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A POLARIZED ION SOURCE FOR THE BERKELEY 88-INCH CYCLOTRON[*] [†]

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ABSTRACT

A polarized proton and deuteron source for the Berkeley 88-inch cyclotron has been built and presently is being tested. The source, of the "atomic beam" type,[1] is mounted vertically above the cyclotron, its beam being injected axially into the machine through a hole in the upper yoke. The axial injection system is described elsewhere.[2]

The source is of rather conventional design. Our main aim has been to use the best features of the most successful sources in operation in various laboratories, making improvements in design as far as possible. This provides a dependable system, flexible enough to leave room for future developments of the various parts.

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[*] Work performed under the auspices of the U.S. Atomic Energy Commission.

[†] Expanded version of paper presented at the 1969 Particle Accelerator Conference, Washington, D. C., March 5-7 1969.

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I. PRINCIPLE OF OPERATION

An atomic beam of hydrogen or deuterium is produced by dissociating H_2 of D_2 gas in a discharge tube, and by collimating the beam with a series of diaphragms in a differential vacuum system.

The beam is injected into a sextupole magnetic field, where it is split into its hyperfine-structure (hfs) components. Half of the components (two for hydrogen, three for deuterium) converge toward the symmetry axis of the field and are transmitted; the other half is lost against the sextupole magnet and the vacuum enclosure walls. At the end of this stage, in a weak magnetic field the beam would be only partially polarized.

Full polarization is achieved by the adiabatic passage method[3] as follows: the atomic beam passes through an oscillating magnetic field of the proper frequency and orientation, superimposed on a static magnetic field which presents a low longitudinal gradient. In this field transitions among the hfs states are induced.

The fully polarized atomic beam is thereafter ionized by electron impact in a static magnetic field. The ions are extracted, acceleratred and focused at a location suitable for the injection into the cyclotron.

Means are provided to measure the density of the atomic beam and the ion current. A simple polarimeter allows one to measure the deuteron tensor polarization before injection. The vector polarization of the proton and deuteron beam cannot be measured by simple means at low energies.

The source has been designed to give up to 10 μA of protons and deuterons with energy up to 20 keV and polarization ± 1 (protons), ± 2/3 (deuterons, vector), ± 1 (deuteron, tensor).

II. THE DISSOCIATING UNIT AND THE ATOMIC BEAM FORMING SYSTEM

The overall feature of the source, on the cyclotron vault shielding roof is shown in the Figs. 1, 2, and 3.

The first element from the top is the "hairpin" pyrex dissociator tube, in which H_2 and D_2 molecules are dissociated into atoms. The dissociating discharge is of the electrodeless type, driven by a 1.5 kW, 20 MHz self-excited oscillator, capacitively coupled to it. The use of this type of oscillator has proved convenient, since its operation remains stable during rapid variations of the physical parameters of the discharge, such as pressure and temperature. The gas is admitted to the discharge tube through a remotely operated gas metering valve, coupled with an automatic pressure regulator.[4] Operating pressure in the discharge is in the range of 2 Torr, with gas flow in excess of 100 atm cc per minute.

The atomic beam is formed and collimated by three orifices. The first pierced at the end of the glass tube, shows a double-conical shape and forms, together with the second, a Laval nozzle-skimmer arrangement.[5] The diameter of these orifices is 2.5 mm and their separation, in the best experimental operating conditions is 4 mm. The third orifice, located at the sextupole entrance has a diameter of 4 mm and is 7 cm away from the second. Second and third orifices are pierced through tantalum inserts, the choice of Ta being suggested to minimize possible damaging effects by the ions outstreaming from the dissociator. The geometry of the orifice system is shown in Fig. 4.

Pressure inside the Laval nozzle arrangement is 10^{-2} Torr, maintained by a 1000 CFM roots blower.[6] At this pressure the mean free path of the hydrogen atoms is about 1 cm. The gas flow out of the discharge tube is .1 Torr-liter/sec in the present conditions, or approximately 10^{19} atoms/sec, of which, according to the Laval nozzle theories, about 10^{17} should be contained in the final beam.[7]

The pressure in the "collimation region", between the second and the third orifice, is 10^{-4} Torr, maintained by two 10-inch Hg diffusion pumps with freon and LN baffles. The choice of Hg instead of oil diffusion pumps has been made to avoid the polymerization of vacuum oil due to the very reactive atomic hydrogen.

The sextupole and r.f. transitions housing are evacuated by means of an 12-inch oil diffusion pump with LN baffle giving an operating pressure of 2×10^{-6} Torr. The neutral beam intensity is monitored here with a compression gauge, consisting of an ion gauge fitted to a bottle furnished with a 4 mm diameter × 10 cm length intake tube. The pressure rise in the gauge with the beam "on" is proportional to the beam density. The collimation and the shape of the beam is checked easily with MoO targets, sensitive to atomic hydrogen. At the end of this section, the polarized beam shows a cross section less than 1 cm in diameter (see next).

The ionizer housing is evacuated by a 1500 l/sec electro-ion pump[8] at a pressure of the order of 10^{-7} Torr. To avoid as far as possible the presence in the ionizing region of unpolarized hydrogen from the background and contaminations of oil vapors and water, the ionizer is surrounded by a double wall enclosure cooled with LN. An LN baffle with an axial channel is also provided at the ionizer housing entrance, from the sextupole side, which represents a very high impedance to gas background and practically zero impedance to the beam.

III. THE SEXTUPOLE

The sextupolar lens is shown in Fig. 5. The electromagnet yoke is 48 cm in diameter and 50 cm in length. The magnetic gap is longitudinally tapered from 7 mm at the entrance to 16 mm at the end. The excitation is accomplished by means of six 12-turn coils, water cooled, wound around each pole and fed by a 32 V-200A DC power supply, stabilized within a few percent. The pole tips are assembled in a single unit and are removable to allow for future improvements.

