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**Synchrotron Emission from the
Ring Electrons in EBT**

T. Uckan
N. A. Uckan

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SYNCHROTRON EMISSION FROM THE RING ELECTRONS IN EBT

T. Uckan

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ABSTRACT

The energy spectrum of the synchrotron radiation emitted by the relativistic ring electrons in ELMO Bumpy Torus (EBT) has been calculated for various classes of isotropic and anisotropic ring electron distribution functions. Calculations have been carried out for present (EBT-I/S) and planned (EBT-P) experiments. The ring temperatures in EBT-I and EBT-S are ~ 200 and ~ 500 keV, respectively. The projected ring temperature in EBT-P is ~ 1000 – 1500 keV. The calculations indicate that the radiation is predominantly in higher harmonics ($l \geq \gamma^2/2$) and the radiation spectrum monotonically decreases and becomes almost flat at high frequencies, as observed in the experiments. With increasing temperature and anisotropy, the total emission increases, the slope of the spectrum decreases, and the peak of the spectrum moves to higher frequency. The ratio of the extraordinary wave intensity to ordinary wave intensity decreases with temperature but increases with anisotropy. Calculated spectra and relative intensity levels of EBT-I and EBT-S are found to be in reasonable agreement with the experimental measurements. Both measurements and calculations show that synchrotron losses are low in EBT-I and EBT-S. However, in future experiments (EBT-P, reactor, etc.), radiation losses will play an important role in determining the ring power balance. Correlations of calculated intensity variations with temperature, density, beta, anisotropy, etc., are given that can be used as a useful tool for comparison of theory and experiment, as well as in the determination of ring properties and scaling of the radiation with ring parameters.

1. INTRODUCTION

The key element of the ELMO Bumpy Torus (EBT) concept¹ is the high-beta, hot electron rings² formed in each sector of the torus as a natural consequences of the electron cyclotron heating (ECH). The local magnetic wells produced by these hot electron rings stabilize the toroidally confined plasma,³ as demonstrated in EBT experiments^{2,4} (EBT-I/S) and the Nagoya Bumpy Torus (NBT).^{4,5} In addition to other experimentally observed features of the rings (i.e., diamagnetic effects, electrostatic potential, bremsstrahlung distribution, etc.),⁴ measurements of the synchrotron emission spectrum emitted by the relativistic hot electrons can be utilized as a useful diagnostic method in determining the ring properties (i.e., distribution function, density, temperature, etc.) and their scaling with operating conditions in different devices. Initial measurements of synchrotron emission in EBT have been carried out using a fast-sweeping superheterodyne receiver in the frequency range 80-110 GHz.⁶ Similar measurements have also been made on NBT using a radiometer at frequencies of ~10 and ~35 GHz.⁷ In the near future, the University of Maryland will perform experiments on EBT-S at two fixed frequencies (80 and 140 GHz) using two superheterodyne receivers.⁸

In order to make use of the synchrotron emission measurements as a diagnostic tool, theoretical models^{9,10} are being developed to analyze the experimental results. In this paper the emission spectra for various classes of isotropic and anisotropic distribution functions are obtained for the parameter range of interest for the EBT ring plasma. In the calculations the plasma dispersion effects ($\omega_p^2 \ll \omega_c^2 < \omega^2$, where ω_p and ω_c are the characteristic ring electron plasma frequency and cyclotron frequency, respectively) and absorption are neglected. Because of the relativistic temperatures ($T \sim 0.2-2$ MeV) of the ring electrons, the emission is in higher harmonics ($\omega = \ell\omega_c$, with $\ell \gg 1$), and the inequality $\omega_p^2 \ll \omega^2$ is satisfied for all but possibly the lowest harmonics. The angular distribution of emission for these relativistic electrons peaks in a direction perpendicular to the magnetic field B (i.e., near $\theta \approx \pi/2$, where θ is the observation angle

measured from the magnetic axis). Also, the observation angle in the experiments⁶ is $\theta = \pi/2$. Therefore, the interest in this paper is restricted primarily to $\theta = \pi/2$, and the expressions developed herein are valid for the purpose of making comparisons of experimental results with the theoretical spectrum. As will be discussed, a deviation from the perpendicular direction ($\theta \neq \pi/2$) could, however, provide additional information on the ring properties (such as anisotropy, etc.).

Spatial profiles of ring electron density and temperature (determined from fits to the experimental data) and a consistent profile for the magnetic field (deduced from the pressure balance) are included in the analysis. The emission spectrum and its dependence on ring parameters and distribution functions are calculated for present (EBT-I/S) and planned (EBT-P) experiments. The measured ring electron temperatures⁴ in EBT-I and EBT-S are ~ 200 and ~ 500 keV, respectively. The projected ring temperature in EBT-P is ~ 1000 – 1500 keV. Calculated spectra and relative intensity levels of EBT-I and EBT-S are in reasonable agreement with the experimental measurements.

