DEVELOPMENT AND VERIFICATION OF MATHEMATICAL MODEL FOR HALO CURRENT IN ITER

Shahab Ud.Din Khan*, Yuntao Song, Jinxing Zheng, Shanshuang Shi,
Institute of plasma physics,
Chinese academy of sciences,
Hefei, Anhui, P.R.China.
shahab@ipp.ac.cn

Salah Ud-Din Khan
Sustainable Energy Technologies Center,
College of Engineering, King Saud University,
Riyadh, Saudi Arabia

***Abstract*— Confined plasma by magnetic field is appear to be abundant and durable source of energy for future aspects. Tokamak is the most advanced device under controlled condition of magnetic field and current flowing in plasma. The interaction of plasma with vacuum vessel gives halo current following poloidal direction with strong outward magnetic force towards vessel. The vertical disruption events caused by this halo current creates an engineering problem for fusion reactor. Therefore, in this paper, toroidal magnetic field Btor and halo current Ihalo were calculated by mathematical formulation and technique. Since, experimental data has already been got from the EAST experiment, therefore, the aim is to developed and investigate an analytical model and computationally evaluate with theoretical calculations. For this case, vertical disruption events of plasma facing components including the balancing sideways forces due to asymptotic poloidal halo current will be evaluated and examined. The results obtained will be useful for equalizing the simulation and experimental results. The research will be extended to developed new models for other Fusion reactors.**

***Keywords*— plasma shape, halo current, theoretical approach, plasma cross section, EAST.**

I. INTRODUCTION (*HEADING 1*)

A potentially environmental friendly source of safe energy with an abundant course of fuel supply is considered to as fusion energy. A new technology for developing fusion energy is to use hydrogen isotopes, deuterium (D) and tritium (T)[4-6] as a combine effort for building up of International Thermonuclear Reactor (ITER) [7-9] named as Tokamak, which will come into operation in 2020. This is the most advanced and promising approach of harnessing fusion energy to confine magnetic field in torus shaped plasma device (Tokamak)[1-3]. The working mechanism is such as to heat up the fuel in an extremely high temperature environment (>100M0C) of plasma state with considerable density and energy confinement time. Amount of handsome work has already been published contingent with plasma shape, halo current and plasma equilibrium properties by numerical techniques. These techniques includes plasma shaping [10-12], plasma equilibrium in tokamak[13], halo current [14,15] and plasma current, shape controller and identification, plasma scenario of small aspect ratio.[16-17]. During the operational state of EAST, there is a need to analyze the chaotic behavior (initial-to-final plasma state) to maintain the plasma in the same orbit for the long pulse generation. In this paper, we have transformed and modified plasma shape model. For calculating the cross section of current loop, we developed Bx and Bz coordinate by using plasma shape model and magnetic fields point B_r and B_θ. This gives us magnetics field points and displacement when VDE start and magnetic field flux changes. For this calculation, we can get two conducting points, which is the essential part of halo current calculations. For this case, vertical disruption events of plasma facing components including the balancing sideways forces due to asymptotic poloidal halo current have been evaluated and examined. Toroidal magnetic field B_{tor} and halo current I_{halo} have been calculated by mathematical formulation and technique.

II. PLASMA SHAPE AND MAGNETIC FIELD POINTS DESCRIPTIONS

In the current research, we evaluate the new model for calculating different aspects of Tokamak reactor. The poloidal field is internally generated and produced altogether due to toroidal currents in primary winding. Many work have been published about plasma shape [11, 12]. The plasma shape is describe as

$$R' = R_0 + a_p \cos(\theta + \delta \sin\theta)$$
$$Z' = Z_0 + k a_p \sin\theta \tag{1}$$

Here k is elongation, δ is triangularity, a is minor radius, and R_0 is the major radius. The proposed shape model allows an effective way to study the shape of plasma behavior of main plasma characteristics under controlled conditions including sensitive dependent on initial condition based on isolated points. By using the algebraic techniques, we build Bx and Bz by using shape model (1). The model is given as under.

