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ABSTRACT

A racetrack microtron is described, which is patterned after a similar machine at the University of Western Ontario. The LRL microtron produces 10 mA park currents at 60 pulses per second. Only modest shielding and air cooling are required. An external beam is either used directly or converted to bremsstrahlung.

Introduction

The microtron is an electron accelerator, originally proposed by Veksler,[1] which is characterized by expanding orbits, all of which are tangent to a single line. A microwave cavity is positioned at the point of common tangency so that electrons in each orbit pass through it and are accelerated. The conventional microtron employs a uniform magnetic field. The resonance condition requires that successive orbits differ in length by an integral number (usually 1) of wavelengths corresponding to the cavity frequency. The resonance and phase-stability properties of the orbits contribute to making the extracted beam much more monoenergetic than that available from an electron linear accelerator. Yet, because of the large separation of orbits opposite to the point of tangency, extraction of the microtron beam is no more difficult than in the linear accelerator. However, by comparison, interest in the development of the microtron has been less, and the output power attained thus far is somewhat smaller than from linear accelerators of the same energy.

The principal application for the microtron has been as an injector for high-energy electron accelerators.[2,3] They have also found use as neutron sources,[4] and in other applications.[5]

The Conventional Microtron

The resonance conditions in the conventional microtron consist of the requirements that the time needed for the first orbit be an integral number of periods of the cavity oscillation, and also that the difference in time between successive orbits be an integral multiple of the cavity period. These conditions imply the existence of two integers, n_0 and n, each equal to or greater than unity, such that the time T_k required to traverse the <u>k</u>th orbit is

$$T_k = n_0 \tau + kn\tau, \tag{1}$$

where τ is the cavity period. Introducing the Cyclotron Equation (in SI units), and defining W_i as the injection energy in terms of

m_0c^2, and ΔW as the incremental energy in terms of m_0c^2, gives

$$r_k \approx \frac{m_0c}{Be}(1 + W_i + k\Delta W), \tag{2}$$

$$\Delta W = \frac{Be}{2\pi m_0} n\tau, \tag{3}$$

$$W_i \quad \frac{n_0}{n} \Delta W - 1. \tag{4}$$

The choice of τ is governed by the availability of suitable microwave equipment, and nearly all microtrons thus far constructed have utilized S-band components, with $\tau^{-1} \approx 3$ GHz. Design of the most compact magnet for a given final energy would require, re Eq. 1, the maximum value of B consistent with Eq. 3. For example, for the minimum value of n, which value also affords the most efficient operation, and for B = 0.18 tesla, then $\Delta W = 1.7$, which is reasonably attainable. However, according to Eq. 3, quite high injection energies are then required, i.e., $W_i = 0.7$, assuming also that n_0 has its minimum value. The required injection energy can be reduced by operating with a magnetic field enough lower that $\Delta W \approx 1$.

Achievement of efficient injection has proved to be the foremost obstacle to the development of the conventional microtron. Practical solutions in terms of a gun external to the cavity have been found by Swedish[3] and Soviet[2] groups, and in terms of a gun internal to the cavity by another Soviet group.[6]

The Racetrack Microtron

The racetrack microtron was proposed by Moroz,[7] and independently by Roberts.[8] In the racetrack design, each pole piece is divided into four sectors, in order to provide Thomas focusing. In the conventional microtron, only weak axial focusing is found, resulting from the action of cavity fields. As shown in Fig. 1, two of the sectors are split along the pole diameter. The existence of this gap allows the cavity and gun to be placed in a relatively field-free region, which greatly simplifies problems of operation. In addition, the magnetic gap is no longer determined by the cavity dimensions, and may be made quite small, with consequent economy in magnet design. Finally, the possibility of varying the spacing of the gap containing the cavity has the effect of decoupling the dependence of the injection energy on the incremental energy, as is shown below.

