COMMISSIONING THE CHALK RIVER SUPERCONDUCTING CYCLOTRON

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Summary

The Chalk River superconducting cyclotron, when injected with beam from the Chalk River 13 MV tandem Van der Graaff accelerator, will accelerate all ions from lithium (to 50 MeV/u) to uranium (to 10 MeV/u). Following successful development trials of the cyclotron magnet and rf accelerating system and installation of the magnetic extraction channel, the cyclotron is now assembled in its vault. Commissioning is in progress. Initial operation with beam will be injection of an iodine beam from the tandem and acceleration to 10 MeV/u.

Introduction

The Chalk River superconducting cyclotron was conceived as a booster accelerator for the 13 MV MP tandem at Chalk River[1]. Figure 1 shows the plant layout at Chalk River, as it exists now, from the ion source, through tandem and cyclotron to the interim target line which completes Phase I of the project. Phase II, when approved, will extend the output beam line to existing target rooms and the QD3 magnetic spectrometer. A new 8π spectrometer, under development as a joint venture between CRNL and two Canadian universities[2], will be a major new piece of experimental equipment.

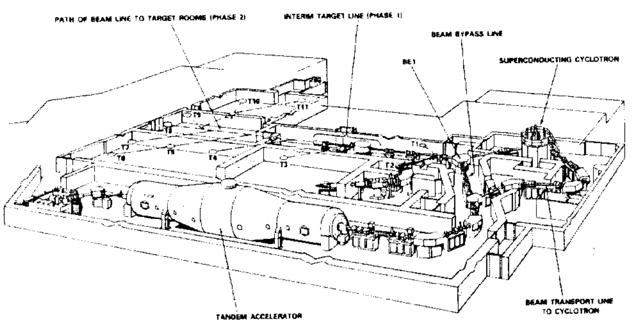

Fig. 1 The Chalk River Tandem Accelerator Superconducting Cyclotron system (TASCC).

Negative ions, from lithium to uranium, are generated and accelerated in the 300 kV injector and accelerated through the column of the MP tandem. A gridded-gap prebuncher, containing cavities resonant at first and second harmonic frequencies of the cyclotron accelerating voltage, produces a time focus of the bunched beam at the tandem stripper channel to minimize longitudinal phase-space dilution of the stripped beam. The beam leaving the tandem passes through an analyzing dipole, for charge-state selection and energy stabilization and is then rebunched in a two-gap drift-tube buncher. This buncher produces a time focus at the injection stripper foil in the cyclotron. The foil, located in a magnetic valley, inside a dee, is positioned at fixed azimuth but variable radius to accommodate the range of ions accepted by the cyclotron. Horizontal and vertical steering dipoles in the yoke wall of the cyclotron make small corrections to the injection orbit.

The cyclotron has four-fold magnetic symmetry (Fig. 2). This provides four magnetic valleys in which to locate four accelerating dees. Since the centre axis of the cyclotron is not required for ion sources it accommodates two coaxial-line tuners, each supporting a pair of dees. The whole accelerating structure then forms a single resonant cavity, which is capacitatively driven by a single power amplifier, making for a compact, simple and stable rf system.

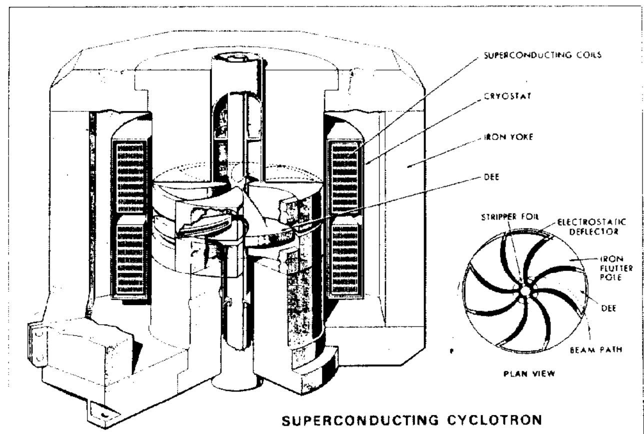

Fig. 2 The Chalk River superconducting cyclotron diagrammatic.

The magnet is excited by two separately-driven copper-stabilized superconducting niobium-titanium pancake-wound coils, divided into inner and outer pairs. Orbit isochronism is set approximately by adjusting the inner and outer coil currents and fine tuning obtained by adjusting the positions of 104 saturated steel trim rods, located 13 in each of the four upper and four lower magnetic flutter poles.

