# Developing the Chalk River Superconducting Cyclotron for Operation in $\pi$-Mode

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*Abstract*

The Chalk River Superconducting Cyclotron [1] operates in two rf modes. In the $\pi$-mode, the voltages on the four dees move in opposition in adjacent dees, giving rise to high rf surface currents in the cavity wall under the magnetic hills, and to vertical asymmetries in the dee excitation. Studies on a half-scale rf model of the accelerating cavity have confirmed the current distribution and the magnitude of the vertical asymmetries. Cavity cooling provided in the initial design required augmentation for $\pi$-mode operation, but the magnet cryostat prevents access to the outside of the cavity. Additional cooling has been installed with cooling lines passing through high-rf-field regions to demountable cooling plates. Concurrently, instrumentation leads have been added to provide extra diagnostics of beam trajectories entering the extraction system. The added cooling has enabled operation of the cyclotron up to 65% of design rf power at the highest $\pi$-mode frequency, permitting acceleration up to a specific energy of 50 MeV/u, close to the magnetic focussing limit of the cyclotron.

## I. RF MODES

The four dees in the Chalk River Superconducting Cyclotron may be excited in two rf modes: the 0-mode, in which all four dees are in phase, and which is used to accelerate in the range of specific energies 5.2 - 21.5 MeV/u, at the fourth harmonic; and the $\pi$-mode, in which opposite dees are in phase and adjacent dees in anti-phase, and which is used at the sixth harmonic to accelerate in the range 3 - 5.2 MeV/u, and at the second harmonic to accelerate in the range 21.5 - 50 MeV/u.

## II. OVERHEATING

The midplane rf cavity of the cyclotron is lined with copper sheet, which is stabilized mechanically by an external rough vacuum, to balance the internal high vacuum. Water-cooling pipes are attached to the outer surface of the copper liner, inside the rough vacuum space, according to the expected internal rf current distribution. However, for reasons of magnetic and cryogenic system space requirements, cooling pipes could not be located under the magnetic hills, either on the hill faces or at the outer wall of the midplane, except at Hill B (Figure 1) where the beam leaves the cyclotron along the extraction trajectory. Development tests of $\pi$-mode cavity operation, which were performed using a dummy supporting enclosure [2], seemed to indicate that thermal conduction along the cryostat wall would provide sufficient cooling for the areas not directly cooled. Estimates of heat load from heating rate measurements indicated a total midplane load of no more than 1% of the total cavity power. Separate tests using simulated heating on the cryostat inner wall showed the capability of each valley sector to cope with a load of 2 kW.

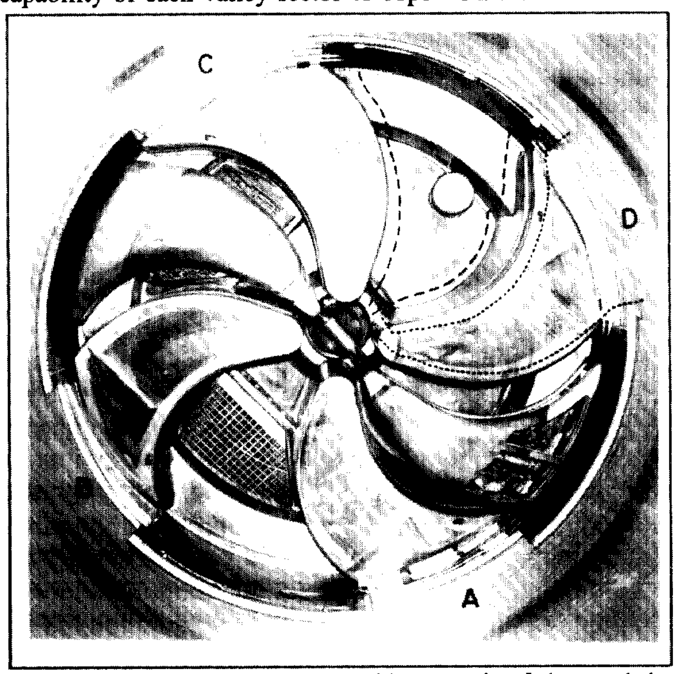


**Figure 1**. Midplane of cyclotron with one pair of dees and the lower pole removed. The dashed line shows the path of valley currents. The dotted line shows the current route along the hills in $\pi$-mode.

