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RADIATION MEASUREMENTS FROM AN INVERTED
RELATIVISTIC MAGNETRON

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Abstract

We report microwave emission measurements from an inverted relativistic magnetron comprising an outer cylindrical field emission cathode and an inner coaxial anode with embedded vane resonators. The magnetron operates in the π mode at a frequency of ~ 3.6 GHz, and voltages of 1-2MV. The RF power is ~ 500 MW.

I. INTRODUCTION

The magnetron^{1,2} is one of the most efficient and rugged devices for generating microwaves at decimeter and centimeter wavelength ranges. Power levels from tens of watts to hundreds of kilowatts can be achieved with conversion efficiencies as high as 80%. In recent years³⁻⁹ a new class of pulsed magnetron devices has come into existence which are capable of extending the existing powers by more than two orders in magnitude. This has resulted in the generation of unprecedented powers in the range of hundreds of megawatts to several gigawatts, (albeit at reduced efficiencies of 10%-35%).

To achieve efficient conversion of energy from a stream of free electrons to electromagnetic radiation, near synchronism must be attained between the velocity of the electrons and the phase velocity of the wave. In crossed-field devices, of which the magnetron is a typical example, this synchronism occurs between electrons undergoing a $\vec{v} = \vec{E} \times \vec{B} / B^2$ drift in orthogonal electric and magnetic fields, and an electromagnetic wave whose velocity is reduced by a slow-wave structure comprised of a periodic assembly of coupled resonant cavities.

The device is illustrated schematically in Fig. 1. It comprises a smooth cylindrical cathode of radius r_c enclosing a coaxial cylindrical anode of radius r_a . The electrons, emitted from the cathode by field emission^{4,10} are subjected simultaneously to two quasi-steady fields acting at right angles to one another: a uniform, axial magnetic field B_{oz} produced by magnetic coils, and a radial electric field $E_{or}(r)$ generated by applying a voltage V between the electrodes. As a result, a space-charge cloud forms,

partially filling the interaction gap ($r_c - r_a$); the electrons undergo azimuthal rotation having a sheared, radially dependent velocity $v_\theta = E_{or}(r)/B_{oz}$. To achieve this "Brillouin flow equilibrium," the strength of the magnetic field must exceed the critical field for "magnetic insulation", given by^{4,10}

$$B_{oc} = (m_0 c / e d_e) (\gamma_0^2 - 1)^{1/2}, \quad (1)$$

where e and m_0 are the electron charge and rest mass, respectively, $\gamma_0 = 1 + (eV/m_0 c^2)$ and $d_e = (r_c^2 - r_a^2)/2r_a$ is the effective cathode-anode gap width.

Embedded in the anode block is a periodic assembly of vane-type resonators⁴ whose function is to create slow modes (phase velocity $< c$) with which the circulating electrons can interact. Once the system is assembled, the inner electrode (anode) is connected to the positive terminal of a pulsed high voltage accelerator. The outer, field emission cathode is grounded. Table I gives a summary of the experimental parameters and dimensions of two tubes (M8 and M10) and Table II gives their (approximate) mode frequencies computed by a method^{1,4} described elsewhere.

The eight-vane (M8) and ten-vane (M10) tubes are designed with the view (see section III) of testing two magnetrons radiating at the same π -mode frequencies but having widely different cathode-anode gap widths d . This is achieved by changing the number of vane resonators from eight to ten as the gap width is changed from 1.38cm to 0.84cm, respectively.

It is clear from Fig. 1 that the configuration of the magnetrons under present investigation is inverted compared to the typical magnetron^{1,2,3,4} which has an outer (grounded) anode and an inner (negative) cathode. In this latter, con-

figuration a sizeable fraction⁴ of the electrons emitted by the cathode flow axially along the magnetic field lines to ground. The electrons, therefore, do not circulate and do not participate in the RF interaction. Thus, they provide an undesirable "shunt" current⁴ which reduces the efficiency of the device. In low voltage magnetrons the shunt current can be suppressed by placing electrostatic shields at both ends of the cathode. However, in high voltage relativistic magnetrons this technique cannot be used because at the large field strengths that exist there (≥ 200 kV/cm), all materials emit and arcing occurs readily. The inverted magnetron obviates the problem of the shunt current. With the grounded cathode now on the outside, any electrons flowing axially from the cathode return to it with no loss of energy.