In a perfect sextupole, the field components are:

$$B_\theta = B_0 \left(\frac{r}{r_0}\right)^2 \cos 3\theta \quad ,$$

$$B_r = B_0 \left(\frac{r}{r_0}\right)^2 \sin 3\theta \quad ,$$

$$B = B_0 \left(\frac{r}{r_0}\right)^2 \quad .$$

In this field, the radial force acting on a neutral atom of magnetic moment μ is:

$$F = -\operatorname{grad}(\mu \cdot B) = -\mu \operatorname{grad} B = -2\mu\,(B_0/r_0^{\,2})r$$

provided that B is strong enough to allow one to disregard the dependence of μ itself on B.

In the sextupole strong field μ equals + one Bohr magneton for two hfs components of hydrogen out of four, and three of deuterium out of six. For these components the force is focusing and harmonic. The presence of other field harmonics than the 3rd (sextupole) induces different forces on the beam. Higher order harmonics, multiples of 3, are usually present, since they derive from the shape of the pole tips, which are different from the 3rd order hyperbolas of a perfect sextupole. Lower order harmonics come from defects of manufacture.

The sextupole field has been measured at various locations along its axis, by means of a set of rotating coils with one side on the axis, and a current integrator and recorder. Fourier analysis of the measured curves has been done, showing that components other than the 3rd have amplitudes of only a few percent of the 3rd harmonic. The harmonic content does not seem to depend much on the absolute value of the field.

The sextupole focusing effect on the beam is shown by the MoO pictures of Fig. 6, taken with the sextupole "off" and "on", at a position some 50 cm downstream from the sextupole at the ionizer location.

IV. THE R.F. TRANSITIONS

Vector and tensor polarization, P_z and P_{zz}, can be defined in the following way:

$$P_z = \frac{N_+ - N_-}{\Sigma N} \qquad P_{zz} = 1 - 3\frac{N_0}{\Sigma N}$$

$\Sigma N = N_+ + N_-$, $N_0 = 0$, for protons

$\Sigma N = N_+ + N_0 + N_-$, for deuterons

N_+, N_0, N_- represent the occupation numbers of the hfs states.

With reference to the energy diagrams of Figs. 7 and 8 the hydrogen and deuterium atoms after the sextupole occupy the two and the three upper states respectively. Their polarization, in a strong magnetic field such as the cyclotron's, would be zero. To achieve complete polarization the following system of adiabatic transitions has been adopted:

Protons: $1 \to 3$, $B_0 = 5$ gauss, $f = 7.5$ MHz, which yields: $P_z = -1$

Deuterons: $1 \to 4$, 8 gauss, 7.5 MHz, $P_z = -2/3$, $P_{zz} = 0$

$3 \to 5$, 80 gauss, 331 MHz, $P_{zz} = -1$, $P_z = 1/3$

$2 \to 6$, 80 gauss, 458 MHz, $P_{zz} = +1$, $P_z = 1/3$.

Note in addition that:

- the beam is ionized in a strong axial magnetic field; by reversing the direction of the field the vector polarization changes its sign;

- the deuteron tensor polarization is not pure. However, in doing experiments with this beam, it will be possible to subtract the results (such as the cross sections) for the two last cases, to eliminate the vector contribution.

The two transitions, weak field (8 gauss) and intermediate field (80 gauss) are to be operated one at a time. We regard this as a considerable advantage over other systems which should use various transitions at the same time in different combinations.

The two transition magnets are much the same. They have been designed as plug-in units, inserted in their place through a port in the sextupole housing side. With this arrangement the two units can be removed in a matter of minutes.

In the weak field transition, the oscillating magnetic field should be oriented perpendicularly to the static, adiabatic, field. It is produced accordingly by a 1 cm diameter - 3 cm long coil through which the beam passes. The 7.5 MHz oscillator (5 W output power) is a very small unit completely contained in the vacuum.

In the intermediate field transition, the oscillating field must be parallel to the static field. Therefore it is produced by a hairpin loop, formed by a couple of 3 cm long plates parallel to the beam, bridged at one side. The 300 - 400 MHz oscillator is of the tuned-plate, tuned-grid type (150 W output) and is connected to the coil by a 1.5 m long cable.

V. THE IONIZER

The ionizer has been manufactured by ANAC Company,[9] according to the Auckland University (New Zealand) design.[10]

The atomic beam is ionized by electron collision in a cylindrical region 1 cm diameter and 12 cm long, where a 1500 gauss magnetic field parallel to the axis is present. The sign of this static field can be reversed to allow changing the sign of the polarization of the beam.

The electrons are produced and accelerated to about 500 volts at the entrance side of the device. A negative voltage at the exit end (about 2 kV) repels the electrons back, so that they can oscillate back and forth throughout the "ionization column", being confined in a cylindrical sheet by the action of the magnetic field. The negative electrodes provide as well the extraction of the positive ions from the ionizer, and the positive beam is shaped and properly accelerated by means of a subsequent system of electrostatic lenses.

The energy of the ion beam from the ionizer might be a given fraction of the dee voltage in the cyclotron, to provide centering of the first orbits on the center of the machine.[11] Moreover, as a study of the axial injection system has shown, the best results can be obtained accelerating this beam at definite values of its energy for every final energy in the cyclotron.[12] Accordingly the ionizer voltage with respect to ground, which defines the ion energy, must be varied over a wide range, from 5 to 15 kV.

This requirement means an achromatic optical system for the ionizer, that was not provided with it, to give a waist at the entrance of the axial transport line over this energy range. To solve the problem, the original ionizer optics have been modified by adding a third cylindrical electrode to the "focus" gridded lens and placing at some distance a second gridded "einzel" lens. (Fig. 1.) The first lens is to form a beam waist at a fixed position, about 10 cm past the grid, for a wide range of beam energies. The second lens provides the transfer of this waist to another waist in the most suitable position for the axial injection line.

Ionizer efficiency, according to the manufacturer, is up to 10^{-3}; emittance of the first waist about 1,600 mm-mrad-keV$^{1/2}$, normalized at 5 keV.

VI. POLARIMETER AND CONTROLS

The tensor polarization of a deuteron beam can be evaluated at low energy, by measuring the asymmetry of the neutrons or of the alphas produced in the reaction: $d(t,n)\alpha$.