If s_k is the length of the field-free regions in the <u>k</u>th orbit, then, assuming sharp discontinuities between uniform and field-free regions, the time needed to complete the <u>k</u>th orbit is

$$T_k = \frac{2\pi m_0}{Be}(1 + W_i + k\Delta W) + \frac{s_k}{v_k} . \qquad (5)$$

In order that T_k be equal to an integral number of cavity periods, s_k/v_k either must be equal to a constant or must be proportional to the total energy in the <u>k</u>th orbit. In the latter case, the resonance conditions are similar to those in the conventional microtron. In the former case, one chooses n as in Eq. 3, and chooses n_0 according to the expression

$$\frac{2\pi m_0}{Be}(1 + W_i) + \frac{s_k}{v_k} = n_0 \tau . \qquad (6)$$

Hence, Eq. 1 is valid for the racetrack as for the conventional microtron. In practice, the former alternative has been adopted,[9] but the constancy of s_k/v_k has been guaranteed only approximately by making s_k constant for all orbits, and by assuming $v_k \approx c$. The latter assumption has proved satisfactory for the second orbit and beyond, but is sufficiently poor in the region of the first orbit so that special shimming of the pole pieces is necessary near the cavity.

The injection requirements may be seen by recasting Eq. 6 into the form

$$W_i = \frac{\Delta W}{n}\left(n_0 - \frac{s_k}{v_k \tau}\right) - 1 . \qquad (7)$$

Since $v_k \tau$ is a reasonably small number, i.e., 10 cm, W_i can be arbitrarily reduced by adjustment of the gap spacing s_k. From the standpoint of practicality, the spacing is adjusted for the desired injection voltage with $n_0 = 2$, since the presence of the cavity precludes the possibility of attaining the smaller gap spacing necessary for $n_0 = 1$. The constant n, however, remains at unity.

Design

The LRL Racetrack Microtron has been patterned very closely after a machine designed and constructed at The University of Western Ontario, in Canada.[9-11] A detailed analysis of the theory of the racetrack microtron and of the design parameters for the UWO machine is to be found in Ref. 9. The LRL machine differs in details of the designs of the vacuum system, microwave system, magnet, and electron gun. The characteristics of the LRL machine are summarized below.

Physical Description

The accelerator itself measures 24×32×15 in., and is mounted on a wheeled cart which also contains the electron gun and radio-frequency modulators, the microwave system, and various motors, blowers, and control and diagnostic equipment. The cart is connected by cables to the control area, 20 feet away, and there is a 5-ft-high, 12-in.-thick wall of heavy concrete blocks between the two. The experimental area measures about 12×10×10 ft, adjacent to the machine. Controls for the machine are housed in two 6-ft racks, not including an oscilloscope mounted separately. An overall view of the machine is shown in Fig. 2.

Acceleration Chamber

The acceleration chamber is a stainless steel cylinder 8 in. high, 20 in. o.d. Access is provided by six ports around the periphery. Two ports accommodate sliding seals for the pole-piece adjustment shafts. One is for a Faraday cup which moves diametrically across the electron orbits for beam sampling and tuning. Another port contains the beam-extraction tube. The fifth port mounts a gate valve, air lock, and sliding seal for a retractable electron gun. The remaining port is for the vacuum rough-pumping line.

The acceleration chamber is provided with two 1-in.-thick mild steel lids sealed by Viton "O" rings. The upper lid has three 4-in. ports. One mounts an 80-liter/sec ion pump, which maintains a vacuum of 1×10^{-6} torr in the chamber. The center port is for viewing, and the other contains a blower-cooled finned copper radiator which is in contact with the microwave cavity. The lower lid has two ports, one of which is used for a vacuum gauge. The microwave waveguide and electron-gun power leads enter the chamber through the other lower port.

Magnetic Circuit

The magnetic field is produced by four magnetic sectors with a variable-length drift space between two of them. This configuration is achieved by having two movable sets of pole pieces within the acceleration chamber. The magnetic gap measures 0.280 in. between the shaped sectors, which are bolted to steel base plates. Each such assembly is supported on steel balls in grooves to allow movement normal to the principal machine diameter, the motion being controlled by motor drives through shafts and sliding seals. The pole-piece assemblies are in contact with additional steel blocks and the steel chamber lids. Around each lid is a coil of 8000 turns of #26 copper wire with taps at each 2000 turns. The coils are connected in series, with 100 mA at 270 V producing a field of 1500 G in the sector gaps. The magnetic circuit is completed by two sets of steel yokes 3/4 in. thick external to the tank. The UWO machine uses 2.5-in.-thick yokes; the thinner yokes represent a 550-lb weight saving, with no sacrifice in efficiency. As shown in Fig. 1, one of the pole pieces is partially cut away to allow extraction of the eighth orbit. This results in a reduction in the gap field, which is corrected by means of a trim coil wound around the yoke adjacent.

