C-2W装置における高温、安定、長寿命FRCプラズマの生成

Formation of Hot, Stable, Long-Lived Field-Reversed Configuration Plasmas on the C-2W Device

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TAE Technologies (formerly named "Tri Alpha Energy," established in 1998) is privately funded, based out of state-of-the-art plasma research facilities in Orange County, California. Over the last 20 years, TAE has continued to build on our early technology and evolve our advanced beam-driven field-reversed configuration (FRC) approach to realize/develop a commercially competitive clean fusion energy. An FRC is a high-β prolate compact toroid (CT) that has the following attractive features: simple axisymmetric geometry that facilitates a translation along a central axis; extremely high β and associated economic attractiveness; its unrestricted natural divertor system facilitating heat removal and exhaust engineering; and it may also enable the use of advanced, aneutronic fuels such as D-^{3}He and p-^{11}B.

TAE's research has been devoted to producing a high temperature, stable, long-lived FRC plasma state by neutral-beam injection (NBI) and edge biasing/control. Previous C-2U experiments have demonstrated drastic improvements in particle and energy confinement properties of FRC's, and the plasma performance obtained via ~10 MW NBI has achieved plasma sustainment of up to 5 ms and plasma/diamagnetism lifetimes of 10+ ms [1]. The emerging confinement scaling, whereby electron energy confinement time $\tau_{E,e}$ is proportional to a positive power of the electron temperature T_e, is very attractive for higher energy plasma confinement; accordingly, exploration of the observed confinement scaling law at an order of magnitude higher T_e is one of the key ongoing research objectives.

New experimental device, C-2W (also known as "Norman," shown in Fig. 1; the world's largest CT device), has been constructed with the following key subsystem upgrades from C-2U: (i) higher injected power (up to ~21 MW), optimum and adjustable energies (15–40 keV), and extended pulse duration (up to ~30 ms) of the NBI system; (ii) installation of inner

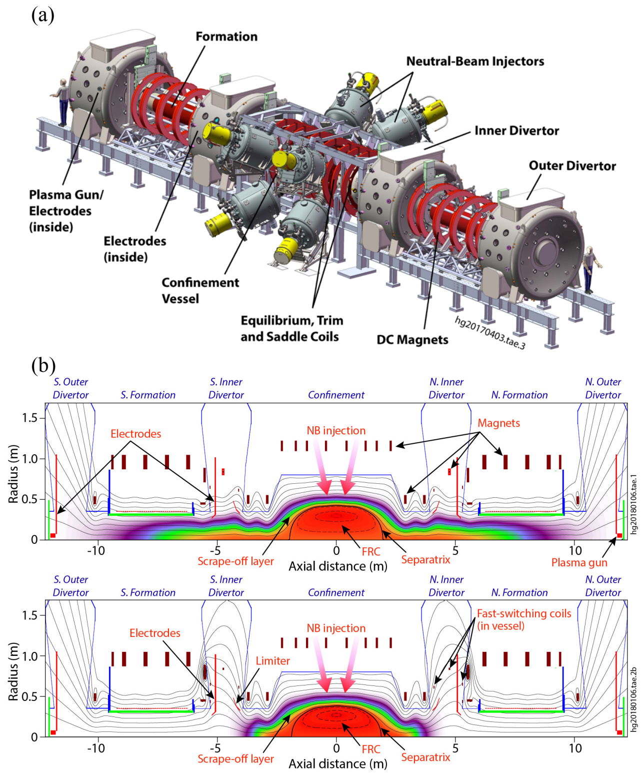

FIG. 1. (a) C-2W experimental device, "Norman"; (b) Sketches of FRC magnetic topology and density contours in 2 different operating regimes (edge biasing using outer divertors or switched to inner divertors), simulated by the 2-D MHD LamyRidge equilibrium code.

divertors with upgraded edge-biasing electrode systems, which allows for higher biasing voltage and longer pulse operation (30+ ms), and in-vacuum fast-switching (ramp-up/down) magnets that allow to vary/optimize the field profile for effective FRC translation as well as to produce a thermal insulation of the peripheral plasma with field expansion; (iii) increased overall stored energy in the FRC formation pulsed-power systems to produce better target FRCs for effective NBI heating and current drive; (iv) fast external equilibrium and mirror-coil current ramp-up capability for plasma ramp-up and control; (v) installation of trim/saddle coils for active feedback control of the FRC plasma; and (vi) enhanced overall diagnostic suite. A remarkable side note is the fact that TAE spent only ~1 year to achieve first plasma on C-2W; which includes the time for dismantlement of the C-2U device as well as for the construction and initial commissioning/conditioning of the C-2W device and subsystems.

