CURRENT STATUS OF THE SUPERCONDUCTING CYCLOTRON AT CHALK RIVER

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ABSTRACT

The Chalk River Superconducting Cyclotron has now been in operation for more than three years. The K=520 instrument, designed as the energy booster for the 15 MV Tandem Accelerator, will eventually accelerate beams from lithium (50 MeV/u to uranium (10 MeV/u). The cyclotron is described, with emphasis on recent developments. Six new beams have been developed over the last year, indicating rapid progress towards full commissioning of the machine.

INTRODUCTION

The Chalk River Superconducting Cyclotron was conceived as the energy booster for the laboratory's electrostatic MP Tandem accelerator. Together, these two accelerators are the centre of the Chalk River Tandem Accelerator Superconducting Cyclotron (TASCC) facility. An injector recently equipped with a Trainor modified[1] Hiconex 860 ion source provides negative ions of almost any element with high intensity ($\geq 10\mu A$), good emittance, and high stability. Beams are injected into the Tandem accelerator at 200 kV. The Tandem, in service since 1972 and upgraded several times, was equipped with new tubes in early 1988, and is now commissioned to 15 MV. Tandem beams are injected into the cyclotron for post-acceleration or delivered directly to the experiments via a by-pass line. The beam distribution system servicing the laboratory's three major experimental facilities (the 8π-Spectrometer, the Large Scattering Chamber, and the On-line Isotope Separator) was commissioned in July 1988. All other beam lines are to be completed later this year.

The cyclotron is specified to accelerate ions from lithium (50 MeV/u) to uranium (10 MeV/u). It delivered its first beam[2], ^{127}I at 10 MeV/u, late in 1985 and a second beam, ^{127}I at 5.6 MeV/u, several months later[3]. Since then, planned facility shutdowns (12 months in total) have hampered the development of new beams. The time was used to develop the cyclotron towards a fully engineered, reliable accelerator capable of reaching the full range of its original specifications. Much progress has been made, and new beams have been developed.

DESCRIPTION OF THE CYCLOTRON

While all subsystems of the cyclotron have undergone some development, the machine's basic concept and its innovative features have proven themselves and consequently have remained unaltered. Figure 1 shows a cut-away of the cyclotron, exposing its main design features. The main machine parameters are given in Table 1.
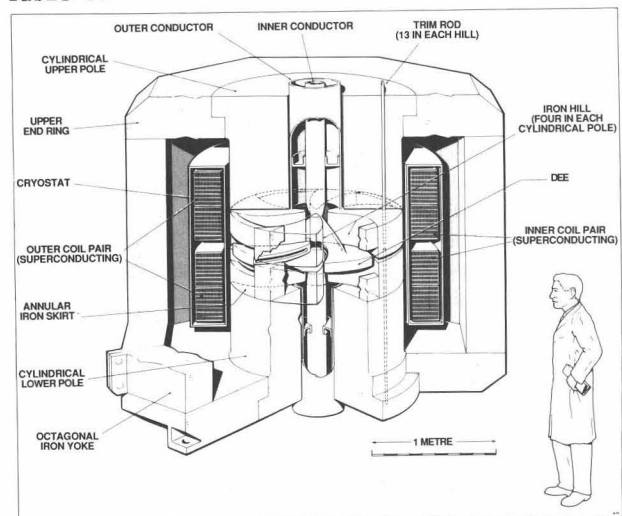

Fig.1 Schematic view of the Chalk River Superconducting Cyclotron

The cyclotron has four-fold magnetic symmetry. This provides four magnetic valleys in which to locate four accelerating dees. The Tandem beam is injected radially into the cyclotron's midplane through a magnetic valley. Thus, the centre axis is not required for beam injection and this space is used to accommodate two coaxial-line tuners, each supporting a pair of dees. The whole accelerating structure forms a single resonant cavity, which is capacitively driven by a single power amplifier. The magnet is excited by two separately driven copper-stabilized superconducting niobium-titanium pancake-wound coils, divided into inner and outer pairs. An isochronous field is set up using computed values of the currents in the outer and inner coil pairs and the axial position of 13 trim rods located in each of the eight magnetic flutter poles.

