Long Sustainment of FRC-Equilibrium by Use of Center Solenoid in TS-4

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Abstract. This paper addresses a basic equilibrium/ confinement question whether a Field Reversed Configuration (FRC) with balanced amount of magnetic and thermal energies, is sustained solely by inductive magnetic flux (magnetic energy) injection of center solenoid (CS). A new finding is that the preferential injection of magnetic energy causes significant increase in thermal energy of the FRC to maintain the FRC-equilibrium. A quasi- steady state of the high-beta (volume averaged beta ~ 0.6-0.7) FRC for 0.15 ms (~energy confinement time of conventional FRCs) was achieved through the use of the present low power Center Solenoid Current Drive (CSCD). This successful result leads us to the next stage steady sustainment experiment of an FRC by increased capacitor bank energy.

1. Introduction

Sustainment of the high-beta configuration is the most urgent problem in the present decaying plasma experiment of Field Reversed Configuration (FRC). The present candidates for solution are rotating magnetic field (RMF) and neutral beam injection (NBI). The formation and sustainment of an FRC plasma with the use of RMF technique was studied in the STX (smaller Star Thrust Experiment) at the University of Washington [1]. Also in the TCS (Translation, Confinement, and Sustainment) device, long-time current drive by RMF was successfully demonstrated [2]. Field reversal was maintained during the RMF was applied. However FRCs formed by RMF alone generally are limited to low temperatures and densities. The first NB injection experiment into an FRC plasma was carried out in FIX (FRC Injection eXperiment) [3]. Although the neutral beam was injected obliquely to the geometric axis in FIX (not tangentially to the torus), extension of the lifetime of the FRC was obtained due to improvement of energy confinement caused by the electron heating through the NBI [3,4]. Since high energy beam ions to be injected tangentially into an FRC would merely pass through the core plasma region because of its low confinement magnetic field, magnetic flux amplification of an FRC is necessary for tangential injection of NB.

The slow formation of an oblate FRC by axially colliding two spheromaks with opposing helicities has two major advantages over the other formation methods of an FRC (figure 1): (1) large initial poloidal magnetic flux, (2) center solenoid (CS) coil insertion for

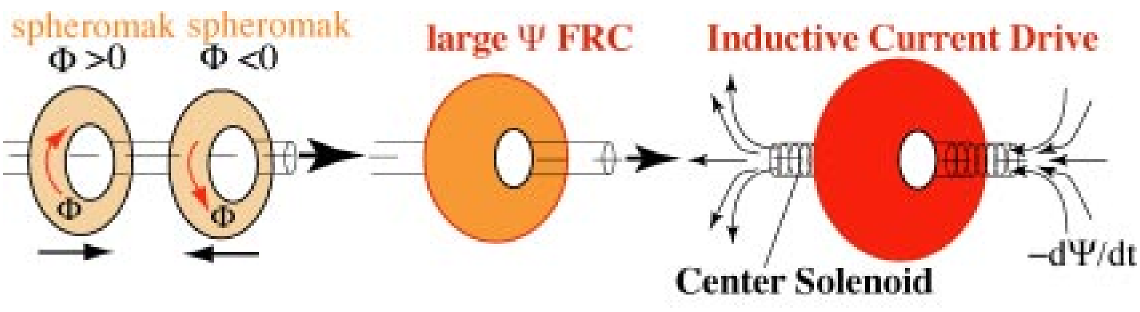


FIG. 1. Schematic of slow formation of an FRC and its CSCD.

Center Solenoid Current Drive (CSCD). The initial poloidal flux typically 15 mWb in TS-4 is ten times larger than that of conventional theta-pinch FRCs and the slow formation method also enable us to install a CS coil along the geometric axis. Current amplification of an FRC using CS coil was successfully demonstrated in the past TS-3 experiments [5]. It was observed that the toroidal plasma current was amplified by a factor of 1.8. This method also extended the lifetime of the FRC for ~100 μs [6]. The current amplification by CS coil has also been planned in MRX in order to produce a target plasma desired for neutral beam injection [7]. Our final goal is long sustainment of an FRC over 1ms (> particle confinement time of conventional FRCs) using the CS coil in TS-4. An important question arises whether an FRC-equilibrium with balanced amounts of the magnetic and thermal energies is sustained solely by magnetic energy injection of CSCD. We studied for the first time, the energy-balance robustness of FRC equilibrium: whether the thermal energy is maintained or causes the major disruption under the preferential magnetic energy injection of CSCD.

