OBSERVATIONS OF PLASMA STIMULATED ELECTROSTATIC SIDEBAND EMISSION AND HARMONIC DISTORTION: EVIDENCES OF OVER-DENSE PLASMA GENERATION INSIDE A MICROWAVE DISCHARGE ION SOURCE

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Abstract

Microwave discharge ion source (MDIS) is used in many applications including accelerators based neutron generators on suitable target through D-D or D-T fusion. In this device, the electromagnetic (EM) pump wave ($\omega_0$) can propagate through plasma beyond cut-off plasma density by changing its polarity and/or decomposing into different daughter waves through which it transfer its energy and produces over dense plasma. In the present experiment, the plasma stimulated emission spectra was measured in the frequency range 0.5\omega_0 to 3\omega_0 to understand the different probable energy decay channels role: e.g. Electron Bernstein waves (EBWs), Ion cyclotron waves (ICWs), Lower hybrid oscillations (LHOs), Ion Bernstein waves (IBWs) and Ion Acoustic Waves (IAWs) etc. Present experimental device, MDIS contains eight distinct cavity modes under vacuum conditions (also called vacuum mode) within 300 MHz bandwidth around pump wave ($\omega_0$) of the launched MW. Some of these vacuum modes are found to match with the plasma induced modes (plasma mode) and depends on the different plasma loading conditions. Resonant interaction between these two types of modes (vacuum mode and plasma mode) leads to the parametric decay into another lower frequency microwave and also electrostatic ion/electron type waves. The energy decays through different ion-type waves by parametric instability is studied by observing the different side-bands generation around the pump frequency ($\omega_0$) and also around the electron cyclotron (EC) harmonic frequencies. The density threshold of each electrostatic IAWS/ICWs was measured by stepping pump wave amplitude and external magnetic field. The IAWs lines appeared at lower density threshold than the ICWs emission lines. The measured IAWs and ICWs ranges from 238-873 kHz and 1.2 - 3 MHz respectively with a density jump from 9.3x10^{16}/m^3 to 4.9x10^{17}/m^3. At higher density (>3.3x10^{17}/m^3), the electrostatic ICWs lines dominates over the IAWs thereby yielding negligible damping through ion waves.

1. INTRODUCTION

Electron cyclotron resonance heating (ECRH) by launching an electromagnetic wave (EM wave) of frequency in the range of 1 - 100 GHz, is an auxiliary plasma heating tool in fusion reactors [1-3]. During the propagation of such electromagnetic (EM) pumping wave, it suffers scattering from different plasma layers of different plasma conditions and correspondingly generates electrostatic (ES) sideband frequencies. The scattered EM and electrostatic side bands around the pumping wave and its harmonics are experimentally observed in such machines at the high density plasma locations [4-5]. The low frequency sideband waves can strongly be absorbed accompanied by rapid heating (turbulent) of electrons or ions through parametric decay processes [6-10]. Theoretical considerations show that the frequency spectrum around pumping frequency and its growth rate is directly linked with the plasma density [11]. There is a threshold plasma density vis.-a-vis. with threshold input power of the pump wave (or launched MW) where parametric decay starts dominating. Generation of sidebands in the frequency spectrum around the pump wave frequency is the signature of parametric decay and over-dense plasma condition. Energy associated with other resonant modes also able to create over-dense plasma by overcoming apparent critical density barrier for pump wave propagation. In this regard, different probable energy decay channels are: Electron Bernstein waves (EBWs), Ion cyclotron(IC) waves, Lower hybrid oscillations (LHOs), Ion Bernstein waves (IBWs) and Ion Acoustic (IA) Waves etc. [12-14].