The resonant cavity can be operated in 0-mode or π-mode, with the two pairs of dees either in phase or antiphase. In zero mode, the harmonic mode is always h=4, whereas in π-mode two operating regimes are used, h=2 and h=6.

INJECTION AND EXTRACTION

In preparation for injection into the cyclotron, the beam is bunched in the gridded-gap prebuncher located between ion injector and Tandem accelerator. Its grid structure suffered initially from short lifetime (several weeks) and has been replaced by an open venetian blind arrangement with very much longer mean time between failure. The prebuncher contains two cavities tuned to the cyclotron fundamental and 2nd harmonic frequencies, to approximate a saw-tooth waveform at the grid. The bunches reach a time focus at the tandem stripper canal to minimize the effects of energy spread from straggling.

The injection beam line[4] to the cyclotron consists of three achromats, including the cyclotron. Emittance matching is achieved by optimizing three matching quadrupoles. A drift tube harmonic buncher, located between the first two achromats, rebunches the beam to give a time focus at the stripper foil near the center of the cyclotron. The foil, whose position can be adjusted radially, strips the incoming beam for injection into the first accelerated orbit. Figure 2 shows a mid-plane section of the cyclotron.

The bunching efficiency is typically 50%. The bunch length as measured with a beam pulse detector just ahead of the cyclotron is less than 4° rf, including injection phase jitter of about $\pm$ 1/2°.

Single turn resonant extraction from the cyclotron is initiated using the outermost trim rods. The beam then enters an electrostatic
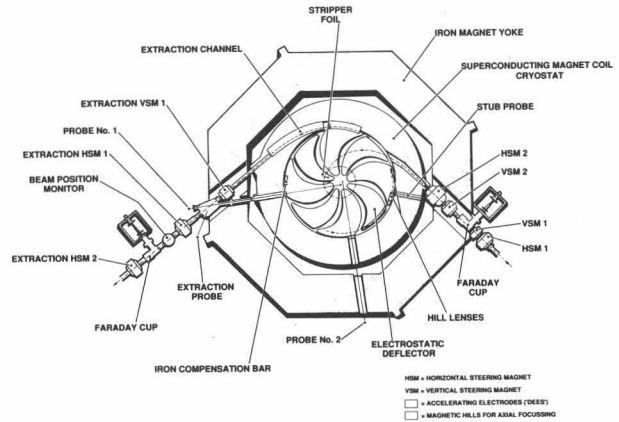

Fig. 2 Midplane section of the cyclotron

channel where it is deflected into the magnetic extraction channel. Radial focusing is maintained by saturated iron lenses, hill lenses 1 and 2, located on the wall of the coil cryostat. The magnetic extraction channel[5] is comprised of 78 separate dipole superconducting coils and 12 saturated iron gradient bars. In its narrowest part the cryogenic beam pipe is only 8 mm high and 12 mm wide. The channel is 1.2 m long.

ENGINEERING IMPROVEMENTS

Improvements incorporated since the 11th Cyclotron Conference have resulted in increased reliability of almost all cyclotron subsystems. Only a few major examples can be given here. At the cryogenics plant, a second screw compressor and an auxiliary plant monitoring system have been installed. The main magnet is now monitored under satellite computer control. The rf driver amplifier was rebuilt and new tuning procedures were established. Numerous improvements were made in the probe computer, the control computer and in the beam dynamics code SUPERGOBLIN. Extensive mechanical changes have been made to the trim rod drive train. A precision measurement bridge has been built to locate accurately all components in and near the midplane. Also, a collapsible tuner and flexible supply lines have been designed, to allow us to open and close the cyclotron within a few hours.

MIDPLANE BEAM DIAGNOSTICS

Midplane diagnostic instrumentation is essential for the correct setting of the machine's operating parameters. Improvements have been made to all diagnostic tools, and several have been added. Two radial probes, P1

and P2, (see Fig.2) are used to track the turn pattern of the accelerated beam from the centre of the machine out to the extraction radius. Each has five 1 mm wide fingers of 12 mm total height which allow us to detect vertical beam displacements, and an integral plate for total beam intensity measurements. Difficulties were encountered with early versions of these probes, such as overheating, rf interference and cross talk between fingers. These problems were particularly severe in π-mode operation. These problems have been overcome successively. The latest design provides for increased cooling, concentric rf shields and reduced outgassing under high beam load. It also incorporates a seventh sensing element, a wire capable of probing the beam with high spacial resolution. The axial and radial beam position information from these probes is used to check rf phase, orbit centering, and field isochronism.

