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Lawrence Livermore National Laboratory

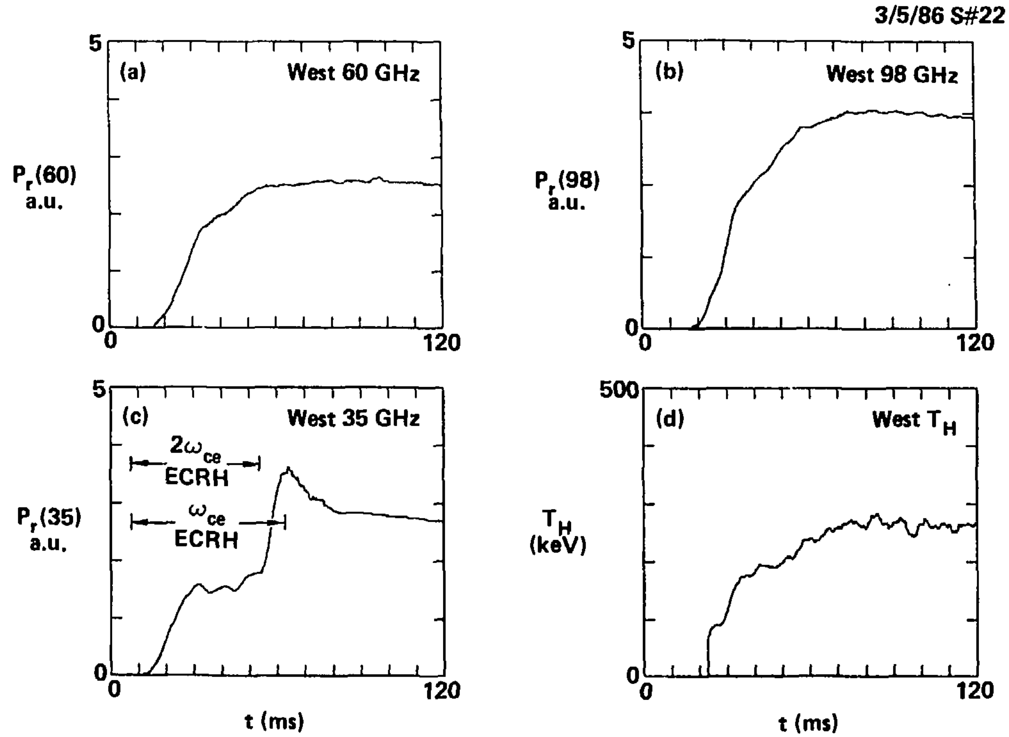
3/5/86 S#22
(a)
West 60 GHz
$P_r(60)$ a.u.
(b)
West 98 GHz
$P_r(98)$ a.u.
(c)
West 35 GHz
$2\omega_{ce}$ ECRH
ω_{ce} ECRH
$P_r(35)$ a.u.
(d)
West T_H
T_H (keV)
5
0
120
500
t (ms)

Figure 3

Optically Thin Perpendicular Electron-Cyclotron

Emission from Hot Electrons in TMX-U

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ABSTRACT

Optically Thin Perpendicular Electron-Cycloton Emission from Hot Electrons in TMX-U.* R. A. James, Lawrence Livermore National Laboratory, C. J. Lasnier and R. F. Ellis, University of Maryland - Perpendicular electron-cyclotron emission (PECE) from relativistic (T_H ~ 100 to 400 keV) hot electrons within the thermal-barrier region of TMX-U is detected at 35, 60, 94 and 98 GHz. For the operating regime of TMX-U these signals are optically thin ($\tau \ll 1$) and thus proportional to the radial hot electron line density. A relativistic code is used to calculate the theoretical temperature dependence of the perpendicular emission coefficient, $j_\perp(\omega, T_H)$, for each of the detected frequencies. This dependence has been verified experimentally by x-ray measurements of the hot electron temperature, T_H. The observed qualitative agreement demonstrates that optically thin PECE signals can be used to determine the temporal evolution of T_H. An inability to absolutely calibrate the present PECE waveguide system has prevented quantitative agreement.

