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CIRCUIT AND PLASMA SIMULATION FOR THE DESIGN OF ZT-40

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Summary

ZT-40, a toroidal Z pinch, uses its driving circuits to produce programmed magnetic fields. The field profiles must lie within certain bounds in order to meet the criteria imposed by the physics. The driving circuit design is complicated by the strong influence of the plasma on the circuit performance. The plasma appears to the driving circuit as time varying inductance and resistance. Since the inductance comprises from 20 to 80% of the total inductance, depending on the plasma configuration and the circuit, driving circuit performance is not easily calculated. The ZT-40 field requirements are presented and the proposed circuits are discussed. The modeling used to include the plasma as an electrical component with time varying inductance and resistance is described. The results of representative calculations are given.

Introduction

ZT-40 is a toroidal reversed field pinch being built at Los Alamos Scientific Laboratory. ZT-40 has been described in other papers presented at this symposium. In this paper, I want to discuss how ZT-40's circuits were designed.

The experimenters who will run ZT-40 have drawn up a set of operating criteria that they want the machine to meet. These criteria consist, in part, of certain programmed field risetimes, amplitudes and pulse lengths that the driving circuits must produce. The plasma in the torus has a strong effect on the driving circuits and this prevents the use of standard circuit theory for the driving circuit design.

There are several ways that the plasma affects the circuit action. The driving circuits are used to produce perpendicular magnetic fields. One field is in the theta direction and is designated B_θ. The other field is parallel to the minor axis of the torus and is denoted (by an abuse of notation) B_z. These fields produce currents in the plasma and the plasma thus acts as if it forms a pair of transformer secondary circuits, one transformer driven by the B_θ driving circuit and the other driven by the B_z driving circuit. The changing shape of the plasma appears to the external circuit as a changing inductance and resistance. The changing inductance causes L-dot voltages to appear so the plasma affects the circuits in a decidedly non-linear manner.

The changing inductance also results in a cross coupling between the driving circuits. Since one of the driving circuits is capable of changing the plasma configuration, it can change the inductance and L-dot voltage seen by the other circuit. This can so change the current in the latter circuit that it can fail to produce the desired magnetic field.

For these reasons it is necessary that the plasma be included as an electrical element in the design of the circuit.

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Magnetic field requirements for ZT-40

There are several possible operation modes for ZT-40. In the following, I will describe only four. Three correspond to relatively fast rise of the magnetic fields. These are the Matched Mode, the Standard Mode and the Padua Mode. The fourth made is a slow rise mode and is called Slow Mode 1.

Figure 1 shows the programmed fields needed for the Matched Mode. The rise in B_z from t_0 to t_2 is produced by the bias bank; this bank must be capable of driving the bias field to 0.6T. The B_θ field from t_1 to t_2 is the preionization pulse. The fast bank producing the B_θ field is fired at t_2 and must be capable of pushing B_θ to 0.6T at its crowbar time, t_4. The fast B_z-I_θ bank is fired at t_3 and drives B_z negative; this reverse field needs to be able to reach -0.5T. The B_z-I_θ bank is crowbarred at t_5.

This mode is called the Matched Mode because the B_θ and B_z field risetimes are about the same during the time following the firing of their respective driving banks.

The risetimes of the various fields are also prescribed. Table I lists the requirements on the banks. The most stringent of these are the risetimes and the $\dot{I}$ values.

TABLE I
Bank and Performance Requirements for Matched and Padua Modes

Bank	τ µsec	I MA	$\dot{I}$ initial A/s	B Max T
Bias (I_θ-B_z)	50-100	3.5	ns	≤ .6
Reverse (I_θ-B_z)	2-4	7.0	$5\times10^{11} \le \dot{I} \le 5\times10^{12}$	.6 to -.5
Main (I_z-B_θ)	≤2	7.2	$\ge 5\times10^{11}$	≤.6

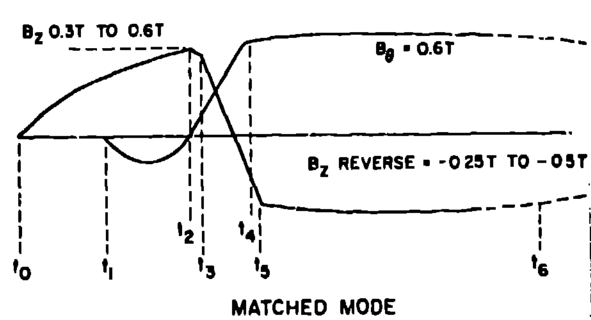

Fig. 1. Ideal Matched Mode magnetic field profiles.

