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OPTIMIZATION OF A MAGNET CIRCUIT DESIGN FOR A CYLINDRICAL MASS SPECTROMETER

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1.0 INTRODUCTION

This report summarizes the results of an optimization effort to achieve a minimum weight configuration for a magnetic section circuit (MSC) used in the magnetic portion of a double-focusing mass spectrometer.

A prototype magnetic circuit which had been designed and fabricated on a previous contract was found to provide the required magnetic field uniformity. However, the basic approach for controlling the magnetic leakage field involved boundary matching techniques which were not efficient. Compensation magnets, which were introduced into the magnetic circuit at the outer sector boundaries, actually increased the total amount of magnetic flux outside the active focusing zone. In effect, the unused portion of magnetic flux occurring in the fringing fields external to the structure was being supplied by a major fraction of the compensation magnet material (see Figure 1). Consequently, a weight penalty had been incurred from these sources of flux leakage.

To circumvent the flux leakage problem, we have reconsidered the MSC circuit as an enclosed magnetic circuit. In this scheme, flux leakage is inhibited by arranging compensator magnet pairs between the main wedge magnets and an outer magnet sleeve (general-purpose steel) as shown in Figure 2. The triangular-shaped compensator magnets, having alternating radial magnetization orientation as indicated by the arrows, are ideally suited for developing the radial magnetomotive forces which match perfectly the magnetic potential variation with azimuthal angle associated with the wedge magnets. For the ideal system having true radially and azimuthally magnetized magnet components, no flux passes into the outer ferrous sleeve because the compensation magnets are designed to operate at the normal coercivity point ($B = 0$, $H = H_c$). However, given the monodirectionality of the rare-earth cobalt magnet materials, some field distortions can be expected in fabricated structures. These departures from the ideal field production patterns are expected to be most severe with designs having few (4 or less) wedge magnets.

