OBSERVATION OF HIGH-FREQUENCY OSCILLATIONS IN THE TUMAN-3M OHMIC PLASMAS

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Abstract

The use of ADCs with sampling rate of 2.5 GHz allowed observation of magnetic oscillations in the frequency range of 0.3 to 1.25 GHz. In this range comb-like spectra have been found in the ohmically heated plasma with average density $0.5\text{-}1.3{\cdot}10^{19}$ m^{-3}. The wave generation has character of bursting emission which correlated with spikes of the gamma-ray intensity. Deconvolution of gamma-ray spectra allowed to conclude that emission bursts arose when maximum of runaway electron energy attains 4-5 MeV. According to analysis the anomalous Doppler resonance of runaway electrons may lead to excitation of whistler waves in the above frequency range. Bursts of waves may contain 40 to 60 peaks with frequency gaps increasing with frequency from 16 to 26 MHz at density 0.5-0.6 10^{19} m^{-3}. At higher density (0.8 10^{19} m^{-3}) number of peaks reduced to 35 and frequency gap became constant. Possible explanation for the comb-like shape of the whistler spectrum are internal reflections from cut-off layers and conversion of whistlers into magnetized plasma waves and back.

1. INTRODUCTION

The first mentions of waves excited by accelerated electrons appeared long ago [1]. These waves are observed in cosmic [2], atmospheric [3] and laboratory plasmas [4,5,6]. Such waves, arising in the frequency range of $\omega_{ci} < \omega < \omega_{ce}$, are usually whistlers or high frequency electron plasma waves [7,8,9]. The dispersion of these waves is described by the wave equation for cold magnetized plasma [10,11]. The importance of studying whistlers is due to the possibility of using them for angular scattering of runaway electrons (RE) [5,8], which are extremely dangerous for the first walls of modern and future thermonuclear devices [12].

In tokamaks, whistlers have so far been observed at DIII-D [6,9], where they appear as numerous irregular discrete modes in the 100-200 MHz range, which is significantly below the lower hybrid frequency ω_{LH} and roughly corresponds to 8th-10th harmonics of the Ion-Cyclotron Resonance frequency. The frequency of the observed modes followed the magnetic field and depended weakly on density. It was found that the frequency gaps are caused by the presence of spatial resonances provided by toroidal periodicity and reflections from the cut-off regions. Besides, plasma emission in the presence of energetic electrons was detected at the FTU tokamak [13,14], where the emission frequency corresponded to the lower hybrid frequency, and at the FT-2 tokamak [15], where intense bursts in the LH range (0.2-1.0 GHz) were observed in the ohmic regime. It should be noticed that RE driven instabilities causing rapid increase of the perpendicular energy, so called “fan” instabilities, were observed in the early tokamaks, [16,17]. Theory explaining these bursts by excitation of magnetized electron plasma waves was developed [18] though frequencies of these waves are substantially higher than the whistlers’ ones.

Besides above-mentioned observations of whistlers, two types of high frequency magnetic oscillations have been found in the experiments with low-density ohmic plasma in TUMAN-3M [19]. First, the oscillations with relatively long duration (0.1-1 ms) characterized (1) by a high frequency range – from 120 to 290 MHz, which is substantially higher than Ion Cyclotron Resonance frequency, (2) by frequency decrease throughout the entire duration time and (3) by absence of an explicit harmonic structure. Detected frequency gap between discrete spectral peaks varies from 18 to 60 MHz. An analysis has shown this type of emission has signatures of whistlers excited by energetic electrons. Second, short timescale oscillations (10-20 μs) characterized by clear harmonic structure with up to 7 detectable harmonics and by lower range of fundamental harmonic frequency – 18-40 MHz. In some shots splitting of harmonics with small gaps of ~ 4.2 MHz was found. Total number of satellites can be as high as 6 instead of a single peak harmonic. The second type of the emission was named High Frequency Emission (HFE) since typical values of fundamental frequency is higher than ω_{ci}.

This report presents first observations of plasma emission in the TUMAN-3M in the range of 0.3-1.25 GHz. The experiments were performed in ohmic plasma with relatively low average density – 0.4-1.3 10^{19} m^{-3}. In section 2 a characterization of the observed emission is presented, in section 3 estimations of a RE maximal energy using gamma-ray spectrometry are reported. Section 4 summarizes the obtained results.

