DESIGN AND TEST OF PROTOTYPE SUPERCONDUCTING EXTRACTION CHANNEL MODULES FOR THE CHALK RIVER SUPERCONDUCTING CYCLOTRON

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Summary

The active magnetic portion of the extraction system for the Chalk River superconducting cyclotron is divided into nine segments, referred to as modules, each of which provides radial steering and radial focusing. Two kinds of modules are used: one has iron bars to give a fixed focusing gradient and the other has superconducting coils to give a variable focusing gradient. Both kinds have similar arrangements of superconducting coils to provide variable steering. All coils in the modules are racetrack types arranged to minimize perturbation of fields in the acceleration region. Full scale prototype modules of the fixed gradient type have been built, using Nb_3Sn and Nb-Ti superconductor, and tested. The Nb-Ti version has operated up to short sample critical current at a maximum conductor field exceeding 5 T. A prototype module of the variable gradient type has been made with Nb-Ti conductor and has also operated up to short sample critical current. Magnetic and mechanical design features of these modules are described and test results presented.

Introduction

This paper describes magnetic and mechanical design features of prototype superconducting extraction modules that have been developed for the Chalk River superconducting cyclotron and gives test results. A status report[1] for this cyclotron project and a report on extraction system beam dynamics[2] appear elsewhere in the proceedings of this conference.

The general features of this extraction system have been described earlier[3], but some modifications have been made since. Briefly, the active magnetic parts of the proposed system are divided into two channels. Each consists of a series of short linear modules separated by small drift lengths. The first channel contains three identical modules which have magnetically saturated iron bars to generate a fixed radial focusing gradient and superconducting coils to provide variable steering. The second channel contains six identical modules that have superconducting coils to provide variable radial focusing and variable steering.

Both channels reside in the bridge region of the main coil cryostat and channel 1 protrudes partly into a hill gap (the cryostat inner wall is suitably bulged to accommodate this). A superinsulated beam pipe, cooled with ≈ 100 K helium gas, passes through a rectangular access hole in all modules. A small local helium can surrounds the modules and isolates the bridge vacuum from the helium bath that cools them. Liquid helium is supplied to the local helium can from the lower main coil vessel. Boil-off gas is vented through the upper main coil vessel or the channel current lead system to a gas recovery system.

Modules are interconnected electrically to form four independently driven groups: channel 1, channel 2 gradient windings, and two sections of channel 2 steering windings having three modules per section.

The major changes in active element design are that a set of racetrack coils replaces saddle windings and their perturbation compensation coils for steering and that the iron bars, instead of a superconducting coil, counteract phase space distortions induced when the beam crosses rapidly changing fringe fields near a hill edge.

Magnet Design

Superconductor

Table 1 summarizes parameters of filamentary superconductors used to wind prototype modules. Coils having Nb_3Sn conductor (bronze matrix and no stabilizing copper) were wound using the "wind and react" technique. For coil protection, turns within a layer were in contact, but layers were separated with fiberglas (0.05 mm thick). In some cases thin copper foil (0.03 mm thick) was used to improve this contact. Fiberglas was also used as insulation between coils and support structure. The Nb_3Sn conductor required reaction in a vacuum furnace at 700°C for 24 hours. This conductor was used in a channel 1 prototype module as well as in most of the model coil development studies.

Table 1

Some Parameters of Multifilamentary Superconductor used to Wind Prototype Modules

Conductor		Nb-Ti	Nb-Ti	Nb_3Sn
Copper/Superconductor Ratio		1.25	1.4	0
Number of Filaments		361	60	1500
Filament Twist Pitch (mm)		12.7	12.7	25
Insulation		formvar	formvar	none
Diameter (mm)		0.5	0.5	0.5
Critical Current at 4.2 K (A). Magnetic Field	5 T	168	220	300
	3 T	250	340	375
Reference		4	5	6

To circumvent difficulties associated with coil protection and handling of brittle reacted Nb_3Sn conductor Nb-Ti was investigated. It has lower current density and lower critical temperature than Nb_3Sn, but avoids the requirement for furnace reaction and therefore allows a wider selection of insulation and structural materials. Polyimide and mylar (thickness 0.03 mm) were used to insulate coils from the support structure. The Nb-Ti conductor with a copper to superconductor ratio of 1.25/1 was used to wind a channel 1 module and a channel 2 gradient structure. The other Nb-Ti conductor was used to wind the steering coils of the channel 2 prototype module.