The experimental set-up is presented in section 2. The experimental result of the fast ramp-up of magnetic flux of the FRC is presented in section 3. The experiment of the long sustainement of the FRC is described in section 4. In section 5, our summary and concluding remarks shall be described.

2. Experimental Setup

2.1. TS-4 Merging Device

The TS-4 Merging/ CT (Compact Torus) device is three times larger than TS-3. As shown in Fig. 1, another important modification from TS-3 is to utilize flux-cores for toroidal flux injection instead of electrodes. These modifications extend the lifetime of compact torus plasmas from that of TS-3. The TS-4 device has two flux-cores as shown in figure 2. Each flux-core has a set of poloidal (PF) and toroidal (TF) coils for poloidal and toroidal flux injection by inductive method. They can produce the two initial spheromaks whose toroidal field B_t polarities are determined by those of the TF coil currents. The center conductor is located along the center axis to maintain the plasma stability against the n=1 (tilt, shift) modes. It is equipped with center solenoids (CS) and an external toroidal field coil, which was not

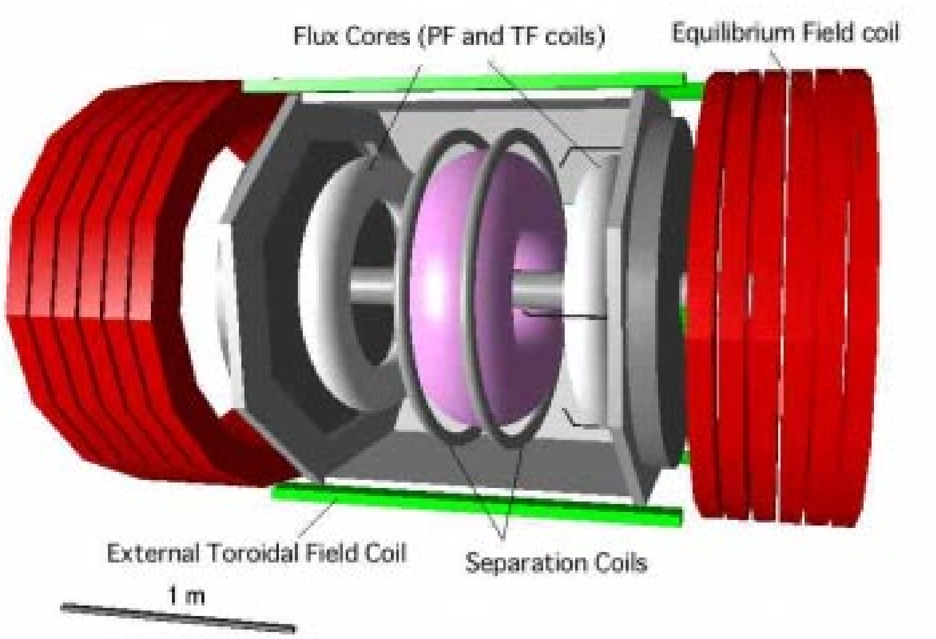
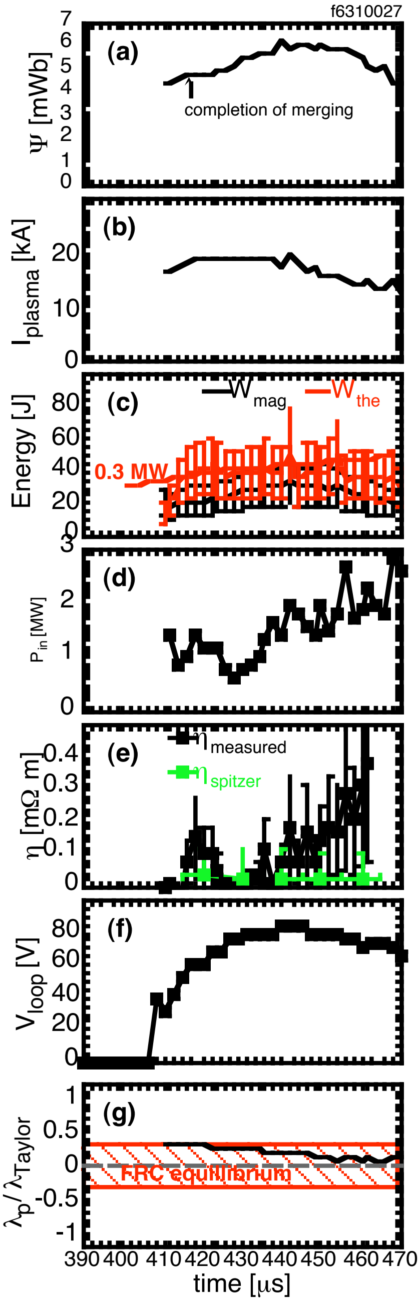


