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Modeling of Lithium Granule Injection in NSTX with M3D-C1

A. Fil, E. Kolemen, A. Bortolon[1], N. Ferraro[2], S. Jardin[2], P.B. Parks[1], R. Lunsford[2], R. Maingi[2]

Princeton University, NJ 08540, USA
[1]General Atomics, PO Box 85608, San Diego, CA 92186, USA
[2]Princeton Plasma Physics Laboratory, Princeton, NJ 08543, USA
email: afil@princeton.edu

Abstract

In this paper we present high level simulations of pedestal control by Lithium Granule Injection (LGI) in NSTX. A model for small granule ablation has been implemented in the M3D-C1 code [1], allowing the modeling of realistic Lithium granules injections. 2D simulations in NSTX L-mode and H-mode plasmas are done and the effect of granule size, injection angle and velocity on the ablation time are studied. For H-mode cases, the local pressure perturbation triggered by the granules is highly dependent on the solid granule size. A change of the granule velocity allows one to inject more particles at the pedestal top.

1 Introduction

Real-time pedestal control is a crucial topic for future fusion reactors and ITER where pedestal has to be kept large Edge-Localized-Modes (or ELMs) free for heat flux management purposes as well as stationary against many perturbations. All this while keeping high plasma performance. Many different control schemes have been developed and tested to adjust and regulate the pedestal at DIII-D and other devices. NSTX-U is now operational and it is planned to test them on it. All these techniques aim at changing the pedestal parameters to impact ELMs characteristics. In particular, gas puffing [2] injects impurities at the plasma edge to control the plasma pedestal density, 3D magnetic perturbations [3] creates an edge stochastic layer increasing the transport (which lowers the pedestal pressure gradient), Lithium Granule Injections (LGI) [4] induce pressure perturbations triggering ELMs and can thus change the ELM frequency and their impact on the Plasma Facing Components (PFCs). The final aim of this work would be to combine all these methods in an adaptive and automatic pedestal control algorithm for tokamaks. Such a capability could allow one to explore new innovative scenarios such as the Super H-Mode [5] or Lithium induced ELM-free regimes. In order to reach this goal, it is important to understand the physics bases for how the different control actuators affect the pedestal. It has been observed many times that a control scheme that work for a specific machine or a regime might not be applicable to all of them. This is especially the case for future reactors such as ITER.

In this paper, we focus on the LGI technique and we present high-level numerical simulations with the M3D-C1 code. M3D-C1 [1] is a state-of-the-art 3D full-MHD code with realistic geometry and is being developed to study the plasma response when several actuators are triggered (gas puffing, 3D magnetic perturbations and LGI). Experimentally, plasmas with Lithium granule injections have already been done on DIII-D [6] and a LGI system has recently been installed on NSTX-U. As it is using Lithium and not Deuterium pellets, LGI is essential if one want to decouple ELM control and plasma fueling. DIII-D experiments have demonstrated a robust ELM-pacing and an triggering efficiency higher than 80% for 0.9 mm Lithium granules but some concern exists because of the variability of triggered-ELM sizes. Indeed, for "Hybrid" ELMy H-mode scenarios the increase of ELM frequency induced a reduction of ELM amplitudes but for low-torque ITER baseline scenarios, an increase of the ELM frequency by LGI-pacing did not directly translate in ELM size mitigation. The modeling of these discharges and future NSTX-U discharges will shed some lights on the causes of the different behaviour between these scenarios.

In this paper, we first present the implementation of granule ablation models in M3D-C1. We will then present the results of 2D NSTX LGI simulations which investigate the pressure perturbation triggered by different granule sizes, injection angle and velocity.

2 Modeling of Lithium granule injection in M3D-C1

For this study, two models have been implemented in the code M3D-C1 to calculate the ablation rate of the Lithium granule. The first one [7] [8] is a Neutral Gas Shielding Model calibrated on DIII-D experimental measurements of the Lithium granule ablation rates. The second one [9] is valid for small size granules (sub-mm) where the contribution of plasma ions to the granule ablation is not negligible. In both cases, the granule is modeled as a varying density source which is a Gaussian multiplied by the normalized ablation rate A_r. The width of the source is defined by the realistic granule radius r_p multiplied by a arbitrary parameter. This parameter allows to change the size of the ablation cloud experimentally observed around the granule. Note that this is the only "free" parameter of the granule model and that experimentally its value is imprecise (between 5-100 times the solid granule radius). Its impact on the simulations will be discussed in section 3.

