

Preliminary Design of Alborz Tokamak

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Abstract The Alborz tokamak is a D-shape cross section tokamak that is under construction in Amirkabir University of Technology. The most important part of the tokamak design is the design of TF coils. In this paper a refined design of the TF coil system for the Alborz tokamak is presented. This design is based on cooper cable conductor with 5 cm width and 6 mm thickness. The TF coil system is consist of 16 rectangular shape coils, that makes the magnetic field of 0.7 T at the plasma center. The stored energy in total is 160 kJ, and the power supply used in this system is a capacitor bank with capacity of $C = 1.32$ mF and $V_{\max} = 14$ kV.

Keywords Toroidal field · Toroidal coil · Aspect ratio · Major and minor radius · FEM

Introduction

The tokamak is a toroidal plasma confinement system, the plasma being confined by a magnetic field. The principal magnetic field is the toroidal magnetic field [1]. Alborz tokamak is a D-shape cross section tokamak and the most important part of the design of this tokamak is the design of TF coils and its power supply.

Some tokamaks has circular cross section [2, 3] but many of advanced tokamaks have typically D-shape or non-circular cross section [4–19] and some of them has superconducting field coils [12–20].

In this paper we are present the design of TF coils and give the major parameters of tokamak like major radius, maximum plasma current, number of TF coils, number of total turns and current per turn for a non-circular cross section TF coil. And we assume that some of the parameters like maximum current carrying by the cooper cable, the capacity of the power supply, maximum operational voltage, required safety factor, aspect ratio and the cross section shape of vacuum vessel and the toroidal magnetic field in plasma center, are known.

In addition we must consider about the magnetic field ripple. The magnetic field ripple is inversely proportional to the number of TF coils and by increase of their number is decreased [21]. Number of TF coils is normally about 12–36 coils [22, 23]. The ripple magnitude due to the finite number of TF coils and the size of the ports of vacuum vessel, determine the number, size and shape of TF coils [24]. Axisymmetry of magnetic field topology insures good classical particle confinement. However, due to discreteness of the TF coil system, it is unavoidable to have some ripple component in the toroidal magnetic field [24, 25].

The TF coils are wound around the vacuum vessel. The vacuum vessel provides a suitable condition for plasma shaping, baking, confinement, stability and supervising [22, 23, 26].

In some tokamaks for investigate of toroidal field behavior, use a detailed Finite Element Method (FEM) [7, 27–29] and in this paper we use a detailed 3D finite element method for all component of TF coils.

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Calculation of Major and Minor Radius and Turn Numbers of TF Coils

At first we consider about the assumptions. The goal is the design of a tokamak with D-shape cross section, that has a

aspect ratio of 3 ($A = R/a = 3$). We expect that the toroidal magnetic field at the center of the vacuum vessel is 0.7 T. The power supply used in this system is a capacitor bank of 1.32 mF, and $V_{\max} = 14$ kV that has energy of $E = \frac{1}{2} CV^2 = 129$ kJ. Currently, the range of safety factor on the edge of plasma for stable operation of tokamaks is usually between 3 and 4, while it takes on a minimum value of unity at the axis of plasma due to nonlinear sawtooth oscillation [30]. To satisfy this criteria, we set the safety factor 3 ($q = 3$). The coil material is cooper and it's area is 5 cm × 6 mm, that can carry 12 kA of transient current, that is $I_{\max} = 12$ kA. Thus the circuit diagram of power supply and TF coils is depicted in Fig. 1, that V is the power supply voltage.

After switch S is closed, the stored energy in C transfer to L , and gives

$$\frac{1}{2} CV_{\max}^2 = \frac{1}{2} LI_{\max}^2$$

for $C = 1.32$ mF, $V_{\max} = 14$ kV, $I_{\max} = 12$ kA, gives

$$L = 1.8 \text{ mH}$$

and the cycle period is

$$T = 2\pi\sqrt{LC} = 9.68 \text{ ms}$$

The magnetic field inside a toroidal solenoid is

$$B_T = \frac{\mu_0 NI}{2\pi R}$$

B_T is toroidal magnetic field, N is the number of turns, I is turn's current, and R is major radius.

By substitution of $I = 12$ kA, $B_T = 0.7$ T, and $R = 3a$ gives

$$N = 875a$$

and the inductance of a toroidal coil with N turn is

$$L = \mu_0 \frac{N^2 r^2}{2R} \tag{1}$$

where r is minor radius of coil. For insulation and assembly pieces and to avoid of sharp variation of magnetic field of adjacent coils, we put a distance of 5 cm between coils and vacuum vessel. And since the width of cable is 5 cm, the minor radius of TF coils is

$$r = a + 0.05 + 0.025 = a + 0.075 \text{ m}$$

as depicted in Fig. 2.

