PROBE DIAGNOSTIC COMPLEX OF TOKAMAK FT-2

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Experimental investigations of peripheral processes in tokamak plasma are necessary to create a reliable theoretical model of the anomalous transverse particle and energy transport. These investigations take on particular interest in light of the discovery and intensive study of regimes with improved plasma confinement (H-mode), that have emphasized a close relationship between peripheral processes (specifically the nature of the peripheral microturbulence and particle fluxes attributed to it) and plasma parameters in the main part of a tokamak.

It will be introduced the description of history of measuring probe device, diagnostic circuits of the FT-2 tokamak. Suggested method based on using of multi-electrode Langmuir probes provides time dependency of local parameters of peripheral plasma such as electron temperature, density of particles, potential of plasma, and also demonstrates behavior of particle drift. Using one of electrodes as high-frequency antenna gives an additional possibility to investigate an interaction of tokamak plasma and electromagnetic wave of low-hybrid diapason.

Measurement technique is based on the use of three movable five-electrode Langmuir probes, located in the same transverse cross-section of the chamber, allowing obtaining data in the limiter shadow region inclusive the whole poloidal bypass of the torus.

Diagnostic circuits provide the first processing of signal in frequency diapason up to 500 kHz without galvanic connection between probe electrodes and registration device. Diagnostic circuits also include the spectrum analyzer of electromagnetic radiation. Experimental results demonstrate the possibilities of the diagnostic complex.

1. INTRODUCTION

The most progress on the way to control nuclear fusion is to be observed in toroidal devices with magnetic plasma confinement. The processes proceeding in a peripheral zone in toroidal devices with magnetic confinement affect to plasma parameters in the main part of tokamak. Essentially anomalous transversal transfer in boundary layer is connected to fluctuations of plasma parameters (density, electron temperature, potential).

Experimental investigations of peripheral processes in a tokamak plasma are necessary to create a reliable theoretical model of the anomalous transverse particle transport and limiting transverse transport conditions. These investigations take on particular interest in the light of the discovery and intensive studies of regimes with improved plasma confinement (H-regimes), that have emphasized a close relationship between peripheral processes, specifically the nature of the peripheral microturbulence and particle fluxes attributed to it. It is necessary to say that even a small limitation of transverse transport means essential reduction of the sizes and cost of thermo nuclear reactor. Electric probe is the main method of diagnostics of local peripheral plasma parameters. Other diagnostic methods can be used to prove probe measurements and in some cases to get an additional (complementary) information. In most cases at comparison probe diagnostic results with the data of others diagnostics enough agreement was observed.

Suggested method based on using of multielectrode Langmuir probes provides time dependency of local parameters of peripheral plasma such as electron temperature, density of particles, potential of plasma and also demonstrates behavior of particle drift at the frequency band up to 500 kHz. It also allows measuring local densities of quasystationary and fluctuation particle drift fluxes and to investigate lower-hybrid electromagnetic waves (RF diapason).

In experiments of the additional plasma heating by lower hybrid electromagnetic waves measurements can be passed with high resolution in a limiter shadow practically for every poloidal angle value.

Measurement technique is based on the use of three movable five-electrode Langmuir probes, located in the same transverse cross-section of the chamber, that allows to obtain data in the limiter shadow region inclusive of the whole poloidal bypass the torus.

2. THE CONSTRUCTION OF THE FIVE-ELECTRODE PROBE

Five-electrode probe has a number of advantages in comparison to well-known three-electrode probe and used before for plasma investigations in the tokamak FT-2 four-electrode probe. In particular the results of three-electrode probe measurements are correct only in case of homogeneous plasma in scale of distance between electrodes and four-electrode probe allows measuring only one projection of the electric field and plasma drift during one impulse. Five-electrode probe hasn't such shortcomings. Its construction is show at the picture 1.

Probe electrodes are made of molybdenum. They are situated into ceramics tubes. Electrode 1, 3, 5 are situated in the same plane, electrodes 2 and 4 are in another one plane and these planes are parallel to each other and while measurements they orient perpendicular to toroidal magnetic field.

The vacuum inlet allows moving the probe by the small radius and by poloidal angle. The picture of probe projection to poloidal plane is center electrode axial symmetrical. The angle between lines, at which electrodes ends' picture is situated, is 90 degrees. Such construction, as it will be shown below allows measuring both of the projections of the electric field intensity vector to poloidal plane and plasma fluxes during the one tokamak's impulse (not during two impulses as has been while using four-electrode probe).

