Ядерные энергетические установки, включая проектирование, эксплуатацию и вывод из эксплуатации (05.14.03)

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Влияние электродной поляризации и динамического эргодического дивертора на характеристики прерывистых всплесков плотности плазмы в токамаке

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Изучены прерывистые всплески плотности плазмы, зафиксированые Ленгмюровскими зондами в периферийной области токамака TEXTOR. Они появляются в результате турбулентных процессов переноса плазмы — зарождения и передвижения различных когерентных турбулентных структур. Данные процессы мешают протеканию управляемого термоядерного синтеза — ухудшают удержание плазмы, вызывают повышенную тепловую нагрузку на стенку вакуумной камеры и другие компоненты, расположенные вблизи плазмы, а также их сильную эрозию вместе с нежелательным захватом трития. Следовательно, изучение турбулентных процессов переноса плазмы и динамики когерентных турбулентных структур — одна из важнейших задач на пути осуществления управляемого термоядерного синтеза, особенно в контексте разработки и усовершенствования методов внешнего контроля турбулентных процессов переноса плазмы. Метод электродной поляризации и динамический эргодический дивертор часто используются для внешнего воздействия на термоядерную плазму и управления процессов турбулентного переноса.
Следует отметить, что изучение временных характеристик всплесков плотности плазмы и их радиальной зависимости позволяет лучше понять и глубже вникнуть в физическую природу турбулентных процессов переноса плазмы и динамику когерентных турбулентных структур.
В настоящей работе временные характеристики всплесков плотности плазмы и их радиальная зависимость изучены в двух различных режимах — с электродной поляризацией и динамическим эргодическим дивертором. В обеих случаях наблюдаются похожие изменения характеристик прерывистых всплесков — средний темп всплесков возрастает, а их средняя длительность уменьшается по сравнению с омическим режимом. Причина заключается в том, что электродная поляризация и отдельные режимы динамического эргодического дивертора вызывают изменения радиального электрического поля. Это похожим образом воздействует на динамику когерентных турбулентных структур и процессы переноса плазмы посредством сдвигового полоидального течения, которое возникает вследствие электрического дрейфа из-за существования радиального электрического и тороидального магнитного полей, перпендикулярных друг к другу.
После детального исследования и усовершенствования должно стать возможным применение определённых режимов динамического эргодического дивертора в роли бесконтактной поляризации для внешнего контроля турбулентного переноса плазмы в термоядерных установках.

Ключевые слова: турбулентность плазмы, процессы турбулентного переноса, когерентные турбулентные структуры, электродная поляризация, динамический эргодический дивертор, термоядерный синтез, токамак.

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Influence of Electrode Biasing and Dynamic Ergodic Divertor on Characteristics of Intermittent Density Bursts in a Tokamak

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Intermittent bursts of plasma density measured by Langmuir probes at the edge of TEXTOR tokamak are studied. These bursts appear as a result of turbulent plasma transport processes involving the formation and propagation of various coherent turbulent structures. Such processes impede controlled thermonuclear fusion: they degrade plasma confinement and entail increased heat load on the vacuum chamber walls and other components located near plasma; they also entail strong erosion of these components along with unwanted capture of tritium. Therefore, investigation of turbulent plasma transport processes and dynamics of coherent turbulent structures is one of the most important tasks to be solved for implementing controlled thermonuclear fusion. This is especially important in the context of elaborating and improving the methods for externally controlling the turbulent plasma transport processes. The electrode biasing method and a dynamic ergodic divertor are frequently used for externally influencing thermonuclear plasma and controlling turbulent transport processes.

It should be noted that by studying the temporal characteristics of plasma density bursts together with their radial dependence it becomes possible to get better understanding of and deeper insight into the physical nature of turbulent plasma transport processes and dynamics of coherent turbulent structures.

In this article, the temporal characteristics of plasma density bursts and their radial dependence are studied in two different modes: with electrode biasing and with a dynamic ergodic divertor. Conformable changes in the characteristics of intermittent bursts are observed in both cases. Namely, the average burst rate increases, and the average burst duration decreases in comparison with the ohmic regime. This is due to the fact that electrode biasing and certain regimes of the dynamic ergodic divertor cause changes in the radial electric field. This has a conformable effect on the dynamics of coherent turbulent structures and plasma transport processes through a shear poloidal flow, which emerges as a consequence of electric drift due to nonuniform radial electric field and toroidal magnetic field, which are perpendicular to each other.