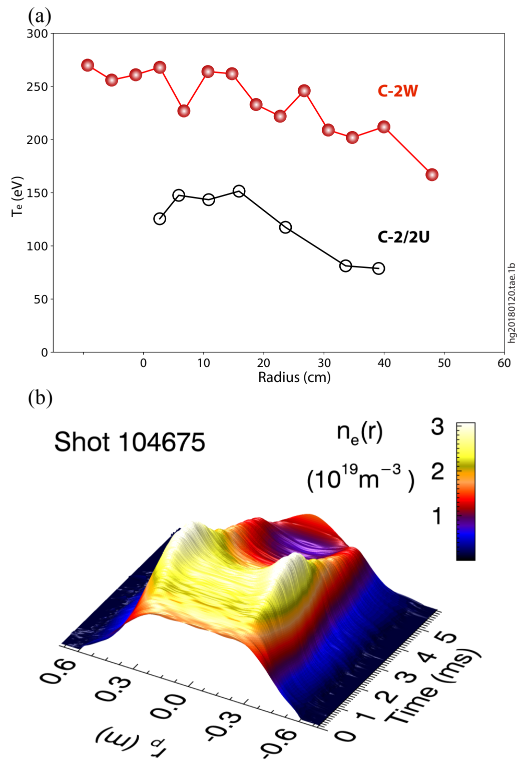

FIG. 2. (a) Electron temperature profiles at right after FRC collision/merging (t~0.05 ms) obtained in C-2/2U and C-2W; (b) density profile time evolution in C-2W. Both Thomson scattering and interferometer systems are located in the device midplane.

C-2W experiments have commenced and already produced dramatically improved initial FRC conditions after translation and collisional merging, in which FRCs have successfully translated through the inner divertors with adequate guiding magnetic fields by in-vessel fast-switching coils, followed by a collision and merging of the 2 FRCs in the middle of the confinement vessel with relative speeds of up to ~1000 km/s. The high initial translational kinetic energy of the colliding FRCs yields high thermal energy post merging via shock heating (predominantly in the ion channel). As anticipated by design and also in our simulations, the merged initial FRC state exhibits much higher plasma temperatures (in both electrons and ions), larger volume, and more trapped flux compared to C-2U, providing a very attractive target for effective NBI on C-2W. Figure 2(a) shows T_e profiles, measured by multipoint Thomson scattering and obtained immediately after FRC collision/merging in typical C-2/2U and C-2W experiments. The 250+ eV T_e profile (total electron and ion temperature, T_e+T_i, exceeding 1.5 keV) in C-2W, is testament to the improved initial FRC conditions produced by the upgraded formation pulsed-power systems. The electron density profile measured by far-infrared interferometer, shown in Fig. 2(b), exhibits the expected hollowness, corroborating a typical FRC structure. Edge biasing/control experiments using outer-divertor plasma guns and electrodes have demonstrated a clear stabilization of FRC global modes (e.g. toroidal modes n=1 and 2); thus, improving plasma confinement and prolonging FRC lifetime (up to ~9 ms) via improved beam-to-FRC coupling enabled by the stabilized plasma. Good wall conditioning, using titanium gettering systems in the confinement vessel and all 4 divertors, also plays an important role in the observed FRC performance improvement; particularly with regards to effective NBI and edge biasing. New experimental campaign with magnetic field flaring/expansion at inner-divertor area, as depicted in Fig. 1(b), has recently commenced and already shown some characteristic change in the open-field-line / edge plasma behavior. This paper will review/feature highlights of the C-2W program along with recently obtained experimental results.

[1] H. Gota *et al.*, Nucl. Fusion **57**, 116021 (2017).