurity radiation, and to the continuity equations. Such an approach allows to model, within the framework of simple 1D fluid equations, the effects related with the cross-field transport of neutrals and plasma on the divertor performance, in particular, for the detached plasma regimes presently envisaged in ITER.

I. Geometry

We will consider simple slot divertor geometry (see Fig. 1) where the axis x, y and z are the "radial", "poloidal" and "toroidal" coordinates respectively (Δ_p and Δ are the plasma column and slot widths). We will assume that magnetic field is in the y, z plane and $b=B_y/B<<1$, where B_y and B are the poloidal and total magnetic fields strengths respectively.

II. Equations

We will use fluid equations for the plasma flow along the magnetic field coupled to neutral fluid like equations where neutral - sidewall interaction is taken into account:

Momentum balance equations

$$\frac{\partial}{\partial t}(MnV) = -b\frac{\partial}{\partial y}\left(MnV^2 + P_p + \pi_{p,||}\right) - MnNK_{iN}\left(V - U_{||}\right) + MnNK_I U_{||}, \qquad (1)$$

$$\frac{\partial}{\partial t}(MNU_{||}) = -\frac{\partial}{\partial y}\left(b\left(P_N + MNU_{||}^2\right) - b'\frac{\partial}{\partial y}\eta_N b'\frac{\partial U_{||}}{\partial y}\right) - b'\frac{\partial}{\partial y}(MNU_{\perp}U_{||})$$

$$+\delta MnNK_{iN}\left(V - U_{||}\right) - \delta MnNK_I U_{||} - \nu_W^{(m)} MNU_{||}, \qquad (2)$$

$$\frac{\partial}{\partial t}(MNU_{\perp}) = -b'\frac{\partial}{\partial y}\left(P_N + MNU_{\perp}^2 - \eta_N b'\frac{\partial U_{\perp}}{\partial y}\right) - b\frac{\partial}{\partial y}(MNU_{\perp}U_{||})$$

$$-\delta MnNK_{iN}U_{\perp} - \delta MnNK_I U_{\perp} - \nu_W^{(m)} MNU_{\perp}, \qquad (3)$$

$$eEn = -b\frac{\partial(nT_e)}{\partial y} - 0.71nb\frac{\partial T_e}{\partial y} \qquad (4)$$

Energy balance equations

$$\frac{\partial \varepsilon_i}{\partial t} = -b\frac{\partial}{\partial y}\left\{\left(\frac{MV^2}{2}+\frac{5}{2}T_i\right)nV - b\kappa_{i,\parallel}\frac{\partial T_i}{\partial y}\right\} + eEnV$$

$$-(\varepsilon_i - \varepsilon_N)nNK_{iN} + \varepsilon_N nNK_I + Q_{ie} + Q_i^{heat}, \tag{5}$$

$$\frac{\partial \varepsilon_e}{\partial t} = -b\frac{\partial}{\partial y}\left\{\frac{5}{2}nT_eV - b\kappa_{e,\parallel}\frac{\partial T_e}{\partial y}\right\} - eEnV$$

$$-E_{R,N}nNK_{R,N} - \xi_{imp}n^2 L(T_e) - Q_{ie} + Q_e^{heat}, \tag{6}$$

$$\frac{\partial \varepsilon_N}{\partial t} = -\frac{\partial}{\partial y}\left\{\left(\frac{MU^2}{2}+\frac{5}{2}T_N\right)N(bU_\parallel + b'U_\perp) - \kappa_N\frac{\partial T_N}{\partial y}\right\}$$

$$+\delta(\varepsilon_i - \varepsilon_N)nNK_{iN} - \delta\varepsilon_N nNK_I - \nu_W^{(\varepsilon)}N(\varepsilon_N - T_W), \tag{7}$$

Continuity equations

$$\frac{\partial n}{\partial t} + \frac{\partial}{\partial y}(bnV) = nNK_I - S_{W,p}, \tag{8}$$

$$\frac{\partial N}{\partial t} + \frac{\partial}{\partial y}\left\{N(bU_\parallel + b'U_\perp)\right\} = -\delta nNK_I + S_{W,N}, \tag{9}$$

where $\delta = \Delta_p/\Delta$, $b = B_y/B$, $b' = (1-b^2)^{1/2}$,

$$\varepsilon_N = \frac{MU^2}{2} + \frac{3}{2}T_N, \qquad \varepsilon_i = \frac{MV^2}{2} + \frac{3}{2}T_i, \qquad \varepsilon_e = \frac{3}{2}T_e,$$

$$\nu_W^{(..)} = \left(C_W^{(..)} \tau_W + C_{Ni}^{(..)} \tau_{Ni} + C_{NN}^{(..)} \tau_{NN} \right)^{-1},$$

$$\tau_W = \frac{\Delta}{V_{T,N}}, \qquad \tau_{Ni} = K_{iN}\, n \left(\frac{\Delta_p}{V_{T,N}} \right)^2, \qquad \tau_{NN} = K_{NN}\, N \left(\frac{\Delta}{V_{T,N}} \right)^2,$$

n (V) and N ($\vec{U}$) are the plasma and neutral densities (velocities), P_p and P_N are the plasma and neutral pressures, $P_p=n(T_e+T_i)$; $\pi_{(..)}$ are the plasma and neutral viscosity terms, $S_{W,N}$ is the neutral source from the side walls, and $S_{W,p} = n\left(D/\Delta^2\right)$ is the plasma sink due to plasma diffusion onto the sidewalls, the coefficients $C_W^{(..)}$, $C_{Ni}^{(..)}$, and $C_{NN}^{(..)}$ determind neutral momentum and energy transport onto the sidewalls. The ionization, hydrogen radiation/ionization energy loss, and ion-neutral collision (charge exchange and elastic) rate constants are denoted by K_I, K_R, and K_{iN}, respectively. We omit here the influence of the thermal force on the relative velocities of plasma and neutral species and the heat transport.

