On the possibility of tokamak fueling by high velocity jet produced by plasma gun

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Introduction

Recently an injection of supersonic gas jet was suggested as a technique of future reactor fueling alternative to a pellet injection. Experiments on tokamak fueling by jets were performed on Tore Supra [1], later the jet with similar parameters was injected into ASDEX-Upgrade to control ELMs [2]. In these experiments jets did not penetrate deep into the plasma core. As was demonstrated in the simulations [3] such jet is getting ionized by ambient electrons at a time scale of the order of 1 μs after crossing the separatrix.

After ionization the jet, which motion across the magnetic field is controlled by $\vec{E} \times \vec{B}$ drift, decelerates due to emission of Alfven wave [3]. The deceleration time in experiments on Tore Supra and ASDEX-Upgrade is of the order of 1-2 μs. Thus the penetration depth should be of the order of 1-2 mm.

In the recent experiments performed on Globus-M [4] the fueling material was injected by plasma gun. This principally novel technique allows to inject a plasma jet with velocities up to 100 km/s, which is 2 orders of magnitude larger than that achieved by Laval nozzle, while the jet density and size are close to ones of traditional gas jet achieved in [1,2]. It was possible to create both plasma and neutral jets in the experiment. The reasonable penetration was observed in both cases.

In the present paper the penetration of fast plasma or neutral jet has been simulated and analyzed. It is shown that the jet should stay inside the plasma which is consistent with interferometer measurements and local density measurements performed by Thomson scattering technique.

Experimental results

In the experiments on Globus-M the jet was accelerated by plasma gun up to velocities of $V_0 = 100$ km/s. The jet density was about $10^{21} \, \mathrm{m^{-3}}$, the jet size in the direction transverse to the direction of $\vec{V}_0$ is about 9 cm, which are similar to one achieved in [1,2]. Varying the

distance from the gun to the separatrix one could achieve either ionized or neutral jet because with larger distance the jet have time to neutralize due to recombination.
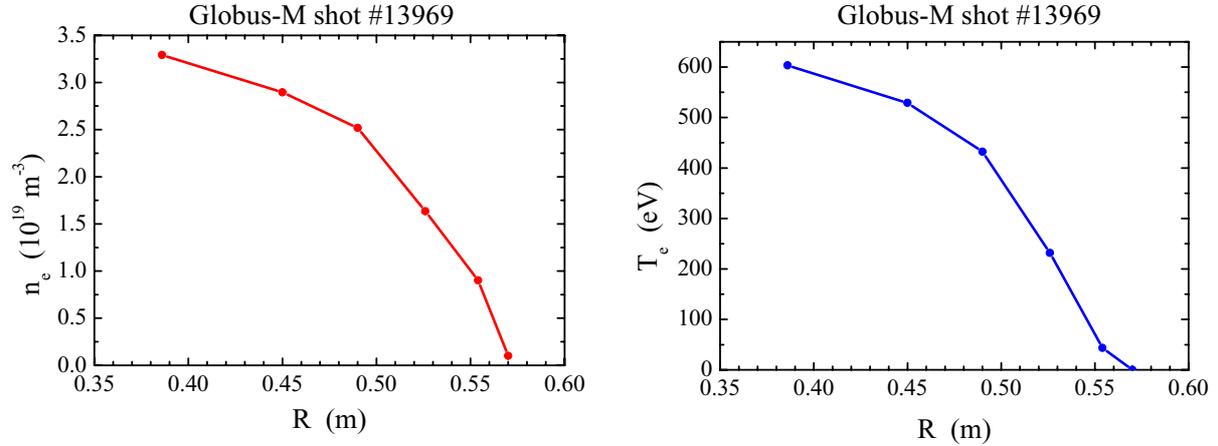

Fig. 1. Ambient plasma density and temperature profiles before the jet injection

The density rise in the tokamak after the jet injection was measured by interferometers and by Thomson scattering technique. The density rise was registered mainly at plasma periphery at timescale of less that 0.5 ms, which is much faster that diffusion timescale, independently of initial ionization state of the jet. This indicates that the jet penetrates deep into the Globus-M plasma. Series of injection with different parameters demonstrated that for higher background plasma density smaller density rise after the jet injection was observed.

