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Plasma-Materials Interactions Test Facility

Taner Uckan

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PLASMA-MATERIALS INTERACTIONS TEST FACILITY

Taner Uckan

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ABSTRACT

The Plasma-Materials Interactions Test Facility (PMITF), recently designed and constructed at Oak Ridge National Laboratory (ORNL), is an electron cyclotron resonance microwave plasma system with densities around 10^{11} cm^{-3} and electron temperatures of 10–20 eV. The device consists of a mirror cell with high-field-side microwave injection and a heating power of up to 0.8 kW (cw) at 2.45 GHz. The facility will be used for studies of plasma-materials interactions and of particle physics in pump limiters and for development and testing of plasma edge diagnostics.

I. INTRODUCTION

The Plasma-Materials Interactions Test Facility (PMITF) is a single-cell mirror device that produces steady-state test plasmas with electron cyclotron resonance (ECR) heating using a 2.45-GHz microwave source. As shown schematically in Fig. 1, the test facility consists of three identical magnetic field coils arranged to produce the mirror field and also set up a solenoid field that makes high-field-side microwave injection possible. This arrangement has a number of advantages. For example, it provides excellent access to the central-cell plasma. In addition, as discussed in Sec. III, it avoids the low-density cutoff region in the mirror cell, so that higher densities can be produced using high-field-side injection.

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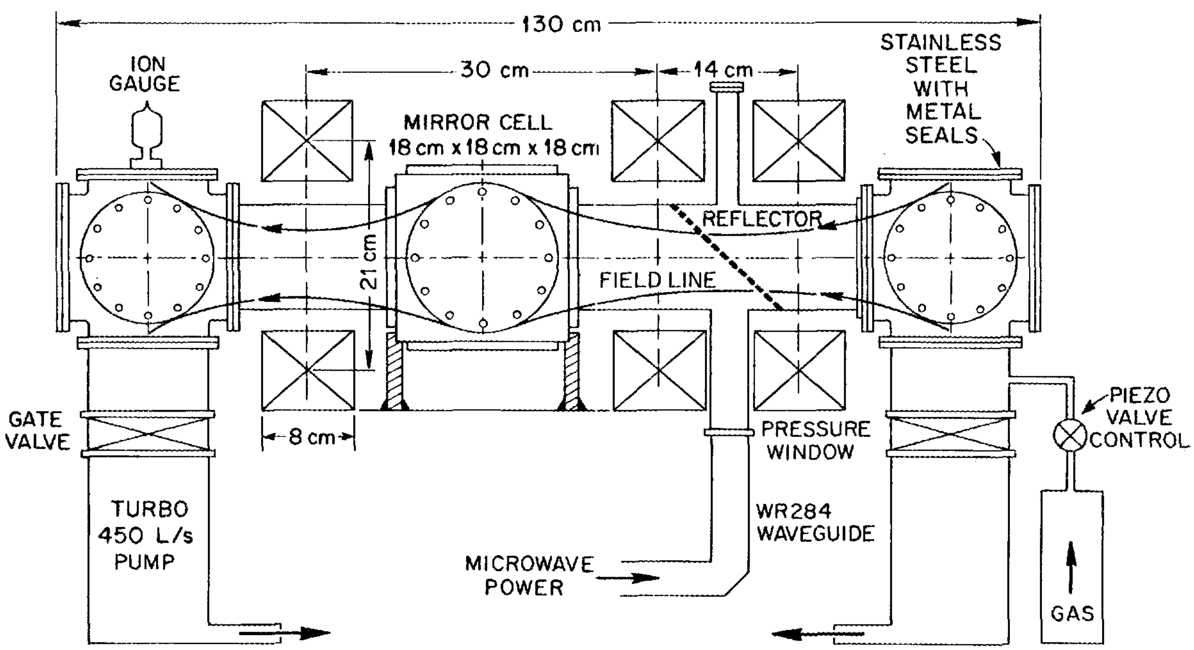

Fig. 1. Schematic of PMITF, a mirror device with high-field-side injection that uses the electron cyclotron resonance for plasma production and heating.