The relative number of alphas produced at an angle θ is related to P_{zz} by:[13]

$$\sigma(\theta) = \sigma_0[1 - \frac{1}{4} (3 \cos^2 \theta - 1) P_{zz}] \quad .$$

Measuring $\sigma(\theta)$ will allow measuring of P_{zz}. On this line a very simple polarimeter has been built, as a plug-in unit, which we believe could prove very useful to check the source performances. The polarimeter consists of a water cooled tritium target holder and two solid state alpha counters. The tritium target is tilted at 45° with respect to the deuteron beam. The counters are placed to count alphas at 148° and 90°. The asymmetry in the number of alphas counted at these two angles is:

$$A = \frac{\sigma(148^\circ)}{\sigma(90^\circ)} = \frac{1 - 0.289\, P_{zz}}{1 + 0.250\, P_{zz}} \quad .$$

From a measurement of A, P_{zz} can be calculated:

$$P_{zz} = \frac{1 - A}{0.289 + 0.250\, A} \quad .$$

The polarized ion source and axial line controls have been gathered together in a 5-rack console plus other racks, by the side of the system above the cyclotron vault shielding roof. Some of the most important controls will be also operated remotely from the cyclotron control room. Figure 9 shows the control area on the vault roof.

Controls include:

- a vacuum system general panel, with vacuum gauges and safety interlocks;
- gas handling system controls;
- dissociator power control;
- sextupole current and adiabatic transitions magnets and oscillators control;
- ionizer interelectrode and overall voltage control;
- ionizer emission control.

VII. SOURCE PERFORMANCE

The first operation of the source has been satisfactory. A polarized beam current up to .7 μA has been measured through the axial line. Then a polarized proton beam has been injected into the cyclotron, accelerated to 20 MeV, extracted and transferred to a scattering chamber. Here the polarization, measured by scattering on C^{12} resulted in 85 ± 5% (spin "up") and 83 ± 5% (spin "down"). During the acceleration test the beam current had the following values in the various stages of the system: 200 nA at the beginning of the injection line, 6 nA at the cyclotron extraction radius, 2 nA in the extracted beam, .4 nA in the scattering chamber.

The ion background was quite high in the axial line: 3 or 4 times greater than the polarized beam itself. The background beam however proved to contain very little non-polarized hydrogen and was mostly rejected by the cyclotron.

Work is in progress to improve the source performance, as far as the intensity and the degree of polarization are concerned.

ACKNOWLEDGMENTS

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FIGURE CAPTIONS

Fig. 1. Polarized ion source. Assembly drawing.

Fig. 2. General view of the source. The screening cage of the high-voltage section has been partially removed to show the ionizer box.

Fig. 3. View of the source from the west side.

Fig. 4. Laval nozzle and atomic beam collimator.

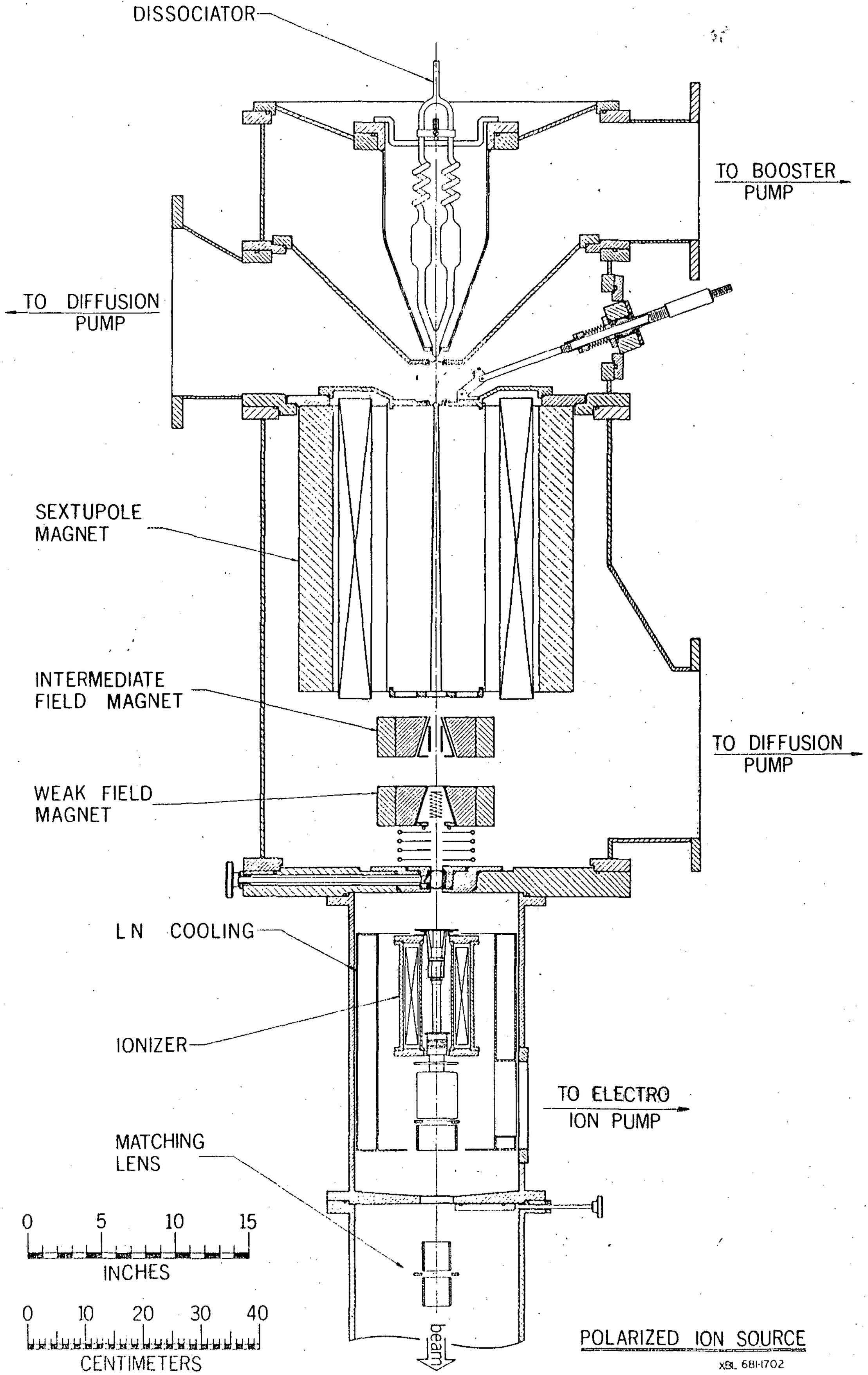
Fig. 5. Sextupolar magnetic lens with removable pole tips.