However, when the rf structure was installed in the magnet cryostat, operation in $\pi$-mode gave rise to overheating at the outer cavity wall, which threatened the integrity of midplane seals in the cryostat and the mechanical stability of the cryostat inner wall, even at an rf power level of only 15 kW.

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In 0-mode the charge on the dee-to-ground capacitance can change by a current that flows up the tuner stem and down the tuner outer conductor, across the valley floor to the midplane. To first order, the voltage on each dee pair oscillates with reference to the potential of its own valleys, with the small coupling capacitor $C_C$ (shown in the equivalent circuit of Figure 2) maintaining the two dee pairs in phase, so that there is no current flow between top and bottom of the cavity. In

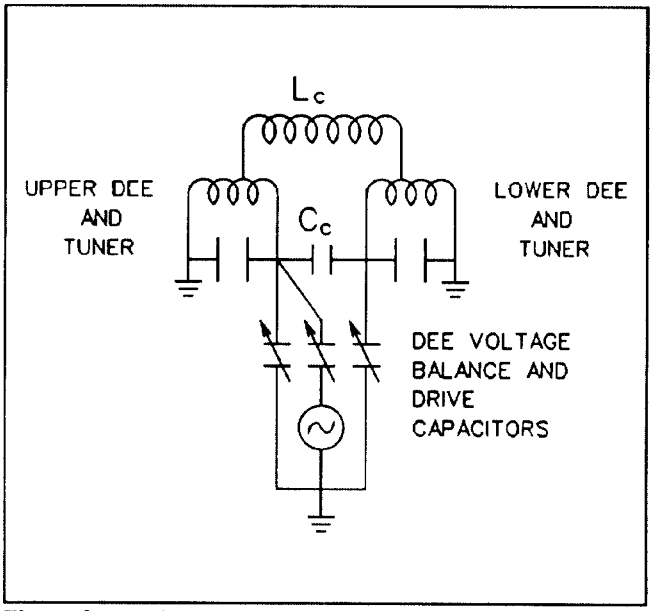


**Figure 2**. Equivalent circuit for 0- and $\pi$-modes of the accelerating cavity.

$\pi$-mode, charge has to flow from one dee pair to the other. The most direct path is along the edges of the hills, and down the outer cavity wall from one end of the structure to the other, represented as the inductor $L_C$. The current paths in the two modes are indicated in Figure 1. The cooling pipes on the outside of the cavity surface on the sides of the hills seem to provide sufficient cooling for the hill surface currents, but cooling on the cryostat wall around the valley panels was too remote from high-current areas on the vertical wall "under" the hills to be effective. The hill edge currents also coupled into the radial probe stems, causing disastrous overheating in the initial probe design, which had no effective stem cooling.

## III. Half-scale Modeling

*A. Cavity Outer Wall Currents*

A precise half-scale model of the accelerating cavity was constructed and wall currents measured to confirm the distribution of the heat sources in the outer cavity wall. Typical results of these measurements are shown in Figure 3. Using the tuner short-circuit current as a reference, valley currents near the convex dee-edge are similar in the two modes, but elsewhere, local surface current densities in $\pi$-mode can be five times higher than found anywhere in 0-

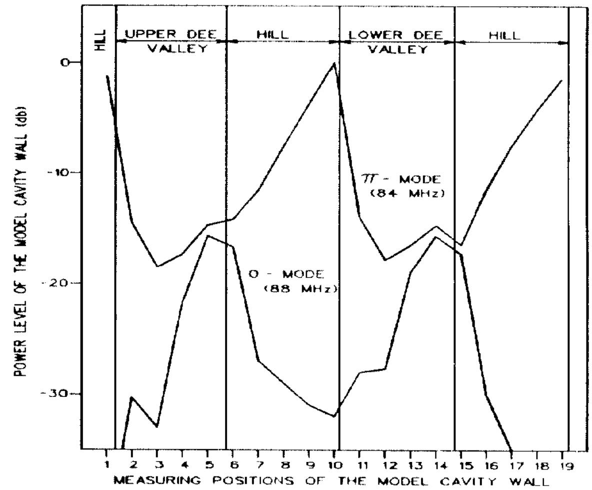


**Figure 3**. Loop probe measurements of cavity wall currents around the half-scale model circumference.

mode. In particular, the highest densities occur at the outer cavity wall, under the hills, and near the convex side of each hill, as indicated by thermometers inside the cryostat in the actual cyclotron. These locations are close to the radial probe ports and the hill lens #2 element of the extraction system.

