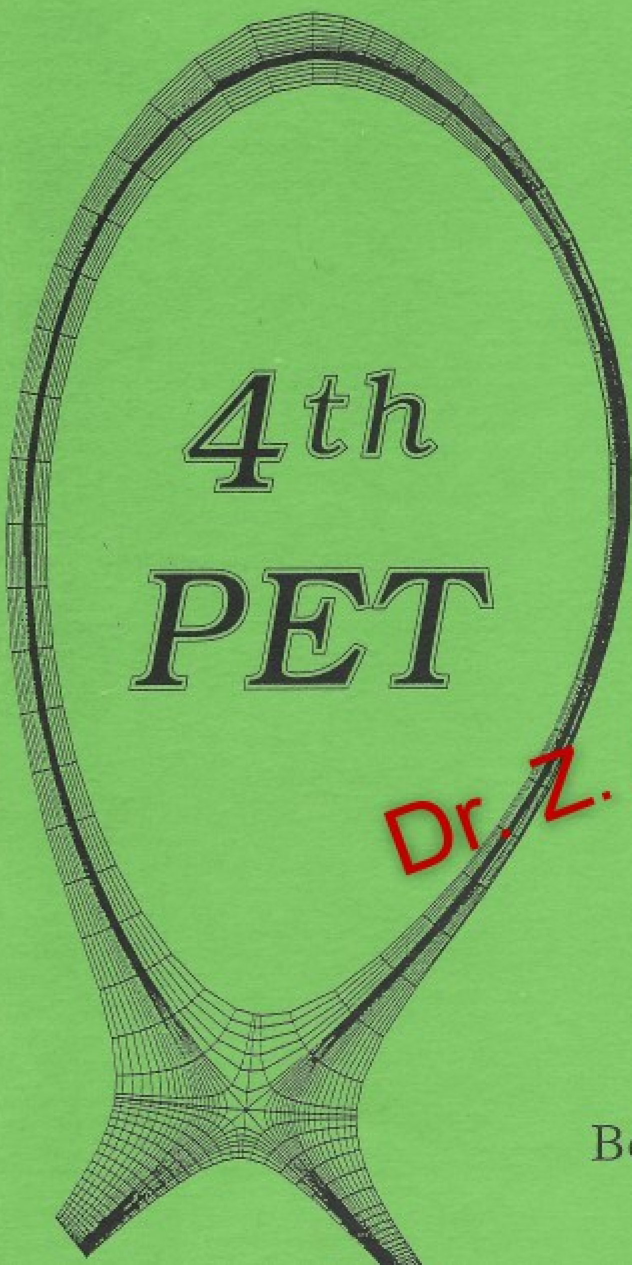
MAX-PLANCK-INSTITUT FÜR PLASMAPHYSIK
GARCHING BEI MÜNCHEN

4th International Workshop on

Plasma Edge Theory in Fusion Devices

4 - 6 October 1993
Villa Monastero,
Varenna, Italy



Book of Abstracts

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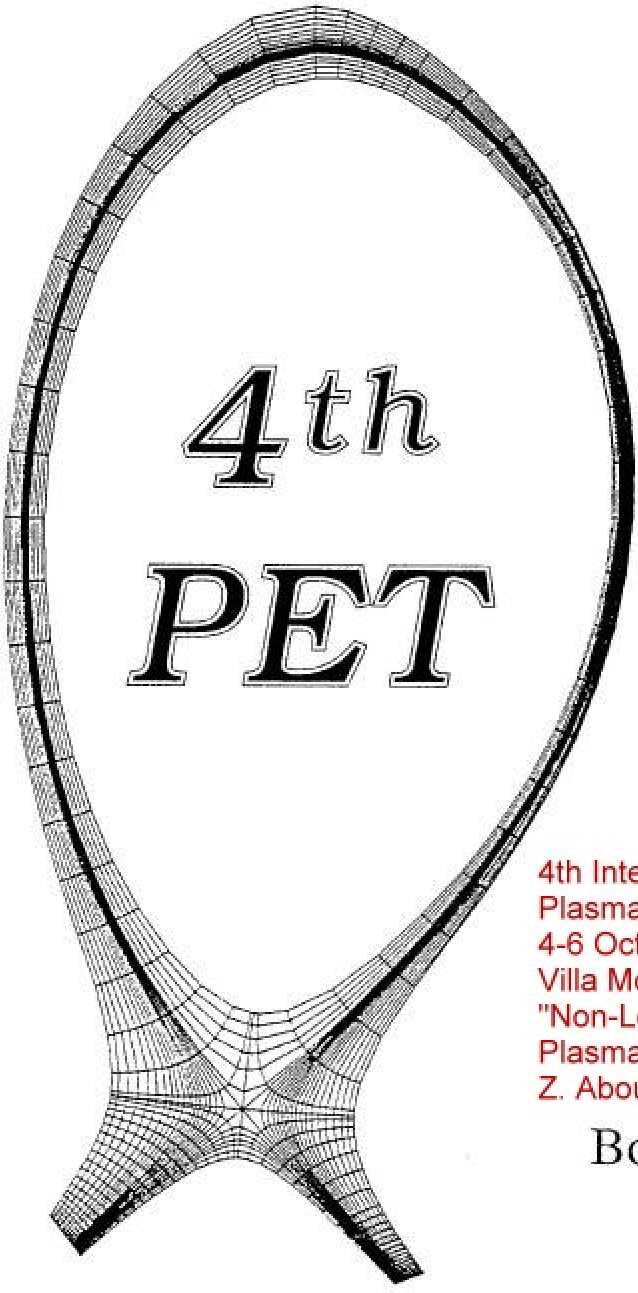

4th International Workshop on
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"Non-Local Transport in a Tokamak
Plasma Divertor with Recycling" .
Z. Abou-Assaleh,

Book of Abstracts

NON-LOCAL TRANSPORT IN A TOKAMAK PLASMA DIVERTOR WITH RECYCLING

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The plasma transport, including particle and energy fluxes, near a divertor plate with recycling has been modeled using an electron kinetic code (Fokker-Planck International)[1,2] in conjunction with a two-fluid ambipolar code. The effects of ionization, excitation, and charge exchange of the hydrogen atoms are included. The electron energy distribution calculated by the kinetic code shows a large deviation from Maxwellian, especially near the plate. This departure from Maxwellian is due to the transport of the suprathermal electrons from the scrape-off layer, and also due to the absorption of the fast electrons by the target plate. Therefore, the heat flux near the plate is shown to be non-local, in that it is not determined uniquely by the local plasma parameters. We modified the numerical value of the coefficient of the electron classical heat flux in the fluid code in order to reproduce the kinetic results. Results from the kinetic and fluid calculations including the classical heat flux correction factor will be presented.

