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Studies on Impurity Seeding in a Tokamak Plasma: Simulation and Comparison with Aditya-U Experiments

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Impurity seeding in tokamak plasmas is of current interest as it is seen to modify plasma turbulence, improve plasma confinement time, and reduce heat loads on plasma facing materials. In this work, we present numerical simulation studies of Neon, Nitrogen and Argon impurity seeding and compare our results with corresponding seeding experiments on Aditya-U tokamak.

In our simulation study, we have modeled the fluctuations of plasma density, electron temperature and vorticity/potential to arise from two-dimensional (2D) interchange plasma modes. A neutral impurity is then added to examine its influence on the turbulence. A fluid model is used for the evolution of the impurities. The model incorporates anomalous plasma transport effects that are self-consistent with the plasma-impurity interactions [1, 2]. The interchange plasma turbulence is normally dominant in the tokamak boundary region whereas near the core region since the pressure gradient is relatively flat the interchange plasma turbulence is not important. The impurities in this region have been described using a zero-dimensional (0D) as well as one-dimensional (1D) model with the impurities existing at multiple charged states due to electron impact ionization. The relative abundance of these charged states has been described as a function of the electron temperature in the 0D model. In 1D model the effect of plasma turbulence has been simulated by an adhoc high diffusion coefficient to obtain radial profiles.

Neon, Nitrogen, and Argon gases have been individually injected as impurities in the numerical simulations so that the effect of Neon-plasma, Nitrogen-plasma, and Argon-plasma interactions can be distinctly identified. The Neon, Nitrogen, and Argon species undergo different chemical reactions in the presence of the plasma electrons and these have been taken into account using appropriate cross sections for ionization, radiative recombination, dissociation, etc. The cross sections have been sourced from Open-ADAS and Amjuel data bases. For the edge and SOL regions we have used a 2D modeling where the plasma conductivities have been varied smoothly in the edge-to-SOL transition regions. In the SOL region, ions at different masses have been used to reach the limiter/divertor material plates at a common sound speed. All the ionized species such as Ne^{1+} to Ne^{+10}, and N^{1+} to N^{7+} have been considered as the edge electron temperature can be sufficiently high to ionize these species. In the Aditya-U tokamak impurity seeding experiments have already been done using Neon and Argon and there are plans to seed Nitrogen in the near future.

Using heuristic arguments based on the steady state electron conservation and neutral continuity equations we have estimated the optimum amount of gas required for an effective impact of the seeding on the plasma. It is found that this is primarily determined by the plasma and gas diffusion rates. There is an upper limit to the amount of injected gas beyond which the plasma and gas radial profiles will become nonphysical. Using numerical simulations, we have further refined this estimate and found the amount to be quite close to that arrived at in ADITYA-U experiments.

Neon gas has a low ionization rate compared to Nitrogen gas and its radiative cooling effect is more at higher temperatures compared to Nitrogen (N_2). This indicates that N_2 seeding can provide a strong electron source and its seeding results will be distinctly different from Ne seeding results. Nitrogen gas seeding involves two neutral gas components, namely, N_2 and N (atom). N_2 is normally at low temperature and before reaching thermal equilibrium it can dissociate or ionize. But N can be at thermal equilibrium with the plasma, therefore, it may be more energetic compared to N_2. Both N and N_2 neutrals have been used in our simulations to investigate their impact on plasma turbulence and contrast their impact with similar influences arising from Ne seeding.

Earlier we had simulated the evolution of plasma turbulence in the presence of only singly charged species [3]. Here, in this work, a larger range of ionized species (Ne^{1+} to Ne^{10+} and N^{1+} to N^{7+}) have been used in the numerical simulations (1D and 2D) to study their impact on plasma turbulence. Such highly charged states have also been observed in Aditya-U experiments. Our 2D simulations have further investigated the dynamics of the ionization fronts as well s the radiation fronts of each charged species for Ne and N seedings. We have also calculated plasma transport from the simulation data of Ne, N, and Ar seedings and found that the radial transport velocity and its poloidal shear are significantly modified. The strongest change of the shear is found in the case of N. Argon seeding increases plasma confinement in the tokamak boundary region as strong radiation cooling makes the temperature gradient to become sharp.

References

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