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Abstract

It is shown experimentally that the lower-hybrid current drive "density limit" is a function of the rf source frequency. While in previous 800 MHz experiments this limit occurred at $\overline{n}_e = 6 \times 10^{12}\,\mathrm{cm}^{-3}$, with a newly installed 2.45 GHz, 100 kW rf system on the Versator II tokamak fully rf-driven discharges have been achieved at densities up to $\overline{n}_e = 1.0 \times 10^{13}\,\mathrm{cm}^{-3}$, without increasing the toroidal magnetic field ($B \leq 13\,\mathrm{kG}$, $\omega_{pe}^2/\omega_{ce}^2 > 1$). Incremental current increases in ohmically heated discharges have been observed at densities exceeding $\overline{n}_e = 2.0 \times 10^{13}\,\mathrm{cm}^{-3}$.

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Lower-hybrid current drive experiments in recent years have demonstrated quasi-steady-state sustainment of toroidal plasma currents in tokamaks with no assist from the ohmic heating (OH) transformer.[1,2] The rf-driven currents are generated when momentum is transferred to resonant superthermal electrons from unidirectionally traveling slow waves. Because such waves can be launched from phased arrays of waveguides, lower-hybrid current drive is attractive for applications to toroidal reactor devices. However, before useful extrapolation of present-day results can be carried out, certain discrepancies between experimental observations and theory must be resolved. In particular, the steady state current drive efficiency, $\eta = nIR/P$, where n is the density, I is the rf-generated current, R is the major radius, and P is the injected rf power, is predicted to scale approximately independently of density.[3] While this scaling has been confirmed experimentally over substantial density intervals,[2] nearly every experiment to date has encountered a "density limit": namely, above a critical density the current drive efficiency suddenly decreases and current drive effects disappear.[4] To summarize, efficient lower-hybrid current drive is observed only when $\omega/\omega_{LH} > 2$, where $\omega_{LH} = \omega_{pi}/(1 + \omega_{pe}^2/\omega_{ce}^2)^{1/2}$.[5,6]

In previous OH-assisted 800 MHz experiments on Versator,[4] the current drive density limit occurred at $\overline{n}_e \simeq 6 \times 10^{12}\,\mathrm{cm}^{-3}$. The PLT 800 MHz density limit in H_2 occurs at a similar value,[1] namely $\overline{n}_e \simeq 8 \times 10^{12}\,\mathrm{cm}^{-3}$. Recently, higher frequency lower-hybrid experiments have demonstrated quasi-steady-state current drive at higher densities.[2,6] However, in these experiments the toroidal magnetic field tends to increase with frequency and density so that the dielectric constant remains relatively low ($\omega_{pe}^2/\omega_{ce}^2 \sim 0.2$), and low-$n_\parallel$ waves remain accessible to the plasma core. Consequently, the variation of the current drive density limit with frequency for a given device and magnetic field has not been explored. Furthermore, the physical mechanism responsible for the "density limit" is not well understood.[6] In this letter, we report the first direct experimental comparison of the lower-hybrid current drive density limit at two different frequencies, namely 800 MHz and 2.45 GHz. The experiments were carried out on the MIT Versator II tokamak ($R = 40.5\,\text{cm}$, $a = 13\,\text{cm}$, $B \leq 15\,\text{kG}$).[4] Fully rf-driven discharges, with the ohmic heating primary open-circuited, have been achieved at densities up to $\overline{n}_e = 1.0 \times 10^{13}\,\text{cm}^{-3}$ with 80 kW of net injected rf power at a frequency of 2.45 GHz. The toroidal magnetic field has remained in the same range as that used in the earlier 800 MHz experiment. Therefore, in the present experiments the parameter $\omega_{pe}^2/\omega_{ce}^2$ has exceeded unity, and the density limit has been raised by nearly a factor of two.

For the 2.45 GHz current drive studies, a new 100 kW, 40 ms rf system was constructed. Up to 95 kW of net rf power has been coupled to the tokamak plasma through an outside port with a 4-waveguide array antenna (waveguide dimensions are $1.0\,\text{cm} \times 8.64\,\text{cm}$). With the antenna phased at +90°, the Brambilla rf power spectrum decreases nearly monotonically from $n_{\|} = ck_{\|}/\omega = 1$ to $n_{\|} = 5$, with 75% of the total power launched in the direction of the initial electron ohmic drift (positive $n_{\|}$ direction). The spectrum of the 2.45 GHz antenna is nearly identical to that of the 800 MHz 4-waveguide side-launch antenna used earlier.[4] Optimal coupling to the plasma is achieved for +90° phasing, with reflectivities typically 5 - 10% for $\overline{n}_e \geq 6 \times 10^{12}\,\text{cm}^{-3}$.

