Solenoid-Free Toroidal Plasma Start-Up Concept Utilizing Only the Outer Poloidal Field Coils and a Conducting Center-post

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Abstract. Eventual elimination of in-board ohmic heating solenoid is required for the spherical torus (ST) to function as a compact component test facility (CTF) and as an attractive fusion power plant. An in-board ohmic solenoid, along with the shielding needed for its insulation, can dramatically increase the size and, hence, the cost of the plant. Advanced tokamak reactor designs also assume no in-board solenoid to reduce the size and cost of the plant. In addition, an elimination of in-board solenoid greatly reduces the coil stresses and simplifies the coil design. Here, we examine two complementary solenoid-free plasma start-up approaches: the one utilizes only the outer poloidal field coils to create a relatively high quality field null region while retaining significant poloidal flux and the another takes advantage of the poloidal flux stored in the conducting center-post to create a start-up condition similar to that of the conventional ohmic solenoid method. We find that it is therefore indeed possible to come up with a promising configuration, which produces a quality multi-pole field-null and sufficient loop-voltage needed for plasma initiation and significant poloidal flux for subsequent current ramp-up. The present solenoid-free start-up concept, if proven feasible, can be readily extended to larger higher field devices due to relatively simple physics principles and favorable scaling with the device size and toroidal field.

1. Introduction

In the fusion research conducted worldwide, the ohmic heating solenoid has been commonly used to start-up tokamak, spherical torus (ST), and other toroidal plasmas aiming to develop an attractive fusion power source. A conventional ohmic solenoid is placed in the in-board side of the toroidal plasma. However, looking toward attractive/economical fusion power plants, the in-board ohmic solenoid places a high premium on the cost of the plant. An in-board ohmic solenoid, along with the shielding needed for its insulation, increases the size and, hence, the cost of the plant. This problem tends to become particularly challenging for the ST reactors because their tight inboard radial spacing makes the placement of ohmic solenoid, and related neutron shielding and blanket impractical [1]. Indeed, ST-based fusion systems including the CTF (Component Test Facility) [2] and power plant designs (e.g., ARIES-ST [3]) assume complete elimination of the ohmic solenoid. It is also worthwhile to note that the designs for much higher aspect-ratio advanced tokamak reactors such as the ARIES-AT [4] assume no inboard solenoid. However, at the present time, there is no proven method available for a solenoid-free start-up of tokamak/ST reactors.

There are a number of promising non-inductive start-up and current ramp-up concepts based on direct current drive by radio frequency waves and neutral beam injection. The ARIES-ST uses a current ramp-up concept utilizing the pressure driven bootstrap current over-drive. The helicity injection based start-up concepts are being pursued in spheromaks and STs. While those methods have produced significant levels of plasma current ~ a few hundred kAs, since those non-inductive methods are generally very plasma physics intensive, a considerable physics R&D effort will be required to extend those techniques to an order of magnitude higher multi-MA regimes needed for the next generation devices. Various solenoid-free inductive plasma start-up methods are also being pursued at sub-MA level with some successes. The MAST experiment routinely uses in-vessel poloidal field (PF) coils at larger major radii for solenoid-free plasma initiation and current ramp-up by means of merging and compression [5]. This approach could however limit the horizontal mid-plane access needed, for example, for the removable blanket modules for CTF. There is an idea of creating a hot ST plasma by merging two STs as demonstrated in the TS-3 device [6]. Recently, this concept was tested on MAST producing significant plasma current of ~150 kA. However, this concept thus far requires internal coils to initiate plasma formation.

Recently, JT-60U has demonstrated solenoid-free start-up by utilizing only the outer PF coils which produced 150 kA of plasma current [7]. Strong MW level ECH pre-ionization was used to help initiate the plasma even without creating a field null. Similarly on TST-2, with about 100 kW of ECH, it was possible to initiate the plasma of up to 10 kA [8]. Interestingly, with strong ECH heating, both JT-60U and TST-2 experiments could start the plasma current with relatively large negative (radially unstable) vertical field which is an intriguing result.

