Experimental Study on the Practicability of a Self-Created Spherical Tokamak in the Coilless STPC-EX Machine

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Abstract. The aim of this study is to identify the physical basis of the alternative self-organization mechanism that exists on the STPC-EX machine and to determine complementary features with respect to present compact toroid concepts. In the STPC-EX machine, there exist two solenoids placed inside the centeral passive floating conductive hollow rod and externally onto flux conserver. These are in a passive state and they do not have an important role in the self-created spherical tokamak plasma (SCSTP) in the STPC-EX machine. In this study, conventional diagnostic tools are used and for photographic recording, the method of open shutter integrated post-fogging is chosen. Two annular coaxial plasma current sheets, one within the other in the same direction, are created and flow on the surface of the central conductive hollow rod. Consequently, the spherical tokamak is configured by a new creation mechanism called the dual-axial z-pinch. High betas of 0.4 - 0.6 and aspect ratios of up to 1.25 can be obtained.

1. Introduction

At present, in spherical tokamak experiments, such as START and MAST [1] (UK), TST and TS3-4 [2] (Japan), NSTX [3] (USA) and GLOBUS [4] (Russia), the toroidal magnetic fields are usually generated by using non-conventional centerpost coils connected to a central high current active rod. Firstly, the alternative spherical tokamak (AST) system was considered from the viewpoint of current drive [5] and profile control [6] mechanisms by means of numerical schemes. Secondly, the paramagnetic spherical tokamak with plasma centerpost (STPC) machine - its conceptual design and computational experimental results, as well as the cross-sectional layout of the construction - was presented [7]. The preliminary experimental results and their assesssment obtained from the STPC-E (experimental version of STPC) machine, whose building has recently been completed were given in Ref. [8]. Essentially, the constructional properties of the STPC-E and STPC-EX machines are identical. In this study, the main differences between these machines arised from the operating conditions are given.

2. Coilless STPC-EX machine

2.1. Constructional properties

In the STPC-EX machine, four simulated single turn, high current toroidal field coils, placed at 90^0 angular intervals, are controlled by four magnetically driven plasma guns (MDPG) combined with an energetic pulse forming line (EPFL). The main parts of these toroidal field coils consist of the shock heated, time varying and non-linear plasma belts in the flux conserver and the complementary back-strap at its outside. The poloidal current is completed by the pre-programmed SCR switch and the output terminal of the EPFL. In order to produce either pre-ionization or pre-heating, a separate internal spheromak-like fast compact toroid injector (FCTI) is added. According to the experimental results on STPC-EX the toroidal and poloidal current contours created by the mutual inductance of the hot plasma belts generated by the MDPG, are in helical form. On the other hand, the main plasma current channel is composed of the helical double twisted currents of $\mathbf{I_t}$ and $\mathbf{I_p}$ and their self-created magnetic fields $\mathbf{B_p}$ and $\mathbf{B_t}$ respectively.

2.2. Operating conditions and diagnostics

The reference data for optimum operating conditions of the STPC-EX machine for the SCSTP mode are as follows: Using He gas, $n_e=10^{20}$- 10^{22} m^{-3} ; t_{conf}= 45-60 ms; T_e= 30-45 eV; input energy of EPFL is 2.5 kJ; input energy of FCTI, W_i= 400 – 800 J; for W_i= 600 J, the startup time is 40-90 μs; for W_i= 400 J, the startup time is 250-380 μs; the velocity of the thermalized plasma belt is $5.4x10^4$– $3.5x10^6$ cms^{-1}; the average input power density $< P_{ohm}>= \eta J_{pl}^2$ is 37.8 kWm^{-2} and maximum turn-on time of PFL is 12 μs; for arrival of the belt packet to the center t_{arv}, the condition of $t_{arv}> t_{on}$ must be fulfilled. The diagnostic tools used in this study were: compensated surface resistivity probe, magnetic, electrical probes and total magnetic flux loops. In addition, for photographic recording, the method of open-shutter integrated post-fogging with density filters is chosen. By means of the above mentioned diagnostic techniques, the experimental data obtained are evaluated by the MHD activity of SCSTP**.**