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MASTER

Introduction

Perpendicular electron-cyclotron emission (PECE) is presently being detected from mirror confined hot electrons within the thermal barrier region of the Tandem Mirror Experiment-Upgrade (TMX-U). Measurements are made at 35 GHz (ω/ω_{ce} = 2.5), 60 GHz (ω/ω_{ce} = 4.3), 94 GHz (ω/ω_{ce} = 6.7) and 98 GHz (ω/ω_{ce} = 7.0). This paper discusses the method whereby these signals are used to calculate the time evolution of the hot electron temperature, T_H.

To accomplish this task, a relativistic code[1] has been used to calculate theoretically the temperature dependence of the perpendicular emission coefficient, $j_{\perp}(\omega,T_H)$ for the frequencies of interest. Using this method, we have obtained excellent qualitative agreement between the PECE code predictions and x-ray measurments of T_H.

Received Power

The power captured by the receiving antenna at frequency ω, over a bandwidth $\Delta\omega$ is given by[2]

$$P_r(\omega) = \Delta\omega \int I_\omega(\theta,\phi)\, A(\theta,\phi)\, d\Omega \tag{1}$$

where $A(\theta,\phi)$ is the antenna reception pattern and $I_\omega(\theta,\phi)$ is the radiant intensity.

For a Maxwellian energy distribution, the equation for radiation transfer, in the limit of optically thin emission, becomes:

$$I_\omega = I_{BB}\,(1 - e^{-\tau}) \approx I_{BB}\,\tau \tag{2}$$

where $\tau = \int \alpha(\omega)\, n_H(r)dr \approx \alpha(\omega) \int n_H(r)dr$ is the optical depth, $\alpha(\omega)$ is the absorption coefficient per electron, $I_{BB} = (\kappa T_H)/(2\pi\lambda^2)$ is the black-body intensity per unit frequency, and $n_H(r)$ is the radial hot electron density.

Using Kirchoff's law in the single particle limit, $I_{BB} = j(\omega)/\alpha(\omega)$, and assuming that the temperature is uniform and that the antenna pattern is "filled" by the emission, $\int A(\theta,\phi)d\Omega = \lambda^2$, then for perpendicular emission ($\theta = 90^{\circ}$) we have:

$$P_r(\omega) = \Delta\omega\, \lambda^2\, j_{\perp}(\omega,T_H) \int n_H(r)dr \tag{3}$$

where $j_{\perp}(\omega,T_H)$ is the perpendicular emission coefficient per electron. This power is then attenuated by waveguide losses before being detected by the receivers.

Experimental Comparison with Theory

Experimentally all three frequencies are detected by the same horn antenna and their respective antenna patterns are "filled" by the hot electron emission. Thus, $\int n_H(r)dr$ is the same for each detected frequency. The ratio of powers of any two detected frequencies is then proportional to the ratio of perpendicular emission coefficients, for example:

$$\frac{P_r(94)}{P_r(35)} = C(94/35)\,\frac{j_\perp(94,T_H)}{j_\perp(35,T_H)} \quad ; \qquad (4)$$

where C(94/35) is the ratio of the receiver bandwidths, wavelengths and waveguide attenuations at 94GHz and 35GHz.

Figure 1 shows the theoretical calculation from the PECE code for the perpendicular emission coefficient, $j_\perp(\omega,T_H)$, as a function of temperature, T_H, for the detected frequencies. These calculations are for a Maxwellian distribution in energy with a 45^o loss-cone angle.

