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Evaluation of applicability of 2D iron core model for two-limb configuration of GOLEM tokamak

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HIGHLIGHTS

- Axisymmetric tokamak iron core model was developed and applied to GOLEM tokamak.
- The core of this tokamak is highly non-axisymmetric by having only two limbs.
- Model was sufficient to characterize change of magnetic fields by this core.
- Dimensions of modelled axisymmetric parts needed to vary with toroidal angle.
- Full 3D model is being developed.

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ABSTRACT

This paper presents evaluation of applicability of 2D iron core model for highly non-axisymmetric two limb configuration of GOLEM tokamak (former CASTOR). Presented results explain the long-term discrepancy between measured magnitudes of external poloidal field and those calculated by air-core approach on this tokamak. The model has been applied to two poloidal planes at different toroidal angles in the vacuum vessel region and has shown that close to central column of the transformer, it is possible to correct for 3D effects by variation of chosen dimensions of axisymmetric iron core model. Satisfactory agreement of the 2D model results with the measured distribution of B_R field component was achieved.

1. Introduction

A number of tokamaks, including the largest presently operating device JET, use the iron core within their plasma current drive systems. This is advantageous because of lower power consumption of such systems and weaker stray fields at the cost of eventual saturation of the core, as well as change of magnetic field configuration in vicinity of the core and of plasma equilibrium. More details on iron core influence on MHD equilibrium can be seen in Refs. [1–3] for tokamaks JET, T-15 and TUMAN-3 respectively. Also, Ref. [4] shows influence of poloidal field change by ferromagnetic core on determination of vertical plasma column position for tokamak GOLEM (former tokamak CASTOR). Hence, for proper interpretation of resonant magnetic perturbation experiments aiming for ELM mitigation (see Refs. [5–9]) on tokamaks using iron core, it is necessary to quantify influence of core. Since perturbative fields are generated by non-axisymmetric configuration of saddle coils distributed along outer wall of tokamak chamber [9], the problem becomes of 3D character. However, standard approach to iron core model of tokamaks is 2D axisymmetrical, as it is sufficient for inherently axisymmetric equilibrium reconstruction problems [1–3]. Therefore, this paper describes the first stage of developement of a 3D open-source iron core simulation code for calculation of magnetic fields in iron core tokamaks. Namely, an investigation of applicability of axisymmetric 2D approach for intrinsically non-axisymmetric configuration of tokamak GOLEM ($R = 0.4$ m, $a = 0.085$ m, $B_t < 0.5$ T, $I_p < 4$ kA, operated at the Czech Technical University) is carried out to provide both first insight into problem and a reference for future 3D code.

Following section briefly introduces general principles of used integral-based ferromagnetic boundary model. Section 3 describes shape and dimensions of both real GOLEM core, as well as of its 2D

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axisymmetric approximation. Section 4 then investigates the applicability of such model to experimental data, with findings being summarized in Section 5.

2. Integral model of ferromagnetic boundary

Ferromagnetic medium generally reacts to presence of external magnetic fields by induction of eddy currents, refered to as *coupled currents* σ, that screen the external sources [10]. In this model, the whole ferromagnetic material is represented as conditions on continuity of magnetic flux ψ and tangential magnetic field intensity H_{tan} on both sides of iron-air boundary. Ref. [11] shows how in that case the image currents, represented by three-dimensional surface current density vector σ which is induced along this boundary, sufficiently characterize influence of core on magnetic field. The problem is thus transformed into finding a solution of set of generally non-linear equations [10]:

$$\sigma(\mathbf{r}) - \frac{\lambda}{2\pi}\int_S \left(\sigma(\mathrm{r}') \times \frac{\mathbf{r}-\mathrm{r}'}{|\mathbf{r}-\mathrm{r}'|^3}\right) \times \mathbf{n}(\mathbf{r})\mathrm{d}S'$$

$$= \frac{\lambda}{2\pi}\int_V \left(\mathbf{j}(\mathrm{r}') \times \frac{\mathbf{r}-\mathrm{r}'}{|\mathbf{r}-\mathrm{r}'|^3}\right) \times \mathbf{n}(\mathbf{r})\mathrm{d}V'. \quad (1)$$

