# Experimental Results on the STPC-E Machine with an Alternative Non-Inductive Current Drive

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**Abstract.** At the Maastricht Conference, A 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. In this study, the preliminary experimental results and their assessment obtained from the STPC-E (experimental set-up version of STPC) machine whose building has recently been completed is given. In order to form and control the plasma core of a spherical tokamak in the STPC-E machine, a novel non-inductive current drive method is applied. In this method, an energetic pulse forming line and its direct coupling open circuit transverse termination have been connected to form the plasma core of a spherical tokamak. The measured basic plasma parameters of the STPC-E machine are: rms electron density, $n_e^{rms} = 10^{20}$-$10^{22}$ $m^{-3}$ in confinement time, $t_{conf}$ =45-60 ms, electron temperature, $T_e$ =30-45 eV, average plasma current, $<I_{pl}>$=1.5-1.8 kA in helical form, maximum toroidal and poloidal magnetic fields $B_t^{max}$ =1.2 kG, $B_p^{max}$ =0.8 kG and sustainment time, $t_{st} \cong 10$ ms. Increasing the number of STPC-E machine's modules, it is possible to extend the sustainment time up to 100-120 ms orders.

## 1. Introduction

The methods of plasma production, heating and confinement are well known. Taking into consideration of fusion reactor scales, in the updated experimental devices, the non-inductive current drive [1], RF current drive [2], helicity injection [3], bootstrap current generation [4] and beam and compact toroid injections [5,6] methods, realized by different techniques, are applied to the tokamak and spherical tokamak systems. In this case, in order to heat the plasma, the wave heating and current drive mechanisms are applied as an associated complex procedure [7]. In this study, a magnetically driven plasma gun connected with an energetic pulse forming line by a different internal structure, is inserted into the flux conserver directly and for the purpose of either the production, heating and control of the spherical tokamak plasma, or current drive, a novel method has been submitted. In addition, this method has been applied to the conceptual design of STPC [8] and preliminary experimental results obtained from a modified version of the STPC-E machine are discussed.

## 2. STPC-E Machine

The STPC-E system is based on a modular design concept. At STPC-E, a simulated single turn, high current toroidal field coil is controlled by a **M**agnetically **D**riven **P**lasma **G**un combined with an **E**nergetic **P**ulse **F**orming **L**ine (MDPG+EPFL). The main parts of the toroidal field coil consist of the shock heated, time varying, non-linear plasma belt in the flux conserver and the complementary back strap at the outside. The poloidal current loop is completed by the pre-programmed trigatron switch and EPFL. The complete STPC-E is formed by the multisegmented MDPG+EPFL system modules located around the flux conserver. In order to produce either pre-ionization or pre-heating, a separate internal **F**ast **C**ompact **T**oroid **I**njector (FCTI) is added to this MDPG+EPFL assembly. Each module consists of three MDPGs together with one EPFL, one FCTI and one trigatron switch. In addition, at STPC-E; a central solenoid is added in order to control the interlink between toroidal and poloidal field lines in the flux conserver centre. Moreover, for controlling the eddy currents created at the flux conserver, two passive rods are connected separately to the top and bottom walls of the flux conserver near to the centre. For single-null poloidal divertor in STPC-E , an external solenoid is employed.

## 3. Current Drive

In order to form and control the plasma core of the **S**pherical **T**okamak (ST) in the STPC-E machine, an **A**lternative **N**on-**I**nductive **C**urrent **D**rive (ANICD) method is applied. This novel method; can be described as being analogous to the conventional **RF**-**N**on-**I**nductive **C**urrent **D**rive (RNICD) mechanism. In the ANICD method, an EPFL and its direct coupling open circuit transverse termination are used in place of the RF power amplifier and its launching electrostatic antenna as employed in the RNICD method. Furthermore, the operating mode of ANICD is time domain whereas it is frequency domain for RNICD. In STPC-E, the poloidal and toroidal magnetic fields are produces in a different way, having the possibilities of ANICD without utilizing any conventional ohmic heating transformer. Because of the noticeable level of temperature and density gradients of the plasma belts, pushed towards the centre of the flux conserver by Lorentz forces, either toroidal or poloidal bootstrap current is generated. On the other hand, through the influence of the helicity injection of the MDPGs, a second current drive mechanism comes into existance.

