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THE CHALK RIVER HEAVY ION SUPERCONDUCTING CYCLOTRON

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Summary

A detailed study of an isochronous cyclotron as an energy booster accelerator for the Chalk River 13 MV MP Tandem Van de Graaff has been undertaken. The cyclotron is intended primarily for heavy ions but would accelerate all ions from Li^{+3} to U^{+33} to at least 10 MeV/u. NbTi superconducting coils supplemented with cylindrical iron poles provide an average magnetic field of $\sim$ 5T out to the extraction radius (0.65 m). Four saturated iron sectors with spiral edges provide focussing. Bunched ions are injected from the Tandem into the cyclotron midplane and stripped at the innermost orbit. An eight gap spiral edged rf structure provides 0.6 - 0.8 MV of accelerating voltage per turn. Electrostatic deflection initiates single turn extraction of the beam.

Introduction

A review[1] by nuclear physicists at Chalk River showed that a booster accelerator added to the existing MP Tandem facility would open up attractive research areas using heavy ion beams. Such a booster should provide a variable energy beam up to 10 MeV/u for heavy ions and up to 50 MeV/u for lighter ions. The beam should be of high quality with a maximum energy spread of the order of 0.05%. Desirable intensities would be 10^{12} particles/sec for the light ions and 10^{10} particles/sec for the heaviest ions. A study of various possible accelerators was begun in March 1972, climaxing with the proposal of a novel isochronous cyclotron,[2,3] which exploits existing superconducting magnet technology[4]. The preliminary estimated cost ($2.2M, 1973 dollars, for accelerator plus support systems) is generally lower than for other plausible boosters. Furthermore, the concept requires no new technology, but a new combination of existing technologies. In 1963 Berg[5] proposed superconducting coils for a cyclotron magnetic field, but adequate development was lacking. Recently others also have proposed heavy ion cyclotrons based on superconducting magnets, notably the group from Michigan State University (MSU)[6].

At Chalk River a computational and experimental study of a full scale model of the magnet and rf system has begun. This study is expected to last about two years. It is anticipated that major components of the model will be transferable to the final machine with minimum changes. Construction of the complete machine and experimental facility will depend on the successful outcome of these studies and confirmation of acceptable cost estimates.

General Description

The superconducting cyclotron is a four sector AVF machine with high magnetic fields and compact size. Its geometry as presently conceived is shown in Fig. 1. Unlike the original air-cored concept[2,3] much of the coil bore is filled by two cylindrical iron poles connected to an iron yoke. Four pairs of spiralled iron flutter poles attached to the cylindrical poles generate the azimuthally varying focussing field. Iron "skirts" (see Fig. 1) located between the flutter poles aid field isochronizing. Axially movable iron rods are proposed for field trimming. Accelerating voltage is generated with two coaxial resonators located on axis on either side of the midplane. Two dees are attached to each resonator creating eight accelerating gaps. The maximum average midplane field of 5T is 3-4 times larger than in most conventional cyclotrons, reducing the physical size substantially. The iron in the coil bore is fully saturated.

A bunched Tandem beam is stripped on the cyclotron midplane for capture on the innermost orbit and accelerated to an electrostatic extractor in about 100 turns. The expected operating region is given in Fig. 2 as a plot of specific energy against atomic mass number. Details are discussed below.

Injection

The major component of the injection system is the MP Tandem with its negative ion source. A harmonic buncher, located between the ion source and Tandem, tailors the beam for acceptable final energy spread of the accelerated cyclotron beam. Calculations indicate that the buncher can compress $\sim$ 45% of a monoenergetic dc beam into 3° of cyclotron rf phase. With no flat topping of the rf waveform the output energy spread from a perfectly isochronized cyclotron is $\sim$ 0.04%. Less beam is compressed into the 3° phase width if the ion source has a significant incoherent energy spread. For example, 50 eV spread in a 250 keV negative uranium beam causes a factor of two reduction. This effect is less severe for the lighter ions.

The stripper foil is located at the tangent point of the injection trajectory and the equilibrium orbit of the captured beam. For a fixed trajectory into the cyclotron and fixed extraction radius the stripper must be movable to accommodate the full range of ion beams. Requirements are eased if beam steering is used prior to entry.