3. THE PRINCIPLE OF ELECTRON TEMPERATURE AND PLASMA DENSITY MEASUREMENTS

Classical one-electrode probe suggested by Langmuir at the beginning of plasma physics, allows measuring electron temperature, density and also to estimate plasma potential value. The method consists of getting current-voltage characteristic with its further processing. Exists two-electrode probe method, but it also supposes volt-ampere characteristic's measuring. If plasma parameters vary essentially by time, that is necessary to get probe characteristic, these methods are unfitted. Three-electrode probe allows measuring local electron temperature and density as a time-function and it doesn't suppose getting volt-ampere characteristic.

Let us define the potential of the floating Langmuir probe using the condition of equality of ion and electron currents to it:

$$I_i = I_e \exp\left(-\frac{e(\phi_{pl} - \phi_f)}{T_e^{(+)}} \right) \quad\text{........(1)}$$

where I_i is ion saturation current, I_e is electron saturation current, ϕ_{pl} is plasma potential, ϕ_f potential of the floating probe, e is elementary charge, where we can find:

$$\phi_f = \phi_{pl} + \frac{T_e}{e}\ln\left(\frac{I_i}{I_e}\right) \text{......(2)}$$

Three-electrode probe is a combination of floating probe and two-electrode probe, which is in saturation condition. Let us define the potential of positive electrode of saturated probe using the condition, that the summary current to the two-electrode probe is zero:

$$I_i - I_e\exp\left(-\frac{e(\phi_{pl} - \phi^{(+)})}{T_e^{(+)}}\right) + I_i = 0\text{......(3)}$$

(one of the electrodes collects ion saturation current and the sum of these free currents should be equal to zero). From this equation we can find:

$$\phi^{(+)} = \phi_{pl} + \frac{T_e}{e}\ln\left(2\frac{I_i}{I_e}\right)\text{......(4)}$$

If in the experiment potential difference between positive electrode of the two-electrode probe and the floating electrode is estimating, so it is easy do find electron temperature T_e, because from equations (2) and (4) we can find:

$$\delta\phi = \phi^{(+)} - \phi_f = \frac{T_e}{e}\ln 2\text{.......(5)}$$

The density n can be calculation from Bohm's formula for ion saturation current:

$$I_i = 0.4neS_{eff}\sqrt{\frac{2T_e}{m_i}}\text{.......(6)}$$

where S_{eff} – square of effective gathering surface of the probe. It is taken that in strong magnetic field S_{eff} is equal do double square of the probe projection to poloidal plane. The formula (5) is true only if all of the electrodes are the same and plasma is homogeneous in scale of distance between electrodes. At the periphery of plasma column of small tokamak the scale of plasma non-homogeneity is order of 1 mm. That is why more correct approach to measurement of local electron temperature is necessary. We define with upper indexes "+", "-", "0" the values, according to positive and negative electrodes of two-electrodes probe and to the floating electrode respectively. Current balance in case of non-homogeneous plasma becomes:

$$I_i^{(+)} - I_e^{(+)}\exp\left|-\frac{e(\phi_{pl}^{(+)} - \phi^{(+)})}{T_e^{(+)}}\right| + I_i^{(-)} = 0\text{.......(7)}$$

therefore the potential of positive electrode is:

$$\phi^{(+)} = \phi_{pl}^{(+)} + \frac{T_e^{(+)}}{e}\ln\left|\frac{I_i^{(-)} + I_i^{(+)}}{I^{(+)}}\right|\text{.....(8)}$$

The difference U between the potential … and floating potential in the positive electrode of two-electrode probe arrangement point is:

$$U = \phi^{(+)} - \phi_f^{(+)} = -\frac{T_e^{(+)}}{e}\ln\left|\frac{I_i^{(-)} + I_i^{(+)}}{I^{(+)}}\right|\text{......(9)}$$

4. ESTIMATION OF PLASMA PARAMETERS WITH FIVE-ELECTRODE PROBE

It is considered that all the electrodes are situated in the same plane supposing plasma homogeneity in longitudinal direction. Let $\varphi_f(1)$, $\varphi_f(3)$ and $\varphi_f(5)$ are floating potentials in 1, 3 and 5 electrode arrangement points. Electrodes 2 and 3 are used as a two-electrode probe, the polarity depends on the measure regime and can be changed. Let for example electrode 2 be positive. Electrodes 1 and 3 are located on two sides from it at the same distance. The floating potential in the electrode 2 arrangement point is approximated by arithmetic mean of potential volume and it allows to space dependency of plasma parameters approximation with linear functions. When $\varphi_f(1)$, $\varphi_f(3)$ and $\varphi_f(2)$ are gauged, U can be found from equation:

$$U \approx \phi^{(2)} - \frac{\phi_f^{(1)} + \phi_f^{(3)}}{2}\text{......(10)}$$