Other than the diagnostic interest, there is also an interest in the study of synchrotron emission from the ring electrons in order to determine the total radiation losses and its scaling with ring parameters. The dominant ring power losses are synchrotron radiation, drag cooling, and scattering.^{2,4} In EBT-I and EBT-S the ring sustaining power is modest⁴ and primarily determined by drag cooling and scattering because the synchrotron losses are calculated (and measured) to be low. However, in future experiments, predicted ring temperatures ($T > 1$ MeV) will be in the synchrotron-dominated regime and radiation losses will play an important role in determining the ring power balance.

In Sec. 2, basic expressions for the energy spectrum of the synchrotron radiation are given for isotropic and anisotropic distribution functions. Results for present and planned experiments are presented in Sec. 3. Section 4 summarizes the findings.

2. EMISSION SPECTRUM OF SYNCHROTRON RADIATION

A. Basic Equations and Assumptions

The expression for single electron emissivity (i.e., the energy radiated per unit solid angle $d\Omega$, per unit frequency interval $d\omega$, per second) can easily be approximated by Schott-Trubnikov results^{11,12} for the frequency range of interest ($\omega_p^2 \ll \omega_c^2$) and is given by¹² (in mks units)

$$\begin{aligned} \eta_\omega(\omega, \beta, \theta) &= \frac{e^2 \omega^2}{8\pi^2 \epsilon_0 c} \sum_{\ell=1}^{\infty} \left[\left(\frac{\cos \theta - \beta_{\parallel}}{\sin \theta} \right)^2 J_{\ell}^2(x) + \beta_{\perp}^2 J_{\ell}^{\prime 2}(x) \right] \delta(y) \\ &= \frac{e^2 \omega^2}{8\pi^2 \epsilon_0 c} \sin^{-2} \theta (1 + p^2)^{-1} \sum_{\ell=1}^{\infty} \{ [\sqrt{1 + p^2} \cos \theta - p_{\parallel}]^2 J_{\ell}^2(x) \\ &\quad + p_{\perp}^2 \sin^2 \theta J_{\ell}^{\prime 2}(x) \} \delta(y) \quad (1) \end{aligned}$$

Here, $\omega_c = eB/m_0 c \gamma = \omega_{c0}(1 - \beta^2)^{1/2} = \omega_{c0}(1 + p^2)^{-1/2}$; $\beta_{\parallel} (= v_{\parallel}/c)$ and $\beta_{\perp} (= v_{\perp}/c)$ are dimensionless velocities parallel and perpendicular to the magnetic field B , respectively; $p_{\parallel}$ and $p_{\perp}$ are the electron momenta expressed in units of $m_0 c$ (m_0 is the rest mass of the electron); ϵ_0 is the permittivity of the free space; J_{ℓ} and $J_{\ell}' [\equiv \frac{d}{dx} J_{\ell}(x)]$ are Bessel functions and their derivatives; and θ is the observation angle measured from the magnetic axis. In Eq. (1), the argument of the Bessel function is

$$x = \frac{\omega}{\omega_c} \beta_{\perp} \sin \theta = \frac{\omega}{\omega_{c0}} p_{\perp} \sin \theta \quad (2)$$

and the argument of the δ function is

$$\begin{aligned}
 y &= \ell \omega_c - \omega(1 - \beta_{\parallel} \cos \theta) \\
 &= (1 + p^2)^{-1/2} [\ell \omega_{c0} - \omega(\sqrt{1 + p^2} - p_{\parallel} \cos \theta)] .
 \end{aligned} \tag{3}$$

Considering the propagation at exactly $\theta = \pi/2$, one finds from Eq. (1) that the emissivity is made up of two parts:¹² one is associated with the ordinary wave ($E \parallel B$, the electric vector oriented along B),

$$\eta_{\omega}^{(o)}\left(\frac{\pi}{2}\right) = \frac{e^2 \omega^2}{8 \pi^2 \epsilon_0 c} \sum_{\ell=1}^{\infty} \beta_{\parallel}^2 J_{\ell}^2(\ell \beta_{\perp}) \delta(\ell \omega_c - \omega) , \tag{4}$$

and the other with the extraordinary wave ($E \perp B$),

$$\eta_{\omega}^{(x)}\left(\frac{\pi}{2}\right) = \frac{e^2 \omega^2}{8 \pi^2 \epsilon_0 c} \sum_{\ell=1}^{\infty} \beta_{\perp}^2 J_{\ell}^2(\ell \beta_{\perp}) \delta(\ell \omega_c - \omega) . \tag{5}$$

