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RF-Induced Electron Endloss from an ECRH Mirror Plasma

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Measurements are presented which indicate that rf-induced endloss is the dominant mechanism for the loss of hot ($E > 50$ keV) electrons from an electron cyclotron resonance heated (ECRH) mirror plasma, exceeding collisional loss by factors of 10–1000. This loss increases sharply with rf power, scaling as P_{rf}^2 relative to collisions. This is due in part to the increase in field strength, for which a linear scaling with P_{rf} is shown, and in part to the change in plasma parameters produced by larger powers. The rf-induced endloss depends strongly on magnetic field and peaks at low field when the nonrelativistic ECRH resonance is located near the mirror peak.

Electrons in a mirror-confined, electron cyclotron resonance heated (ECRH) plasma diffuse in velocity-space, and may cross the loss-cone boundary and be lost, due to electric fields arising from collisions and rf waves. It has been shown both theoretically¹⁻⁴ and experimentally^{3,5} that the rf-induced loss can exceed collisional loss in such a plasma. However, the diffusion of relativistic electrons in a steady-state ECRH plasma, where the electrons are well above the adiabatic barrier to rapid diffusion,^{1,6,7} is not well-understood. A key measurement of diffusion in such a device is the measurement of endloss, for endloss is directly related to the flux of electrons across the loss-cone boundary in velocity-space. In this letter we present endloss measurements made in three experiments on the Constance B mirror, which illustrate the factors which play a role in this process. The first experiment investigates the overall dependence of steady-state endloss on ECRH power, in which case the plasma parameters change with power. The second experiment singles out the dependence on the rf electric field strength by studying the endloss from plasmas which are created with the same initial parameters, but are subsequently given a second pulse of rf which is of variable power. The third experiment investigates the dependence on ECRH resonance position by varying the mirror magnetic field strength; this is important since it is likely that the variation of rf-induced endloss with magnetic field strength will be the most sensitive test of theoretical models.

Constance B is an R=2 ECRH mirror with a single baseball coil.⁸ A 10.5 GHz klystron launches up to 4 kW of ECRH power into the chamber. The diagnostics include a microwave interferometer, diamagnetic loops, soft and hard x-ray detectors, gridded electrostatic endloss analysers capable of discriminating against electrons up to 5 keV in energy, and scintillator probes which are used to measure the endloss power of electrons above the 50 keV range energy of the aluminum entrance window.

The soft and hard x-ray measurements have produced time-resolved plasma bremsstrahlung spectra for photon energies from 2 keV to 1.5 MeV. These spectra identify a hot electron component which, for 1 kW of ECRH power, is heated at a constant rate of 450 keV/s and reaches a steady-state temperature of $T_h = 400$ keV. The gridded endloss analysers identify a cold, Pastukhov-confined electron component with $T_c = 150$ eV. In addition, these analysers suggest the existence of a warm, magnetically confined component with $T_w \approx 2$ keV. This component is micro-unstable and produces rf emission at frequencies below the heating frequency.⁹ The interferometer indicates an average midplane plasma density $n_t = 2.5 \times 10^{11}$ cm⁻³, 50% of which is due to the hot component.

The hot electrons are well above the adiabatic barrier to diffusion,^{6,7} calculated to be at the energy $E = 20$ keV for an electric field strength of 15 V/cm measured outside of the plasma. Three mechanisms are present in this plasma which randomize the relative phase between the hot electron

cyclotron motion and the rf wave to allow diffusion to take place: collisions with neutral atoms, electrons, and ions, multiple resonances, and, when present, rf fields produced by the warm electron microinstability. A hot electron experiences multiple resonances because the resonance condition

$$\omega - l\omega_c - k_{\parallel}v_{\parallel} = 0,$$

where $\omega_c = eB/\gamma mc$, may be satisfied by a single electron at many locations in the mirror with nonzero k_{\parallel} and $l = 1$ and 2 . Thus, a relativistic theory of multi-resonant electron diffusion in the adiabatic regime is required; to our knowledge, no such theory exists in the literature. For this reason, we will limit the following discussion to experimental findings.