$$B_x = B_r \cos\theta - B_\theta \cos(\frac{\pi}{2} - \theta) = B_r \cos\theta - B_\theta \sin\theta$$
$$B_z = B_r \sin\theta + B_\theta \sin\left(\frac{\pi}{2} - \theta\right) = B_r \sin\theta + B_\theta \cos\theta \tag{2}$$

978-1-4799-8264-6/15/$31.00 ©2015 IEEE

Magnetic field produced by a circle current loop [24]:

$$B_r = \frac{\mu_0 I}{2\pi r}\frac{z-b}{\left[(a+r)^2+(z-b)^2\right]^{\frac{1}{2}}}\left[-K(k)+\frac{a^2+r^2+(z-b)^2}{(a-r)^2+(z-b)^2}E(k)\right]$$

$$B_\theta = \frac{\mu_0 I}{4\pi r}\frac{1}{\left[(a+r)^2+(z-b)^2\right]^{\frac{1}{2}}}\left[K(k)+\frac{a^2-r^2-(z-b)^2}{(a-r)^2+(z-b)^2}E(k)\right] \quad (3)$$

$$K(k)=\int_0^{\pi/2}\frac{d\alpha}{\sqrt{1-k^2\sin^2\alpha}}, \qquad E(k)=\int_0^{\pi/2}\sqrt{1-k^2\sin^2\alpha}\,d\alpha$$

a and b are the radius and z-axis coordinate of current loop, R and Z are the radius and $z-axis$ coordinate of the calculated point, $K(k)$ and $E(k)$ are the first type and second type of elliptic integral. $R_0 = 1.7 \sim 1.8, B_0 = 3.5T$, plasma current $I_P \le 1MA$. toroidal magnetic field [15]

$$B_{tor}(R) = 5.3T\frac{R_0}{R} \quad (4)$$

The template is used to format your paper and style the text. All margins, column widths, line spaces, and text fonts are prescribed; please do not alter them. You may note peculiarities. For example, the head margin in this template measures proportionately more than is customary. This measurement and others are deliberate, using specifications that anticipate your paper as one part of the entire proceedings, and not as an independent document. Please do not revise any of the current designations.

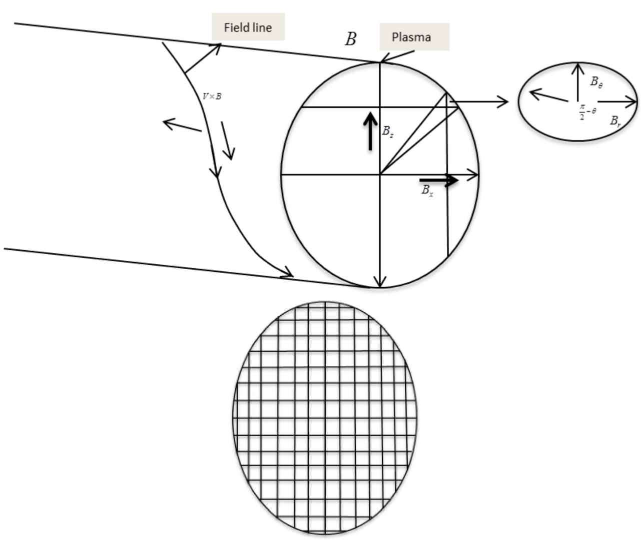

Fig1. Shown the one cross section of current loop, magnetic points are Bx and Bz. 195 points are in right side.

Each cross section depends on a, b, r and z. For one cross section, the peak values of r, z is (±5.2, ±4.37) therefore ($Br_{max,up}$, $Br_{max,down}$)= (0.3918 , -0.3847). Then the current loop of magenetic field rang is $(Bx, Bz)_{max}$ = (0.3862, 0.1698). If poloidal halo current at the inboard wall (R=3.4m) I_{halo} = 3.25 MA and a toroidal field at this location of B_{tor} = 9.7T the pressure on the inboard wall becomes 1.47 MPa [26].

