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Design of a 3rd Harmonic Electron Cyclotron Emission Diagnostic for Ballooning Mode Fluctuations in PBX-M

P. P. Woskov, J. Kesner, B. Lane, S. Luckhardt,
J. S. Machuzak, D. Y. Rhee, and D. R. Cohn

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

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Abstract

A third harmonic electron cyclotron emission diagnostic using ultrawide bandwidth ($\approx$ 40 GHz) heterodyne receivers centered on 120 GHz with 14 channels per radial view is described for localized, long wavelength ($5 \lesssim \lambda \lesssim 50$ cm), fast time response ($\approx$ 1 μs) fluctuation studies in the PBX-M tokamak. The optically gray emission signal will have a $\gamma\, \tilde{n}_e/n_e + (3/\beta)\tilde{T}_e/T_e$ dependence on temperature and density fluctuations where $\gamma \leq 1$ and $1 \leq \beta \leq 3$ depending on local optical depth. Electron temperature fluctuation sensitivity is estimated to be $0.2\% \leq \tilde{T}_e/T_e \leq 2.9\%$ depending on local optical depth and fluctuation frequency in the 0.1 -1 MHz range. Spatial resolution of approximately 3 cm radially and 5 cm vertically are estimated for 2 keV plasmas with low suprathermal electron emission.

Introduction

Localized temperature and density fluctuation diagnostics in a fluctuation wavelength range ($0.1 < k < 1$ cm^{-1}) are likely to play a key role in advancing our understanding of confinement in magnetic fusion devices. This fluctuation wavelength range is currently diagnosed with difficulty in tokamaks. However, it is an important range because density fluctuations due to turbulence and drift waves are known to peak here [1]. In addition, ballooning modes which may be an important instability that could limit high beta and second stability tokamak operation [2], fall in this range. Very little experimental data exists on ballooning modes.

Conventional microwave to infrared scattering density fluctuation diagnostics cannot provide spatially localized or wavenumber resolved information in this wavelength range because the Bragg condition

$$k = \frac{4\pi}{\lambda_o} \sin\frac{\theta}{2} \tag{1}$$

where k is the fluctuation wavenumber, λ_o is the diagnostic wavelength and θ is the scattering angle, cannot be satisfied for diagnostic wavelengths that can access the plasma unless the scattering angle is made so small that the scattering volume is essentially chord averaged.

Infrared forward scattering in the Raman-Nath regime [3] by either imaging the forward diffracted signal [4] or by phase contrast imaging [5] has been shown to provide k resolution in this fluctuation range. Use of crossed beams can make possible non-chord averaged spatially resolved measurements. However, this is a rather difficult diagnostic to implement, requiring throughput access across the entire plasma cross section being diagnosed and the optical imaging of the signal on a many detector array.

By comparison electron cyclotron emission (ECE) is a relatively simple, passive (in contrast to active laser and particle beam techniques), and single view localized (in contrast to x-ray tomography) diagnostic of electron temperature and its fluctuations when viewing an optically thick harmonic [6]. It is sensitive to density fluctuations as well when viewing an optically thin harmonic. MHD modes can be observed by looking at either temperature or density fluctuations.

Analytical Basis

PBX-M is ideally suited for ECE diagnostics because of its high aspect ratio (> 5). When the aspect ratio is equal to 5 as shown in Figure 1, the second harmonic, as defined by $2\omega_c$ where ω_c is the electron cyclotron resonance frequency, is not overlapped across the entire plasma cross-section. In addition the third harmonic, $3\ \omega_c$, is not overlapped for most of the plasma cross-section from the outside to over three-fourths of the distance toward the inside wall. Therefore the 1/R dependent emission frequencies for these harmonics can be uniquely related to radial location.

PBX-M has as a goal to operate at fairly high densities approaching 10^{14} cm^{-3}. To avoid cutoffs and refraction the PBX-M ECE fluctuation diagnostic must make use of the third harmonic. For a nominal central field of 1.5 Tesla, this would correspond to a frequency range of 105 to 140 GHz.