2. CHARACTERIZATION OF THE EMISSION IN THE RANGE OF 0.3-1.25 GHZ

Magnetic oscillations have been measured using array of magnetic probes sited at internal surface of circular cross-section of the vacuum vessel ($r_{vv} = 0.257\ m$). Detailed description of the array setup is given in [20]. The array consists of 16 probes which are placed equidistantly in the poloidal direction in a single meridional cross-section, between adjacent toroidal field coils. Two of the probes were equipped with ADCs with sampling rate of 2.5 GHz. One – at poloidal angle 33 degrees upwards from equatorial plane at the low field side and second – at poloidal angle 123 degrees upwards from the equatorial plane at the low field side. Other probes in the array were equipped with ADCs with sampling rate of 0.5 GHz. Another two probes with 2.5 GHz ADCs were placed in the equatorial plane at the low field side at toroidal angle 12 degrees from “array” cross-section, between adjacent toroidal field coils.

Measurements were performed in series of discharges with toroidal field at vessel axis ($R_0 = 0.55\ m$) $B_t(0) = 0.72 - 0.92\ T$, plasma current $I_p = 120 - 140\ kA$, average density $\bar{n}_e = (0.4 - 1.3) \cdot 10^{19}\ m^{-3}$. In addition to the array of fast magnetic probes a standard set of diagnostic tools have been used in the experiments. The set includes electromagnetic loops and Mirnov coils, 10-channel microwave interferometer, array of Surface Barrier Diodes for Soft X-Ray (SXR) detection, H/D-alpha detectors, Neutral Particles Analysers, Hard X-Ray (HXR) detectors for emission measurements. Setup of the HXR diagnostic includes two tangentially directed HPGe (High Purity Germanium) gamma spectrometers. One of them (“ch-t-vol”) directed to minimize gamma-rays scattered by surrounding metallic structures collects emission preferably from plasma volume. Other one (“ch-t-lim”) directed to low field side tungsten limiter collects emission arising due to interaction of REs with the limiter. The both detectors are calibrated to provide spectra of gamma-rays. The DeGaSum deconvolution code [21] is applied to obtain spectra of accelerated electrons from measured gamma-ray spectra.

The use of ADCs with sampling rate of up 2.5 GHz in the recent experiments made it possible to detect bursts of oscillations, which spectra extended to 1.25 GHz. Example of the spectrogram obtained in deuterium plasma with the average electron density $\bar{n}_e = 0.67 \cdot 10^{19}\ m^{-3}$, toroidal magnetic field is $B_t(o) = 0.83\ T$ is shown in Figure 1. Duration of the high-frequency bursts was in the range of 10-100 µs. In few cases, the bursts duration extended to 400 µs. The highest frequency in the spectrum is close to $4\omega_{LH}$, and the minimum is $\sim 2\omega_{ci}$, where ω_{LH} is the Lower Hybrid frequency, ω_{ci} is the deuterium Ion Cyclotron Resonance frequency at the strong magnetic field side of the torus. Observed oscillations were identified as whistler waves.

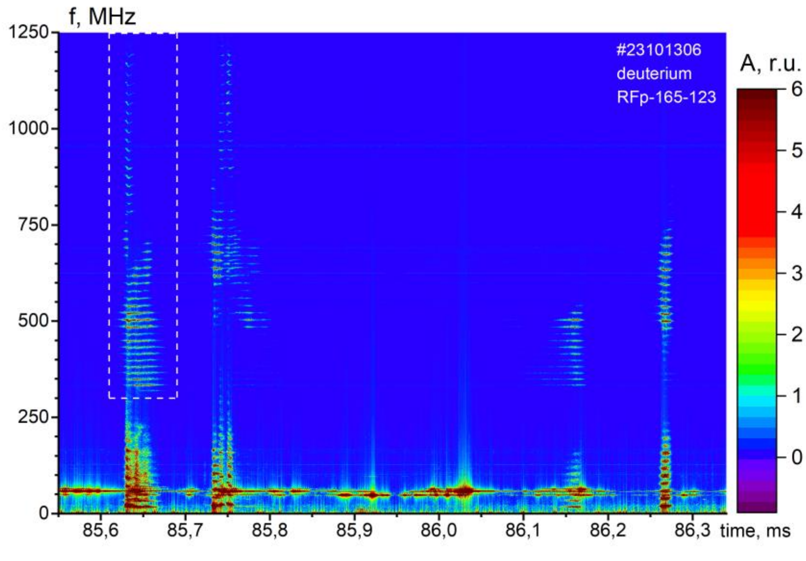

Fig.1 Spectrogram of a sequence of high frequency bursts observed in a shot with $\bar{n}_e = 0.67 \cdot 10^{19}\ m^{-3}$, $B_t(0) = 0.83\ T$. *Framed area is shown in Figure 2 with extended scale.*