The accelerated beam is extracted at a radius of 650 mm. Turn separation is increased by using the outermost trim rods to set up a first-harmonic orbit precession at the $\nu_r=1$ resonance. The beam enters an electrostatic channel where it is deflected into the magnetic extraction channel. Radial focusing is maintained in this part of the orbit by saturated iron lenses, located on the wall of the coil cryostat.

The magnetic extraction channel is comprised of 78 separate racetrack dipole superconducting coils and 12 saturated iron gradient bars, assembled in 9 active modular units and one passive unit (Fig. 3). The coils are wound from copper-stabilized niobium-titanium and the whole assembly is immersed in a liquid helium tank fed from the lower main magnet coil vessel.

Vacuum in the midplane region is provided by two 1500 L/s cryopumps located in two of the valleys. These pumps, suspended from the upper pole, behind rf shielding grids, are fed automatically by batches of liquid helium, transferred from the top of the main coil liquid helium vessel.

The main parameters of the cyclotron are given in Table 1.

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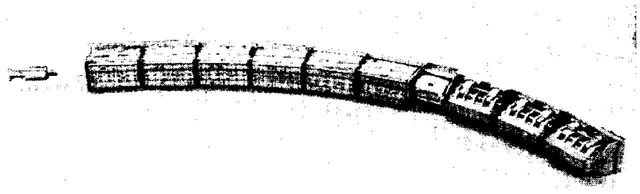

Fig. 3 The superconducting extraction channel before welding into its liquid helium container. (The "strongback" on which the modules are mounted is 80 mm high.)

Progress towards Commissioning

The last major subsystem of the cyclotron to be developed was the extraction system. Development of superconducting coils was completed late in 1983 and prototype extraction modules were built and tested. In June 1984, the full set of 9 active extraction system modules had been wound and tested in a 5 T background field, and the task began of assembling them on the channel strongback and welding them into their cryogenic containment. This containment consisted of a superinsulated and helium gas cooled beam pipe through the module apertures and a helium vessel fitted closely to the outside of the modules. The complete channel system with leads was mounted in a special test cryostat, operated at full current at zero background field and then transferred to the magnet cryostat midplane.

When the magnet cryostat had been reinsulated and closed up it was removed from the development laboratory and installed in the newly-constructed cyclotron vault. During vacuum tests prior to positioning in the yoke a series of cracked tubes were found in the main radiation shield cooling manifolds. Analysis showed that chloride-bearing soft solder flux in the shield demountable joints had migrated to the 304 stainless steel manifold where it had set up intergranular corrosion cracking. It was found necessary to rebuild the complete shield lower manifolds from desensitized 321 stainless steel and to blank off the upper manifolds which, following the channel installation, were no longer accessible.

During this time the outer superinsulation was removed and replaced several times. To speed up this process the outer superinsulation layer was finally made from a double, overlapping set of pre-assembled "blanket" units. It was possible to remove this layer and replace it in about three hours (nine man hours). Its performance is very close to that of a permanently-taped lamination of a comparable number of layers taking four man weeks for installation. The initial assembly of the blanket units occupied two man weeks.

After the cryostat had been closed up and was undergoing the final leak test before being installed in the yoke, a leak was found to have opened in the extraction channel beam pipe (Fig. 4). This leak bridges the cryostat and midplane vacuum spaces and is not significant except when the midplane vacuum is let up to atmosphere to give access to the acceleration cavity. At such times the beam pipe is perfused with an atmosphere of helium, and the leak rate is then too small to affect the helium boiloff rate from the cryostat.

Table 1

The Chalk River Superconducting Cyclotron

Magnet Poles:	Compact, four spiral sectors (50° maximum spiral angle)
	Diameter 1386 mm
	Injection radius 145-220 mm
	Extraction radius 650 mm
	Pole gap (including copper facing) 34 mm in hills
	640 mm in valleys
Magnet Coil:	Superconducting Nb-Ti, 25:1 copper:superconductor
	6.2×10^6 Ampere-turns maximum
	Weight 10 tonnes (18 tonnes with cryostat)
	Operating temperature 4.5 K
Yoke Weight:	150 tonnes
Ion Energy Limits:	Bending 520 q^2/a MeV/u
	Focusing 100 q/a MeV/u
Accelerator System:	4 dees 100 kV maximum
	rf frequency 31-62 MHz
	harmonics used 2, 4, 6
Field Trimming:	Coil divided into outer and inner coil pairs separately excited. 13 saturated iron trim rods in each flutter pole, 104 in all, positioned by stepping motor geared drives.

