A COMPACT PERMANENT MAGNET CYCLOTRON FOR ACCELERATOR MASS SPECTROMETRY

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We describe the development of a Cyclotron Mass Spectrometer (CMS) for the detection of trace amounts of rare isotopes. A compact low energy cyclotron optimized for high mass resolution has been designed and fabricated. The CMS has high sensitivity and is designed to measure ^{14}C at abundances of 10^{-12}. A novel feature of the CMS is the use of permanent magnets to energize the 30 cm diameter iron poles of the cyclotron. Axial injection is used, employing a spiral inflector. Preliminary measurements of the magnetic field show that it has a uniformity on the order of 7 parts in 10^4 over most of the acceleration region.

1 Introduction

Accelerator mass spectrometers (AMS) are currently being used very successfully for the detection and measurement of trace elements and for the determination of isotopic abundance ratios. Continuing advances in the state of the art are accompanied by steady growth in diversity and scope of the applications, as is apparent from the proceedings of periodic international topical conferences.[1] The present status and outlook have been well summarized by J. Davis, who mentions novel uses of AMS, e.g. in industry and even in forensic work, in addition to the usual archeological, geoscientific, environmental, and biomedical applications.[2] In connection with the latter in particular, Davis points out that there is an increasing need for the development of smaller machines, optimized for ^{14}C and ^{3}H, and specialized for medical work.

The most common systems use tandem accelerators, starting out with negative ions. Smaller, low-energy cyclotrons for use in mass spectrometry have been under development for some time, at various locations.[3-5]

In this paper, we describe a small low-energy cyclotron designed to accelerate ^{14}C ions, for biological research and for medical applications. It differs from other cyclotrons in that its magnetic field is energized by an assembly of permanent magnets rather than by a coil system. The resulting loss in variability of the field strength is acceptable because the instrument is intended to be used for only one single ion mass with charge 1, although scaling of injection energy, rf frequency and dee voltage could be used to accelerate other ions. The advantage of the permanent magnet design lies in the gain in compactness and simplicity of operation. No coils or power supplies and no cooling are required for the magnet. This reduces the utility requirements for the spectrometer system as a whole. This reduction and the small size and weight make the system "portable", conceivably permitting utilization in medical studies in hospitals, or for environmental monitoring in trucks or airplanes. Progress on this program was reported at the last Cyclotron Conference.[6,7]

The first small CMS project was suggested at LBNL in the early 1980s by R.A. Muller and co-workers.[8] They also proposed the use of permanent magnets at the time, but failed to obtain funding.[9] The realization of the present device is a result of recent increases in demand for specialized machines.

2 CMS Design

2.1 System Considerations

The use of a cyclotron as a mass spectrometer arises from its inherent high resolution for charge/mass discrimination. For ^{14}C, a mass resolution of about 1800 is needed to separate ^{14}C from ^{13}CH. The resolution of a CMS is approximately:[4]

$$R \approx 3 \times n \times H \qquad (1)$$

where n is the number of turns that in-phase particles make in a synchronous field before extraction and H is the rf harmonic number. The overall size of the machine is dictated by the mass resolution needed, the turn separation needed to clear the center region, and the injection energy. Better center region clearance requires a larger magnet, which is more expensive, or it requires a smaller injection radius, making the transit time worse for high harmonics. So a compromise has to be made giving good transmission in the center region and a large enough injection radius to give a good transit time factor.

In this design H is 15 and the minimum number of orbits is 40, giving the required R = 1800. With a 5 keV injection energy and a turn separation of 2 mm at injection the energy gain per turn would be 500 V, and the extraction radius 9 cm. We have conservatively designed the CMS for an extraction radius of 12 cm, corresponding to an energy of 50 keV. For ^{14}C in a 1 T field, the fundamental frequency is 1.1 MHz and the the rf freq is 16 MHz. Table 1 shows the specifications of the cyclotron.

Figures 1 and 2 show plan and elevation views of the CMS. Beam is accelerated by a 180 degree dee and a "strip" dummy dee. Particle orbits were calculated with a simple tracking program. Three probes at 120 degrees apart can be used for beam detection. Beam is deflected by a short electrostatic deflector into the external beam channel. A tracking code was used to follow particles in the channel, with Poisson being used to calculate the magnetic field. Particles emerging from the accelerator are detected using a microchannel plate detector.