In each burst of oscillations one can see 2-3 groups of harmonics. First group – lowest frequencies, from 0 to 300 MHz, was described and analyzed in [19]. Second group – frequencies from 300-350 GHz to 700-800 GHz. Third group – frequencies from 700-800 to 1250 GHz – appears less frequently. This group is absent in bursts at t=86.16 and 86.27 ms. Two higher-frequency groups of harmonics marked by quadrangle in Figure 1 are shown using enlarged scale in Figure 2. Another feature of the spectrogram should be noticed. In the observed comb structure frequency gap between adjacent harmonics varies with the frequency, the higher frequency, the larger frequency gap. The gap is different in the both: within each group and between the groups. The feature is highlighted in Figure 3, where spectrum at Δt=85.628-85.634 ms is presented.

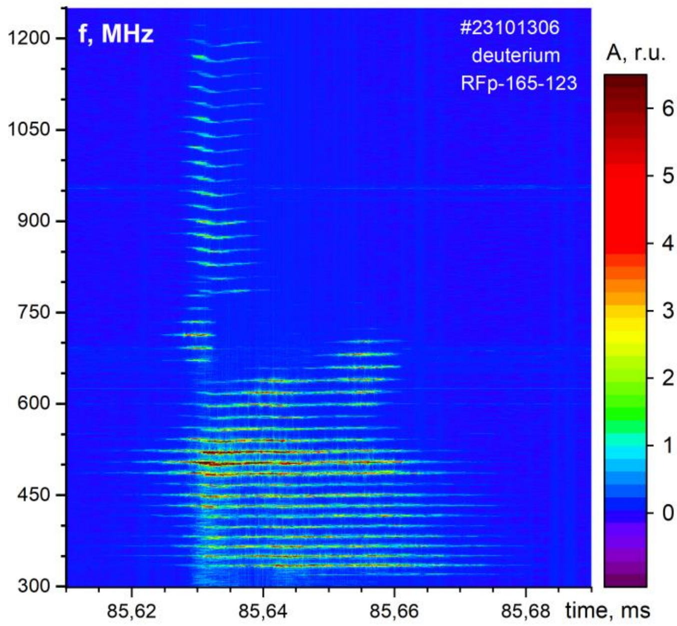

Fig.2 Enlarged spectrogram of a high frequency burst observed in a shot with $\overline{n}_e = 0.67 \cdot 10^{19}\ m^{-3}$, $B_t(0) = 0.83\ T$ *shown in Figure 1.*

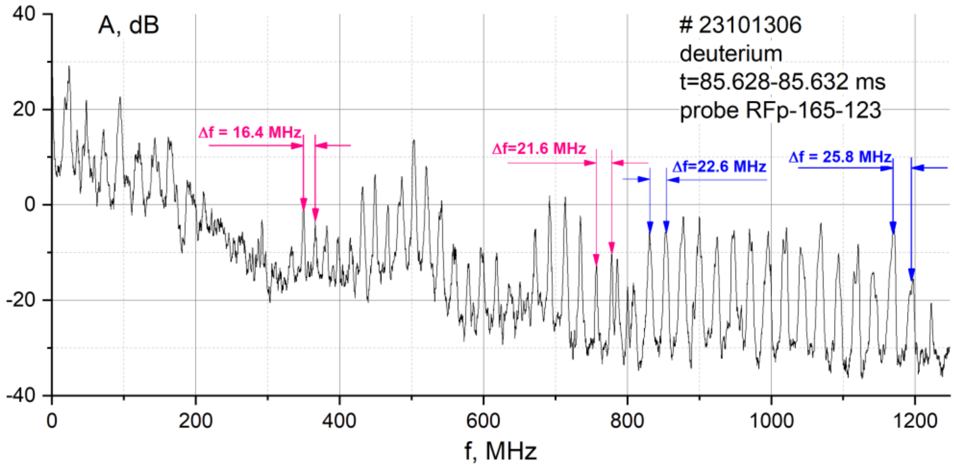

Fig.3 Spectrum of a high frequency burst observed in a shot with $\overline{n}_e = 0.67 \cdot 10^{19}\ m^{-3}$, $B_t(0) = 0.83\ T$.
Frequency gap gradually increased with harmonic frequency.