2. Basic Concept of Outboard Inductive Start-up Utilizing Outer PF Coil System

A fundamental challenge for using only the outer PF coils for the start-up purpose is the difficulty of creating a sufficiently high quality field null region at the same time retaining significant poloidal flux Ψ needed for subsequent current ramp-up. With limited PF coil sets, it is usually difficult to improve the quality of the field null region without reducing the available Ψ. However, a carefully chosen proper set of PF coils can offer a promising possibility. This was done by performing the static vacuum field numerical modeling to seek the optimal PF coil position and currents for producing field null at a desired location. The condition to be met for null formation is that the first, second, and third derivative of flux Ψ with respect to the major radial coordinate R vanish, i.e., $d\Psi/dR = 0$, $d^2\Psi/dR^2 = 0$, $d^3\Psi/dR^3 = 0$, at the given location in the case of total five PF coils involved. If $R = R^*$ is the desired location of the field null, the total poloidal flux Ψ can be written as $\Psi(R^*) = \sum_{i=1}^{5}\sum_{j=1}^{N_i} w_{ij} I_i G(R^*, R_{ij})$ where G is the Green's function, I_i is the current of the ith coil, N_i is the number of segments in the ith coil, w_{ij} is the number of turns in the jth segment of the ith coil, and R_{ij} is the major radius of the coil segment. Then, the equations to be solved become

$$\sum_i\sum_j w_{ij} I_i \left.\frac{\partial G}{\partial R}\right|_{R=R^*} = 0, \quad \sum_i\sum_j w_{ij} I_i \left.\frac{\partial^2 G}{\partial R^2}\right|_{R=R^*} = 0, \quad \sum_i\sum_j w_{ij} I_i \left.\frac{\partial^3 G}{\partial R^3}\right|_{R=R^*} = 0, \qquad (1)$$

which can be expressed, after a straightforward arrangement, in the form of

$$\begin{pmatrix} I_3 \\ I_4 \\ I_5 \end{pmatrix} = -\left(\underline{\underline{A}}^{-1} \cdot \underline{\underline{B}}\right)\begin{pmatrix} I_1 \\ I_2 \end{pmatrix}, \qquad (2)$$

where $\underline{\underline{A}}$ and $\underline{\underline{B}}$ are 3×3 and 3×2 matrix, respectively, consisting of the derivatives of the Green's function. Therefore, once two coil currents are prescribed it is possible to find the current of the other three coils that satisfy the constraints. For the case of four coils, only one current is required to satisfy the constraints. That of course assumes Eq. (1) describes three linearly independent equations. This is the basic reason that the coils must be of sufficiently different types to make these equations sufficiently linearly independent to yield interesting solutions. One should also note that a careful choice of the coil location is also quite important since the coil position can affect the higher order gradients. In the numerical code, an algorithm was utilized to scan the coil position to search for an optimized condition.

In *FIG. 1(a)* for the next-step ST (NSST) [9], we show that three basic types of PF coils can create a quality ‘multi-pole’ field null while retaining significant Ψ. The small-radius Coil #1 produces a vertical field B_Z (at the mid-plane) that decreases toward larger R. The large diameter Coil #2 produces a nearly uniform Helmholtz-type B_Z. The vertical field B_Z produced by Coil #3 placed near the outer mid-plane actually increases with radius near the coil. By adding Coil #1 and #3, one can create a B_Z profile which is peaked at the major axis but relatively flat at the field null region at $R \sim 2.5$ m as shown in *FIG. 1(b)* since the field gradient of Coil #1 and #3 are opposite in that region. One can then null out the field in the null region by subtracting the relatively uniform field from Coil #2 which would create a high quality field null with very small higher order field gradients of sufficient size ~0.3 m while retaining significant Ψ in the in-board side as shown in *FIG. 1(c)*. A number of possible PF coil configurations are possible depending on the design needs of a particular device. If a larger horizontal mid-plane access is needed for the blanket modules for a CTF, one can replace the Coil #3 coils with two sets of coils with much larger horizontal access of ~2 m as shown in *FIG. 1(d)* with similar field-null and available flux.