Using these curves, the theoretical ratio of perpendicular emission coefficients for two frequencies

$$R_{th}(\omega_1/\omega_2) = \frac{j_\perp(\omega_1,T_H)}{j_\perp(\omega_2,T_H)} \qquad (5)$$

can be calculated as a function of T_H. In Figure 2, the theoretical ratio (right-hand axis) for 94GHz and 35GHz, $R_{th}(94/35)$, is compared to the experimental ratio (left-hand axis):

$$R_{exp} = \frac{j_\perp(94,T_H)}{j_\perp(35,T_H)} = \frac{P_r(94)}{P_r(35)}\;\frac{1}{C(94/35)} \qquad (6)$$

as T_H, a Maxwellian fit to the high energy x-ray spectrum varied from 100 keV to 400 keV. All data pertains to the afterglow plasma, approximately 30ms to 50ms after the second harmonic ($2\omega_{ce}$) ECRH is turned off. While good agreement for the other ratios, $R_{exp}(94/60)$ and $R_{exp}(60/35)$ was obtained, $R_{exp}(94/35)$ is shown as it exhibits the greatest relative change.

The strong qualitative agreement illustrated in Figure 2 demonstrates that the detection of perpendicular electron-cyclotron emission at two optically thin frequencies can be used to determine the temporal evolution of T_H. The systematic difference (factor of 2) is believed to be due to internal wall reflections and an inability to absolutely calibrate the entire waveguide system. These problems will be eliminated by the installation of a quasi-optical focusing mirror and a Macor microwave beam dump[1].

Temporal Evolution of T_H

The temporal evolution of T_H is calculated by using the 60GHz and 98GHz signals, Figure 3a and b. The 35GHz signal, Figure 3c, is not used for this purpose because it exhibits attenuation during the duration of the ECRH pulse. This attenuation is most likely absorption by the "warm" ($T_W \approx$ 10-20 keV) mirror confined electrons that exist during the shot, but which quickly decay after the ECRH is switched off. Their rapid loss, also observed in the x-ray spectrum[3], explains the sharp increase in the 35GHz signal shortly after the end of the ECRH pulse.

To calculate $T_H(t)$, we first calculate the ratio:

$$R_{exp}(98/60)\ (t) = \frac{j_\perp(98,T_H)}{j_\perp(60,T_H)}\ (t) = \frac{1}{C(98/60)}\ \frac{P_r(98)}{P_r(60)}\ (t) \qquad (7)$$

using the detected power at 98GHz and 60GHz, and the estimated waveguide attenuations and receiver bandwidths. This ratio is then normalized by a constant, C^*, such that at t = 100ms this new ratio, $R_{exp}^{norm}(98/60)(t) = C^* R_{exp}(98/60)(t)$, is equal to that predicted by the PECE code but using the afterglow high energy x-ray temperature, T_H^{x-ray}, i.e.,

$$R_{exp}\ (98/60)\ (t = 100ms) = \frac{j_\perp(98, T_H^{x-ray})}{j_\perp(60, T_H^{x-ray})} \qquad (8)$$

Thus $$C = \frac{R_{exp}^{norm}}{R_{exp}}\ (t = 100ms)$$

The normalized ratio, R_{exp}^{norm} (98/60) (t), is then compared to a look-up table (calculated by the PECE code) for $j_\perp(98, T_H)/j_\perp(60, T_H)$ vs T_H over the range 10keV $\leq T_H \leq$ 600 keV. Linear interpolation is used for values that fall between points in the table. Thus, $T_H(t)$, Figure 3d, is generated from the power detected by two optically thin PECE signals.

Acknowledgements

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References

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2. G. Beketi, Radiation Processes In Plasmas (Wiley, New York, 1966) Chaps. 1, 2 and 10.

