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ENGINEERING FEASIBILITY EVALUATION OF A PERISTALTIC PINCH

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ABSTRACT

A recent proposal for reducing the end loss of a linear theta pinch is to produce moving magnetic mirrors at the coil ends. The concept entails the sequential pulsing of an axially arranged series of two-turn coaxial coils. The electrical design of such a system presents some unique problems.

Ideally, the individual pulse circuits should be completely independent. This would facilitate the design by eliminating interactive effects. In practice, the circuits must be interconnected through isolating inductors to enable the production of a uniform biasing magnetic field. Moreover, the coils must be located physically close together. This produces strong magnetic coupling between the pulse circuits, which can seriously affect the shape and speed of the inward-moving magnetic-mirror field.

Possible systems were modeled for the NET-2 circuit analysis code. The models took account of the inductive coupling between the individual circuits in the model.

The results show that an increasing magnetic mirror can be produced provided the radius of the theta pinch is not too great compared to the intercoil spacing. The peristaltic field can be maintained for several cycles in the inner coils. The voltage hold-off requirements on the pulse circuit switches are found to be severe, but not impossible to meet.

I. INTRODUCTION

Peristaltic compression has been proposed by Burke¹ to increase the compression ratio and decrease the end losses of a theta pinch. These end losses occur because the theta-pinch field is predominantly axial and the field does not act on plasma moving parallel to it. Therefore, plasma moving toward the ends is unimpeded by the field and streams out the ends of the pinch. The end losses can be reduced by placing magnetic mirrors at the ends of the theta-pinch coil. Coils positioned at the ends of a linear theta pinch are energized synchronously to produce a magnetic field that moves axially toward the center of the system. Plasma blobs would be formed from part of the outward, axially streaming plasma and reinjected into the central portion of the discharge tube. The peristaltic pinch concept is not new. A similar system was

discussed by Tuck² in 1966. However, there appears to have been no evaluation made of this idea from the standpoint of the practical electrical circuit requirements. The following describes an evaluation of a system similar to that required by Burke.

The system evaluated was assumed constructed of presently available capacitors and spark gaps. The evaluation was made by modeling the system using the NET-2 circuit analysis code.³

II. DESCRIPTION OF THE SYSTEM

The system proposed by Burke employs 40 two-turn coils at each end of a linear one-turn theta-pinch coil. Each individual coil is of 0.64-cm-diameter wire and has a radius of 5 cm with the center-to-center separation between the turns being 0.95 cm. The coils are spaced along the axis on centers

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spaced 2.54 cm apart. Coils at one end are connected in series with symmetrically positioned coils at the opposite end. This insures that, at the very least, these coils will operate in phase. The system chosen for analysis was the Burke system without the central theta-pinch coil. Before programming the complete system, a preliminary study was carried out on 1/8 of the system. The 1/8 system circuit is shown in Fig. 1. The combination S1, C1, and L1 represents a 10-kV bias bank composed of 170- μ F capacitors. It is used to match the central coil field. The components S2 and L2 represent a crowbar for this bank. The horizontal inductors on the left, labeled L101, L201, ..., L102, are isolating inductors used to prevent the short-circuiting of the pulsing currents by the slow bias bank.

The system of 10 peristaltic coils is represented by the vertical inductors L11, L21, ..., L12. The power source for the peristaltic coils consists of the spark gaps, inductors, and capacitors designated (S31, L3, C31), ..., (S35, L7, C35). The capacitors are single, standard 1.85- μ F, 60-kV units. The inductance values were chosen to correspond to the combined inductance of one such capacitor in series with a standard Scyllac-type spark gap. The switches in these circuits are closed sequentially to produce the wave.

The 1/8 system circuit was studied first because positive answers from it would make further study unnecessary. Thus, if the proper traveling magnetic intensity can be achieved on this short system, in spite of the greater end-to-end mutual inductive coupling, then it can certainly be achieved on the full system. Also, it is much easier and cheaper to learn the idiosyncrasies of this type of circuit using a small version.

