Comparative Study of CT Equilibrium and Stability Using Controlled Current Drive : Compact RFP, Spheromak, and ST in a Single Device

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Abstract. A comparative experiment of low-aspect ratio ($A \approx 1.5$) torus plasmas: compact RFPs, spheromaks and STs has been performed in the TS-3 and 4 CT devices. Especially, a compact RFP with q_0 as large as 0.3 was found to have low-n dynamo mode $n = 3$ while a spheromak with $q_0 \approx 0.5$ had $n = 2$ mode. Under OH current sustainment, magnetic fluctuation and loop voltage of CT were observed to increase inversely with its q-value. A new edge-current drive was developed by use of axial CT merging, realizing a balanced current drive together with the OH current drive. This current drive was found to reduce the dynamo fluctuations of compact RFP and spheromak by factor of 3. The multiple CT merging can be a promising edge-current drive because of its intermittent current drive and its detailed control of current profiles using varied size of colliding CTs.

1. Introduction

Reversed-field pinches (RFPs), spheromaks, and tokamaks are all toroidal plasmas with internal plasma currents. They have potentials to improve their stabilities, betas and reactor feasibilities by decreasing their aspect ratios (A). It is well-known that the spherical tokamak (ST) with $A \approx 1.5$ has both of high-beta ($\approx$ 20%) property and long confinement time ($\approx$ 4ms) in the medium-class device START [1]. The compact RFP with $A < 1.5$ [2] is now expected to reduce the number of rational surfaces in the plasma core region. It possibly realizes a single-mode dynamo with improved confinement, because the transport degradation of RFPs is caused mainly by dynamo-mode coupling between nearby rational surfaces. It is also noted that MST [3] and RFX [4] suppressed the dynamo activity itself artificially using flux-swing of toroidal field (TF) coil. Induction of TF and OH coils injected balanced amount of toroidal and poloidal fluxes into the RFPs, eliminating a need for flux-conversion (dynamo) from poloidal to toroidal unlike the conventional RFPs. Though this method improved the confinement time significantly, a new edge-current drive has to be developed to extend it to the long-term / steady current-drive.

We have started a comparative experiment of compact RFPs, spheromaks and STs in the TS-3/4 CT devices [5–7]. Especially, we produced a compact RFP with $A \approx 1.5$ for the first time. Equilibrium and stability of those CTs were compared experimentally with each other. It is noted that a new controlled edge-current-drive for those CTs was performed using axial CT merging. As shown in Fig. 1, the CT merging injects selectively toroidal flux (edge poloidal current) into the target CT. Together with OH toroidal current drive, this method enables us to make a new balanced / controlled drive of poloidal and toroidal currents. This edge current-drive has several advantages over the induction of TF coil [3]: it realizes (1) intermittent / continuous edge current drive, (2) detailed current profile control using size of the colliding CT and (3) significant ion heating ($<$ 10 MW) due to reconnection[5]. This paper addresses three important issues of comparative CT study under the controlled current sustainment: (1) formation of a

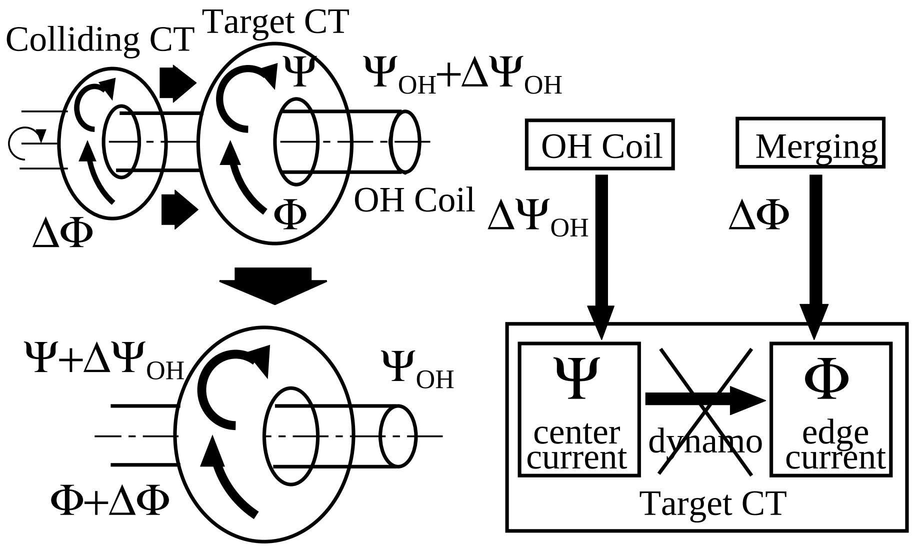

FIG. 1. Comparative study of CT stability under balanced current drive of merging / OH coil.

compact RFP with $A \approx 1.5$, (2) equilibrium and stability study of all CTs and (3) suppression of dynamo using edge-current drive of CT merging.