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In all cases conductor was flattened to a rectangular cross section in a rolling mill. Dimensions are given in later sections. Flattening aids winding control, improves packing fraction and reduces the amount of epoxy in the windings after vacuum impregnation[3].

Superconductor leads to and from individual coils were fastened onto supporting pieces of copper either by soft soldering (Nb-Ti) or by brazing (Nb_3Sn). Brazing was done in vacuum before conductor reaction.

Variable Steering

Figure 1 shows in cross section the layout of the six coils that make up the steering system of both channels. These coils are symmetrically arranged about the vertical axis and the midplane. Two of them, centered on the vertical axis, are identical double pancakes. The other four are identical and spool wound onto stainless steel racetrack bobbins. The circled dots and crosses indicate direction of current flow out and into the paper respectively to generate a field directed toward the top of the diagram. Coil dimensions, location and number of turns were established with the aid of computer programs which were used to obtain acceptable field profiles in the beam region and small perturbation fields in the acceleration region while satisfying space constraints and magnetic limits of the conductor. Cross-sectional dimensions for both channels are identical except for the dimensions labeled A and B. The straight section length of the pancakes is 82 mm for both channels, but is 96 mm for racetracks in channel 1 and 99.2 mm for racetracks in channel 2. The number of turns in channel 1 and channel 2 coils are respectively 30 for pancakes and 35-1/2 arranged in 6 layers for each racetrack and 32 and 41-1/2 arranged in 7 layers. The steering field amplitude is 1.7 mT/A.

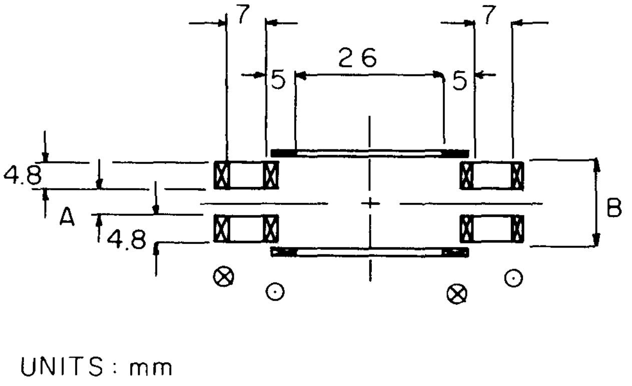

Fig. 1 Cross section of the steering winding configuration for channels 1 and 2 prototype modules.
Channel 1: A = 4.0 mm, B = 15.3 mm.
Channel 2: A = 7.4 mm, B = 19.0 mm.

Conductor cross-sectional dimensional for Nb_3Sn were 0.25 mm x 0.76 mm for all coils. For Nb-Ti they were 0.28 mm x 0.86 mm for pancakes and 0.36 x 0.74 mm for racetracks.

Fixed Gradient

Figure 2 gives the cross-sectional dimensions of the Armco iron bars which generate the radial focusing gradient for channel 1. These bars reside in regions where the field from the main magnet coils exceeds 2 T in all operating situations, thus ensuring magnetic saturation. The bars can be conveniently modeled with surface currents of density 1.72×10^6 A/m. Each bar is 86 mm long. The radial gradient is 35 T/m on axis in the middle of the module.

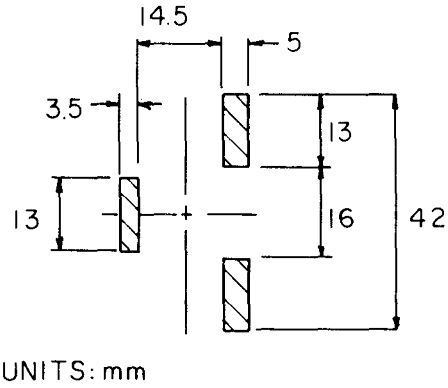

Fig. 2 Cross section of iron bar configuration for generating a radial focusing gradient in channel 1 prototype module.

