Achievement of Field-Reversed Configuration Plasma Sustainment via 10 MW Neutral-Beam Injection on the C-2U Device

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The world's largest compact-toroid device, C-2, has been upgraded to C-2U at Tri Alpha Energy to achieve sustainment of field-reversed configuration (FRC) plasmas by neutral-beam (NB) injection (NBI) and edge biasing [1, 2], and the C-2U experiment is characterized by the following key system upgrades: increased total NB input power from ~4 MW (20 keV hydrogen) to 10+ MW (15 keV hydrogen) with tilted injection angle; enhanced edge-biasing capability inside of each end-divertor for boundary and stability control. C-2U experiments with those upgraded systems have successfully demonstrated dramatic improvements in FRC performance. As anticipated, there are strong effects of the upgraded NB injectors on FRC performance such as: i) rapid and strong accumulation of fast ions (about a half of initial thermal pressure replaced by fast-ion pressure); ii) fast-ion footprint largely determines FRC dimensions; iii) double-humped electron density and temperature profiles; iv) FRC lifetime and global plasma stability scale strongly with NBI power; and v) plasma performance correlates with NB pulse duration in which diamagnetism persists several milliseconds after NB termination due to accumulated fast ions. The key accomplishment on C-2U is sustainment of advanced beam-driven FRCs with a macroscopically stable and hot plasma state for up to 5+ ms, limited only by hardware and stored energy constraints such as the NBs' pulse duration (flat-top ~8 ms) and current sourcing capability of end-on plasma guns. Furthermore, plasma diamagnetism in the best discharges has reached record lifetimes of over 11 ms, timescales twice as long as C-2. In this regime fast ions are well trapped and nearly classically confined, suppressing broadband magnetic turbulence as well as enhancing fusion reactivity via beam driven collective effects. Density fluctuations near the separatrix and in the scrape-off layer have also been dramatically suppressed by a combination of NBI and $E \times B$ shearing via plasma-gun edge biasing, thereby improving confinement properties. The demonstrated sustainment of beam-driven FRCs in C-2U is an extraordinary achievement for the FRC and innovative confinement concepts communities, and may lead to intriguing possibilities for fusion reactors.

References

[1] M. Tuszewski, *et al.*, Phys. Rev. Lett. **108**, 255008 (2012).
[2] M. W. Binderbauer, *et al.*, Phys. Plasmas **22**, 056110 (2015).

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Abstract. Tri Alpha Energy's experimental program has demonstrated reliable field-reversed configuration (FRC) formation and sustainment, driven by fast ions via high-power neutral-beam (NB) injection. The world's largest compact-toroid device C-2U was upgraded from C-2 with the following key system upgrades: increased total NB input power from ~4 MW (20 keV hydrogen) to 10+ MW (15 keV hydrogen) with tilted injection angle; enhanced edge-biasing capability inside of each end divertor for boundary/stability control. C-2U experiments with those upgraded systems have successfully demonstrated dramatic improvements in FRC performance and sustained advanced beam-driven FRCs with a macroscopically stable and hot plasma state for up to 5+ ms, in which the plasma diamagnetism in the best discharges has reached record lifetimes of over 11 ms, timescales twice as long as C-2. Our zero-dimensional power balance analysis shows substantial improvements in equilibrium and transport parameters, in which electron energy confinement time strongly correlates with electron temperature. The demonstrated sustainment of beam-driven FRCs in C-2U is an extraordinary achievement for the FRC and innovative confinement concepts communities, and may lead to intriguing possibilities for fusion reactors.

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 solenoidal coils located outside of a simply connected vacuum vessel. The averaged beta value of FRCs is nearly unity: $\langle\beta\rangle = 2\mu_0\langle p\rangle/B_e^2$ ~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. Another attractive feature of the FRC is its potential for a fusion reactor with low-cost construction due to the simple geometry, and FRCs may also allow the use of advanced, aneutronic fuels such as D-^{3}He and p-^{11}B.

