IMPURITY ANALYSIS AND MODELING OF DIII-D RADIATIVE MANTLE DISCHARGES

J. Mandrekas, W.M. Stacey
Georgia Institute of Technology

M. Murakami, M.R. Wade
ORNL

G. L. Jackson
General Atomics

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Impurity Analysis and Modeling of DIII-D Radiating Mantle Discharges[1] J. MANDREKAS, W.M. STACEY, Georgia Institute of Technology, M. MURAKAMI, M.R. WADE, Oak Ridge National Laboratory, G.L. JACKSON, General Atomics — Predictive simulations of recent radiating mantle DIII–D discharges with non-intrinsic seeded impurities such as Ne, Ar and Kr, have been carried out. These L–mode and ELMing H-mode discharges often exhibit confinement improvement following the impurity injection. The simulations are performed with the 1-1/2D transport code GTWHIST, which has the capability to calculate the transport of all the charge states of several impurity species along with the main plasma particle and energy transport. The importance of neoclassical effects on the impurity transport, as well as the effect of the enhanced edge radiation on the edge pedestal pressure, the edge pressure gradient, and bootstrap current are also discussed.

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☐ Prefer Oral Session
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John Mandrekas
John.mandrekas@me.gatech.edu
Georgia Institute of Technology

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OUTLINE AND SUMMARY

- Experiments with non-intrinsic, seeded impurities are important for the Advanced Tokamak mission of DIII-D.
- The enhanced edge (mantle) radiation due to the injected impurities lowers the exhaust power from the plasma core, affects edge stability due to the reduction of the edge pressure gradient, and can lead to enhanced confinement due to stabilization of micro-instabilities.
- In this work, results from coupled main plasma and impurity charge state transport simulations are presented for *L*-mode upper-biased Double-Null discharges with Neon (shot 098775) and Argon (shot 098787) injection, as well as the accompanying reference discharge without impurity injection (shot 098777).
- Good agreement between simulation and experimental results is obtained using simple transport models for the main plasma and the impurity charge states.

The GTWHIST 1½-D Transport Code

- Standard time-dependent plasma transport code, solving the flux-surface averaged particle and energy balance equations in the plasma core.
- 2D fixed-boundary MHD equilibrium solver (VMEC)
- Models for the calculation of gas puffing fueling, neutral beam heating and current drive, pellet fueling, and other sources and sinks.
- Self consistent calculation of the transport of all charge states of several impurities (C, O, Ne, Ar, Fe, Kr)
- Choice of various empirical and theory-based transport models

EQUATIONS in GTWHIST

Particle Transport

$$\frac{\partial}{\partial t}\left(V'n_j\right) = -\frac{\partial}{\partial \rho}\left(V'\tilde{\Gamma}_j\right) + V'S_j^p - V'\frac{n_j}{\tau_{\parallel}}$$

Energy Transport

$$\frac{3}{2}\frac{\partial}{\partial t}\left[\left(V'\right)^{5/3} n_e T_e \right. = -\left(V'\right)^{2/3}\frac{\partial}{\partial \rho}\left[V'\tilde{Q}_e + \frac{5}{2}V'T_e\tilde{\Gamma}_e \right. +$$

$$\left(V'\right)^{5/3}\left[Q_E^e - \sum_Z \sum_q n_e n_q^Z L_q^Z\left(T_e\right) - Q_{ei} - Q_{\parallel e}\right]$$

$$\frac{3}{2}\frac{\partial}{\partial t}\sum_j\left[\left(V'\right)^{5/3} n_j T_j \right. =$$

$$-\left(V'\right)^{2/3}\sum_j\left\{\frac{\partial}{\partial \rho}\left[V'\tilde{Q}_j + \frac{5}{2}V'T_i\tilde{\Gamma}_j\right] + \left(V'\right)^{5/3}\left[Q_E^i + Q_{ei} - Q_{\parallel j}\right]\right.$$

Multi-charge state impurity transport

$$\frac{1}{V'}\frac{\partial}{\partial t}\left(V'n_q^Z\right) + \frac{1}{V'}\frac{\partial}{\partial \rho}\left(V'\tilde{\Gamma}_q^Z\right) = I_{q-1}^Z n_{q-1}^Z - \left(I_q^Z + R_q^Z\right)n_q^Z + R_{q+1}^Z n_{q+1}^Z - \frac{n_q^Z}{\tau_{\parallel q}^Z} + S_q^Z$$

$$\tilde{\Gamma}_q^Z = -D_q^Z\left\langle\left|\nabla\rho\right|^2\right\rangle\frac{\partial n_q^Z}{\partial \rho} + n_q^Z v_q^Z\left\langle\left|\nabla\rho\right|\right\rangle$$

TRANSPORT MODELS

Main Plasma

- A simple *L*-mode Bohm-like transport model[1] has been used for the main plasma particle and energy transport:

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

$$\chi_e = \alpha_e \chi_B, \quad \chi_i = \alpha_i \chi_B, \quad D = \alpha_n \chi_B$$

- An optional pinch term can be added to the particle transport:

$$v_p = -2C_V \left(\frac{D}{a}\right. \rho^{\alpha_V}$$

Impurities:

- A fixed-shape transport model has been used for the impurities. All charge states are assumed to have the same diffusion coefficient:

$$D_Z = D_{Z0}\left(1 + c_1 \rho^{c_2}\right)$$

$$V_Z = -2C_{VZ}\left(D_Z / a\right) \rho^{\alpha_{vz}}$$

The transport coefficients of the impurity charge states are independent of the main plasma transport coefficients.

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[1] M. Erba, et al., *Plasma Phys. Control. Fusion* **37** (1995) 1249.

MODELLING OF REFERENCE DISCHARGE 98777

- We first model the reference (no injected impurities) discharge 98777.
- The simulation starts at about 0.5 s when the plasma has reached its steady-state shape (a, R, κ, δ).
- Best agreement with experiment is obtained if we use $\alpha_e = 4.0\times10^{-4}$, $\alpha_i = 4.64\times10^{-4}$ and $\alpha_n = 3.3\times10^{-4}$ in the transport model.
- No pinch term is assumed in the particle transport. 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.
- An intrinsic carbon concentration of 1.24% was assumed, raising the peak value of the Z_{eff} to about 1.4, consistent with TRANSP analysis results[2].

