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Final CRADA Report – NFE-21-108605 Time-Dependent Boundary Modeling to Inform Design of SPARC Diagnostic and Actuators

J.D. Lore (ORNL)
J-S. Park (ORNL)
S. De Pascuale (ORNL)
B. Lomanowski (ORNL)
A. Creely (CFS)
A. Kuang (CFS)
M.L. Reinke (CFS)

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Fusion Energy Division

TIME-DEPENDENT BOUNDARY MODELING TO INFORM DESIGN OF SPARC DIAGNOSTIC AND ACTUATORS

J.D. Lore, J-S. Park, S. De Pascuale, B. Lomanowski (ORNL), A. Creely, A. Kuang, M.L. Reinke (CFS)

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OAK RIDGE NATIONAL LABORATORY
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ABSTRACT

The purpose of this work was to inform the design of diagnostic and actuator systems for a new experimental facility for Commonwealth Fusion Systems (CFS), called SPARC [Creely2020], using time-dependent plasma boundary simulations with the Scrape Off Layer Plasma Simulator (SOLPS) code [Wiesen2015].

The SPARC tokamak is a device that aims to demonstrate fusion energy production and high-field plasma operating scenarios. The developed technologies will be incorporated into a net-electricity pilot that will demonstrate approximately 200MW of electric power. A major difference from other private industry fusion companies is the use of a standard aspect ratio, but at a high magnetic field strength, which provides a well-established physics basis and a modest extrapolation to reactor operation.

Time-dependent simulations were used to inform the design of main-chamber plasma facing components, which are protected by feedback control of the heat and particle loads during high power operation. The simulations provide the timescales and magnitudes of plasma and neutral particle response useful for determining the position and operation of diagnostics and actuators that will enable control. The plasma response and phase-space diagrams also provide input into advanced model-based control schemes, which are envisioned for later SPARC operation. Model-based control can reduce the risk of component failure, which would require expensive in-situ repairs and the associated delays, by predicting the system response to actuators over a short time-horizon.

1. STATEMENT OF OBJECTIVES

The objective of the work was to simulate the time-dependent plasma boundary behavior expected in SPARC to inform the design of diagnostics, actuators and plasma facing components. The schedule of the work was to enable the SPARC design team to incorporate this input, and scope feedback control systems to reduce the damage to the PFCs during high power operations.

To achieve this, the boundary plasma transport code SOLPS is used. The code takes as input information about the SPARC configuration, including the CAD design, magnetic equilibrium, and predictions from core transport models. Time-dependent simulations are required to assess the effect of and requirements for 1) dynamic control of neutral pressure through louvers, 2) the gas puff rates for establishing dissipative divertor conditions, 3) dynamic reattachment, and 4) boundary plasma diagnostics used for control.

A major portion of the work is in the development of full time-dependent simulations using SOLPS. This means that the plasma is evolved using the B2.5 code while considering the dynamics of the neutral particle distribution with the kinetic Monte-Carlo code EIRENE [Reiter2005]. The time-dependent workflow was to be employed in at least three SPARC plasma scenarios, which may incorporate different plasma equilibria (shape), power levels, line averaged density (main ion and electron density profile), or transport model (heat flux width). The simulations are used to generate data from synthetic diagnostics relevant for control such as neutral gas manometers, impurity spectroscopy, and heat flux measurements. The high-level objectives were to explore the plasma and diagnostic response to actuators, assessing 1) The benefit of and response time requirements for dynamic control of divertor neutral pressure through use of louvres and adjustable throughput inner and outer divertor pump-arounds, 2) the maximum impurity and fueling puff rates needed to establish dissipative divertors early in the pulse, relative to the lower, steady- state puffing rates needed to maintain divertor conditions, 3) dynamic re-attachment from loss of divertor fueling and response of PFC temperature rise, 4) the dynamic response of the divertor plasma relative to the time-dependent response and signal to noise ratio for planned boundary plasma diagnostics, including low-fidelity, D-T compatible sensing approaches.

2. BENEFITS TO THE FUNDING DOE OFFICE'S MISSION

The time-dependent boundary plasma simulation capability and demonstrated application for tokamak and diagnostic design developed by this work can be applied to the design of DOE sponsored experiments, such as a fusion pilot plant, aligned with the Office of Fusion Energy Sciences (FES) program goal to "build the knowledge needed to develop a fusion energy source."

