Transformer Schemes for Tokamak Reactors

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Introduction

The Tokamak principle of plasma confinement is based upon a large toroidal current in the plasma providing the necessary poloidal magnetic field. This current is initially generated by having the plasma act as a one-turn secondary of a transformer; energizing the primary side of the transformer produces an electric field that causes breakdown and ionization of the gas and drives the necessary plasma current. Once the desired operating condition is attained and $\beta_{pol} \simeq \sqrt{A}$, the diffusion-driven-current, according to neochassical theory, is sufficient to maintain the current; no electric field is required. If the diffusion-driven-current is nonexistent (there is no experimental indication of it as yet), then the necessary electric field to maintain the plasma current is small and can be obtained by a slowly rising primary current in the transformer. In this case the Tokamak reactor is a pulsed device but the burn time per pulse can conceivably be quite long so that the reactor can be considered to be quasi-steady state during the burn.

In this FDM, we discuss various schemes for the primary side of the transformer and the relative merits of air-core versus iron-core coupling of the primary and secondary. Numerical comparisons are based on the A=5, R=12.5m design presented at the Texas meeting, but the general conclusions should be valid for reasonable variations in the parameters.

General Considerations

During the burn the plasma current, I_p, is presumed to be constant at the design value I_f. For simplicity we assume that I_p rises linearly in time during the startup.

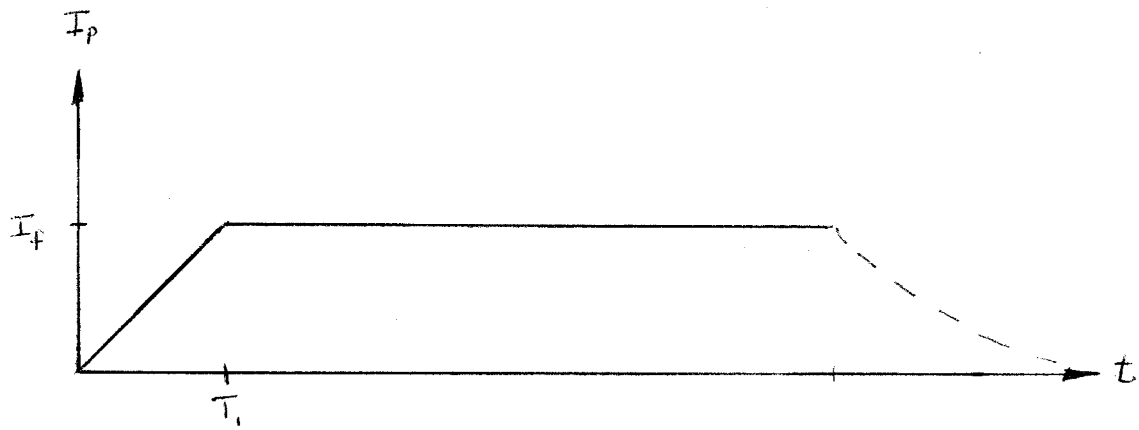
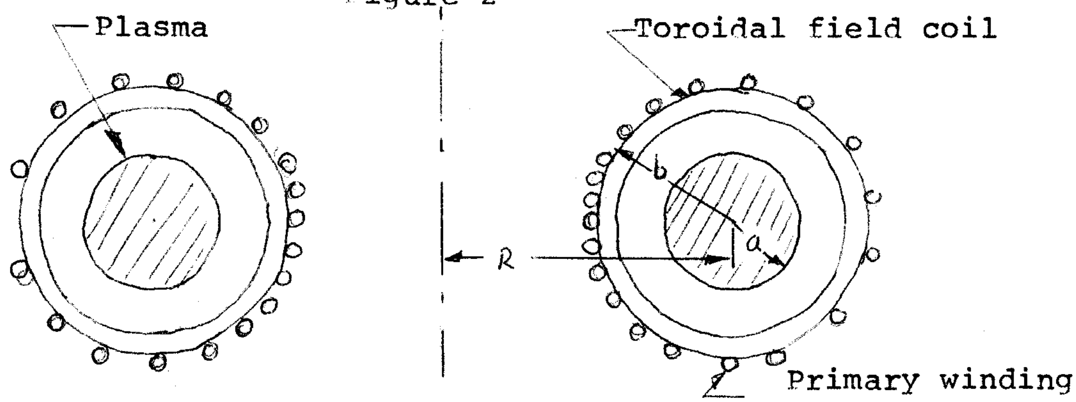


