SIMULATIONS OF DIII-D DISCHARGES WITH IMPURITY SEEDING

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SUMMARY

- Injection of recycling impurities (Ne, Ar, Kr, etc.) into tokamak plasmas has been used in several experiments.
- Part of the original motivation was the reduction of the divertor heat loads through the creation of a radiating plasma mantle, as well as edge profile modification for AT operation.
- Recent observations of significant confinement improvement following impurity injection due to suppression of core turbulence, have made impurity seeding an important tool for the understanding of transport mechanisms in tokamak plasmas and the comparison of theory-based turbulence and transport models with experimental measurements.
- In this work we present impurity transport analysis of several DIII-D shots with impurity injection from the 1999 and 2000 campaigns. Most of these shots are L-mode negative central shear DN discharges exhibiting various degrees of confinement improvement in most transport channels following the impurity injection.

COMPUTATIONAL TOOLS AND MODELS

- Our simulations are performed with the 1½-D transport code GTWHIST which 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 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:

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

- A fixed-shape transport model has been used for the impurity charge states:

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

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

$$V_Z(\rho) = -C_{vz0}\left(\frac{D_Z(\rho)}{a}\right)\left(1 - f_{vzp}\rho^{\alpha_{vz}}\right)$$

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

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

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

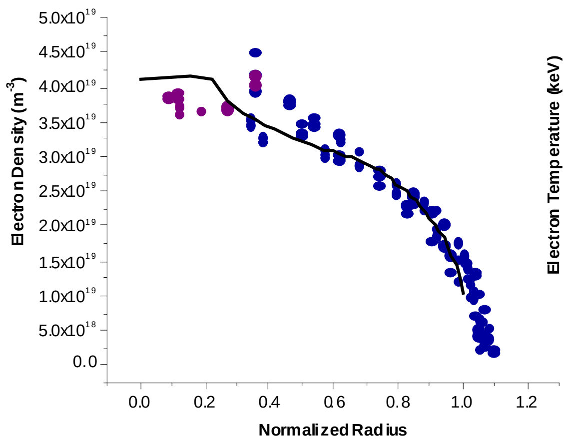
$$\tilde{\Gamma}_q^Z = -D_q^Z\left\langle\left|\nabla\rho\right|^2\right\rangle\frac{\partial n_q^Z}{\partial \rho} + n_q^Z v_q^Z\left\langle\left|\nabla\rho\right|\right\rangle$$

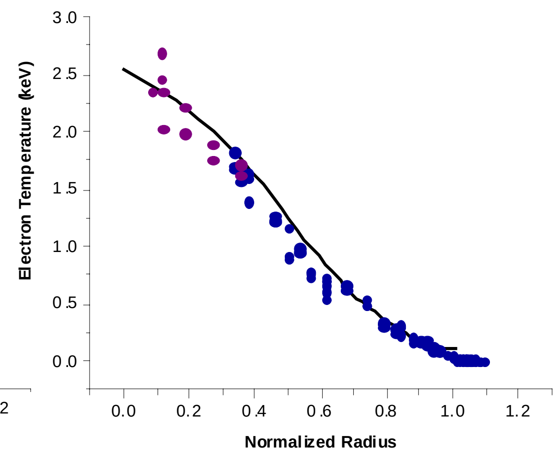
Simulation of 98777,98775, 98787 and 98794 discharges

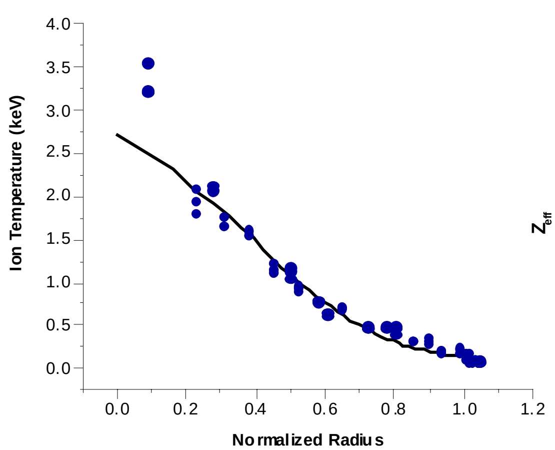
- Here, we present results from the simulations of the 98777 (reference), 98775 (Neon), 98787 (Ar) and 98794 (Kr) discharges from the 1999 campaign.
- The transport model multipliers α_e, α_i, α_n and C_V are adjusted for the reference (no injected impurities) discharge 98777, until good agreement with the measured plasma profiles (n_e, T_e, T_i) is obtained.
- The observed confinement improvement is taken into account by reducing the transport coefficient multipliers α_e, α_i and α_n following impurity injection (Ne, Ar, or Kr).
- For the impurity injected discharges (98775, 98787 and 98794), the parameters of the impurity transport model (assumed to be the same for all the charge states) are adjusted until good agreement with the experiment is obtained.
- The results of the simulations are compared with measured profiles of selected charge states (C^{+6}, Ne^{+10}, Ar^{+16}) and with the experimentally obtained radiated power profiles.