In order to realistically simulate the actual electromagnetic behavior, it is essential to perform dynamic calculations including vacuum vessel and other conducting objects which could induce wall eddy currents. The wall eddy currents generally slow down flux changes and reduce the generated peak loop voltage. The field null creation can be also significantly affected. However, it is relatively straightforward to account for them by numerical means by solving a coupled circuit equation with the conducting structures assumed as hundreds of divided ring elements:

$$\mathbf{L} \cdot \dot{\vec{I}} + \mathbf{R} \cdot \vec{I} = \vec{V}_c + \vec{V}_s t, \tag{3}$$

where $\mathbf{L}$ is a square matrix composed of self and mutual inductance between elements and $\mathbf{R}$ represents a resistance matrix. The row vector $\vec{I}$ consists of current flowing in each conducting element and $\dot{\vec{I}}$ denotes its time derivative. $\vec{V}_c$ and $\vec{V}_s$ represent the piecewise linear bias voltage. Equation (3) was solved by the eigenmode expansion method. The waveform of the optimized coils was sought through an optimization procedure in which optimization was performed by χ^2 minimization. In practice, the coil current and bias voltage found by the optimization procedure should be checked to confirm whether the values were within the capability of the coil power supplies.

One can also take advantage of the wall eddy currents by transferring the coil current to the vacuum vessel, which is much closer to the plasma. In principle, one can design the vacuum vessel and other conducting structures to actually aid the plasma start-up. For the NSST geometry, a dynamic calculation [10] yields that it is possible to create a reasonable quality field null region with ≤ 20 G for over 0.3 m diameter region while retaining sufficient loop-voltage of ~7 V for plasma initiation and Ψ of more than 4 Wb needed for the subsequent current ramp-up toward multi-MA level current. This is equivalent to $E_T{\cdot}B_T / B_P > \sim 1$ kV/m, which is a typical condition for an ohmic start-up without strong pre-ionization. In the calculation, the Lloyd criteria [11] for the plasma initiation with sufficient pre-ionization of $E_T{\cdot}B_T / B_P \geq 0.1$ kV/m was sustained over 0.5 m diameter volume which is similar to the DIII-D plasma minor radius for a duration of 10 ms, which should be long enough for the plasma avalanche process to occur. On JT-60 with strong ECH pre-ionization, a successful solenoid-free start-up was achieved with even lower Lloyd parameter of ~0.02 kV/m. It is then possible to relax the field null condition, which should yield even more flux available for the plasma current ramp-up.