Microwave System

Microwave power is supplied by one RK5586 or DX276 S-band radar magnetron, operating at 2780 MHz. Either magnetron can supply 800 kW peak power with a duty cycle of 0.001. The magnetron is mechanically tuned (by a small motor) and air cooled (fins and blower). Power is supplied at 30 kV and 60 A in a 3-μsec pulse by a thyratron-switched pulse-forming network and pulse transformer. The network is subresonantly charged from a d. c. power supply.

Microwave power typically is fed through a coaxial-to-waveguide coupler, a 10-db ferrite isolator, a glass vacuum window, and a short section of waveguide to the accelerating cavity. The cavity is a flat cylinder, machined from a block of OFHC copper. It is 3.230 in. i. d. and 1.090 in. wide, with 0.500×0.250-in. electron beam slots in its sides. The cavity is coupled to the waveguide by a circular opening of 0.845 in. diameter. The "Q" of the cavity is 3000 under load. The present microwave system develops more than 1 000 000 V peak across the cavity. Even at maximum power, electrical breakdowns in the cavity have not been a problem. The waveguide components outside the acceleration chamber are internally pressurized with 15 psig of dry nitrogen, as otherwise some arcing within the waveguide occurs. A view of the magnetron and isolator is shown in Fig. 3.

Electron Injection

Electrons are supplied by a Philips Type B impregnated cathode of 3 mm diameter, operated at 1100° C. The cathode assembly is mounted in a magnetically shielded modified Pierce geometry. The electrons emitted from the gun are deflected by an electromagnet 90 deg into the cavity entrance slot. Since these cathodes require replacement after 100 to 200 hours of operation, the entire gun-electromagnet structure may be withdrawn from the microtron through a valve into an air lock to permit rapid changing of the cathode. Thus, it is not necessary to lose the vacuum in the acceleration chamber in order to service the electron gun. The emission current, about 120 mA, is pulsed on for a 2 μsec at an injection potential ranging up to 25 kV. The pulse, which is delayed about 1 μsec from the start of the microwave pulse, is derived from a thyratron-switched pulse-forming network followed by a pulse transformer. The pulse-forming network is sub-resonantly charged from a d. c. power supply. Figure 4 shows the gun assembly and deflecting electromagnet.

At the conclusion of the microtron research program, the electron gun described above was still under development and had not yet produced an accelerated beam. The machine performance data reported in this paper were all taken with an earlier gun design, identical to that used in the UWO machine, and which was mounted on the accelerating cavity. This gun could be serviced only by sacrificing the vacuum in the acceleration chamber.

Shielding

The microtron acceleration chamber, coils, and magnet yokes provide quite effective shielding from the radiation resulting from high-energy electron impacts within the chamber. In addition, 0.5 in. of Pb was placed around the outside of the chamber wherever the chamber wall was directly visible. Two concentric Pb cylinders, 10 in. long, and measuring together 2 in. i.d. and 10 in. o.d., were placed around the bremsstrahlung converter foil on the end of the beam exit pipe. This shield limits the intense x-ray beam to a 60-deg cone. In general, radiation levels are small everywhere except within the x-ray cone, where they may reach several roentgens per minute.

Performance

The LRL microtron delivers a beam of 6.5- to 7.5-MeV electrons in a 1.6-μsec pulse of 10 mA peak current at a repetition rate of 60 pulses per second. No attempt has been made to increase the pulse current, duration, or rate, as the experiments being performed did not demand more intense beams, and the present shielding would have had to be augmented considerably for higher radiation levels.

Electrons are injected and accelerated as described above, until the eighth orbit, where a steel tube shields off the magnetic field, allowing 100% of the eighth orbit beam to be extracted opposite the accelerating cavity. The electrons emerge through a 0.001-in. stainless steel vacuum window in a 1/8-in. diam beam, 48 in. from the extraction point. No external beam focusing is used. For most experiments, the beam then strikes a gold target 0.080 in thick, for conversion to bremsstrahlung radiation. Alternatively, it may be used for direct electron irradiation, or may be stopped in a sliding-wedge and Faraday-cup apparatus which may be remotely moved and monitored to determine the energy of the electrons from their range in aluminum. Beam energy may be varied smoothly over a limited range by varying the main magnetic field, the power to the microwave cavity, and length of the low-field drift space. The UWO machine, at 6.0 MeV, produced 40 mA peak, with an energy spread in 90% of the current of 73 keV.[10]