The PMITF has recently been designed and constructed at Oak Ridge National Laboratory (ORNL), where it will be used primarily for studies of plasma-materials interactions and of particle physics in pump limiters and for plasma edge diagnostics development. So far, using up to 0.8 kW of continuous-wave (cw) microwave power at 2.45 GHz, plasma densities around 10^{11} cm^{-3} and electron temperatures of about 12–20 eV, depending on the value of the base pressure (usually around 10^{-4} Torr), have been obtained.

This paper is organized as follows: In Sec. II, the basic device parameters and characteristics are introduced. The power coupling technique for high-field-side injection is discussed in Sec. III. Finally, the plasma performance, as measured by Langmuir probes, is presented in Sec. IV, together with a brief discussion.

II. DEVICE PARAMETERS

The PMITF is about 130 cm long and is made of stainless steel. Its joints are sealed with metallic gaskets. The three magnetic field coils have about 15,500 ampere-turns and produce 0.1 T on axis. The distance between the first and second coils, which form the central cell, is 30 cm; between the second and third coils, 14 cm. The magnetic field variation on the device axis is shown in Fig. 2. The mirror ratio is about 2.4 for the central cell and about 1.02 for the solenoid field produced by the second and third coils, which allows high-field-side injection.

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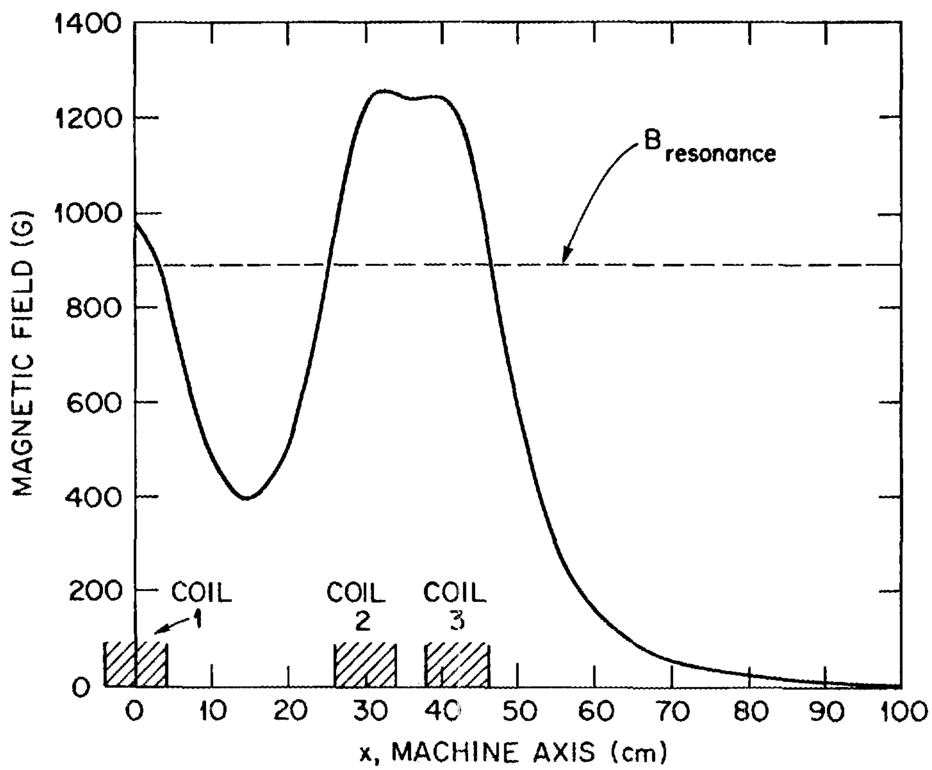

Fig. 2. Magnetic field variations on the PMITF axis. The mirror ratio is 2.4, and the magnetic field on the coil center is about 0.1 T.

