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ADVANCED ACCELERATOR METHODS: THE CYCLOTRINO

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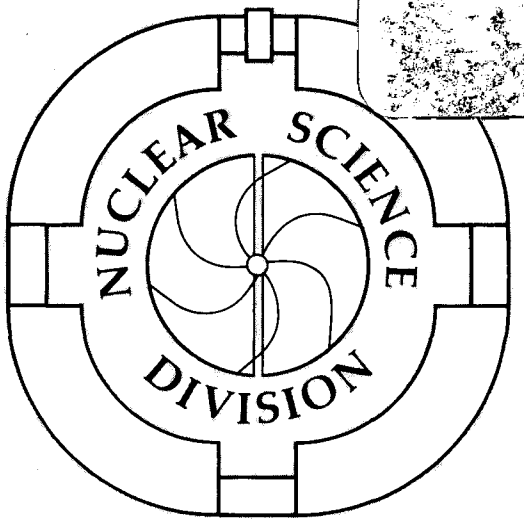
April 1987



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DISCLAIMER

Advanced Accelerator Methods: the Cyclotrino

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If one were to design a new accelerator today to do AMS measurements, some techniques could be used which are not typical in high energy physics accelerators. As an example of the application of such non-standard techniques, we will discuss the small cyclotron ("cyclotrino") at Berkeley. [1-5] ***

There were some very specific requirements for the small cyclotron. We envisioned a machine which would be: 1) low cost--low enough to be affordable by a small university or college (say under $100,000); 2) small size--so that it could be installed in an existing room; 3) easy to operate--so that a full time accelerator operator would not be needed; 4) low energy--this is consistent with the previous requirements, in that low energy operation lends itself to smaller size, lower cost, and easier operation (less than 100kV output beam energy in our case); and 5) operation with ^{14}C. There are two reasons for ^{14}C operation; firstly, ^{14}C is still the isotope of greatest interest in AMS

studies, secondly, ^{14}C is one of the easiest species to design for in terms of resolution requirements (rejection of unwanted masses) and in terms of attainable beam currents.

RESOLUTION

The resolution requirements when looking at ^{14}C are still quite stringent. There are a few interferences. By "interferences", we are specifically referring to those unwanted masses that are nearby. Our mass resolution peak has to be narrow enough to look at ^{14}C and reject these other nearby masses. ^{14}N is extremely close in mass (about one part in 80,000). We decided not to attempt to design the machine to mass select ^{14}C from ^{14}N. That difficult task is not necessary. We can use negative carbon ions as are used in tandem accelerators; since nitrogen doesn't form negative ions we avoid ^{14}N interference. Then, the nearest unwanted species is the molecular ion ^{13}CH. We must address this interference, since we will have some hydrocarbons in our machine (because of hydrocarbons in the sample, and trace amounts of oils and other hydrocarbons on surfaces in the machine). Some hydrocarbons will inevitably be produced, so we must reject ^{13}CH from ^{14}C. The mass difference is approximately .06% (about one part in 1,800). There will also be some $^{12}CH_2$, which is a little further away in mass. But the closest interference we must contend with is ^{13}CH.

Besides these nearby interferences, we have an additional mass resolution requirement. We require that the tail of the mass resolution curve drop very low and remain very low a long way out. (Fig. 1) A relatively large number of ^{12}C and ^{13}C ions come from the ion source. We can try to separate them out by various means before they enter the cyclotron, but we are still going to have a lot of ^{12}C and ^{13}C compared to ^{14}C. In modern carbon there is about ten orders of magnitude more ^{13}C and about 12 orders of magnitude more ^{12}C than the ^{14}C we are looking for. And if we want to look at older carbon, say 30,000 years old, we have about 2 orders of magnitude less ^{14}C

than in modern carbon, so these ratios are worse by two orders of magnitude.

These requirements for the machine are fairly stringent. Often, with analytical equipment such as traditional mass spectrometers, one can achieve a narrow resolution, but the tails do not have the required suppressions of 12 to 14 orders of magnitude for distant masses. Further, there are often ripples appearing in a resolution curve; even if a machine does achieve extremely high rejection, this is generally not maintained over a broad range of unwanted masses. But due to the presence of ^{12}C and ^{13}C we must achieve very high off-mass rejection, and must retain it even for distant masses.

CYCLOTRON OPERATION

Most readers are probably aware of basic cyclotron operation, but let me provide a short review. In a cyclotron, we have conductive plates which are known as dees, named that because of their shape. Their plan and cross-sectional views are shown in Fig. 2. Each dee is actually a pair of plates, formed by an upper and a lower plate. One pair is usually grounded and the other pair is driven by a high voltage radio frequency (RF) source. There is a magnetic field which passes out of the plane of the dees. An ion, say a negative ion, located in the plane, will undergo stable cyclotron orbits in the plane, and it will do this at some cyclotron frequency which is independent of the orbit radius and independent of the ion's velocity. As the ion gains energy, it moves around in a larger orbit but remains at the same cyclotron frequency. So we can resonantly pump energy into the ion by setting the radio frequency on the RF dee to the cyclotron frequency of the ion. We can thus pump it up from a small radius to a larger radius orbit.

In our case, we start with a three centimeter radius on injection of the ion beam; we extract at a ten centimeter radius, at approximately 30 keV. We have approximately 8 millimeters between the top and bottom of the dee and about 1 millimeter between the

grounded dee and the RF dee.

This basic cyclotron design can be improved by using a few tricks. As the ion is circulating, undergoing cyclotron oscillations in the magnetic field, it is electrically shielded while it is between the RF dee plates, then gets accelerated at the gap because the electric field has the proper phase to accelerate it. It is shielded as it goes through the half orbit between the grounded dee plates, the electric field reverses by 180° and the ion is again accelerated at the gap crossing. Notice that while it is shielded, the radio frequency could go three half cycles instead of one half cycle, and the ion would still be accelerated at both crossings of the gap. Thus we can run the radio frequency at any odd harmonic of the basic cyclotron frequency. This has been done previously, but it is not standard operation, at least it is not standard to use very high harmonics as we do. We run up to the 15th harmonic - going from the 11th to the 15th. That gives us an advantage in mass resolution. Suppose that an ion of the proper mass is resonant in the machine, and another kind of ion is off in mass slightly. The off-mass ion may still get accelerated, and increase in radius, but eventually it will fall out of phase with the radio frequency and won't accelerate any more. It won't go out any further and won't reach the extraction radius, and we won't see it in the detector. If we raise the radio frequency to a higher harmonic, this falling out of phase will happen sooner, and we will get better resolution. In fact, the resolution of a cyclotron is proportional to the product of the number of turns and the harmonic number it is operated at.

Our machine operates with approximately 50 turns on the 11th to 15th harmonic, with approximately 500 to 1000 volts p-p of RF. The cyclotron frequency is about one megahertz for a one Tesla field, so the RF supply runs at about 11 to 15 megahertz.

Notice that it is the electric field near the gap which causes the acceleration. If one dee is grounded and the vacuum vessel is grounded, as most cyclotrons are, we can

omit most of the grounded dee without changing the field distribution. Thus the grounded dee typically is just a narrow strip near the gap, called the "dummy dee". Even the earliest cyclotrons built by Ernest Lawrence used a dummy dee rather than a full dee on the grounded side.

FOCUSING

Another important point regarding cyclotron operation is that as the ions orbit they must be confined near the median plane between the two plates of each dee. A restoring force is needed to focus the ions toward the median plane, otherwise they will drift and hit one of the dees and will be lost. So, focusing along the axis of the magnet is extremely important.

The simplest way to accomplish this axial focusing, as used in the early cyclotrons, is "weak focusing", which is accomplished by providing a radial gradient in the B field. The cross section of the pole pieces of such a magnet is shown in Fig. 3. The B field falls off with increasing distance from the center. The pole pieces are contoured to make the B field fall off at a known rate. That causes the field lines to bow as shown; analysis of the orbits shows that this tends to give a restoring force to the ions and causes them to stay near the median plane. This is a simple and effective way to provide a focusing force. However, as the field falls off, the cyclotron frequency changes and that would ruin our resolution. We would be unable to obtain the required resolution to separate ^{13}CH from ^{14}C with this method. So we must look for another method.

