ENHANCED PLASMA PERFORMANCE IN C-2W ADVANCED BEAM-DRIVEN FIELD-REVERSED CONFIGURATION EXPERIMENTS

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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, whose operating energy range is in 15–40 keV that can be tuned/controlled during a shot. TAE's current experimental device, C-2W (a.k.a. "Norman"), is the world's largest compact-toroid (CT) device and has made significant progress in FRC performance [1,2]. It produces record breaking, stable, high temperature advanced beam-driven FRC plasmas, dominated by injected fast particles and sustained in steady state, which is primarily limited by NB pulse duration. The NB power supply system has recently been upgraded to extend the pulse length from 30 ms to 40 ms, which allows for a longer plasma lifetime thus better characterizing and further enhancing FRC performance. A new insertable gas-injection system has been developed and deployed in the mirror region of the C-2W confinement section, which enables to inject and fuel sufficient particles at a proper radial location in the open-field-line regions to maintain plasma density and bias current from electrodes. Google's machine-learning framework for experiment optimization [2,3] has been routinely used in C-2W. Together with real-time control systems for FRC shape/position control [4] as well as for electrode biasing and particle fueling, C-2W operations have now reached to a matured level where the machine can produce hot, stable, long lived and repeatable plasmas in a well-controlled manner.

In recent C-2W experiments, adequately-controlled external magnetic-field profile throughout the machine and proper gas injection/fueling have led to more effective edge biasing from electrodes to globally stabilize FRC plasma. It allows to improve the efficiency of NB-to-FRC coupling as well as to accumulate more fast ions inside the FRC, therefore more plasma heating and current drive are obtained. Due to the synergistic effect of efficient edge biasing and NB injection as well as by dedicated plasma and machine optimization efforts in C-2W, FRC plasma state has significantly advanced to a much higher level than the previously-reported good FRC condition [2] as shown in Fig. 1. Note that for simplicity and performance comparison at a quiescent phase in 2 different shots, initial FRC formation phase (t < 5 ms) is not shown in the figure. Some highlights and key features of the recent enhanced plasma performance (for instance in shot #143348) are as follows: (i) excluded-flux radius of FRC is sustained at ~0.45–0.5 m until NB termination at 40 ms, while FRC length and volume

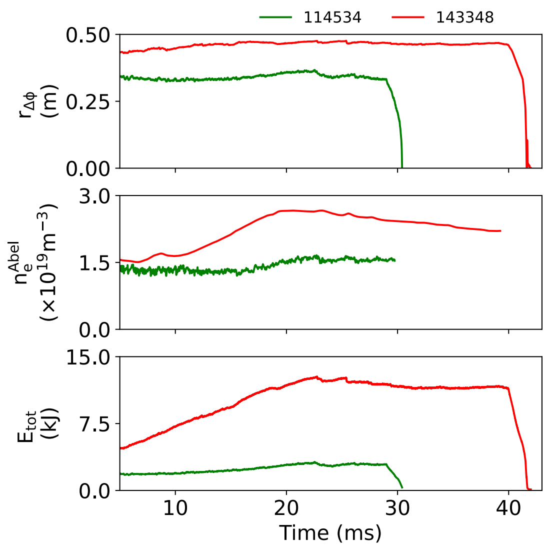

FIG. 1. Time evolutions of excluded-flux radius, averaged electron density inside FRC separatrix, and total energy of FRC for recent C-2W shot 143348 (red), compared with previously-reported good shot 114534 (green) [2].

can be increased and controlled by external magnetic-field reshaping during a shot in either feedforward or feedback control mode as designed [4]; (ii) plasma density (i.e., internal plasma pressure) goes up by 50–100% during a shot depending on field shaping and particle fueling scheme, which is also indicative of injected fast particles accumulation; (iii) as a result of the internal pressure increase, plasma energy also goes up significantly; and (iv) based on an equilibrium reconstruction, fast-ion pressure is comparable to or greater than thermal plasma pressure at a quiescent phase. In this particular shot #143348, the external magnetic field profile in the confinement section was reshaped during t = 4–24 ms, after which it stayed constant until the end of the discharge. Under some operating conditions, electron temperature T_e of FRC plasmas can reach up to ~1 keV at the peak inside the FRC separatrix, measured by mid-plane Thomson scattering system. Estimated trapped poloidal flux ϕ_p (based on rigid-rotor model) is also significantly increased up to ~15 mWb at an equilibrium phase, indicating the effect of current drive via NB injection.

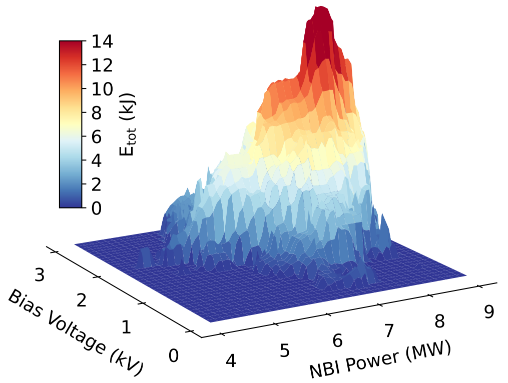

FIG. 2. Plasma total energy (at peak value) as functions of NB injection power (total injected neutral power from 8 NB injector systems) and edge-biasing electrode voltage for ensembled C-2W shots at a quiescent phase.

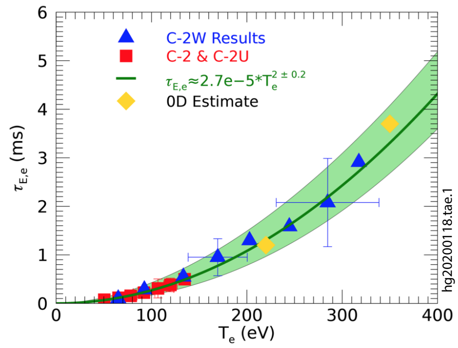

FIG. 3. Global electron energy confinement time as a function of electron temperature in C-2/2U and C-2W.

FRC performance is well correlated with both NB injection and edge biasing from electrodes. Figure 2 shows plasma total energy E_{tot} (at a peak value of each shot) as functions of NB's injected neutral power and edge-biasing electrode voltage for ensembled C-2W shots in the recent experimental campaign. As can be clearly seen, higher E_{tot} is obtained with higher NB injection power and biasing voltage on electrodes, which indicates the importance of those systems to produce decent and high-energy FRC plasma conditions. E_{tot} is estimated by integration of one-dimensional pressure reconstruction along the geometrical axis (z-axis). The 1-D reconstruction corresponds to paraxial approximation (highly elongated plasma) with the assumption of sharp boundary between plasma and surrounding magnetic field.

Based on a careful global power balance analysis detailing input/loss channel characteristics and plasma timescales, there appears to be a strong positive correlation between T_e and energy confinement time. The previously reported C-2/2U scaling of the electron energy confinement time $\tau_{E,e}$ [5] still persists at the higher T_e (i.e., collisionless plasma regime) in C-2W, as shown in Fig. 3. Given uncertainties in the measurements and assuming the power-law model, regression analysis shows that $\tau_{E,e}$ is approximately proportional to T_e^2 when fitting for the entire ensemble of the C-2W data set. Newly obtained even higher T_e shots are being analyzed to validate the scaling law that will be reported at the conference.

Extensive effort on plasma/machine optimizations as well as on plasma diagnostics and characterization of FRC has been made over the past few years. This paper will review the highlights of recent C-2W experimental campaign and results on significantly advanced FRC performance. Future plan of C-2W experiments as well as prospects of TAE's fusion program will also be reported.

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