In the present laboratory experiment, 2.45GHz pump wave ($f_0 = \omega_0/2\pi$) is launched in a Microwave (MW) Plasma discharge. The spectrum is taken below and above the critical density (~7.4x 10^{16}/m^3) for different plasma absorbed power in the range of 30-160 W, under static applied magnetic field, and pressure conditions. A RF probe is used to pick up all the plasma oscillations in the plasma in the frequency range 0.5 $\omega_0$ to 3 $\omega_0$ using handheld Spectrum Analyser. The different ranges of frequencies are selected by different band-pass
filters. During the experimental campaign, eight different cavity resonant modes (multi-mode) are detected inside the vacuum cavity within ± 300 MHz bandwidth of the pump frequency. Multiple mode frequencies supported by the cavity (without plasma, called as vacuum modes) are excited selectively by tuning the absorbed power, gas pressure and magnetic field intensity. It is found that some of the vacuum modes overlap with the modes exists during plasma operation under some experimental conditions. With the increase in absorbed power, the plasma density above the critical density is achieved for the launched MW (pump wave). In that condition, nearby three distinct plasma induced modes around the launched one (2.45 GHz), are also observed. This indicates that MW power from some of the vacuum modes is getting coupled resonantly through these plasma induced modes and is responsible for increasing the plasma density far beyond the critical density. Consequently, these dominant plasma modes are decayed parametrically and/or scattered in the over-dense plasma. Considering the dispersion relation it is understood that the MW power associated with these sidebands are decayed through the electrostatic branches energizing the electrons and ions which are evident in the observed frequency spectrum. The distortion around the 2nd harmonic (2\(\omega_0\)) of pump wave is reported in the present manuscript.

2. METHODS

A schematic view of the plasma diagnostic setup is shown in figure 1 below. Four ring magnets (1.38 T each) surround the plasma chamber co-axially to distribute magnetic field lines (B) in mirror-B as well as high-B configurations modes. Each ring magnet dimension (ID, OD and length) is (100 mm, 180mm OD and 30 mm). A boron nitride (BN) plate is placed at the inner plasma-grid surface to get higher extracted ion current density and also to visualize the different plasma distribution pattern on its surface contributed by different cavity modes. The extraction grid is designed to float at 50 kV maximum during beam extraction phase of operation.

![FIG. 1: Schematic of diagnostics set up for the microwave discharge plasma.](image)

Microwave is produced by a 2 kW MW generator capable of operating in continuous or pulsed mode. A bi-directional coupler is used to detect the forward and reflected power spectrum of different resonant modes with and without the plasma. The breakdown of N\(_2\) gas in vacuum is done by injecting the magnetron set-power from 50W to 700W. The plasma reflection increases with increase in set power in the range of 40-70%. Hence, mentioning the plasma absorbed power is more meaningful than the set power and is used throughout the manuscript. To examine the resonating structure of the vacuum chamber, a part of experimental campaign is dedicated to the exploration of different auto-frequencies (also called as cavity modes) present inside the cavity. A RF probe detects frequencies inside the cavity with and without plasma in the range of 0.5 \(\omega_0\) to 3\(\omega_0\) which are displayed in a handheld spectrum analyser. Out of the above mentioned frequency range; a particular band under concern (such as pump frequency and its 2nd harmonic region) is selected by means different band pass filters. In spite of launching single mode MW, different cavity auto-frequencies are observed inside the cavity volume around the pumping frequency (2.45 GHz). The other resonant modes are cavity configuration geometry dependent and are originated which occur due to the attachment of some extra components such as, ridge waveguide, the HV break part and the vacuum window etc. These extra dimensions cause to excite different
resonant modes near to the driving frequency. The ridged waveguide increases the bandwidth of propagating frequency so as to enable the pumping frequency band (2.425-2.475 GHz) to resonate with any one of the resonant-modes of the cavity and thus are also responsible in creating the plasma. The chamber is regularly maintained at base pressure \( \approx 1 \times 10^{-6} \) mbar and all the frequency emission spectra are observed in the pressure range of \( 2 \times 10^{-3} - 1 \times 10^{-3} \) mbar.

The plasma floating potentials are recorded by two independent single Langmuir probe circuits simultaneously as shown in figure 1. A time-varying signal of floating potentials separately coming from the two probe tips is identified in a battery powered oscilloscope. The k-vector of the plasma waves is constructed by aligning the plane of two probes in the perpendicular as well as parallel direction with respect to the B-field. The phase difference of the floating potential of each probe divided by their separation measures the wavenumber k.

