PFC/JA-88-26

A High Power, 600 μm Wavelength Free-Electron Laser

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June 1988

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This work was supported by the Air Force Office of Scientific Research and the National Science Foundation.

Submitted for publication in: Physical Review Letters.

A HIGH POWER, 600 μm WAVELENGTH FREE ELECTRON LASER*

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Abstract

We report high power emission (18 MW) at a wavelength of $\lambda = 640\,\mu$m and a bandwidth $\Delta\lambda/\lambda < 0.04$ from a superradiant free electron laser (FEL) excited by a 2 MeV, 1 kA electron beam. Comparison of the experiment with a nonlinear simulation yields good agreement. Theoretical extrapolation to a tapered wiggler experiment shows that power levels of $\sim$ 140 MW could be achieved with an efficiency of $\sim$ 7%.

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The outstanding capabilities of free electron lasers (FEL) are their high power outputs, reasonable efficiencies and wavelength tunability. In this paper we present what we believe is the highest power output (18 MW) and highest efficiency ($\sim 1\%$) in a wavelength regime[1-3] ($\sim 600\,\mu$m) that has not been studied extensively.

The experimental arrangement is shown in Fig. 1. The Pulserad 110A accelerator ($V = 2$ MV, $\tau \simeq 30$ ns) energizes a multielectrode field emission electron gun[4] which produces a high current, low emittance electron beam ($I \sim 900$ A, $\Delta V/V < 0.005$). A thin solenoid lens focusses the electron beam into a 0.79 cm radius stainless steel evacuated drift tube which also acts as an overmoded circular waveguide for the radiation. A bifilar helical wiggler magnet (with periodicity $\lambda_w = 3.14$ cm) is wound onto the outside of the stainless steel drift tube. An adiabatic entrance taper is provided by a series of resistive termination loops[5] which gradually tap current from one winding to the other. A second thin solenoid lens focusses the electron beam entering the drift tube to a beam waist such that the electron beam is matched into the helical wiggler field. The electron beam is then transported and focussed through the wiggler interaction region by means of the focussing provided by the strong helical wiggler magnetic field. In contrast to many previous FELs operated at relatively low beam energies and high currents,[1,2,6,7] there is no applied axial guiding magnetic field in the wiggler interaction region.[8]

The radiated output power is measured with a combination of a Spectra-Physics model 360001 Joule-calorimeter and a Laser Precision model 1540S pyroelectric pulse detector. The total output energy is measured with the calorimeter. Wavelength filters (conducting meshes used in reflection) limit the wavelength range observed by the calorimeter to $330\mu\,\mathrm{m} < \lambda < 1000\,\mu$m. The pulse shape of the output radiation is measured with the pyroelectric detector. The output power is calcu-

lated by dividing the measured output energy by the time (FWHM) of the radiation pulse. An output power of 18 MW at the FEL operating wavelength of 640 μm has been measured under single pass, superradiant operation.

The growth rate $\Gamma = (1/P)dP/dz$ of the electromagnetic wave is obtained[6] by measuring the output power as a function of the wiggler interaction length z. This length is varied by moving a transverse kicker magnet along the length of the wiggler, thereby turning the electron beam into the drift tube wall and terminating the interaction. The data, shown in Fig. 2, for two different wiggler strengths B_w, clearly show the regions of exponential gain and, in the case of the stronger wiggler field, the region of saturation[9] of the FEL.