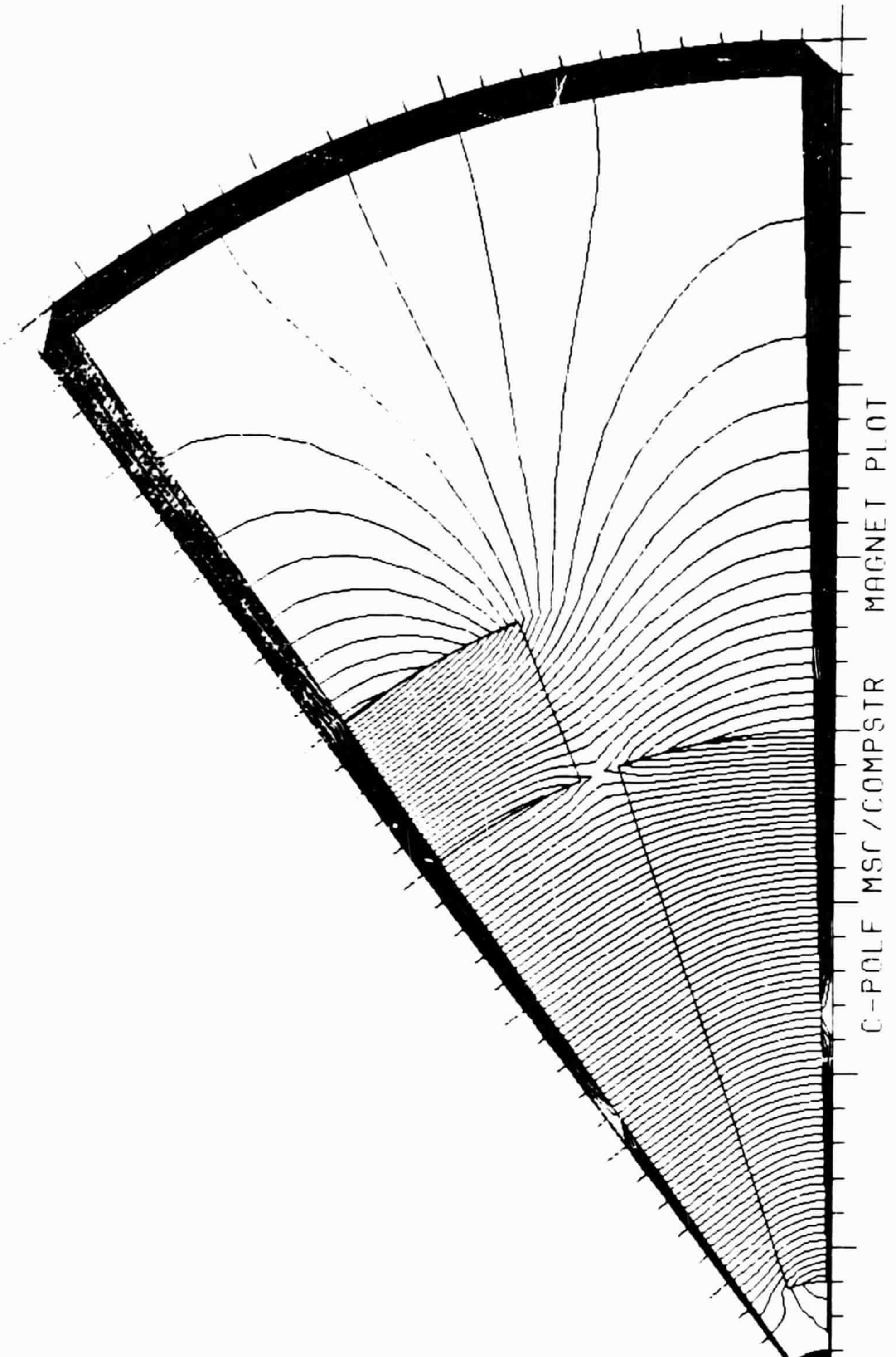

Figure 1. Flux Plot for a Magnetic Sector Circuit with Original Flux Compensator Magnet.