Most large machines presently use what is called "strong focusing", also known as sector focusing. Basically, with strong or sector focusing there is an azimuthal variation in B field around the cyclotron. A plan view of such a pole piece is shown in Fig. 4. Some regions of the pole piece are raised with respect to the rest. This

creates relatively sharp edges between weak and strong magnetic field regions. Focusing takes place when the ions cross the edges. We could have utilized strong focusing, but these designs are usually complex (the curves are complicated and difficult to machine, especially for the small device we wished to build) and this type of complexity was not needed.

Another type of focusing, which every machine has, is electrostatic focusing. (Fig. 5) In actuality, it is not really electrostatic because the field between the dee and the dummy dee is not static; it is an RF field. But on a short time scale, for the time it takes the ion to go through the gap region, it is approximately electrostatic. If the ion accelerates going through this region, if it is going faster as it leaves the gap region than when it entered, there is a net focusing force toward the median plane that is proportional to the ion's velocity difference on the two sides of the gap. Every machine has some amount of electrostatic focusing, but usually it is insufficient to focus the ions and to confine them to the median plane. In our case, however, it does provide sufficient focusing. Basically, this works because we are running at a high harmonic and therefore we get some averaging of the "electrostatic" field for the slowly-moving ions of small orbit radii, which reduces the focusing at small radii and makes focusing more uniform as we expand out in radius. We use electrostatic focusing exclusively; we don't employ any other focusing method to confine the ions.

APPARATUS

A photograph of the machine is shown in Fig. 6. The present version is not quite "tabletop". (It would require a strong table; the magnet weighs several tons!) The large object on the left is a 12-inch Varian NMR-type laboratory magnet. The power supply for the magnet is behind it. The magnet is approximately four feet high. The large rectangular tank is a vacuum vessel that holds the detector and some of the

electronics for the machine. Our compressor for the cryopump is beside and below the vacuum tank. The cryopump is attached to the other side of the tank, out of view. Notice that in this machine, the magnetic field gap is vertical and the field direction is horizontal, which differs from most cyclotrons you have probably seen. The racks of electronics against the back wall include high voltage supplies, preamps, amplifiers and thresholding electronics for the detector. Our signal generator may be of interest. It is an economical ham radio transciever, which has proven to be quite adequate for our needs. Transmitting frequencies are synthesized from an oven controlled crystal; this provides a sufficiently stable RF frequency for our application. We also use an RF broad band amplifier. This is not essential, we could drive the cyclotron from the transceiver directly, but the broadband amp can handle more severe mismatches than can the transciever.

The power requirements for this machine are, of course, much less than for a large cyclotron. We use about 500 watts for the magnet (3kW at full power), about 1 kW for electronics and RF supply, and about 2 kW for the vacuum pump.

Note also that the machine could be made significantly smaller. The electromagnet is the largest object in the picture, and the major limitation in terms of size. If a permanent magnet were used instead, the machine would be significantly smaller, as well as lighter in weight and somewhat lower in power consumption. The electromagnet, however, is very convenient for development of the system, since it is easily tuned.

A view from the other side is shown in Fig. 7. Again the vacuum tank is visible, which has the detector inside. The cryopump is also visible now, and in this view the apparatus is rolled out of the magnet to expose the "finger" region that sticks into the magnet. This finger is about an inch wide and contains the main components of the cyclotron.

Fig. 8 shows, schematically, the inside of the finger region. The orientation of the dee and the dummy dee can be seen. The RF drive point is in the lower right. A probe can be inserted from the top to measure beam current for diagnostics. The extractor is in the upper left--we will discuss it later. The ion source is contained in the central region.

We use a miniature cesium-sputter negative-ion source, shown schematically in Fig. 9. A positively-charged cesium beam comes from a cesium source, curves in the B field, and strikes a carbon target. The cesium beam is initially accelerated to about 100 eV just in front of the cesium source. The carbon target is biased at about 3kV, which gives the cesium an extra 3keV to sputter carbon from the target. Negatively-charged carbon is thus sputtered off and accelerated to 3keV. The carbon ions curve the opposite direction in the B field, just missing the cesium source, and gaining enough energy on two crossings of the gap to miss the carbon target the second time around. We can get about 1 μA of cesium ions and about 1 ~~μA~~ nA of carbon ions from this arrangement. This is enough for testing, but is not nearly enough for making ^{14}C measurements.

Fig. 10 shows a photograph of the cesium source. It is basically cesium oxide in a metal can about 6mm in diameter and about 2 cm long. A heater wire heats it to about 1100 °C, evaporating cesium, which is ionized as it leaves a porous tungsten surface. The cesium source is biased at about 100V; the grid and copper shield are grounded.

A photograph of the central region is shown in Fig. 11. The dee and the dummy dee, the cesium source, and the carbon target can be seen as they appear in the machine. The carbon target consists of evaporated carbon on a molybdenum substrate; you can see the darkened spot where the cesium beam focuses. This again is biased at about -3kV behind a grounded grid.

The entire finger region with the cover removed is shown in Fig. 12. The dee

and the dummy dee, the RF drive, the central region with the source, and our dee probe, which also contains a Hall probe to measure B field, are seen in perspective. The extractor is at the upper left, and the detector is out of sight to the left.

The extractor consists of an electrostatic channel. We have a very thin curved septum, which is underneath the aluminum plate. There is a curved aluminum piece visible through the opening. The two are parallel (concentric, actually, since they're both curved) and there is a gap of about two millimeters between them. We apply an electric field across the gap. The extractor is purely electrostatic. Large machines often use electrostatic extractors as well, but they generally require high voltages and can only deflect the ions through a small angle. We are able to provide a large deflection angle to the ions, and don't need more than about 3kV to do so, because our accelerated ions are only at 30 to 40 keV.

The detector was specifically designed for the small cyclotron and is somewhat unusual. [5] It is a microchannel plate detector, shown schematically in Fig. 13. It contains a polished aluminum dynode; the ion beam comes in a defining slit, striking the dynode at grazing incidence. That creates from 10 to 30 secondary electrons which come off of the dynode. They are then accelerated through about a 1 kV potential across a one centimeter gap. The detector is located inside a magnetic shield to avoid deflecting these secondary electrons. The secondary electrons separate as they drift in the electric field, and fall into different pores of the microchannel plate. The microchannel plate is run in saturation mode; any pore that an electron hits gives a saturated pulse. The result is a total pulse that is proportional to the number of secondary electrons that were created at the dynode. By setting thresholds in our amplifiers we can discriminate a high energy (30-40 keV) ion, which makes many secondaries, from a low energy ion, which makes just a few. That is how we are able to supress the background enough to detect only the high-energy ^{14}C without interference from other lower-energy ions. Our background is

approximately three counts an hour. We might have been able to get it a little lower, but since our ion source was not stable for any longer than 1/2 hour there was little need to reduce the background.

RESULTS ****

How does this all work? Does it work? A curve of the resolution that we get when looking at mass 12 is shown in Fig. 14. Of course, we really want to operate at mass 14. But mass 12 provides a bigger peak, so it is more convenient for obtaining a resolution curve. At the highest currents, the beam was not sent into the detector, but into a current collector. On the vertical axis is the count rate (a log scale). The horizontal axis shows the frequency the machine is tuned to; increasing frequency corresponds to decreasing mass. This, then, is a mass resolution curve. If we observe the peak and then move off a part in 1800, (remember this is the difference we need to distinguish between ^{14}C and ^{13}CH), our signal is down below the background level of about a count every twenty minutes. We have dropped 11 1/2 orders of magnitude from the peak down to the background. We actually hit the background before we even get to a part in 1800 offset. This resolution would probably be good enough at mass 14, even if the count rate is no lower than the background. We believe it is well below the background, but couldn't verify it. So we don't have any problems with resolution. We have enough resolution in this machine to separate ^{14}C from ^{13}CH. The basic limitation here is the current from our ion source. The miniature ion source which we used does not produce enough current for us to be able to see ^{14}C. The ^{14}C level is about a factor of 50 below the background. We need to increase source current by a factor of 50 or lower the background. Lowering the background is not really practical, because the source is not stable for a long enough time.

