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Modeling of High-Pressure Argon Jet Penetration into a Tokamak

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Introduction

High-pressure noble gas jet injection is a prospective way to mitigate a disruption in modern tokamaks. Such experiments were performed recently on the DIII-D tokamak [1], where the penetration of the Argon jet up to the tokamak central region has been observed. This result could be interpreted as the penetration of an almost neutral jet: ionized particles would move quite differently due to the interaction with magnetic field.

The noble gas cloud is heated mainly by depletion of the energy flux carried by hot background particles, penetrating into the cloud along the magnetic field lines. This energy is spent to the cloud expansion (mainly along the magnetic field lines), ionization and the radiation losses. Whether the cloud remains neutral or ionized depends on the balance of the incoming power, radiation losses and cooling due to expansion along the magnetic field. One should also take into account the effect of electrostatic shielding, i.e. the fact that the parallel current should be zero [2].

The partially ionized jet expands freely along the magnetic field lines but its cross-field motion is affected by an interaction with the magnetic field. To provide motion of the jet ions in the radial direction a polarization electric field of dipole type should appear. Physical mechanisms, which could cancel the polarization, are discussed in [3-5]. It was unclear whether they can stop the jet within the time interval necessary for the jet to reach the tokamak center.

To answer these questions the modeling of high-pressure Argon jet penetration into a tokamak is performed. It is demonstrated that for the parameters typical for the DIII-D tokamak the jet can penetrate deep inside the central parts of the plasma. Ionization states distribution model is developed for Argon and applied to the modeling. Physical mechanisms of jet motion in radial and poloidal directions are investigated.

Model

The initially neutral jet in a tokamak plasma expands in B-parallel and B-perpendicular directions and becomes partially ionized. The ionized particles expand freely along the magnetic field lines while the cross-filed motion is affected by an interaction with the magnetic field. At some time instant, ionization sets in at the jet periphery and the expansion in the poloidal direction comes to a full stop. The respective stopping radius should be considered as the transverse jet size for further field-aligned simulations.

Jet motion in the radial direction is provided by the polarization of the jet and the radial $\vec{E}\times\vec{B}$ drift (the initial jet velocity is $\vec{V}_0 = \frac{\vec{E}_0\times\vec{B}}{B^2}$). The polarization electric field of dipole type $E_0 = V_0 B$ should appear (see Fig.1). In [5] two mechanisms which can cancel cloud polarization are studied - Alfven conductivity and ∇B-induced current. Then the jet dynamics in the low field side direction of the tokamak is given by (1) (see [5] for the details)

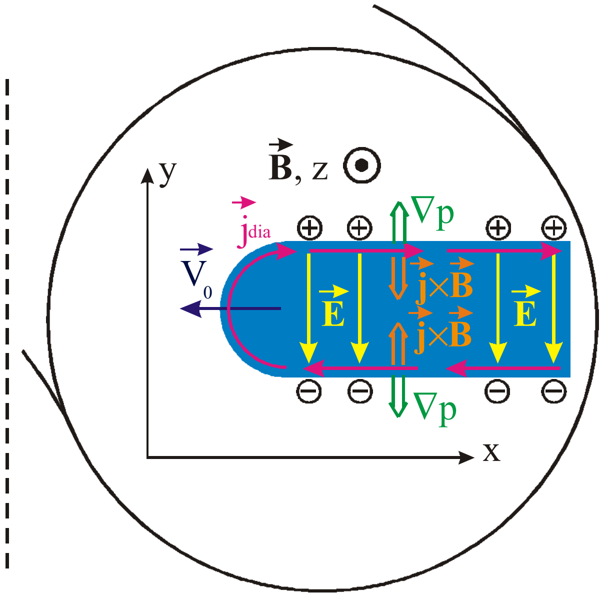

Fig.1. Force balance and electric field in the jet penetrating into the tokamak.

$$\frac{(M_N + M_I)}{B^2}\frac{dE_y}{dt} = -2\Sigma_A(E_y - E_0) + \frac{2M_I(T_e + T_I)}{BRm_I}, \qquad (1)$$

where M_I, M_N are integral masses of jet neutrals and ions, m_I is the mass of jet ions, R is the tokamak major radius $\Sigma_A = (\mu_0 c_A)^{-1}$ is the so-called wave conductivity (see [3] for details). Estimations made for the parameters of experiment [1] show that the electric field relaxation time is much larger than that needed for the jet to reach the tokamak center. So the electric field and corresponding velocity in the radial direction remain almost constant, which coincides with experimental observations.

The jet in hot tokamak plasma is simulated by means of the modified LLP code [6]. To model jet expansion along the magnetic field lines single-fluid 1D MHD equations together with the ionization states distribution, energy and flux depletion of the energetic particles and self-consistent electric field are solved in Lagrangian coordinates

$$\frac{\partial\rho}{\partial t} + (\nabla\cdot\rho\mathbf{v}) = 0, \qquad \rho\frac{\partial\mathbf{v}}{\partial t} + \rho(\mathbf{v}\cdot\nabla)\mathbf{v} = -\nabla p,$$

$$\frac{3}{2}\frac{\partial p}{\partial t} + \frac{3}{2}(\nabla\cdot p\mathbf{v}) = -(\nabla\cdot\mathbf{q}) - p(\nabla\cdot\mathbf{v}) - Q_{ioniz} - Q_{rad\_losses}, \qquad \mathbf{q} = -\chi\nabla T + \mathbf{q}_{inc}.$$

Here $\nabla\cdot\mathbf{q}_{inc}$ is energy deposition from the ambient electrons and ions. The equation $j_{\parallel} = 0$ was added to calculate the self-consistent electric field. The ionization and recombination processes are calculated on the base of the ionization states distribution model developed for Argon.

$$\frac{dy_i}{dt} = n_e\left(y_{i+1}R_{i+1} - y_i(I_i + R_i) + y_{i-1}I_{i-1}\right), \qquad n_e = \sum_i i \cdot n_i\,, \qquad n_i = y_i\frac{\rho}{M}.$$

Energy loss due to radiation is modeled with corona radiation loss function. The opacity effects are not discussed in the present work. The background particle penetration, ionization state distribution and radiation losses are calculated in a self-consistent manner. The particle and energy flux depletion of hot background particles in the jet due to collision interaction with the cold particles is determined by stopping length calculations applied to both electrons and ions. The poloidal expansion of Argon gas is simulated by means of time-dependent 1.5D MHD code. The resulting stopping radius obtained at the end of calculation is used then as the transverse jet size (r_0).