However, in the inverted magnetron configuration, the extraction of the RF power poses a problem. The RF fields are strongest in the vane resonators which are on the inside of the tube and at high electrical potential. One technique^{4,12} is to connect the vane resonators by means of slot couplers to a central, coaxial cavity, and transmit the microwave power axially, out the front of the device. This requires a complicated, highly overmoded RF circuit, numerous closely spaced vane resonators and a high voltage isolation transformer.¹² We have chosen a more primitive system in which the RF fields are coupled directly out of the cathode-anode gap and across the electron space charge cloud. This is done by attaching a section of C band waveguide to a slot cut in the cathode wall, as is illustrated in Fig. 1. The waveguide is butt-mounted with its broad wall aligned along the axis of the magnetron. This orientation couples the axial component of the

RF magnetic field in the cathode-anode gap to the RF magnetic field of the TE_{01} mode of the waveguide. The second waveguide shown in Fig. 1 is connected to a matched dummy high-power load; its purpose is to provide a measure of symmetry in the coupling and reduce the possibility of unevenly loading the internal RF structure of the magnetron. We point out that our coupling schema is far from optimal, and we believe that only a fraction of the available RF power generated in the device reaches our external diagnostics.

II. EXPERIMENTS

The electric field between cathode and anode is provided by the Physics International Pulserad 110A high voltage facility. The axial magnetic field is generated^{4,10} by two pulsed magnetic field coils surrounding, and coaxial with, the cylindrical electrodes. Typical voltage and current characteristics of the M8 magnetron as function of the axial magnetic field are shown in Figs. 2 and 3, respectively. The three sets of data in each figure correspond to three different Marx generator charging voltages (30kV, 40kV, and 50kV) employed in all of our experiments. The overall voltage-current characteristics are similar to those observed in conventional^{3,4} relativistic magnetrons.

The radiation emanating from the magnetron via the C-band waveguide is attenuated by ~ 100 db with the aid of precision calibrated attenuators and directional couplers and is rectified in a calibrated crystal detector. Figure 4 shows the total power emitted as a function of axial magnetic field. We see that power levels in excess of 400MW are achieved. The bell-shaped curves

shown in Fig. 4 are very similar to those obtained for relativistic magnetrons operating in the conventional (noninverted) configuration.^{3,4}

The frequency spectrum is measured by means of a solid-state dispersive line⁴ having a resolution better than ~ 50 MHz. The observations are plotted in Fig. 5 as a function of the axial magnetic field. It is seen that at low magnetic fields the frequency increases linearly with magnetic field suggesting that one is observing some form of collective cyclotron radiation.¹³ In this regime of magnetic fields B_z and voltages V (see Fig. 2), B_z is at or a little below the critical magnetic field B_{0c} given by Eq. (1). At higher magnetic fields well above the critical magnetic field B_{0c} , the oscillation frequency becomes virtually independent of B_z as expected when true magnetron oscillations set in. The measured frequency is now close to but slightly higher than the π mode frequency determined by computations and magnetron cold tests (see Table II). The small upward frequency shift relative to the cold test frequency is probably due to the presence of electron space charge in the cathode-anode gap which tends to make the effective gap width smaller and the mode frequency higher. (This is equivalent to "current-pushing" in conventional, nonrelativistic magnetrons.)

Knowledge of the emitted microwave power P_μ , magnetron voltage V , and current I , allow one to derive the tube efficiency defined as the ratio of P_μ/VI . This quantity is plotted in Fig. 6 as a function of the axial magnetic field. The maximum efficiency obtained is $\sim 12\%$.

All observations presented hitherto refer to the eight-vane

(M8) magnetron. A similar study of the ten-vane (M10) magnetron reveals characteristics very similar to the M8 device. For example, in the M10, the maximum RF power achieved is 515MW at an axial magnetic field of 6.65kG, voltage 1.62MV, and a current of 9kA. The resulting efficiency is 3.5%. This is considerably lower than that obtained with the M8 magnetron. Indeed, this lowered efficiency is the main difference between the M10 and M8 devices: although the absolute RF power level obtained from the M10 is equal to or greater than that obtained from the M8 magnetron, the enhanced currents drawn by the former cause an efficiency reduction by a factor of two or more.

III. DISCUSSION

We have observed intense ($\sim 400-500\text{MW}$) narrow band ($\leq 50\text{MHz}$) microwave radiation at a frequency of $\sim 3.7\text{GHz}$ from an inverted relativistic magnetron which is free from the undesirable shunt currents⁴ that often plague magnetrons built in the conventional manner. The available radiation is probably much in excess of what emanates from our simple waveguide-coupled system. Our coupling schema suffers from two defects. First, we couple to the relatively weak radiation field which exists in the cathode-anode gap rather than coupling to fields in the vane resonators. Secondly, a dense electron space charge cloud intervenes between the output waveguide and the center of the magnetron causing attenuation of the electromagnetic field at the extraction point.