4 *Device Parameters*

The device was designed around the existing coils. The mirror ratio $M = 2.4$ was chosen so that optimum ECR heating takes place for the electrons that are confined within the volume defined by the clear-bore magnetic field configuration. This requirement corresponds to locating the resonance zone close to the coils, as shown in Fig. 2. The mirror ratio also maximizes the midplane plasma radius, which is desirable. The coil current center, 10.5 cm, and the mirror ratio were used in the magnetic field calculations[1] to find the 30-cm coil separation.

The magnetic field line plot in Fig. 3 indicates that the coil throat diameter of about 13 cm limits the size of the plasma in the mirror cell. Furthermore, the large (10-cm-diam) spool piece that goes into the mirror coils establishes a plasma diameter of about 14 cm in the mirror cell and about 7 cm in the mirror throats. The central cell is a cube, 18 cm on a side, that has 10-cm access ports in the four exposed sides.

One 450-L/s turbomolecular pump is located at each end of the device, as shown in Fig. 1. The base pressure in the vacuum chamber is about 10^{-7} Torr; during plasma production, around 10^{-4} Torr is used.

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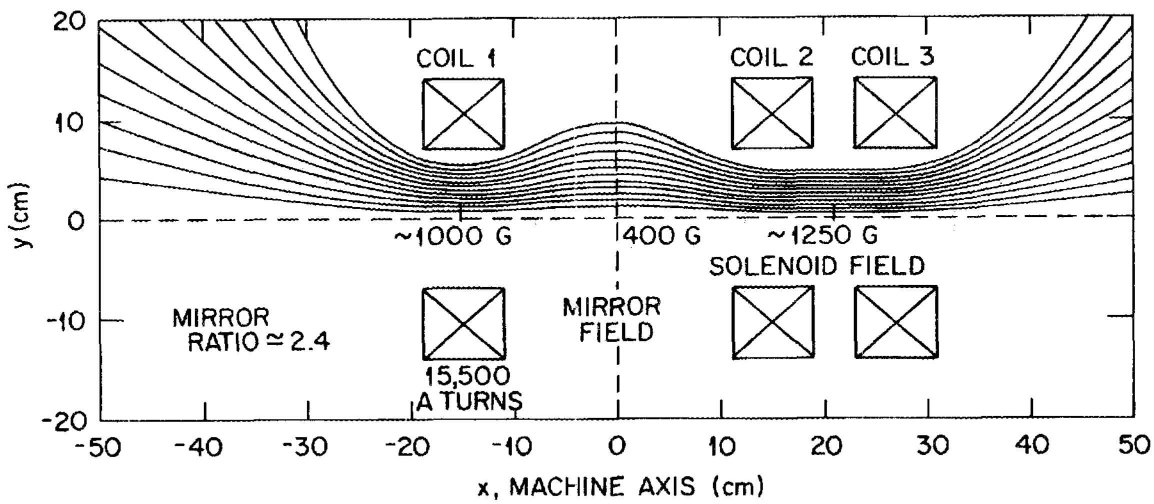

Fig. 3. Field lines in PMITF. The lines are plotted at intervals $\Delta y = 0.4$ cm starting from $y = 0.8$ cm at the coil throat, $x = -15$ cm. When 10-cm-diam spool pieces are inserted into the mirror coils, the size of the plasma is determined by the last field line that grazes the spool pieces (Fig. 1). This last field line in the device is 3.6 cm from the axis in the coil throat (coil 1) and 6.8 cm from the axis in the midplane of the mirror cell.

III. COUPLING OF MICROWAVE POWER

The plasma in the PMITF is produced and heated by the electron cyclotron resonance. The 2.45-GHz microwave power (2.45 GHz $= \omega/2\pi$) is introduced to the chamber with a WR284 waveguide through a pressure window. When the propagating wave reaches a region in which the magnetic field has the value required for electron cyclotron resonance, $B_{\mathrm{resonance}} = 0.0875$ T, the power transfer to the electrons becomes maximum as a result of the so-called "cyclotron damping" process. A CMA diagram[2] that describes wave propagation in a cold electron plasma is shown in Fig. 4.

