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Analysis of DIII-D Radiative Edge Discharges

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Abstract

Coupled plasma and multi-charge state impurity transport simulations are performed to analyze recent DIII-D discharges with a strong radiating edge resulting from the injection of non-intrinsic impurities. Good agreement between the simulations and the experiment is obtained using a Bohm model for the main plasma ion and energy transport and a simple fixed-shape model for the transport of the impurity charge states.

1 Introduction

Recently, several DIII-D discharges with non-intrinsic seeded impurities (Ne, Ar and Kr) covering a wide range of operating regimes have been carried out. These discharges exhibit a strong radiating mantle and are very important for the Advanced Tokamak mission of DIII-D. The enhanced edge radiation, besides reducing the exhaust power from the plasma core, can have an important effect on the operating characteristics of the device. Edge radiation modifies the edge pressure gradient, therefore directly affecting the edge stability properties of DIII-D, while the presence of impurities in the core improves confinement believed to be due to the stabilization of micro-instabilities. In this paper, the results of main plasma and impurity transport simulations are presented and compared to the experiment for an L-mode upper-biased Double Null discharge with Ne injection (DIII-D shot 098775) and the accompanying reference discharge without Ne injection (DIII-D shot 098777). Both discharges had $I_p = 1.2$ MA, $B_T = 1.6$ T and neutral beam power $P_{NB} = 4.5$ MW. The Ne injected discharge exhibited a significant confinement improvement following the impurity injection [1,2].

2 Models and assumptions

The 1 1/2-D core plasma transport code GTWHIST [3] has been used in these simulations. This code has the capability to simultaneously compute the transport of all the charge states of several impurity species along with the main plasma particle and energy transport, a significant advantage for modeling plasmas with large impurity concentrations. The main plasma particle and energy transport is described by a simple Bohm-like model of the form:

$$\chi_B = \frac{|\nabla(n_e T_e)|}{e n_e B_T} a q^2 \tag{1}$$

$$\chi_e = \alpha_e \chi_B,\ \chi_i = \alpha_i \chi_B,\ D = \alpha_n \chi_B \tag{2}$$

where n_e and T_e are the electron density and temperature, a is the minor radius, B_T the toroidal magnetic field, q the safety factor and α_e, α_i, α_n are adjustable dimensionless coefficients. This model has been shown to predict well several JET L-mode discharges [4] and, with the addition of a GyroBohm term, it has been used in ITER transport simulations [3,5]. An optional pinch term can be added to the particle transport, $\nu_p = -2C_V(D/a)q^{\alpha_\nu}$, where ρ is the normalized radius and C_V and α_ν are adjustable coefficients. Notice that a positive C_V corresponds to an inward pinch. The diffusion coefficients of the impurity charge states are assumed to be independent of the main ion transport coefficient following their own fixed-shape transport model,

$$D_Z = D_{Z0}\,(1 + c_1\rho^{c_2}) \tag{3}$$

with an optional inward convective term of the form

$$V_Z = -2C_{VZ}\,(D_Z/a)\,\rho^{\alpha_\nu z} \tag{4}$$

In Eqs. (3) and (4), D_{z0}, c_1, c_2, C_{VZ} and α_{nuz} are adjustable coefficients, ρ is the normalized radius and a is the minor radius.

3 Results of simulations

The simulations for both the reference and the Neon-seeded discharges start at about 0.5 s, when the plasma has reached its full shape (a, R, κ, δ), and end at t=1.6 s, near the peak of the plasma stored energy. A flat current density profile is assumed at the beginning of the simulation so that the central safety factor remains above 1.0 at all times, eliminating sawteeth. This is in agreement with the experimental observations which show a sawteeth-free discharge up to t=1.65 s.

3.1 Reference discharge

We first try to model the reference discharge (DIII-D shot 098777 with no Ne injection). We find that best agreement with the experiment is obtained if we use the values $\alpha_e = 4.0 \times 10^{-4}$, $\alpha_i = 4.64 \times 10^{-4}$ and $\alpha_n = 3.0 \times 10^{-4}$ in Eqs. (1) and (2). For comparison, $\alpha_e = \alpha_i = 3.3 \times 10^{-4}$ in the JET simulations [4]. No pinch term is assumed in the particle transport and therefore the shape of the density profile is determined by the gas-puffing source at the edge and by the fueling source due to 4.5 MW of NB injection. Although no injected impurities were present in the reference discharge, an intrinsic Carbon concentration of 1.24 % was assumed, raising the peak value of the Z_{eff} to about 1.4, consistent with the results of the TRANSP analysis [2].
In Fig. 1, a comparison between the simulation and the experiment at t=1.6 s is shown. The solid lines refer to the results of the numerical simulation and the symbols refer to the experimental measurements from various DIII-D diagnostics. In the χ_i plot, the squares refer to the effective χ_i from a TRANSP analysis of the experimental data. It can be seen that the agreement between simulation and experiment is very good.

