A VARIABLE FIELD MAGNETIC EXTRACTION CHANNEL FOR ORIC*

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Summary

An improved magnetic beam extraction channel for the Oak Ridge Isochronous Cyclotron (ORIC) has been designed to significantly reduce the external field disturbance and provide uniform in-channel field. This will make beam extraction near $\nu_r = 1$ more predictable. The new channel consists of an iron tube of constant cross section with independently adjustable windings, both inside and outside the iron. The windings have a $\cos\theta$ current density distribution. The iron tube is 1 meter long with a bore of 6 cm; aperture for beam is 4 cm. The external field is negligible except for small perturbations in the field arising from the geometry modifications required at the ends so that the beam can enter and leave. The field reduction inside the channel is variable from 0.4 to 0.6 Tesla without significant change in either the internal field uniformity or the external field level.

Introduction

The extraction system arrangement for ORIC is shown in Fig. 1. The device labeled "compensated-iron magnetic channel" must provide a field reduction that is adjustable from about 0.4 Tesla to 0.6 Tesla. Uniformity of the field inside this channel and a minimum external field are also important characteristics for assuring good quality beam and predictable extraction conditions. Since the initial operation of the cyclotron in 1963, a channel using iron and current carrying conductors in two separately adjustable circuits has been used.[1] Recent insights gained from a more precise knowledge of the beam orbit behavior close to extraction radius have motivated redesign of the extraction channel to achieve reduced disturbance on the circulating beam and a more uniform field reduction inside the channel. The original channel was formed with coils and an iron box that are rectangular in cross section (Fig. 2), but curved from end to end to follow the beam path. The radial beam aperture varies from 2.7 cm at the entrance to 5.9 cm at the exit. Both the flare and the rectangular channel shape contribute to the non-uniformity of the internal field and to the external field disturbance.

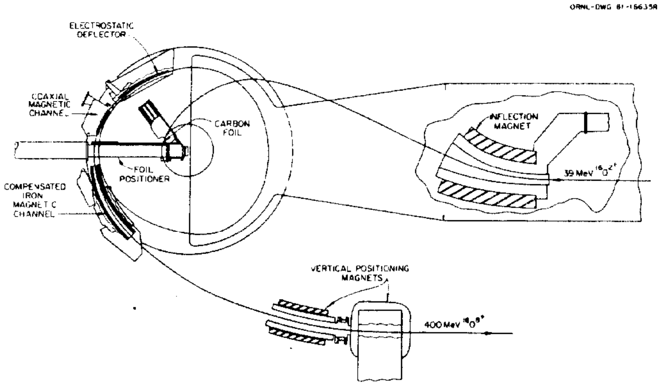

Fig. 1. Extraction system arrangement for ORIC showing location of "compensated-iron magnetic channel."

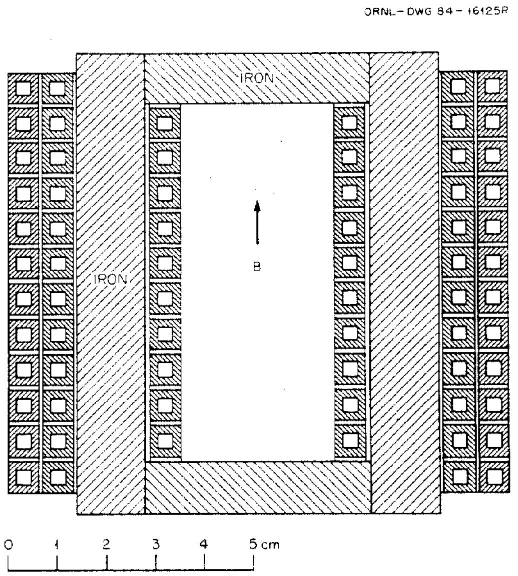

Fig. 2. Cross section of the existing extraction channel with separately powered inside and outside coils. In this channel the iron contributes about 0.07 Tesla reduction (~ 10% of the total).

Channel Design

The new extraction channel design has a constant cross section with conductors and iron placed as shown in Fig. 3. The beam aperture is 4 cm and the length is 100 cm. It is well known that a $\cos\theta$ distribution of current density yields an internal field that is uniform.[2,3] We have chosen, as a practical method of winding the coils, to distribute the current with constant spacing along the field direction (z) on the surface of a cylinder (Fig. 4). This can be shown to be a good approximation of a $\cos\theta$ current density distribution. This arrangement gives a field that is nearly uniform within the coil and has approximately a $1/r^2$ fall-off outside.

An interesting feature of coils of different radii constructed with the same z-spacing of conductors is the fact that they produce the same internal field for the same conductor current. As will be seen, this property can be used to explain the internal field of the iron cylinder.

