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# Feedback controller input design for ignition of deuterium–tritium in NSTX tokamak

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## ABSTRACT

Nuclear fusion is a nuclear reaction in which two or more atomic nuclei (such as a deuterium–tritium) come very close and then collide at a very high speed and join to form a new high energy nucleus (Helium). Determination of accurate plasma horizontal position during plasma discharge is essential to transport it to a control system based on feedback. The solutions of Grad-Shafranov equation (GSE) analytically can be used for theoretical studies of plasma equilibrium, transport and magneto hydrodynamic stability. Here we have presented specific choices for source functions, kinetic pressure and poloidal plasma current, to be quadratic in poloidal magnetic flux and derive an analytical solution for Grad-Shafranov equation. With applying this solution to NSTX tokamak, we calculated poloidal magnetic flux, toroidal current density and normalized pressure profiles for this tokamak. Toroidal and poloidal flows can considerably change the equilibrium parameters of tokamak. These effects on the equilibrium of tokamak plasmas are numerically investigated using the code FLOW. As a comparative approach to equilibrium problem, the code is used to model equilibrium of NSTX tokamak for case pure toroidal flow. Comparison of the results of these two methods for NSTX tokamak shows good agreement between two and that our analytical solution can be served as good benchmark against the equilibrium code FLOW.

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## Introduction

For stationary and ideally conducting plasmas, magneto hydrodynamics (MHD) equations plus Maxwell's equations reduce to the two-dimensional, nonlinear, elliptic partial differential equation commonly referred to as the Grad-Shafranov equation (GSE):

$$-\left(\frac{\partial^2 \psi}{\partial R^2} - \frac{1}{R} \frac{\partial \psi}{\partial R} + \frac{\partial^2 \psi}{\partial Z^2}\right) = \mu_0 R^2 p'(\psi) + FF'(\psi) \equiv \mu_0 R j_\varphi, \quad (1)$$

where  $j_\varphi$  is the toroidal current density, the stream function  $\psi$  is the poloidal magnetic flux per radian,  $F = RB_\varphi = \frac{\mu_0 I_{pol}(\psi)}{2\pi}$  where

$I_{pol}$  is the poloidal current,  $p'(\psi) = \frac{dp}{d\psi}$  and  $FF'(\psi) = \frac{d}{d\psi} \left( \frac{1}{2} R^2 \right)$  are arbitrary functions of  $\psi$ . In toroidally confined plasma, the Grad-Shafranov equation, in general, a nonlinear partial differential equation, describes the hydro magnetic equilibrium of the system. The solution of the GS equation provides the magnetic field, the current density, and the kinetic pressure inside axisymmetric plasma in hydro magnetic equilibrium.

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Having analytical solutions to this equation is convenient to configure physical equilibria as a basis for theoretical studies of transport, waves and stability. Also they can be served as good benchmarks for testing numerical MHD equilibrium codes. The GS equation is an elliptic partial differential equation (PDE) for the poloidal magnetic flux  $\psi$  that labels the magnetic surfaces in axisymmetric plasma equilibrium. The equation contains two arbitrary functions  $p(\psi)$  and  $F(\psi)$  that specify the dependence of the kinetic pressure and the poloidal plasma current on the magnetic flux  $\psi$  [1]. Many natural phenomena are described by systems of nonlinear PDE's, which are difficult to be solved analytically, as long as a general theory for completely solving nonlinear PDE's is not yet available. The simplest analytical solution to the inhomogeneous GSE is the well known Solov'ev equilibrium [2–10] and corresponds to source functions ( $p$  and  $F$ ) linear in Ref.  $\psi$ . Equilibrium of this type has been extensively used for equilibrium, transport and stability studies. However the Solov'ev equilibrium solutions are over constrained in shape or in poloidal beta (plasma current). From the same Solov'ev equilibrium case, by expanding the solution of the homogeneous equations in a polynomial form in  $r$  (of fourth degree) and  $z$  (of second degree) and assuming up/down symmetry, it is possible to describe the plasma shape by four parameters [3]. By using particular source functions for the GSE, it is found a class of exact analytical solutions [4,5,11–20]. Also, it is presented a new family of solutions where the plasma pressure is linear in Refs.  $\psi$ , while the squared poloidal current has both, a quadratic and a linear  $\psi$  term [21–27]. An exact solution of the large-aspect ratio approximation with an additional assumption of a simple relation between the magnetic flux and the current density was constructed [28–30]. Analytical equilibrium solutions for tokamak plasmas are difficult to find since the equations governing the equilibrium are highly nonlinear. Therefore numerical solutions are always useful. Among those, the FLOW code is developed for the study of axisymmetric tokamak equilibrium in the presence of toroidal and poloidal flow for NSTX tokamak [8]. FLOW was originally designed for spherical tokamaks. It has been repeatedly observed in several devices that when the plasma rotates either toroidally or poloidally, both the energy transport as well as the macroscopic stability improves significantly (the plasma rotation can be either spontaneous or driven by neutral beam injection or radio frequency heating). These effects on the equilibrium of tokamak plasmas are numerically investigated using the code FLOW. FLOW solves the GS-Bernoulli system of equations with a multi grid approach including finite pressure anisotropy. The code input requires the assignment of a set of free functions of the poloidal magnetic flux  $\psi$ , which depend on the so called closure equation governing the temperature(s) or entropy. Though, FLOW can solve the equilibrium equation with arbitrary flow [31–34]. In this paper, in Section **Special analytical solution to the GSE** we have represented the special analytic solution for GS equation using specific choices for the free functions ( $p$  and  $F$ ). It is done with determining the finite number of unknown expansion coefficients in the three term solution. Then we apply the results to NSTX tokamak. In Section **Study of equilibrium by FLOW code**, as a comparative