1. Z. Abou-Assaleh, J. P. Matte, T. W. Johnston, and R. Marchand, Contrib. Plasma Phys. 32 (1992) 3/4, 268-272.

2. J. H. Rogers, J. S. De Groot, Z. Abou-Assaleh, J. P. Matte, T. W. Johnston, and M. D. Rosen, Phys. Fluids B. 1 (1989) 4, 741.

INTRODUCTION

Aim:

Modelling of the divertor plasma in a tokamak (Particles and energy transport along the magnetic field line)

Methods:

Electron kinetic / ion fluid code (FPI)

1D and 2-fluid code

Iteration FPI code ↔ modified fluid code

INTRODUCTION

Why use a kinetic modelling ?

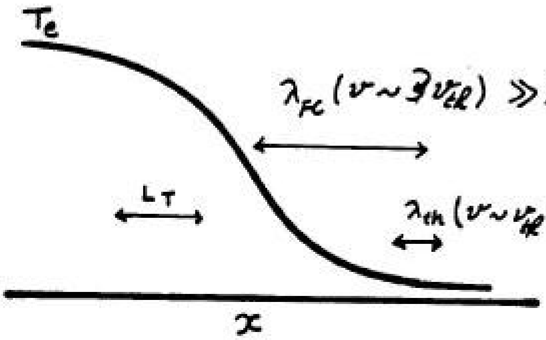
Why not use a fluid code with Spitzer-Härm (SH) formula for the electron heat flux?

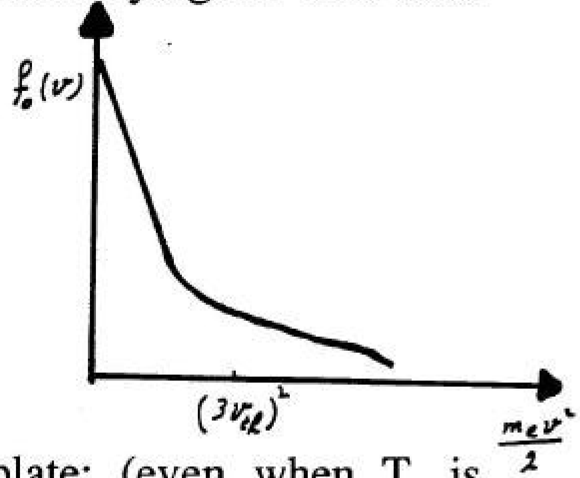
The Spitzer-Härm formula is: $q^e_{SH} = -\chi^e_{SH} \dfrac{dT_e}{dx}$, $\chi^e_{SH} \propto T_e^{5/2}$

Condition of validity: $\lambda_{th} < \lambda_{FC} < L_T = \left(\dfrac{1}{T_e} \dfrac{dT_e}{dx} \right)^{-1}$, $\lambda \propto V^4$

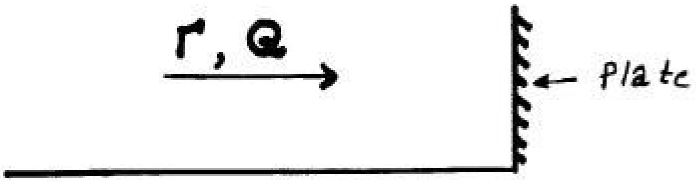
λ_{th}: mean free path of the thermal electrons,

λ_{FC}: mean free path of the electrons carrying the heat flux.

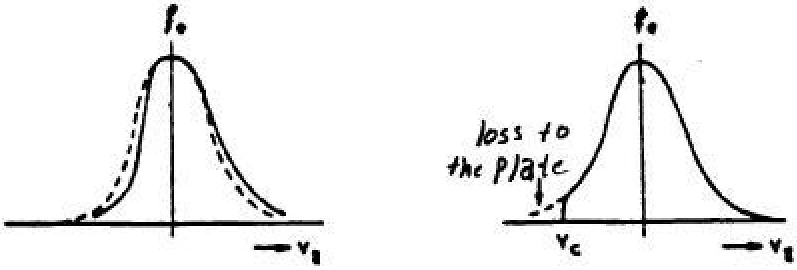




Truncation of $f(V)$ because of the plate; (even when T_e is uniform).



Maxwellian
$f_e(v_x)$



In the edge plasma:

- Recycling, ionization and excitation of the neutral particles cool the plasma: create a steep temperature gradient.

- Plasma contact with the plate: truncation of the velocities distribution.

Therefore:

- violation of the classical heat flux and

- deviation of the velocity distribution from Maxwellian

demands a kinetic electron Fokker-Planck treatment for accurate results.

Fluid Code

The following equations are advanced in time:

-Continuity:

$(n=n_e=n_i\ ,\ V=V_e=V_i)$

$$\frac{\partial}{\partial t}n+\frac{\partial}{\partial x}(nV)=S_n$$

-momentum:

$$\frac{\partial}{\partial t}(m_i nV)+\frac{\partial}{\partial x}\left(m_i nV^2+P_e+P_i-\frac{4}{3}\eta\frac{\partial V}{\partial x}\right)=S_p$$

Plasma production rate:

$$S_n = n_n\ n_e\ <v_e\sigma_I(v_e)>$$

Momentum transfer rate:

$$S_p = n_n\ n_e\ <v_e\sigma_I(v_e)>\ m_i\ V_n$$

$P_{e,i} = n\ T_{e,i}$

η is the viscosity

Electron energy:

$$\frac{\partial}{\partial t}\left(\frac{3}{2}nT_e\right)+\frac{\partial}{\partial x}Q_e=V\frac{\partial}{\partial x}P_e+E_{ei}+S_e$$

Ion energy:

$$\frac{\partial}{\partial t}\left(\frac{3}{2}nT_i+\frac{1}{2}m_i nV^2\right)+\frac{\partial}{\partial x}\left(Q_i-\frac{4}{3}\eta V\frac{\partial V}{\partial x}\right)=-V\frac{\partial}{\partial x}P_e-E_{ei}+S_i$$

Particle energy transfer rate:

$$S_i=n_n n_e<v_e\sigma_I(v_e)>\frac{m_i V_n^2}{2}$$

Electron energy loss rate:

$$S_e=-n_n n_e<v_e\sigma_I>E_I-n_n n_e<v_e\sigma_E>E_E$$

e-i energy exchange:

$$E_{ei}=3\frac{m_e}{m_i}\frac{n}{\tau_{ei}}(T_e-T_i)$$

$$\tau_{ei}=\frac{3\sqrt{m_e}}{4\sqrt{2\pi}}\frac{T_e^{3/2}}{\ln\Lambda e^4 nZ^2}$$