The Standard Mode is very similar to the Matched Mode; the principal difference is that the reversing time of B_z is to be approximately twice as long as in the Matched Mode. Thus the timing diagram of Fig. 1 applies to the Standard Mode provided that the difference, t_5-t_3, is made about twice as long. From a circuit standpoint, this means that what works for the Matched Mode will work for the Standard Mode if extra inductance is added.

The timing diagram for the Padua Mode is shown in Fig. 2. T_0 is shown well ahead of the preionization bank fire time, t_1. This allows a bias field to be used if desired. The fast $I_\theta-B_z$ bank is fired at t_2; t_2 is chosen so that B_z will be a maximum at t_3. At t_3, nearly complete ionization of the plasma is assumed and the B_z field existing at that time is trapped inside the plasma. At the same time, the main bank (I_z-B_θ) is fired. It rises until it is crowbarred at t_4. The fast $I_\theta-B_z$ bank is crowbarred at t_5.

The three fast modes are intended to be power crowbarred. The present design calls for 10 kV banks to supply the power crowbar energy. These banks will also require crowbarring and t_6 in Figs. 1 and 2 corresponds to the firing of the $I_\theta-B_z$ power-crowbar crowbar switch.

The desirable field programming of the possible slow modes has not been completely defined. One possibility would be similar to that shown in Fig.3. This mode is designated Slow Mode I. In Slow Mode I, the $I_\theta-B_z$ bias bank is used to produce a bias field before the preionization bank provides a plasma. The I_z-B_θ power crowbar bank will be switched at this time to produce a long slowly rising pulse. Figure 3 is taken from computed results for one Slow Mode I circuit under consideration. The sudden end is due to saturation of the iron in the driving circuit transformers. In this example, the B_z field falls off too rapidly. This can be corrected by adding inductance to the B_z driving circuit.

Electrical circuit description

The external driving circuits used to calculate the Matched and Padua Mode performance are shown in Figs. 4 and 5. The bias bank consists of 170µF, 10 kV capacitors ignitron switched and crowbarred. It produces a slowly rising B_z field that is trapped inside the plasma at ionization time. Long cables provide isolation and connect it to the Mixer. The fast $I_\theta-B_z$ bank uses 1.65µF, 60 kV capacitors and is spark gap switched. It is connected to the crowbar switch header by low inductance cables. In the

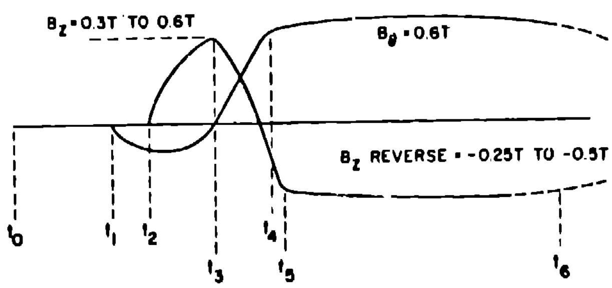

Fig. 2. Ideal Padua Mode magnetic field profiles.

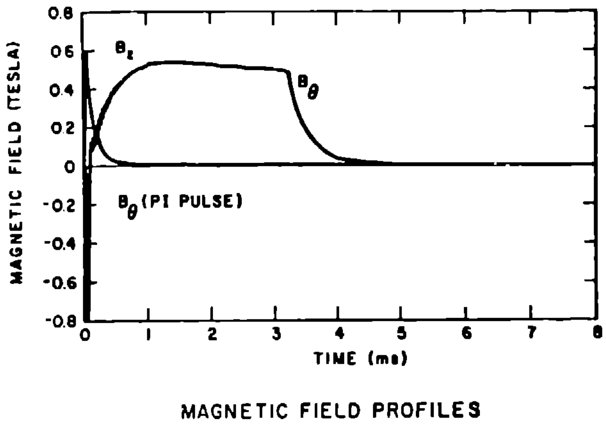

Fig. 3. Example of field profiles in Slow Mode I operation.