The granule ablation rate is calculated at each time-step as $A_r = C(n_e, T_e, r_p) \times X_m$, where r_p is the granule radius and (n_e,T_e) are the electron density and temperature of the background plasma at the granule position. $C(n_e, T_e, r_p)$, the non-dimensional ablation coefficient, depends on the species parameter and is determined by solving the gas dynamic equations for the ablation flow for each set of (r_p, n_e, T_e). A function fitting these results is used in M3D-C1. X_m is the usual law used for strongly shielded cryogenic pellets. The granule radius r_p and thus the source width is decreasing as the granule is ablated by the plasma, as $\frac{\delta r_p}{\delta t} = -C(n_e, T_e, r_p) \times X_p$. More details on the model can be found in [8][9].

3 Results

The simulations start from experimental NSTX equilibrium, electron density and temperature profiles. Two target plasmas are used, a L-mode and a H-mode plasma (plasma discharge 129015). The H-mode case ($B_T = 0.44T$, $I_p = 0.785MA$, $a = 0.627m$) simulation is initiated 0.4s after the start of the discharge, in an inter-ELM zone. The top of the pressure pedestal is at $R = 1.46m$ (see Figure 2). In these plasmas, we inject Lithium granules with different radius, initial velocity, source width and injection angle, as summarized in table 1:

r_p (in mm)	Inj. velocity (in m/s)	Source width (in cm)	Inj. angle (in degrees)
0.2-1	50-200	1-5	-70 to +70

H-mode high gradient pedestal makes simulation harder and typically requires high resolution meshes around the pedestal region. We thus started by simulating NSTX L-modes before moving to H-mode cases. Overall, it takes between 0.2 and 3 milliseconds for the pellet to being totally ablated, which is in the ballpark of experimental values observed in DIII-D, for example. The penetration depth and the ablation time is strongly dependent on the background plasma and can be up to one order of magnitude shorter in H-mode than in L-mode, mostly because of the higher density and temperature that the granule faces. As the final aim is to pace ELMs, let us focus on the H-mode simulations.
In these simulations, the granule starts propagating inward at $R = 1.5m$ with a constant velocity. When entering into the plasma, the granules trigger a large and localized density increase as can be seen in Figure 1. On a short timescale, electron conduction along the field lines reheats this high density region and leads to a localized plasma pressure increase. An example of pressure increase due to the injection of a $0.8mm$ granule is shown in Figure 2.

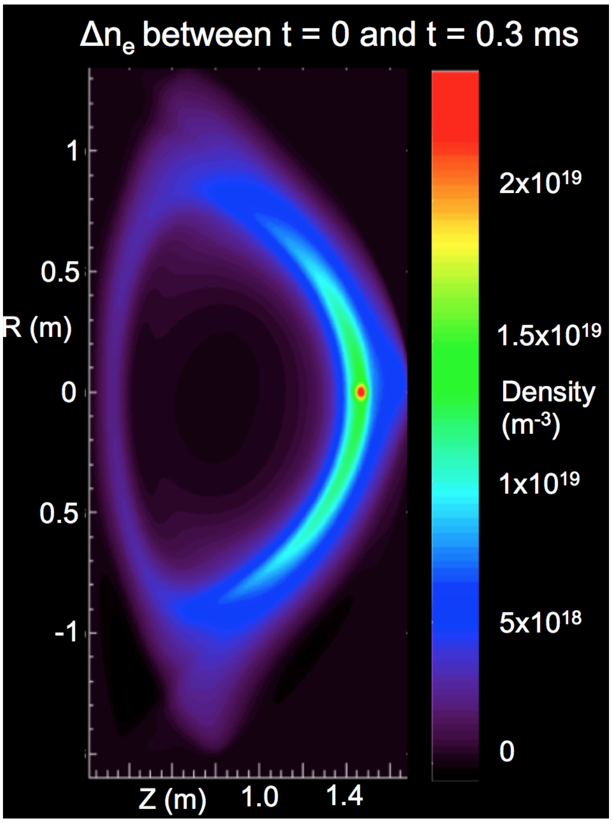

Figure 1: Poloidal cross section of the density increase due to the injection of a $0.8mm$ granule in a NSTX H-mode plasma. Difference of the density between the start of the injection and $t = 300\mu s$ after the injection.