Table 1: Cyclotron design Parameters

Parameter	Description
Ion source	Magnetic multicusp
Ion Species	Carbon 14
Injector type	Spiral inflector
Injection energy	5 keV
First orbit radius	4 cm
Extraction radius	12 cm
Extraction energy	50 keV
Pole face radius	15 cm
Pole gap	1.6 cm
Magnetic Field	1 T
Field Source	SmCo Magnets

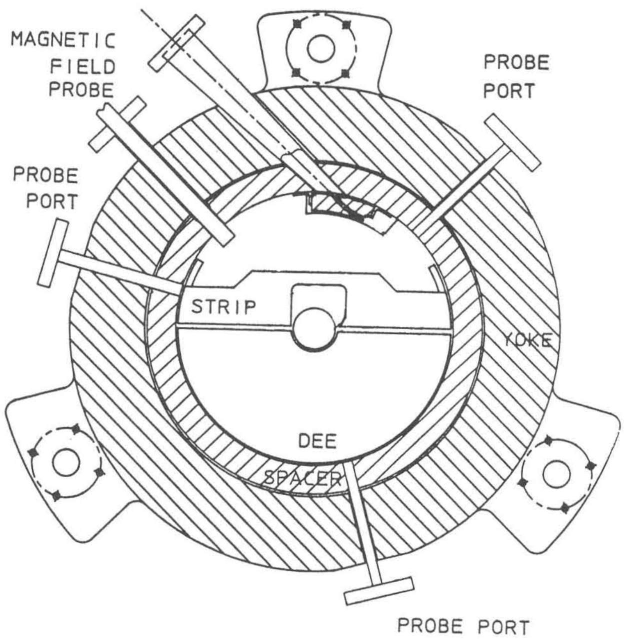

Figure 1: Plan View of the cyclotron.

2.2 Ion Source and Injection System

To suppress the ^{14}N background, $^{14}C^-$ is used, since ^{14}N does not form a negative ion. The ion source typically used in accelerator mass spectrometers is a cesium sputter ion source. However, we have experimented in the use of a magnetic multicusp source for this project.[10] In these devices, negative ions from gas phase precursors are formed directly in the discharge plasma. Recent experiments have shown that C^- can be formed in these sources as well.[11] Further research is necessary to optimize this type of source for C^- production. If successful, it will provide a simple to operate, high throughput source of negative ions without the need for the graphitization process used with sputter ion sources.

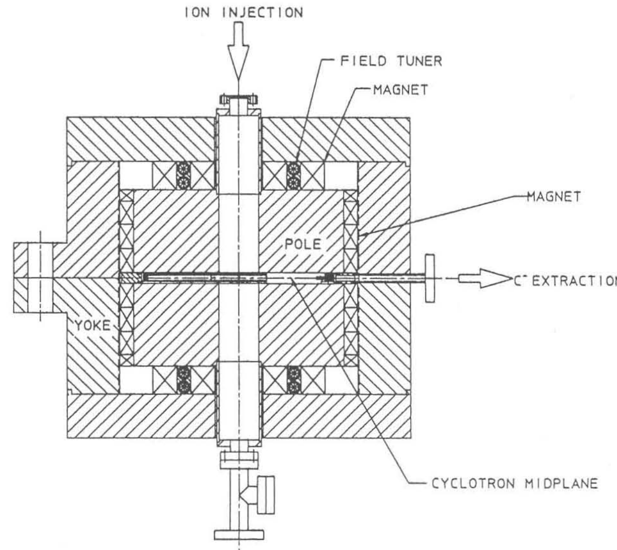

Figure 2: Elevation view of the cyclotron.

After production, the ions are transported to the cyclotron, where they are injected axially using a spiral electrostatic inflector, Figure 3. The inflector geometry has been optimized with the computer codes CASINO, RELAX3D and Poisson so that the emittance of the ion beam coming out of the inflector matches the acceptance of the cyclotron.

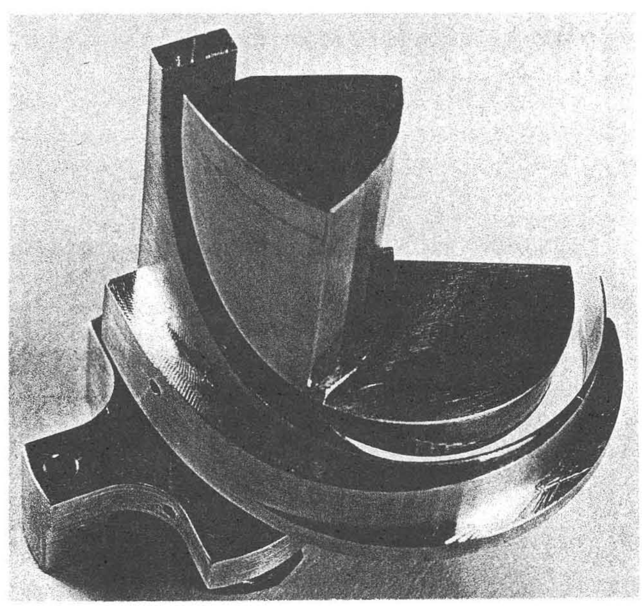

Figure 3: Spiral inflector.