When density was increased to $0.8 \cdot 10^{19}\ m^{-3}$ the frequency gap became larger ~ 33-34 MHz and has a weak dependence on frequency, see Figure 4 and Figure 5. It should be noticed; that frequency gap increases with increasing toroidal magnetic field. Lowering the magnetic field in the shots #23101707 and #23101709 by factors of 0.91 and 0.89, respectively, resulted in the corresponding gap decreases by factors of 0.92 and 0.9. Observed tendency indicates proportionality of the frequency gap to magnetic field, though scale of B_t variation in the experiment was limited. Typical magnitude of the frequency gap in the studied spectra varies from 15 to 40 MHz

– the quantities, which are much higher than ω_{ci}. This allows to suggest that the observed features of the spectra are formed as a result of the existence of cavity resonances in the tokamak vessel.

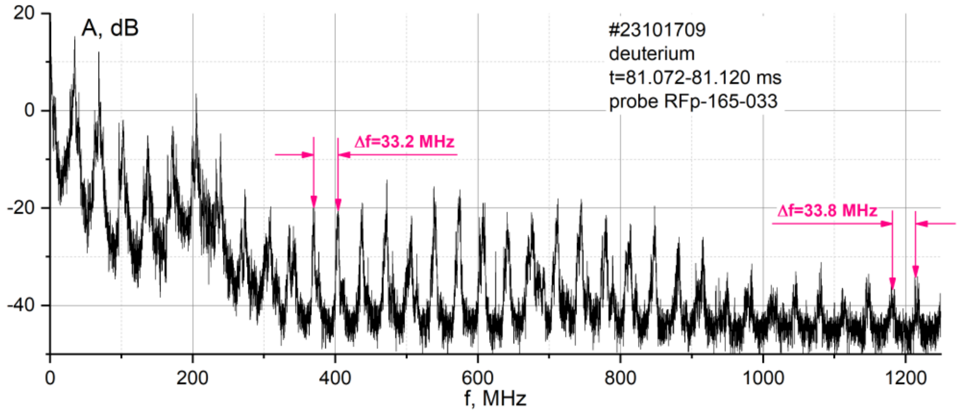

Fig.4 Spectrum of a high frequency burst observed in a shot with $\overline{n}_e = 0.8 \cdot 10^{19}\ m^{-3}$, $B_t(0) = 0.81\ T$. *Dependency of frequency gap on frequency is essentially weaker than in the shot with lower density (Fig. 3).*

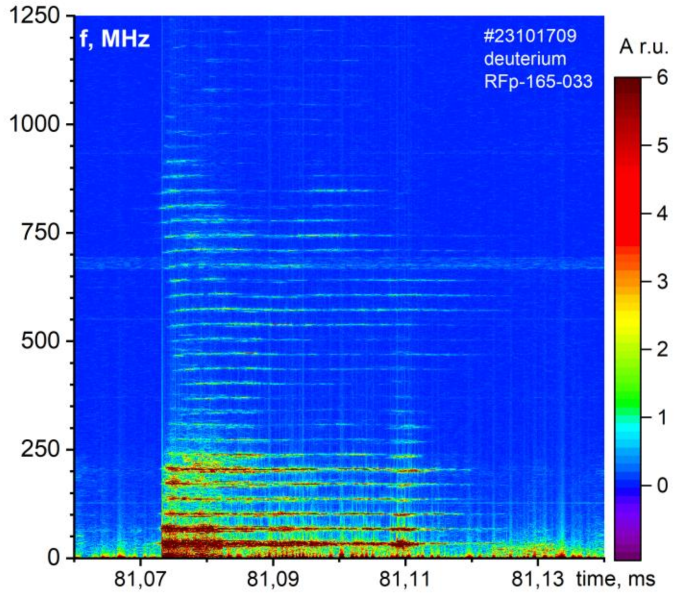

Fig.5 Spectrogram of a high frequency burst observed in a shot with $\overline{n}_e = 0.8 \cdot 10^{19}\ m^{-3}$, $B_t(0) = 0.81\ T$. *In contrast to lower density discharge shown in Figures 1 and 2 no separate frequency groups could be specified.*

