*36th EPS Conference on Plasma Phys. Sofia, June 29 - July 3, 2009 ECA Vol.**33E**, P-1.180 (2009)*

Efficiency of massive gas injection for increase of plasma density in TEXTOR experiments on disruption mitigation.

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A disruption mitigation system is essential for the reliable ITER operation. The most critical issue to be dealt with by such a system is the suppression of runaway (high-energy) electrons. To suppress the runaway production the total electron density must be increased to about 10^{23} m^{-3} in a few milliseconds.

Massive gas injection (MGI) is considered as a candidate to provide this density. However, experiments in TEXTOR [1, 2] and JET [3] demonstrated that only a small fraction of atoms released by the fast injection system reaches the plasma core before possible runaway generation. In this contribution we analyze gas flow from the reservoir to plasma and show that unsteady flow in the delivery tube can explain the observed M-dependence of the mixing efficiency in TEXTOR.

Model of gas flow in a delivery tube. Initially ($t < 0$) the high pressure reservoir of volume V, i.e. a MGI valve, is sealed with a piston (figure 1). The initial conditions in the reservoir are: density ρ_0, sound speed c_0, adiabatic exponent γ and velocity $u_0 = 0$. On a trigger the orifice is quickly opened and the gas is delivered into plasma via a vacuum tube of length L. The delivery process is essentially non-stationary, as a consequence the gas pulse is considerably flattened along the tube. For the case of equal diameters of the plenum, orifice and tube, and of an instantaneous opening, a centered rarefaction wave runs into the reservoir from $x = 0$ until it is reflected at the closed end. The gas-vacuum contact surface runs to the right with the velocity of $2 \cdot c_0/(\gamma - 1)$. The solution of this classical problem is [4]:

$$\frac{u}{c_0} = \frac{2}{\gamma+1}\left(1+\frac{x}{c_0\cdot t}\right) \tag{1}$$

$$\frac{\rho}{\rho_0} = \left(\frac{2}{\gamma+1} - \frac{\gamma-1}{\gamma+1}\frac{x}{c_0 t}\right)^{\frac{2}{\gamma-1}} \tag{2}$$

By integrating the product $\rho \cdot u$ the relative number $\bar{N} = N/(\rho_0 \cdot V)$ of particles delivered beyond x until time t can be found as ($n \equiv 2/(\gamma - 1)$, $\xi \equiv x/(c_0 \cdot t)$ and A is cross-sectional area of the tube):

$$\bar{N}(t) = \frac{A\cdot K\cdot x}{V}\cdot\frac{n^n}{(n+1)^{n+1}}\cdot\sum_{k=0}^{n+1}\frac{(-1)^{k-1}\cdot(n+1)!}{(n-k+1)!\cdot k!}\cdot\left(1-\left(\frac{\xi}{n}\right)^{k-1}\right), \tag{3}$$

which for an atomic gas $\gamma = 5/3 \Rightarrow n = 3$ takes the form:

$$\bar{N}(t) = \frac{A\cdot K\cdot x}{V}\cdot\frac{27}{256}\cdot\left(-4+\frac{3}{\xi}+2\cdot\xi-\frac{4}{9}\xi^2+\frac{\xi^3}{27}\right) \tag{4}$$

Here we introduced a correction factor K, which will be discussed below.

In figure 2 the number of particles $\bar{N}(t)$ is presented for three gases He, Ne, Ar for the TEXTOR setup ($V = 50$ ml, $K = 0.25$, $L = 1.5$ m). Dashed vertical lines indicate thermal quench times t_{TQ} found in experiment with a corresponding gas. Timescales of gas delivery are comparable (for He) or even much longer than that of gas-plasma interaction. For heavy gases only a small

