26th EPS Conf. on Contr. Fusion and Plasma Physics, Maastricht, 14 - 18 June 1999 ECA Vol.23J (1999) 533 - 536

A Paramagnetic Spherical Tokamak with Plasma Centerpost

S. Sinman[1] and A.Sinman[2]

[1]*Middle East Technical University, Electrical and Electronics Engineering Department*
06.531 İnönü Bulvarı, Ankara Turkey
[2]*Nuclear Fusion Laboratory, Turkish Atomic Energy Authority*
06983 Saray, Ankara, Turkey

Introduction

At present, on the spherical tokamak systems such as START [1] experiment (UK), TST and TS3-4 [2] (Japan), under construction NSTX [3] (USA) and Globus [4] (Russia), the toroidal magnetic field is usually generated by using a central active rod instead of the conventional centerpost toroidal coils. But differently, in this spherical tokamak system proposed, toroidal magnetic field is generated by the multi-plasma-belts in the flux conserver. So, being an altemartive concept from others, it is named by Spherical Tokamak with Plasma Centerpost (STPC).

Previously, the Alternative Spherical Tokamak (AST) system had been taken into consideration from the viewpoint of current drive [5] and profile control [6] mechanisms conceptually. The goal of this study is to realize a simple, small scale compact toroid, having a different internal structure. In the preliminary design of STPC machine, main contributions to operating condition in context are: low operating voltage (2.040 kV), fairly high current (5-7 kA), extended operating period (1 O-25 ms), low aspect ratio (1.24 .5) with electron temperature of 30-70 eV and electron density of $n_e=3\times10^{20}m^{-3}$–$6\times10^{20}m^{-3}$. In this paper, the fundamental principles and the computational experimental results of the conceptual design of STPC and the perspective of this practical system are presented.

Description of STPC machine

At the geometrical axis of a cylindrical floating flux conserver, a floating conducting tube having a solenoid inside it has been placed. Two axially symmetrical semi-circular anode electrodes have been fixed near-by the upper surface of flux conserver. The grounded, segmented cathodes have been settled down on the periphery of a circular ceramic case taking' place near to the bottom surface of the conserver. At the outside of flux conserver an isolated cylindrical back-strap assemble in the shape of squirrel cage has taken part. Semi-circular anodes have been connected to the upper side of the back-strap radially. The lines of fence of the cage and the segmented cathodes are one by one connected to the Pulse Forming Line (PFL) and the thyristor switches respectively. Thus, in the flux conserver, a poloidal plasma current loop is completed (see in Fig. 2.).

Operating scenario

(i) At the stand-by phase, between the two semi-circular anodes and the segmented cathodes, the electrical fields are builded up. (ii) Besides this electrical fields, an artificial ellipsoidal volume formed by means of the equipotential surfaces is came into existance. (iii)

Although an appropriate gas pressure is present, at the start-up phase, due to the distance between the electrodes and the low operating voltage, a breakdown is not yet **occured.** But, when the central solenoid and /or Fast Compact Toroid **(FCT)** injector are drived, a corona discharge is initiated and then by means of the poloidal field generated, the electrons in the equipotential volume are commenced to access into avalanche. Consequently, the break-down **occures.** (iv) At the on-set phase, by means of the Lorentz force, the cylindrical belt packet keeping its axially symmetrical structure improves towards the **center** of flux conserver. Thus, a plasma core having a toroidal axis formed by the magnetic flux contours came into **existance.**

Belt functions

There are two derived functions, **characterizing** the belts given by $f_{blt1}=a_{blt}^3/(cz^2+d^2)$ and $f_{blt2}=\{Ln(-z^2+1)^{1/2}+1\}/c_z-d$ where z is the distance between cathode and anode, a_{blt} is belt radius, c and d are the geometrical constants of belt packet.