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References

1. V. Veksler, Doklady Akad. Nauk 44, 393 (1944).
2. K. A. Belovintsev, A. Ya. Belyak, A. M. Gromov, E. M. Moroz, and P. A. Cherenkov, At. Energ. 14, 359 (1963).
3. O. Wernholm, Arkiv Fysik 26, 527 (1964).
4. V. D. Anan'ev, P. S. Antsupov, S. P. Kapitsa, I. M. Matora, V. N. Melekhin, L. A. Merkulov, and R. V. Khar'yuzov, At. Energ. 20, 106 (1966).
5. S. P. Kapitza, At. Energ. 18, 255 (1965).
6. S. P. Kapitza, V. P. Bykov, and V. N. Melekhin, J. Exptl. Theoret. Phys. (USSR) 41, 368 (1961).
7. E. M. Moroz, Doklady Akad. Nauk 108, 436 (1956).
8. A. Roberts, Ann. Phys. 4, 115 (1958).
9. H. R. Froelich, Theory and Design of a Race-Track Microtron with Application to the Generation of Millimeter Waves (Ph. D. Thesis), University of Western Ontario, London, Ontario, Canada, 1962.
10. E. Brannen, H. Froelich, and V. Sells, Can. J. Phys. 43, 1555 (1965).
11. V. Sells, H. Froelich, and E. Brannen, J. Appl. Phys. 36, 3264 (1965).