3.2 Discharge with Neon injection

Having established good agreement with the reference discharge, we then proceed to model the discharge with Neon injection (DIII-D shot 098775). In this discharge, Neon

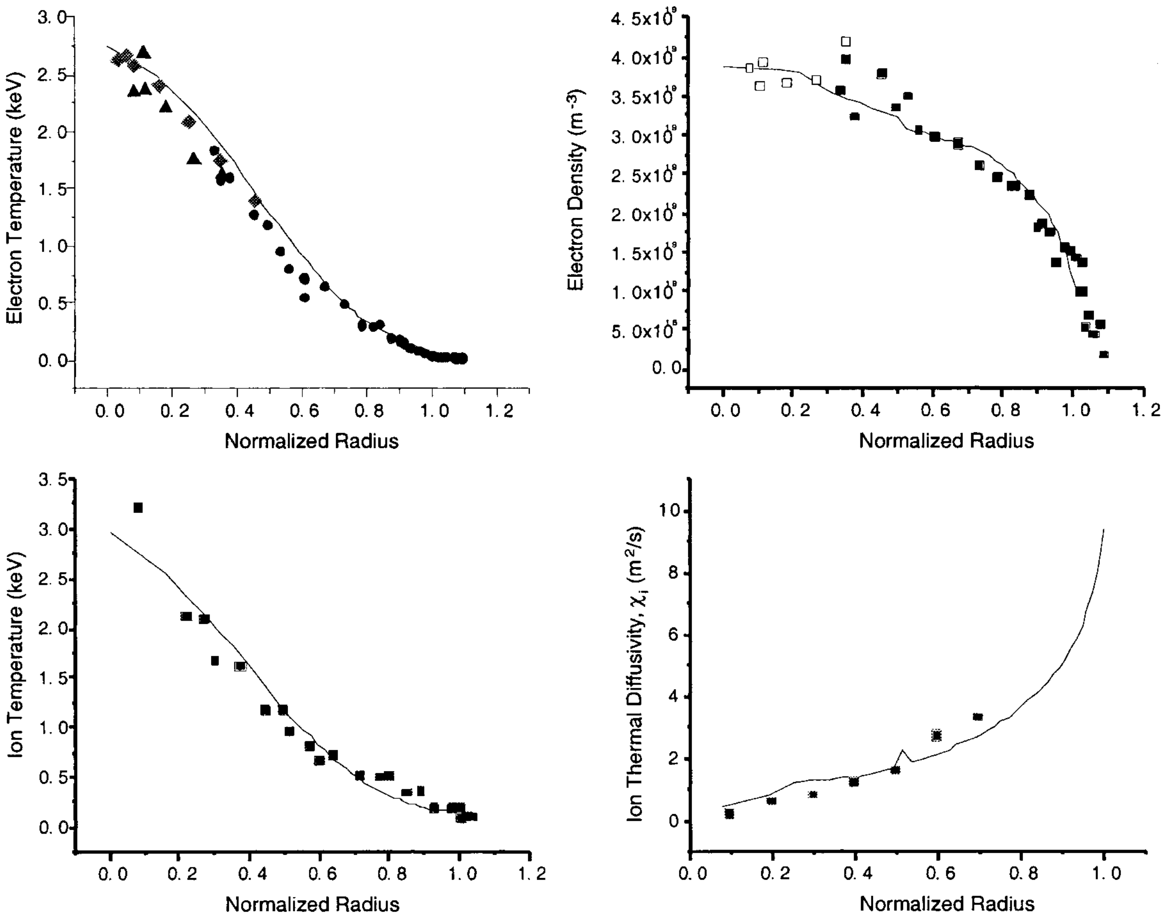

Fig. 1: Comparison of simulation and experiment for shot 098777 at time 1.6 s (symbols - experimental data or TRANSP results for χ_i; solid line - GTWHIST).