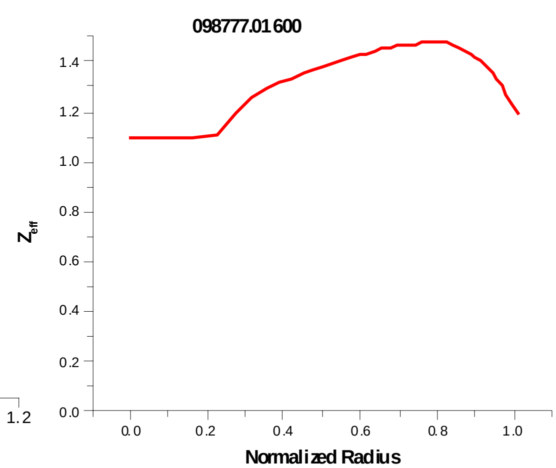
Reference Discharge 098777

98777 @ 1600 ms



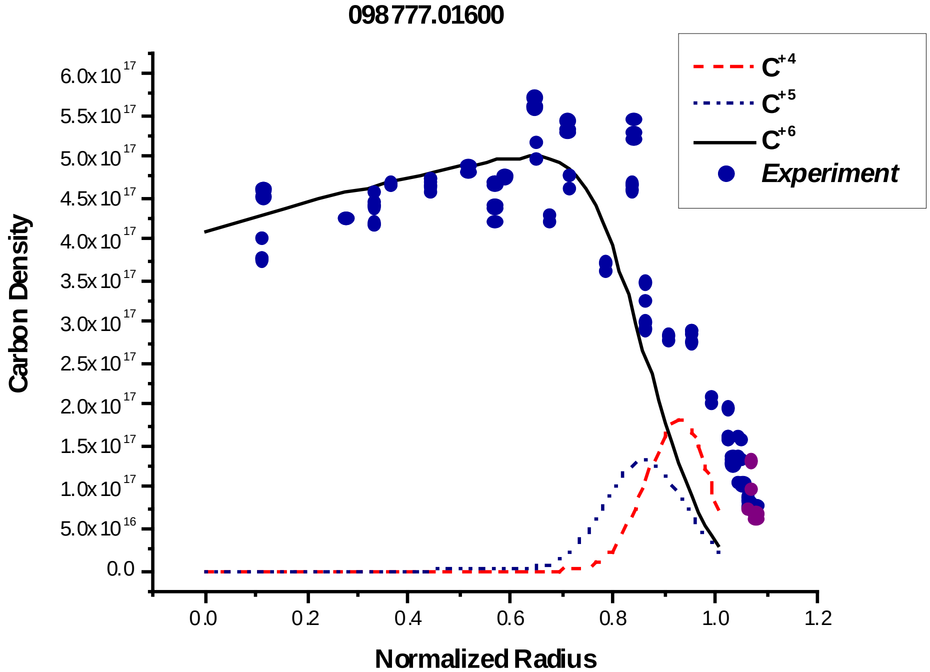


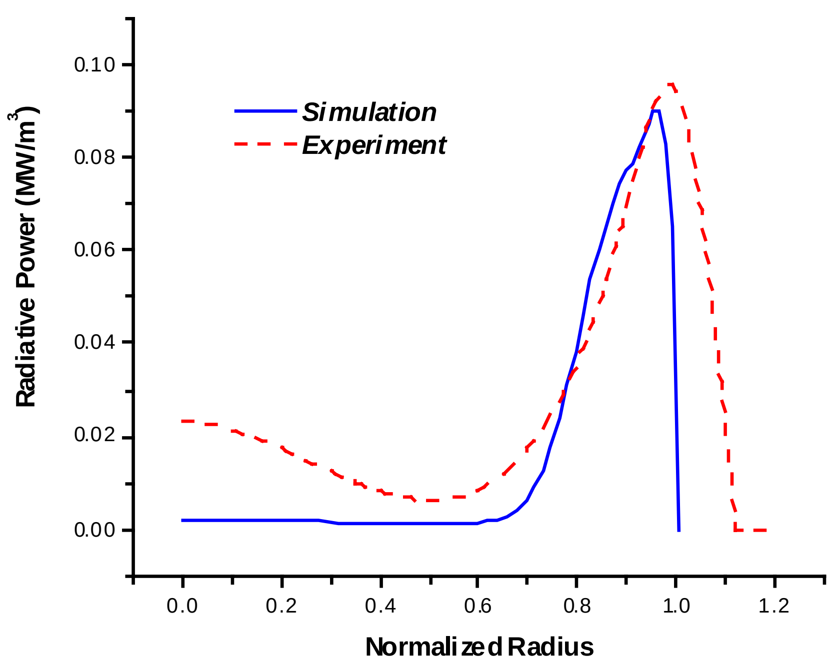




J. Mandrekas, 08/03/00

98777 @ 1600 ms

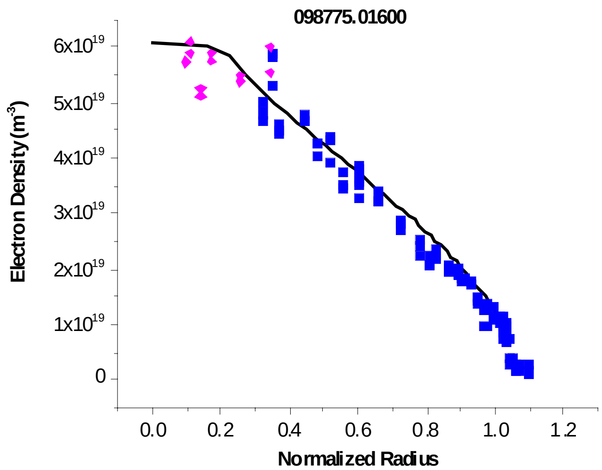


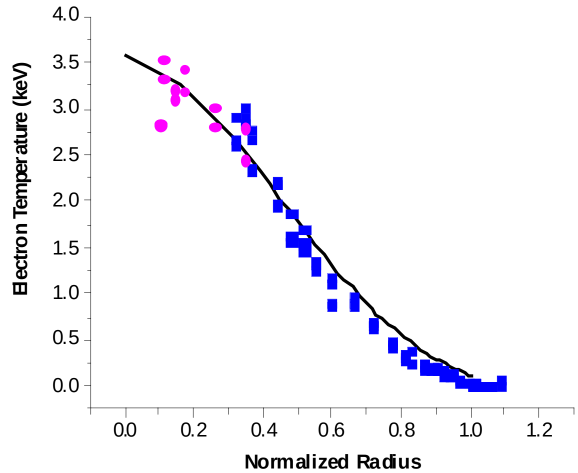


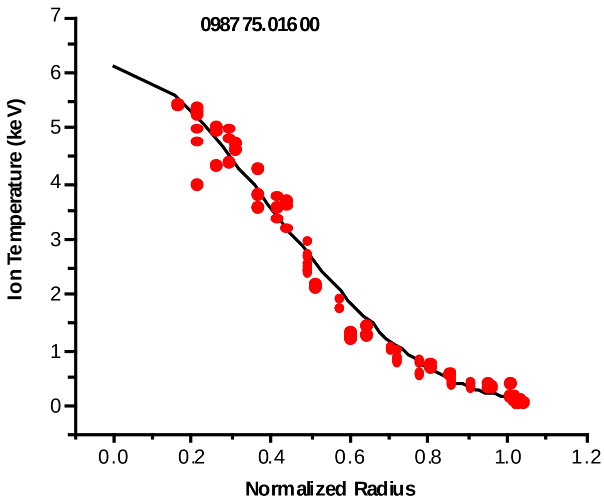
J. Mandrekas, 08/03/00

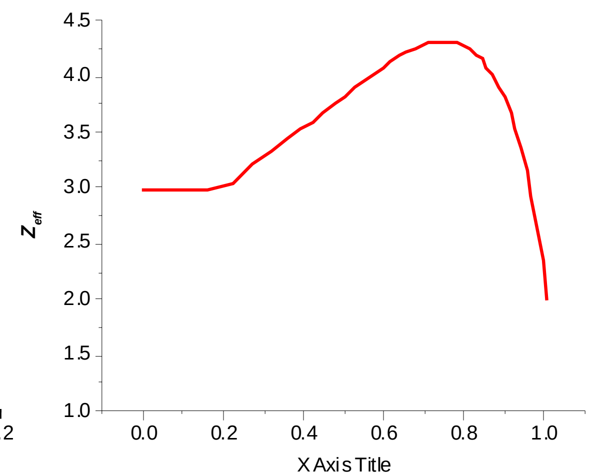
Neon Injected Discharge 098775

98775 @ 1600 ms





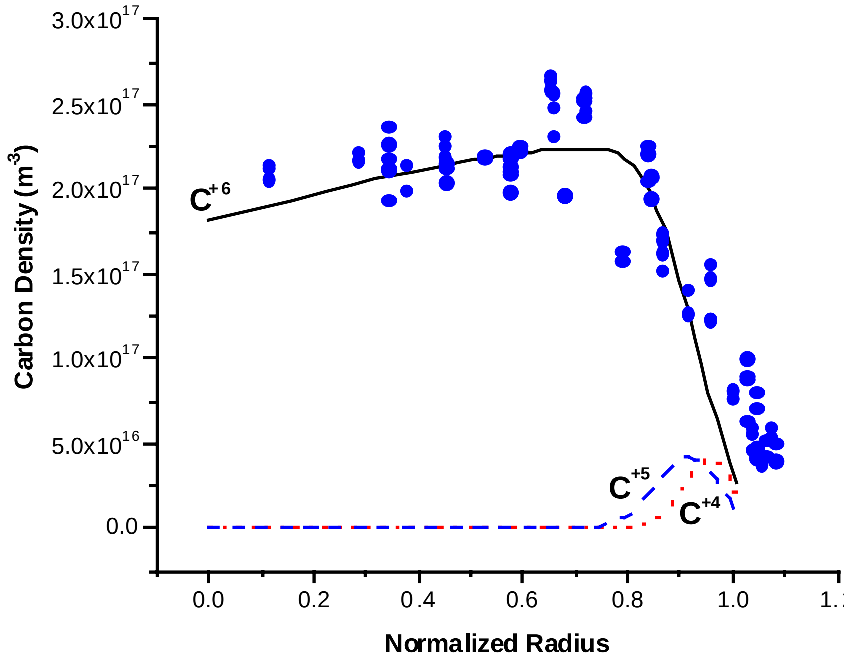


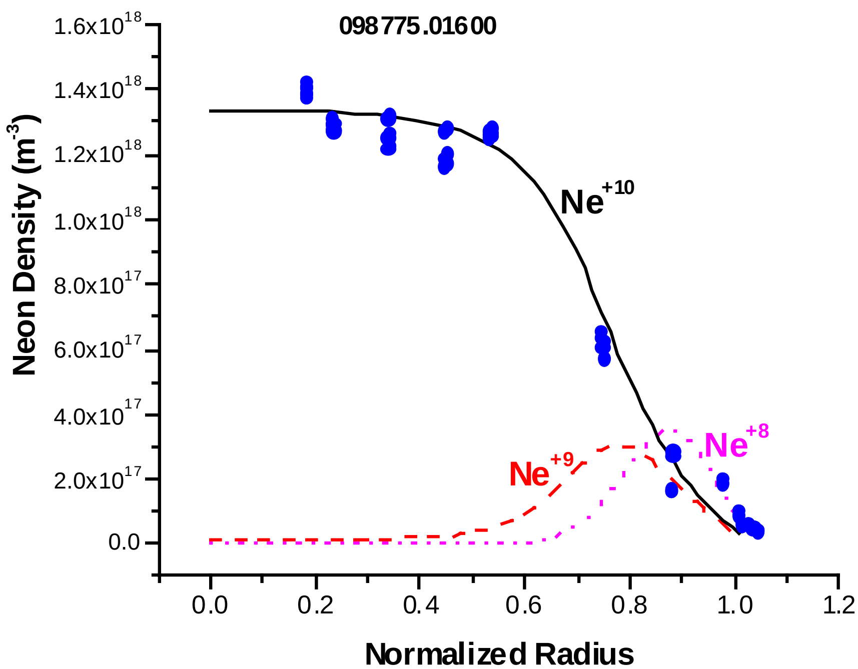


J. Mandrekas, 10/14/00

Carbon and Neon Charge State Comparison

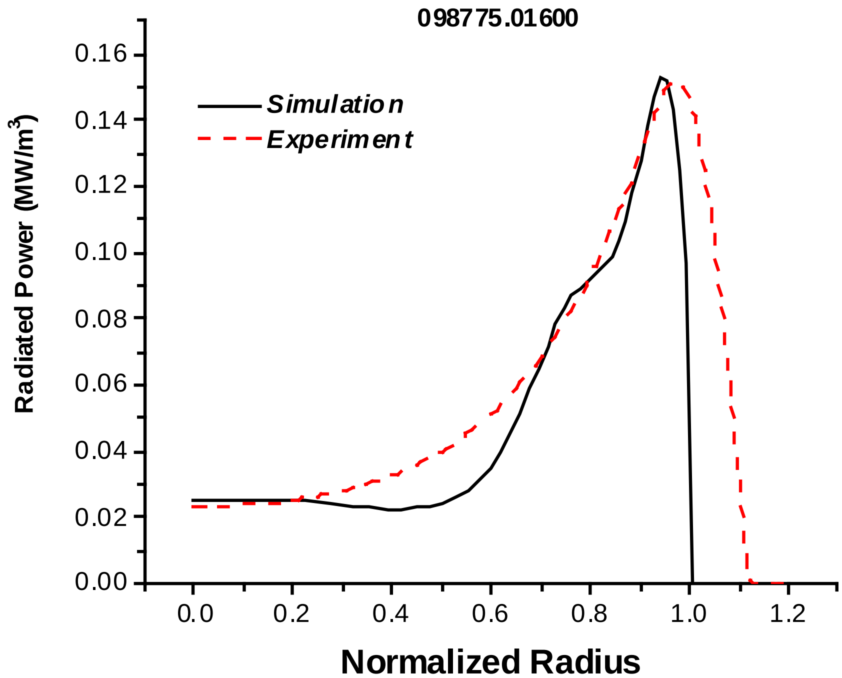
98775 @ 1600 ms

