



# Achievement of field-reversed configuration plasma sustainment via 10 MW neutral-beam injection on the C-2U device

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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 achieved sustainment of advanced beam-driven FRCs with a macroscopically stable and hot plasma state for up to 5+ ms. Plasma diamagnetism in the best discharges has reached record lifetimes of over 11 ms, timescales twice as long as C-2. 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-ion population by NB injection. Power balance analysis shows substantial improvements in equilibrium and transport parameters, whereby electron energy confinement time strongly correlates with electron temperature; i.e. the confinement time in C-2U scales strongly with a positive power of  $T_e$ .

Keywords: field-reversed configuration, compact toroid, neutral-beam injection, current drive, plasma sustainment, aneutronic fusion

(Some figures may appear in colour only in the online journal)

## 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 near unity:  $\langle\beta\rangle = 2\mu_0\langle p\rangle/B_e^2 \sim 90\%$ , where  $\mu_0$  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 lower-cost construction due to the simple geometry and high magnetic efficiency. FRCs may also provide for the use of advanced, aneutronic fuels such as  $D\text{-}^3\text{He}$  and  $p\text{-}^{11}\text{B}$ .

Studying aspects of FRC plasma sustainment by neutral-beam (NB) injection (NBI) and additional particle fueling are the main goals of the C-2/C-2U experiments at Tri Alpha Energy. The world's largest CT device, C-2 [3], was upgraded to C-2U [4] (illustrated in figure 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 prior FRC experiments [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, synergistically 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  $\sim 4$  MW (20 keV hydrogen) to 10+ MW (15 keV hydrogen) with tilted injection angle as shown in figure 1, and enhanced edge-biasing capability inside of each end-divertor for boundary/stability control. The upgraded NB system (higher NB input power with higher 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-to-FRC coupling and reduced shine-through losses; and current drive.

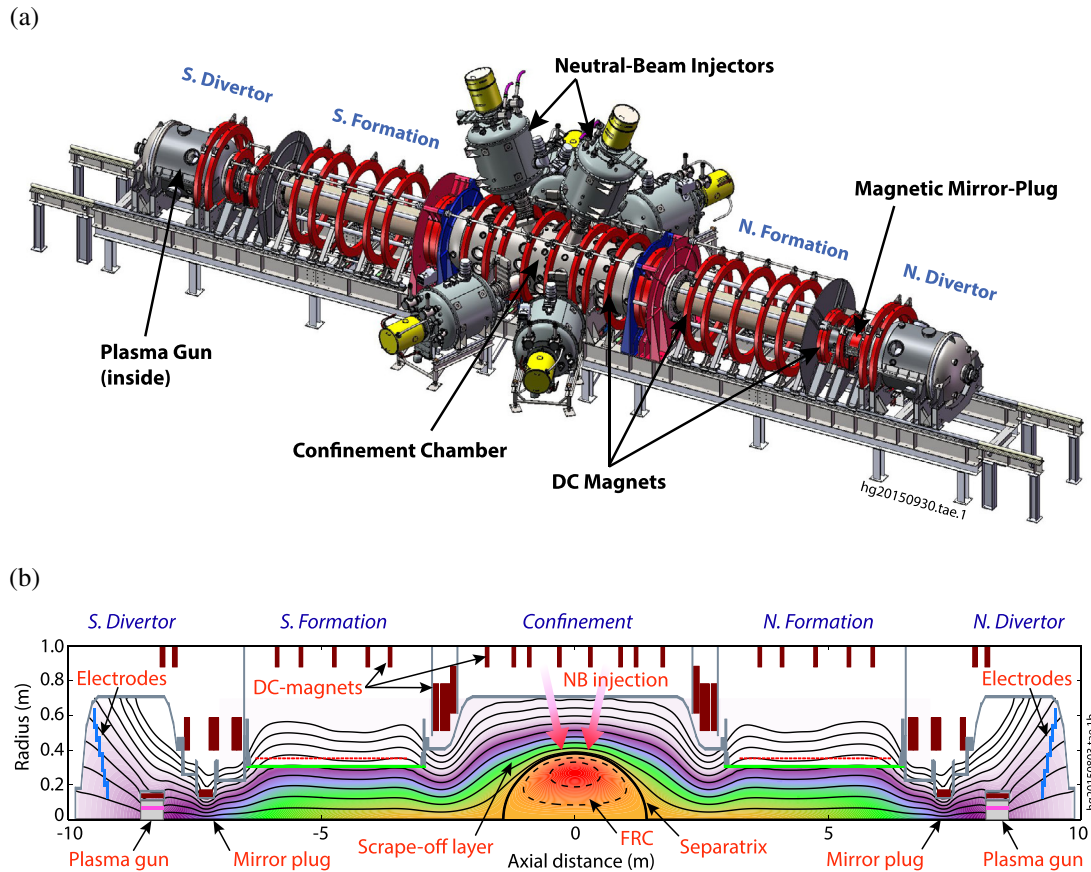
In fact, C-2U experiments with upgraded NBI and edge-biasing systems exhibit far better FRC performance than obtained in C-2 HPF regimes [8]. As anticipated, there are strong effects of the considerable fast-particle population (details can also be seen in [8]): (i) rapid accumulation of fast ions (about 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 (examples shown in figures 11 and 18 of [4] for C-2, and C-2U experiments also show the same trend); 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 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 help to suppress broadband magnetic turbulence. A combination of NBI and  $E \times B$  shearing via plasma-gun edge biasing reduces density fluctuations near the separatrix and in the scrape-off layer (SOL), thereby improving confinement properties [9]. There also appears to be a strong positive correlation between  $T_e$  and the energy confinement time. In addition, the particle confinement time is more than  $10\times$  greater than predicted by the conventional FRC scaling [10].