2.3 Magnet Design

A novel aspect of the cyclotron design is the use of permanent magnets to produce the magnetic field. This has two advantages. First, the overall size and weight of the magnet structure are reduced, as the magnet coils and power supplies are eliminated. Second, the electrical power and cooling requirements of the instrument are reduced. With permanent magnets, the CMS will be transportable and could be placed aboard aircraft, small boats, or in field locations. Their use will also reduce operational costs. The magnetic field in the midplane is 1 T. For high mass resolution, the orbits need to be isochronous; a flat magnetic field uniform to about 2 parts in 10^4 must therefore be maintained. A flat field without flutter was selected since it is a simpler configuration for this very low energy and the high harmonic provides adequate electrostatic axial focussing.[12]

A conceptual design for the magnet was developed by one of the authors, Klaus Halbach. As shown in Figures 2 and 4 permanent magnet material is placed around the iron pole pieces. The permanent magnets for each pole are grouped into 2 sections, the "crown" section and the "barrel" section. For example, as shown in Figure 4, for the upper pole the crown section is placed above the pole and directs magnetic flux down into the pole and gap. The barrel section is placed outside the pole and directs flux inward toward the pole and gap. The pole is machined to high accuracy since it is what the gap "sees" and thus determines the accuracy of the magnetic field. The permanent magnet comes in blocks, which can be of coarser arrangement since they are farther from the midplane. A cylindrical yoke completes the magnetic path.

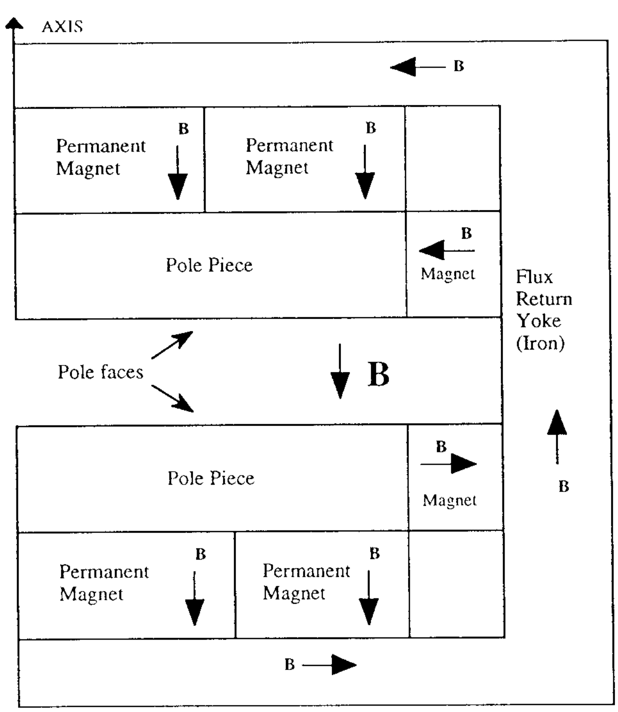

Figure 4: Schematic drawing of permanent magnet ("Magnet") locations.

After the conceptual design, calculations were performed to optimize the geometry. Initially, a program which analytically calculated the indirect and direct magnetic fluxes from various candidate configurations was used to define the dimensions of the magnets, poles, and yoke. The computer program POISSON was then used to verify and optimize this solution. Poisson calculations of the median plane field, shown in Figures 5 and 6 assume an optimum position for the barrel magnets.

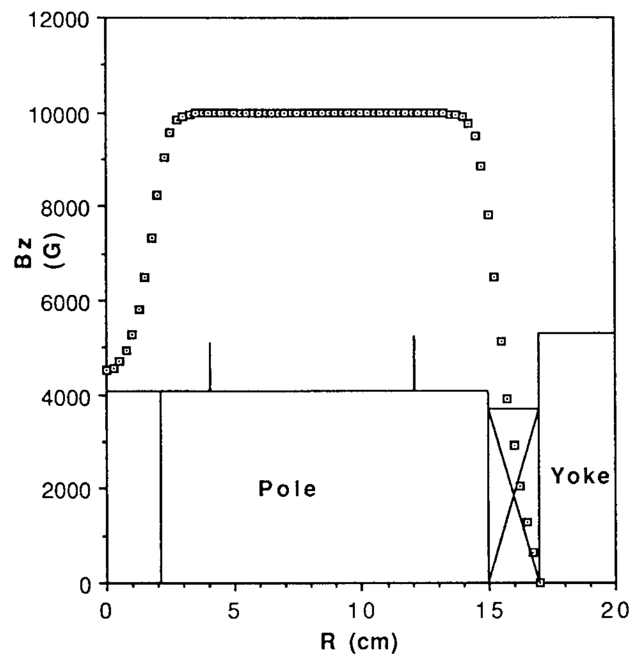

Figure 5: Poisson calculation of field in midplane.