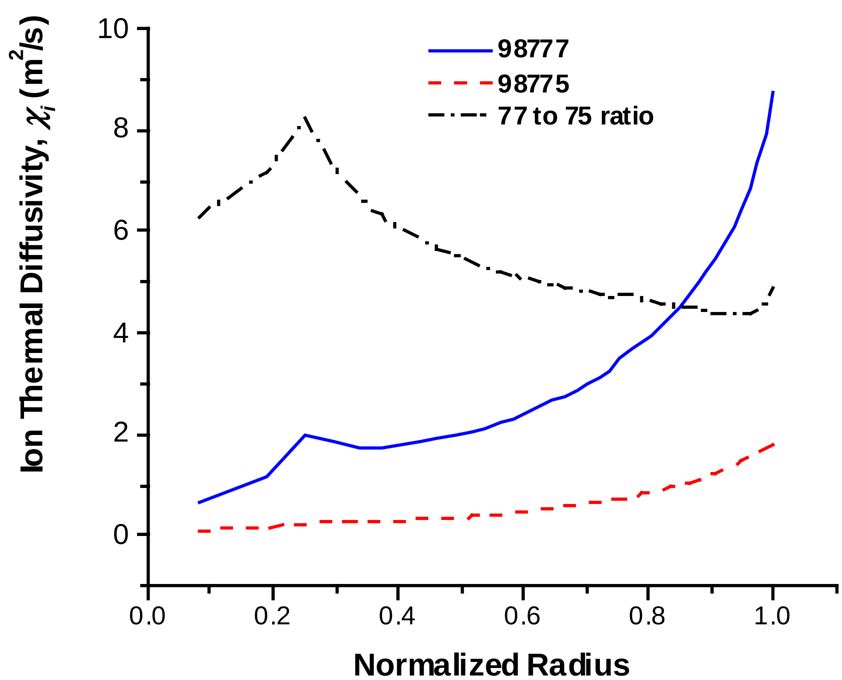




J. Mandrekas, 08/03/00

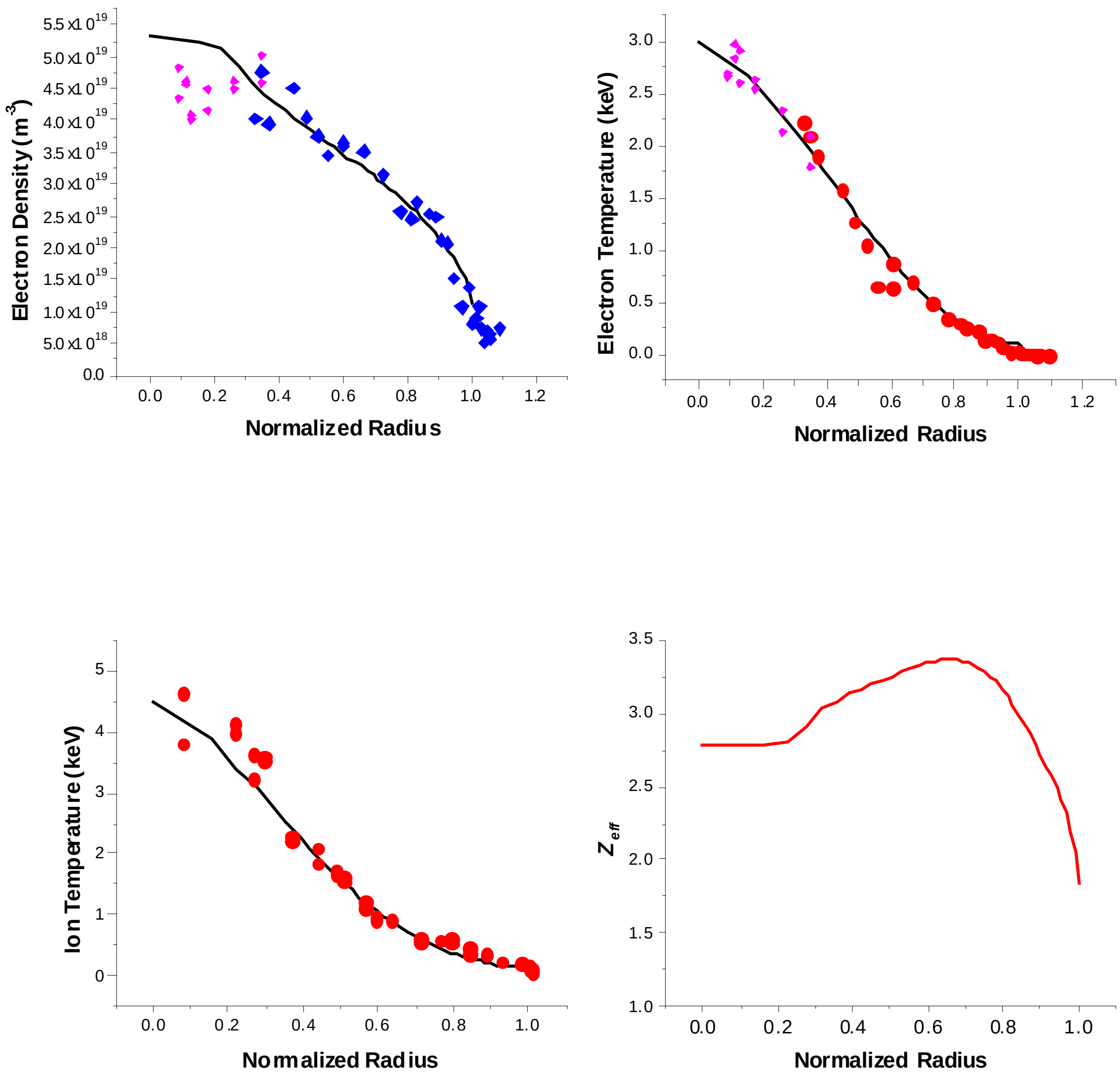
98775 @ 1600 ms





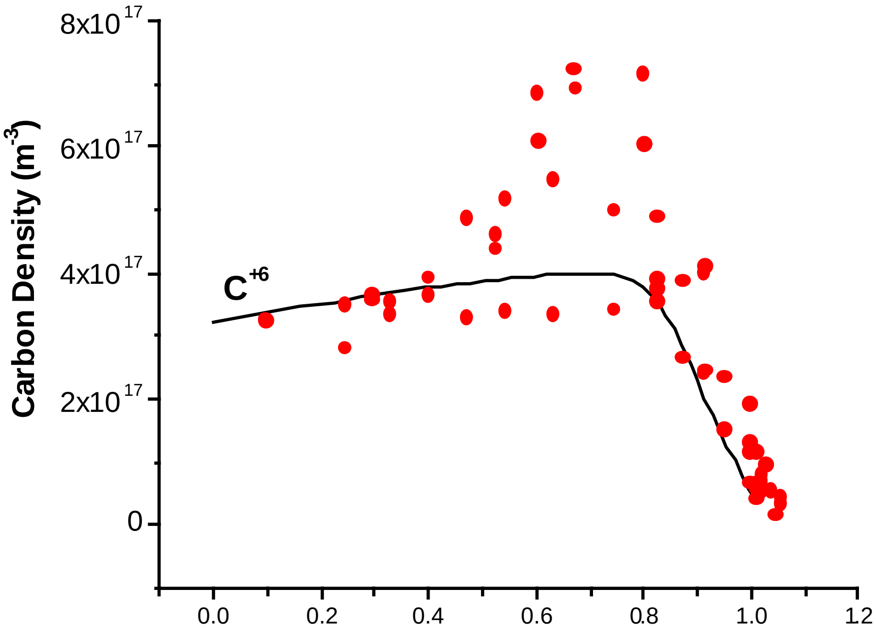
Argon Discharge 098787

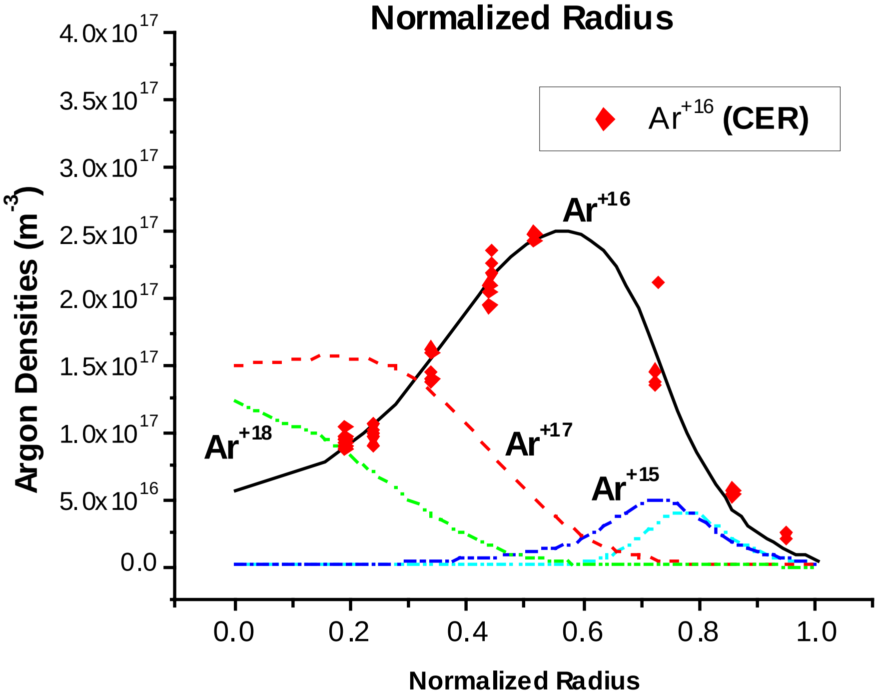
98787 @ 1600 ms



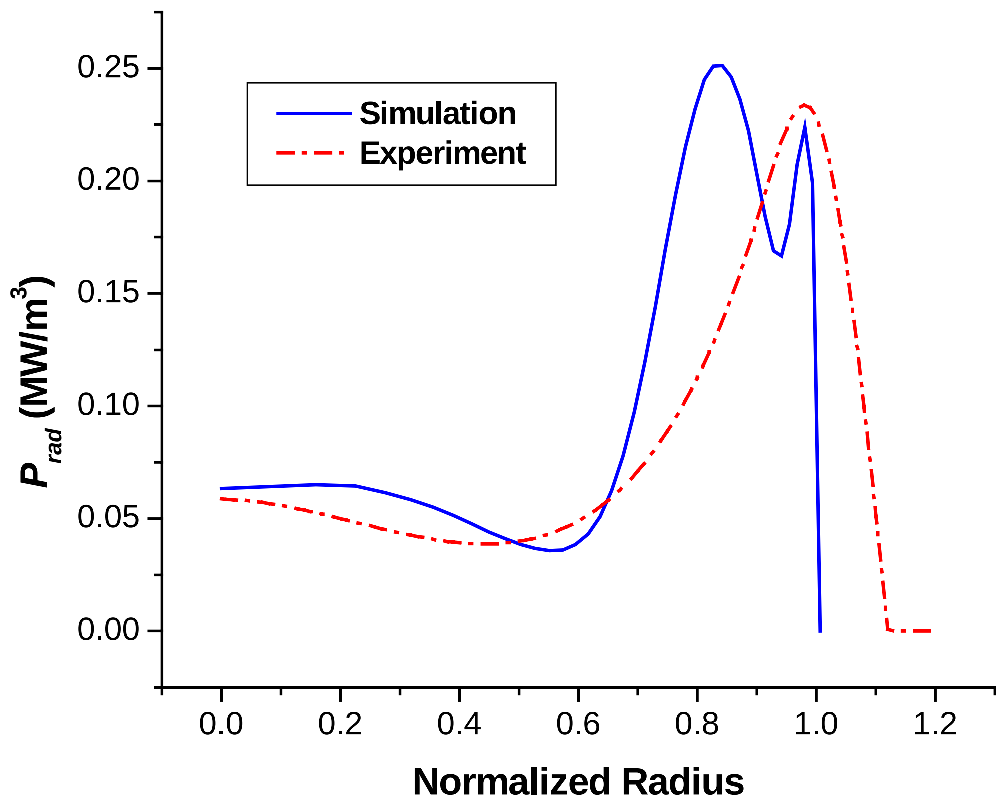
Carbon and Argon Charge State Comparison

98787 @ 1600 ms





Comparison of Radiated Power Profiles

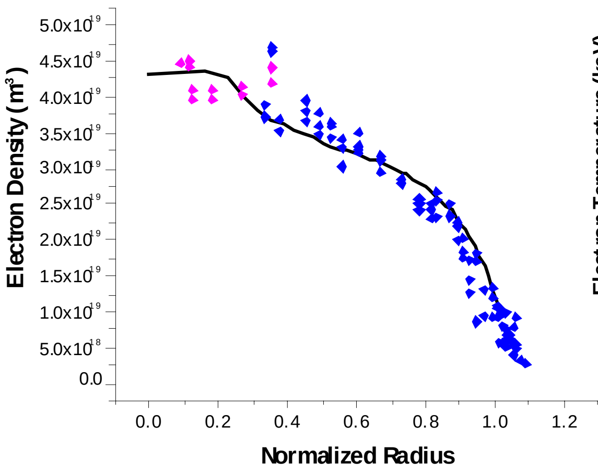


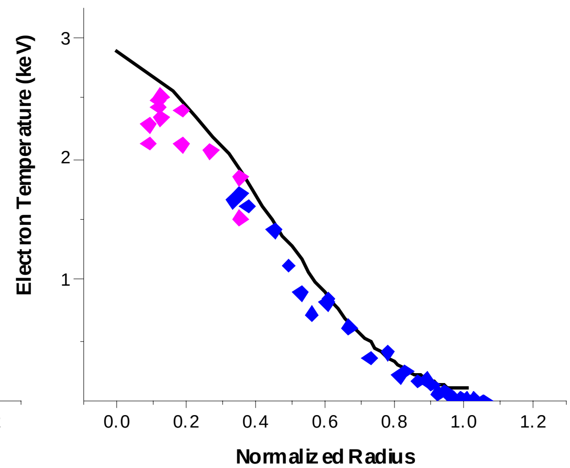
Krypton Discharge 098794

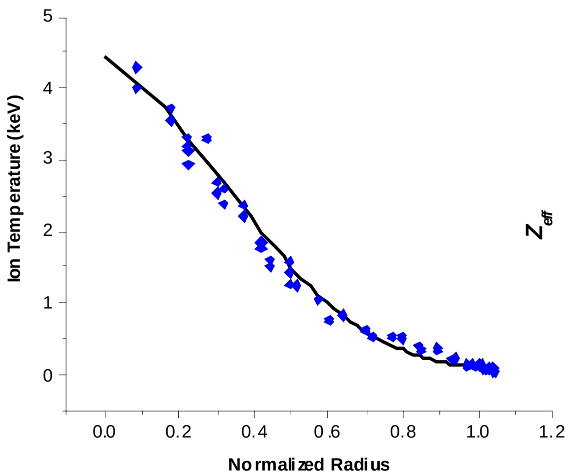
- Kr charge state data are not available, so no direct comparison of calculated Kr charge state densities or concentrations is possible.
- Simulation uses same parameters as 98777 but improved ion transport. Electron diffusivity and particle diffusion and pinch velocity coefficients, as well as particle sources (NB, recycling, edge puffing) are the same as in 98777.
- Kr source is adjusted to match measured radiation from the core (~ 1.5 MW) and P_{rad} profile from bolometer measurements.
- Two transport models for Kr were used: One with constant D_z (for all Kr charge states) and no pinch, and one with a parabolic-like D_z and outward pinch velocity.
- It was found that an average Kr concentration of 0.052% gives good agreement with measured core radiation.

