FORMATION OF HOT, STABLE, LONG-LIVED FIELD-REVERSED CONFIGURATION PLASMAS ON THE C-2W DEVICE

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Abstract

TAE Technologies' research is devoted to producing high temperature, stable, long-lived field-reversed configuration (FRC) plasmas by neutral-beam injection (NBI) and edge biasing/control. The newly constructed C-2W experimental device (also called "Norman") is the world's largest compact-toroid (CT) device, which has several key upgrades from the preceding C-2U device such as higher input power and longer pulse duration of the NBI system as well as installation of inner divertors with upgraded electrode biasing systems. Initial C-2W experiments have successfully demonstrated a robust FRC formation as well as its translation into the confinement vessel through the newly installed inner divertor with adequate guide magnetic field. They also produced dramatically improved initial FRC parameters with higher plasma temperatures (T_e up to 300 eV; total electron and ion temperature >1.5 keV) and more trapped flux (up to ~15 mWb, based on rigid-rotor model) inside the FRC immediately after the merger of collided two CTs in the confinement section. As for effective edge biasing/control on FRC stabilization, a number of edge biasing schemes have been tried via open-field-lines, in which concentric electrodes located in both inner and outer divertors as well as end-on plasma guns are electrically biased independently. As a result of effective outer-divertor electrode biasing alone, FRC plasma diamagnetism duration has reached up to ~9 ms which is equivalent to C-2U plasma duration. Magnetic field flaring/expansion in both inner and outer divertors plays an important role in creating a thermal insulation on open-field-lines to reduce a loss rate of electrons, which leads to improvement of the edge as well as core FRC confinement properties.

1. INTRODUCTION

A field-reversed configuration (FRC) is a high-beta compact toroid (CT) which has closed-field-line and open-field-line regions of poloidal axisymmetric magnetic field with no or small self-generated toroidal magnetic field [1,2]. The FRC topology is generated by the plasma's own diamagnetic currents, which are of sufficient strength to reverse the exterior magnetic field, and only requires external solenoidal coils located outside of vacuum vessel. The averaged beta value of FRCs is ~1: $\langle\beta\rangle = 2\mu_0\langle p\rangle/B_e^2$ ~90%, where μ_0 is permeability of free space, $\langle p\rangle$ is the average plasma pressure, and B_e is the external magnetic field. The edge layer outside of the FRC separatrix coalesces into axial jets beyond each end of the FRC, providing a natural divertor, which may allow extraction of energy without restriction. The FRC has its potential for a fusion reactor with low-cost construction and minimal maintenance due to its simple geometry. FRCs may also allow the use of advanced, aneutronic fuels such as D-^{3}He and p-^{11}B.

In the past C-2 [3,4] and C-2U [5,6] FRC experiments at TAE Technologies studying aspects as well as demonstration of the FRC plasma sustainment by neutral beam (NB) injection (NBI) and edge biasing/control were the primary goals, at which the world's largest CT device, C-2, was upgraded to C-2U with key upgrades of NBI and edge biasing systems. One of the key accomplishments in the C-2 experiments was the demonstration of the high-performance FRC (HPF) regime, which was set apart by dramatic improvements in confinement and stability compared to other FRC devices [4,7-9]. HPF plasma discharges have also demonstrated increasing plasma pressure and electron temperature, indicating an accumulation of fast ions as well as plasma heating by NBI. Electrically biased end-on plasma guns and effective wall-surface conditioning also played important roles in producing HPF plasmas, synergistically with NBI. In order to further improve HPF plasma parameters, the C-2U experimental program commenced after various key system upgrades from C-2, including increased total NB input power from ~4 MW (20 keV hydrogen) to ~10+ MW (15 keV hydrogen, higher current at reduced beam energy) with tilted injection angle, and enhanced edge-biasing capability for boundary/stability control. The upgraded NBI and edge biasing systems enabled significant plasma performance advances and had a profound impact on C-2U performance such as: (i) rapid accumulation of fast ions (about half of the initial thermal pressure replaced by fast-ion pressure); (ii) fast-ion footprint largely determines FRC dimensions; (iii) double-humped electron density and temperature profiles (indicative of substantial fast-ion pressure); (iv) FRC lifetime and global plasma stability scale strongly with NB input power; and (v) plasma performance correlates with NB pulse duration in which diamagnetism persists several milliseconds after NB termination due to accumulated fast ions. Under the optimum C-2U operating conditions, plasma sustainment for ~5+ ms as well as long-lived plasma discharge of up to 10+ ms were successfully achieved [6], in which the performance was mostly limited by hardware and stored energy constraints such as the NB's pulse duration and the current sourcing capability of the end-on plasma guns. Furthermore, with careful 0-D global power-balance analysis [10,11], there appeared to be a strong positive correlation between electron temperature T_e and energy confinement time; i.e., the electron energy confinement time $\tau_{E,e}$ in C-2U FRC discharges scales strongly with a positive power of T_e [6,11], which is basically the same characteristics/trend as observed in C-2 [4]. This positive confinement scaling is very attractive, and similar features of temperature dependence have also been observed in other high-beta devices such as NSTX and MAST, whereby the energy confinement time scales nearly inversely with collisionality [12,13].

In order to improve further FRC performance as well as to overcome engineering constraints mentioned above, the C-2U device has been again upgraded to C-2W (also called "Norman," shown in Fig. 1) with substantial system upgrades, at which the C-2U device was completely dismantled and the brand-new experimental device C-2W was constructed within one year of engineering time. The C-2W device has 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 divertors with upgraded edge-biasing electrode systems, which allow for higher biasing voltage and longer pulse operation (30+ ms), and in-vacuum fast-switching magnet coils (current up and down in a few milliseconds) inside the inner divertors that allow to vary/optimize the field profile for effective FRC translation as well as to produce a thermal insulation of the peripheral plasma; (iii) increased overall stored energy in the FRC formation pulsed-power system to produce better target FRCs for effective NBI heating and current drive; (iv) fast external equilibrium/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 to investigate and characterize both core FRC and open-field-line plasma performances.