Velocity of the belt

Being R_0 and *a are* major and minor plasma radii, $U=(R_0+a)/(R_0-a)$, the velocity of the belt packet can be expressed by $v_x(t)=1/m_e\int_0^t J_y(t)B_z(t)dt\int_0^R\int_0^a LnUdRda$. This function is in multiple integral. The first term of the equation is devoted to Lorentz force and the double integral term defines the cross section of magnetic flux contours depending on R_0 and a. The functions, $J_y(t)$ and $B_z(t)$ *are* the complementers. Due to the structural property of the STPC machine, the belt current, $I_y(t)$ formulates either the current density, $J_y(t)$ or the magnetic flux density, $B_z(t)$. The integration of both terms has been solved by the Taylor's polynominal approximation method. Consequently, it have been obtained two complementary weighting functions of $f(\omega_1)$ and $f(\omega_2)$ **defined** by $f(\omega_1)=0.33T_{on}^{-2}t_{st}^3I_0^2-0.25T_{on}^{-3}t_{st}^4I_0^2+0.12T_{on}^{-4}t_{st}^5I_0$ and $f(\omega_2)=0.08\alpha^{-3}U^4+0.5/\alpha U^2-0.17\alpha^{-2}U^3+Ln\alpha U$, where, T_{on} *is* over-all turn-on time of on-set phase and *a is* the correction factor of Taylor's polynominal approximation. The magnitude of belt velocity is, $|v_{blt}|=1.76\times10^{-3}f(\omega_1)f(\omega_2)/S$, where S is the area of belt in $[m^2]$. Using $|v_{blt}|$, it is possible to calculate the electron velocity distribution function.

Energy balance

The requirement and minimum requirement energies of STPC are expressed by $W_{Rq}=W_e[eV]V_{Pl}[m^3]n_e[m^{-3}]/\phi_{Overall}$ and $W_{Rqm}=I_y^{blt}(t_{st})V_{PFL}(t_0+)t_{st}$ .On the other hand, the stored energy of PFL is $W_{PFL}=0.5\sum C_{PFL}V_{ch}^2$, where the belt current, $I_y^{blt}(t)=I_0\{1-exp(-t_{st}/T_{on})\}$, $I_0=V_{PFL}/\sum Z_{sys}$ V_{ch} *is charging* voltage of **sectionalized** LC **type** PFL, $\phi_{Overall}$ is efficiency, V_{PFL} is terminating voltage of on-set phase, Z_{sys} is total input impedance of STPC system For optimum impedance matching, the maximum sustainment time and two-way-travel-time must be $2t_{st}=t_w$.

Results and discussions

By means of above consecutive equations, reference data to be found for **STPC** machine **are as** follows: $V_{ch}=3kV$, $I_0=5kA$, $Z_{sys}=0.6\Omega$, $W_{PFL}=9kJ$, $T_{on}=0.2ms$, *if* $2t_{st}=t_w$ **than** $t_{st}=2.4ms$ but if $2t_{st}\neq t_w$ **than** $t_{st}=2.4-6.2ms$, $W_{blt}=2.88-3.78kJ$, $R_0=0.08m$, $a=0.067m$, $A=1.2-1.4$,

$Vol_{blt}=0.087 m^3$, $W_{drift}=44.18 eV$, $<P_{ohm}>=\eta J_{pl}^2=37.8 kWm^{-2}$, $<n_e>=2\times10^{20} m^{-3}$, $<T_e>=34 eV$, $|v_{blt}|=1.34\times10^7 ms^{-1}$, $B_z=0.4-1.2 kG$, $B_p=0.8-1.5 kG$ and $I_{pl}=4.5-6.0 kA$ including bootstrap current. It should be noted that, for computational experiment, the predetermined numerical values of system parameters of STPC have been held a good deal lower. The reason of this is to **realize** a small scale STPC machine in the first step. Figure 1 shows the two main factors affecting the belt velocity. The first factor is the turn-on time, T_{on} and the second one is the belt current, I_y^{blt}. In the equilibrium condition, in order to be interlinked the toroidal and poloidal field line contours, for arrival time of belt packet, T_{arv}^{blt} to the **center,** the inequality of $T_{arv}^{blt} > T_{on}$ must be **fulfiled.** By this situation, a helical magnetic field formation, just like in that of tokamak systems may be obtained. In this example given, due to the **utilization** of only one Nova1 Magnetically Driven Plasma Gun and the selection of lower values of belt current and operating voltage, the toroidal field strength becomes lower ***{Ref. [5], Eq. (12)}***. This result **affects** the magnetic **helicity** injection mechanism negatively ***{Ref. [6], Eqs (23,25)}***. Nevertheless, because of the **different** internal structure of STPC and its operating principle, the three-dimensional adiabatic compression in the central position of the belt packet including **soft** pinch is expected. Therefore, the **normalized** boot-strap current ***{Ref. [6], Eq, (21)}*** and ohmic heating power density in equilibrium phase will be able to arrive to the **sufficient** values. Finally, by the results based on the above consideration, it is possible to establish a projection and to realize a medium size STPC machine.

