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APRIL 2009
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MHD SIMULATIONS OF MASSIVE GAS INJECTION INTO ALCATOR C-MOD AND DIII-D PLASMAS

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This is a preprint of an invited paper to be presented at the 49th Annual Meeting of the Division of Plasma Physics, November 12-16, 2007, in Orlando, Florida, and to be published in Phys. Plasmas.

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Work supported by the U.S. Department of Energy under DE-FG03-95ER54309, DE-FG02-04ER54762, and DE-FG02-04ER54758

GENERAL ATOMICS PROJECT 03726
APRIL 2009
ABSTRACT

Disruption mitigation experiments using massive gas injection (MGI) on Alcator C-Mod [I.H. Hutchinson, et al., Phys. Plasmas 1, 1511 (1994)] and DIII-D [J.L. Luxon and L.G. Davis, Fusion Technol. 8, 441 (1985)] have shown that MHD plays an important role. The 3D MHD code NIMROD [C.R. Sovinec, et al., J. Computational Physics 195, 355 (2004)] has been extended to include atomic physics taken from the KPRAD code to perform simulations of MGI. Considerable benchmarking of the code has been done against Alcator C-Mod for neon and helium gas jet experiments. The code successfully captures the qualitative sequence of events observed in MGI experiments up to the end of the thermal quench. Neon jet simulations also show quantitative agreement with the experimental thermal quench onset time. For helium gas jets, we show that a small percent boron density can significantly alter the results even in the presence of a helium jet with three orders of magnitude higher density. The thermal quench onset time is considerably over-predicted unless boron radiation is included. A DIII-D helium jet simulation shows a faster rise time for total radiated power than the experiment, but comparable amplitude. Similar to the important role of boron in C-Mod, carbon radiation is a significant factor in DIII-D helium jet simulations and experiments.
I. INTRODUCTION

Research on disruption mitigation techniques is being pursued on a number of tokamaks, including DIII-D [1-4] and Alcator C-Mod [5-7]. While these machines are able to withstand a large number of disruptions, the three potential dangers associated with disruptions all scale unfavorably toward larger devices, such as ITER [8,9]. Disruptions can result in: 1) strong forces generated by poloidal currents in the vessel, 2) large heat fluxes to the divertor surfaces, and 3) multi-MeV runaway electron beams. The last of these complications scales most unfavorably, due to an avalanche amplification process of a seed runaway population; the exponent of the avalanche factor \( A = e^{\gamma t} \) is approximated by \( \gamma t \approx 2.5 I_p \) (MA) [9], such that scaling from DIII-D to ITER, \( A \) increases by roughly a factor of \( 10^{15} \). Massive gas injection (MGI) experiments on DIII-D and Alcator C-Mod have demonstrated success at reducing poloidal in-vessel currents and divertor heat fluxes, but uncertainties remain about runaway electrons, both because these machines are not expected to generate them in large numbers, and because they are not well diagnosed. Furthermore, the effectiveness of MGI for mitigating any of the three effects on a larger device is uncertain without better understanding the relevant physics and how it scales.

The experimental sequence of events observed during MGI experiments on DIII-D is illustrated in Fig. 1, showing data from discharge 122516. Initially, a few ms elapse between the valve opening and the first indication of gas reaching the plasma edge. Next, the edge temperature drops on a time scale of \( \approx 2 \) ms. The edge cooling is followed by the growth of the \( m=2 \) and \( m=1 \) magnetic signals successively. The central electron temperature then collapses on a \( \approx 1 \) ms time scale. Finally, the longer current quench phase of the disruption begins.