The harmonic resonances plotted in Figure 1 assume only the presence of the vacuum toroidal field. With a plasma there can be additional poloidal and toroidal field components that can add and subtract to the total field and consequently affect the diagnostic's localization. In high beta experiments on PBX-M, these components will be much larger than in typical tokamak experiments. However even an extreme case, of a poloidal field 20% of the vacuum toroidal field, would only increase the total field by 2% because the fields add vectorially.

The ECE intensity from a thermal plasma is given by

$$I_{ece} = I_{bb}\ (1 - e^{-\tau_\ell}) \tag{2}$$

where

$$I_{bb} = \frac{\omega^2 T_e}{8\pi^3 c^2} \tag{3}$$

is the emission level of a blackbody at a temperature T_e and

$$\tau_\ell = \frac{\pi}{2} \frac{\omega^2_{pe} R}{\ell \omega_c c} \frac{2^{2\ell-1}}{(\ell-1)!} \left(\frac{kT_e}{2m_e c^2} \right)^{\ell-1} \tag{4}$$

is the optical depth in a tokamak of harmonic ℓ where R is the tokamak major radial component. The form of the optical depth given here is that of Engelmann and Curatolo [7] which is valid for nonrelativistic electron temperatures $T_e \lesssim 8$ keV.

For PBX-M plasmas the optical depth for third harmonic emission will be $\tau_3 \lesssim 1$, a region referred to as optically gray. In this case it can be shown that the fluctuating component of the emission will have a $\gamma \tilde{n}_e/n_e + (3/\beta)\, \tilde{T}_e/T_e$ dependence where $\gamma \lesssim 1$ and $1 \leq \beta \leq 3$ are determined by the local optical depth. The fluctuation signal will be strongly dependent on electron temperature with a weaker radial dependence on electron density. This should not pose a problem for a gross identification of ballooning modes, but for a detailed interpretation of the radial structure, electron and temperature profile data from other diagnostics must be used.

Spatial resolution for a horizontally viewing diagnostic geometry will be determined in the radial direction by relativistic Doppler broadening given by

$$\Delta r = R \sqrt{2\pi\ell} \frac{kT_e}{m_e c^2} \tag{5}$$

For typical PBX-M parameters (R = 1.6 m and T = 2 keV) this corresponds to a radial resolution of 2.8 cm. In the vertical and toroidal dimensions the spatial resolution is diffraction limited which for a Gaussian beam is given by

$$\Delta h = 1.27\, F^{\#} \lambda_o \tag{6}$$

where F# =L/d is the plasma viewing optics f-number with L the focal length and d the clear aperture. At 100 GHz and with an F# of 14 this would correspond to a resolution of approximately 5 cm.

Experimental Design

The ECE diagnostic system will be composed of a single sideband ultrawide bandwidth ($\approx$ 40 GHz) heterodyne receiver in the 100 to 140 GHz range, 14 intermediate frequency (IF) channels using state of the art multiplexer filters, a quasi-optical antenna, and an overmoded circular TE_{11} transmission line with a TE_{11} to HE_{11} mode converter at the antennna. The bandwidth of this fixed frequency local oscillator (LO) system is sufficient to view the entire unoverlapped third harmonic emission in PBX-M at a field of 1.5 Tesla.

The quasi-optical antenna and transmission line system are illustrated in Figure 2. The corrugated horn will produce a Gaussian antenna beam which is focused by the teflon lens into the plasma through a wedged quartz window. The HE_{11} corrugated horn mode will be converted to a circular TE_{11} mode for transmission in a 12.7 mm diameter copper guide with a transition to WR-8 guide at the receiver. Miter bends will be used if necessary. A viewing dump [8] constructed of a suitable absorbing vacuum material such as macor, boron nitride, or silicon carbide will be used on the inner vacuum vessel wall. Transmission line losses are estimated to be -1.5 dB for a 10 m long line from the horn to receiver. An additional -1.2 dB loss is expected due to reflections at the lens and window surfaces.