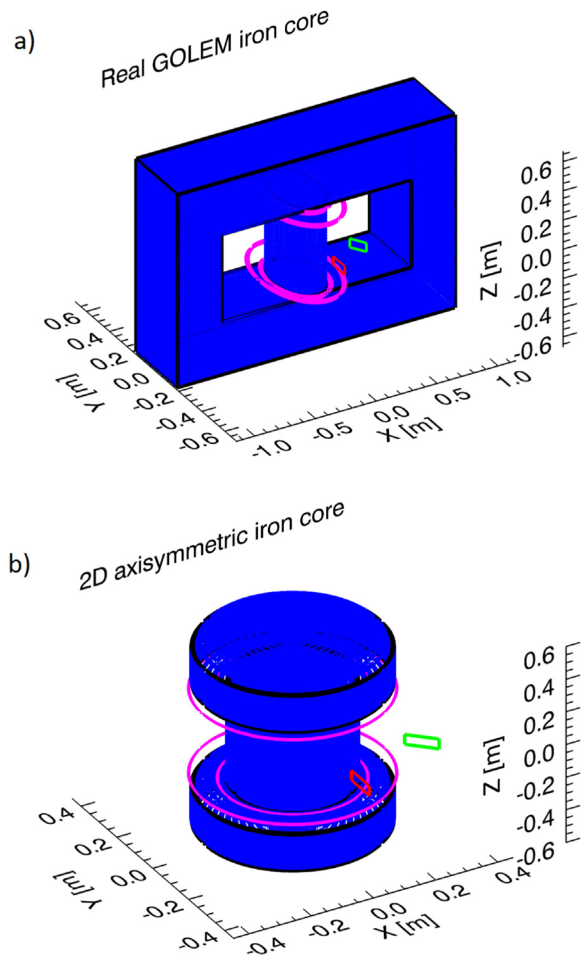

Fig. 1. Transformer core of tokamak GOLEM. (a) represents dimensions of real core. (b) shows its modelled 2D equivalent used in paper. Measurement took place at two different toroidal angles: red $\phi = \pi/2$ and green $\phi = \pi/4$. Poloidal coils used for generation of measured field are represented as purple rings. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

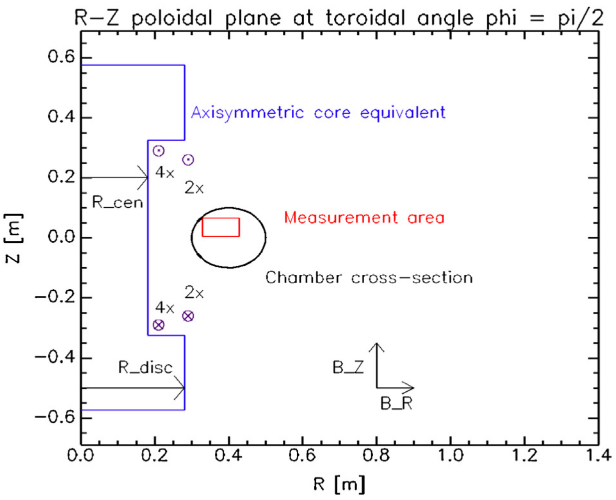

Fig. 2. Poloidal plane at $\phi = \pi/2$ of Fig. 1b. Caption specifies polarities and turn numbers of used coils, location of measurement area within circular cross section chamber, and components of $\mathbf{B}_\theta = [B_R, B_Z]$.

