A magnetically self-shaping septum for beam deflection*

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ABSTRACT

Septum magnets for deflecting charged particles at $\beta \geqslant 0{\cdot}5$ were developed with deflection strength equivalent to that of an electrostatic deflector with a gradient exceeding 200 kV/cm. Composed of thin-current-carrying sheet conductors, they are self-shaping and assume the same radius of curvature as the beam to be deflected when the end-points are properly adjusted. The maximum field reduction obtained is limited mainly by the tensile strength of the septum and by the power that can be removed from the thin sheet conductors. As an example of the design, a one-kilogauss unit for the Oak Ridge Isochronous Cyclotron (ORIC), in which $\beta \leqslant 0{\cdot}38$, will operate at 4000 A. The water-cooled septum is 4 cm wide and 0·3 cm thick; the 1-cm section centred in the beam is thinned to 0·075 cm. The radial aperture is 1·8 cm; an equivalent electrostatic deflector would require nearly 200 kV across this gap. A conventional electrostatic septum could also be made to conform to the beam shape; requiring only a few amperes, this could substantially increase the extraction efficiency.

1. INTRODUCTION

The first element in most extraction systems is an electrostatic deflector, followed by some form of magnetic channel,[1,2] when required. If large extraction efficiencies are to be achieved, the septum of the deflector must be thin and properly shaped and positioned. The material in the septum for a conventional electrostatic deflector is usually tungsten, tantalum, copper, or, as in the case of ORIC, graphite. Residual radiation in the septum and its ability to dissipate large amounts of power mainly influence the choice of material. For example, a water-cooled copper septum is capable of removing large amounts of power and operates at modest temperatures. The residual activity in the copper septum

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will be much larger than that in the graphite septum for a given beam loss. The septum is usually shaped to fit an orbit calculated from field measurements.

In fixed energy machines and in cyclotrons with programmed orbits, and operating at fields below saturation, the beam path is fixed. But in variable-energy variable-particle cyclotrons, such as ORIC, the optimum shape may vary substantially. Because of increased hill saturation in ORIC in changing from 20-MeV to 65-MeV protons, the radius of curvature of a large portion of the septum must be changed several cm by means of an external drive.

A magnetic channel was developed with a septum as thin as that usually found in electrostatic systems. An all-magnetic extraction system can operate at low voltages and can function in smaller magnetic gaps than that required for an electrostatic system. The current in the magnetic channel can be regulated and controlled so as to maintain a precisely established deflected beam path.

2. DESIGN CONSIDERATIONS

2.1 *Electrostatic vs magnetic deflection*

The relative strengths of electrostatic and magnetic deflectors may be expressed by:

Gradient, in kV/cm = $300B\beta$, where B is in kG and $\beta = v/c$.

Therefore, protons at 53 MeV will be deflected equally well by a 1 kG magnetic field or by an electrostatic gradient of 100 kV/cm, as shown in Fig. 1. For energies above 53 MeV, the magnetic field equivalent to the 100 kV/cm gradient decreases until only 0·5 kG is required for 320-MeV protons.

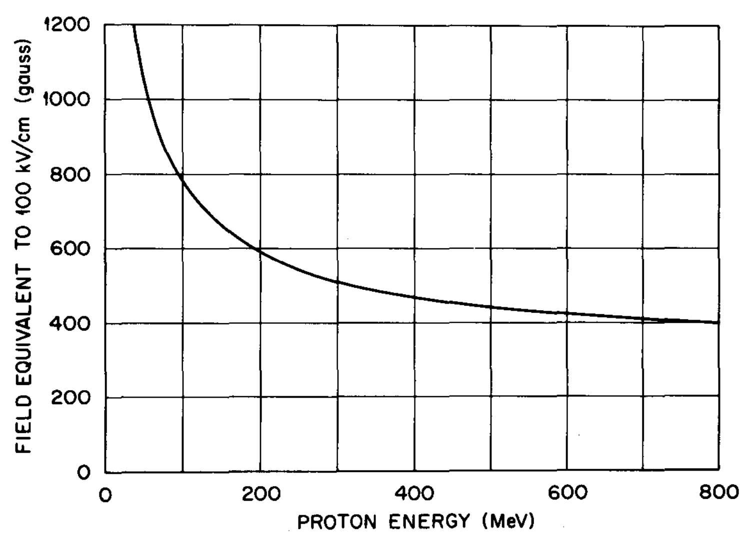

Fig. 1. Magnetic field equivalent to a 100 kV/cm electrostatic gradient vs proton energy