## 4. Formation and Optimization

On the surface of the floating passive central rod of the STPC-E machine, a **S**pherical **T**okamak **P**lasma (STP) has been formed by the selforganization process. Figure 1 shows the formation of STP in the STPC-E machine, but the formation of the STP and the enclosed surroundings of the passive floating central electrode at the centre of the flux conserver occur by means of EPFL, having linear step by step discharge with a duration of 10.5 ms, as shown in Fig. 4. Thus, the integration of startup, onset and sustainment phases can be described. From Fig. 1, the STP's aspect ratio is found to be 1.7-2.2. According to the experimental results on STPC-E, it should be noted that the toroidal and poloidal current contours created by the interactive hot plasma belts generated by the MDPGs are helical in form. In this situation, taking into consideration the classical inductive coupling, a simulated electronic-coupling coefficient has been achived at its ideal value of K=1. In other words, the plasma belts and the current contours have constituted a different type of non-inductive coupling mechanism. On the other hand, the main plasma current channel has been composed by the helical double twisted currents $I_z$ , $I_\theta$ and magnetic fields $B_\theta$ , $B_z$ . From the first experimental results, it has been observed that the radius and the length of the central rod affect the aspect ratio and the elongation of the STP. For this reason, in order to optimize the internal structure of the STPC-E machine, an analytical model has been developed. In this model, the known components of toroidal co-ordinates have been parameterized by the classical geometrical parameters of the STP, converting to the 3-D rectangular co-ordinates, given by the expressions as follows:

$x = (R\text{-}a\varepsilon)\cos\varphi\ /1\text{-}\delta\varepsilon\cos\zeta$ , $y = (R\text{-}a\varepsilon)\sin\varphi\ /1\text{-}\delta\varepsilon\cos\zeta$ and $z = a\kappa(1\text{-}\varepsilon^2)^{1/2}\sin\zeta\ /1\text{-}\varepsilon\cos\zeta$

where R, a, ε, κ and δ are *the major radius, the minor radius, the inverse aspect ratio, the elongation and the triangularity* of the STP, respectively. In the expressions, φ and ζ imply the toroidal and poloidal angles between 0 and 2π. Two typical rectangular 3-D plot examples of the STP are given in Fig. 2. In cases (a) and (b) in this figure, the parameters have been selected as R = 0.21 m, a = 0.11 m, ε = 0.5, κ = 2, δ = 0.5 and R = 0.275 m, a = 0.22 m,

$\varepsilon = 0.8$, $\kappa = 2$, $\delta = 0.25$ respectively. As mentioned before, the aspect ratio has been changed from 1.9 into 1.25. In order to imagine the configurations more easily, the above plots have been drawn with a tilt angle of $\theta = 70^0$ and the lower ones with $\theta = 0^0$.

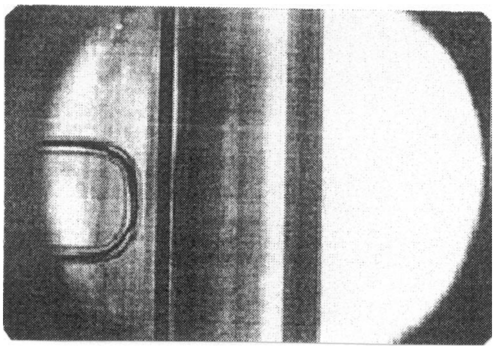

*FIG. 1. Photograph taken from circular diagnostic window by means of the open-shutter integrated post-fogging method. Here, FCTI has exposed the right side of the film beforehand, with an operating time of 60-70 μs in the onset phase.*