The extraction trajectory can also be monitored by a movable stub probe and newly installed fixed horizontal and vertical scrapers mounted in hill lenses 1 and 2 respectively. Also new is the Six Finger Array at the entrance of the extraction channel. It consists of four jaws surrounding the channel entrance and two additional jaws to detect beam spill on the protrusion accommodating the first element of the extraction channel. The masterpiece of our new diagnostic devices is the extraction probe, which tracks the beam trajectory along the long and narrow extraction channel. It consists of a split head, Figure 3, (right-left at present, four quadrants in the near future) mounted on a long flexible drive strip. The assembly is inserted under computer control over a length of 2.5 m from outside the cyclotron.
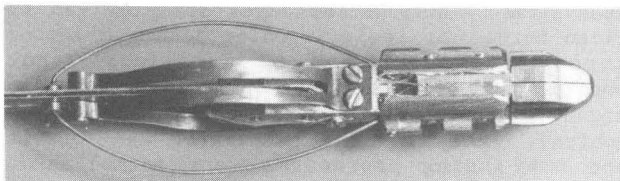

Fig. 3 Extraction channel probe head

DATA ACQUISITION

The probe system is operated through a satellite LSI-11 control computer which is also used to collect the diagnostic information. The probe computer has been linked to a Concurrent 3230 system, and an extensive data evaluation package (PATTURN) has been written. This enables us to analyze beam parameters within minutes of taking a scan. Another new program guides us in calculating corrections in trim rod settings to improve orbit centering. Together, the extended diagnostic and analytical capabilities aid us greatly in developing new beams.

THE ELECTROSTATIC DEFLECTOR

The deflector[6] is located in a dee, subtends 31° and has a beam aperture of 7 mm. The septum and sparking plates are molybdenum, the deflector electrode is stainless steel. High voltage is supplied to the deflector electrode through a standard high voltage cable and a series resistor, a short column (20 mm long) of flowing high resistivity water located in the body of a coaxial support insulator for the deflector electrode.

At present, the operation of the deflector is limited to 60% of design voltage of 100 kV. This limitation is imposed by leakage currents: Above 60 kV across the deflector electrodes, any increase in power supply voltage results merely in increased leakage. Numerous tests failed to pinpoint the origins of the leakage current. Neither a change of insulator material (boron nitride, Macor, Teflon) nor of their geometry, nor of their mounting orientation (parallel or perpendicular to the magnetic field) has resulted in significant improvements. Other modifications like the introduction of pumping slots into the septum support rails and the installation of rf shields to avoid heating did not lead to any change in performance. A new current limiting resistor has been built (but is not in use yet) to replace the water resistor. It is equipped with a capacitive divider which will allow us to diagnose, and hopefully eliminate, the cause of excessive leakage.

THE 1/2 SCALE MODEL

The design of the dees (with one unidirectional stem for each pair) gives rise to electric fields which are asymmetric about the midplane and may cause vertical beam oscillations. Such oscillations are commonly observed when beam acceleration is first set up. Usually operating conditions can be found where after 10 to 20 orbits the amplitude dampens out to below 2 mm, peak to peak. However, significant vertical deflections can re-occur, for as yet unknown reasons, after the resonant extraction and then pose serious operating limitations. A 1/2 scale model of the accelerating structure has been built to study the asymmetries. Figure 4 shows results at 46 MHz for π-mode excitation. The gap voltage decreases with decreasing radius, as expected, but more strongly than calculations[7] had indicated. In both modes a large difference is found between the voltages at the upper and lower lip and between the leading and trailing edges of the dees. In addition, a strong asymmetry has been measured between the upper and lower hill cladding in π-mode only. All asymmetries become more pronounced with increasing frequency.
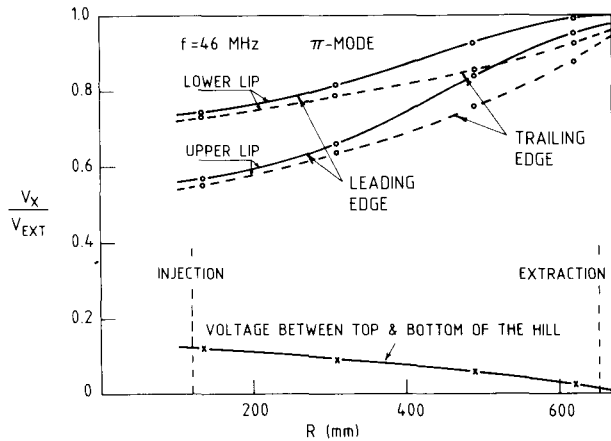
Fig. 4 Dee and hill voltage as a function of radius