After detailed investigations and refinement, it should become possible to use certain regimes of the dynamic ergodic divertor as a means of contactless biasing for externally controlling the turbulent plasma transport in thermonuclear installations.

Key words: plasma turbulence, turbulent transport processes, coherent turbulent structures, electrode biasing, dynamic ergodic divertor, thermonuclear fusion, tokamak.

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Intermittent positive bursts of plasma density detected by Langmuir probes at the edge of the TEXTOR tokamak are investigated. Burst temporal characteristics together with their radial dependence are studied in two different regimes — with electrode biasing and dynamic ergodic divertor (DED). Conformable modification of intermittent burst characteristics are observed in both regimes. Namely, the average burst rate increases and the average burst duration decreases compared to Ohmic conditions. The reason should be that biasing and certain regimes of DED cause the modification of radial electric field which has conformable effect on the dynamics of coherent turbulent structures and plasma transport through $\mathbf{E_r}\times\mathbf{B_t}$ induced sheared poloidal rotation. In principle, after detailed investigations and refinement, it might be possible to use certain regimes of DED as “contactless biasing” for the external control of plasma turbulent transport in fusion devices.

I. Introduction

Investigation of plasma turbulent transport at the edge of tokamaks is one of the most important and interesting tasks of modern fusion research. The transport is highly bursty, intermittent and has a strongly convective character. Large turbulent events — density bursts bring important contribution to such transport. Density bursts are formed intermittently on diffusive background and propagate radially outwards at a speed which is a fraction of the ion sound speed. This can result in degradation of confinement, strong erosion and heat load on the first wall and other plasma facing components together with unwanted retention of tritium. It is very important to understand the physical nature of bursty turbulent transport in general and in particular in the context of developing the methods and tools for its external control.

Investigation of temporal characteristics of intermittent density bursts such as burst rate, inter-burst time and burst duration together with their statistical properties is an efficient method for better understanding of turbulent transport in tokamak edge plasma [1 — 4]. The present paper reports on the results of such investigation of intermittent density bursts measured at the edge of the TEXTOR tokamak by means of reciprocating Langmuir probe in two different regimes — with electrode biasing [5] and dynamic ergodic divertor (DED) [6].

On the TEXTOR tokamak two methods are used for external control of plasma turbulent transport, namely electrode biasing [5] and the DED [6 — 8]. Both have strong influence on edge plasma transport and electrode biasing can even trigger the transition from low to high confinement mode [5].

II. Experimental setup

During the analyzed biasing discharges of TEXTOR (major radius R = 1.75 m and minor radius a = 0.475 m), the plasma current was I_p = 200 kA, the toroidal magnetic field

B_t = 1.9 T, the line average density of plasma 1×10^{19} m^{-3}, and the biasing voltage V_{bias} = 150 V. In order to bias the TEXTOR plasma canoe-shaped electrode is inserted in it. The biasing voltage is applied between the electrode and toroidal belt limiter (which is grounded to the liner) in the stationary Ohmic phase of the discharge. A first radial scan with the probe is made during the Ohmic phase, and a second one during the biasing phase. The probe head is installed at the equatorial plane on low-field side (LFS) of the torus and consists of seven pins. Ion saturation current I_{sat}, floating potential V_{fl} and electron temperature T_e were measured (part of the pins were set-up as a triple probe) in the same way as described in the papers [7, 8]. The sampling frequency is 500 kHz. The radial electric field is obtained from the derivative of the plasma potential $V_{pl} = V_{fl} + 2.5T_e$ [9]. The same measurements have been performed during discharge with DED for which the conditions were the following: I_p = 250 kA, B_t = 2.25 T, the line average density of plasma 1.5×10^{19} m^{-3}, DED current I_{DED} = 3 kA. On the TEXTOR tokamak the DED principally consists of sixteen magnetic perturbation coils mounted in the vacuum vessel on high field side of the torus. The coils are helically wound and parallel to the field lines on the magnetic flux surface the safety factor of which equals to 3. The current can be distributed in different ways in the DED coils and the base poloidal/toroidal modes 12/4, 6/2 and 3/1 can be obtained. The DED current is applied in the stationary Ohmic phase of the discharge. For the discharge under study the base poloidal/toroidal mode 6/2 is used. A first radial scan with the probe is made during Ohmic phase, and a second one during DED.