III. QUESTIONS TO BE ANSWERED

The study was proposed to provide answers to a number of questions about the action of the circuit. The most important thing to know about the system is whether or not it is possible for the peristaltic circuits to act independently enough to produce the required inward moving magnetic intensity wave. The close positioning of the coils results in substantial mutual inductance coupling between these circuits and this could be sufficient to prevent the formation of the wave. Given that the wave can be produced, we need to know how small the isolating inductors can be before significant degradation of the wave occurs and how much voltage the unfired spark gaps in the peristaltic current must hold off. This voltage will be greater than the capacitor charge voltage because of inductively induced emf's from the fired circuits. A final question is how long can the initial phase relation between the peristaltic circuits be maintained. For an actual plasma experiment, the initial phase relation needs to be held approximately, and for about three cycles.

IV. COMPUTATIONAL DETAILS

In the circuit of Fig. 1, each two-turn coil is shown as a single inductor. To code the system

Fig. 1. One-eighth system NET-2 circuit model.

for NET-2, the effective inductance of the coil and its effective mutual inductance to every other peristaltic coil in the system needs to be calculated. The coil self-inductance can be found from the matrix relations

$$\begin{bmatrix} L_{11} & L_{12} \\ L_{21} & L_{22} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \end{bmatrix} = \begin{bmatrix} \phi_1 \\ \phi_2 \end{bmatrix}.$$

This applies to the individual turns in a single coil. These are here arbitrarily denoted 1 and 2.

The flux through the coils is, by definition,

$\phi_{\text{coil}} = L_{\text{coil}} I_{\text{coil}}$. The coil flux is the sum of the flux through the turn turns

$$\phi_{\text{coil}} = \phi_1 + \phi_2,$$

and the coil current is

$$I_{\text{coil}} = I_1 + I_2.$$

Since $I_1 = I_2$ because of the series connection of the turns, solution yields:

$$L_{\text{coil}} = 1/2(L_{11} + L_{12} + L_{21} + L_{22}). \quad (1)$$

For non-coincident coaxial coils (i.e., $i \neq j$), L_{ij} is calculated quite accurately by the formula for circular loops,

$$L_{ij} = \mu_0 \sqrt{r_i r_j} \left\{ (2/k - k) K - 2/k E \right\}, \quad (2)$$

where

$$k^2 = 4 r_i r_j / \{ (r_i + r_j)^2 + (z_i - z_j)^2 \}; \quad (3)$$

K = complete elliptic integral of the first kind,

E = complete elliptic integral of the second kind,

r_i = radius of the i^{th} loop,

z_i = axial position of i^{th} loop.

For a self-inductance of a single loop, Kirchoff's approximate formula was used,

$$L_{ii} = \mu_0 r_i \left\{ \ln \frac{8r_i}{a} - 1.75 \right\},$$

a = the radius of the conductor.

The coefficients of coupling between the peristaltic coils can be found from

$$m_{\alpha\beta} = M_{\alpha\beta} / \sqrt{L_{\alpha} L_{\beta}}; \quad (4)$$

$M_{\alpha\beta}$ is the mutual inductance between coil α and coil β . The values of L_{α} and L_{β} are found from formula (1). The mutual inductance is

$$M_{\beta\alpha} = \phi_{\beta} / I_{\alpha};$$

this is the ratio of the flux in circuit β due to current in circuit α . For a system of four turns, we have the relation

$$\begin{bmatrix} L_{11} & L_{12} & L_{13} & L_{14} \\ L_{21} & L_{22} & L_{23} & L_{24} \\ L_{31} & L_{32} & L_{33} & L_{34} \\ L_{41} & L_{42} & L_{43} & L_{44} \end{bmatrix} \begin{bmatrix} I_{\alpha}/2 \\ I_{\alpha}/2 \\ I_{\beta}/2 \\ I_{\beta}/2 \end{bmatrix} = \begin{bmatrix} \phi_{\alpha 1} \\ \phi_{\alpha} \\ \phi_{\beta 1} \\ \phi_{\beta 2} \end{bmatrix}.$$

