Development of a Compact Permanent Magnet Cyclotron for Accelerator Mass Spectrometry*

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Abstract

We describe the development of a new instrument for the detection of trace amounts of rare isotopes, a Cyclotron Mass Spectrometer (CMS) A compact low energy cyclotron optimized for high mass resolution has been designed and is under construction. The instrument has high sensitivity and is designed to measure carbon-14 at abundances of < 10^{-12}. A novel feature of the instrument is the use of permanent magnets to excite the iron poles of the cyclotron, giving a field uniformity on the order of 1 part in 10^4. The instrument uses axial injection, employing a spiral inflector. The instrument is nearing completion, with most major components completed.

I. INTRODUCTION

Measuring the abundance of trace isotopic constituents has applications in many fields, such as archaeology, biomedicine, geology and geochemistry, and environmental research. In general, these applications require a very high sensitivity and selectivity. The combination of the samples being very dilute in the isotope desired ($<10^{-10}$) and containing other atoms and molecules with almost the same atomic or molecular weight makes essential a detection scheme with high sensitivity *and* specificity (or resolution.)

One method of high-sensitivity detection is Accelerator Mass Spectrometry (AMS). In this technique, the sample of interest is ionized, and a charged-particle accelerator is used to detect single atoms of the isotope of interest. The first use of an accelerator as a mass analyzer was made in 1939 by Alvarez, who measured ^{3}He at natural abundance using a cyclotron. [1] The "modern" era of AMS began in 1977, when Muller proposed using a cyclotron for carbon and beryllium measurements [2,3], and the groups at the Univ. of Rochester, and McMaster Univ. demonstrated ^{14}C detection with tandem accelerators. [4,5] AMS has developed into a powerful tool for the detection of trace quantities of rare isotopes. Virtually all AMS is now performed on large tandem accelerators. Analysis of isotopes that are present in samples at a level of 1 part in 10^{15} has been achieved.

Recently, the original idea of using a cyclotron as the accelerator has been revived, with the new wrinkle that the cyclotron be small and that the accelerating voltages be modest. In this incarnation, the technique has been dubbed Cyclotron Mass Spectrometry (CMS.) Here, the large tandem accelerator is replaced by a compact, low-energy cyclotron. Previous work at Lawrence Berkeley Laboratory (LBL) demonstrated the principle of these devices and showed that CMS can have much higher sensitvity than the scintillation methods used routinely in biomedical research for ^{14}C. [6,7] As a result, several small cyclotron mass spectrometers are now under development around the world. [8,9]

This paper describes the program now underway at LBL to improve the performance and operating characteristics of CMS. The design is discussed and the status of the construction of the CMS is given.

II. CMS DESIGN

A. System Considerations

The overall size of the machine is dictated by the species to be measured, the injection energy of the ion, and the mass resolution needed. For ^{14}C, a mass resolution of about 1800 is needed to separate ^{14}C from ^{13}CH. The resolution of a CMS is described by [7]

$$R \approx 3 \times n \times H, \quad (1)$$

where n is the number of orbits the particles make before extraction and H is the harmonic of the fundamental cyclotron frequency that the accelerating RF is operating on. For ^{14}C in a 1 T field, the fundamental frequency is 1 MHz. H might be 15, so that the minimum number of orbits would be 40. With modest energy gain per turn, ≤500 V, it is possible to achieve this figure with an extraction radius of ≤ 9 cm. We have conservatively designed the instrument for an extraction radius of 12 cm, corresponding to an energy of 50 keV.

Figure 1 shows a schematic diagram of the LBL CMS system. To improve the performance over existing devices, changes are being made in the ion source and the injection system. This will lead to enhanced sensitivity and increased sample throughput. In order to reduce the size, weight, and complexity of the system, the magnetic field of the cyclotron will be produced by permanent magnets rather than electromagnets. These improvements are described below.

B. Ion Source and Injection System

The ion source typically used in AMS is a cesium sputter ion source. However, at LBL, substantial experience has been obtained in developing negative ion sources for fusion and ion

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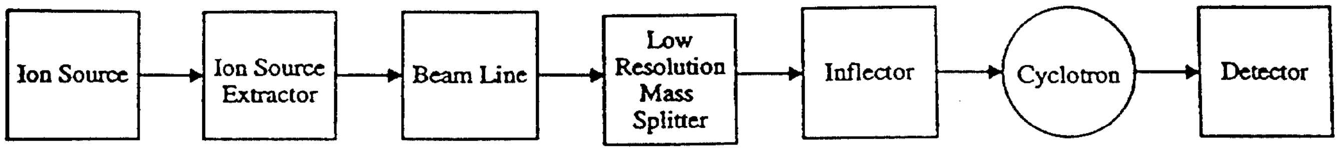

Fig 1 Schematic diagram of the cyclotron mass spectrometer

implantation applications using magnetic multicusp sources.[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. Further research is underway 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.

After production, the ions are transported to the cyclotron, where they are injected axially. Axial injection, in general, is very efficient in delivering the ions into the cyclotron midplane. We have designed a spiral inflector, an electrostatic channel which twists or "tilts" as it guides the ions down the axis of the machine and into the midplane. Figure 2 depicts the complicated shape of the inflector, showing the inner surfaces of the electrodes. The inflector shape has been optimized so that the emittance of the ion beam coming out of the inflector matches the acceptance of the cyclotron. This was accomplished using an ion trajectory program which takes into consideration the spatial variation of the magnetic fields in the cyclotron for the inflector design and a second trajectory program which calculates the cyclotron midplane trajectories, including electrostatic focusing effects.

C. 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 minimized. 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.