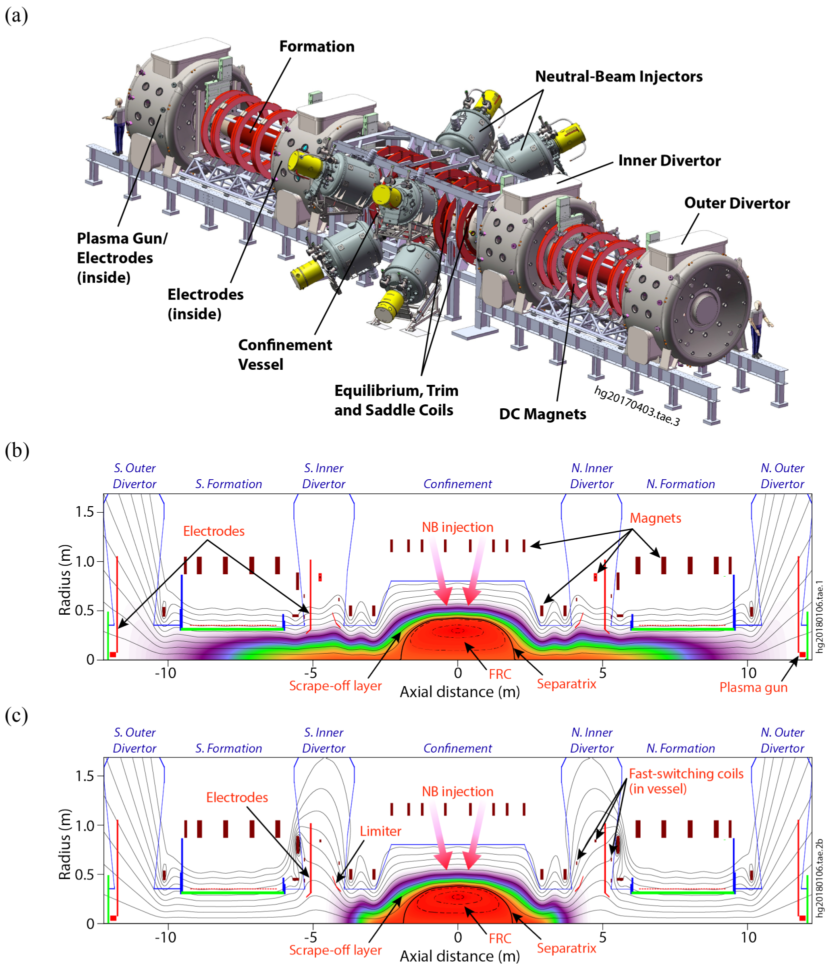

FIG. 1. (a) Illustration of the C-2W experimental device, Norman. Sketches of FRC magnetic topology and density contours, simulated by the 2-D MHD LamyRidge equilibrium code, in (b) outer-divertor operating mode and (c) inner-divertor operating mode with flared magnetic field.

The main goals of the C-2W experimental program to be accomplished are as follows: (i) demonstrate plasma ramp-up by NB heating and current drive; (ii) improve edge/divertor plasma performance to achieve high electron temperature both at the plasma edge and inside the core; (iii) develop plasma control on the time scale significantly longer than L/R vessel-wall time and plasma confinement times, and demonstrate controllable plasma ramp-up; and (iv) explore a wide range of plasma parameters such as plasma temperature, magnetic field and plasma size to confirm the previously emerged/obtained energy confinement scaling [6,11]. There are also several key intermediate milestones to accomplish in scientific and engineering aspects on the C-2W experimental program in order to ensure that each subsystem of the machine operates within its designed parameters as well as to accelerate the program towards the main goals: for instance, producing a robust FRC formation and translation through inner divertors; establishing adequately controllable magnetic-field structure in the inner divertor area to change from guiding straight magnetic field for FRC translation to flared field structure, as can be seen in Figs. 1(b) and 1(c); transferring edge-biasing regions from outer to inner divertors as inner-divertor magnetic field gets flared; demonstrating the first of the kind active-feedback magnetic flux and plasma control on FRC experiments; demonstrating sufficient particle refueling for plasma ramp up; and, establishing effective wall conditioning in the confinement vessel (CV) and high vacuum/pumping capability in all four divertors to reduce outgassing / secondary electron emissions from vessel-wall surfaces, thus improving open-field-line plasmas.

In the paper, C-2W experimental apparatus and plasma diagnostic suite including newly-upgraded/developed subsystems are described in Sec. 2. Key highlights and accomplishments of early C-2W experimental campaigns as well as characteristics of newly-obtained FRCs under different operating regimes are described in Sec. 3. Lastly, a summary is provided in Section 4.

2. C-2W EXPERIMENTAL DEVICE, NORMAN

2.1. Experimental apparatus overview

The C-2W experimental device, shown in Fig. 1(a), is the world's largest theta-pinch, CT collisional-merging system, newly built at TAE Technologies to form high flux, high temperature, stable and long-lived FRC plasmas. The C-2W device was constructed in the same place where the preceding C-2U device was located; the previous C-2U experimental program had executed for ~1 year and then the machine was dismantled completely for C-2W. Figures 1(b) and 1(c) illustrate typical FRC magnetic flux and density contours in the C-2W device under two different operating conditions with and without magnetic field flaring in the inner divertors; these density contours are obtained from a two-dimensional magnetohydrodynamic (MHD) numerical simulation performed with the LamyRidge equilibrium code [14].

The C-2W device has ~30 m in overall length and consists of the central confinement section surrounded by 2 newly-installed inner divertors, 2 field-reversed theta-pinch (FRTP) formation sections, and 2 outer divertors, in which these 7 sections can be independently isolated in terms of its vacuum boundary by large gate valves. The CV is made of Inconel that has the inner-wall radius r_w ~0.8 m with thin wall thickness whose resistive wall time is about 2–3 ms; this allows for magnetic-field ramp up/down as required during a plasma discharge. Because of the relatively short wall time of the CV, adequately controlled external magnetic field is important and critical to FRC plasma confinement as well as for plasma ramp up. The divertor vessels are made of stainless steel and have a large internal volume to accommodate a high volumetric pumping during a plasma discharge; furthermore, each divertor has its own internal cryogenic pumping system with titanium gettering and LN_2 cooling system in place to enhance pumping capability in divertors. The formation tubes are made of quartz, which are approximately ~3.5 m in length and ~0.6 m in diameter. The overall C-2W device accommodates an ultra-high vacuum (typical vacuum level is at in the range of high 10^{-10} to low 10^{-9} Torr) with adequately set up wall conditioning systems such as titanium (sublimation / cathodic arc) gettering and LN_2 cooling systems.

