Note

$P_H/S$—tokamak’s limit as a result of the plasma sheath breakdown

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Abstract

It was noted earlier [1] that high performance regimes of many tokamaks were achieved in the condition of plasma heating power $P_H$ limited from above. The exceeding of this limit usually ended as a plasma collapse. The analysis of the high performance regimes of well known tokamaks which operated during the last 50 years has shown that the values of such 'permissible' $P_H$ grow approximately linearly with the area $S$ of the first wall surface facing to the plasma. The paper attempts to explain the existence the $P_H/S$ limit for high performance tokamak regimes as a consequence of the vacuum breakdown of the plasma sheath in the area of a plasma contact with the vessel wall and unipolar arcs which followed it.

Keywords: tokamak, first wall, power load, plasma sheath, unipolar arcs, vacuum breakdown

1. Introduction

As it was noted earlier [1], the maximum achievable neutron power of the future steady-state tokamak-reactor based on the current fusion technology and ITER Physics [2] should be limited by the average thermal load of its first wall $P_H/S$ not higher than 0.3–0.4 MW m$^{-2}$, where $P_H$ is total power of plasma heating (during the steady-state operation it is equal to the total plasma energy losses) and $S$ is area of the first wall of tokamak vessel surface facing plasma.

The main argument of the existence of this phenomenological $P_H/S$-limit is the fact that for more than 50 years of active tokamak operation from the first Russian tokamaks TM-2 and T-3 up to JET the parameter $P_H/S$ for their high performance shots remained approximately constant between 0.1 and 0.3 MW m$^{-2}$ [1]. It is true for almost all known tokamaks despite the fact that maximum values $P_H$ and hot plasma temperatures increased approximately 100 times during this period. A violation of the $P_H/S \approx 0.2$ MW m$^{-2}$ limit usually led to the development of large or small disruptions. In ITER, this parameter is expected to be close to 0.2 MW m$^{-2}$ [2]. Figure 1 presents the maximal values of $P_H/S$ parameter obtained in high performance shots for a number of well-known tokamaks [3–13] with significantly different sizes and powers of plasma heating $P_H$ ($P_H/S$–$P_H$ diagram). The highest values of $P_H/S$ were usually achieved in the conditions of the first wall protection by low Z (Li, Be, +B) materials, or, as it was in the case of ASDEX-U [10], when the periphery of the plasma column was cooled by the non-coronal radiation of impurities N$_2$ + Ar which were injected into the divertor scrape-off layer (SOL) during the discharge. As it was shown for the first time by experiments on TFTR [3], an effective method of expanding of the acceptable level of $P_H$ is the use of lithium as a protective coating of the tokamak first wall. The injection of lithium in TFTR (see figure 1) allowed to raise the 'permissible' value $P_H/S$ up to the level 0.3–0.4 MW m$^{-2}$ [4] compared with 0.2 MW m$^{-2}$ in experiments with one graphite bumper. However further increase of $P_H/S$ up to the level of 0.5 MW m$^{-2}$ [5] (square in figure 1) led to the development of
minor disruption and subsequent degradation of a plasma discharge. The visible growth of the $P_{\text{H}/S}$ limit in process of increasing of radiation cooling of plasma boundary allows assuming that its nature is caused by plasma bombardment of the first wall, which progressively weakens under the cooling of the plasma periphery by the impurity radiation.

2. Plasma heat flows and the sheath potential

Since Langmuir times it has been known (for example, [15]) that the potential sheath equal to $\sim 3T_e$ arises near the plasma-wall boundary. This decreases the electron flow on the wall with simultaneous acceleration of ion flow. The crash of this sheath as a result of the spontaneous splash of local secondary electron emission at the wall or its vacuum breakdown (for example, [16]) can cause a local wall overheating with its melting and development of so called ‘cathode spots’ which will be accompanied by ejection of wall erosion products into the plasma with its cooling up to a local or total collapse. That is a conventional mechanism of the development of so called unipolar arcs [15].

Figure 2 shows a picture of unipolar arc event on the target coated by Li and placed in the scrape-of layer (SOL) of T-11M with Li-limiter [17] in the light emission of Li$^+$ (549 nm) during the transient phase of plasma shot (time exposition $\sim 0.3$ ms).

The clear visible trace of the ionized erosion product (Li$^+$) goes along the magnetic field from target into the SOL. Probably the separate filaments, which are sometimes observed in high power regimes of tokamak operations (for example, [18]) had the same physical nature.

Upon reaching the high performance regimes tokamak experimentalists should avoid the arcs or extremely weaken their influence by cleaning of the first wall from organic and other films (first wall conditioning). However, with increasing the power of plasma heating it is becoming more difficult. From the practice of real tokamaks it is known that, despite the use of various limiters and divertors, a significant part of the tokamak first wall surface contacts electrically with the boundary of the plasma column, in particular, due to the destruction of magnetic surfaces during the development of various types of peripheral turbulence. The width of the corresponding plasma sheath should be equal to Debye radius by order of magnitude. That means, the electric field $E$ near the...
first wall of tokamak in the area of real contact with plasma, should be proportional to \((n_e T_e)^{1/2} \sim P_e^{1/2}\), where \(P_e\) is the electron pressure in this area. But from the other side the electron pressure is a main determined parameter of the heat flow \(P_{W/S} \sim P_e T_e^{1/2}\) from plasma to the wall along magnetic field. If we assume that the electric field \(E\) near the first wall in the area of the plasma contact is limited by some critical value, above which the vacuum breakdown or arc develops with formation of ‘cathode spots’, we should expect the existence of a corresponding limit of the permissible value \(P_{W/S}\) like one, which we can see in figure 1. In particular, if we assign the typical plasma density near the tokamak plasma boundary \(3 \cdot 10^{19} \text{ m}^{-3}\) and \(T_e = 30\text{ eV}\), the value of \(E\) on the place of contact will be about \(5 \cdot 10^8 \text{ V m}^{-1}\), which is in the typical range of vacuum breakdown \(10^6 \text{--} 10^8 \text{ V m}^{-1}\).

3. Discussion

It is known, that the probability of a vacuum breakdown decreases in the presence of different kinds of films deposited on electrodes. If we take into account that during the tokamak discharge erosion products of plasma facing component collected gradually as films on the first wall of the vessel, it can explain the observed reduction of the \(P_{W/S}\) limit with increasing of the discharge duration (for example see Tore Supra in figure 1). From this point of view for the steady-state tokamak operation there follows a strict requirement of removal of erosion products from the tokamak vessel during the whole operational cycle. As we can see from figure 1, the tokamak first wall coating by materials with low \(Z\) can significantly increase the ‘permissible’ limit of \(P_{W/S}\) and accordingly plasma energy. It is possible that the increase of the toroidal magnetic field \(B_T\), as it follows from both examples of the ‘high \(B_T\) tokamaks’- Alcator C-Mod and TFTR (figure 1), also contributes to the growth of the ‘permissible’ \(P_{W/S}\) values.

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