3. EXPERIMENTAL RESULTS

3.1 Electrostatic sideband emission

Measurement of characteristic frequency oscillations of MW discharge plasma have been carried out systematically for different power levels, pressure levels and magnetic field values. Frequency characteristics of plasma stimulated emission are obtained at different input power levels during the transition of plasma from under-dense to over dense state. At first, the spectrum in vacuum cavity is measured to identify different cavity modes available inside the chamber. Results shown below (fig. 2 and table-1(column 1)) show different vacuum modes inside the cavity which can be considered as independent pump waves.

\[
\text{FIG 2. Fundamental possible resonant modes exist in the experimental cavity and express in table-1.}
\]

\[
\text{TABLE 1: COMPARISONS BETWEEN VACUUM INDUCED MODES AND PLASMA INDUCED MODES (AS SHOWN IN FIGURE 4) IN MDIS FOR FIXED POWER OF 70 W AND PRESSURE 1.5 \times 10^{-4} MBAR.}
\]

<table>
<thead>
<tr>
<th>Mode</th>
<th>Vacuum cavity induced mode frequency (GHz) and peak no. (figure 2)</th>
<th>Plasma induced mode frequency (GHz) and peak no. (see figure 4) at 70 W</th>
<th>Normalized intensity(Vacuum and plasma mode)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{TE}_{111} )</td>
<td>2.2879 and (1)</td>
<td>2.457 ( (f_0) ) and (pump wave) #1</td>
<td>0.28 and 0</td>
</tr>
<tr>
<td>( \text{TE}_{111} )</td>
<td>2.3782 and (2)</td>
<td>Not appeared</td>
<td>0.579 and 0</td>
</tr>
<tr>
<td>( \text{TE}_{111} )</td>
<td>2.4079 and (3)</td>
<td>Not appeared</td>
<td>0.64 and 0</td>
</tr>
<tr>
<td>( \text{TE}_{111} )</td>
<td>2.4569 and (4)</td>
<td>2.5339 and #2</td>
<td>1 and 1.1</td>
</tr>
<tr>
<td>( \text{TE}_{111} )</td>
<td>2.53988 and (5)</td>
<td>Not appeared</td>
<td>0.37 and 2.75</td>
</tr>
<tr>
<td>( \text{TE}_{111} )</td>
<td>2.56845 and (6)</td>
<td>2.6323 ( (f_3) ) and #3</td>
<td>0.38 and 0</td>
</tr>
<tr>
<td>( \text{TE}_{111} )</td>
<td>2.63289 and (7)</td>
<td>Not appeared</td>
<td>0.32 and 2</td>
</tr>
<tr>
<td>( \text{TM}_{010} )</td>
<td>2.69138 and (8)</td>
<td>2.6881 ( (f_4) ) and #4</td>
<td>0.27 and 0.8</td>
</tr>
</tbody>
</table>
The density jump with increase in absorbed power is observed in this source. The electron plasma and ion plasma frequency is determined from the recorded density rise as a function of absorbed power. Figure 3 shows the variation of density in terms of electron plasma frequency \( f_{pe} \) and ion plasma frequency \( f_{pi} \) with power. It indicates that due to the density jump, \( f_{pe} \) jumps from fundamental to 2\(^{nd}\) harmonic of the launched MW frequency (~ 2.45 GHz) at power threshold of 70W. The \( f_{pi} \) changes from ~12 MHz to ~ 30 MHz within the above mentioned power range.

