BREAKTHROUGH IN FIELD-REVERSED CONFIGURATION FORMATION AND SUSTAINMENT VIA NEUTRAL-BEAM INJECTION IN C-2W

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TAE Technologies (TAE) is pursuing an alternative approach to magnetically confined fusion, which relies on field-reversed configuration (FRC) plasmas composed of energetic and well-confined particles by means of a state-of-the-art tunable-energy neutral-beam (NB) injector system. The NB's energy range is 15–40 keV, which can be tuned and controlled during a shot in feedforward or feedback control mode. TAE's current experimental device, C-2W (a.k.a. "Norman") shown in Fig. 1, is the world's largest compact-toroid (CT) device and has made significant progress in understanding FRC physics and in overall FRC performance since 2017 [1-3]. C-2W produces record-breaking, stable, high-temperature advanced beam-driven FRC plasmas, dominated by injected fast particles and sustained in steady state for up to 40 ms, which is primarily limited by NB pulse duration. Over the course of C-2W experimental campaigns since its debut, we have spent a large amount of time characterizing and optimizing FRC plasma performance through various machine configurations and upgrades. As previously reported in Refs. [1,2], the conventional FRC formation technique, so-called field-reversed theta-pinch (FRTP) formation method, had been one of the important elements in C-2W to produce a decent initial FRC plasma condition via collisional-merging CTs in the confinement vessel (CV). Together with sufficient plasma stabilizations by edge biasing, NB injection (NBI), and plasma control systems, we have obtained reliable FRC plasma formation and sustainment in a well-controlled manner.

Here, we report that closed magnetic field topologies (i.e., field-reversed configurations) have been successfully created using energetic ion current via NBI in C-2W. This is the long-sought generation of an FRC by NBI which has been attempted but with no success in past experiments on other fusion devices. In this scheme, energetic beam neutrals are trapped by an initial seed plasma in the CV, leading to a direct source of toroidally directed energetic ion current and resulting current drive. Magnetic flux trapping occurs gradually, and fully-formed FRCs are generated in ~10 ms. This technological breakthrough in NBI current drive results in FRCs that exhibit macroscopic stability in quiescent equilibrium for the duration of NBI. Our results demonstrate a new way of forming closed magnetic field topology for fusion energy, which offers technological simplifications that can significantly decrease the cost of a future fusion power plant. The C-2W device has undergone dramatic reconfiguration with the removal of the vestigial FRTP formation sections and outer divertors, resulting in a more compact version of C-2W, now newly called "Norm" instead of "Norman."

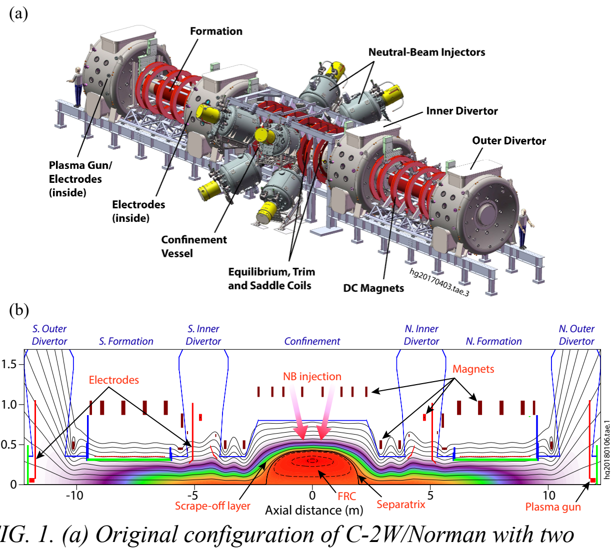

FIG. 1. (a) Original configuration of C-2W/Norman with two FRTP formation sections and four divertors; (b) A sketch of FRC magnetic topology and density contours, calculated by 2D multifluid force-balanced LReqMI equilibrium code [6].

As an example of FRC performance comparison, Fig. 2 shows the typical evolutions of FRC plasma parameters (excluded-flux radius, spatially averaged electron density and temperature, and thermal energy) for three distinct shots under different operating conditions and machine configurations: #114534 (black) – FRTP formation method in Norman configuration; #119076 (blue) – NBI formation method in Norman configuration; #165195 (red) – NBI formation method in Norm configuration. Note that NBs are terminated at around ~30 ms in shots #114534 and #119076, while for shot #165195 NBs are terminated at ~40 ms. In the conventional FRTP formation, it can be clearly seen that FRC radius and thermal energy are relatively high around $t \sim 0$ due to the initial CT collisional merging, after which plasma parameters stay mostly constant. On the other hand, for the NBI formation cases in both Norman and Norm configurations, FRCs are slowly generated and sustained until the NB termination. We have now demonstrated a reliable FRC formation via NBI with a significant increase in thermal energy in time.