There are complex magnet and control systems on C-2W that have much more operating flexibility and reliability compared to the previous C-2U device. Figure 2 shows a layout of the C-2W magnet systems, which includes the confinement equilibrium and mirror coils, saddle and trim coils, in-vacuum fast-switching coils, DC formation coils, and mirror plug coils; all the coil configuration is symmetrically arranged relative to the machine midplane (z=0). Note that FRTP formation coils (pulsed-power systems) are not shown in Fig. 2 for simplicity. A set of DC magnets and power supplies, previously used on C-2U got repurposed to C-2W, generates a quasi-static axial magnetic field, B_z, in the formation and outer divertor regions. All other coils specified above and its associated power supplies including formation pulsed-power systems were newly designed and developed for C-2W. There are basically 2 major operating phases in the C-2W experimental program where equilibrium magnetic fields stay constant in phase 1 or ramp up in phase 2; the typical magnetic fields in those phases are B_z ~0.1 T and ramped up to ~0.3 T, respectively, at which a mirror ratio of the magnetic fields in the confinement section is about 3.0–3.5 even during and after the field ramp. Current waveforms of each equilibrium and mirror coils are independently controlled, which allows for an adequate and flexible control of external magnetic field profile as well as plasma shape and position. Trim coils are placed beneath each of the equilibrium coils, as shown in Fig. 2, that can also be operated independently to correct error fields as well as to perform an active feedback control. Saddle coils are deployed non-axisymmetric around the CV that can be operated either passively with a shorted-coil configuration or actively with power supplies for plasma position control; there is also a capability of active feedback plasma position control in the active saddle-coil setup. There are in-vacuum fast-switching coils inside the inner divertors in order to provide adequate guide magnetic fields during FRC translation and then to quickly flare the fields (by reversing coil current within a few milliseconds), as depicted in Figs. 1(b) and 1(c). Magnetic mirror plugs are placed in between the formation and divertor sections at each side that can produce a strong magnetic field up to ~1 T. The mirror-plug coils as well as confinement mirror coils play an important role in contributing to the open-field-line plasma confinement with field expansion in both divertors.

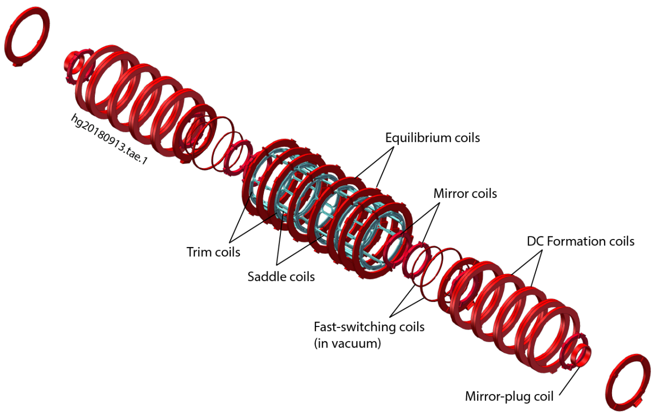

FIG. 2. Layout of C-2W magnet systems. Pulsed-power formation coils/straps inside DC formation coils are not displayed.

FRC plasma is generated by newly-upgraded pulsed-power systems in the formation section that is basically the same dynamic FRTP formation technique as that of utilized in C-2 [3]. The formation pulsed-power systems consist of Bias modules for negative-bias magnetic field, Main-Reversal (MR) modules for main theta-pinch magnetic field, and Rotating Magnetic Field (RMF) modules for deuterium gas pre-ionization in the formation section; as a side note, previously used ringing Pre-Ionization (PI) system is no longer used in C-2W. Each module has substantial system upgrades from the previous C-2/2U pulsed-power systems, in which the stored energies of each system increased significantly as well as system reliability and operating performance have improved considerably. Due to such improved overall pulsed-power system performance, the generated FRC plasma in the formation section has more magnetic and kinetic energies contained, thus getting transferred to higher thermal energy at the CT collisional-merging process as observed in C-2 [3,15].

To control open-field-line plasmas as well as to provide sufficient radial electric field for $E\times B$ shearing around the FRC separatrix, coaxial plasma guns and concentric annular electrodes are installed inside of each outer divertor as illustrated in Fig. 1(b). This edge-biasing/control configuration with a capability of magnetic field flaring at end divertors is essentially the same as C-2U [5,6], but C-2W edge-biasing system has more functionality and flexibility in terms of its operations such as higher voltage/potential that can be applied on electrodes with longer pulse duration up to ~30 ms. Furthermore, similarly designed/developed annular electrodes (with a hole in the center of electrodes, required for FRC translation) as well as funnel limiters are installed in both inner divertors as shown in Fig. 1(c). Electrical potentials on those inner-divertor electrodes / limiters as well as on outer-divertor electrodes can be controlled independently by power supplies, which is the key of C-2W experiments, together with magnetic field control in the CV and divertor regions, for effective edge/boundary control of FRCs via open-field-lines / scrape-off layer (SOL). The role of SOL and divertors is not only to provide a favorable boundary condition for the core FRC plasma but also to handle energy and particle exhaust from the core. There is a halo region, outside of the SOL, with open-field-lines contacting to the limiters and wall of the CV; it contains low temperature, low density partially ionized plasma sustained by power flow from the plasma core, beam ions, and warm neutrals.