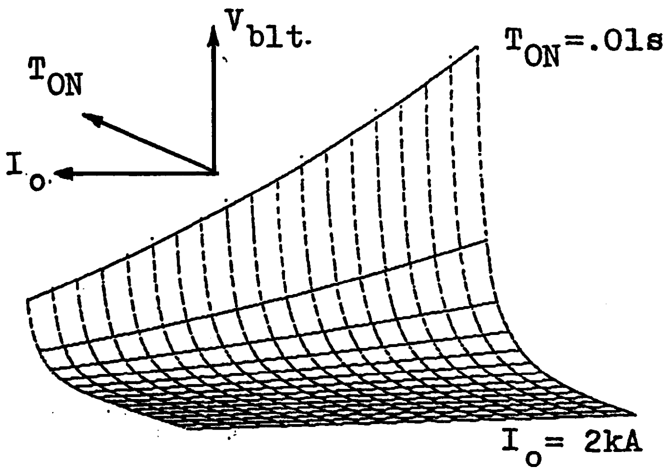

FIG. 1.

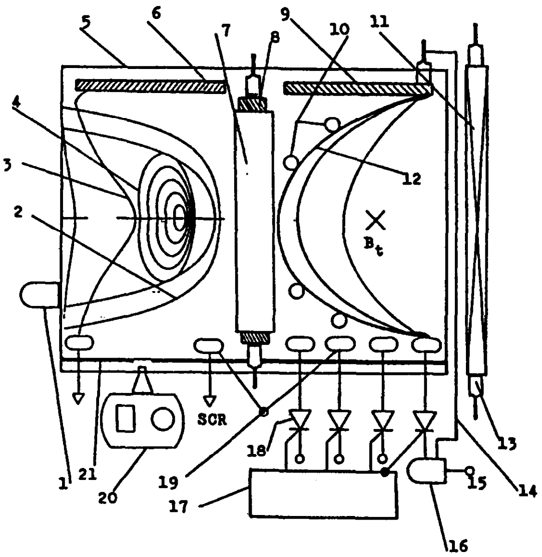

FIG. 2.

Figure I. The computational results of phenomenologically simulation from plasma core model [7],[8]. Velocity of the belt packet, v_{blt}, as a function of turn-on time T_{on} and initial belt current I_0, where x axis is I_0=1.0-2.0 kA, y axis is T_{on}--0.1-0.01 s and z axis is v_{blt}=5.4×10^4-3.5×10^6 ms^{-1} for I_0=2.0 kA. Figure 2. Two different cross-sectional layout of the conceptual design of STPC machine. At the left-hand, typical example of controlled prolate current profile, in equilibrium phase, based on the model [6] and at the right-hand, the internal structure of STPC machine and related auxiliary equipment are given. The numerical points in the figure are as follows: 1) FCT injector in flux conserver; 2) Belt formed by PFL having a flat shape; 3) Belt formed by PFL in exponential character; 4) Poloidal current loop formed; 5) Floating cylinderical flux conserver; 6) Left part of the semi-circular anode; 7) Floating passive central rod; 8) Central solenoid; 9) Right part of the semi-circular anode; 10) Passive stabilization ring to prevent the deformation of belts; II) External solenoid; 12) Dense and hot belts to be pushed by Lorentz Force: 13) External solenoid feedthrough;

14) Cylindrical squirred cage back-strap assemble; 15) To power supply; 16) Pulse forming line (PFL); I?') Programmable control unit of thyristor (SCR) switches; 18) Thyristor switch; 19) Segmented special cathodes; 20) Vacuum system; 21) Circular ceramic support to fix segmented cathodes.