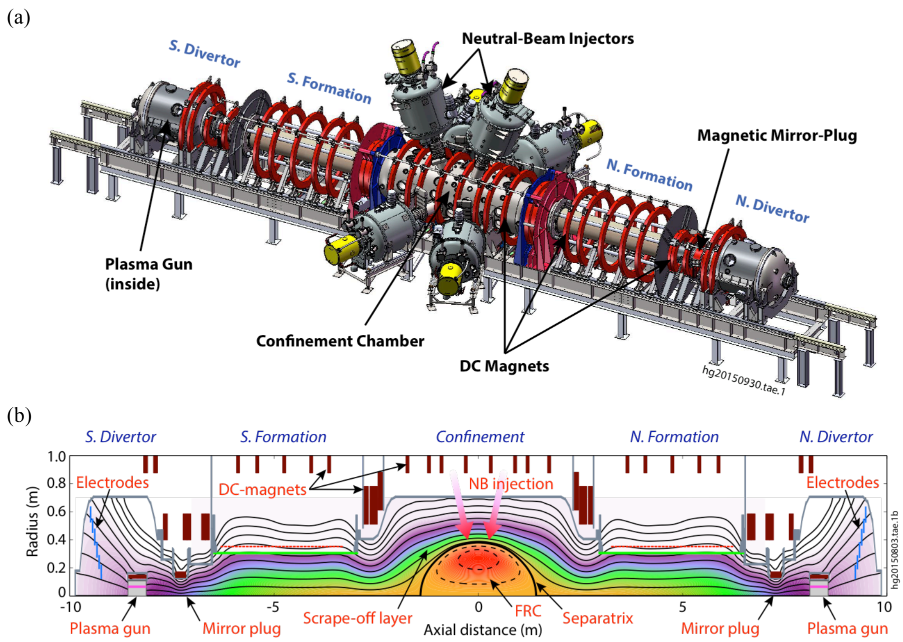

FIG. 1. (a) C-2U experimental device, (b) Sketch of FRC magnetic topology and density contours, simulated by the 2-D MHD LamyRidge equilibrium code.

Studying aspects of FRC plasma sustainment by neutral-beam (NB) injection (NBI) and additional particle fueling is the main goal of C-2 / C-2U experiments at Tri Alpha Energy. The world's largest CT device, C-2 [3], has been upgraded to C-2U [4] (illustrated in Fig. 1) to achieve sustainment of FRC plasmas by NBI and edge biasing. One of the key accomplishments of the C-2 experiments was the demonstration of the high-performance FRC (HPF) regime, which is set apart by dramatic improvements in confinement and stability compared to other FRC devices [4-7]. C-2's HPF plasma discharges have also demonstrated increasing plasma pressure and electron temperature, which indicates an accumulation of fast ions as well as plasma heating by NBI. Electrically biased end-on plasma guns and effective in-vessel wall-surface conditioning also played important roles in producing HPF plasmas, synergetically with NBI.

In order to enhance fast-ion effects and further improve FRC performance towards plasma sustainment, the C-2U experiment is characterized by the following key system upgrades: increased total NB input power from ~4 MW (20 keV hydrogen) to 10+ MW (15 keV hydrogen) with tilted injection angle as shown in Fig. 1, and enhanced edge-biasing capability inside of each end-divertor for boundary/stability control. The upgraded NB system (higher NB input power with high current at lower beam energy, angled and tangential co-current injection) alone has demonstrated significant advantages and had a profound impact on C-2U performance: e.g. reduction of peripheral fast-ion losses; increased core heating; rapidly established dominant fast-ion pressure; better NB plasma coupling and reduced shine-through losses; and current drive.

In fact, C-2U experiments with upgraded NBI and edge-biasing systems exhibit far better FRC performance than obtained in C-2 HPF regimes [8]. As anticipated, there are strong effects of the considerable fast particle population: (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. The key accomplishment on C-2U is sustainment of advanced beam-driven FRCs with a macroscopically stable and hot plasma state for up to 5+ ms, limited only by hardware and stored energy constraints such as the NB's pulse duration and current sourcing capability of end-on plasma guns. In this well-sustained FRC regime fast ions are almost classically confined and then suppressing broadband magnetic turbulence as well as density fluctuations near the separatrix and in the scrape-off layer (SOL) by a combination of NBI and $E \times B$ shearing via plasma-gun edge biasing, thereby improving confinement properties [9]. There appears to be a strong positive correlation between T_e and energy confinement time, and particle confinement time is more than 10× greater than that of conventional FRC scaling predictions [10].