In this paper, the C-2U experimental apparatus and diagnostic suite are described in section 2. Key system components and operational elements necessary to obtain HPF operating conditions as well as detailed characteristics of the 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

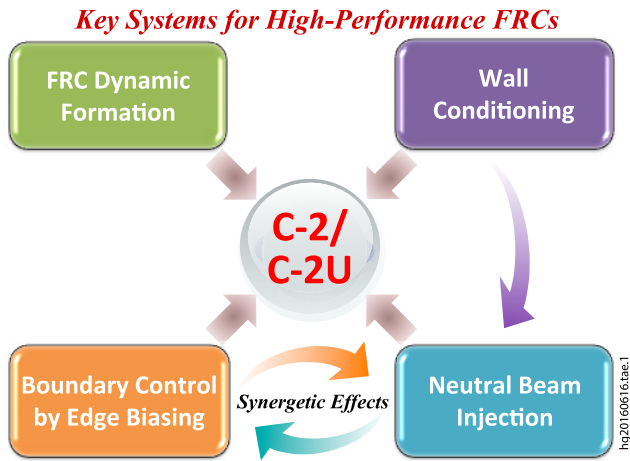
The C-2U device, shown in figure 1(a), is a large theta-pinch, CT-merging system, built by Tri Alpha Energy to form relatively high flux, high temperature FRC plasmas [4, 8]. Figure 1(b) illustrates typical FRC magnetic flux and density contours in the C-2U device. These contours are obtained from a 2D magnetohydrodynamic (MHD) numerical simulation performed with the LamyRidge equilibrium code [11]. The C-2U device has an overall length of  $\sim 20$  m 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,  $r_w \sim 0.7$  m) approximately conserves magnetic flux inside the vessel wall. However, the stainless-steel wall has a skin time of  $\sim 5$  ms so that for long-lived plasma discharges (lifetimes greater than 5 ms) finite magnetic-flux leakage needs to be taken into account for accurate determination of magnetic fields and other associated and post-processed plasma/physics parameters [12]. 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, whereby the axial-field profile and amplitude can be controlled by particular coil/power-supply configurations. The



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

typical magnetic field is  $B_z \sim 0.1$  T in the confinement region with an end-mirror ratio of 3.0–3.5. There are magnetic mirror plugs between the formation and divertor sections at each side that can produce a strong magnetic field up to  $\sim 1.5$  T, which corresponds to a plug-mirror ratio of  $\sim 15$  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 figure 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 with the divertor vessel walls. 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, providing 10+ MW (15 keV hydrogen) of increased total NB input power with higher current at lower beam energy. The upgraded setup also provides the ability for tilted NB injection with angles in the range from  $65^\circ$  to  $75^\circ$  relative to the machine axis and with an average radial impact parameter of 0.19 m; note that C-2's NB system had a perpendicular ( $90^\circ$ ) injection setup in the NB-injection planes at  $z = \pm 0.5$  m. These features improve coupling between the beams and the target FRC plasma, even under pronounced axial FRC shrinkage after a few milliseconds.