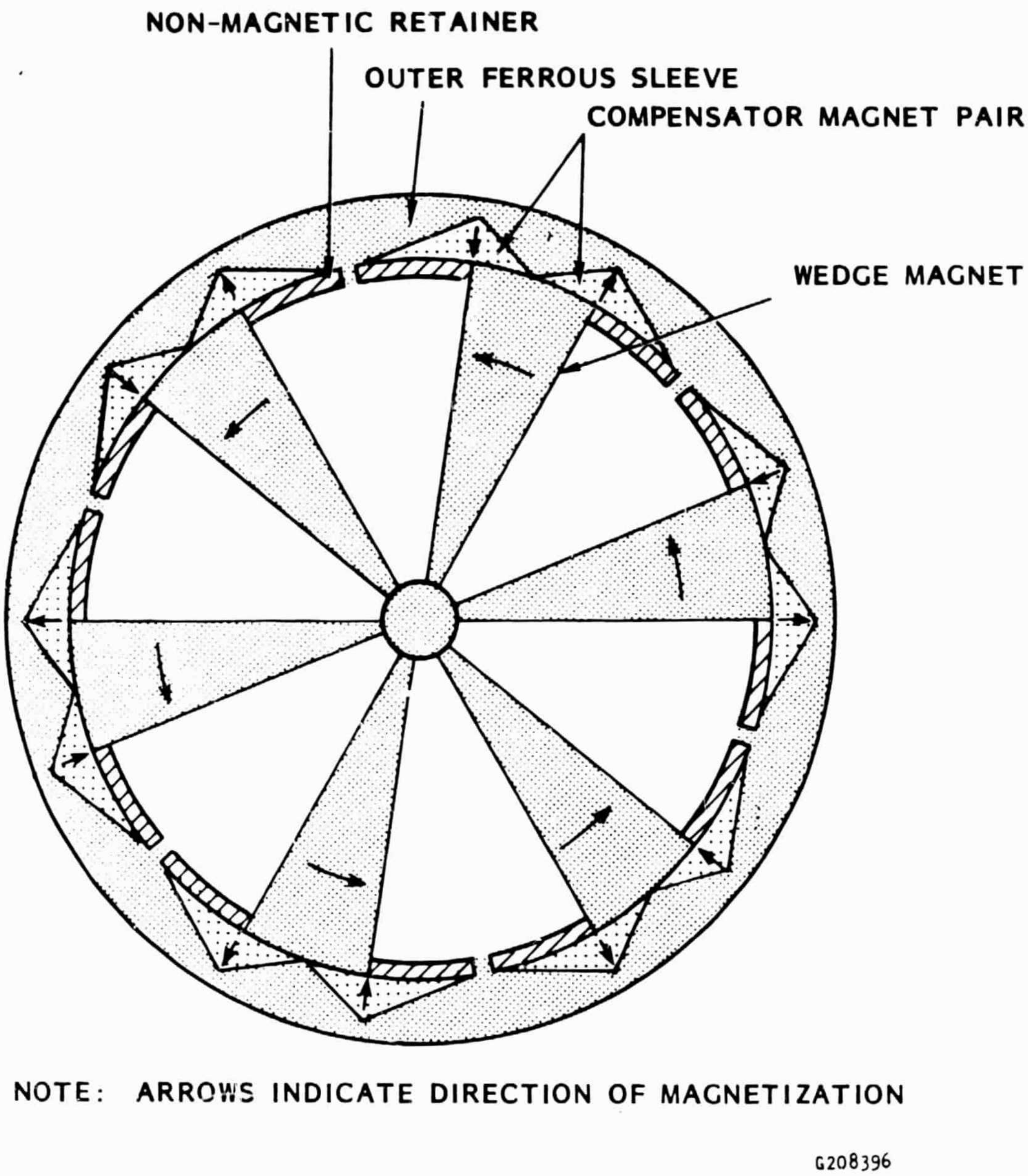

Figure 2. Magnetic Sector Circuit with New Boundary Matching Structure. 63% Transparency Factor Design.

Weight saving is derived from two sources. First, the compensator magnets are substantially smaller than the earlier design and second, the magnetic outer shell serves a dual role as a mechanical support structure as well as a mechanical housing for the compensator magnets.

Another feature to recommend the new conceptual approach to the MSC structure, in addition to the more compact design, is the ability to provide a selectable combination of peak magnetic field and ion-transmission, transparency factor. A simple formulation of the "optimum" design parameters enables us to preselect the magnetic focusing field level for differing ratios of the gap to magnet wedge angles for a given set of magnetic materials (see next section).

2.0 MAGNET CIRCUIT DESIGN FORMULATION

In this section, we indicate a method for choosing the compensator magnet dimensions for the "optimized" MSC design. The working model for this analysis is shown schematically in Figure 3 for a polar sector containing one half period of this rotationally symmetric structure. In the representation, the left-hand and right-hand boundaries are at the same magnetic potential as the outer magnetic sleeve, and the wedge magnet face (part way along the vector r_m in Figure 3) is coincident with a maximum potential surface as drawn.

Assuming that the permanent magnet material is magnetized everywhere to the same magnetization level, M, then we may derive a simple expression for the magnetic field in the gap in terms of the fraction transparency parameters, f_g:

$$f_g = |\theta_g|/(|\theta_g| + |\theta_m|) \qquad (1)$$

where θ_g is the angular separation between magnet faces in the vacuum gap and θ_m is the angular width of a wedge magnet. From the conservation of flux ($\tilde{\nabla} \cdot \tilde{B} = 0$) and from the vanishing curl of the field intensity ($\tilde{\nabla} \times \tilde{H} = 0$) for a steady-state system