The receiver, shown in Figure 3, has a much larger bandwidth than previously used in this type of system [9]. It will have a 100 GHz high pass filter following the scalar feedhorn to prevent viewing ECE emission in the receiver's lower sideband. The RF signal will be downconverted in frequency from 102-140 GHz to 2-40 GHz with a mixer having a 6.5 dB conversion loss and 100 GHz Gunn diode LO. The mixer will have a ~40 GHz instantaneous IF bandwidth which is possible with planar circuit technology and Schottky barrier beam lead diodes [10]. The resulting ultrawide IF bandwidth will be amplified by a broadband amplifier from 2-40 GHz which is just now becoming available commercially [11,12]. Monolithic microwave integrated circuit (MMIC) and microwave integrated circuit (MIC) technologies have improved to the point of providing workable low noise (~12 dB noise figure) and moderate gain (~10 dB) ultrawide bandwidth amplifiers. The resulting system noise temperature assuming a 4 dB front end loss is estimated to be T_S = 50,000 K or 4.3 eV at the plasma.

The amplified signal will be split into 14 individual channnels from 2 to 40 GHz with a combination of a diplexer and two 7 channel multiplexers [13]. An off-the-shelf diplexer will split the IF bandwidth into two channels of 2-18 GHz and 18-40 GHz. Additional amplification will be provided by commercially available amplifiers for each of these frequency ranges [12] following the diplexer. Another off-the-shelf multiplexer can easily be modified to provide 7 channels of approximately 2.3 GHz bandwidth which will range from 2 to 18 GHz. A 7 channel multiplexer from 18-40 GHz with approximately 3 GHz bandwidths can also be fabricated with suspended substrate stripline technology [13].

The 18-40 GHz multiplexer is technically harder to design, and correspondingly higher in cost (factor of approximately 3) than lower frequency multiplexers; however, an alternative receiver design based on two 0.1-18 GHz IF receivers to cover a ~ 40 GHz bandwidth would cost approximately the same. Relative phase measurements between channels across the entire emission spectrum for fluctuation wavenumber determination would also be more reliably accomplished with a receiver using only one mixer/LO combination. The output 2.3 and 3 GHz multiplexer channel bands would be detected with square law detector diodes and amplified with 30 dB of voltage gain before being digitized.

The fluctuation level sensitivity of this instrument is given by the well-known result of radiometer theory which was experimentally verified for tokamak ECE [14]

$$\frac{\tilde{I}_{ece}}{I_{ece}} = \frac{1}{\sqrt{\Delta f \tau}} \tag{7}$$

where Δf is the channel bandwidth and τ is the integration time. Maximizing the channel bandwidth to correspond to the ~2 GHz Doppler broadening at 2 keV minimizes the observable fluctuations without sacrificing spatial resolution. The integration time is limited by the flucutation frequencies of interest, which in this case for Ballooning modes are expected to fall in the 0.1 to 1 MHz range. The corresponding fluctuation level sensitivity therefore falls in the range $\tilde{I}_{ece}/I_{ece}$ = 0.9 - 2.9% = $\gamma\, \tilde{n}_e/n_e + (3/\beta)\tilde{T}_e,T_e$ for the 2.3 GHz channels. This would also be the sensitivity to electron temperature fluctuations if the plasma is optically thick (γ = 0, β = 3). However if the plasma is optically thin ($\gamma = \beta = 1$) and $\tilde{n}_e/n_e = \tilde{T}_e,T_e$ then the observable fluctuation threshold would decrease to $\tilde{T}_e/T_e$ = 0.2 - 0.7%.

