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FREE ELECTRON LASER OR
CYCLOTRON MASER INSTABILITY?

G. Bekefi
J. Fajans

Plasma Fusion Center
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139 USA

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G. Bekefi and J. Fajans

Department of Physics and the Plasma Fusion Center

Massachusetts Institute of Technology

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ABSTRACT

An analysis of recent free electron laser experiments in combined wiggler and strong axial magnetic fields shows that near resonance, $\Omega_{||} = k_w v_{||}$, the proximity of the cyclotron maser instability precludes an unambiguous identification of the radiation mechanism ($\Omega_{||}$ is the cyclotron frequency in the axial field, k_w is the wiggler wavenumber, and $v_{||}$ the axial electron velocity).

Experiments carried out several years ago¹ have shown that extreme caution in data interpretation must be exercised when the electrons of a free electron laser are subjected simultaneously to a periodic wiggler magnetic field and a strong axial guide magnetic field. The reason is that in the neighborhood of the resonance $\Omega_{||} = k_W v_{||}$ the free electron laser^{2,3,4,5} (FEL) and cyclotron maser⁶ (CM) instabilities have similar radiation frequencies; consequently they may coexist and they may be difficult to separate. Indeed, the two instabilities could well be coupled, leading to complicated spectral characteristics. In the above $\Omega_{||} = eB_{||}/m_0 \gamma$ is the relativistic cyclotron frequency in the guide field; $\gamma = (1 - \beta_{||}^2 - \beta_{\perp}^2)^{-\frac{1}{2}}$ is the total relativistic energy factor; $\beta_{||} = v_{||}/c$ with $v_{||}$ as the axial electron velocity and $\beta_{\perp} = v_{\perp}/c$ with v_{\perp} as the transverse velocity induced by the wiggler magnetic field; $k_W = 2\pi/\lambda$ is the wiggler wave number with λ as the wiggler period.

In this note we examine the spectral characteristics of two recent FEL experiments. We find that in the parameter regime where $\Omega_{||}$ is near but slightly above the value $k_W v_{||}$, the proximity of the FEL and CM instabilities precludes an unambiguous identification of the radiation mechanism, unless very careful mapping of relevant parameters is undertaken. In making this assessment we compare experimental radiation characteristics with those predicted by FEL and CM theories.

In the first experiment,^{7,8} shown in Fig. 1, the radiation characteristics are studied near resonance by determining the beam energy γ , necessary to observe radiation of a given fixed frequency (12.33 GHz) as a function of $B_{||}$, with the wiggler field strength B_W held constant (190 G). The solid dots and the vertical lines are from measurements. The vertical lines indicate that in this region of $B_{||}$ and γ , a given frequency is emitted over a broad band of electron energies. This implies that for a given fixed beam energy the radiation would be emitted over a wide frequency band, in accordance with theoret-

However, we prefer the former. It¹⁰ takes cognizance of the fact that the strength of the wiggler field increases radially with distance from the wiggler axis, and that it has an axial component. However, it assumes that all electrons enter the wiggler exactly on axis, and that they then spiral out to helical, axis encircling orbits. Although this model does not take into account the finite electron beam thickness, and non-axis encircling orbits, experiments⁸ and computer simulations¹³ indicate that it yields better agreement with experiment than does 1d theory which neglects radial variations of the wiggler field and its axial field component. The authors of Ref. 11 prefer the 1d theory:¹¹ to simulate 3d effects, they increase the on-axis wiggler field strength by 8%, a correction which is said¹⁴ to represent the field seen by the average, off-axis situated electron.

Figure 3 illustrates frequency tuning obtained by variation of the wiggler field amplitude, observed for six different values of the radiation frequency. The solid curves represent experimental observations.¹¹ Next to each resonant maximum are shown four solid dots, each representing a theoretical prediction. For purposes of clarity, and in order to illustrate general trends, corresponding points are joined by straight lines.

The family of points labelled 1 and 2 represent 3d and 1d FEL theory respectively, for the case of TE_{11} mode excitation. The cross (x) on the bottom spectrum stands for 1d FEL theory of the TM_{01} mode of excitation. The family of points labelled 3 and 4 denote 3d CM Theory, for TM_{01} and TE_{11} mode of excitation, respectively. It is clear from Fig. 3 that in the parameter range explored the predictions of the FEL and CM theories are quite close to one another. The proximity of the two instabilities, combined with the large experimental widths of the resonances makes identification of the radiation mechanism very difficult.