The C-2U device has more than 60 diagnostic systems installed along the confinement vessel, formation sections, and divertor regions to investigate FRC plasma performance and behavior as well as to characterize the overall machine operating state. The diagnostic suite of C-2U [13] consists of a fundamental set of instruments inherited from the C-2 program [14] along with a few new systems and a number of significant enhancements and upgrades. Much of the diagnostics expansion and improvements were driven by an increased focus on the open-field-line plasma, which appears to have considerable 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 analysis. Typical C-2U discharges generate over 1 gigabyte of data per shot, including analysis movies and computations. Overall, the C-2U diagnostics suite 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.



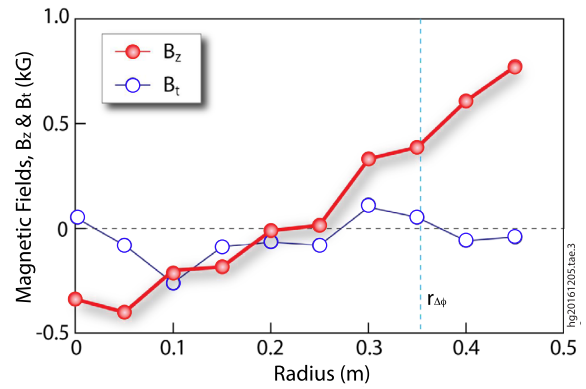
**Figure 2.** Key approaches to obtain HPF and advanced beam-driven FRC regimes in C-2/C-2U experiments.

### 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 [5]. To achieve HPF operating conditions the following key approaches, as illustrated in figure 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 control; (iii) effective control and edge plasma biasing near the FRC separatrix via end-on plasma guns and concentric ring electrodes inside the end divertors; and (iv) NB injection into FRCs for current drive and plasma 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]. While C-2U inherited key systems/elements for HPF operating conditions from C-2, the significantly upgraded NB and edge-biasing systems as well as extensive FRC/system optimization processes led to further improved FRC performance, ultimately showcasing an ‘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 ( $r_{\Delta\phi}$ )  $\sim 0.35$  m, length  $\sim 3$  m, rigid-rotor poloidal flux  $\sim 5$ – $7$  mWb, total temperature ( $T_i + T_e$ ) up to  $\sim 1$  keV, and electron density  $\sim 2$ – $3 \times 10^{19} \text{ m}^{-3}$ . The merged FRC state was directly measured and verified by probing the internal magnetic field structure using a multi-channel magnetic probe array located in the machine midplane ( $z = 0$ ) [15]. Although the internal