III. Main consideration

Intermittent positive bursts of plasma density are detected at the edge of the TEXTOR tokamak by Langmuir probes (see Fig. 1).

Langmuir probes are most widely used tools for this purpose [10 — 14]. It should be noted that two-dimensional imaging is also capable to detect bursty transport events in tokamak edge plasma [15 — 17]. Bursty plasma transport is widely observed in various fusion devices such as tokamaks [18 — 25], stellarators [26, 27], linear devices [10, 23, 28 — 30], reversed field pinches [31, 32] and simple magnetized toroidal devices [33, 34].

In the Ohmic phase of the TEXTOR biasing discharge we observe intermittent positive bursts of the ion saturation

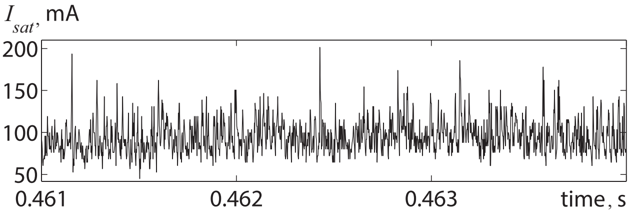

Fig. 1. Raw signal of ion saturation current I_{sat} measured at the edge of the TEXTOR tokamak

current I_{sat}. First step of their investigation is selection procedure — bursts in I_{sat} signal are selected by threshold method. Only the bursts with amplitude higher than the selected threshold are studied. After burst selection procedure their temporal characteristics — burst rate and burst duration are calculated. Their radial dependence during the biasing discharge is presented in the Fig. 2.

During biasing the average burst rate increases and the average burst duration decreases compared to the Ohmic phase. It must be mentioned that a similar modification of intermittent burst temporal characteristics during biasing has been already observed on the CASTOR tokamak [1]. The reason of such modification is that biasing generates a strongly nonuniform radial electric field, changes the radial electric field which already existed in Ohmic phase (see the Fig. 3) and imposes stronger sheared poloidal rotation on the plasma. The sheared poloidal rotation splits coherent structures, which are responsible for the appearance of intermittent bursts [10], into smaller structures and moves them faster in poloidal direction [1]. As a result the Langmuir probe detects more bursts in biasing phase

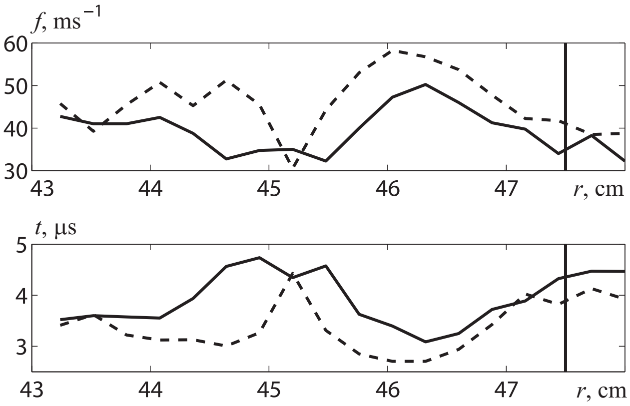

Fig. 2. Dependence of the I_{sat} average burst rate f (upper graph) and average burst duration t (lower graph) on the radial coordinate r. Solid lines correspond to the Ohmic phase and dashed lines to the biasing phase of the TEXTOR discharge #112172. Vertical line shows the radial position of the limiter

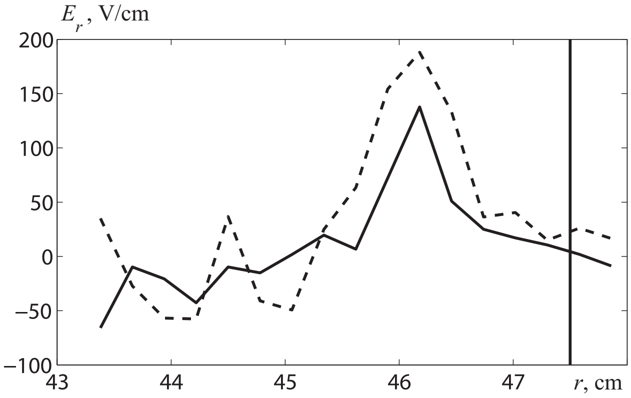

Fig. 3. Dependence of the radial electric field E_r on the radial coordinate r. Solid line corresponds to the Ohmic phase and dashed line to the biasing phase of the TEXTOR discharge #112172. Vertical line shows the radial position of the limiter

of the discharge and their average duration decreases [1]. The global consequence of this is the improvement of confinement, which has been studied experimentally in many tokamaks (see example [35 — 37]).