Thus

$$L = \mu_0 \frac{N^2 (a + .075)^2}{2R} \tag{2}$$

by substituting of (1) in (2) gives

$$N = 160, \quad a = 0.15, \quad R = 0.45$$

Winding of TF Coils

By attention to major and minor radius of vacuum vessel and the width of cables (5 cm), the schematic of the vacuum vessel as viewed from above is depicted in Fig. 2.

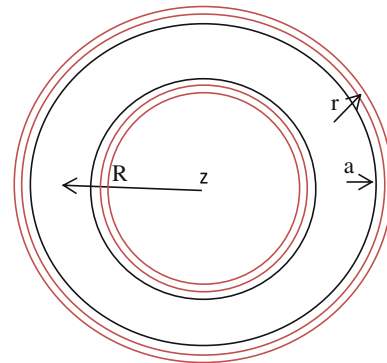


Fig. 2 Schematic diagram of tokamak from above

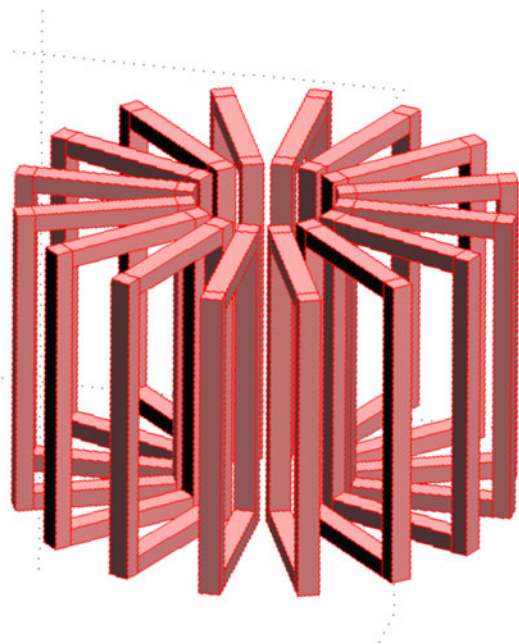


Fig. 3 Schematic diagram of toroidal coils

Fig. 1 The circuit diagram of power supply and TF coils

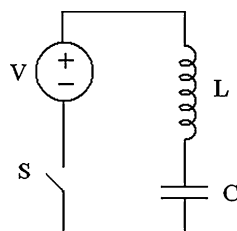


Table 1 Parameters of Alborz tokamak

Parameters	Value
Toroidal magnetic field (in $R = 0.45$ m) (T)	0.7
Minor radius (m)	0.15
Aspect ratio	3
Edge safety factor	3
Maximum plasma current (kA)	116
Number of TF coils	16
Number of total turns	160
Total stored energy (kJ)	129
Current per turn (kA)	12

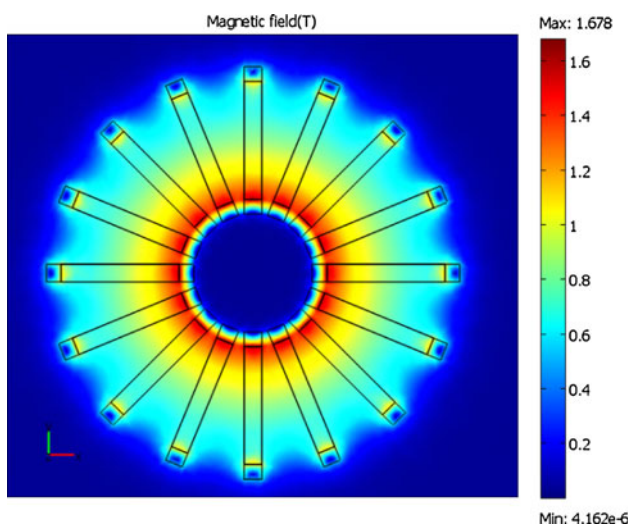


Fig. 4 Toroidal magnetic field from above

By consideration of ports for diagnostic and vacuum systems, and gas injection, we must arrange the TF coils to n group. Because the requirement port diameter is about

10 cm and by consider to its caps and junctions, we need 14 cm width and width of a cable is about 9 mm. The circumference of outer side of vacuum vessel is $2\pi \times 0.6$ m. then

$$160 \times 0.009 + n \times 0.14 = 2\pi \times 0.6 \rightarrow n = 16$$

Thus the number of coils is 16 and the number of turns per coils is 10.

The schematic of TF coils is depicted in Fig. 3.