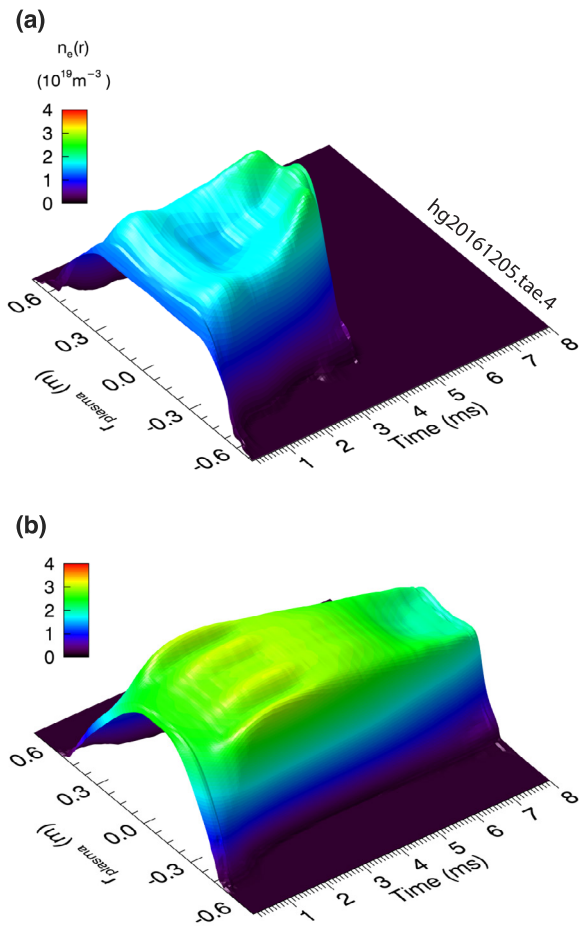


**Figure 3.** Radial profiles of axial and azimuthal magnetic fields,  $B_z(r)$  and  $B_t(r)$ , measured by internal magnetic probe array mounted in the midplane of the confinement vessel.

probe array strongly degrades the FRC performance in terms of its configuration lifetime and radial displacement (offset from the  $z$ -axis), the measured  $B_z$  radial profile clearly shows a field-reversed structure after the CT collisional merging (time around  $100 \mu\text{s}$ ), as shown in figure 3. Each of the two translated plasmoids exhibits significant toroidal fields with opposite helicity, and a residual toroidal magnetic field ( $B_t$ ) appears to at least transiently persist inside the separatrix after merging.

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. In typical C-2U FRCs the dominant impurities without wall conditioning are oxygen, carbon and nitrogen, mainly coming out from the chamber walls and small virtual leaks from trapped volumes inside the vessel. The gettering has significantly reduced the neutral recycling based on deuterium Balmer-alpha emissions ( $\lambda \sim 656 \text{ nm}$ ) by a factor of 4–5 compared to operation without wall conditioning. Most dominant impurity concentrations such as oxygen and carbon are also reduced by orders of magnitude, based on survey spectrometer measurements.

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, as illustrated in figure 1(b) and produce a hot ( $T_e \sim 30$ – $50 \text{ eV}$ ,  $T_i \sim 100 \text{ eV}$ ) tenuous ( $\sim 10^{18} \text{ m}^{-3}$ ) 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 suppresses the toroidal mode  $n = 2$  rotational instability (without applying a quadrupole magnetic field which breaks the FRC azimuthal symmetry and so causes rapid stochastic diffusion of the NB fast-ion orbits). Electrically-biasing of plasma guns and electrodes also produces  $E \times B$  velocity shear just outside of the FRC separatrix, yielding improved FRC confinement properties and stability.



**Figure 4.** 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 using CO<sub>2</sub>/FIR interferometer system located in the machine midplane [18, 19].

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 beam trapping and fast-ion confinement inside the FRCs.