According to formula (9) we have:

$$U = \frac{T_e^{(2)}}{e}\ln\left(1 + \frac{I_i^{(4)}}{I_i^{(2)}}\right)\text{.......(11)}$$

So, when ion saturation current to electrodes 2 and 4 and the potential of electrode 2 , when it is turned on as a positive electrode of two-electrode probe, and floating potentials $\varphi_f(1)$,$\varphi_f(3)$ are measured, from equations (10) and (11) electron temperature in electrode 2 arrangement point can be found. Using electrode 4 as a positive electrode of two-electrode probe such a way T_e in electrode 4 arrangement point can be defined

$$U \approx \phi^{(4)} - \frac{\phi_f^{(5)} + \phi_f^{(3)}}{2}\text{.......(12)}$$

The volume of T_e can be found from equation:

$$U = \frac{T_e^{(4)}}{e}\ln\left(1 + \frac{I_i^{(2)}}{I_i^{(4)}}\right)\text{.......(13)}$$

Necessary to say that approximated volumes can be compared with real floating potentials of probes 2 and 4, which are measured in a special probe regime. Saturation currents to the probes 2 and 4 densities n(2) and n (4) can be found from Bohm formula.

Define an axis passing through the ends of the electrodes 3 and 1 as x and an axis passing through the ends of the electrodes 3 and 5 as y. The construction of the probe is so that the axes x and y are perpendicular to each other. projections of the electrical field intensity to the axes x and y can be found from the formula for floating potential:

$$E = \frac{\phi_{pl}^{(3)} - \phi_{pl}^{(1)}}{\ldots} \approx \frac{\phi_f^{(3)} - \phi_f^{(1)}}{\ldots} - \frac{3\,\partial T_e}{\ldots}\text{.......(14)}$$

$$E_y = \frac{\phi_{pl}^{(3)} - \phi_{pl}^{(5)}}{\ldots} \approx \frac{\phi_f^{(3)} - \phi_f^{(5)}}{\ldots} - \frac{3\,\partial T_e}{\ldots}\text{.....(15)}$$

Where Δx is a distance between electrodes 3 and 1, Δy is a distance between 3 and 5 (these distances are equal). The volume of $\ln(I_e/ I_i)$ is supposed to be the same for all the electrodes of the probe and in working formulas it is taken as 3.0 (the ratio Ie/Ii can be expressed by the combination of constants from equations of saturation currents). Local density volume of quasystationary particle flux can be found from equation:

$$\vec{\Gamma} = cn\left[\vec{E}\times\vec{H}\right]/H^2 \text{.......}(17)$$

(to define quasystationary volumes of plasma parameters, fluctuation components of probe signals are suppressed by low frequency filter. The covariation volume

$$\left\langle n^{\sim} \vec{E}^{\sim} \right\rangle$$

that is necessary for calculating of fluctuation flux density

$$\vec{\Gamma}^{(\sim)} = c\left[\left\langle n^{\sim} \vec{E}^{\sim} \right\rangle \times \vec{H}\right]/H^2 \text{.......}(18)$$

is calculated by the analog module of processing probe signals.

5. THE DESCRIPTION OF THE DIAGNOSTIC COMPLEX

Described complex of the diagnostic mediums consists of five main electronic devices: the analog module of initial processing probe signals, the module of coordination and operation of regimes, five-channel block of optoelectronic galvanic attenuators, five-channel block of buffer scaling cascades and the analog module of covariation calculating. The first and the second of them have galvanic coupling with the tokamak camera, at which during discharge high potential _is being collected. In this connection signals are being propagated to recording equipment through galvanic decoupling channels, which provide a constant voltage of isolation 1.5 kV and a shot-term voltage 3kV (till 10 ms). Galvanic decoupling channels have a wide pass band. The analog module of covariation calculating is based by high-speed operational amplifier and integral chips of multiplication of analogue signals.