Figure 4 shows the number of ablated atoms injected in the simulations following the granule position. The larger the granule is the larger is the penetration depth and the number of particles injected. Figure 4 also shows that if the number of particles injected at the pedestal top is

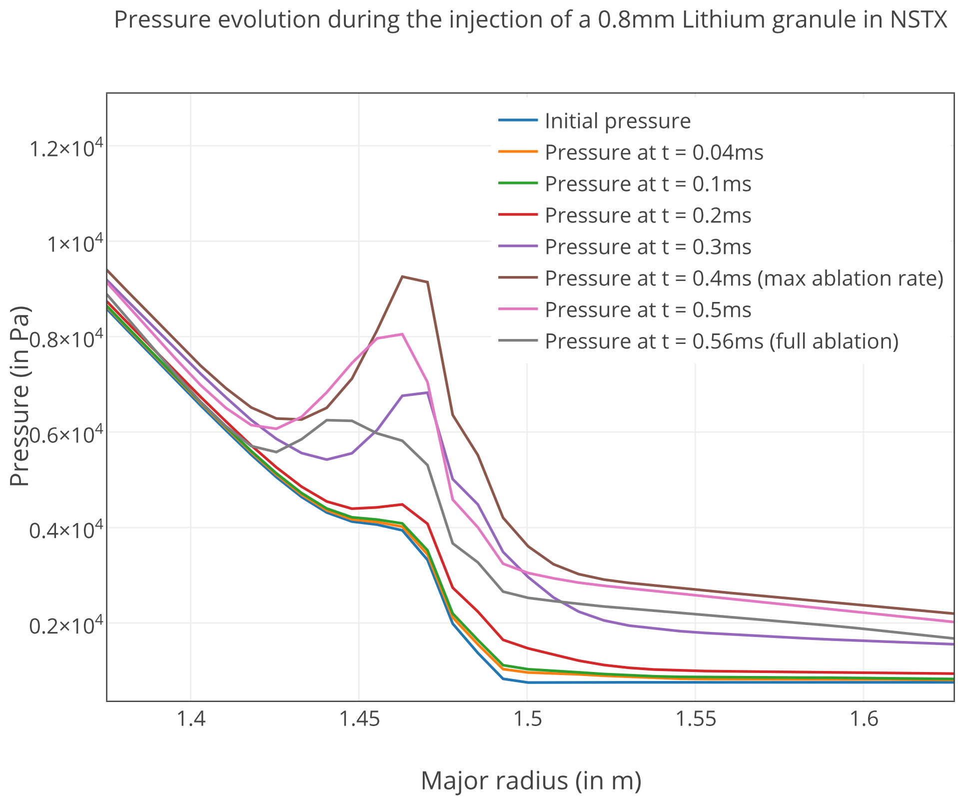

Figure 2: Successive pressure profiles at the poloidal plan where the granule is injected. A large increase of the pedestal pressure is observed.

higher for large granules, so is the fueling of the plasma inside the separatrix. A compromise has to be found between the efficiency of ELM-pacing and the reduction of confinement due to lower edge temperatures.