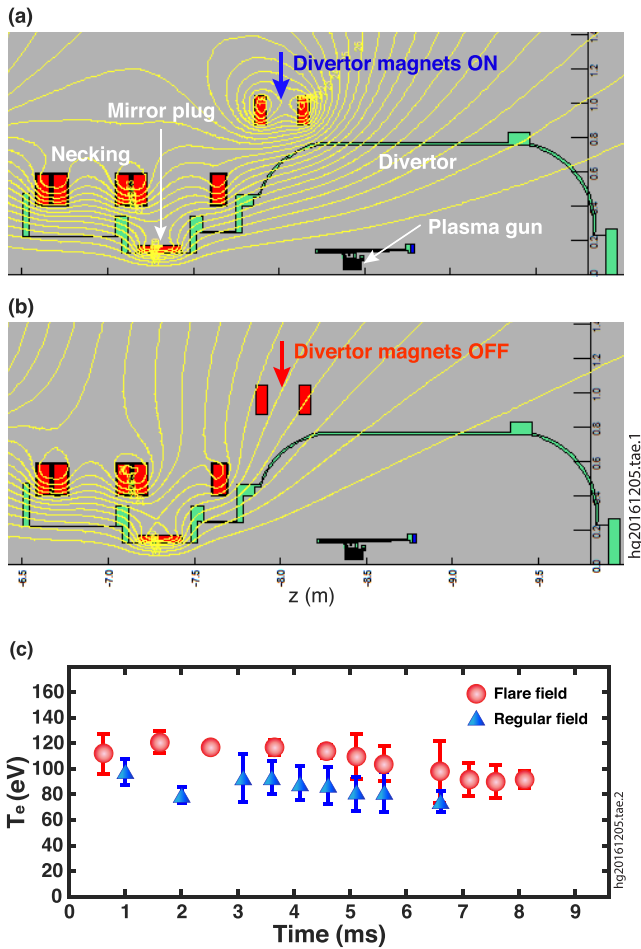
The C-2U NBs are injected tangentially to the FRC current (co-injection) and provide current drive. The fast ions, created primarily by charge exchange, have large betatron orbits that add to the FRC azimuthal current, and the strong fast-ion population significantly improves FRC stability and confinement properties. Initial FRC parameters, obtained through dynamic CT-collisional-merging formation, are well 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 in C-2U due to the  $\sim 10$  MW NBI (compared to C-2's  $\sim 4$  MW NBI) right from the beginning of the plasma discharges. After a few milliseconds the fast-ion pressure becomes comparable to the plasma pressure (example shown in figure 4 of [8]). Once the fast-ion pressure becomes dominant, it is the footprint of the fast ions, as determined by the beam-injection angle and externally applied magnetic field, which determines the axial extent of the FRC [16, 17]. 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 figure 4. 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 ( $r_{\text{null}} \sim 0.25$  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 field-null radius [19]. This feature is indicative of the presence of the substantial fast-ion pressure in C-2U, and Q2D simulations corroborate the ‘double-humped’ profile due to the fast ions [16, 17]. 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 and experimental observation can be seen in figure 5 where the electron temperature in the FRC core is increased by 20–30% (on average throughout the discharge) due to magnetic-field expansion in the end-divertor area. As illustrated in figures 5(a) and (b), turning the set of external divertor magnets ‘ON’ and ‘OFF’ produces either strongly-bundled or widely-flared magnetic flux lines inside the divertors. 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 are well correlated with 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 main 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



**Figure 5.** Magnetic topology of (a) regular and (b) flared magnetic fields in C-2U end divertors; (c) time evolution of core electron temperature under flared (circle) and regular (square) magnetic fields in the divertors.  $T_e$ , measured by multipoint Thomson scattering system in the midplane [20], is averaged inside the separatrix as well as shot averaged for each data set.

enhancing fusion reactivity via beam driven collective effects. In the FRC core, ion-scale turbulence is absent, and only weak electron-scale modes have been detected ( $0.04 \leq k_\theta \rho_e \leq 0.4$ ,  $5 \leq k_\theta \rho_s \leq 50$ , where  $k_\theta$  is toroidal wavenumber,  $\rho_e$  and  $\rho_s$  are the electron gyroradius and the ion sound gyroradius, respectively) by multichannel Doppler Backscattering (DBS) reflectometry [9, 21]; while, in the surrounding boundary layer of the SOL plasma, ion- and electron-scale turbulence is observed once a critical density gradient is exceeded. However, density fluctuations near the separatrix and in the SOL have been dramatically suppressed by a combination of NBI and  $E \times B$  shearing via plasma-gun/electrode edge biasing, thereby improving global confinement properties.