Fig. 15 shows a curve at mass 14, which is what we are really interested in.

The ^{13}CH peak is shown. When we tune off to where the ^{14}C should be, there are no counts, which is expected because we don't have enough current to see the ^{14}C even with modern abundance. You can see that here the resolution is even sharper than it was with ^{12}C. This is because the mass 12 resolution plot was run at the 11th harmonic, and this is at the 13th. We are also running at a somewhat higher frequency and resolution seems to be better when we go to higher frequencies.

FUTURE PLANS

One conclusion from these curves is that we need more beam current. That's what we are currently working on. We are planning to obtain an external, Middleton-type source from General Ionex Corporation, a CO_2 source, and to inject the beam into the machine externally. We hope this will be accomplished within the year.

We have a novel method [6] to inject the beam by bouncing it off an electrostatic mirror, radially into the machine. (Fig. 16) We plan to follow an external source with some initial mass separation (using some type of magnetic separator), eliminating most of the mass 12 and 13 ions. Electrostatic lenses will focus the beam into the machine. The beam will then curve in the B field of the machine, and bounces off of an electrostatic mirror into its initial orbit.

We have also considered operation with other isotopes such as ^{129}I; the beam current would be a little better for ^{129}I than for ^{14}C, but we would have to inject with very low energy. We suspect that the emittance of the Middleton-type source would preclude the use of ^{129}I with the present machine. However, with a lower-emittance source ^{129}I may be practical to use.

SUMMARY

To summarize, we use several new and unusual, advanced techniques in the

small cyclotron. It is run at low energy, using negative ions, at high harmonics. We use electrostatic focusing exclusively. The ion source and injection system is in the center, which unfortunately does not give enough current, but our new system should solve that. We use an electrostatic extractor that runs at low voltage, under 5 kV, and a microchannel plate detector which is able to discriminate low energy ions from the ^{14}C. We have found that the resolution is sufficient for ^{14}C dating and a higher intensity source should allow us to date a milligram size sample of 30,000 year old material with less than 10% uncertainty (similar to other AMS methods). We do not suggest the small cyclotron as a competitor to a tandem or to another facility, but as a complementary technique. We hope that the things we have learned with the cyclotron that may assist those who are intending to build other facilities. In particular, we have learned that some of the new techniques and advanced methods that are available are quite helpful in designing a machine. We suggest that any new machine coming on line be flexible enough to allow new techniques to be used in its design and development. Even if the machine has already been designed, it is helpful to be near a center of accelerator design expertise in order to make modifications on the machine to improve its efficiency and throughput.

REFERENCES

[1] R.A. Muller, T.S. Mast, P.P. Tans, and J.J. Welch, Proc, Symp. on Accelerator Mass Spectrometry, Argonne Nat. Lab Report ANL/PHY-81-1 (1981).

[2] J.J. Welch, K.J. Bertsche, P.G. Friedman, D.E. Morris, R.A. Muller, and P.P. Tans, Proc. AMS '84, Nucl. Instr. and Meth. B5 (1984) 230.

[3] J.J. Welch, PhD Thesis, Lawrence Berkeley Lab Report LBL-21255 (1984).

[4] J.J. Welch, K.J. Bertsche, D.E. Morris, R.A. Muller, to be published, Nucl. Instr. and Meth. (1986).

[5] P.G. Friedman, to be published, Lawrence Berkeley Lab Report LBL-17804 (1986).

[6] D.E. Morris, to be published, Nucl. Instr. and Meth. 248 (1986) 297.

NOTES

* Presently at Stanford Linear Accelerator Center, Stanford, CA

** This talk was prepared and presented by K.J. Bertsche

*** The submitted manuscript has been authored by a contractor of the U.S. Government under contract No. DE-AC03-76SF00098. Much of the material presented here is summarized from references 1-5; the reader should see these references for more details.

**** This section is a summary of the results presented in references 3 and 4. For additional performance data, please see these references.

ADVANCED ACCELERATOR METHODS

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Collaborators:

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Jim Welch
Don Morris
Peter Friedman

ACCELERATOR MASS SPECTROMETRY

YOUNG FIELD

MANY ADVANCES

NEW METHODS AVAILABLE FOR NEW DESIGNS

REQUIREMENTS FOR SMALL CYCLOTRON ("CYCLOTRINO")

LOW COST

SMALL SIZE

EASE OF OPERATION

LOW ENERGY (<100 keV)

OPERATION WITH ^{14}C

RESOLUTION REQUIREMENTS

INTERFERENCES (NEARBY MASSES)

^{14}N		
^{13}CH	~0.06%	1:1800
$^{12}CH_2$	~0.09%	1:1100

TAIL REJECTION (DISTANT MASSES)

MODERN CARBON:

$$^{12}C : {}^{13}C : {}^{14}C \sim 10^{12} : 10^{10} : 1$$

$t_{1/2}$ = 5730 YEARS

30,000 YEARS = ~6 HALF LIVES

= ~1% MODERN ABUNDANCE

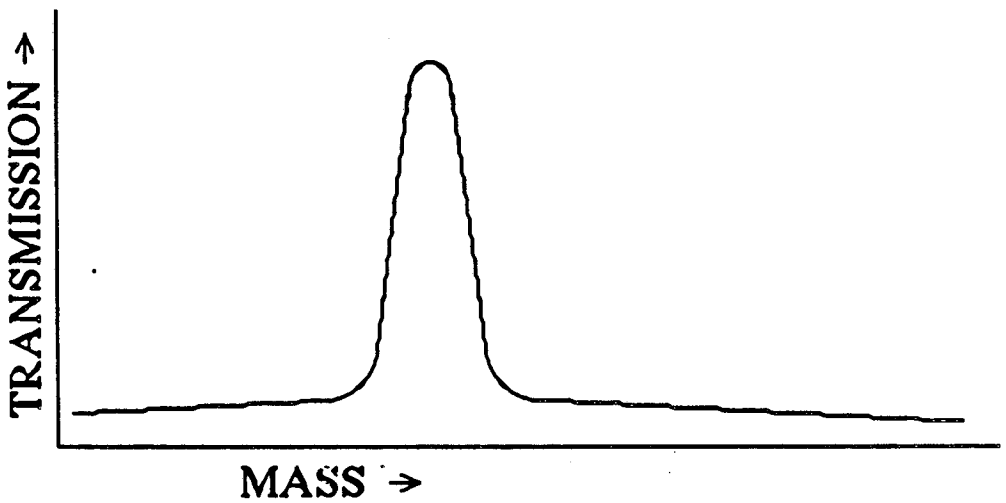

Fig. 1

BASIC CYCLOTRON OPERATION

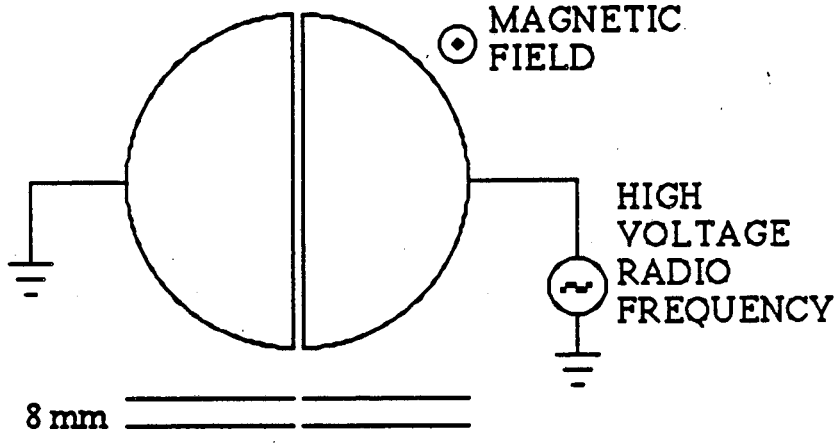

Fig. 2

B ~ 1 T = 10 kG

f_{cyc} ~ 1 MHz

INJECTION	~ 3 cm	~ 3 keV
EXTRACTION	~ 10 cm	~ 30 keV

V_{RF} ~ 500-1000 V p-p

N ~ 50

H ~ 11 to 15

RESOLUTION ~NH

AXIAL FOCUSING

WEAK FOCUSING (RADIAL B-FIELD GRADIENT)