FIG. 2. Schematic of TS-4 CT/ Merging Device.



(h)

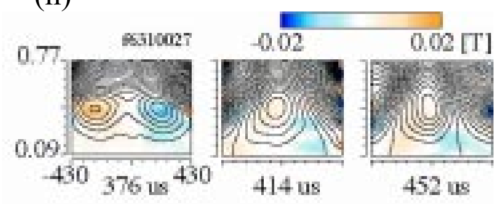


Fig. 3. Waveforms of (a) the poloidal flux, (b) plasma current, (c) plasma magnetic and thermal energies, (d) input power to the FRC, (e) resistivities on axis, (f) loop voltage, (g) poloidal eigen value of the FRC sustainment by CSCD. Its poloidal flux contours with toroidal field amplitude are shown in (h).

used in these experiments. The major radius and separatrix elongation of compact toroids in this experiment were about 0.4~ 0.5 m and 0.5-0.7, respectively.

The TS-4 device has a set of four center solenoids. The duration of the inductive current drive and input power can be varied by the combination of the coil arrangement. Two capacitor banks with stored energy of 50 kJ and 260 kJ were used properly for the fast flux ramp-up and long sustainment experiments, respectively. The inner coils (separation coils as shown in figure 2) were utilized to compensate for the leakage flux of the CS and to control the decay index of equilibrium field in combination with the equilibrium field coils.

2.2. Diagnostics

A 2-D array, which consisted of B_z and B_t magnetic probes on the r-z plane, was used to directly measure 2-D magnetic field profile for calculation of flux contour. Another four magnetic probes were installed toroidally on the midplane to measure toroidal mode activity of CTs. Its maximum resolutions of toroidal mode were two in amplitude and one in phase.

The loop voltage (V_{loop}) was measured by a complete flux loop, toroidally installed inside a vacuum vessel at R = 0.1 m (see figure 1). In this paper V_{loop} denotes the loop voltage measured by this flux loop. These data were used to calculate the 2-D spatial profiles of the toroidal electric field E_q and the toroidal current density j_q. Then input power P_{in} to a torus can be calculated from the following procedure:

$$P_{in} = \int_{\Psi>0} V_\theta \cdot j_\theta \, dS = \int_{\Psi>0} \left\{ \left(-\frac{\partial \Psi}{\partial t} + V_{loop}\right) \cdot j_\theta \right\} dS \quad \text{--- (1)}$$

where the poloidal flux Ψ is counted from the surface of the center post. The plasma resistivity $\eta_{measured}$ at the magnetic axis was simply obtained by using the following formula:

$$\eta_{measured} = \left.\frac{E_\theta}{j_\theta}\right|_{on\ axis} = \frac{1}{2\pi R}\left.\frac{(-\frac{\partial\Psi}{\partial t} + V_{loop})}{j_\theta}\right|_{on\ axis} \qquad (2)$$

where R is the major radius.

An electrostatic double probe was inserted to measure the electron temperature T_e at R=0.6 m on the midplane. T_e was obtained from the multi-shot scan of the probe current-voltage relation.