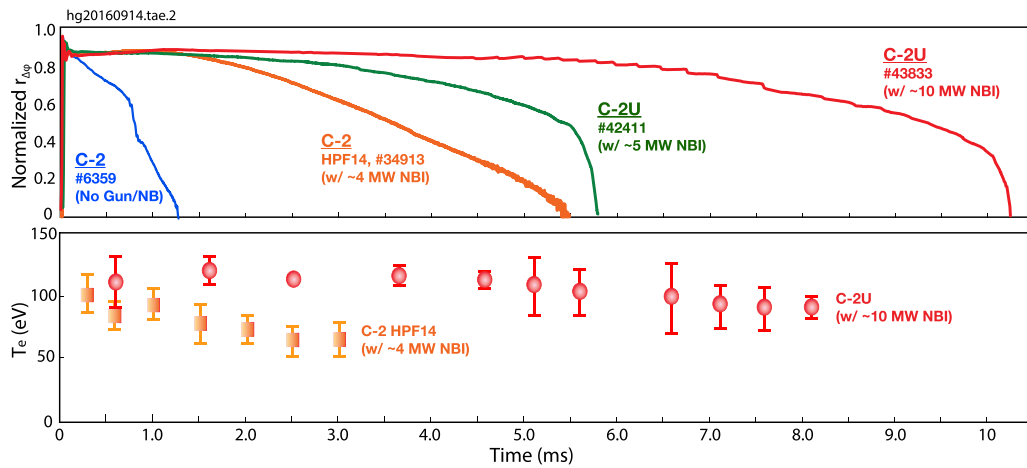
Our previous experimental device, C-2, had initially no NBI or edge-biasing capabilities and could produce only  $\sim 1$  ms FRC plasma lifetime, as seen in figure 6; the lifetime was then limited by MHD instabilities such as  $n = 1$  and 2 modes. After extensive experimental runs with FRC/system optimization processes, C-2 produced HPF plasma regimes by combined effects of plasma-gun edge biasing and  $\sim 4$  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 between NB input power and FRC performance, particularly in the improved energy decay time and FRC plasma lifetime. 1 and 2D transport simulations, Q1D [22] and Q2D [16, 17], 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 with upgraded NB systems.

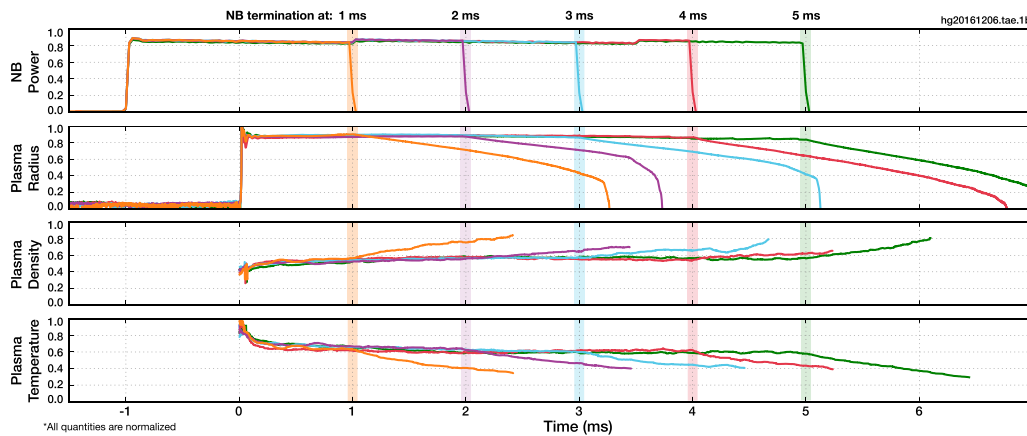
The C-2U experimental program commenced with various upgraded systems as previously described. The increased NB input power (higher current at reduced beam energy) and tilted beam-injection angle were the biggest changes from C-2. However, even with a reduced NBI power at  $\sim 5$  MW the C-2U FRC performance already showed significant improvements in many aspects, in particular plasma decay rate and FRC lifetime as seen in figure 6. 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 in C-2U. Furthermore, C-2U shots with  $\sim 10$  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 figure 6; 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 figure 6. The plasma radius in C-2U w/ $\sim 10$  MW NBI is essentially being kept constant for  $\sim 5+$  ms, while there is instantaneous decay associated with all other traces from C-2 and C-2U w/ $\sim 5$  MW NBI, although there is an indication of improved decay rate with higher NBI powers. Sustainment of  $\sim 5+$  ms of the other critical plasma quantities such as plasma density, temperatures and magnetic flux has also been observed in C-2U with  $\sim 10$  MW NBI. As shown in figure 7, 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-ion population. Note that the sustainment in C-2U is limited by pulse-length constraints arising from finite stored energy in the power supplies of many critical systems, such as NB injectors (flat-top duration  $\sim 8$  ms) and edge-biasing equipment (pulse duration  $\sim 5$ – $7$  ms depending on discharged current/energy from the plasma-gun electrode during a shot).

