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## CYCLOTRONS DESIGNED FOR PRECISION FAST-NEUTRON CROSS-SECTION MEASUREMENTS

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During the past twenty-five years, the constant-frequency cyclotron has demonstrated its value in many laboratories throughout the world. Its principal virtues have included substantial currents (ranging up to milliamperes) and moderate energies (up to about 20 Mev). These characteristics have been largely exploited in the study of nuclear properties, the production of unstable isotopes, and as a neutron source. In recent years the use of nuclear reactors has tended to make the latter two uses somewhat less important. Reactors, however, are not suitable for the production of monoenergetic neutrons, particularly in the high-energy region. Accordingly, particle accelerators are still invaluable for such purposes, and for such uses as the production of pulsed neutron sources for time-of-flight experiments.

Other characteristics of cyclotrons have, however, impaired their usefulness in fields in which homogeneity and variability of energy, freedom from background radiation, and critical beam trajectories with respect to the target are of particular importance. Such fields are those involving precision cross-section measurements of all kinds, production of monokinetic high-energy neutrons, investigation of resonance phenomena, and the like. In such investigations, the operating characteristics of cyclotrons have usually been less advantageous than those of linear accelerators such as the Van de Graaff and others. Since the maximum energy so far attained by these variable-energy dc accelerators is in the neighborhood of 6 Mev, it is obvious that a successful attempt to ameliorate these cyclotron limitations would permit an extension of such precision measurements as given above to a region of growing practical importance and of considerable physical interest.

A cyclotron designed with these aims in view should possess a number of special characteristics, both of the performance of the machine itself and also of the laboratory in which it is housed. The experiments under consideration are most conveniently performed using an external or deflected beam of the accelerated particles. Moreover, it is desirable to have available particle beams of the usual light isotopes, protons, deuterons, tritons, and helium ions. There is growing interest today in the acceleration of heavier ions such as those of carbon, nitrogen, and even heavier elements, and the possibility of using these should also be kept in mind. This external beam should be either continuously variable in energy, or variable in small easily controlled steps, from the peak energy available in the cyclotron to as low a value as is feasible. The latter figure should, of course, at least overlap the peak energies available from Van de Graaff generators. In addition to the feature of variability, there should be accurate determination of the energy at the values used, and the homogeneity of energy both in space (across the target dimensions) and in time should be compatible with the type of experiment to be performed. Currents of the order of microamperes or more of these ions should be focused on a target assembly of small dimensions (of the order of a few square centimeters or less) at such a distance from the cyclotron as to permit adequate shielding of the experimental equipment from the background radiation from the accelerator. Particularly for work involving neutrons, this target assembly should also be well removed from walls or other surfaces that can act as sources of scattered neutrons. Such of these requirements as involve target geometry are frequently difficult to achieve in existing cyclotron laboratories, and are most easily realized either by constructing a machine with these requirements in mind from the start, or by remodeling and relocating the cyclotron in a building designed with these aims in view. Modern developments in the field of particle focusing--in particular those using quadrupole magnetic fields--now make the focal requirements attainable, and ion currents now available--in the milliampere range--make it possible to achieve the somewhat contradictory goals of adequate target current and energy homogeneity.

Cyclotrons for precision cross-section measurements, whose designs were influenced by considerations such as those discussed above, have recently been installed at the Livermore laboratory of the University of California Radiation Laboratory and at the Los Alamos Scientific Laboratory. The remainder of this paper is devoted to a discussion of these machines as representative of present activity in this field. No attempt is made to give much general engineering detail, since more complete descriptions will be published elsewhere. Attention is directed primarily to those aspects which make the cyclotrons suitable for these applications and to the manner in which these characteristics have been obtained. It is known that other laboratories in this country, and probably also abroad, are interested in similar devices. For example, a somewhat smaller machine at the University of Rochester has recently been reported.1)

## THE RADIATION LABORATORY 90-INCH CYCLOTRON

The 90-inch cyclotron installed at the Livermore laboratory is a new machine and was designed for the purpose of producing monoenergetic neutrons in the energy range from 2 to 30 Mev using the (p, T), (d, d), and (d, T) reactions. It will accelerate particles over these energy ranges:

| | |
|---|---|
| Protons | 2.6 Mev to 14.0 Mev, |
| Deuterons | 5.2 Mev to 12.5 Mev, |
| Tritons | 7.7 Mev to 8.3 Mev. |

Doubly charged helium ions can, of course, be accelerated under essentially similar conditions to twice the energies listed for deuterons. No experiments using heavier ions have yet been carried out. The corresponding frequency and the approximate magnetic field limits are 4.0 to 9.3 megacycles/sec and 2600 to 8600 oersteds.