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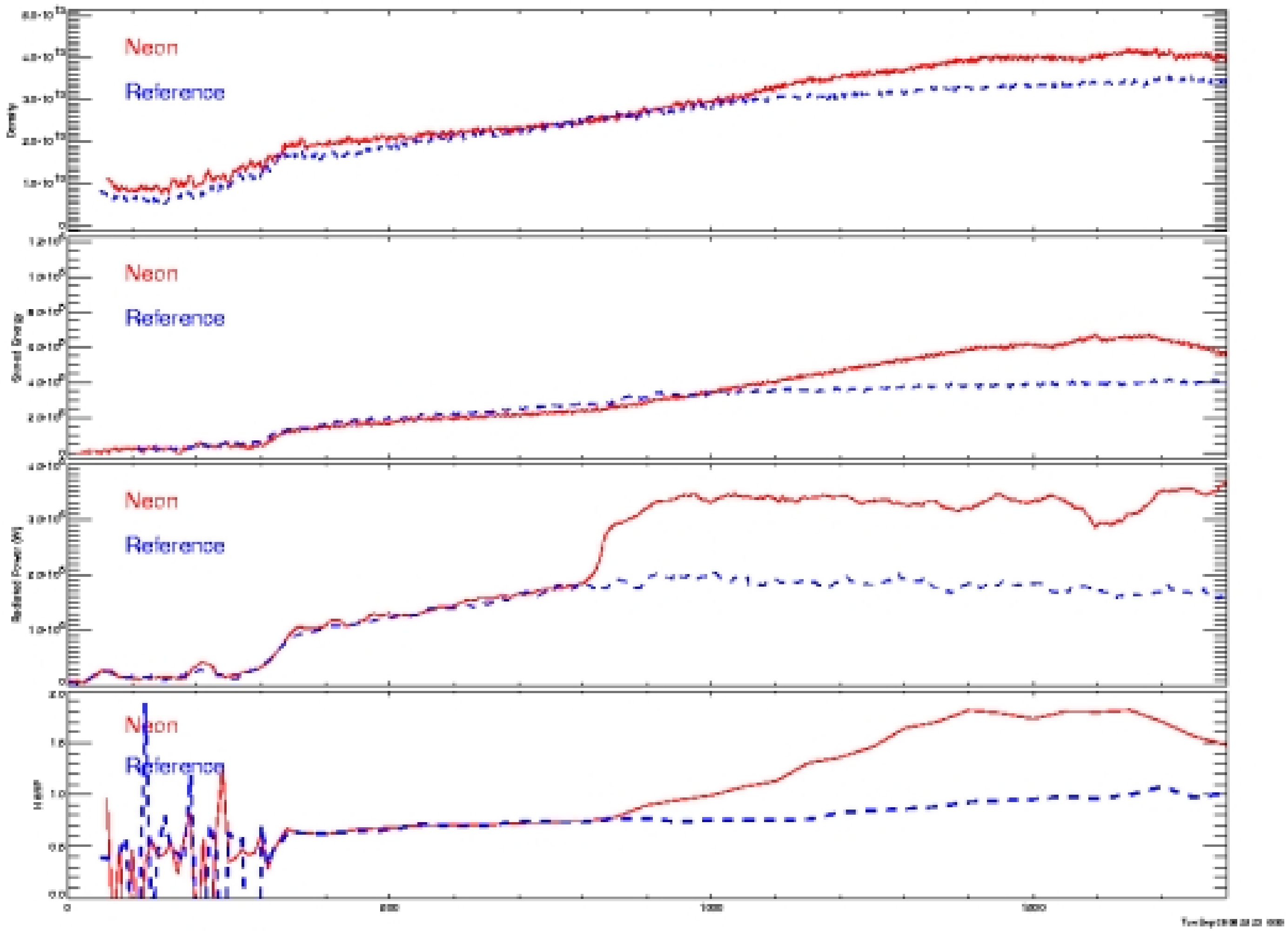
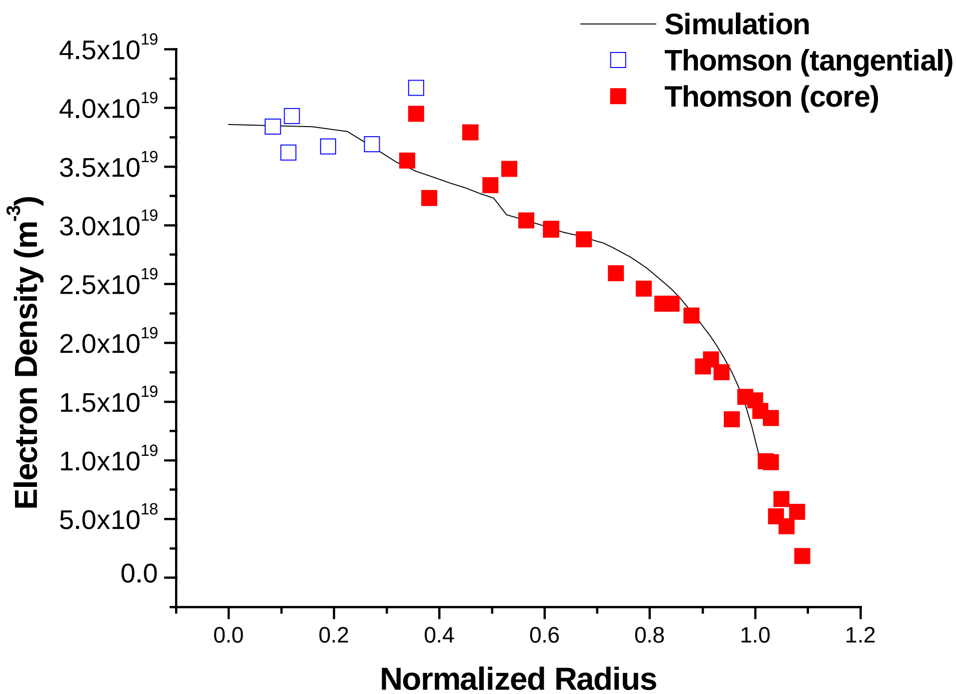
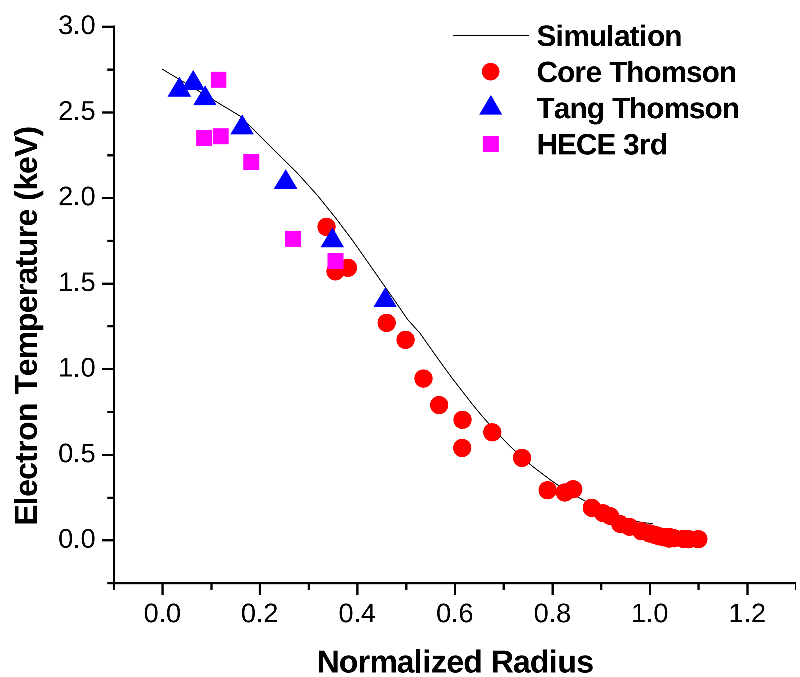