To close system of the equations (1) - (9) we impose usual boundary conditions for plasma equations at the target.

III. Boundary Condition for Neutral Fluid Equations in SOL Plasma on Material Surface

To impose boundary conditions (BC) for neutral fluid equations in a SOL plasma at a material surface it is necessary to consider the neutral distribution function in front of material surface (see Fig. 1). It is useful to distinguish (at a distance from the material surface of about a neutral charge exchange mean free path) three kinds of atomic neutrals, so that the total neutral distribution function f_N can be written as

$$f_N = f_{Ni} + f_{(+)} + f_{(-)} , \qquad (10)$$

where f_{Ni} is the distribution function of the neutrals generated by ion recombination at the surface and backscattering as a neutrals, $f_{(+)}$ is the distribution function of the incoming neutrals onto the surface, and $f_{(-)}$ is the distribution function of the neutrals leaving the surface due to reflection of the incident neutrals.

To describe the relation between incoming and outcoming particles one can use the "reflection" operator $\hat{R}$ describing all the features of the ion/neutral reflection from a material surface. In the general case one gets

$$f_{out}(\vec{v}) = \hat{R}\left(f_{in}(\vec{v}')\right) \equiv \int \Omega(\vec{v},\vec{v}')f_{in}(\vec{v}')d\vec{v}' , \qquad (11)$$

where Ω is the kernal relating the incoming and outgoing particles. Using the operator $\hat{R}$ one gets the following relation for the function f_{Ni},

$$f_{Ni} = \hat{R}\left(\hat{S}\left(f_i\right)\right) , \qquad (12)$$

where f_i is ion distribution function at the entrance into the presheath, and operator $\hat{S}$ describes the modification of function f_i after the transition through the presheath and sheath. For the functions $f_{(+)}$ and $f_{(-)}$ one has $f_{(-)} = \hat{R}\left(f_{(+)}\right)$. The function $f_{(+)}$ describes neutrals incoming onto the target at a distance from the material surface of about a neutral charge exchange mean free path where the neutral and ion distribution functions are similar. Thus, one has

$$f_{(+)} = g_{(+)} f_i(\vec{v}) \cdot \Theta(-v_{norm}), \tag{13}$$

$$f_{(-)}(\vec{v}) = g_{(+)} \hat{R}\left(f_i(\vec{v}') \cdot \Theta(-v'_{norm})\right), \tag{14}$$

where $g_{(+)}$ is the numerical factor describing the density of incoming ions; v_{norm} is the component of the velocity vector normal to the material surface; $\Theta(x)=1$ for $x>1$, and $\Theta(x)=0$ for $x<0$.

Putting expressions (12)-(14) in Eq. (1) one has

$$f_N = \hat{R}\left(\hat{S}(f_i)\right) + g_{(+)}\left\{f_i \cdot \Theta(-v_{norm}) + \hat{R}\left(f_i \cdot \Theta(-v'_{norm})\right)\right\}. \tag{15}$$

Assuming that the total neutral density near the target, N, is known, the factor $g_{(+)}$ can be found from Eq. (15)

$$g_{(+)} = \frac{N - \int \hat{R}\left(\hat{S}(f_i)\right) d\vec{v}}{\int \left[f_i \cdot \Theta(-v_{norm}) + \hat{R}\left(f_i \cdot \Theta(-v'_{norm})\right)\right] d\vec{v}}. \tag{16}$$

Thus, from Eqs. (15), and (16) one, finally, has the expression for the neutral distribution function near the material surface

$$f_N = \hat{R}\left(\hat{S}(f_i)\right) + \left\{f_i \cdot \Theta(-v_{norm}) + \hat{R}\left(f_i \cdot \Theta(-v'_{norm})\right)\right\}$$
$$\times \frac{N - \int \hat{R}\left(\hat{S}(f_i)\right) d\vec{v}}{\int \left[f_i \cdot \Theta(-v_{norm}) + \hat{R}\left(f_i \cdot \Theta(-v'_{norm})\right)\right] d\vec{v}}. \tag{17}$$

Knowing the distribution function (17) one can use it to calculate the energy and momentum fluxes needed to close the system of neutral fluid equations containing second derivatives of the neutral velocity (viscosity term) and temperature (heat conduction term).

However, the general expression (17) is very difficult to use in fluid codes since it contains 3 dimensional integrals over velocity space (see Eq. (11)) and, therefore, is very time consuming.

To simplify the problem we will assume that when $\hat{R}$ operates on any distribution function of incoming particles, f, it gives a half Maxwellian distribution function of reflected particles, that is

$$\hat{R}(f) \rightarrow f_{1/2}^{Max}(\vec{v}) = 2N_f \left(\frac{2T_f}{\pi M}\right)^{3/2} \exp\left(-\frac{Mv^2}{2T_f}\right) \Theta(v_{norm}) , \qquad (18)$$

where the density N_f (N_{Ni}, and $N_{(-)}$) and temperature T_f (T_{Ni}, and $T_{(-)}$) of r eflected particles have to be determind by the basic scalar properties of reflection which are described by the particle, R_N, and energy, R_E, reflection coefficients.