Indeed, we believe that the RF power within the magnetron itself is comparable in magnitude to the power in the electrons. We base this on the results of Fig. 3 where a sharp cur-

rent increase is seen to occur at a magnetic field ($\sim 4.5\text{kG}$) at which the emitted RF power is maximum (Fig. 4). This resonance behavior in the current can occur only if the RF electric field builds up to a level comparable to the externally applied electric field. We note that such current enhancement during strong RF oscillations is typical of the highly efficient, low voltage magnetrons, but has not been seen previously in relativistic magnetrons of the conventional²⁻⁹ (noninverted) type. The fact that this was not seen in previous relativistic magnetrons suggests that RF generation was less efficient, possibly due in part to large axial shunt currents.

A comparison between the large gap (1.38cm) M8 magnetron and the narrow gap (0.84cm) M10 magnetron exhibits very similar characteristics, except that the M10 draws more current and its efficiency is smaller by approximately a factor of two. The lessened efficiency is thought to be due to the fact that a narrow gap partially shorts out the azimuthal component of the RF electric field in the cathode-anode space. Therefore, the device is less conducive⁴ to strong space charge spoke formation, which is necessary for efficient microwave generation.

ACKNOWLEDGEMENTS

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13. We note that at or near Brillouin equilibrium the ratio of the cyclotron to plasma frequencies is constant and approximately equal to unity. Thus, the observed radiation at low B_z may well be connected with collective plasma oscillations.

TABLE I. Summary of operating parameters of two inverted relativistic magnetrons (the nomenclature is that used in Fig. 1).

Voltage	0.9 - 2.1 MV	
Current	1 - 14 kA	
Pulse length	30 ns	
Axial magnetic field	2 - 6 kG	
Quantity	M8 Magnetron	M10 Magnetron
Number of vanes	8	10
Anode radius r_a	2.92 cm	3.76 cm
Cathode radius r_c	4.30 cm	4.60 cm
Gap width d	1.38 cm	0.84 cm
Anode length L	5.07 cm	4.64 cm
Vane radius r_v	1.28 cm	2.55 cm
Vane angle θ	30°	20°

TABLE II. Computed (and measured) mode frequencies of the M8 and M10 inverted magnetrons. Mode designations conform to those used in References 1 and 4.

Mode	Frequency (GHz)	
	M8	M10
Calculated		
1	1.10	<0.95
2	2.15	1.72
3	3.10	2.48
4	--	3.15
π	3.53	3.69
2π (0)	>4.7	>4.7
Measured (cold test)		
π	--	3.67

CAPTIONS TO FIGURES

- Fig. 1. Schematic diagram of the M8 inverted relativistic magnetron.
- Fig. 2. Voltage as a function of the axial magnetic field for the M8 magnetron.
- Fig. 3. Current as a function of axial magnetic field for the M8 magnetron (● 30kV Marx-bank charging; ▲ 40kV; ○ 50kV).
- Fig. 4. Radiated power in the 3.2-5.9GHz frequency range as a function of the axial magnetic field for the M8 magnetron (● 30kV Marx-bank charging; ▲ 40kV; ○ 50kV).
- Fig. 5. Radiation frequency as a function of the axial magnetic field for the M8 function (● 30kV Marx-bank charging; ▲ 40kV; ○ 50kV).
- Fig. 6. Magnetron efficiency as a function of the axial magnetic field for the M8 magnetron (● 30kV Marx-bank charging; ▲ 40kV; ○ 50kV).

