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A Magnetic Mirror Field System for Reb-Plasma Interaction Experiment

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ABSTRACT

A pulsed 1:2 ratio mirror magnetic field system for REB-Plasma interaction experiments is described. Magnetic field design aimed at an axisymmetric field configuration in 30 cm plasma chamber extending over an axial distance of 1.5 m, with uniform field over 50 cm in the central region and rising smoothly at ends to double the field value at the centre. Design procedures are described.

The field coils connected in series are powered by a condenser bank consisting of 6 nos. of 14 μF 20 KV condensers connected in parallel. The condenser bank is discharged through the coils by means of ignitrons end in order to obtain a long duration magnetic field, an ignitron connected across the field coils is used to crowbar the circuit near the peak of the discharge current.

The magnetic field field measurements confirm the design.

1. Introduction

In the relativistic electron beam (REB) - Plasma interaction experiment at Physical Research Laboratory, the plasma is to be confined in a mirror magnetic field for durations of the order of tens of milliseconds. In this note we describe a pulsed 1:2 ratio mirror magnetic field system which has been designed and fabricated for this purpose. Magnetic field design aims at an axysymmetr configuration in a plasma chamber of 30 cm diameter extending over an axial distance of 1.5 m, with field nearly uniform over 50 cm distance in the central region and rising to double its value at the centre towards both the ends. The magnetic field configuration is also symmetric around vertical axis passing through the centre of plasma chamber.

2. Design Procedure & Construction.

The design procedures are based on the minimisati n of a weighted sum of the squared deviations from the desired field profile and the power dissipated in the coils for a given coil configuration. Such a minimisation yields a set of simultaneous equations, which in certain special cases turn out to be linear, depending upon the parameters with respect to which the linearisation is carried out. Such simultaneous equation can then be solved to obtain the desired parameters.

Let us consider a system having N coaxial coils and let us choose M points along the axis of these coils where the desired field strength is specified. Let us also specify the position of the centres of each of the coils on the axis and set down a procedure for calculations for those values of ampere-turns in each of the coils which yield best-fit to the specified field configuration. In the following the coils carry an index n and the points at which the desired field is specified, carry on index m. If the desired field at point m is designated by H_m , then the deviation d_m from this field is given by

$$d_m = H_m - \sum_{n=1}^{N} i_n h_{nm} \qquad \dots \quad (1)$$

where i_n is the current in amperes through n^{th} coil and h_{nm} is a geometrical factor which gives magnetic field produced at point m by n^{th} coils from a unit current following through it. If r_{nm} represents the distance between point m and centre of n^{th} coil, along the axis, then we may write [1].

$$h_{nm} = \frac{0.2\pi\, \eta_n a_n^2}{(r_{nm}^2 + a_n^2)^{3/2}} \qquad \dots \quad (2)$$

if the coils under consideration has winding depth & width which are much smaller than its radius. Here η_n is the number of turns in the coils and a_n its radius. For coils having finite width and depth we have[1]

$$h_{nm} = \frac{\eta_n a_{in}}{2b_n(a_{2n}-a_{in})}\left[\frac{F(\alpha_n,\beta_n+\gamma_{nm})+F(\alpha_n,\beta_n-\gamma_{nm})}{2}\right]$$

where

$$F(\alpha_n,\beta_n) = \frac{4\pi\beta_n}{10}\ln\frac{\alpha_n+(\alpha_n^2+\beta_n^2)^{1/2}}{1+(1+\beta_n^2)^{1/2}} \quad \ldots(3)$$

Here $\alpha_n = a_{2n}/a_{in}$ is the ratio of outer radius a_{2n} to the inner radius a_{1n} and $\beta_n = b_n/a_{1n}$ is the ratio of the half-width b_n to the inner radius. If ρ_n represents the resistance of the n^{th} coil, the power dissipated in the n^{th} coil is given by

$$P_n = i_n^2\rho_n \quad \ldots \quad \ldots(4)$$

we can now construct a function χ^2 defined as

$$\chi^2 = \sum_{m=1}^{M} W_m d_m^2 + \sum_{n=1}^{N} W_p i_n^2 \rho_n \quad \ldots(5)$$

which essentially represents a weighted sum of the squared deviations from the specified field configuration at all test points and the power dissipated in all the coils. When the function χ^2 is minimised with respect to a set of parameters, the resulting values of those parameters yield a configuration giving best fit to the specified field profile and the procedure also results in optimising the power dissipation.