Electron heat flux

$$Q_e = Q^e_{conv.} + Q^e_{cond.}$$

where:

$$Q^e_{conv.} = \frac{5}{2} T_e n V$$

$$Q^e_{cond.} = q_{SH} \left[1 + \frac{|q_{SH}|}{f n T_e (T_e/m_e)^{1/2}} \right]^{-1}$$

f electron heat flux limit factor

$$q_{SH} = -\chi^e_{SH} \frac{\partial T_e}{\partial x} \ , \quad \chi^e_{SH} = 6 n T_e \tau_{ei}$$

Ion heat flux:

$$Q_i = Q^i_{conv.} + Q^i_{kin.} + Q^i_{cond.}$$

where:

$$Q^i_{conv.} = \frac{5}{2} T_i n V \ , \quad Q^i_{kin.} = \frac{1}{2} m_i V^2 n V$$

$$Q^i_{cond.} = -\chi_i \frac{\partial T_e}{\partial x} \ , \quad \chi_i = 3.9 \frac{n T_i \tau_i}{m_i}$$

In general:

$$Q_e > Q_i \ , \quad Q^e_{cond} > Q^e_{conv}$$

$Q^i \gg Q^i_{cond}$, $\quad Q^i \gg Q^i_{kin}$ except at the plate

Fokker-Planck International Code
FPI

The FPI code developed and used to simulate laser-plasma interaction (by J.P. Matte and J. Virmont).

In the FPI code:

- electrons are treated kinetically,
- ions and neutrals are treated as fluids,
- one-dimension in space (x),
- two-dimension in velocity space v_x , $v_\perp$.

Electron Kinetic model

The electron distribution function is:

$$f(X,V,t)=f(x,v_x,v_\perp,t)=f(x,v,\mu,t)=\sum_{l=0}^{N} f_l(x,v,t)P_l(\mu)$$

where $v=(v_x^2+v_\perp^2)^{1/2}$, $\mu=v_x/v$

The electron kinetic equation is given by:

$$\frac{\partial f}{\partial t} + v_x\frac{\partial f}{\partial x} + \frac{eE}{m_e}\frac{\partial f}{\partial v_x} = \left(\frac{\partial f}{\partial t}\right)_{(e-i,e-e)} + \left(\frac{\partial f}{\partial t}\right)_{(e-n)}$$

(1) (2) (3) (4)

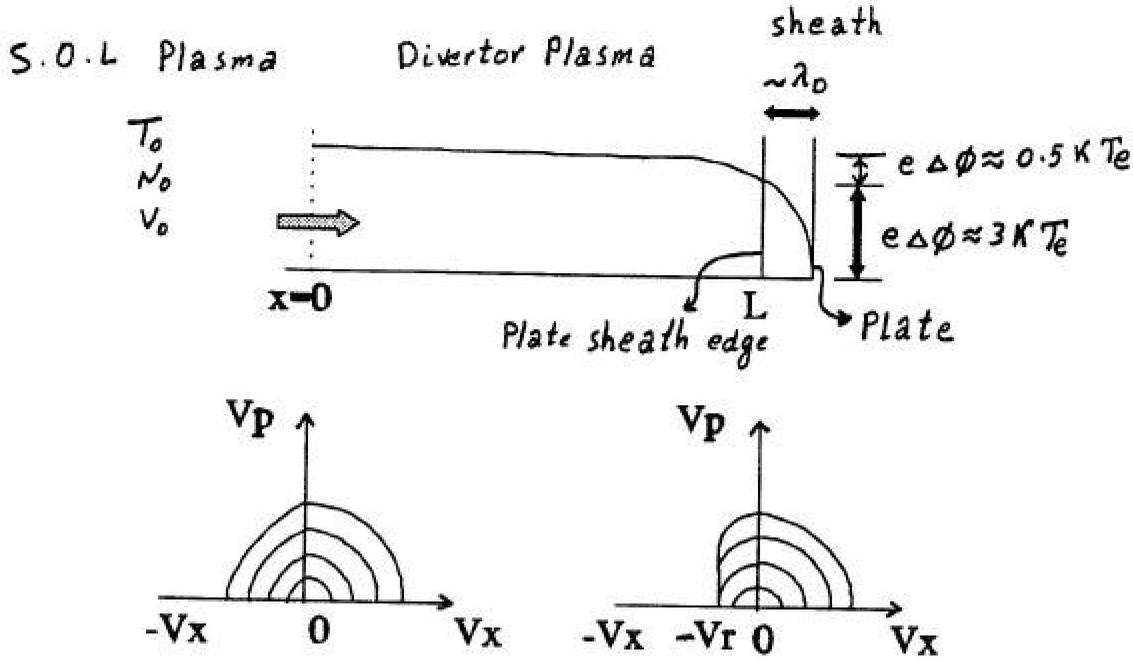
f_l 's are advanced in time including:

(1) advection,
(2) acceleration du to the self consistent E-field,

Fokker-Planck:
(3) e-e,e-i Coulomb scattering,
including hot ions (Davydov),

Boltzmann:
(4) e-n collision: non-elastic (ionization, excitation),
elastic ("AURORA").

Boundary Conditions
FPI



Plasma source (x = 0):

- Ions: Ni, Vi and Ti are fixed
- Electrons: Te fixed. Zero current ($\Gamma_e = \Gamma_i$) is imposed as follows: incoming particles are absorbed and an appropriate current with half-Maxwellian distribution at this temperature is emitted.

Plate sheath edge (x = L):

- Ions: outgoing ions are absorbed by the plate.
- Electrons: zero current ($\Gamma_e = \Gamma_i$) is imposed as follows: low energy ($< \frac{1}{2} m_e V_r^2$) electrons are reflected so that the flux of higher energy electrons is equal to the ionic current.

V_r is calculated by assuming $J_i = J_e$:

$$n_i V_i = \frac{4\pi}{3} \int_0^\infty f_1^*(v) v^3 dv$$

$$\frac{1}{2} m_e V_r^2 = e \Delta\phi$$

where $$\Delta\phi = \phi_{(sheath\ edge)} - \phi_{plate}$$

and

$$V_i(plate) = \sqrt{V_i^2(sheath\ edge) + \frac{2e\Delta\phi}{m_i}}$$

Boundary Conditions
Fluid code

Plasma source (x = 0):

[illegible], $V = V_{e,i} = V_0$, $T_{e,i} = T_0$ are fixed.

$\frac{dn}{dx}\Big|_{x=0} = 0$, $v_0 = 0$

Plate sheath edge (x = L):

The outgoing plasma is absorbed.

Ion drift velocity: $V \geq c_s = \sqrt{(T_e + T_i)/m_i}$

Ion heat flux: $Q_i = 3.5\ T_i\ n\ V$

Electron heat flux:

$$Q_e = 2\ \delta\ T_e\ n\ v\ ,\ (\delta = 3),$$

FLUID AND FOKKER-PLANCK HYBRID ITERATION

FLUID CODE

Moves ions ect. quickly, but electron heat flow is approximate.

