HIGH-FIDELITY WARPX SIMULATIONS OF LONG-LIVED ADVANCED FRCS

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1. INTRODUCTION

TAE Technologies, Inc. is a privately funded corporation focused on the development of nuclear fusion technology using steady state, magnetically confined plasmas in the field-reversed configuration (FRC), which the Office of Fusion Energy Science identified as a leading candidate for advanced fusion energy. This alternate magnetic confinement system has been developed at TAE Technologies, Inc. in the C-2 [1], [2], C-2U [3], [4], and C-2W [5], [6] series of devices. One of the remarkable achievements of these experiments has been the demonstration of long-lived FRCs [5] - the configuration achieves a steady state in the experiment with its lifetime limited only by the facility's power supplies. We refer to these long-lived FRCs as "Advanced FRCs", which we define as an FRC maintained by neutral beam injection (NBI), core fueling and electrode biasing, with scrape-off-layer pumping and electron heat confinement provided by expander divertors. From the definition of the Advanced FRC, it is clear that the simulation of this configuration requires numerical tools that can account for the particle and energy source terms used to maintain the experimental plasma. In this paper we present recent developments in simulation infrastructure that enable studies of equilibrium, stability, and transport of this configuration. We also demonstrate validity of the approach by comparing simulation results to experimental data from the C-2W experiment.

2. MOTIVATION

As described above, two critical actuators that allow long-lived FRCs in C-2W include the NBI and electrode biasing. NBI provides a substantial population of energetic ions, with Larmor orbits comparable in size to the FRC, and many are betatron orbits rather than drift orbits. It has long been theorized that such energetic ions would stabilize FRCs against tilt [7]. In C-2W, termination of the NBI causes swift plasma disruption, as shown on the left of Fig. 1, where plasma density is seen to decay rapidly once the NBI power is reduced, clearly indicating the importance of NBI in maintaining FRC stability. Similarly, experimental campaigns in C-2W have found that effective biasing of the electrodes in the expander divertors is imperative to achieve long-lived shots. A supporting example is shown on the right of Fig. 1, where experimental data from a so-called "bias termination" shot is presented. In this shot, the electrode biasing was reduced from ~2 kV to 0 V after a quiescent plasma state was reached. After bias termination, an increase in MHD mode activity is observed from magnetic probe signals. A gradual decrease in the plasma radius after bias termination indicates an enhanced plasma loss rate which adversely affects the plasma pressure and confined thermal energy.

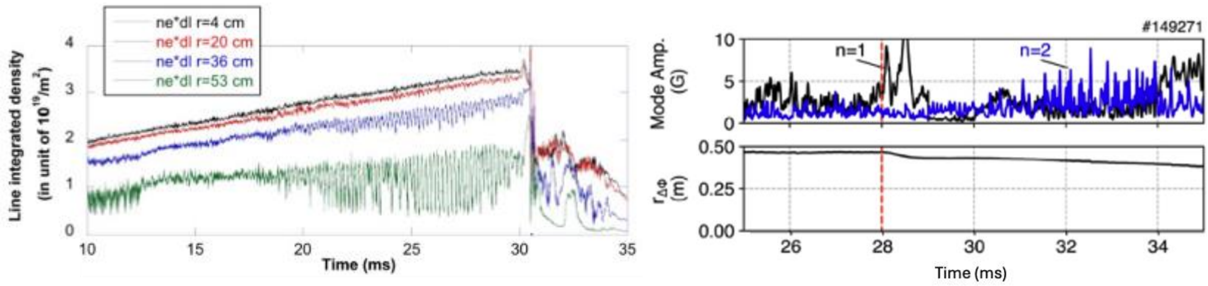

Figure 1: *(Left) Multi-chord line-integrated plasma density across the plasma radius from 4 cm to 53 cm showing increased plasma density over time. 11 MW of NBI power is delivered to FRC up to 30 ms. At 30 ms, NBI power is reduced to 5 MW to verify its role in FRC stabilization and sustainment. The data comes from the C-2W plasma shot #134771. (Right) Time evolution of n = 1 and n = 2 mode amplitudes and excluded-flux radius. Edge biasing is terminated at ~28 ms (red dashed lines). Figure reproduced from Ref. [6]; data comes from C-2W plasma shot #149271.*

3. NEW DEVELOPMENTS AND RESULTS

To capture these critical experimental actuators in simulation, several models have recently been added to the open-source Particle-In-Cell (PIC) code, WarpX [8]. Specifically, an Ohm's law solver (hybrid-PIC) was added to allow global stability simulations to be performed at relatively low computational cost [9]. A Direct-Simulation Monte Carlo (DSMC) module was added [10] to model the NBI source term via binary charge exchange collisions between thermal ions and energetic neutrals injected to match the experimental NBI setup. It has been found that electrode biasing can be captured by application of an appropriate boundary condition on the electric-field within the evolution of hybrid-PIC simulations. This results in the realistic propagation of torsional Alfvén waves that establish radial electric fields in the plasma, which result in bulk plasma rotational shear and corresponding stabilization of rotational modes. Beyond this, a new semi-implicit electrostatic solver [11] was also added to WarpX to study the effect of electrode biasing on the electron population (electrons are treated kinetically in the ES-PIC case, as opposed to as a neutralizing fluid in the hybrid-PIC approach). The culmination of these new models is that we demonstrate (for the first time) stable, long-lived FRC evolution in a 3d simulation, as shown in Fig. 2.

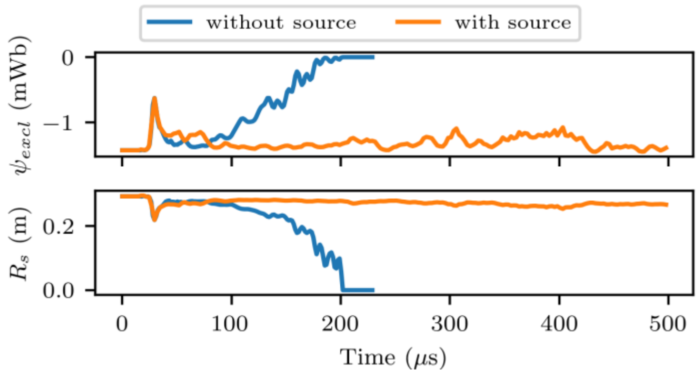

Figure 2: *Demonstration of how including particle and energy source term models in simulation of the Advanced FRC leads to a long-lived FRC. Time traces of the excluded flux* **(***top) and separatrix radius (bottom) are shown for an equilibrium evolved with and without source terms.*

The hybrid-PIC method has previously been shown to reproduce MHD activity in traditional FRCs. The current paper extends those results by demonstrating the validity of the integrated model (hybrid-PIC with particle and energy source terms) to simulate the Advanced FRC, through comparisons to C-2W results. Specific attention is given to dynamics that are not present in traditional FRCs but arise in the Advanced FRC precisely due to the critical source terms described above. Such effects discussed in the paper include an n = 0 axial bounce mode due to the bunching of energetic ions, an n = -2 microburst mode [12] driven by the energetic ion population with associated ion acceleration, and plasma rotation control due to *ExB* drift from a radial electric field created through electrode biasing.

This new integrated modeling capability is now being used to optimize actuator design parameters for TAE's next step Advanced FRC device, Copernicus. Numerical experiments are being performed to find ideal operating conditions that maximize particle and energy confinement times.

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