The observations are compared with a theoretical analysis of the experimental configuration based on the nonlinear simulation code ARACHNE[10]. This simulation numerically integrates a set of coupled nonlinear differential equations which govern the evolution of an arbitrary number of transverse electric (TE) and/or transverse magnetic (TM) waveguide modes as well as an ensemble of electrons. The analysis is fully three-dimensional and self-consistently includes the overlap of the electron beam and the radiation field of each mode. The electron trajectories are integrated using the complete Lorentz force equations in the presence of a three-dimensional representation of the helical wiggler field, and includes the effects of betatron oscillations and velocity shear on the interaction. Neither self-field nor space-charge effects are included in the simulation, which is valid in the strong-pump Compton regime of operation. The collective dielectric effect of the beam upon the waveguide modes is included self-consistently in the analysis. For the data shown in Fig. 2, the measured power gains of 56 ± 3 dB/m for $B_w = 1275$ G and 70 ± 6 dB/m for $B_w = 1510$ G are consistent with the results of the ARACHNE code for a beam

temperature of $\Delta V/V \sim 0.0025$. This is the effective temperature at full width (and $1/e$ point) due to nonzero beam emittance, and is in good agreement with the measured beam emittance which gives $\Delta V/V < 0.005$ (our resolution limit).

The spectrum of the output radiation is measured with a grating spectrometer[11]. The measured spectrum for a 2.3 MV, 930 A electron beam, at a wiggler field strength of 1275 G is shown in Fig. 3, along with the calculated spectrum from ARACHNE. The measured spectral width is approximately $\Delta\lambda/\lambda \sim 0.04$. The observed wavelength corresponds predominantly to the excitation of the lowest (TE_{11}) mode of the circular waveguide, with a small TM_{11} component ($< 5\%$).

In conclusion, the measured output power of 18 MW at the measured frequency of 470 GHz represents an order of magnitude increase in the available power for any FEL source operating in the $\sim 600\,\mu$m wavelength regime. The corresponding efficiency of 0.8% represents a two order of magnitude increase in efficiency for an FEL operating in this wavelength regime.[1-3] Increasing the wiggler field amplitude from 1275 G to 1510 G yields an output power of 25 MW for the same wiggler length. Inspection of Fig. 2 shows that this output power might be increased even further in the 1510 G case by terminating the beam earlier.

We note that simple *one-dimensional* criteria[12] suggest that the experiments described above are in the so-called collective (Raman) regime where RF space charge effects cannot be neglected in general. Nonetheless, the ARACHNE simulation (which neglects space charge effects) is in very close agreement with the experimental observations. This suggests that for out experiment three-dimensional effects lead to a substantial reduction in the magnitude of the space charge fields and their effect on the interaction.

Previous experiments have noted substantial increases in efficiency when the wiggler field amplitude is tapered[13,14] . An example of the possible effect of tapering the wiggler field amplitude in this experiment is shown in Fig. 4, where the ARACHNE simulation is extended in the axial direction, for both a tapered and an untapered wiggler. The parameters for the simulation shown in Fig. 4 are identical to those in Fig. 3 used in comparison with our experiments. As can be seen in the figure, for the case of the tapered amplitude wiggler, the output power reaches a maximum of 142 MW, corresponding to a 6.6% efficiency. Maintaining the parameters of the electron beam constant, but changing the wiggler period to $\lambda_w = 2.2$ cm and the initial wiggler field amplitude to $B_w = 3100$ G(to provide more latitude in the tapering process), results in a maximum possible output power of 263 MW at a frequency of 498 GHz.

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Figure 1. The schematic layout of this experiment, and typical voltage, beam current, and microwave output waveforms.

Figure 2. Observed output power as a function of wiggler length, for two different wiggler pump strengths, $B_w = 1275\,\mathrm{G}$, and $B_w = 1510\,\mathrm{G}$. $V = 2.0\,\mathrm{MV}$, $I = 780\,\mathrm{A}$.

Figure 3. The measured output spectrum for a 2.3 MV, 930 A electron beam; wiggler pump strength $B_w = 1275$ G. The measured output power is $P_{out} = 18\,\mathrm{MW}$.

Figure 4. The output power as a function of wiggler length for a tapered and untapered wiggler as calculated with ARACHNE. The parameters of the simulation are: $V = 2.3\,\mathrm{MV}$, $\Delta V/V = 0.25\%$, $I_b = 930\,\mathrm{A}$, $B_w = 1275\,\mathrm{G}$, $\lambda_w = 3.14\,\mathrm{cm}$, beam radius $= 0.4\,\mathrm{cm}$. The output frequency is 470 GHz. The on-axis amplitude of the wiggler field used in the simulation is shown at the top of the figure.