Prior simulations of MGI [10], and comparison with Alcator C-Mod experiments [6] support a shallow penetration model of MGI in which the gas jet cools the edge of the plasma and contracts the current channel, destabilizing MHD modes. The subsequent stochastization of the flux surfaces and the associated enhanced transport is primarily responsible for the core thermal quench, as opposed to radiation from impurities deposited or mixed into the core. This scenario is also supported by magnetic fluctuation measurements of \( m = 1/n = 1 \) and \( m = 2/n = 1 \) modes on DIII-D [3]. However, the MHD turbulence itself may play some role in mixing impurities into the core. Such mixing during the thermal quench is desirable, since a critical electron density (free + bound) is required to stop runaway avalanching during the current quench phase [11]. More
detailed MGI simulations are needed to understand impurity mixing by MHD, and also to create a predictive model of MGI that can be applied to both present and future tokamaks. This motivates the development of an extended version of the NIMROD [12] MHD code to include accurate modeling of the atomic physics and the impurity species mixing.

Fig 1. DIII-D discharge 122516 show the experimental sequence of event for an MGI experiment with an argon gas jet.
II. DISRUPTION MITIGATION SIMULATION CODE

The name NIMRAD will be used to refer to the coupling of the NIMROD MHD code and the KPRAD atomic physics code [13]. KPRAD is a 0D code that calculates the ionization, recombination and radiation rates for a given impurity species and evolves the charge state population with no equilibrium assumption. Within the framework of NIMROD (a 3D MHD code), KPRAD is called at every grid point at each time step to update the impurity species charge state populations, and to compute source terms to be included in the NIMROD evolution equations for the density and temperature. The NIMRAD equations are as follows:

\[
\rho \frac{d\vec{V}}{dt} = -\vec{V} \rho + \vec{J} \times \vec{B} + \vec{V} \cdot \mu \rho \vec{V} \quad ,
\]  
\[
\vec{E} + \vec{V} \times \vec{B} = \eta \vec{J} \quad ,
\]  
\[
n_e \frac{dT_e}{dt} = (\gamma - 1)[n_e T_e \vec{V} \cdot \nabla \vec{V} + \vec{q}_e - Q_{loss}] \quad ,
\]  
\[
q = -n \left[ \chi_{\parallel} \hat{b} + \chi_{\perp} (I - \hat{b}) \right] \nabla T \quad ,
\]  
\[
\frac{d\tilde{n}_e}{dt} + n_e \vec{V} \cdot \nabla \vec{V} = \nabla \cdot D \nabla n_e + S_{ion/rec} \quad ,
\]  
\[
\frac{d\tilde{n}_i}{dt} + n_i \vec{V} \cdot \nabla \vec{V} = \nabla \cdot D \nabla n_i + S_{ion/3-body} \quad ,
\]  
\[
\frac{d\tilde{n}_z}{dt} + n_z \vec{V} \cdot \nabla \vec{V} = \nabla \cdot D \nabla n_z (S_{ion/rec}) \quad .
\]

Equations (1) and (2) are identical to the usual NIMROD momentum equation and Ohm’s law, except that the mass density, \(\rho\), and the pressure, \(p\), include the impurity species contribution, and the resistivity, \(\eta\), is proportional to the local value of \(Z_{eff}\) (in addition to a \(T_e^{-3/2}\) dependence). In Eq. (3), the final term (\(Q_{loss}\)) is the sum of all of the energy loss terms calculated by KPRAD, which includes line radiation, bremsstrahlung, ionization energy, and dilution (isobaric) cooling of the plasma due to the addition of impurities. The Ohmic heating is also absorbed into that term. The usual quasi-neutrality expression \(n_e = n_i\) is replaced here by the expression \(n_e = n_i + n_z \langle Z \rangle\) (with electron
density \( n_e \), deuterium ion density, \( n_i \), impurity density \( n_z \), and impurity average charge, \( \langle Z \rangle \), such that three continuity equations are required for four unknowns. Each of the continuity equations contains the usual advection and (numerical) diffusion terms, in addition to a source/sink term which is computed by KPRAD. The deuterium is not assumed to be fully ionized, since at the low temperatures sometimes obtained during MGI, 3-body recombination can become significant. The electrons source/sink term includes contributions from ionization and recombination of both the impurities and the deuterium.