3. Fast Flux Ramp-up Experiment

The first question was whether an FRC-equilibrium with balanced amounts of the magnetic and thermal energies is sustained solely by magnetic energy injection of CSCD. The fast ramp-up of FRC was first carried out by strong CSCD of the CS coil. The capacitor bank with stored energy of 50 kJ was utilized for the inductive current drive. We found that the FRC equilibrium is robust against preferential injection of magnetic energy by CSCD.

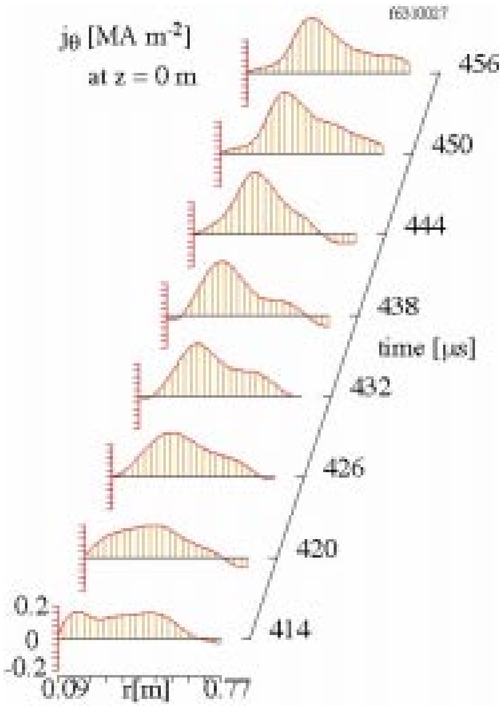


Fig. 4. Time evolution of radial profile of the toroidal current density at the midplane.

Figures 3 (a)-(g) shows the waveforms of (a) the poloidal flux Ψ, (b) plasma current I_{plasma}, (c) magnetic and thermal energies W_{mag}, $W_{thermal}$, (d) input power P_{in} to the FRC by the CSCD, (e) resistivity $\eta_{measured}$ calculated from eq. (2) at the magnetic axis (null) and the parallel spitzer resistivity $\eta_{spitzer}$ calculated from measured electron temperature, (f) one turn loop voltage V_{loop}, (g) normalized poloidal eigen value $\lambda_p/\lambda_{Taylor}$ of the FRC during the CSCD. The poloidal flux contours with toroidal field amplitude are also shown in Fig.3 (h). The one turn loop voltage V_{loop} was increased to about 80 V until t=430 μs and kept > 60 V until t=460 μs. $W_{thermal}$ was calculated from the volume integration of the thermal pressure determined by the MHD equilibrium condition. Vertical error bars for W_{mag} and $W_{thermal}$ were determined from signal to noise ratio, calibration error for the magnetic probe signals and the error of the calculation. Poloidal eigen value $\lambda_p \equiv \mu_0 I/\Psi$ was employed as a key parameter to measure the equilibrium property, where I is the poloidal current. The state with λ_p~0 represents an FRC state with B_t~ 0 and that with

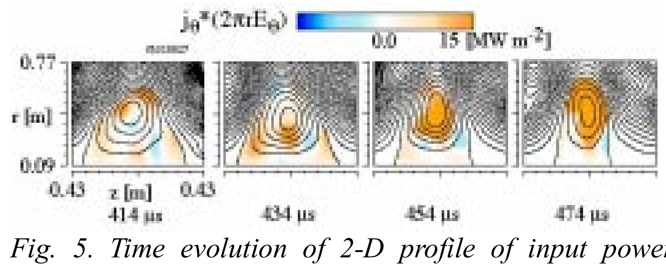


Fig. 5. Time evolution of 2-D profile of input power density from the CS to the FRC.