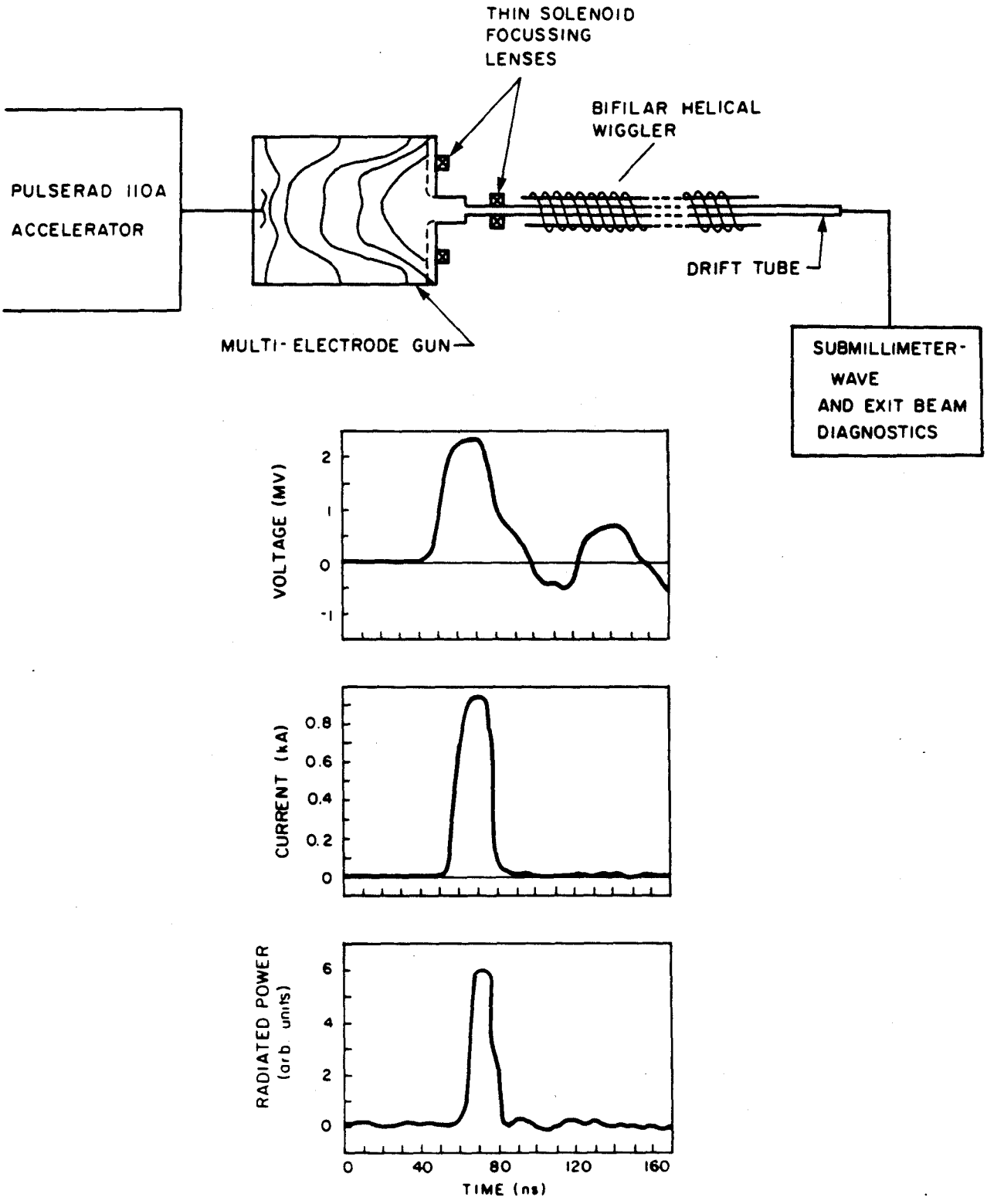

Fig. 1