3. Concept of Center-post Start-up

Here, we present a variant of induction concept, which takes advantage of the single-turn copper toroidal field (TF) coil inner leg envisioned for the ST-reactors. If the ST device has a solid copper center-post such as the case for CTF and power plant, one can store significant poloidal flux in the center-post to further aid the breakdown and current ramp-up. The poloidal flux Ψ trapped in the center-post inherently has a small stray field (like an ohmic solenoid), so additional flux provided in this manner should present greater flexibility to the solenoid-free start-up. The present concept can be also extended to tokamak reactors by placing a metal ‘cylinder’ in the central region. The cylinder could also be a part of the vacuum vessel, shields, and/or the support structure. The basic idea is to use the outer PF coils to charge up the center-post or the centrally placed metal cylinder. Using a set of outer PF coils energized in the same polarity, one could envision charging the center-post to significant magnetic field value. For example, if the applied magnetic field can be 8 T as shown in *FIG. 2(a)*, a center-post with 0.5 m radius as in the case for the NSST or the CTF-like device can store nearly 6 Wb of magnetic flux. This type of flux is sufficient to generate multi-MA of plasma current. If the center-post is 1 m radius like the ARIES-ST, the stored Ψ can be 24 Wb. These flux values represent a significant fraction of Ψ needed to ramp up the current in both CTF and ARIES-ST reactors. It should be also noted that the present concept can be extended to higher aspect-ratio tokamak reactors. For example, if a conducting flux storage shell which can be a part of the vacuum vessel, neutron shielding and/or support structure of mean radius of 3.5 m is installed in a R = 6 m advanced tokamak reactor, even a modest field of say 3 T can store over 100 Wb of Ψ in this structure. This level of Ψ should be sufficient to start 10 MA level advanced tokamak reactor. Once the center-post is charged up, one can then program the PF coil currents to create an appropriate null field region needed for the plasma initiation. Since the center-post is very conducting, the flux is trapped inside the center-post for a much longer time compared to more resistive vacuum vessel and support structures as shown in *FIG. 2(b)*. Since Ψ is trapped primarily in the center-post after other wall eddy currents die away, one is left with a situation very similar to a conventional ohmic solenoid with very small fringing stray field which can be easily cancelled by applying a small amount of vertical field. This is a very favorable time to initiate the discharge. The poloidal flux in the center-post would decay with the natural resistive time t_r or $exp(-t/t_r)$. The induced loop-voltage also decays with similar waveform. This type of waveform is compatible with a typical inductive (ohmic) start-up waveform since it takes more voltage to breakdown and ramp the current up in the more resistive (colder) initial plasma stage. In the case of a conducting central storage cylinder, it is possible to choose the wall material and thickness to control the effective resistive time to suit the specific needs of a reactor. Application of supplemental plasma heating and/or current drive would give an additional knob for the plasma initiation and current ramp-up.

A numerical simulation of this concept was conducted with two sets of outer PF coils as shown in *FIG. 3* for the NSST like device configuration. It should be noted that the present concept should work essentially with any number of PF coils of various sizes placed at various locations. *FIGURE 3(a)* shows the temporal evolution of Ψ at R = 1 m. The expanded scale during the time of interest near the plasma initiation point is shown in *FIG. 3(b)*. The toroidal current waveform is shown in *FIG. 3(c)*. The Ψ change due to the PF coil current swing induces toroidal current both in the vacuum vessel as well as in the center-post. Since the center-post is much less resistive, the current persists long after the vacuum vessel wall current dies away. In *FIG. 3(d)*, there is a significant Ψ of over 2 Wb still remaining in the center-post even at t = 7 sec. In *FIG. 4(a)*, the induced stray field from the center-post flux is shown. The field is relatively small (~120 G) and uniform around mid-plane for R > 1 m. At

B_T ~ 2.5 T, this type of stray field represents $E_T{\cdot}B_T / B_P$ > ~0.1 kV/m with a modest loop voltage of 5 V which can be initiated with ECH pre-ionization. This type of stray field can be easily cancelled by applying a small amount of vertical field in the opposite direction. Moreover, this type of stray field is similar to the one generated from the ohmic solenoid and therefore well suited for the plasma initiation. As comparison, the stray field from a typical ohmic solenoid is shown in *FIG. 4(b)*. Clearly, one can increase the available flux as the Lloyd condition can be relaxed.

4. Discussions and Conclusions

In this paper, we presented two complementary inductively-based concepts to aid the solenoid-free start-up for future ST and tokamak reactors. The ST configuration with a combination of three types of out-board PF coils placed outside the vacuum vessel can create a good quality field null region while retaining significant volt-second capability for current ramp-up. For NSST, a high quality multi-pole field null can be created near R = 2.5 m while the nearest Coil #3 is placed at R = 3.1 m with adequate NBI/diagnostic access. Sufficient flux Ψ as large as about 4 - 5 Wb is available for ramping up the plasma current to a few MAs for the next generation ST devices such as NSST without using an ohmic solenoid. The concept should scale well to larger higher field devices since the amount of flux tends to go up as square of the major radius ($\Psi \propto R^2$) and linear with the toroidal magnetic field. The PF coil system due to its simplicity is relatively attractive from the engineering point of view. It consists of relatively simple circular coils placed outside vacuum vessel so that the coil system can be made accessible. The concept provides sufficient flexibility in the coil positions to accommodate the special needs of particular device configurations. Through careful engineering design, it should be possible to further optimize the PF coil system to match the start-up requirements of a particular device.