3. TECHNICAL DISCUSSION OF WORK PERFORMED BY ALL PARTIES

The Fusion Energy Division at Oak Ridge National Laboratory previously performed steady-state SOLPS of SPARC through a Strategic Partnership Project (SPP) to inform early design and scoping studies of the SPARC divertor. [Lore2020, Kuang2020]. The initial work in this project was to develop and demonstrate time-dependent SOLPS simulations of SPARC with both the plasma (B2.5) and neutral transport (EIRENE) modules of the code run in a dynamic mode. Demonstration of dynamic plasma response relevant to boundary control, with EIRENE still run in a time-independent manner, was demonstrated in parallel via an internally funded Laboratory Directed Research and Development project [Lore2023, DePascuale2023, Kaptanoglu2023, Park2023].

For full time-dependent response, the Monte-Carlo kinetic neutral transport code EIRENE must be run in a dynamic mode. To test this capability, a problem with a fixed plasma solution was studied to examine the neutral gas response to an actuator. The SPARC design team was interested in a louvre actuator which can open and close to restrict gas transport through a duct system connecting the plasma volume to the pump (see Fig. 1). This actuator could be used to control the neutral pressure near the outer strike point, where the highest fluxes may occur. The neutral gas pressure has been shown to be a strong driver of the level of detachment, which expresses the reduction in divertor fluxes from an unmitigated level.

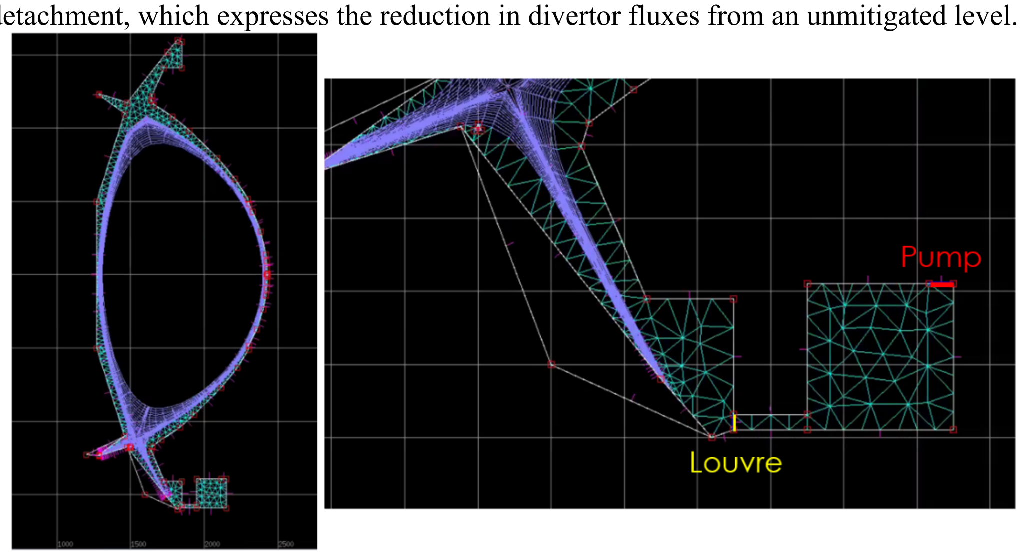

Figure 1. SOLPS grid for the SPARC v2e geometry, with a simplified series of volumes for the pumping duct and the Louvre actuator.

Neutral particles in the simulation are initiated from volume or surface recombination processes or sourced directly from gas puff actuators. In a quasi-steady-state simulation, the particles are followed until their end of life (e.g., absorption, ionization), or until a maximum particle lifetime is reached. The maximum lifetime prevents extremely long trajectories if the neutral particle is trapped in a vacuum region without absorbing surfaces where ionization does not occur. In a dynamic simulation the particles are stopped after a defined time and stored in a census array to be relaunched on the next iteration. The problem is that, depending on the timestep and the plasma conditions determining the particle lifetime, the census array may grow to a very large size making successive calls prohibitively computationally expensive. The timestep must therefore be selected such that the number of particles in the census array can saturate without overflow. Table 1 lists a number of timestep values and the corresponding saturated number of census particles for a characteristic SPARC simulation. It can be seen that timesteps below 1e-5 seconds are not practical. In order to explore these parameters, several bugs in this infrequently used part of the code base were fixed with fixes submitted back to the main repository.