Fig. 1 shows the signals relevant to the present discussion. There are two ECRH pulses, which extend from $t = 0.2 - 1.2$ s and again from $t = 1.6 - 1.9$ s. The gas supply is turned off at $t = 1.3$ s so that during the second ECRH pulse only hot electrons are present. Thus, there are three phases: 1) the steady-state phase (which we take from $t = 1.1 - 1.2$ s), 2) the collisional decay phase ($t = 1.2 - 1.6$ s), and 3) the hot electron plasma with a second pulse of ECRH applied ($t = 1.6 - 1.9$ s). We will present data obtained with three experiments. In the first, the first ECRH pulse power is varied. In the second, the plasma is always heated with 2 kW of ECRH power in the first pulse, but the second pulse power is varied. In the third, both ECRH pulses are fixed at 4 kW and the magnetic field is varied. The two measurements of endloss are the diamagnetic loop (DML) decay rate and

the scintillator probe (SP) light current, which is proportional to the power density of electrons impinging upon it. The DML is circular and located near the mirror field minimum; the SP is located on the axis of the machine just outside of the mirror field maximum.

Fig. 2 shows results from the first experiment. In this case the plasma parameters change with heating power. The power loss during the heating phase exceeds the collisional loss by factors of 10–1000 for the range of powers studied. The losses in the steady-state phase are due to both applied rf fields and rf fields produced by the warm electron microinstability.⁹ Fast digitization of the SP signal indicates that the microinstability, which occurs in 5 μ s bursts every 500 μ s, accounts for 25–50% of the hot electron endloss. Both the steady-state and collisional losses satisfy power-law scaling relations: the steady-state loss scales with ECRH power as $P_{rf}^{3.2}$ and the collisional loss scales as $P_{rf}^{1.2}$.

Fig. 3 displays the results of the second experiment. There is no warm plasma present during the second pulse, and therefore no microinstability rf fields,⁹ so that the rf-enhancement of the endloss in the second pulse is due to the applied rf alone. In this case, the loss scales linearly with P_{rf} , whether measured by the DML decay or the SP signal. A linear dependence on P_{rf} is also predicted by quasi-linear theory,² but the assumptions of that theory are invalid for the super-adiabatic electrons of this experiment. At this point, the agreement seems coincidental. The positive value of the DML

decay rate for zero second pulse power is the collisional decay rate $\nu_c \approx 0.3$ s⁻¹. The SP signal remains at the collisional level for $P_{rf} \leq 0.3$ kW. This effect has been seen on all experiments of this type: there is no enhanced loss of electrons with $E > 50$ keV for very low values of P_{rf} . The existence of a threshold power is a key result which must be predicted by a successful theory of rf diffusion. Note that the DML decay rates during the second pulse exceed the collisional decay rates by a much smaller margin than do the corresponding SP signals. This is an indication that the electrons with lower energies, which contribute to the DML signal, have smaller rf-induced losses relative to collisions than do the electrons with $E > 50$ keV. This has also been seen with the SP: when the experiment was repeated with an aluminum entrance window on the SP with a range energy of 150 keV, it was found that almost all of the collisional loss was from electrons with energies between 50 and 150 keV, whereas 80% of the rf-induced loss was from electrons above 150 keV. The endloss energy distribution is clearly an important measurement; such measurements are currently being performed, and will be reported at a later date.

Fig. 4 shows the results of the third experiment. The rf-induced endloss is measured during the second pulse, when the microinstability is not present. The range of magnetic fields shown is that in which a plasma is produced. In this experiment, the resonance locations, hot electron temperature, and plasma profile change, and it is difficult to say which produces

the dominant effect. It can be concluded, however, that the rf-induced endloss depends strongly on mirror magnetic field strength, and is largest relative to collisional loss for low magnetic fields at which the nonrelativistic resonance is near the mirror field maximum.