Magnet

The major components of the magnet system are the superconducting coils, the iron yoke, the flutter poles and the trim rods. The trim rods are a change from the original air-cored concept, as is the replacement of the iron shield by a yoke and cylindrical pole pieces in the coil bore, which reduces required ampere-turns.

Superconducting Coils

The two superconducting coils are shown schematically in Fig. 1. Each coil has a winding cross section of 0.65 m high by 0.2 m wide and an inside diameter of 1.5 m. The vertical gap between them (bisected by the machine midplane) is 0.12 m. Each coil is split electrically into an inner and outer member (with respect to the machine midplane) to aid field shaping. The coils are pancake wound, 32 pancakes per coil with 42 turns per pancake.

The conductor is multifilament NbTi twisted with a 50 mm pitch and mounted in a copper matrix of cross section 17.0 mm x 4.0 mm. The maximum hoop stress is estimated to be $\sim$ 60 MPa, which can be supported by copper without stainless steel reinforcement. To generate an average field of 5T each coil needs 3×10^6 ampere-turns. The overall current density is 2300 A/cm^2 (the conductor current density is $\sim$ 3400 A/cm^2).

The coils are contained in a liquid helium cryostat, each coil being in its own separate helium bath within the cryostat. The thermal loads are expected to be distributed roughly equally among transfer tube, current leads and radial bracing. A CTI-1400 helium liquefier with four compressors and a capacity of 100 W at 4.5 K should meet the requirements. It is estimated that about 25 W will maintain the coils at the operating temperature. The cooldown time from room temperature is expected to be $\sim$ 150 hours. The cryostat will fit closely to the cylindrical poles. Access space is provided between cryostat and yoke.

Yoke

In the original concept, the coils had a large bore dictated by the field shaping method and a closed iron cylinder surrounded the whole machine for magnetic and partial radiation shielding. In the present concept the yoke maintains the shielding while the iron poles extending from the top and bottom of the yoke allow substantially smaller coils with decreased magnetic fields at the windings. Hoop stresses become low enough to no longer require stainless steel reinforcing, thus simplifying construction.

The two cylindrical pole pieces are 1.38 m in diameter and extend to 0.32 m from the midplane. The yoke is 2.7 m high with an outside diameter of 4.3 m. Other alternative configurations are also being considered.

Flutter Field

The azimuthally varying field needed for axial focussing is generated by four pairs of saturated iron poles located symmetrically 20 mm above and below the median plane, increasing the field locally by $\sim$ 1.6 T. Axial focussing is further increased by spiralling the pole edges. At the maximum average field of 5 T focussing is adequate for 10 MeV/u uranium beams. This method of generating the focussing field has the unusual characteristic that the flutter factor depends inversely on the square of the average field[7]. Thus at lower fields improved axial focussing allows higher specific energy beams as shown in Fig. 2.

Field Trimming

The average radial field profile must be adjustable to obtain isochronism over the range of ion beams. It is proposed to vary two parameters to accomplish this: the current distribution in the coils and the localized gap between flutter pole pairs. If the ratio of the currents in the inner and outer members of the superconducting coil is altered a general change is caused in the radial profile. The magnet gap can be changed locally by moving cylindrical iron rods in vertical holes which extend from the flutter pole face to the top (and bottom) of the yoke. Rod movement to create a void 60 mm high in a flutter pole is equivalent to having $\sim 10^5$ A circulating on the void wall. The void acts as a small high current trim coil close to the midplane. Calculations and 1/4 scale model experiments with saturated nickel ($\mu_0 M_s \doteq 0.6$ T) suggest that a 1% field change is possible with about 13 rod positions per flutter pole. The diameters would be 40-60 mm and the radial spacing would be $\sim$ 1 rod diameter. The estimated force to hold a rod in position is manageable, $\sim 10^4$ N. An alternative to iron rods would be trim coils such as those proposed by the MSU group[6].