2.2 *Magnetic fields from sheet conductors*

Computer program MAGMAP[3] was used to calculate the magnetic fields produced with 4-cm wide sheet conductors in several configurations, see Fig. 2.

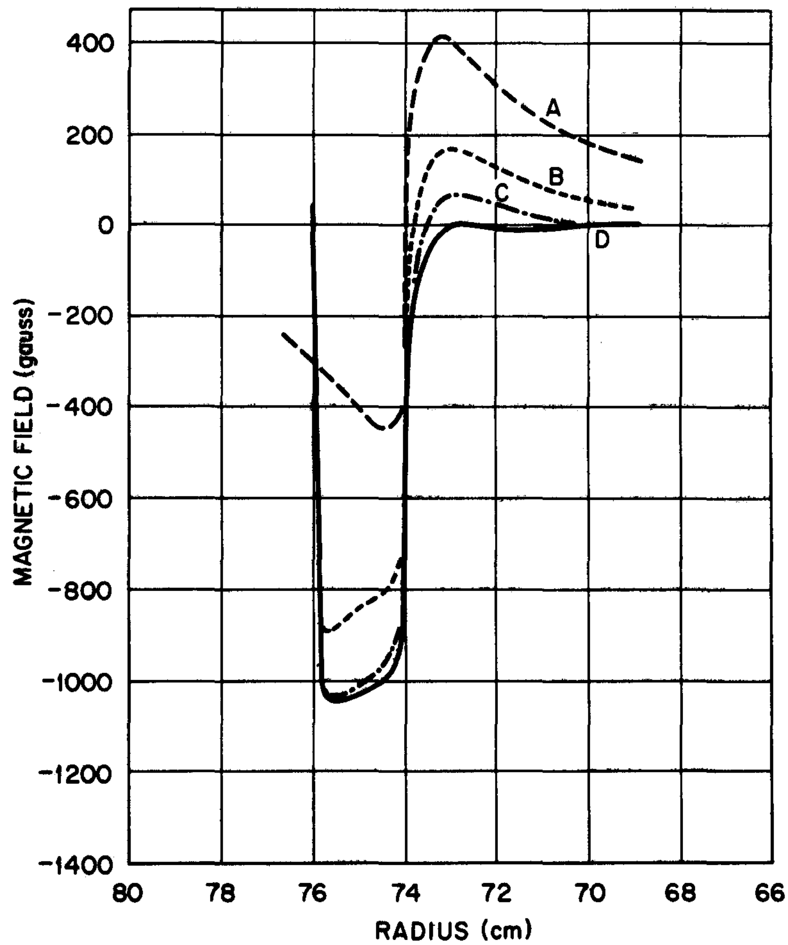

Fig. 2 (A) Field vs Radius for a 4-cm wide conductor operating at 4000 A; (B) for a pair of the above conductors spaced 2-cm;,(C) for the same pair with a pair of 2000 A compensating coils; and (D) for the above conductors with a second pair of three-turn 255-A compensating coils

For the configuration of Fig. 3 the calculated fields for various septum thicknesses are shown in Fig. 4.

Note that the fringe field can be made to either increase or decrease with radius as the thickness of the 1-cm section of the septum is changed. The field gradient inside the channel can also be changed from positive to negative by adjusting the septum thickness and the thickness of the central 1-cm strip of the conductor that parallels the septum. The field from the conductors shown in Fig. 3-B was computed for the ORIC radius as tabulated in Table 1.