6. THE SPECTRUM ANALYSIS

On the tokamak FT-2 interaction of plasma with low-hybrid electromagnetic waves is being investigated. Using of such wave is one of the methods of additional plasma heating. During interaction with plasma injected wave can break up to derived waves with another frequencies. Probe diagnostic allows investigating of spectral structure for different areas of periphery and for different charge passing conditions, observing by the way local plasma parameters. The signal from one of the electrodes, working as a RF antenna, through the separating capacitor and the inductive galvanic attenuator comes to radio-diapason frequency spectrum analyzer of sequential type, that consists of the voltage control generator (VCG), the mixer and the amplitude detector. The VCG is controlled by single sawtooth impulse of 1 ms duration, during which the frequent spectrum in a range of 750-950 MHz is being registered. Results are registered by the digital system of data gathering. The low-hybrid wave (920 MHz) is excited by two-wave-guide grill.

7. SOME EXPERIMENTAL RESULTS

Diagnostic possibilities of the probe measuring complex can be illustrated by the data obtained as a result of experimental researches of peripheral processes, accompanying transition to improved plasma confinement regime. In the tokamak FT-2 this regime was created in experiments on additional low-hybrid plasma heating. Impulse of heating initiated the mode with enlarged approximately twice life time of particles and energy (H-mode). That regime was most precisely fixed after the termination of the low-hybrid impulse. Probe measurement in detail have allowed researching of the dynamics of peripheral poloidal distribution of charged particles density, Te and electrical field. Special attention was given to fluctuation induced particle drift flux and to evolution of fluctuation characteristics. The poloidal step of measurements was 20-30 degrees and radial step was 1 mm. Transition to improved plasma confinement regime is accompanied by a significant modification of special distribution of peripheral plasma parameters. In particular radial gradients of density essentially increase, that is illustrated by a figure 3.

It is revealed about double decrease of the integral value of radial fluctuation particle drift flux, which is the most essential factors defining development of space structure of plasma parameters in scrape of layer. Reduction of the flux value is connected apparently to observed decrease of instant fluctuation values of electrical field and density of particles (fig.4)

Radial and poloidal dependences of local values of calculated effective diffusion coefficient for two instances (H and L-regimes) are given in a figure5. In this figure negative values correspond to radial transport from center to periphery. Presence of positive values demonstrates a complicated picture of drifting fluxes, when particle flux is directed along a gradient of density. From the figure5 essential decrease of effective radial diffusion coefficient during the transition to improved confinement regime is clear.

8.CONCLUSION

The probe diagnostic complex of tokamak FT-2 has extensive possibilities. It allows getting an amount of information, arranging advantages of Langmuir and high-frequency probes. Local plasma parameters and characteristic of their fluctuations as a function of time can be defined with high space resolution in conditions of essential peripheral plasma unhomogeneity Measurements can be passed during impulse of low-hybrid heating and at the same time high-frequency wave decay spectrum data can be obtained.

The number of new experimental data is obtained, in particular it is discovered, that initiated by impulse of additional low-hybrid heating transition to improved confinement regime is accompanied by essential decrease of peripheral radial particle transport, which is rode by quasystationary and fluctuation drift. Poloidal-radial distributions of effective coefficient of radial diffusion and their evolution during the LH-transition are obtained.

Decrease of the influence of fluctuation drift to radial particle transport is connected to suppression of fluctuation plasma density and electrical field correlations.

