Impurity gas injection studies

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Introduction

Impurity seeding is important

1. to reduce heat loads on material plates
2. Plasma detachment→Scrape-off layer (SOL) broadening→ reduction of power density on material plates
3. (sometimes) to provide radiative improved confinement
4. possible means of disruption mitigation in tokamaks.

Objectives

Many tokamaks have used Neon and Nitrogen as impurity: It is observed that,

1. Radiative cooling takes place via highly charged ions.
2. These form near LCFS and then propagate radially inward direction [N Bisai et al, NF 59 (2019)].

Effects of these ions are very complex - many issues are still open:

1. What is the optimum amount of impurity seeding?
2. Role of various charged species on plasma turbulence

Motivated by the above, simulation using ADITYA parameters are done. Cooling/radiative fronts of highly charged specifies are studied.

Plan of this talk

1. Model equations for turbulent plasma-neutral interactions
2. To indicate importance of T_e : 0D Simulation and results
3. Coupling of anomalous-transport self-consistently: 2D Simulation and results
4. Conclusions

Neon seeding results will be presented.

5. Works related to Aditya(not related to impurity seeding)

Model Equations

3F interchange plasma turbulence has been used to couple plasma-neutral gas [N Bisai et al, POP 22, 022517 (2015)]

$$\frac{dn}{dt} - D\nabla_\perp^2 n + g\left(T_e\frac{\partial n}{\partial y} + n\frac{\partial T_e}{\partial y} - n\frac{\partial \phi}{\partial y}\right) = \langle \nabla_\parallel J_{e\parallel}\rangle + \Sigma S_e$$

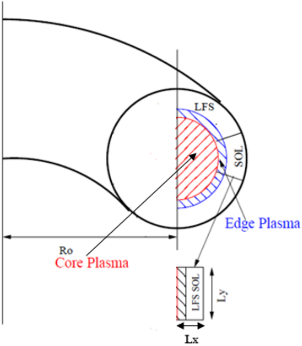
$$\frac{d\nabla_\perp^2\phi}{dt} - \nu\nabla_\perp^4\phi + \frac{g}{(n+n_{pol})}\left(T_e\frac{\partial n}{\partial y} + n\frac{\partial T_e}{\partial y}\right) = \langle \nabla_\parallel J_\parallel\rangle$$

$$\frac{dT_e}{dt} - k_e\nabla_\perp^2 T_e + \frac{2}{3}g\left(\frac{7}{2}T_e\frac{\partial T_e}{\partial y} + \frac{T_e^2}{n}\frac{\partial n}{\partial y} - T_e\frac{\partial \phi}{\partial y}\right) = \frac{\langle \nabla_\parallel q_\parallel\rangle}{n} + \Sigma S_{Te}$$

where $\langle \nabla_\parallel J_{e\parallel}\rangle = \chi_0\chi_{edge}(x)\bar{T}_e^{3/2}\{\phi - T_e\ln(n)\} - \sigma_0\sigma_{sol}(x)f_{cs}n\sqrt{T_e}e^{\Lambda-\phi/T_e}$,
$\langle \nabla_\parallel J_\parallel\rangle = \chi_0\chi_{edge}(x)\frac{\bar{T}_e^{3/2}}{(\bar{n}+\bar{n}_{pol})}\{\phi - T_e ln(n)\} + \sigma_0\sigma_{sol}(x)f_{cs}n\sqrt{T_e}(1-e^{\Lambda-\phi/T_e})$,
and $df/dt = \partial f/\partial t + [\phi, f]$

Simulation regions and input parameters for Aditya

Simulation regions



Parameters used for normalization

$n = 5.0 \times 10^{18}/\mathrm{m}^3$

$T_e = 16\mathrm{eV}$

$B = 1\mathrm{Tesla}$

Derived Parameters

$\rho_s = 4 \times 10^{-4}\mathrm{m}$

$c_s = 4 \times 10^{4}\mathrm{m/s}$ (H atoms)