was injected at 0.8 seconds and it was followed by substantial confinement improvement, which was correlated with strong reduction of turbulence [1]. While a lot of progress has been made recently towards a theoretical understanding of the impurity-induced confinement improvement [1,2], a convenient theory-based model for use in transport simulations is not yet available. Therefore, in our simulations, the observed confinement improvement is taken into account by reducing the transport multipliers α_e, α_i and α_n in Eq. (2) following the Neon injection. Best agreement with the experimental profiles was obtained by reducing α_e by a factor of 2, α_i by a factor of 7 and keeping α_n the same. The overall transport reduction is consistent with results obtained from a TRANSP analysis of the experimental data [2]. The resulting confinement enhancement factor relative to the ITER-89P scaling, H_{89P}, is equal to 1.8 at t=1.6 s, compared to 1.0 for the reference case at the same time. Notice that since χ_B in Eq. (1) depends on the local plasma parameters and their gradients, the radial profiles of the transport coefficients for the Neon injected discharge are not necessarily similar to those of the reference discharge. It was also found, in contrast to the reference case, that an inward pinch term in the main ion transport was necessary in order to match the measured density profile. An inward convective velocity of the form described in section 2 was used, with C_V=1 and α_ν=1. The charge states of the intrinsic C and injected Ne impurity species are transported along with the main ions using the transport model described by Eqs. (3) and (4). It was found that using $D_{Z0} = 1\ m^2/s$, $c_1 = 1.0$, $c_2 = 2$, C_{VZ} =0.5 and α_{VZ} =2.0 gives the best agreement with the experimental results. It should also be noted that following the Neon injection, the Carbon density decreased by more than a factor of 2. This has been taken into account in our simulations by reducing the intrinsic Carbon source just after the Neon injection. The results of our simulations are plotted and compared to the experimental data at t =1.6 s in Figs. 2 and 3. Fig. 2 shows the comparison of the main plasma profiles with the experiment, while in Fig. 3 the computed densities of the most important charge states of C and Ne are plotted and compared to the experimental data for the fully ionized state (C^{+6} and Ne^{+10}) as measured by the charge exchange recombination (CER) diagnostic. It can be seen that the agreement between simulation and experiment is very good. The discrepancy in the Z_{eff} comparison in the outer part of the plasma is due to the fact that the experimental Z_{eff} contains only the contributions from the fully ionized states of Carbon and Neon (C^{+6} and Ne^{+10}) while the Z_{eff} from the transport simulation includes the contributions from all the impurity charge states.