In earlier Versator 800 MHz current drive studies, the plasma current was sustained by a combination of rf and inductive ohmic current drive.[4] The rf generated currents were inferred from the incremental current increases and loop voltage drops observed during rf injection. Recently, the OH system has been modified to allow the primary circuit to be opened prior to the injection of rf power. With the OH primary open-circuited, the plasma current decays typically on a time scale of $\tau_{L/R} \sim 15\,\mathrm{ms}$, inducing a positive loop voltage. When sufficient 2.45 GHz rf power is injected at densities $\bar{n}_e \leq 1.0 \times 10^{13}\,\mathrm{cm}^{-3}$, the current decay is arrested and the plasma current is maintained at a constant level with zero loop voltage [see Fig. 1]. For the "flat-top" discharge shown in Fig. 1, 17 kA of current was maintained for 15 ms with 78 kW of 2.45 GHz rf power. The density, $\bar{n}_e = 1.0 \times 10^{13}\,\mathrm{cm}^{-3}$, is 70% above the 800 MHz density limit. Microwave interferometric density profile measurements indicate that $n_e(0) > 1.4 \times 10^{13}\,\mathrm{cm}^{-3}$. Since the toroidal field decays during the rf pulse from an initial value of 11.0 kG to a final value of 9.2 kG, this implies that the parameter $\omega_{pe}^2(0)/\omega_{ce}^2(0)$ increases from 1.1 to 1.7 during the rf pulse, a record value for a fully rf-driven discharge. Correspondingly, the minimum $n_{\|}$ value accessible to the plasma core ($n > 1 \times 10^{13}\,\mathrm{cm}^{-3}$), increases from $n_{\|} = 2.3$ to $n_{\|} = 2.6$. We note that for a given $n_{\|}$ value, accessibility is worse for a higher frequency wave, and accessibility also becomes worse at higher densities and/or lower toroidal fields (higher values of $\omega_{pe}^2/\omega_{ce}^2$).[6] Hence, accessibility is expected to be worse for the 2.45 GHz discharge in Fig. 1 than for the lower density 800 MHz rf-driven discharges.[4] In spite of this, the current drive density limit has been raised substantially by increasing the frequency of the rf source.

In order to determine the 2.45 GHz current drive efficiency, $\eta = nIR/P$, data from flat-top discharges with densities in the range $\bar{n}_e = (0.2 - 1.0) \times 10^{13}\,\mathrm{cm}^{-3}$ has been plotted in Fig. 2. In Fig. 2(a) the product of the line-averaged density $\bar{n}_e$ and the rf-driven current I is plotted versus the injected rf power P, while in Fig. 2(b), I/P versus $\bar{n}_e$ is shown. Both plots are consistent with the efficiency scaling of Fisch,[5] with $\eta = .0072\,(10^{20}\,\mathrm{m}^{-3})(\mathrm{kA})(\mathrm{m})/(\mathrm{kW})$ (shown by the solid curves). All of the data here was obtained in H_2 discharges, at an average toroidal field of 10–12 kG, and with +90° relative waveguide phasing. Flat-topping is also possible, though 5–10% less efficient with +60° and +120° phasings; other phases (including −90°) produce substantially less rf current, as expected, and to date flat-topping the toroidal plasma current has not been possible.

The plasma hard x-ray emission has been measured with a collimated 3" × 3" NaI scintillator detector before and during quasi-steady-state 2.45 GHz current drive. The detector is located below the tokamak where it views the center of the plasma along a vertical chord aimed at a recessed top port. This configuration, along with sufficient lead shielding, effectively eliminates any background x-ray flux from the tokamak walls and limiters. As shown in Fig. 3, for current drive discharges at $\bar{n}_e = 7 \times 10^{12}\,\mathrm{cm}^{-3}$, the level of x-ray emission from the plasma is negligible in the 7 ms period before the application of the rf pulse. The injection of 85 kW of rf power generates an energetic electron tail extending to at least 200 keV, which corresponds to a minimum value for the resonant wave spectrum of $n_{\parallel} = 1.4$. The slope of the spectrum ($\sim 20\,\mathrm{keV}$) remains nearly constant during the quasi-steady-state discharge.