Assuming that R_N= const. while R_E depends on the incident particle energy ($R_E \equiv R_E(\ldots)$), from Eqs. (12)-(14), (17), and (18) one has

$$2T_{(-)} = \left(2T_i + Mv_\parallel^2/2\right) R_E\left(2T_i + Mv_\parallel^2/2\right) , \qquad (19)$$

$$2T_{Ni} = E_{Si} R_E(E_{Si}) , \qquad (20)$$

$$N_{Ni} = j_{p,\perp} R_N \sqrt{\pi M/2T_{Ni}} , \qquad (21)$$

$$N_{(+)} = \left\{N - N_{Ni}\right\}\left\{1 + R_N\sqrt{T_i/T_{(-)}}\right\}^{-1} , \quad (22)$$

$$N_{(-)} = \left\{N - N_{Ni}\right\}\left\{1 + \sqrt{T_{(-)}/T_i}\,/\,R_N\right\}^{-1} , \quad (23)$$

$$j_{(+),\perp} = \sqrt{2T_i/\pi M}\, N_{(+)} , \quad (24)$$

where $N_{(+)}$ is the density of oncoming neutrals; $v_{||}$ is parallel plasma flow velocity; $j_{p,\perp}$ and $j_{(+),\perp}$ are the ion and incoming neutral fluxes onto the surface; E_{sh} is characterized the energy of the ions after their passing through the sheath. Note that the relations (19)-(13) was obtained with assumption that the inclanation of the magnetic field line to the surface is small.

From Eqs. (18)-(14) one can easy calculate neutral energy flux onto material surface, $q_{N,\perp}$, and neutral parallel, $\Pi_{N,||}$, and perpendicular, $\Pi_{N,\perp}$, momentum flux needed to close the system of neutral fluid equations

$$q_{N,\perp} = E_{sh} R_N R_E\left(E_{sh}\right) j_{p,\perp}$$

$$+ \left(2T_i + Mv_{||}^2/2\right)\left[1 - R_N R_E\left(2T_i + Mv_{||}^2/2\right)\right] j_{(+),\perp} , \quad (24)$$

$$\Pi_{N,||} = N_{Ni} T_{Ni} + N_{(+)}\left(T_i + Mv_{||}^2\right) + N_{(-)} T_{(-)} , \quad (25)$$

$$\Pi_{N,\perp} = N_{Ni} T_{Ni} + N_{(+)} T_i + N_{(-)} T_{(-)} . \quad (26)$$

IV. Results

We have investigated SOL plasma behavior for the following input parameters: poloidal length 1 m, $b = B_y/B = 0.1$, $C_W^{(..)} = 1$, $C_{Ni}^{(..)} = C_{NN}^{(..)} = 0$, $\delta = \Delta_p/\Delta = 0.02$ (which correspond to Knudsen like regime of neutral transport), $\Delta = 0.05$ m, averaged plasma density was 10^{20} m^{-3}. We neglected plasma diffusion to the sidewalls and sidewall's neutral sources and assumed 100% plasma recycling at the target. Electron and ion heating sources was equal and located at a halh of the poloidal length upstream (total heat flux in poloidal direction was 50 MW/m^2).

We investigated the effect of impurity radiation losses (neon) on the SOL plasma parameters assuming coronal equilibrium and $\xi_I(y)$=const.

We have found (see Figs. 2-4) that increasing the radiation losses plasma detaches from the target and plasma density "hemp" moves away from the target.

V. Conclusions

Strong energy radiation losses in the SOL plasma causes the decrease of the heat flux to the recycling region. Decrease of the heat flux into recycling region below some critical value leads to

- plasma pressure drop
- decrease of the plasma and heat fluxes on the target
- PLASMA DETACHMENT