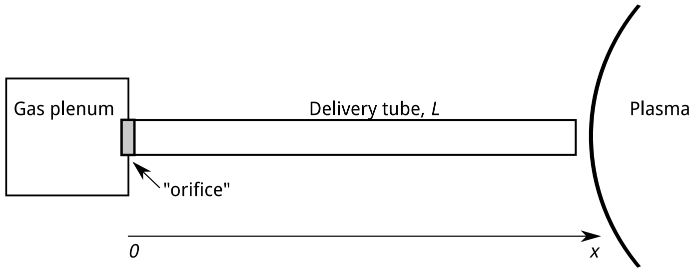

Figure 1: *Scheme of gas delivery to plasma*

fraction of gas at the front is able to disrupt plasma by cooling the $q = 2$ surface.
To conclude, the dynamics of the gas delivery is essential for interpretation of the MGI fuelling efficiency.
Comparison of the flow model with measurements. The real flow is more complicated and can be divided into the following regions: unsteady flow, steady state flow, and final rarefaction wave caused by orifice closing. The model solution is valid for the initial gas front, as shown below for the valves used in TEXTOR and in JET [5]. However, due to gas expansion close to the orifice (orifice size is smaller than the tube diameter) ρ_0 in equation 2 is to be corrected by a factor $K = K(S_{orifice}/S_{\mathrm{tube}})$, that also appears in the delivery rate (eq. 3).
Figure 3 shows a comparison of the model solution (eq. 2) with density measurements performed by a laser interferometer at three locations [6]. The jumps observed at $L = 4.485$ m (green curve) are thought to be caused by a reflection at the tube end, while variations at the beginning (black curve) are due to mechanical disturbances. The model predicts the density evolution with an accuracy of about 30%.
Similar measurements are available for three different diameters of the valve orifice. This allows us to find the correction K for the valve used in TEXTOR to be 0.25 ± 0.07. A more elaborated analysis will be reported elsewhere.
The non-stationary solution is found to be valid up for $\xi \geq 0.65$ (figure 3). For TEXTOR this amounts to about 2.1 ms for He and 6.7 ms for Ar, i.e. these times are shorter than plasma disruption times (see also figure 4b). Therefore the model solution is sufficient for TEXTOR.
Discussion of the mixing efficiency. Previously, the impurity density in the plasma after the

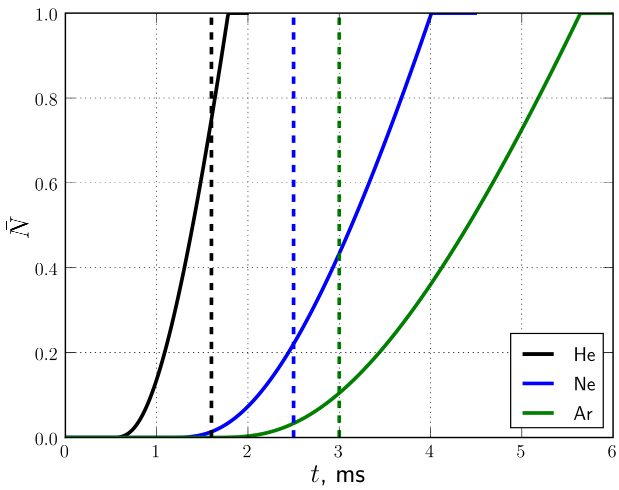

Figure 2: *Number of delivered particles as function of found in the experimenttime. Dashed lines mark disruption onset found in the experiment.*

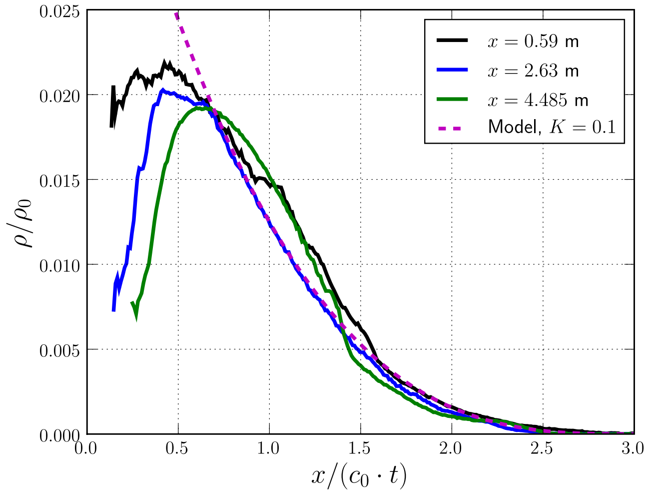

Figure 3: *Comparison of the model with interferometric density measurement (neon, $c_0 \approx 450$ m/s, $S_{orifice}/S_{tube} \approx 0.06$).*

thermal quench caused by MGI in TEXTOR was determined by a 0d code of the current quench [1, 2]. The model describes runaway generation, current decay and power balance between ohmic heating and impurity radiation. The model has one free parameter - impurity density, which could be found by fitting experimentally measured plasma current with an accuracy better than a factor of 2.