III. HALO CURRENT CALCULATION METHOD

During plasma operation, a low poloidal current flows in the outer region and during VDE operations, it increase as the q-values is also raises and the toroidal magnetic field flux increases as well in plasma area. In this situation, plasma touches the passive structure and the halo current runs through the passive structure. There is a need to apply Lorentz forces into the passive structure aside from plasma. This will react only with vertical displacement by withdrawal a vertical force from the plasma. In addition, radial forces is also been transferred to this halo current and the total forces on the vessel will be the sum of all forces due to halo and eddy currents i.e.,

$$F_h + F_{p,v} + F_{p,c} = 0 \quad (5)$$

Therefore, the total force on the vessel is expressed as,

$$F_{eddy} + F_{halo} = F^{total}_{eddy,halo} \quad (6)$$

Finally, total vertical and radial forces can be write as,

$$\sum_{i=-2.3}^{4.0} Fv_i + \sum_{j=-0.7}^{142} F_{rj} = \sum_{i=-2.3,\, j=-0.7}^{4.0,142} F^{tolal}_{v_i,r_j} \quad (7)$$

Mathematical formulation of forces act on the plasma is following as below [25]:

$$F_{side,bal,2} = \tfrac{1}{2}\cdot B_{tor}(R_p - a_p)\cdot I_{halo}\cdot u_{shift,peak}\begin{cases} VDE\ SLOW \quad UP \\ VDE\ SLOW \quad DOWN \end{cases}$$

$$F_{side,bal,2} = \tfrac{1}{2}\cdot B_{tor}(R_{inboard})\cdot I_{halo}\cdot u_{shift,peak}\begin{cases} VDE\ SLOW \quad UP \\ VDE\ SLOW \quad DOWN \end{cases} \quad (8)$$

$$u_{shift}(\phi) = C\delta r_p \cdot \sin\phi + \delta z_p \cdot \cos\phi$$

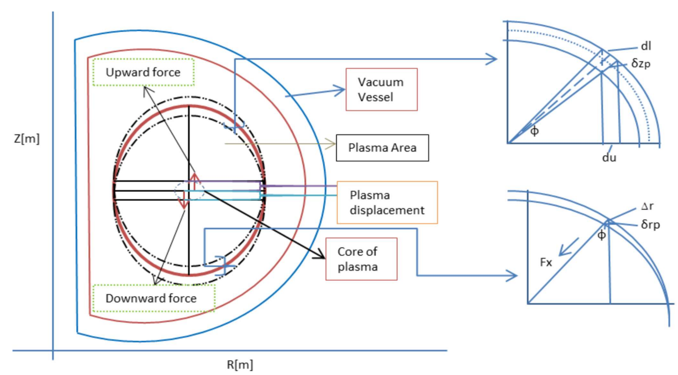

Fig 2. Shown the plasma vertical displacement , forces act on plasma, The plasma horizontal movement can be describe by geometrically, vertical and radial kink mode amplitude is δz_p, δr_p, and asymmetric change by du, dz and ΔR.

For right estimation of plasma, the pattern received from the halo current due to kink mode is more like asymmetric in nature[29]. There is only one asymmetry which observed as toroidal peak of the halo currents. The value of torroidal peaking factors[14] is 0.75(Ihalo/Iplasma) for slow and downward VDEIII and when the vertical displacement starts, halo current also been considered for outer region as well. In two conducting points, VDEIII up/down plasma areas moves and touches the wall. The unbalanced forces acted upon the vessel as a part of the plasma halo current flows through the vessel. The output of these halo currents in the vessel is more likely from DINA analysis [27]. The total force which is vertical in nature acted upon the passive structure can be analytically calculated using the following formula for each listed halo current [28].

$$F_{vertical} = \int_{R1}^{R2} B_{tor} \cdot I_{poloidal} dR \tag{9}$$

Where, R1-radial coordinate of exit point of halo current, R2-radial coordinate of enter point of halo current $B_{tor} = 5.3T \cdot 6.2m$.