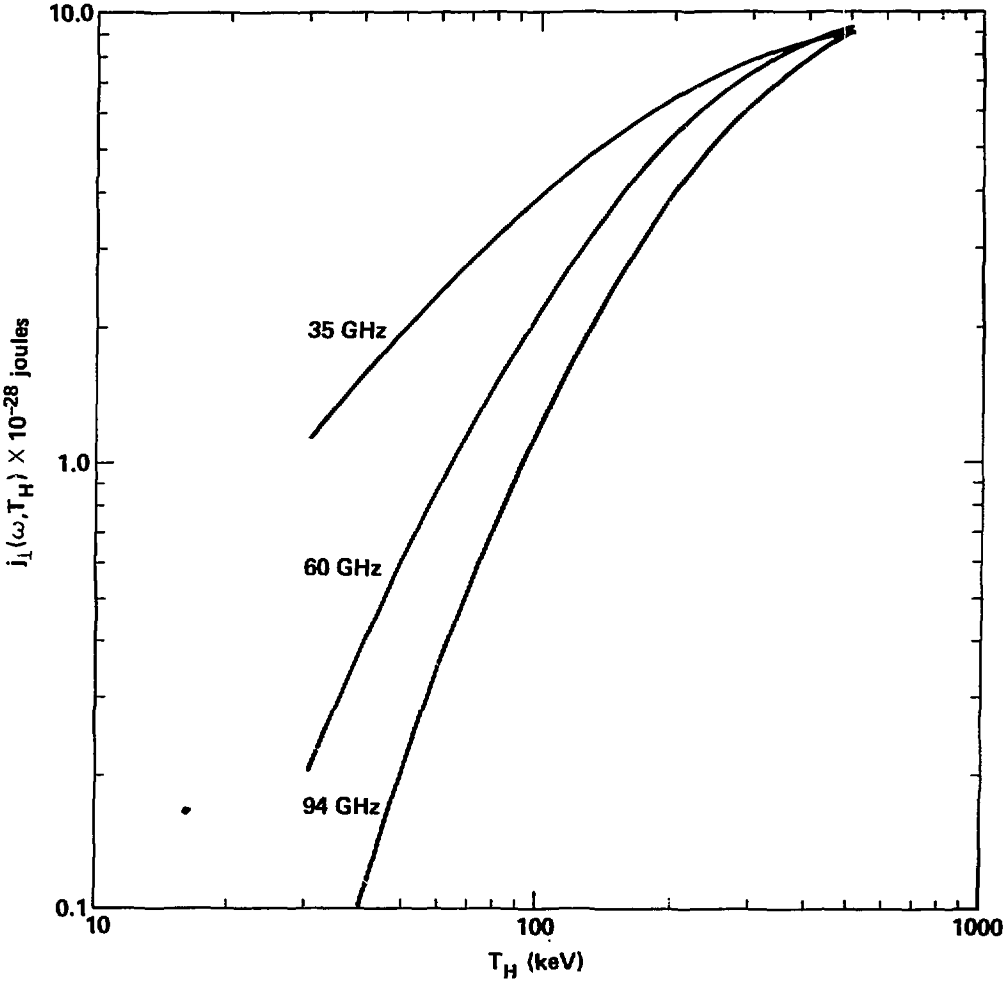
3. E. H. Silver, J. F. Clauser and B. H. Failor (these proceedings).

Figure Captions

Figure 1: PECE code calculations of the perpendicular emission coefficient, $j_\perp(\omega,T_H)$, as a function of T_H for 35, 60 and 94 GHz.