**FIG. 3:** Variation of electron and ion plasma frequency due to plasma density variation with power corresponding to launched MW mode

The launched pump frequency (2.45 GHz) is actually having bandwidth of 50 MHz but the plasma induced resonant modes spread up around this launched mode within bandwidth of ~300 MHz (see figure 4). The frequency deviation of each plasma modes (see figure 4) from their corresponding vacuum modes is verified with analytical calculation which is discussed later in section 4 [15-16]. Out of available eight vacuum modes in the present experiment, mainly three modes (peak no. 3, 4 and 5 in fig.2) contribute to the plasma heating primarily. The different cavity dependent resonant modes without plasma (as shown in fig.2) and how their characteristics are modified in presence of plasma with different impedance matching conditions are shown in figure 4 and Table 1 (2\(^{nd}\) column). In figure 4, interaction of multiple plasma modes is also shown for different power coupling scenarios. The resonant MW power absorption through these modes (peak #1, \( \text{TE}_{111} \) at 2.457 GHz, peak #2, \( \text{TM}_{111} \) at 2.533 GHz and peak #3, \( \text{TE}_{111} \) at 2.6323 GHz and peak #4, \( \text{TM}_{010} \) at 2.688 GHz) causes’ different populations of plasma density as per their respective cut-offs and resonant conditions. In case of less matched condition (30% matching), the MW power is not coupled enough to generate higher plasma density. Correspondingly only two side frequencies (one low and one high) around the four plasma induced modes (figure 4) is only visible. For 77% matching case, the MW coupled power is sufficiently large. Hence, the MW electric field corresponding to the plasma modes at peak #2 and #3 (see figure 4) generates two lower and one
upper sideband frequency. The extra lower sideband (f' or f'') appeared in higher coupled-power case probably the signature of Lower Hybrid Oscillation (LHO) [13], due to the fact f_{ci} < f_{LHO} < f_{ce}. The difference between the plasma mode frequency (2.45 GHz or 2.53 GHz) and the electron plasma frequency (f_{pe}) gives the ion plasma frequency (f_{pi}) as per the selection rule reported in the reference [17] and is shown in figure 4. The selection rules are:

\[ f_0 = f_1 \pm f_2 \text{ (conservation of kinetic energy)} \]
\[ k_0 = k_1 \pm k_2 \text{ (conservation of momentum).} \]

Here, f0, f1, f2 and k0, k1, k2 are frequencies of pump wave, scattered pump wave and electrostatic ion/electron wave and their corresponding wavenumbers respectively.

Figure 5 shows there is no sidebands present around the pumping wave (f0) below the absorbed power of 50 W. There is one additional dominant distinct peak (2.43 GHz) observed downshifted from pump frequency which is nothing but the electron plasma frequency (f_{pe}) corresponding to the plasma density \(7.32 \times 10^{16} \text{m}^{-3}\). With increase in power (30-50W), the density increases, so f_{pe} gets closer to the pumping frequency 2.45GHz. A broad peak identified as ion cyclotron resonance peak appears because of resonant interaction of gyrating ion wave at the resonance with the scattered electromagnetic pump wave.

**FIG. 5:** Frequency spectrum features around launched pump frequency \(f_0\) (\(\Delta f = f - f_0\)) for different input power which corresponds to characteristics emission from plasma at the under dense condition.

**FIG. 6:** Electrostatic low frequency emission lines (number of IAWs lines dominates ICWs lines) with absorbed power from 90 W to 130 W in over-dense plasma.

With further increase in power from 70 W to 80 W, density jumps and so f_{pe} jumps (f_{pe} \approx 4.37GHz) iconically to the region of \(2^{\text{nd}}\) harmonic (4.9 GHz) of the launched MW (figure 3). The moment (at 70W) the electron density \(9.3 \times 10^{16} \text{m}^{-3}\) reaches just above the critical density for pump wave and so, the \(2^{\text{nd}}\) harmonic takes
part of resonance plasma heating in stead of primary pump wave. Primary pump wave is scattered/reflected from the corresponding critical density surface. In addition, a significant amount of energy transfer occurs through damping of low frequency electrosttaic (LFES) type waves (~100 kHz – 10 MHz range) in the over-dense region which is shown in figure 6 below [10], since ES waves do not see any density cutoff. This energy channelling through the LFES waves is an indication of the parametric decay of the launched MW and its different resonant modes, as indicated in fig.4. Figure 6 shows four plasma modes are getting decayed parametrically into LFES waves which are seen in their respective sidebands. The LFES waves are recognized as IAWs and ICWs from the dispersion relation will be discussed later in detail in the manuscript. In figure 6, the sidebands around the plasma modes #1, #2, #3 and #4 for 90 W and 100 W powers, is recognised as IAWs. These IAWs vary in the frequency range of 238 - 873 kHz. Whereas, the number of ICWs peak is found to be more than the IAWs peak in the 130 W case. The frequency of ICWs ranges from 1.2-3.8 MHz’s.

