Experimental Study on a New Spherical Tokamak Configuration Scheme Employing by means of Spherical Snow-Ploug

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Abstract. The aim of this study is to identify the physical bases of an alternative self organization mechanism that exist on STPC-EX machine and to determine complementary features with respect to present compact toroid concepts. Here, either simplified operational properties of STPC-EX or the demonstration of spherical tokamak plasma (STP) creation using the spherical snow-plough (SSP) by dual-axial z-pinch (DAZP) and / or self reversed field pinch combined with DAZP are presented. The spherical tokamak plasma in the envelope of SSP is shaped relating to m = 0 mode of DAZP. In this procedure, the basic objects to be characterised at the conventional STP, are controlled by principal structural geometry of STPC-EX setup and previously selected reference data of current-launcher. The main points achieved on this study have been: aspect ratio = 1.2 - 1.6; averaged beta = 0.46 - 0.62; elongation = 4 - 6; triangularity = 0.42 - 0.58; sustainment time = 4.3 - 6.5 ms; energy confinement time = 45 - 136 ms; plasma temperature = 118-177 eV (irreversible heating by adiabatic compression); electron density = 10^{20}- 10^{22} m^{-3}. From the conceptual point of view this study has given a possibility for approach to the fission-fusion hybrids.

1. Introduction

In the topical perspective of a spherical tokamak plasma is similar to the fundamental themes of a classical tokamak such as; the transport, the turbulent, the equilibrium, the MHD activities, the configurational, effects and so on can be defined. At present, on the 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 and poloidal magnetic fields are usually generated by using non-conventional centerpost coils connected to the central high current active rod. As the revolution of the STPC-EX machine firstly ,the alternative spherical tokamak (AST) system had been taken into consideration from the profile control mechanisms by means of numerical schemes [5]. At the Maastricht Conference, the paramagnetic spherical tokamak with plasma centerpost (STPC) machine consisting of the conceptual design and the computational experimental results, as well as the cross-sectional layout of the constructional properties of the STPC machine were presented [6]. The viewpoint of current drive and the preliminary experimental results and their assessment obtained from STPC-E (experimental version of STPC) machine whose building has recently been completed were given in [7]. Essentially, the constructional properties of STPC-E and STPC-EX machines are identical. Main difference of these machines arises from the operating conditions with two different programmable states, such as internal and / or external magnetic field coils or coil-less modes. In this experimental study; the spherical tokamak plasma to be shaped at the STPC-EX machine [8] on coil-less mode, by means of the different controllable and reproducible alternative self organisation processes, such as the dual-axial z-pinch and / or the conventional self reversed field pinch combined with the dual-axial z -pinch are demonstrated.

2. Coil-less STPC-EX machine

In the STPC-EX machine; four simulated single turn, high current toroidal field coils are controlled by four magnetically driven plasma guns (MDPG) placed with 90^0 angular intervals, combined with 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 complementary back-strap at the outside of flux conserver. The poloidal current is completed by the pre-programmed SCR switch and the output terminal of EPFL. In order to produce either pre-ionisation or pre-heating, a separate internal spheromak-like fast compact toroid injector (FCTI) is added. According to the experimental results on STPC-EX; it should be noted, the toroidal and poloidal current contours created by the mutual inductance of hot plasma belts generated by the MDPG, are helical in form. On the other hand, the main plasma current channel has been composed by the helical double twisted currents of I_t and I_p and self-created magnetic fields of B_p and B_t respectively.

2.1. Operating conditions and diagnostics

The reference data of optimum operating conditions of STPC-EX machine for the self-created spherical tokamak plasma mode are as follows: He gas used; $n_e=10^{20}$- 10^{22} m^{-3} ; t_{conf} = 45-136 ms; T_e= 45-70 eV; input energy of EPFL is 3.0 kJ; input energy of FCTI, W_i = 400 – 800 J; for W_i = 600 J, the start-up time is 40-90 μs; for W_i = 400 J, the start-up time is 250-380 μs; velocity of thermalized plasma belt is 5.4×10^4– 3.5×10^6 cms^{-1}; average input power density $< P_{ohm}>= \eta J_{pl}^2$ is 54 kWm^{-3} and maximum turn-on time of PFL is 12 μs; for arrival time 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 are: the compensated surface-resistivity probe, magnetic, electrical probes and total magnetic flux loops. In addition; for photographic recording, open-shutter integrated post-fogging with density filters method is prefered.