We conclude from these experiments that rf-induced endloss is the dominant hot electron loss mechanism in ECRH mirror plasmas. The first experiment shows that the steady-state loss scales as P_{rf}^2 relative to collisions, and the second experiment shows that a linear scaling with P_{rf} occurs when the plasma parameters are held constant, with no rf-enhanced loss of electrons with $E > 50$ keV occurring for powers below a threshold power of 0.3 kW. Finally, we have found a strong dependence on magnetic field, with the rf-induced endloss peaking relative to collisional endloss at low fields when the nonrelativistic resonance is near the mirror peaks.

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References

- ¹A.J. Lichtenberg and G. Melin, *Phys. Fluids* **16**, 1660 (1973).
- ²I.B. Bernstein and D.C. Baxter, *Phys. Fluids* **24**, 108 (1981).
- ³M.E. Mauel, *Phys. Fluids* **27**, 2899 (1984).
- ⁴A.J. Lichtenberg, M.A. Lieberman, J.E. Howard, and R.H. Cohen, *Phys. Fluids* **29**, 1061 (1986).
- ⁵H. Boehmer, H. Goede, and S. Talmadge, *Phys. Fluids* **28**, 3099 (1985).
- ⁶F. Jaeger, A.J. Lichtenberg, and M.A. Lieberman, *Plasma Physics* **14**, 1073 (1972).
- ⁷M.A. Lieberman and A.J. Lichtenberg, *Plasma Phys.* **15**, 125 (1973).
- ⁸D.L. Smatlak et. al., MIT Plasma Fusion Center report in progress.
- ⁹R.C. Garner, M.E. Mauel, S.A. Hokin, R.S. Post, and D.L. Smatlak, submitted to *Phys. Rev. Lett.*

Figures

FIG. 1. Time evolution of: a) SP light current (proportional to hot electron endloss power density), b) DML flux, c) line density, d) unstable rf, e) 10.5 GHz rf (both are rf power incident upon a waveguide located inside the chamber), and f) H_2 gas pressure. The ECRH power (4 kW in this case) is applied in square wave from $t = 0.2 - 1.2$ s and again from $t = 1.6 - 1.9$ s. The midplane vacuum magnetic field $B_0 = 3.2$ kG.

FIG. 2. Hot electron endloss vs. heating power as measured by SP current. The points represent averages from $t = 1.1 - 1.2$ s for the steady-state case, and from $t = 1.4 - 1.5$ s for the collisional case, with straight-line fits of $y \propto x^{3.2}$ and $y \propto x^{1.2}$, respectively. $B_0 = 3.2$ kG.

FIG. 3. Rf-induced loss vs. second pulse power as measured by a) DML decay rate and b) SP current. The SP points are averages from $t = 1.7 - 1.8$ s and the DML decay rates are the slope of a least-squares fit to $\ln(\text{DML})$ between $t = 1.7$ s and $t = 1.8$ s. The error bars represent shot-to-shot variation. The initial plasma is formed with 2 kW of heating power, and $B_0 = 3.2$ kG.

FIG. 4. The ratio of rf-induced loss to collisional loss vs. midplane vacuum magnetic field B_0 as measured by a) DML decay rate and b) SP current. The rf-induced part is taken from $t = 1.7 - 1.8$ s (second pulse) and the collisional part from $t = 1.4 - 1.5$ s. Both ECRH pulses are at 4 kW.