It is planned that two of these ultrawide bandwidth receivers be built. The ECE diagnostic will then simultaneously acquire temperature and density fluctuations at 14 volumes along each of two horizontal chords; one equatorial chord will provide information to the radial mode structure, while an off-equatorial chord will provide signals dependent on a combination of the radial and poloidal structure of the mode. The second chord could also be displaced toroidally for sampling toroidal structure. Such a simultaneous k_r, k_θ, and k_ϕ measurement capability has not been previously attempted by ECE fluctuation diagnostics.

The data acquisition electronics would include 100 kilosamples per second digitizers for all 28 channels to economize on cost, and 2 or more fast transient digitizers of at least 20 megasamples per second for fast fluctuation studies in select channels.

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Figure Captions

Fig. 1 Frequencies of the first five electron cyclotron harmonics as a function of major tokamak radius. The shaded areas indicate frequency overlapped regions.

Fig. 2 Illustration of the receiver front end components for the PBX-M ECE diagnostic.

Fig. 3 Block diagram of a 14 channel ultrawide heterodyne receiver using commercially available components for electron cyclotron emission fluctuation diagnostics.

ELECTRON CYCLOTRON HARMONICS

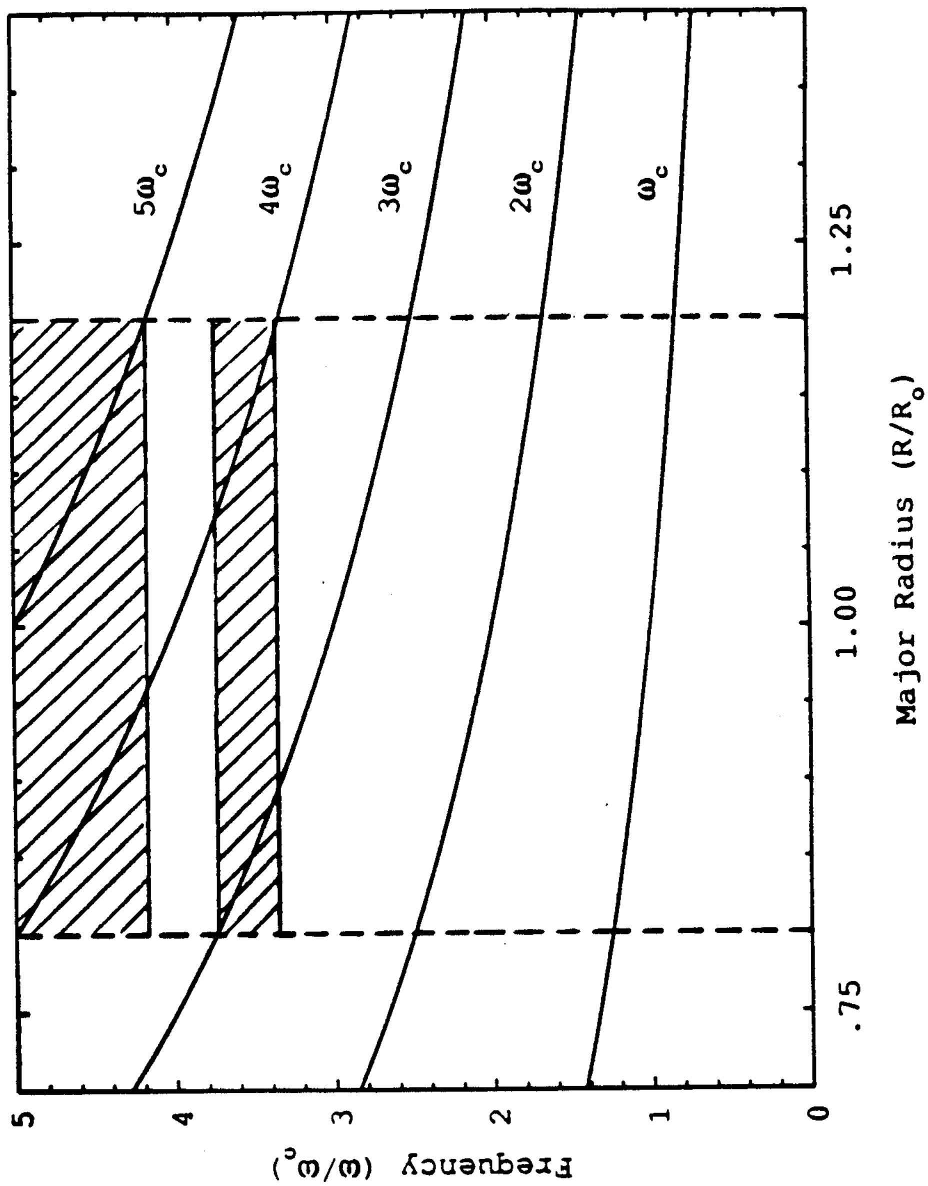

Fig. 1

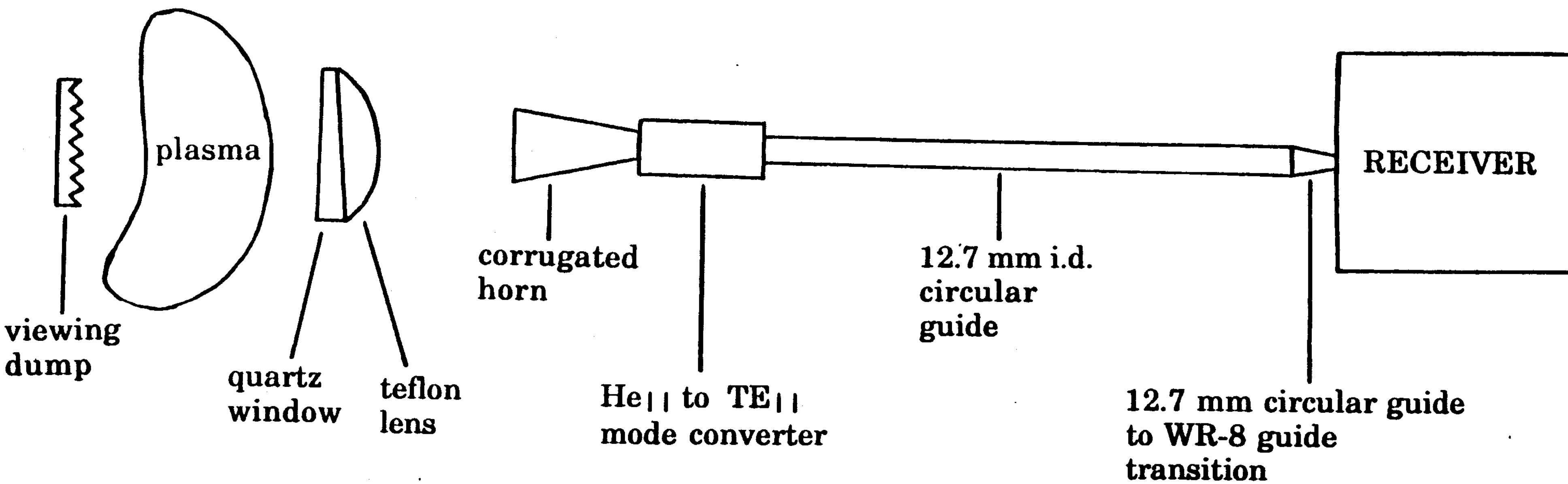
viewing
dump
plasma
quartz
window
teflon
lens
corrugated
horn
He_{11} to TE_{11}
mode converter
12.7 mm i.d.
circular
guide
12.7 mm circular guide
to WR-8 guide
transition
RECEIVER