The last term of Eq. (7) appears in brackets because it is not included as part of the NIMROD advance. Within KPRAD, the individual population of every charge state is tracked, and is updated due to ionization and recombination inside the KPRAD routine. The charge state populations are then summed to produce a total impurity density, and only the advection and diffusion terms are computed as part of the NIMROD time advance. Following the NIMROD advance, an average charge of \( \langle Z \rangle = (n_e - n_i)/n_z \) is necessitated by quasi-neutrality. The stored charge state densities from the previous KPRAD step must be modified to agree with the new required \( \langle Z \rangle \) and the new total impurity density. This adjustment is made at the beginning at the of the next KPRAD step. The slight adjustment of the charge state populations each step is in lieu of solving a separate continuity equation for each charge state, which is undesirable with respect to required CPU time, especially for the higher \( Z \) impurities.

NIMRAD requires as input a neutral density deposition rate as a function of space and time for the gas jet. The neutral jet penetration is not very well understood experimentally or theoretically, but observations suggest that the penetration of the neutrals is quite shallow, and further assimilation of the impurities is due to mixing of the ions. In these simulations, the initial jet penetration is set to 1 cm. The total particle injection rate for C-Mod and DIII-D are taken from the results of a gas dynamic code. The injection for the simulations is done poloidally and toroidally symmetrically, and the volume of the total injection region is divided into the particle injection rate to get at neutral density deposition rate. Inside the 1 cm penetration layer, the neutral deposition rate falls off exponentially as a function of temperature (\( \sim \exp \left( T_{1\text{cm}} - T \right)/T_0 \), with \( T_0 \) equal to the species first ionization energy). At the initial edge temperatures of hundreds of eV, the injection has a very steep exponential fall-off, but the neutral deposition profile becomes much wider as the edge temperatures drop to only a few eV. The impurity density evolution itself is fully 3D and 3D neutral injection is possible, but will be reserved for future studies as understanding of the neutral gas injection in the experiments improves.
For both Alcator C-Mod and DIII-D the experimental Lundquist numbers \( S = \frac{\tau_{L/R}}{\tau_A} \) fall in the range of \( 10^7 - 10^8 \), which would be very computationally expensive to match in the simulations. Instead, in each case, the resistivity is artificially enhanced by a factor of \( E = 100-900 \). The reduction of the L/R time will also result in a reduction of the reconnection time, which will be a hybrid of the L/R and Alfvén times. The reconnection time will scale as \( S^{-\alpha} \), with \( 0 < \alpha < 1 \), where \( \alpha = 0.6 \) is the appropriate scaling for a tearing mode [14], and \( \alpha = 0.4 \) was the scaling found in prior disruption mitigation simulations [10]. Since the reconnection time will be an important in determining the thermal quench time in these simulations, it is desirable to scale the radiation rates, and other relevant time scales in the same way. In the following simulations, all of the atomic physics rates (ionization, radiation, recombination) as well as the thermal transport coefficients, \( \chi_\perp \) and \( \chi_\parallel \), and the gas injection rate, are scaled as \( S^{0.5} \). This leaves the L/R time itself as the only important time that scales significantly differently than the others. The result will be relatively fast resistive diffusion when the simulations are re-scaled to compare with experiments. This becomes important during the current quench phase, but should not be as significant in the thermal quench phase. In the Ohmic heating term, the resistivity is only enhanced by the square root of the enhancement factor that appears in the Ohm’s law, so as to obtain the correct balance between radiation and Ohmic heating. Consequently, not all magnetic energy that is dissipated resistively is converted to thermal energy. This choice of rescaling and the underlying assumption about reconnection are approximations which require validation against experimental results.
III. RESULTS

