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Paper

Massive Gas Injection Plans for Disruption Mitigation Studies in NSTX-U

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Predicting and controlling disruptions is an important and urgent issue for ITER and impacts the designs for reactors based on the ST and Tokamak concepts. Disruptions have been such a ubiquitous feature of tokamak operations for decades that, while work is in progress to develop reliable methods to avoid disruptions, some may be unavoidable. For these cases, a fast discharge termination method is needed to minimize the deleterious effects of the disruption, particularly the generation of large populations of runaway electrons. Massive Gas Injection (MGI) is one approach to addressing this difficult issue for ITER. NSTX-U plans to compare MGI from different poloidal locations to assess the gas penetration efficiency. We are starting to model gas penetration using DEGAS-2 and it appears that the scrape-off-layer plasma may place limits on the achievable gas penetration fraction to the separatrix.

Keywords : MGI, disruption, mitigation, NSTX

1. Introduction

At present Massive Gas Injection (MGI) appears to be the most promising method for safely terminating discharges in ITER[(1)-(4)]. MGI involves the rapid injection of gas with an inventory several times the inventory of the plasma discharge. Usually some fraction of the injected gas has a high-Z component such as argon or neon. Requirements for the mitigation of disruption effects fall into three categories: (1) Reducing thermal loads on the first wall; (2) reducing electromagnetic forces associated with “halo” currents, i.e. currents flowing on open field lines in the plasma scrape-off layer; and (3) suppressing runaway electron (RE) conversion in the current quench phase of the disruption. To accomplish these in ITER, it is projected that about 500 kPa-m^3 of helium with some noble gas fraction will be required.

The present understanding of disruption mitigation using massive gas jets is based on work conducted on DIII-D, Alcator C-MOD, ASDEX-U, JET and other large tokamaks, and is summarized in Ref. (1)-(4). Recent experimental results have shown that the cold front from the edge, which has been cooled by a MGI pulse, needs to reach the q=2 surface for the onset of rapid core cooling to occur. On ITER, it is not known if a simple MGI pulse from multiple locations would be adequate because of its larger minor radius, the increased transit times for the neutral gas, and the larger scrape-off-layer (SOL) flows expected in it. Insight into ways for reducing the total amount of injected gas and optimizing the injection locations would further help with the design of a suitable system for ITER.

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NSTX-U can offer new insight by injecting gas into the private flux and lower x-point regions of its divertor discharges to determine if this is a more desirable location for massive gas injection. Injection from this new location has two advantages. First, gas injected directly into the private flux region does not need to penetrate the scrape-off-layer. Second, because the injection location is nearer the high-field side in standard D-shaped cross-sections, the injected gas should be more rapidly transported to the interior as known from high-field side pellet injection and from high-field side gas injection on NSTX. By comparing massive gas injection from this new location to injection of a similar amount of gas from the outer mid-plane, NSTX-U can provide additional knowledge to disruption mitigation physics and new data for improving computational simulations. To plan for these experiments, an effort has been initiated to model the gas penetration using the DEGAS-2 code[(5)(6)]. Initial results from these simulations suggest that gas penetration to the separatrix could be significantly affected by plasma parameters outside the separatrix.

2. Experimental and Computational Plans for NSTX-U MGI Studies

2.1 Experimental Plans The planned upgrade to NSTX will double its toroidal field to 1 T, plasma current to 2 MA, NBI heating power to 12 MW and increase the pulse length from the present 1.5 s to 5 s. NSTX-U will be a 0.93 m major radius, 0.62 m minor radius device.

The primary goal of the MGI experiments in NSTX-U is to compare the gas penetration efficiency as gas is injected from the different poloidal locations shown in Fig. 1. These are (1a) the private flux region, (2) the mid-plane region, (1b) high-field side outer SOL region, high-field side inner SOL region and (3) outer

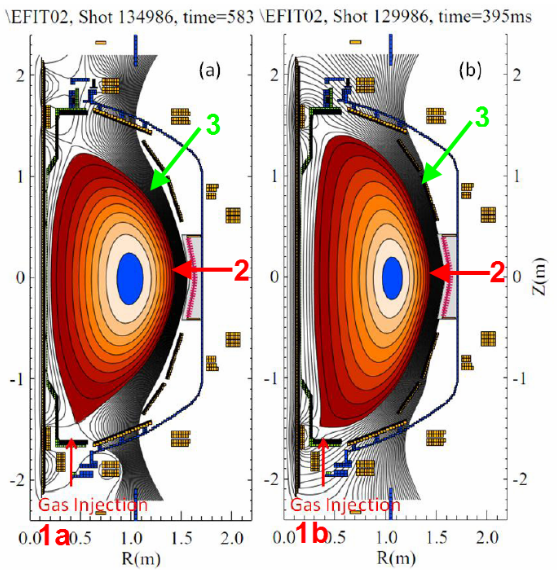

Fig. 1. Shown are the planned Massive Gas Injection locations on NSTX-U: 1a: Private flux region, 2: mid-plane injection, 1b: high field lower SOL region and 3: outer SOL above the mid-plane; The blue central region is an artifact of the EFIT plotting program and has no special signifcance