The cyclotron is at one end of a large building, not originally designed for the purpose, and in the same area is located a 0.5-Mev Cockroft-Walton accelerator. The two machines share a common control and particle-counting area. The cyclotron magnet, which is arranged with a horizontal field, is located in a pit 18 feet deep and the horizontal deflected beam passes through a concrete shielding wall 5 feet thick to the center of a 40-foot cubical experimental room. The cyclotron pit is roofed with movable concrete slabs 2.5 feet thick for radiation protection. All shielding is with concrete of normal composition.

The magnet yoke is based on a C-shaped cross section rather than the more usual H-section, and the magnetic field is horizontal. This permits vertical removal of the accelerator electrode assembly and the deflector system (see Fig. 1). As indicated earlier, the peak magnetic field has been limited to approximately 8500 oersteds. This was done to minimize the variation with the operating field of the radial and azimuthal field components. This in turn necessitates the large final orbit radius of 35 inches to attain the desired energies. The magnetic gap is 12 inches minimum, and 280,000 ampere turns are required to reach a field of 8500 oersteds. The magnet contains about 300 tons of steel and the oil-cooled coils containing 8.5 tons of copper are excited by a dc generator with current regulation to one part in fifteen thousand.

An unusual feature is the cam-shaped protuberance at the bottom of the magnet poles. The deflected ion beam undergoes sufficient radial deflection to enable it to emerge from the magnet at this point and hence normal to the fringing field of the magnet. This reduces the subsequent spreading of the beam, and by adjustment of the shape of the field at this region, some convergence can be produced. Azimuthal distortions in the magnetic field are introduced, however, which require careful correction. Because it was desired to use a single accelerating electrode--and, in consequence, sparking problems might be expected to limit the energy gain per revolution of the ions--a radial magnetic field gradient was adopted that amounts to only a 1% decrease in field from the center to the 35-inch radius. Shimming of the magnetic field was accomplished by machining the poles, and a field tolerance of 0.1% was adopted in these corrections. Minor variations, particularly in the azimuthal sense, can be produced in operation by energizing a series of pole-face windings. The windings near the center of the machine are circular; those at larger radii are quadrant-shaped, and they have a maximum effect of 0.2% at 8000 oersteds.

The arrangement of equipment in the vacuum chamber is shown in Fig. 1. The single accelerating electrode hangs from a quarter-wave resonant stem, and the whole assembly can be withdrawn vertically for repair or adjustment. For the higher frequency range (6.4 megacycles/sec and above), the electrical length of the stem is shortened by means of the grounding switch indicated.

This switch must carry total rf currents of over 9000 amperes, or about 70 amperes for each linear inch of switch. The switch consists of a large number of 1/8-inch-wide fingers. Experience has indicated that switches of this type can safely handle about 300 amperes per inch. Continuous variation of resonant frequency in these two ranges is provided by motion of grounded liner panels which vary the electrode capacity to ground. The range of travel of these motor-driven panels is from contact to a maximum of three inches' clearance. In operation a minimum of 3/4 inch is usual. As smaller clearances correspond to lower-energy particles and hence to a lower electrode voltage, sparking problems are not strongly dependent on liner position. The shape of the electrode and its attachment to the stem were determined from model experiments, and result in a constant voltage to ground along the mouth of the electrode. A motor-driven capacitor at the rear of the electrode is automatically adjusted to keep the electrode system correctly resonant with the driving amplifier.

The radiofrequency system is designed to produce an electrode voltage in all ranges of twice the threshold value required to accelerate the ions. Accordingly the maximum peak voltage to ground is about 175 kilovolts and requires an exciting power of about 180 kw. It is a driven system beginning with a low-power crystal-controlled oscillator. One hundred crystals are used to cover the frequency range in 55-kc steps. The final amplifier, using an RCA A-2332 shielded grid triode, is designed to put out 380 kw at 79% efficiency. Grid neutralization of a form insensitive to frequency is used, and the grid inductance is a foreshortened parallel line and is tuned by motor-driven motion of the shorting plane. A servo system driving the trimmer capacity prevents temperature variations and other causes from detuning the resonator. Essentially the phase angle across the final amplifier is detected and supplies a signal to a servo amplifier which actuates the trimming capacitor. This system maintains the phase angle constant within 1°, thus keeping the resonator in almost perfect tune and permitting the inherent high efficiency of the amplifier and the frequency stability of the crystal-controlled oscillator to be utilized.