Modeling

For the jet penetration modeling the approach described in [3] was used. The heating, expansion and ionization of the jet penetrating towards the tokamak center are calculated for the ambient plasma profiles shown in Fig. 1. It is found that the initially neutral jet is getting ionized within $\tau_i = 0.5$ μs, i.e. penetrates up to 5 cm assuming constant velocity $\vec{V}_0$.
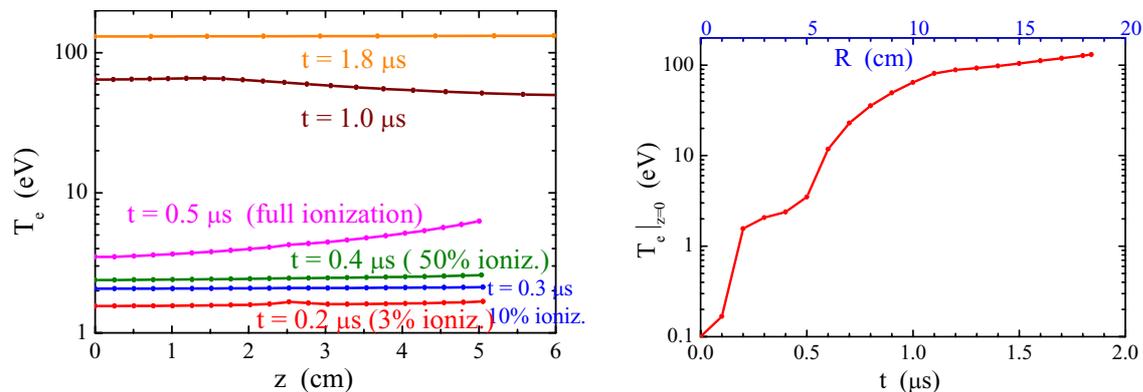

Fig. 2. Evolution of the jet temperature. Left: profiles along the magnetic field; Right: central (z=0) temperature versus time

Temporal evolution of jet temperature is shown in Fig. 2. Note that the timescale of full ionization is of the same order as in experiments on Tore-Supra and ASDEX-Upgrade [1,2].

The penetration of ionized jet in the injection direction is provided by polarization electric field $\vec{E}_0 = [\vec{B} \times \vec{V}_0]/B^2$ and $\vec{E} \times \vec{B}$ drift. However, this polarization (and jet velocity $\vec{V}_{jet}$) reduces due to, first, currents in the Alfven wave emitted into the ambient plasma (the effect of so-called Alfven conductivity), and, second, vertical ∇B-induced currents according to [3]

$$\frac{M_i}{B^2}\frac{d\vec{V}_{jet}}{dt} = -2\Sigma_A \vec{V}_{jet} + \frac{2M_i(T_e + T_i)}{B^2 R^2 m_i}\vec{R} \,, \tag{1}$$

where $M_i = \int_{-\infty}^{\infty} m_i n_i dz$, n_i - jet ions density,

$\Sigma_A = \dfrac{2}{\mu_0 c_A}$, $\vec{R}/R$ - unit vector directed outwards.