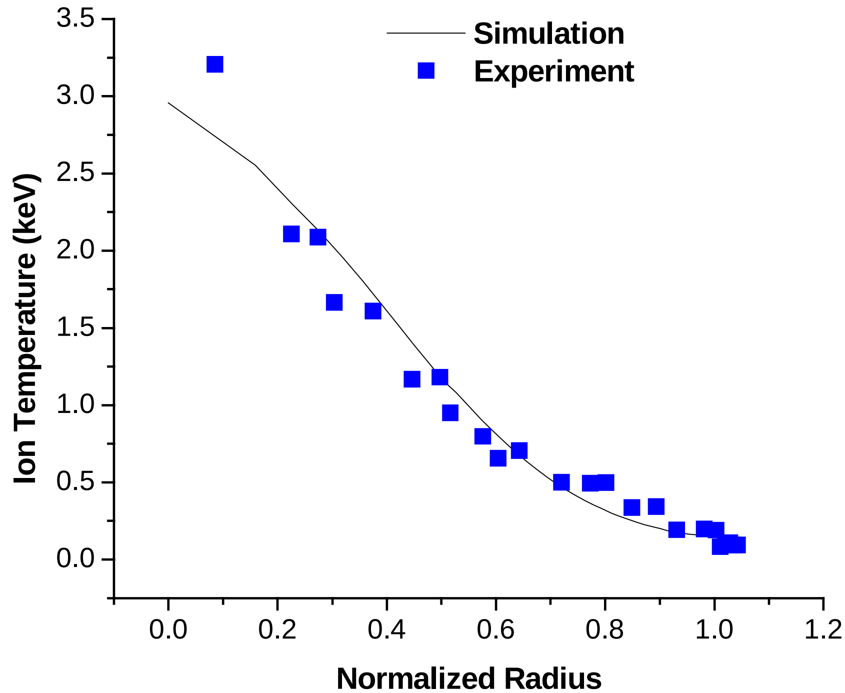
[2] M. Murakami, et al. "*Transport Studies of Radiating Mantle Discharges with Confinement Improvement in DIII-D*," presented at the RI-Mode Workshop, Culham, 1999.