Generally, during DED operation open stochastic magnetic field lines (study of their influence on turbulent transport can be found in [38, 39]) appear in plasma boundary and radial magnetic connection between the edge plasma and wall is created. Electrons move faster than ions along the radial magnetic field lines. As a result the radial electric field is modified in the plasma [7, 8]. Since the radial electric field is modified during DED operation and at the same time different DED regimes have different influence on plasma [7], one can presume that in a certain DED regime we may get the modification of intermittent bursts resembling the case of electrode biasing. Indeed, such DED regime was found among many different ones used on TEXTOR. During DED phase of such discharge I_{sat} average burst rate increases and average burst duration decreases compared to the Ohmic phase (see the Fig. 4).

All these modifications are conformable to those observed during electrode biasing. The main reason should be the modification of the radial electric field by DED presented in the Fig. 5 which shows that the radial position of the shear layer practically does not change in the DED regime, but the radial electric field is stronger (more negative) inside this layer compared to Ohmic conditions. The electric field slightly decreases outside the shear layer, but the difference between the positive and negative peaks of the field (which also do not change their radial location) around the shear layer increases during DED. Thus, the sheared poloidal rotation is stronger during DED. As a result coherent structures are splitted into smaller structures which move faster in poloidal direction and modification of intermittent burst characteristics resemble those observed during electrode biasing.

As it has been already mentioned above, the radial electric field has been calculated as radial derivative of plasma potential $V_{pl} = V_{fl} + 2.5T_e$. Electron temperature fluctuations together with floating potential fluctuations bring their contribution into E_r, but these contributions depend on discharge conditions.

In Ohmic (see the Fig. 6) and biasing phase (see the Fig. 7) of biasing discharge temperature brings significant contribution only in a narrow radial region between $r = 45.5$ cm and $r = 46.5$ cm.

The contribution of temperature fluctuations to the radial electric field E_r are quite similar in Ohmic and biasing phase of the TEXTOR biasing discharge. This is not surprising, because radial profile of temperature during biasing does not change significantly (see the Fig. 8).

During the Ohmic phase of DED discharge temperature contribution to E_r is significant at all radial positions (see the Fig. 9).

In the DED phase of the same discharge the situation is different. Temperature contribution decreases dramatically (see the Fig. 10).

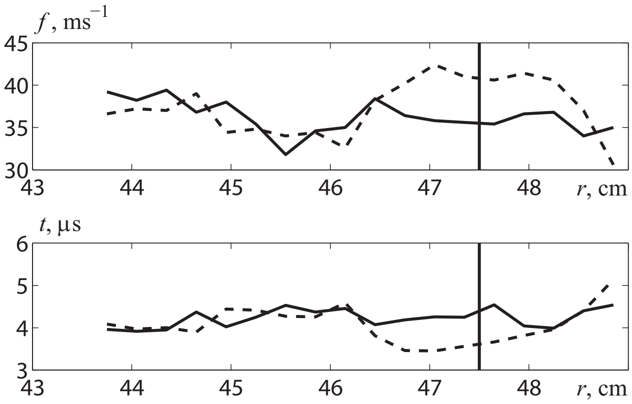

Fig. 4. Dependence of the I_{sat} average burst rate f (upper graph) and average burst duration t (lower graph) on the radial coordinate r. Solid lines correspond to the Ohmic phase and dashed lines to the DED phase of the TEXTOR discharge #111626. Vertical line shows the radial position of the limiter