$\Omega_s = 1.0 \times 10^{8}$ rad/s

Dimensionless numbers used in BOUT++ simulation

$g = 6.5 \times 10^{-4}$

$\sigma_0 = 2.0 \times 10^{-4}$

$\chi_0 = 6.0 \times 10^{-4}$

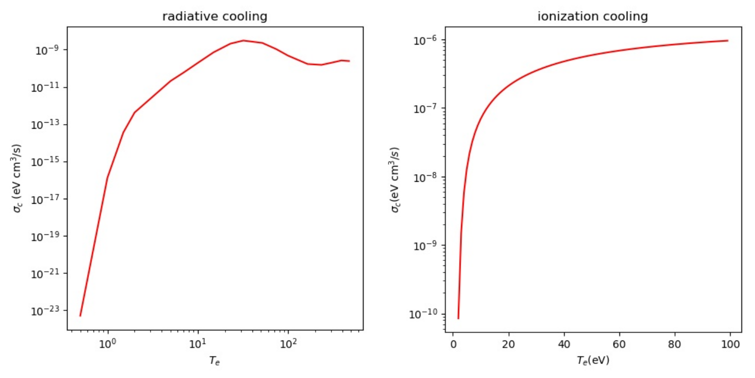
Plasma-Neon reactions used in the Model

$$\begin{array}{cc}
e + Ne = Ne^{+} + 2e & \text{ionization} \\
e + Ne^{+} = Ne + h\nu & \text{recombination} \\
e + Ne^{+} = Ne^{*} & recom - excitation \\
e + Ne^{+} = Ne^{2+} + 2e & \text{species-ionization} \\
\vdots & '' \\
e + Ne^{2+} = Ne^{+} + h\nu & \text{species-recombination} \\
e + Ne^{3+} = Ne^{2+} + h\nu & '' \\
\vdots & ''
\end{array}$$

Cross-sections (T_e) obtained from OPEN ADAS, and Amjuel Databases. 10 ionizations, 10 recombination cross-sections have fitted algebrically.

Radiative cooling and ionization energy loss cross-sections

Radiative cooling and ionization cooling cross-sections



Approximate estimate of amount of Ne seeding:

Amount of Ne seeding can be estimated

$$D\frac{\partial}{\partial x}\left(\frac{\partial n}{\partial x}\right) = -\xi_{ion} nNe$$

$$D_N\frac{\partial}{\partial x}\left(\frac{\partial Ne}{\partial x}\right) = \xi_{ion} nNe$$

$$=> D\frac{\partial n}{\partial x} + D_N\frac{\partial Ne}{\partial x} = c$$

D includes all transport processes, here $Ne/n \sim D/D_N \sim 0.2/200.0 = 0.001$. This about 0.1% that matches the experimental values in Aditya Tokamak.

0D Model Equations

Only sources and sinks of plasma density, gas, and neon ions are taken into account. These equations are;

$$\frac{dn}{dt} = \Sigma_i \sigma_i(T_e)n - \Sigma_r \sigma_r(T_e)n$$

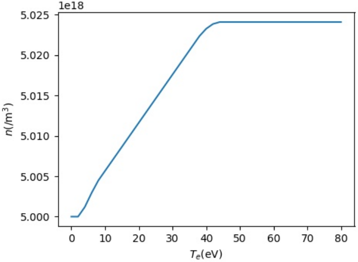
$$\frac{dNe}{dt} = -\sigma_i nNe + \sigma_{r1} nN_e^+$$

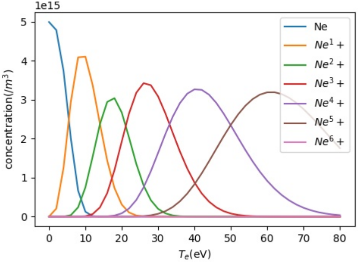
$$\frac{dNe^+}{dt} = -\sigma_{i1} nNe^+ + \sigma_{r2} nNe^{2+}$$

$$\vdots$$

⇒only 8 equations have been solved as the function of T_e. Evolution of $Ne^{7+} - Ne^{10+}$ is not considered as these appear at higher T_e.

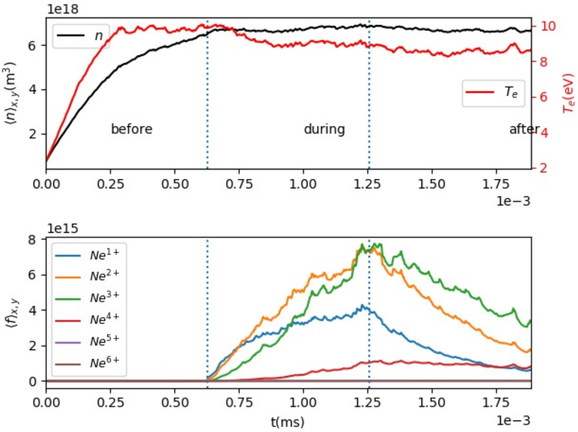
0D model results





- n increases with T_e because of gas ionization.
- Higher species appear at higher temperature.