Minimisation with respect to currents $i_n = 1, N$, leads to a set of equations

$$\partial\chi^2/\partial i_n = 0 \;;\; i_n = 1, N \quad \ldots(6)$$

which can be solved to obtain currents in different coils placed at known positions. Using equations (1) and (5) the set of equations represented by (6) may be rewritten as

$$\frac{\partial^2 \chi^2}{\partial i_j} \equiv -2 \sum_{m=1}^{M} W_m H_m h_{jm} + 2 \sum_{m=1}^{M} W_m h_{jm} \sum_{n=1}^{N} i_n h_{nm} + 2 W_p \rho_j i_j = 0 \; ; \; j = 1, N \quad \ldots (7)$$

or alternately

$$\sum_{\substack{n=1 \\ n \neq j}}^{N} i_n A_{jn} + i_j A_{jj} = C_j \; ; \; j = 1, N \quad \ldots (8)$$

where

$$\left.\begin{aligned} C_j &= \sum_{m=1}^{M} W_m H_m h_{jm} \\ A_{jn} &= \sum_{m=1}^{M} W_m h_{nm} h_{jm} \\ A_{jj} &= \sum_{m=1}^{M} W_m h_{jm}^2 + W_p \rho_j \end{aligned}\right\} \quad \ldots (9)$$

All the equations in the set of simultaneous equations represented by (8) are linear in currents i_j, $j = 1, N$ and can be solved to obtain values of currents for different coils. The set can be also represent in the matrix form as

$$[A] \times [I] = [C] \qquad (10)$$

where $[A]$ & $[C]$ are NXN matrices having elements given by equation (9) and $[I]$ is the N-element column vector having currents i_j, $j = 1, N$ as its elements. Equation (10) can then be solved to obtain $[I]$ as follows:

$$[I] = [C][A^{-1}] \quad \ldots \quad \ldots (11)$$

where $[A^{-1}]$ is the inverse of matrix $[A]$.

As an alternate to minimising χ^2 with respect to currents, one could carryout minimisation with respect to ampere-turns for each coil.

The minimisation was carried out using a Fortran programme, based on the logic outlined above & developed for designing axi-symmetric magnetic field systems. The desired field profile was achieved by an iterative procedure which involved adjustment of coil positions and calculating ampere-turns in each coil, alternately. The deviations at test points were all given equal weights and similarly all the power terms were given equal weights. However, the weights W_p were always chosen smaller than the weights W_m and a certain amount of optimisation was necessary in the ratio of W_p to W_m to obtain the desired fit with optimal power dissipation.

For the purpose of designing, the field strength at test points was taken as a parabolic function of the axial distance of the test point from the centre. The axial profile which emerged from the minimisation along with the test field profile are shown in Fig.1.

The system which evolved from such a design procedure (Fig.2) consists of 28 nos. of 40 cm inner diameter 5 cm wide coils. The number of turns in each coil was adjusted such that current required is same for all the coils. The coils were made by binding 2.5 cm wide copper tape into the centre and out again to form a 5 cm wide double-pancake coil. From this configuration a field strength of 1.5 K. Gauss/K. Amp. can be obtained at the centre.