*B. Vertical Asymmetries in the Midplane*

Measurements on the model with a capacitive probe show voltage differences, between the upper and lower edges of the dee gap at inner radii, in both 0-mode and $\pi$-mode, of as much as 20% of the mean dee voltage, caused by the vertical geometric asymmetry of the dees. In $\pi$-mode, an additional vertical voltage arises across the hill gap from the currents flowing between top and bottom of the cavity.

The resulting vertical field components in the accelerating gaps affect the beam motion, particularly at low radii. At optimum rf phase, the vertical impulses tend to be compensating, except for motion either side of the stripper foil. The effect is that the charge change causes the first turn to suffer a large vertical deflection with the motion damping in subsequent turns. This leads to a loss in injection efficiency by scraping on the vertical aperture.

## IV. Augmented Cavity Cooling

The model measurements confirmed the intuitive analysis of the $\pi$-mode heating problem, but the magnet cryostat prevented access to the outside of the cavity for attaching additional cooling where indicated. A single access port to the midplane region remained unused, through the upper pole. Through this port (on the floor of the valley between hills marked "A" and "D" in Figure 1) a four-branch water manifold was introduced. Demountable supply-and-return connectors, sealed with O-rings, were set on the manifold at valley floor level, and were shielded from rf with a grounded copper dome. Cooling lines were then run within the cavity, from the manifold, to four locations where extra cooling was most critically required. Ideally, the cooling lines would have been fastened to the cavity surface to eliminate induced rf currents, but the vulnerability of the cavity liner made this hazardous. Instead, the lines were carefully separated and positioned about 6 mm from the cavity surface, coming into contact only when they entered the midplane gap. Essential pipe-to-pipe contacts were stabilized by soldering with indium. Crossing the outer end of the hills, contact of the lines was maintained with the cavity surface. Lines passing round to the next hill sector crossed the valley at the low corner of the midplane region, well clear of the dees, and were firmly anchored at three locations. In close to 10 000 hours of rf operation there has been no sign of any rf action around these cooling lines.

The cooling was applied to silver-plated copper plates fitted with heavy contact springs, which bridged the cavity wall at the outer edges of the hills. These plates diverted the $\pi$-mode currents away from the areas where cavity wall heating had been excessive.

The four hill sectors (marked A,B,C and D in Figure 1) were treated differently in detail. Sectors C and D each contain one radial probe port. They were cooled in series by a single cooling branch having one bridge plate in each sector. The probes enter the midplane through ring-contact grounding springs. The springs were moved to the bridge plates to prevent rf currents being guided to the backs of the plates. The remounting lost the precision of the spring location, so probe guide bushings were incorporated in the spring mounts and the springs strengthened.

In sector A, two cooling streams were employed. One stream cooled the two hill lens mounting brackets, in series. The second stream was used to cool a short bridge plate, which protected instrumentation lines in the sector from rf currents. Radiofrequency heating of the hill lens was stabilised and a cooling path for the heat established, by replacing the detachable copper covers on the lenses with heavy silver plating. Further, the attachment of the lenses to their (now cooled) mounting brackets was modified, very simply, to ensure a good thermal path to the bracket. An additional benefit from this treatment was the elimination of arcing between the lenses and the hill surfaces.

Sector B, which contains the beam extraction port, had been cooled in the initial design, partly because access was possible from within the cryostat, as for the valley region cooling, but also because the wall in that sector protruded into the mid-plane. The remaining (fourth) cooling branch was therefore used to support and cool instrumentation lines to a set of beam scrapers situated round the extraction port.

The instrumentation signal lines, introduced as part of the cavity cooling modification, consisted of bundles of UT 34 semi-rigid coaxial cable encased in copper sleeves. The sleeves were thermally and electrically bonded to convenient cooling lines at intervals of 80 mm, with pure indium solder. The instrumentation lines carry signals from thermometers located on the hill lenses, and from beam scrapers at the extraction port, and at hill lens apertures. The beam scrapers have proved essential in locating and directing the accelerated beam through the extraction system.

With the added cooling at the cavity walls, hill lenses and probe ports, and with cooling added also to the electrostatic deflector electrode [3], operation of the cyclotron has been made possible in $\pi$-mode, at up to 65% of design specification power. With this capability, beams of 50 MeV/u $^{12}C$, with currents up to 140 nA, have been extracted, proving the cyclotron to the maximum specific energy for the original design focussing limit specification.

## V. ACKNOWLEDGEMENTS

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