Neon
Reference
Density
Neon
Reference
Stored Energy
Neon
Reference
Radiated Power (W)
Neon
Reference
H98P

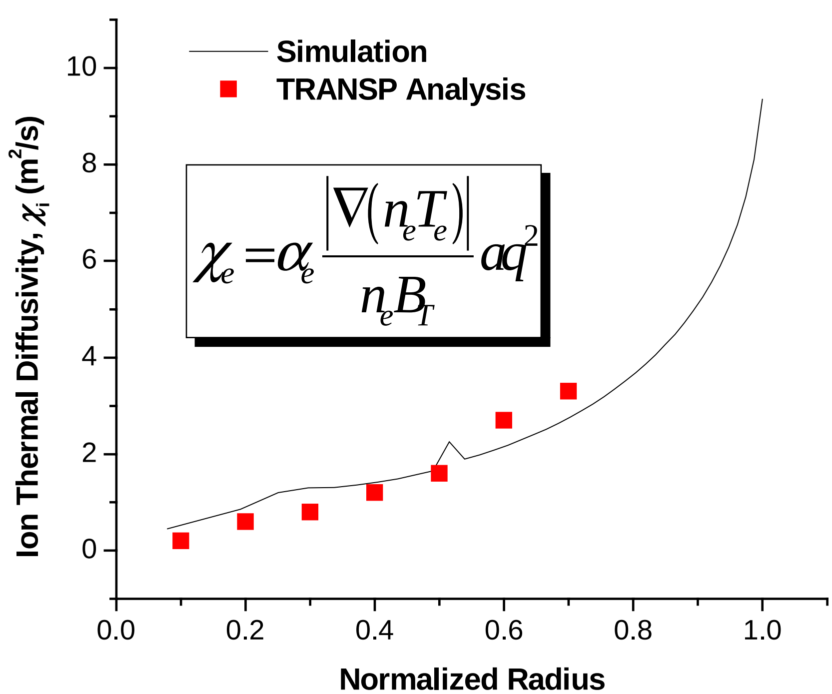
Comparison of Simulation and Experiment for Shot 098777 at t = 1600 ms.