3. Power supply and switching system.

All the coils are connected in series and are powered by a condenser bank consisting of 6 nos. of 14 μF 20 kV condensers connected in parallel. The condenser bank is charged by a constant current source. The charging is done automatically initiated by a trigger pulse and the voltage level to which the bank charges can be preselected. Details of the charging circuit are given elsewhere[2]. It essentially consists of a variable auto-transformer (variac) coupled to a low r.p.m. reversible motor. The A.C. voltage from this variac is stepped up and rectified by a high voltage rectifier circuit which powers the condenser bank. Voltage at the bank is sensed and compared with the present voltage. At the time of coincidence the power input to variac is cut-off, the control motor is reversed and bank-triggering circuit awaits a triggering pulse.

The condenser bank is discharged through the field coils by means of Ignitron switch connected between the condenser bank and the field coils, and triggered by the trigger pulse (Fig.3). In order to obtain a long-duration slowly decaying non-oscillatory field, another Ignitron connected across the field coils is used to crowbar the circuit near the peak of the discharge current. The trigger pulse for the crowbar Ignitron is generated from the bank discharge trigger pulse through an appropriate delay circuit. The magnetic field then decays from its peak value with an e-folding time $\sim L/R$, where L is the inductance of the field coil system and R, the resistance of the circuit.

The field coil system placed around the stainless steel vessel, is fed from the condenser bank by means of an air cored co-axial cable. The total inductance of the system is estimated to be $\sim$7.0 mH. The capacitor bank, having 84 μF capacity, when charged to 20 kV, the maximum permissible voltage, is capable of delivering a peak current of 2.5 K Amps in the field coils. Thus maximum field strength which can be attained with this configuration is 3.75 K Gauss at centre and 7.5 K. Gauss at the mirror ends. Higher fields can in principle be obtained, limited by the strength of the coil bindings and supporting structure, by increasing the capacitance in the capacitor bank.

The field coils have a total resistance of $\sim 0.1\,\Omega$ and hence by crowbaring, the magnetic field can be made to decay from its peak value with an e-folding time $\sim$70 m secs.

4. Results.

The measurements of the magnetic field confirm to the values estimated on the basis of design data. A magnetic field of $\sim$1.5 Gauss/Amp is obtained at the centre.

Fig.4 (a) shows typical current pulse when the condenser bank is discharged through the field coil system without triggering the crowbar Ignitron. Fig. 4 (b) gives the time profile of the current when the crowbar Ignitron is triggered near the peak of the current pulse. The current is found to decay with an e-folding time $\sim$75 m sec. It is observed that positioning of the trigger pulse for the crowbar Ignitron, critically determines the time profile of the current decay as well as its repeatability.

References:

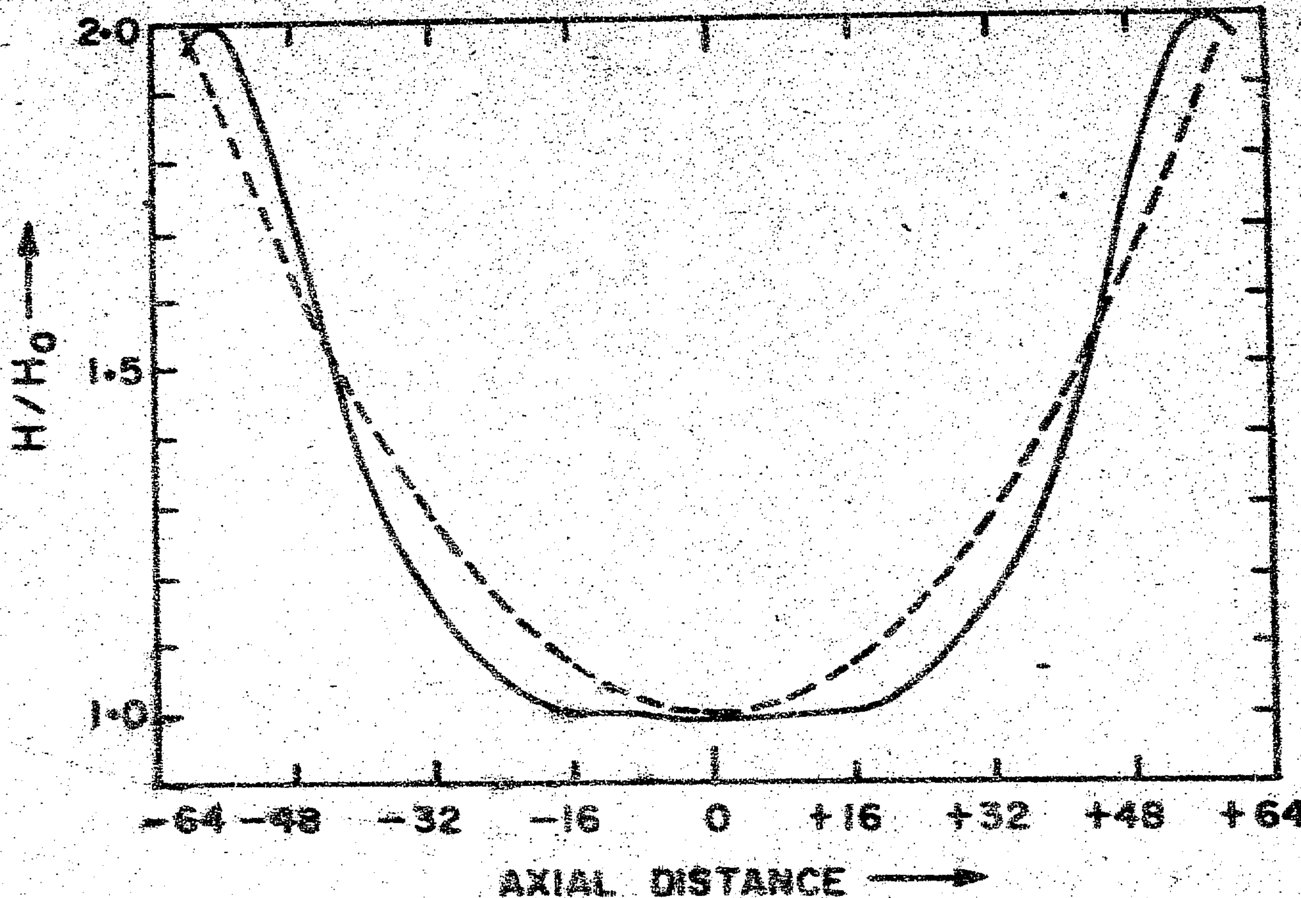
1. D.B. Montgomery; Solenoid Magnet Design; (M.I.T. Press: Cambridge, Mass.)
2. K.S. Lali & Y.C. Saxena: PRL Technical Note No.TN-79.

Fig.1 Field profiles for a 1:2 ratio magnetic mirror configuration. Dashed curve is the parabolic profile assumed for the design purposes and solid curve is the profile obtained through the fitting.

Fig.2 Coil configuration, obtained from the fitting, for 1:2 ratio magnetic mirror system. This configuration produces a field of 1.5 Gauss/Amp at the centre.