In conclusion then, we find that in a strong axial guide magnetic field

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12. In Ref. 11 the predicted radiation frequency corresponding to the parameters of Fig. 2a was erroneously calculated from Eqs. (5), (6), and (7) to occur at 67 GHz. Similarly, the predicted frequencies of the two spectra of Fig. 2b were erroneously calculated to be at 78 GHz and 96 GHz respectively. The two spectra in Fig. 2c were incorrectly predicted to occur at the same frequencies as the corresponding spectra of Fig. 2b.

CAPTIONS TO FIGURES

- Fig. 1. Beam energy required for radiation of frequency 12.33GHz as a function of the axial magnetic field.^{7,8} Solid curves are from 3d FEL theory, and dashed line is from 3d CM theory, both for the TE₁₁ mode; $k_w=1.904\text{cm}^{-1}$; $B_w=190\text{G}$; TE₁₁ mode cutoff frequency = 6.92GHz.
- Fig. 2. Emission spectra.¹¹ (a) TE₁₁ mode; (b) TM₀₁ mode at left and TE₁₁ mode at right; (c) TM₀₁ mode at left and TE₁₁ mode at right. Solid vertical arrows are from 3d FEL theory, and dashed arrows from 1d FEL theory; $\gamma=3.40$; $k_w=2.094\text{cm}^{-1}$. TE₁₁ mode cutoff frequency = 16.27 GHz; TM₀₁ mode cutoff frequency = 21.25GHz.
- Fig. 3. Frequency tuning by variation of B_w . Solid curves are experiment.¹¹ Points 1 : 3d FEL Theory for TE₁₁ mode. Points 2 : 1d FEL theory for TE₁₁ mode. Points 3: 3d CM theory for TM₀₁ mode. Points 4 : 3d CM theory for TE₁₁ mode. x : 1d FEL theory for TM₀₁ mode. $\gamma=3.40$. $k_w=2.094\text{cm}^{-1}$.