Eirene simulation time (s)	**Saturated number of census particles**
1e-3	3e3
1e-4	2e4
1e-5	2e5
1e-6	>1e6 (not practical)

Table 1: Scan of EIRENE simulation time and resulting saturation level for the census array, indicating settings where the simulation becomes impractical.

While computational demands set the lower bound for the EIRENE timestep, the value should be kept small to resolve fast dynamics and reduce numerical error in the simulation. Figure 2 shows simulation results where the louvre was changed from an open (transparent) to a partially closed (semi-transparent) state at t = 0. The 2D images on the left show the molecular density, where the density in the pumping region (behind the louvre) has dropped due to the reduced conductance in the duct. The right panels show time traces of the average neutral density in the pump volume for four EIRENE timesteps, 1e-3, 1e-4, 1e-5 and 1e-6 seconds from top to bottom. The largest timestep does not sufficiently resolve the characteristic timescale, while the smallest timestep simulation is stopped due to the census array becoming full.

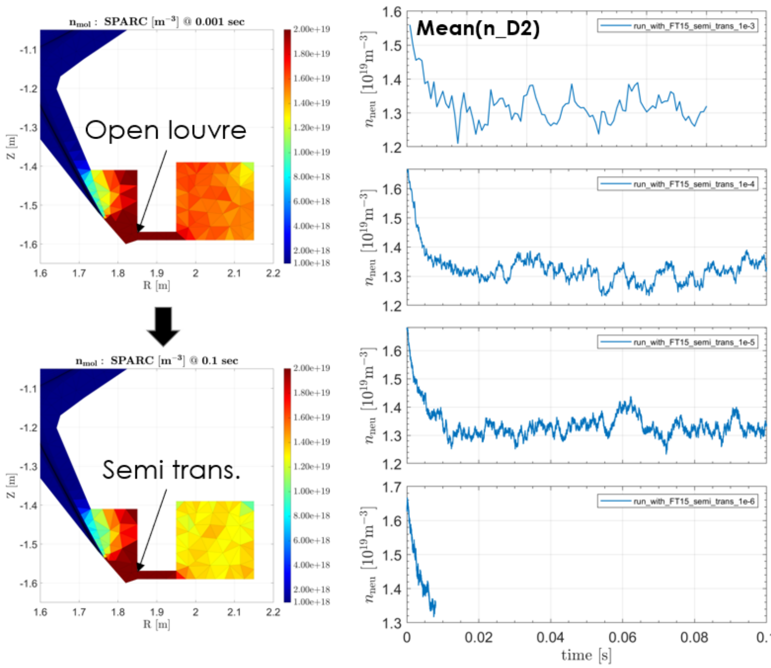

Figure 2 Left: Density distribution of fully relaxed molecules under open louvre and semi-transparent conditions. Right: Time evolution of molecule density transitioning from a fully relaxed open condition to semi-transparent at t=0. EIRENE time steps of 1e-3, 1e-4, 1e-5, and 1e-6 are displayed from top to bottom.

The EIRENE simulation was compared to a semi-analytic model for pressure evolution [Lore2019], as shown in Figure 3 for a case where the duct length was increased by a factor of 4 to result in a timescale that could be better resolved by the simulation. The characteristic timescale was shown to be approximately consistent with the semi-analytic calculation.