approach to equilibrium problem for NSTX tokamak, we have showed the results of a numerical study carried out with the equilibrium code FLOW developed to study fixed boundary equilibria with toroidal flows. Following this section, a brief comparison between these two approaches is presented. In Section **Study of equilibrium by FLOW code** we briefly discuss about results.

## Special analytical solution to the GSE

The magnetic field is related to the poloidal flux  $\psi$  by:

$$B_\phi = \frac{F(\Psi)}{R}, \quad B_p = \frac{\nabla\Psi \times e_\phi}{R}, \quad (2)$$

where  $B_\phi$  and  $B_p$  are toroidal and poloidal magnetic fields. We choose the free functions  $p(\psi)$  and  $F(\psi)$  to be quadratic in Ref.  $\psi$  [9]:

$$p = p_{\text{axis}} \left( \frac{\Psi^2}{\Psi_{\text{axis}}^2} \right), \quad F^2 = R_0^2 B_0^2 \left[ 1 + b_{\text{axis}} \left( \frac{\Psi^2}{\Psi_{\text{axis}}^2} \right) \right] \quad (3)$$

Here  $\Psi_{\text{axis}}$ ,  $p_{\text{axis}}$  and  $b_{\text{axis}}$  are constants related to the values of  $\Psi$ ,  $p$  and  $F$  on axis and  $R_0$  and  $B_0$  are the major radius and vacuum toroidal field at the geometric center of the plasma. With these choices and specific normalization, the GS equation reduces to:

$$4\epsilon^2 x \frac{\partial^2 \psi}{\partial x^2} + \frac{\partial^2 \psi}{\partial y^2} + (\alpha x + \gamma) \psi = 0. \quad (4)$$

We used these normalizations:  $\Psi = \Psi_{\text{axis}} \psi$ ,  $R^2 = R_0^2 x$ ,  $z = ay$ ,  $\epsilon = \frac{a}{R_0}$ ,  $\gamma = \left( \frac{a R_0 B_0}{\Psi_{\text{axis}}} \right)^2 b_{\text{axis}}$ ,  $\alpha = \left( \frac{a R_0 B_0}{\Psi_{\text{axis}}} \right)^2 \beta_{\text{axis}}$  and  $\beta_{\text{axis}} = \frac{2\mu_0 p_{\text{axis}}}{B_0^2}$ . The solution of Eq. (4) is found by separation of variables:

$$\psi = \sum_m X_m(\rho) Y_m(y), \quad (5)$$

where  $x = \frac{-iy}{\sqrt{\alpha}}$ . Solution of the  $Y_m$  equation for an up/down symmetric configuration (like NSTX) is given by:

$$\frac{d^2 Y_m}{dy^2} + k_m^2 Y_m(y) = 0, \quad Y_m(y) = \cos(k_m y), \quad (6)$$

where  $k_m$  is the  $m$ th separation constant, which can be real or imaginary and we should determine it. The  $X_m(\rho)$  equation reduces to:

$$\frac{d^2 X_m}{d\rho^2} + \left[ -\frac{1}{4} + \frac{\lambda_m}{\rho} \right] X_m = 0, \quad (7)$$

with  $\lambda_m = -i \frac{\gamma - k_m^2}{4\epsilon\sqrt{\alpha}}$  and the solutions of  $X_m(\rho)$  are Whittaker functions [10]. The solution of  $X_m(\rho)$  is given by:

$$X_m(\rho) = Im[a_m W_{\lambda_m, \mu}(\rho) + b_m M_{\lambda_m, \mu}(\rho)]. \quad (8)$$