Results of numerical simulation

Calculations are performed for the parameters typical for DIII-D tokamak. Jet parameters are taken from the experiment [1]. Jet expansion starts at $t = 0$ with given cloud density $n_0 = 4\cdot10^{24}m^{-3}$, temperature $T_0 = 300K$, cloud size $z_0 = r_0 = 7.5cm$ (cylindrical symmetry is assumed) and ionization degree $\alpha = 0$ (this value corresponds to a jet temperature of about 300K). Jet velocity is $V_0 = 250m/s$. The modeling is performed until the jet reaches the tokamak center, provided there is no radial deceleration, $t_{center} = a/V_0$, where a is the tokamak minor radius. (For DIII-D it means 2.5 ms). Background density and temperature profiles are supposed to be known.

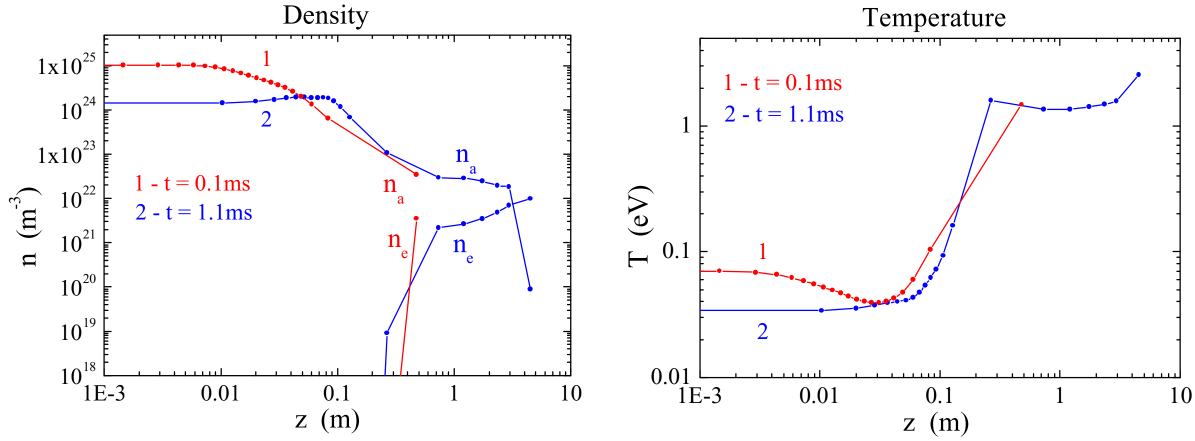

Fig.2. Simulation profiles along the magnetic filed lines (z-coordinate) for two different moments. (n_e, n_a are electron and neutral densities correspondingly).

In Fig.2 the two characteristic regions are clearly seen. The first one at the outer part of the cloud is a region where hot incident electrons can penetrate. The second inner region is a cold and dense region where hot background carriers are not able to reach. Temperature in this part remains very low (~300*K*). Most of the particles are situated in the second region. No significant ionization takes place in the inner region. Consequently the radiation losses in this region are close to zero for any model. For the outer region a more sophisticated radiation loss model is needed and it is under development. On the basis of the results obtained one can conclude that for DIII-D parameters the jet remains neutral and is hence able to penetrate into the central parts of a tokamak.

To model the evolution of the transverse jet size the poloidal expansion of Argon gas is simulated by means of 1.5D MHD code. Results obtained show that an ionization degree of the order of 5% reached at the end of the calculation is enough for the diamagnetic currents flowing in the partially ionized boundary to stop the perpendicular motion. This conclusion is verified by the time evolution profile of the transverse jet size presented in Fig.3. It can be also concluded that the transverse size does not change significantly (by a factor of two) during jet penetration.

While penetrating into the central tokamak regions the jet can cool the hot background plasma. However the model with cooling effect taken into account gives qualitatively the same results as the one without this effect.

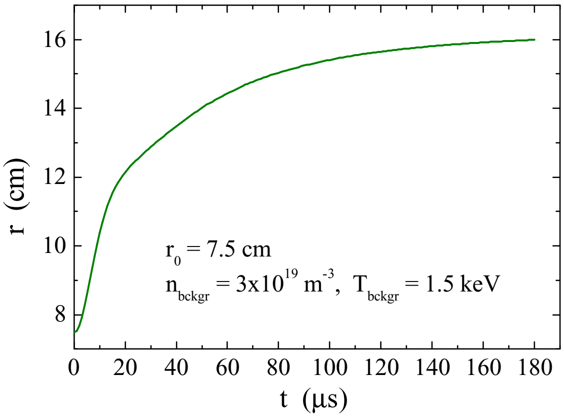

Fig.3. Time evolution of the jet transverse size.

Conclusions

Simulations demonstrated that supersonic heavy ion jet could penetrate deep into plasma of modern tokamaks remaining almost neutral in accordance with experimental observations.

Acknowledgements

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