2.2. Dense plasma creation by stepping discharge

On the conventional pulsed discharge; the gas pressure, the pulse height, the pule duration and or repeatation rate are the basic collective dischage parameters of a gas breakdown. Whereas, in the stepping discharge (STPD) procedure, this above mentioned collective discharge parameters are not necessary.

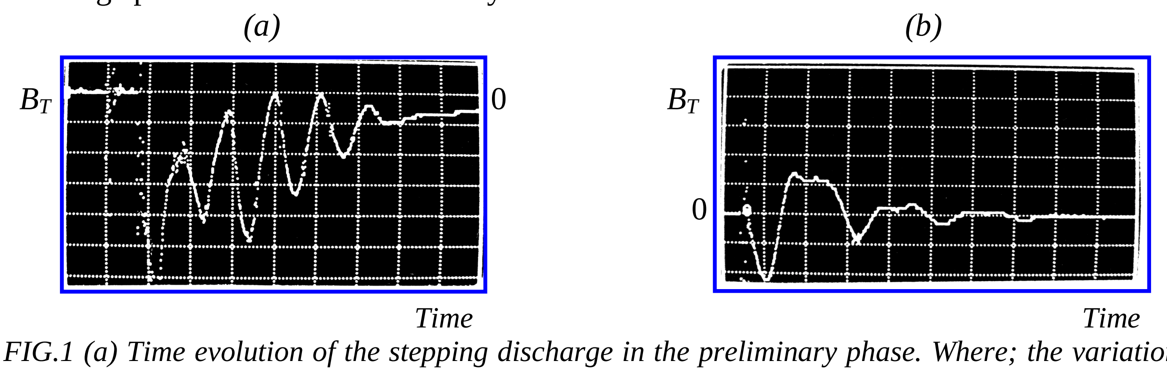

FIG.1 (a) Time evolution of the stepping discharge in the preliminary phase. Where; the variation of the toroidal magnetic field in time, $B_T(t)$. Time-scale: 10 μs/div.and vertical-scale: 0.035 T/div.FIG.1 (b) Typical stepping discharge oscillogram taken from the STPC-EX set-up at the final phase.Here; the toroidal magnetic field versus time, $B_T(t)$. Time-scale: 3.5 ms/div., vertical-scale: 0.07 T/div.

The basic operational principle of the STPD depends on the shut-down of the open ended terminal of the EPFL at the stand-by. Its attitude is converted by means of the hot and dense (≅ 10^{22} m^{-3}) plasma core produced by the FCTI (see section 2).Thus, the repeated discharge steps last up to the exhausting of the magnetic energy of the EPFL in time; according to magnitude and conditions of $Z_0 > Z_p$, $Z_0 < Z_p$ and $Z_0 = Z_p$ where, Z_0 and Z_p are the charactetistic impedance of the EPFL and complex plasma core impedace respectively.For the assessment of the time-domain oscillogrammes (Fig.1(a) and (b), the termination model for the STPD is developed [7] upon transmisson line theory.

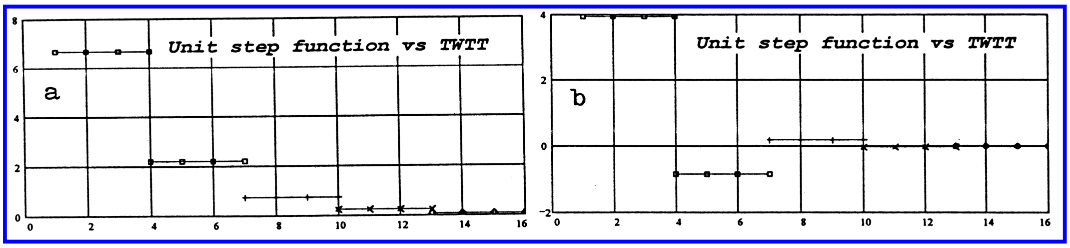

FIG. 2. (a) and (b) two typical examples based on termination model, such as $Z_0 < Z_p$ and $Z_0>Z_p$ where, Z_0 and Z_p are the characteristic impedance of the EPFL and Z_p the magnitude of the complex plasma core impedance respectively.