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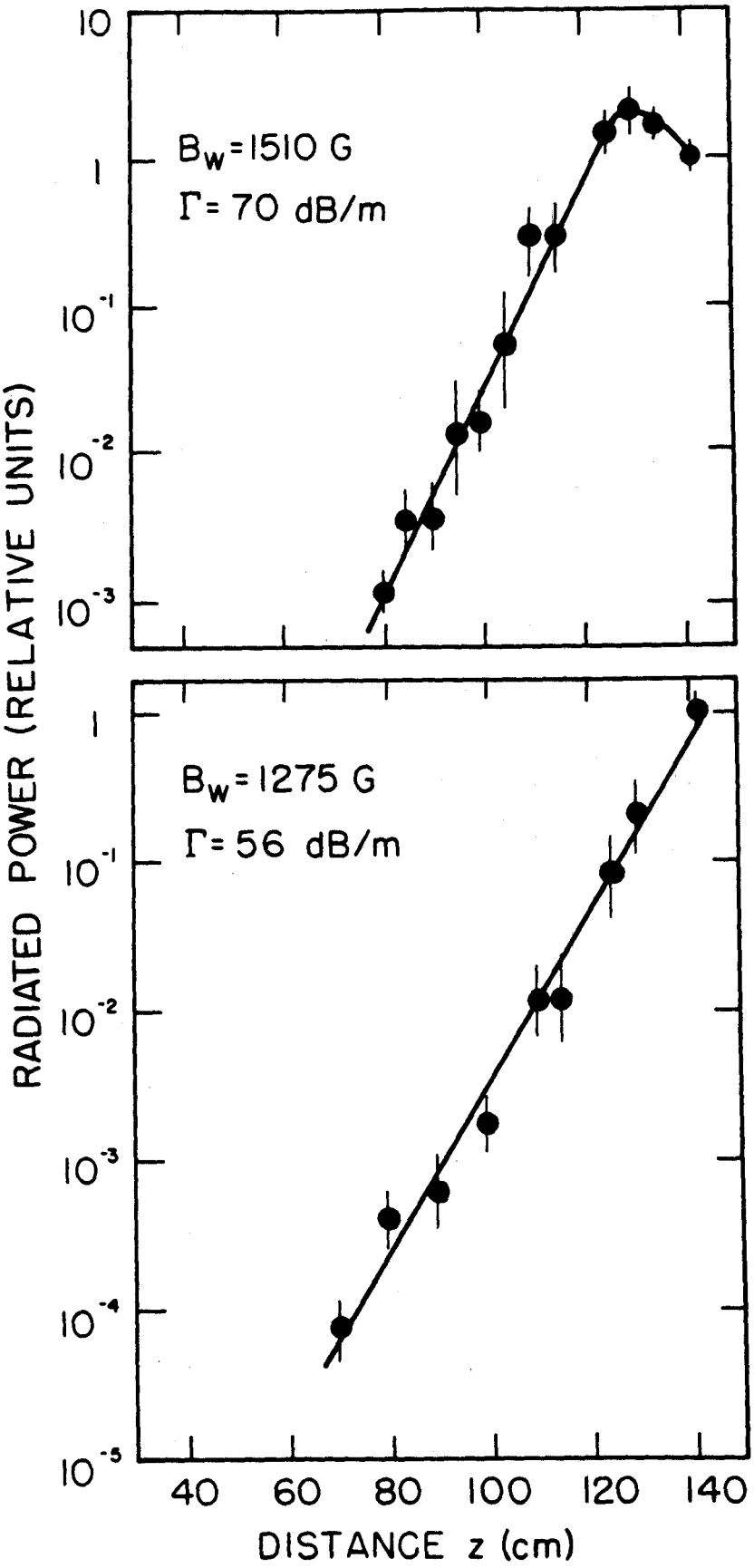