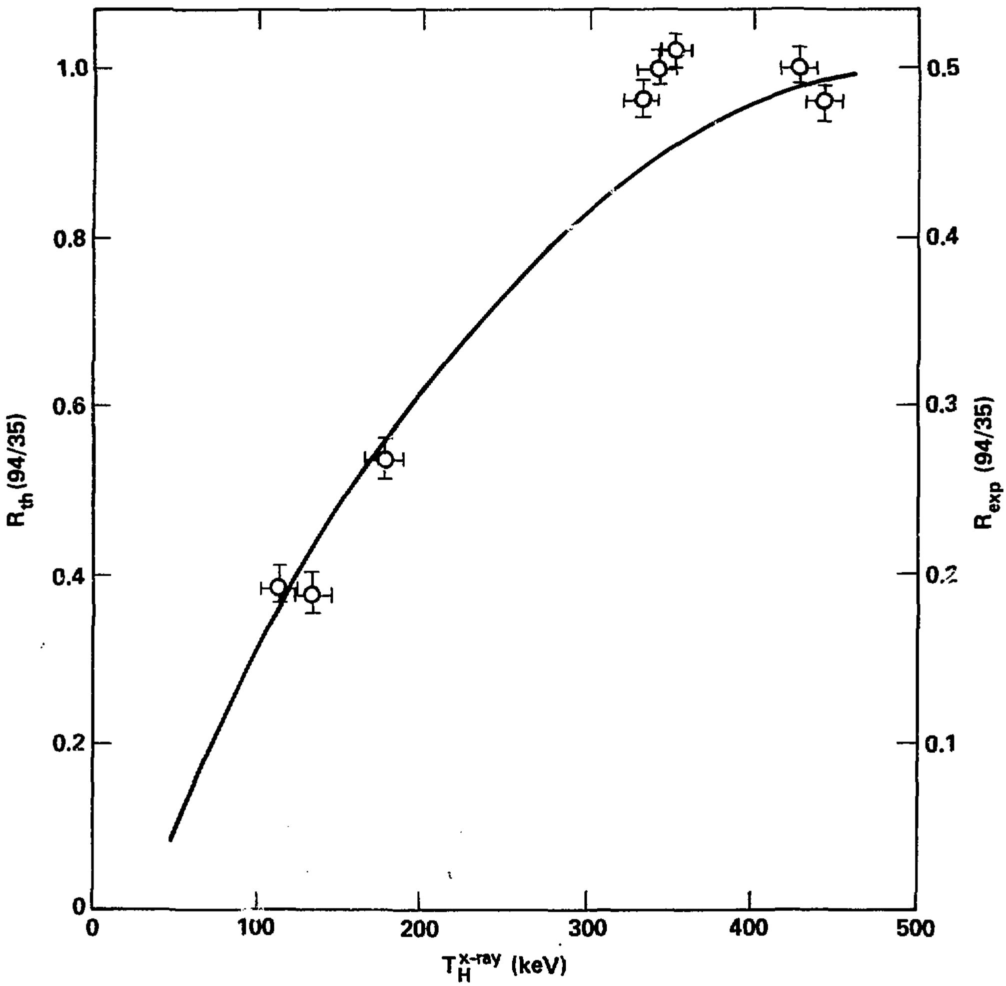
Figure 2: Comparison between $R_{th}(94/35)$ and $R_{exp}(94/35)$ as a function of T_H. $R_{th}(94/35)$ is the PECE code prediction for the ratio of perpendicular emission coefficients of 94GHz and 35GHz. $R_{exp}(94/35)$ is the experimentally calculated value.

Figure 3: Sample PECE signals showing the temporal history of: a) 60GHz, b) 98GHz, c) 35GHz and d) the hot electron temperature, $T_H(t)$, derived from the ratio of the $P_r(98)$ and $P_r(60)$, and using the PECE code calculations for $R_{th}(98/60)$. For this shot the afterglow x-ray temperature $T_H^{x\text{-}ray}$ = 265 keV. This is a Maxwellian fit to the high energy x-ray spectrum. This data has been normalized to T_H = 265 keV at t = 100 ms.



10.0
1.0
0.1
10
100
1000
35 GHz
60 GHz
94 GHz
$j_\perp(\omega,T_H) \times 10^{-28}$ joules
T_H (keV)

Figure 1



1.0
0.8
0.6
0.4
0.2
0
0.5
0.4
0.3
0.2
0.1
0
100
200
300
400
500
R_{th} (94/35)
R_{exp} (94/35)
$T_H^{x\text{-ray}}$ (keV)

Figure 2