SOL region above the mid-plane. The gas throughput rates and the gas composition are to be established based on results from DEGAS-2 modeling now underway. The secondary objective is to assess the reduction in divertor heat loads and halo currents. The importance of the q=2 surface proximity to the plasma edge will be studied by gas injection at different times during the discharge as the q=2 surface evolves. The eventual goal of these studies would be to design a system for NSTX-U that could automatically trigger the MGI system based on input received from sensor provided data on an impending disruption.

2.2 Simulations using the DEGAS-2 Code The amount of gas injected in MGI experiments in present tokamaks varies from 100 Pa.m^3 to over 2000 Pa.m^3, considerably less than the projections for ITER. The fraction of this gas that penetrates the separatrix also varies widely, with penetration efficiencies of over 20% being reported for cases that have a short MGI pulse(4). To better quantify the amount of gas required in a MGI pulse we have initiated a DEGAS-2 Monte-Carlo code simulation effort to understand the extent of gas penetration through the SOL region and private flux regions. In addition to supporting NSTX-U needs, this simulation effort focuses on fundamentally studying the edge penetration issues to the separatrix, which is needed for predicting gas penetration efficiencies in ITER. This work complements other 3-D MHD modeling, initiated by the ITER organization, of the gas dissipation inside the separatrix.

The results presented here are preliminary. The code employed is not yet capable of simulating energetic SOL flows and so does not yet correctly reflect edge conditions that would exist in a high power discharge. A more energetic plasma in the SOL would increase the gas ionization rate in this region and reduce gas penetration. Development of the detailed modeling of the edge SOL flows is underway but it is beyond the scope of the present paper. Because self-consistent SOL flows and plasma parameters are not modeled, an explicit comparison of mid-plane injection to private flux region injection is not possible at this time.

As the first step in developing the full model to simulate the effect of increasing the SOL parameters we have conducted simulations in which the background plasma density and temperature are artificially increased, such as would happen when the auxiliary power of a plasma discharge is increased. In these simulations, deuterium molecules are launched at the injection port with a 300 K thermal energy distribution and a cosine angular distribution about the normal to the surface. As the molecules penetrate the plasma, they undergo ionization, dissociation, and elastic scattering; resulting molecular ions are assumed to be ionized, dissociated, or recombined immediately. Any product atoms are then tracked through the plasma and can undergo ionization and charge exchange(5)(7). The particle track terminates upon ionization of the atom. Along the particles' paths, the volumetric source of plasma ions is accumulated in each computational zone. The penetration fraction is then the ratio of the volume integrated sum of those source rates over zones inside the separatrix to the gas puff rate.

For these simulations plasma parameters from NSTX discharge 128339, a lower single null 1 MA discharge with 1 MW of neutral beam power was used. The computational mesh needed for DEGAS-2 has been generated by the UEDGE code(8)(9) for this discharge and was previously used in a different study(10). Plasma conditions at 300 ms are used; the plasma shape is similar to that shown in Fig. 1(a). At the midplane, the total mesh width is 5.5 cm. The outer edge of the mesh is 8.1 cm from the vessel wall, which is also the location for the mid-plane gas injection location. The separatrix is located 9.9 cm from the gas puff location. Outside the UEDGE mesh, between that mesh and the vessel wall, there is a coarser DEGAS-2 mesh. Here, DEGAS-2 subroutines break the background region into a series of small interlocking triangles. Within each of these triangular "zones", all parameters (source rates, densities, temperatures, etc.) are constant.

The background plasma is located between the UEDGE mesh and the vessel walls. In this region, a reference plasma density of 5×10^{18} m^{-3} and electron temperature of 25 eV was assumed. The background plasma density and temperature were each then increased to 2 times, 5 times and 25 times the reference values.

Figure 2 shows the deuterium ionization rate for the four cases. The vertical line marks the location of the separatrix. The rapidly decreasing ionization rate inside the separatrix for the cases with background plasma means that there is that much less neutral deuterium in this region for ionization.