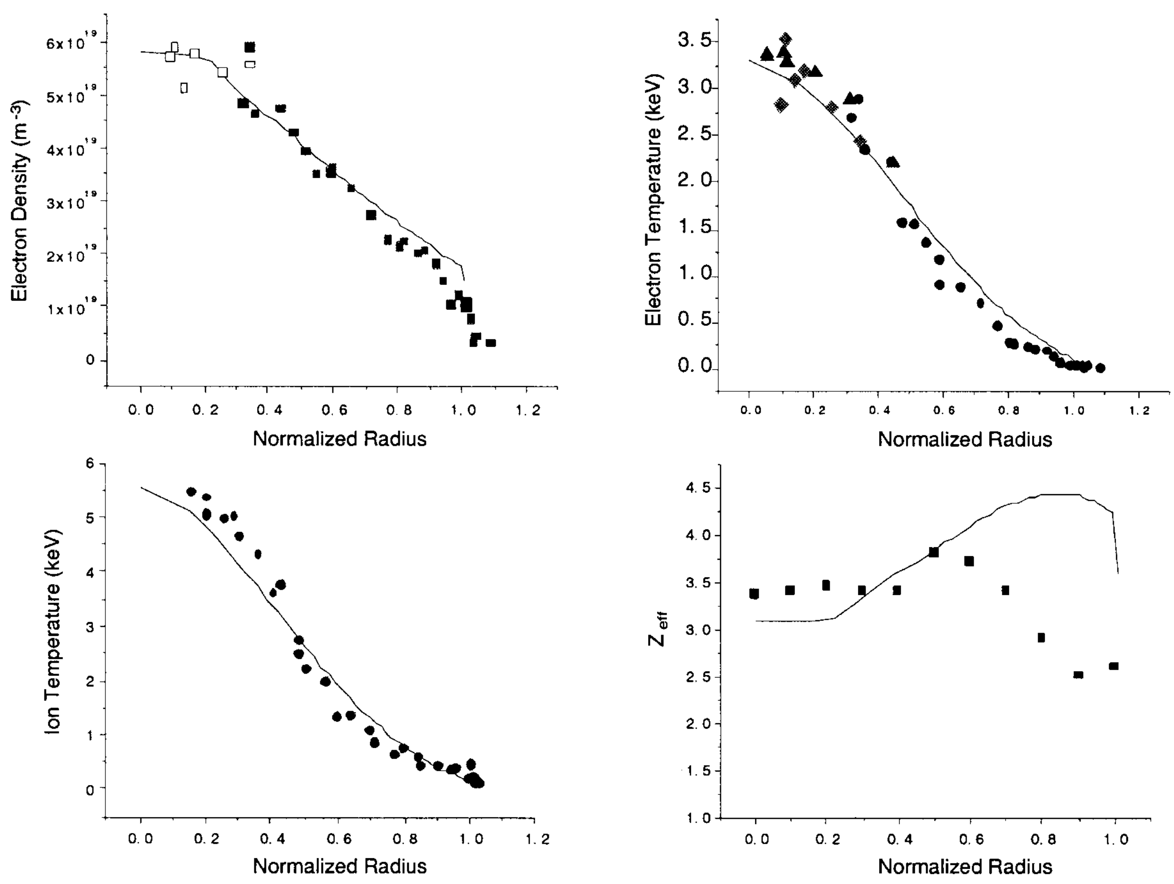

Fig. 2: Comparison of simulation and experiment for shot 098775 at time 1.6 s (symbols - experimental data or TRANSP results for Z_{eff}; solid line - GTWHIST)

The numerical simulation predicts that 1.2 MW of power is radiated from the plasma core, which is about 14% lower than the power estimated from a fit to the data from the bolometer arrays. The predicted radiated power profile agrees well with the profile derived from a bolometry inversion of the experimental data.

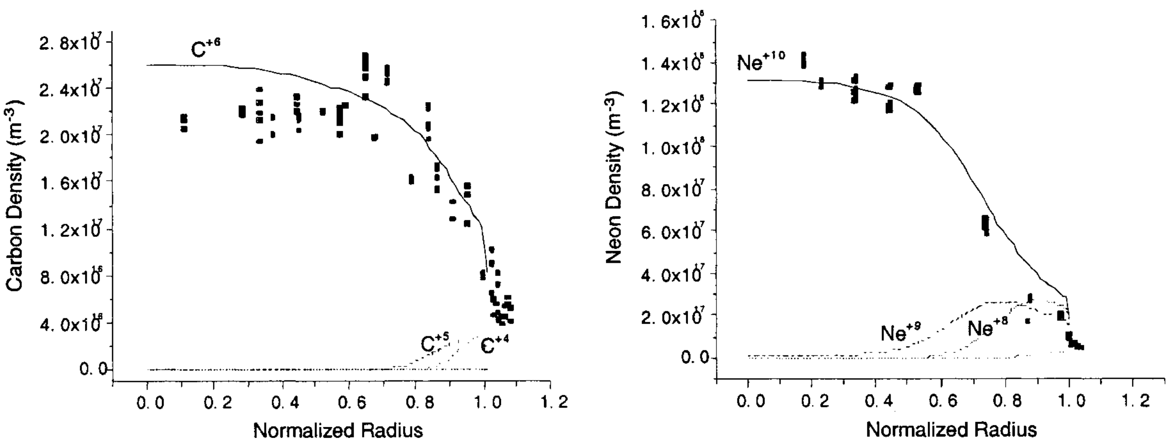

Fig. 3: Profiles of selected C and Ne charge states, and comparison with the CER measured profiles of the fully ionized states (C^{+6} and Ne^{+10}). (Symbols - CERFIT data; lines - GTWHIST).

4 Conclusions

Results from plasma and impurity transport simulations of an L-mode Neon-injected DIII-D discharge and its accompanying reference discharge show good agreement with the experimental data. A simple L-mode Bohm-like model for the main plasma transport and a fixed-shape model for the transport of the impurity charge states have been used and appear to be adequate in reproducing the most important features of these discharges. The observed confinement improvement is modeled by reducing the electron and ion thermal diffusivity multipliers of the Bohm transport coefficient following the impurity injection. It was also found that an inward particle pinch was necessary in order to explain the observed peaking of the electron density profile following the Neon injection.

References

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