In this paper, C-2U experimental apparatus and diagnostic suite are described in Section 2. Key systems / elements to obtain HPF operating condition as well as detailed characteristics of newly-obtained advanced beam-driven FRCs are described in Section 3; in addition, key C-2U experimental results including plasma sustainment are also discussed. Lastly, a summary is provided in Section 4.

2. C-2U Experimental Device and Diagnostic Suite

The C-2U device, shown in Fig. 1(a), is a large theta-pinch, CT-merging system, built at Tri Alpha Energy to form relatively high flux, high temperature FRC plasmas [4,8]. Figure 1(b) illustrates typical FRC magnetic flux and density contours in the C-2U device; these contours are obtained from a two-dimensional magnetohydrodynamic (MHD) numerical simulation performed with the LamyRidge equilibrium code. The C-2U device has ~20 m in overall length and consists of a central confinement region surrounded by two field-reversed theta-pinch (FRTP) formation sources and two divertors. The stainless-steel confinement chamber (inner-wall radius, r_w ~0.7 m) approximately conserves magnetic flux inside the vessel wall; however, for long-lived plasma discharges magnetic-flux leakage needs to be taken into account for accurate magnetic-field calculations and other associated and post-processed plasma/physics parameter calculations. The formation tubes are made of quartz, which are approximately 3.5-m long and 0.6-m in diameter; the C-2U vacuum vessel accommodates ultrahigh vacuum. A set of DC magnets generates a quasi-static axial magnetic field, B_z, throughout the device, for which we can arrange a coil/power-supply configuration to control the axial-field profile and amplitude. The typical magnetic field is B_z ~0.1 T in the confinement region with an end-mirror ratio of 3.0–3.5. There are magnetic mirror plugs in between the formation and divertor sections at each side that can produce a strong magnetic field up to ~1.5 T, which corresponds to a plug-mirror ratio of ~15 compared to the central confinement section. The mirror plugs play an important role in contributing to the open-field-line plasma confinement as well as assisting plasma-gun operation inside of the end divertors. As shown in Fig. 1(b), two coaxial plasma guns are located on axis inside of each divertor, and there are concentric annular electrodes behind the plasma guns to control open-field-line connection/contact to divertor vessel wall. Both, plasma guns and electrodes, are important for edge biasing as well as radial electric field control in C-2U. Six brand new C-2U NB injectors, located in the confinement vessel, were substituted for those used in C-2, comprising the following key changes: increased total NB input power from ~4 MW (20 keV hydrogen) to 10+ MW (15 keV hydrogen) with higher current at lower beam energy; tilted NB injection angle in a range of 65°–75° relative to the machine axis to improve coupling between the beams and the target FRC plasma.

The C-2U device has more than 60 diagnostic systems installed on the confinement vessel, formation sections, and divertor regions to investigate FRC plasma performance and behaviors as well as to characterize the machine operating state. The diagnostic suite of C-2U [11] consists of a foundation set of instruments inherited from the preceeding C-2 program [12] along with a few new systems and a number of enhancements and upgrades. Much of the expansion and improvements were driven by an increased interest in the open-field-line plasma, which has a large impact on the core FRC and overall system performance. Signals and data from individual diagnostics are transferred to a data-acquisition (DAQ) system that acquires over 1000 channels on every C-2U discharge. The acquired raw data is generally post-processed into plasma parameters and then stored on databases such as MDS+ and MySQL for further data analysis. On typical C-2U discharges data greater than 0.5 gigabytes is generated after each shot, including analysis movies and computations. Data on the FRC plasma performance is provided by a comprehensive suite of diagnostics that includes magnetic sensors, Langmuir probes, interferometry, Thomson scattering, VUV/visible/IR spectroscopy, bolometry, reflectometry, neutral particle analyzers, fusion product detectors, multi-chord far-infrared polarimetry, and multiple fast imaging cameras. 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.