The  $a_m$  and  $b_m$  are unknown expansion coefficients that must be determined. Both  $\rho$  and  $\lambda_m$  are purely imaginary quantities while  $X_m$  must be purely real, then we only keep imaginary parts of Whittaker functions. For our model the Whittaker parameter is  $\mu = \frac{1}{2}$ . With maintaining three terms in the summation of  $\psi$ , we have:

$$\psi(\rho, y) = \sum_{m=1}^3 [Im[a_m W_{\lambda_m, \mu}(\rho) + b_m M_{\lambda_m, \mu}(\rho)]] \cos(k_m y) \quad (9)$$

There are six unknown expansion coefficients (i.e. the  $a_m$ ,  $b_m$ ) and three unknown separation constants (i.e. the  $k_m$ ) that must be determined. These coefficients are determined with specific conditions. These conditions are:

$$\begin{aligned} \Psi(R_0 + a, 0) &= 0, \quad \Psi(R_0 - a, 0) = 0, \quad \Psi(R_0 - \delta a, \kappa a) \\ &= 0, \quad \Psi_R(R_0 - \delta a, \kappa a) = 0, \quad \Psi(R_{axis}, 0) \\ &= \psi_{axis}, \quad \Psi_R(R_{axis}, 0) = 0, \quad \frac{1}{R_c} \equiv -\frac{(1 - \hat{\delta})^2}{\kappa^2 a}, \end{aligned} \quad (10)$$

where  $\hat{\delta} = \sin^{-1} \delta$ ,  $\delta$  is triangularity,  $a$  is minor radius and  $\kappa$  is elongation. Also  $R_c$  is curvature radius for inboard midplane. Based on empirical experience, we define separation constants as:

$$k_1 = 0, \quad k_2 = i\hat{k}_2, \quad k_3 = \frac{\pi}{\kappa}\hat{k}_3 \quad (11)$$

With  $\hat{k}_2$ ,  $\hat{k}_3$  real and of order unity. We will assume that appropriate values for  $\hat{k}_2$ ,  $\hat{k}_3$  are given once the plasma geometry has been chosen. The primary inputs for the solution procedure are the inverse aspect ratio  $\epsilon$ , the elongation  $\kappa$ , the triangularity  $\delta$ , and the parameters  $\alpha$  and  $\gamma$ . The secondary input parameters are the major radius  $R_0$ , the vacuum toroidal field  $B_0$  and the toroidal current  $I$ . For NSTX tokamak, these input data depicted in Table 1.

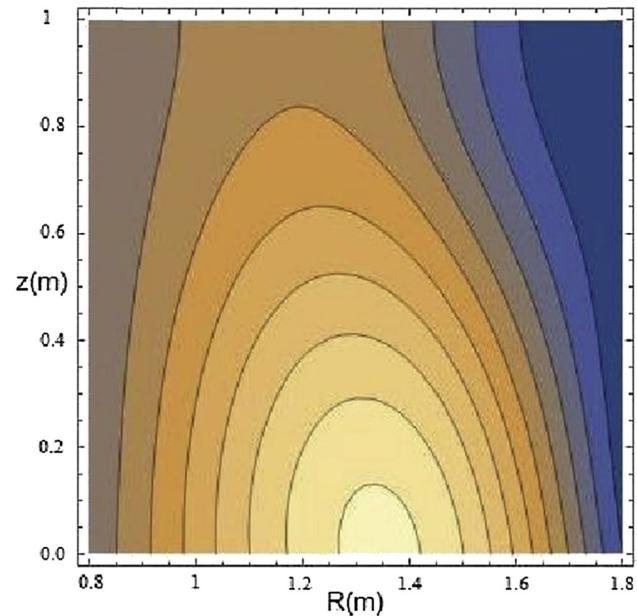
The final form of the solution for  $\psi$  is given by:

$$\begin{aligned} \psi(\rho, y) &= (a_1 W_{\lambda_1, \frac{1}{2}}(\rho) + b_1 M_{\lambda_1, \frac{1}{2}}(\rho)) + (a_2 W_{\lambda_2, \frac{1}{2}}(\rho) \\ &+ b_2 M_{\lambda_2, \frac{1}{2}}(\rho)) \cos(k_2 y) + (a_3 W_{\lambda_3, \frac{1}{2}}(\rho) \\ &+ b_3 M_{\lambda_3, \frac{1}{2}}(\rho)) \cos(k_3 y). \end{aligned} \quad (12)$$