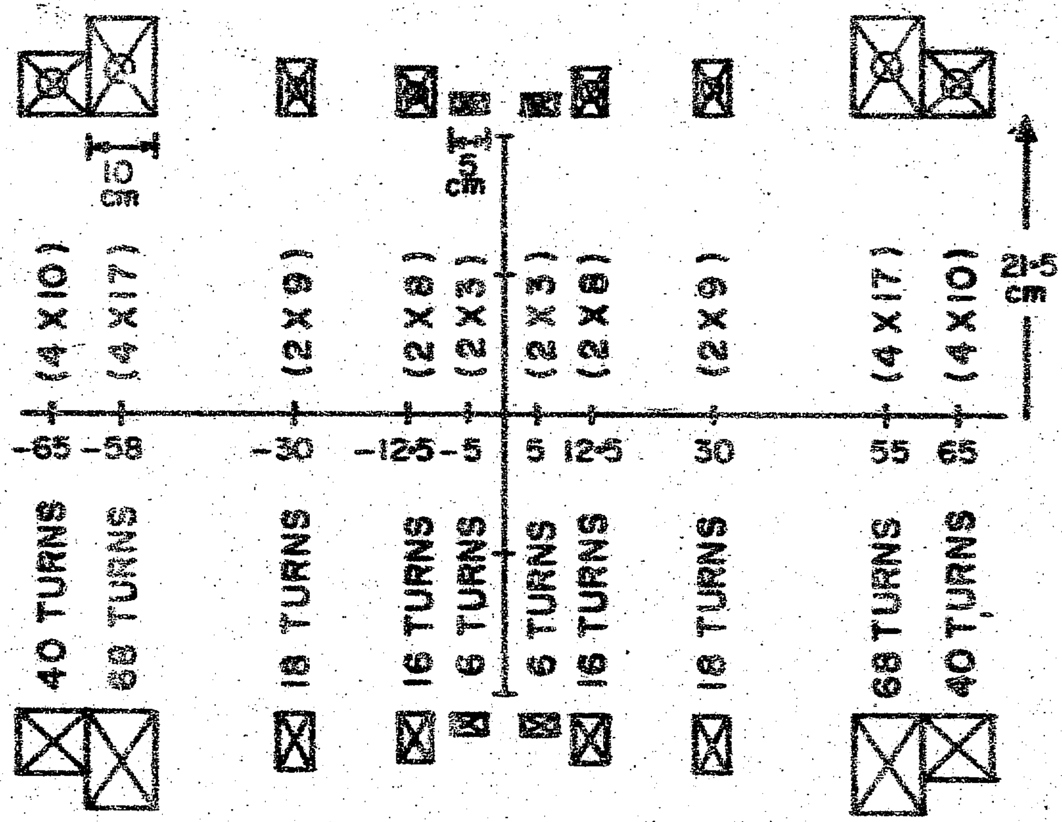
Fig.3 Power and switching system for the field coils.

Fig.4 Time profiles for the currents flowing through field coils. a) current without crowbar, b) current with crowbar Ignitron triggered near the peak value of the current.



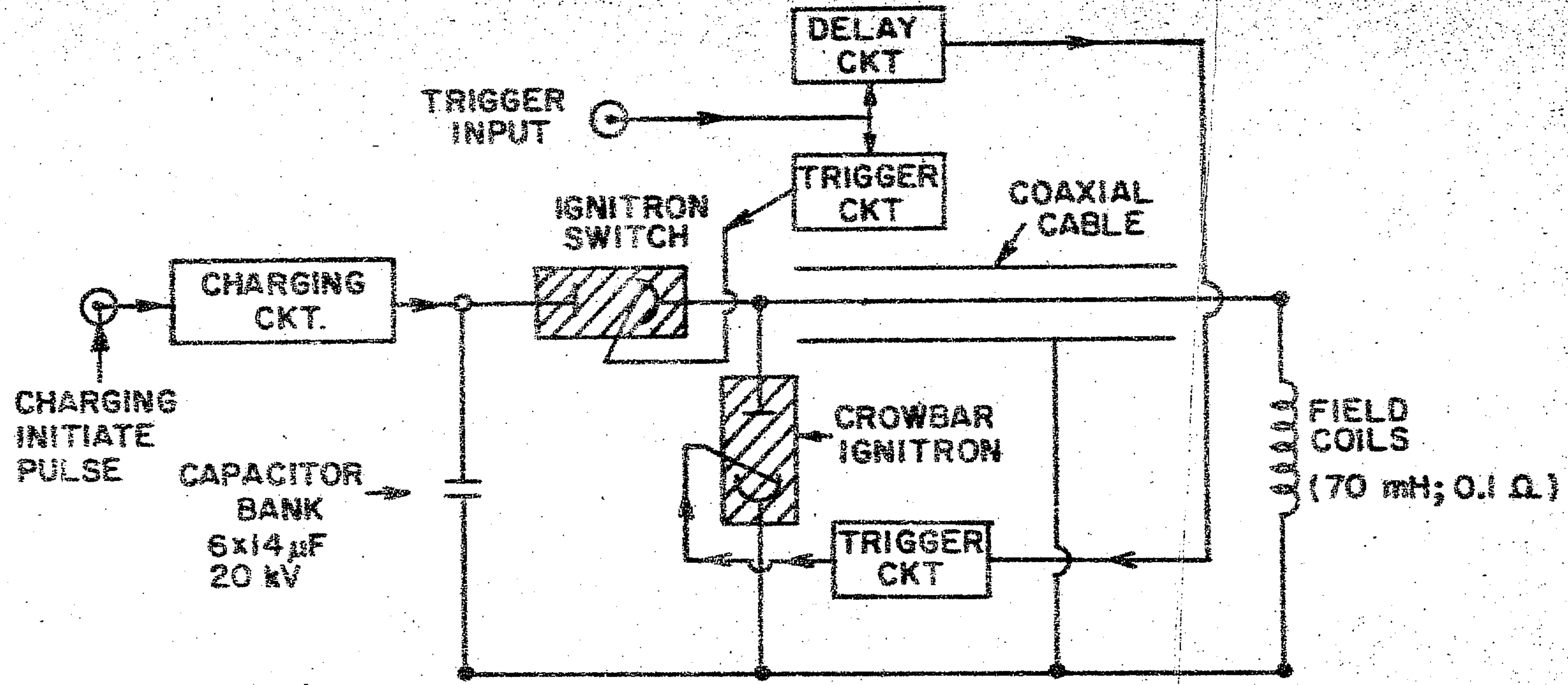
<u>1:2 MAGNETIC MIRROR FIELD PROFILES</u>