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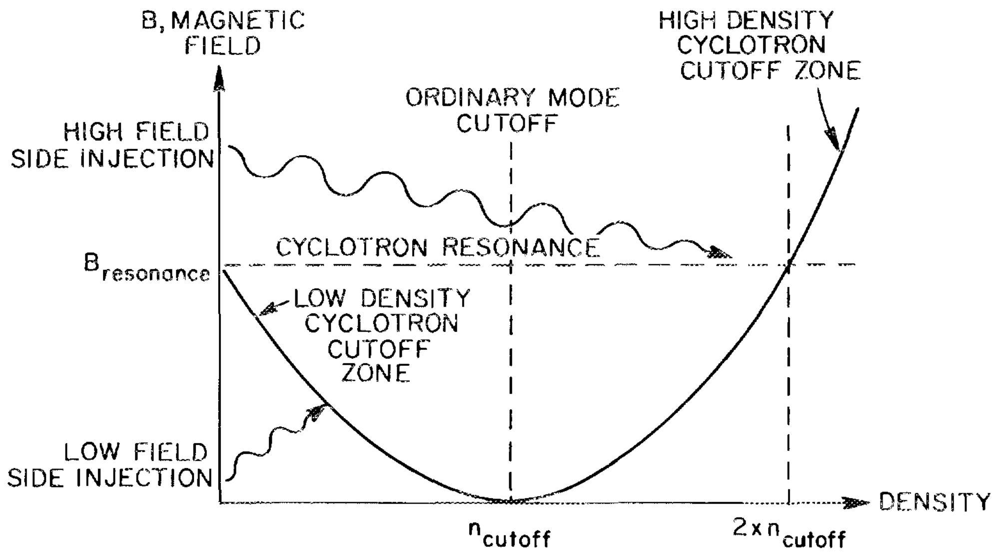

Fig. 4. Regions of cyclotron resonance and low- and high-density cutoffs. Injecting the microwave power from the high-field side of the device allows the electron density to be above the cutoff density of $n_{\mathrm{cutoff}} \simeq 7.4 \times 10^{10}$ cm^{-3} for the 2.45-GHz microwaves used.

If the microwave power were launched from the low-magnetic-field side of the device, where $B < B_{\mathrm{resonance}}$, which in this case is from the midplane of the mirror cell where the field is about 0.03 T, then the presence of the low-density right-hand cutoff region would prevent the propagation going toward the cyclotron resonance zone, which is close to the mirror coils, as shown in Fig. 5. However, this can be avoided by using high-field-side ($B > B_{\mathrm{resonance}}$) injection, as demonstrated in several experiments.[3] In this case, the microwave power is introduced to the device from the coil throat. This microwave coupling technique is illustrated schematically in Fig. 5. The third coil is placed very close to the second mirror field coil to generate a solenoid field of 0.125 T that makes high-field-side injection possible. Then the waveguide between the coils directs the power toward a perforated reflector, placed at an angle of 45° to the machine axis. The reflected wave propagates parallel to the magnetic field as an extraordinary-mode wave so that, at the cyclotron resonance region, maximum power absorption by the electrons takes place.[4] With this launching technique, plasma densities can be as high as a factor of two above the ordinary-mode cutoff density of $n_{\mathrm{cutoff}} = (\omega/2\pi)^2/81 \times 10^6 \simeq 7.4 \times 10^{10}\ \mathrm{cm}^{-3}$, provided that the heating source can deliver the necessary power.