Since the channel is positioned between the pole tips of the cyclotron magnet in a region where the base field intensity is 1-2 Tesla, the channel iron is essentially fully saturated, and its effect can be closely

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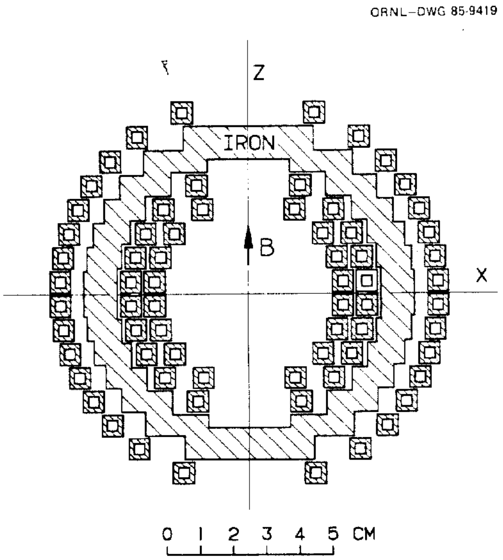

Fig. 3. Cross section of new channel design. The inside coil conductors and the outside coil constitute two separately powered circuits. In this design the iron does not contribute to the field reduction. The conductor is 6.35 mm (1/4 in.) square with a 3.18 mm square water passage. Conductors of the inner most coil (coil 1) are centered on a circle of 2.9 cm radius. Coils 2 and 3 are centered on circles of 3.6 and 5.7 cm, respectively.

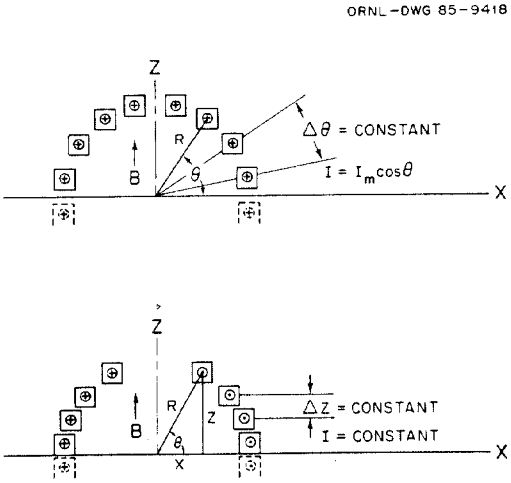

Fig. 4. Two arrangements for achieving cosθ current density distribution which result in uniform field inside and $1/r^2$ fall off outside.

approximated using the method of surface currents.[4] In our computations, each step on the surface of the iron (Fig. 5) has been represented by a single current filament, as has each of the coil conductors. For the iron, a saturation value of B_0 = 2.08 Tesla has been used, corresponding to a surface current of 16542 ampere-turns/cm. A small error in the assumed saturation value merely changes the coil currents required to simultaneously achieve both external compensation and the internal desired field. The configuration of the iron also results in a cosθ current density distribution, and since there are two iron surfaces with opposing currents, the field contribution of the iron is zero inside the channel and has a $1/r^2$ fall-off outside.

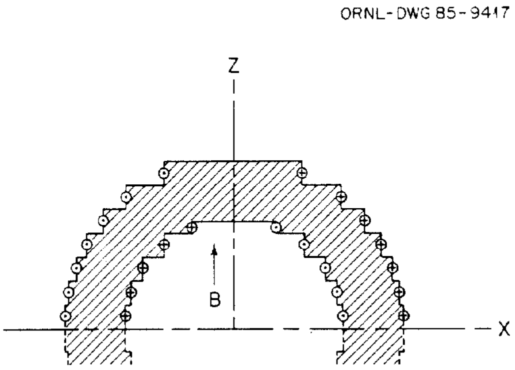

Fig. 5. Filament representation of surface currents on uniformly magnetized or saturated iron used to compute the field due to the iron. Positive inside surface filaments are paired with negative inside surface filaments having the same z. Outside surface filaments are similarly paired.

In an "ideal" channel of this configuration, but without openings in the ends for beam, any field reduction from 0.4 to 0.6 Tesla inside the channel can be achieved by suitable choice of coil currents, with a maximum current of 2600 amps, while at the same time having everywhere zero external field. The inside and outside coil currents required to achieve these conditions are illustrated by Fig. 6. These curves can be computed from the data in Table I by choosing a current for coil 3 and finding the appropriate current for coils 1 and 2 in series so that the contributions at 10 cm from the center of the channel sum to zero. The field at all other points external to the channel is also essentially zero. Calculated uniformity inside the channel is ~ ± 0.3%.