GRAPHITE-COATED CATHODE

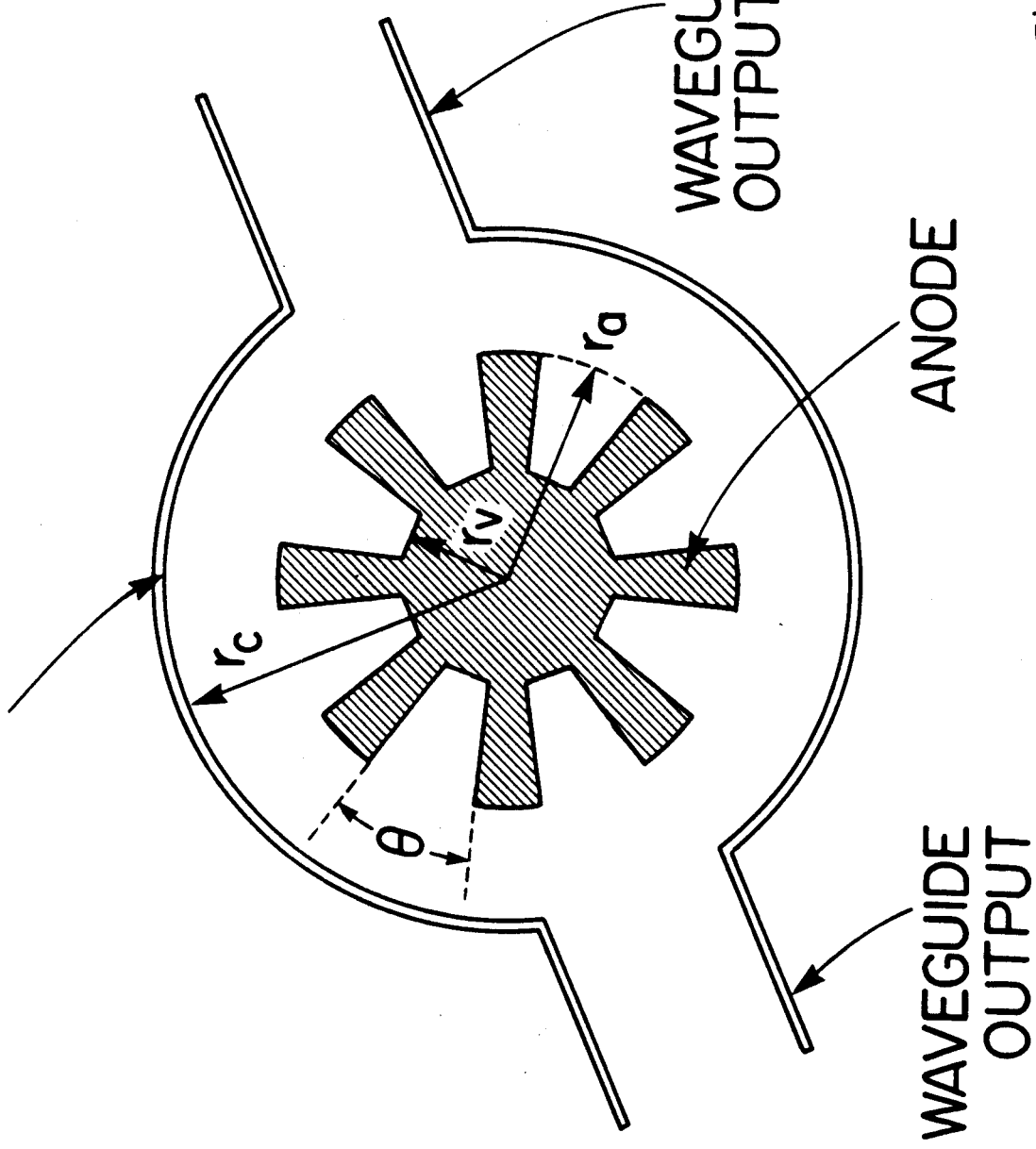


Fig. 1
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