In addition to sustaining currents at constant levels with 2.45 GHz rf, it has also been possible to ramp up the plasma current, with negative loop voltage, at densities $\bar{n}_e \leq 7 \times 10^{12}\,\mathrm{cm}^{-3}$. Ramp-up rates as high as 190 kA/s, for periods up to 15 ms (limited by the vertical field system), have been recorded at a density of $\bar{n}_e = 7 \times 10^{12}\,\mathrm{cm}^{-3}$.

The efficiency of converting rf energy to poloidal field energy was $\eta = 0.06 \pm 0.02$, where $\eta \equiv \Delta(\frac{1}{2}LI^2)/(P_{rf}\Delta t)$, with $L = L_{int} + L_{ext}$. The uncertainty in the efficiency lies in the determination of the internal inductance from equilibrium measurements, since for these discharges $\beta_\theta \sim \ell_i/2$. Nevertheless, this level of efficiency is consistent with the ramp-up theory of Fisch and Karney.[7]

Because of the relatively low 2.45 GHz rf power level available to date ($P_{net} \leq 95\,\mathrm{kW}$), rf current flat-top and ramp-up discharges have been restricted to densities at or below $\bar{n}_e = 1 \times 10^{13}\,\mathrm{cm}^{-3}$. At higher densities, with the OH primary open-circuited, current drive is still observed as evidenced by reduced plasma current decay rates, loop voltage drops, and increases in the $2\omega_{ce}$ emission. As shown in Fig. 4(a), the plasma current decay rate ($-dI/dt$) increases approximately linearly with density up to $\bar{n}_e = 1.7 \times 10^{13}\,\mathrm{cm}^{-3}$. At still higher densities, the incremental current increase ΔI, due to rf injection into ohmically heated plasmas, has been measured as a function of density [see Fig. 4(b)]. While ΔI decreases with density over the range $(1.4 - 2.5) \times 10^{13}\,\mathrm{cm}^{-3}$, there is no sudden disappearance of current drive effects at any particular density. In Fig. 4(c), $2\omega_{ce}$ emission data from the discharges with the OH primary open-circuited (dots) are combined with data from the OH-assisted discharges (triangles) to form a continuous curve from $\bar{n}_e = 1.0 \times 10^{13}\,\mathrm{cm}^{-3}$ to $2.5 \times 10^{13}\,\mathrm{cm}^{-3}$. The data indicate qualitatively that current drive effects (i.e., suprathermal electron tails) are still present at densities at least three and possibly four times the 800 MHz density limit. The fact that current drive effects at the highest densities are so small is attributed to the low rf power level available and to poor accessibility ($\omega_{pe}^2(0)/\omega_{ce}^2(0) > 3$).

From the 2.45 GHz results presented in this work, we can conclude that the 800 MHz density limit is not due to the inaccessibility of low-$n_{\|}$ waves to the plasma center. Since the $n_{\|}$ spectra launched from the 800 MHz and 2.45 GHz antennas are similar, and since the toroidal field was the same for each frequency, the penetration of the higher frequency waves at higher densities is expected to be worse. This analysis is confirmed by ray tracing calculations which include toroidal wave propagation effects. We may also conclude, from the x-ray measurements, that the 800 MHz density limit cannot be due to the disappearance of a preformed electron tail above a critical density. Fully rf-driven discharges with the 2.45 GHz system have been achieved with negligible levels of hard x-ray emission ($E_\gamma > 20\,\mathrm{keV}$) from the initial ohmic target plasma, indicating that operation in the low density "slideaway" regime[8] is not a necessary condition for lower-hybrid current drive. Furthermore, slideaway phenomena during current drive should not depend on the driving frequency, especially in the present experiment where the launched wave spectrum was the same for both 2.45 GHz and 800 MHz.

In summary, by raising the rf driving frequency from 800 MHz to 2.45 GHz, the current drive density limit has been increased at least by a factor of three in the Versator II tokamak. t these densities $\overline{\omega_{pe}^2}/\omega_{ce}^2 \geq 1$. As a consequence of these results, several theoretical models of the current drive density limit may be eliminated. The most likely remaining explanation of the density limit is a shift of strong rf interaction from electrons to ions, either due to parametric instabilities [9,10] or due to quasilinear ion Landau damping.[10] Experimental investigations of ion tail production and parametric excitation at both 800 MHz and 2.45 GHz will be carried out in the near future.