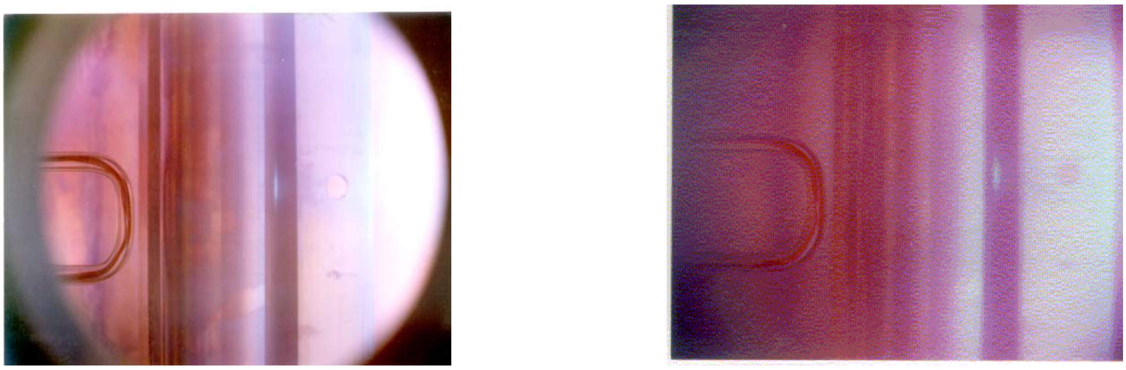
3. Results and discussions

3.1. Effects of stochastic helices on toroidal current

Before the detailed physical and/or theoretical treatments, we studied experimentally the effects of the expected self generating characteristics of the SCSTP configuration (Fig. 1). In this manner, we determined the fundamental operating conditions of the FCTI and MDPG+EPFL. There exists an angular distribution function for the angle between the velocity vector of SCSTP's thermalized electrons and the self-produced toroidal field vector. So, using the average value of angular differences in the range of 0 to π and the experimetal data on T_e and B_t, the most probable helix radii, ρ_h and their pitch length, λ_p have been calculated. The experimental data taken from STPC-EX are: at T_e= 84 eV (thermal), B_t= 0.8 kG, ρ_h= $2.3x10^{-2}$ cm, λ_p= 0.2 cm; at T_e= 6.4 keV (non-thermal drift in the belt), B_t= 1.2 kG, ρ_h= 0.13 cm, λ_p= 1.1 cm; and at T_e= 550 eV (high energy tail), B_t= 200 G, ρ_h= 0.23 cm, λ_p= 2.0 cm. These results show that non-thermal electrons are the more effective in the self-formation of the SCSTP current channel owing to the longer λ_p. Because of the temperature and density gradients in the plasma belt pushed towards the center of the flux conserver by Lorentz forces, either toroidal or poloidal bootstrap currents are generated. In addition to the interaction with the self-toroidal magnetic field and plasma belt currents that are formed by magnetic helicity injection, a second current drive mechanism comes into existance [8]. Moreover, both of these currents are supported by the above mentioned stochastic helices.

3.2. Photographic results

As clearly identified in Figure 1, during STPC-EX operation, if the EPFL and FCTI are both in the on state, then the elongated, low aspect ratio (1.72-1.9) SCSTP is perfectly configurated (Fig.1 (a)). On the other hand, in the case of the off state of the EPFL, with only the FCTI on state (on the right side of the pictures), a fairly diffused spheromak-like compact toroid (SLCT) plasma is formed (Fig.1 (b)). In Figs 2 (a) and (b), the chopper sampling field density oscillograms, obtained by a multiturn magnetic loop located at a distance of 4.0 cm from the wall of the flux conserver are given. In the pictures, the lower traces are in time-domain integration of upper ones. Here, the *x* and *y* axes are 1.0 ms/div and 370 G/div respectively. In the oscillograms of Fig.2 (b), the commence of the energy transport instabilties in the on-set phase of the SCSTP, due to the increase of input energy level of the FCTI from W_i = 600 J to W_i = 800 J, are shown.



(a) *(b)*

FIG. 1. (a) The SCSTP formation by FCTI + EPFL (b) The SLCT formation by only FCTI.