The initial velocity at which the granule is injected also changes the penetration depth and the particles deposition as can be seen on Figure 5. For this case, granules at 50 and 100 m/s inject the same number of particles at the pedestal top but the 50m/s one leads to a smaller fueling. Note here that the current model does not include grad B effects which may brake the granule. These effects will be included and tested in future work.
The angle of injection can also decrease the penetration depth as can be seen on Figure 6. This figure present the injection of a 1mm granule in NSTX H-mode with varying angles of injection. No significant differences have been observed between upward and downward injections.
In all these simulations, the local density is increased by the granule injection and leads to an increase of the local pressure. Figure 2 shows the pressure evolution after a granule injection (0.8 mm at 100 m/s and 5 cm ablation cloud) in a NSTX H-mode plasma. Figure **??** shows that the pressure perturbation at maximum ablation is higher for larger granules. These simulations are only 2D and thus MHD modes such as ELMs are not destabilized. However, we can already affirm that the local pressure threshold for ELM triggering will be reached faster with large granules with high injection velocities. 3D simulations are on-going to specify this

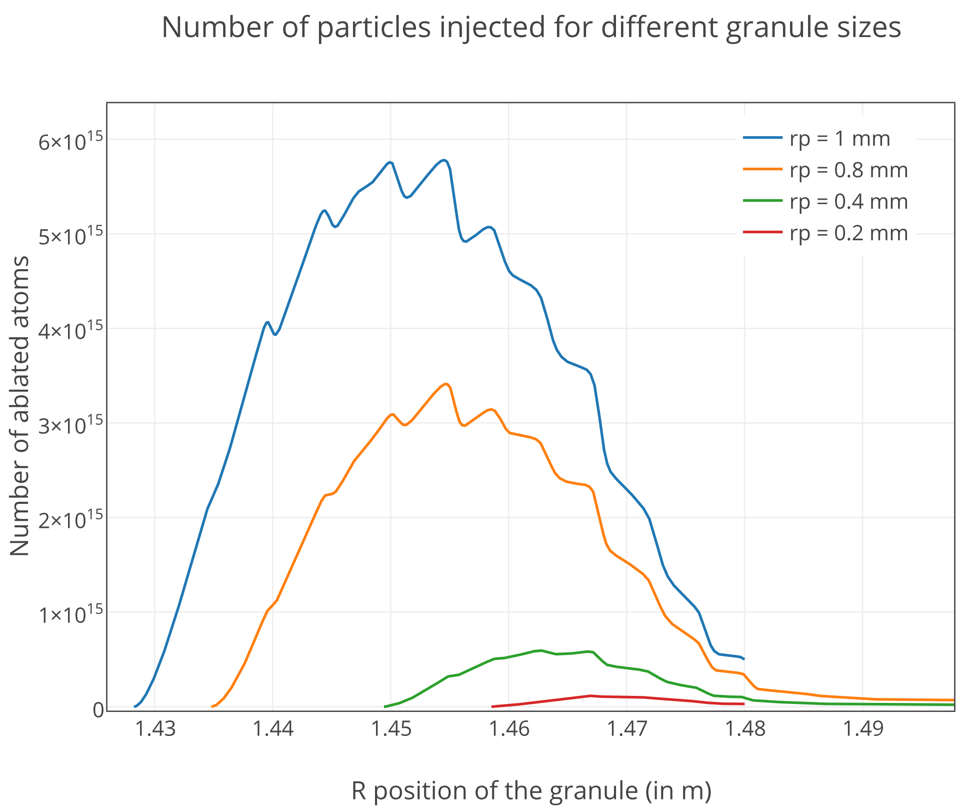

Figure 3: Number of ablated atoms injected when the granule is penetrating into the plasma. The top of the pressure pedestal is at $R = 1.46m$ for this NSTX discharge.

threshold and the impact of granule parameters on ELMs properties. Note that a higher injection velocity will also increase the penetration depth of the granule and decrease the plasma temperature inside the separatrix. As it has an impact on confinement, a compromise will have to be found between the efficiency of ELM-pacing and the edge temperature decrease.

Finally, the impact of the size of the ablation cloud has been tested. Three simulations have been done, injecting granule of same sizes (i.e. same number of particles and ablation rate) but with a wider source, i.e. larger ablation cloud. The lower value (1 cm) is constrained by numerical limitations of the current grid. In our simulations, the density increase is larger for small width sources but within the range tested (1-5cm) it has a small impact on the induced pressure perturbation.

4 Discussion and perspectives

These simulations show that the local pressure perturbation at the pedestal induced by LGI increases with granule size and decreases with velocity. To avoid a too large decrease of the temperature inside the separatrix, one can inject granules with an injection angle or by decreasing the injection velocity.