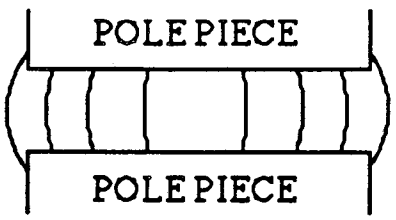

Fig. 3

STRONG FOCUSING (SECTOR FOCUSING,

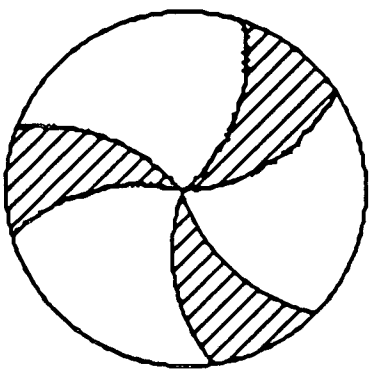

Fig. 4

ELECTROSTATIC FOCUSING

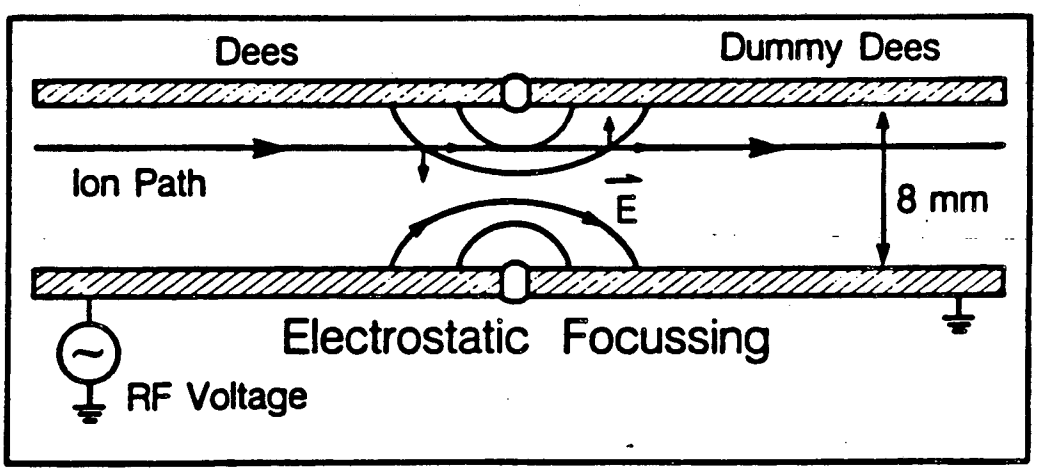

Fig. 5

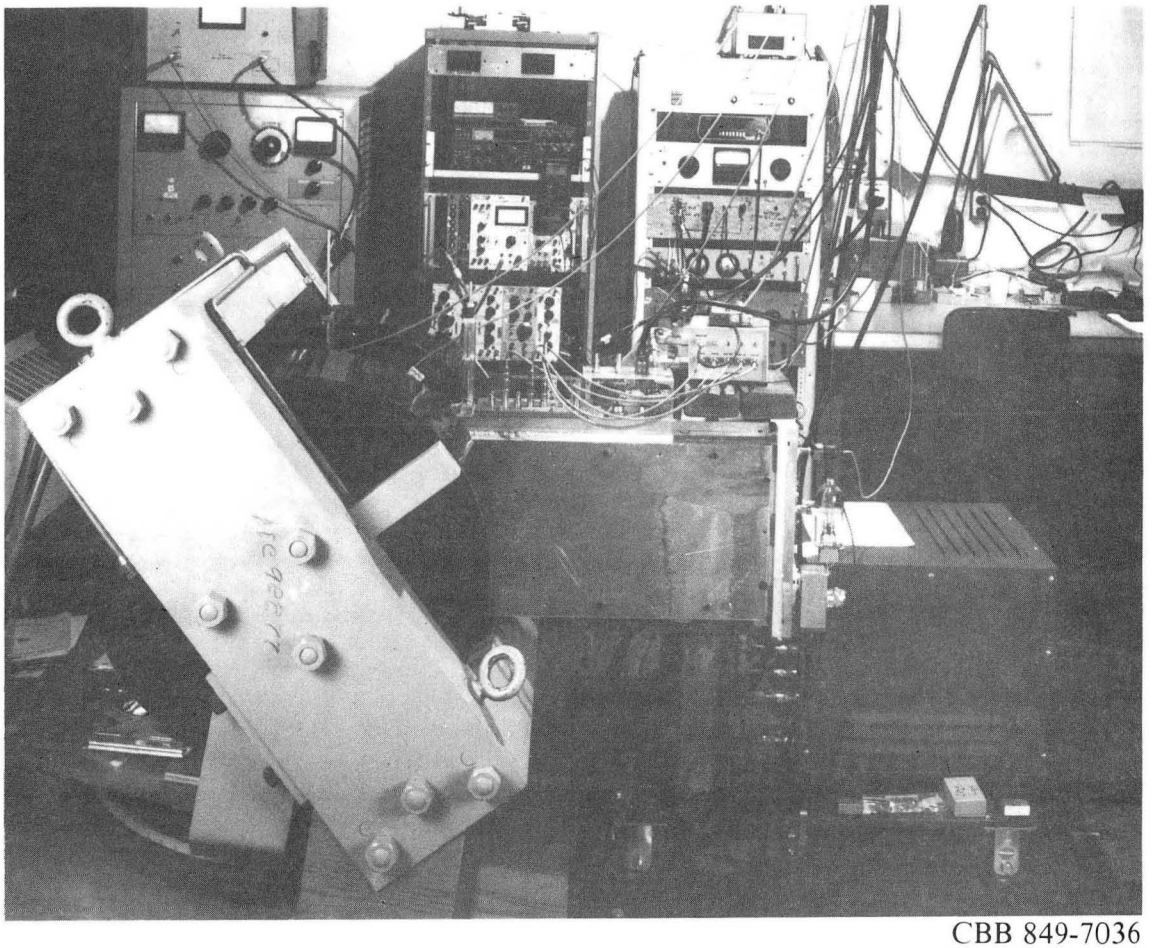

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Fig. 6

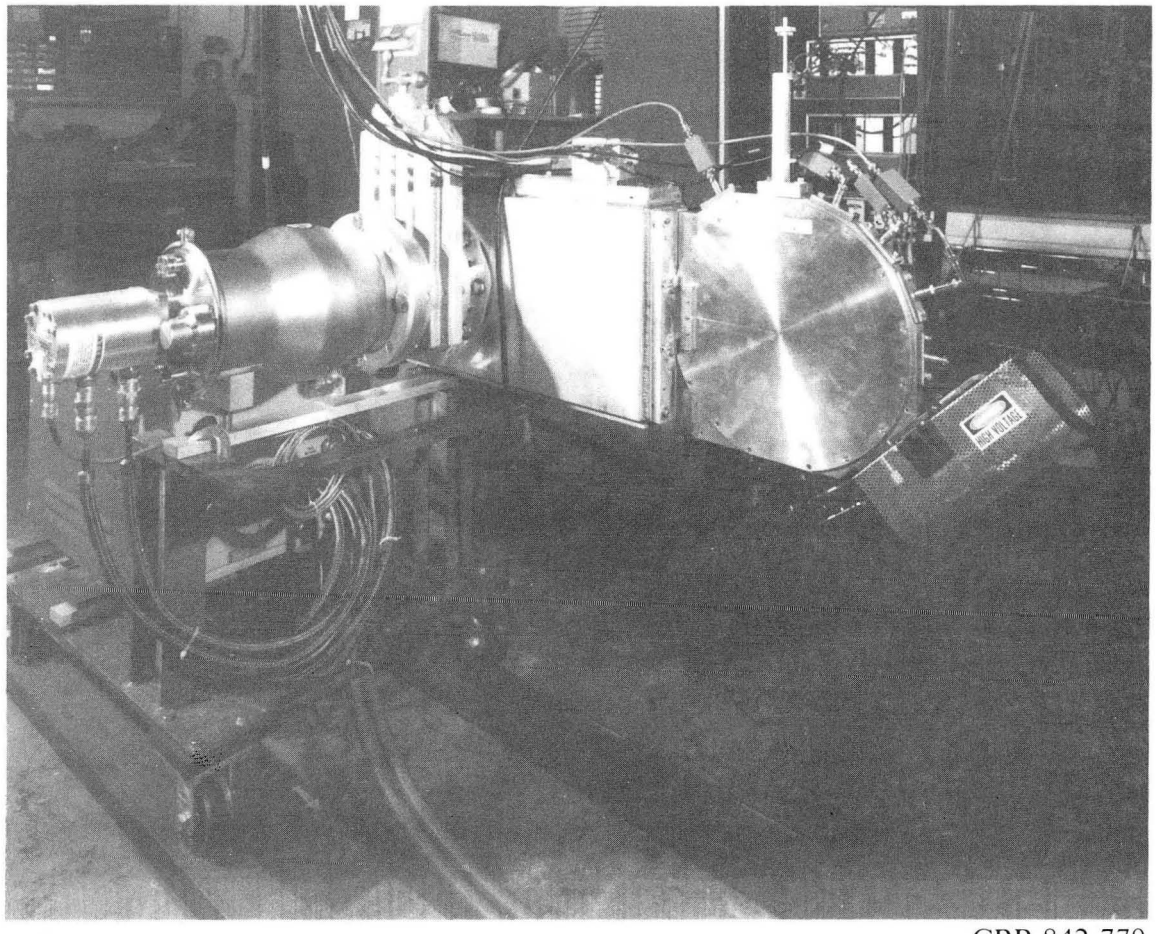