3. ESTIMATIONS OF A RUNAWAY ELECTRON MAXIMAL ENERGY USING GAMMA-RAY SPECTROMETRY

Typical example of the burst generation could be seen in Fig.6. Here in frame f) number of gamma-quanta collected by HPGe detectors during 100 μs is shown. Channel "ch-t-lim" acquired quanta produced in tungsten limiter by RE hits. Channel "ch-t-vol" acquired quanta born mainly in plasma volume. Simultaneous bursts on spectrogram, frame a), and spikes on signals of gamma detectors, frame f), indicate the key role of the REs in burst generation mechanism. In frame e) results of calculation of maximal energy in RE spectrum obtained using DeGaSum deconvolution code. The bursts appear when energy of REs reaches 4-5 MeV. It should be noticed that spectrogram in Figure 6 is obtained using 250 MHz ADC since 2.5 MHz ADCs weren't available in this campaign. In order to be sure that high frequency bursts exist in the shots under consideration the spectrograms obtained by

250 MHz ADCs in the both experimental campaigns. Some traces of aliaces of higher frequency oscillations are well visible in frame a). Note, excess of E_{max} defined using data in channel "ch-t-vol" over E_{max} defined using data in channel "ch-t-lim" is due to some overload of electronics in this channel, which cannot be fixed during the experimental series. As it is seen in frame a) the bursts of emission are damped when RE beam fall out of the plasma.

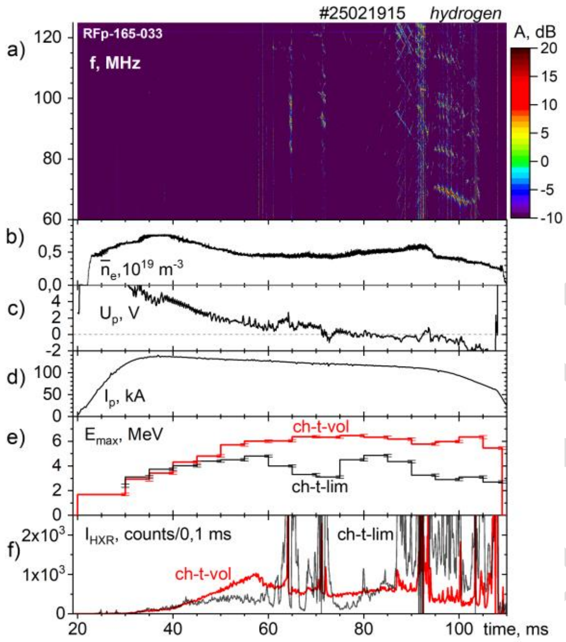

Fig.6 Spectrogram of a high frequency burst observed in a shot with $\overline{n}_e = 0.5 \cdot 10^{19}\ m^{-3}$, $B_t(0) = 0.85\ T$. – a); average density evolution – b); Loop voltage and plasma current – c) and d), respectively; maximum energy of RE and evolution of gamma-rate in tangentially viewing channels – e) and f), respectively.

4. SUMMARY

Application of ADCs with sampling rate of 2.5 GHz allowed observation of magnetic oscillations in the frequency range of 0.3 to 1.25 GHz. In this range comb-like spectra have been found in the ohmically heated plasma with average density $0.5\text{-}1.3\cdot10^{19}$ m^{-3}. The wave generation has character of bursting emission which are correlate with spikes of the gamma-ray intensity. Deconvolution of gamma-ray spectra allowed to conclude that emission bursts arose when maximum of runaway electron energy attains 4-5 MeV. According to consideration [8] the anomalous Doppler resonance of RE may lead to excitation of whistler waves in the above frequency range.

Bursts of waves may contain 40 to 60 peaks with frequency gaps increasing with frequency from 16 to 26 MHz at density 0.5-0.6 10^{19} m^{-3}. At higher density (0.8 10^{19} m^{-3}) number of peaks reduced to 35 and frequency gap became constant. Possible explanation for the comb-like shape of the whistler spectrum are internal reflections from cut-off layers and conversion of whistlers into magnetized plasma waves and back.

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