# Physics of neutral gas jet interaction with magnetized plasmas

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It is critical to study the physics and transport dynamics of plasma and neutral interactions during the neutral gas jet injection. A 3D neutral transport module called *trans-neut* [Z H Wang, et al., Nucl. Fusion 54 (2014) 043019], has been developed within the original BOUT++ boundary plasma turbulence framework and it has been well benchmarked and validated. It has found that the penetration depth of gas jet fueling obviously increases with the increase of the injection velocity for both different neutral gas jet injection fluxes and the same injection flux. It has also simulated both fast component (FC) and slow component (SC) of neutral gas jet injection and validated with the HL-2A experiment results which are consistent well with each other.

## 1. Introduction

Density control and fuel retention are two critical issues for future fusion devices with long pulse and high performance of plasma discharge. Active fuelling is a useful method to maintain the plasma density. It is critical to understand the physics and transport dynamics during the plasma fuelling process. With different penetration depth and fueling efficiency, there are three major injection methods: gas puffing (GP), pellet injection (PI) and neutral gas jet injection (NGJI) or supersonic molecular beam injection (SMBI)[1,2]. The key technique difference between NGJI and GP is the Laval nozzle of NGJI. It leads to a *directed group fluid velocity* of molecules during NGJI, which is much different from the *individual isotropic thermal speed* of molecules during GP. NGJI propagates inwards depends on both *convective* and *diffusive* transport while GP depends only on the *diffusive* transport (i.e., isotropic in all directions). The plasma temperature will be highly reduced in the edge during NGJI or GP, and the temperatures of the fueling particles (i.e., Franck-Condon atoms dissociated from the molecules) will also be decreased due to the high collisions (i.e., charge-exchange) with the background plasmas in the edge. It leads to much low individual isotropic thermal speed of molecules and atoms and then much low thermal diffusive transport. With the remaining drive of the convective transport, NGJI can continue to propagate inwards, while GP loses the only diffusive drive and mainly stagnates in the edge.

Plasma and neutral interactions involve the transfer of charge, momentum, and energy in ion-neutral and electron-neutral collisions. Thus, a seven field fluid model of gas jet fueling, which couples plasma density, heat, and momentum transport equations together with neutrals density and momentum transport equations of both molecules and atoms, is obtained by reduction of the Braginskii equations with source and sink terms due to plasma and neutral interactions. The behavior of neutral atoms and molecules in tokamak geometry has been investigated with a newly developed 3D neutral transport module called *trans-neut* [3], within the original BOUT++ boundary plasma turbulence framework. Simulations on penetration characteristics have also been conducted with *trans-neut* module [4]. So far, *trans-neut* module has been well benchmarked with TPSMBI code in both 1D slab and cylindrical coordinates under various simulation conditions relevant and crucial for NGJI modeling [5,6], and the simulation of mean profiles variation during NGJI with *trans-neut* has been validated well with the HL-2A experimental measurements[7]. Both fast component (FC) and slow component (SC) of NGJI fueling were first observed in the HL-2A experiment [8]. It was simulated recently [9], but it has not been validated with the experiment.

In this paper, the physical model is shortly described in Sec.2. The numerical conditions are briefly introduced in Sec.3. Simulation results and validations with the experiments are illustrated in Sec.4. Finally, the principal results are summarized in Sec.5.

## 2. Physical model

A seven-field fluid model which couples plasma density, temperatures and parallel velocity transport equations together with atomic density, molecular density and radial velocity transport equations has been developed in the Ref. [2] by reduction of the Braginskii equations [10] with source and sink terms. Please read the Ref. [2] for more details.

## 3. Numerical initial conditions for validation

In order to validate the simulation results with the experiment, the first NGJI pulse at 501ms of Shot # 11606 was finally selected to be used for the validation. The numerical initial profiles of plasma density and electron temperature are obtained by polynomial fitting of the experimental data, as shown in Fig. 1. Profiles of plasma density and electron temperature are measured by microwave reflectometry and electron-cyclotron emission, respectively. The numerical initial profile of ion temperature is assumed equal to that of electron temperature since there is no measurement of ion temperature in the shot selected.