FOKKER-PLANCK (FPI) CODE

Some ion dynamics but with electron kinetics, too slow on ion timescale.

SOLUTION

Iterate fluid modified by FPI
Use Te(FPI) and force qe to agree with FPI by correcting each grid point with correction factors:

$$CFQ = q_{e\text{-}FPI} \,/\, q_{e\text{-}fluid}(T_{e\text{-}FPI})$$

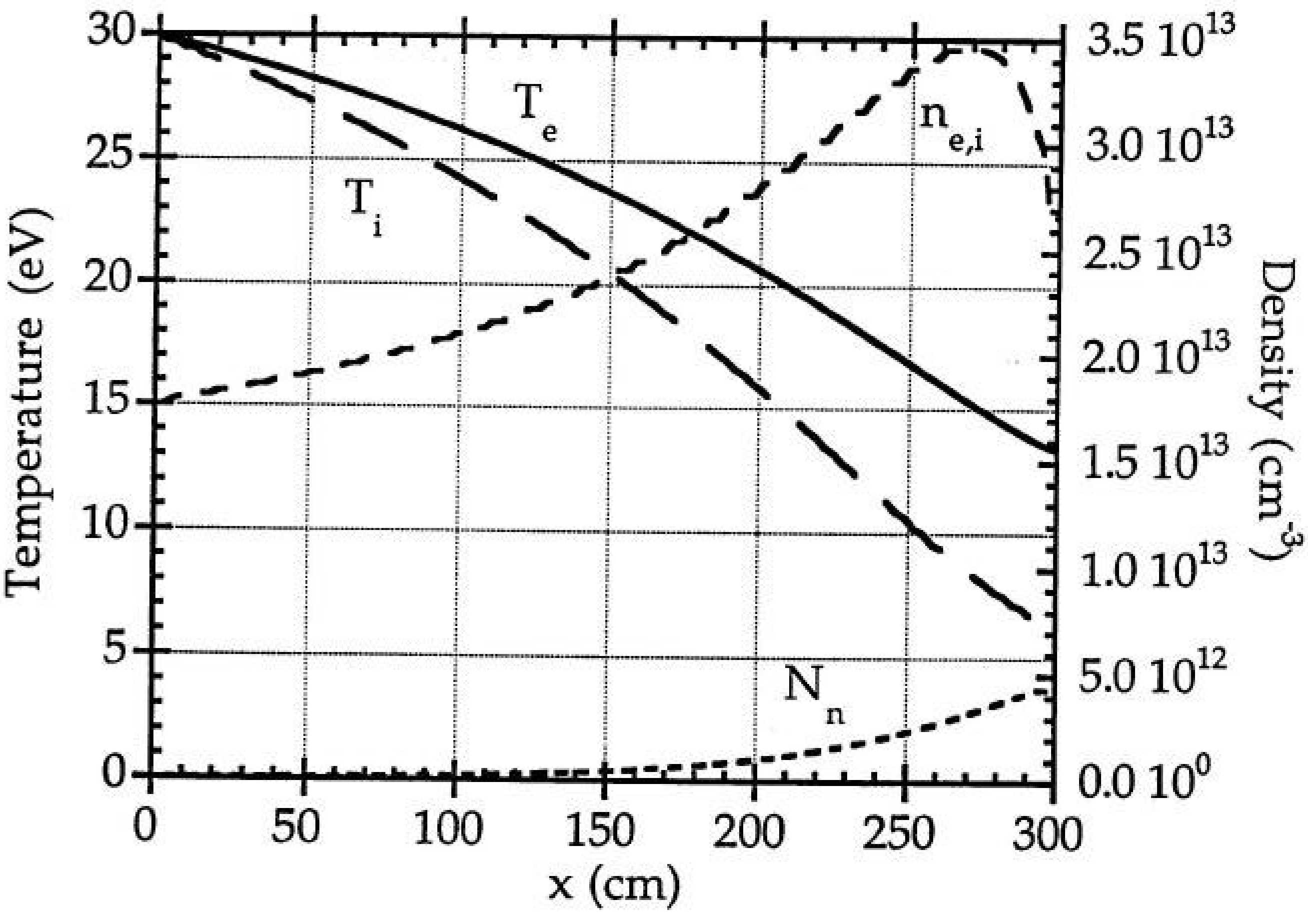
ITERATE UNTIL NO FURTHER SIGNIFICANT CHANGE

FINAL RESULT

Profile consistent with electron kinetic but at affordable cost.