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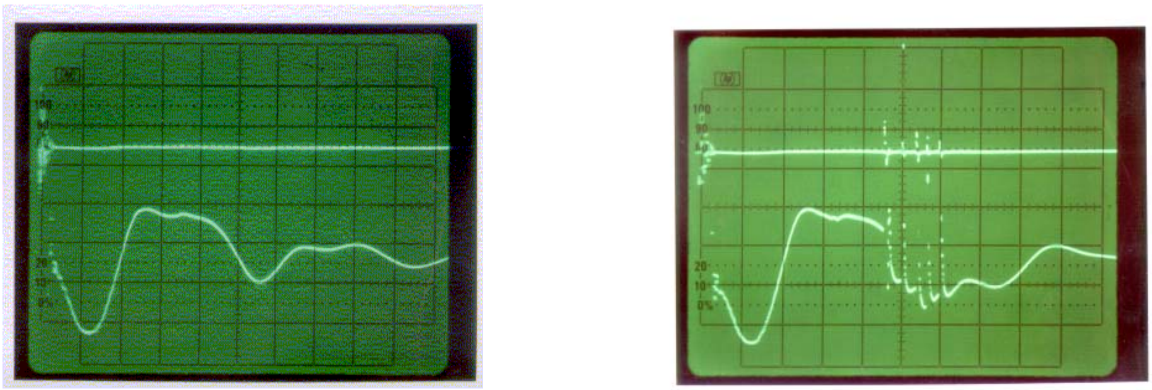

(a) *(b)*

FIG. 2. Magnetic loop signals in (a) stable and (b) unstable states of SCSTP.

4. Novel ST self-creation mechanism

4.1. Preliminary Phase

This phase is composed of the following periods:

4.1.1. Start-up

According to the predetermined operating programme, the energy capacitor banks of the EPFL and FCTI on the STPC-EX machine come into operation first. So, in 6-10 s, the EPFL reachs the selected energy level of 3.5-5 kJ and passes to the standby position. After 5-6 s, the FCTI also arrives at its working condition of 1.5-2.0 kJ energy. According to the operating programme, in 0.5-1.5 s, STPC-EX comes to the overall startup state and after just a few miliseconds, it turns into the onset position.

4.1.2. Formation of the SLCT

In the STPC-EX onset position, in the first 60-80 μs, the SLCT created by the FCTI surrounds in a cylindrical fashion the entire surface of the floating conductive hollow rod (FCHR). The tail electrons (<6.5 keV) of compressed SLCT ionize the neutral helium gas (0.07-0.120 Torr) in the flux conserver. So, as a result, the hot plasma core (5-16 eV) that is formed is loaded by the open-ended EPFL terminal.

4.2. Interaction with moving plasma belt and FCHR

As a result of Lorentz force, part of the belt current pushed, after touching the surface of the central FCHR which is perpendicular to poloidal surface of the SCSTP, at the system center, flows along its surface. Thus, many annular coaxial plasma current sheaths, one within the other in the same direction, are created.

4.3. Creations of separatrix and dual-axial z-pinch

Figure 3 shows the reference tools of the dual-axial z-pinch formation, before the self-created non-cofigurative spherical tokamak plasma.

