Fusion Engineering and Design 86 (2011) 41–44

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

# All-metal transformer core for a low aspect ratio tokamak

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ARTICLE INFO

*Article history:*
Received 20 May 2010
Received in revised form 27 July 2010
Accepted 2 August 2010
Available online 15 September 2010

*Keywords:*
Spherical tokamak
Fusion design

ABSTRACT

A novel concept for incorporating an iron core transformer within a axisymmetric toroidal plasma containment device with a high neutron flux is described. This design enables conceptual design of low aspect ratio devices which employ standard transformer-driven plasma startup by using all-metal high resistance inserts between the toroidal field windings. This design avoids the inherent problems of a multi-turn air core transformer which will inevitably suffer from strong neutron bombardment and hence lose the integrity of its insulation, both through long term material degradation and short term neutron induced conductivity. A full 3-dimensional model of the concept has been developed within the MAXWELL program and the resultant loop voltage calculated. The utility of the result is found to be dependent on the resistivity of the high resistance inserts. Useful loop voltage time histories have been obtained using expected resistivities.



## 1. Introduction

The spherical torus concept [1] has been proposed as an attractive component test facility (CTF) [2] and also as an alternative configuration for a DEMO reactor [3]. However, none of the proposed neutron producing low aspect ratio devices incorporate a transformer for plasma startup. None of the discussions in these proposals go into detail as to the method of plasma formation, and the while some potentially promising experimental methods have been proposed for solenoid free formation of low aspect ratio plasmas (see e.g. [11–13]) the sufficiency and scalability of these methods have yet to be demonstrated. Additionally, to date all experimental spherical tori that have achieved edge safety factors that are of interest to reactor have had a transformer [4–7]. These facts motivate the investigation of a solenoid concept that is reasonably resistant to the intense neutron environment that is anticipated in proposed future low aspect ratio plasma confinement devices.

## 2. The all-metal center stack concept

An internal wound air core coil is quickly rejected when considering a transformer at low aspect ratio. Multi-turn coils require insulation that will hold off high voltage (typically several kV) during the startup phase of the device. This implies relatively thick insulation that must survive intense neutron flux at high fluence. However, it is fairly simple to imagine using an iron core transformer that has the driving coils on the part of the iron core that are protected by the neutron shield. The high voltage insulation can then be protected from the neutron flux. For such a device, the iron core should be located inside the toroidal field legs (i.e. the maximum major radius of the iron should be less then the minimum major radius of the TF coil), so as to avoid saturation of the iron by the toroidal field. If the iron in the center stack is saturated, it would obviate the utility of the transformer. Most existing ST reactors/component test facility designs implement a solid copper center conductor. However, the eddy currents induced in an iron core surrounded by a solid ring of copper would substantially reduce the loop voltage induced by the transformer action of the iron. It is therefore necessary to introduce toroidal breaks in the center stack so as to reduce the flow of these eddy currents. In particular, metal wedges are introduced between now discrete TF conductors to break up the eddy currents. The question then becomes is there an interesting configuration of realistic wedges that would provide sufficient toroidal resistance in the centerstack to allow the break up of the eddy currents while maintaining sufficient cross-section of copper to maintain low vertical resistance sufficient to carry the toroidal field current.

Fig. 1 shows a top down view of a cross-section of a typical design of this concept. The central region is the iron core, the dark colored wedges are the eddy current reducing high resistance inserts and the light colored larger wedges are the toroidal field conductors. The variables in such a design are the radius of the iron core relative to the total radius of the toroidal extent and total number of the wedges. There are numerous factors that might drive these design choices. It is not the intent of this paper to optimize these design choices for any given configuration, but rather to demonstrate that for reasonable choices of the design parameters it is possible to

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doi:10.1016/j.fusengdes.2010.08.001

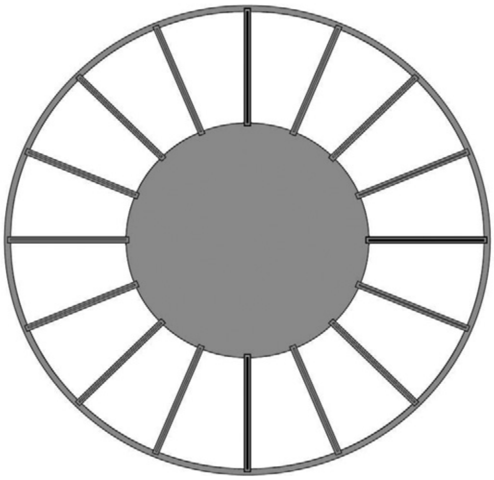

**Fig. 1.** Horizontal cross-section view of the center portion of the all-metal center stack. The central region is ferritic material, surrounded by copper wedges, which are in turn separated by resistive inserts.

obtain a useful loop voltage for ramping the plasma current in an ST. This can be considered a proof-of-principle calculation. It should be noted that in a real device the resistivity of the materials in the center stack would increase with time. While this increase would increase the total power consumed in the toroidal field coils, it would decrease the toroidal eddy current decay time and thereby improve the penetration of the transformer flux through the copper.