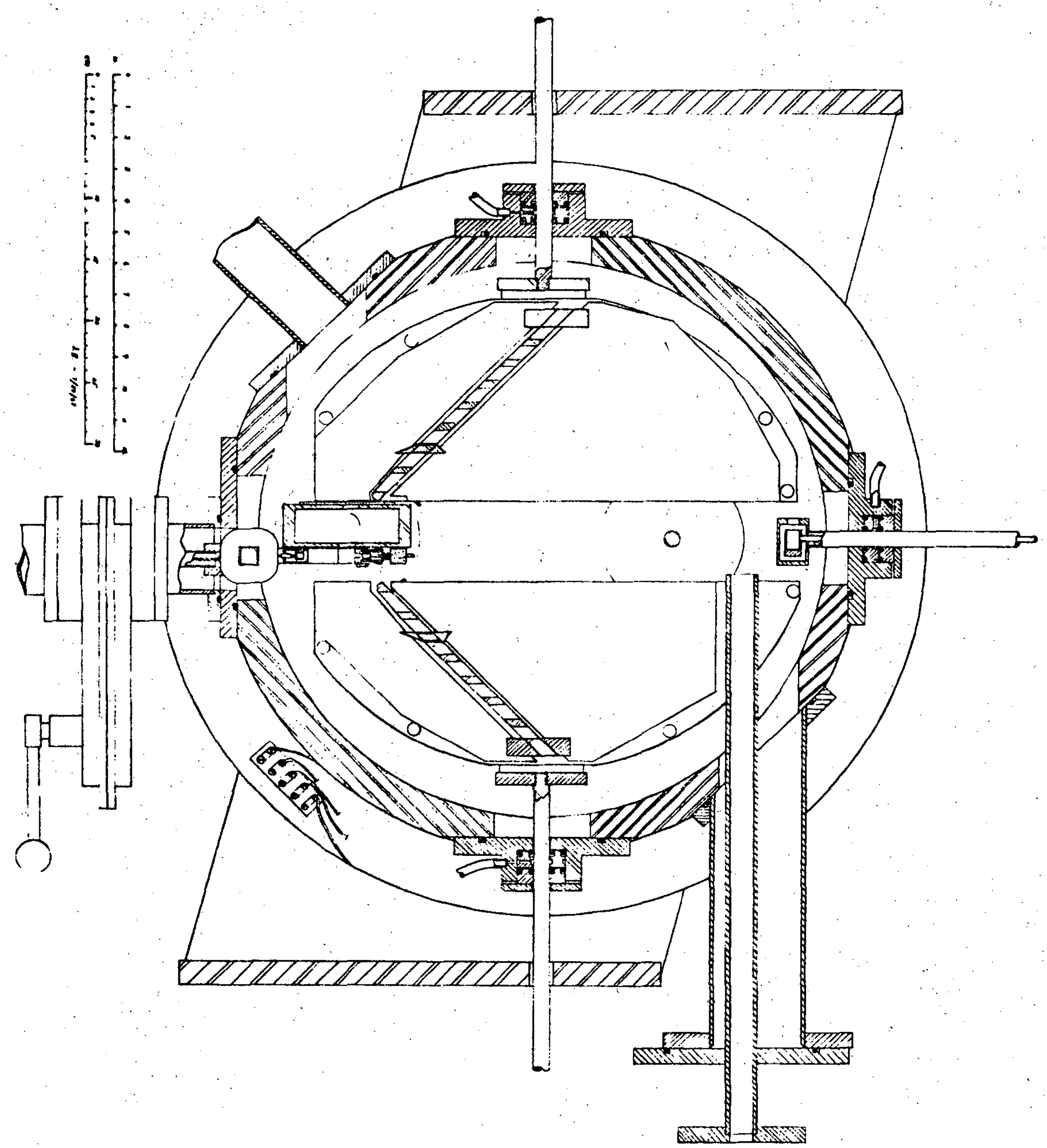
Figure Captions

Fig. 1. Sketch showing pole pieces and cavity.

Fig. 2. Overall view of microtron and supporting cart.

Fig. 3. Magnetron, ferrite isolator, and transition waveguide.

Fig. 4. Retractable electron gun.