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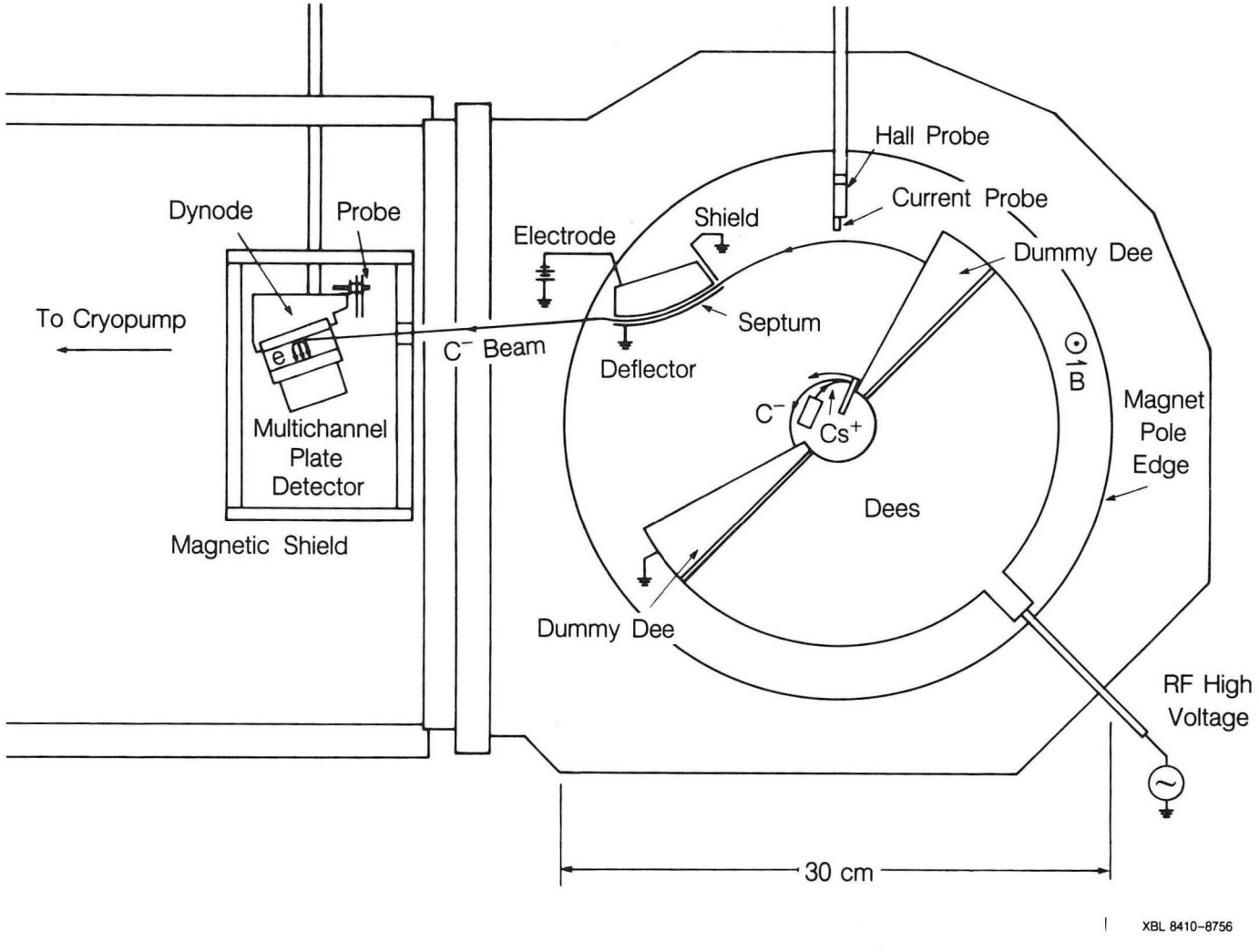
Fig. 7


Hall Probe
Current Probe
Dummy Dee
Shield
Electrode
Dynode
Probe
To Cryopump
Septum
C⁻ Beam
Deflector
⊙1B
Magnet
Pole
Edge
C⁻
Cs⁺
Multichannel
Plate
Detector
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Dummy Dee
RF High
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Fig. 8