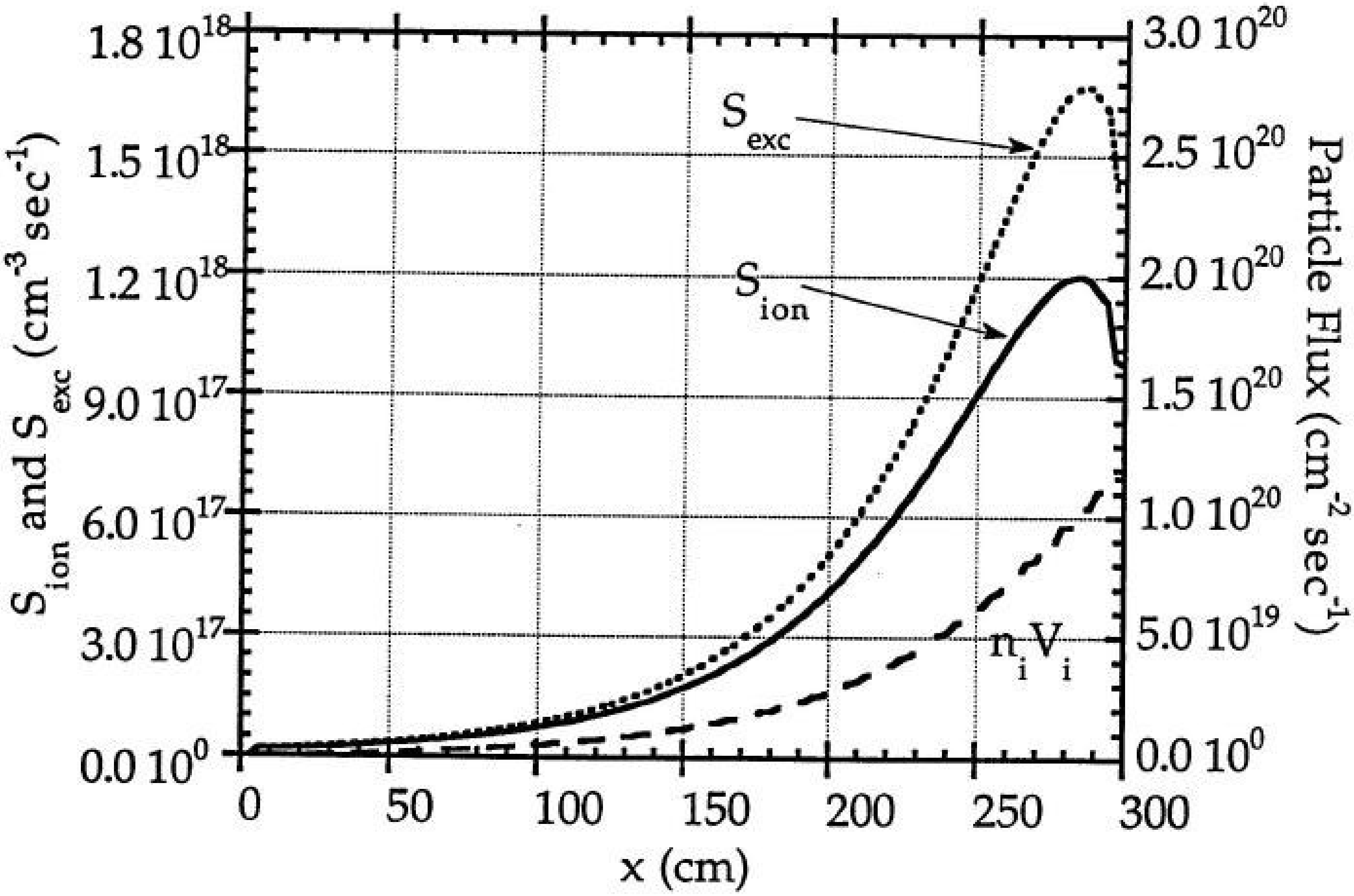
FLUID CODE SIMULATION
WITH f=0.2

T_e , T_i , n_i and n_n vs x



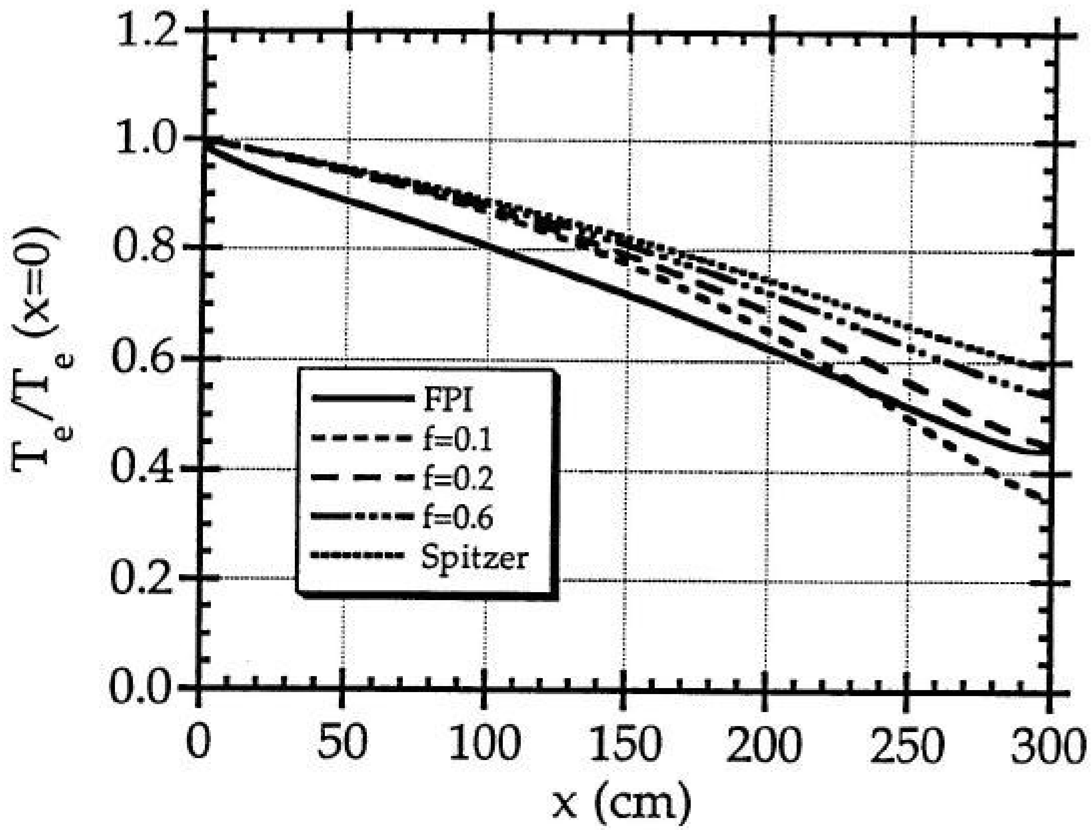
FLUID CODE SIMULATION
WITH f=0.2

n_iV_i , S_{exc} and S_{ion} vs x



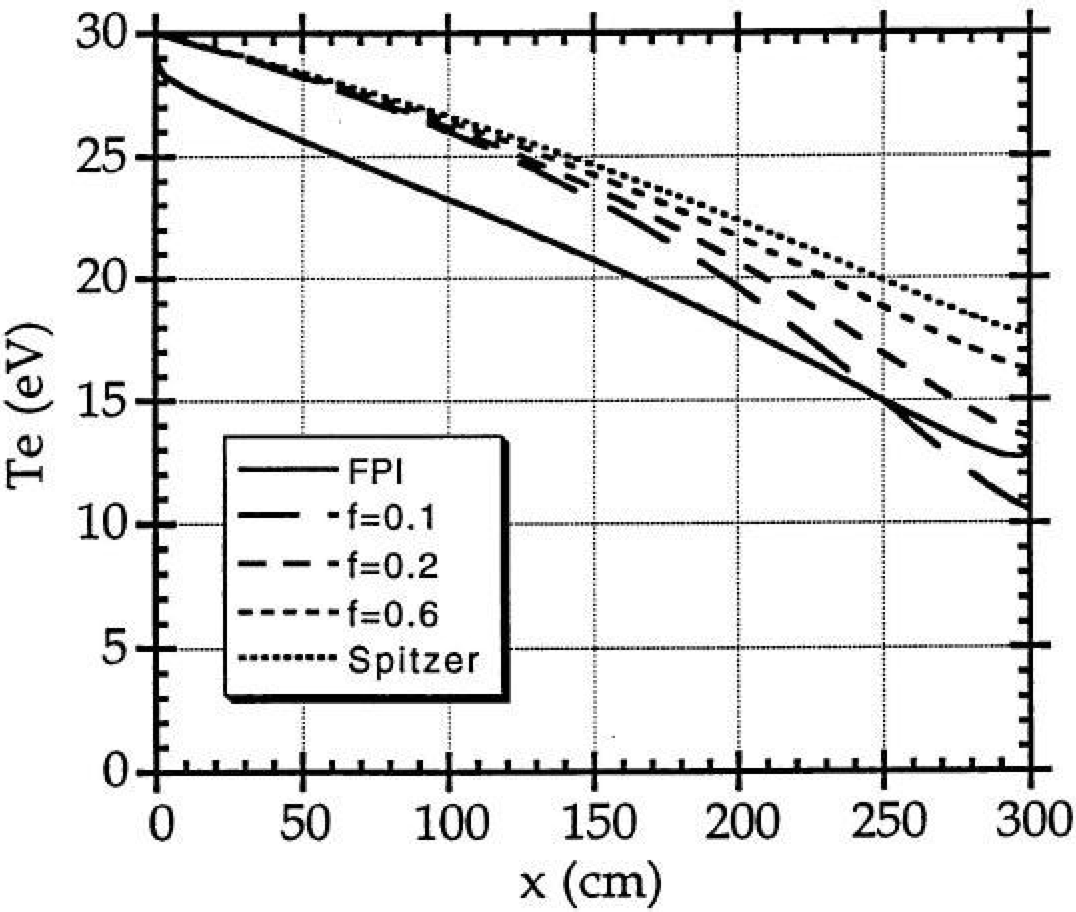
FOKKER-PLANCK AND FLUID SIMULATIONS

Profile of T_e



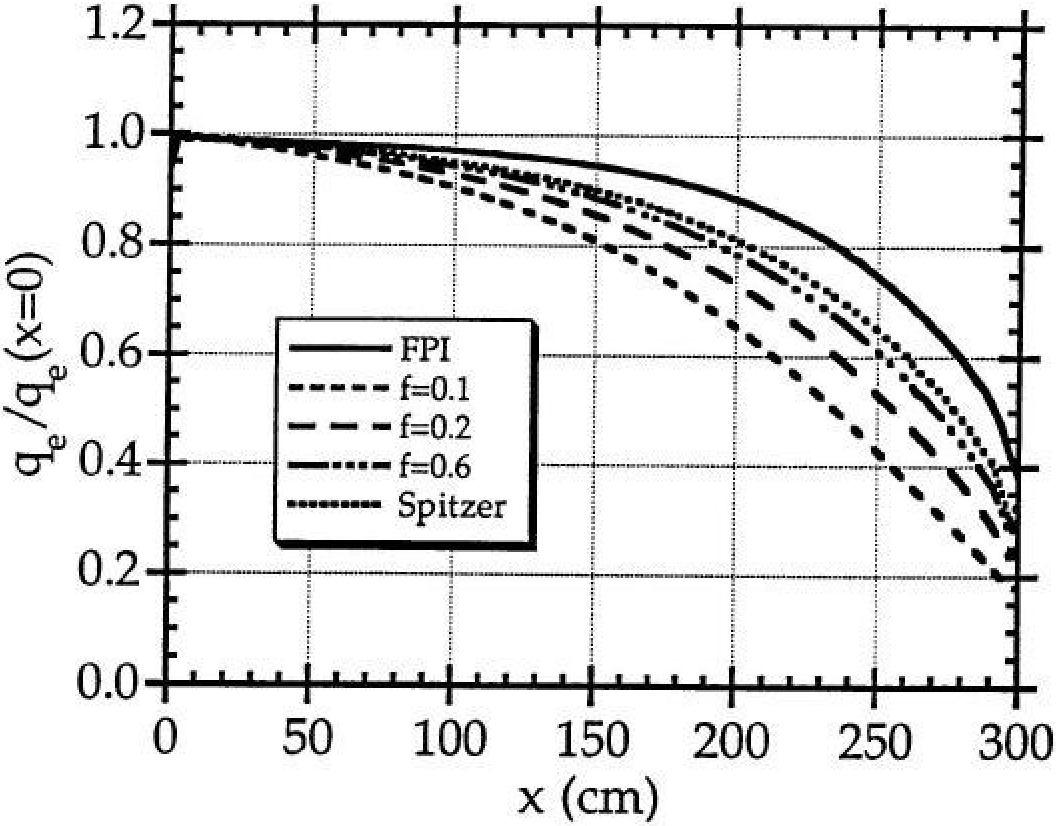
FOKKER-PLANCK AND FLUID SIMULATIONS

Profile of T_e



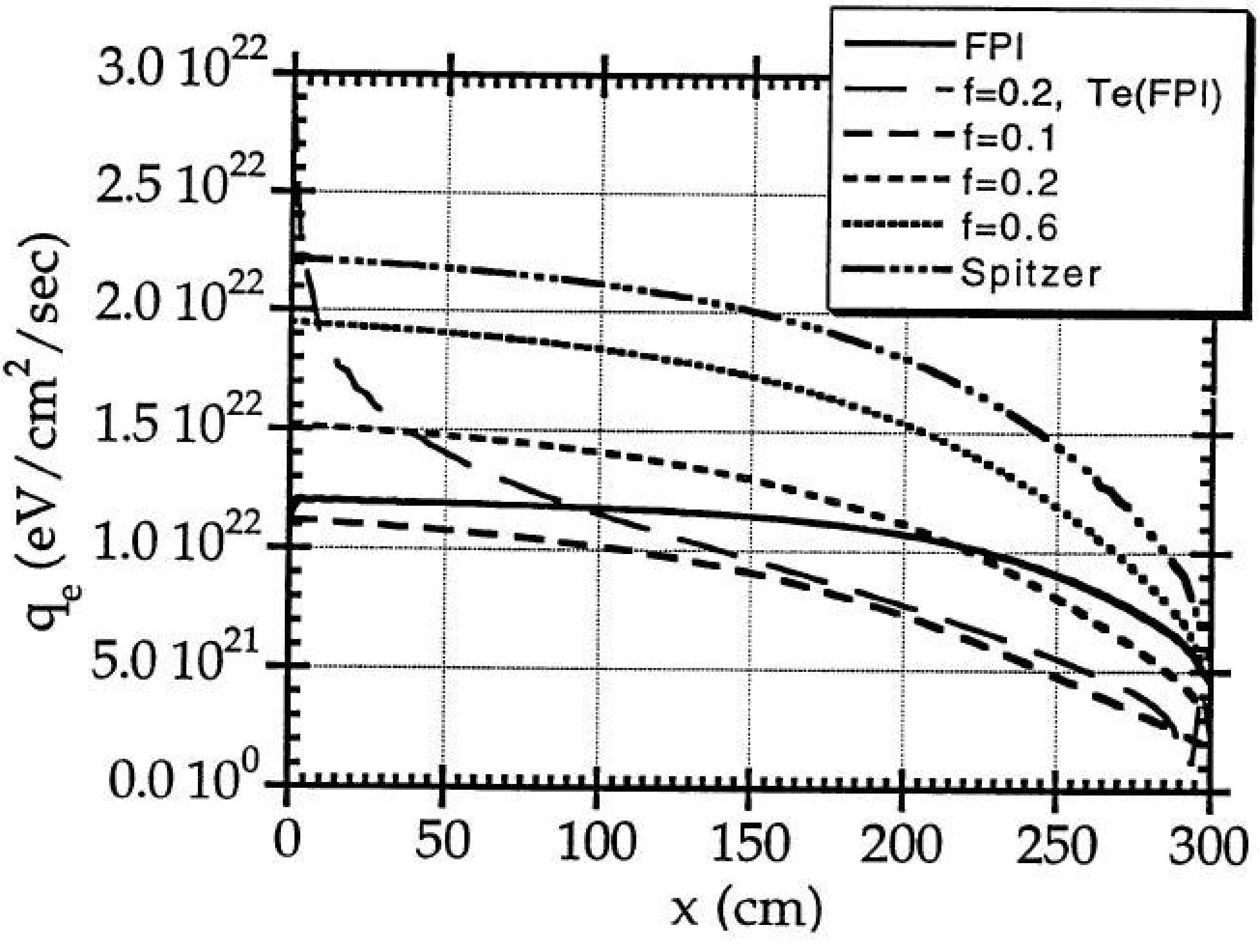
FOKKER-PLANCK AND FLUID SIMULATIONS