3. C-2U Experimental Results

3.1. Advanced Beam-Driven FRC Regime

A high-performance FRC equilibrium state was firstly obtained/achieved in the C-2 device. To achieve HPF operating conditions the following key approaches, as illustrated in Fig. 2, are necessary: (i) dynamically colliding and merging two oppositely directed CTs for robust FRC formation; (ii) active vessel-wall conditioning using titanium and/or lithium gettering systems for background neutral and impurity reduction; (iii) effective control and edge plasma biasing near the FRC separatrix via end-on plasma guns and concentric ring electrodes inside divertors; and (iv) NB injection into FRCs for current drive and heating. The main characteristics of the C-2 HPF regime include: macroscopically stable plasma discharges, dramatically reduced transport rates (up to an order of magnitude lower than the non-HPF regime), long-lived and record diamagnetism lifetimes, and emerging global energy confinement scaling with strongly favorable temperature dependence [4]. In order to enhance fast-ion effects by NBI and further improve FRC performance towards plasma sustainment, the C-2 device was upgraded to C-2U with the following key system upgrades: increased total NB input power with tilted injection angle, enhanced edge-biasing capability inside of each end-divertor for boundary/stability control, and optimized axial magnetic-field profile and amplitude in the confinement and formation sections. The key systems/elements for HPF operating conditions are basically the same in both C-2/C-2U experiments, but significantly upgraded NB and edge-biasing systems as well as extensive FRC/system optimization processes led to further improved FRC performance, ultimately showcasing an

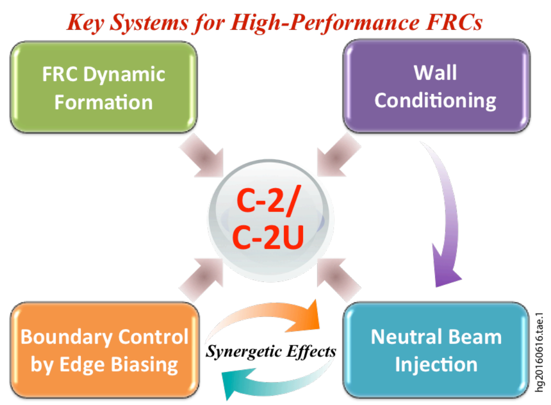

FIG. 2. Key approaches to obtain HPF regimes in C-2/C-2U experiments.

"advanced beam-driven FRC" equilibrium state in C-2U.

In C-2/C-2U experiments FRCs are produced/formed by colliding and merging two oppositely-directed CTs using FRTP scheme in the formation sections; this flexible, well controllable dynamic FRC formation technique [3] allows to form various initial target FRC plasma states for performance characterizations including NBI optimization. Typical FRC plasma states right after the CT-collisional-merging process have the following plasma properties: excluded-flux radius ~0.35 m, length ~3 m, rigid-rotor poloidal flux ~5–7 mWb, total temperature (T_i+T_e) up to ~1 keV, and electron density ~2–3×10^{19} m^{-3}.

In order to effectively inject beam particles into the FRC plasmas, a titanium gettering system has been deployed in the C-2U confinement chamber as well as in the divertors for further impurity reduction and additional vacuum pumping. Reducing background neutrals outside of the FRC is one of the key elements for better NB injection efficiency with mitigated charge-exchange losses. The gettering system covers over 80% of the total surface area of the inner vessel wall and has significantly reduced the neutral recycling by a factor of 4–5 compared to operation without wall conditioning.

Another key component for good FRC performance and further improvement of NBI effects is edge/boundary control. To this end, two plasma guns are mounted inside of each divertor and produce a hot (T_e ~30–50 eV, T_i ~100 eV) tenuous (~10^{18} m^{-3}) plasma stream. The guns also create an inward radial electric field (E_r < 0) that counters the usual FRC spin-up in the ion diamagnetic direction and mitigates the n=2 rotational instability without applying quadrupole magnetic fields. Furthermore, we typically apply a negative potential (about –1 kV) on the central electrode of each plasma gun to enhance the edge-biasing capability for stability control. The electrically-biased plasma guns also produce E×B velocity shear just outside of FRC separatrix, yielding improved FRC confinement properties and stability. Better plasma centering (less n=1 wobble motion) is also obtained from line-tying to the plasma-gun electrodes. Hence, NBs are injected into near-axisymmetric FRC discharges, which improves fast-ion confinement inside the FRCs.