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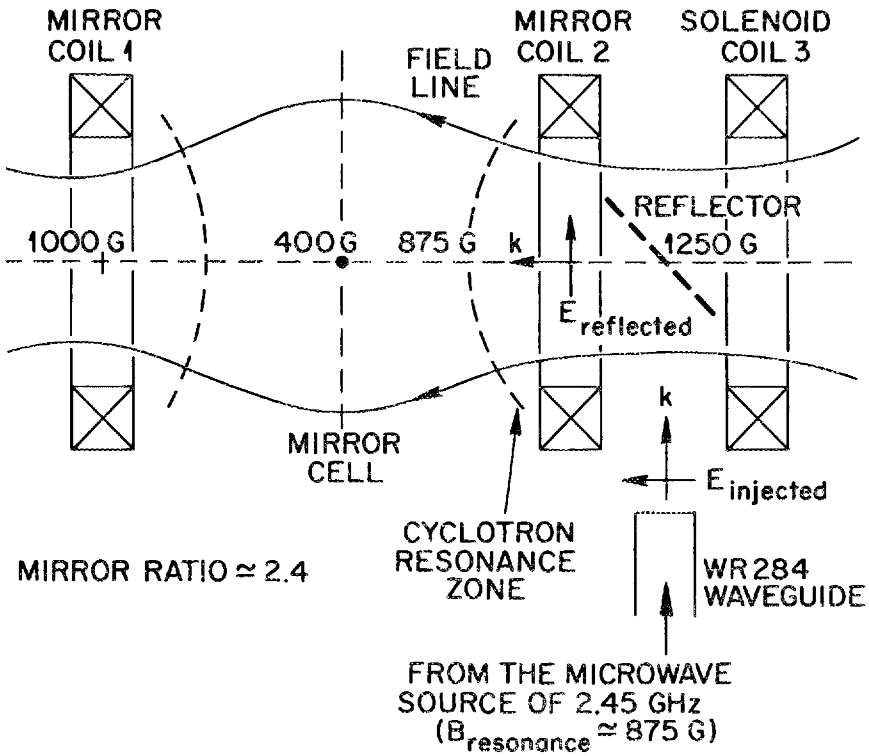

Fig. 5. The microwave coupling technique used in PMITF. Here **k** is the propagation vector, and $\mathbf{E}_{\mathrm{injected}}$ and $\mathbf{E}_{\mathrm{reflected}}$ are the electric field vectors before and after their reflection from the perforated plate. The reflected wave propagates as an extraordinary-mode wave and dumps its power to the electrons at the cyclotron resonance zone, where $B_{\mathrm{resonance}} \simeq 0.0875$ T.

IV. PLASMA PERFORMANCE AND DISCUSSION

The plasma discharge behavior in the mirror cell is monitored with a television camera through a viewing port that also has a radiation detector. The transmitted and reflected microwave powers to and from the vacuum chamber are continuously monitored with a pair of crystal detectors. A set of tuning stubs is used in the transmission line to match the plasma load to the generator. Measurements show that, within the operating range of the device, no more than 10% of the power is reflected to the generator, which is protected with an isolator.

During the discharge a well-confined, quiescent plasma is observed when the operating base pressure is kept around (1–3) $\times$ 10^{-4} Torr for a working gas of hydrogen. Plasma performance is highly reproducible.

Langmuir probes are used to measure the plasma density n_e and temperature T_e at the center and at the edge of the device. Results are obtained by comparing the probe electron current with the applied probe voltage, as displayed in Fig. 6. At the center of the mirror cell, $r = 0$, it is found that

$$n_e \simeq 10^{11} \text{ cm}^{-3}$$

and

$$T_e \simeq 17.5 \text{ eV} ,$$

while at the edge of the plasma, $r \simeq 6.5$ cm,

$$n_e \simeq 5.5 \times 10^{10} \text{ cm}^{-3}$$

and

$$T_e \simeq 13 \text{ eV} .$$

These measurements were carried out at 1.5×10^{-4} Torr of H_2 with a heating power of about 500 W. During device operation, neither X-radiation nor microwave leakage was observed.