It is important to note that the approach taken here of inserting metal wedges to create higher toroidal resistance in the center stack is not optimal. If it were instead possible to use thin insulators to hold off the voltage induced by interfering with flow of the induced eddy currents this would improve the concept substantially. However, there is an open question requiring some investigation as to whether the insulators would survive in the harsh neutron environment. Unlike the high voltage insulators required for the air core transformer, the voltage stand off for the eddy current insulators would only have to hold off a small fraction of the single-turn loop voltage (typically 0.1 V). Also, because the voltages are so low, the thickness of such films could be very small (0.1 mm or less). This means that issues of material strength degradation could be much reduced. It may well be possible to use such films in place of the metallic wedges considered here. Additionally, since the neutron flux from a fusion reactor would be quite low during the plasma current ramp up phase, and subsequently the loop voltage would be ∼0 V once the neutrons are being produced, problems associated with neutron induced conductivity would be minimal. Ceramic coatings have been considered for fusion magnet insulation in the past (see e.g. Ref. [8]) and work has been done on the changes to electrical properties of insulators (see e.g. Ref. [9]), but dedicated research and development on this topic would be helpful in the context of the proposed concept for the spherical tokamak.

However, because no materials research would be required in the case of the metallic inserts, this case is considered here. Hopefully the results of this calculation will motivate research into the use of thin insulating films for use in the (nearly) all-metal center stack in a low aspect ratio tokamak.

## 3. Model description

The modeling approach adopted for this calculation was to be fully realistic in 3D geometry with realistic model for the ferritic material that includes non-linear effects such as hysteresis and saturation. Full geometry and accurate materials properties is important for demonstrating that realistic parameter choices lead to useful loop voltage profiles. The MAXWELL [10] finite element electromagnetics analysis code was used for performing the calculations.

In order to minimize the computational requirements, care was taken to make a highly symmetric model so that the periodic boundary conditions could be used within the MAXWELL environment. The model has 16 toroidal field windings and eight separate

