PLASMA OSCILLATIONS PROPAGATING ALONG THE MAGNETIC FIELD IN THE URAGAN-2M TORSATRON

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The spectral and correlation analysis were applied to study interferometry date measured in two toroidally spaced transverse sections. The oscillation frequency increase for higher magnetic field and decrease with density rising which cold be attributed with existance of Alfven eigenmodes. Calculated frequency values cold be higher that from spectral analysis. This may be due to presence of impurities in plasma.

PACS: 52.55.Hc; 52.55.Hc

INTRODUCTION

The tokamak experiments have revealed the existence of longitudinal waves, the excitation of which is connected with the presence of energetic particles in plasma; therefore, they are also identified as energetic particle modes or Alfven eigenmodes [1]. The first observations of Alfven eigenwaves in stellarators were made at W7-AS [2], where the so-called global Alfven eigenmodes were excited by a high-energy ion beam. In his monograph [3], K. Miyamoto has demonstrated the possibility for existence of the toroidicity-related Alfven-wave discrete eigenfrequency or the toroidal Alfven eigenmode (TAE-mode). The occurrence of energetic particle modes in the U-2M facility may be possible, because with a similar method of plasma generation, energy of ions much higher than the ion temperature values were observed in the U-3M torsatron [4].

The present work is a continuation of the previous studies [5] based on the experimental data obtained in 2008 at the Uragan-2M torsatron, and is devoted to investigating the discovered oscillations that are propagating along the magnetic field.

PLASMA OSCILLATION ANALYSIS

In the U-2M torsatron experiments, the plasma was generated by RF fields of frequencies below Alfven frequencies [5] excited by two antennas, namely, K1 antenna having a wide wavelength spectrum (λ= 80…1068 cm), and K2 antenna having a narrow spectrum (λ= 50…120 cm). As the quasi-stationary discharge phase of density $(2…3.5)\cdot10^{12}$ cm^{-3} was attained, the fluctuations of up to 300 kHz of the transmitted microwave were observed. The detected oscillations cannot be identified as the previously observed low-frequency fluctuations of up to 60 kHz. For registration of the oscillations, the microwave interferometry in two toroidally spaced transverse sections was used, succeeded by the correlation/spectral analysis. The microwave probing scheme is presented in Fig. 1. The magnetic surface structure is conventionally shown by oval curves. The microwave interferometry in use enabled us to measure the mean density along both the chord passing through the magnetic axis, where the density is maximal, and the chord displaced from the magnetic axis by a distance of 8.2 cm. The ratio of mean densities on the two chords makes it possible to judge whether the peak density is on the magnetic axis or is displaced from it. The two-chord interferometry provides information on the density profile if it is represented as:

$$N(r) = N_0 \cdot [1-(r/a)^q], \quad (1)$$

where N_0 – is the maximum density, a – is the radius of the extreme undamaged surface, q – is the exponent. With two-chord mean density measurements by microwave interferometers, the parameters N_0 and q are determined from the following formulas:

$$\frac{\overline{N}_{later}}{\overline{N}_{centr}} = \frac{q+1}{q}\cdot\left\{1-\frac{\overline{a}}{\overline{a}-\overline{r}}\cdot\frac{1}{q+1}\cdot\left[1-\left(\frac{\overline{r}}{\overline{a}}\right)^{q+1}\right]\right\}, \quad (2)$$

$$\frac{N_0}{\overline{N}_{centr}} = \frac{q+1}{q}, \quad (2a)$$

where $\overline{a}$ – is the mean radius of the last undamaged surface, $\overline{r}$ – is the minimum spacing between the magnetic axis and the lateral chord.