Acknowledgments

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Figure Captions

Fig. 1. Typical shot of a fully rf-driven 2.45 GHz discharge at $\bar{n}_e = 1.0 \times 10^{13}\,\mathrm{cm}^{-3}$ with the OH primary open-circuited.

Fig. 2. "Flat-top" rf discharge ($\dot{I}_p \simeq 0, V_L \simeq 0$) efficiency plots for H_2, $\Delta\phi = +90°$, $B \simeq 1.0$–$1.2\,\mathrm{T}$: (a) I/P vs. $\bar{n}_e$, (b) $\bar{n}_e I$ vs. P. Solid curves: $\eta = .0072\,(10^{20}\,\mathrm{m}^{-3})(\mathrm{kA})(\mathrm{m})/(\mathrm{kW})$.

Fig. 3. Hard x-ray emission along the central vertical chord measured before and during 2.45 GHz rf-driven discharges with $\bar{n}_e \simeq 7 \times 10^{12}\,\mathrm{cm}^{-3}$, $P = 85\,\mathrm{kW}$, $\Delta\phi = +90°$.

Fig. 4. (a) dI/dt vs. $\bar{n}_e$, with and without rf power ($75 - 90\,\mathrm{kW}$), for discharges with the OH primary open-circuited, (b) incremental current increrase ΔI (5 ms into the rf pulse) vs. $\bar{n}_e$ for OH-sustained discharges, $P_{rf} = 75 - 90\,\mathrm{kW}$, (c) cyclotron emission $I_{2\omega_{ce}}$ vs. $\bar{n}_e$ for the discharges in a) dots and b) triangles.