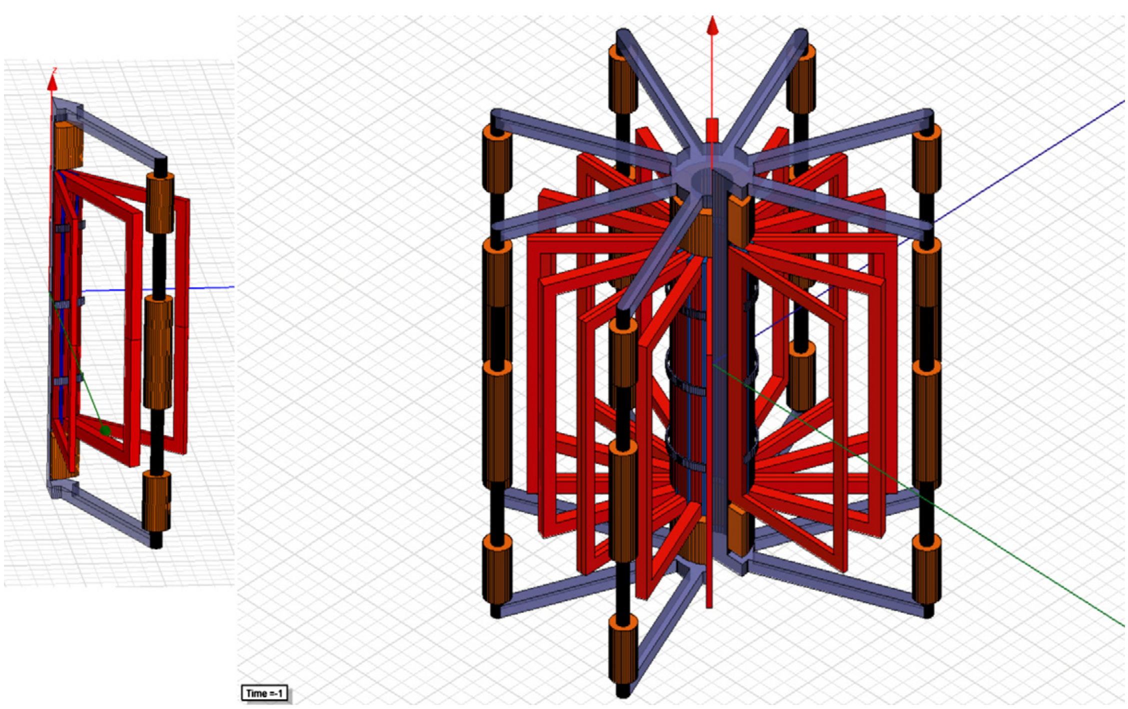

**Fig. 2.** (a) Single (1/8) sector of the model. The copper TF coil is shown in red, iron in purple, Inconel is in blue. The superconducting coils that drive the system are in orange. (b) A 3/4 sector of the same model for visualization. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

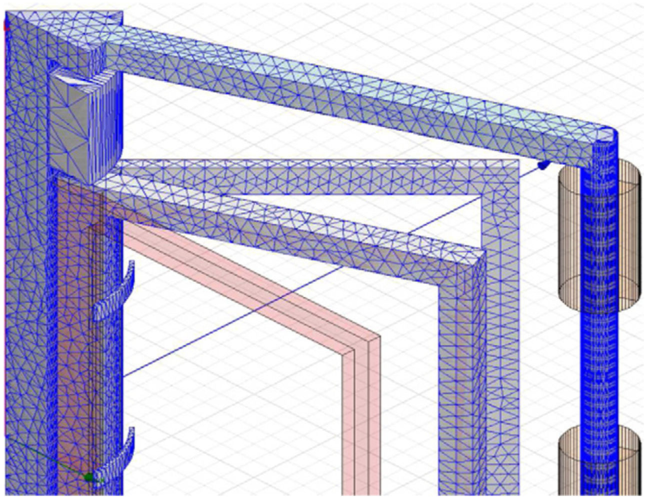

**Fig. 3.** Close up view of the sector model showing the discretization of the material.

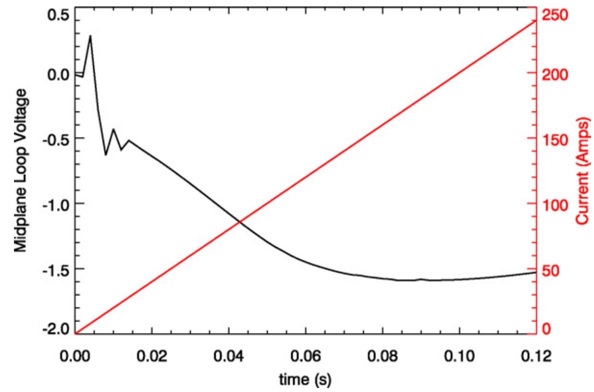


**Fig. 4.** Time history of the applied current waveform in the external coils (in red). Resultant voltage waveform on the device midplane. The loop voltage reaches 1.5 V, which should be enough to achieve plasma breakdown and ramp up (in black). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

iron transformer legs. This enables the use of a sector model that represents 1/8th of the total system. A representation of the sector model is shown in Fig. 2. Also shown in the figure, for clarity, is a 3/4 sector view of the model. The red color represents the copper of the toroidal field turns and the gray represents iron. The orange cylinders on the outboard part of the iron are the transformer primary coils. The light grey bands around the center stack are high resistance sectors which are used as diagnostics to measure the toroidal voltage. The current induced in the bands is multiplied by the resistance of the loop to obtain the single-turn voltage. This is the primary diagnostic for this calculation. Also visible in this figure are the high resistance metal inserts that are used to break up the toroidal eddy currents. Fig. 3 shows the discrete finite elements in the cross-section for the model. For reference, the radius of the iron in this model is 25 cm and the radius of the copper TF is 50 cm. These values were chosen arbitrarily, but may be similar to the values anticipated for machine designs, such as the CTF.

## 4. Results

The model was run with a high value of the resistance for the wedge materials. An example material for the wedges is Inconel which has a resistivity $\rho_{\mathrm{Inconel}} = 1.2 \times 10^{-6}$ Ohm m, which is 75 times higher than that of copper. However, since Inconel is substantially stronger than copper, it not necessary that the wedges be solid. Careful design of the inserts can lead to large increases of the effective toroidal resistance of these objects. How much material can realistically be removed from the high resistance inserts requires a detailed engineering analysis of the specific insert design, which is not the purpose of this paper, but it is an important question.