For an assembly of electrons, the radiation emitted per unit volume dV , per unit frequency interval $d\omega$, and per unit solid angle $d\Omega$ is then written as

$$j_{\omega}^{(o,x)} \equiv \frac{d^3 p_{\omega}^{(o,x)}}{d\omega d\Omega dV} = n_R \int d^3 p f(\vec{p}) \eta_{\omega}^{(o,x)}(\vec{p}) , \tag{6}$$

where n_R is the ring electron density and $f(\vec{p})$ [$\int d^3 p f(\vec{p}) = 1$] is the ring distribution function. In writing Eq. (6), it is assumed that the total power radiated by all electrons in the plasma is a simple superposition of single-particle emissions, a valid assumption provided collective effects (such as instabilities) do not lead to coherent emission over some spectral bandwidth. Also, under the conditions of

interest ($\omega^2 \gg \omega_p^2$, where ω is the emission frequency), the refractive properties of the medium are neglected.

Assuming the hot electron ring is a cylindrical shell of finite length L_R (in each sector) and is located at a mean radius of a_R with a half-width of δ_R , one can write the power radiated from the unit axial length as

$$\langle I_{\omega}^{(o,x)} \rangle \equiv \frac{d^2 p_{\omega}^{(o,x)}}{d\omega d\Omega L_R} = 2\pi \int_{a_R - \delta_R}^{a_R + \delta_R} r dr j_{\omega}^{(o,x)} \quad (7)$$

In Eq. (7), the self-absorption of the radiation has been neglected.

The radial profiles of density and temperature are assumed to be parabolic

$$[n_R(r), T_R(r)] = (n_o, T_o) \left[1 - C_{n,T} \left(\frac{r - a_R}{\delta_R} \right)^2 \right] \quad (8)$$

where n_o, T_o represents the peak values of ring density and temperature at $r = a_R$ and C (C_n or C_T) is constant and determined from fits to the experimental data.

From the pressure balance equation, the modification to the magnetic field due to the hot electron rings can be approximated as

$$B(r) \approx B_o(r) [1 - \beta_R(r)]^{1/2} \quad (9)$$

where β_R is the ring beta and $B_o(r)$ is the vacuum magnetic field and is assumed to be uniform along the magnetic axis z within the ring length L_R . To a good approximation,

$$B_o(r) \approx B_{oo} \left[1 - \alpha \left(\frac{r}{R_B} \right)^m \right] \quad (10)$$

where B_{00} is the midplane field (at $r = 0$), R_B is the magnetic field scale length in the radial direction in the absence of the high-beta ring, and α and m are constants which can be obtained from fits to the exact field calculations. (The magnetic field at the ring location $r = a_R$ is $\sim 0.6-0.7B_{00}$ with $\beta_R = 0$.) Here, the neglect of nonuniformity in the magnetic field in the axial direction z corresponds to the neglect of line broadening of the emitted radiation. This is generally justified¹² because the primary mechanism for line broadening is spread in electron energy, which is fairly large for the ring temperatures of interest in comparison with any other broadening mechanisms.

B. Emission for Isotropic and Anisotropic Distribution Functions

In case of perpendicular propagation ($\theta = \pi/2$), expressions for the emission coefficient can be represented by relatively simple and compact formulas for some classes of distribution functions.⁹ Among those are any class of isotropic [i.e., $\partial f(p, \psi)/\partial \psi = 0$, where ψ is the angle between $\underline{B}$ and $\underline{\hat{p}}$] and any anisotropic distribution function of the form

$$f(\underline{\hat{p}}) = f_{\perp}(p_{\perp})f_{\parallel}(p_{\parallel}) \quad (11)$$

When f is isotropic (but not necessarily Maxwellian), Eq. (6) reduces to

$$j_{\omega}^{(0,x)} = \frac{e^2 \omega}{4 \pi \epsilon_0 c} (m_0 c)^3 n_R \sum_{\ell \geq \omega/\omega_{c0}} f[p_{*}(\omega)] p_{*}^3(\omega) S_{\ell}^{(0,x)}[\beta_{*}(\omega)] \quad (12)$$

where

$$p_{*}^2(\omega) = (\ell \omega_{c0}/\omega)^2 - 1 \quad (13)$$

or equivalently

$$\beta_{\#}^2(\omega) = (\omega/\ell\omega_{co})^2 p_{\#}^2(\omega) = 1 - (\omega/\ell\omega_{co})^2, \quad (14)$$

and

$$S_{\ell}^{(o,x)}(\beta_{\#}) = \int_0^{\pi} d\psi \sin \psi \begin{cases} \cos^2 \psi J_{\ell}^2(\ell\beta_{\#} \sin \psi) & (o) \\ \sin^2 \psi J_{\ell}^2(\ell\beta_{\#} \sin \psi) & (x) \end{cases} \quad (15)$$

Equation (12) is the final expression for the emission coefficient j_{ω} for any arbitrary class of isotropic distribution functions. A special case of this class is the Maxwellian distribution and is used in the numerical calculations presented in the next section.