The impurity density having been determined, it was possible to estimate the so-called mixing efficiency, which is the ratio of the found density to the expected one:

$$M.E. = \frac{n_{imp}}{f \cdot N/V_T}, \tag{5}$$

where N is the total number of injected atoms, f is the fraction of atoms that was expected to be injected before the thermal quench and V_T is the TEXTOR volume. The fraction f was estimated without taking into account the flow dynamics:

$$f = 1 - \exp\left(-\alpha(t - t_0)\right) \tag{6}$$

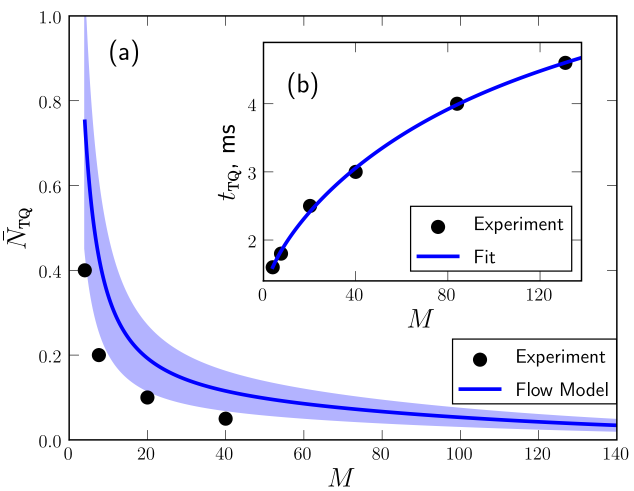

Figure 4: *(a) comparison of the number of particles delivered into plasma before disruption with that found by modelling of the current quench. (b) dependence of the thermal quench time on the gas mass.*

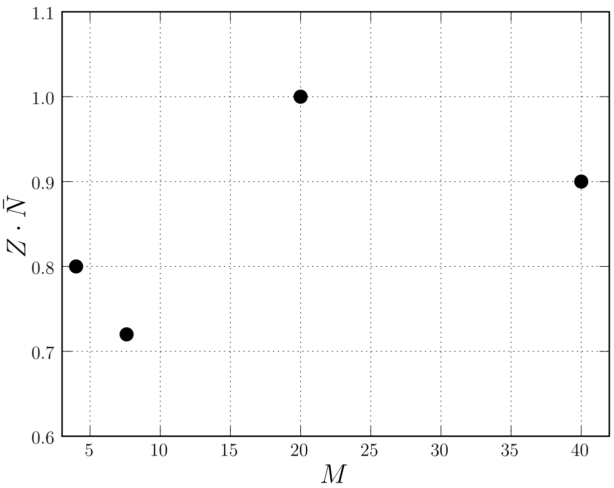

Figure 5: *Efficiency of increasing total electron density*

where α is the density decay rate in the valve [7] and t_0 is the tube travel time taken from the experiment. The values of f were in the range 70 – 100%, i.e. within the accuracy of the estimation it was about 100%, for all used gases. The mixing efficiency estimated in such a way has a pronounced dependence on the gas mass M ("experiment" in figure 4a).

Figure 4 demonstrates a comparison between the mixing efficiency found by fitting the current quench ("experiment") with the number of particles delivered into plasma before thermal quench (there is an experimental evidence, that only those atoms can be sufficiently mixed [8]). Disruption times were taken from experiment (figure 4b). The modelled data reproduce the trend in M-dependence found in experiment.

It is also interesting to compare the total number of injected electrons $Z \cdot \bar{N}$ for different gases (figure 5). The significant drop in the mixing efficiency for large M compensates the large number of bound electrons, i.e. there is no preferable gas from the point of view of runaway suppression.

Conclusions. The dynamics of particle delivery rate is important for the interpretation of MGI experiments. In particular, this explains the drop of the mixing efficiency with mass M. The mixing efficiency corrected for the number of particles delivered into the vessel does not depend on M and is about 50% for TEXTOR conditions.

The TEXTOR data also show that the total number of electrons delivered before disruption does not depend on the gas species. The slow delivery rate of heavy gases compensates their large number of bound electrons. It is still to be clarified if this depends on the distance to valve, plasma energy, etc.

A scaling to ITER is not yet possible, since the scaling of thermal quench times remains unknown. Nevertheless, it is clear, that the development of gas injection system should focus on increasing the gas delivery rates, and that location of the injection system can be critical.

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