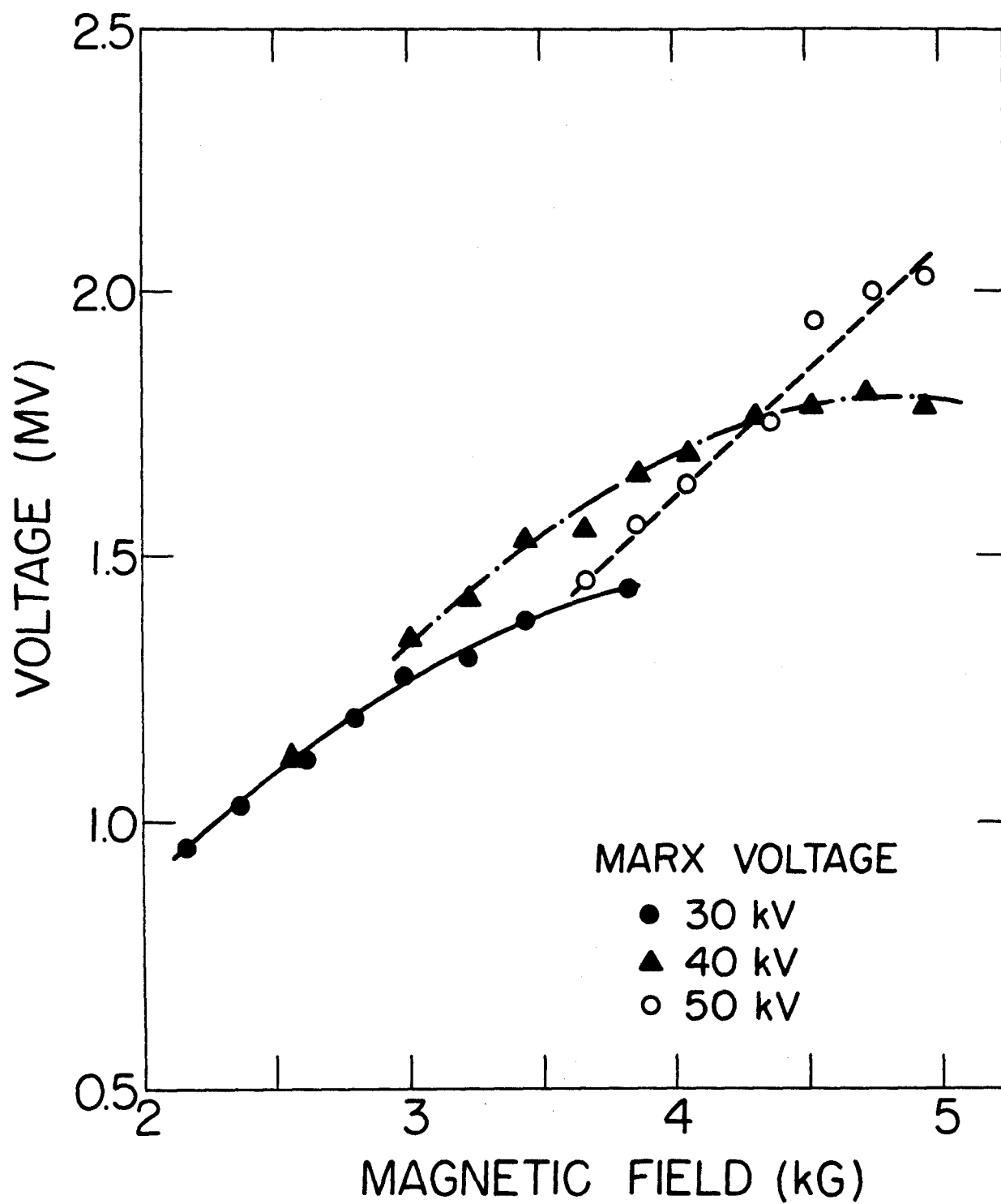


Fig. 2
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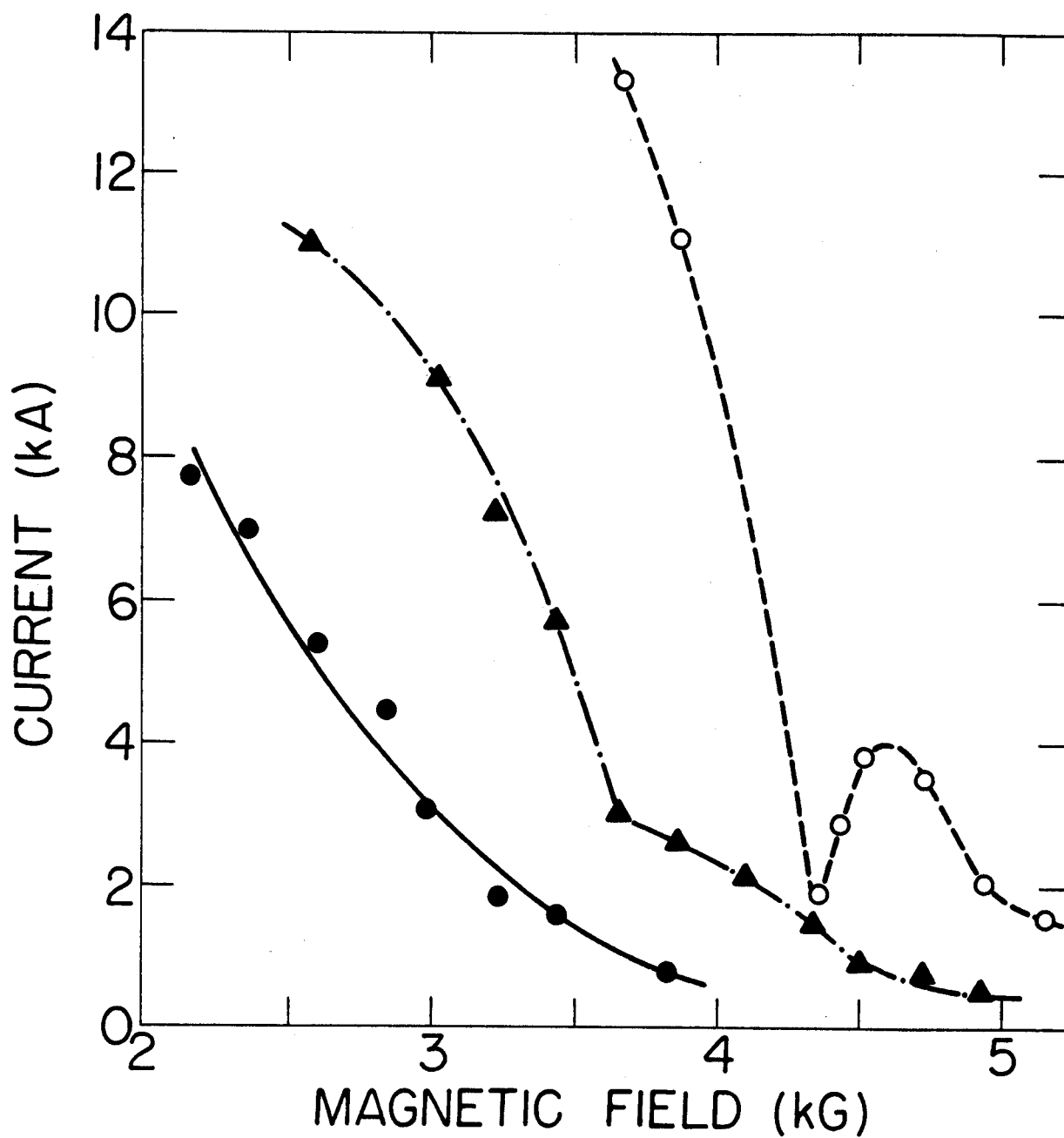