3. Description of new ST configuration scheme

3.1. Preliminary phase

In Figure 3, during this phase, either the simplified constructional properties of STPC-EX set-up or start-up and on-set periods of the self-creation mechanism with non-configurative spherical tokamak plasma (STP) are illustrated.

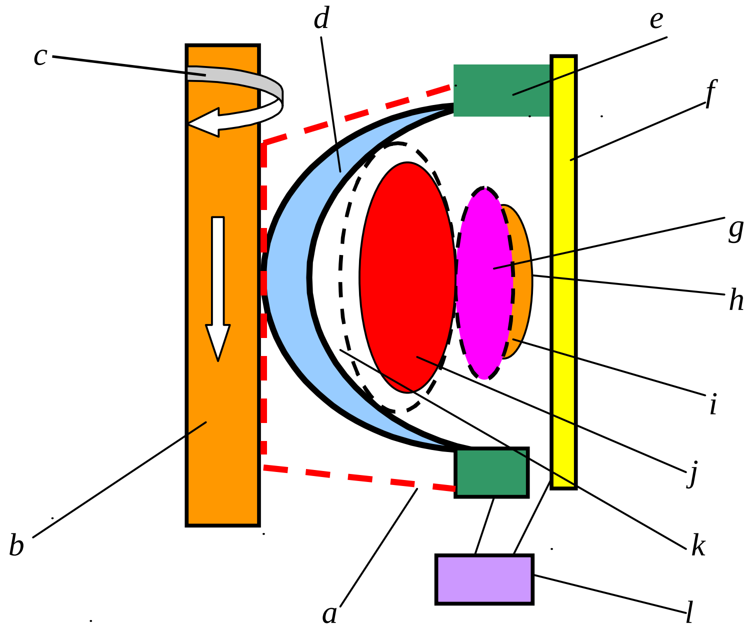

FIG. 3. (a) Final position of the formed and pushed plasma belt (FPPB); (b) Floating conductive hollow rod (FCHR); (c) Poloidal magnetic field of the plasma belt touched to FCHR; (d) Formed and pushed belt before final position; (e) Anode electrode of the magnetically driven plasma gun (MDPG),

(f) Back strap electrode of MDPG; (g) Cross section of the plasma current channel (PCC) in the on-set case; (h) Cross section of PCC at the start-up ; (h) Inter-linked poloidal magnetic field of PCC the crossing state; (i) Compressed PCC before on-set ; (j) Approximate position of compressed PCC before snow-plough state; (k) Approximate form and position moving poloidal magnetic field before snow-plough state with magnetic piston formed in the final phase; (l) Cathode electrode of MDPG combined with direct electrostatic current launcher.

3.2. Final phase

Figure 4 shows the demonstration of spherical tokamak plasma (STP) creation using spherical snow-plough (SSP) with dual-axial Z-pinch (DAZP).