The ring electrons preferentially gain perpendicular energy as a result of electron cyclotron heating. The parallel and perpendicular temperatures ($T_{\parallel}$ and $T_{\perp}$) can be different with the result that the momentum distribution will be anisotropic. If one can represent the distribution function in a separable form as in Eq. (11), the emission coefficient is then given by

$$j_{\omega}^{(o,x)} = \frac{e^2 \omega}{4 \pi \epsilon_0 c} n_R (m_0 c)^3 \sum_{\ell > \omega/\omega_{co}} \int_{-p_{\#}(\omega)}^{p_{\#}(\omega)} dp_{\parallel} f_{\parallel}(p_{\parallel}) f_{\perp}[p_{\perp*}(\omega, p_{\parallel})] \begin{cases} p_{\parallel}^2 J_{\ell}^2[\ell\beta_{\perp*}(\omega, p_{\parallel})] & (o) \\ p_{\perp*}^2 J_{\ell}^2[\ell\beta_{\perp*}(\omega, p_{\parallel})] & (x) \end{cases} \quad (16)$$

where

$$\begin{aligned} p_{\perp*}^2(\omega, p_{\parallel}) &= p_{*}^2(\omega) - p_{\parallel}^2 = [(\ell\omega_{cO}/\omega)^2 - 1] - p_{\parallel}^2, \\ \beta_{\perp*}^2(\omega, p_{\parallel}) &= \beta_{*}^2(\omega) - \beta_{\parallel}^2 = (\omega/\ell\omega_{cO})^2 p_{\perp*}^2(\omega, p_{\parallel}). \end{aligned} \quad (17)$$

In general, one wants an f of the form represented by Eq. (11) that reduces to (a) the isotropic Maxwellian for $T_{\perp} = T_{\parallel}$ and (b) the 2-D Maxwellian $f(p) \sim f_{\perp}(p)\delta(p_{\parallel})$ for $T_{\parallel}/T_{\perp} \rightarrow 0$. Because of the difficulty in finding a simple relativistic equilibrium distribution function f with both of these limiting behaviors and because the ECH plasma is expected to be quite anisotropic in temperature, the second requirement was selected for asymptotic behavior. Hence, the following distribution function is used in the numerical calculations:

$$f(\vec{p}) = f_{\perp}(p_{\perp})f_{\parallel}(p_{\parallel}) = A_{\perp}\exp(-\epsilon_{\perp}/T_{\perp}) \times A_{\parallel}\exp\left(-\frac{m_0c^2}{2T_{\parallel}}p_{\parallel}^2\right), \quad (18)$$

where $\epsilon_{\perp} = m_0c^2(1 + p_{\perp}^2)^{1/2}$ and $A_{\perp}$ and $A_{\parallel}$ are the normalization constants.⁹ In the limiting case of no parallel motion (2-D Maxwellian), Eq. (18) reduces to

$$f(\vec{p}) = f_{\perp}(p)\delta(p_{\parallel}) = A\exp(-\epsilon/T)\delta(p_{\parallel}), \quad (19)$$

and one finds $j_{\omega}^{(0)} = 0$ and

$$j_{\omega}^{(x)} = \frac{e^2\omega}{4\pi\epsilon_0c} n_R(m_0c)^2 \sum_{\ell \geq \omega/\omega_{cO}} p_{*}^2(\omega) f_{\perp}[p_{*}(\omega)] J_{\ell}^2[\ell\beta_{*}(\omega)] \quad (20)$$

For a deviation from perpendicular propagation ($\theta \neq \pi/2$), expressions are, in general, quite complex and Eq. (1) should be used in the derivations. It is shown in Ref. 11 that for $\theta \neq \pi/2$ the radiation intensity falls off more rapidly for an anisotropic distribution than for an isotropic one. Thus, the measurements made with $\theta \neq \pi/2$ can provide useful information on the ring anisotropy. In general, radiation intensity has the form

$$j_{\omega}^{(o,x)}(\theta) = \frac{e^2 \omega}{4 \pi \epsilon_0 c} (m_0 c)^3 n_R \sum_{\ell \geq \omega/\omega_{co}} \int d\psi \sin \psi \tilde{p}_{*}^2(\omega, \theta, \psi) \cdot f[\tilde{p}_{*}(\omega, \theta, \psi)] G_{\ell}^{(x,o)}[\tilde{p}_{*}(\omega, \theta, \psi)] , \quad (21)$$