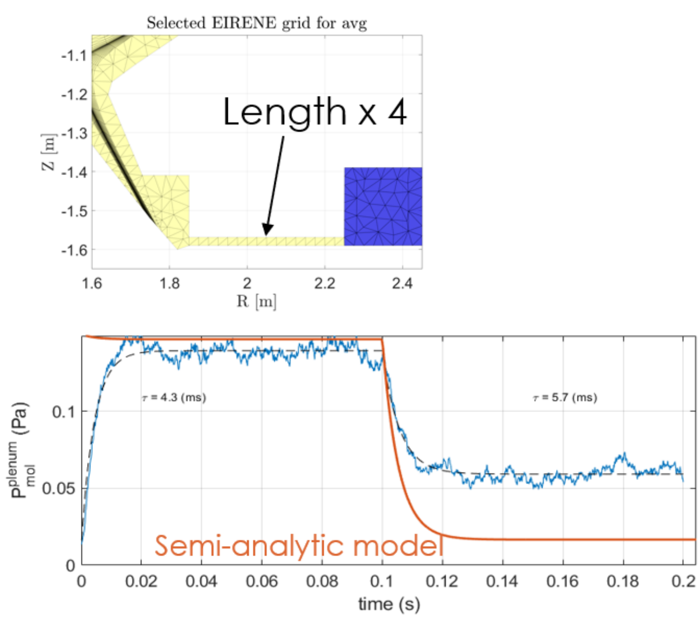

Figure 3 Comparison of the time evolution of neutral pressure between the time-dependent EIRENE and the semi-analytic model using modified pump conductance (with adjusted model geometry).

An important result was obtained by comparing the effect of a louver actuator with that of a gas puff. Both result in an increase in the neutral pressure near the strike point, however the louvre has an increased engineering complexity as compared to a gas valve, which must be present already for fueling and impurity seeding. Figure 4 shows two dimensional distributions of the neutral pressure before (left) and after closing the louvre (top right) and increasing the gas puff (bottom right). Qualitatively the effect in the plasma volume (not in the pump volume) are similar. These simulations were performed for the fully coupled time-dependent simulation, with both B2.5 and EIRENE run dynamically.

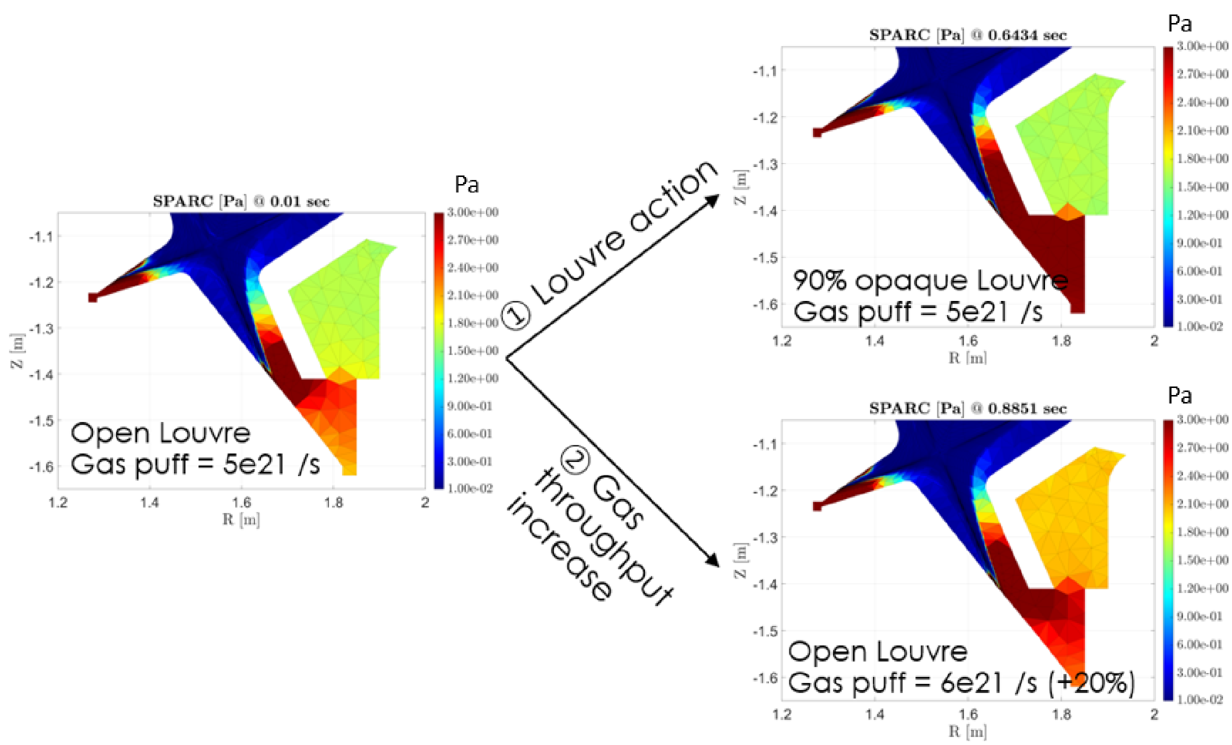

Figure 4 Left: Initial neutral pressure distribution under open Louvre condition with a gas throughput of 5e21/s. Right: Neutral pressure distributions resulting from two different actuators: a 90% opaque Louvre (top) and a 20% increased gas puff with an open Louvre (bottom)."