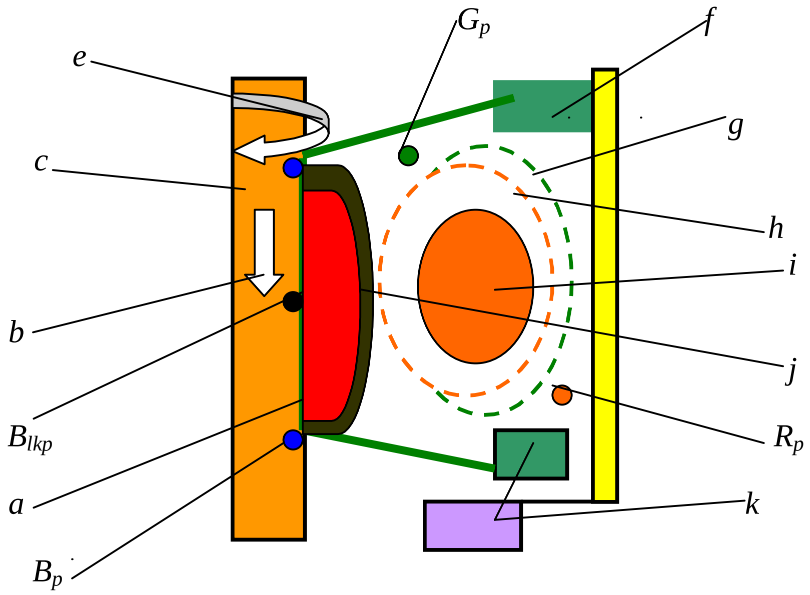

FIG. 4. (B_p) where, magnetic pressure greater than kinetic pressure; (a) Final position of the FPPB at the equilibrium state; (B_{lkp}) where, kinetic pressure greater than magnetic pressure in the equilibrium state with spherical snow-plough starting; (b) Direction of belt current touched on the cylindrical surface of FCHR during spherical snow-plough equilibrium state; (c) FCHR as in (Fig. 3(b)), (e) Direction of poloidal magnetic field at the spherical snow-plough equilibrium state; (G_p) Direction of the toroidal magnetic field generated by belt current is out of paper; (f) As in (Fig. 3(e); (g) Inductive poloidal current contour of the belt during spherical snow-plough equilibrium state; (h) Poloidal magnetic field of compressed plasma channel before into equilibrium state of snow-plough; (i) Approximate cross section plasma current channel before irreversible heating by adiabatic compression; (j) Current carrying sheath acts as a magnetic piston to be formed by compressed plasma core; (R_p) Direction of toroidal magnetic field generated by inductive poloidal current contour of compressed plasma core is into paper; (k) As in (Fig. 3. (l)).

4. Results and discussions

The approximate diagrams seen in Figs (3) and (4) have been drawn by reconstruction method. The data used in this process contains: the photographic records taken by the open shutter integrated post-fogging technique with density filter at the equilibrium states at either the preliminary phase or the final phase; the recorded time domain oscillogams (e.g., Figs (a) and (b)) at these phases; the time varying axial and radial flux signals obtained in the both above mentioned phases, by using magnetic probes and loops located selected position on the toroidal and poloidal surfaces of created plasma medium. From the correlational results of the data obtained, it has been understood that the formation of the spherical snow-pough is arise with the major role of dual-axial z-pinch and the self-created reversed field pinch processes together. The preliminary phase starts by the loading of EPFL with the spheromak like compact toroid (SLCT) created by the FCTI. Besides, startup of the STPD seen in Fig.1(a) continues about 60 μs. In the plasma medium produced in this period, the paramagnetic-diamagnetic toroidal magnetic field transformation comes into existance. The absolute value of this transform is 0.21T (Fig.1 (a)). Just after, STPD begins (Fig.1 (b)) and it lasts about 14 ms. In the first half period of the STPD lasting 1.75 ms.The repeated plasma current channels (Fig.3 (h, g, j)) and their poloidal fieldes (Fig.3 (i, k)) together moving towards to the FCHR Fig.3 (b)) joins into startup period. This mentioned dynamic phenomenons take part in the cross section of the plasma belt package touched with FCHR (Fig.3 (d)). The plasma belt currents touching to FCHR, are in fact composed of many coaxial current sheaths (Fig.3 (d)). This evolution 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 sheat 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 (Fig.3 (c)) and the poloidal magnetic field of the toroidal plasma current channel (Fig.4 (h)), the dual-axial z-pinch (DAZP) effect commences. The first period of the STPD and the final phase simultaneously start (i.e., the delay between the preliminary and final phase is 1.75 ms). Neverthelless, this phase lasts 7.2 ms, along the second period of the STPD (Fig.1 (b)). In the coilless mode of STPC-EX, the self-creation of toroidal field is produced by the following two ways: (a) the self toroidal field of the time varying plasma belt in the equilibrium state (Fig.4 (green line, G_p)) and (b) the reversed field of the plasma current contours in the case of inductive coupling by the plasma belt in equilibrium state (Fig.4 (g, h, R_p)). These constitutions are interacted by the poloidal field of the compressed plasma current channel (CPCC) (Fig.4 (h)) effecting from either the outside or or inside. As a result, CPCC turn-on into the reversed field pinch mode (RFP). Consequently, the spherical tokamak is constructed by the first CPCC and second one formed by DAZP and RFP respectively, coming together co-axially by means of the magnetic piston (Fig.4 (j, B_p, B_{lkp})) effect of spherical snow-plough, (Fig.5 (a)) on the surface of FCHR.