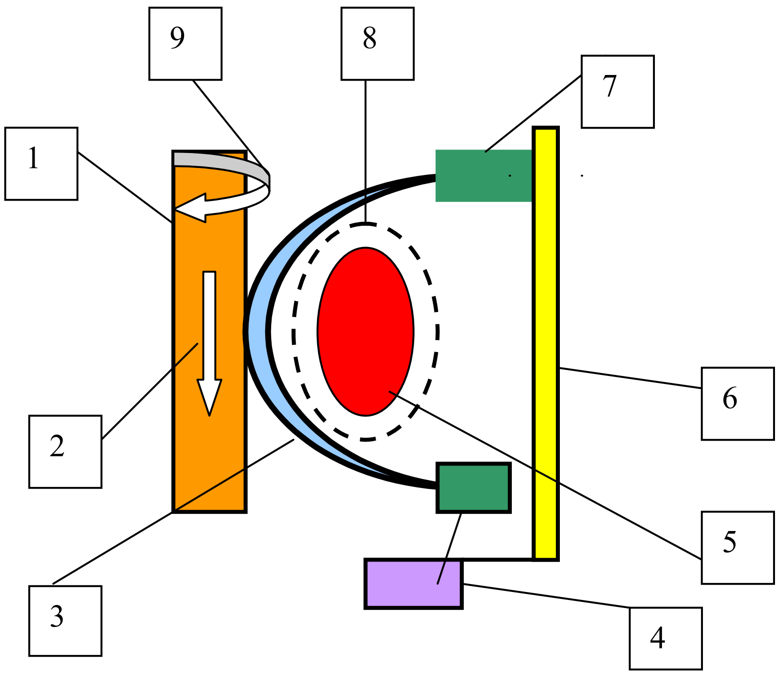

FIG.3. (1) Floating conductive hollow rod (FCHR), (2) Direction of plasma-belt current touched on the cylindirical surface of FCHR, (3) Formed and pushed plasma belt, (4) Cathode electrode of magnetically plasma gun (MDPG) combined with direct electrostatic current-launcher, (5) Cross section of plasma current-channel, (6) Back-strap electrode of MDPG, (7) Anode electrode of MDPG, (8) Poloidal magnetic field of plasma current-channel, (9) Poloidal magnetic field of the plasma belt touching to the FCHR.

The plasma belt currents touching to the FCHR, are in fact composed of many coaxial current sheaths. When the magnetic pressure produced by the initial, first current sheath group touching the FCHR reaches sufficient levels, it begins to move away from the next current sheath group (Fig. 3 (3)). This evolution, together with the separatrix obtained, come into a stable state in 2-10 μs. In this case, through the effect of mutual inductance between the separated current sheath groups, the current vectors would be in opposite directions. So, by means of the poloidal magnetic field produced by the separated current sheath groups at the surface of the FCHR, a conventional z-pinch effect commences. The similarity between dual-axial z-pinch (DAZP) and the conventional z-pinch (CZP) can be specified as follows. In the DAZP case, for the same MHD activity, we have the poloidal magnetic field of the toroidal plasma current channel (Fig.3 (8)) and the poloidal magnetic field of the plasma belt touching the central floating tube (Fig.3 (9 and 1)) instead of the axial and azimuthal magnetic fields in a CZP. Thus in the DAZP state, by means of two separate self created poloial magnetic fields, a typical spherical snowplow model can be realized. Here, the major role is played by the FCHR (Fig.3 (1)) placed at the center of the flux conserver (see section 2.1) On the other hand; by the superposition of poloidal and toroidal magnetic fields, produced by the cylindirical plasma and plasma belt currents respectively, the procedure transforms into DAZP system in the m = 0 mode and an equilibrium state in which the sustainment time is 5-6.5 ms. Owing to the stored magnetic energy in the belts, this procedure continues to the end of the pinched phase. Consequently, the SCSTP formed along the central FCHR and pushed outwards by the kinetic pressure, and finally compressed by the self-created toroidal field, is held in stable equilibrium with a fairly high magnetic shear.

5. Conclusions

The main points achieved are as follows : A new hybrid non-inductive current drive method has been applied to the STPC-EX machine. With the long pitched electron helices in the SCSTP, produced by the self-created toroidal and poloidal magnetic fields, it has been experimentally determined that the magnetic helicity and bootstrap currents would be able to integrate; In this hybrid method, the direct electrostatic current-launcher associated with the EPFL has been utilized. The dual-axial z-pinch has yielded a fairly high beta of 0.4-0.6 at the SCSTP. A controllable self-organization process is realized by the predetermined optimum operating conditions of the STPC-EX machine. By using a smaller diameter for the central floating conductive hollow rod, it is possible to reduce SCSTP's present experimental value of 1.9 for the aspect ratio to 1.25 [8]. Consequently, the evaluation of the total magnetic energy equilibrium state by means of the overall experimental data obtained has shown that, including the generation of $\mathbf{B_p}$ and $\mathbf{B_t}$ magnetic fields, the creation of a new magnetic energy system has been realized in the belts formed by the **MDPG**s of **STPC-EX**.

References

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