Simulation
Experiment
Ion Temperature (keV)
Normalized Radius
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.0
0.2
0.4
0.6
0.8
1.0
1.2



Simulation
TRANSP Analysis
$\chi_e = \alpha_e \frac{\left|\nabla(n_e T_e)\right|}{n_e B_T} a q^2$
Ion Thermal Diffusivity, χ_i (m^2/s)
Normalized Radius
10
8
6
4
2
0
0.0
0.2
0.4
0.6
0.8
1.0

Modeling of Neon –Seeded Discharge 98775

- In this discharge, Neon was injected at 0.8 seconds, followed by substantial confinement improvement, which was correlated with strong reduction of turbulence[3].
- No theory-based transport model explaining this confinement improvement and appropriate for use in predictive transport simulations is yet available.
- In our simulations, the observed confinement improvement is taken into account by reducing the transport coefficient multipliers α_e, α_i and α_n following 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. In addition, an inward pinch term ($C_V = 1$, $\alpha_v = 1$) was necessary to match the observed peaking of the density profile.
- The overall transport reduction is consistent with results obtained from a TRANSP analysis of the experimental data[3].

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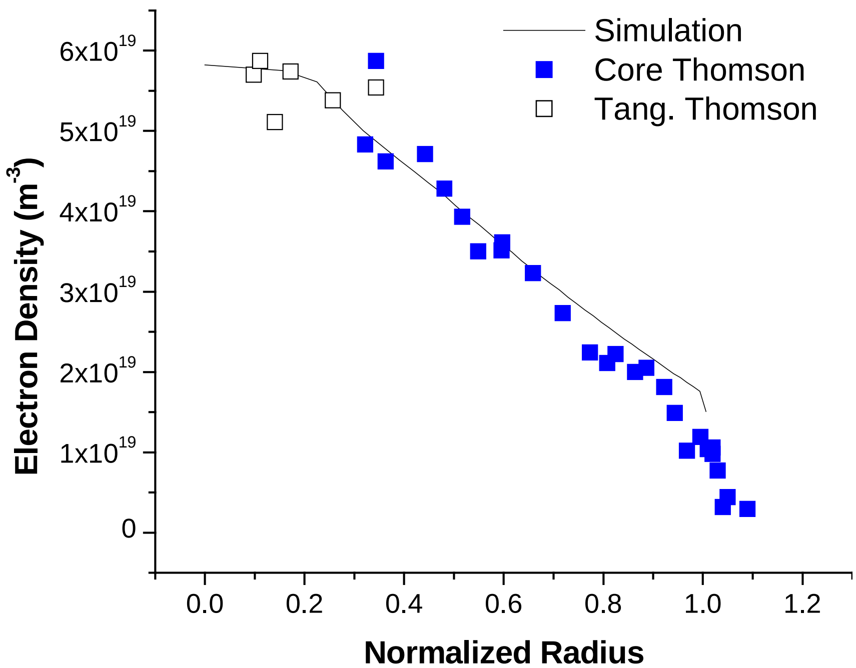
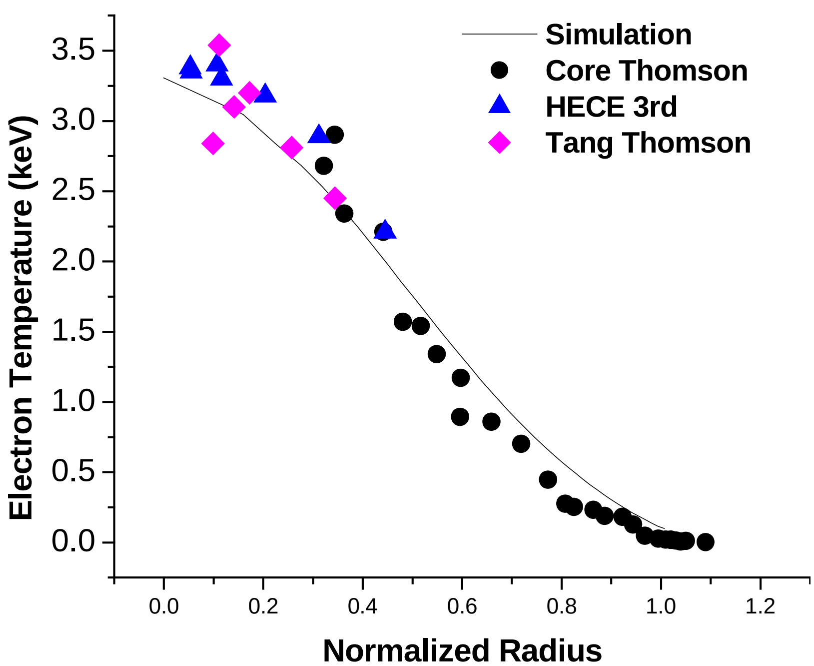
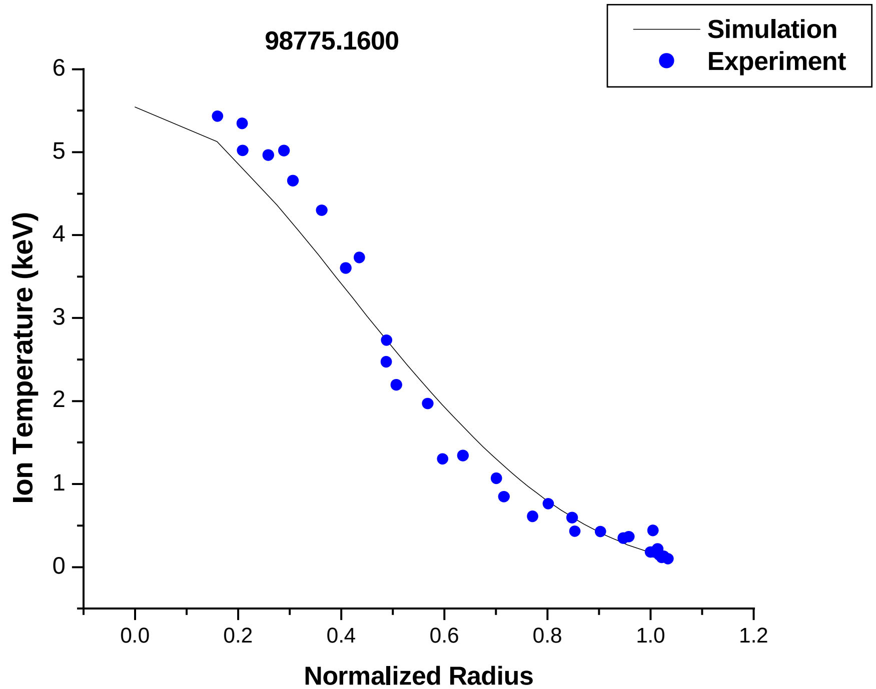
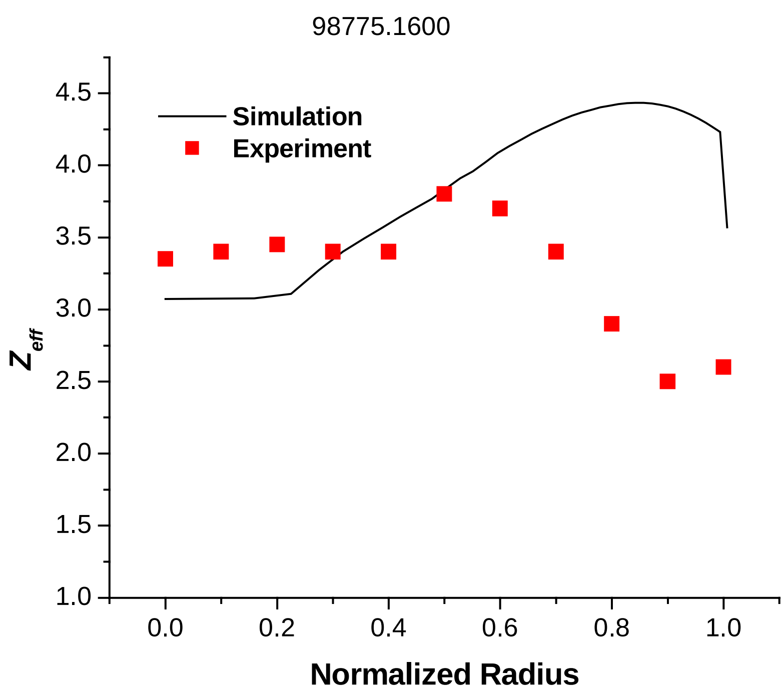
[3] McKee, G. et al., *"Impurity-Induced Suppression of Turbulence and Transport in DIII-D,"* presented to the Transport Task Force, Portland, OR, 1999, submitted to *Phys. Rev. Lett.*; M. Murakami, et al. "*Transport Studies of Radiating Mantle Discharges with Confinement Improvement in DIII-D*," presented at the RI-Mode Workshop, Culham, 1999.