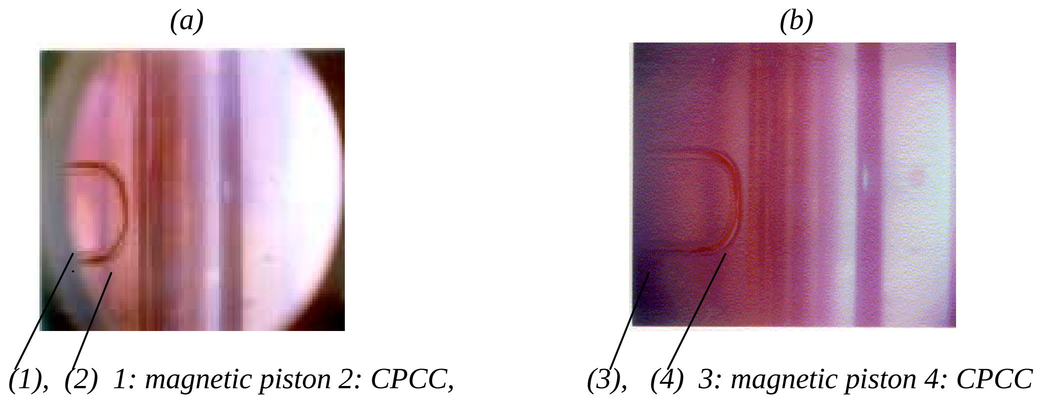

FIG. 5. in (a) and (b), typical photographic results: (a) perfectly created spherical tokamak plasma; (b) fairly diffused spheromak like compact toroid. Experimental results show that for a perfect spherical tokamak configuration, it is sufficient not only optimum belt velocity, but also the speed of magnetic piston of the spherical snow-plough action. As seen detailed in Figs 3 and 4, this results commence by the MHD activities of both DAZP and RFP, during the created plasma core transport.

5. Conclusions

The STP in the envelope of SSP is shaped relating to m = 0 or 1 < m < 3 modes of DAZP. In this procedure, the basic objets to be characterised at the conventional STP are controlled by the geometry of FCHR and previously selected reference data of MDPG combined with electrostatic current-launcher. For instance, the aspect ratio and elongation are depending on the distance between FCHR and back-strap of MDPG, the belt velocity and the length of FCHR and piston velocity (dynamic state of DAZP). On the other hand, triangularity is changing with respect to the belt thickness surrounding the FCHR cylindrically. The STPC-EX is operating in the Helium gas mantle under the dynamic vacuum. Although at the centre of flux conserver, the FCHR made of Aluminium causes to impurity; bearing in mind the self-sputtering properties, the internal structural material can be modified by different special a low-Z, conductive ones. In addition, inner surface of the flux conserver can be coated low-Z material known. Due to the special interior structure of STPC-EX, a part of the electrode system can be transformed into single-null toroidal divertor. By means of a merging program support, the sustainment time of STP can be risen up to 150 - 400 ms, modifying by the operating system by means of multi-electrostatic current-launcher group. Thus, it is possible to be operated on the STPC-EX by the higher power range under the weaker electrodes erosion on the MDPG. The main points achieved on this study have been: aspect ratio = 1.2 - 1.6; < beta > = 0.46 - 0.62; elongation = 4 - 6; triangularity = 0.42 - 0.58 in the case of belt velocity = 5.4×10^4 cms^{-1} - 3.5×10^6 cms^{-1} and electron density = 10^{20} - 10^{22} m^{-3}; plasma temperature = 118 - 177 eV (irreversible heating by adiabatic compression); sustainment time = 6.3 - 8.5 ms; energy confinement time = 45 - 136 ms. All above results have been taken at m is 0 modes of DAZP and RFP. According to the results of toroidal and poloidal flux contours determined, it has been understood that the self RFP has influence upon excessively the magnetic piston velocity.

It is well known that, on the fusion energy development path, the spherical tokamak is complementary to advanced high beta, high boot-strap current friction and H mode. Up to date, in return the STPC-EX as a small scale set-up, due to its different design philosophy; it has been possible to carry out versatile experimental and conceptual studies on compact toroids. From the conceptual point of view, this study has given a possibility for approach to the fission-fusion hybrids, although it is a complementary properties of the former ones.

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