The case considered for the high resistance insert was $\rho_{\mathrm{eff\_Insert}} = 400\,\rho_{\mathrm{Cu}}$, which corresponds to ~20% metal content for the inserts. This choice can be understood by considering to the following requirements. The maximum amount of flux available is easily calculated $\Psi_{\max} \sim \pi r_{\mathrm{iron}}^2 [2B_{\mathrm{sat}}]$ where $r_{\mathrm{iron}}$ is the radius of the iron core, and $B_{\mathrm{sat}} \sim 2$ T is the saturation field of iron. This gives $\Psi_{\max} \sim 0.75$ Wb for the model described above. If we require $V_{\mathrm{loop}} \sim 1$ V a good estimate of the required eddy current decay time required can be determined by $V_{\mathrm{loop}} \sim \Delta\Psi/\tau_{L/R}$ where $\tau_{L/R}$ is the eddy current decay time in the center stack, $V_{\mathrm{loop}}$ is the single-turn loop voltage and $\Delta\Psi$ is the flux swing in the iron. From this relation we find the required eddy current decay time is $\tau_{L/R} = 0.75\,\mathrm{Wb}/1\,\mathrm{V}) = 0.75$ s. If the toroidal field coils are approximated as an infinitely long annular cylinder the inductance and resistance for the eddy currents can be expressed: $L_{\mathrm{cyl}} = B_{\mathrm{cyl}} \cdot \pi a_{\mathrm{Cu}}^2/I$, $R_{\mathrm{cyl}} = 2\pi a_{\mathrm{Cu}} \rho_{\mathrm{eff}}/(z_{\mathrm{Cu}}\delta_{\mathrm{Cu}})$ with $B_{\mathrm{cyl}} = \mu_0 I/z_{\mathrm{Cu}}$ where $L_{\mathrm{cyl}}$ and $R_{\mathrm{cyl}}$ are the inductance and resistance of the annular cylinder, $a_{\mathrm{Cu}}$ is the radius of the cylinder, $z_{\mathrm{Cu}}$ is the unit length of the cylinder, $\delta_{\mathrm{Cu}}$ is the thickness of the annulus, $B_{\mathrm{cyl}}$ is the magnetic field inside the cylinder due to the eddy current, and $I$ is the magnitude of the eddy current. One can then estimate the required toroidal resistance according to the formula $\tau_{L/R} \sim \mu_0 \sigma_{\mathrm{eff}} a_{\mathrm{Cu}} \delta_{\mathrm{Cu}}/2$. This gives a required effective conductivity of $\sigma_{\mathrm{eff}} \sim 10^7$ [Ohm m]$^{-1}$. This corresponds to roughly 1/16 the conductivity of copper. The effective toroidal resistivity of the non-iron part of the center stack can be expressed as $\rho_{\mathrm{eff}}/\rho_{\mathrm{Cu}} = 1 - f_\theta + [\rho_{\mathrm{Insert}}/\rho_{\mathrm{Cu}}][f_\theta/f_R]$, where $f_\theta$ is the fraction of the circumference that is taken up by inserts, and $f_R$ is the fraction of the radius of the insert that contains material. Using these expressions, one finds a required resitivity for the inserts of $\rho_{\mathrm{eff\_Insert}} \sim 400\,\rho_{\mathrm{Cu}}$.

The current in the primary coils was ramped linearly according to the waveforms indicated in Fig. 4. The resulting loop voltage profile obtained at the vertical midplane of the device is also shown in Fig. 4. As is evident in the figure, voltages in excess of ~1 V are attained. This should be sufficient for plasma current breakdown ramp up in the presence of external plasma heating sources and applied current drive. The time delay between the ramp of the coil current and the appearance of the voltage on the midplane is due to the finite current diffusion time of the eddy currents through the copper in the toroidal field coils. The roughness of the time dependence of the loop voltage on the midplane is due to the finite time resolution of the model and the discrete sampling of the B–H curve of iron in the region of highest magnetic permeability (i.e. at low magnetic field).

## 5. Summary

A novel all-metal design has been investigated for the center stack of a low aspect ratio torus. The loop voltage that is achieved with this design is shown to be useful for tokamak startup. Design of the metal inserts between the TF turns can substantially affect the device performance, so research and development on the design of these inserts will strengthen then conclusions of this paper. Future work involves incorporating a model for this device in an axisymmetric plasma equilibrium code, calculation of forces, and design of viable support structures and cooling channels.

## Acknowledgement

This work was supported by the U.S. Department of Energy Grant under contract number DE-AC02-76CH03073.

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