XBL 687-1385

Fig. 1

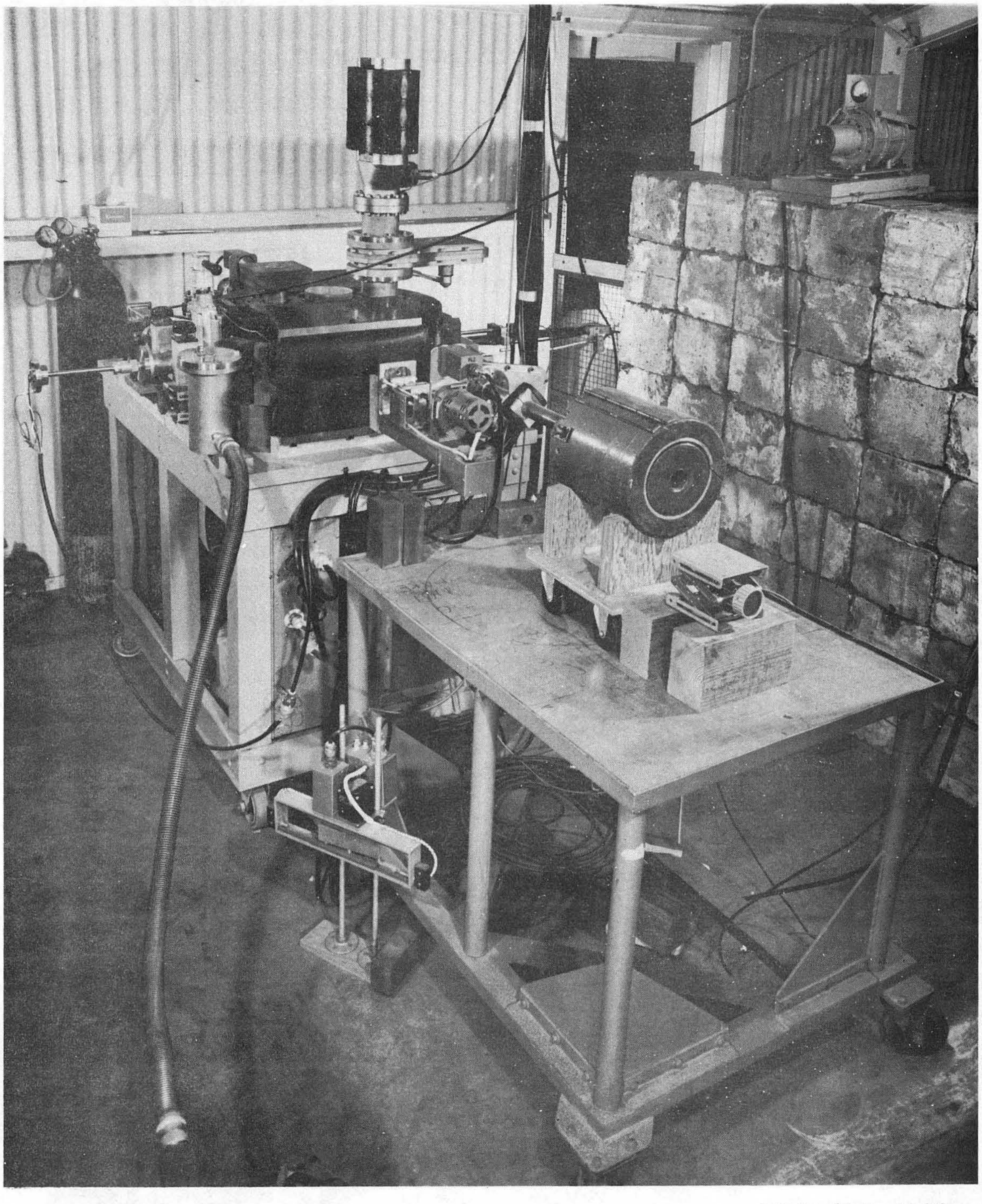


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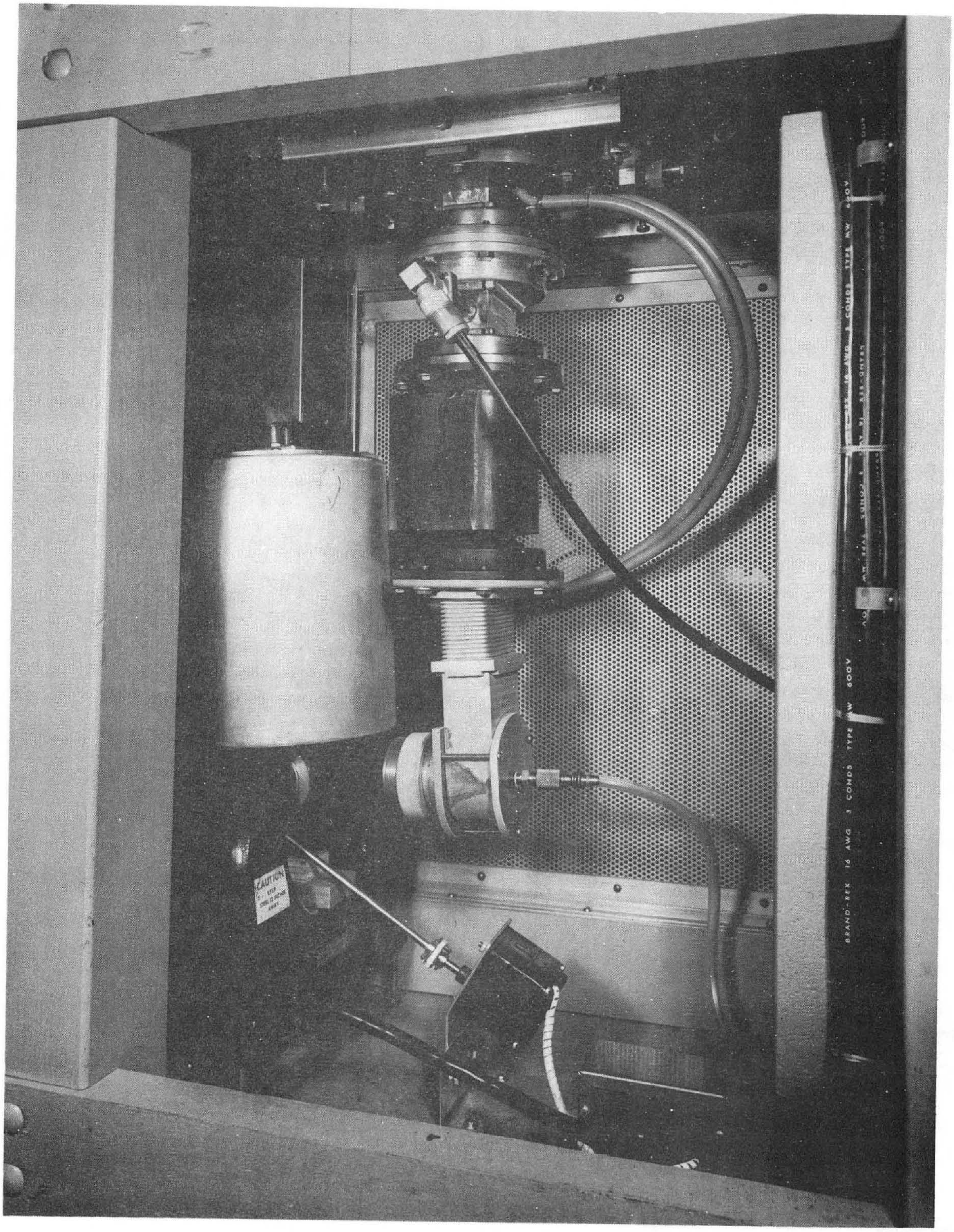
Fig. 2