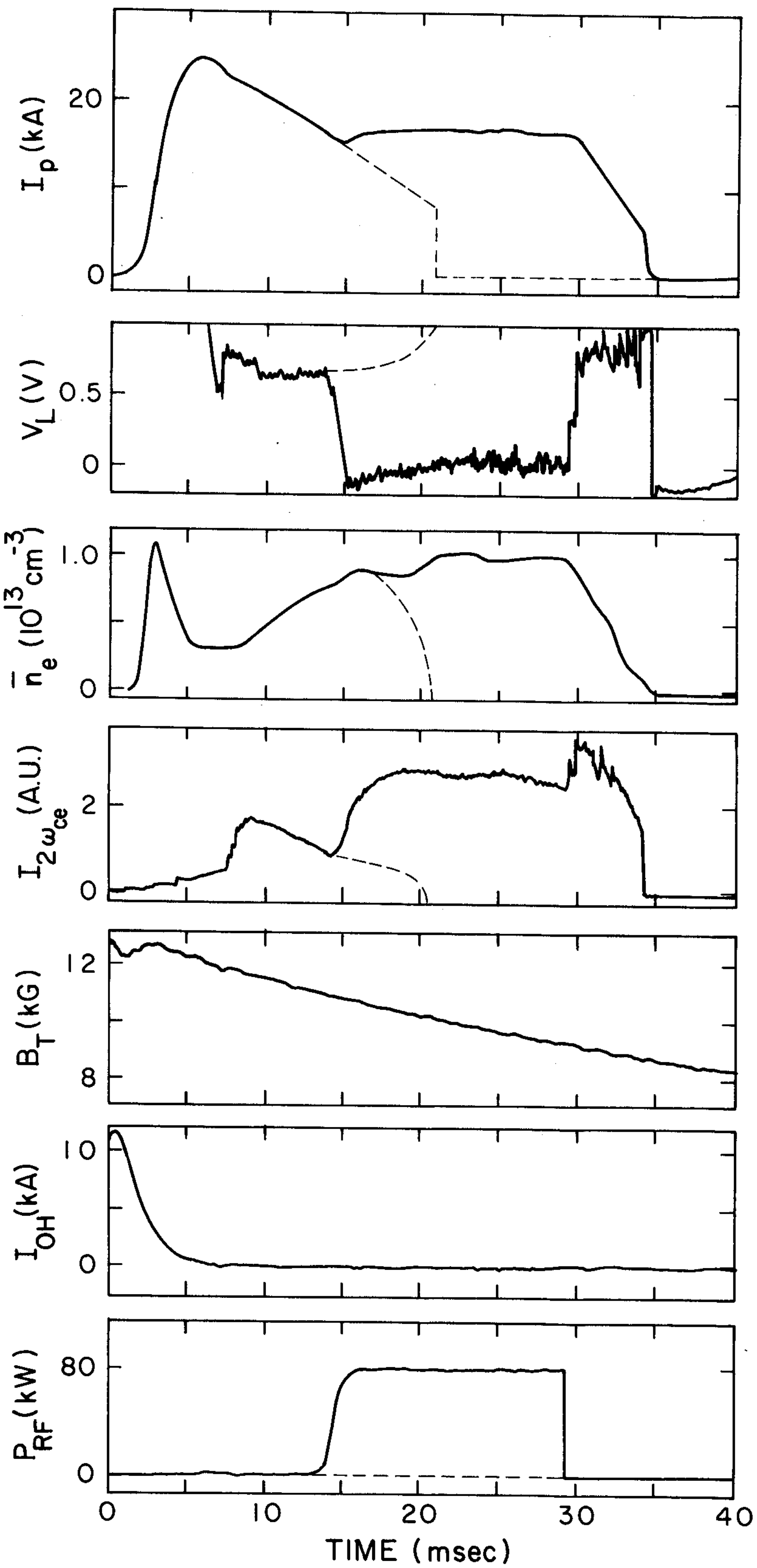

Fig. 1
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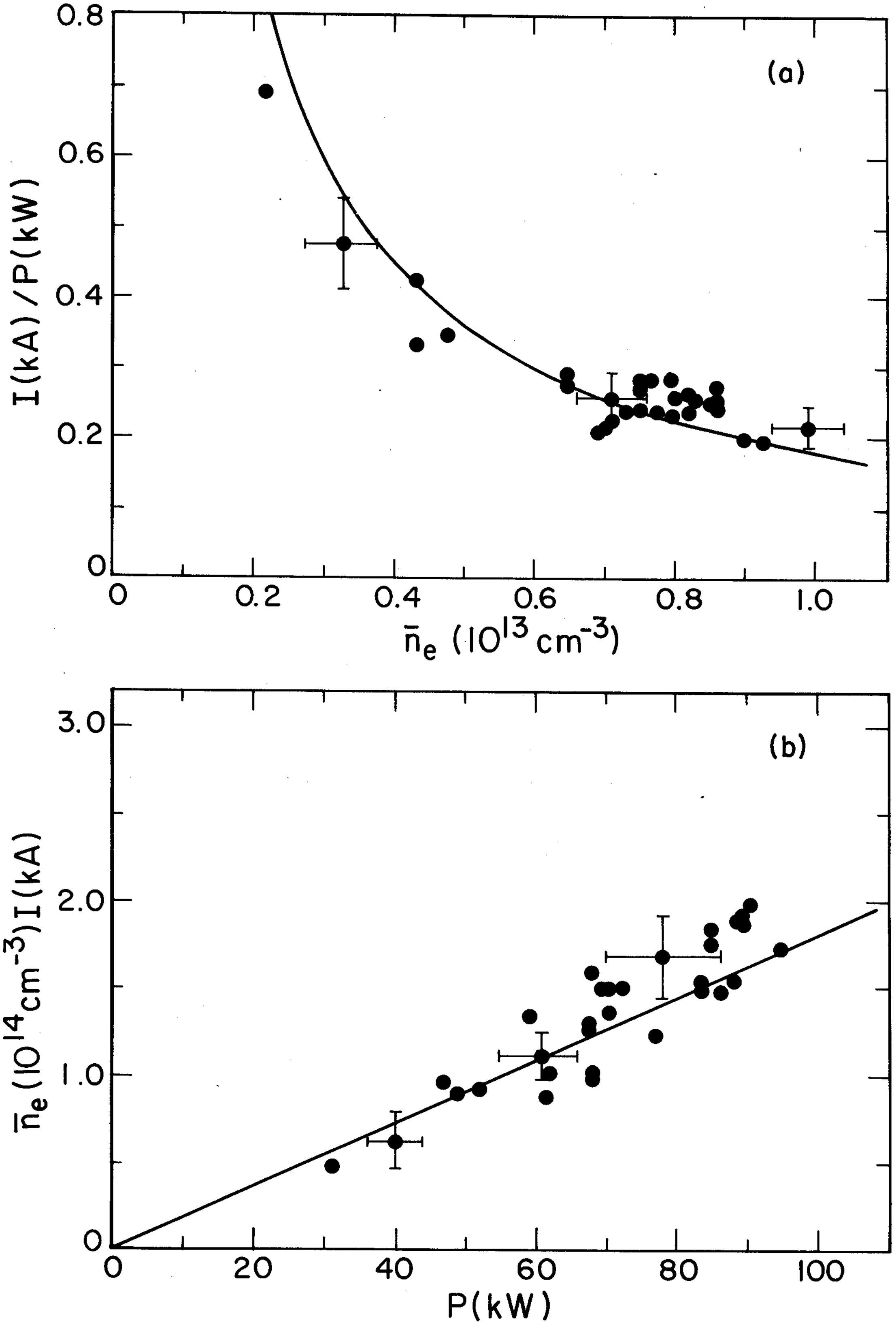