DASHED CURVE IS THE DESIRED PROFILE AND FULL CURVE PROFILE OBTAINED FOR CALCULATED AMPERE-TURNS OF FIELD COILS



COIL CONFIGURATION FOR (1:2) MAGNETIC MIRROR FIELD

3 KG FIELD AT CENTRE FOR 2KA CURRENT



POWER AND SWITCHING SYSTEM
FOR FIELD COILS

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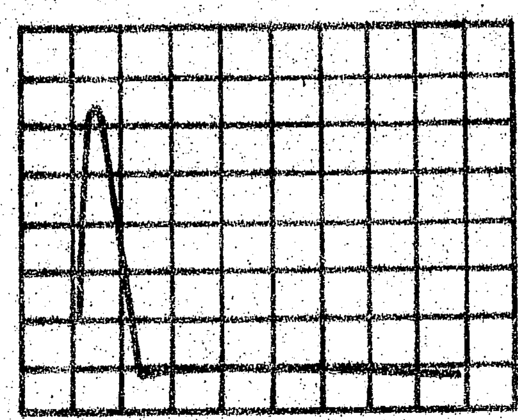
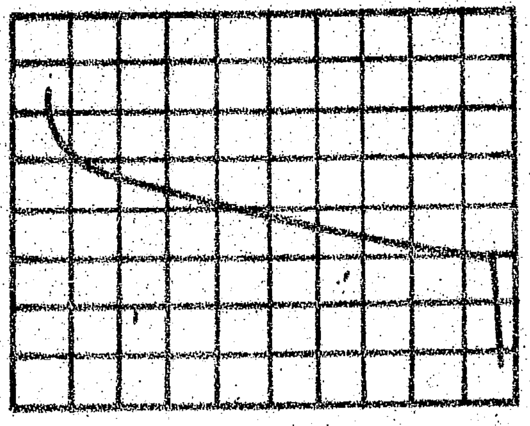


Current through magnetic field coils without crow-bar. Vertical scale 100 Amp/div. Horizontal scale 2 mSec/div.



Current through magnetic field coils when the crow-bar circuit is triggered near the peak. Vertical scale 100 Amp/div. Horizontal scale 5 mSec/div.