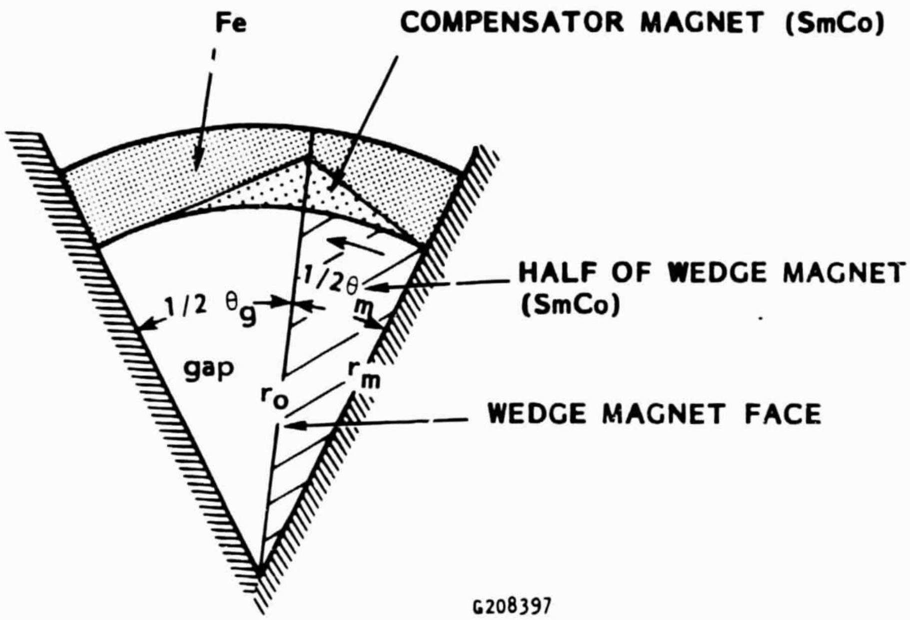

Figure 3. Geometrical Layout of an MSC Sector.

with negligible convection current, we may show that the magnetic flux density in the gap is uniform and has a value:

$$B = (1-f_g)\ 4\pi M \qquad (2)$$

To arrive at this expression, we have used the relation (emu):

$$B = H + 4\pi M, \qquad (3)$$

where, for an "ideal" permanent magnet, M is independent of the flux density, B, over the range of interest in the second quadrant of the hysteresis loop (assuming SmCo material). The magnetization, $4\pi M$, is assumed to be equal to the remanent flux density.

Now, we may obtain an expression for the radial thickness, h, of the compensator magnet with:

$$h \equiv r_o - r_m, \qquad (4)$$

where r_m is the radial location of the wedge magnet and r_o is the extreme radial location of the compensator magnet in the plane of the wedge magnet face (Figure 3). Using the same magnetostatic arguments as before, the following relationship is derived (assuming $B_r = 0$ everywhere):

$$h = \frac{1}{2} r_m\ \theta_m\ f_g\ (1 - f_g) \qquad (5)$$

A plot of the cofactor to the magnet azimuthal arc length is shown in Figure 4. The maximum magnetic energy supplied to the gap occurs at a value of 0.5 for the transparency factor. Magnetic efficiency remains high even to a transparency factor value as high as 0.7 (70% transparency).

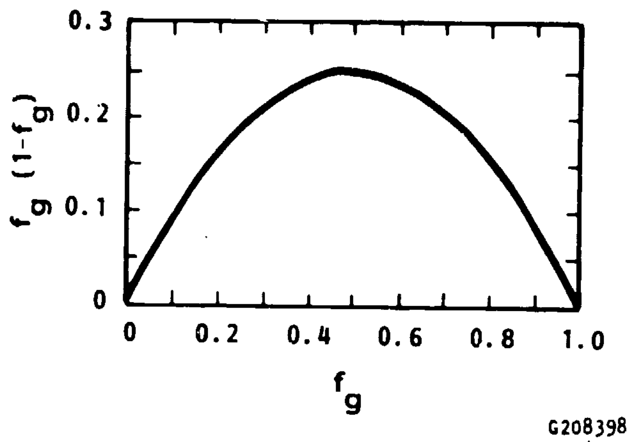

Figure 4. Co-Factor Plot.

3.0 MAGNETIC CIRCUIT ANALYSIS

To verify the validity of the formulation of the previous section, we have performed simulations in polar coordinates, assuming that the structure has infinite extent in the axial direction. Setting the magnization level at 0.9 T, we obtained a gap field of nearly 0.45 T in the case of 50% transparency and 0.27 T in the case of 67% transparency. Flux plots for these two cases are reproduced in Figures 5 and 6, respectively. (Staircased representation of the compensator magnet results from the limitation of the simulation code for which boundaries must coincide with the radial columns and azimuthal rows of the relaxed Liebmann net.) These plots correspond to a six-pole design with a four-inch outer diameter at an axial plane where the diameter of the wedge magnet aperture is 0.8 inches.

While the simulation shows signs of incomplete relaxations after 5000 iterations, the flux density tabulations indicate clearly the basic effectiveness of the compensator magnets in suppressing leakage flux in the radial direction. Thus, the results of the computer calculations confirm the flux confinement properties as well as the height determination, Equation 5.

4.0 WEIGHT SAVING

Weight reduction for the compensator magnet is approximately a factor of two relative to the earlier MSC design at 50% transparency. No weight saving otherwise is to be derived except with the more compact structural confinement afforded by the outer "soft" magnet shell. How much weight saving is a matter of overall system consideration, not proper to this design study.