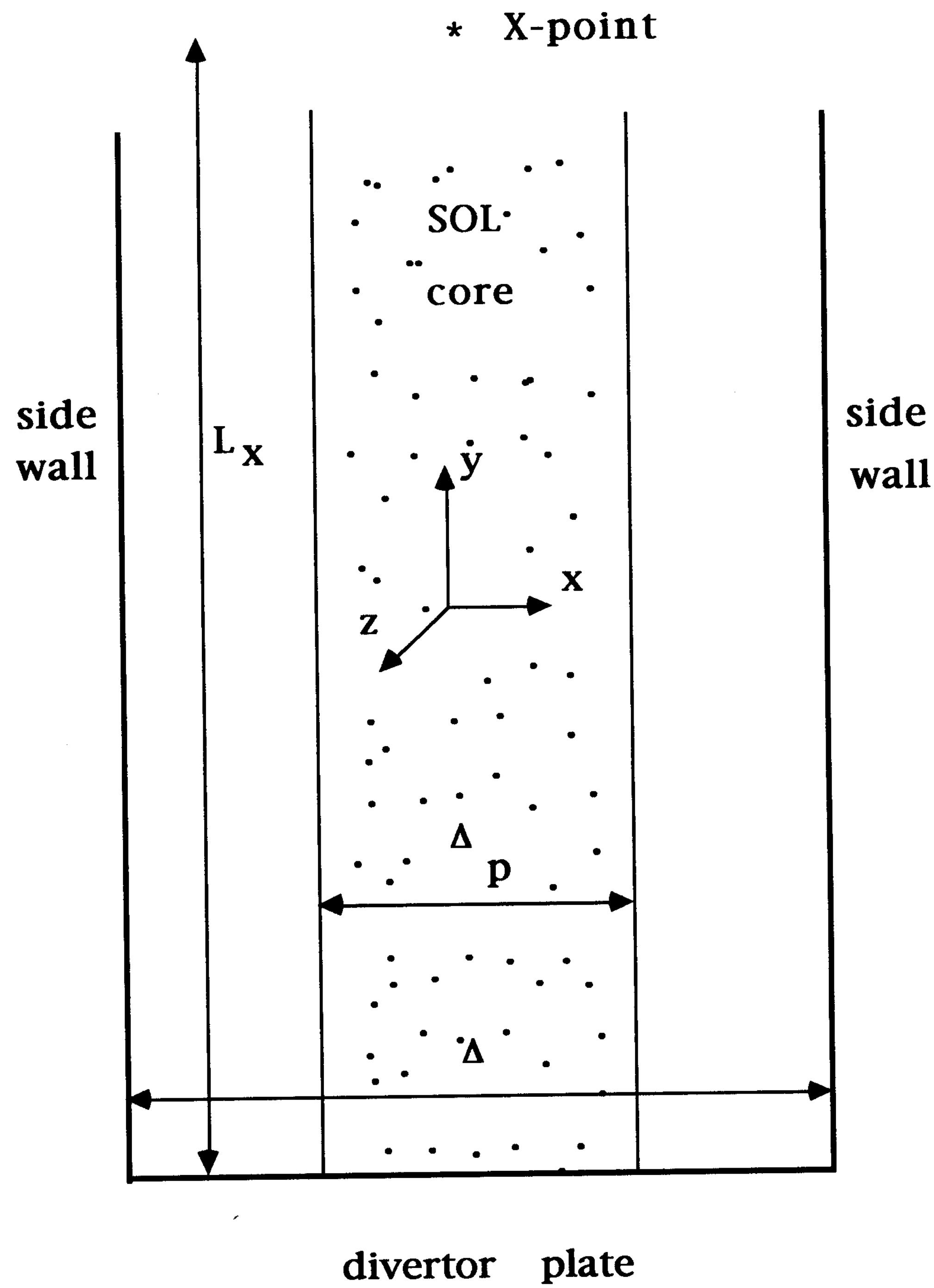
Figure Captions

Fig.1. Geometry of the problem.

Fig. 2. Dependencies of electron temperature, and the ratio of heat flux onto the target versus total incoming flux on ξ_I.

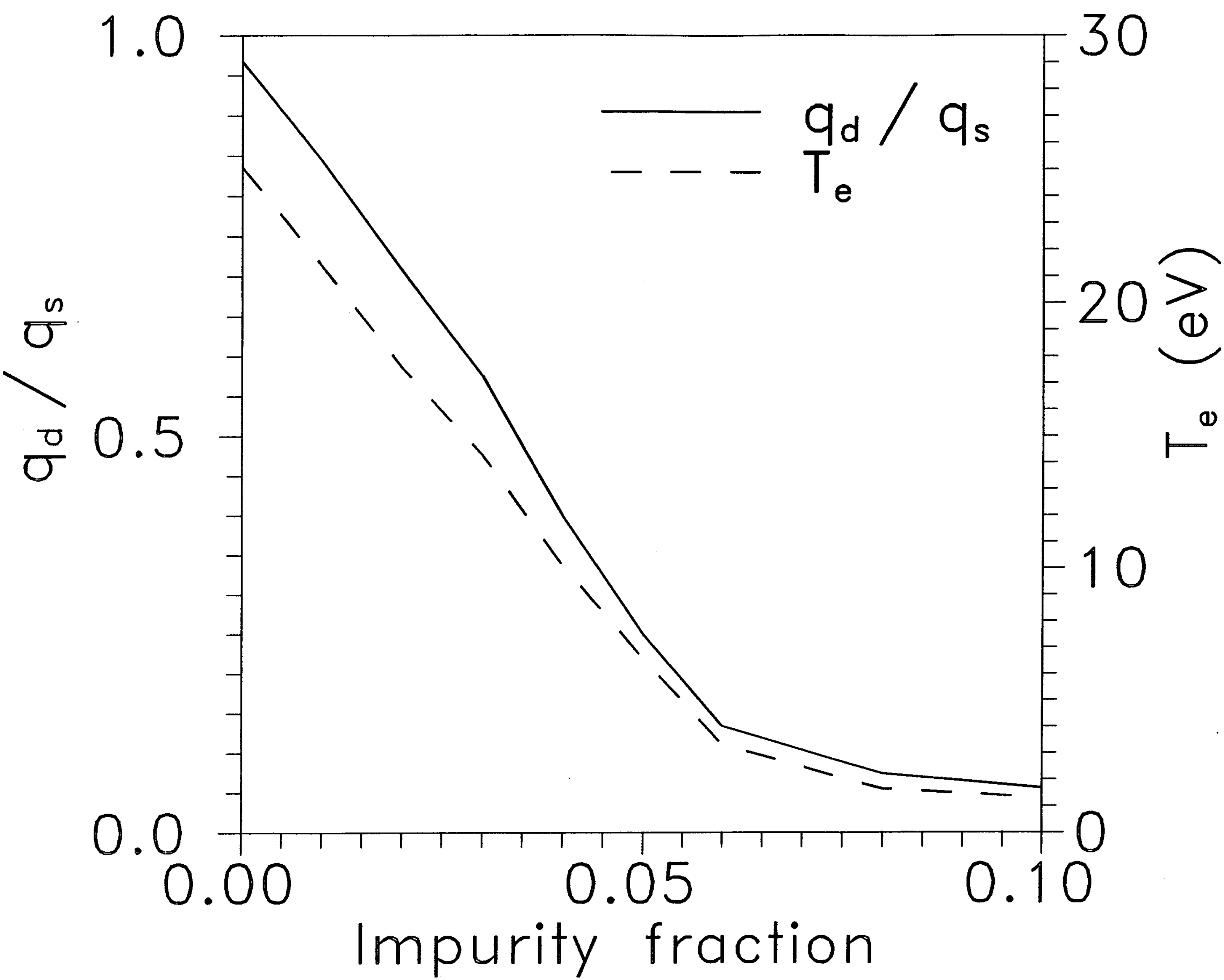
Fig. 3. Plasma parameter (temperatures; plasma, n, and neutral, N, densities; plasma pressure, P) and energy loss profiles for $\xi_I = 0.01$.