Variable Gradient

Figure 3 gives the cross section of the variable gradient structure, which consists of four racetrack coils. Each coil has nine layers of 18 turns per layer wound onto an insulated stainless steel bobbin. The coils are symmetrically located about the midplane. As indicated by the circled dots and crosses the pair of coils on the left hand side carry current in the opposite direction to those on the right hand side. This arrangement causes only small perturbation fields in the accelerator region. The gradient generated in the beam region per ampere of current in the windings is 143 mT/m.

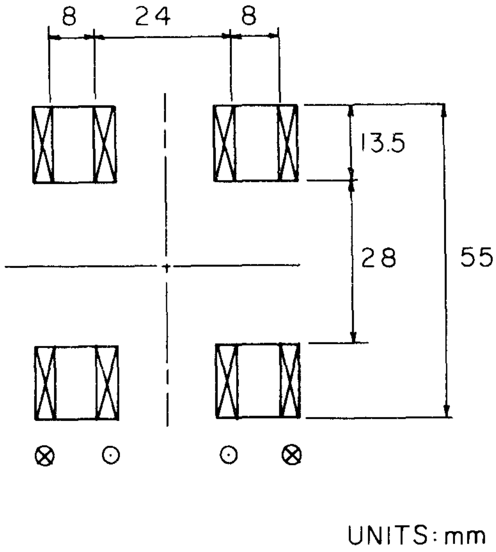

Fig. 3 Cross section of variable gradient winding configuration for channel 2 prototype module.

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Mechanical Design

Channel 1

Figure 4 shows the steering coils and the iron bars fixed in position on a stainless steel support structure. The main support member is a rectangular open-ended box structure made in two halves and electron beam welded together. The walls of the box are vacuum tight and form the outer envelope for the beam pipe superinsulation vacuum when all modules are assembled together. The left hand iron bar is welded inside the box at one end and at the other end is captured in a restraining piece, thus avoiding mechanical stress arising from differential contraction on cooling. The other bars are located in machined grooves on the outer surfaces of the box and welded to central supports that are arranged to allow differential motion on cooling.

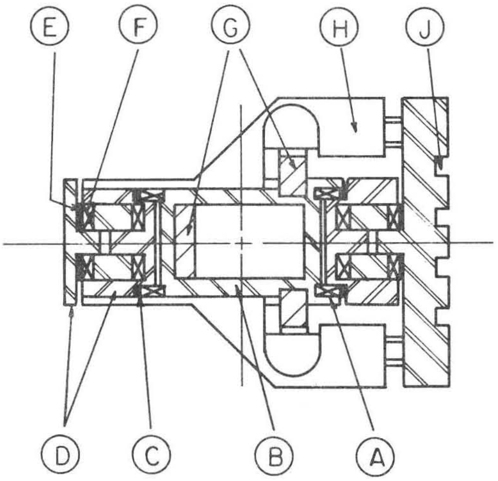

Fig. 4 Channel 1 module cross section: A - pancake coils; B - box structure; C - copper rail; D - racetrack clamps; E - copper pressure plate; F - racetrack coil; G - iron focusing bars; H - clamping straps; J - location of external lap joint connections.

The racetrack coils are mounted in pairs in stainless steel clamps. Insulated copper strips, 0.75 mm thick, act as pressure plates and provide mechanical support for the lead conductors on the outer layers. Silicon bronze screws provide a precompression force on each racetrack of 4000 N. The copper strips are soldered or brazed to other pieces of copper that support the conductor and lead it to the broad outer face of one of the racetrack clamps where external connections are made to the module via lap joints.