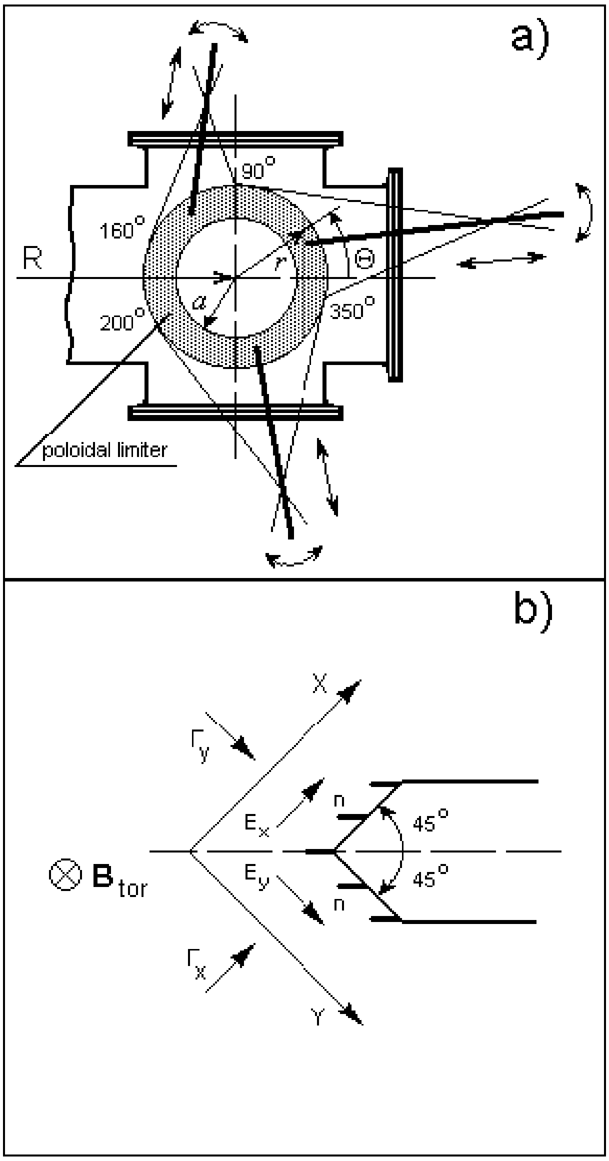

Fig.1
a) Position of the movable five-electrode probes in a diagnostic parts
b) Geometry of the experiments

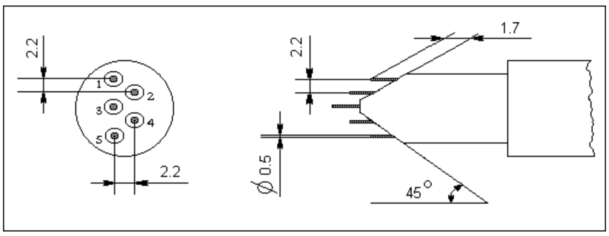

Fig.2
Design of the five-electrode probe head
1,3,5 – floating electrodes; 2,4 – saturated double probe

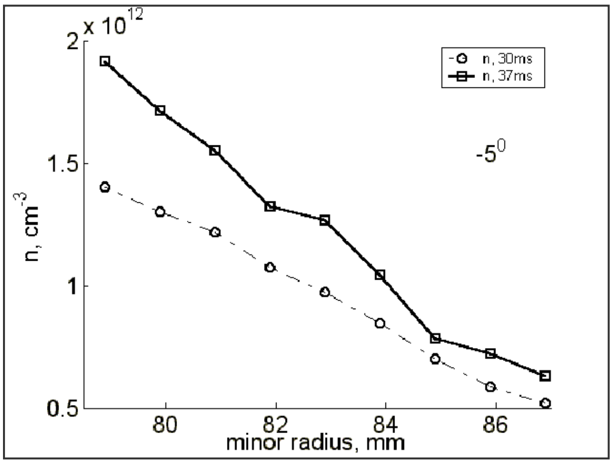

Fig.3
Radial dependence of density for two moments of time

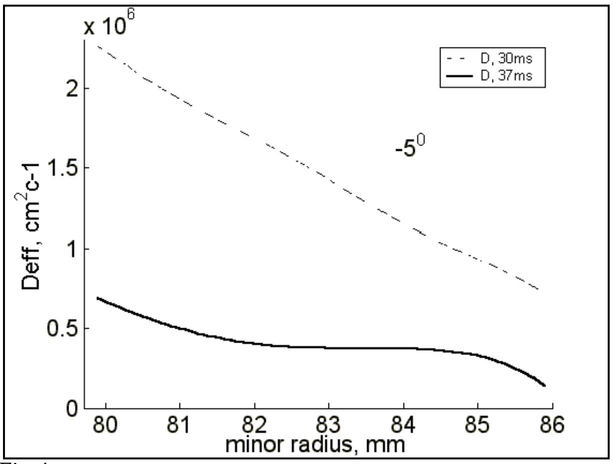

Fig.4
Radial dependence of effective diffusion coefficient for two moments of time

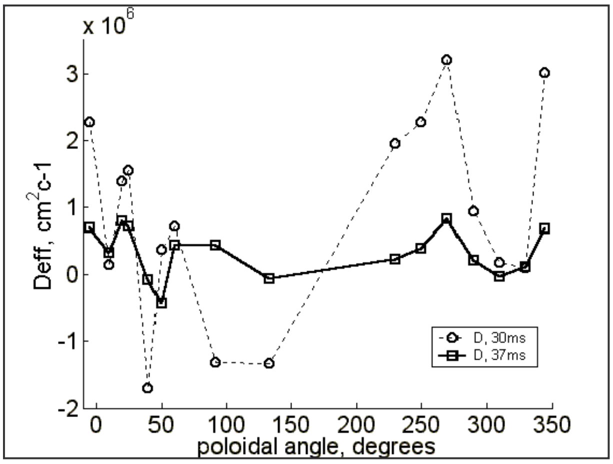

Fig.5
Poloidal dependence of effective diffusion coefficient