A. Alcator C-Mod neon simulations

A series of Alcator C-Mod simulations have been performed with both neon and helium gas jets. Time traces for the kinetic and magnetic energy spectra for a neon simulation are seen in Fig. 2. This simulation is run with the resistivity enhanced by a factor of 400, so that $S = 5 \times 10^4$, compared with the experimental value $S = 2 \times 10^7$. All other time scales are enhanced by a factor of 20. The results are presented with the time base multiplied by 20 and the total radiated power reduced by that factor, so that they can be compared directly with experiment. The perpendicular and parallel thermal diffusion in this case are given by the formulas:

$$\chi_{\perp} = 10 \left(\frac{2000}{T}\right)^{1/2} \frac{1}{B^2} \text{m}^2/\text{s}; \quad (8a)$$

$$\chi_{\parallel} = 10^{10} \left(\frac{T}{2000}\right)^{5/2} \text{m}^2/\text{s}. \quad (8b)$$

This yields initial values of $\chi_{\perp}$ of 0.4 m$^2$/s in the core and 1.5 m$^2$/s at the edge, of the same order as experimentally measures values during normal H-Mode operation [15]. Although the Braginskii [16] scaling is used (neglecting the density dependence), the values are much larger.
In Fig. 2(c) the total radiated power is seen to maintain a constant value for about the first 1.5 ms. This is the initial gas penetration phase, before MHD begins to destroy flux surfaces. At around 1.5 ms, the total radiated power spikes to nearly 1 GW as the $n \geq 1$ modes become large, producing stochastic flux surfaces, and initiating the core thermal quench. The 1.5 ms delay between the initialization of edge cooling and the core thermal quench falls within the data scatter for this time delay as measured experimentally [7], which for neon falls between just under 1 ms and nearly 2 ms. This time delay is altered by varying the coefficient of Eq. (8a). With perpendicular thermal transport increased by a factor of 10, the temperature and current gradients during the edge cooling phase are shallower, and the MHD modes grow more slowly, producing a delay exceeding 2 ms. However, with the coefficient reduce by a factor of 10, the inward propagation of the cold front is slow, and the time delay also increases. Therefore, an optimum in the perpendicular thermal transport coefficient seems to exist for triggering a fast thermal quench.
Figure 3 is a set of magnetic field line puncture plots from just before and immediately following the radiated power spike. In this case the flux surfaces are totally destroyed by the end of the thermal quench and remain so as the current quench ensues. A series of temperature profiles before and during the core temperature collapse is shown in Fig. 4(a). Figure 4(b) is a temperature profile sequence from an Alcator C-Mod neon gas jet experiment, obtained from Thomson scattering measurements. Even after the thermal quench onset, the C-Mod core Thomson measurements are reliable because: a) line and continuum radiation are well rejected outside the spectral range of the Thomson, and b) the detection circuits are high-pass filtered in order to effectively reject background signals varying on time scales longer than 100 ns. The edge Thomson measurements, however, are not reliable following the quench onset.

![Magnetic field line puncture plot for three times during the C-Mod neon, \( S = 5 \times 10^4 \) simulation.](image)

Both the simulated and measured profiles show the slow inward propagation of a cooling wave followed by a rapid drop in the core temperature, with each of these two stages occurring on approximately the same time scale in the simulation and the experiment, although the cold front propagates further in the simulation prior to the core collapse. The corresponding sets of density profiles for the simulation and experiment appear in Fig. 5. The density near the edge is the most significant discrepancy between the simulations and experiments. Whereas high Z gas jet experiments do not show a large density rise in the early thermal quench phase (at least inside of \( r/a = 0.8 \) [7]), the neon simulations do produce a significant increase in edge density as far in as \( r/a = 0.6 r/ \). All gases produce a core density increase during the current quench experimentally [7]. In the simulation, once the core temperature falls near to the first ionization energy, the gas injection model itself produces a rise in core density. Very little MHD induced mixing is observed.
Fig. 4. (a) Temperature profiles for five times during the C-Mod neon simulation. (b) Thomson scattering $T_e$ profiles from repeatable C-Mod neon gas jet experiments, with profiles taken at four times.