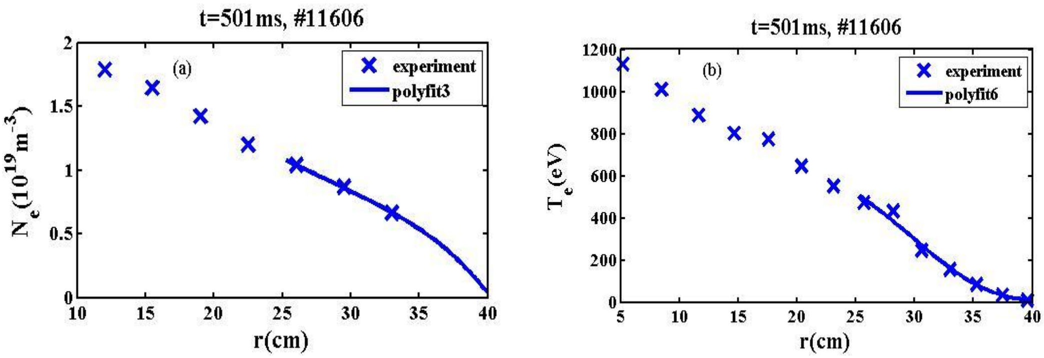


**Fig. 1** Experimental data and fitted profiles (a) electron density and (b) electron temperature.

## 4. Numerical simulation and validation

4.1 NGJI penetration characteristic

We also studied the molecular penetration depth variation with the NGJI fluxes. It finds that the penetration depth of molecules strongly depends on the radial convective transport of NGJI and it increases with the increase of the injection velocity for both the same injection flux and also the different injection fluxes. Since the molecules are mainly dissociated and then ionized at the inward injection beam front, the main reaction region moves deeper away from the edge region with a larger injection velocity, so that the plasma density is mainly increased at the front of injection beam deeper inside of the separatrix rather accumulated in the SOL. Please read the Ref. [4] for more details.

4.2 Validation with the experiment on FC and SC of NGJI

It shows the spatio-temporal evolution of $D_\alpha$ signal during the first NGJI pulse of shot # 11606 and radial profiles of $D_\alpha$ intensity for FC and SC in Fig.2. Typical characteristics of FC and SC are illustrated. In the view of time line, the NGJI pulse obviously split up in to FC and SC (Fig.2 (a)). The key difference between FC and SC is the penetration depth of FC is 3-4 cm deeper than SC (Fig.2 (b)).

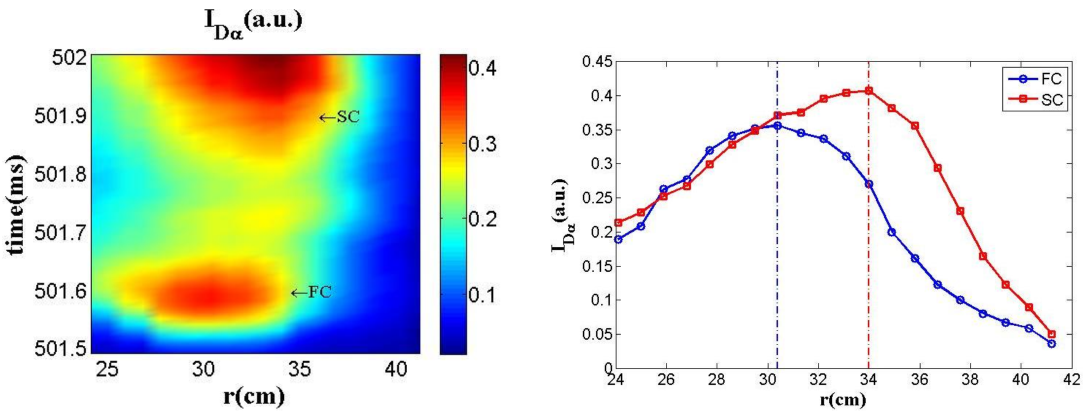


Fig. 2 Typical experimental results of $D_\alpha$ signal for FC and SC of NGJI on HL-2A. (a) spatio-temporal evolution

of $D_\alpha$ signal during the first NGJI pulse of shot # 11606, (b) radial profiles of $D_\alpha$ intensity for FC and SC.

The simulation results of spatio-temporal evolution of $D_\alpha$ intensity during NGJI and radial profiles of $D_\alpha$ intensity for FC and SC are shown in Fig. 3. We can see the simulation results of typical features are consistent well with experimental measurements within the first 0.5 ms, mainly the separation of FC and SC and the relationship of the penetration depths between them. The simulation results are qualitatively consistent with the experiment results. The mechanism of FC and SC has been well discussed earlier in the Ref. [9], while it focuses on the comparison and validation with the experiment here.

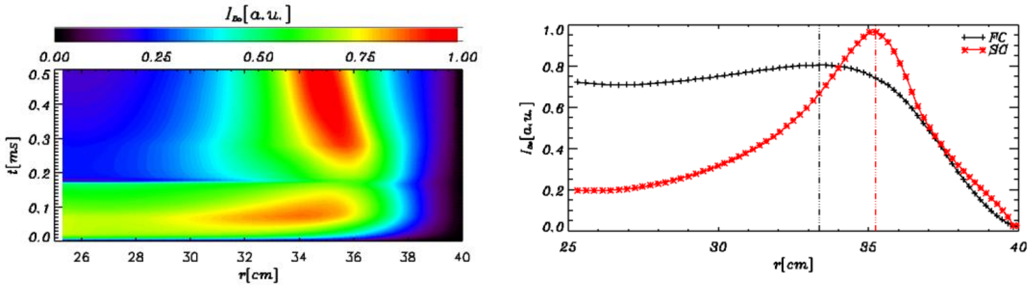


**Fig.3** Simulation results of $D_\alpha$ intensity for FC and SC of NGJI. (a) Spatio-temporal evolution of $D_\alpha$ intensity, (b) radial profiles of $D_\alpha$ intensity for FC and SC.

## 5. Summary

We have further found that the penetration depth of gas jet fueling obviously increases with the increase of the injection velocity for both the same injection flux and also the different injection fluxes. Both fast component (FC) and slow component (SC) of neutral gas jet injection has been simulated and validated with the HL-2A experiment results which are consistent well with each other.

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