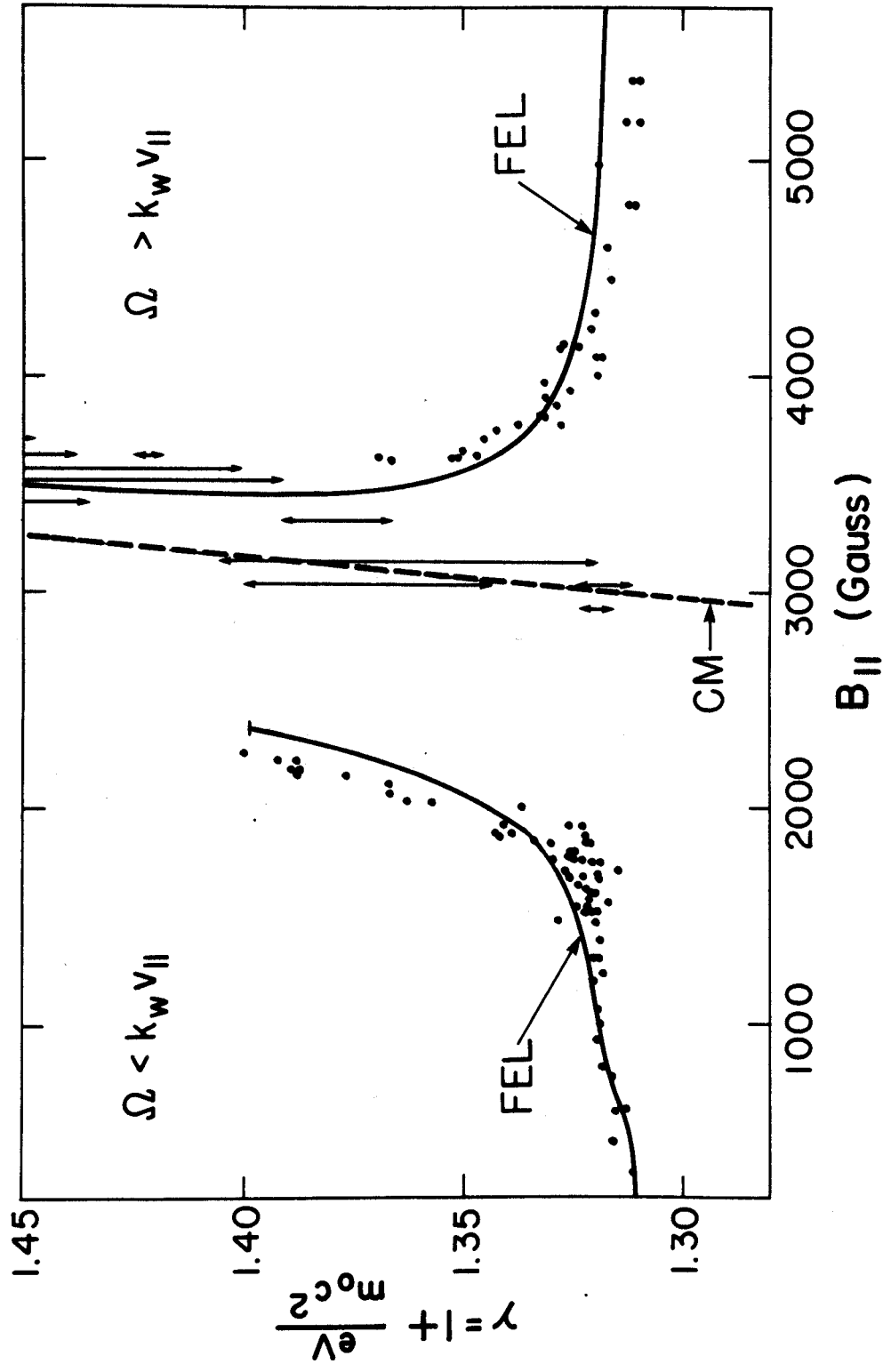


Fig. 1
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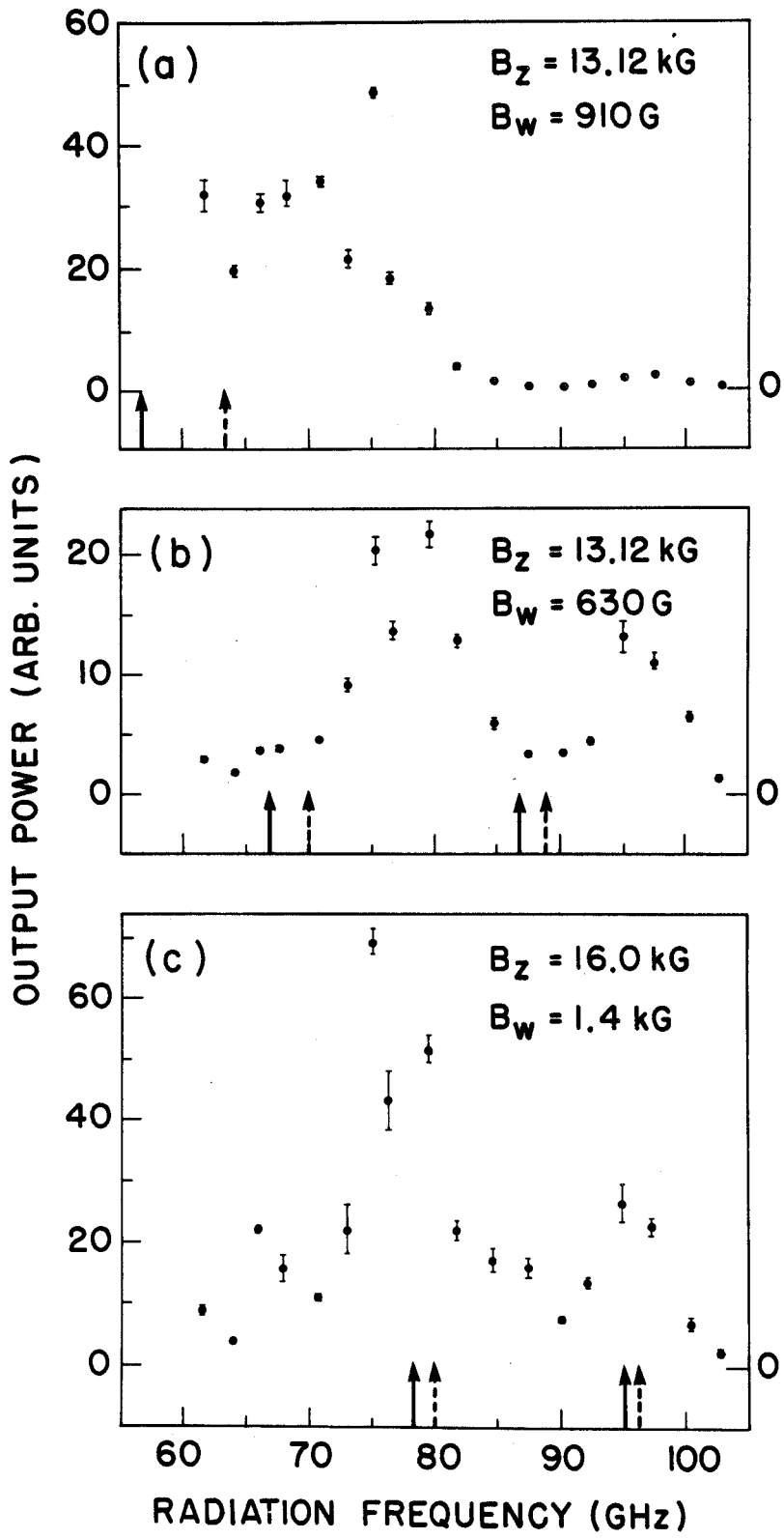