Eight newly-upgraded NB injectors are installed on the CV as shown in Fig. 1(a) for plasma heating, current drive, and partial particle refueling. The C-2W NBI system has the following key features: NB's input power and pulse duration increased from ~10 MW (15 keV hydrogen, co-current injection) / ~8 ms in C-2U to 13+ MW (fixed energy of 15 keV hydrogen) / up to ~30 ms in C-2W phase 1 operations that can be further increased up to ~21 MW with tunable beam energy of 15–40 keV (4 out of 8 NBs have tunable energy capability) in phase 2 operations; tilted NBI angle in a range of 65°–75° (presently fixed at 70°) relative to the machine axis with average NBI impact parameter at ~19 cm to enable sufficient coupling between the beams and the target FRC plasma. The NBs provide energetic particles with a large orbit size crossing inside and outside of the FRC separatrix that stabilize global MHD modes; they also provide a significant amount of fast ion population and pressure inside the core, thus producing an advanced beam-driven FRC plasma. In phase 2 operations increase of the beam energy will reduce charge-exchange loss resulted in ramping up of total NBI power as well as increasing fast-ion and plasma pressure, at which the external magnetic field in the CV needs to be also increased/ramped up, accordingly.

Plasma particle inventory (amount of fuel) must be controlled to maintain proper densities for NB capture, which is required in the presence of particle losses from the core that is unavoidable. A plasma refueling system must be capable of matching the particle losses as well as increasing the total particle inventory if desired. Azimuthal current in FRC flows across magnetic field lines and thus sustainment of total pressure gradient in the core is essential for sustainment of trapped flux and FRC magnetic configuration. Without central refueling and heating the trapped magnetic flux decays due to finite plasma resistivity across magnetic field. To that end, there are three main particle refueling systems deployed on C-2W: multi-pulsed CT injector systems near the CV midplane [16,17], cryogenic pellet injector system [18], and gas puffing systems at both ends of the CV (near confinement mirror regions) as well as near mirror-plug regions for open-field-line plasmas. Contrary to the cryogenic pellet injection (over dense and cold gas), CT refueling system can supply hotter plasma particles and thus will result in lesser plasma cooling [17]. Gas puffing in the CV cannot provide effective core refueling but can be used for the edge density control.

2.2. Plasma diagnostic suite

The C-2W device is planned to have more than 50 plasma diagnostic systems installed on the CV, inner / outer divertors, and formation sections. The role of the plasma diagnostic suite is to investigate and characterize not only core FRC plasma performance but also open-field-line plasmas at various areas such as SOL/Jet regions and inside divertors. Figure 3 illustrates a schematic view of C-2W showing 4 distinct zones (Core, SOL/Jet, Divertors, and Formation) of diagnostics interest, in which some abridged diagnostics at each zone are also listed. To support C-2W experiments towards the program goals the diagnostic suite has been significantly upgraded from the previous diagnostic suite in C-2U [19]. Much of the expansion and improvements were driven by a highly increased interest in the open-field-line plasma, which has a large impact on the core FRC and overall system performance. Furthermore, some key plasma parameters (e.g., temperatures, density / pressure, and magnetic flux) are expected to evolve as increasing NB input power as well as ramping up external magnetic field so that designing/implementing broad operating range and functionality in each diagnostic system is essential on C-2W. As shown in Fig. 3, plasma performance and parameters at different zones/areas are investigated and provided by a comprehensive suite of diagnostics that includes magnetic sensors [20], Langmuir probes [21], far-infrared interferometry / polarimetry [22], Thomson scattering [23], VUV/visible/IR spectroscopy, bolometry, reflectometry [24], energy analyzer [25], neutral particle analyzers, fusion product detectors, secondary electron emission detectors [26], and multiple fast imaging cameras [27]. In addition, extensive ongoing work focuses on advanced methods of measuring separatrix shape and plasma current profile that will facilitate equilibrium reconstruction and active control of FRCs. More detailed information of the C-2W diagnostic suite can be found elsewhere [28]. Signals and data from individual diagnostics are transferred to a data-acquisition system that acquires about 2500 channels on every C-2W discharge for now and will increase more as new diagnostics, measurements, and/or other subsystems come online. The acquired raw data is post-processed into plasma parameters and then stored on a physics database for further data analysis. Some raw data gets processed immediately after acquiring fast signals even during a plasma discharge and then used for an active feedback control. On typical C-2W discharges ~4 gigabytes of data are currently generated after each shot, including analysis movies and computations; this data size will also increase as more signals get acquired and post processed for physics parameters.

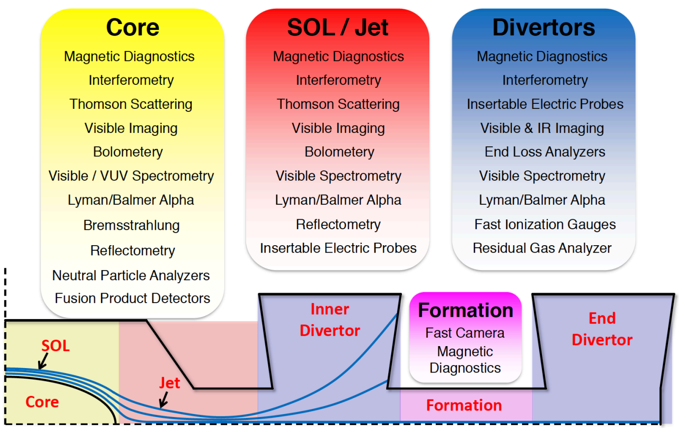

FIG. 3. Schematic of C-2W showing 4 distinct zones/regions of diagnostics interest such as Core, SOL / Jet, Divertors, and Formation with abridged list of instruments.

3. C-2W EXPERIMENS AND RESULTS – OPERATION PHASE 1

C-2W is a brand-new experimental device with substantially upgraded various subsystems from C-2U as described in previous sections so that early C-2W experimental program was mostly devoted to subsystem commissioning as well as to explore new operating parameters/settings, particularly in the formation pulsed-power systems and magnetic field profile, including inner divertor area. In order to gain an early assurance of the system functionality as well as to develop and ensure a robust FRC formation and translation scheme, C-2W experiments had commenced with a single-sided configuration where a half of the device was initially constructed and operated while the other half was still being constructed. A remarkable side note is the fact that TAE spent only ~1 year to produce/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 of the C-2W device. In C-2W operation phase 1 there are two major operating configurations/conditions: keeping strong magnetic field at inner-divertor regions (in other words, without magnetic field flaring) so that C-2W can operate as C-2/2U like machine configuration; and flaring magnetic field at inner-divertor regions with transferring edge biasing/control areas from outer to inner divertors. It basically changes the operating machine configuration from Fig. 1(b) to Fig. 1(c). This section describes (i) key physics/engineering elements to produce an advanced beam-driven FRC plasma on C-2W, (ii) early experimental results using single-sided machine configuration to ensure and validate a robust FRC formation as well as its translation through inner divertor, and (iii) newly obtained experimental results with a full C-2W machine configuration in operation phase 1 – with / without flaring magnetic field at inner-divertor regions but no field ramp-up or NB input power increase.

