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EXTRACTION SYSTEM MODEL EXPERIMENTS FOR THE CHALK RIVER SUPERCONDUCTING CYCLOTRON

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Abstract.- The extraction system for the Chalk River superconducting cyclotron consists of one electrostatic deflector, located in a dee, followed by several magnetic elements which are made up of magnetically saturated iron and/or superconducting windings. None of these are movable. Model studies for the electrostatic deflector and one of the superconducting windings are described.

1. Introduction.- This paper gives a report of model studies which are part of ongoing development work for extraction system components in Chalk River's superconducting cyclotron. A status report for this cyclotron project appears elsewhere in the proceedings of this conference[1]. Various features of the system have been discussed earlier[2]. To put the model studies in context major system components are first outlined (revisions to the system of reference 2 are noted), then the model studies and results are described. Experiments to date have concentrated on the electrostatic deflector and a superconducting radial gradient winding in one of the magnetic channel elements.

Figure 1 shows a midplane plan view of the cyclotron and identifies schematically the extraction system elements and their locations. The line marked '0' indicates the θ=0 axis for a polar co-ordinate system whose origin is at the machine center. Extraction begins with a beam having adequate turn separation ($\gtrsim$ 5 mm) entering an electrostatic deflector, which is located in a dee, at a radius r=0.65 m and θ=162°. The deflector subtends 31° and has a nominal radial aperture of 7 mm. The maximum operating voltage is calculated to be $\lesssim$ 90 kV. Precessional extraction will be used to enhance turn separation, the required first harmonic field bump being generated with the outermost set of trim rods[1]. At θ=204° the beam enters the first of two radially focusing lenses made from magnetically saturated iron. These control radial beam growth and significantly aid beam deflection[2]. Typical values of focusing gradient and intrinsic bias field at the lens centers are 13.5 T/m and -0.05 T. The beam enters the first of two extraction channels at θ=295° and r=0.696 m. Each of these channels consists of a series of short linear modules separated by small drift lengths. The first channel has three modules and the second channel has five. Each module of the first channel has a saturated iron radial focusing structure and a superconducting compensating winding. The latter counters radial phase space distortion induced when the beam crosses rapidly changing fringe fields near a hill edge. The radial focusing gradient (in a module) is $\sim$ 30 T/m. The first channel ends at θ=324°. Modules in the second channel contain no iron, but use superconducting windings to generate a variable radial focusing gradient. These are discussed later. Modules of both channels have superconducting windings

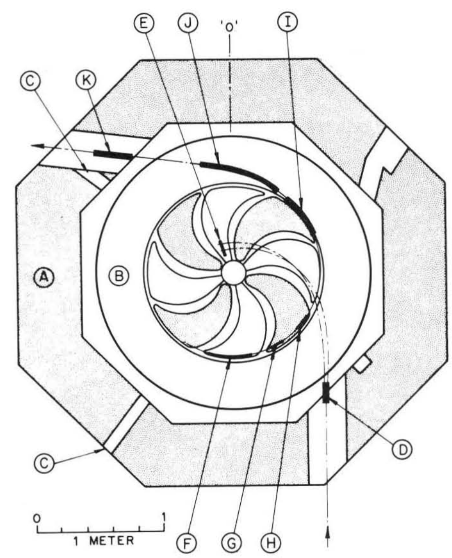

Fig. 1 Midplane plan view of the cyclotron: A - yoke; B - cryostat; C - diagnostic probe holes; D - injection steering dipole; E - stripper foil; F - electrostatic deflector; G, H - iron lenses; I - first magnetic channel; J - second magnetic channel; K - extraction steering dipole.

to generate variable bias fields, which may be either positive or negative, and which steer extracted beams out of the cyclotron along an approximately constant trajectory. Bias fields of the first channel are independent of those of the second. The second channel begins at θ=330° and subtends 45°. Fixed iron elements (not shown in Fig. 1) are located on the inner wall of the cryostat diametrically opposite the lenses and iron gradient structures to compensate unwanted first harmonic fields from these latter iron components.