The final amplifier drives the resonator through a 50-ohm coaxial line which is electrically a half wave length at the highest frequency and which is loop-coupled at the resonator. In the low-frequency range a larger loop area is required than in the high-frequency range. This requirement was met by making the loop in the form of a 50-ohm parallel-plane transmission line which extends on both sides of the grounding switch. Thus, in switching from the low-frequency range to the high, the grounding switch serves not only to shorten the electrical length of the resonator but also to reduce the effective area of the coupling loop, the remainder of the loop structure above the grounding switch now becoming a part of the transmission line driving the resonator.

In order to break through the multipactoring region, electrode voltage is built up quickly. This is accomplished by pulsing on the screen voltage on a tube in the amplifier chain, all other voltages having been previously applied. In order to establish electrode voltage, the resonator must first be tuned to the signal frequency. This is done through the use of a small oscillator which applies a few volts to the electrode, enough for the control circuits to tune it to the correct frequency before application of the main power.

Automatic control of the power supplies to prevent damage through sparking or other failures is provided electronically by means of various "fault diverters." An electrode spark removes the driving power for a few seconds;

a power arc (for example, in the output tube) results in immediate shorting of the power supply through an ignitron and in subsequent opening of the primary circuit. These provisions permit the use of a "stiff" power supply and result in improved electrode-voltage stability.

To minimize sparking problems resulting from surface contamination with organic films, mercury pumps are used with a total speed of 5000 liters per second. The design of these pumps and of the associated vacuum equipment is conventional, as is that of the ion source and other units not specifically described.

The electrostatic deflector system covers a total angle of about 150° and is split into two separately adjustable sections. Adjustments may be made from the control console. The maximum field applied is 55 kv per centimeter with the maximum gap of 1.0 inch. The total radial deflection is 17 inches. After leaving the main magnetic field at the cam, the ion beam enters an iron channel which shields it from the stray field of the cyclotron magnet.

The geometry of the external beam is shown in Figure 2. After leaving the cyclotron it enters a double-focusing magnet, which turns the beam and brings it to a focus at the middle of the five-foot shielding wall where a slit system is energy-selective. As the beam emerges on the other side of the wall, another (similar) magnet brings the beam to a focus at the neutron-producing target at the center of the experimental pit. The purpose of this steering arrangement is to minimize at the neutron target background radiations coming from the accelerator and from the energy-selective slits. For charged-particle work in another part of the experimental pit, the second steering magnet is turned off and the first magnet is adjusted to focus the beam at the charged-particle target.

The cyclotron has now been operated for two months, but only with internal beams of protons. Beams up to 600 microamperes have been accelerated to full radius with no especial difficulty, at several frequencies corresponding to final proton energies ranging from 3 to 13 Mev. The machine operates easily and stably. The first beam was found within five minutes of the initial turn-on. An external beam has not yet been attempted; the deflector system is now being installed.

## THE LOS ALAMOS 42-INCH CYCLOTRON

This cyclotron was originally set up at Harvard University and, during the war years, was moved to the Los Alamos Scientific Laboratory. It has recently been extensively rebuilt and relocated in a new building. In its present form it is designed to accelerate ions in these energy ranges:

| | |
|---|---|
| Protons | 3.5 Mev to 9 Mev, |
| Deuterons | 7 Mev to 17.5 Mev, |
| Tritons | 10.5 Mev to 12 Mev. |

Doubly charged helium ions can also be used, the energies (for $He^4$) being double those indicated for the deuteron range. Some preliminary acceleration of quadruply charged carbon ions has also been accomplished. It is planned also to accelerate $He^3$ ions. The frequency and magnetic field ranges for the ions listed in the table are from 8.6 to 14 megacycles per second and from

5600 to 18,000 oersteds.

The cyclotron, which operates with the usual vertical field, is located in a concrete vault in a recently constructed research building. The shielding walls are four and five feet thick, and a removable ceiling of concrete blocks is four feet thick. The deflected ion beam (see Fig. 3) passes through one of the walls into an experimental vault with heavy concrete walls and a removable ceiling. This room is used for charged-particle work and for neutron work in which background is not a severe problem. It is planned to carry the beam a further 50 feet into an area having light steel walls and such that the minimum distance from the target to a scattering surface will be 20 feet. This low-background area will be used for neutron time-of-flight experiments and others in which low background is of paramount importance.