These parameters can be obtained by using permanent magnet material to energize soft iron poles pieces. This is shown schematically in Fig. 3. Magnet material, such as samarium cobalt, is placed in contact with the iron pole pieces. The iron concentrates and directs the magnetic flux to

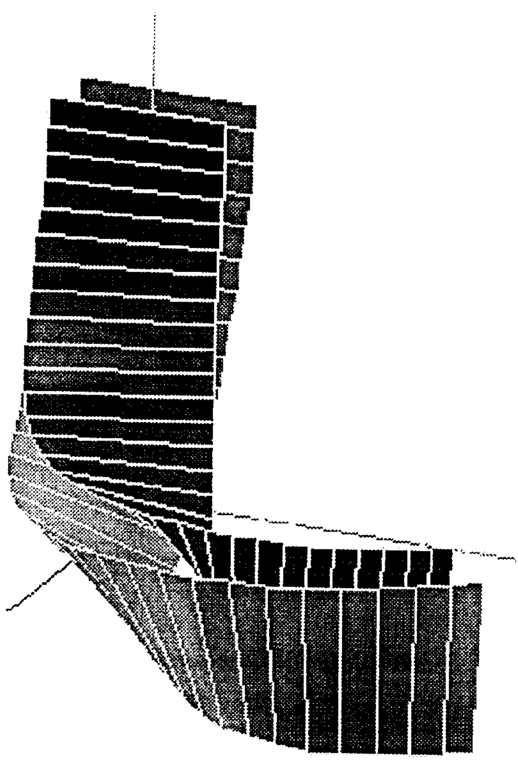

Figure 2 Spiral inflector used for axial injection

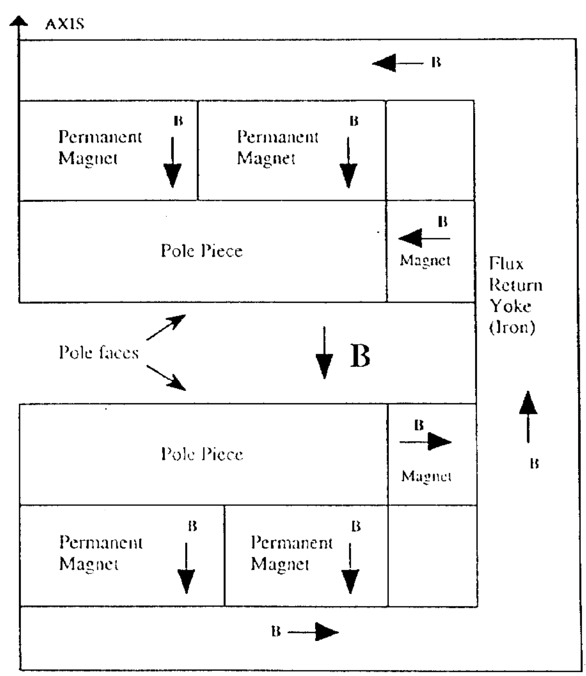

Figure 3 Schematic diagram of the design for the permanent magnet system.

the pole faces. For one pole, the magnets are oriented so that the magnetization vector points toward the pole face. For the other pole piece, the magnets are oriented so that the magnetization points away from the pole face. A magnetic flux return ('yoke') connects the magnets to complete the circuit. The midplane of the accelerator is placed between these poles. As shown in Fig. 4, calculations of the magnetic field using the computer program POISSON indicate that the field should be uniform to approximately +/- 2 parts in 10^4 throughout the acceleration region, and +/- 1 part for the majority of the trajectory.

III. PROJECT STATUS

The advanced CMS is being designed and optimized for use with ^{14}C. Some of the operating characteristics are shown in Table 1.

With one exception, all major subassemblies of the CMS have been fabricated, including the poles, yokes, pole spacer ring, and ion extraction channel. The exception, the spiral inflector, has been designed and is presently being fabricated. The CMS should be assembled by the fall of 1993, with demonstration of ^{14}C detection to follow.

Parameter	Description
Ion source	Magnetic multicusp
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

Table 1 Cyclotron design Parameters

IV. CONCLUSIONS

Cyclotron mass spectrometry (CMS) is a potentially powerful analytical technique with applications ranging from studies of global warming constituents to the biological metabolism of pollutants and pathogens. A development program is now underway which will increase the sensitivity and improve operational characteristics, such as transportability and sample preparation, while at the same time reducing the cost of the instrument and its operation. These improvements will make CMS more widely available for routine analysis of trace materials.

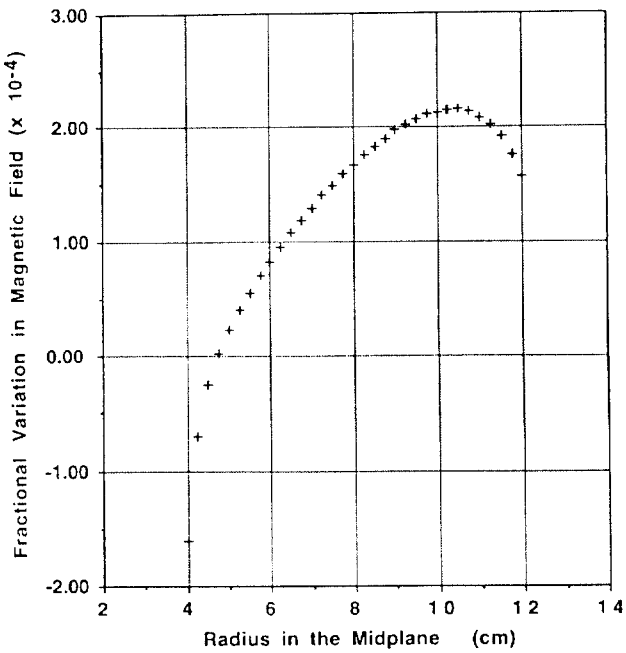

Figure 4 Fractional variation in the magnetic field from its mean value.

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