3D Plasma-Core model **has** been performed. In this coverage; the radii distribution **function** of toroidal and poloidal **flux** densities and current densities in time domain **[7], [8] are** as follows: $B_z(t,t) = \gamma(1+\exp(-r)\cos(rt) - \exp(-r) - \cos(\lambda r))$,

$B_\theta(R,T) = (1/\varepsilon)\exp(-R/t) + R/\varepsilon - (1/t)\exp(-R/t)\sin(\beta R) + (R/\varepsilon)\exp(-R/t)\cos(\beta R)\beta$,

$J_z(r,t) = (r/\varepsilon)\exp(r/t)\sin(\beta r)$,

$J_\theta(R,t) = \gamma(-(\exp(-R)\cos(Rt) + exp(-R) - (\sin(Rt)t) + \exp(-R) + \sin(\lambda R)\lambda$ where t **is time,** r is the distance **from** estimated centre of the current channel, R is the distance **from** axis of the flux conserver, γ is dependent **function** and ε is inverse weighting **function** of the belt current of the PFL and finally λ and β are weighting **function** of aspect ratio and elongation. For statistical evaluation, typical operating condition of STPC having four **PFLs,** are given above.

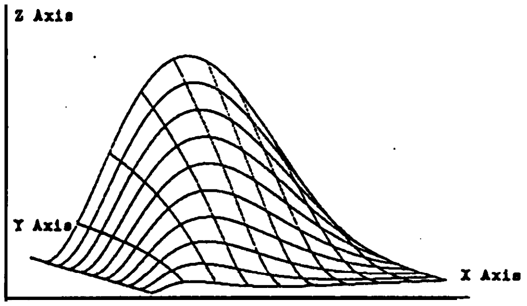

FIG. 3.

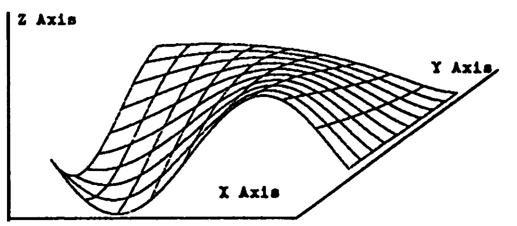

FIG. 4.

FIGs.3.and 4. Calculated time evaluation of radial profiles of $J_z(r,t)$ and $J_\theta(R,t)$ respectively. In the figures; time scale in y axis is 200 μs/div, radii R and r in x axis are 0.65 cmldiv and z axis is arbitrary scale.

REFERENCES

[1] MORRIS, W., for the MAST edge and **divertor** physics team, (SYKES, A., Chief Scientific Investigator) in Report of Research Co-ordination Meeting, *14-l* 8 December 1998 Vienna, F 1 **-RC-73** 1, IAEA, Vienna (1999) 230.
[2] ONO, Y., ibid., p. 247.
[3] PENG, M., and **MAJESKI,** R., and Contributing Researchers, ibid., p. 262.
[4] GUSEV, V. K., et **al.,** ibid., p. 145.
[5] SMMAN, S. and **SINMAN,** A., in Plasma Physics and Controlled Nuclear Fusion Research 1994 **(Proc. 15th Int. Conf.** Seville, **1994),** Vol. 2, IAEA, Vienna (1995) 303.
[6] **SINMAN,** S. and **SINMAN,** A., in Fusion Energy 1996 **(Proc. 16th** Int. **Conf.** Montreal, **1996),** Vol. 2, IAEA, Vienna (1997) 297.
[7] **SINMAN,** A., in Activity Report, (Time Period Covered: June 1996 – November **1997), 2nd** RCM in IAEA – HQ, 15-l 7 December 1997 Vienna, Austria, in press.
[8] **SINMAN,** S. and **SINMAN,** A., in IAEA Technical Committee Meeting on Spherical Tori and Fourth International Workshop on Spherical Tori, Book of Abstracts, p. **10, 26-28** October 1998, University of Tokyo, Japan.