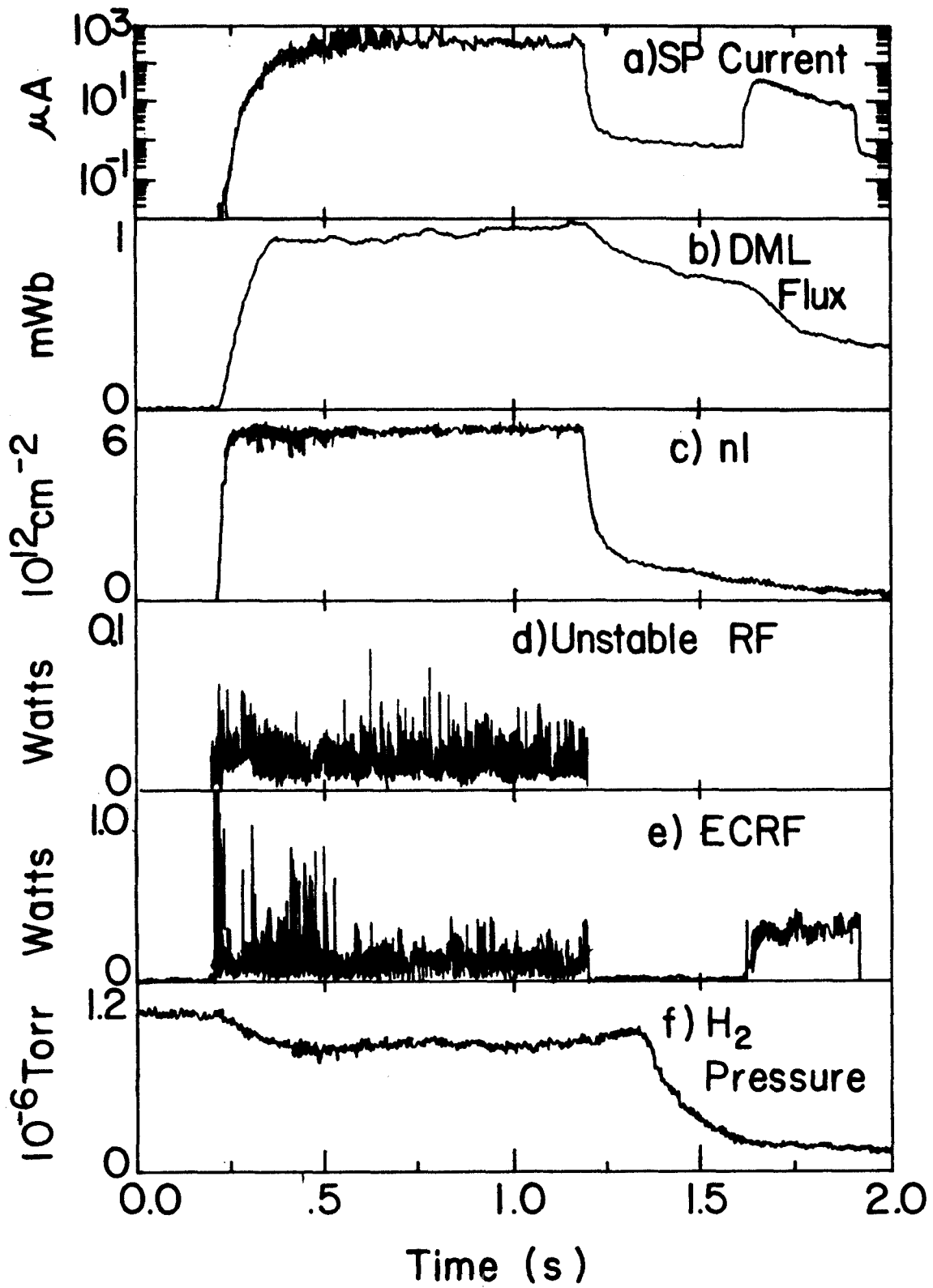


FIGURE 1.