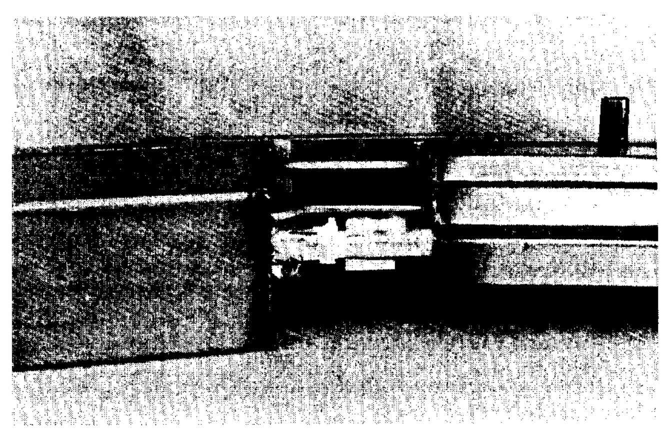

Fig. 4 Close up of the extraction channel beam pipe as it passes from Channel 1 (saturated iron gradient elements) to Channel 2 (superconducting gradient elements).

The thermal shield circuit of the cryostat has been modified to give three separate shield flows. The first, to the main cryostat shield, returns to the liquefier heat exchanger to maximize thermal efficiency. The second cools the extraction beam pipe and provides a shield for the extraction magnets against the deposition of energy from lost beam (allowing up to a distributed 100 W without having to turn the beam off). The third, provides transfer tube thermal shielding. The last two, because of their uncertain return temperature, return directly to the circulating compressor suction.

Installation of the cryostat in the magnet yoke and cooldown occurred in mid-March 1985. Cooling for the cryogenic system is provided by a new Koch 2800HR liquefier (essentially equivalent to two CTI 1400 machines). With the compressors available, (1 Koch RS and 3 CTI 1400) circulation of helium is 9 mol/s, giving 55 L/h liquid helium production with no nitrogen precooling or about 90 L/h with liquid nitrogen. At present we are operating in a very stable mode, liquefying directly into the magnet cryostat, using the 1000 litre liquid storage dewar as a buffer to absorb fluctuations in production. Owing to thermal instabilities, believed to originate in the storage dewar neck we have as yet been unable to stabilize the cryostat level while operating in the preferred mode, that is liquefying into the dewar and transferring liquid to the cryostat as required.

Measurements showed an increase of 15 L/h in the helium boiloff rate to a total of 41 L/h (at a level of 600 L) due to the addition of the 8 x 300 A leads for the extraction channel and the channel itself with its small clearances between warm and cold surfaces at the inner midplane of the cryostat. This increase has been partially countered by improvements to the helium transfer lines between liquefier and cryostat. The three lines are all shielded along most of their length, the 4.6 K delivery and return lines by an internal shield cooled by gas which leaves the liquefier at about 50 K, and the 50 K shield line by the shield return stream at about 100 K. (Figure 5 shows the configuration of a typical transfer line.)

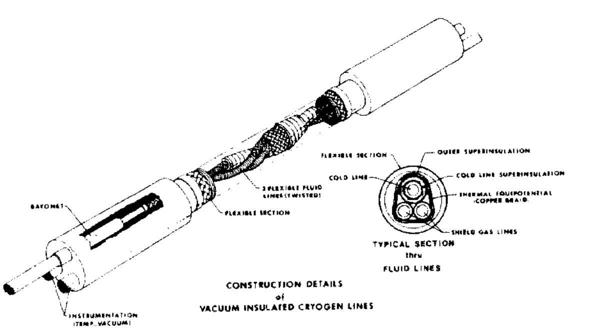

Fig.5 Typical construction of the cryogen transfer lines.

Field Alignment

Once the magnet cryostat was cooled down and filled with liquid helium the first task was to align the magnet system. The lower pole is dowelled into the yoke and its vertical axis of magnetic symmetry is taken as the reference axis of the magnet system. By a series of field maps with poles saturated (150 A in inner coils and 50 A in outer coils) and displacing trim rod set #10, measuring first with upper rods fully retracted, then lower rods retracted, then all rods at zero retraction, it was possible to separate the eccentricity of the field measuring apparatus from that of the upper pole. These were both centred then the inner current raised to 600 A. With the major field contribution then coming from the coil, the eccentricity of the coil could be determined and corrected by adjusting the tension in the radial bracing bars.

Next the "zero" positions of the individual trim rods was determined by plotting the field "dimple" round each rod at various retraction configurations.

After the field profile and magnetization of the injection steering magnets is checked in the presence of a 4 Tesla main magnet field the field measuring apparatus will be removed to permit the installation of rf dees, cryopumps, foil changer, and lower pole trim rod drives.