Fig. 5. (a) Electron density profiles for five times during the C-Mod neon simulation. (b) Thomson scattering $n_e$ profiles from repeatable C-Mod neon gas jet experiments, with profiles taken at four times.
An estimate of the potential for runaway avalanching during and after the thermal quench can be made according to the formula $E_c = 0.12 n_{e,20}$, where $E_c$ is the critical electric field for avalanching, and $n_{e,20}$ is the electron density (free + bound) in units of $10^{20}$ m$^{-3}$. In Fig. 6 we plot the ratio of the electron density to the critical electron density needed to suppress runaways given the local electric field $E = \eta j_\phi$. The Spitzer value of the resistivity based on the actual temperature (not the enhanced value) is used. Regions with this value below one have the potential for avalanching. But, this does not imply that runaways should be observed on C-Mod since: 1) we have not estimated the runaway electron source term, 2) the amplification factor on C-Mod is small, and 3) high energy electron losses due to magnetic fluctuations have not been accounted for. Even prior to the core $T_e$ collapse, regions with $n(n_{\text{crit}} < 1$ exist at the boundary of the cold front, where the temperature is reduced, and the current density is increase due to the contracting current profile (Fig. 7). Immediately after the thermal quench, the core current density is more than twice its initial value.

Fig. 6. The ratio of the (free + bound) electron density to the critical density required to stop runaway avalanching at three times during the neon simulation. Dark red regions have $n/n_{\text{crit}} \geq 1$.

Fig. 7. Toroidal current density at four times during the C-Mod neon simulation.
To investigate the effects of the Lundquist number reduction and rescaling of the results, two more neon simulations were run with the resistivity enhanced only by a factor of 100 or 225, and all other time scales by a factor of 10 or 15 respectively. Figure 8 shows the thermal quench onset time plotted versus the time rescaling factor ($E^{1/2}$). Early in the simulation, radiated power levels nearly overlay for all three cases. The thermal quench onset for all three cases falls within the C-Mod data scatter, and when linearly extrapolated to a rescaling factor of unity, a value of 0.8 ms is obtained, which is approximately the minimum value obtained experimentally. The MHD growth rates should appear identical on the rescaled time base if the $S^{-0.5}$ assumption were correct. In fact, the rescaled linear growth rate is slower for the highest $S$ case than for the lowest (Fig. 9), suggesting a weaker $S$ scaling. Rescaling these simulations by a weaker power of $S$ in order to match the growth rates would also have the effect of moving the onset times closer together, which further supports the slightly weaker scaling. However, a truly self consistent check would require repeating the simulations with all of the times rescaled differently. To obtain a saturated amplitude scaling of the $n=1$ mode, longer simulations reaching a more clearly saturated state would be required.

![Figure 8](image)

Fig. 8. Thermal quench onset times for three C-Mod neon simulations with different resistivity enhancement factors ($E$).
B. Alcator C-Mod helium simulations

Experiments with helium gas jets on Alcator C-Mod typically have a longer delay between the edge cooling and the thermal quench than with neon jets, as well as a longer thermal quench duration [7]. A helium NIMRAD simulation is run at $S = 5 \times 10^4$, with parameters identical to the neon simulation at that Lundquist number. As seen in the plot of total radiated power (Fig. 10), the helium gas jet simulation takes considerably longer to produce a thermal quench than the neon simulation — more than 7 ms. This greatly exceeds the experimental time of around 2-2.5 ms. Two events can be observed in the radiated power trace. The first is a step occurring just after 5 ms. Examining the magnetic field structure just before and after this event [Fig. 11(a,b)], we see that it is associated with a major rearrangement of the field lines. Although not on perfect surfaces, the field lines remain concentric until about 5.3 ms, when the configuration very quickly becomes stochastic. The merely incremental increase in total radiated power associated with the stochastization of the fields stands in contrast to the neon simulations. After about 7.3 ms, a large spike in radiated power finally occurs. The field line structure [Fig. 11(c)] reveals this to be associated with a large 1/1 event, which convects heat from the core to the edge faster than parallel conduction. A comparison of temperature and density profiles is shown in Figs 12 and 13. From the temperature profiles it is clear that the predominant difference in the thermal quench timing is related to a slower initial
penetration of the cold front into the edge plasma. For instance, the experimental edge cooling depth at 0.8 ms exceeds the simulated cooling at 0.8 ms and is quite comparable to the simulated edge cooling at 5.3 ms. The electron density in the helium simulation differs from the neon simulation insofar as the density increase tends to push further inward relative to the location of the cold front.