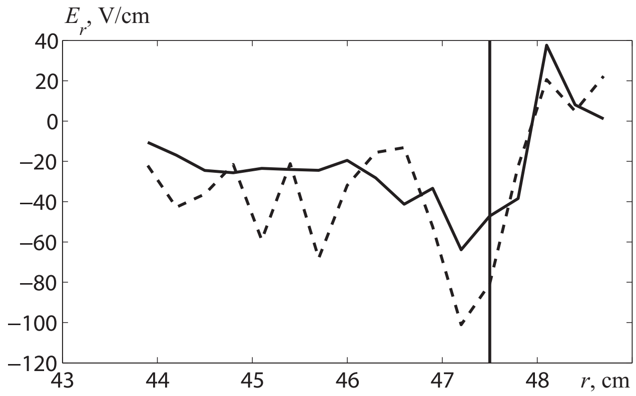

Fig. 5. Dependence of the radial electric field E_r on the radial coordinate r. Solid line corresponds to the Ohmic phase and dashed line to the DED phase of the TEXTOR discharge #111626. Vertical line shows the radial position of the limiter

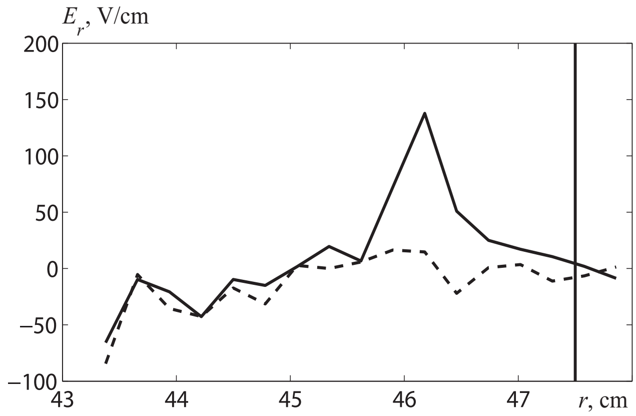

Fig. 6. Dependence of the radial electric field E_r on the radial coordinate r during Ohmic phase of the TEXTOR discharge #112172. Solid line corresponds to the E_r calculated with contribution of temperature and dashed line to the one calculated without contribution of temperature. Vertical line shows the radial position of the limiter

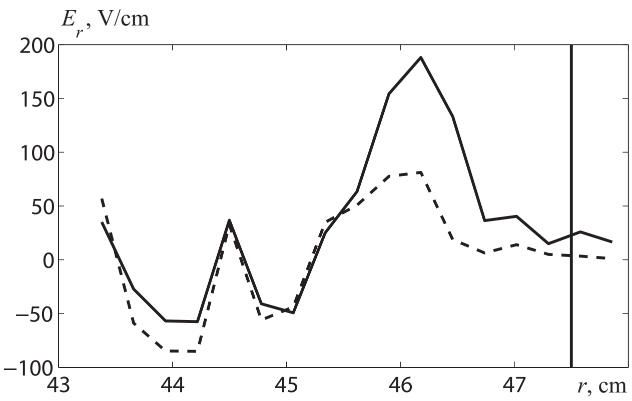

Fig. 7. Dependence of the radial electric field E_r on the radial coordinate r during biasing phase of the TEXTOR discharge #112172. Solid line corresponds to E_r calculated with contribution of temperature and dashed line to the one calculated without contribution of temperature. Vertical line shows the radial position of the limiter

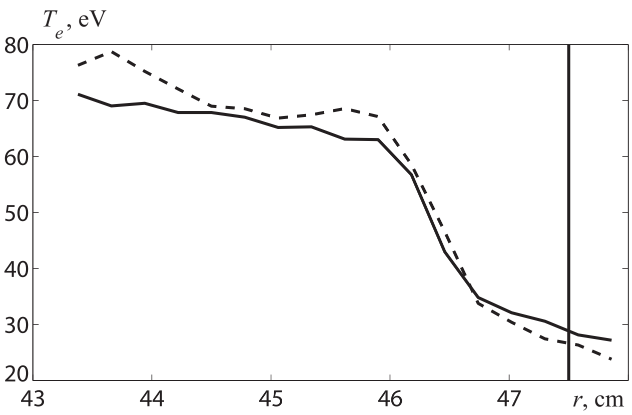

Fig. 8. Dependence of plasma electron temperature T_e on the radial coordinate r. Solid line corresponds to the Ohmic phase and dashed line to the biasing phase of the TEXTOR discharge #112172. Vertical line shows the radial position of the limiter