Fig. 4. Plasma parameter (temperatures; plasma, n, and neutral, N, densities; plasma pressure, P) and energy loss profiles for $\xi_I = 0.1$.



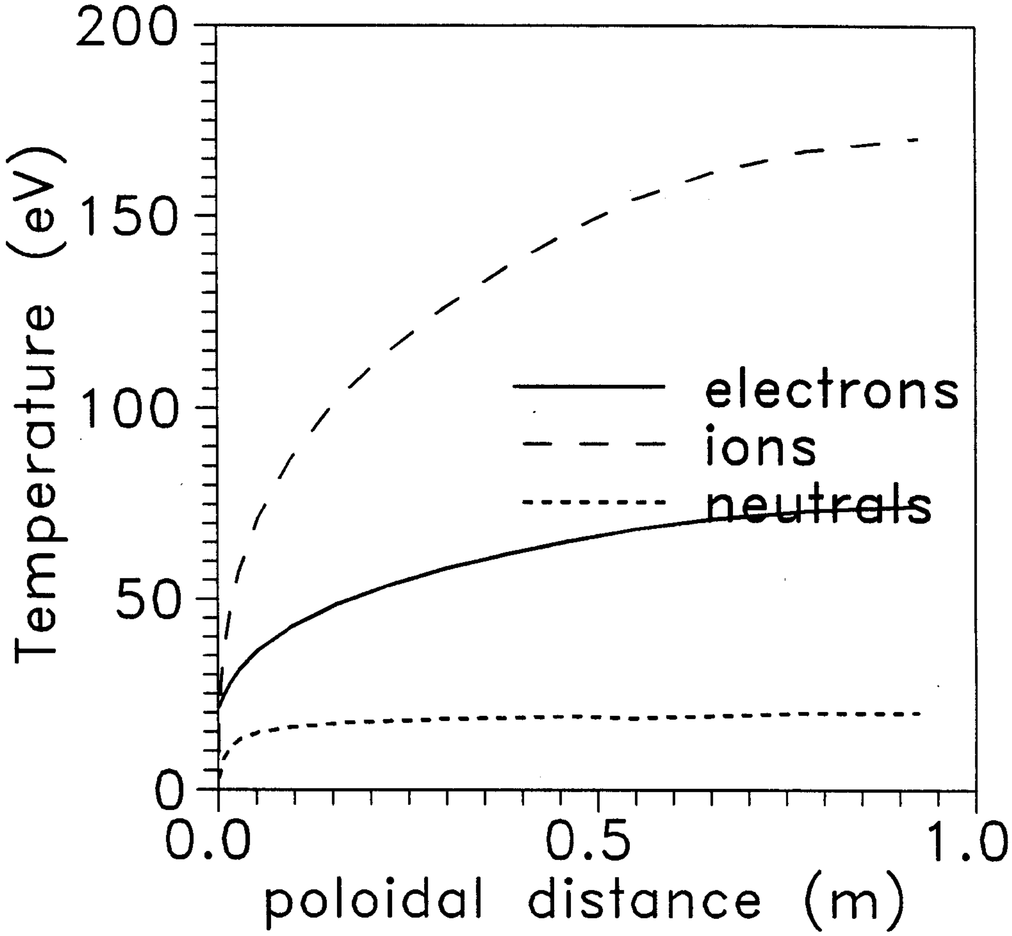
* X-point
SOL
core
side wall
L x
y
x
z
side wall
Δ p
Δ
divertor plate

Fig. 1.