TABLE 1. CALCULATION OF HORIZONTAL FORCES AND TILTING MOVEMENTS [29]

Fx	$\pi \cdot I_p \cdot \frac{\partial B_{pol}}{\partial z} \cdot R \cdot \delta z_p$	-4.8 MN
Fy	$\pi \cdot B_{tor} \cdot I_p \cdot \delta z_p - \pi \cdot I_p \cdot \frac{\partial B_{pol}}{\partial R} \cdot R \cdot \delta r_p$	64.77-6.88 = 57.9 MN
Fz	0	0
Mx	0	-278.6 MNm
My	$-\pi \cdot B_{tor} \cdot I_p \cdot R_p \cdot \delta r_p$	-269.1 - 17.6 = -372.9 MNm
$F_{sideways}$		58.1MN

The considered electromagnetic forces on the divertor is applied to the VV at the interfaces in addition to the forces $F_{div,in}$ and $F_{div,out.}$ The amount of values dependent upon the corresponding part of the total halo current flowing through the corresponding areas and the start –end locations of these currents. The forces like F_{SH1}, F_{SH2}, F_{TS} neither taken into account by applying the pressure due to halo current flowing through the VV nor by applying divertor cassette reaction forces. These must be applied in different ways as, If R1 = 4.3, R2 = 3.5, for $F_{div,in}$ with plasma current 1.45MA so $F_{vertical}$ will be -9.75, R1 = 4.04, R2 = 3.53, for F_{SH1} with plasma current 1.62MA so $F_{vertical}$ will be -7.21 , R1 = 4.04, R2 = 3.53, for F_{SH2} with plasma current 1.26MA so $F_{vertical}$ will be -5.58 and R1 = 6.82, R2 = 7.62, for F_{TS} with plasma current 4.26MA so $F_{vertical}$ will be -15.53 according to experimental data [25-26], these calculations depends on current loop of magnetic field points (3). The plasma horizontal movement can be describe by geometrical such as vertical and radial kink mode amplitude is δz_p, δr_p, and asymmetric change can be describe by du, dz and ΔR.

IV. CONCLUSION

With this backdrop, the proposed shape model allows an effective way to study the shape of plasma behavior of main plasma characteristics under controlled conditions including sensitive dependent on initial condition based on isolated points. Furthermore, the transformation of plasma shape model has been developed. This transformation can calculate plasma each cross section by Bx and Bz coordinates. These coordinates give us magnetics field points and displacement when VDE start and magnetic field flux changes. However, we get two conducting points that can provide the halo current percentages. The interaction of plasma with vacuum vessel gives halo current following poloidal direction with strong outward magnetic force towards vessel. Toroidal magnetic field B_{tor} and halo current I_{halo} have been calculated and analyzed by mathematical formulation and technique. Vertical disruption events of plasma facing components including the balancing sideways forces due to asymptotic poloidal halo current has been evaluated and examined. The results obtained will be useful for equalizing the simulation and experimental results.

ACKNOWLEDGMENT

The first author shows sincere appreciation to Dr.Song and Dr.Salah Ud-Din for their valuable advises and also contribution in solving the computational model. All the authors are very thankful to ASIPP,CAS for carrying out and funding this research.

REFERENCES

[1] Wesson, J. Tokamaks (Oxford Univ. 2011).

[2] Kenro Miyamoto. Plasma physics for nuclear fusion. ISBN 0-262-13145-5.

[3] J. Li, et al. A long-pulse high-confinement plasma regime in the Experimental Advanced Superconducting Tokamak. Nature physics. DOI: 10.1038/NPHYS2795 (2013).

[4] Giuseppe Ambrosino, and Raffaele Albanese. Magenitic control of plasma current, position and shape in Tokamak. IEEE Control Systems Magazine (2005).

[5] M. Mitchellwaldrop. The Fusion upstarts. Nature, 511, (2014).

[6] Hawryluk, R. J. Results from deuterium-tritium tokamak confinement experiments. Rev. Mod. Phys. 70, 537587 (1998).

[7] Keilhacker, M. et al. High fusion performance from deuterium-tritium plasmas in JET. Nucl. Fusion 39, 209234 (1999).

[8] httpwww.iter.org.