The bias winding configuration has been changed from that given in reference 2. These windings are now located on the surface of a cylinder in the style of a conventional saddle magnet winding. Difficulties in placing adequate compensating windings in the limited available space to remove bias winding perturbations from the acceleration region prompted the change. Compensation windings now occupy regions formerly taken up by the bias windings. The modular structure of the channels is also a change from those in reference 2. A modular approach offers advantages of easier fabrication, easier testing outside the cyclotron and the capability of making position adjustments to fit to a reference trajectory.

2. Electrostatic Deflector.- The distinguishing features of this deflector system arise from it being located in a dee. High voltage cannot be fed in at the midplane from outside the cyclotron in the usual manner of using a radially oriented feedthrough. (A region of high rf fields would have to be crossed without shorting it out.) Instead, a high voltage cable comes down the upper dee stem and through the dee top interior to connect to a cylindrical transition structure which in turn connects to the deflector electrode. The top surface of the dee has two cylindrical bulges. The transition structure fits under one and also serves as one of two mechanical supports. The other support is under the other bulge.

Figure 2 gives a cross sectional view of the deflector system, which also represents the model that was built for out-of-magnet development studies. However in the model experiments a piece of suitably shaped copper replaces the top and end surfaces of the dee.

Computer calculations of electrostatic equipotentials and surface electric fields were made, using a SLAC gun program[3], to aid in choosing conductor dimensions and profile shapes. Simple insulator shapes, particularly those shown in Fig. 2, could be calculated as well for the case of no insulator charging phenomena. As discussed later, charging is believed to limit performance of the cylindrical transition.

Experiments were performed for the high voltage cable and its vacuum fittings, for the support insulator in the cable-to-deflector transition and for testing of the full deflector model. The voltage source was a 160 kV, 1.5 mA dc power supply (negative polarity) having a 1 MΩ resistance at the output in series with a cable of ∿ 300 μF capacitance. Experiments were conducted at pressures in the range 10^{-3} - 10^{-4} Pa in an oil free stainless steel vacuum system. X-rays generated by vacuum sparks were monitored with a Victoreen 440 meter.

The high voltage cable is a custom-made, vacuum tight coaxial cable approximately 3 m long. The solid copper outer conductor has an outside diameter of 18.2 mm, the Teflon dielectric outer diameter is 16.3 mm and the solid copper inner conductor has a diameter of 4.8 mm. This cable follows several bends to get from the top of the cyclotron down a dee stem to the transition section in the dee. The tightest bend is through 45° on a 72 mm bending radius. A full length of cable, bent into the required shape and with one end terminated in vacuum was satisfactorily tested up to 120 kV with sparks induced at the vacuum termination. A short length of this cable (300 mm) functioned as a high voltage vacuum feedthrough to connect to the transitions section in development experiments.

Figure 2 shows the main features of a full scale transition that was built and tested. The cable outer conductor transforms via an electrical stress relief collar into the outer stainless steel conductor of the transition (anode). This conductor consists of three sections. Two of them butt together to clamp the

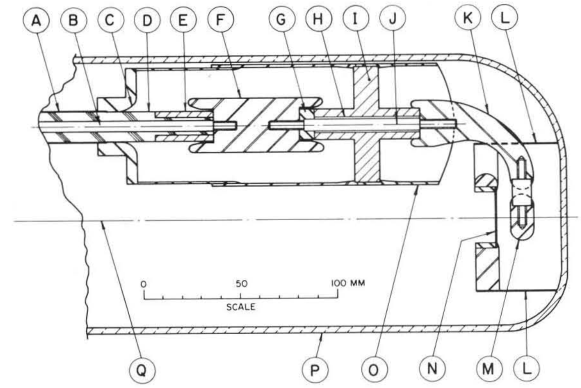

Fig. 2 Cross sectional view of the electrostatic deflector system: A - cable outer conductor; B - cable center conductor; C - stress relief collar; D - cable dielectric; E - boron nitride sleeve; F - center conductor coupling; G - spacer; H - insulator metal sleeve; I - boron nitride insulator; J - insulator center conductor; K - high voltage connection to deflector electrode; L - sparking plates; M - deflector electrode; N - septum; O - transition section outer conductor; P - dee envelope; Q - midplane.