Let's consider two processes separately. Due to emission of Alfven wave the jet decelerates exponentially and penetrates up to $V_0 \tau_\Sigma$, where $\tau_\Sigma = B^2/2M_i\Sigma_A$. Similarly to [1,2], $\tau_\Sigma \approx 0.8 \ \mu s$, but on Globus-M $V_0\tau_\Sigma \approx 8$ cm is comparable to minor radius. Consequently, the deep penetration up to $V_0(\tau_i + \tau_\Sigma) \approx 12$ cm is possible, while on ASDEX-Upgrade $V_0\tau_\Sigma \approx 1.5$ mm $<< a$, and jet practically could not cross the separatrix. Note that τ_Σ is inversely proportional to $n_0^{1/2}$
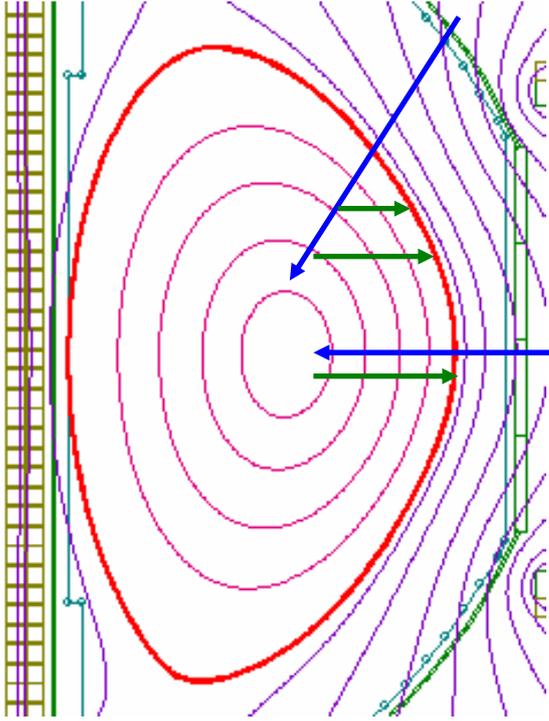

Figure 3. Schematic view of the jet motion in the Globus-M tokamak. Blue arrows shows initial jet direction, green ones – displacement caused by ∇B-drift

(the ambient plasma density) and proportional to n_i, therefore for higher ambient plasma density and lower jet density the penetration depth would be smaller.

The ∇B-induced current leads to acceleration towards the LFS, however, this current in the jet expanding along the magnetic field vanishes at timescale $R\sqrt{m_i/(T_e + T_i)}$ due to rotational transform [3]. The jet velocity also decreases to zero on the same timescale, and for the displacement towards the LFS one can get [3]

$$\Delta x = \sqrt{\frac{Rm_i n_i l_z^2 V_0}{Br}} \cdot \sqrt[4]{\frac{\mu_0}{\pi n_0 m_0}} \tag{2}$$

Here l_z is the initial jet size along the magnetic field, r is the jet size in poloidal direction, which, as it demonstrated by numerical calculation of jet expansion, remains almost constant [3]. For the Globus-M parameters $\Delta x \approx 14$ cm.

Thus, in such a simplified consideration, the jet injected from the LFS, penetrates up to about 12 cm until it is stopped by Alfven conductivity, and then is shifted at about 14 cm outwards due to ∇B-drift (see Figure 3). In reality both processes are going simultaneously and a rigorous consideration is rather complex, but one can expect that significant part of injected particles should be deposited inside the separatrix, mainly at the plasma periphery, since $V_0(\tau_i + \tau_\Sigma) \approx \Delta x$. This is consistent with experimental observations.

The weak sensibility of particle deposition to the initial ionization degree of the jet is explained by rather fast ionization, so that the ionization time is smaller that any other characterizing time in the problem.

On the tokamak fueling by plasma gun.

From the model considered one can realize that for modern large tokamak and future reactor ITER fueling it is necessary to continue developing the plasma guns in the following directions. First is the density rise to make the jet particle contents comparable to reactor one. The denser jet will also increase τ_Σ and the penetration depth. Second is switch to HFS injection so that the ∇B-drift would be directed towards the tokamak center.

Conclusions

The model [3] for gas jet penetration into the tokamak is applied for the high-velocity jets accelerated by plasma gun on Globus-M. The model predictions are consistent with experimental observations. It is demonstrated that with high velocities achieved by plasma gun it is possible to get a deep jet penetration into the tokamak plasma.

Acknowledgements

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