The C-2U NBs (total injected power up to 10+ MW, 15 keV hydrogen) are injected tangentially to the FRC current (co-injection) at an angle of 70° (relative to the machine axis) and with an average radial impact parameter of 0.19 m, which permits current drive. The fast ions, created primarily by charge exchange, have large betatron orbits that add to the FRC azimuthal current, and the strong fast-ion population significantly improves FRC stability and confinement properties. Initial FRC parameters, obtained through dynamic CT-collisional-merging formation, are suitable for NB capture (shine-through and first orbit losses < 10%) and for fast-ion confinement; there is a significant and faster beam-ion build-up due to the ~10 MW NBI (compared to C-2's ~4 MW NBI) right from the

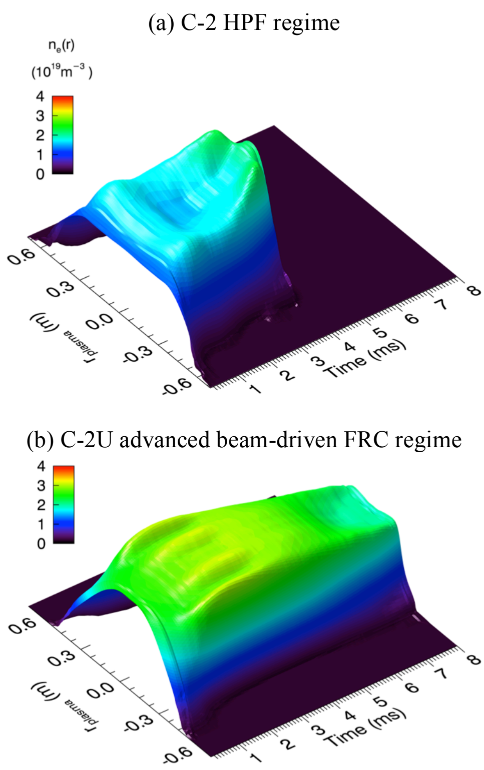

FIG. 3. Typical time evolutions of radial electron density profile in (a) C-2 and (b) C-2U. The plots are obtained from a large ensemble of similar plasma discharges.

beginning of the plasma discharges in C-2U. After a few milliseconds the fast-ion pressure becomes comparable to the plasma pressure. Comparing equilibrium density profiles in C-2 HPF and C-2U advanced beam-driven FRCs readily demonstrates the significant difference produced by the fast-ion pressure. Typical time evolutions of the radial electron density profiles in C-2/C-2U experiments are illustrated in Fig. 3. While the overall plasma radius in C-2U is not very different from C-2, there is a clear difference around the field-null radius (r_{null} ~0.25 m) with the appearance of a "double-humped" structure on top of the typical hollow center and steep separatrix gradients; the two density peaks are located on either side of the null field radius. This feature is indicative of the presence of the substantial fast-ion pressure in C-2U. The radial betatron oscillations of the fast ions lead to a broad fast-ion distribution that modifies the electron profiles accordingly. Together with other key elements of the beam-driven FRC regime and improvements described above, this upgraded NB system had a profound positive impact on C-2U performance: e.g. reduction of peripheral fast-ion losses, increased core heating, better NB-to-FRC coupling and reduced shine-through losses, and current drive.

The fast ions injected by the NBs travel both inside and outside of the FRC separatrix in large betatron orbits and slow down in a few milliseconds. Since there is a large interdependence between the FRC core and open-field-line / SOL plasma in terms of the particle and energy transport processes, improving confinement properties in the SOL is as important as in the core region, especially with the presence of large-orbit fast ions. A good example can be seen in Fig. 5 of Ref. 8 where the electron temperature in the FRC core was increased by 20–30% (on average throughout the discharge) due to magnetic-field expansion in the divertor area. Field expansion can cause different field-lines / flux-surfaces to make contact with the end-on plasma guns, thereby creating stronger E_r/r near the separatrix. The field expansion may also produce some thermal insulation for the SOL electron population. These improvements in the open-field-line region could explain the observed improvement in plasma confinement and higher electron temperature in the FRC core.