RF Structure

Efficient extraction requires complete

beam separation between the last two orbits. This imposes a lower limit on the accelerating voltage. Electrical breakdown fixes the upper limit. In the present design a minimum orbit separation of 2 mm at extraction is chosen (which does not include enhancement from the $\nu_r = 1$ resonance). The rf system must therefore provide 0.6 - 0.8 MV per turn. Eight accelerating gaps are used, which keeps the voltage per gap reasonably below the breakdown limit. Four dees are located in the spaces between the four pairs of flutter poles, as shown in Fig. 1. The dees are mounted on two quarter wavelength resonators located on the machine centerline, one on either side of the midplane. As indicated in the 1/10-scale model shown in Fig. 3 each resonator has two diametrically opposed dees connected to it. The resonators are tuned with sliding shorts and are operated either in phase (harmonic number h=4) or antiphase (h=2). Experiments with the model show that the required tuning range of 23-47 MHz for specific output energies of 3-50 MeV/u can be attained in this geometry. It is expected that about 100 kW of rf power will drive the resonators to 100 kV peak voltage, giving voltages per turn of 0.8 MV for h=4 and 0.6 MV for h=2.

Extraction

Beam extraction in a high field cyclotron is difficult. The ratio E/(vB) gives a quantitative indication of this for electrostatic deflection, where E is the deflecting electric field, v the particle velocity and B the magnetic field. In this cyclotron E/v is roughly comparable to that in conventional machines. Since E is usually near its upper limit (breakdown), the ratio is decreased by a factor of 3-4, with a corresponding reduction in attainable deflection.

A comparison of the ratio E/(vB) for beams of interest shows that the most difficult beam to extract will be carbon at 50 MeV/u. Preliminary calculations indicate that such a beam can be deflected into an escape trajectory by two electrostatic deflectors in adjacent sectors operating at 130 kV/cm. However, strong radial defocussing occurs. A beam 2 mm wide at the extractor grows to $\geq$ 50 mm wide after 2/3 of a revolution from start of deflection - the radial position is near the outer edge of the coils. The magnetic field decreases at the rate of 14 T/m.

Some methods of avoiding strong radial defocussing seem plausible with various kinds of magnetic channels following the electrostatic deflectors. One possibility proposed by the MSU group[6] is to use a superconducting pipe which excludes the magnetic field from the interior. Present activities at Chalk River aim at studying the limits of some magnetic channels which do not exclude flux.

It is intended to explore the $\nu_r = 1$ resonance to increase orbit separation at the start of extraction.

Current Status

Computer studies exploring iron and coil configurations to provide isochronism and focussing are underway as well as computer modelling of the extraction problem. Small scale model experiments continue, but major effort is directed to preparation for full scale magnet and rf system experiments. Installation of the first major component to be acquired, the helium liquefier, has begun. The superconductor and the iron for the magnet should be ordered shortly.

References

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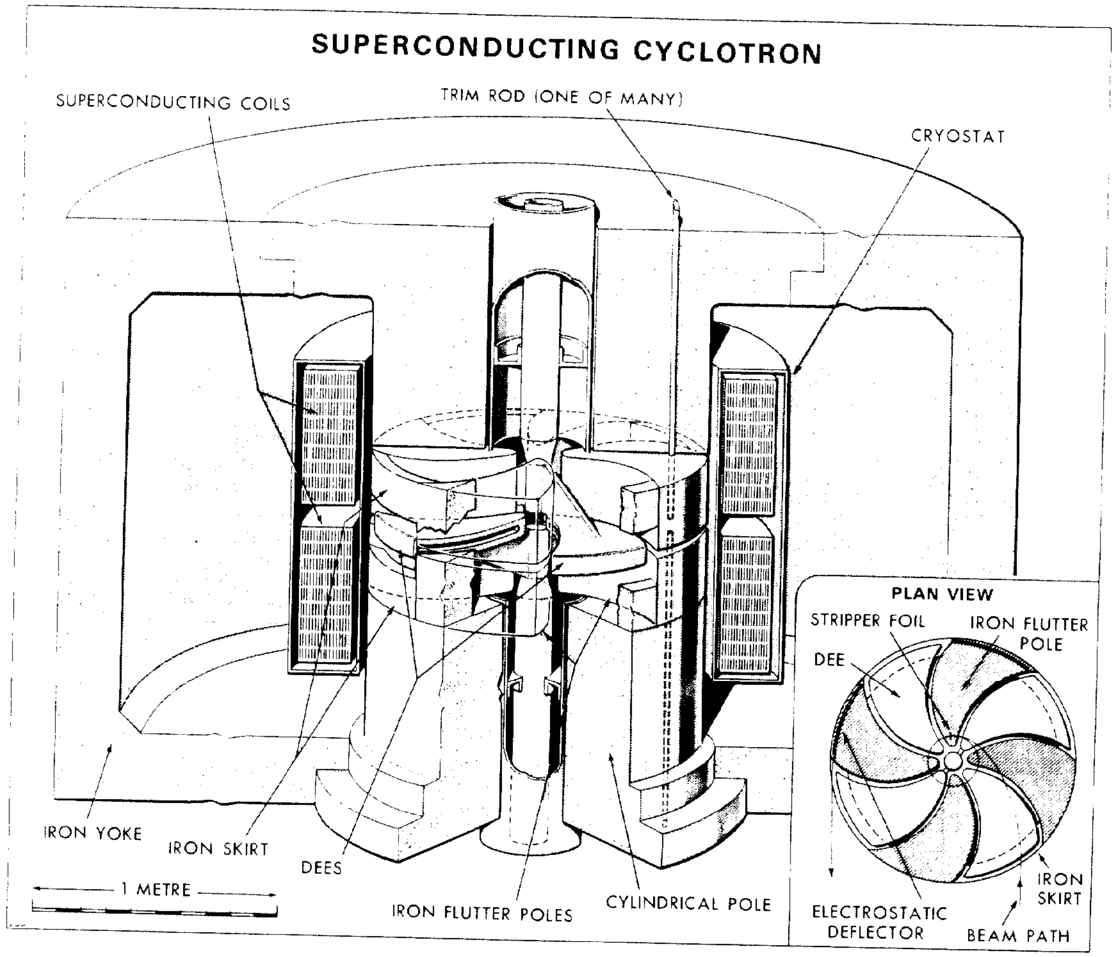