Because the ionization fraction would depend both on the plasma parameters and the depth over which this condition exists, this study should crudely approximate the effect of increasing SOL density and temperature. The results show that the gas penetration fraction drops dramatically even for a factor of two increase in the plasma parameters. The gas penetration fraction is 33% for the case with no background plasma. It drops to 16% for the case with the reference plasma and to 7%, 3% and 1% respectively for the cases of increasing plasma density and temperature.

These results would suggest that more energetic plasma conditions in the SOL should make it more difficult for gas injected from the mid-plane to penetrate past the separatrix. However, if gas is injected directly into the private flux region, and does not need to cross the SOL, the penetration fraction should be higher so long as the private flux region plasma is much less energetic than plasma in the SOL. This should be the case as

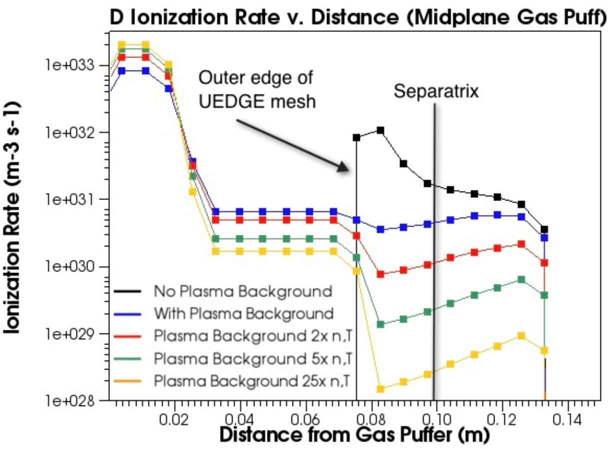

Fig. 2. Ionization rates for the case of mid-plane gas injection with increasing plasma density and temperature in the region between the outer UEDGE mesh and vessel walls; The ionization rates are for a molecular deuterium injection rate of 10^{30} molecules/s

the bulk of the exhaust power from tokamak plasmas flows through the SOL, eventually being deposited on divertor plates.

To put this in perspective, the private flux region in ITER is predicted to have an electron temperature of less than 2 eV and an electron density of below 2×10^{20} m^{-3} (11). Representative values for these two parameters for detached DIII-D plasmas are an electron temperature of less than 1 eV and electron density less than 5×10^{19} m^{-3} (12). The relatively low electron temperature in the private flux region in both ITER and DIII-D is due to active gas puffing in the divertor region to obtain a detached divertor configuration, which is necessary to reduce divertor heat loads. The electron temperature and electron density in the SOL at the mid-plane region of ITER is predicted to be about 100 eV and 2×10^{19} m^{-3} (13). The corresponding values for DIII-D are an electron temperature less than 20 eV and an electron density less than 3×10^{18} m^{-3} (14). The parameters for the NSTX-U could be expected to similar to those for DIII-D.

These simulations will be extended to include more energetic plasma conditions realistic of the anticipated 12 MW of neutral beam power that would exist in NSTX-U. The plasma parameters in the SOL will be modeled self-consistently, including the impact of energetic SOL flows. The injected gas density will be increased to reflect the real conditions that exist in a MGI pulse. MGI experiments thus far(15) have shown that the presence of high-Z impurities (argon, neon) in addition to helium or deuterium is essential to rapidly quench the plasma. The required fraction of these high-Z gases to be entrained in a bulk low-Z MGI carrier gas, while retaining the fast gas transit times made possible by the low-Z carrier gas, needs to be quantified to improve the MGI system design. Previous studies on NSTX have shown that 12 Pa.m^3 of helium is adequate to disrupt a NSTX discharge. Results from these simulations would provide quantitative estimates for the amount of carrier gas, noble gas fraction and required response time and proximity of the gas injector to the NSTX-U plasma. Eventually such information is also needed for the ITER plasma.

In summary, the planned experiments and simulations are expected to contribute to the understanding of important physics questions related to the MGI experiments in support of NSTX-U, ITER and future ST based machines. The primary study to be conducted would be to understand the gas penetration efficiency as a function of poloidal gas injection location and variations in plasma parameters, especially at the edge. The second objective would be assessing the resulting reduction in divertor heat loads and halo currents. Supporting DEGAS-2 studies would contribute to quantifying the MGI system requirements aimed at minimizing the gas throughput and maximizing the gas penetration through the separatrix.

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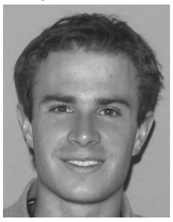

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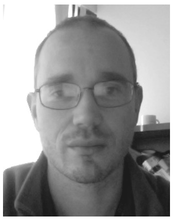

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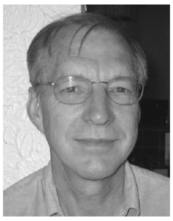
Dennis Mueller



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