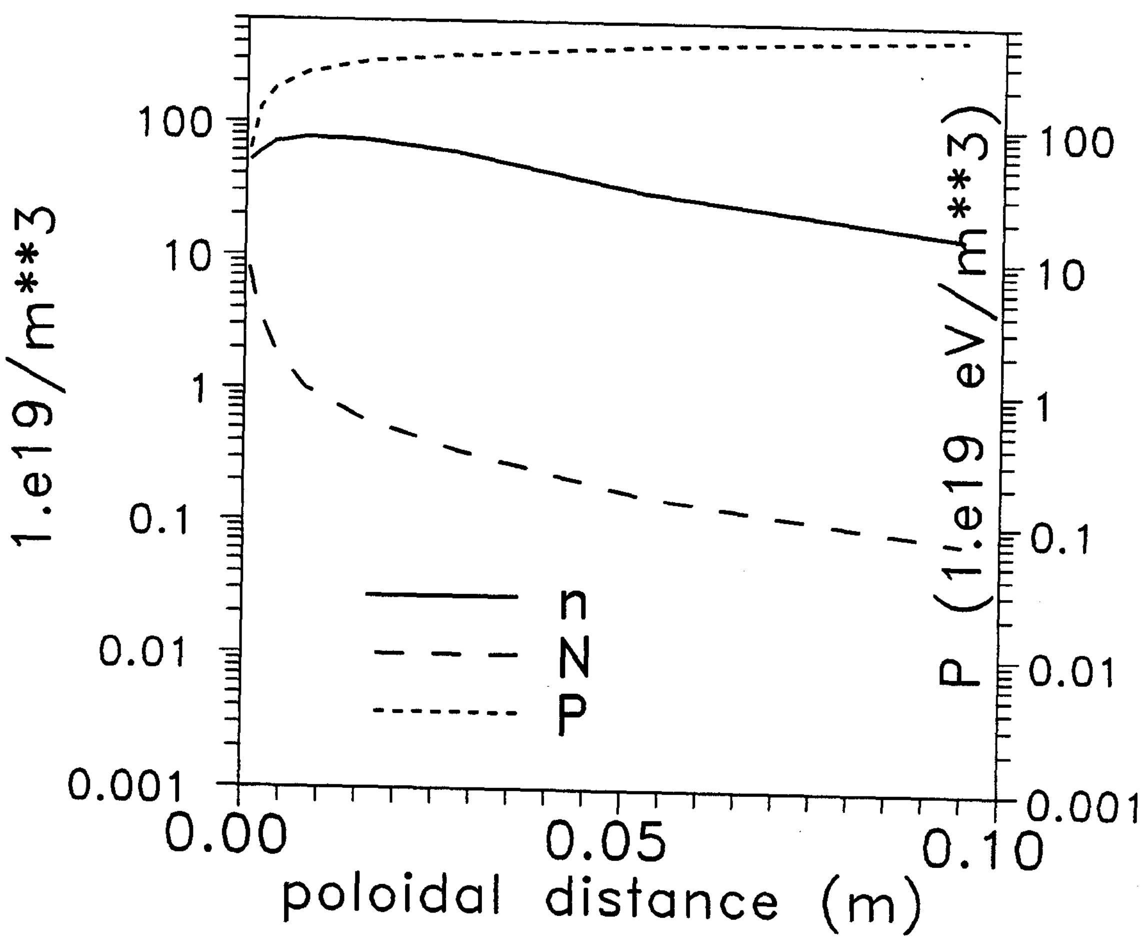


1.0
0.5
0.0
q_d / q_s
30
20
10
0
T_e (eV)
q_d / q_s
T_e
0.00
0.05
0.10
Impurity fraction

Fig. 2

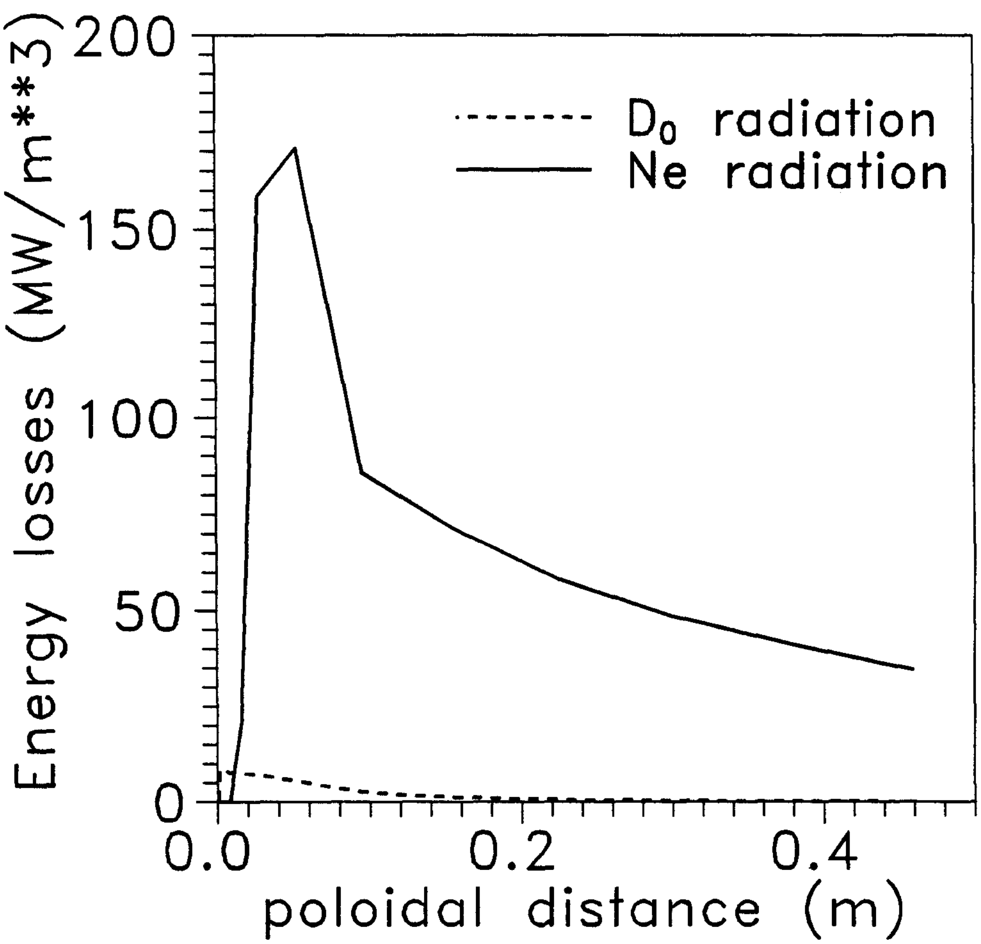

200
150
100
50
0
Temperature (eV)
0.0
0.5
1.0
poloidal distance (m)
electrons
ions
neutrals