Injection System

While the cyclotron was being moved from the development laboratory, work was in hand to set up the injector and bunchers. The beam line system is described elsewhere in these proceedings[3]. In early 1984 it was found that many of the diagonal members of the column supporting structure in the 13 MV tandem electrostatic accelerator had cracks in the glass insulators and these were returned to the manufacturer for tensile test and repair. After reinstallation of the column, preliminary tests of the bunchers were performed, with a 30 MeV C^{3+} beam. In late 1984, an accelerator tube was found to be leaking through pores which had developed in the vinyl acetate cement. The tube was removed and after a successful test heating, all the tubes were returned to the manufacturer and the cemented joints re-fused by baking. The tandem was reassembled and tested to 15 MV without the tubes. Tests with the tubes in place are now in progress. Conditioning is approaching 13.5 MV, the desired operating level.

The injection stripping foils are expected to have a lifetime of the order of hours and thus must be renewed frequently. Foils are supplied from a magazine located on the top of the cyclotron and loaded onto a transport chain which carries them down the upper tuner stem into a dee. The chain positions each foil at its correct radius for the particular ion being injected. Details of the foil changer system[4] are described elsewhere in these proceedings.

RF System

The rf system including the low energy buncher, high energy rebuncher, low level drive and phasing system and the cyclotron dee power amplifier have been installed. The bunchers have been tested with beam and the power amplifier operated into a dummy load. Installation of the accelerating structure dees in the magnet will start soon.

The rf accelerating system was earlier operated to full voltage under manual control. The full rf system has now been interfaced to the control computer and is operable via the computer from the main control room. Start up of the dees may require local control to break through the multipactoring levels. Since the 1982 tests, improvements have been made to the cooling in the dees and in the power amplifier. Parasitic suppression was improved in the power amplifier and a trombone tuner fitted to the amplifier drive line to tune out harmonic resonances.

Beam tests of the bunching system are described elsewhere in these proceedings[5]. For these tests a 150 keV $^{12}C^{1-}$ beam was bunched by the low energy buncher, accelerated to the tandem terminal at 7.5 MV, stripped, and accelerated back to ground potential. Approximately 100 nA of 30 MeV $^{12}C^{3+}$ was selected at the first beam line dipole and transported through the energy analyzer following the high energy buncher. Bunch lengths of 1.6 nS (FWHM) or 20° phase length at 35 MHz were measured at the high energy buncher.

The phase stabilization circuits were shown to operate effectively for beam currents of 100 nA or greater. Beam phase jitter from transit through the tandem is reduced from ± 3° to ± 1/2° by the phase stabilization.

Rebunching of the 20° bunches can not be demonstrated until the beam line to the cyclotron is complete. However, the high energy buncher produced the expected energy dispersion in the following bending magnet (at the phase control slits), independently verifying that high energy buncher voltage was sufficient to rebunch to the 3° required for the required 4×10^{-4} energy resolution at the cyclotron.

Diagnostic Probes

The system of diagnostic probes for the cyclotron beam[6] is described in detail elsewhere in the proceedings. Two quasi-radial probes are set 90° apart in azimuth and may be moved on carriages from outside the cyclotron to a radius of 135 mm along lines offset 40 mm from the cyclotron centre. The first of these probes passes 30° downstream from the injection stripper foil azimuth. Two types of interchangeable probe head are used, a differential radial head and a five element axial head.

In order to make the best use of the two radial probes at 90° and to cope with problems of analyzing probe turn pattern signals for the commissioning ion, iodine accelerated to 10 MeV/u, which will have a radial betatron frequency close to unity, a turn pattern analysis code has been prepared and tested. This code will correlate information from the two probes and derive estimates of the orbit eccentricity and radial and axial betatron frequencies.

A third split-plate stub probe is built into the cryostat wall and may be moved out to intercept the beam 20° downstream from the exit of the electrostatic extraction deflector.

Provision has been made for a flexible probe to be moved up the extraction channel beam pipe to sense the beam orbit along the channel.

The probe system is operated through a satellite LSI-11 control computer which communicates with the main system computer, a PDP-11/44, via CAMAC highway resident memories. It is intended that other cyclotron subsystems such as the cryogenic system and the cyclotron coil power supply and interlock system will be ultimately controlled by similar dedicated satellite computers.

Extraction

A radial precession of the extraction orbit centre will be initiated by introducing a first harmonic magnetic bump via the outermost trim rods. This will enable the beam to clear the septum of the electrostatic deflector, which will then move the beam out further and steer it into the entrance port of the magnetic channel. Fixed radial focusing and steering between the electrostatic and magnetic channel sections is maintained by saturated iron bar elements mounted on the cryostat wall. Compensation for central field perturbations is provided by additional iron bars located diametrically opposite.