3.1 Harmonic distortion

As discussed before, a part of the experimental activities is devoted to find out a co-relation between the 2nd harmonic distortion and the instability occurred in the overdense plasma. It is seen in figure 7 and 8(a) that during the $f_{pe}$ jump (near P=70W in figure 3), there is an increase in emission intensity at 2nd and 3rd harmonics of launched MW of frequency $f_0 = 2.45$GHz. As soon as $f_{pe}$ is more than 2.45 GHz due to density increase, emission intensity corresponds to 2nd harmonic sharply increases. The efficient electron heating (limited by density) occurs in the vicinity of integral multiples of electron cyclotron (EC) frequency. A strongest emission peak at 2nd harmonic at 80W input power is observed because at this power level density reaches equivalent to the 2nd harmonic of EC in upper hybrid frequency ($2f_0 = 4.9$GHz). After that it decreases with increase in power. It implies that 2nd harmonic of pump wave is getting absorbed due to the resonance with the electron plasma frequency in the 2nd harmonic range. From 100W onwards, the third harmonic emission peak increases clearly indicating no electron heating. This is because the $f_{pe}$ for density, $2.9 \times 10^{17}$m$^{-3}$, is in the region of 2nd harmonic EC frequency only.

![FIG.7](a): Full plasma oscillation spectrum (range: 0.5$a_0$ to 3$a_0$) under different plasma absorbed power. (b) Focus of the 2nd harmonic zone of figure 7(a)

![FIG.8](a): Different harmonics emission intensity with plasma density jump and their sideband peak deviation, identified as parametric instability of pump wave
The frequency peaks developed (see figure 7) near the 2nd harmonic ($\omega_{ce}/\omega_0 = 1.9$) due to the non-potential oscillations ($\omega_{pe} < \omega < 2\omega_{ce}$) and also the emission peaks at $\omega_{ce}/\omega_0 = 2$ due to the 2nd harmonic of the pump wave with the natural mode of the electron longitudinal plasma oscillations identify the instability in a plasma[18]. The above information, as described in previous reports is still insufficient to ensure the type of instability which is also observed in the present experimental results (see figure 8a and b). It reveals that the intensity of frequency peaks (figure 8a) at 1.9 $\omega_0$ is invariant to the plasma density rise. With increase in density (figure 8b), the frequency deviation of emission peak at 1.9$\omega_0$ from 2$\omega_0$ decreases sharply. So, the instability also increases [18] sharply at this density jump (see figure 8b). Another new feature in the frequency spectrum to describe the instability appropriately is the behaviour of frequency peaks at 1.74 $\omega_0$ which is shown in figure 7. It is evident that intensity and position at this peak changes simultaneously with change in power from 40 W to 60 W. The intensity and its growth rate clearly identify the instability here. The frequency at 1.74 $\omega_0$ can ensure the instability more appropriately than the peak at 1.9$\omega_0$ because the former peak shows its deviation (from 2nd harmonic) and intensity, both vary simultaneously with the density transition. But the latter one shows only the frequency deviation with respect to density transition as shown in figure 8(b). Detailed information about this peak will be studied later.