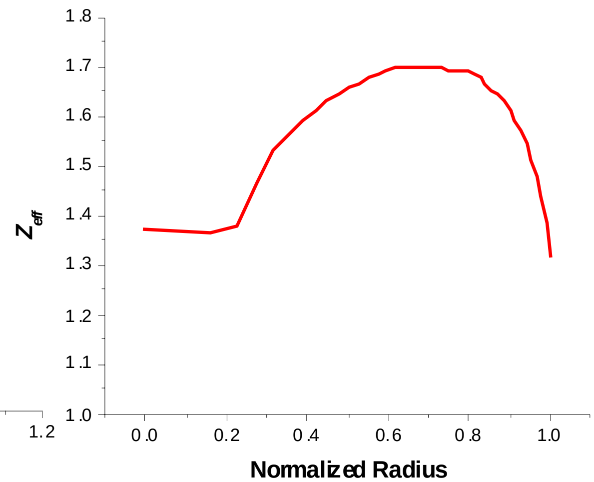
Plasma Profiles

98794 @ 1600 ms



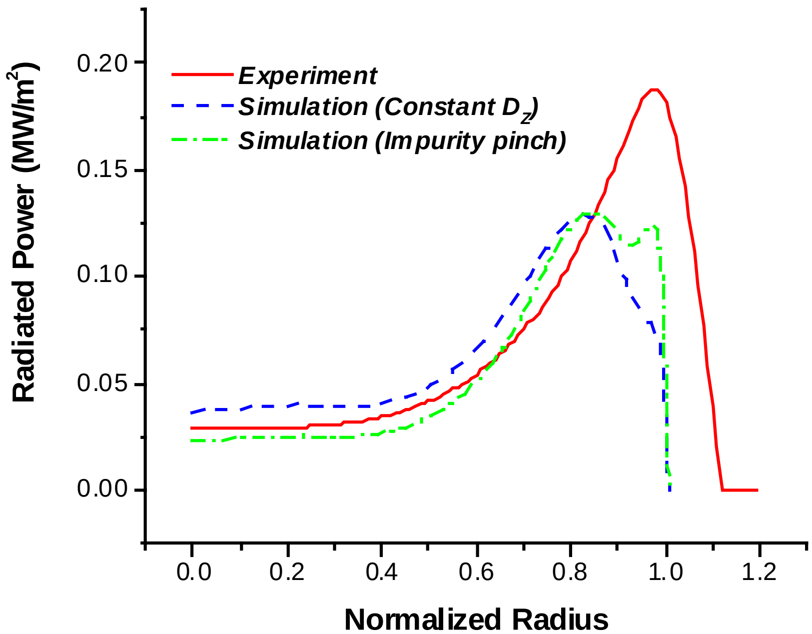


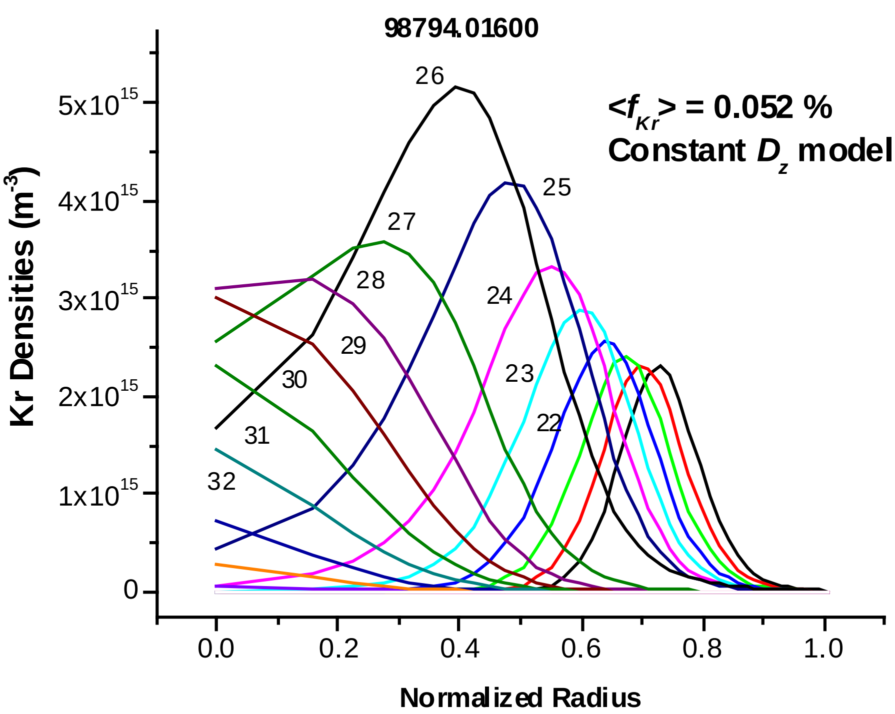




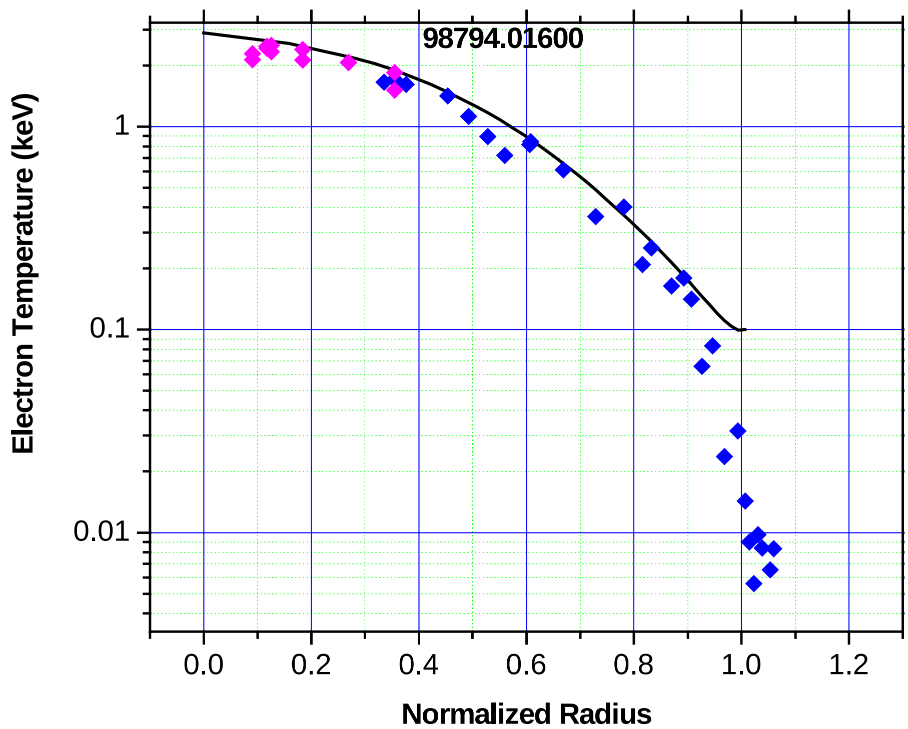
Radiation Profiles and Kr Charge States

98794 @ 1600 ms



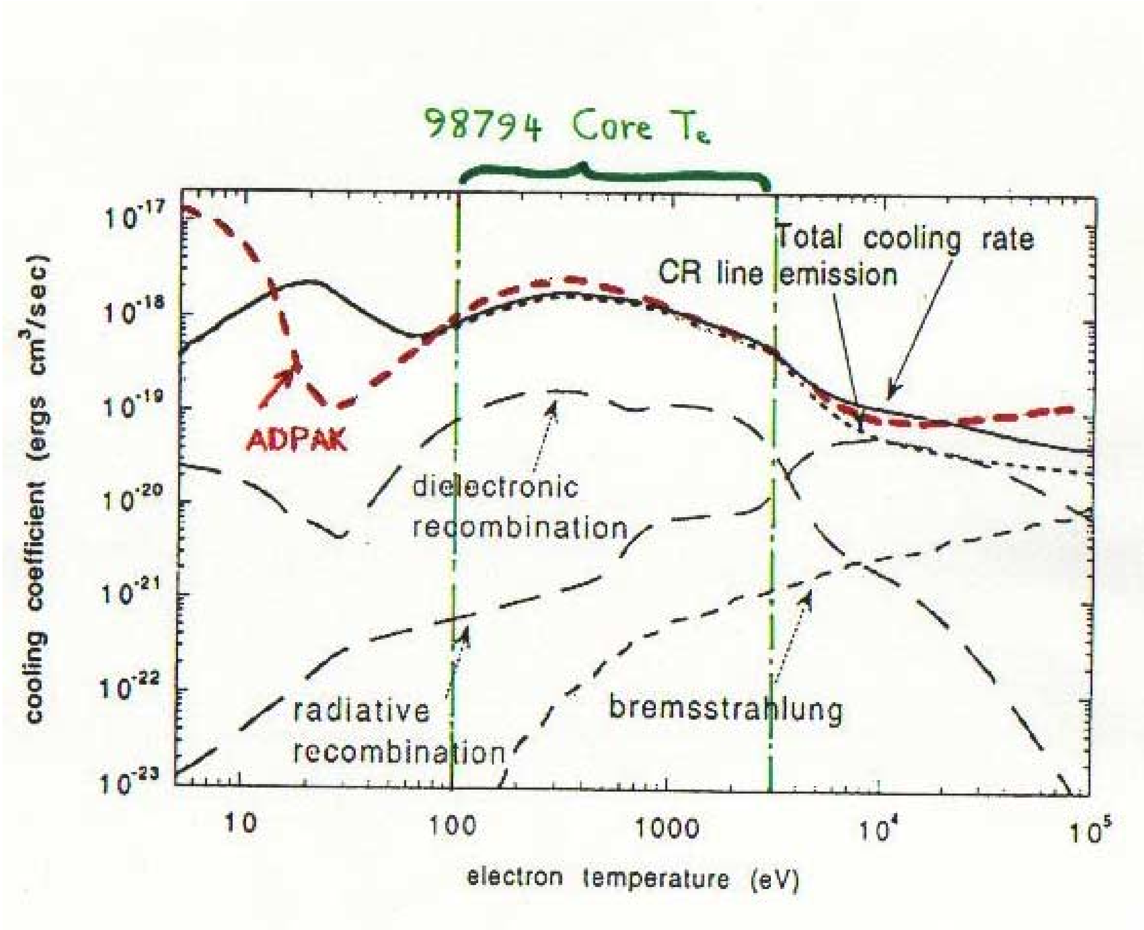


- **ADPAK** rates appear to be adequate for our electron temperature range:



Kr Radiative Cooling Rate Comparison

(K.B. Fournier, et al., Atomic Processes in Plasmas, 1998)



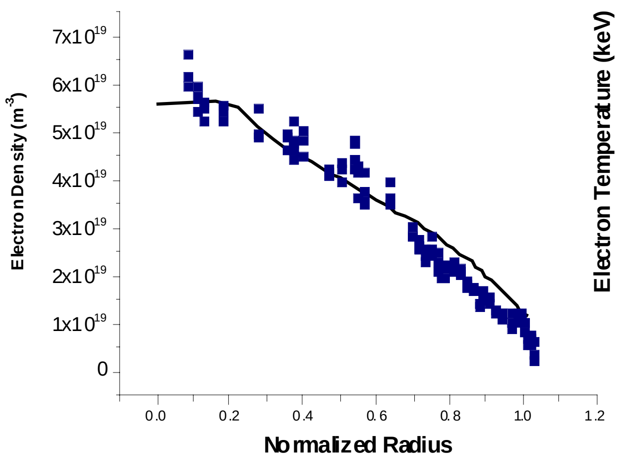
Simulation of 103205 and 103209 discharges

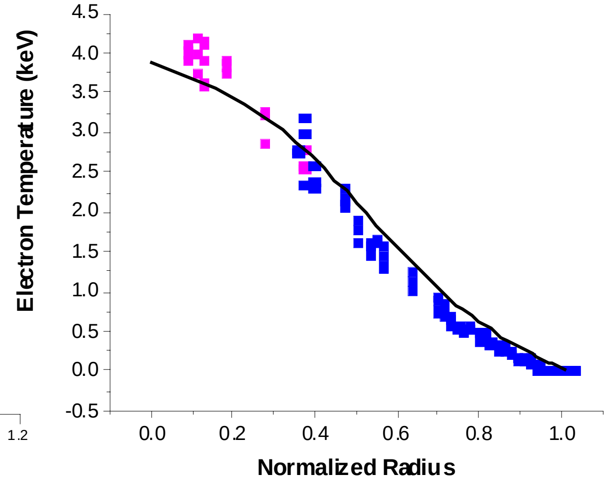
- These are optimized Neon-injected discharges with different currents and magnetic fields (q_{95} and B_T scan) designed to study the physics of confinement improvement with impurity injection.
- Main plasma transport is very similar to the 098775 discharge.
- Neon transport appears to be different. An outward convective term was necessary in order to match the experimental data, while an inward pinch term was used in the modeling of the 98775 shot.
- Agreement with experimental radiated power (P_{rad}) profiles is also good, although the presence of both upper and lower divertor radiation in these shots makes the inversion of the bolometer data more difficult[2].