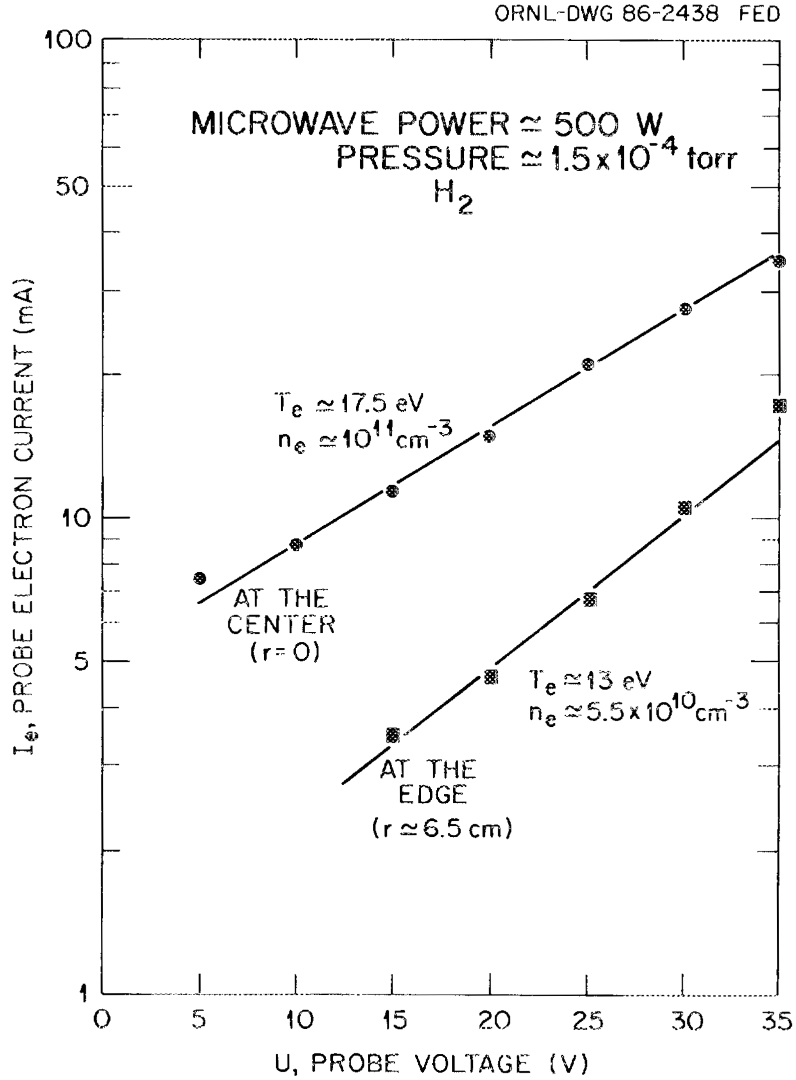

Fig. 6. Langmuir probe measurements. At the mirror center $T_e \sim 17.5$ eV and $T_e \simeq 10^{11}$ cm^{-3}, while at the edge $T_e \sim 13$ eV and $n_e \simeq 5.5 \times 10^{10}$ cm^{-3} when 500 W of microwave power is applied.

In addition to a newly installed movable Langmuir probe, the plasma diagnostics are

1. an H_α monitor,
2. a visible monochromator,
3. calorimeter probes,
4. a residual gas analyzer (RGA), and
5. ion gauges.

The measured central plasma density $n_e(r = 0) \gtrsim n_{\rm cutoff}$ indicates that microwave power is used efficiently in creating high-density plasmas. The device generator output power will be raised to 1.5 kW (cw) in the near future, and higher plasma densities are expected.

Finally, the cw nature of the facility makes it very convenient to carry out various tests and checks of diagnostics during their development phases. The turnaround time is also relatively short, about two hours, which makes the device attractive from the operational point of view. Figure 7 is a photograph of the PMITF.