3.1. Advanced beam-driven FRCs

As previously identified and discussed in C-2/2U experiments, producing a well stable initial target FRC for effective NBI is the important key to achieve/obtain a beam-driven FRC plasma state since it typically takes ~1 ms for the injected fast ions to accumulate and develop sufficient pressure inside the FRC. A high performance FRC (HPF) equilibrium state was firstly obtained in the C-2 device, and then further improved/advanced in C-2U to a beam-driven FRC plasma state via increased power of NBI and effective edge biasing/control in which FRC plasma was successfully maintained for 5+ ms. To achieve both HPF and beam-driven FRC operating conditions in C-2/2U, the following key elements / approaches were necessary: (i) dynamically colliding and merging two oppositely-directed CTs for a robust FRC formation; (ii) effective wall conditioning inside vacuum vessels, e.g. using a titanium gettering system, for background neutral and impurity reduction; (iii) effective edge/boundary control around the FRC separatrix via end-on plasma guns and concentric annular electrodes inside end divertors; and (iv) effective NBI into FRCs for current drive and heating. The main feature/characteristics of those high-performance beam-driven FRC regimes are: macroscopically stable plasma discharges, dramatically reduced transport rates (up to an order of magnitude lower than the non-high-performance FRC regime), high fast-ion population/pressure inside the FRC, long-lived plasma/diamagnetism lifetimes, and emerging global energy confinement scaling with strongly favorable temperature dependence.

The key elements specified above for C-2/2U experiments are still important and critical to the C-2W experimental program. In order to enhance fast-ion effects by NBI as well as to further improve FRC performance towards the program goals, those key elements (i)–(iv) have been significantly upgraded in C-2W as described in Sec. 2; furthermore, a few more key elements are added/included in C-2W which are (v) adequate particle refueling into FRC core and edge for plasma density control, and (vi) actively controllable external magnetic field for plasma shape/position control. Those additional elements are critical, particularly in the second phase of operations, for the expected FRC plasma ramp-up with increased NB input power of up to ~21 MW. Under no plasma ramp-up experimental condition in C-2W, such as operation phase 1, the key elements to produce a decent (stable, long lived, and hot) FRC plasma state/condition are basically the same as C-2/2U experiments even with slightly different machine configuration (e.g., presence of inner divertors, larger diameter of the CV); however, significantly upgraded NBs and edge biasing/control systems as well as extensive FRC/system optimization processes have been leading to further improved FRC performance, ultimately showcasing an "advanced beam-driven FRC" equilibrium state in C-2W.

3.2. Validation of robust FRC formation and translation

FRCs are produced/formed by colliding and merging two oppositely-directed CTs using FRTP method in the formation sections. This flexible, well controllable dynamic FRC formation technique [3] allows to form various initial target FRC states primarily for an effective NBI study as well as for plasma performance optimization. This formation technique was well established initially on C-2, and also used in C-2U without major upgrade in the pulsed-power systems. In C-2W the formation pulsed-power system has been significantly upgraded to form more robust FRCs as well as better target for NBI. Another important change from C-2/2U to C-2W is that the current device has a big divertor in between the formation section and the CV as illustrated in Fig. 1, so that the formed FRC in the formation section has to be robust enough in order to translate through the inner divertor (~1 m gap without a conducting wall/shell) without too much degradation of the FRC.

To test and verify a proper FRC formation/translation with the inner divertor, C-2W experimental program had commenced early as part of several key subsystem commissioning using one side of the device, in which the formation pulsed-power system, inner-divertor fast-switching coils, mirror-plug coil, and confinement equilibrium/mirror coils were thoroughly tested for each functionality as well as to characterize/optimize FRC formation and translation at the early phase of experiments. In this early test/commissioning of the single-sided machine configuration, relatively good FRC plasma was initially formed in the formation section and then successfully translated through the inner divertor with adequate guide magnetic field applied by the in-vacuum fast-switching coils as well as confinement mirror coils; the translated FRC plasma then had an axial speed of 150–200 km/s entering into the CV even with slightly reduced pulsed-power voltages, and it reached all the way to the other end of the CV and reflected off at the confinement-mirror region by the strong magnetic field. This successful test of FRC formation and translation was also simulated by the LamyRidge code using the actual experimental setup/settings as its input parameters, and the result has shown a consistent picture of the FRC formation/translation characteristics. As an example of the successful FRC formation/translation in the single-sided C-2W configuration, Fig. 4 shows a time sequence of the simulated FRC plasma (density contour) at 3 phases of the formation, translation through inner divertor, and near the end of translation in the CV. Note that this particular test plasma discharge (and simulation) is under high density and slow FRC translation condition. During this FRC formation/translation study in both experiment and simulation, it was clearly observed and verified that having an adequate guide magnetic field (using in-vacuum fast-switching coils) inside inner divertor is critical for FRC translation but it also has to have a proper balance of magnetic field amplitudes and axial profile generated by the fast-switching coils and confinement mirror coils; otherwise, FRC does not properly penetrate through the inner divertor and mirror region at which the translated FRC can be either bounced off / gotten trapped inside the inner divertor or torn apart (partially translated through but some got reflected).