Here the first two-turn coil contains turns 1 and 2, while the second coil contains turns 3 and 4. Each turn carries one-half the total coil current. The total flux in the second circuit, ϕ_{β} , is equal to the sum $\phi_{\beta 1} + \phi_{\beta 2}$. Carrying out the matrix multiplications and using the fact that we are concerned only with the flux in circuit β due to I_{α} .

$$\phi_{\beta} = \phi_{\beta 1} + \phi_{\beta 2} = (L_{31} + L_{32} + L_{41} + L_{42}) I_{\alpha}/2$$

$$\text{and } M_{\beta\alpha} = 1/2(L_{31} + L_{32} + L_{41} + L_{42}). \quad (5)$$

The L_{ij} are computed using formula (2). The values of $m_{\alpha\beta}$ were calculated from (3) and used as input to NET-2.

The criterion chosen to evaluate circuit performance was the magnetic field on the axis. The field was assumed to be generated by line current loops positioned at the center of each turn. Thus, each two-turn coil was treated as two loops. The axial field is given by

$$B(z) = \frac{\mu_0}{2} \sum_{i=1}^{\text{No. of turns}} \frac{I_i r_i^2}{(r_i^2 + (z - z_i)^2)^{3/2}}. \quad (6)$$

For a fixed z position, this reduces to a weighted sum of the currents

1/2 No. of coils

$$B(z) = \sum_{\alpha=1} W_{\alpha} I_{\alpha}. \quad (7)$$

If the center of the coil system is chosen as the origin, the W_{α} is given by

$$\frac{\mu_0 r^2}{2} \left\{ \frac{1}{(r^2 + (z - z_1)^2)^{3/2}} + \frac{1}{(r^2 + (z - z_2)^2)^{3/2}} + \frac{1}{(r^2 + (z - z_3)^2)^{3/2}} + \frac{1}{(r^2 + (z - z_4)^2)^{3/2}} \right\}$$

where the subscripts 1 and 2 refer to the two turns of a single coil at one end and 3 and 4 refer to the two turns of the symmetrically positioned coil at the other end. Use of these precomputed weights reduces the work required of NET-2 and also saves space in the computer.

V. RESULTS OBTAINED ON THE ONE-EIGHTH SYSTEM

The initial set of runs established that the size of the isolating inductors had negligible shunting effect on the action of the peristaltic inductors provided the isolating inductors were 2 μH or

larger. Two microhenries is approximately 5 times the total self-inductance in a single peristaltic circuit. A peristaltic field effect was also observed. This effect decreased as the firing times of the peristaltic circuits were brought closer together. Figure 2 gives a set of plots of the B field on the axis for peristaltic circuit firings set at $\Delta t = 300$ ns apart. The crest of the wave does not move at a speed corresponding to the firing times but the changing slope results in an inwardly moving wave, which would push plasma toward the center. Figure 3 is a similar set of plots for the

Fig. 2. Axial magnetic field intensity produced with 300 ns spacing between closings of the peristaltic circuit switches in the 1/8 system.

Fig. 3. Axial magnetic field intensity produced with 100 ns spacing between closings of the peristaltic circuit switches in the 1/8 system.

case where the spacing between firings is set at $\Delta t = 100$ ns. Here an in-moving wave is also evident, but it is very shallow. A standard mirror coil set at the end of the theta pinch could probably do better.

It was postulated that the rapid rise of the field at the center, which results in the loss of the wave trough, was due to the strong mutual coupling between the coils. If so, this effect could be reduced by using a longer peristaltic system.

The effect of the coupling could be checked on the 1/8 system by increasing the radius of the peristaltic coils. This was done by increasing the coil radii to 10 cm. The result was that the magnetic field rose as if the coils were driven by a common source. No peristaltic effect was noticeable. A set of curves of magnetic field intensity for this case is shown in Fig. 4.