2.3 *Conductor forces*

A current carrying wire or 'hot wire' is often used in a cyclotron to determine the beam path in the region of the deflector. A thin, current-carrying sheet conductor will assume the same shape as the path of a charged particle if the end points are properly adjusted. The radius of curvature at each point along the sheet will be inversely proportional to the magnetic field in which the conductor is located. The radial force on a conductor in a magnetic field, Fig. 5, is given by:

$F = BI/9810$, where F is in kg/cm, B in kG, and I in A.

The force will be radially outward when the current flow is in the direction to decrease the field on the outside of the conductor—a very suitable condition for a current carrying sheet septum. The tension developed in the current-carrying conductor in a magnetic field is:

$T = \rho F$, where T is in kg, ρ in cm, and F in kg/cm.

3. DESIGN DEVELOPMENT

3.1 *Test channel*

A straight test channel 75 cm long, Fig. 6, was fabricated from the conductors shown in Fig. 3-B. The available power supply limited the current to 1000 A;

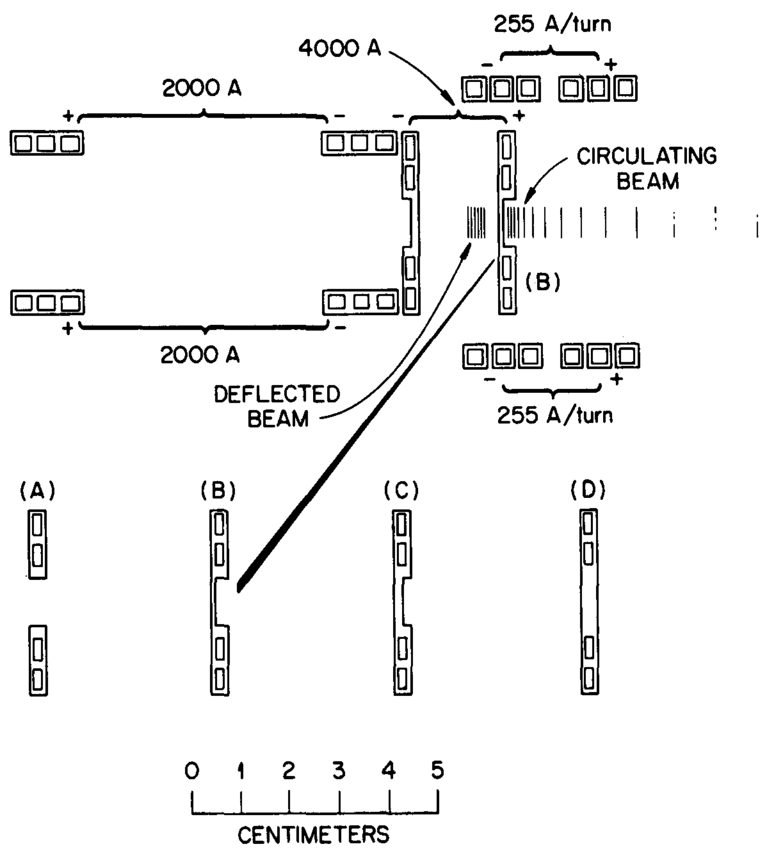

Fig. 3. The configuration of conductors and magnitude of currents for the test channel. The 1-cm wide beam section was open in Section A, 0·075-cm for Section B, 0·150-cm for Section C, and 0·300-cm for Section D

at slightly less than 1 V the resistance for the system was less than 0·001 ohms. A similar system operating at 4000 A will require only 16 kW. The channel was first operated as an air-cored system because the field calculations were for an iron-free system. The channel was then placed in the 8-cm gap of an iron-cored magnet. The fringe field from the channel was found to be slightly higher than the calculated and measured air-cored field. When the channel was in the iron gap the current in the second set of compensating coils was reduced 20% to obtain the field vs radius shown in Fig. 7. Test holes 0·25-cm wide by 0·5-cm long were machined into the septum so that a Hall probe could be inserted to measure the field continuously from inside the channel, through the septum, and into the circulating beam region. These holes reduce the radial field gradient between the deflected beam and circulating beam side of the septum but contribute little to the fringe field 1-cm from the conductor.