Comparison of Simulation and Experiment for Shot 098775 at t = 1600 ms.



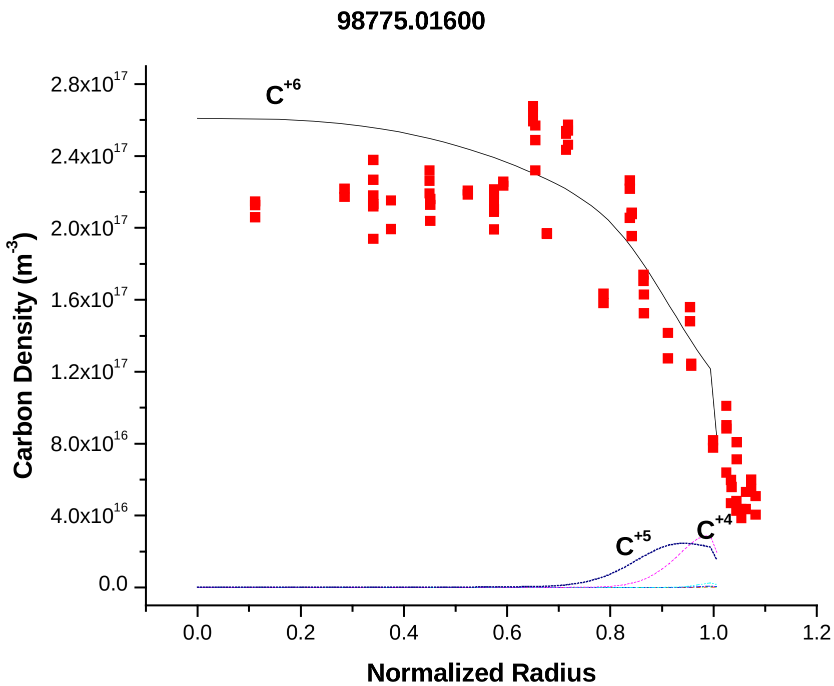


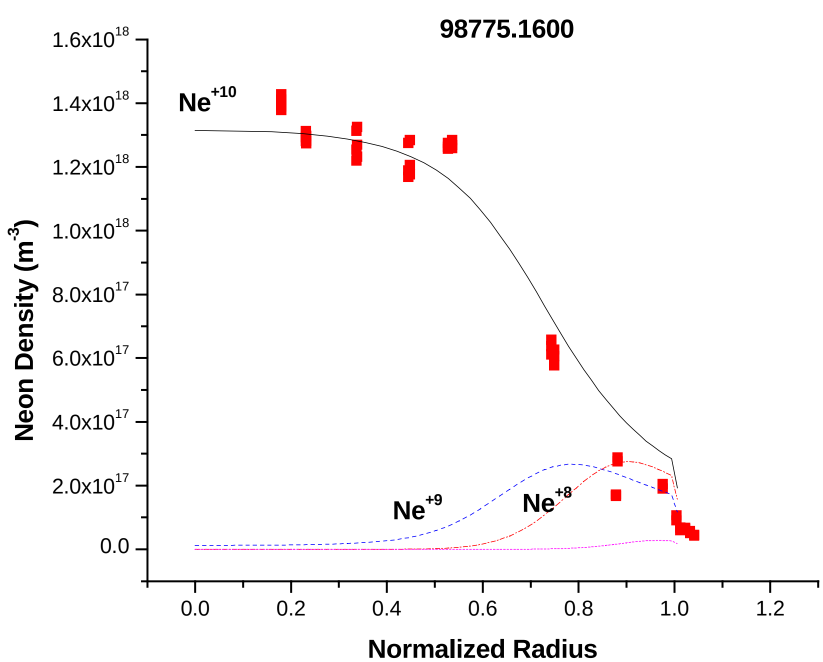




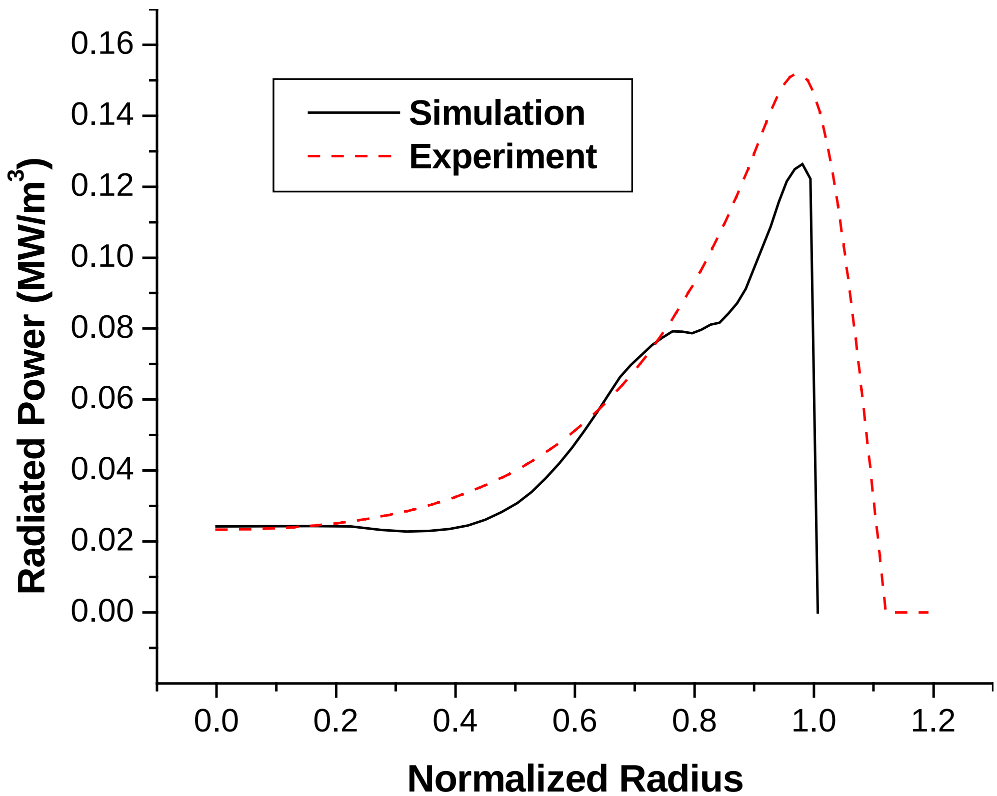
- Notice that the experimental Z_{eff} contains only the contributions from the fully ionized states of Carbon and Neon (C^{+16} and Ne^{+10}).

Comparison of calculated C and Ne charge states with CER data.





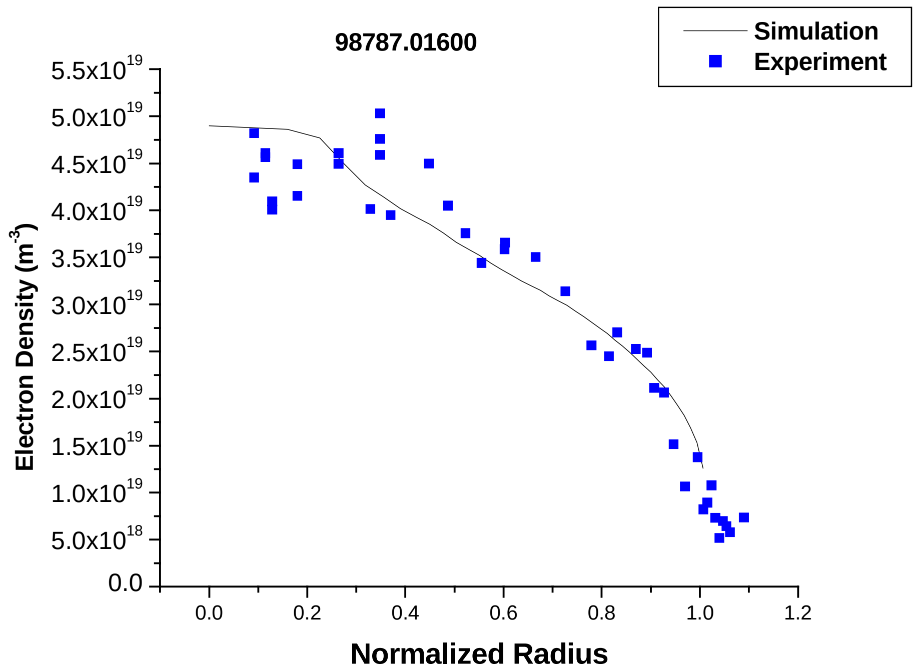
Comparison of simulated radiation power profile with fit to data from the bolometer arrays