Figure 5 shows a second significant result of the model measurements, the power density distribution in the cavity wall, measured at 19 locations along the outer perimeter of the midplane. No danger of overheating exists in 0-mode, whereas in π-mode precarious areas are clearly pin-pointed. These coincide with sites where damage has occurred in the cyclotron. Measurements of this type will allow us to develop solutions without endangering the cyclotron itself.

CHARGE STATE DISTRIBUTIONS

In each of the two successive accelerators at TASCC beam stripping is used, gas stripping in the Tandem, foil stripping in the cyclotron. Since few measurements are available, and we found universal predictions for silver beams to be unreliable, we initiated measurements for a number of beams and energies. Results will be reported elsewhere[8].

NEW BEAMS

Six new beams were extracted from the cyclotron, all over the last nine months. Their location in the mass-energy plane is given in Figure 6. In addition, the two previously extracted iodine beams were revisited. Beams of bromine, silver, and iodine, were selected because of copious production from the ion source. For these beams the cyclotron was operated between 3.19 and 3.90 T, 32.1 and 48.6 MHz, and with a deflector voltage between 28 and 55 kV. For seven of these beams the cyclotron was operated in 0-mode with h=4. A beam of ^{127}I at 5.12 MeV/u was the first π-mode beam accelerated and extracted, thereby proving the feasibility of this acceleration mode for h=6.
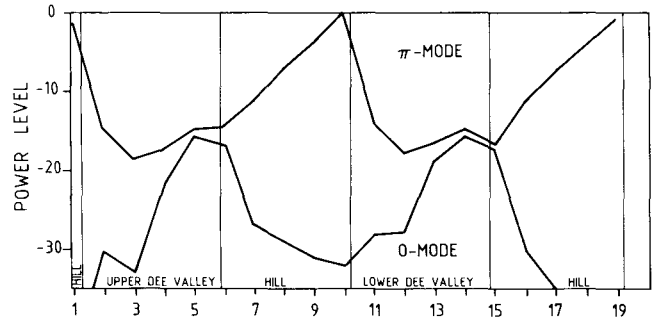

Fig. 5 RF power level (dB) at 19 positions along the cavity wall

The extraction efficiency, defined as the ratio of the extracted to the orbiting beam, was found for all but one beam to be between 25 and 35%. Whether this limitation is imposed by machine parameters or whether it is the temporary limit of the operators' dexterity is unclear at this time. The exception is ^{127}I at 10 MeV/u with an extraction efficiency of 60%, similar to the figure obtained three years ago. Clarification will require further beam studies and extensive beam dynamics calculations.