Fig. 2
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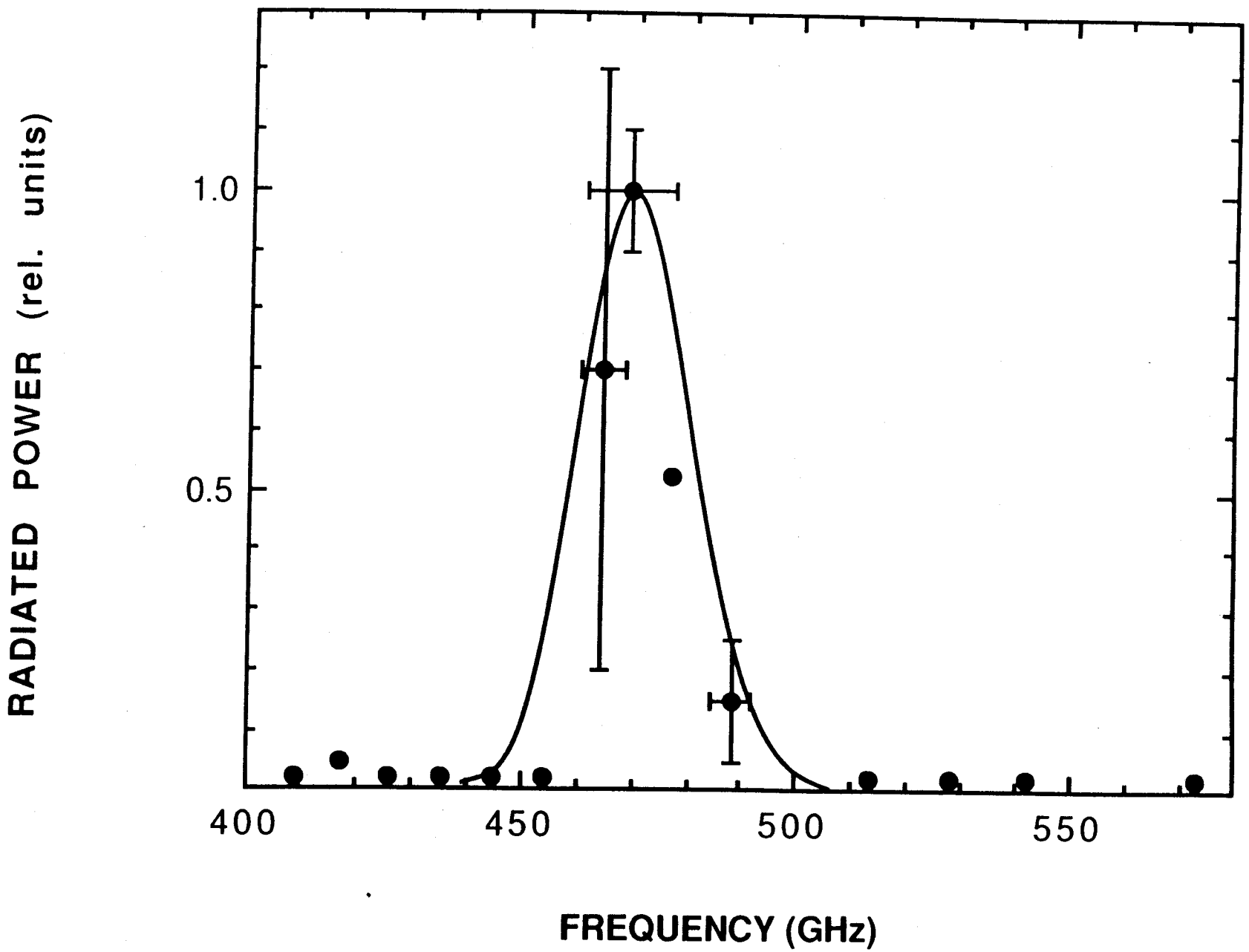