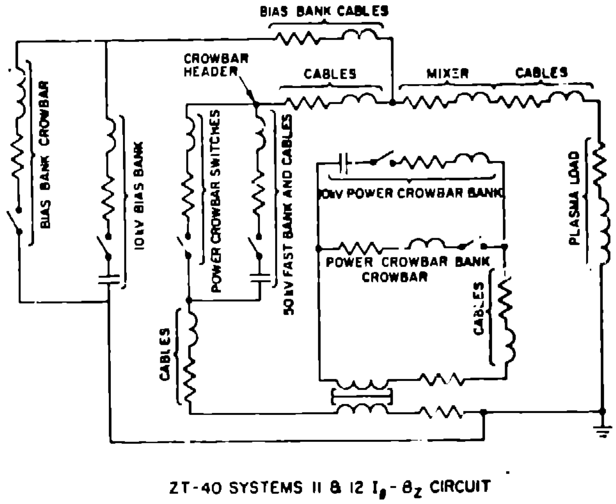

Fig. 4. Matched and Padua Mode $I_\theta-B_z$ circuit.

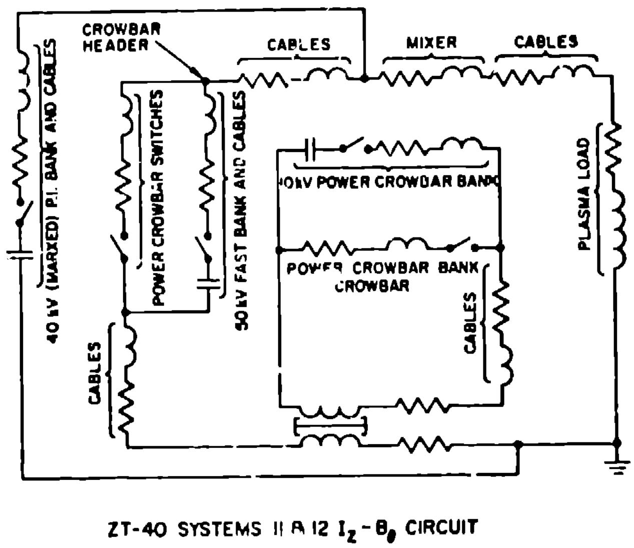

Fig. 5. Matched and Padua Mode I_z-B_θ circuit.

Matched and Standard Modes, this bank reverses that portion of the bias field that remains outside the plasma. The trapped field is, of course, not affected. In the Padua mode, this bank also produces all or most of the trapped field.

The fast bank is connected to the load through Hirano transformers.[1] The transformers couple slow high-capacity 10 kV capacitor banks to the load. These banks are both series- and crowber-switched by ignitrons.

The I_z-B_θ driving circuit is quite similar to the I_θ-B_z circuit. The 40 kV Marxed preionization bank takes the place of the bias bank but otherwise the circuits, except for values, are the same.

The problem of the circuit design for ZT-40 is to determine component values, i.e., capacity sizes, cable lengths, charge voltages and turns ratios, that are mechanically feasible and that will produce the desired programmed fields when driving the changing plasma load.

Electrical modeling of the plasma

The accurate modeling of the plasma is exceedingly difficult and the more accurate the model the longer will be the required computing time. On the other hand, too poor a model will not permit adequate circuit design.

The sharp boundary snowplow model represents a compromise. This model is very good during the initial stages when accurate estimates of risetimes and rates of rise are needed. During the late portion of the discharge its accuracy decreases because the physical plasma developes a difuse boundary.

The equation of motion for the snowplow model is:

$$r_p = \frac{\frac{r_p}{\mu_0 \rho_0}(B_{z_0}^2 - B^2 - B_z^2) + 2 r_p r_p^2}{(r_{p_0}^2 - r_p^2)}$$

B_{z_0} is the value of the bias field trapped by the preionization of the gas; ρ_0 is the gas fill density and r_{p_0} is the initial radius of the plasma. Since $r_{p_0} = r_p$ at preionization time, a small value is added to the denominator to remove the singularity. The value used is 10^{-9} which, in this case, amounts to assuming that the plasma implosion starts at 0.2 microns from the discharge tube wall.

The sharp boundary model allows the inductance of the plasma load and its L-dot contributions to be calculated by the formulas:

$$L = \mu_0\left(\sqrt{R^2 - r_c^2} - \sqrt{R^2 - r_p^2}\right)$$

$$\dot{L} = -\frac{\mu_0 r_p \dot{r}_p}{\sqrt{R^2 - r_p^2}}$$

$$L_z = \mu_0 R \ln\left(\frac{r_w}{r_p}\right)$$

$$\dot{L}_z = \frac{-\mu_0 R \dot{r}_p}{r_p}$$

here R is the major radius of the torus, r_c is the coil radius and r_w is the inside radius of the Z-pinch primary. The formulas for L_z and $\dot{L}_z$ are approximations in that the plasma and Z-pinch primary are treated as if they form a straight coaxial line.