2. Experimental Setup

Figures 2(a) and (b) show the experimental setup of the TS-3 device for this comparative experiment and the initial setup of our up-scaled device TS-4 that just started initial operation, respectively. The TS-3 device utilizes a set of poloidal coils and electrodes and the TS-4 device does a fluxcore with poloidal and toroidal coils for poloidal and toroidal flux injection. They enable us to produce all type of CTs / STs with center q-value, q_0 ranging from 0.1-30 in a single device. In TS-3, one or two CTs with major radii of 0.2m were produced around the two PF coils in a cylindrical vacuum vessel with diameter of 0.8 and length of 1m. A center OH coil was also used to sustain poloidal fluxes (toroidal currents) of the CTs. A 2-D array of magnetic probe was used to measure 2-D magnetic field profile on the r-z plane for calculation of flux contour and q profile. The 2-D array was composed of five internal and two external probe arrays, which were covered with thin (5mm) glass tubes. Another 32 magnetic probes were located toroidally around the separatrix on the midplane to measure toroidal mode activity of CTs. A visible light tomography system composed of 36 optical fibers was also located on the midplane to measure internal mode structures of those CTs. A polichrometer and electrostatic probes were used to measure radial profiles of ion and electron temperatures and electron density.

3. Experimental Results

In our TS-3/4 devices [5, 7] we produced all types of CTs (aspect ratio $A \approx 1.5$) with q-values from 0 to 30, using induction of the PF coils and z-discharge between electrodes under external toroidal field of the TF coil. Figure 3 shows q-values and poloidal flux contours of compact RFP, spheromak and ST, which were measured directly by the 2-D array of magnetic probes. The q-value was observed to increase with the center TF coil current I_{tfc}. Their q-values increase (ST) or decrease (RFP) sharply at the edge, because of their strong toroidal effect. It is noted that the

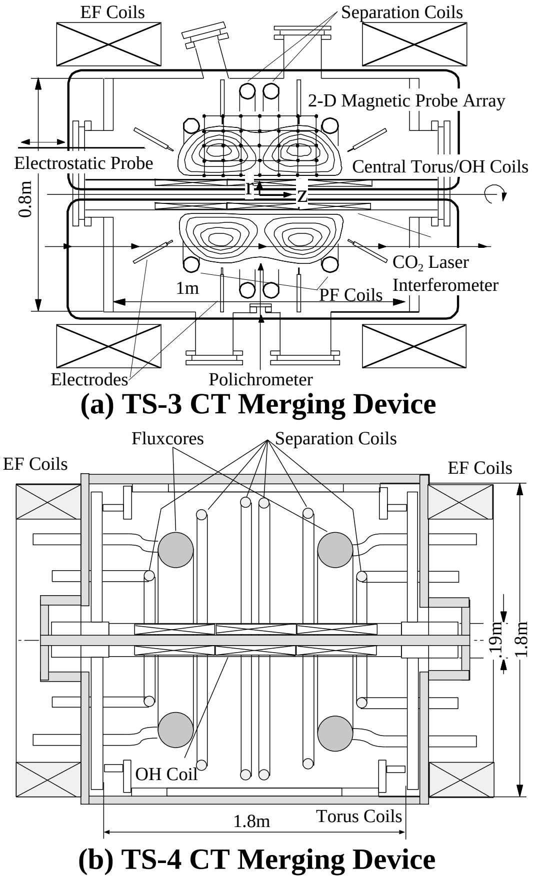

FIG. 2. (a) TS-3 CT merging device and (b) TS-4 CT merging device.

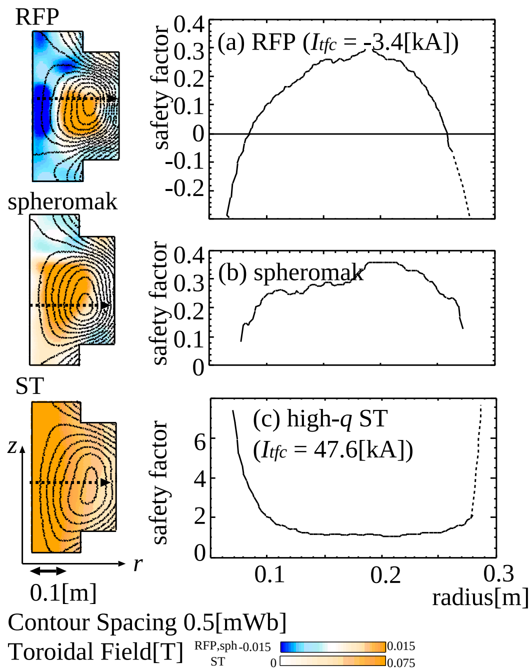

FIG. 3. Radial q profiles of compact RFP (a), spheromak (b) and ST (c) and their magnetic surfaces.