Fig. 3
Close, Palevsky, Bekafi

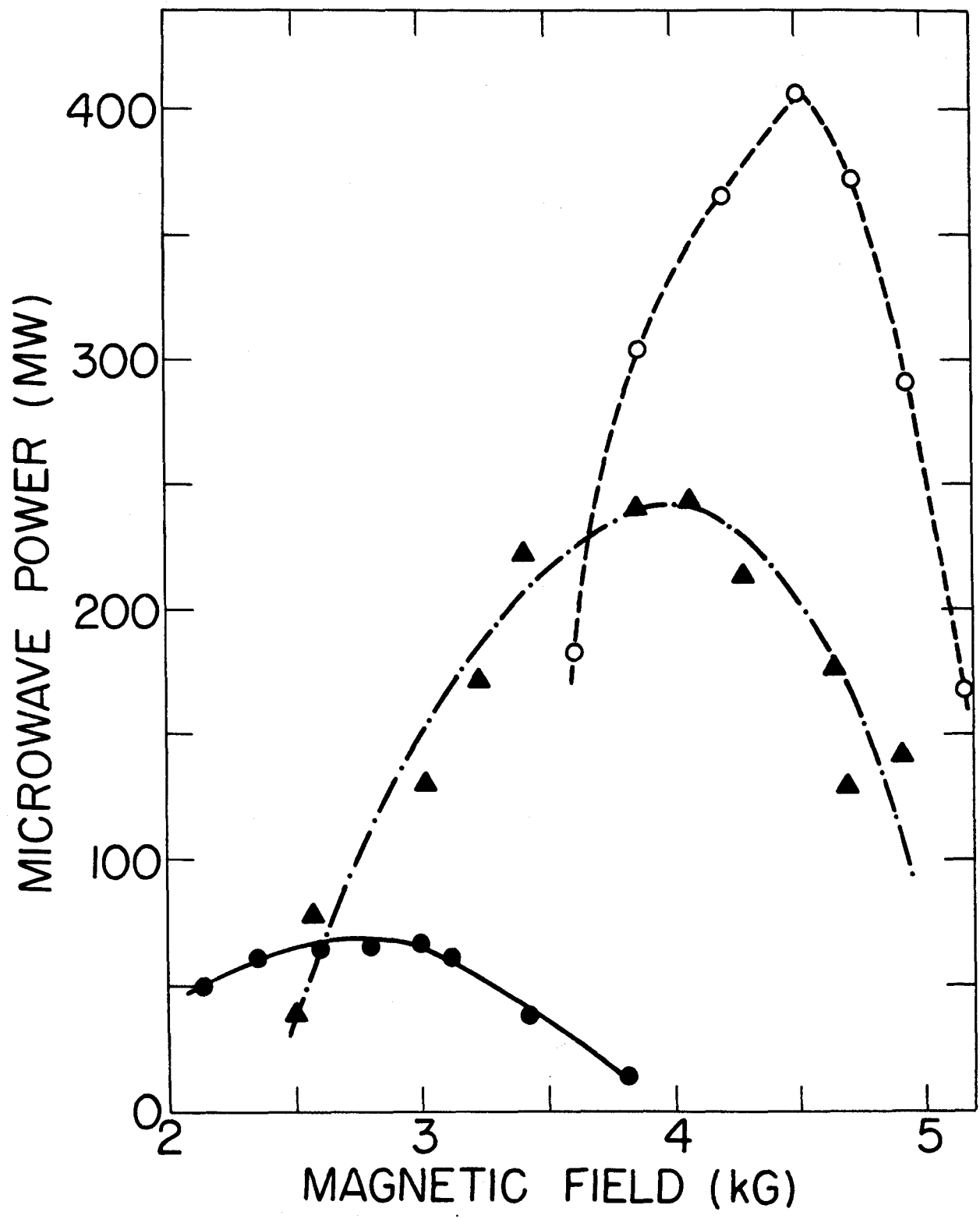


Fig. 4
Close, Palevsky, Bekefi