Fig. 6. MoO pictures of the hydrogen beam with the sextupole "off" and "on".

Fig. 7. Hyperfine structure levels of hydrogen.

Fig. 8. Hyperfine structure levels of deuterium.

Fig. 9. Polarized ion source and axial injection control area.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TO BOOSTER PUMP
TO DIFFUSION PUMP
SEXTUPOLE MAGNET
INTERMEDIATE FIELD MAGNET
TO DIFFUSION PUMP
WEAK FIELD MAGNET
LN COOLING
IONIZER
TO ELECTRO ION PUMP
MATCHING LENS
0 5 10 15
INCHES
0 10 20 30 40
CENTIMETERS
beam
POLARIZED ION SOURCE
XBL 681-1702

Fig. 1.

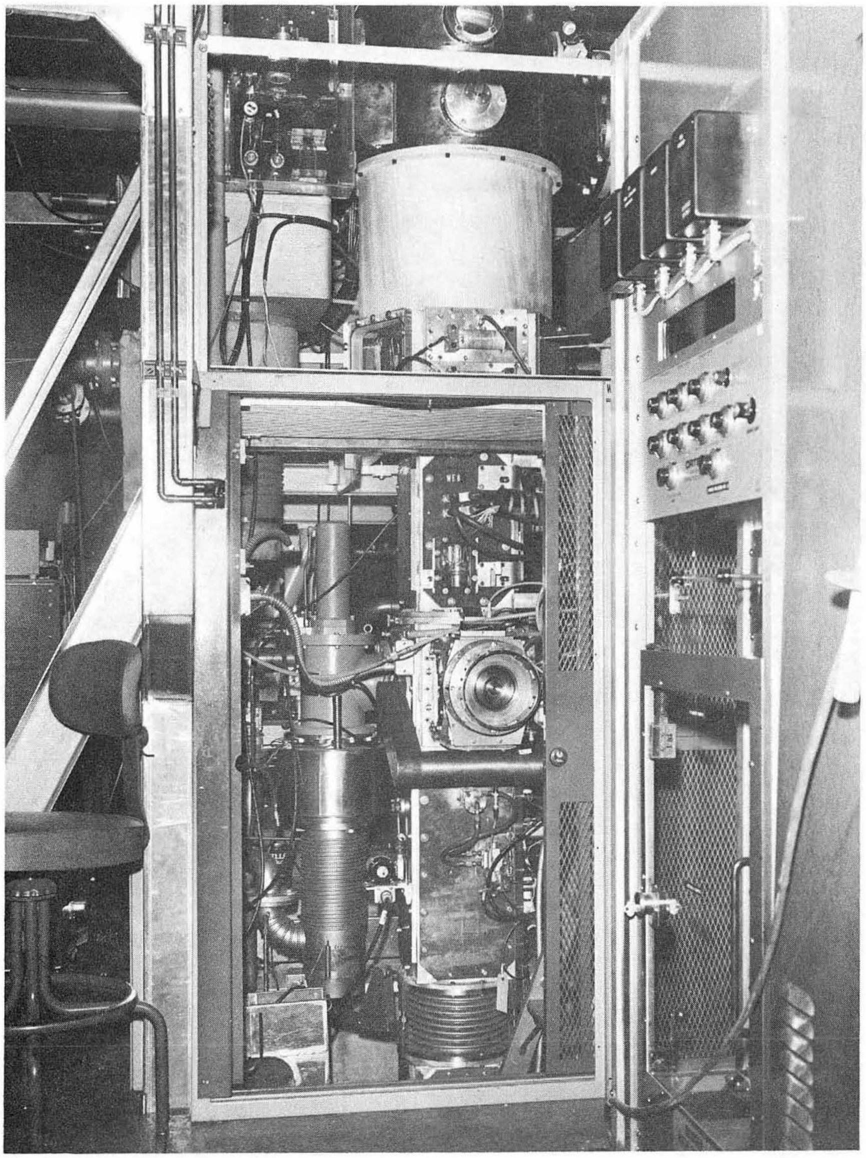

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Fig. 2.