where $\tilde{p}_{*}(\omega, \theta, \psi)$ satisfies the relation

$$\ell \omega_{co}/\omega = (1 + \tilde{p}_{*}^2)^{1/2} - \tilde{p}_{*} \cos \psi \cos \theta \quad (22)$$

and

$$G_{\ell}^{(x,o)}(\tilde{p}_{*}) = \begin{cases} \frac{\tilde{p}_{*}^2 (1 + \tilde{p}_{*}^2)^{1/2} \sin^2 \psi}{|\cos \psi \cos \theta - \tilde{p}_{*}(\ell \omega_{co}/\omega)|} J_{\ell}^2 \left(\frac{\omega}{\omega_{co}} \tilde{p}_{*} \sin \theta \sin \psi \right) \\ \frac{[\sqrt{1 + \tilde{p}_{*}^2} \cos \theta - \tilde{p}_{*} \cos \psi]^2 (1 + \tilde{p}_{*}^2)^{1/2}}{\sin^2 \theta |\cos \psi \cos \theta - \tilde{p}_{*}(\ell \omega_{co}/\omega)|} J_{\ell}^2 \left(\frac{\omega}{\omega_{co}} \tilde{p}_{*} \sin \theta \sin \psi \right) \end{cases} \quad (23)$$

A special case of simple loss cone distribution^{10,13}

$$f(p, \psi) = A(\psi_0) \exp(-\epsilon/T) U(\psi, \psi_0) \quad (24)$$

is used for calculations in the next section. Here, $A(\psi_0)$ is the normalization constant, and

$$U(\psi, \psi_0) = \begin{cases} 1 & \psi_0 < \psi < \pi - \psi_0 \\ 0 & \text{otherwise} \end{cases}, \quad (25)$$

where ψ_0 is the loss cone angle ($\psi_0 = 0$ corresponds to isotropic distribution and limit of $\psi_0 \rightarrow \pi/2$ represents pure perpendicular motion) and ψ is the angle between $\underline{B}$ and $\hat{p}$ (i.e., pitch angle $\cos \psi = p_{\parallel}/p$). In limiting the case of $\theta = \pi/2$ and $\psi_0 = 0$, Eq. (21) reduces to Eq. (12).

3. RESULTS FOR PRESENT AND PLANNED EXPERIMENTS

Using the experimentally measured ring temperatures and densities,^{4,14} the radiation spectra for EBT-I and EBT-S are calculated for several choices of the ring electron distribution functions discussed in the previous section. The projected parameters for EBT-P are deduced from scaling relationships obtained from the present experiments. The typical parameters used in these calculations are given in Table I.

The extraordinary and ordinary wave intensities for EBT-I, -S, and -P are shown in Fig. 1 for the isotropic Maxwellian distribution. Several features of the spectra can easily be seen in Fig. 1. The peaks at low frequencies are mainly the contributions of lower harmonics ($k < 10$), and the emission spectrum peaks around a frequency $\omega = \omega_{\max} \cong 0.5 \omega_{ce} \gamma^2$. However, the bulk of the emission comes from part of the spectrum $\omega \gtrsim \omega_{\max}$. Because of the smearing of successive harmonics and pronounced overlapping, spectra monotonically decrease and become almost flat at high frequencies, as observed in the experiments.⁶ The slope of the spectrum decreases with increasing temperature (i.e., spectra for EBT-P are flatter than those for EBT-S, which are flatter than those for EBT-I). There is almost an order of magnitude increase in intensity levels in going from EBT-I to EBT-S and from EBT-S to EBT-P due to hotter and denser ring plasmas. In the

frequency range 80-110 GHz, the ratio of the extraordinary wave intensity levels (average) is

$$\langle I^{(x)} \rangle_{\text{EBT-S}} / \langle I^{(x)} \rangle_{\text{EBT-I}} \cong 8 ,$$

which compares reasonably with the experimental observation of the intensities in this frequency range.⁶ (The experimental value⁶ is $I_{\text{EBT-S}}^{(x)} / I_{\text{EBT-I}}^{(x)} \cong 6$.)

As can be seen from Fig. 1, whereas most of the power is in the extraordinary wave component the ratio of the extraordinary wave intensity to the ordinary wave intensity decreases with temperature. That is, $I^{(x)} / I^{(o)} \cong 10$ in EBT-I, $\cong 6$ in EBT-S, and $\cong 4$ in EBT-P. The slope of the ordinary wave spectrum is somewhat larger than the extraordinary wave.