After assembly, measurements of the magnetic field were made. These are shown in Figure 7. As can be seen, within the acceleration region between 5 cm and 12 cm, the field is flat to within 7 parts in 10^4. This small deviation was anticipated since slightly larger than optimum barrel magnets were installed, to be cut back later for shimming. The field is slightly outside this range at a 4-5 cm radius, where the first 5 turns occur, but this contributes only a negligible amount of phase shift and axial defocusing.

3 Status

A permanent magnet CMS has been designed and constructed to demonstrate a system which would be cost-effective and readily available. Initial measurements of the magnetic field show that the field uniformity is within expectations. Development to demonstrate beam acceleration continues at a low level, limited by funding.

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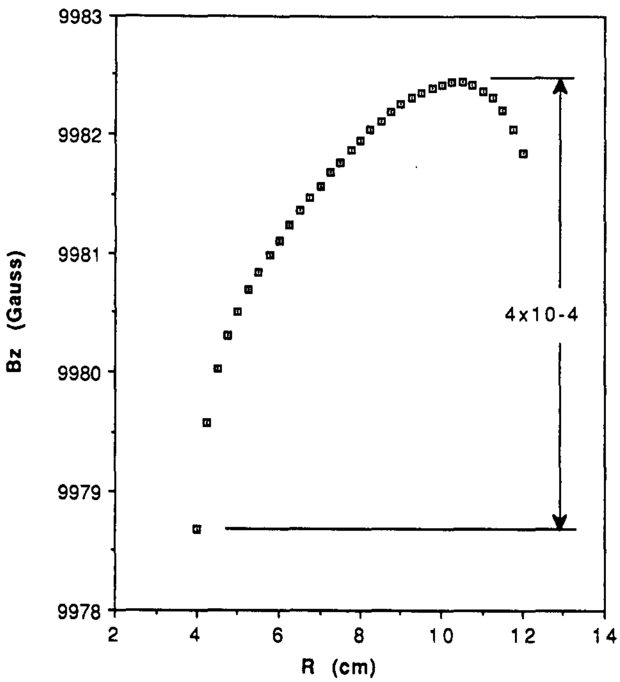

Figure 6: Poisson calculation of field in midplane in acceleration region.

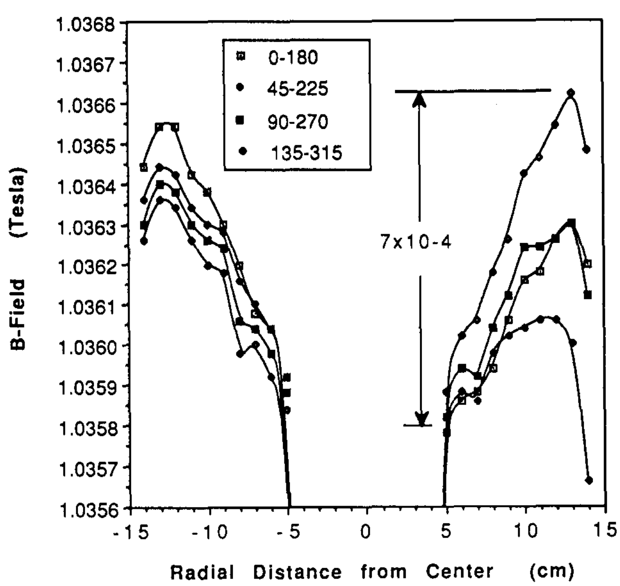

Figure 7: Magnetic field measurements across 4 diameters in midplane.

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References

1. Proc. 6th Int. Conf. on AMS, Canberra-Sydney, Australia, 1993. Published in Nucl. Instr. and Meth. B 92, pp 1-524 (1994).
2. J.C. Davis, ibid. pp.1-6.
3. K.J. Bertsche et al., Nucl. Instr. and Meth. B 29, 105 (1987).
4. K.M. Subotic, J. Phys. G: Nucl. Part. Physics 17, S363 (1991).
5. M.B. Chen et al., Nucl. Instr. and Meth. B 92, 213 (1994).
6. A. T. Young et al., Proc. 13th Int'l Conf. on Cyclotrons and their Applications, Vancouver, Canada, 1992, p. 705.
7. C. Y. Li et et al., Proc. 13th Int'l Conf. on Cyclotrons and their Applications, Vancouver, Canada, 1992, p. 561.
8. J. Goldhaber, LBL News Magazine, vol. 7 (Spring/Summer 1982) p. 22.
9. R.A. Muller, private communication.
10. Leung, K.N. et al., Rev. Sci. Instru. 61, 2378 (1990).
11. K.N. Leung et al., Proceedings of the 13th International Conference on Cyclotron and Their Applications, Vancouver, Canada, 1992, p. 312.
12. J.J. Welch et al., Nucl. Instr. and Meth. B18, 202 (1987).