[9] Sadiq Usman, Shahab Ud-Din Khan, Salah Ud-Din Khan. Internal Transport Barrier in Tokamak Plasma. LAP Labert Academic Publishing. ISBN-14 978-3-659-22934-3 (2014).

[10] C.E. Kessel a, T.K. Maub, S.C. Jardin a, F. Najmabadi b. Plasma profile and shape optimization for the advanced tokamak power plant. ARIES-AT. Fusion Engineering and Design. 80. 63–77. (2006).

[11] S.V.Putvinskjj, plasma confinement in the m = 1, n = 1 kink distorted tokamak central core. Nucl. Fusion 33. 133. (1993).

[12] A. Bondeson, G. Wad, H. Lijtjens. Resistive toroidal stability of internal kink modes in circular and shaped tokamaks. Physics of Fluids B: Plasma Physics. 4. doi: 10.1063/1.860041. (1992).

[13] S.E.Sharapov. Lecture 2B. Australian National University. Canberra. 7-9. (2010).

[14] C. Bachmann[a,], at al. Specification of asymmetric VDE loads of the ITER tokamak. Fusion Engineering and Design. Volume 86, Issues 9–11, Pages 1915–1919. (2011)

[15] Paolo Bettini[a], at al. Numerical modeling of 3D halo current path in ITER structures. Fusion Engineering and Design. Volume 88, Issues 6–8, Pages 529–532. (2013)

[16] G. Ambrosino a, M. Ariola a, A. Pironti a, F. Sartori b. A new shape controller for extremely shaped plasmas in JET. Fusion Engineering and Design. 66-68. 797-802. (2003).

[17] A.A.Kavin, V.A.Belyakov, S.A.Bulgakov, Y.A.Kostsov, E.N.Rumyntsev, S.A.Galkin, L.M.Degtyarev, A.A.Ivanov, Y.Y.Poshekhonov, V.A.Yagnov. Numerical simulation of plasma equilibrium and shape control in tight tokamak GLOBUS-M. Fusion technology 1996. Proceedings of the 19th symposium on fusion technology. Lisbon. Portugal. 16-20. Pages 821–824. (1997).

[18] Hogun Jhang , C.E. Kessel , N. Pomphrey , Jin-Yong Kim , S.C. Jardin , G.S. Lee. Simulation studies of plasma shape identification and control in Korea Superconducting Tokamak Advanced Research. Fusion Engineering and Design. 54. 117–134. (2001).

[19] Wan, Y. Overview of steady state operation of HT-7 and present status of the HT-7U project. Nucl. Fusion 40, 1057-1068 (2000).

[20] Normile, D. Waiting for ITER, fusion jocks look EAST. Science 312, 992-993 (2006).

[21] Wan, B. N. Recent experiments in the EAST and HT-7 superconducting tokamaks. Nucl. Fusion 49, 104011 (2009).

[22] Li, J. & Wan, B. N. Recent progress in RF heating and long-pulse experiments on EAST. Nucl. Fusion 51, 094007 (2011).

[23] Fuyuno, I. China set to make fusion history. Nature 442, 853-858 (2006).

[24] Yuntao Song, et al. Tokamak Engineering Mechanics. ISBN 978-3-642-39574-1. (2014).

[25] Christian Bachmann. Asymmetric Forces on the ITER Plasma in Kink Mode in Subsequent Halo Currents in the VV. ITER_D_28P25D v1.0. (2015).

[26] Christian Bachmann. M. Sugihara. Remarks on the Load Specification for the ITER Vacuum Vessel for an Asymmetric VDEIII Slow Downward. ITER_D_27LH9A v1.0. (2015).

[27] Halo current data for VDE_DW_slow. ITER_D_24ZANM. (2006).

[28] Evaluation of the DINA Analysis Concerning the Poloidal Halo Currents in the ITER VV and Divertor During a VDE III Slow Downward Event: ITER_D_24KTKN

[29] Forces on the ITER Vacuum Vessel due to the Plasma in Kink Mode During a VDEIII with Slow Current Quench, ITER_D_26RLC9.