The intensity levels and radiation spectra do depend on the distribution function and the anisotropy level. This effect is shown in Fig. 2 for EBT-S. In Fig. 2, one can compare the spectra at the same values of temperature ($T_{\perp} = \text{constant}$) or average kinetic energy ($\langle W \rangle = \text{constant}$) for three different distribution functions (e.g., isotropic Maxwellian $T_{\perp} = T_{\parallel}$, two-temperature $T_{\perp} / T_{\parallel} = 5$, and 2-D Maxwellian $T_{\parallel} = 0$), discussed in Sec. 2. While the intensity increases with anisotropy ($T_{\perp} / T_{\parallel}$), the slope of the spectrum decreases. The structures of the spectra are found to be similar in all three cases (for both $T_{\perp} = \text{constant}$ and $\langle W \rangle = \text{constant}$); however, the peaks of the intensity move to higher frequencies as the temperature and anisotropy increase. Comparisons of the isotropic and anisotropic cases for EBT-I, EBT-S, and EBT-P are given in Table II for both $T_{\perp} = \text{constant}$ and $\langle W \rangle = \text{constant}$.

Although Fig. 2 is for the extraordinary wave, similar behavior is observed for the ordinary wave. In Fig. 3, the variation of the ratio of these two intensities [i.e., $I^{(x)} / I^{(o)}$] with the temperature and distribution function is given. The ratio of intensities in the two polarizations exhibits a similar dependence on temperature both for isotropic Maxwellian and for two-temperature or bi-Maxwellian (with $T_{\perp} / T_{\parallel} = 5$) cases; however, the ratio increases with anisotropy. The

dependence on temperature is stronger at low temperatures. That is, $I^{(x)}/I^{(o)} \sim T^{-\alpha}$, where $\alpha \sim 0.5-1.0$ for $T < 500$ keV and $\alpha < 0.1$ for $T > 1500$ keV. The curves in Fig. 3 are deduced from the calculated spectra for EBT-I, -S, and -P in that they are continuous and are found to be nearly independent of device geometry, magnetic field, beta, etc. The solid curves in Fig. 3 are for $\omega = 150$ GHz; however, the variation of the ratio within the frequency range 80-250 GHz is found to be modest (<20%). Although one can deduce temperature information from the ratio of intensities in the two polarizations at two widely separated frequencies at low temperatures ($\lesssim 200$ keV), it is very difficult to obtain a conclusive answer for temperatures characteristic of EBT-S (or EBT-P) unless the resolution of the measurements is better than 10-20%.

In case of loss cone distribution, at $\theta = \pi/2$, the ratio of intensities is found to be insensitive to the loss cone angle for $\psi_0 < 60^\circ$ (see Fig. 4). For large angles ($\psi_0 > 70^\circ$), however, the intensity ratio in the two polarizations increases drastically (up to a factor of ~ 2 at $\psi_0 = 75^\circ$ and ~ 4 at 80°), as shown in Fig. 4. Again, the ratio is observed to be weakly dependent on the frequency. In comparison with isotropic distribution, at $\theta = \pi/2$, the change in intensity level is less than 50% for $\psi_0 < 45^\circ$, and about a factor of 2-4 increase in intensity is found for $\psi_0 > 60^\circ$. The effect of loss cone is more pronounced for $\theta \neq \pi/2$, in which emission falls with θ more rapidly for loss cone distribution than for isotropic distribution. In particular, for an observation angle $\theta < \psi_0$, one finds the ratio $I_{\text{isotropic}}^{(x)}(\theta)/I_{\text{loss cone}}^{(x)}(\theta)$ to be more than an order of magnitude.¹⁰

The intensity also changes with ring beta, as illustrated in Fig. 5. In comparing vacuum field calculations with finite-beta results, about 20% reduction in intensity level is observed in EBT-S ($T = 500$ keV) for a ring beta of $\sim 35\%$.

The changes in intensity with temperature and beta are shown in Figs. 6-8 for EBT-I, -S, and -P. In order to eliminate the density dependence, intensities in Figs. 6-8 are normalized with appropriate densities corresponding to each device. Because the ring volume in the experiments is observed to be nearly constant^{2,4,14} (i.e., independent

of operating conditions), the ring beta is proportional to the ring stored energy (diamagnetic flux). Thus, the correlation of measured radiation intensity with stored energy will yield similar curves to those in Figs. 6-8 from which one can make a comparison of theory and experiment for determining the ring distribution function. For all of the three distribution functions (see Figs. 6-8), dependence of intensity to temperature is found to be much stronger in EBT-I than in EBT-S. That is, $I^{(x)} \sim T^\alpha$, where $\alpha \sim 2.5-3$ for EBT-I, $\alpha \sim 1-1.3$ for EBT-S, and $\alpha \sim 0-0.3$ for EBT-P. Results from Figs. 6-8 are summarized in Table III.