Figure 1

We choose T_1 such that the average dI_p/dt during the current rise stage of the discharge is similar to that in present experiments. This gives $T_I \sim 1/2$ sec. Our task is to determine the core flux and primary current required to generate the plasma current waveform above. We consider three cases: a) air-core, normal primary conductors; b) air-core, superconducting primary c) iron-core, superconducting primary. The primary winding are assumed to be arranged as shown in Fig. 2. The turns are distributed such that the magnetic flux is confined to the region of space outside the toroidal field coils. For simplicity we assume the toroidal field coils are round and have minor radius b; corrections for D-shaped coils are not necessarily small, but should not change the general conclusions of this paper.

Figure 2



The plasma resistance is shown in Table I for various values of the electron temperature. For $T_1 \sim 1$ sec, the inductive reactance during the current rise is $\omega L \sim 2\times10^{-5}$ ohm. Thus for Te $\lesssim$ .05 Kev the plasma acts like a resistive load, and for Te $>$ .05 Kev the plasma is an inductive load. Because of the rapid heating rate at low temperature, the time spent in the resistive region is small. As a first approximation one can neglect the resistive period and assume that over the entire time of current rise the plasma acts like a perfect conductor with "frozen" poloidal flux.

TABLE I

Electron Temperature (Kev)	Resistivity* (ohm-cm)	Resistance (ohms)
.01	2×10^{-3}	8×10^{-5}
0.1	8×10^{-5}	3×10^{-6}
1.0	3×10^{-6}	1×10^{-7}
10	1×10^{-7}	5×10^{-9}

* based on Spitzer resistivity.

The inductance of the plasma increases as the poloidal field of the plasma soaks into the blanket; this process will continue for a few seconds after T_I. This requires an increase of the core flux to maintain constant I_p. Thus the required waveform for the core flux is that shown in Fig. 3.

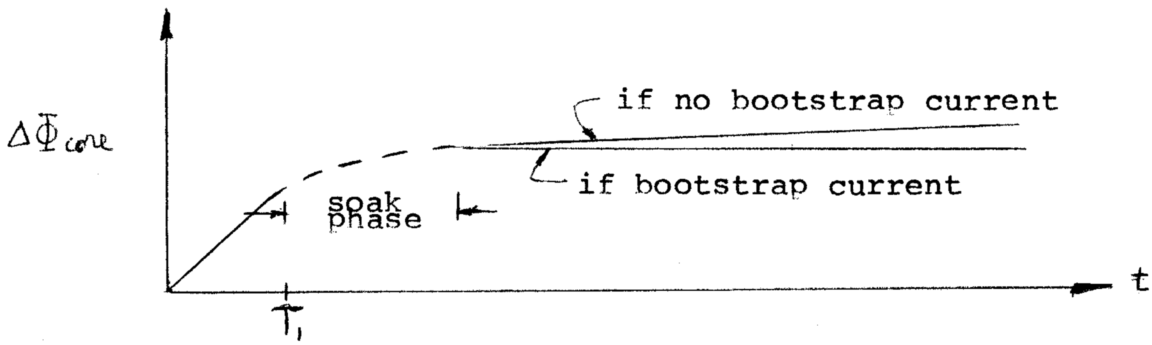


Figure 3

After the soak phase has terminated the core flux is held constant if the bootstrap current is present, or is increased slowly to make up for the resistive drop if the bootstrap current does not appear. In this case we need

$$\frac{d\Phi_{core}}{dt} = IR = .042 \ \frac{\text{webers}}{\text{sec}}$$

for the Wisconsin design. If one reserves 10% of the available core flux for the burn phase, then the burn time T_b that can be achieved is given by

$$1/10 \ L_p I_f = (\text{Res}) \ I_f T_b$$

This gives

$$T_b = \frac{\mu_0 a^2}{20\rho} (\ln 8A - 1.75)$$

where ρ is the resistivity. For the Wisconsin design, $T_b \approx 760$ sec. (the burn time will be shorter if the resistivity is anomalous).