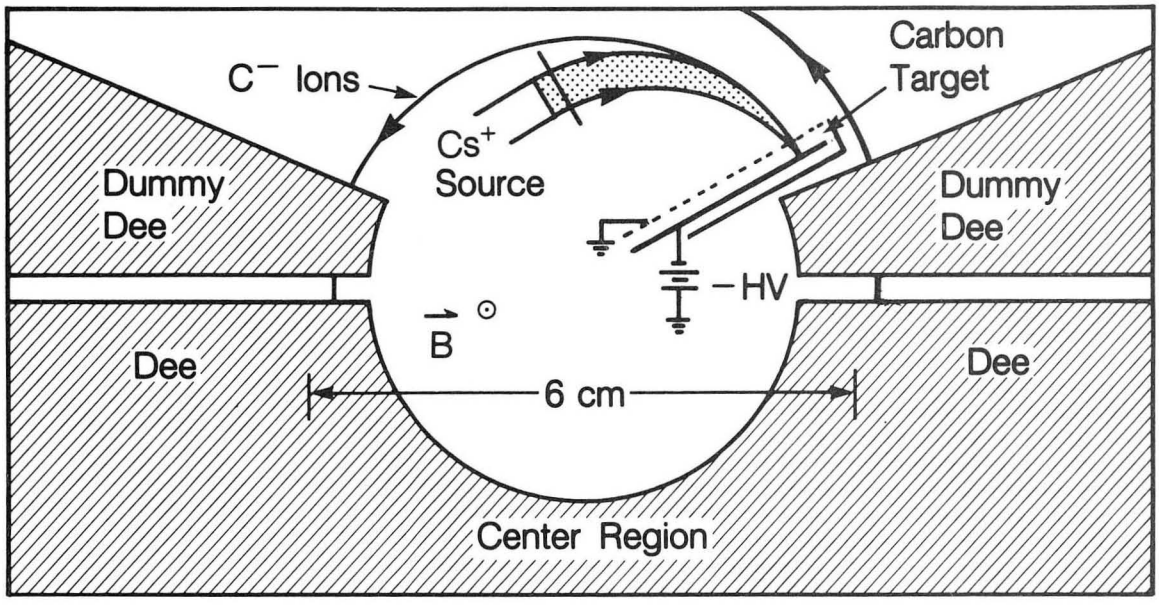

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Fig. 9

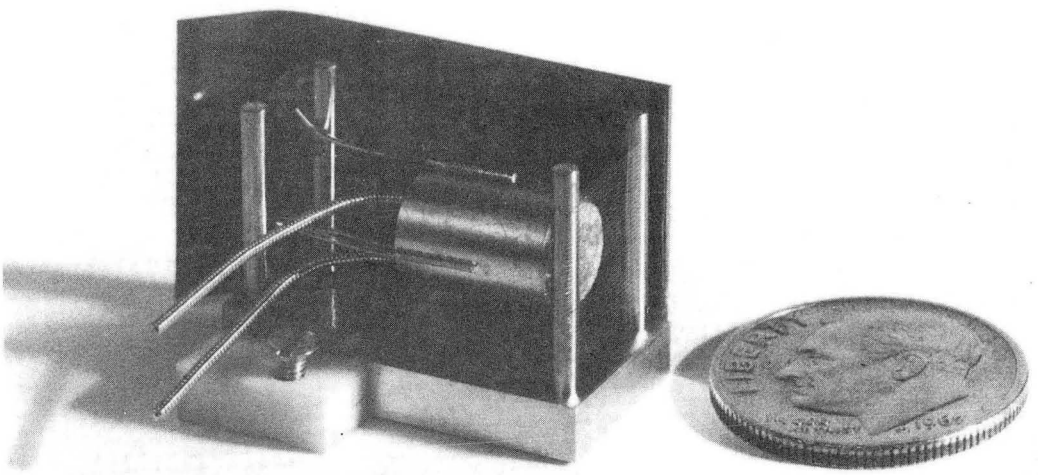

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Fig. 10

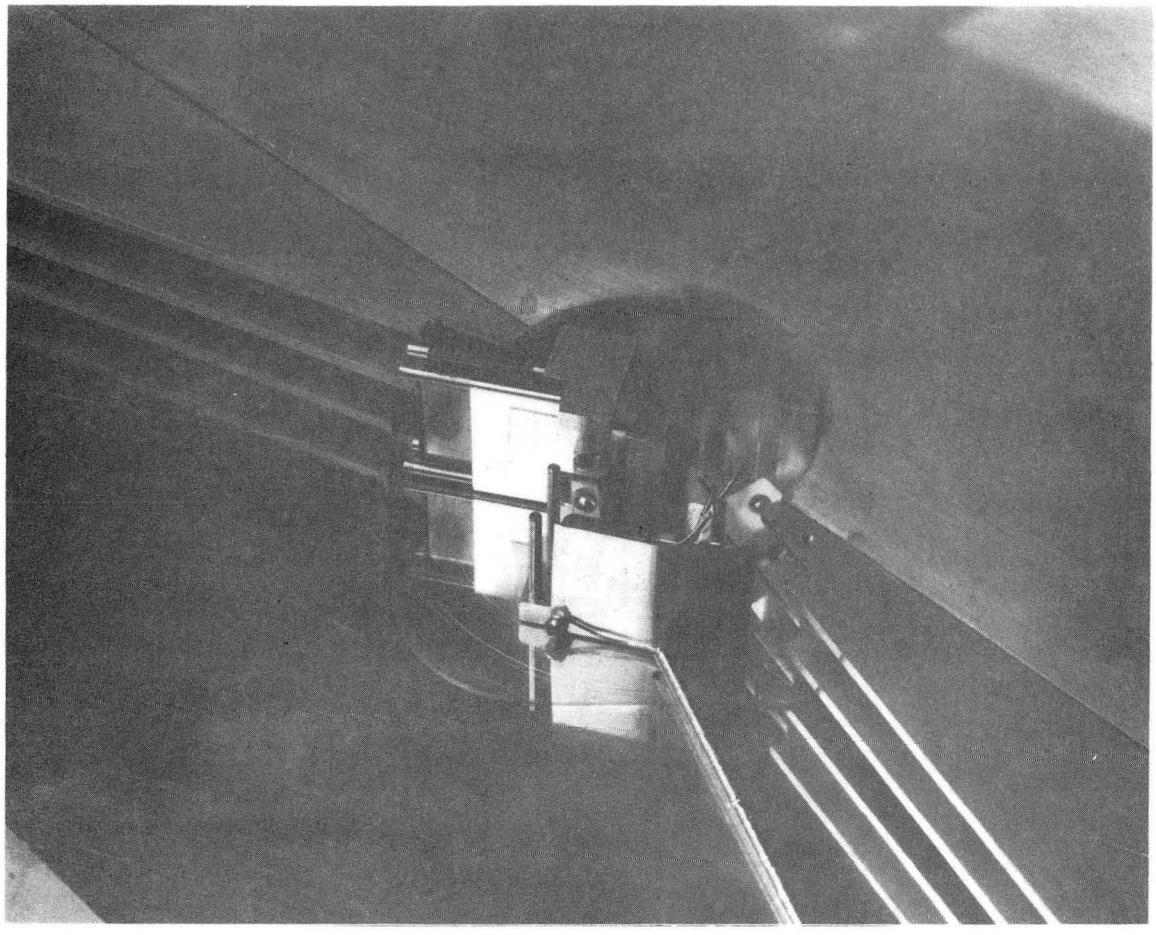

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Fig. 11

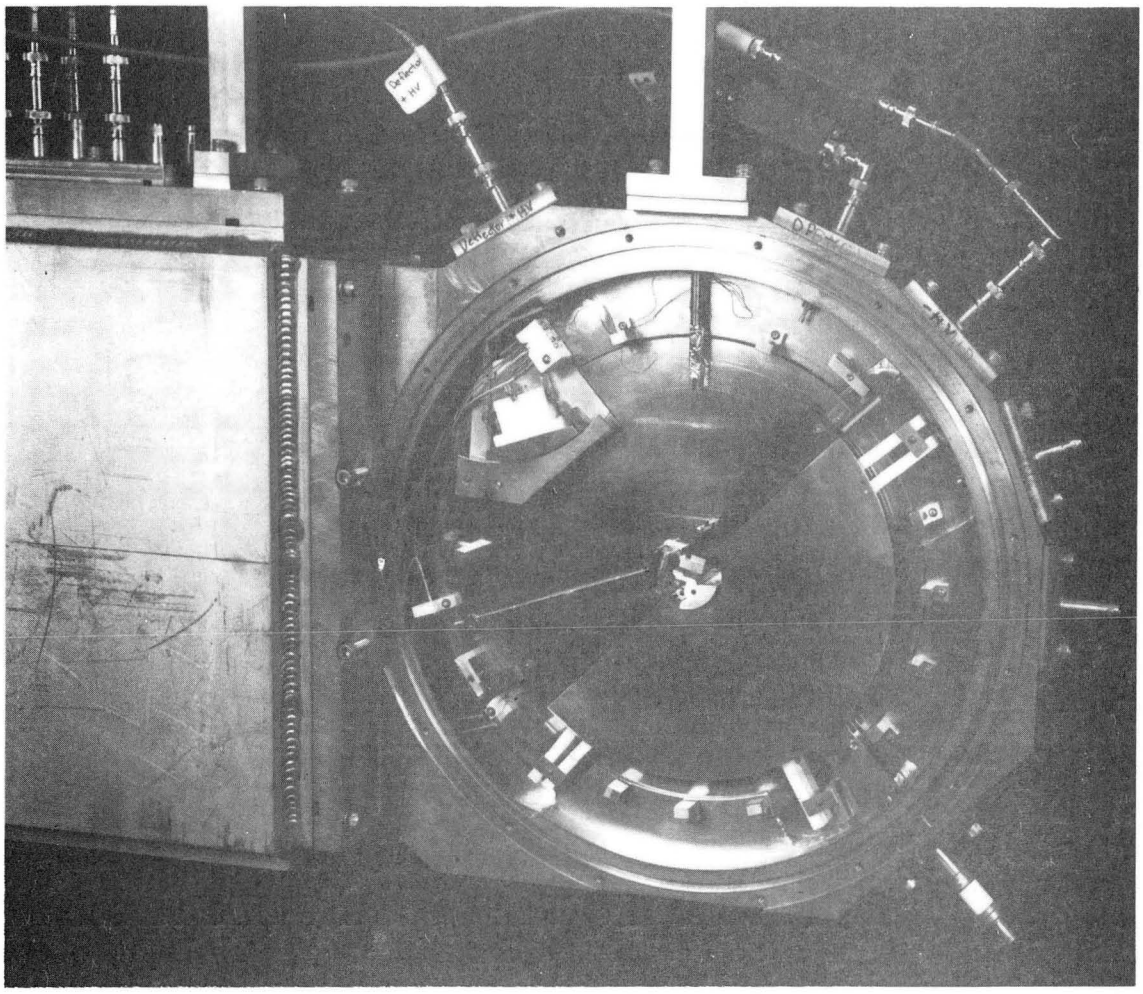