Fig. 10. Radiated power vs time for the C-Mod helium jet simulation (without boron).

Fig. 11. Magnetic field line puncture plots at three times for the C-Mod helium jet simulation.
Neglected in the first helium jet simulation is radiation from intrinsic impurities in the plasma. C-Mod plasmas have some small percentage of boron due to boronization of the walls. Although the density is quite small compared to the massive helium jet, the coronal radiative cooling rate of boron compared to helium at temperatures of a few eV is roughly three orders of magnitude higher.
[17], so that boron could play a significant role in the edge cooling once helium has begun to cool the edge. A second helium simulation is carried out with identical parameters to the first except that a constant boron density of $4 \times 10^{18} / \text{m}^3$ is assumed. The full atomic physics is not tracked for the boron, as with the helium. Rather, coronal radiation levels are assumed. The addition of this level of boron to the plasma shortens the thermal quench delay to 3.4 ms as evidenced in the radiated power trace (Fig. 14). Unlike the case of the pure helium jet, the stochastization of the field lines (Fig. 15) is associated with a large radiated power spike, not merely an incremental increase.

Fig. 14. Radiated power vs time for the C-Mod helium jet simulation with boron radiation included.

Fig. 15. Magnetic field line puncture plots at three times for the C-Mod helium jet simulation with boron radiation included.

C. DIII-D helium simulation

DIII-D gas jet experiments have been performed with $\text{H}_2$, He, Ne, and Ar gas [2-4]. Thorough DIII-D benchmarking for several of these gas species, including scans of important parameters, will be left for future work. Here we focus on preliminary DIII-D modeling which highlights the specific diagnostic capabilities available on DIII-D but not C-Mod for model/experimental comparison. In DIII-
D MGI experiments, fast time scale measurements of radiated power are made that can be directly compared with NIMRAD simulation results. A NIMRAD simulation is run with $E = 900$ ($s = 10^5$, compared with $S_{DIII-D} = 9 \times 10^7$). The thermal transport coefficients take the same form as Eq. [8(a-b)], except that a reference temperature of 3500 eV is used in place of the 2000 eV reference temperature in each equation. Figure 16 shows the total radiated power measure during shot 128226, which is a helium gas jet discharge. The measured radiated power is separated into helium radiation (which dominates early in time) and carbon radiation (which dominates later on). The radiated power in this discharge grows slowly to its peak amplitude, which occurs near the thermal quench onset time of 2.5 ms. The NIMRAD helium jet simulation, which includes a carbon density of $10^{18}$ is also plotted. This carbon fraction does not account for the possibility of additional sputtered carbon after the gas jet is fired. The NIMRAD radiated power rises on a faster time scale than the experiment, but reaches a comparable peak amplitude. However, within the 4 ms simulation time, a thermal quench is not triggered at this carbon fraction.

![Fig. 16. Time trace of the measured radiated power for the DIII-D helium jet experiment 128226. Total experimental radiated power is separated into helium and carbon radiation. Radiated power from NIMRAD simulation with background carbon density of $10^{18}$/m$^3$ is also plotted.](image-url)
IV. DISCUSSION AND CONCLUSIONS