Here, **n** represents normale to surface S, **j** is density of all the other currents beside σ and $\lambda = (\mu_r - 1)/(\mu_r + 1)$. Used model is hence of integral character, similar to those used in Refs. [3,2,10]. Main advantages of use of integral methods in tokamak iron

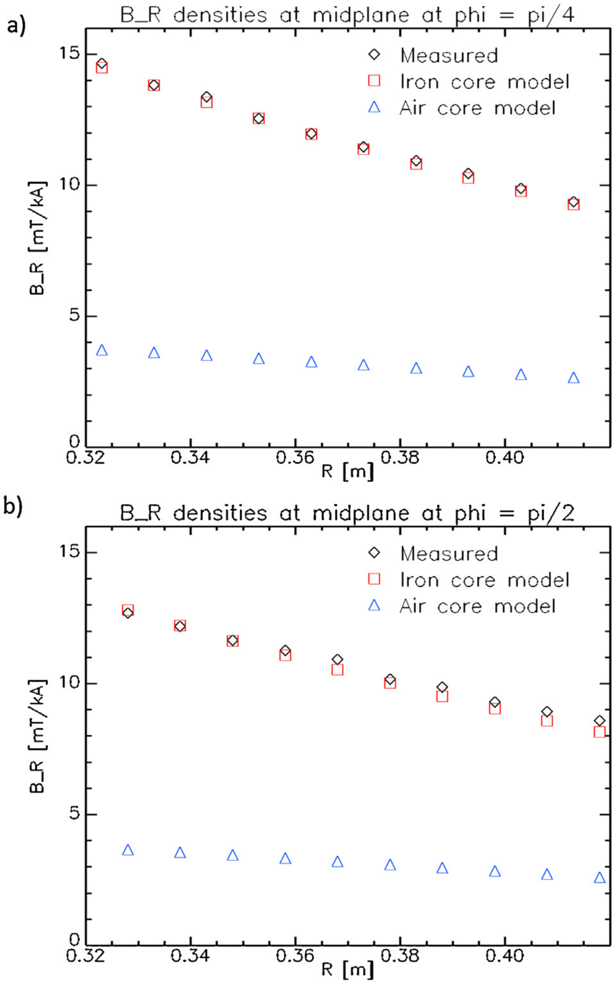

Fig. 3. B_R density on midplane. Models of $\mu_r > 100$ and of $\mu_r = 1$ respectively. $\phi = \pi/4$ (a, with $R_{disc} = 1.4R_{cen}$) and $\phi = \pi/2$ (b, with $R_{disc} = 1.28R_{cen}$).

core model are in avoidance of large number of modelled elements, that would be necessary otherwise for larger distances from core at finite-elements method approach [12]. If transformer surface (and hence σ) is discretized into filaments, a set of equations for σ_i is obtained. Its solution $\sigma_i = \sigma_i(\lambda)$ and $\lambda = \lambda(|\mathbf{B}_i|)$ due to $\mu_{r_i} = \mu_{r_i}(|\mathbf{B}_i|)$ and therefore $\sigma_i = \sigma_i(\mathbf{B}_i)$. However at the same time $\mathbf{B}_i = \mathbf{B}_i(\sigma)$ since local magnetic field depends not only on external sources, but also on all of the induced currents in ferromagnetic medium as well. Publications [2,1] provide some examples on how this non-linearity issue can be approached by iteration, using $\mu_r(|\mathbf{B}_i|)$ dependency obtained by analytical approximation and experimental data interpolation respectively.