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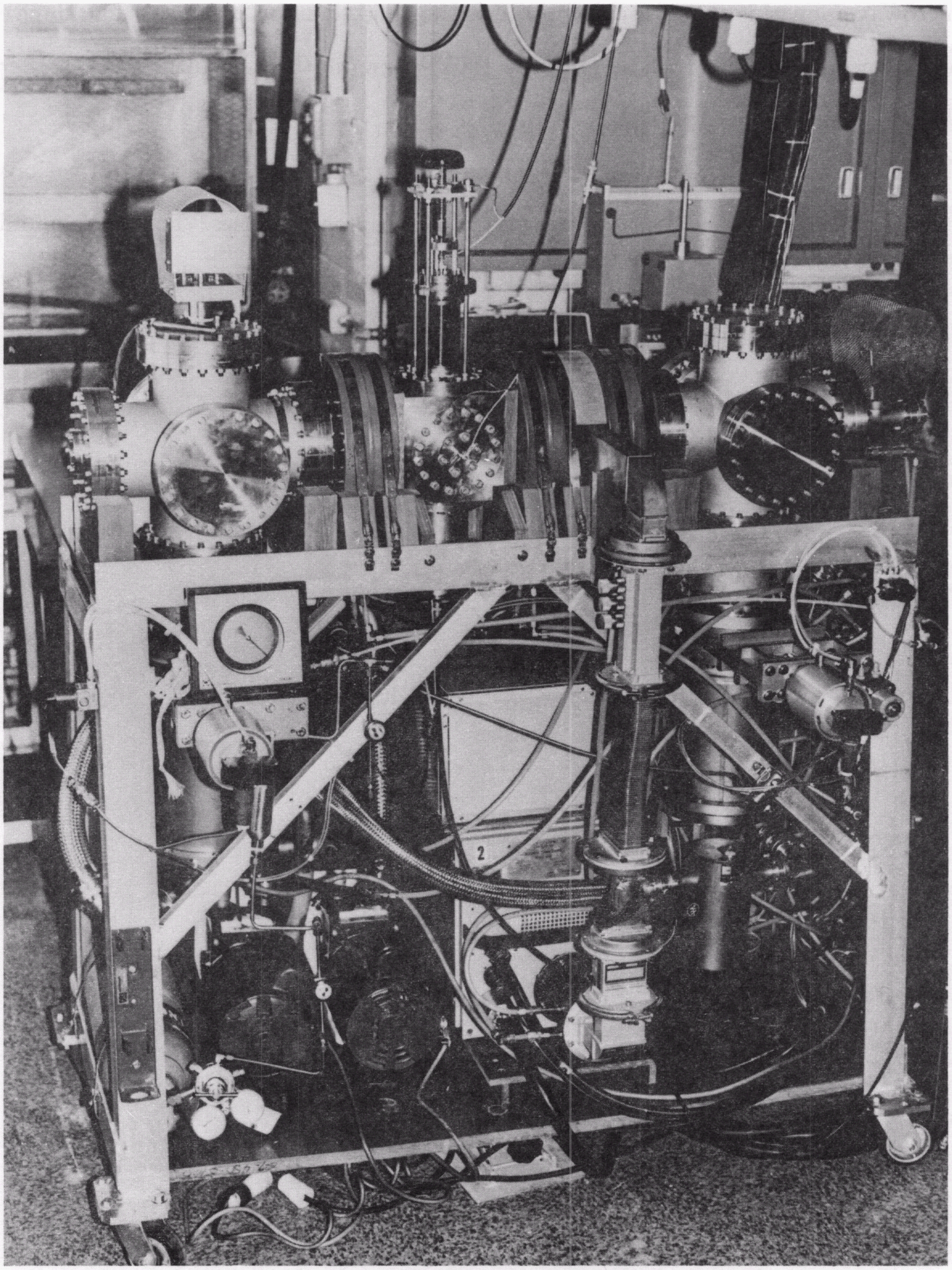

Fig. 7. Photograph of PMITF.

REFERENCES

1. R. T. Santoro et al., *An EBT Reactor System Analysis and Cost Code*, Oak Ridge National Laboratory Report No. ORNL/TM-9026, 1984.

2. W. P. Allis, S. T. Buchsbaum, and A. Bers, *Waves in Anisotropic Plasmas* (MIT Press, Cambridge, Mass., 1963).

3. For example, see C. P. Moeller et al., *Phys. Fluids* **25**, 1211 (1982).

4. F. F. Chen, *Introduction to Plasma Physics and Controlled Fusion* (Plenum Press, New York, 1984).

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