2D Simulation Results (Neon)



Higher species appear with time with (self-consistent) coupling with turbulence.

2D results: Dynamics of *Ne* ions during and after gas seeding

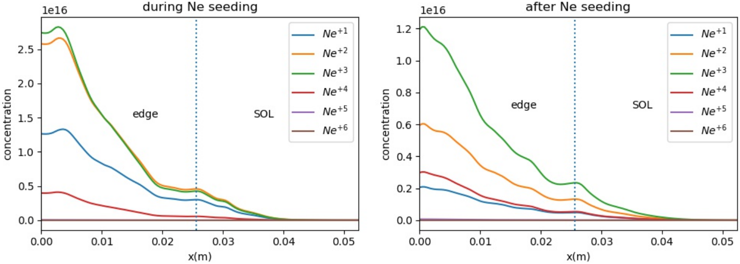
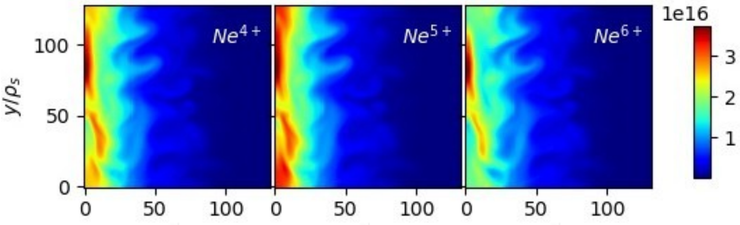


Figure: Concentration of species fractions during (left), and after (right) Neon gas seeding.

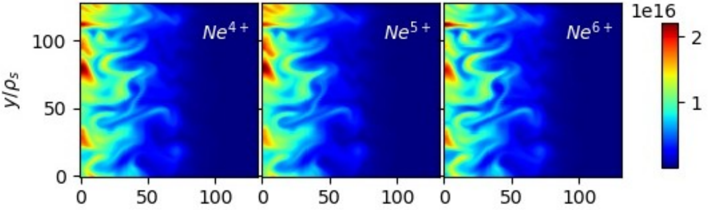
⇒After gas puff the higher species fraction stays for longer duration of time and their concentration decay slowly.

Species during and after Ne gas seeding(continue)

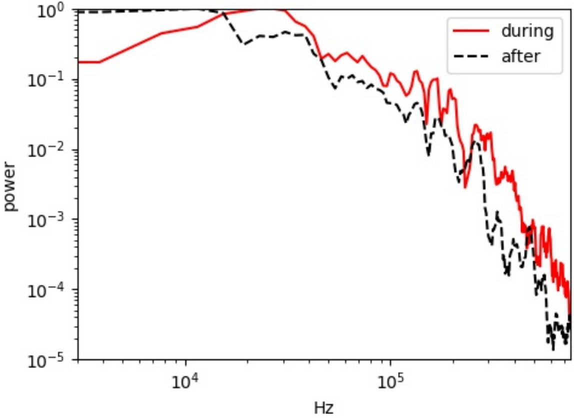
During Ne seeding



After Ne seeding



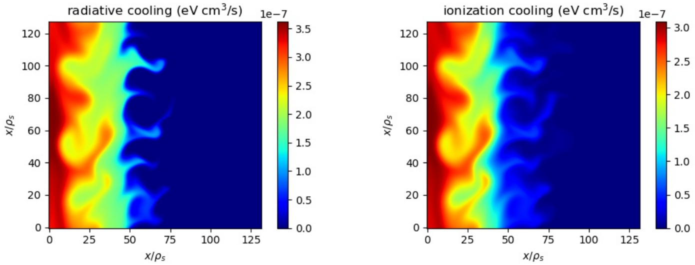
Frequency spectrum during and after gas seeding



- After gas seeding, frequency shifts towards lower power than during the gas seeding.

Radiative and ionization cooling

Radiative cooling has bound-to-bound (bb), bound-to-free components. bb is normally higher.

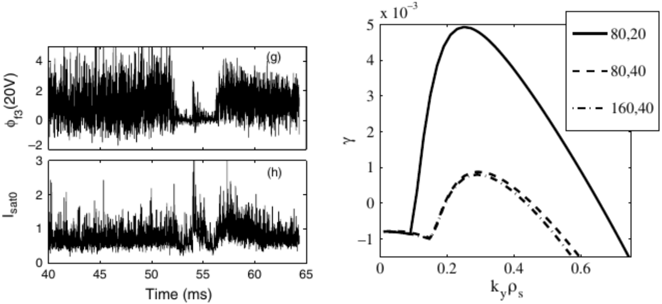


Radiative cooling and ionization cooling are same order of magnitude?