Table 1. MAGNETIC FIELD VS RADIUS FOR ORIC SEPTUM MAGNET

Radial increment (cm)	*Radius* (cm)	*Field* (gauss)	*Radial increment* (cm)	*Radius* (cm)	*Field* (gauss)
	76·00	29·4		73·00	2·6
	75·90	−623·7		72·90	4·2
	75·80	−1023·4		72·80	4·5
	75·70	−1036·6		72·70	3·9
	75·60	−1041·9		72·60	2·9
	75·50	−1043·4	0·10	72·50	1·6
	75·40	−1042·5		72·40	0·3
	75·30	−1040·0		72·30	−0·9
	75·20	−1036·8		72·20	−2·0
	75·10	−1033·2		72·10	−2·9
0·10	75·00	−1029·4		72·00	−3·6
	74·90	−1025·5			
	74·80	−1021·2	———		
	74·70	−1016·3		71·00	−1·0
	74·60	−1010·3		70·00	4·9
	74·50	−1002·1		69·00	5·8
	74·40	−990·7		68·00	4·1
	74·30	−974·4		67·00	2·0
	74·20	−951·2		66·00	0·2
				65·00	−1·0
———			1·00	64·00	−1·8
	74·10	−918·4		63·00	−2·7
	74·05	−875·6		62·00	−1·8
0·05	74·00	−582·7		61·00	−1·1
	73·95	−288·0		60·00	−0·8
	73·90	−239·5			
———					
	73·80	−186·3			
	73·70	−136·5			
	73·60	−93·7			
	73·50	−60·1			
0·10	73·40	−35·6			
	73·30	−18·7			
	73·20	−7·7			
	73·10	−1·0			

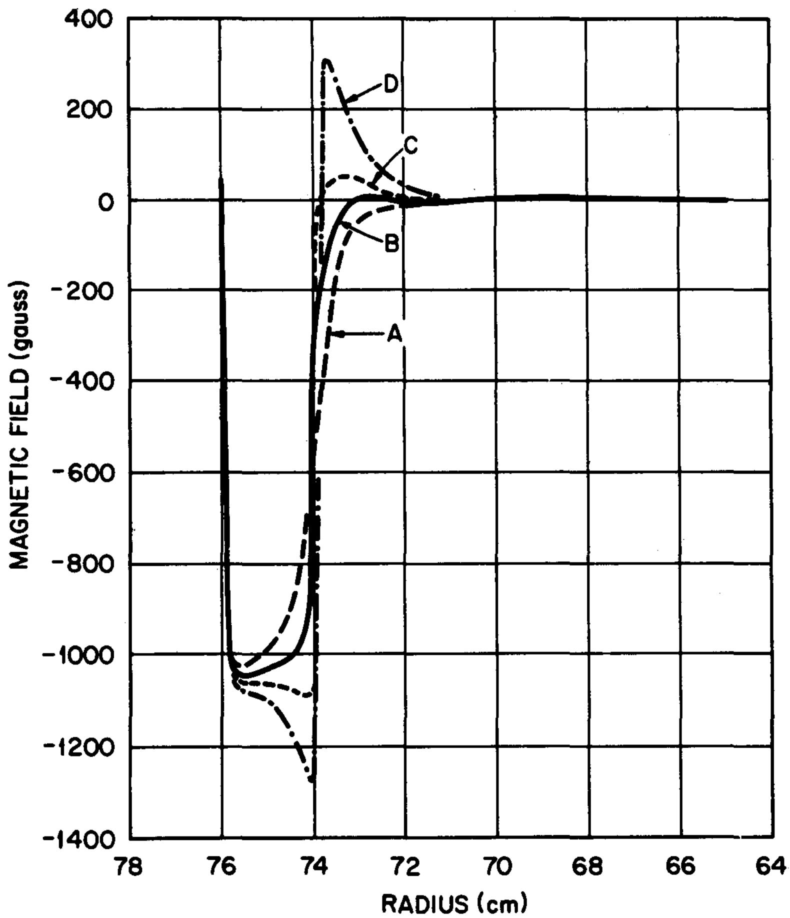

Fig. 4. Field vs Radius for 4000 A in septum thicknesses (A) through (D) in Fig. 3. The first channel for ORIC will use the 0·075-cm thick septum, (B).