4. THEORETICAL ANALYSIS

To find out the vacuum pump mode shift in presence of plasma (as observed in figure 4) analytically, the frequency relation of different modes in terms of electron plasma frequency is written as follows [19].

$$f_{nml}^{TE/TM} = \left(\frac{f_{pe}}{2\pi n} + \frac{c}{2\pi n}(r_{mn}^2 + \left(\frac{b}{a}\right)^2)\right)^{1/2}$$

Where $f_{nml}^{TE/TM}$ are chamber mode frequencies with 3D field pattern, characterized by the integer, $n$ ($\geq 0$), $m$ ($> 0$) and $l$ ($\geq 0$). The $f_{pe}$, $c$, $d$, $a$, and $r_{mn}^2$ ($= r_{mn} \times a$ for TE mode) are electron plasma frequency, speed of light, chamber length, radius and $m$ root of the first derivative of n-order Bessel function respectively. Using the above relation, the plasma induced mode frequency is estimated as 2.5339 GHz at 70 W. So, the shift with respect to vacuum mode frequency (2.4569 GHz) is ~ 80 MHz’s. Hence, the plasma induced mode (figure 4) having peak no. #1 matches peak (4), of the vacuum mode (see figure 2). In the same fashion, the peak #2 (figure 4) also matches with the peak (5) of vacuum mode as shown in figure 2. The last distinct peak #4 in figure 4 is also resonated with peak (8) of the vacuum induced mode with the frequency of 2.69 GHz. The ion plasma frequency is calculated from the electron density which is different for the different plasma induced modes. It ensures that each mode contributes to the heating of plasma and thereby yielding different plasma density populations within the source volume.

5. DISCUSSION

The experimental observations of sidebands as shown in the previous figures 4-7 can be explained through parametric decay and scattering phenomena of the launched MW in the plasma. In the present experiment, X-mode MW is launched using a ridged waveguide from the high field side of one set of the permanent ring magnet, as shown in figure 1. If MW is parallel to the magnetic field axis, it is capable to propagate towards the dense plasma region. However, due to mirror field configuration as in the present setup, MW axis does not exactly coincide with the magnetic axis. As a result both X-mode and O-mode would exist in the plasma irrespective of launching pure X-mode.

The MW launched in X-mode crosses the ECR surface without any energy transfer because the ECR contour (0.0875 T) is screened by the dense plasma. The pump MW is converted into different ES waves (e.g. EBW and different Ion waves) [14]. In addition, MW decays into lower frequency MW (LFMW) which propagates out of the dense plasma region and may see lower cut-off zone outside the main cutoff corresponding to launched MW. The decayed LFMW is scattered back and forth on the different density iso-surfaces mainly in the radial direction. In this way complete absorption of MW normally takes place outside main cutoff. These converted ES waves then crosses the cut-off density and enter into higher density region. As soon as ES waves enter the UHR region ($\omega_{thb}^2 = \omega_{ce}^2 + \omega_{pe}^2$) where plasma density is above cut-off and below 2nd harmonic resonance, are damped and density is increased further. ES waves are categorized as low frequency electrostatic(LFES) named as IAWS, ICWs and lower hybrid oscillations (LHOs) and high frequency electrostatic waves (HFES) such as, electron Bernstein waves (EBWs) etc. [20].

The energy from pump wave decays through different ion-type waves (IAWS/ICWs) by parametric instability and is studied by observing the different side-bands generation around the pump frequency and also around the electron cyclotron (EC) harmonic frequencies. The density threshold of triggering IAWS/ICWs was monitored...
by stepping pump wave amplitude and external magnetic field. The IAWs lines appear at lower density threshold than the ICWs emission lines. The measured IAWs and ICWs ranges from 238-873 kHz and 1.2-3 MHz respectively with a density jump from 9.3×10^{16}/m^3 to 4.9×10^{17}/m^3. At higher density (> 3.3×10^{17}/m^3), the electrostatic ICWs lines dominates over the IAWs thereby yielding negligible damping through ion waves. It is observed that the frequency spectrum is broader compared to that of pump wave due to the plasma surface and/or volume scattering phenomena. The width of the spectrum depends on the plasma density or input power. In addition there are some specific frequency peaks observed within this range which varies systematically with pump wave input power.

6. REFERENCES