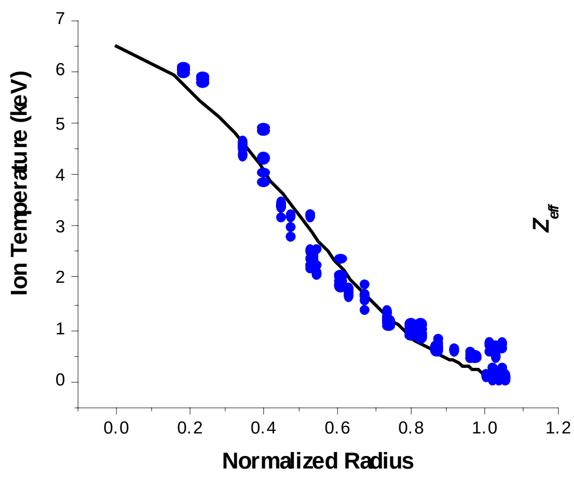
[2] A. Leonard, personal communication, 10/17/2000

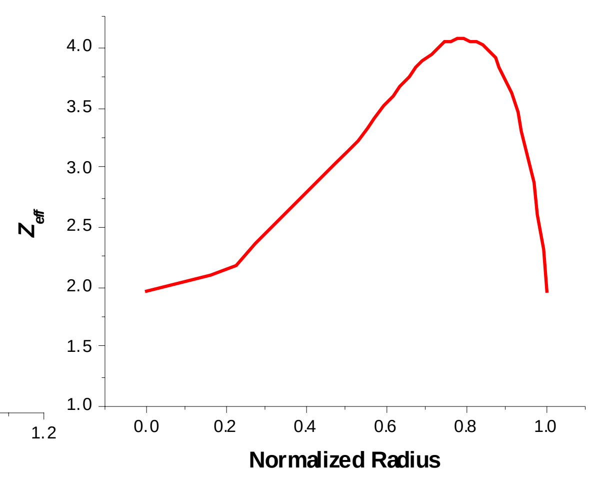
Plasma Profiles

103205 @ 1655 s



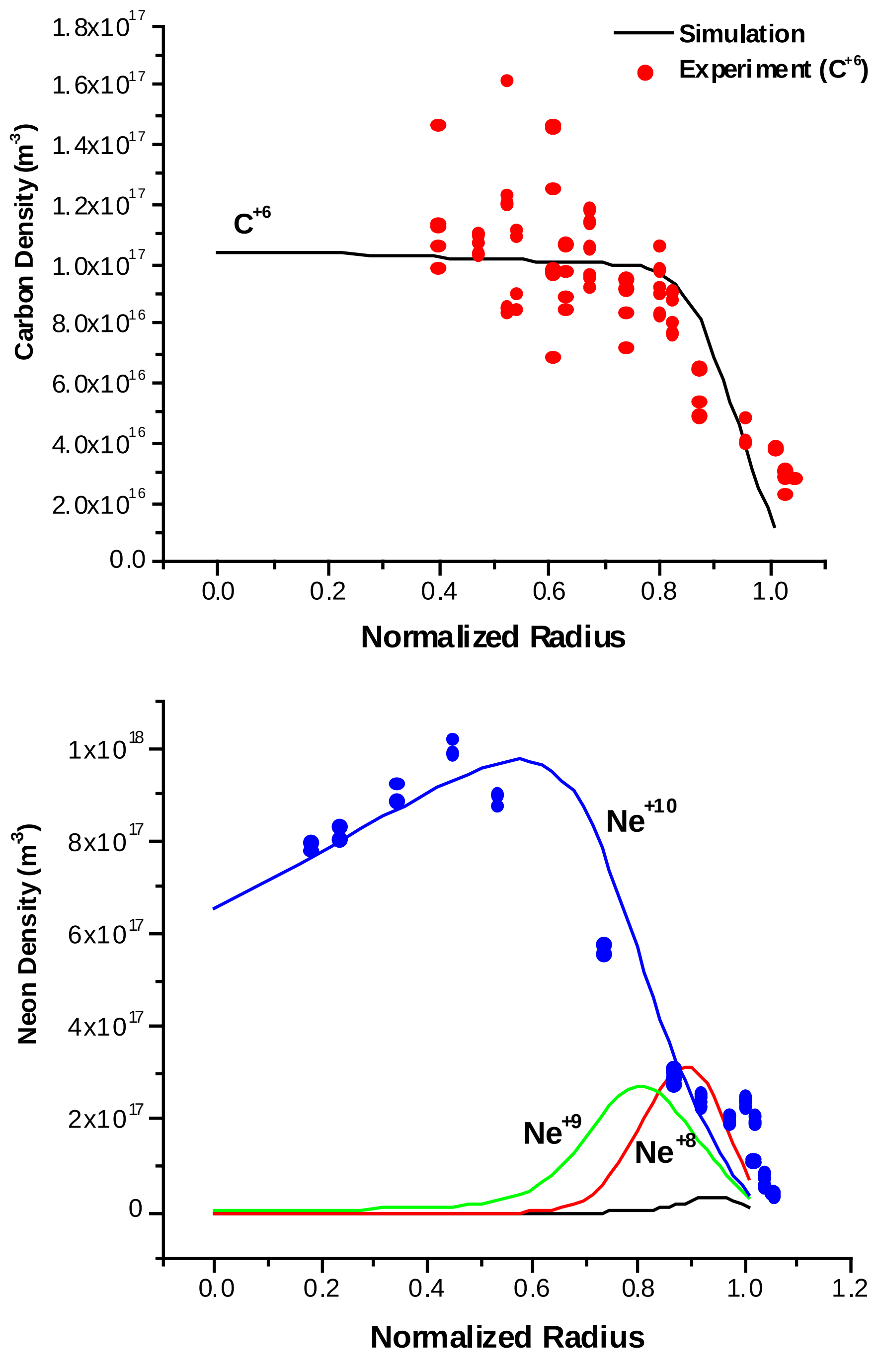






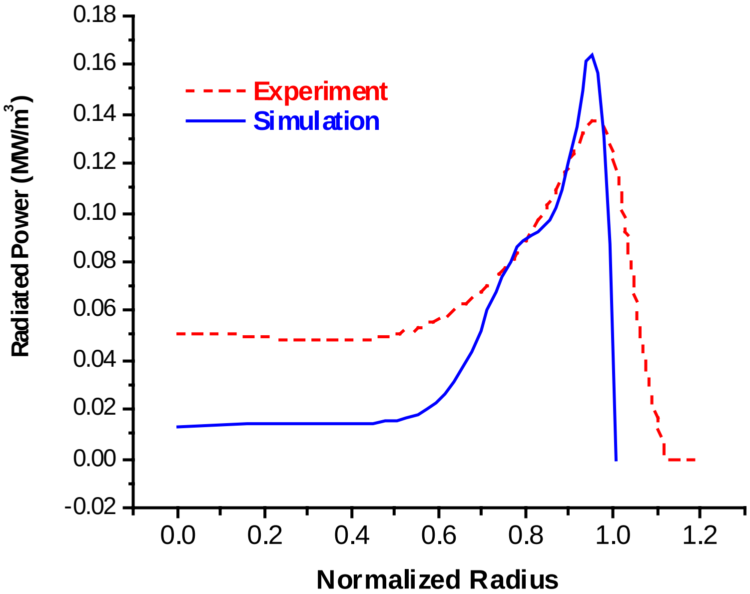
Carbon and Neon Charge States for 103205