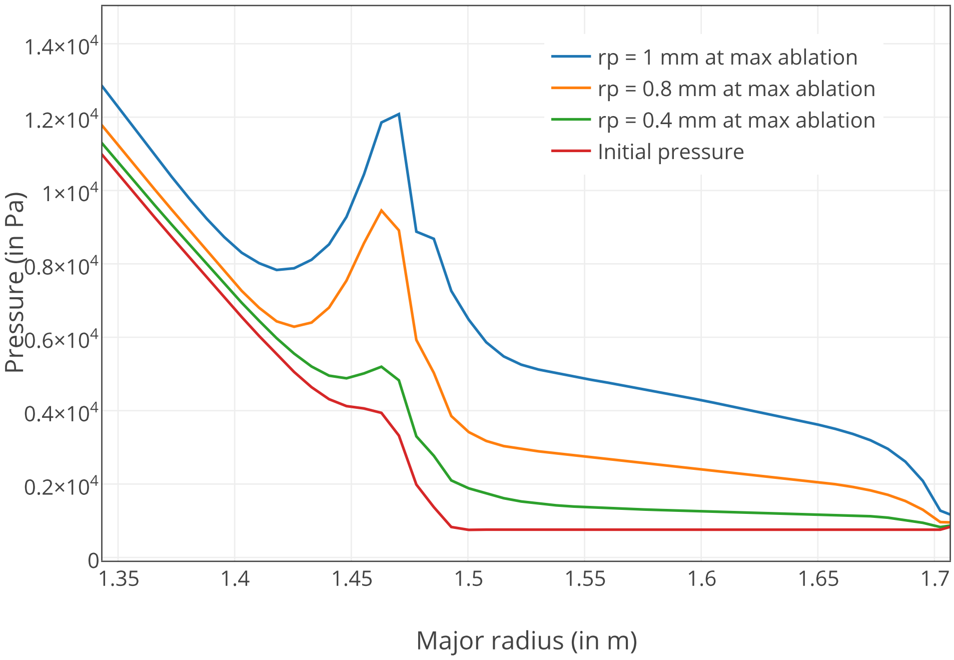

Figure 4: Pressure profile at maximum ablation for different granule sizes.

A LGI system has just been installed on NSTX-U and synthetic diagnostics (interferometry, etc) are currently being implemented in M3D-C1. We will soon be able to compare the edge density increase to experiment and to specify the value we should use in order to do more quantitative simulations. On-going 3D simulations aim at finding the better compromise between fast ELM-pacing and high confinement. Mesh adaptation, mesh packing techniques and high-order 3D finite elements are used to allow simulation of sub-mm granules (as it is already the case in 2D), without constraints on the granule toroidal width. Grad B effects on the granule velocity are also being implemented and their effects will be investigated.

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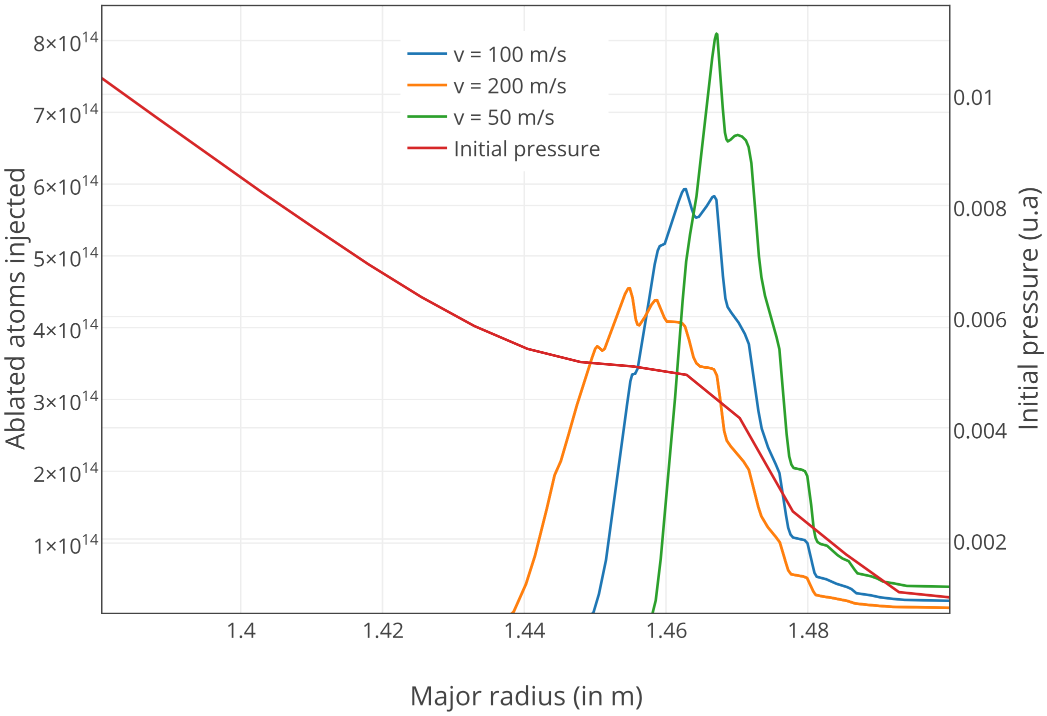