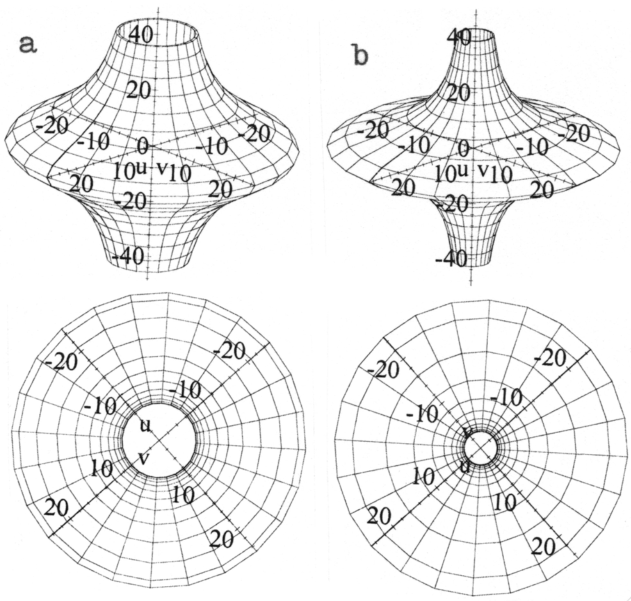


*FIG. 2. 3-D rectangular plot examples of the STP.*

## 5. Results

For the assessment of the time-domain oscillograms taken from the STPC-E machine, the termination model of the ANICD mechanism is developed by using the fundamental principles of the transmission line theory. The principal equations of the model are as follows: *voltage-standing-wave ratio* VSWR, $\rho=(V_i+V_r)/(V_i-V_r)$ where $V_i$ and $V_r$ are the *incident* and the *reflected* voltages at the **P**lasma **C**ore of the **ST** (PC-ST); *reflection coefficient*, $|\Gamma| = (\rho-1)/(\rho+1)$; and the *complex value* of PC-ST, $Z_{pl}=-Z_o(1+\Gamma)/(\Gamma-1)$ where $Z_o$ is the *characteristic impedance* of the EPFL. The *phase angle* of PS-ST is given by $\beta=2\pi t_d/T_p$ where $t_d$ and $T_p$ are the *delay time* and *pulse duration* (two-way travel time) on the oscillograms. The *complex value* of PC-ST may also be given by $Z_{pl}=|Z_{pl}|e^{\pm j\beta}$.The evaluated results obtained from numerical values on the oscillograms (Figs 4 and 5 gives) explain the resistive and/or inductive behaviours of PC-ST. Figure 3 gives two example plots .