Profile of q_e

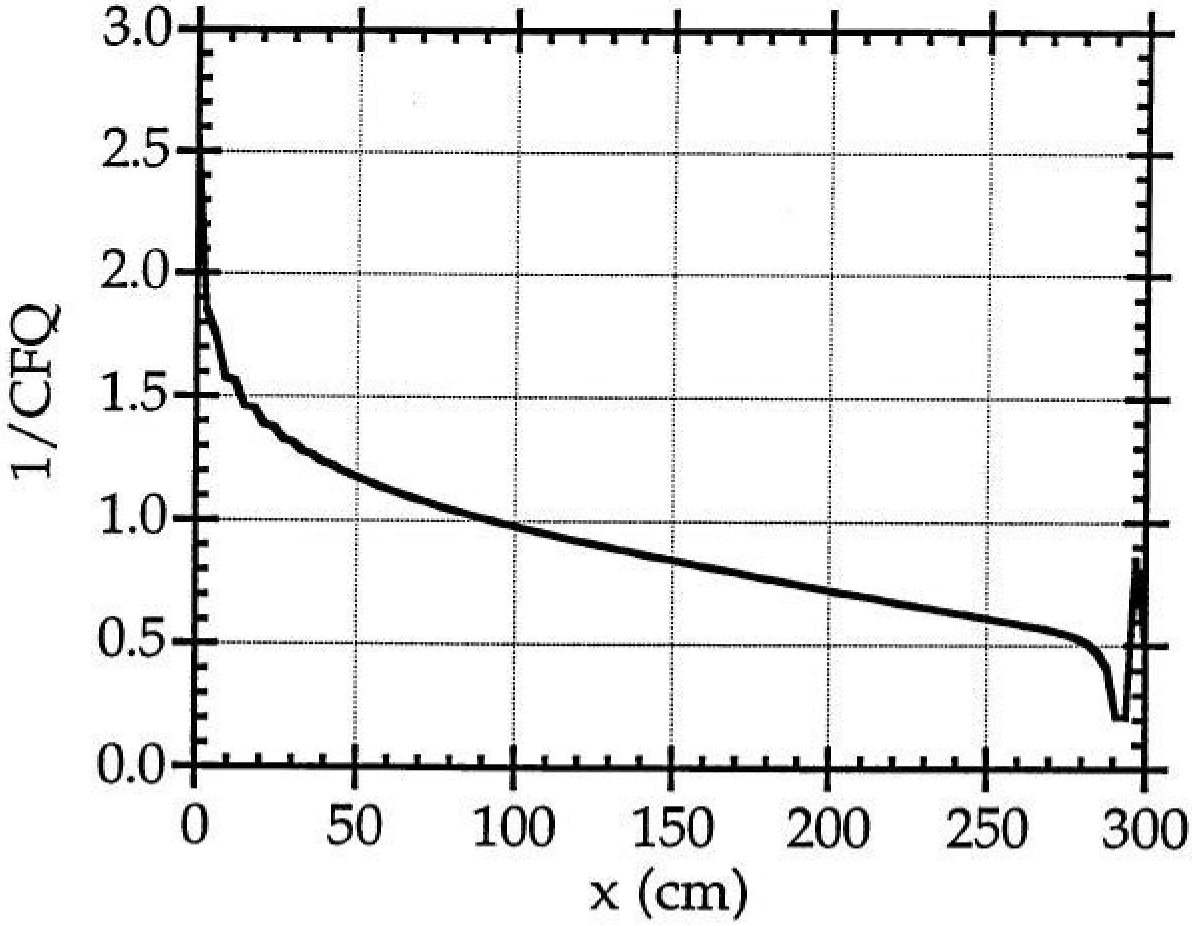


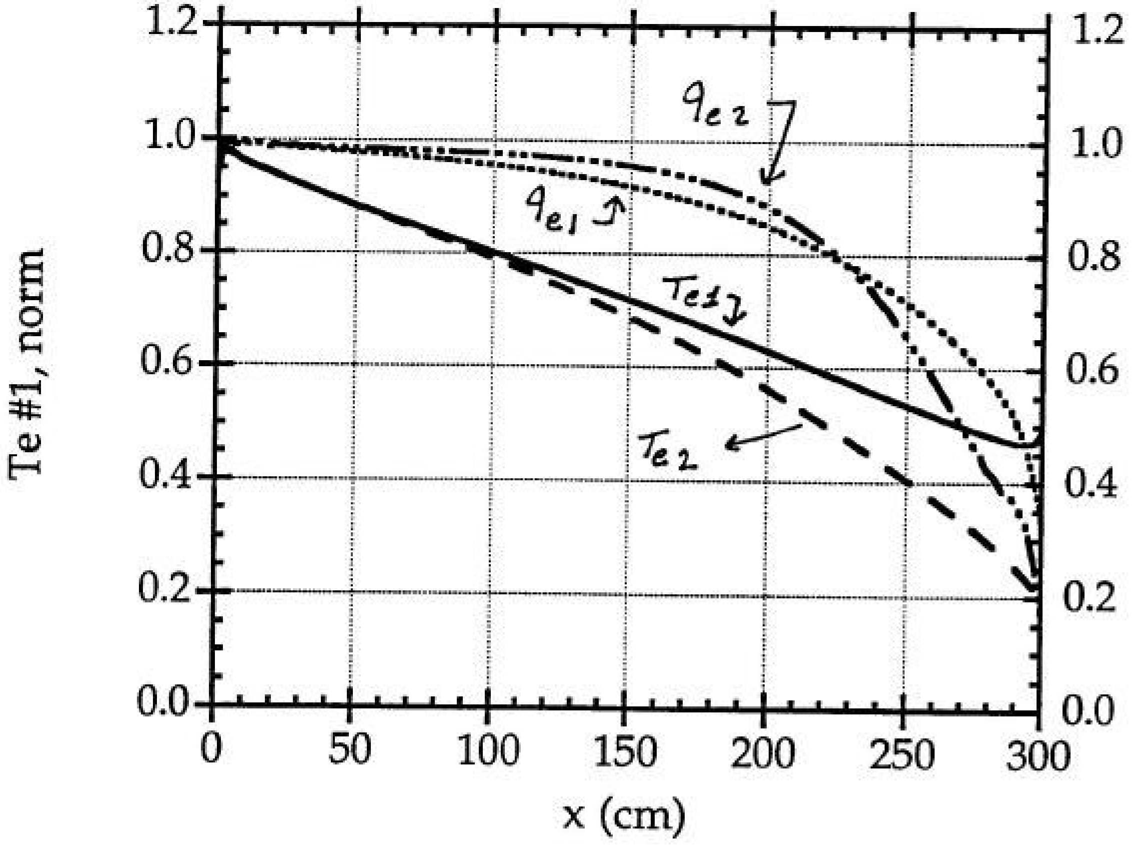
FOKKER-PLANCK AND FLUID SIMULATIONS

Profile of q_e



Profile of the Heat Flux Correction Factor CFQ

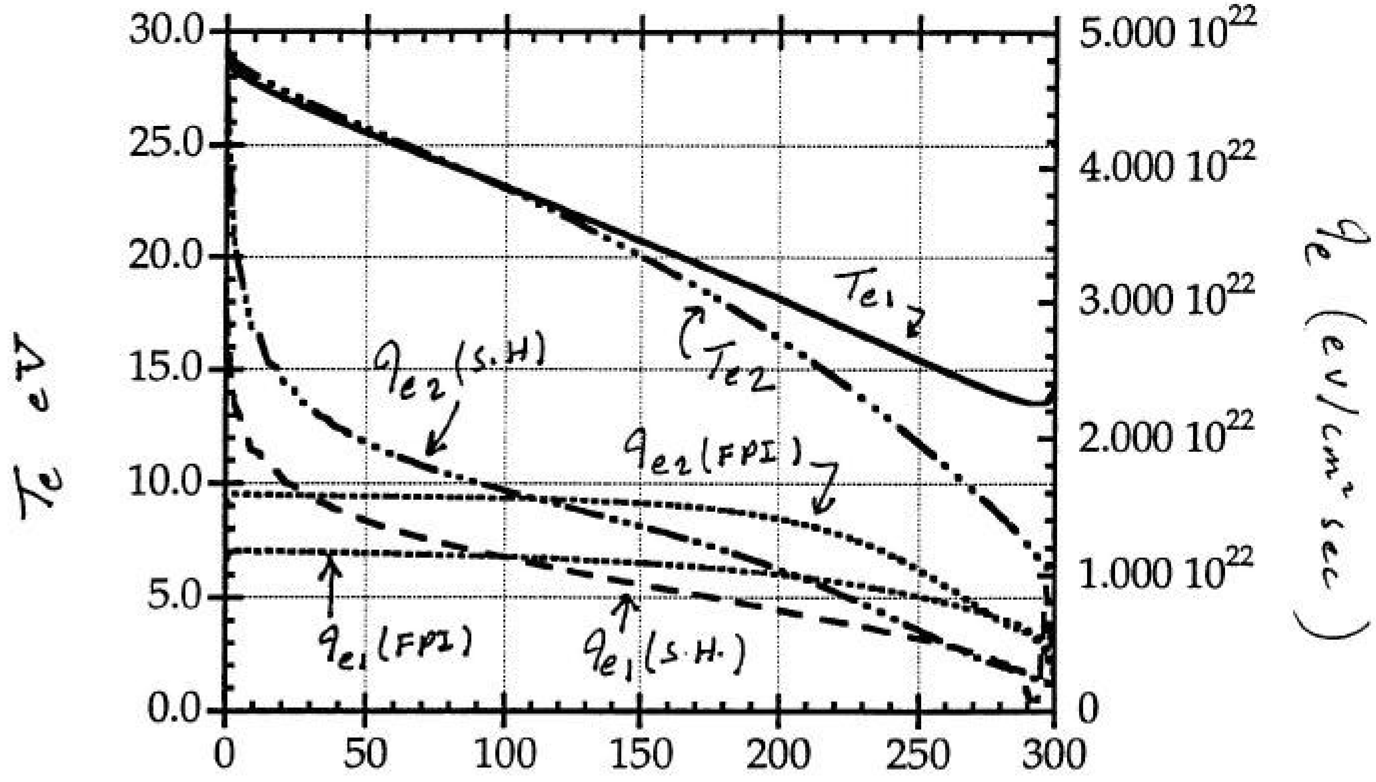




Fokker-Planck Results

#1 : $n_{e,i}$ at $t=0$ is $3\times10^{13}\,cm^{-3}$, Te ——— , q_e .....

#2 : $n_{e,i}$ at $t=0$ is $6\times10^{13}\,cm^{-3}$, Te - - - , q_c —..—..—



#1 : $n_e(t=0) = 3 \times 10^{13}\ cm^{-3}$

#2 : $n_e(t=0) = 6 \times 10^{13}\ cm^{-3}$

(S.H) from T_e (FPI) with $f = 0.2$

$R = 0.9$

CONCLUSION

We model the plasma transport along the magnetic field line in a tokamak divertor:

* Fluid and kinetic simulations.

* Including: ionization, excitation, boundary condition at the sheath edge.

* Hybrid technique was developed which permitted of obtaining an equilibrium solution with the electron kinetic model but with much reduced computer cost.

* Steep temperature gradients.

* The fluid code with electron heat flux limiter f=0.2 gave closer results to the Fokker-Planck calculation at the plate.

* The electron distribution function calculated from the FPI code is not locally Maxwellian, especially near the plate. The deviation from Maxwellian is due to the absorption of the most energetic electrons by the plate and to the non-local transport of high energy electrons.

* Effect of non-Maxwellian electron distribution function on the ionization and excitation of the impurities.