A temperature-dependent resistance based on the classical Spitzer resistivity is also assumed. Using the resistivity

$$\frac{1}{\sigma} = \frac{653}{T_e^{3/2}}$$

the differential equation for the electron temperature (in ^{0}K) is:

$$\frac{dT_e}{dt} = \frac{2T_e}{r_p} \dot{r}_p + \frac{2}{3} \cdot \frac{653\, I^2}{\kappa N_e\, r_p^2\, T_e^{3/2}}$$

where

$$I^2 = I_z^2 + I_\theta^2$$

I_z is assumed to be uniformly distributed over the discharge and I_θ is assumed to be uniformly distributed between r_p and $r_p/2$. A temperature of 1.5eV is assumed to be produced by the preionization bank.

The plasma resistances are given by:

$$R_z = \frac{2\times 653}{T_e^{3/2}} \times \frac{R}{12\, r_p^2} \quad \text{(per sector)}$$

$$R_\theta = \frac{653}{R \ln 2\, T_e^{3/2}} \quad \text{(total).}$$

Since it is known that this resistance model is very poor, the actual coding allows the Spitzer resistance to be multiplied by an arbitrary factor. This allows a qualitative estimate of the importance of the plasma resistance to be made. Checks have shown that large variations in this factor have minimal effect on the circuit performance.

Circuit modeling

The electrical circuits have already been shown in Figs. 4 and 5. The modeling of the electrical components is standard except for the transformers and the main crowbar switches. The transformer model used allows for the saturation of the transformer iron but not for hysteresis or core losses. The modeling is described elsewhere.[2] The core losses are negligible compared to the resistive losses in the rest of the system. Omitting hysteresis is not expected to cause error since the iron will be returned to the same point on the hysteresis loop before each shot.

Since the main crowbar switches can have a determining role on the behavior of the machine after crowbar closure, the resistance associated with them is determined from a current dependent arc drop. The resistance is determined by a formula of the form:

$$R = \frac{k_1}{|I|+1} + k_2 + k_3|I| \quad .$$

This is consistent with the findings of Kesselring.[3] The values of the k_i are chosen to give an arc drop of 100 v at 5 KA, 108 v at 10 KA and 150 v at 100 KA. These values were chosen to agree with a preliminary measurement on the gap proposed for use in ZT-40.

Two choises were available for the programming of the system. One was the use of a circuit design code such as NET 2 while the other was the direct FORTRAN programming of the differential equations. NET 2 was tried first because it allows easy changes in the circuit topology. However run times were found to be prohibitively long so ease of circuit change was sacrificed in favor of the direct programming approach. Running times became over a factor of 1000 shorter. This difference is felt to be due primarily to the non-linearity introduced by the plasma and therefore should not be considered typical of NET 2 on more standard circuits.

Representative results

The present component design values were arrived at by first using the computer code to set rough overall values that would result in acceptable fields and field risetimes. Then values for the various components were estimated and inserted in the code. If these values did not work the components were changed. Sometimes this meant moving the position of a bank to change the inductance of the associated cabling and sometimes a component might be mechanically redesigned to change its electrical characteristics.

The present values reflect a number of iterations of modifing components and then readjusting the other components to ultimately give acceptable wave forms.

Generally speaking, the procedure was a success. Figure 6 shows the computed performance for one case of Matched Mode Operation. The full time history is shown in part a and a time magnified portion showing the critical region from PI firing to I_θ crowbar is given in part b. This run was made for a deuterium fill at 20 mtorr. The compression ratio was approximately 1.5. The bias rises in 77 μs to a peak current of 3.44 MA (B_z=.6T). The main I_z-B_θ bank rises in 1.9 μs to a peak current of 704 KA per sector (B_θ=.6T). The initial rate of rise is 6.07×10^{11} A/s. The I_θ bank is fired slightly after the I_z bank (0.8 μs) and has an initial I-dot of 4.64×10^{12} A/s. At the time the I_θ crowbar is fired the reversed field has reached -0.5T. The reverse field bank reaches this value in 2.3 μs. All these values are within the original specifications give in Table I.

The oscillation on both fields after power crowbar time is due to the oscillation of the preionization bank which is part of the I_z-B_θ circuit. The presence of the plasma reduces the inductance seen by the bank and thus increases the oscillation frequency. The oscillation is transmitted through the plasma motion via the changing inductance into an oscillation in the I_θ-B_z circuit.