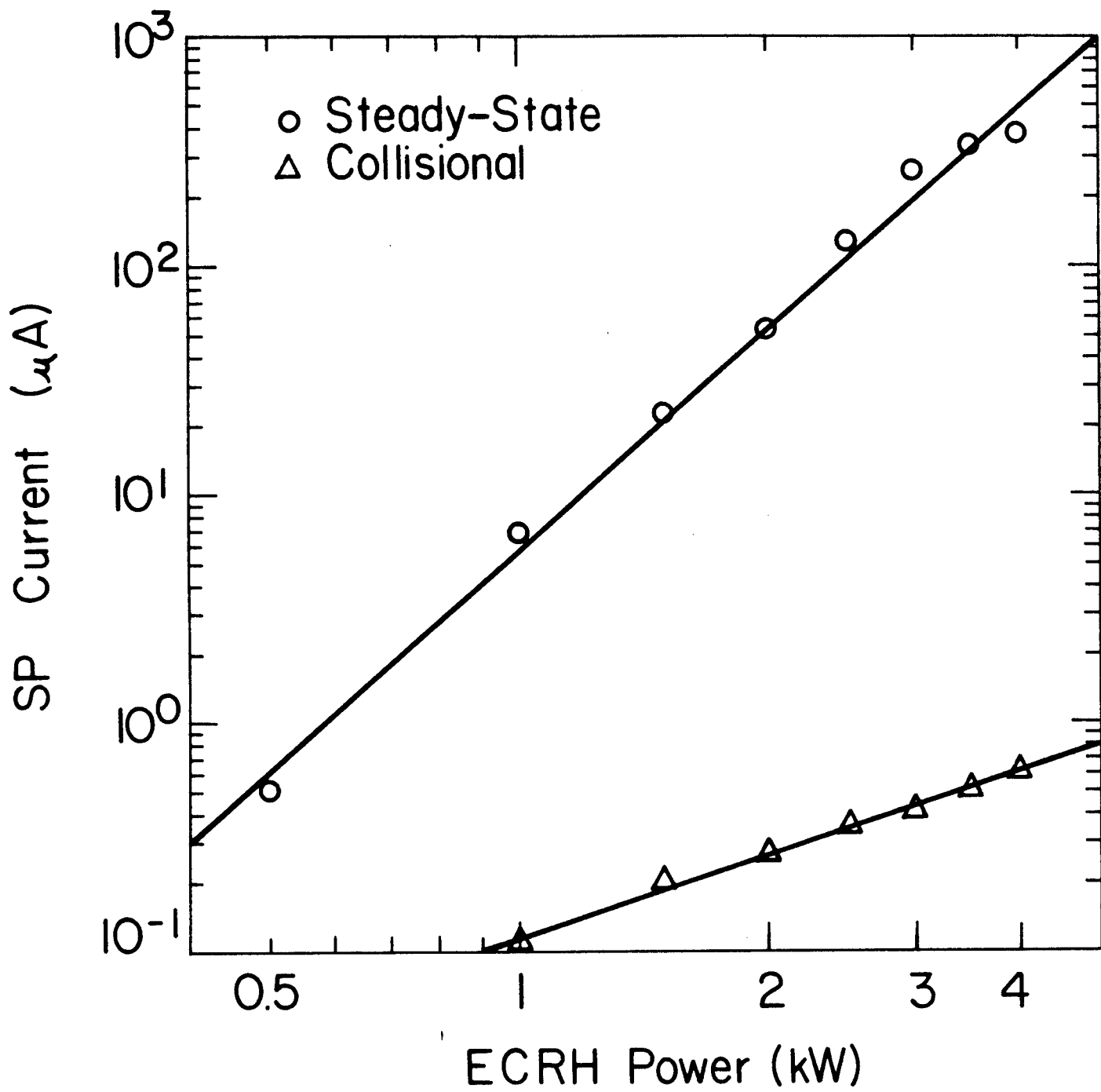


FIGURE 2.