The magnet has a total weight of 100 tons; the pole diameter is 42 inches and the useful ion radius is 19 inches. The peak exciting power is 48 kw, and the magnet current is electronically stabilized to one part in 20,000. The useful magnet gap is about 5 inches. At all field values a radial gradient from center to the final radius corresponding to a 3.5% decrease is provided. In consequence of the wide field variations and the saturation effects at the higher values, this cannot be entirely accomplished by shaping the pole faces. Accordingly, the pole contours and Rose shim give the correct field shape at an intermediate field value. For higher and lower fields, the shape is corrected to the desired value by the use of edge-correcting coils inside the vacuum chamber, which can increase or decrease the field at the larger radii. These water-cooled coils consist of 5 turns top and bottom at a radius of approximately 18 inches, and carry a maximum current of ± 500 amperes. In addition to the radial field shape described above, an azimuthal field dependence modified from the type described by Thomas[2) is used. This consists of three iron sector plates inside the vacuum chamber, top and bottom, and about 50° wide. These shims produce a third harmonic field variation of ± 5% between 6- and 19-inch radii, and decreasing to zero from 6 inches to the center. The use of these shims has proved advantageous in providing additional axial stability and in centering the beam about the geometric center. Some reduction in the threshold electrode voltage is also achieved. Two orbit-centering coils are also provided to aid in centering the ion beam.

The arrangement of equipment in the vacuum chamber is shown in Fig. 3. Two accelerating electrodes are used and are supported by quarter-wave resonant stems in vacuum. Gross frequency changes are accomplished by changing the position of the shorting node, while intermediate values are obtained by varying the electrode capacity to ground. The 90° electrostatic deflector is mounted inside an electrode and hence is shielded from radiofrequency voltages; dc voltages up to 30 kilovolts are used. This low deflector voltage is due to the Thomas-type shims. One of the sectors is centered at the deflector entrance and this, in a cyclotron of this type, corresponds to maximum radial extension of the ions. The subsequent azimuthal reduction of field facilitates extraction and permits reduction of the deflecting field by a factor of 2.5.

The accelerating electrodes have an internal height of two inches and are supported by 8-inch-diameter aluminum tubes, copper-covered, and about 10 feet long. The movable shorting node may be actuated from outside the vacuum chamber and may be set at any desired position. The high-voltage lead and support for the deflector system is coaxial with one of the electrode supports, as can be seen in the figure.

The radiofrequency power is supplied by a self-excited oscillator using two 880 tubes in a push-pull tuned-plate tuned-grid circuit. The maximum electrode potential to ground is 140 kilovolts. The oscillator is driven through the multipactoring region by a booster oscillator capacitively coupled to the grid circuit of the main oscillator. The booster oscillator is automatically biased off when the main oscillator is operating normally. The coupling loop to the electrode stems are 18 inches long and the amount of coupling is adjustable. The motor-driven trimmer capacitors automatically maintain equality of electrode voltage and constancy of frequency. The power supply is protected against overload by a constant-current network.

The beam emerging from the deflector is focused horizontally and vertically by focusing wedges energized by the fringing field, and by the fringing field itself. A parallel beam about 3/8 inch in diameter is obtained at the entrance of the quadrupole focusing magnets. Two horizontal steering magnets and a vertical steering magnet align the beam along the geometric axis of the focusing and analyzing magnets. Energy analysis is obtained by placing slits before and after the analyzing magnet. The relative arrangement of these magnets is illustrated in Fig. 3. A second set of quadrupole strong-focusing magnets is planned to give a focus an additional 50 feet away for low-background neutron work, as was mentioned previously.

The ion source and oil diffusion pumps are essentially conventional in design. The pumping speed is about 5000 liters/sec. for hydrogen. A separate, and smaller, mercury pumping system, together with a gas-recovery system, is provided for use with tritium and $He^3$.

Like the Livermore cyclotron, that at Los Alamos is still undergoing testing, particularly with regard to the external beam optics. Internal beams of more than two milliamperes of protons, deuterons, and helium ions have been obtained, and a deflection efficiency (measured at the entrance to the steering magnet) of about 10% has been established. No attempt has yet been made, however, to work with external beams greater than 100 microamperes. It is believed that the deflector efficiency can be substantially increased. The operation of the accelerator is very stable and reproducible. As the ions are accelerated from a radius of 4 inches to the final 19-inch orbit, the ion-beam intensity decreases by only about 12% which demonstrates the effectiveness of the axial focusing.

Grateful acknowledgement is made to many members of the laboratory staffs, both in California and at Los Alamos, for their contributions to the successful construction of these machines.