Schemes for the Primary

AIR-CORE, NORMAL CONDUCTORS

In order to minimize the time interval during which the primary carries a large current, it is desirable to use the scheme developed by ATC. First, the primary is energized, the plasma is then preionized and the primary current is turned off to drive the current in the plasma. See Fig. 4.

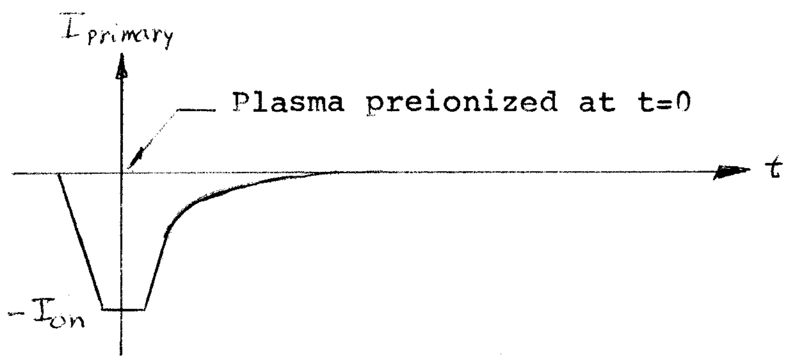


Figure 4

In this scheme, the poloidal flux established by the peak primary current is acquired by the plasma.

$$L_c \; I_{on} = L_p \; I_f$$

$$L_c = \mu_o R \left[\left(1 + \frac{b^2}{8R^2}\right) \ln 8 \frac{R}{b} - 2.25 \right]$$

$$L_p = \mu_o R \left[\ln 8 \frac{R}{a} - 1.75 \right]$$

Thus

$$I_{on} = I_f \; \frac{\ln 8 \frac{R}{a} - 1.75}{\left(1 + \frac{b^2}{8R^2}\right) \ln \frac{8R}{b} - 2.25}$$

For the Wisconsin design $b \approx 6m$

$$I_{on} = 25.4 \times 10^6 \text{ amp-turns}$$

AIR-CORE, SUPERCONDUCTING PRIMARY

With a superconducting primary, one can have large currents flowing continuously without causing excessive energy losses. Thus the peak current can be reduced by swinging from negative to positive in the cycle, as shown in Fig. 5.

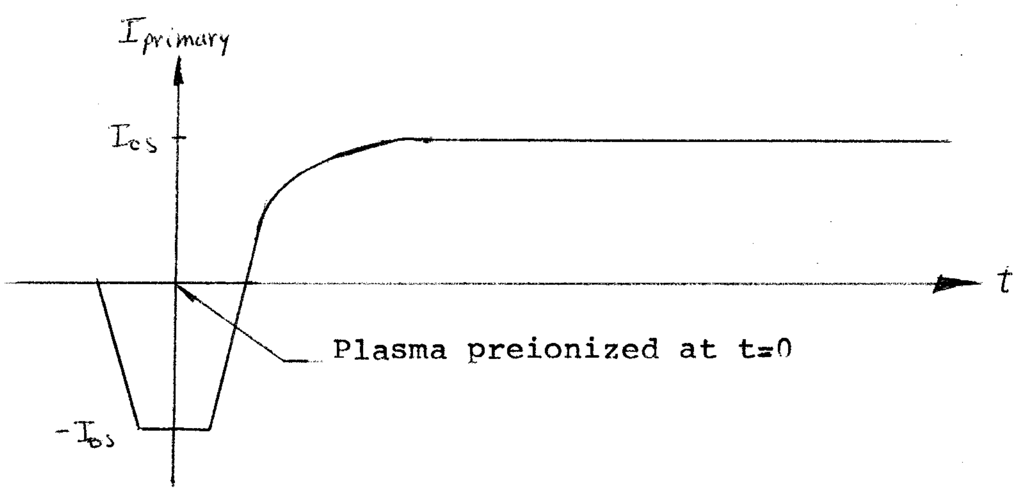


Figure 5

In this case

$$2\ I_{os}L_C = I_f\ L_p$$

or

$$I_{os} = 1/2\ I_f \frac{\ln 8\frac{R}{a} - 1.75}{\left(1+\frac{b^2}{8R^2}\right)\ln\frac{8R}{b} - 2.25}$$

which gives $I_{os} = 12.7 \times 10^6$ amp-turns

IRON-CORE, SUPERCONDUCTING

Addition of an iron-core improves the coupling between the primary and secondary; this reduces the primary current required but may require a larger hole in the center to avoid saturating the iron. Furthermore, one cannot store magnetic flux prior to preionization because the large primary current with an open-circuit secondary will saturate the iron. Hence, the primary current must have the time dependence shown in Fig. 6.