5.0 RECOMMENDATIONS

The new conceptual methods for suppressing flux leakage is sufficiently general, permitting a range of flux levels and transparency factors for the magnetic sector circuit for use in a double-focusing mass spectrometer. Furthermore, the

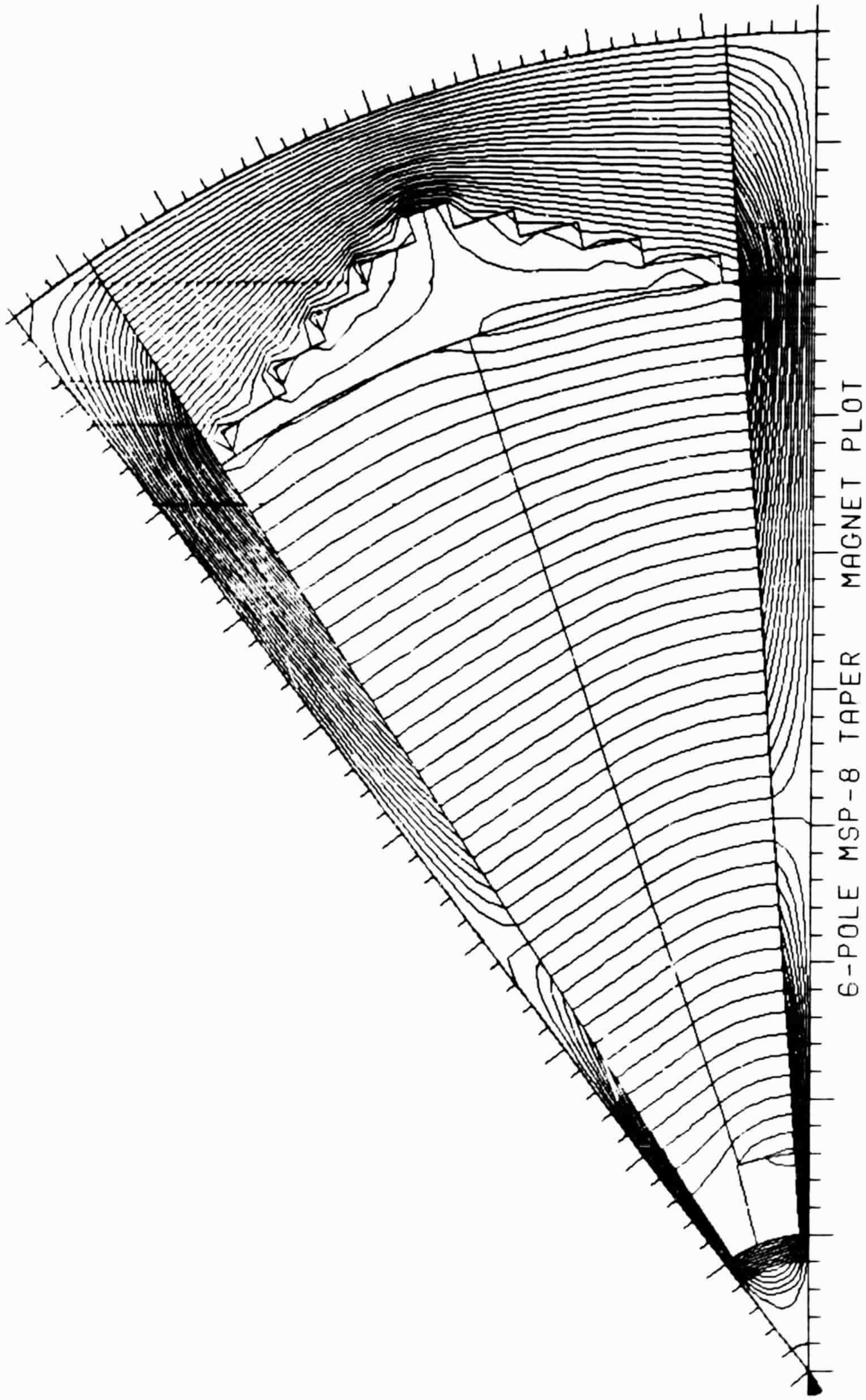

Figure 5. Flux Plot of a Simulated MSC Sector (50% Transparency).