The pancake coils are wound in 1.83 mm wide grooves machined into the top and bottom surfaces of the box structure. Small copper rails, cross section 1.6 mm x 1.6 mm, act as pressure plates which are pressed against the pancake windings by the stepped edges of the racetrack clamping structure. One conductor of the pancake is soldered or brazed to the copper rail. The copper rail is fixed to a copper anchor which is cemented onto the end of a racetrack with an insulating adhesive, as shown in Figure 5. The lead conductor from the innermost layer of the racetrack is soldered (or brazed) onto the copper anchor and onto the copper rail where the electrical joint is made to the pancake. The clamping force for the pancakes is provided through five pairs of stainless steel straps which are attached with screws onto one of the racetrack clamps and pass over the top and bottom surfaces of the box structure. The straps are fixed to the broad face of the other racetrack clamp by silicon bronze screws which provide approximately 4000 N of precompression force on each pancake. Three pairs of the straps have narrow webs to go through 3.2 mm wide, 6 mm long vertical slots in the iron bars. The other straps go around the ends of the iron.

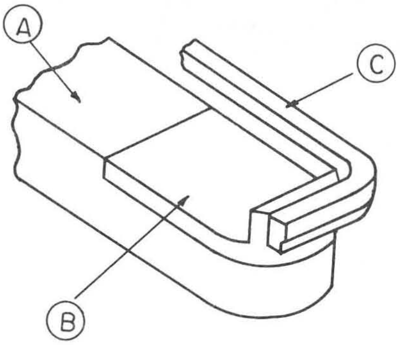

Fig. 5 Copper structure to support superconductor in the transition from a pancake to a racetrack: A - racetrack bobbin; B - copper anchor; C - interconnecting copper rail.

Figure 6 is a photograph of a prototype channel 1 module which shows the mechanical structure. Flanges have been welded onto the ends of the box structure for welding onto a mating flange of a neighbouring module when all modules are assembled to form the complete channel.

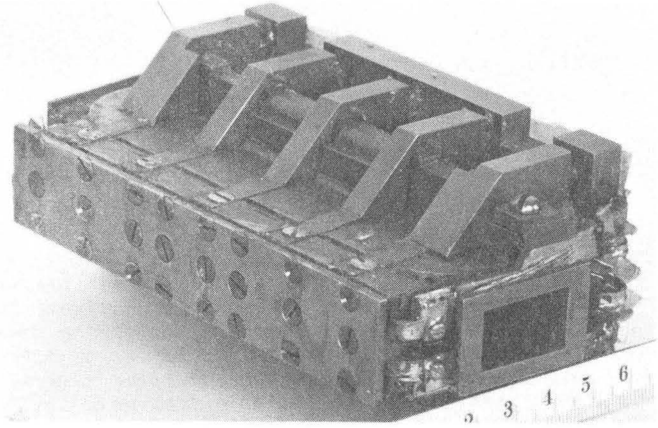

Fig. 6 Photograph of a channel 1 module.

Channel 2

Figures 7 and 8 show the support structure for the steering and gradient coils. The clamping and conductor support details for the steering coils are essentially the same as those for channel 1. The significant difference is that the straps to pull the racetrack clamp structures onto the pancakes are L-shaped brackets. Each of the ten pairs of straps across the top and bottom surfaces of the box structure consist of one stainless steel and one aluminum bronze bracket. Contraction of the aluminum bronze on cooldown helps maintain the precompression forces on the pancake coils.

The gradient racetrack coils are mounted in two aluminum bronze frames that in turn fasten to posts on the steering box structure. A pair of stainless steel bars apply a precompression force of ≈ 10^4 N to each racetrack. One of the bars is fastened to the frame and contains an array of stainless steel set screws

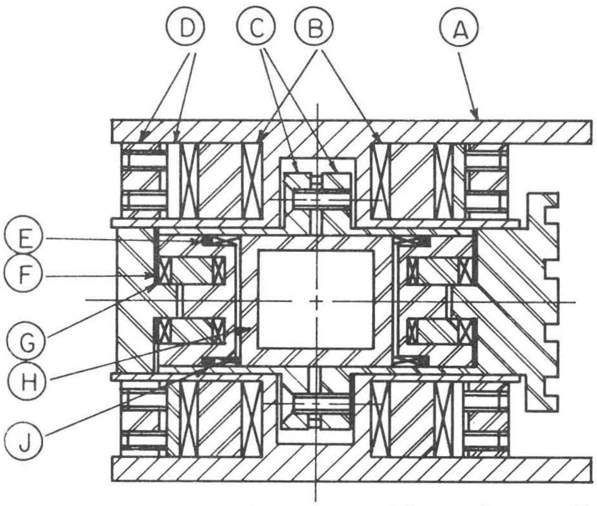

Fig. 7 Channel 2 module cross section: A - gradient support frame; B - gradient racetrack coils; C - L-shaped brackets; D - precompression bars; E - copper rail; F - copper pressure plate; G - steering racetrack coil; H - box structure; J - pancake coil.