3. Axisymmetric model for tokamak GOLEM and experimental arrangement

Assumption of toroidal symmetry and of strictly toroidal external currents, together with use of orthogonality between toroidal and poloidal coordinates, yields that only non-zero components of σ vector in Eq. (1) are those of toroidal direction. However, application of this axisymmetry calls for an appropriate shape and dimensions of 2D core equivalent. While an example of such an equivalent for eight-limb configuration of tokamak JET is described in Ref. [13], for GOLEM core shown in Fig. 1a is its 2D equivalent depicted in Fig. 1b. Poloidal field coil sets are shown in Figs. 1 and 2. Here, current of 600 A maximum per turn was present to generate $\mathbf{B}_\theta$. There were no other external currents beside these present in the experiment, hence local saturation of ferromagnetic medium did not take place, i.e. $\mu_r(|\mathbf{B}|) = \text{const}$. This led to linearization of Eq. (1). Modelled $\mathbf{B}_\theta$ was then calculated from known spatial current distribution of coils and from resultant coupled surface currents of toroidal direction $\sigma_\phi(R_i, Z_i)$ along discretized 2D representation of ferromagnetic boundary. Due to axisymmetry, cylindrical coordinate system is used as shown in Figs. 1b and 2, with radius R identified with distance from major axis and polar angle θ identified with toroidal angle ϕ. In this manner, poloidal field $\mathbf{B}_\theta = [B_R, B_Z]$ (see Fig. 2). $\mathbf{B}_\theta$ was measured inside of tokamak chamber by Hall probe capable of measurement of slowly varying magnetic fields of low magnitude. Namely, B_R component was investigated due to polarity of coils (see Fig. 2). The measurement took place in two poloidal planes at different ϕ, as shown in Fig. 1.

4. Comparison to measured data and discussion

Measurements on midplane in Fig. 3 with comparison to calculation by air core model ($\mu_r = 1$) show significant influence of tokamak core on B_R density magnitude inside the chamber. Application of 2D axisymmetric iron-air boundary model can provide first order correction of changed magnetic field density, as is shown in Figs. 1b and 2. The strong non-axisymmetry of real GOLEM core however leads to necessity of different R_{disc} parameters for

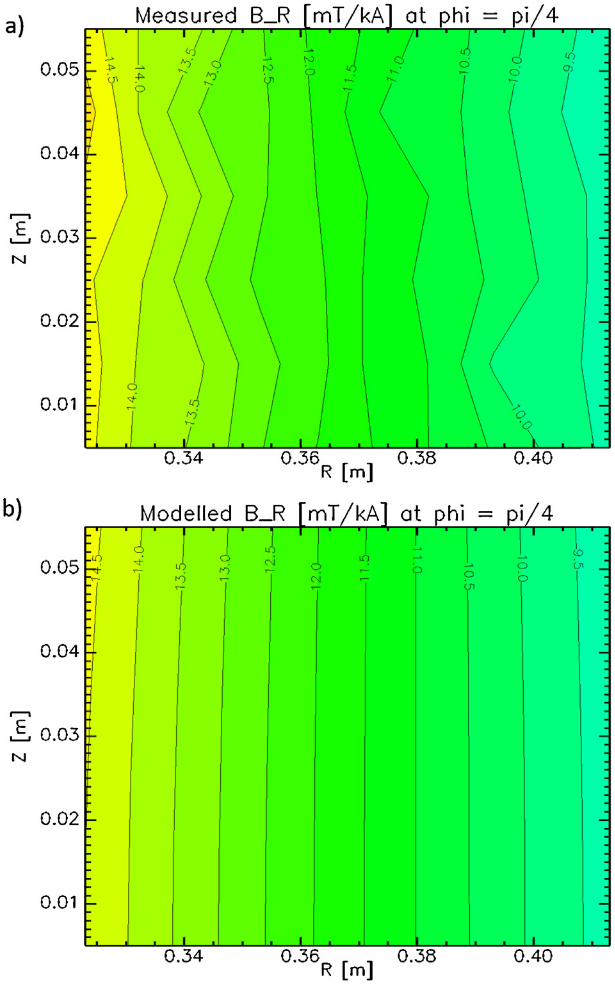

Fig. 4. Poloidal plane profiles of measured (a) and modelled (b) B_R density, $\phi = \pi/4$ with $R_{disc} = 1.4R_{cen}$.