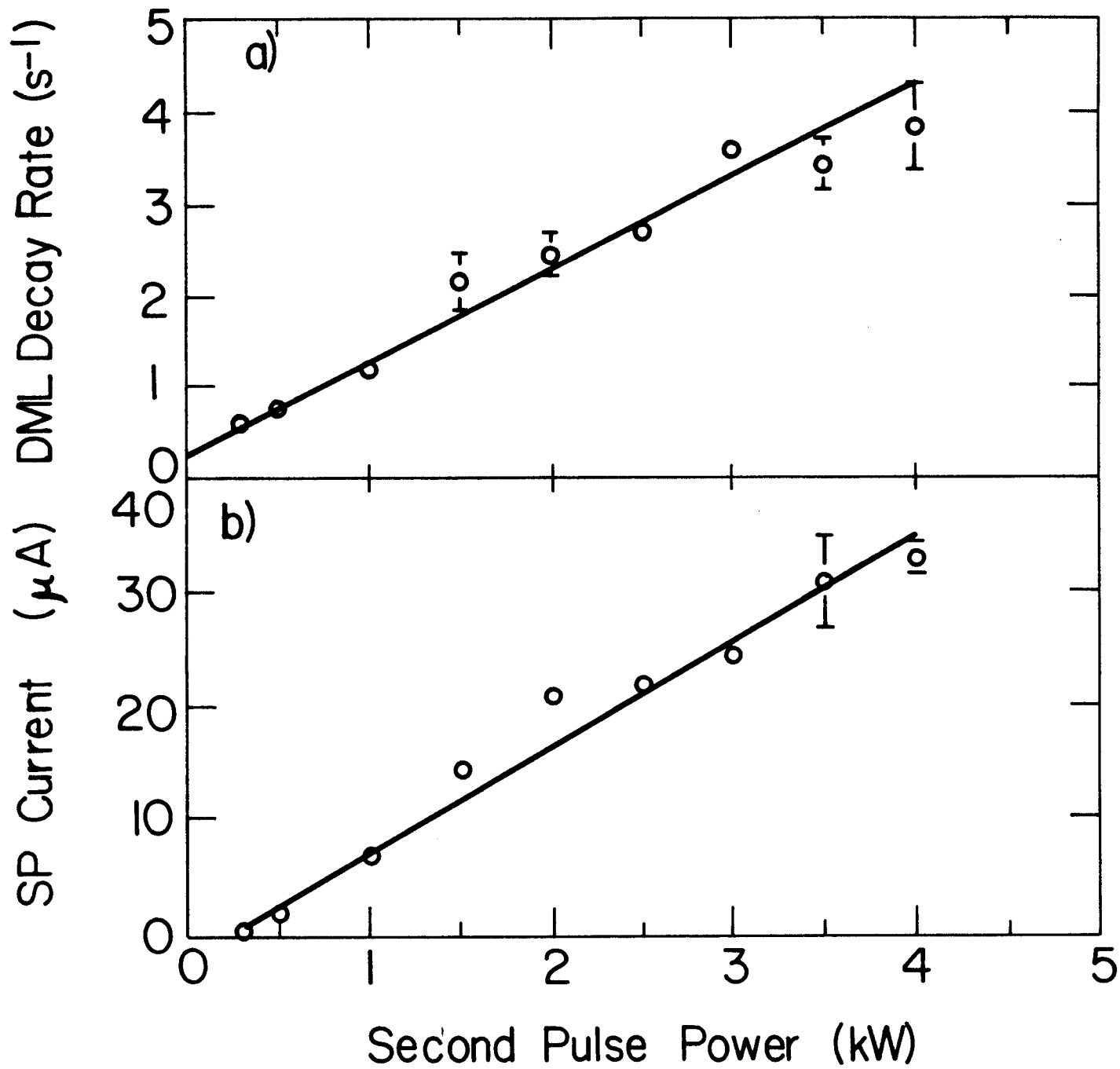


FIGURE 3.