This result shows that this type of system depends critically on the coupling coefficients. If the coefficients are too large the machine will not work. Thus, proper operation depends critically on flux leaking out between coils. This is in contrast to a normal theta pinch where no leakage is assumed. Therefore in designing a system, care must be taken in placing other components near the peristaltic portion since, if the components are metal, they may reduce the leakage flux by blocking it.

1/8 PERISTALTIC SYSTEM $\Delta t = 100$ nsec
20cm DIAMETER COILS

Fig. 4. Axial magnetic field intensity produced with 100 ns spacing between closings of the peristaltic circuit switches in a 1/8 size system using 20-cm-diameter peristaltic coils.

VI. LARGER SYSTEMS

The 1/8 system model had shown that the peristaltic concept had promise but that the system was not long enough to allow a series of inward-moving waves to be formed. To see this effect better, as well as to answer the remaining questions about the system, it was necessary to model a larger system.

A model was made of the full system. This model did not attempt to include all of the 3120 mutual couplings between the peristaltic inductors. Instead, only those coefficients greater than 0.00115 were retained. The attempt to solve the system failed because it was too large for the NET-2 program.

The full system was first halved and then quartered before a successful computation could be made. Some further experimentation showed that all the couplings in the 1/4 system could be included provided the amount of output required was kept small. The 1/4 system used all 191 mutual couplings between peristaltic inductors--the smallest coupling coefficient was 0.000699. The resulting NET-2 code was large enough that the introduction of a single additional x variable card resulted in a storage overflow.

A schematic of the 1/4 system model is shown in Fig. 5. Since the 1/8 system had settled the question concerning the size required for the

Fig. 5. One-quarter system NET-2 circuit model.

isolating inductors, the 1/4 system was modeled using current generators instead of the capacitor banks intended for use in an actual experiment. This resulted in a speed-up of the computation by eliminating the integration necessary to build up the bias current in the coils.

The central magnetic field produced in the 1/4 system, when the spacing between firings (Δt) of the peristaltic circuits was 100 ns, is shown in Fig. 6. The scale is different from that used for the 1/8 system due to the increased coil length. A comparison with Fig. 3, taking into account the scale differences, shows that the 1/4 system produces a wave shape with firings spaced at $\Delta t = 100$ ns, which is comparable to the shape of the 1/8 system wave with $\Delta t = 300$ ns. The speed of the 1/4 system wave is, as expected, at least twice that of the 1/8 system wave.

Figure 7 shows a longer time history of the magnetic field intensity for the 1/4 system with $\Delta t = 200$ ns. This shows the reversal of the field and advance of the next intensity wave.

A direct extrapolation can be made to a longer system by use of this data. Such an extrapolation to a full length system is somewhat pessimistic because the longer system is less affected by the

Fig. 6. Axial magnetic field intensity produced with 100 ns spacings between closings of the peristaltic circuit switches in the 1/4 system.

Fig. 7. Axial magnetic intensity produced with 200 ns spacings between closings of the peristaltic circuit switches in the 1/4 system model.

mutual inductances from the opposite end, even though there are many more interactions. Thus, the extrapolation made from Fig. 7 and shown in Fig. 8 is worse than could be expected from the real system. It shows that in the full length system there is always an in-moving point of high field intensity somewhere along the tube.

Two questions remain to be answered. Concerning the peristaltic switches, NET-2 runs showed that the hold-off voltage required of the spark gaps in the peristaltic circuit was approximately 90 kV. Since

Fig. 8. Estimation of the axial magnetic field intensity that could result* in a full system extrapolated from the results shown in Fig. 7.

the hold-off time is short (less than 5 μ s), this is probably within the capability of a standard Scyllac-type gap.

Concerning the maintenance of the proper phase relation between the individual peristaltic circuits, long computer runs have shown that adequate independence is sustained between the circuits for more than the three cycles required for a test of the concept.

VII. SUMMARY

This study has shown that it should be possible to construct a peristaltic pinch. The components assumed for this study are already available and hence no development should be required. The peristaltic action should be maintained for at least three cycles of peristalsis.

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