Fig. 2
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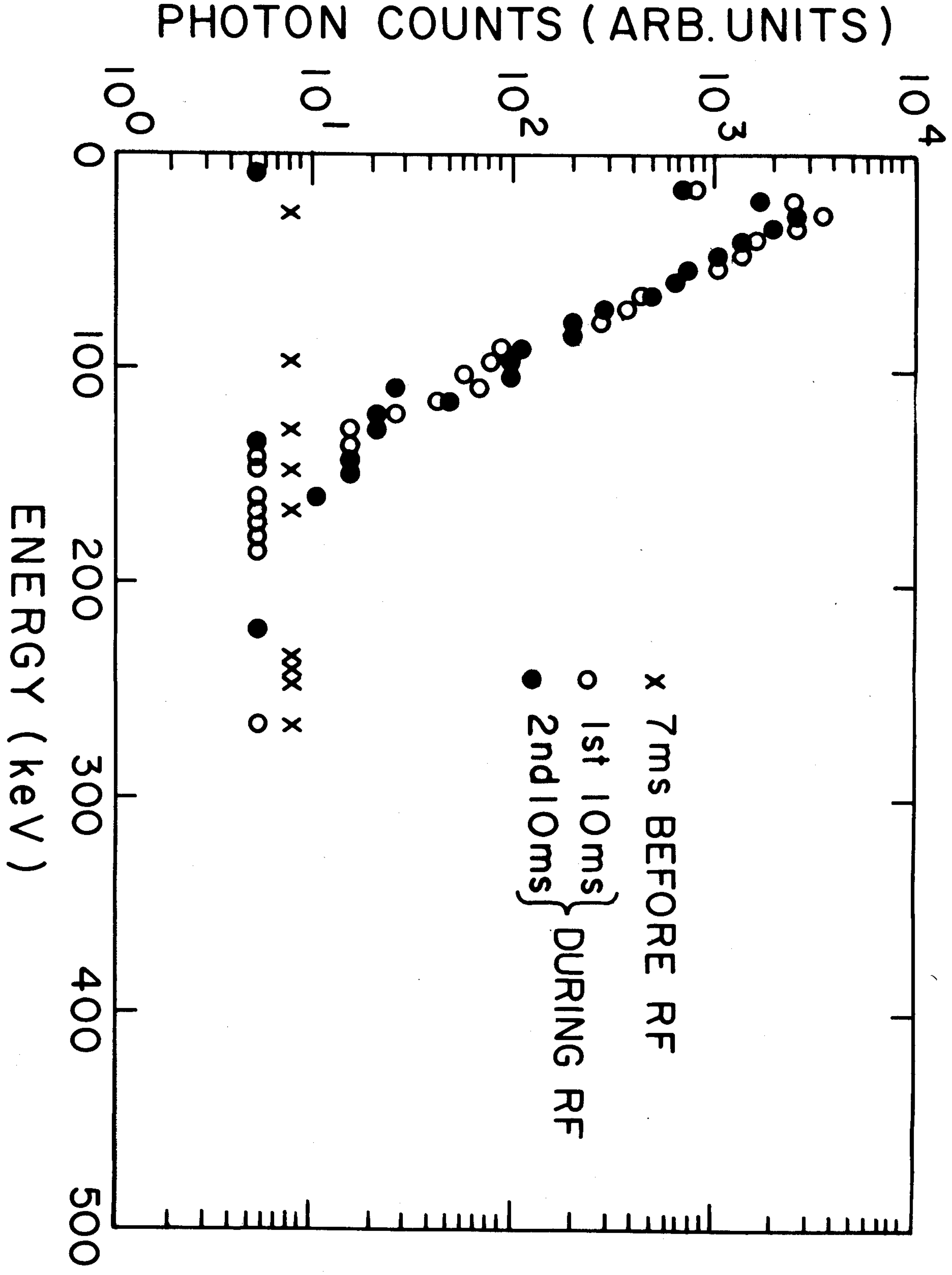