Fig. 3
Kirkpatrick et al

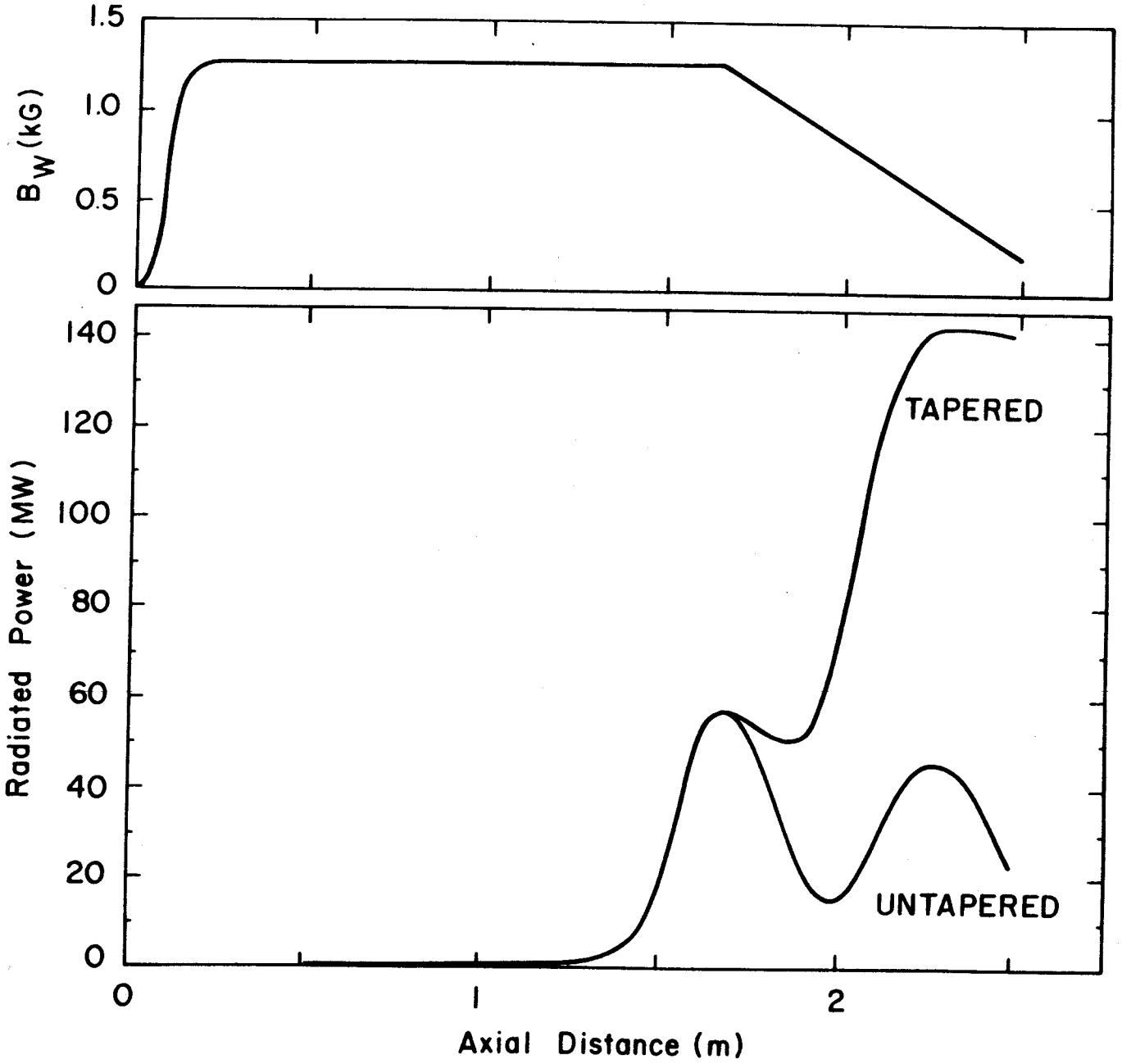

Fig. 4
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