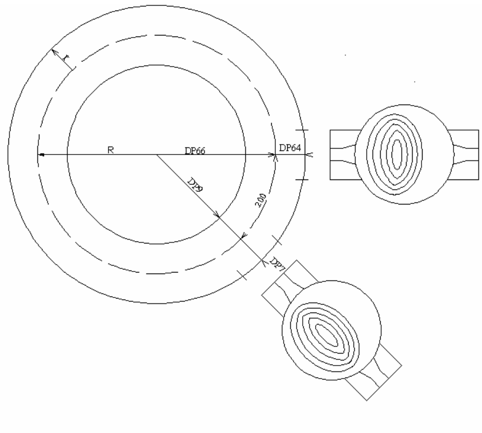

Fig. 1. Scheme of microwave measurements

Reflectometer measurements appear inefficient for observation of long-wavelength oscillations, because for backscattering it is most favorable to have the ratio of the probing wave (λ) to the plasma wave Λ to be $0.1< \lambda/\Lambda < 2$. For the response to long-wavelength fluctuations a high sensitivity is shown by the passing signal with reflection from the rear wall, when the maximum density in the given cross - section is lower than the critical density for the probing wave [6]. The r.m.s transmitted-wave modulation factor values are given by:

$$M = \frac{L\cdot\omega}{2\cdot c}\cdot\frac{N}{N_{cr}}\cdot\frac{\delta N}{N_0}\cdot\left(1-\frac{N}{N_{cr}}\right)^{-1/2}, \quad (3)$$

where δN is the density fluctuation dispersion, N and N_{cr} are the present density and critical density, respectively. The depth of modulation increases when the N/N_{cr} ratio approaches 1. In this case, the condition $\delta N << N_{cr} - N_m$ should be met, where N_m is the highest density in the layer, and the modulation period T_m is much greater than T - the wave travel time in plasma. The calculations described in ref. [6] show that at $T_m/T \approx 30$ the frequency measurement error is insignificant.

The plasma oscillations were investigated through plasma probing by electromagnetic λ=8.2 mm waves along the central chord in one cross-section, and by λ = 12.1 mm waves in the other cross-section along the chord displaced outwards. The mean density was measured on the central and lateral chord, and wave fluctuations were detected. The experimental results underwent the spectral and correlation analysis. The characteristic interferometer signals (responses) in the two cross-sections are shown in Fig. 2. For the analysis of plasma oscillations we have chosen the two interferometer signal regions (Fig. 3) having the densities $N_c = 2\cdot10^{12}$ cm^{-3} and $N_l = 1.7\cdot10^{12}$ cm^{-3} on the central and lateral chord, respectively. The mean density value $N = 1.8\cdot10^{12}$ cm^{-3} between the chords was reached within 2.9 to 4.8 ms from beginning of the discharge, depending on the magnetic field value (Fig. 4). At the voltage U=0 on the antenna K1, the density N_l is higher than N_c, i.e., a hollow density profile was formed, showing a higher level of fluctuation intensity on the lateral chord than the one on the central chord. At U = 5 and 4 kV on the antennas K1 and K2, respectively, the density N_c is higher than N_l, and the oscillation intensity is stronger on the microwave beam that travels along the central chord than the intensity along the peripheral beam.

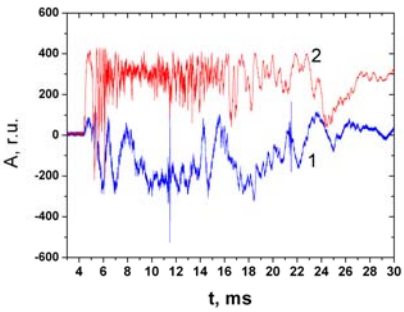

Fig. 2. Interferometer signals in two cross-sections: 1 – central chord, 2 – lateral chord

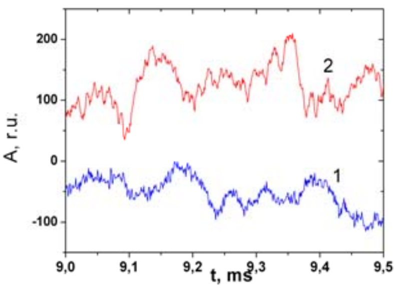

Fig. 3. Interferometer signal sampling in two cross sections: 1 – central chord, 2 – lateral chord

The analysis of microwave signals transmitted through the plasma has shown that in the neighborhood of the maximum discharge density there occur oscillations of ~100 kHz frequency and higher in each channel. To be sure that the oscillations are propagating along the torus, studies were made into the coherence functions (Fig. 5), cross-correlation functions of microwave signals and the cross spectra (Fig. 6).