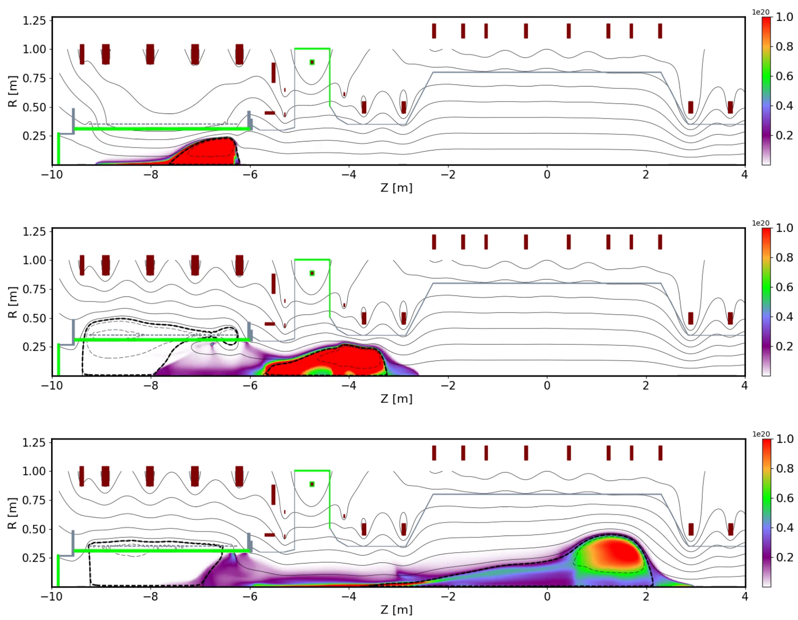

FIG. 4. Two-dimensional MHD simulation of FRC formation and translation in the single-sided C-2W configuration; showing evolution of density contours (in m^{-3}) at FRC formation (top), translating through inner divertor and entering the CV (middle), and fully travelled to the other end of CV.

3.3. Typical FRC performance and key results (in operation phase 1)

C-2W experimental program has continued after a completion of the machine construction, meaning that majority of C-2W subsystems are installed and operational. As described earlier, our intent/objective in this operation phase 1 is to produce a decent, stable FRC target primarily for effective NBI before ramping up internal plasma pressure by increasing NB input power. Double-sided FRC formation, translation, and collisional merging process in C-2W is essentially the same as previous C-2/2U experiments, but things that having the newly-installed inner divertors and FRCs have to get translated properly through the areas were definitely our new experimental check-point to verify and ensure about the experimental program and strategy. As described in Sec. 3.2, FRC plasma formation and translation through the inner divertor is not the big concern but finding and optimizing the best outcome/product after the FRC collisional-merging process remains to be obtained. We have spent a considerable amount of time to map out new operating regimes in many subsystems as well as to optimize FRC performance inside the CV, in which the early experimental campaign was conducted without flaring magnetic field at inner-divertor regions to obtain C-2U like long-lived stable FRC plasmas. Typical FRC plasma state right after the collisional-merging process has the following plasma properties: excluded-flux radius $r_{\Delta\phi}$ ~0.45–0.5 m, length l_s ~2.5–3.0 m, rigid-rotor poloidal flux ϕ_p ~10–12 mWb, electron temperature T_e ~250–300 eV, total temperature ($T_{tot} = T_i + T_e$, based on pressure balance) up to ~1.5–2.0 keV, and electron density n_e ~1.5–3.0×10^{19} m^{-3}.

Remarkable improvements in this initial decent target FRC formation are: forming/translating more energetic FRC (CT plasmoid), much faster translation velocity (relative speed of two colliding FRCs gets up to ~1000 km/s), and very flexible and wide range of operations. 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 seen in C-2/2U [3,15]. 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 in C-2W. Figure 4(a) shows initial T_e profiles, measured by multipoint Thomson scattering system and obtained right after FRC collision/merging in typical C-2/2U and C-2W experiments. The 250+ eV T_e profile (T_{tot} exceeding 1.5 keV) in C-2W is testament to the improved initial FRC conditions produced by the upgraded formation pulsed-power systems. Time evolution of n_e profile measured by 14-chord FIR interferometer is shown in Fig. 4(b) that clearly exhibits the expected hollowness of the radial density profile, corroborating a typical FRC structure. Plasma behaviour inside the CV is also visually monitored by side-on fast-flaming camera as illustrated in Fig. 5(a), which has a wide field of view to see almost entire FRC plasma, and one example image (with oxygen-V line bandpass filter) of typical plasma discharge at t ~1 ms is shown in Fig. 5(b). Football-shaped FRC plasma emission in the CV is clearly seen, and the edge of the emission (boundary of hot/cold plasmas) seems to be consistent with the shape/profile of excluded-flux radius measurement.

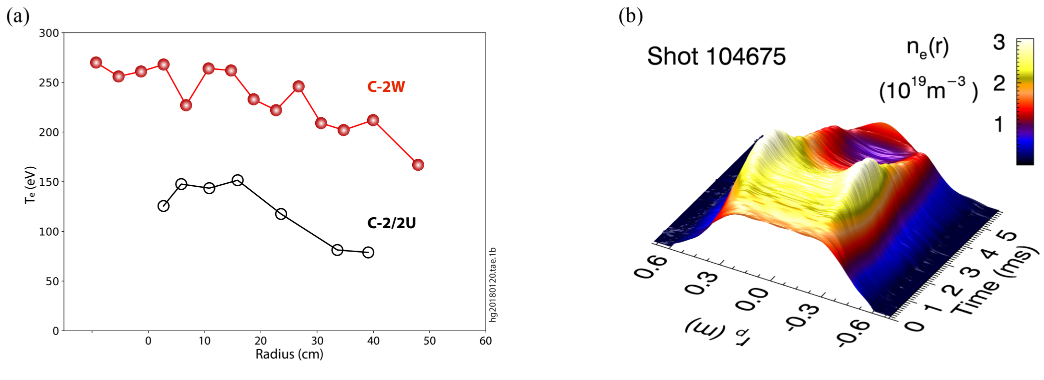

FIG. 4. (a) Electron temperature profiles from midplane Thomson scattering system measured at right after FRC collisional merging (t ~0.05 ms), compared with a typical averaged C-2/2U T_e result; (b) electron density profile time evolution from midplane FIR interferometer in C-2W.