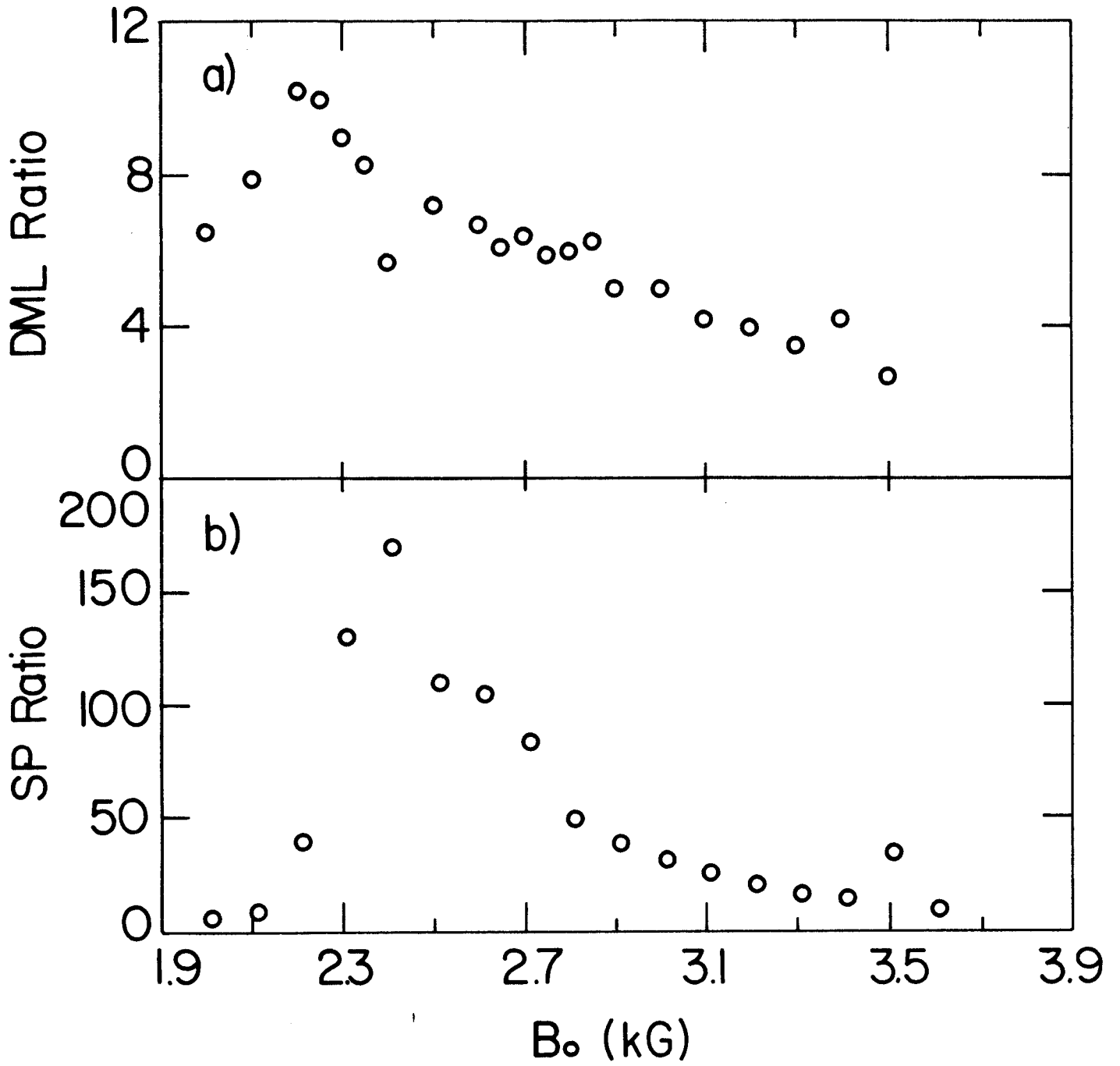


FIGURE 4.