Fig. 2
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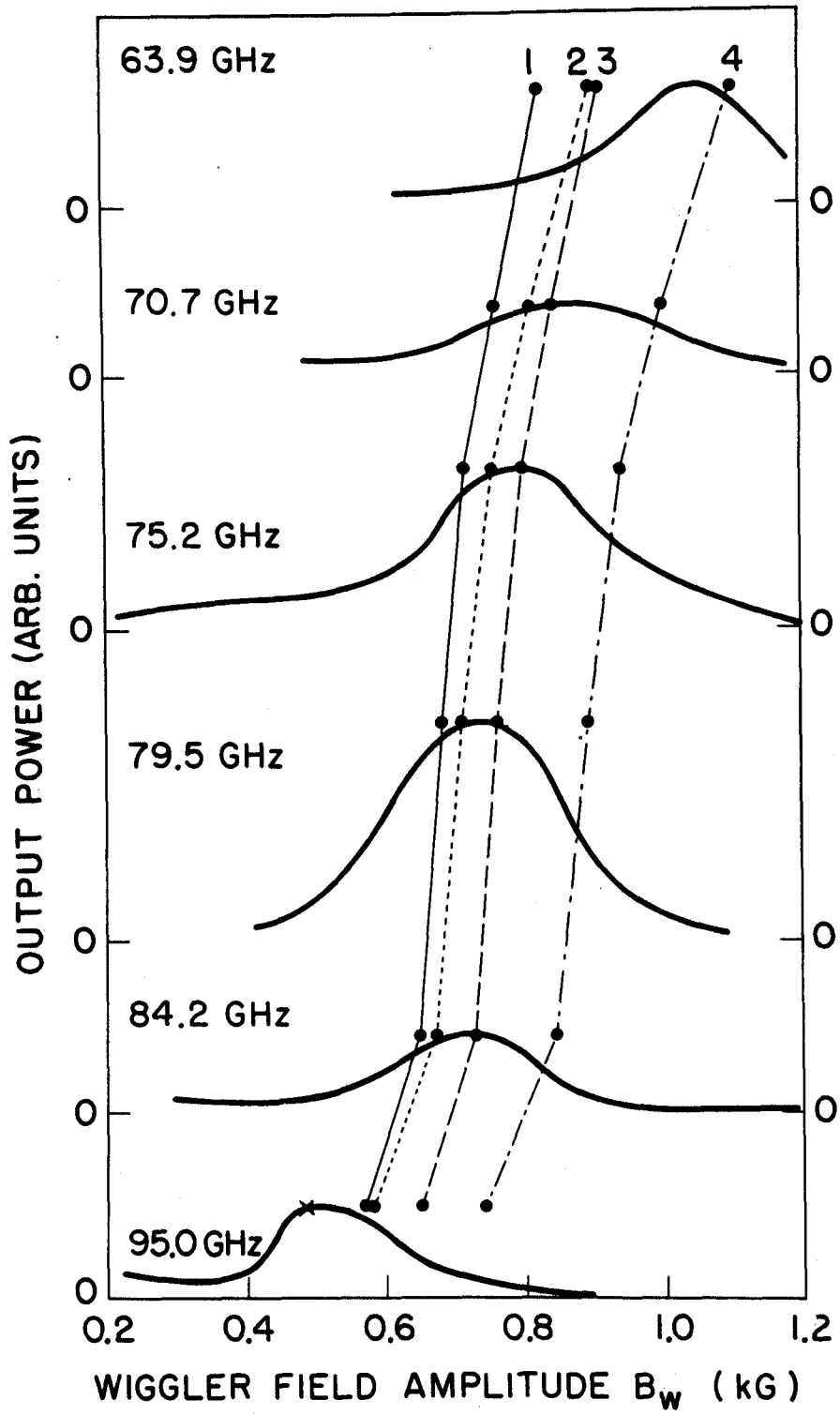


Fig. 3
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