3a



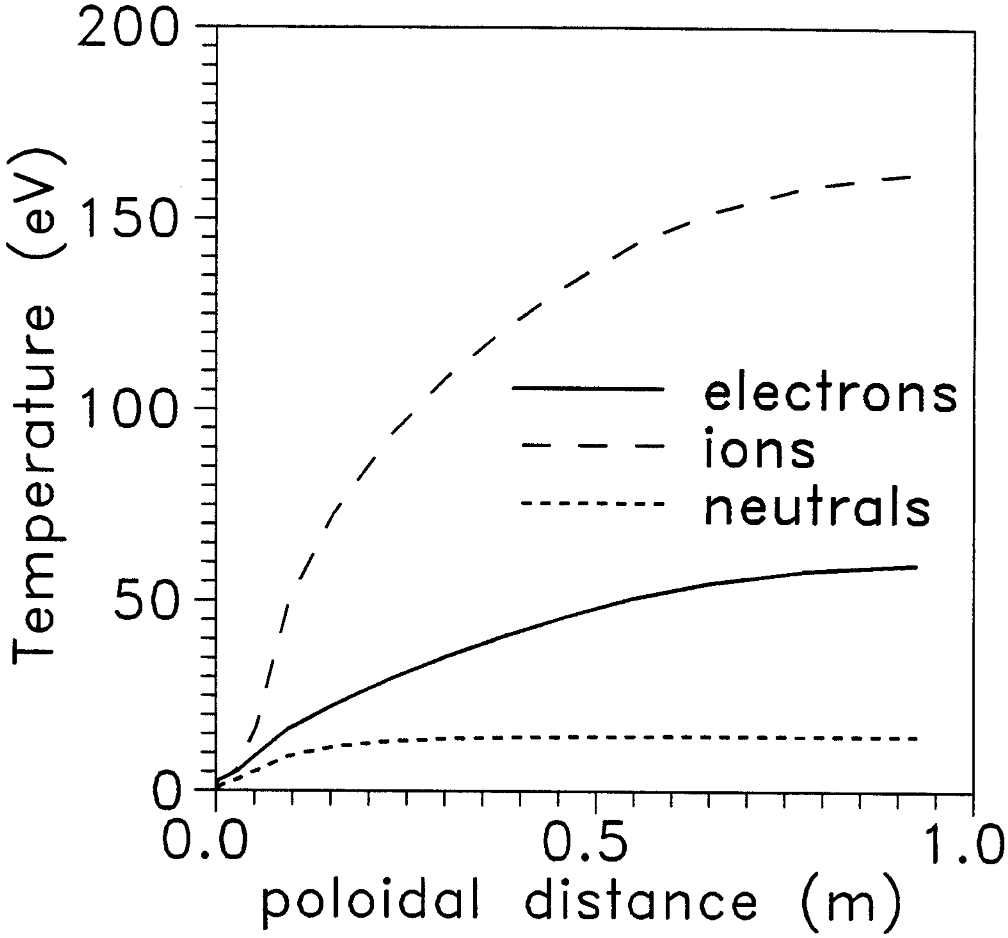
100
10
1
0.1
0.01
0.001
1.e19/m**3
100
10
1
0.1
0.01
0.001
P (1.e19 eV/m**3)
n
N
P
0.00
0.05
0.10
poloidal distance (m)