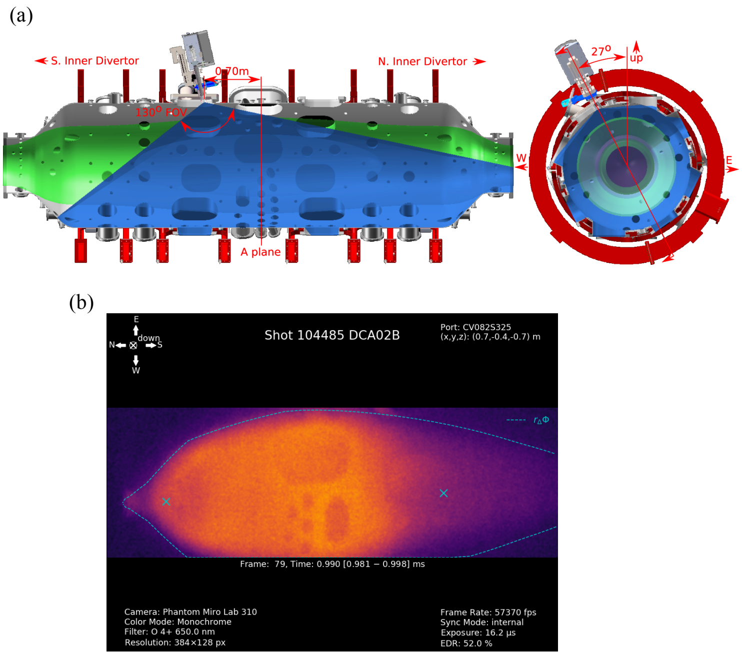

FIG. 5. (a) Illustration of the C-2W CV with fast-framing camera setup and its field of view. (b) Camera image of FRC plasma emission with O-V bandpass filter at t~1 ms in a typical plasma discharge; excluded-flux radius measured by magnetic probes is also overlaid in the image.

In order to effectively inject beam particles into the FRC plasmas without causing too much charge-exchange losses with background neutrals, a titanium gettering system has been deployed inside the CV as well as all 4 divertors for further impurity reduction and additional vacuum pumping capability. Reducing background neutrals outside of the FRC is one of the key elements for better NB injection efficiency. The gettering system inside the CV covers roughly 80% of the total surface area of the inner wall, and has significantly reduced the neutral recycling at the wall as well as greatly improved/reduced impurity content and levels. Newly installed / set up cryo-boxes and titanium arc gettering system with LN_2 cooling system inside divertors have been working great as designed, in which a divertor pumping test indicated that it has achieved up to ~2000 m^3/s pumping capability (for hydrogen) per each divertor. The titanium-arc gettering system can also be operated in between plasma shots/discharges as desired to improve/recover the divertor pumping capability.

As for edge biasing and boundary control on FRC and open-field-line plasmas for stability control, there are several ways/techniques implemented in C-2W divertor areas as described in Sec. 2.1: applying positive or negative voltages/potentials on plasma guns, outer-divertor electrodes, inner-divertor electrodes, and/or funnel limiters relative to the machine ground or even to other biasing systems/points. There are so many different biasing options/configurations using those systems, so mastering the most effective biasing schemes for plasma edge control is one of our most important objectives/milestones to achieve in the C-2W experimental program. Magnetic field at both inner and outer divertors can also be varied by squeezing flux bundles or flaring to change the radial electric field E_r (varying E_r/r), which is important to generate a sufficient $E\times B$ shearing around the FRC separatrix for stability control, and perhaps to contribute to some auxiliary heating on SOL/open-field-line plasmas. Changing magnetic field configuration inside the inner divertors is key to establish a new operating regime that can provide more effective control on SOL/edge plasmas, much closer to the core FRC inside the CV compared to that from outer divertors as can be seen in Fig. 1(c). In the early C-2W experiments the machine was operated as C-2U like configuration, meaning no magnetic field flaring at inner divertor regions, to produce long-lived stable FRC plasmas whose pulse duration has to be long enough in order to transfer edge biasing/control regions from outer to inner divertors. Note that magnetic field switching time (from straight field to flared field configurations) inside inner divertors is about a few milliseconds so that achieving FRC plasma duration of ~5 ms or longer under the no-inner-divertor flaring configuration was one of key early scientific milestones.

Figure 6 shows an example of 3 plasma discharges under different machine configurations with/without edge biasing cases: C-2U like machine configuration (no inner-divertor magnetic-field flaring) with negatively-biased edge control from outer divertors (shot #104989); flared inner-divertor field configuration without active edge biasing at all (shot #107226); and flared inner-divertor field configuration with positively-biased edge control from outer divertors (shot #107322). Under the C-2U like machine configuration using only outer-divertor edge biasing/control, FRC plasma has been successfully lived up to 8+ ms that is long enough plasma duration in order to move to the next operating condition/step, meaning edge biasing/control from inner divertors with magnetic field flaring. During this transition of the operating mode, extensive optimization processes were executed/made on many C-2W subsystems such as pulsed powers, magnets including fast-switching coils inside the inner divertors, edge biasing/control systems and wall conditioning, which resulted in relatively good FRC conditions with higher electron temperature as shown in Fig. 6 (see shots #107226 and #107322). In those inner-divertor operating (field flaring) mode, FRC plasma duration is not quite as long as outer-divertor operating mode because transition of the edge/boundary control regions from outer to inner divertors is not yet adequately performed. However, increase of the initial electron temperature is quite encouraging and promising result in this operation phase 1 before increasing NB input power. Mastering edge biasing/control from the inner divertors is currently our focus in order to further improve core FRC as well as SOL/open-field-line plasmas. Furthermore, upgrade of the NB systems to be tunable energy (15–40 keV) is underway, and the new C-2W operation phase is planned to commence with the fully upgraded NBI system, injecting up to ~21 MW of beam power.