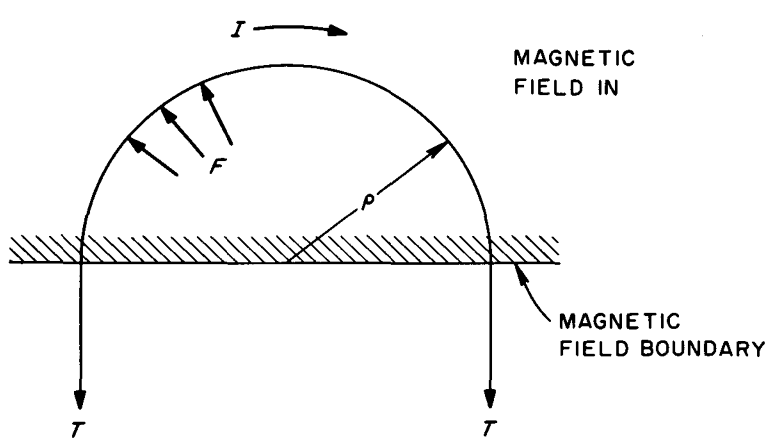

Fig. 5. Schematic diagram showing direction of force on a current carrying conductor in a magnetic field

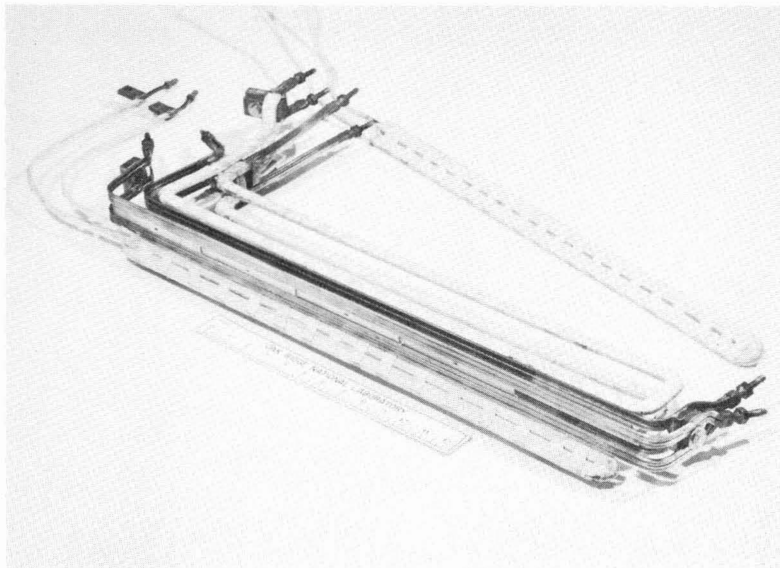

Fig. 6. The straight test channel

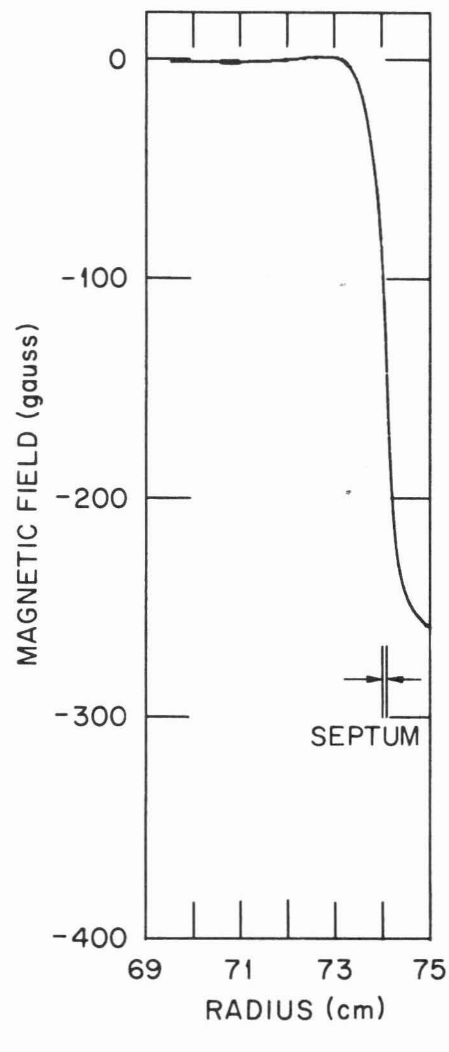

Fig. 7. Measured field vs Radius for 1000 A in the test channel

3.2 *Self-shaping and tension tests*

A pair of copper conductors 0·3-cm by 0·6-cm with 0·075-cm walls were brazed together to form a conductor 0·3 by 1·2-cm. The conductors were strengthened for 4-cm from the support points with copper pieces so as to provide a rigid section that could develop enough torque to overcome the friction forces. The conductors represent half of the septum in Fig. 3-A, except for a small section adjacent to the 1-cm wide beam slot. The conductor, with flexible leads made from 25 copper leaves 1-cm wide by 0·013-cm thick, was placed in a 2·54-cm gap magnet, Fig. 8, where the field was maintained at 17 kG. The current in the test conductor was held constant at 500–750 A while an air-driven cylinder was

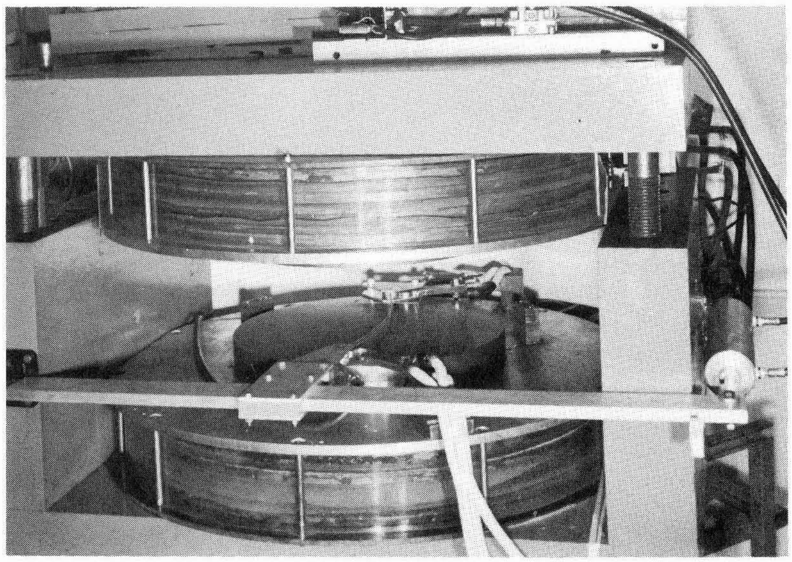

Fig. 8. Set-up for self-shaping and tension test on a 0·3-cm by 1·2-cm copper conductor

used to load the conductor until the desired tension was developed. The air cylinder was actuated for 3000 cycles at 10/min for a period of 5 h. The conductor and flexible leads appeared to be in good condition at the end of the tests. The radius of curvature was changed from 90-cm to 180-cm during each cycle of the test while the tension on the conductor was maintained between 180 and 230 kg, giving a tensile stress on the conductor of 700-900 kg/cm^2. When the stress exceeds 800 kg/cm^2, elongation of the conductor becomes excessive. The tests indicate that a self-shaping septum can be developed that will operate up to 10 years in a cyclotron that averages one septum shape change per day. The tests also indicated that there should be no difficulty in shaping a 0·3-cm thick septum that is operating with a tensile stress of about 800 kg/cm^2.

3.3 *ORIC self-shaping septum magnet*

A septum magnet design for ORIC with the septum and conductors shown in Fig. 3-B is essentially complete, see Fig. 9. Fabrication will begin soon and the magnet will be installed as soon after January 1, 1970 as the ORIC schedule permits.