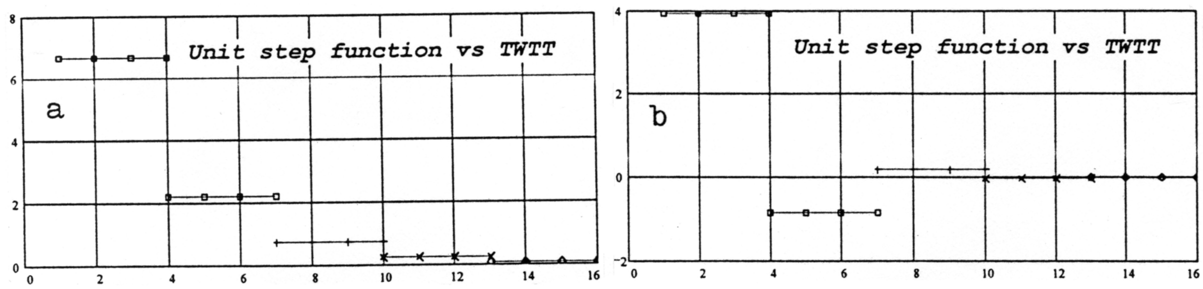


*FIG. 3. Two results (a) and (b) from the termination model of ANICD.*

for different conditions, obtained from the model of ANICD. In plots (a) and (b), $Z_o$= 4Ω and β is constant. In other words, the ST plasma core impedance is purely resistive. But, $Z_{pl}$ is 8Ω in plot (a), whereas in plot (b) it is 2.6Ω. Figure 4 shows the effect on the impedance of PCST at the centre due to non-linear time-varying pushed plasma belts, and therefore, the variation of toroidal field density of the STPC-E machine in time. In this case, $Z_0$ is 4.2Ω and constant. The sustainment time of the stepping discharge is about 10.5 ms. The maximum toroidal field density is 1.2 kG. Figure 5 gives the toroidal field density variation in time of the FCTI at the startup phase. In this figure, paramagnetic and diamagnetic effects are shown in the first 60 μs. The magnitude of difference between the self-generated toroidal field and the diamagnetic field is about 2.5 kG. The compact toroid produced by the FCTI at the onset phase is presented in Fig. 6. The lifetime is about 1.2 ms and the toroidal magnetic field density is about 0.22 kG. Upper traces in Figs 7 and 8 are the derivative signal of the toroidal field density and the lower ones are their integration in time. These oscillograms show the startup phase of the STP in the time domain, where the $x$ axis is 0.1 ms/div and the $y$ axis is 0.370 kG/div. Figure 9 shows the start of instability resulting from increasing the input power of FCTI. In the figure, the $x$ axis is 0.5 ms/div and the $y$ axis is 0.370 kG/div .

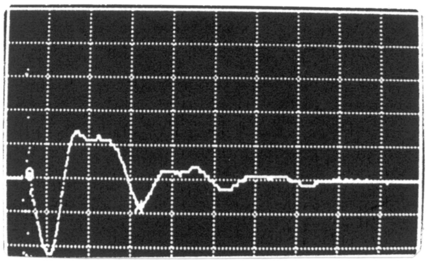

*FIG. 4. The sustainment time of the stepping discharge of the STP is about 10.5 ms; the corresponding maximum toroidal field density is about 1.2 kG.*

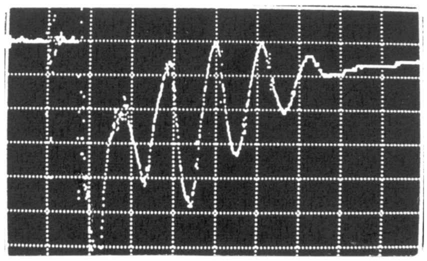

*FIG. 5. Difference between the self-generated and the diamagnetic field (2.5 kG).*

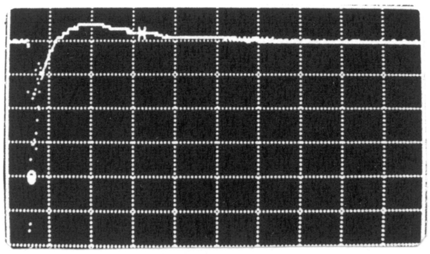

*FIG. 6. Toroidal magnetic field density variation (0.22 kG/div.) in time (200 μs/div) for FCTI during CT injection.*

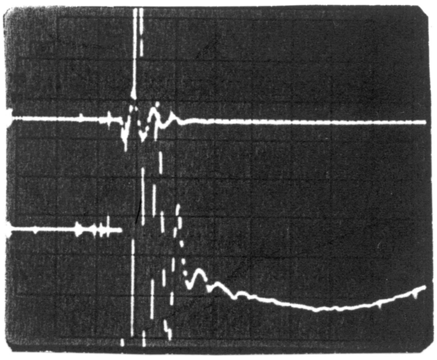

*FIG. 7. Effect of FCTI's input energy, $W_i$ on pre-ionization of the STP. Here, $W_i$ = 400 J.*