Fig. 1: Illustration of the superconducting cyclotron as presently conceived.

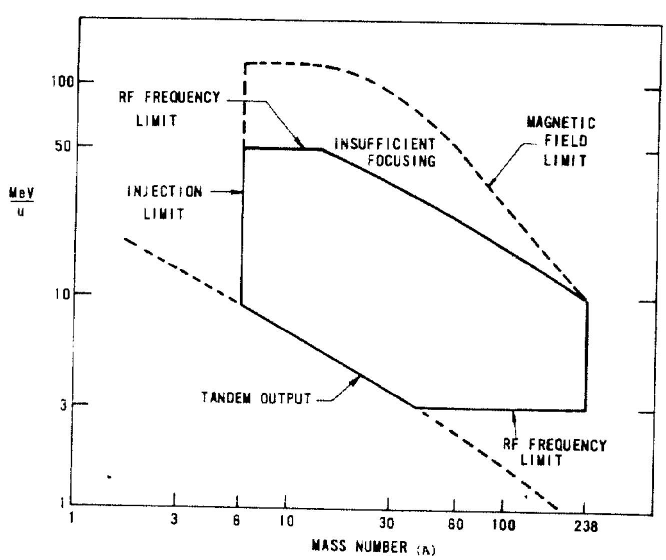

Fig. 2: The expected operating region (bounded by solid lines). The limits are rf tuning, charge stripping, axial focussing and available Tandem output.

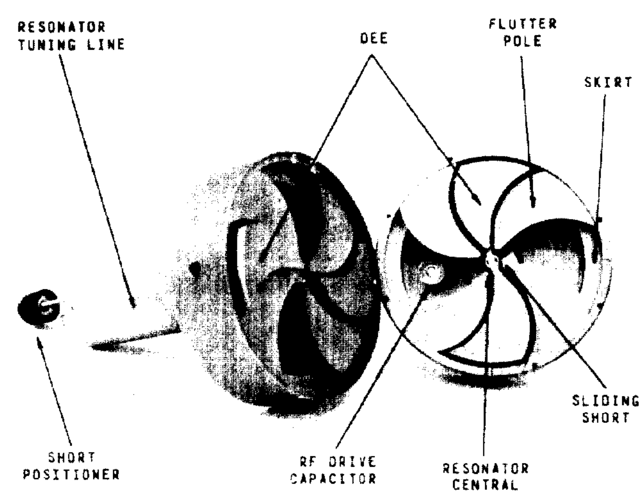

Fig. 3: The 1/10-scale rf model.