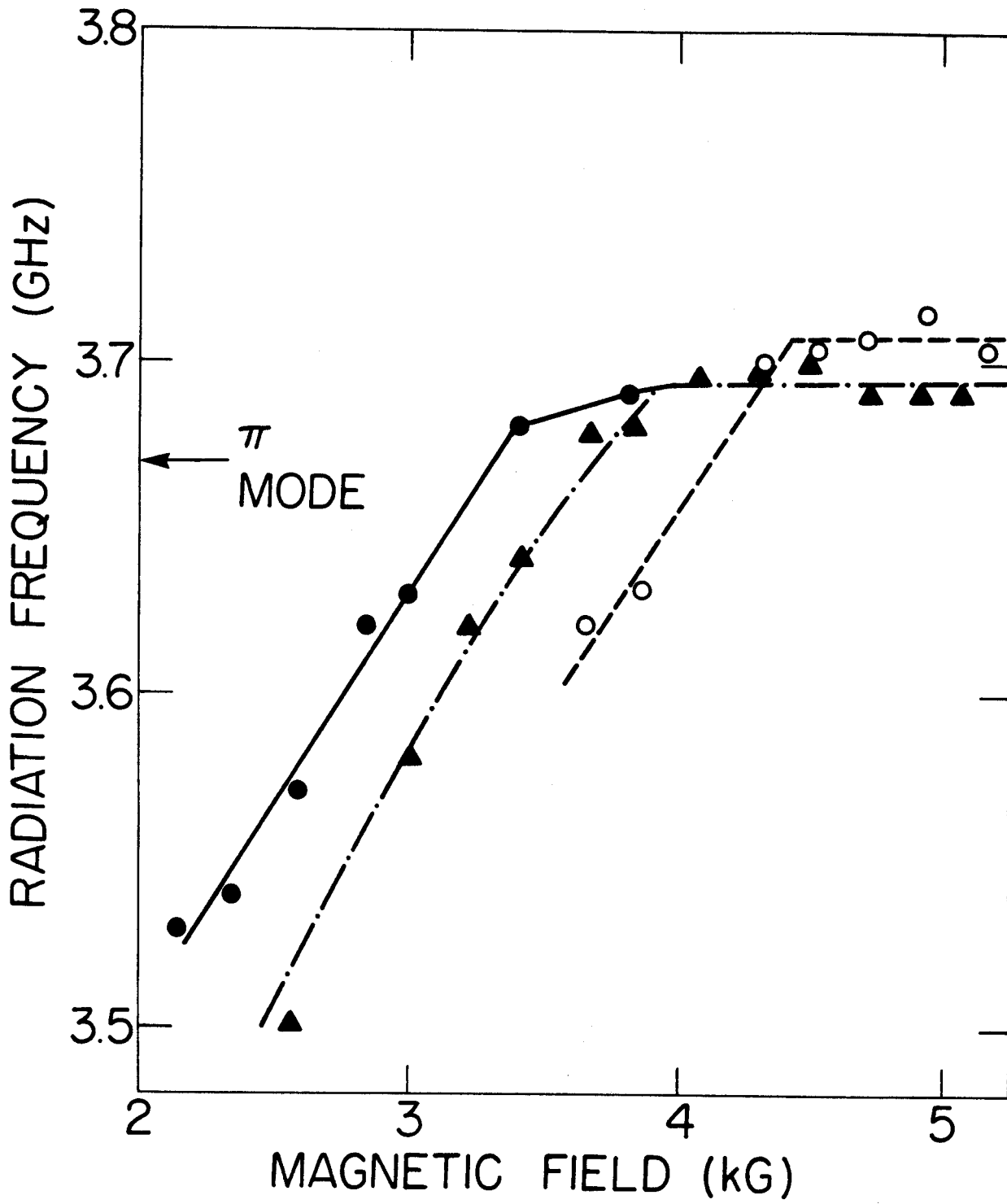


Fig. 5
Close, Palevsky, Bekefi