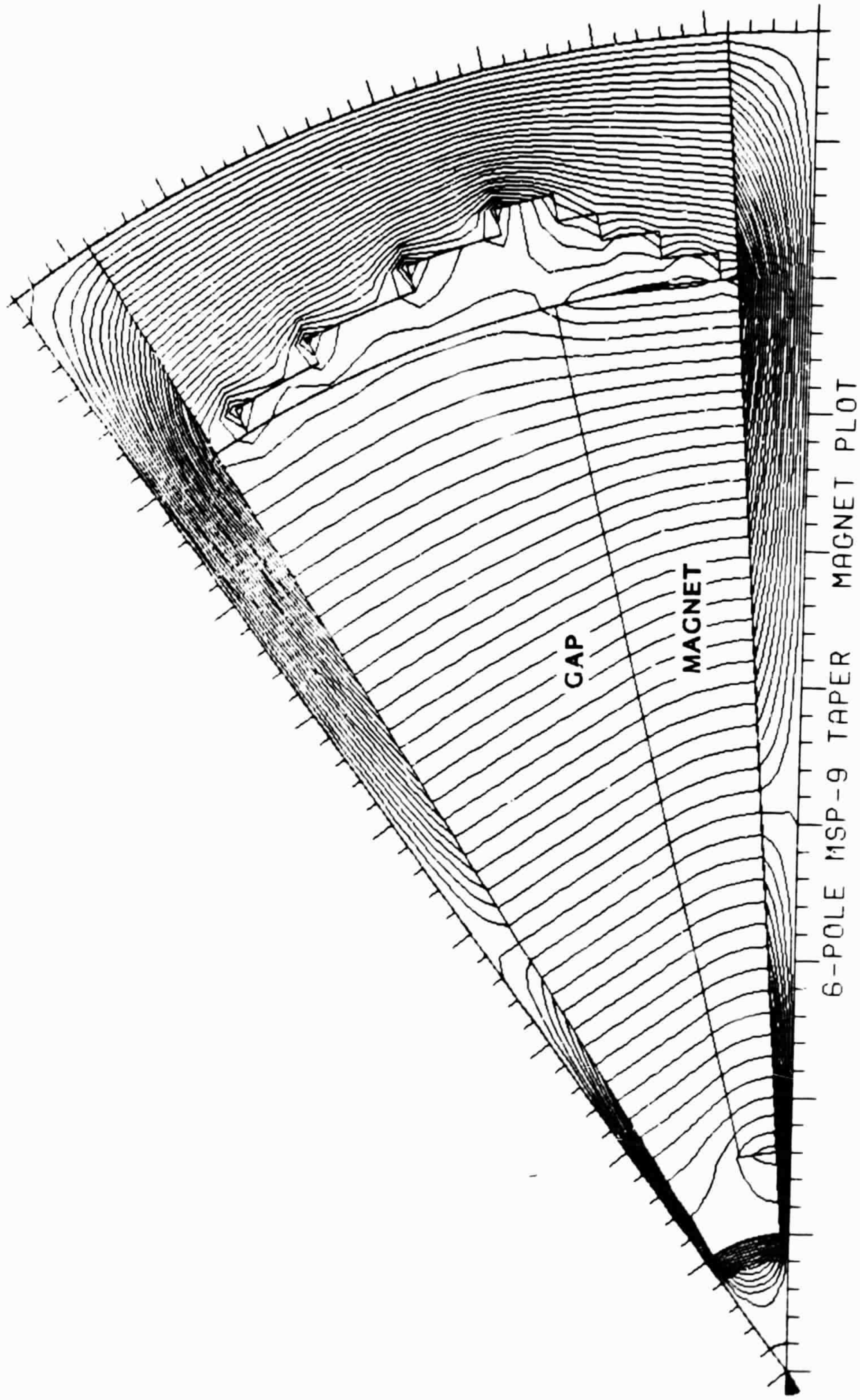

Figure 6. Flux Plot of a Simulated MSC Sector. (67% Transparency)

mechanical fabrication of the new configuration is not expected to complicate assembly significantly (aside from the fabricational cost which is expected to be larger). Thus, a lighter weight and more compact MSC structure appears workable.

Design of the detailed parts, assembly fixtures, and test fixtures should be considered as the next step following decisions concerning the number of poles, transparency factor and magnetic field level.