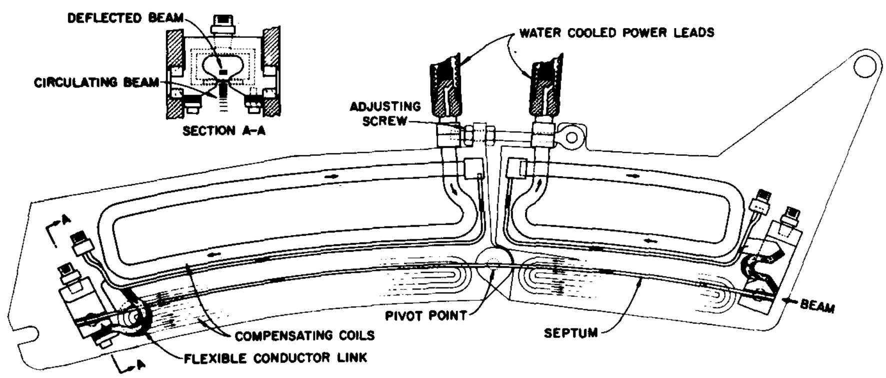

Fig. 9. Septum magnet designed for ORIC, for the conductors shown in Fig. 3-B

3.4 *Self-shaping septum for electrostatic deflector*

The current required to shape a thin current sheet septum is only a few amperes; however, if the radial magnetic force on the septum is to exceed the electrostatic force on the septum by a factor of 5 or 10, then the current required in the septum will be 25-100 A, depending on the electrostatic gradient. For example, the electrostatic and magnetic forces are equal in a system operating at 100 kV/cm when the septum current is 10 A and the magnetic field is 17·5 kG. A septum current of 100 A without a return current nearby will produce a fringe field as shown in Fig. 2-A, except the magnitude will be down by the ratio of the current, that is by 100/4000.

4. FUTURE DEVELOPMENTS

A half-scale version of the septum magnet design for ORIC would have a septum thickness of 0·038-cm and a beam aperture of 0·9-cm and would operate at 2000 A. The radius scale of Table 1 would be reduced to 0·5 and the radial field gradient at the septum would be double. Should larger field reductions be required for some future system, some means of supporting the magnetic load on the system will be necessary. The most likely method will probably involve the use of stainless steel, if it can be mounted out of the scattered beam. The residual activity in stainless steel from charged particles, such as 23-MeV protons, dictate that this must be so. Except for the residual activity problem, stainless steel straps or stainless steel water tubes make excellent structures for a septum. The relative resistance of stainless steel to copper is 42. This means that a fairly large support structure of stainless steel can be used without significantly altering the current distribution in the septum.

The present design for the proposed ORNL heavy-ion cyclotron will use a 4-kG septum magnet at injection, where the turn separation is about 2·5-cm. Septum magnets with fields of 0·2 and 2-kG will follow a small electrostatic deflector.

Self-shaping septums should provide a method for continuously adjusting the curvature of the septum to match the circulating and/or deflected beam paths and thus increase the beam deflection efficiency for electrostatic deflectors and for septum magnets. Thin septum magnets should be more reliable than electrostatic deflectors and should give a more stable deflected beam. They should also provide a better method for extracting higher energy particles than with conventional electrostatic deflectors.

ACKNOWLEDGEMENTS

J. D. Rylander assisted in the design of the various components and F. Irwin in methods of fabrication and testing.

DISCUSSION

Speaker addressed: R. S. Lord (ORNL)

Question by H. L. Hagedoorn (Eindhoven): I have seen your picture representing the magnetic field distribution due to the channel. Could you say what the equivalent first harmonic is and how seriously the radial orbits are disturbed.
Answer: The proposed septum for ORIC is about 30 in long and located at 30 in radius. The field values have been shown in the figures. We plan to trace orbits through the field disturbance, with axial motion included, but this has not been done, as yet. By proper selection of the thickness of the centre region of the septum a wide variety of field gradients can be achieved including alternating gradient. It is felt that a satisfactory arrangement for good orbit dynamics can be achieved.

REFERENCES

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3. Stevens, S. S., private communication.