Another concept utilizes the inboard-side conducting material to store the magnetic flux which is initially charged up by the out-board side outer PF coils. For ST, it is conceivable to utilize the central TF conducting post as the flux storage. The NSST (CTF) size device can provide additional 2 - 4 Wb with this method. The ARIES-ST like device would provide about 10 - 15 Wb. Larger aspect-ratio tokamak reactors can store larger (~100 Wb) magnetic flux. The induced loop voltage is determined by the flux decay rate which can be controlled to some extent by the choice of material and conducting wall thickness which determines the effective resistivity. Like the ohmic solenoid, the stray field generated by the center-post flux is relatively small which would make it suitable for the plasma start-up utilization.

In these solenoid-free start-up concepts proposed, the actual available flux strongly depends on the tolerance to the initial stray field. As shown in JT-60U and TST-2 with strong ECH heating, if some level of stray fields can be allowed, the available flux for these concepts can be correspondingly increased. In addition to ECH, it is therefore worth investigating other means of pre-ionization including plasma and/or 'toroid' injection to minimize the required Lloyd parameter values. The plasma stability in the presence of the eddy currents is an issue that will require further investigation. An accurate equilibrium calculation will give the required amount of vertical and radial fields for proper force balance. The presence of the nearby passive stabilizers should aid the vertical stability, and additional small PF feedback coils can be used if necessary.

Acknowledgements

The authors would like to thank Drs. R. Goldston, R. Hawryluk, J. Menard, and M. Peng for their valuable comments and discussions. Thanks are also due to Dr. S. Jardin for his valuable suggestions on numerical techniques. This work is supported by KAIST and DoE Contract No. DE-AC02-76-CH0-3073.

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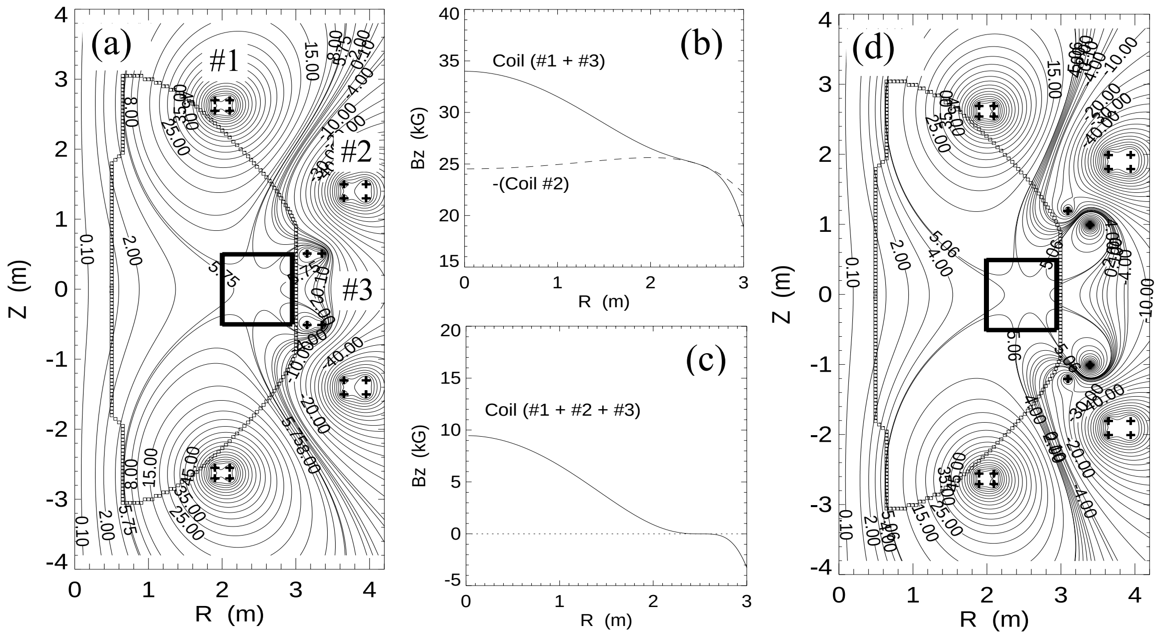