$\lambda_p \sim \lambda_{Taylor}$ indicates the zero-beta Taylor state. The flux amplification of the FRC by a factor of 1.4 was obtained in this shot. It was confirmed that the amount of amplified poloidal flux increases with the loop voltage and the maximum amplification by a factor of 2.0 was achieved. Increment in I_{plasma} was observed to be small compared with Ψ, indicating the increase of plasma inductance. Figure 4 shows time evolution of radial profile of the toroidal current density j_θ measured at the midplane. Peripheral current was increased just after the loop voltage was applied (t =414 μs). In this phase, the applied field penetrated just only the peripheral region of the plasma and Ψ at the axis was increased. An important finding is that the thermal energy increased simultaneously with the magnetic energy during this phase in which the magnetic flux was increased. The heating power is roughly estimated to be 0.3 MW in this early phase of the CSCD. As a result, the high-beta state ($W_{mag} \approx W_{thermal}$) was clearly maintained during the CSCD. The input power from the CS to the FRC calculated from eq. (1) was about 1MW as shown in figure 3(d). Figure 4 shows 2-D color plot of input power density from the CS to the FRC. Power deposition to the core region was quite small from t =414 to 434 μs and the resistivity at the magnetic axis was also small. Therefore, the Ohmic heating was considered to be quite small and increment in the thermal energy was caused by other mechanism of energy conversion from the magnetic energy of the CS. It was also observed that $\lambda_p/\lambda_{Taylor}$ kept in the FRC range of $|\lambda_p/\lambda_{Taylor}| < 0.3$ during the magnetic energy injection. These phenomena indicate that the preferential magnetic energy injection causes conversion of the magnetic energy into the thermal energy in the FRC. The FRC plasma is concluded to have the robustness to self-adjust the thermal energy depending on the magnetic energy injection. In the latter phase of the CSCD, the hollow current profile relaxed to peaked one until t=444 μs and subsequently the current density on the magnetic axis was highly ramped-up. Increment in the resistivity on the axis followed the ramp-up of current density on the axis as shown in Fig. 3(e). The resistivity of the FRC increased up to 10-20 times larger than the classical spitzer resistivity. Then the input power density became large near the magnetic axis, indicating the increase in the Ohmic loss. Then the increment in Ψ was declined. The perpendicular resistivity of the RMF-driven plasma was observed to be enhanced over its classical values by a factor of 10 depending on the RMF amplitude [8]. However clear dependence of the resistivity on the magnetic axis on the applied CS voltage was not observed.

4. Long Sustainment Experiment

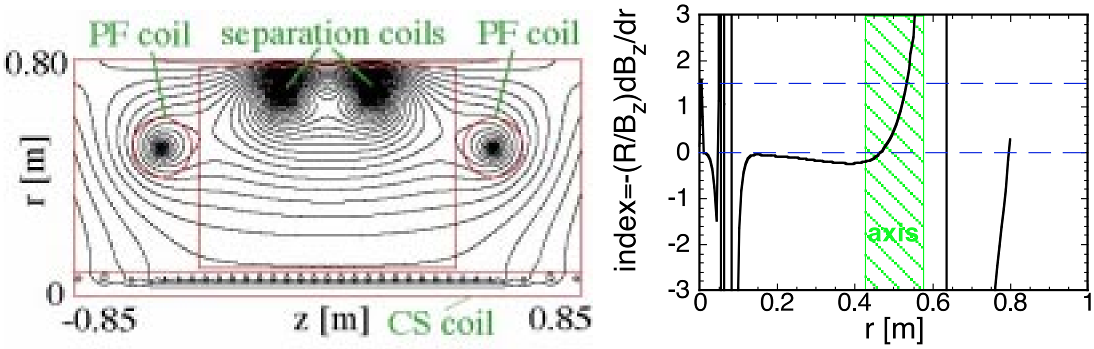


Fig. 6. The calculated vacuum magnetic field lines (left) and the decay-index of equilibrium field (right) at t= 600 μs in Figure 7 (V_{loop}~54 V).