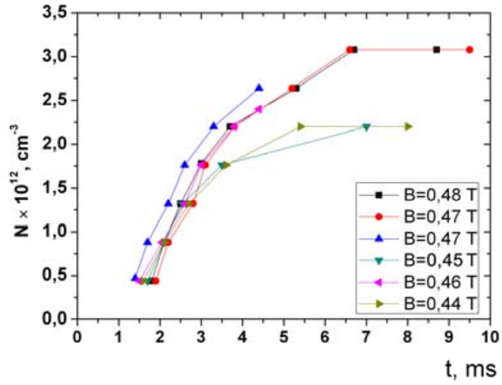

Fig. 4. Time-density relationship

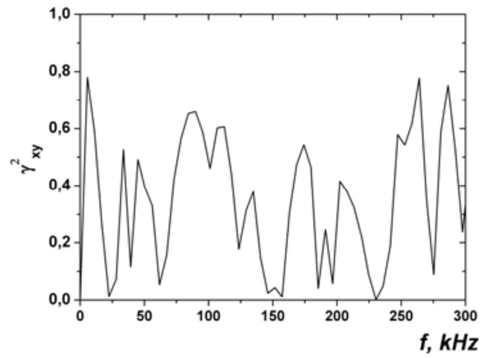

Fig. 5. Coherence function

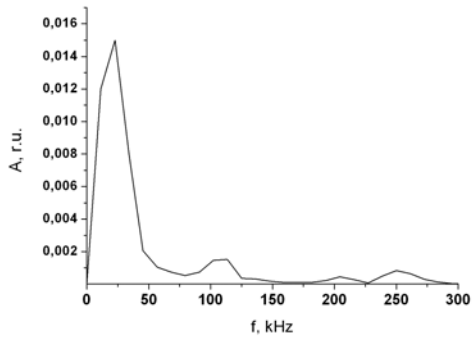

Fig. 6. Cross spectrum

The fluctuation spectra were determined from the Fourier analysis of fluctuations of plasma-transmitted microwave signals in the length intervals of 64 and 128 μs, where the plasma was quasi-stationary. The oscillation characteristics were measured at different magnetic fields for a density of $1.8\cdot10^{12}$ cm^{-3}, and also in a single discharge versus density. It is shown that the oscillation frequency increases with an increase in the magnetic field, and decreases with an increasing plasma density as in the case of Alfven eigenmodes (Figs. 7, 8). Frequencies approaching two- and three-fold frequency values were also observed. The frequencies of cross spectra were in agreement with the frequencies observed in the two channels. The oscillations of up to 60 kHz are independent of the magnetic field value.

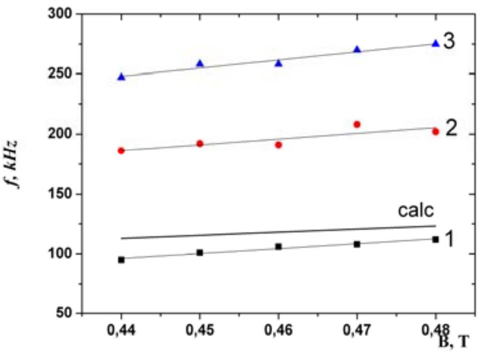

Fig. 7. Oscillation frequency versus magnetic field (1, 2, 3 – frequency harmonics)