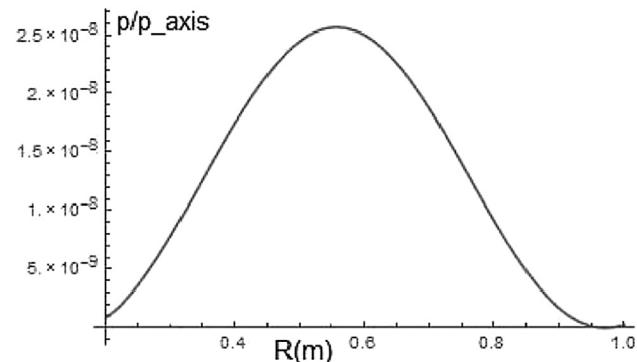
The parameters for calculation of equilibrium for NSTX are  $\gamma = -0.1$ ,  $k_2 = 0.024i$ ,  $k_3 = 1.77$  and  $\alpha = 3.56$  [9]. The resulting flux surfaces for NSTX are illustrated in Fig. 1. Also we calculated the normalized kinetic pressure (from Eq. (3)) and toroidal current density for NSTX tokamak that is depicted in Figs. 2 and 3, respectively. The vanishing of  $\nabla p$  and  $j_\phi$  at the edge, combined with the linear dependence on  $\Psi$ , produces peaked pressure and current profiles. Although some unknown parameters in this method are tuned with experiment but all profiles are realistic.

**Table 1 – Characteristic data for NSTX [9].**

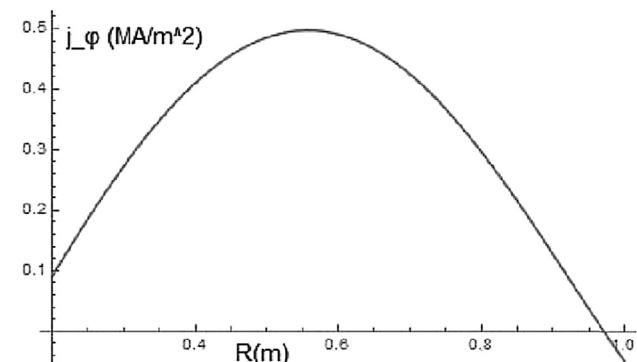
Parameters	Value
$\epsilon$ , inverse aspect ratio	0.79
$K$ , elongation	2.2
$\delta$ , triangularity	0.5
$q_{axis}$ , safety factor on axis	1
$B_0$ , toroidal field (T)	0.43
$R_0$ , major radius (m)	0.85
$\alpha$ , minor radius (m)	0.67
$\beta_t$ , toroidal beta	0.044
$I$ , toroidal current (MA)	0.43
$q_s$ , kink safety factor	5.9



**Fig. 1 – Flux surfaces for NSTX tokamak (due to up-down symmetry, only half of the plasma is shown).**



**Fig. 2 – Normalized pressure ( $p/p_{axis}$ ) profile versus major radius along the midplane ( $z = 0$ ) for NSTX tokamak.**



**Fig. 3 – Toroidal current density ( $j_\phi$ ) profile in  $MA/m^2$  versus major radius along the midplane ( $z = 0$ ) for NSTX tokamak.**

## Study of equilibrium by FLOW code

The basic single fluid model for describing and determining the macroscopic equilibrium and stability properties of plasma is ideal magneto hydrodynamics (MHD). The ideal MHD model is given by:

$$\begin{aligned} \frac{\partial \rho}{\partial t} + \nabla \cdot \mathbf{v} = 0; \quad \rho \frac{d\mathbf{v}}{dt} = \mathbf{J} \times \mathbf{B} - \nabla P; \quad \frac{d}{dt} \left( \frac{P}{\rho^\gamma} \right) = 0; \quad \mathbf{E} + \mathbf{v} \times \mathbf{B} \\ = 0; \quad \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}; \quad \nabla \times \mathbf{B} = \mu_0 \mathbf{J}; \quad \nabla \cdot \mathbf{B} = 0. \end{aligned} \quad (13)$$