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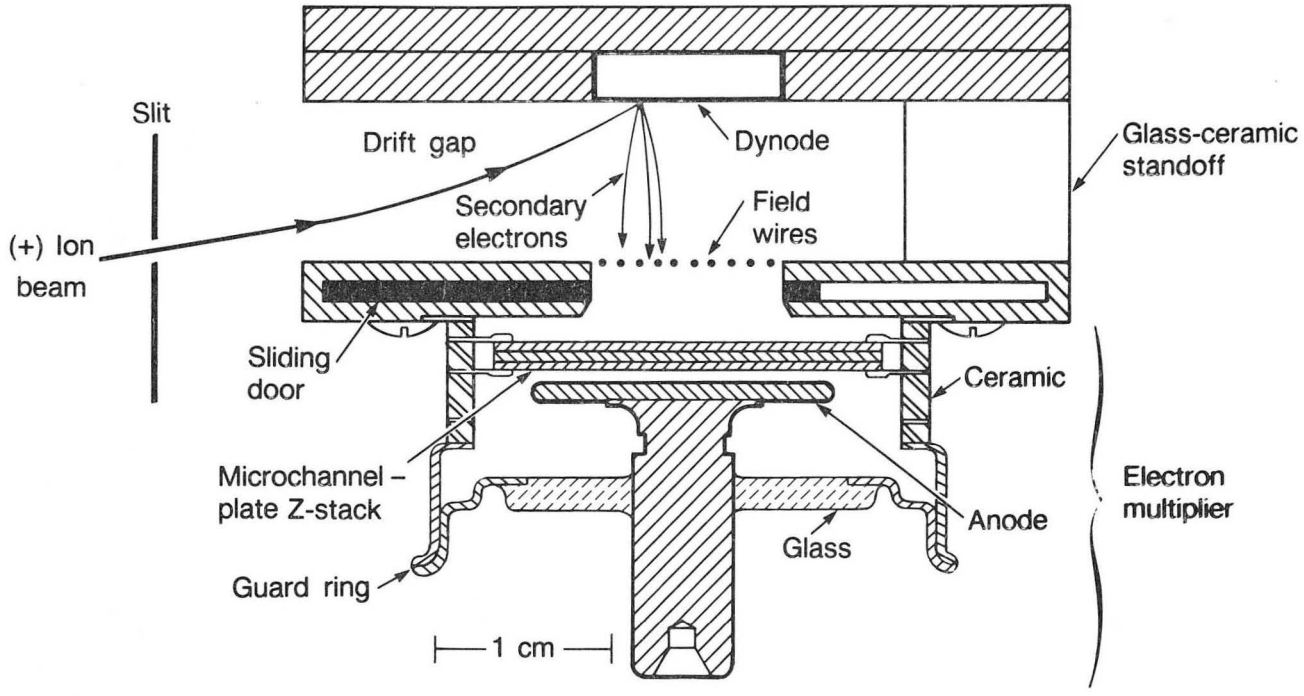
Fig. 12



XBL 8610-11735

Fig. 13

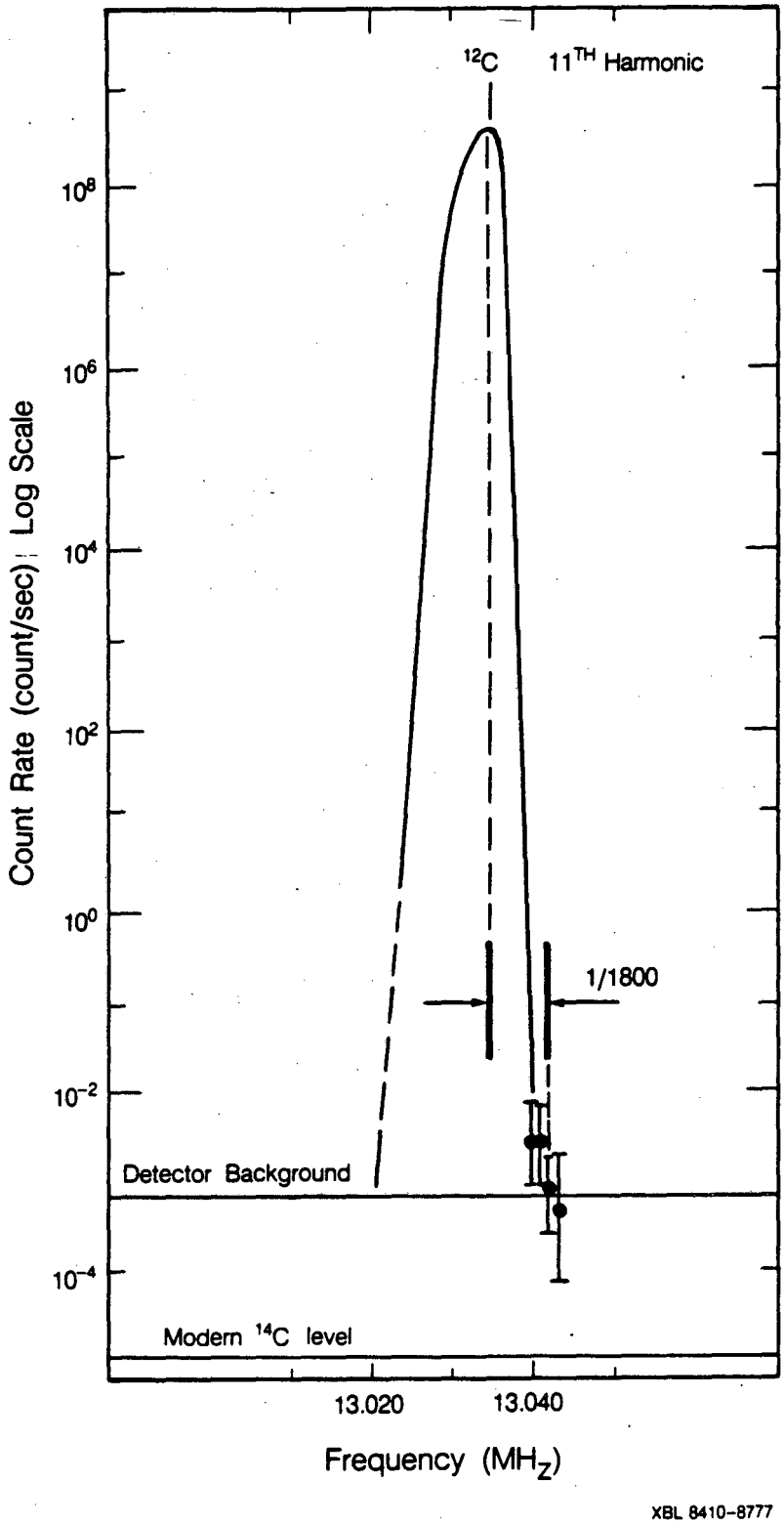

^{12}C
11^{TH} Harmonic
10^8
10^6
10^4
10^2
10^0
10^{-2}
10^{-4}
Count Rate (count/sec) Log Scale
1/1800
Detector Background
Modern ^{14}C level
13.020
13.040
Frequency (MH_Z)
XBL 8410-8777