The same result is quantitatively shown in Fig. 5, where the response of the neutral pressure at the outer strike point, the upstream plasma density, and the downstream electron temperatures are shown. At t = 0 either the gas puff was increased (GP, solid lines), or the louver opacity was increased (opacity, dashed lines). It can be seen that a similar response can be obtained via either actuator.

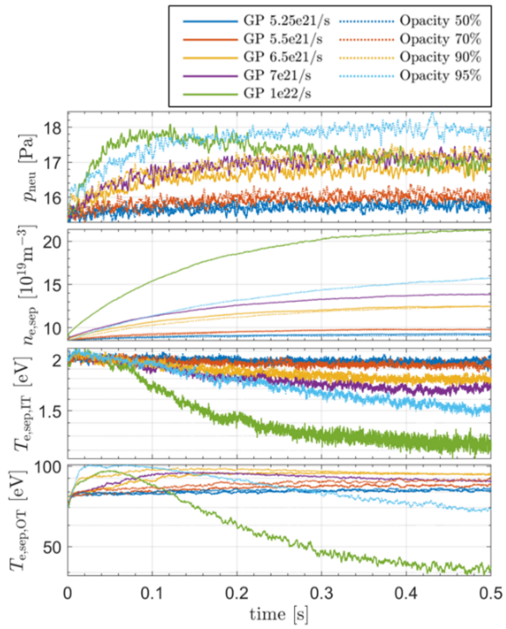

Figure 5 Time evolution of neutral pressure at the outer strike point, electron density at the outer midplane separatrix, and electron temperature at both inner and outer targets. A similar response in the neutral pressure and plasma quantities can be obtained by either louvre action or increased gas puff, demonstrating the equivalence in effects.

Finally, the time-dependent simulations were used to show the dynamic response of the plasma to main ion fueling and extrinsic impurity seeding gas puff actuation. For this study the louvre was not included. This response information is useful both to scope gas valve requirements, but also to develop control strategies. As an example of such simulations, for the gas injection location candidates shown in Figure 6 — inner SOL (ISOL), outer SOL (OSOL) — and outer midplane (OMP), a linear ramp up/down scan of the fueling gas input was performed to obtain the respective plasma responses, as shown in the top left of Figure 7. The corresponding effect on the upstream electron density and the electron temperature at the inner and outer strike points are shown in the left panels. While some of the behavior is expected, for example, the upstream density increased and the temperature at the inner target is reduced at high gas input, the overall response is complex. The right panels show the phase space of upstream density and target temperature for both divertors. It can be seen that strong hysteresis is present, and that for these conditions simultaneous cooling of both divertors is not possible. While the ISOL and OMP cases exhibit similar responses, fueling at OSOL demonstrates less sensitivity to the fueling rate and displays opposite divertor asymmetries. Further study is needed to understand these asymmetries and the non-linear responses or hysteresis in the phase space. Similar response studies have been performed for impurity seeding actuators, yielding a rich phase space. Further study is required to develop control strategies and model-based control systems. Similarly, while the output time traces shown in Fig. 7 are trivial synthetic diagnostics, the full 2D plasma output can be obtained for any dynamic simulation and used to post-process synthetic diagnostic signals for bolometers, interferometers, or other relevant systems.