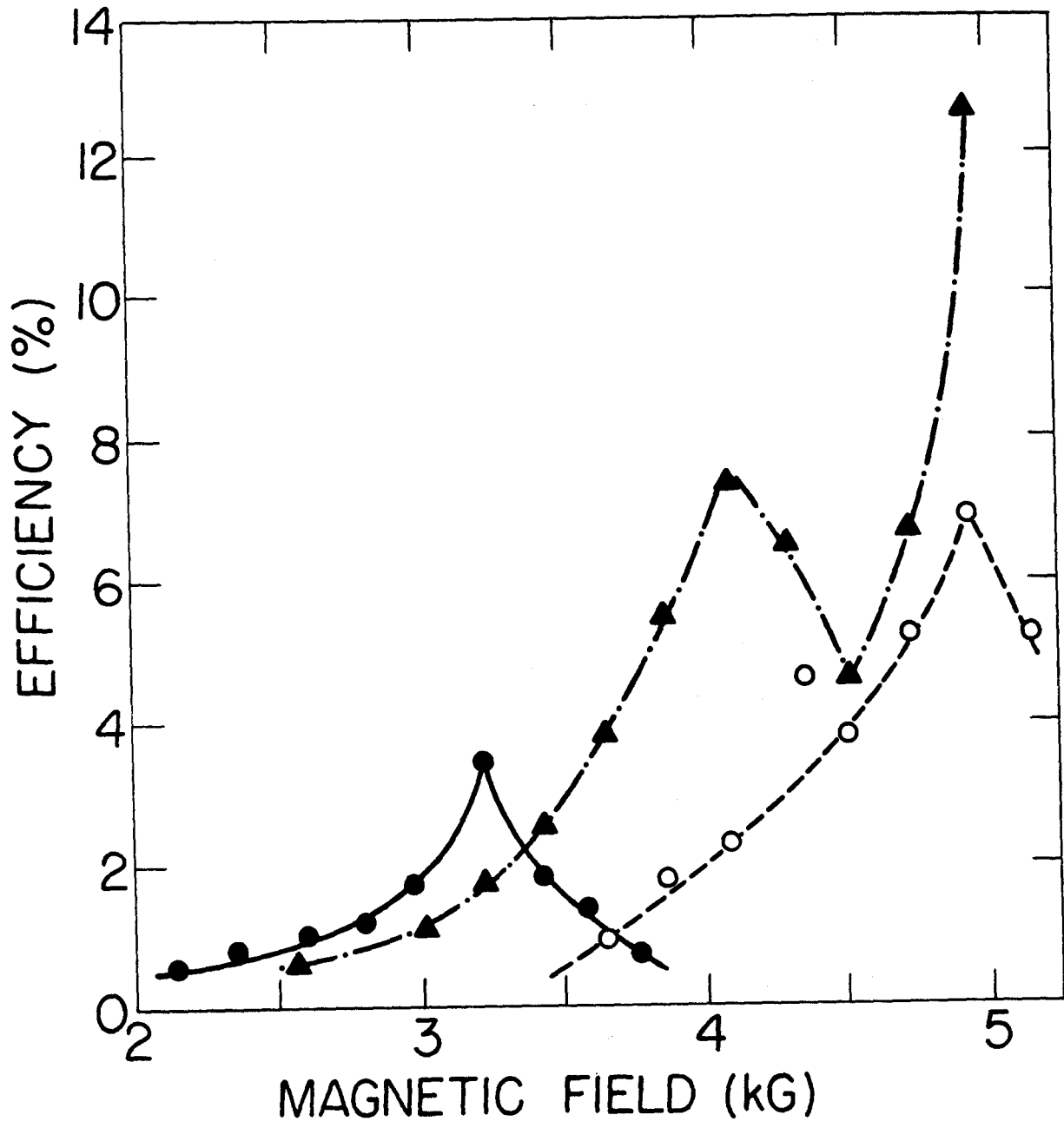


Fig. 6
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