Fig. 14

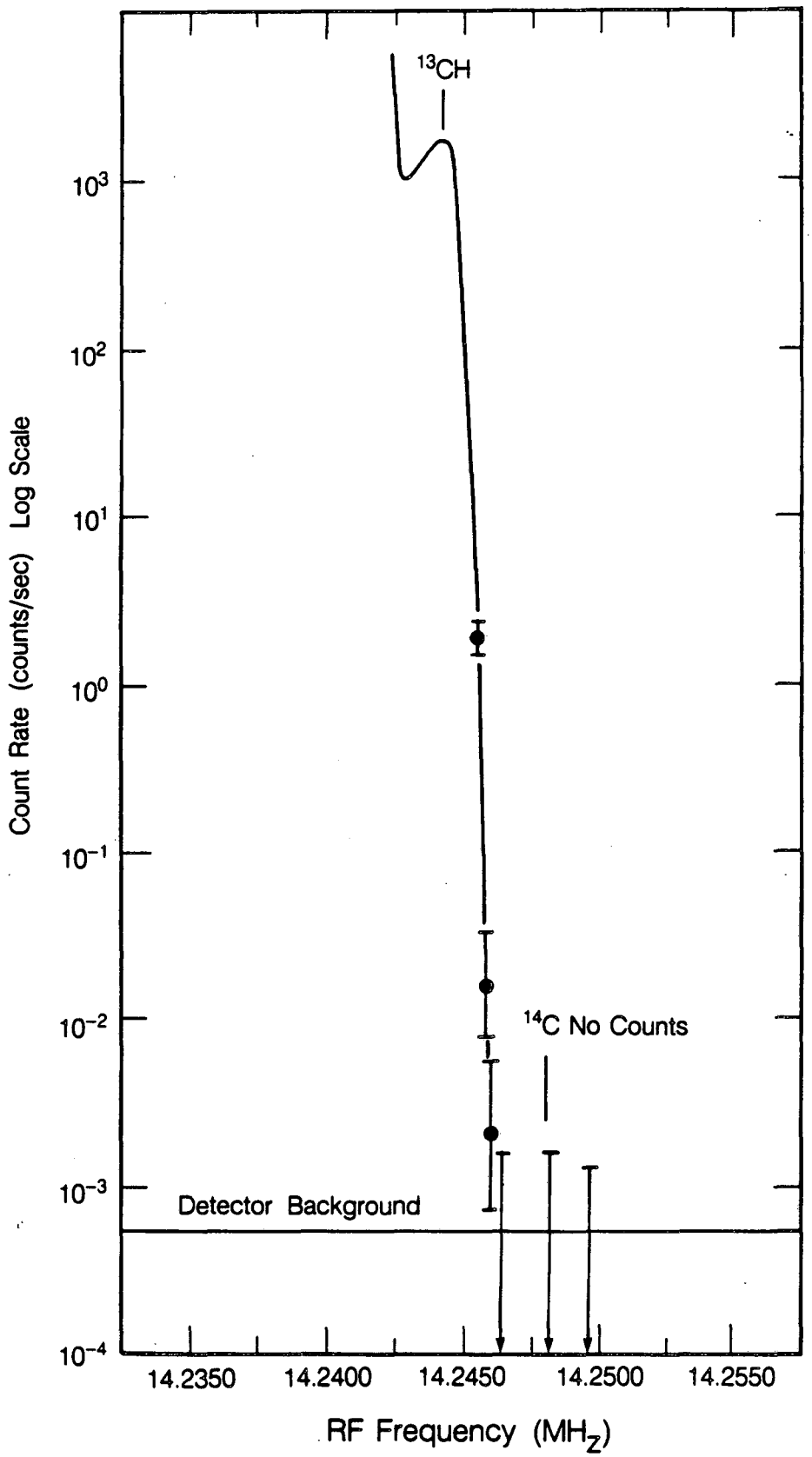

^{13}CH
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
Count Rate (counts/sec) Log Scale
^{14}C No Counts
Detector Background
14.2350
14.2400
14.2450
14.2500
14.2550
RF Frequency (MH_Z)
XBL 8410-8776

Fig. 15

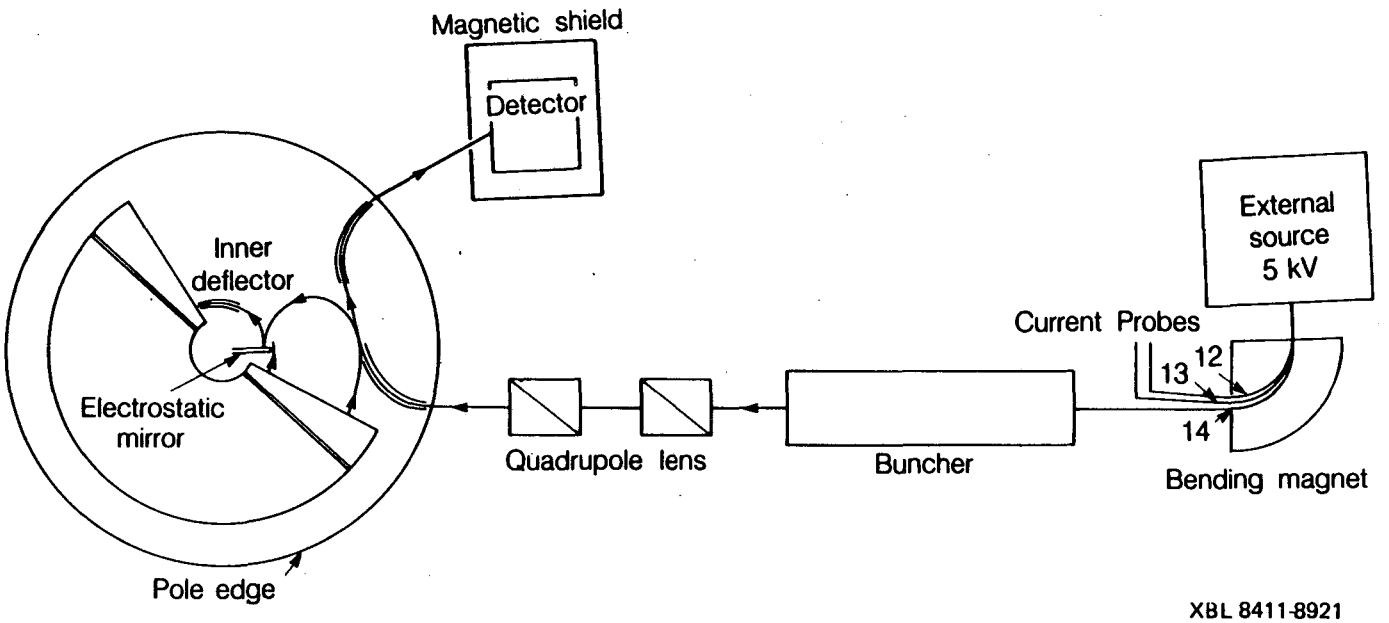

Magnetic shield
Detector
Inner
deflector
Electrostatic
mirror
Pole edge
Quadrupole lens
Buncher
External
source
5 kV
Current Probes
13
12
14
Bending magnet
XBL 8411-8921

Fig. 16

SUMMARY

CYCLOTRINO USES MANY NEW OR UNUSUAL TECHNIQUES:

LOW ENERGY
NEGATIVE IONS
HIGH HARMONIC OPERATION
ELECTROSTATIC FOCUSING
ION SOURCE & INJECTION
ELECTROSTATIC EXTRACTION
MICROCHANNEL PLATE DETECTOR

RESOLUTION IS SUFFICIENT FOR ^{14}C DATING; HIGHER INTENSITY SOURCE SHOULD ALLOW DATING mg-SIZE SAMPLES OF 30,000 YEAR OLD CARBON TO LESS THAN 10% STATISTICAL UNCERTAINTY.

WE WOULD SUGGEST THAT NEW AMS FACILITIES (CYCLOTRON, TANDEM, ETC.) BE FLEXIBLE ENOUGH TO ALLOW R&D INVOLVING NEW ACCELERATOR METHODS.

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