3.6

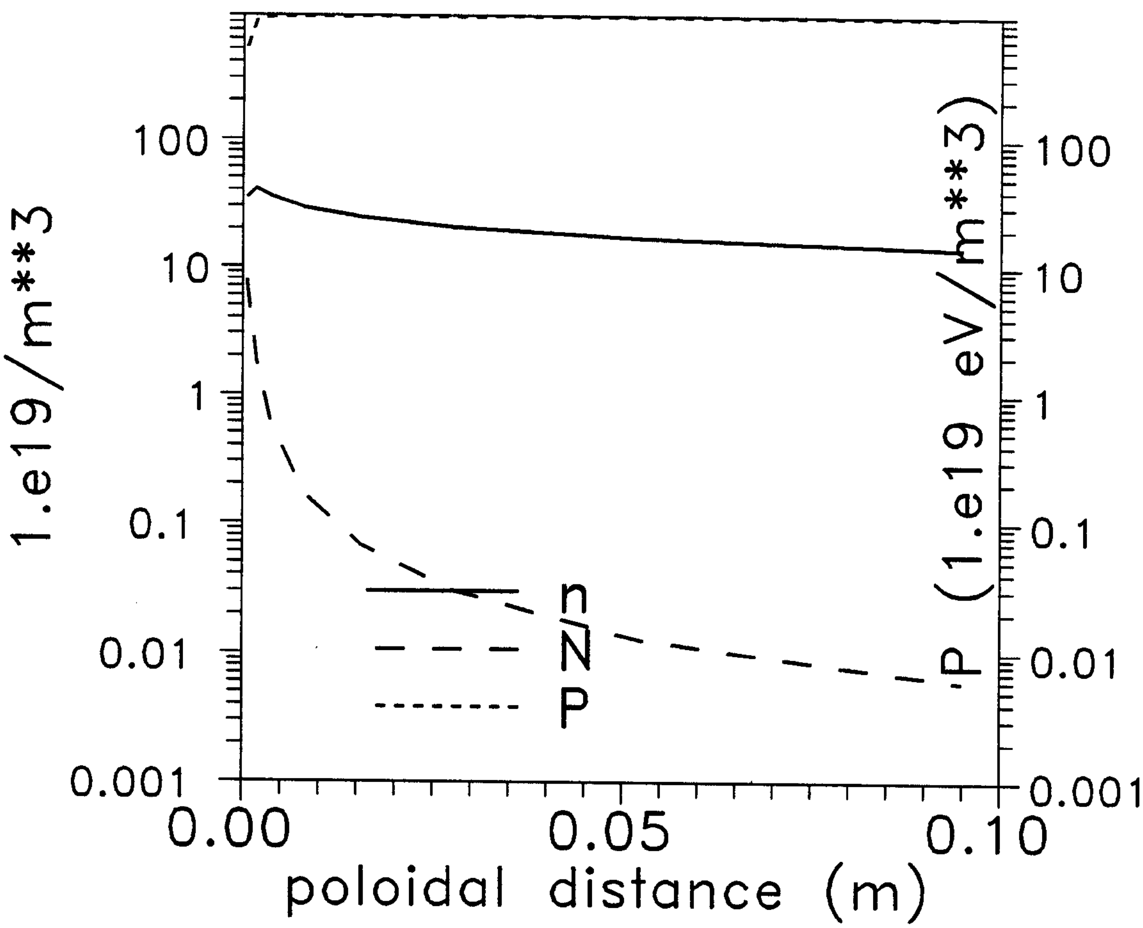


Energy losses (MW/m**3)
200
150
100
50
0
0.0
0.2
0.4
poloidal distance (m)
D0 radiation
Ne radiation

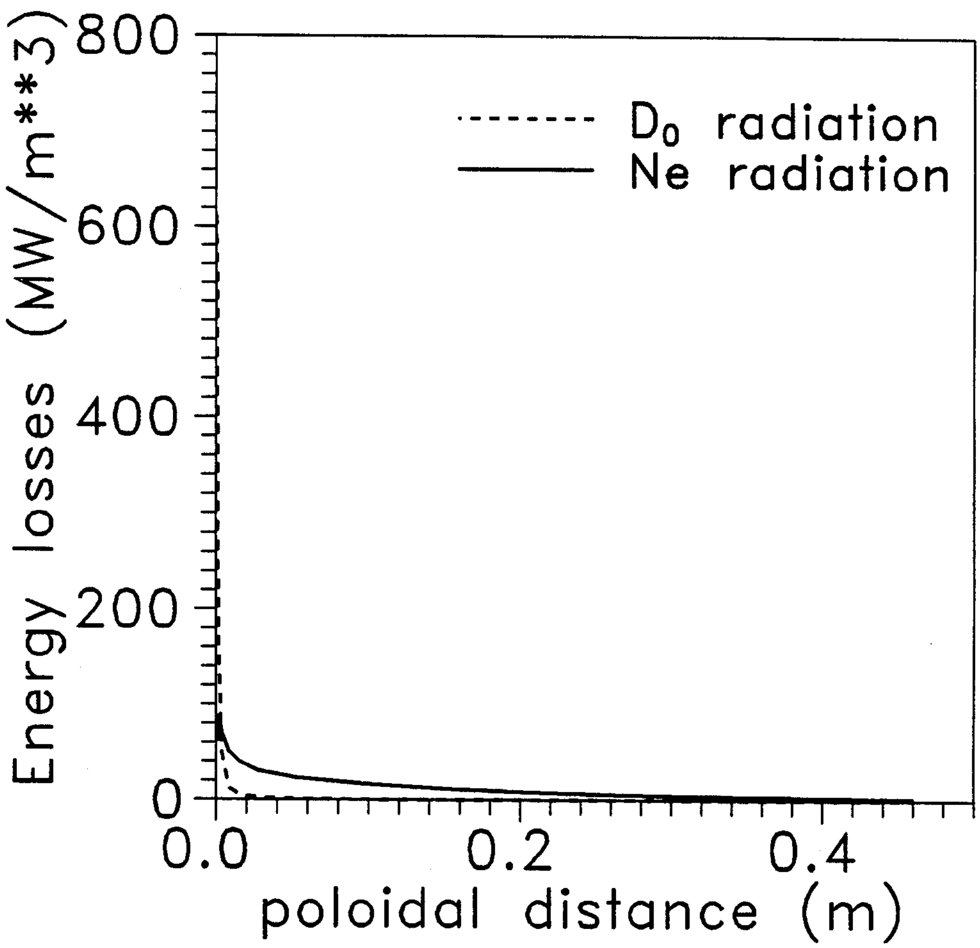
3c


200
150
100
50
0
Temperature (eV)
0.0
0.5
1.0
poloidal distance (m)
electrons
ions
neutrals

4a


100
10
1
0.1
0.01
0.001
1.e19/m**3
n
N
P
P (1.e19 eV/m**3)
0.00
0.05
0.10
poloidal distance (m)

46



800
600
400
200
0
0.0
0.2
0.4
Energy losses (MW/m**3)
poloidal distance (m)
D0 radiation
Ne radiation

4c