We must consider that every coil consist of 10 turns.

Calculation of Plasma Current

By writing Ampere’s law [1] in the form

$$2\pi r B_\theta = \mu_0 I(r)$$

That B_θ is poloidal magnetic field and $I_p(r)$ is plasma current

$$I_p(r) = 2\pi \int_0^r j(r') r' dr'$$

That $j(r')$ is the current density inside r , and by using the

$$q = \frac{r B_\phi}{R_\circ B_\theta}$$

And taking $r = a$, the edge value of q is

$$q_a = \frac{2\pi a^2 B_\phi}{\mu_0 I_p R} = \frac{a^2 B_\phi}{I_p R} \times 10^7 \text{ A.}$$

By substituting of values for this tokamak, for $q = 3$, the maximum value of I_p is

$$I_p = 116 \text{ kA}$$

The parameters of Alborz tokamak are shown in Table 1.

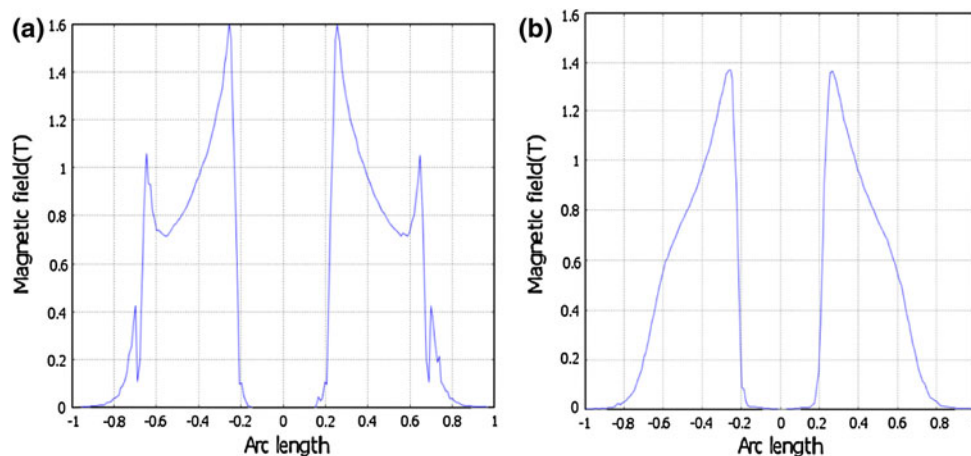


Fig. 5 Toroidal magnetic field in a 0° and b 11.25°

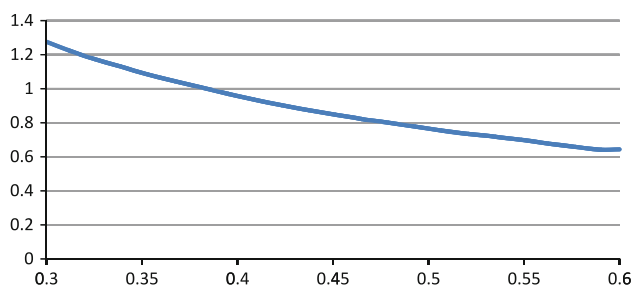


Fig. 6 The average magnetic field varies by $1/R$

Table 2 Expected parameters of Alborz tokamak

Parameters	Value
Toroidal magnetic field (in $R = 0.45$ m) (T)	0.85
Minor radius (m)	0.15
Aspect ratio	3
Edge safety factor	3
Maximum plasma current (kA)	141
Number of TF coils	16
Number of total turns	160
Total stored energy (kJ)	129
Current per turn (kA)	12

Simulation of Toroidal Magnetic Field

Cross section of TF coils is depicted in Fig. 2. Here we simulate the toroidal magnetic field by FEM (Finite Element Method). By using this method, the shape of toroidal magnetic field is as Fig. 4.

Figure 5 illustrated the toroidal magnetic field in $0'$ and $11.25'$. (a) is in $0'$ and (b) is in $11.25'$, that is between coils.

The average magnetic field through 360 degree is as Fig. 6 that varies by $1/R$.

Toroidal field in $R_o = 0.45$ m is 0.85 T.

Summary

By using of capacitor bank of $C = 1.32$ mF and $V_{\max} = 14$ kV as toroidal coils power supply, and by

consider of cooper coils with area of 0.05×0.006 m², we gives $I_{\max} = 12$ kA, that gives a tokamak with $R_o = 0.45$ m, $a = 0.15$ m, and $B_T = 0.85$ T. This tokamak is under construction in Amirkabir university of technology. The expected parameters of this tokamak is shown in Table 2.

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