Fig. 2

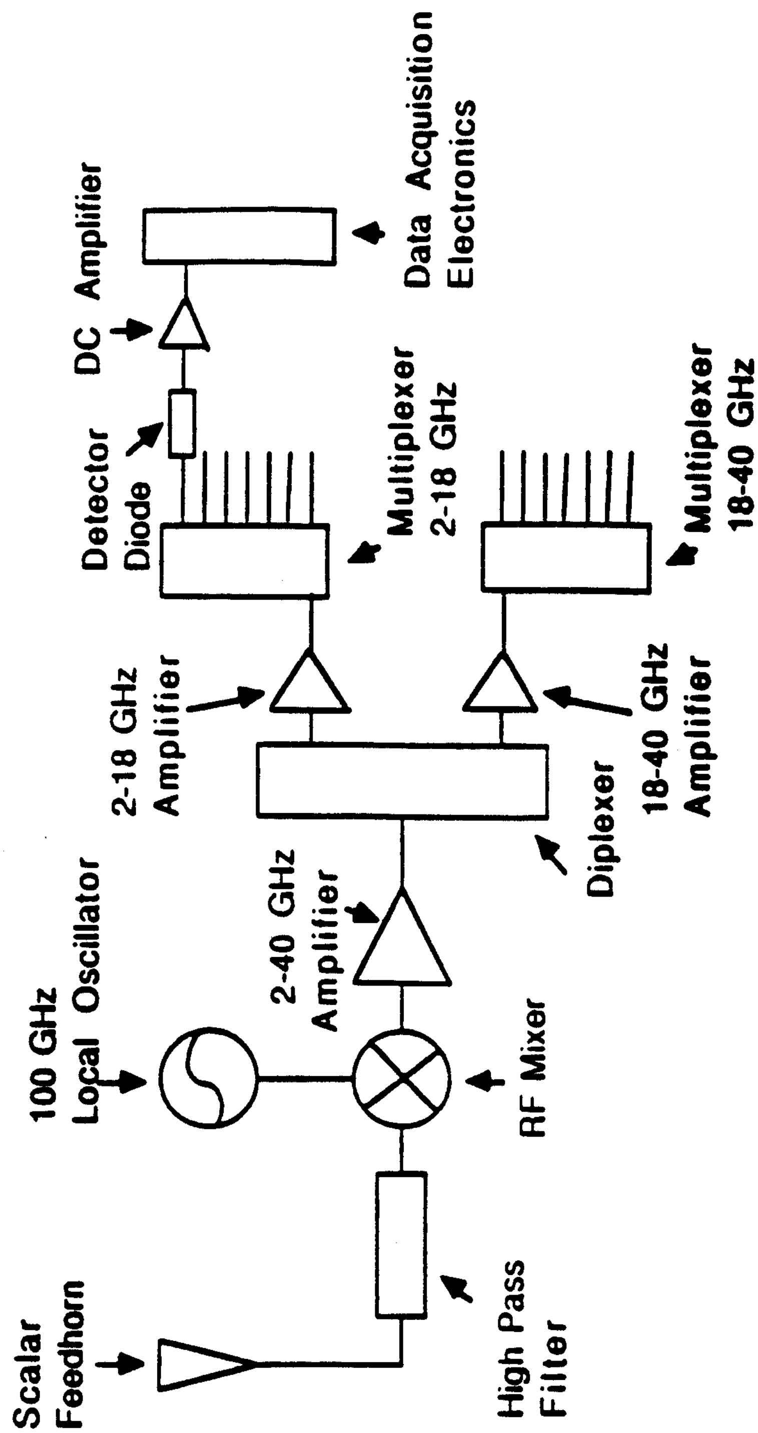
Scalar Feedhorn
High Pass Filter
100 GHz Local Oscillator
RF Mixer
2-40 GHz Amplifier
Diplexer
2-18 GHz Amplifier
18-40 GHz Amplifier
Multiplexer 2-18 GHz
Multiplexer 18-40 GHz
Detector Diode
DC Amplifier
Data Acquisition Electronics

Fig. 3