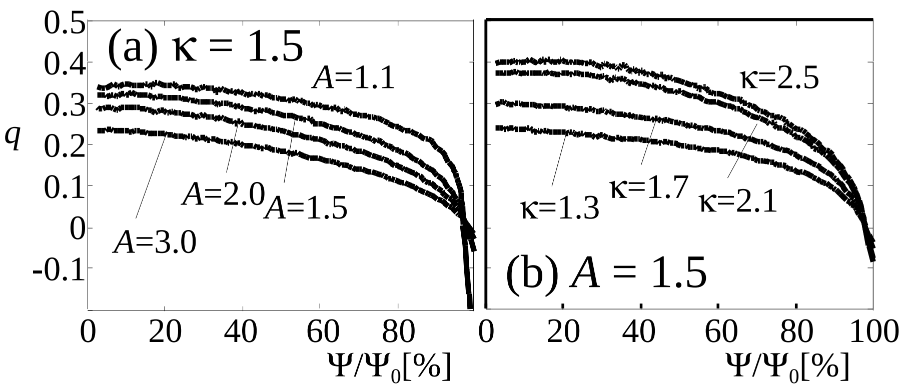

FIG. 4. q-profiles of compact RFPs with varied A and κ.

center q value of RFP is as large as 0.3 because of aspect ratio as low as 1.5. The low aspect ratio RFP was observed to have larger distance between neighboring rational surfaces mainly $n = 3$, $n = 4$ and 5 in comparison with the conventional RFPs. Figure 4 shows examples of equilibrium calculations of the compact RFPs based on assumption of zero beta and a uniform eigen-value. It is observed that q-value of the compact RFP increases with decreasing the aspect ratio A and with increasing elongation κ.

At first, poloidal flux of those CTs were sustained using the center OH coil. Their internal mode structures were measured by visible light tomography that can detect up to $n = 4$ modes.

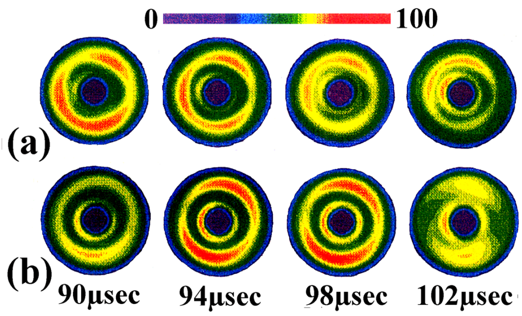

FIG. 5. H_β light emissivity of compact RFP (a) and spheromak (b) on the midplane.

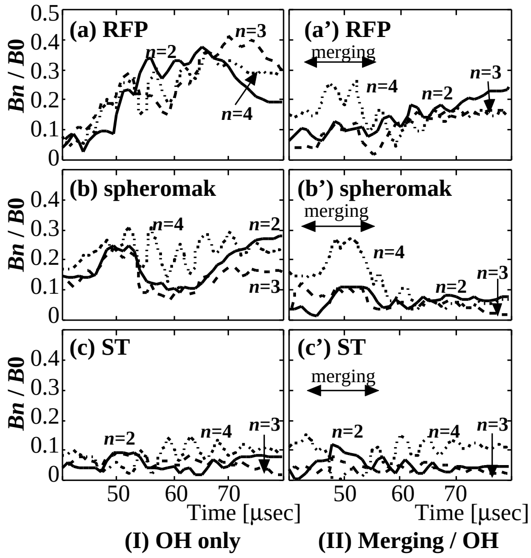

FIG. 6. Toroidal mode amplitudes of compact RFP(a), spheromak(b) and ST(c) under OH current drive and those under balanced current drive of merging / OH coil (a')-(c').

Their internal mode structures were measured by visible light tomography using 36 optical fibers on the midplane. Figure 5 shows the r-θ contours of H_β light emissivity on the midplane for the compact RFP and the spheromak which were sustained solely by the OH coil current (V_{loop}). The center black circle and the edge circle represent the center OH coil and $r = 0.32$m ($\approx$ separatrix position), respectively. An oscillation of toroidal mode number $n = 3$ was clearly observed in the sustained RFP while an $n = 2$ mode in the sustained spheromak. These unstable modes: $n = 2$ and 3 were almost consistent with peak q-values: $q \approx 1/3$ of the RFP and $q \approx 1/2$ of the spheromak, respectively. The compact RFP with higher q had a smaller number of unstable modes in sharp contrast with the conventional RFPs [2]. The unstable modes were attributed to the dynamo activity or flux conversion from poloidal to toroidal, because the CTs with excessive poloidal flux self-generated toroidal flux through these mode activities.