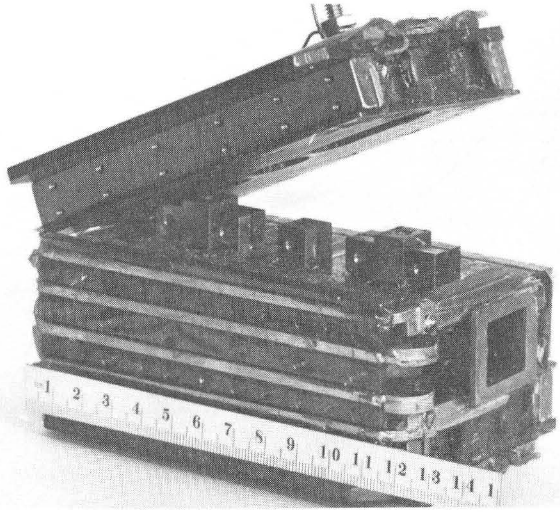

Fig. 8 Photograph of a channel 2 prototype module with the upper pair of gradient coils and support structure raised.

that press the other bar onto the racetrack. On cooldown the frame maintains the precompression. The frame has holes machined in the region between racetrack locations to fit over the ends of the L-brackets on the steering box structure. The racetrack lead conductors are soldered onto copper pieces which are anchored in the racetrack bobbins and support structure for mechanical support of the conductor.

Performance

Test Apparatus

Each module was mounted inside the bore of a superconducting solenoid that could generate a maximum field of 5 T. The solenoid's helium bath provided cooling. The field on axis in a module was monitored with a cryogenic Hall probe and also with a coil and integrator system. A dc current stabilized power supply charged the modules at a rate of 2 A/s. The inductance of each coil in the steering structure was roughly 0.1 mH and that of each coil in the gradient structure about 1.5 mH. Each coil in a module was monitored also with voltage taps.

Channel 1

The dominant feature of the Nb_3Sn module was that an unacceptably long time of more than 20 minutes was required to charge up to a given current. (Based on experiments with single coils a few minutes was expected.) This behaviour resulted from bonding of copper across the outermost turns of the pancake windings, which is thought to be caused by inadequately controlled flow of brazing alloy.

The module wound with Nb-Ti conductor (copper to superconductor ratio of 1.25/1) achieved critical current operation for current in both directions and maximum fields at conductors up to 5.5 T. The self field contribution at the point of maximum field is ≈ 1.5 T for a current of 200 A. A total of 20 training quenches was required. The current configuration giving steering fields aligned in the same direction as the background field required less training than that for field alignment in opposite directions. In the latter case the maximum fields occur at the ends of the racetrack coils.

For operation in the cyclotron, currents required in channel 1 modules wound from 1.4/1 Nb-Ti and operated at 4.5 K are 80% or less of critical current for average central fields in the cyclotron of 3 to 5 T.

Channel 2

The prototype module was wound with Nb-Ti conductor using 1.25/1 copper to superconductor ratio for the gradient structure and 1.4/1 for the steering structure. (The choice was based on conductor availability.) Both structures operated up to critical current. Measured magnetic fields and gradients agreed with calculations. The steering windings operated similarly to those of channel 1, except that the critical current is higher for the channel 2 module.

The gradient structure had a maximum conductor field of 5.9 T, of which the self generated portion is about 1.9 T per 150 A.

Cyclotron operation will require maximum currents in channel 2 modules of 75% and 65% of critical current for the steering and gradient structures respectively if the coils are wound with 1.4/1 Nb-Ti conductor and operated at 4.5 K.

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