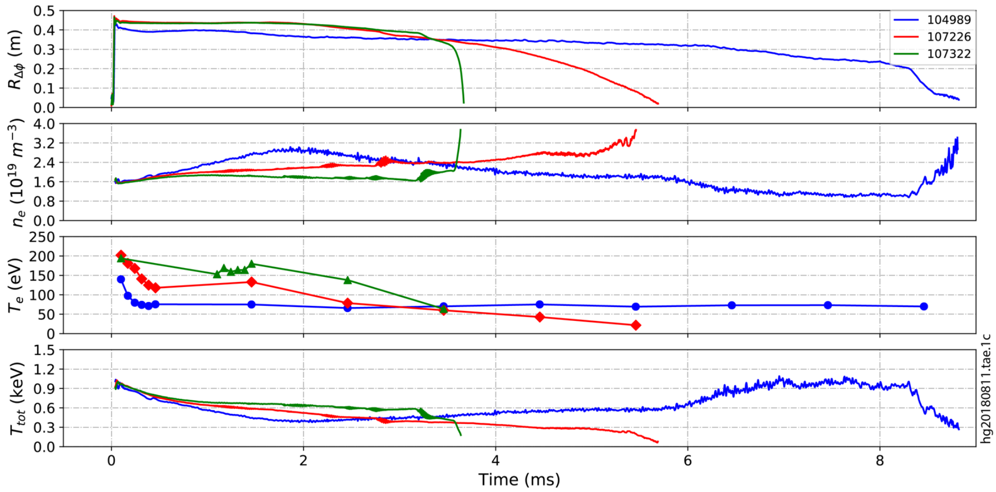

FIG. 6. Typical plasma discharges under different machine configurations: shot #104989 – without inner-divertor magnetic-field flaring with outer-divertor edge biasing, C-2U like configuration; shot #107226 – with field flaring but without edge biasing at all; and shot #107322 – with field flaring and outer-divertor biasing (positively). From the top panel to bottom: excluded-flux radius, electron density, electron temperature, and total temperature.

4. SUMMARY

The C-2W device was newly constructed with substantial various subsystem upgrades from C-2U. C-2W initially demonstrated a robust FRC formation and translation through the newly installed inner divertor with adequate guide magnetic field, and produced dramatically improved initial FRC plasma states/conditions after merging of the two colliding FRCs (relative speed of collision up to ~1000 km/s) as expected from the system upgrades. The merged initial FRC state exhibited much higher plasma temperatures (T_e up to ~300 eV, T_{tot} exceeding 1.5 keV). Stable, long-lived FRC plasmas were obtained by effective edge/boundary control and NBI. Under outer-divertor operation condition (without flaring magnetic field at inner divertor regions) like C-2U configuration, FRC achieved ~9 ms plasma lifetime which is equivalent to C-2U performance. Under inner-divertor operating condition with magnetic field flaring, electron temperature inside FRC appeared to stay hot and increase for a short time. The C-2W NB system is being upgraded further to be able to ramp up injection energy, at which the total injection power goes up to ~21 MW and then FRC plasma pressure is expected to ramp up as well in the next operation phase.

ACKNOWLEDGEMENTS

The authors wish to thank the entire TAE Team for their dedicated work and effort on the C-2W project, our Budker Institute colleagues for many key contributions to our experiments and neutral beam development, other external collaborators including Google, and our shareholders who made this exciting research effort possible.

REFERENCES

[1] TUSZEWSKI, M., Nucl. Fusion **28**, 2033 (1988).
[2] STEINHAUER, L.C., Phys. Plasmas **18**, 070501 (2011).
[3] BINDERBAUER, M.W., *et al.*, Phys. Rev. Lett. **105**, 045003 (2010).
[4] BINDERBAUER, M.W., *et al.*, Phys. Plasmas **22**, 056110 (2015).
[5] BINDERBAUER, M.W., *et al.*, AIP Conf. Proc. **1721**, 030003 (2016).
[6] GOTA, H., *et al.*, Nucl. Fusion **57**, 116021 (2017).
[7] TUSZEWSKI, M., *et al.*, Phys. Rev. Lett. **108**, 255008 (2012).
[8] GOTA, H., *et al*., Fusion Sci. Technol. **68**, 44 (2015).
[9] GUO, H.Y., *et al.*, Nature Communications **6**, 6897 (2015).
[10] REJ, D.J. and TUSZEWSKI, M., Phys. Fluids **27**, 1514 (1984).
[11] TRASK, E., *et al*., Bull. Am. Phys. Soc., CP10.00064 (2016).
[12] KAYE, S.M., *et al.*, Nucl. Fusion **47**, 499 (2007).
[13] KAYE, S.M., *et al.*, Nucl. Fusion **53**, 063005 (2013).
[14] GALEOTTI, L., *et al.*, Phys. Plasmas **18**, 082509 (2011).
[15] GUO, H.Y., *et al.*, Phys. Plasmas **18**, 056110 (2011).
[16] MATSUMOTO, T., *et al.*, Rev. Sci. Instrum. **87**, 053512 (2016).
[17] ASAI, T., *et al.*, Nucl. Fusion **57**, 076018 (2017).
[18] VINYER, I.V., Instruments and Experimental Techniques **57**, 508 (2014).
[19] THOMPSON, M.C., *et al*., Rev. Sci. Instrum. **87**, 11D435 (2016).
[20] ROCHE, T., *et al*., Rev. Sci. Instrum. **89**, 10J107 (2018).
[21] DUBOIS, A., *et al.*, Rev. Sci. Instrum. **89**, 10J115 (2018).
[22] DENG, B.H., *et al.*, Rev. Sci. Instrum. **89**, 10B109 (2018).
[23] ZHAI, K., *et al.*, "Thomson scattering systems on C-2W field-reversed configuration plasma experiment," Rev. Sci. Instrum. (2018) in press.
[24] SCHMITZ, L., *et al.*, "Combination Doppler Backscattering/Cross-Polarization Scattering Diagnostic for the C-2W Field-Reversed Configuration," Rev. Sci. Instrum. submitted.
[25] GRISWOLD. M.E., *et al.*, Rev. Sci. Instrum. **89**, 10J110 (2018).
[26] TITUS, J., *et al.*, "Secondary Electron Emission Detectors for Neutral Beam Characterization on C-2W," Rev. Sci. Instrum. (2018) in press.
[27] GRANSTEDT, E.M., *et al.*, Rev. Sci. Instrum. **89**, 10E103 (2018).
[28] THOMPSON, M.C., *et al*., "Integrated Diagnostic and Data Analysis System of the C-2W Advanced Beam-Driven Field-Reversed Configuration Plasma Experiment," Rev. Sci. Instrum. (2018) in press.