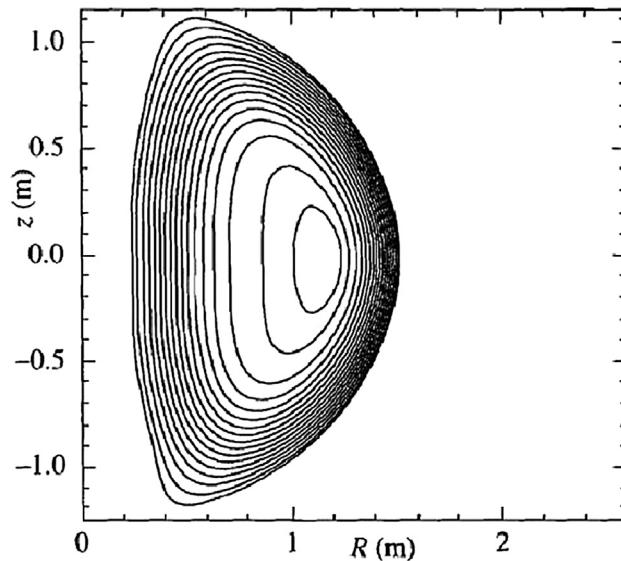
Taking the toroidal component ( $e_\phi$ ) of Eq. (13) and using the axisymmetric properties of the equilibrium leads to the following expression for the toroidal field [11]:

$$B_\phi R = \frac{F(\Psi) + \sqrt{\mu_0} R^2 \Phi(\Psi) \Omega(\Psi)}{\left( 1 - \frac{\Phi^2(\Psi)}{\rho} - \Delta \right)}, \quad (14)$$

where  $F(\Psi)$  is a free function of poloidal flux function  $\Psi$ . Above equation reduces to the standard form  $B_\phi R = F(\Psi)$  in the absence of poloidal flow ( $\Phi(\Psi) = 0$ ) and anisotropy ( $\Delta = 0$ ). Here  $\Phi(\Psi)$  and  $\Omega(\Psi)$  are two free functions of  $\Psi$  describing poloidal and toroidal component of the velocity respectively. The poloidal component of the flow depends exclusively on  $(\Psi)$ , while the toroidal component is a function of both  $\Phi(\Psi)$  and  $\Omega(\Psi)$ . The next step is to take the  $B$  component of the momentum equation, which after a straightforward calculation yields the well known Bernoulli equation [11]. The final step is to take the components of the momentum equation (Eq. (14)) in order to derive the Grad-Shafranov (GS) equation for the poloidal magnetic flux. We observe that the equilibrium model has been reduced to a system of three equations: a) toroidal field equilibrium; b) Bernoulli equation and c) a modified GS equation. These systems of equations can be solved numerically once the free functions of the system have been assigned. The effects of plasma flow on axisymmetric plasma equilibria have been analyzed using the code FLOW. The code solves the combined GS-Bernoulli set of equations describing MHD equilibria with flow and finite pressure anisotropy. FLOW is a finite difference equilibrium code which solves above equations simultaneously [8,11]. We have modeled equilibrium of NSTX tokamak for case pure toroidal flow. In the considered equilibrium, toroidal flow and anisotropy included and the kinetic closure has therefore been used to compute this equilibrium. Fig. 4 shows the contour plot of the magnetic flux  $\Psi$  for NSTX tokamak. The free functions of the system have been assigned in Ref. [8]. The plasma shape in this equilibrium constructed to closely reproduce the NSTX data. Comparing to Fig. 1, we can see good agreement between two methods (our analytical solution for GSE and the equilibrium code FLOW) for NSTX tokamak and that our analytical solution can be served as good benchmark against the equilibrium code FLOW.

## Discussion

The simplest useful mathematical model to describe equilibrium in fusion plasmas is achieved by combining magneto



**Fig. 4 – Contour plot of magnetic flux surfaces for the NSTX tokamak equilibrium computed by FLOW code.**

hydrodynamic (MHD) equations with Maxwell's equations. The final result is the Grad-Shafranov equation. The solutions of Grad-Shafranov equation analytically can be used for theoretical studies of plasma equilibrium, transport and magneto hydrodynamic stability. In this paper, we choose specific choices for free functions ( $p$  and  $F$ ) to be quadratic in Ref.  $\psi$  and derive an analytic solution for Grad-Shafranov equation. This solution is applied to NSTX tokamak and poloidal magnetic flux, toroidal current density and normalized pressure profiles are calculated. The effects of plasma flow on axisymmetric plasma equilibria have been analyzed using the equilibrium code FLOW. The code solves the combined GS-Bernoulli set of equations describing MHD equilibria with flow and finite pressure anisotropy. As a comparative approach to equilibrium problem, we have modeled equilibrium of NSTX tokamak for case pure toroidal flow. The plasma shape in this equilibrium constructed to closely reproduce the NSTX data. Comparison of the results of these two methods (our analytical solution for GSE and the equilibrium code FLOW) for NSTX tokamak shows good agreement between two and that our analytical solution can be served as good benchmark against the equilibrium code FLOW.

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