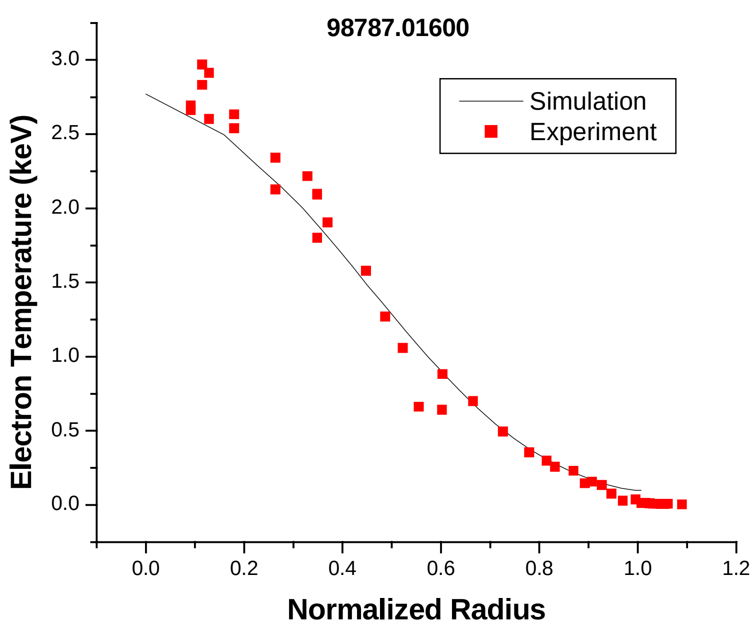


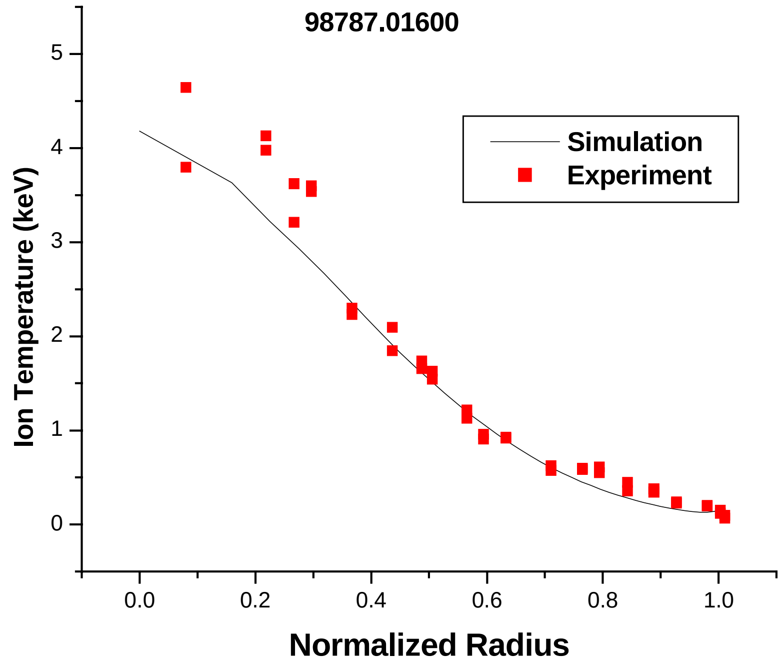
Modeling of Argon –Seeded Discharge 098787

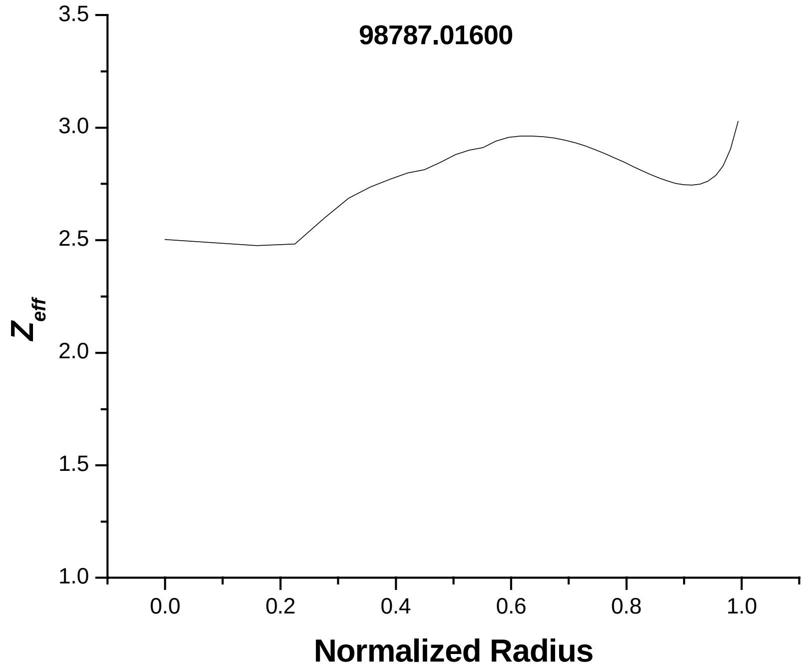
- Similar to Shot 098775, but Argon is injected instead of Neon.
- Confinement improves following Ar injection, but not as much as in the Ne case.
- Good agreement with experimental plasma profiles is obtained by reducing the a_i coefficient of the Bohm transport term by 2.3 (compared to 7 in the Neon case) following the Ar injection.
- The same impurity transport model used in the Neon simulations is used for Argon.
- Good agreement between simulation and experiment for the Ar^{+16} density profile.
- Good agreement between simulation and experiment for the C^{+6} density profile in the edge and central regions.
- The computed P_{rad} profile agrees well with the profile obtained from a bolometric inversion of the experimental data, although the simulated profile peaks at a smaller radius.

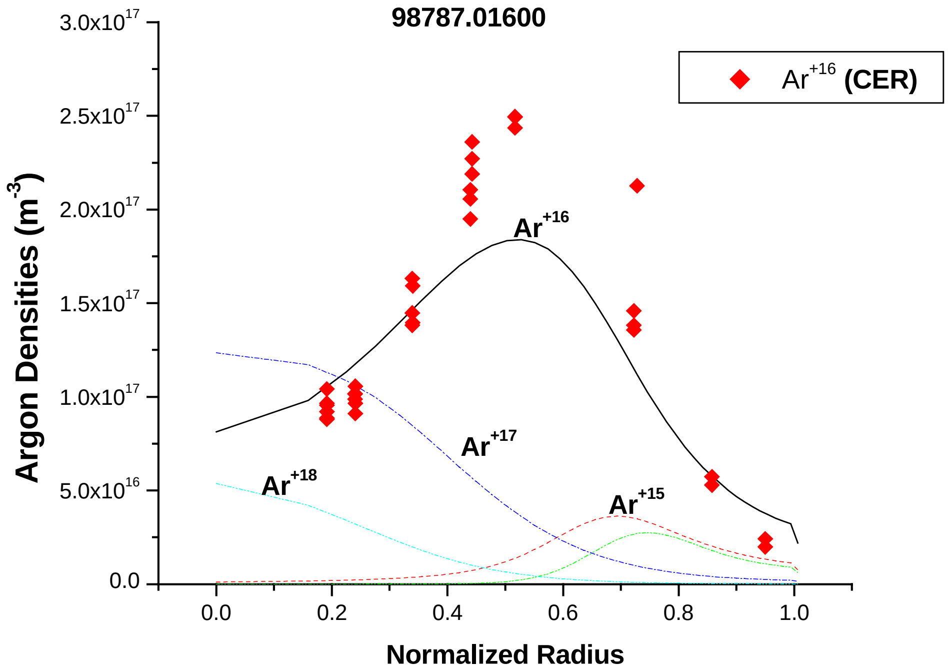
Comparison of Simulation and Experiment for Shot 098787 at t = 1600 ms.