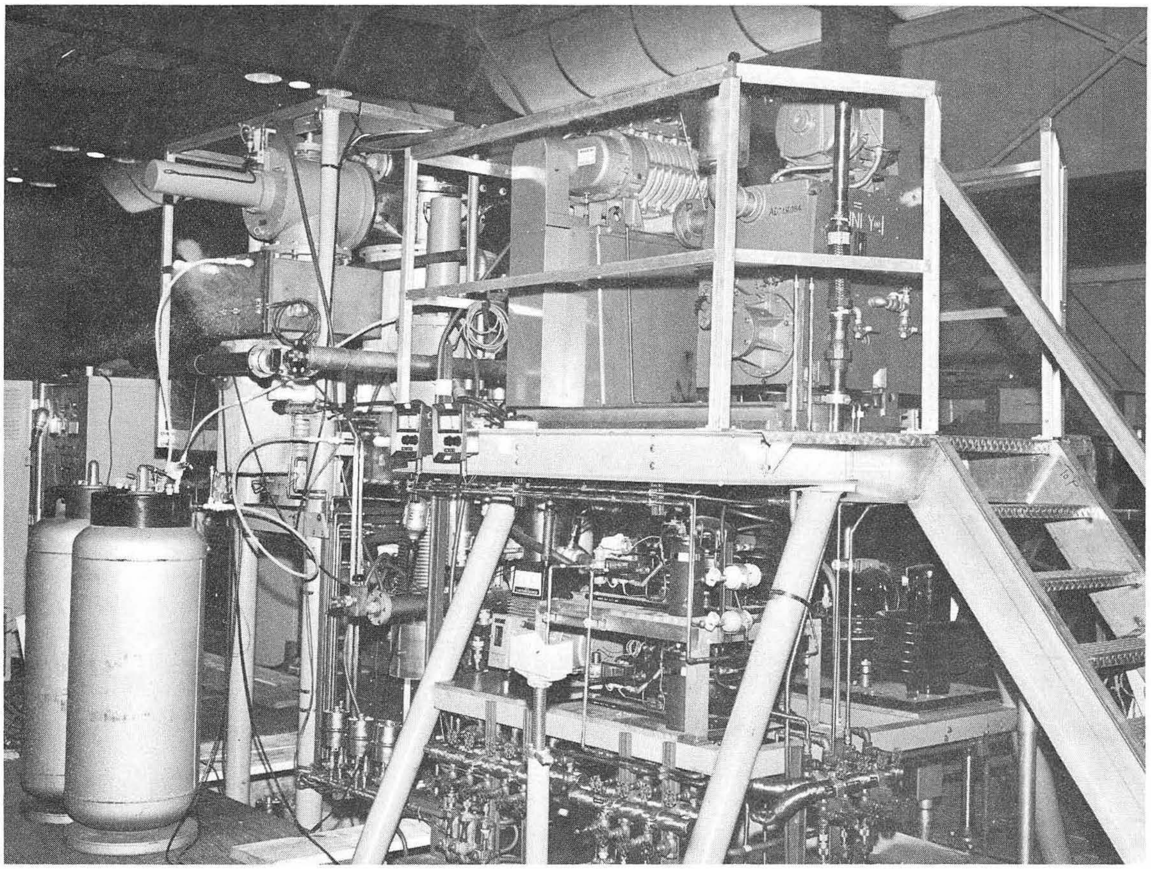

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Fig. 3.

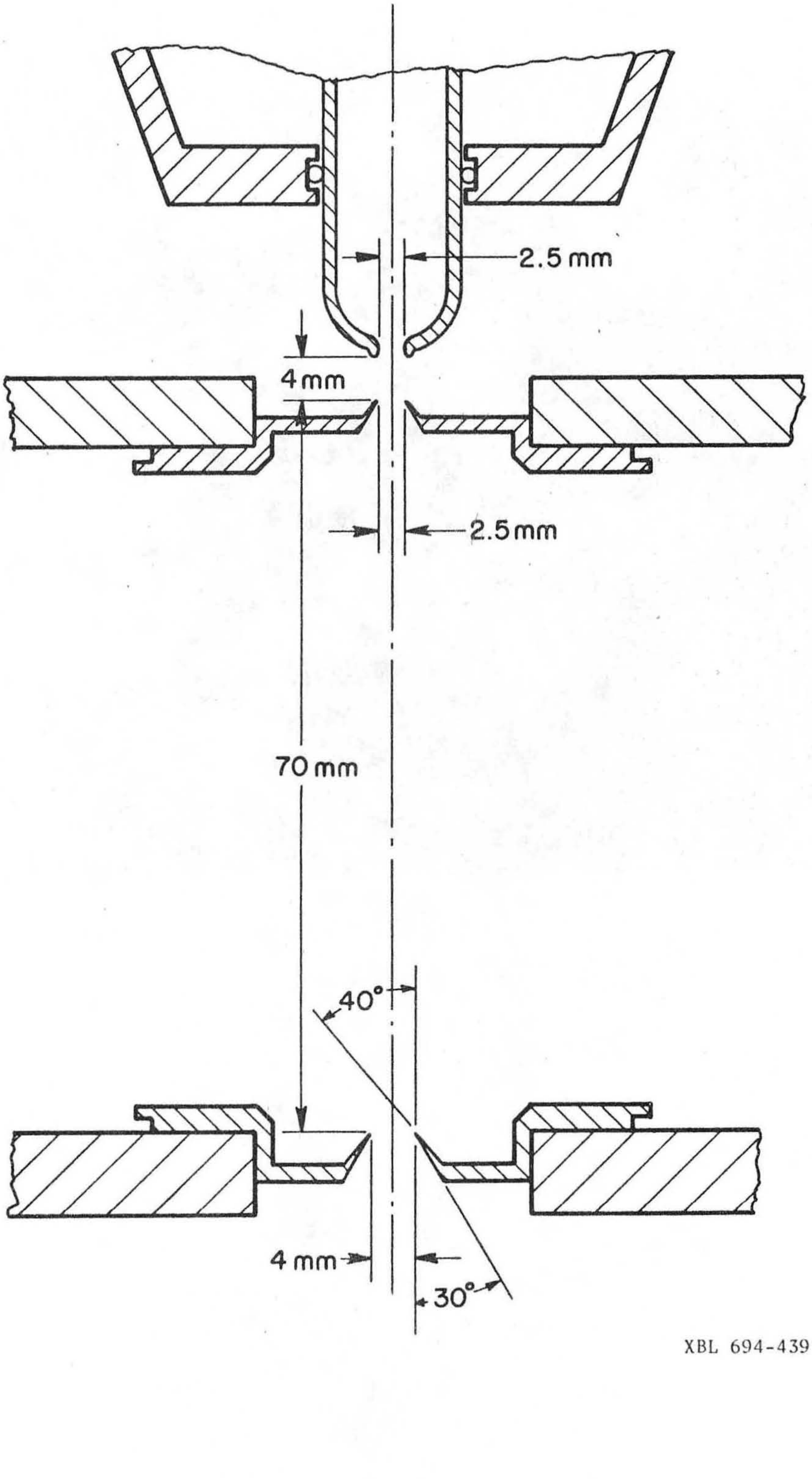

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Fig. 4.