3.2.Process and Achievement of Plasma Sustainment

The primary goal of the C-2 experiments was to study and develop the physics of beam-driven FRC plasma states; while, the mail goal of C-2U experiments was to demonstrate current drive and plasma sustainment by NBI in excess of all characteristics system timescales. Extensive experimental and computational evidence has shown that super-thermal ions slow down and diffuse nearly classically, even in the presence of turbulent fluctuations that drive anomalous transport of the thermal plasma.

In C-2U's advanced beam-driven FRC regime fast ions are well trapped and nearly classically confined, suppressing broadband magnetic turbulence as well as enhancing fusion reactivity via beam driven collective effects. In addition, density fluctuations near the separatrix and in the SOL have also been dramatically suppressed by a combination of NBI and $E{\times}B$ shearing via plasma-gun edge biasing, thereby improving global confinement properties [9].

Our previous experimental device, C-2, had initially no NBI or edge-biasing capabilities and produced ~1 ms FRC plasma lifetime, as shown in Fig. 4; the lifetime was limited by MHD instabilities such as n=1 and 2 modes. After extensive experimental runs with FRC / system optimization processes, C-2 produced HPF plasma regimes by combined effects of plasma-gun edge biasing and ~4 MW NBI; C-2's best performing operating regime, HPF14, successfully demonstrated increasing plasma pressure and electron temperature, which indicates an accumulation of fast ions as well as plasma heating by NBI [4]. Under these well-confined, stable and long-lived HPF conditions in C-2, we observed a clear correlation

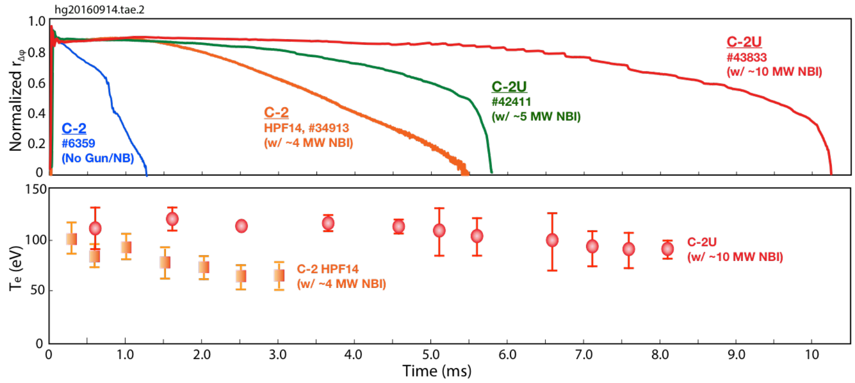

FIG. 4. Top: Normalized excluded-flux radius evolutions in C-2 and C-2U experiments. Bottom: time evolutions of FRC-core electron temperatures under C-2 HPF14 (squares) and C-2U w/ 10 MW NBI (circles) regimes; T_e, measured by multipoint Thomson scattering system in the midplane, is averaged inside the separatrix as well as shot averaged for each data set.

between NB input power and FRC performance, particularly in the improved energy decay time and FRC plasma lifetime. Our in-house 1-D and 2-D transport simulations, Q1D and Q2D, also indicated a high probability of FRC plasma sustainment with an appropriate upgrade of the NB injector systems. This was the initial motivation for the C-2U project to demonstrate FRC plasma sustainment.

The C-2U experimental program commenced with various upgraded systems as previously described. The increased NB input power (higher current at reduced beam energy) and tilted beam-injection angle were the biggest changes from C-2. However, even with a reduced NBI power of ~5 MW the C-2U FRC performance already showed significant improvements in many aspects, in particular plasma lifetime as seen in Fig. 4. It implicitly indicates that other upgraded systems (e.g. edge biasing capability) and optimized operating conditions (e.g. external axial magnetic-field profile) have also contributed to this performance improvement. Furthermore, C-2U shots with ~10 MW NBI increased FRC performance even further and ultimately achieved sustainment of plasma radius and electron temperature in the first 5 milliseconds, as can be seen in Fig. 4; under the best/optimum operating condition, the plasma diamagnetism even reached record lifetimes of over 11 ms, timescales twice as long as C-2.