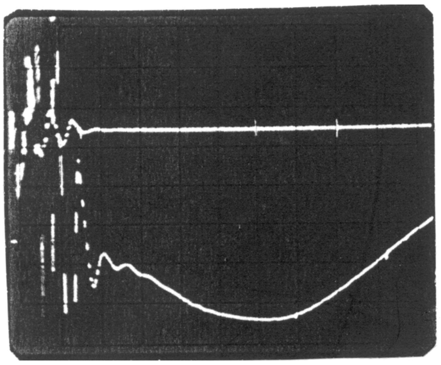

*FIG. 8. Same as Fig.7, but with $W_i$ = 600 J.*

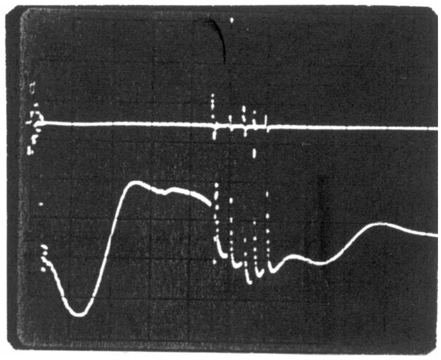

*FIG. 9. Start of energy transport instability between FCTI and the STP core, due to the increase in input energy of the FCTI.*

## 6. Conclusion

The main results achieved in this study are: i) At the STPC-E machine, the eddy currents occurring at the surface of the flux conserver can be controlled. Producing a surrounded magnetic axis through the upper and lower corners of the flux conserver, these controlled eddy currents have been transformed into a cusped type of magnetic field of 150-200 G. Thus, the lifetime of the spheromak-like compact toroid formed at the centre of the flux conserver at the onset phase has been expanded up to 1.2 ms (see Fig. 6). ii) The minimum imput energy level of the FCTI needed for the preionization of the plasma medium has been found to be about 400-600 J. At the operating condition for helium with a pressure of 70 mTorr, a difference of 300 μs between the formation time-lag and the statistical time-lag has been observed (see Fig. 7). If the input energy of the FCTI is raised to 600 J, for the pre-ionization very good reproducibility has been determined and then the formative time-lag has dropped to levels of 50-100 μs (see Fig. 8). In the case of higher FCTI input power, between 800 and 1200 J, due to the strong energy transport between the spheromak-like compact toroid and the spherical tokamak plasmas, in the poloidal plasma current channel the radial instability of low frequency oscillations with 4.3-6.5 kHz has appeared (see Fig. 9). iii) By increasing the number of modules, selecting a different characteristic EPFL impedance with respect to the STP impedance and controlling the discharge with the merging programme, the sustainment time of the STP can easily be extended up to the order of 150 ms iv) The high edge gradient of the electric field of the MDPGs may be the reason for the L-H transition-like mechanism. Therefore, it may be responsible for the improved confinement regime. The measured basic plasma parameters of the STPC-E machine are as follows: Electron densities (rms) and average temperatures at the belt, at FCTI and at STP are $10^{21}$-$10^{22}$ $m^{-3}$,$10^{20}$-$10^{21}$ $m^{-3}$ $10^{20}$-$3\times10^{20}$ $m^{-3}$ and 22 eV, 8.2 eV, 14 eV ($\beta_p \cong 0.4$ max.) respectively (after 3-D adiabatic compression). The overall temperature is 42 eV, $t_{conf}$ = 45-60 μs, $\langle I_p \rangle$ =1.5-1.8 kA in helical form, $B_p^{max}$=0.8 kG and deposition energy efficiency from the capacitor bank to the spherical tokamak is about 0.33-0.45. v) As mentioned above, although on the STPC-E machine, the STP is produced by the self-organization process, according to the experimental results done systematically it has been understood that there exists a controlling and optimization possibility of this mechanism as well. Depending on the classical system parameters of the ST, for the theoretical interpretation of this mechanism, a preliminary model has been developed. Thus, a means scaling and optimization for the STPC-E machine has been obtained.

## References


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