FIG. 1. Outer PF coil plasma start-up configuration for NSST. (a) The Ψ contours with 1 m horizontal mid-plane access for NBI. (b) and (c) Mid-plane vertical field contours as labeled. (d) The flux contours with ~ 2 m horizontal mid-plane access.

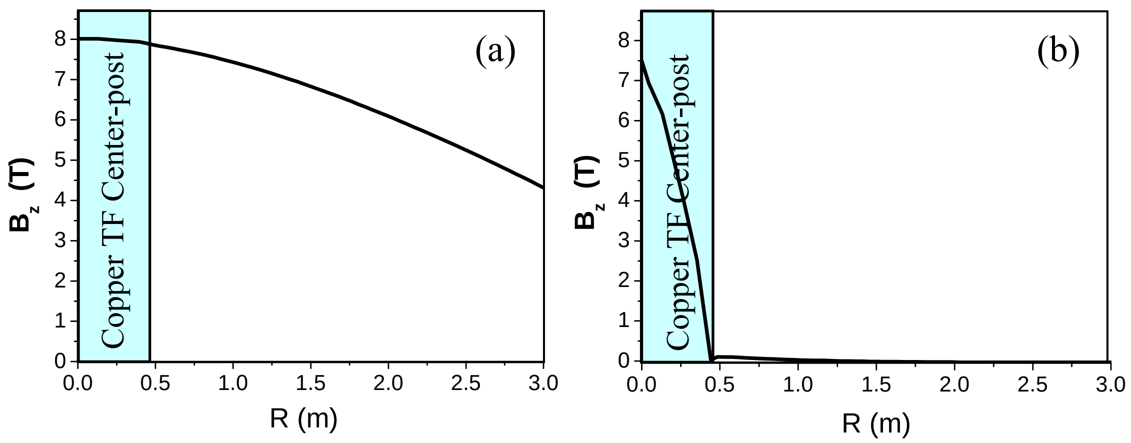

FIG. 2. Evolution of ploloidal field profile. (a) Initial radial profile of poloidal field at mid-plane with the center-post fully charged. (b) Radial poloidal field profile after the poloidal field was ramped down. The flux remains mostly in the center-post.