support insulator into place. The third section fits inside the others and thereby allows the can length to be adjusted. The nominal inside diameter is 60 mm. The center conductor of the transition (cathode) also consists of three pieces, all stainless steel: a cable-to-insulator coupling, insulator center conductor, and an insulator-to-deflector coupling piece.

Several experiments were devoted to termination of the cable center conductor. These were performed with pieces F to K of Fig. 2 removed and F replaced by a hemispherical termination. The conclusions were that to reliably exceed 100 kV without leakage current and x-ray emission the cable should be fitted with a boron nitride sleeve and the termination should be re-entrant to hide the vacuum-insulator-cathode junction. Without the sleeve reliable operation could not be achieved above ∿ 70 kV. Inevitably sparking led to high leakage current. Occasionally sparks caused reduction or elimination of this current. Current decrease also occurred when the pressure was raised to ∿ 10^{-1} Pa. Current did not increase on subsequent pressure reduction until another spark occurred. This behaviour seems consistent with the Teflon near the center conductor termination charging positively because of secondary electron emission. This greatly enhances the local electric fields leading to sparking and leakage current. With the boron nitride sleeve detectable leakage current and x-ray emission did not occur until the voltage was in the range 120-130 kV. Then sparking led to generally similar behaviour to that observed for Teflon at ∿ 70 kV. The sleeve was epoxied onto the Teflon in vacuum after the Teflon surface was treated with a commercial etchant which produces a suitable layer for bonding. Some experiments were also done with a Macor[4] sleeve and a Macor sleeve coated with chromium oxide, the latter having the property of a negative secondary electron emission coefficient[5]. These were abandoned in favor of boron nitride before they were fully explored.

The support insulator is also made from boron nitride. A metal sleeve, vacuum epoxied to the central bore, ensures good contact with the stainless steel center conductor. Connections at the insulator ends are re-entrant. The insulator in the model tests was not made from one piece of boron nitride, but from two. An annular disc and a cylinder were vacuum epoxied together. Insulator experiments (deflector side terminated with a re-entrant hemisphere) showed that the shortest distance between cathode termination and insulator disc limits the maximum reliable operating voltage (this distance was set at ∿ 16 mm).

Finally experiments were performed with the complete deflector model. The deflector electrode is 90 mm long (1/4 of full length). The aperture between tungsten septum and stainless steel deflector is 7 mm. Tungsten sparking plates are located 38 mm above and below the midplane. The connecting piece between deflector electrode and transition center conductor passes through a hole in the upper sparking plate, with the hole edges electrical stress relieved. In out-of-magnet tests the system has operated at 110 kV (i.e. 10% above nominal design voltage) without significant leakage current or x-ray emission. High voltage conditioning is rapid, taking only a few minutes. Tests of the model deflector system in a magnetic field await installation of the dees into the cyclotron magnet.

3. Model Coil Studies.- This section presents some results of experiments in progress which model one of the four series connected windings of a module of the second channel radial gradient structure. The inset of Fig. 3 shows the structure winding cross section and gives nominal dimensions. Mechanically the cross section has mirror symmetry in two planes and electrically is symmetrical about the midplane. However, the right side windings carry current in the opposite sense to the left side windings. (This configuration is revised from that of reference 2.)