Figure 5: Number of ablated atoms injected when the granule is penetrating into the plasma. Injection of a $0.4mm$ granule with different velocities. The top of the pressure pedestal is at $R = 1.46m$ for this NSTX discharge.

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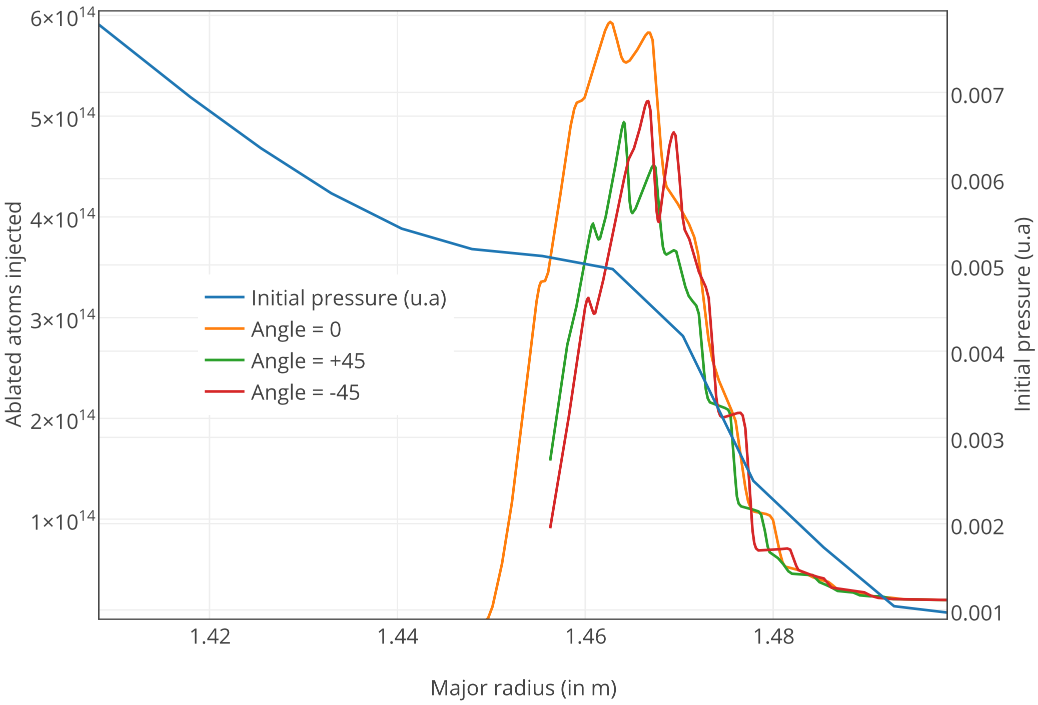

Figure 6: Number of ablated atoms injected when the granule is penetrating into the plasma. Injection of a $0.4mm$ granule with different injection angles (Midplane injection corresponds to 0 degrees). The top of the pressure pedestal is at $R = 1.46m$ for this NSTX discharge.