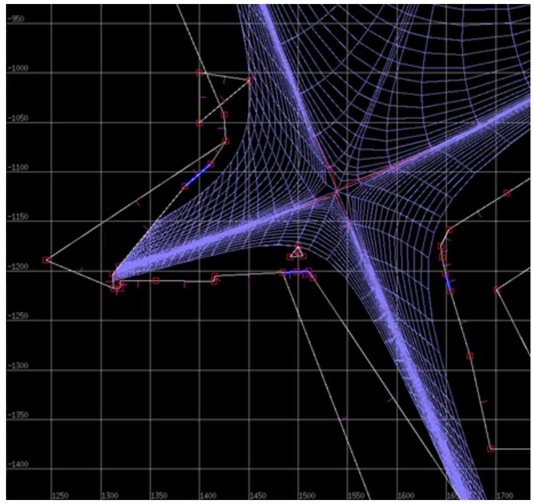

Figure 6 Gas injection locations marked in blue, from left to right: ISOL, PFR, and OSOL

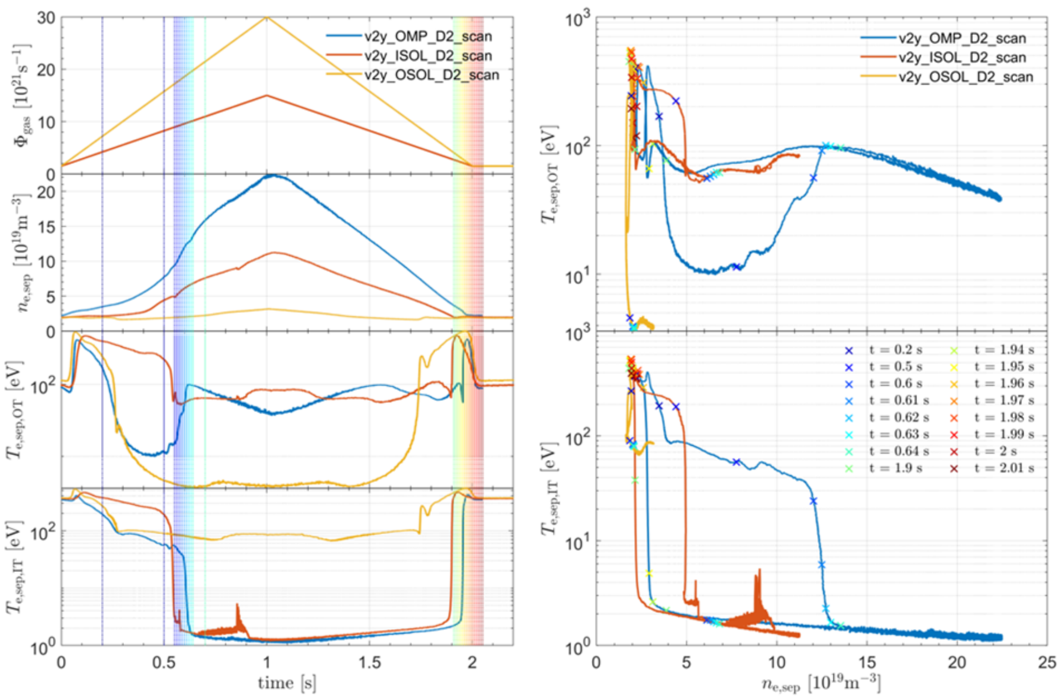

Figure 7. Time evolution of the gas puff actuator and response of the upstream density, and electron temperatures at the outer and inner targets (left panels) for the three different gas injection locations (OMP, ISOL, OSOL). The location of ISOL and OSOL are shown in Figure 6. The right panels show the same data in a phase space representation.

4. PLANS FOR FUTURE COLLABORATION

Oak Ridge National Laboratory and CFS continue to collaborate in the area of boundary plasma simulation and heat flux control through a Department of Energy funded grant “Divertor heat flux control design for high heat flux tokamaks”.

5. CONCLUSIONS

This project successfully developed and demonstrated the capability to perform full time-dependent plasma and neutral transport simulations using SOLPS to inform the SPARC tokamak design. Development of the code source was required with the results committed back to the main repository, and procedures for obtaining physical results were communicated in SOLPS user meetings, in conferences, and in papers to benefit the broader fusion simulation community. The time-dependent simulations were used to evaluate a louver actuator for the vacuum pumping system of SPARC. It was found that the plasma and neutral response at the strike point was similar to that which can be achieved by a gas puff actuator, which is much easier to implement and must already be present in the SPARC design. Dynamic actuation of main and impurity ion gas puffs were used to determine the response of relevant state variables for control, the upstream electron density and the electron temperature at the inner and outer strike points. The system is highly nonlinear, with hysteresis and will likely be very challenging to control. Further study is required to develop reduced models that can be used in a real-time model predictive control strategy.

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