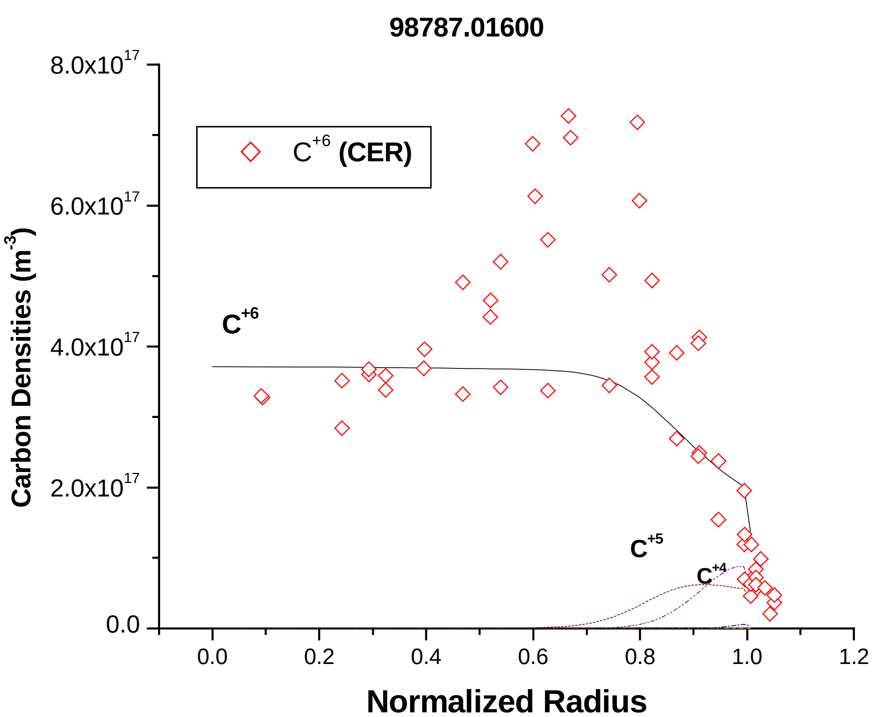



98787.01600
Simulation
Experiment
Ion Temperature (keV)
Normalized Radius
0
1
2
3
4
5
0.0
0.2
0.4
0.6
0.8
1.0


98787.01600
Z_eff
Normalized Radius
1.0
1.5
2.0
2.5
3.0
3.5
0.0
0.2
0.4
0.6
0.8
1.0

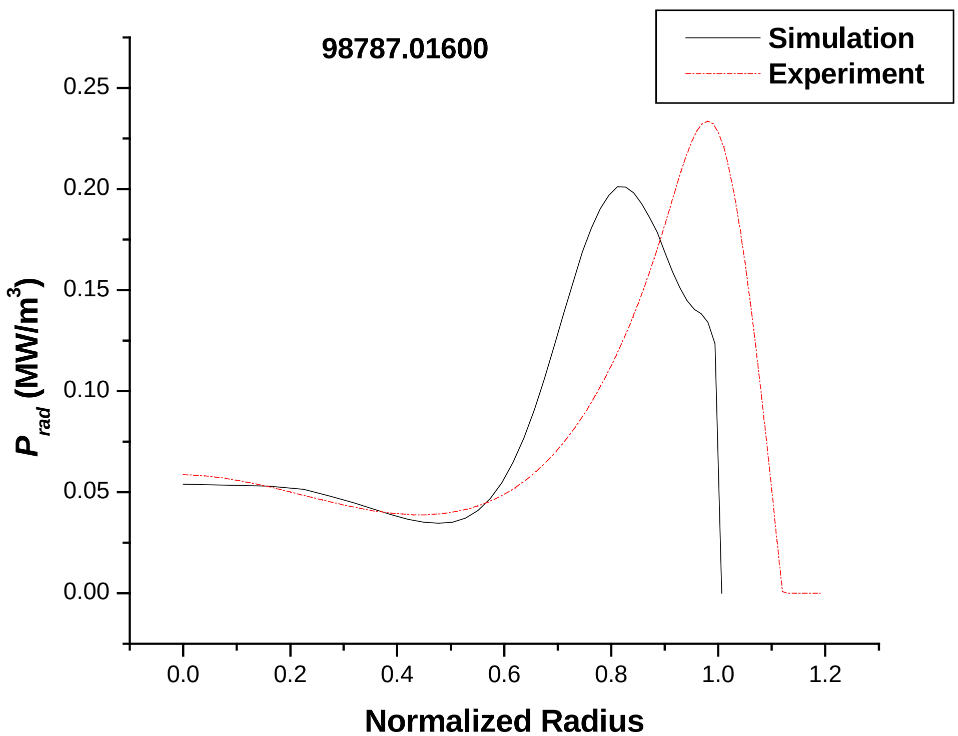


98787.01600
Ar+16 (CER)
Argon Densities (m-3)
3.0x10^17
2.5x10^17
2.0x10^17
1.5x10^17
1.0x10^17
5.0x10^16
0.0
Ar+16
Ar+17
Ar+18
Ar+15
0.0
0.2
0.4
0.6
0.8
1.0
Normalized Radius



98787.01600
C+6 (CER)
Carbon Densities (m-3)
8.0x10^17
6.0x10^17
4.0x10^17
2.0x10^17
0.0
C+6
C+5
C+4
0.0
0.2
0.4
0.6
0.8
1.0
1.2
Normalized Radius

Comparison of simulated radiation power profile with fit to data from the bolometer arrays



CONCLUSIONS & FUTURE PLANS

- Results from coupled plasma and multi-charge state impurity transport simulations of *L*-mode Neon and Argon injected DIII-D discharges and the 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 appear to be adequate in reproducing the most important features of these discharges.
- The observed confinement improvement is modeled by a simple reduction of the transport coefficient multipliers of the main plasma following the impurity injection. It was also found that an inward particle pinch was necessary in order to explain the observed electron density profile peaking, following impurity injection.
- Future plans include the extension of these simulations to other impurity injected DIII-D shots, the implementation and use of a neoclassical model for the transport of the impurity charge states, and the evaluation and eventual use of theory-based models for the energy transport of the main plasma.