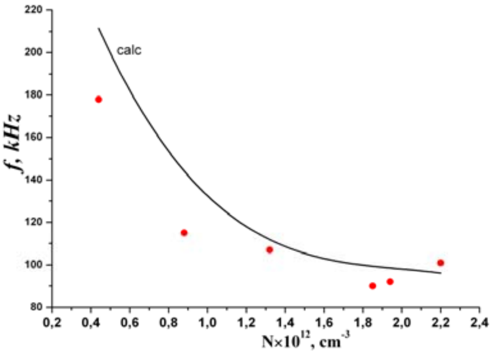

Fig. 8. Oscillation frequency versus density, solid curve – calculations; points – experiment

In the case of Alfven waves, the dispersion relation is written as [1]:

$$f_{TAE} = \frac{V_A \cdot \iota}{4 \cdot \pi \cdot R}, \qquad (4)$$

where

$$V_A = B \Big/ (4 \cdot \pi \cdot m_i \cdot N_i)^{1/2} = 2.18 \cdot 10^{11} \cdot B \Big/ (N \cdot \mu)^{1/2}$$

is the Alfven velocity, μ is the ion-to-proton mass ratio, ι is the rotational transformation angle, R is the torus radius. With impurities present in the plasma, the effective ion-to-proton mass ratio is given by:

$$\mu_{eff} = \Sigma A_i N_i / N_p = (f_{cal} / f_{obs})^2. \qquad (5)$$

At 1-, 2- and 3-order frequencies the oscillation coherence shows higher values (see Figs. 5, 6). Comparison has been made between the calculated (by eq. (4)) and measured oscillation frequencies as functions of the plasma density and magnetic field strength (see Figs. 7, 8). For frequency calculations (Eq. (4)), the following values were taken: magnetic field B = 0.44…0.48 T, the experimentally measured plasma density values (see Fig. 3), R=168 cm, 1/3<ι<1/2 according to the data from ref. [7]. According to formula (5), at B=0.45 T in the range t = 4…8 ms we have N = (1.85…2.02)10^{12} cm^{-3}, μ_{ef} =1.15…1.3.

CONCLUSIONS

Longitudinal oscillations of torsatron U2-M plasma have been investigated on the basis of microwave interferometry signals in two cross-sections spaced apart along the torus axis. The oscillations have been shown to propagate along the torus, and are believed to bear the marks of Alfven eigenmodes. The effective ion-to-proton mass ratio has been estimated.

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Article received 16.10.12

ПЛАЗМЕННЫЕ КОЛЕБАНИЯ, РАСПРОСТРАНЯЮЩИЕСЯ ВДОЛЬ МАГНИТНОГО ПОЛЯ В ТОРСАТРОНЕ УРАГАН-2М

А.И. Скибенко, А.В. Прокопенко, И.Б. Пинос

Спектральный и корреляционный анализы проведены для изучения интерференционных данных, измеренных в двух тороидально отстоящих сечениях. Частота колебаний растет с увеличением магнитного поля и уменьшается с ростом плотности. Это может характеризовать их как собственные альфвеновские моды. Вычисленные значения частоты больше, чем полученные из спектрального анализа. Это возможно из-за наличия в плазме примесей.

ПЛАЗМОВІ КОЛИВАННЯ, ЩО РОЗПОВСЮДЖУЮТЬСЯ УЗДОВЖ МАГНІТНОГО ПОЛЯ В ТОРСАТРОНІ УРАГАН-2М

А.І. Скібенко, О.В. Прокопенко, І.Б. Пінос

Спектральний і кореляційний аналізи проведені для вивчення інтерференційних даних, виміряних у двох тороїдально віддалених перерізах. Частота коливань зростає зі збільшенням магнітного поля і зменшується з ростом густини. Це може характеризувати їх як власні альфвенівські моди. Обчисленні значення частоти перевищують одержані із спектрального аналізу. Це можливо за наявністю домішок у плазмі.