An extended version of the NIMROD code (dubbed NIMRAD) has been developed to include atomic physics from the KPRAD code. This extended capability allows the simulations of disruption mitigation techniques being explored on tokamak experiments, including massive gas injection, and potentially other techniques that involve the injection of impurities. In addition to MHD and atomic physics, a model for the physics of neutral gas jet penetration is necessary for the simulations. The simulation results provide the three pieces of information needed to reliably predict runaway electron production in mitigated plasma — namely electric fields, total (free + bound) electron density, and magnetic field structure. No other measurements or codes provide all of this information, and runaway electrons remain the biggest concern for mitigated disruptions on ITER. The primary purpose of developing the NIMRAD code is to improve upon 0D or 1D scaling from present experiments to ITER by performing ITER simulations directly after successfully benchmarking against several existing devices. However, impurity mixing results from these calculations in conjunction with the experimental data do not shed promising light on the ability of massive gas jets to sufficiently densify the core in ITER. Experimental and theoretical investigations of runaway electron confinement during MGI may make or breaks its usefulness as an ITER disruption mitigation technique.

The code has been benchmarked against Alcator C-Mod and DIII-D data for both neon and helium simulations. Neon simulations have successfully matched C-Mod results in several respects, including thermal quench timing and temperature profile evolution. The thermal quench onset time is found to be sensitive to the perpendicular thermal conduction, but agreement is obtained for experimentally relevant values. The largest discrepancy occurs in the edge density, which is much larger in the simulations than experiments, although better Thomson scattering data outside $r/a = 0.8$ is needed to fully assess the experimental edge density behavior. This discrepancy could be due to differences in ionization fraction, edge particle transport, or impurity deposition (rate or location). Each of these possibilities can be explored through expanded simulations with a more realistic, localized gas jet, and the inclusion of a vacuum region, allowing particles to cross the separatrix. Although boron radiation is not expected be a major contribution in the neon simulations, a slightly lower edge temperature resulting from boron radiation could also significantly impact the ionization fraction. The difficulty in matching the density results may fundamentally arise from the strong sensitivity of the density to the edge $T_e$; for instance, deuterium three-body recombination has a $T_e^{-4.5}$
dependence. In the few eV range of the edge plasmas that are simulated, an inaccuracy of 1-2 eV in the simulation can produce dramatically different density results. On the other hand, the temperature is determined primarily by the balance between Ohmic heating and radiation. The first of these depends only very weakly on density, and radiated power drops with decreasing $n_e$, but in this range tends to increase sharply with $T_e$, (for He or Ne) providing some negative feedback. Consequently, the reverse effect of density on temperature is not expected to be dramatic.

The helium C-Mod simulations results show very poor agreement with data in the absence of background boron radiation, but do considerably better in the presence of a small boron fraction. The DIII-D helium simulation shows comparable radiated power levels to the experiment, but with a faster rise time, which may result from the toroidally and poloidally uniform deposition in the simulations, whereas the real helium jet has some finite spreading time. With an assumed carbon fraction comparable to background experimental levels, the DIII-D simulation also can not produce a thermal quench on a time scale matching the experiment. Accurate modeling of low $Z$ impurity injection experiments will clearly require a detailed understanding of intrinsic impurity levels as well as sputtering that may occur as a result of gas jet injection.

Further extensions of the numerical model, including free boundary simulations and improved impurity deposition modeling may allow improved predictive accuracy. Pushing the simulations parameters closer to experimental levels is also essential, particularly to better understand MHD induced impurity mixing, which may be under-predicted due to the artificially short time scales of the simulations. Wider variation of the Lundquist number is also essential for better validation of the time rescaling assumptions employed in the model, and to determine the implications of the energy balance inconsistencies in the model. Alternate scalings, particularly the weaker scaling indicated by the results, should be tested. Along with continued benchmarking against multiple tokamaks, the development of runaway electron analysis from the code results that includes source terms, avalanching, and parallel losses can be developed to predict the ultimate effectiveness of MGI or other mitigation techniques for ITER.
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ACKNOWLEDGMENT

This work was supported by the US Department of Energy under DE-FG03-95ER54309, DE-FG02-04ER54762, and DE-FG02-04ER54758. This research used resources of the National Energy Research Scientific Computing Center, which is supported by the Office of Science of the US Department of Energy under Contract No. DE-AC02-05CH11231. The authors wish to thank J.W. Hughes for help with the Thomson scattering analysis.