PW - 800

Fig. 3

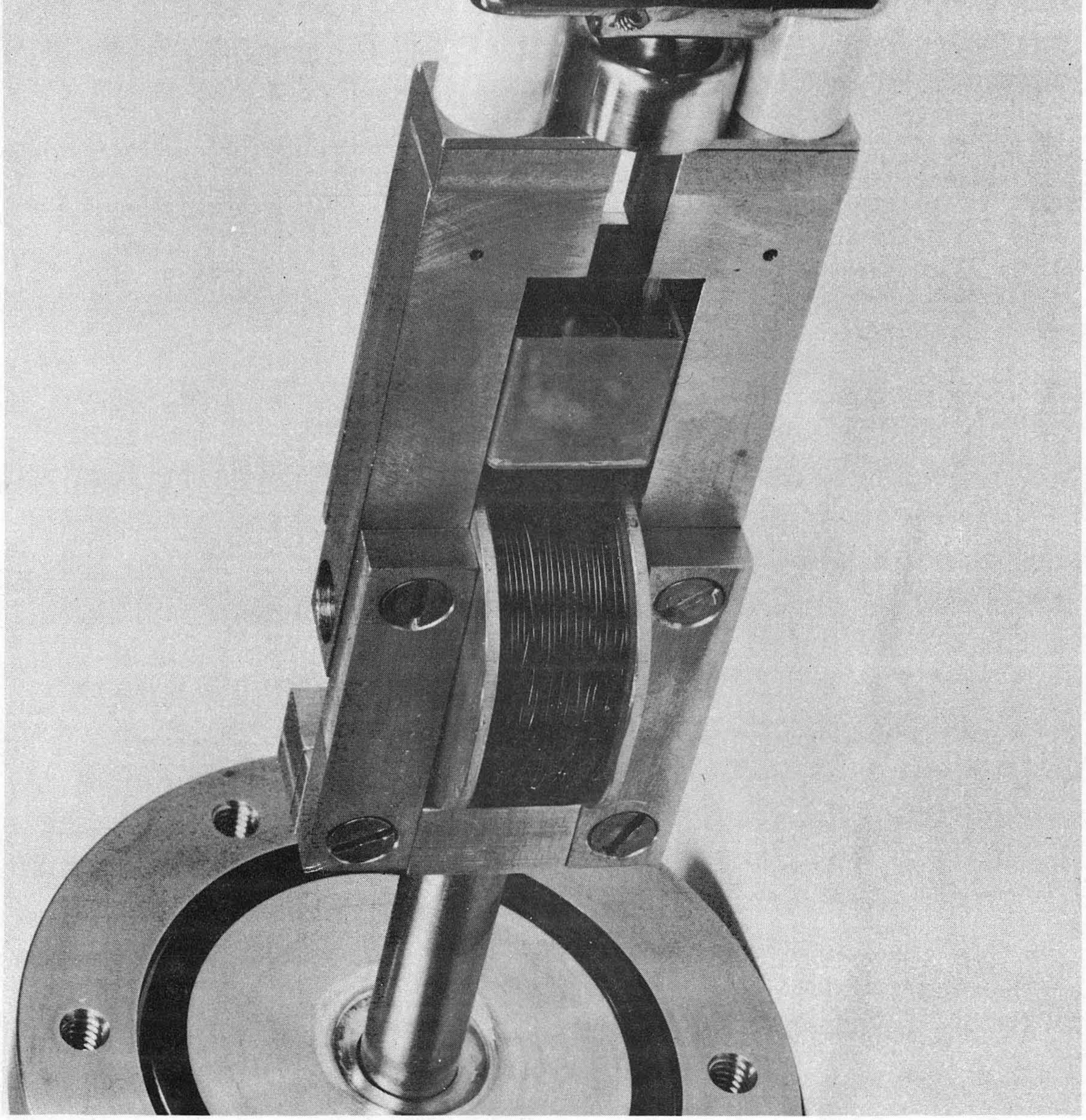


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Fig. 4

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