Correlations of intensity with all of the observable (or measurable) quantities in the experiments (i.e., density, temperature, stored energy which is a measure of ring beta, etc.) can be made as they are shown in Figs. 9 and 10. Figures 9 and 10 are for an EBT-S plasma assuming isotropic Maxwellian distribution, though similar behavior is observed for other distribution functions. For a given density (see Fig. 9), intensity first increases with temperature and, after some critical temperature, either saturates or decreases slightly with increasing temperature (and beta). The saturation temperature increases as the density is increased. From the measurements of the radiation intensity (in x-mode in this case) and stored energy (or beta), one can determine the corresponding ring temperature and density from Fig. 9 or 10.

4. DISCUSSION AND CONCLUSIONS

Expressions for the energy spectrum of the synchrotron radiation emitted by the relativistic, hot electron rings in EBT are presented for several classes of distribution functions. For special cases, these expressions are used to determine scaling of the radiation with ring parameters and to indicate ways to determine ring properties from the measurements of synchrotron emission.

Because of the relativistic temperatures ($T \sim 200-1500$ keV), the bulk of the emission comes from the higher harmonics. In general, the

contributions from lower harmonics ($l = \omega/\omega_{co} < 10$) are modest (approximately a few percent) and a large number of harmonics are used in the calculations [i.e., $l \sim O(10^2)$].

Calculated spectra and relative intensity levels compare reasonably well with the experimental measurements in EBT-I and EBT-S. That is, the radiation spectrum is almost flat at higher frequencies and the slope of the spectrum decreases, but the intensity increases with temperature. In addition, an increase in intensity and a decrease in slope are observed with an increase in anisotropy ($T_{\perp}/T_{\parallel}$).

For the isotropic Maxwellian, the emission spectrum peaks around a frequency $\omega \approx 0.5\omega_{co}\gamma^2$; however, the peak moves to higher frequency as the anisotropy is increased.

The ratio of the extraordinary wave intensity to the ordinary wave intensity decreases with temperature (for isotropic Maxwellian the ratio is ~ 10 for EBT-I, ~ 6 for EBT-S, and ~ 4 for EBT-P) though it increases with anisotropy. (For $T_{\perp}/T_{\parallel} = 5$, the ratio is a factor of $\sim 2-3$ larger than that for $T_{\perp}/T_{\parallel} = 1$.) The dependence of the ratio on temperature is found to be stronger at low temperatures ($I(x)/I(0) \sim T^{-1/2}$ to $\sim T^{-1}$ for $T < 200$ keV); however, it exhibits a very weak dependence on temperature at high temperatures ($\sim T^{-0.1}$). For perpendicular propagation ($\theta = \pi/2$), a significant change in the ratio of intensities is only observed for loss cone angles $\psi_0 > 70^\circ$. The effect of loss cone becomes more important for $\theta \neq \pi/2$, especially for $\theta < \psi_0$. In all cases, the ratio shows very weak dependence on the frequency ($\sim 20\%$).

Correlations of calculated emission spectrum, radiation intensity, etc., with a wide range of ring parameters and/or distribution functions are made. Depending on the information sought, these can be used to deduce properties of the ring plasma from the experimental measurements. For example, information on the ring distribution function can be inferred from comparisons of the theoretical result with the measurement of the ring stored energy and radiation intensity. Similarly, ring anisotropy can be deduced from the ratio of intensities in the two polarizations and so on. However, there are also limitations and difficulties in obtaining conclusive results in most cases due to either limitations of the experimental capabilities (e.g.,

access problem in making measurements for $\theta \neq \pi/2$) or the difficulties in interpreting the model calculations (i.e., because of the relativistic temperatures, harmonics are all smeared out with a pronounced overlapping, resulting in a featureless spectra with not much to distinguish with frequency).

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TABLE I. Typical EBT ring parameters^{4,14}.

	EBT-I	EBT-S	EBT-p ^a
B_{00} (midplane, $r = 0$) (kG)	5.0	7.2	15.0
B_0 (vacuum field at $r = a_R$) (kG)	3.2	5	10.7
ECH frequency (GHz)	18	28	60
Ring radius, a_R (cm)	12	12	18
Ring half-width, δ_R (cm)	1.5	1.5	2.0
Ring temperature, T_0 (keV)	200	500	1000
Ring density, n_0 ($\times 10^{11}$ cm ³)	2.3	3.0	5.0

^aProjected parameters.