The electrostatic deflector will be installed after a beam has been successfully injected and accelerated out to the extraction radius. The high voltage feed line to the deflector electrode has been modified to include a limiting series resistor in the dee. This resistor (greater than 10 MΩ) is a short column of high resistivity flowing water[7] located in the body of a coaxial support insulator. A standard high voltage cable, contained within coaxial teflon and copper tubes, connects to the resistor. Water flows in the annular regions between these tubes and the cable from a header located at the top of the cyclotron. The copper tube forms the vacuum envelope for the high voltage feed system.

The 78 superconducting niobium-titanium magnet windings of the magnet channel are assembled in 9 modules (see Fig. 3). The first three modules contain fixed gradient iron bar elements, the last six have variable gradient windings all in series. The bias or steering windings are powered in three groups with separate excitations, which are shared by related central field perturbation correction windings. The modules are attached to a 316L stainless steel strongback which fits tightly between the helium vessels of the main coil and supports the axial mechanical load of the main coil in the extraction region. The whole coil assembly and its instrumentation is contained in a welded stainless steel tank which is fed with liquid helium from the lower main coil vessel and vents via the electrical lead housing back to the top of the upper main coil vessel. A rectangular section chromium-copper beam pipe (8 x 13 mm in Channel 1 and 12 x 13 mm in Channel 2), which is cooled by helium gas forced at 60-80 K through tubes soldered into its corners, provides internal thermal shielding for the channel, acts as a shield for spilled beam energy and isolates the cryostat and midplane vacuum spaces. The ends of the beam pipe connect with the cryostat outer wall via stainless steel bellows which provide a thermal resistance between the cold beam pipe and the room temperature cryostat wall and enable the beam pipe and channel assembly to move 2 mm radially inward when the cryostat is cooled down from room temperature.

The eight refrigerated electrical leads conducting the channel currents were made from copper foil strips packed into rectangular stainless steel tubes. Designed for an original Nb_3Sn channel magnet concept they are rated at a higher capacity than required for the 200 Ampere design maximum of the Nb-Ti channel and thus contribute a larger heat flux than is strictly necessary, amounting to a total of 6-1/2 watts at optimum cooling flow. However, because of the over-rating, the same cooling flow is adequate whether the leads are carrying current or not, which makes their cooling control simpler than that for the main magnet leads.

Beam Dynamics Computation

SUPERGOBLIN[8], the enhanced accelerated orbit code used to track ions through injection, acceleration and extraction in the Chalk River superconducting cyclotron is described elsewhere in these proceedings. SUPERGOBLIN contains routines to deal with the spiral dee gaps, to compute beam transfer matrices to second order and thus interface with transport codes such as TRANSPORT and TRANSOPTR, to find the reference injection trajectory, and to represent the components of the extraction channel. An option which allows cyclotron parameters searches and fitting, has been used to determine the optimum extraction channel parameters.

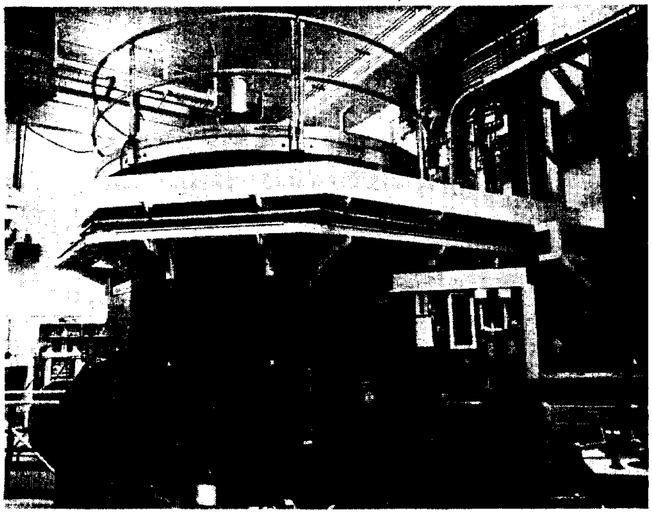

Fig. 6 The cyclotron assembled in its vault.

Conclusions

Figure 6 shows the cyclotron assembled in its vault. At present the magnet alignments are complete. The dees, foil changer, and cryopumps will be installed next and vacuum established in the midplane region ready to receive the first injected iodine beam from the tandem. When the iodine beam has been developed as far as the extraction radius at 650 mm the electrostatic deflector will be installed and work will begin to thread the beam through the extraction channel.

We anticipate an extracted beam of 10 MeV/u iodine by the late summer.

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