Figure 3 gives an isometric view of an experimental coil which models one of the left side windings in the inset. This coil is wound using the "wind and react" technique, which begins with winding unreacted Nb_3Sn superconducting wire[6] on a stainless steel bobbin having parallel vertical sides and a racetrack shaped cross section. Fiberglas tape (E type, 0.18 mm thick) insulates winding layers from each other and from the stainless steel. However, turns within a layer are in contact for coil protection (the superconductor in these experiments has no stabilizing copper). Impregnation with a cryogenically suitable epoxy[7] follows reacting the coil in a vacuum furnace at 700°C for 24 hours. Stainless steel pieces fit over the windings on straight sections of the coil. The cross section of these pieces and that of the bobbin form a circular surface on which is wound 0.5 mm diameter aluminum wire after reaction and potting of the coil (see the half section in Fig. 3). The aluminum wire is also potted. This wire contracts more than the rest of the structure upon cooling, thereby tightly clamping the windings in place. For clarity Fig. 3 does not show additional structure that supports lead wires from the coil nor binding post structure. Coil dimensions are winding height 21 mm, straight section length 118 mm and radius of curvature at the coil ends 4.5 mm. Each winding layer has 35 turns.

This coil structure is tailored to fit into the cross field access hole of a small superconducting magnet which can generate a nominal field of 5 T. The magnet's liquid helium bath cools the coil. A dc current stabilized power supply (2 in 10^4) is used to charge the coils at a rate of 2-3 A/s.

A single layer coil has operated up to 320 A in a 3.7 T field. It showed evidence of conductor motion

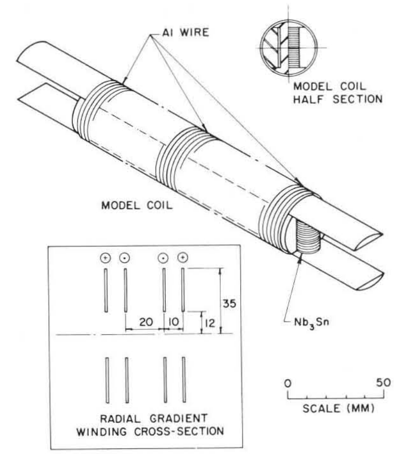

Fig. 3 Experimental coil to model one of four mechanically identical windings which comprise the second channel radial gradient structure. The inset shows the winding cross section of this structure. The circled crosses and dots indicate current flow in and out of the paper respectively. The cyclotron center line is to the left of this section. The cyclotron background magnetic field direction is upwards.

in the lead wires that connect the coil to the binding posts. A double layer coil, with modifications to further restrict the lead wires, operated above 300 A in a 4.6 T field. The minimum requirements for the second channel gradient windings are that such a double layer coil should carry 300 A in a background field of ∿ 4 T. These coils seem to have adequate protection against damage from quenching.

Future work will include a triple layer coil as well as model studies for the bias and compensating winding members of the magnetic channel structures. Also some coils will be studied which are wound with copper stabilized Nb_3Sn small cross section wire.

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References

1. J.H. ORMROD, C.B. BIGHAM, E.A. HEIGHWAY, C.R. HOFFMANN, J.A. HULBERT and H.R. SCHNEIDER, these proceedings.
2. C.R. HOFFMANN, IEEE Trans. Nucl. Sci., NS-24 (1977) 1470.
3. W.B. HERMANNSFELDT, Stanford Linear Accelerator Center Report No. 166, September 1973.
4. Macor is a machinable glass ceramic manufactured by Corning Glass Works, Corning, New York.
5. T.S. SUDARSHAN and J.D. CROSS, IEEE Trans. on Elect. Insul. EI-11 (1976) 32.
6. Conductor NSP2/50 manufactured by Imperial Metal Industries, Birmingham, England. This conductor has 1500 filaments, each of diameter 0.007 mm, a twist pitch of 25 mm, all bronze matrix, and a 0.5 mm overall wire diameter. Quoted short sample current is 305 A in a 5 T field.
7. L.M. SOFFER and R. MOHO, Cryogenic Properties of Polymers (T.T. Serafini and J.L. Long, editors), Marcel Dekker, Publisher, 1968, p.87. Resin # 2 was used.