TABLE II. Comparisons of isotropic and anisotropic distribution functions for EBT-I, -S, and -P for $T_{\perp}$ = constant (case a) and $\langle W \rangle$ = constant (case b).

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	EBT-I			EBT-S			EBT-P		
	$T_{\perp} = T_{\parallel}$	$T_{\perp}/T_{\parallel} = 5$	$T_{\parallel} = 0$	$T_{\perp} = T_{\parallel}$	$T_{\perp}/T_{\parallel} = 5$	$T_{\parallel} = 0$	$T_{\perp} = T_{\parallel}$	$T_{\perp}/T_{\parallel} = 5$	$T_{\parallel} = 0$
Case a: $T_{\perp}$ = constant (keV)	200			500			1000		
$\langle I^{(x)} / I^{(0)} \rangle$ (at 110 GHz)	10	28	—	6	16	—	4	12.5	—
$I_{\omega = 80 \text{ GHz}}^{(x)} / I_{\omega = 110 \text{ GHz}}^{(x)}$	1.5	1.45	1.4	1.1	1.05	1.4	0.95	0.9	0.85
$\langle I^{(x)} / I_{\text{isotropic}}^{(x)} \rangle$ (at 110 GHz)	1.0	1.6	1.9	1.0	1.95	2.3	1.0	2.1	2.4
Case b: $\langle W \rangle$ = constant (keV)	300			750			1500		
$T_{\perp}$ (keV)	200	275	300	500	675	750	1000	1375	1500
$\langle I^{(x)} / I^{(0)} \rangle$ (at 110 GHz)	10	23	—	6	14	—	4	11	—
$I_{\omega = 80 \text{ GHz}}^{(x)} / I_{\omega = 110 \text{ GHz}}^{(x)}$	1.5	1.3	1.2	1.1	1.0	0.95	0.95	0.85	0.85
$\langle I^{(x)} / I_{\text{isotropic}}^{(x)} \rangle$ (at 110 GHz)	1.0	2.9	4.2	1.0	2.5	3.1	1.0	2.25	2.6

TABLE III. Calculated variation of intensity with
temperature [$I(x) \sim T^\alpha$]

		$I(x) \sim T^\alpha$		
		α		
Device	Operating window	$T_\perp = T_\parallel$	$T_\perp/T_\parallel = 5$	$T_\parallel = 0$
EBT-I	$T_\perp \sim 150-250$	2.5 ± 0.2	2.7 ± 0.2	3.0 ± 0.2
EBT-S	$T_\perp \sim 400-600$	0.9 ± 0.1	1.1 ± 0.1	1.2 ± 0.1
EBT-P ^a	$T_\perp \sim 1000-1500$	~ 0	0.25 ± 0.05	0.25 ± 0.05

^aOperating window for EBT-P is a projected range for ring temperature.

FIG. 1. Synchrotron radiation spectrum of the hot electron rings of EBT-I, EBT-S, and EBT-P. The extraordinary and ordinary wave intensities are shown for the isotropic Maxwellian distribution.

FIG. 2. Radiation spectra in EBT-S for various distribution functions for the same values of temperature ($T_\perp = \text{constant}$) and average kinetic energy ($\langle W \rangle = \text{constant}$). Intensity unit is $W/[\text{radian/s}](\text{steradian m})$.

FIG. 3. Computed variation of the ratio of extraordinary wave intensity to ordinary wave intensity with temperature and anisotropy. Solid curve is for 150 GHz. Variation of the ratio within the frequency range 80-250 GHz is shown with dotted band.

FIG. 4. Ratio of extraordinary wave intensity to ordinary wave intensity as a function of loss cone angle in EBT-S within the frequency range 80-150 GHz. Observation angle $\theta = \pi/2$.

FIG. 5. Comparison of emission spectrum without ($\beta = 0$) and with ($\beta_R \approx 35\%$) beta effects for isotropic Maxwellian distribution.

FIG. 6. Computed variation of intensity (normalized to density) with temperature and beta (~stored energy) in EBT-I for various distribution functions.

FIG. 7. Same calculations as in Fig. 6 for EBT-S. Intensity shows weaker dependence on temperature in EBT-S than in EBT-I.

FIG. 8. Same calculations as in Fig. 6 for planned EBT-P experiment. Intensity shows much weaker dependence on temperature in EBT-P than in EBT-S for comparable ring beta.

FIG. 9. Computed intensity as a function of temperature and its correlation with density and beta ($\sim$ stored energy) for isotropic Maxwellian distribution. (Similar correlation is observed for other distribution functions.)

FIG. 10. Correlation of intensity with variations in density, temperature, and beta (same calculations as in Fig. 9 but different representation).

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