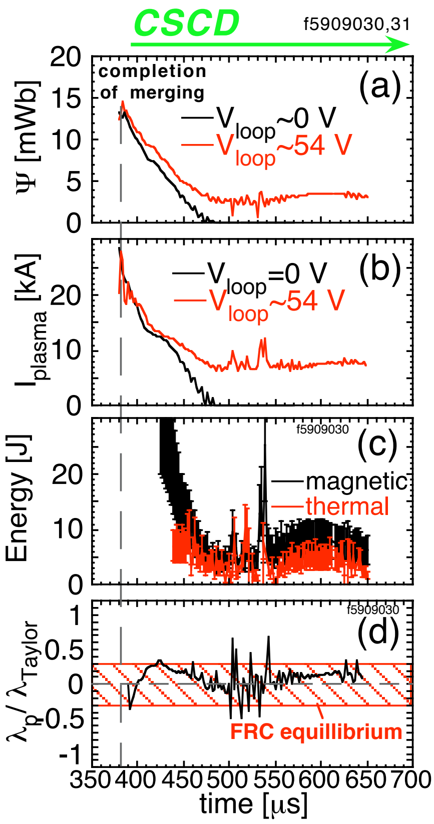


Fig. 7. Time evolutions of (a) the poloidal fluxes and (b) plasma currents of the FRCs with (red) and without (black) CSCD. Time evolutions of (c) magnetic (black), thermal (red) energies and (d) normalized poloidal eigen value of the FRC with CSCD

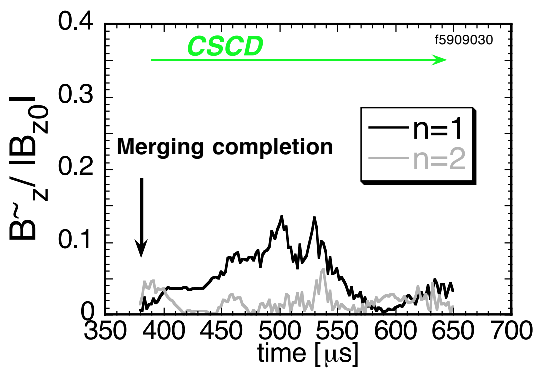


Fig. 8. Time evolution of the toroidal mode amplitude for n=1 and 2 during the CSCD.

Our goal is quasi-steady sustainment of the plasma with the FRC by CSCD based on the self-adjusting equilibrium mechanism mentioned above. The capacitor bank with larger stored energy of 260 kJ was utilized for long-time inductive sustainment of the FRC. A pair of separation coils (shaping coils) was connected in parallel to the CS to compensate for the leakage flux of the CS and to optimize the decay-index of the equilibrium field. Figures 6 show the calculated equilibrium field configuration at t= 600 μs and radial profile of decay-index when the current of 26 kA was excited at each separation coil in the case of V_{loop}~ 54 V in figure 7. It was seen that the magnetic configuration maintains radial and axial stability around the magnetic axis. Figure 7 shows time evolutions of (a) the poloidal flux Ψ and (b) plasma current I_{plasma} of FRCs with and without CSCD. The poloidal flux Ψ was successfully sustained for 0.3ms by the CSCD (V_{loop}~ 54 V) while the FRC without CSCD decayed within 0.1 ms. The steady-phase of I_{plasma}~8 kA and Ψ~ 3mWb was established until the CSCD termination determined by the present capacitor bank energy. It is noted that the volume-averaged beta value ($W_{thermal}$ /W_{mag}) was maintained as high as 0.6 until the discharge termination as shown in Fig.7 (c). As shown in Fig.7 (d), λ_p/ λ_{Taylor} was maintained in the FRC range in agreement with $W_{thermal}$ /W_{mag} indicating robustness of the FRC-equilibrium for the magnetic energy injection. The plasma collapsed at t~ 650 μs due to the decrease in the equilibrium magnetic field. Figure 8 shows time trace of amplitude of the toroidal mode n=1 and 2 during the discharge. No destructive instability was observed for the current sustained FRC until the discharge termination. More detailed control of the decay index of the equilibrium field is required for longer sustainment.

5. Summary and Conclusions

Inductive current drive and long-time sustainment experiments of an oblate FRC were carried out using the CS coil in TS-4. The sustainment of steady plasma current over 0.15ms and the lifetime of the FRC over 0.3ms were achieved by the present low power CSCD experiments. The volume-averaged beta value was maintained as high as 0.6 during the CSCD. No destructive instability was observed for the inductively sustained FRC. The series of CSCD experiments revealed that the oblate FRC with balanced amount of magnetic and thermal energies was sustained solely by magnetic energy injection. It is considered that the injected magnetic energy was directly converted into the thermal energy due to some conversion mechanism except resistivity. This successful result leads us to the next stage quasi-steady sustainment experiment of FRC by increased capacitor bank energy although the large amount of V·s of center solenoid is required.

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