Under the well-confined FRC regimes, such as HPF and advanced beam-driven FRC in C-2/C-2U, and after careful global power-balance analysis [23–25], there appears to be a strong positive correlation between electron temperature and energy confinement time; i.e. the electron energy confinement time in C-2U scales strongly with a positive power of  $T_e$  [4]. The power-balance analysis, detailing loss channel characteristics and plasma timescales, shows substantial improvements



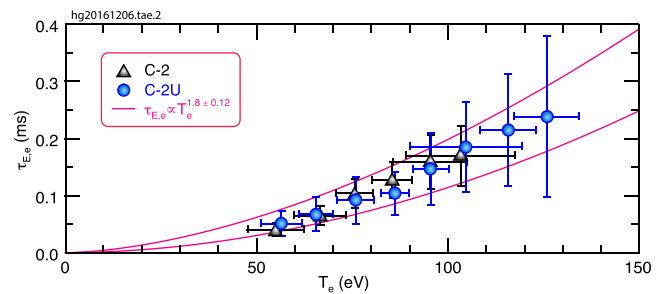
**Figure 6.** Top: Normalized excluded-flux radius evolutions in C-2 and C-2U experiments. Bottom: time evolutions of FRC-core electron temperatures under C-2 HPF14 (squares) and C-2U with 10 MW NBI (circles) regimes;  $T_e$  is averaged inside the separatrix as well as shot averaged for each data set. Note that NBI durations are longer than FRC lifetimes of shots 34913 and 42411, and NBs on shot 43833 are terminated at 10 ms.



**Figure 7.** Correlation between NB pulse duration and plasma parameters such as excluded-flux radius, density (measured by CO<sub>2</sub>/FIR interferometer) and total temperature (estimated from pressure balance). Neutral beams are terminated at 1, 2, 3, 4 and 5 ms in 5 plasma discharges under the same operating condition except for the NB duration, and all quantities are normalized.

in equilibrium and transport parameters, and the previously reported C-2 scaling of electron energy confinement time (see figure 27 in [4]) persists at the higher electron temperature range accessible in C-2U, as shown in figure 8. Given uncertainties in the measurements and assuming the power-law model, regression analysis shows that the electron energy confinement time  $\tau_{E,e}$  is proportional to  $T_e^{1.8}$  when fitting for the entire ensemble of the C-2/C-2U data set. This positive confinement scaling is very attractive, and similar features of temperature dependence have also been observed in other high-beta device such as NSTX, whereby the energy confinement time scales nearly inversely with collisionality [26, 27]. The emergence of this attractive scaling result, paired with the considerable accomplishment of plasma sustainment obtained in C-2U, is very encouraging for the FRC and innovative confinement concepts communities, and may lead to intriguing possibilities for possible future FRC-based fusion reactors.

Moving on to the next step, in order to further improve the FRC performance such as plasma lifetime and temperature, the C-2U device is being replaced by C-2W [8] featuring higher NBI power (>13 MW in phase I and over 21 MW in



**Figure 8.** Global energy confinement time of electrons as a function of electron temperature for ensembles of C-2 (triangles) and C-2U (circles) discharges.

phase II) and longer NB pulse duration (flat-top up to 30 ms) as well as enhanced edge-biasing systems and substantially upgraded divertors. The goal of this device will be to test and validate the emerging energy confinement at higher plasma temperature and elevated system energies; the device will operate at about an order of magnitude higher stored energy than C-2U. A key to increasing the electron temperature of the FRC core and SOL is to reduce the energy loss via the

open-field-line/SOL plasma, for which a new set of inner divertors (located between confinement and formation sections) will be deployed in C-2W.

#### 4. Summary


The C-2U experimental program commenced with various key system upgrades from C-2, which include increased total NB input power to  $\sim 10+$  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-to-FRC coupling with reduced shine-through losses; and current drive. Under optimum C-2U operating conditions, plasma sustainment for  $\sim 5+$  ms was successfully achieved, in which the performance was limited by hardware and stored energy constraints such as the NBs' pulse duration and the current sourcing capability of the end-on plasma guns. 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-ion population. For the well-confined FRC regime global power-balance analysis showed a strong positive correlation between electron temperature and energy confinement time; i.e. the electron energy confinement time in C-2U scales strongly with a positive power of  $T_e$ .

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