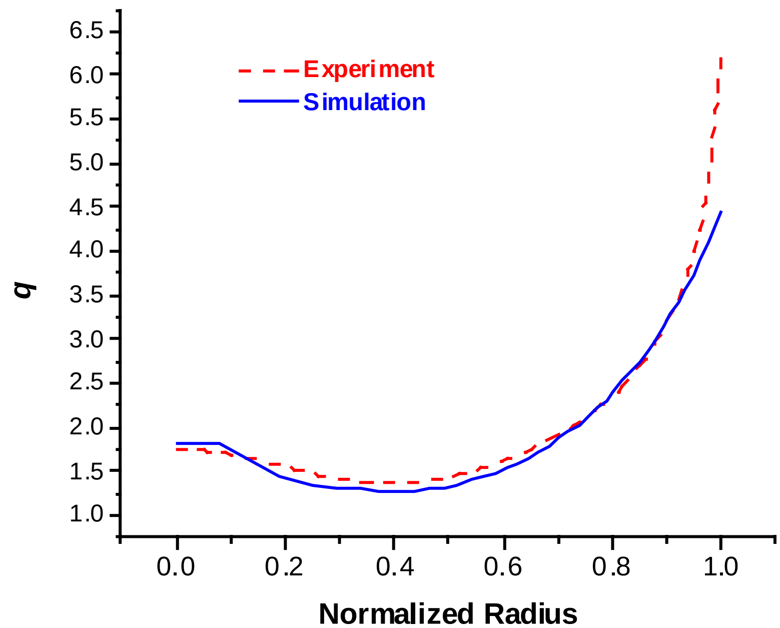
103205 @ 1655 s



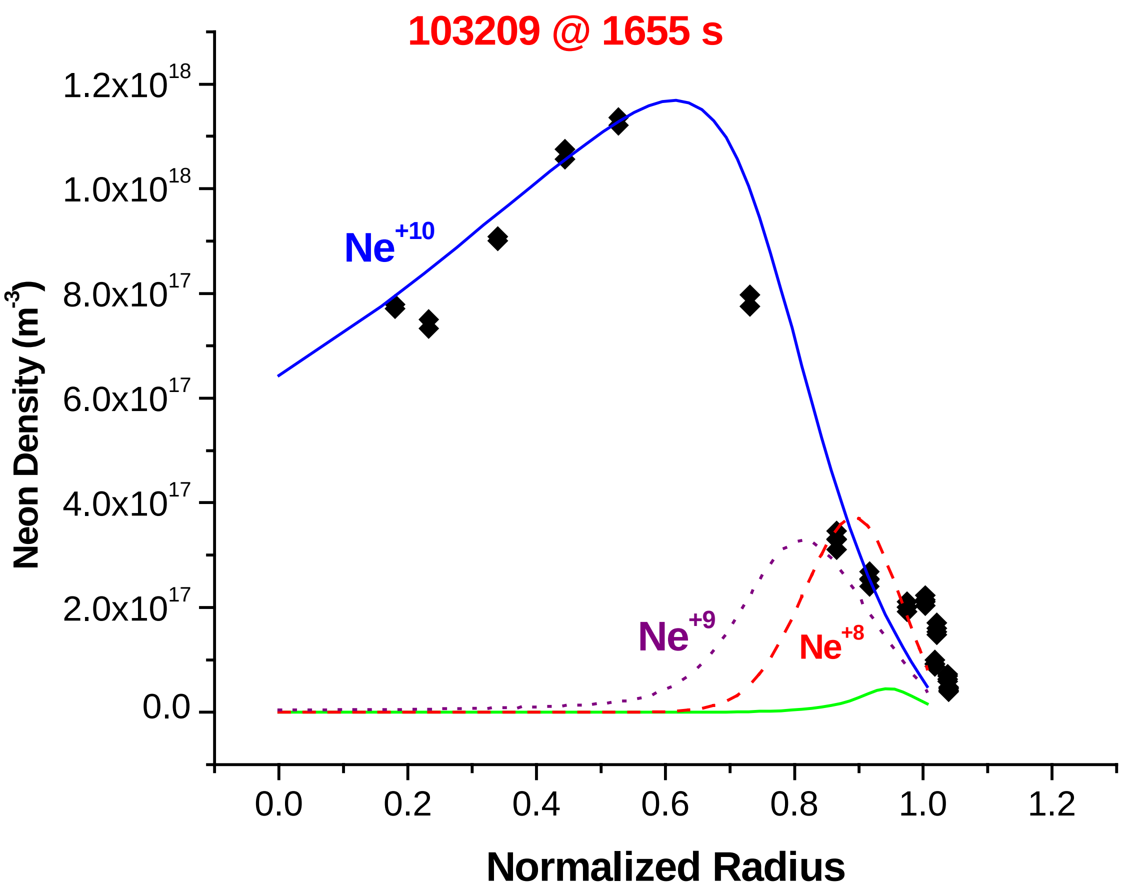
Radiated Power and MHD Safety factor profiles

103205 @ 1655 s



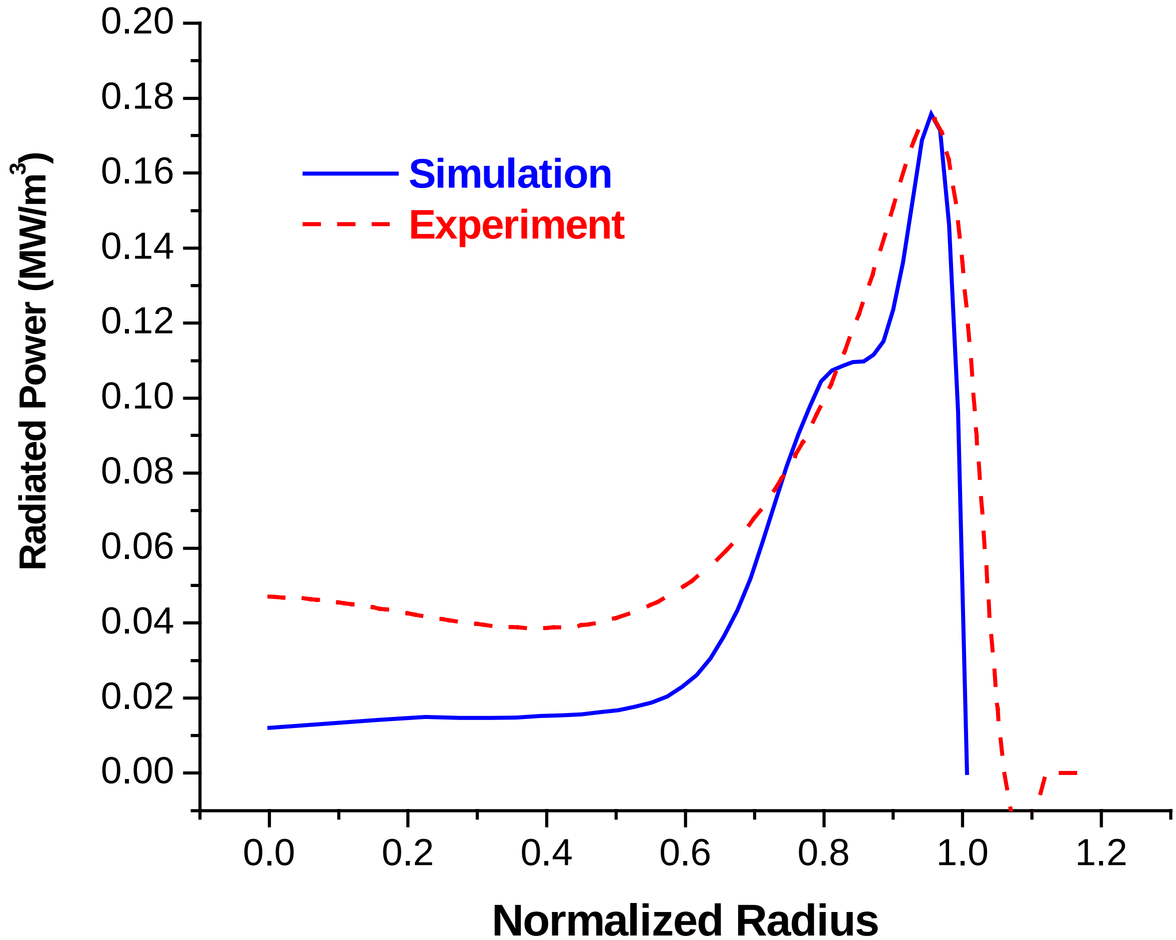


Comparison of Ne^{+10} Density for 103209



- Good agreement between the measured and calculated profiles of the Ne^{+10} charge state.
- A stronger outward convective term was necessary (C_{vz0} = -1.0 compared to -0.7 for the 103205 shot and 0.5 for the 98775 shot)

Radiated Power Profile Comparison for 103209



Comparisons with Theory

- The observed confinement improvement following external impurity injection in DIII-D and other tokamaks is believed to be due to turbulence suppression caused by the radiating impurities.[3]
- In this work, confinement improvement has been taken into account by arbitrarily reducing the multipliers of the Bohm transport model.
- One of the goals of our research is to identify theory-based transport models for the main plasma and impurities that can predict the observed confinement improvement.
- As a first step towards this direction, we evaluated two different models:
  - ♦ A semi-empirical shear correction formula by I. Voitsekhovitch[4].
  - ♦ The **GLF23** routine which is based on R.E. Waltz's comprehensive theory-based transport model[5].