Both C-2 and C-2U experiments achieved great improvements in FRC performance, as evidenced by the temporal evolution of the excluded-flux radius and electron temperature in Fig. 4. The plasma radius in C-2U w/ ~10 MW NBI is essentially being kept constant for ~5+ ms, while there is instantaneous decay associated with all other traces from C-2 (w/ no-Gun/NBI, ~4 MW NBI) and C-2U (w/ ~5 MW NBI), although there is an indication of improved decay rate with higher NBI powers; ~5 ms sustainment of some of other critical plasma quantities such as plasma density and temperatures has also been observed in C-2U with ~10 MW NBI. The C-2U plasma performance, including the sustainment feature, has a strong correlation with NB pulse duration, with the diamagnetism persisting even several milliseconds after NB termination due to the accumulated fast ions. Note that the performance in C-2U is only limited by pulse-length constraints arising from finite stored energies in the power supplies of many critical systems, such as NB injectors (flat-top duration ~8 ms) and edge-biasing equipment (pulse duration ~5–7 ms depending on discharged current/energy from the plasma-gun electrode during a shot).

Under the well-confined FRC regimes, such as HPF and advance beam-driven FRC in C-2/C-2U, and after careful 0-D global power-balance analysis [13,14], there appears to be a strong positive correlation between electron temperature and energy confinement time. Our power-balance analysis, detailing loss channel characteristics and plasma timescales, shows substantial improvements in equilibrium and transport parameters. Previously reported T_e scaling of the confinement time from C-2 experiment [see Fig. 27 in Ref. 4], $\tau_{E,e} \propto T_e^{1.6}$ where $\tau_{E,e}$ is electron energy confinement time, still continues at the higher electron temperature range in C-2U. This very attractive scaling result, paired with the considerable accomplishment of plasma sustainment obtained in C-2U, may lead to intriguing possibilities for possible future FRC-based fusion reactors.

4. Summary

The C-2U experimental program commenced with various key system upgrades from C-2, which include increased total NB input power to ~10+ MW (15 keV hydrogen, higher current at reduced beam energy), tilted injection angle and enhanced edge-biasing capability for boundary/stability control. The upgraded NBI system enabled significant plasma performance advances and had a profound impact on C-2U performance: e.g. reduction of peripheral fast-ion losses; increased core heating; rapidly established dominant fast-ion pressure; better NB plasma coupling with reduced shine-through losses; and current drive. Under optimum C-2U operating conditions, plasma sustainment for ~5+ ms was successfully achieved, in which the performance is limited only by hardware and stored energy constraints such as the NBs' pulse duration and the current sourcing capability of the end-on plasma guns.

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[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] TUSZEWSKI, M., *et al.*, Phys. Rev. Lett. **108**, 255008 (2012).

[6] GOTA, H., *et al.*, Fusion Sci. Technol. **68**, 44 (2015).

[7] GUO, H.Y., *et al.*, Nature Communications **6**, 6897 (2015).

[8] BINDERBAUER, M.W., *et al.*, AIP Conference Proceedings **1721**, 030003 (2016).

[9] SCHMITZ, L., *et al.*, "First Evidence of Suppressed Ion-scale Turbulence in a Hot High-β Plasma", Nature Communications (in press).

[10] HOFFMAN, A.L. and SLOUGH, J.T., Nucl. Fusion **33**, 27 (1993).

[11] THOMPSON, M.C., *et al.*, Rev. Sci. Instrum. **87**, 11D435 (2016).

[12] GOTA, H., *et al.*, Rev. Sci. Instrum. **85**, 11D836 (2014).

[13] REJ, D.J. and TUSZEWSKI, M., Phys. Fluids **27**, 1514 (1984).

[14] TRASK, E., *et al.*, Bull. Am. Phys. Soc., UP8.00018 (2014).