Figure 7 shows computed magnetic field plots for the Padua Mode. These also fall within the required performance limits.

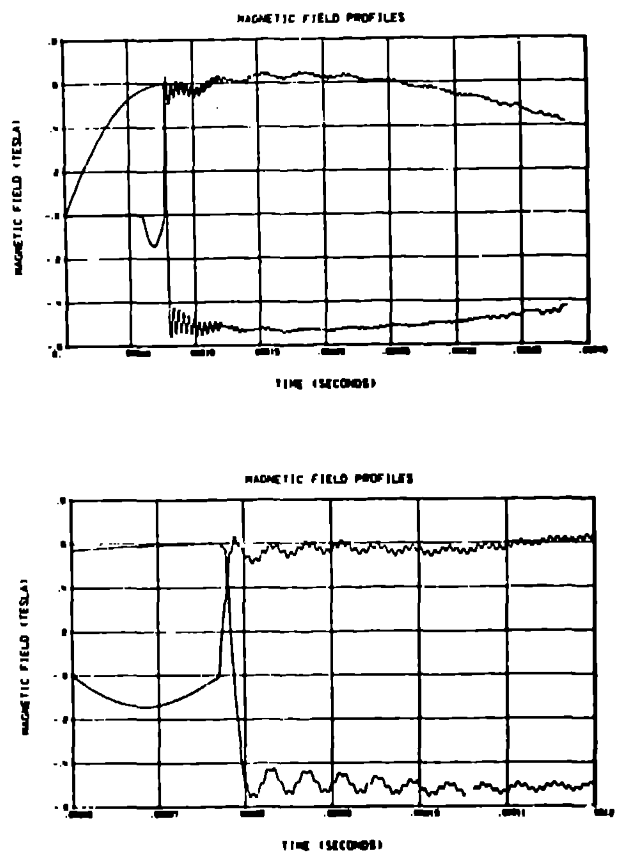

Fig. 6. Computed Matched Mode magnetic field profiles a). full traces, b). magnification of region from P.I. firing through main crowbar switch closures.

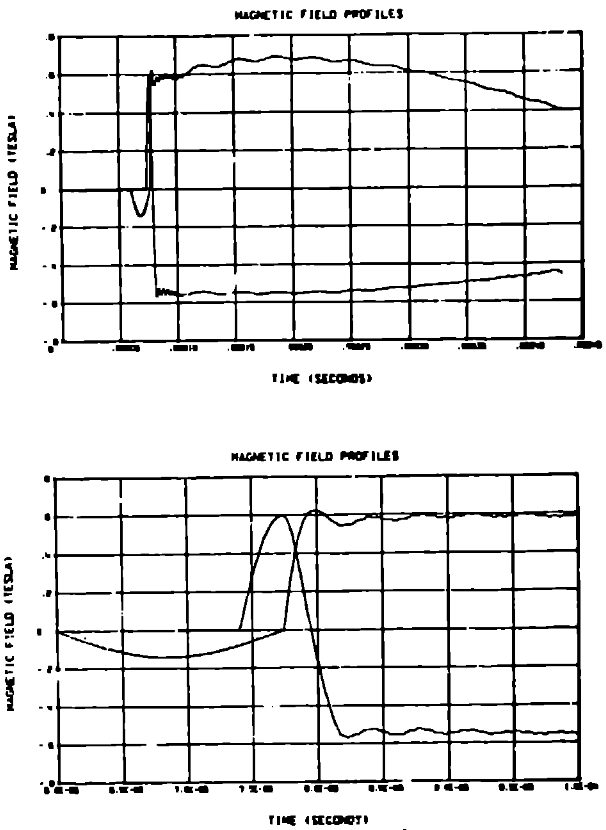

Fig. 7. Computed Padua Mode magnetic field profiles a). full traces, b). magnification of region from r.l. firing through main crowbar switch closure.

Summary, conclusions and future work

The proper design of ZT-40 required the inclusion of the plasma as an electrical component in the circuit since it has major influence on the action of the circuit. The design was carried out using a snowplow model for the plasma motion with Spitzer resistivity determining the plasma resistance. Satisfactory designs have been achieved for the Matched, Standard and Padua Modes.

Circuit design for slow mode operation is continuing. This work is partly exploratory since hard criteria for slow mode operation have not been set. An effort to upgrade the plasma model from the sharp boundary snowplow model to some sort of diffuse boundary model will be made. This improvement is needed since it is known that the snowplow does not describe the plasma in its late stages and thus is not at all good for slow mode work.

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