Figures 6(a)-(c) show time evolutions of toroidal modes from $n = 2$ to 4 for the compact RFP ($q_0 \approx 0.3$), the spheromak ($q_0 \approx 0.4$) and the ST($q_0 \approx 1$) under OH current sustainment. The mode amplitudes tend to decrease with increasing plasma q-value from the RFP to the ST. The 32 magnetic probes around the separatrix enable us to measure the toroidal mode up to $n = 16$. These mode amplitudes tend to decrease with increasing plasma q-value, indicating that the ST had much smaller B-fluctuation than the compact RFP. Though a conducting wall was located relatively close ($r_c = 32$cm) to the separatrix position ($r_s = 30$-32cm), the compact RFP with the lowest q-value had the largest plasma deformation during the dynamo activity. The dominant mode number of dynamo was observed to decrease with increasing q-value in agreement with Fig. 5. An important finding was that the mode amplitudes of the target CT were reduced by factor of 3 when another CT was merged together. Figures 6(a')-(c') show the toroidal mode amplitudes of the target CTs when the colliding CTs had magnetic energies equal to the target CTs for simplicity. Double-headed arrows indicate the merging periods. The merging process injected toroidal flux (or edge poloidal plasma current) into the target CT, while the OH coil injected poloidal flux. A balanced injection of poloidal and toroidal flux shown in Fig. 1 was experimentally demonstrated. The effect of dynamo reduction was most pronounced in the compact RFP with the lowest q-value, suggesting the flux-conversion of

RFPs was attributed to the global mode activities. The loop voltage of the target CTs was also measured with and without CT merging. The loop voltage was reduced by a factor of 2 when CT merging was superposed to OH current drive.

4. Discussions

Our comparative experiment produced the compact RFP with $A \approx 1.5$ for the first time. Its q-profile was uniformly high (≈ 0.3) in the core and fell sharply in the periphery. This high and flat q-profile in the core reduced the number of rational surfaces from the core region. Our visible light tomography and toroidal mode measurements both indicated that the main dynamo mode of the compact RFP was as low as $n = 3$. This fact suggests a new possibility of transport improvement by reducing the aspect ratio of RFP. In agreement with the experiment, our equilibrium calculation indicates that the number of rational surfaces can be reduced to unity ($q = 1/3$) inside $\bar{\Psi} < 0.7$ if its aspect ratio is decreased down to 1.5 and its elongation is increased over 1.5. We also developed the new "intermittent" edge-current drive using the CT merging. Together with the OH current drive, the CT merging realized the balanced current drive of CTs, eliminating a need for flux-conversion from poloidal to toroidal. Our experimental result indicates that this balanced current-drive successfully suppressed the magnetic fluctuation down to 1/3. This dynamo suppression effect was most pronounced in the compact RFP with the lowest q-value. Probably, the dynamo activity of the compact RFPs with low q-value was caused by the global mode while that of the STs with high q-value by some micro mode. The large fluctuation of low-q CTs will be reduced if we set the present conducting shell ($r = 32$ cm) closer the separatrix ($r = 30$ cm) in future.

5. Summary

In summary, a new balanced current drive of CTs was demonstrated for the first time using the axial CT merging and the OH current sustainment. This balanced flux injection / sustainment suppressed the magnetic fluctuation of dynamo activities by a factor of 2-3. The unstable toroidal mode; $n = 3$ mode of compact RFPs and $n = 2$ mode of spheromaks was observed to decrease with increasing q-value of the target CT. This dynamo-reduction effect was the most pronounced in the compact RFP with lowest q-value. The compact RFP with $A \approx 1.5$ was produced for the first time in the TS-3 device. The compact RFP was observed to have higher q-values and fewer resonant surfaces than the conventional RFPs. However, the magnetic fluctuation level of CT was observed to increase inversely with its q-value in the present experimental setup.

References

[1] GRYAZNVICH, M. et al., Phys. Rev. Lett. **80** (1998) 3972.
[2] HO, Y. L. et al., Phys. Plasmas **2** (1995) 3407; JI, H., J. Plas. Fus. Res. **2** (1999) 195.
[3] STONEKING, M. R. et al., Phys. Plasmas **4** (1997) 1632.
[4] BARTIROMO, R. et al., Phys. Plasmas **6** (1999) 1830.
[5] ONO, Y. et al., Phys. Plasmas **7** (2000) 1863; ONO, Y. et al., Phys. Rev. Lett. **76** (1996) 3328.
[6] INOMOTO, M. et al., Fusion Energy 1998, 3, 927.
[7] UEDA, Y. et al., J. Plas. Fus. Res. **2** (1999) 202.