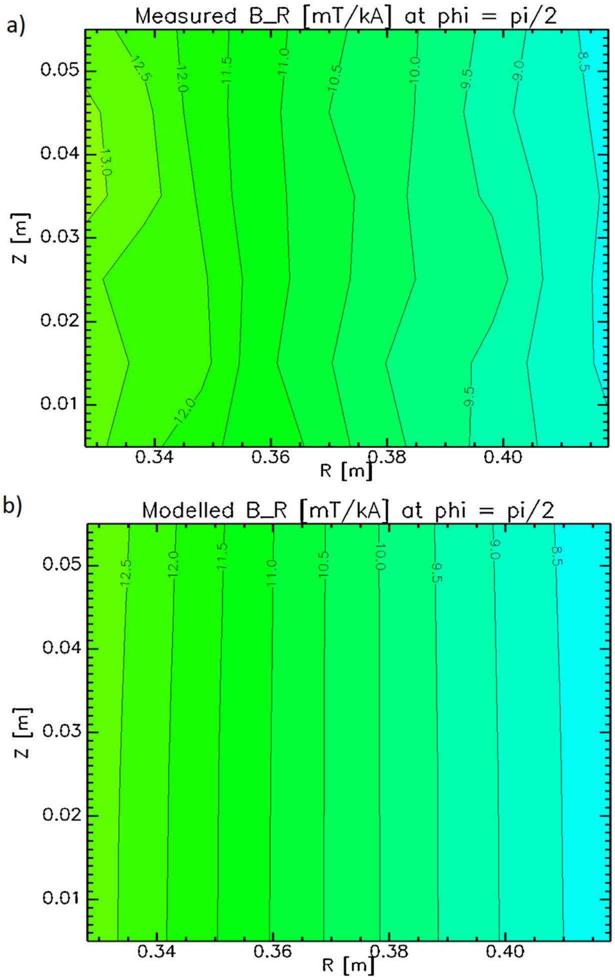

Fig. 5. Poloidal plane profiles of measured (a) and modelled (b) B_R density, $\phi = \pi/2$ with $R_{disc} = 1.28R_{cen}$.

different toroidal angles ϕ with respect to transformer yoke location. While for $\phi = \pi/4$, $R_{disc} = 1.4R_{cen}$ seems to be necessary, for $\phi = \pi/2$, $R_{disc} = 1.28R_{cen}$ is sufficient. Comparisons between measured and modelled B_R densities across the measurement planes as whole are shown in Figs. 4 and 5.

Plots in Figs. 3a and 4 show that 2D axisymmetric approach and used linearized integral boundary model yield satisfactory quantitative description of non-axisymmetrical iron core influence on poloidal fields inside tokamak chamber, at least on poloidal angles closer to transformer yoke location. The same approach however, seems to be able to provide only first order qualitative approximation of B_R quantity for toroidal angles further away from transformer yoke. As can be seen in Figs. 3b and 5 even though adjust in R_{disc} provides approximation of magnitude, discrepancy in gradients of field densities is present. Application of 3D code, once finished, might provide better results and this issue will be investigated in future work.

5. Summary

Developement of 2D reference for future 3D tokamak iron core code yields first approximation of GOLEM (former CASTOR) iron core model, and provides explanation to observed discrepancy between calculated and measured magnitudes of field by poloidal coils on this tokamak described in [4], where air core description was applied. 2D approximation of strongly non-axisymetric core is quantitatively valid for plane which is toroidally closer to transformer yoke and qualitatively valid for plane toroidally furthest from the yoke. Additionally, dimensions of its axisymmetric equivalent must vary with respect to toroidal angle of calculated plane. Future work will contain generalization of code into 3D geometry, along with implementation of $\mu_r(|\mathbf{B}|)$ dependency to provide validity for higher currents as well. Naturally, more measurements on different locations for validation of the code will follow as well.

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