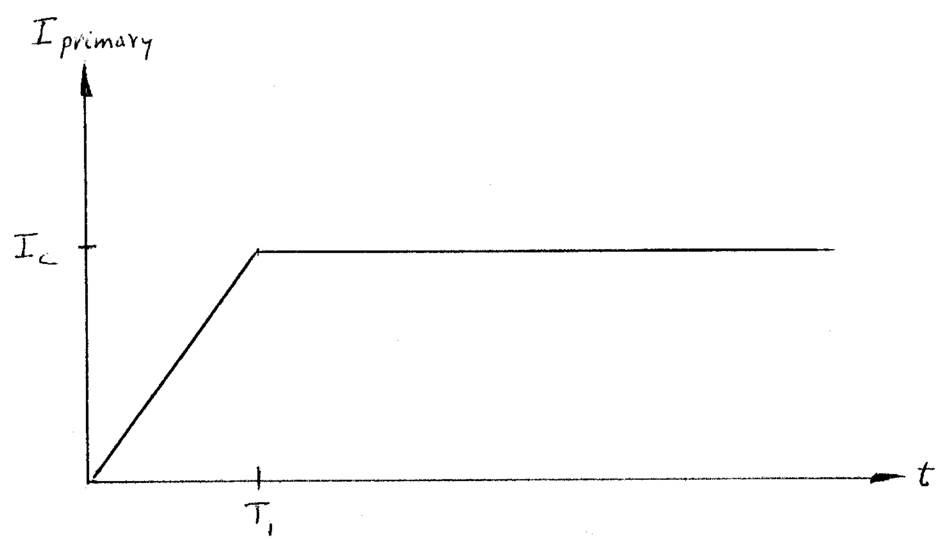


Figure 6

The peak primary current I_c is given by

$$L_c \; (I_c - I_f) = L_p^b \; I_f$$

or

$$I_c = I_f \left(1 + \frac{L_p^b}{L_c} \right)$$

where L_p^b is the internal inductance of the plasma and of the space between the plasma and the iron-core. since μ iron$\gg \mu$o, $L_p^b << L_c$, and

$$I_c \cong I_f = 8.5 \times 10^6 \text{ amp-turns}$$

CENTER HOLE SIZE

Let us now turn our attention to the question of the center hole required by each of these schemes. The air-core normal conducting primary has no fundamental limit on the hole size; reducing the hole diameter increases the magnetic field and the stresses so the limit is technological. The superconducting air-core system requires a core size such that the peak field at the superconductor does not exceed the critical field. Hence

$$\pi r_o^2 \; B_{sp} \geq I_{os} L_c = 1/2 \; I_f I_p$$

where B_{sp} is the critical field for the superconducting primary windings and r_o is the radius of the core.

The iron-core system requires a core size such that the iron is not saturated. If the iron is back-biased to $-B_I$ and then run to $+B_I$ in the cycle, then

$$2\pi r_o^2 \; B_I = L_p^b \; I_f$$

where $L_p^b = \mu_o R \left[\ln \frac{b}{a} + 1/2 \right]$. Note that the iron experiences a magnetic flux change equal to the magnetic flux stored in the plasma and blanket. For the Wisconsin design $r_o = 4.4$ meter if $B_I = 1.5$ Tesla. This implies that a rather large volume of iron is required. For comparison, the superconducting air-core design with $B_{sp} = 8.6$ T requires $r_o = 2.2$m.

Conclusions

We have briefly considered three different schemes for the transformer primary of a Tokamak reactor. The air-core, superconducting primary, system appears to be the better system in that it leads to a smaller core size than the iron-core system; this allows one to use a smaller aspect ratic which results in a higher power density reactor. The peak primary current required by an air-core system does not appear to be sufficiently higher than that required by the iron-core system to offset the economic benefit of a smaller aspect ratio. The superconducting primary also avoids the rather large power losses associated with normal conductors. Furthermore, for a given peak magnetic field in the primary, the superconducting air-core system allows for a smaller core than the normal conducting primary.