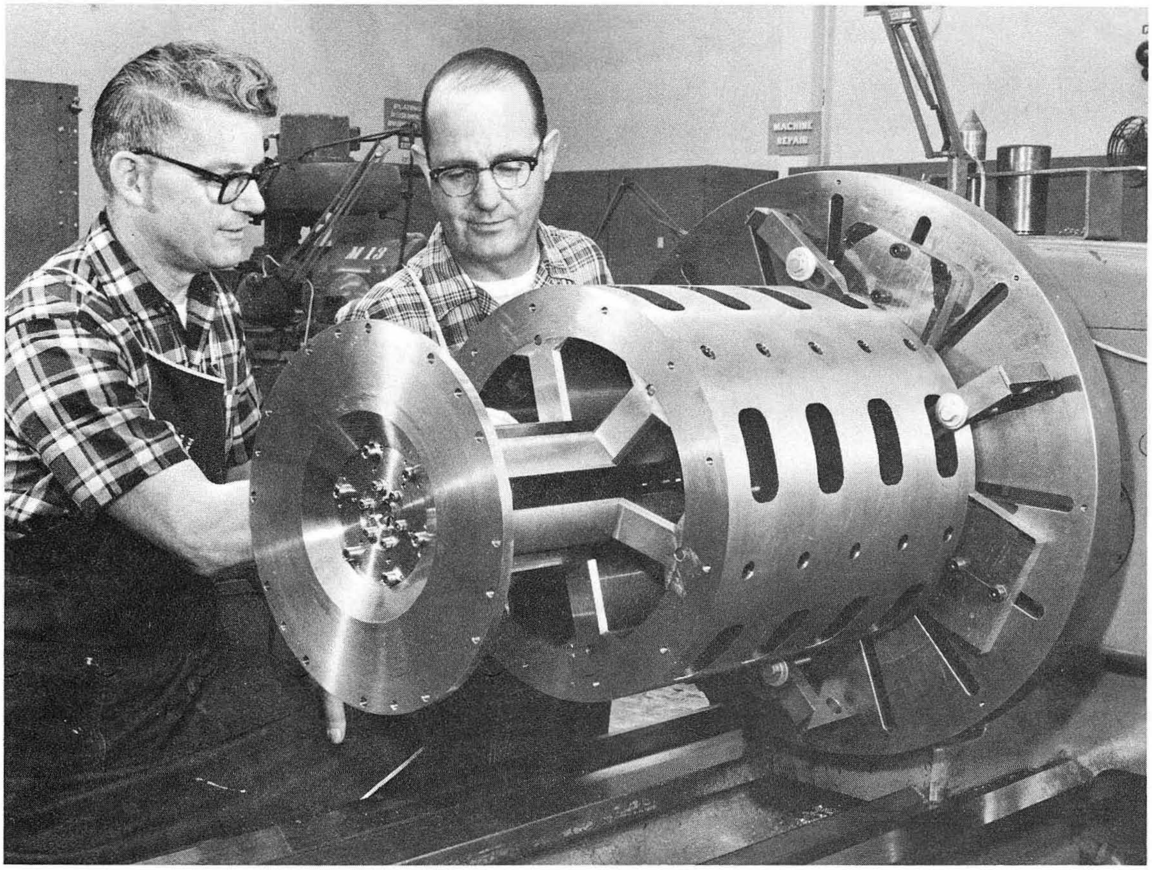

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Fig. 5.