Fig. 3
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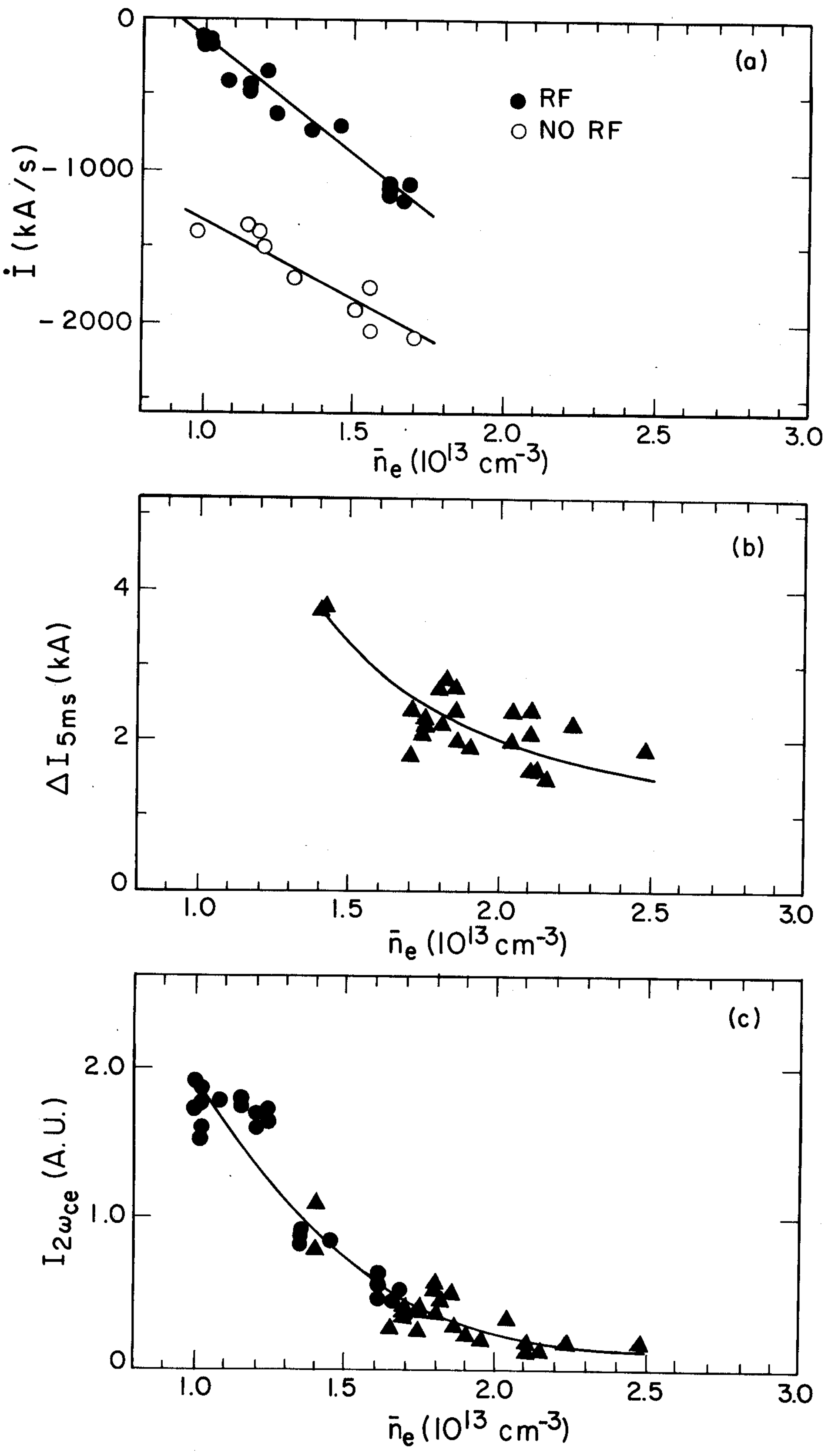

Fig. 4
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