Conclusions

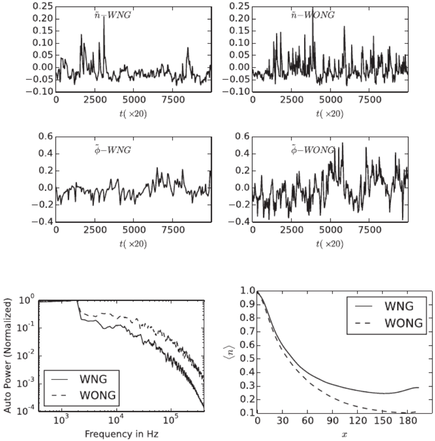
- BOUT++ 2D simulations carried out for model system using 6 Ne ion charged species
- Amount of gas seeding is about 0.1% - relevant for ADITYA tokamak
- Inward propagation of charged species is seen from the movement of radiation and ionization fronts
- After gas termination, highly charged species decreases more slowly than the lower charged species.
- Small scale structures are seen that may play a role in plasma confinement

ADITYA related works



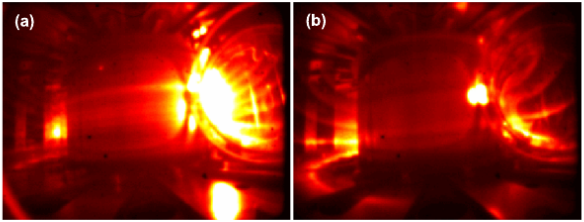
“**Investigation of gas puff induced fluctuation suppression in ADITYA tokamak**”, Jha et al, Plasma Phys. Control. Fusion 51 (2009) 095010

ADITYA related works (continue)



“**Role of neutral gas in scrape-off layer tokamak plasma**”, N. Bisai, R. Jha, and P. K. Kaw, Phys. Plasmas 22, 022517 (2015)

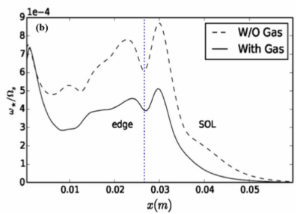
ADITYA related works (continue)

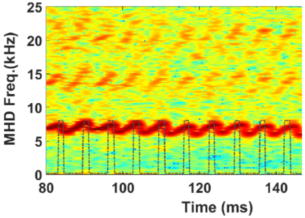


$$\text{Theory} \rightarrow k_y \sim \left(\frac{\sigma}{D+\nu}\right)^{1/4}$$

“**Observation of thick toroidal filaments during the disruptive phase of Aditya tokamak plasma**, Santanu Banerjee et al., Physics of Plasmas 24, 102513 (2017).

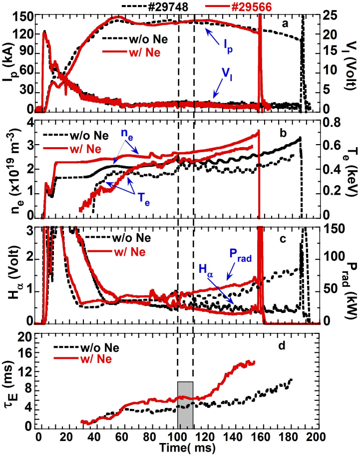
ADITYA related works (continue)

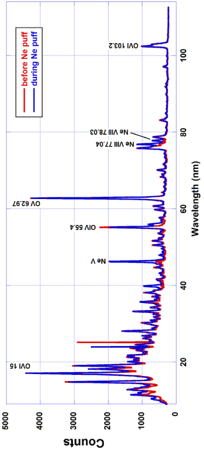




1. “**Overview of operation and experiments in the ADITYA-U tokamak**”, R.L. Tanna et al 2019, Nucl. Fusion 59 112006
2. “**Effect of periodic gas-puffs on drift-tearing modes in ADITYA/ADITYA-U Tokamak discharges**”, Harshita Raj, Accepted in Nucl. Fusion 2020.

ADITYA related works (continue)





“**Dynamics of neon ions after neon gas seeding into tokamak plasma**”, N. Bisai et al., Nucl. Fusion 59 (2019)