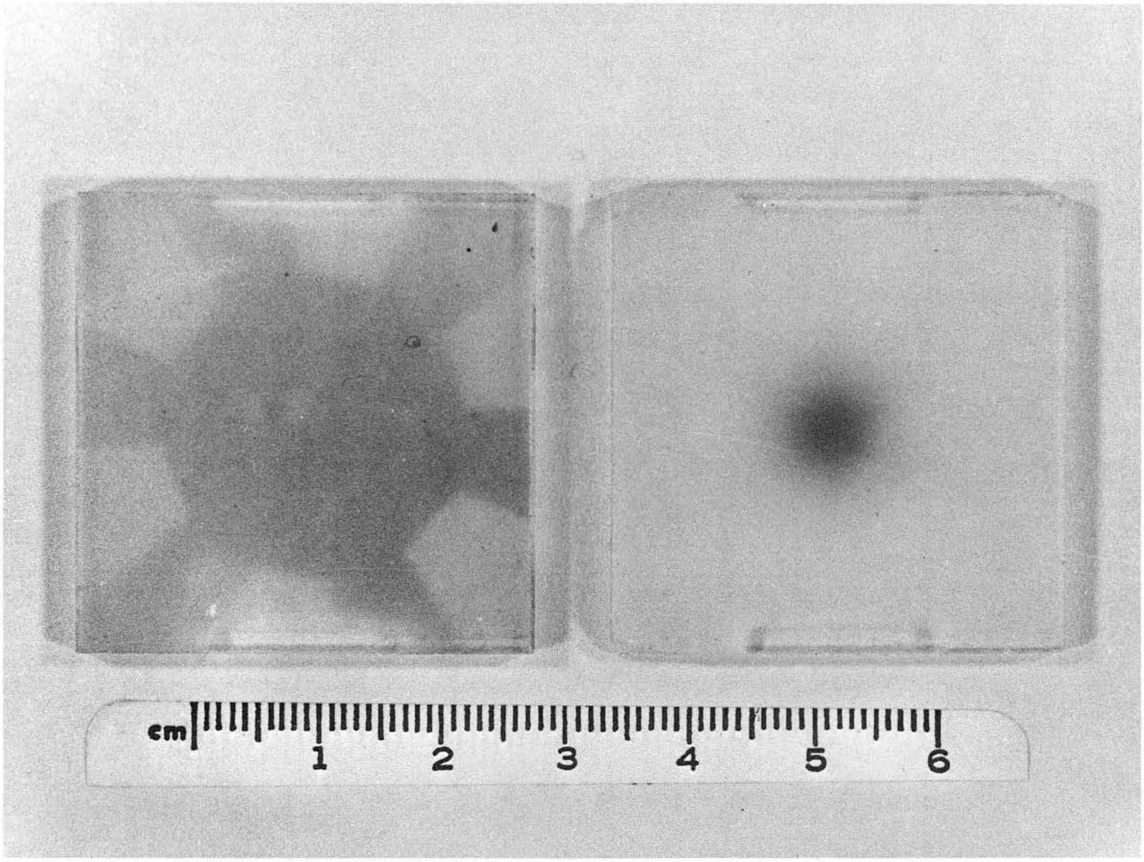

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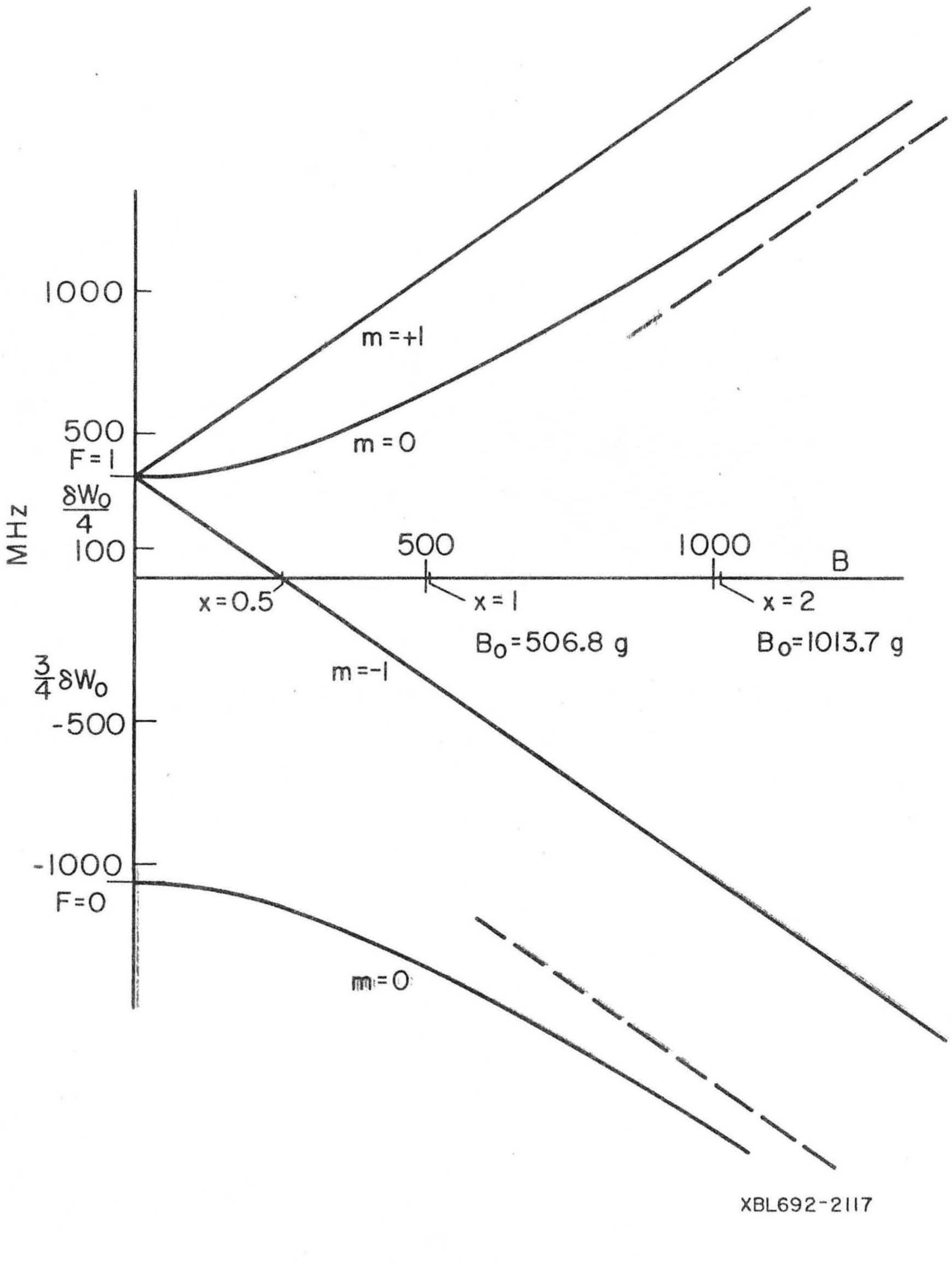
Fig. 6.


1000
500
F = 1
$\frac{\delta W_0}{4}$
MHz
100
$\frac{3}{4}\delta W_0$
-500
-1000
F=0
m =+1
m = 0
m =-1
m = 0
500
1000
B
x = 0.5
x = 1
x = 2
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B_0=1013.7 g
XBL692-2117

Fig. 7.