All beams, again with the exception of ^{127}I at 10 MeV/u, are somewhat unstable in time when observed outside the cyclotron with wobble frequencies of 10 and 60 Hz. However, neither the injected beam nor the resonating system appears to show correlated instabilities. It is noted with satisfaction that the successful parameters for injection, acceleration and extraction are in close agreement with our predictions. This gives us confidence that future beams can be developed at an even higher rate.
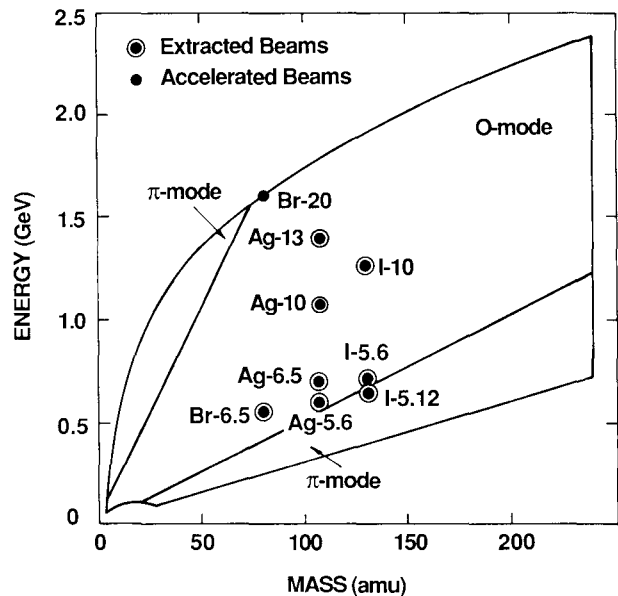

Fig. 6 TASCC beams available as of 1989 May

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FUTURE DEVELOPMENT

While many of the cyclotron's subsystems have now been developed to a satisfactory level, three areas require continued attention: the electrostatic deflector, the extraction efficiency and π-mode heating. However, there are no known insurmountable problems and we expect to reach two major milestones on our ascent to full machine commissioning, ^{28}Si at 25 MeV/u (π-mode, h=2) and ^{79}Br at 20 MeV/u (0-mode, high energy), within the next ten months.

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Table 1

The Chalk River Superconducting Cyclotron

Magnet Poles:
    Four sectors (50° maximum spiral angle)
    Diameter 1386mm
    Inject. radius 145-220mm, extr. rad. 650mm
    Pole gap 40mm in hills, 640mm in valleys
Magnet:
    Nb-Ti, 25:1 copper:superconductor
    6.2×10^6 Ampere-turns maximum
    Coil weight 10 tonnes (18 tonnes with cryostat), yoke weight 150 tonnes
    Operating temperature 4.6 K
Ion Energy Limits:
    Bending 520 q^2/a MeV
Accelerator System:
    4 dees, 100 kV max. rf frequency 31-62 MHz
    harmonics used 2,4,6
Field Trimming:
    Outer and inner coil pairs, separately excited. 13 iron trim rods in each flutter pole, 104 in all.

REFERENCES

1. T.A. Trainor, Proc. Symposium of North Eastern Acclerator Personnel, Oct 1988, Yale University, New Haven, Conn. To be published by World Scientific, Singapore.

2. C.B. Bigham, W.G. Davies, E.A. Heighway, J.D. Hepburn, C.R.J. Hoffmann, J.A. Hulbert, J.H. Ormrod, and H.R. Schneider, Nucl. Inst. Meth. in Physics Research A254 (1987) 237.

3. J.A. Hulbert, C.B. Bigham, W.G. Davies, B.F. Greiner, E.A. Heighway, J.D. Hepburn, C.R.J. Hoffmann, E.H. Lindqvist, J.H. Ormrod, E.P. Stock, and L.W. Thomson, Proc. 11th Int. Conf. on Cyclotrons and their Applications, Tokyo, Japan, Oct 13-17, 1986.

4. W.G. Davies and E.A. Heighway, Nucl. Inst. Meth. in Physics Research A244 (1986) 231.

5. C.R. Hoffmann, J.F. Mouris and D.R. Proulx, Proc. 10th Int. Conf. on Cyclotrons and the Applications, East Lansing, Michigan (1984) 222 (IEEE Cat. No. 84CH1996-3).

6. C.R. Hoffmann and C.B. Bigham, Proc. 1987 IEEE Particle Accelerator Conference, IEEE Catalog No. 87CH2387-9 3 1567 (1987).

7. C. Bieth (GANIL), private communication.

8. G.C. Ball, T.K. Alexander, H.R. Andrews, W.G. Davies and J.S. Forster, "Charge-State Measurements for ^{63}Cu, ^{107}Ag, ^{127}I and ^{197}Au in Carbon for Energies Below 1 MeV/u". To be presented at 13th Inter. Conf. on Atomic Collisions in Solids, Aarhus, Denmark (1989 Aug. 7-11).