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[3] G. McKee, et al., *Phys. Rev. Lett.* **84** (2000) 1922; G. McKee, et al., *Phys. Plasmas* **7** (2000) 1870; M. Murakami et al., EPS 2000.
[4] I. Voitsekhovitch, et al., *Phys. Plasmas* **6** (1999) 4229
[5] R.E. Waltz, et al., Phys. Plasmas **4** (1997) 2482

Shear Reduction Model

- Semi-empirical model combining the effects of the magnetic and $E \times B$ shears. It has been used to model several TFTR, DIII-D and JET discharges with various characteristics (*low rotation shear*, *combined strong magnetic and rotation shear*, *monotonic q-profile cases*).
- The model introduces a shear-correction factor F_{shear} which multiplies the usual *L*-mode JET Bohm transport model:

$$F_{shear} = \frac{1}{1 + \exp\left\{ \dfrac{s_{cr} \left| 1 - f(s_E) \right| - \dfrac{s_m q}{1 + 5 s_m / q^2}}{0.1 q} \right\}}$$

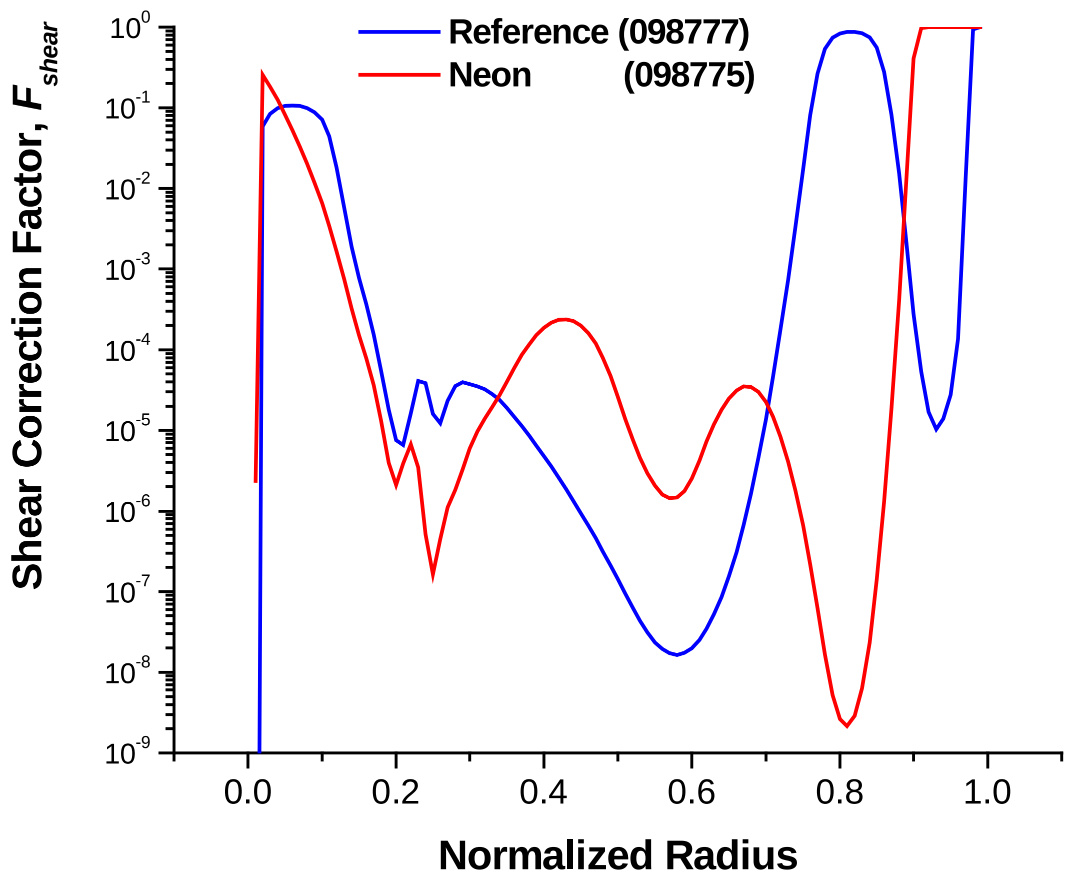
where $f(s_E)$ represents the rotation shear stabilization,

$$f(s_E) \approx \left| \frac{1}{\gamma_{lin,\max}} \frac{\partial}{\partial R} \left(\frac{E_r}{B_\theta} \right) \right|$$

and is estimated as:

$$f(s_E) = C_V c^2 a \left(C_1 \nabla V_{tor} + C_2 \nabla V_{dia} \right) / V_{Ti}^3$$

- The shear correction factor has been evaluated for the reference discharge 98777 and the Neon discharge 98775 using plasma profiles from our simulations.



- The formula predicts significant confinement improvement for both shots, suggesting that this formalism is not appropriate for these discharges.

GLF23 Implementation

- The **GLF23** routine[6] (R.E. Waltz, et al.) has been used to calculate the $E\times B$ shear rate for the 98777 & 98775 shots.
- No actual transport simulation using the χ's from the GLF23 routine has been attempted yet. The shear rates are evaluated by GLF23 using the profiles predicted by our code for the two shots.
- The calculated $E\times B$ shearing rates were compared to the experimentally determined shearing rates (after they were converted from the Hahm-Burrell to the Waltz form).
- Good agreement between simulation and experiment is obtained, strengthening the assumption that an increase in the $E\times B$ shearing rate in the Neon-injected discharge contributes to the observed confinement improvement[7].

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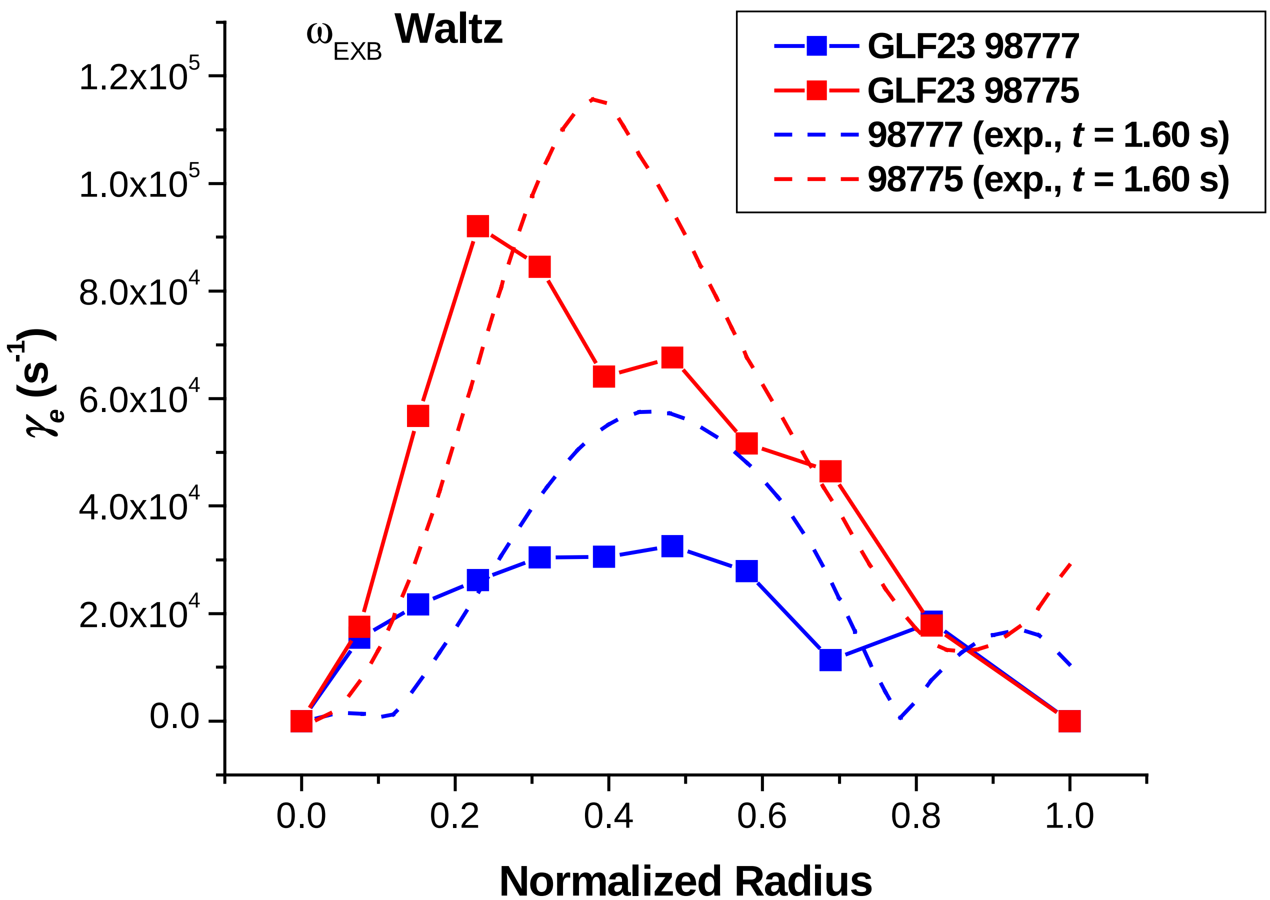
[6] Jon Kinsey, private communication

[7] M. Murakami, et al. "*The Physics of Confinement Improvement with Impurity Seeding in DIII-D*", EPS 2000.

Comparison of Calculated (GLF23) and experimental $E \times B$ shearing rates



CONCLUSIONS

- Good agreement between simulation and experiment has been obtained for a number of recent DIII-D discharges with noble gas impurity seeding.
- Simple empirical and semi-empirical transport models with a few adjustable coefficients have been used for the transport of the impurity charge states and the main plasma particle and energy transport.
- Preliminary simulations have been performed to evaluate the suitability of a number of theory-based transport models.
- Future plans include neoclassical analysis of the transport of the impurity charge states and the implementation of theory-based transport models for self-consistent simulations.