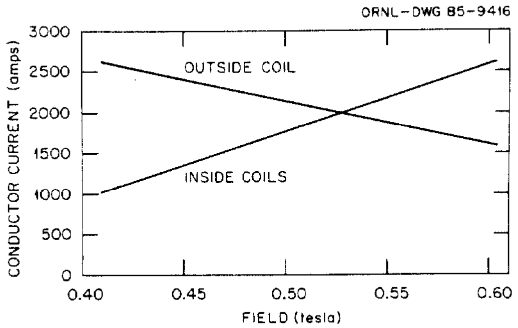

Fig. 6. Required currents in the inside and outside coils to achieve any desired field reduction throughout the operating range for the channel with iron.

TABLE I

	Inside coils		Outside	Iron
	Coil 1	Coil 2	Coil 3	only
I (amps)	2600	2600	2600	--
B_0* (gauss)	-2322.5	-2315.9	-2313.8	1.3
B_{10}** (gauss)	185.0	287.9	733.5	-916.4

*B_0 is the magnetic field in the center of the channel.
**B_{10} is the magnetic field 10 cm from the center of the channel.

When conductors are moved out of their "ideal" position at the ends of the channel to make room for the passage of the extracted beam, the external field is no longer zero near the displaced conductors. Local field disturbances of > 0.1 Tesla would exist near the ends if left uncompensated. However, these high field regions can be largely eliminated by local addition of iron and small adjustments in the positions of a few conductors near the ends. Although such trimming is a compromise because of the variable level of operation, it is quite satisfactory. Analyzed in terms of first harmonic seen by the ORIC circulating beam close to the channel the net disturbance is ~ 3 gauss after trimming. This is a value that can be compensated easily by the cyclotron harmonic correction coils.

Variations

Although this channel was designed specifically for a range of 0.4 to 0.6 Tesla, the fully-compensated field reduction can be extended down to 0.33 Tesla without exceeding 2600 amps by separating the inside coil into two circuits and operating the smaller radius coil with opposite polarity. If a different range is required, it can be obtained by the appropriate selection of iron thickness, or at the expense of power by raising the current to the cooling limit of the conductor (~ 3900 amps).

In principle, it is also possible to achieve the same fields without the iron, but the coil current requirements differ markedly as shown in Fig. 7. If the iron is removed, the outside coil current must be reversed to compensate the external field of the inside coil. Under these conditions the outside coil opposes the field of the inside coil, but is more effective outside the channel than inside. The power requirement for a channel with copper conductors, but without iron, is shown in Fig. 8(a). When iron is added so that the channel has the configuration of Fig. 3, the power is given by curve 8(b). If a channel without iron were required, for example in a region where iron was not uniformly magnetized, a superconducting version would probably be the most practical.

References

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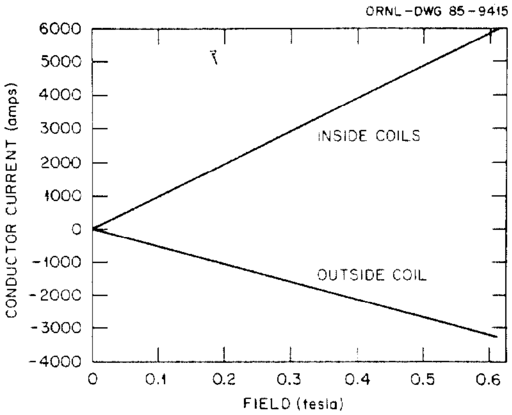

Fig. 7. Operating currents required for a channel with the same coil geometry as Fig. 3, but with no iron.

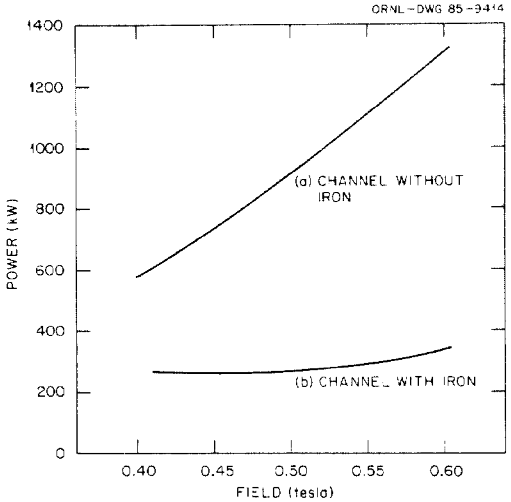

Fig. 8. Power required for a 1-meter-long channel without iron (a) and with iron (b).