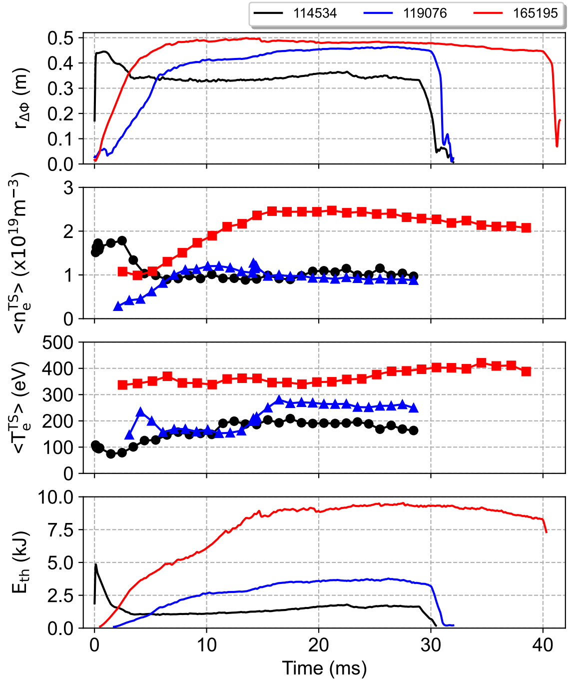

FIG. 2. Time evolutions of excluded-flux radius, spatially averaged electron density and temperature inside FRC separatrix (measured by mid-plane Thomson scattering system), and thermal energy of FRC for shots #114534 (black; via FRTP formation), #119076 (blue; via NBI formation), and #165195 (red; via NBI formation with the FRTP formation sections completely removed).

Here, we used the Q2D code [4] to investigate and study the formation of an FRC via NBI, starting from a mirror configuration. Q2D is a 2D code that couples an MHD model for the thermal plasma with a kinetic model for the neutral beams. The fueling gas and the neutrals produced by wall recycling are treated as a fluid, while the beam neutrals and the neutrals formed by charge exchange are followed by the Monte Carlo code. The Ohm's law used in Q2D includes an anomalous resistivity, which is 5 times the classical Spitzer resistivity. The electron perpendicular conductivity is 20 times the classical Braginski conductivity. These values where used in simulations of the previous C-2 experiment [4,5] to match the evolution of measured quantities and were confirmed for the current C-2W experiments. NBs are modeled using experimental parameters. The simulation shows that the initial positive magnetic field on the axis decreases and is reversed after 2 ms. When the magnetic field on the axis becomes negative, closed magnetic field lines are formed and the magnetic flux trapped inside the separatrix starts to increase. Figure 3 shows a 2D plot of the fast ion current densities and magnetic field lines at t = 2 ms (just before FRC formation), t = 4 ms (after the FRC is formed), and t = 6 ms, where the plots show the transition from a mirror configuration to an FRC.

This paper will review highlights of the recent breakthrough in FRC formation and sustainment via NBI in C-2W. Both experimental observations and simulation results, including current tomography and equilibrium reconstructions, will be presented.

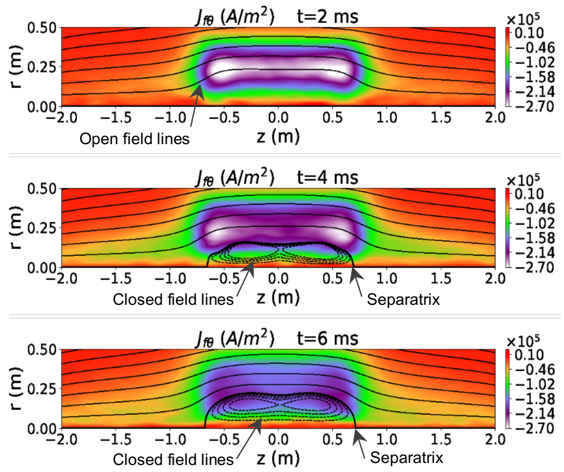

FIG. 3. Q2D simulation results: fast-ion current densities with magnetic field lines at t = 2, 4, and 6 ms. Thick black lines denote FRC separatrix.

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