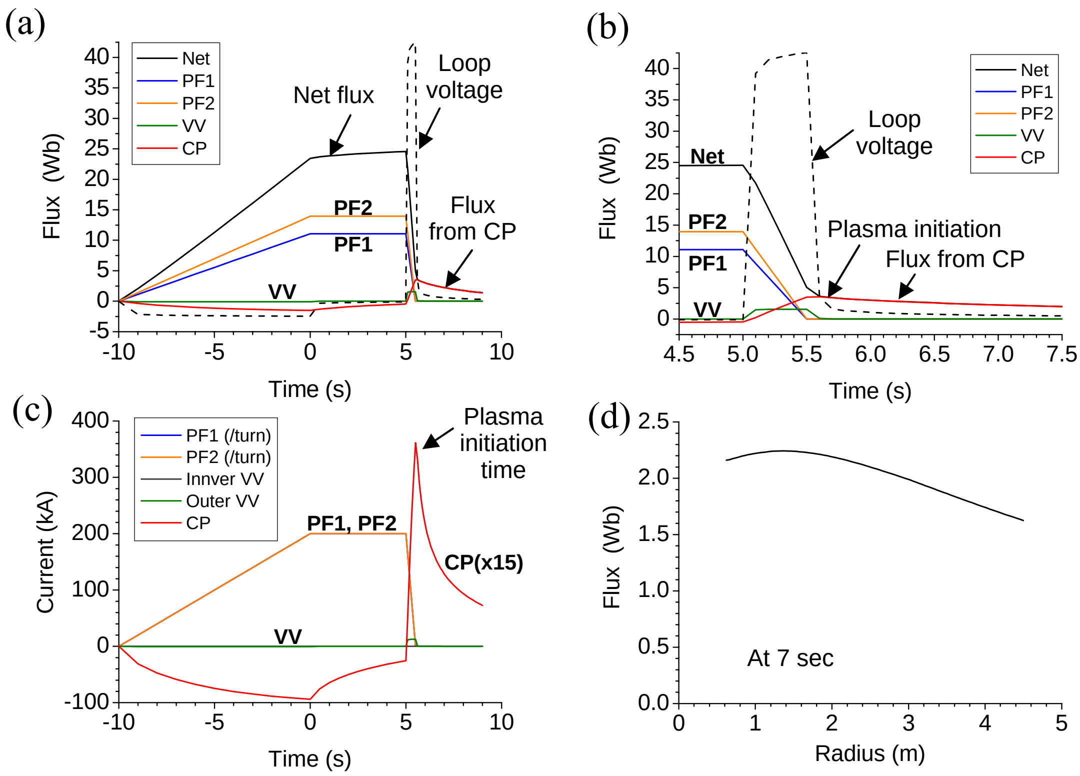

FIG. 3. Numerical simulation results of the center-post start-up. (a) Temporal evolution of poloidal flux Ψ (at R = 1 m) for various components as labeled. (b) Expanded scale during the time of interest. (c) Temporal evolution of currents. (d) Center-post radial poloidal flux profile at t = 7 sec.

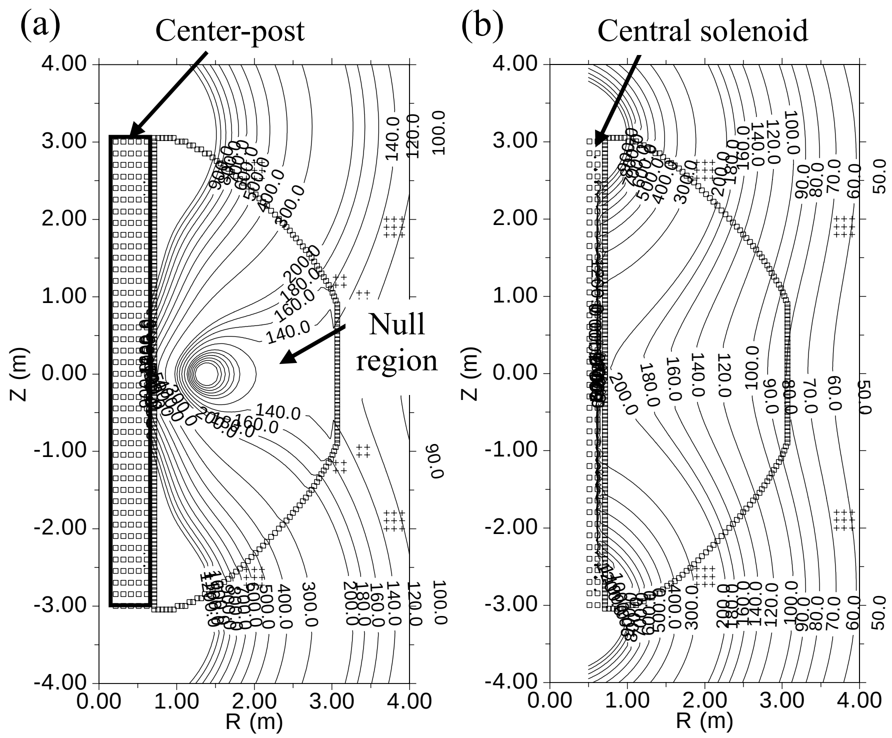

FIG. 4. (a) The poloidal field fringing field pattern due to the center-post. The numbers are in gauss. (b) The fringing field due to the central solenoid.