## References

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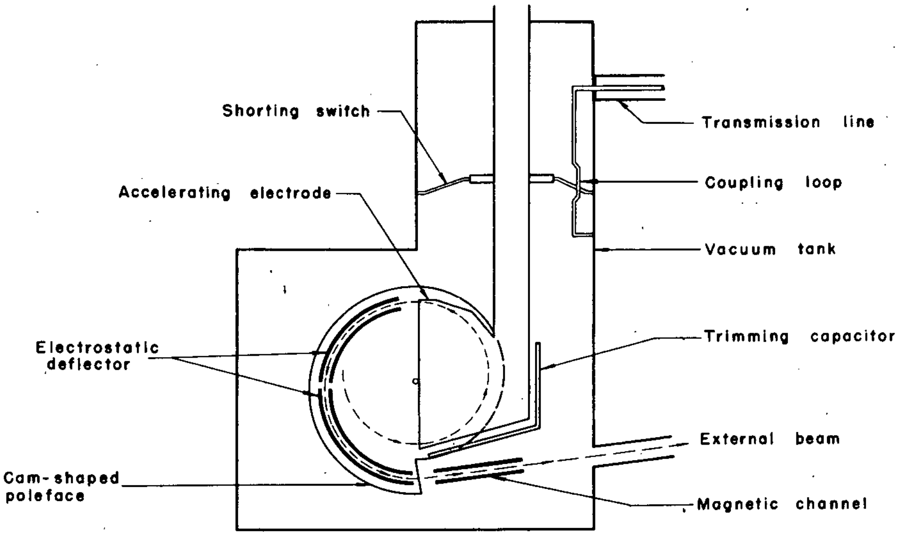

Fig. 1--Vertical cross section of Livermore 90 inch cyclotron, schematic.

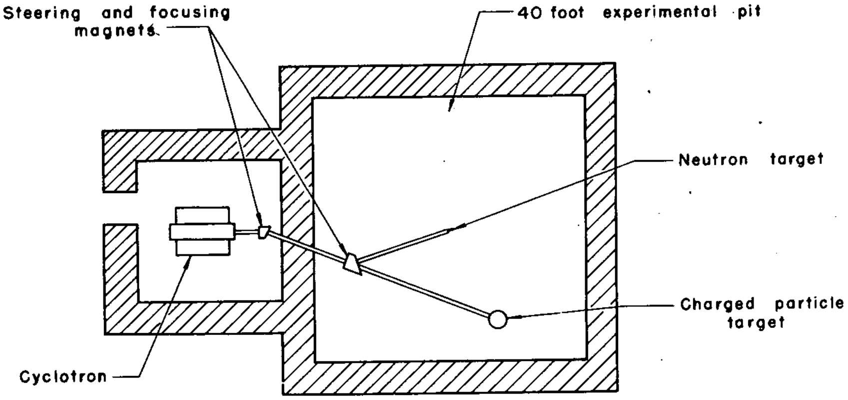

Fig. 2--Plan view of 90 inch cyclotron external beam arrangement.

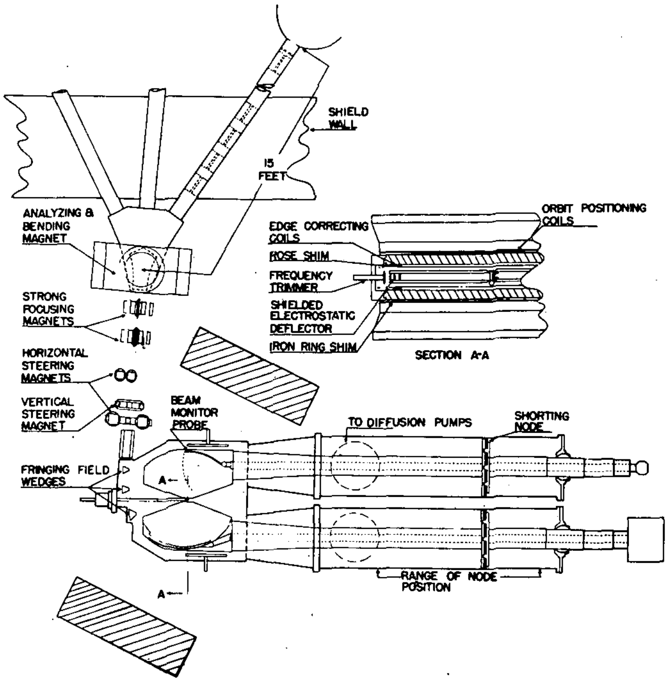

Fig. 3. Schematic diagram of the Los Alamos cyclotron.

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