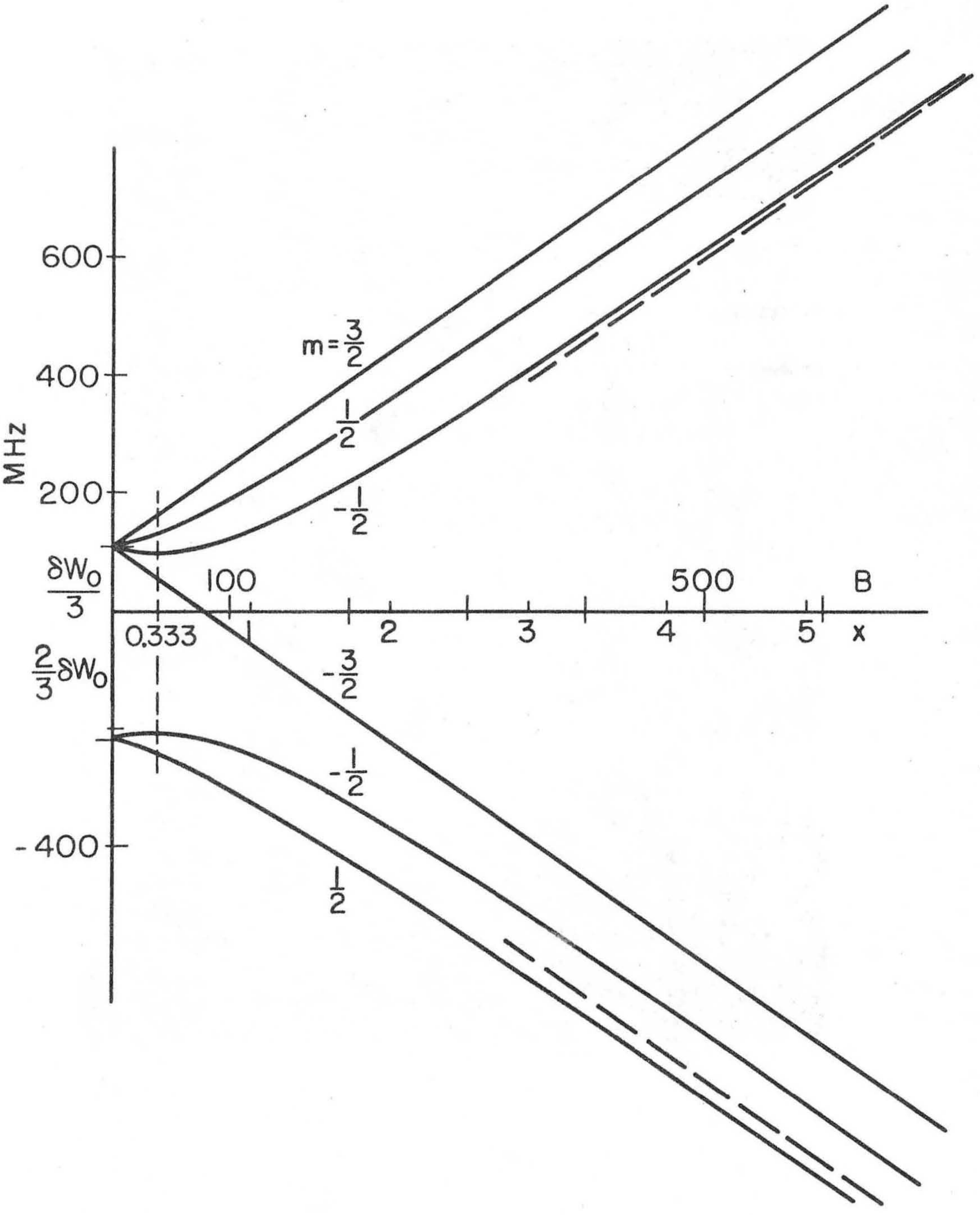

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Fig. 8.

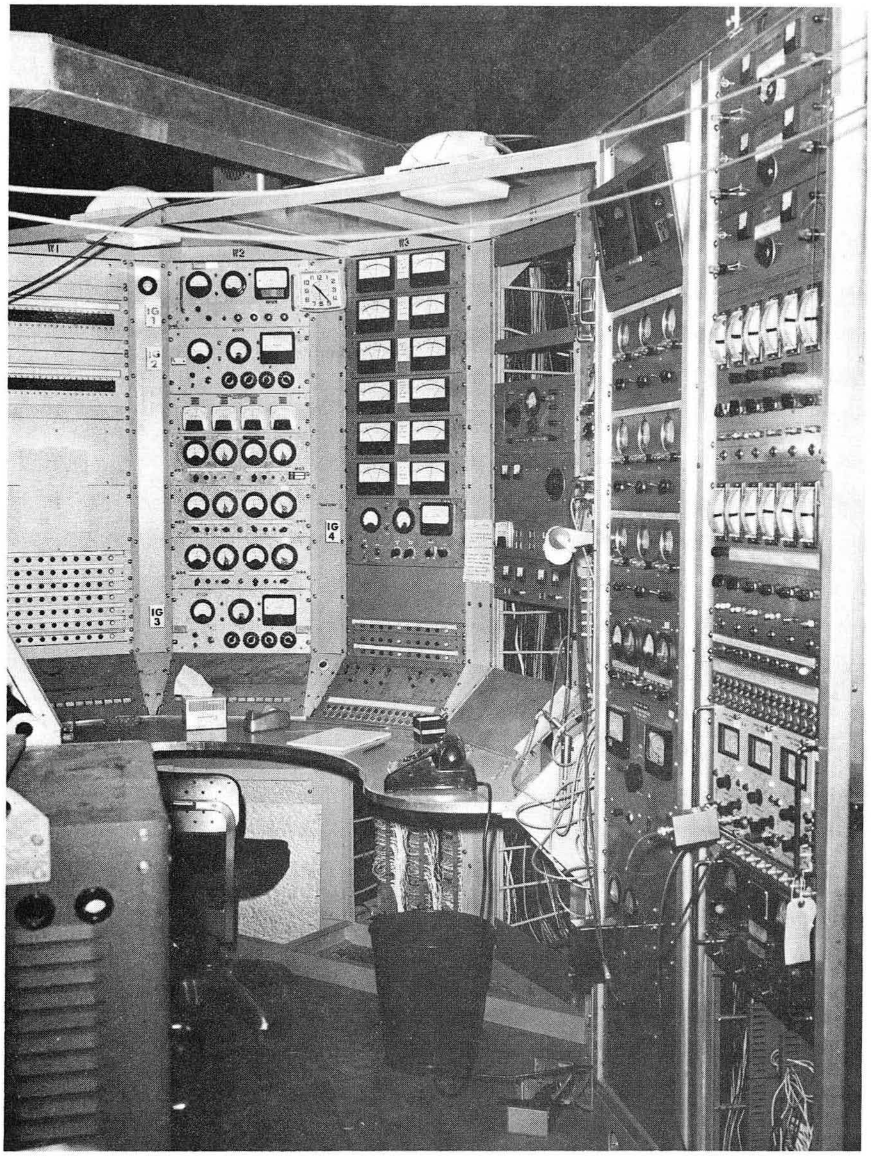

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Fig. 9.

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