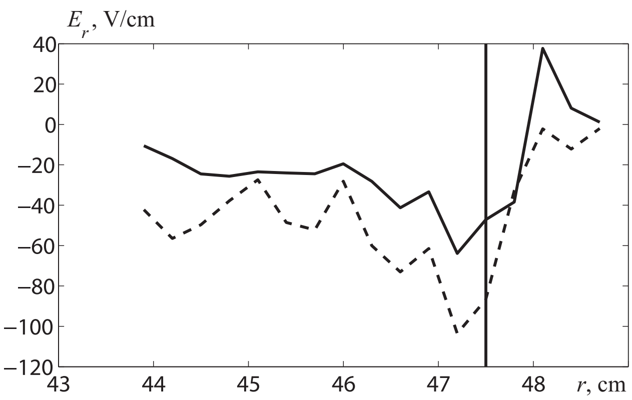

Fig. 9. Dependence of the radial electric field E_r on the radial coordinate r during Ohmic phase of the TEXTOR discharge #111626. Solid line corresponds to the E_r calculated with contribution of temperature and dashed line to the one calculated without contribution of temperature. Vertical line shows the radial position of the limiter

The reason for this dramatic decrease of the temperature contribution to E_r during the DED phase of the discharge is that when DED is applied plasma temperature is strongly reduced (see the Fig. 11).

IV. Conclusion

The study of intermittent burst characteristics at the edge of the TEXTOR tokamak and their modification during electrode biasing and DED regimes is reported. Conformable modifications are observed in two regimes. The reason should be that these regimes modify the radial electric field which has conformable effect on the dynamics of coherent turbulent structures and plasma transport through $\mathbf{E_r}\times\mathbf{B_t}$ induced sheared poloidal rotation. Thus, in principle, after detailed investigations and refinement it might be possible to use certain regimes of DED as “contactless biasing” which will be beneficial for the external control of plasma turbulent transport in next generation fusion devices.

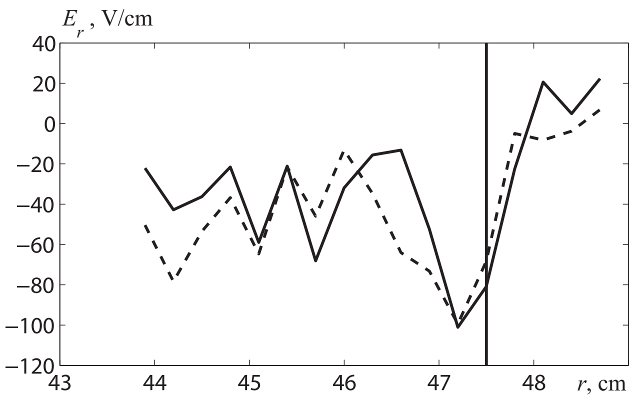

Fig. 10. Dependence of the radial electric field E_r on the radial coordinate r during DED phase of the TEXTOR discharge #111626. Solid line corresponds to the E_r calculated with contribution of temperature and dashed line to the one calculated without contribution of temperature. Vertical line shows the radial position of the limiter

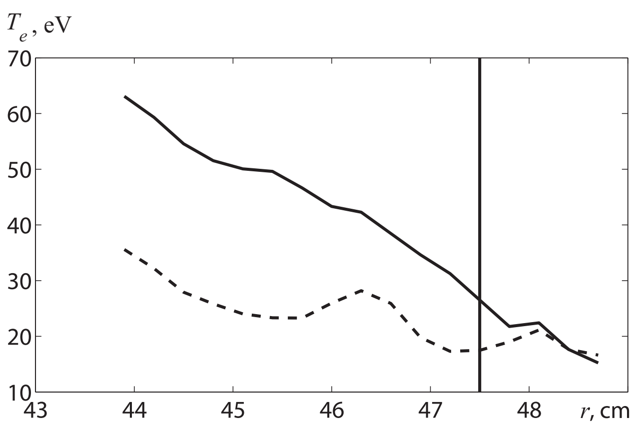

Fig. 11. Dependence of plasma electron temperature T_e on the radial coordinate r. Solid line corresponds to the Ohmic phase and dashed line to the DED phase of the TEXTOR discharge #111626. Vertical line shows the radial position of the limiter

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