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Review of FTU results with the liquid lithium limiter

G. Mazzitelli[a,∗], M.L. Apicella[a], V. Pericoli Ridolfini[a], G. Apruzzese[a], R. De Angelis[a], D. Frigione[a], E. Giovannozzi[a], L. Gabellieri[a], G. Granucci[a], C. Mazzotta[a], M. Marinucci[a], A. Romano[a], O. Tudisco[a], A. Alekseyev[c], I. Ljublinski[d], A. Vertkov[d], ECRH Team[b]

[a] Associazione EURATOM-ENEA sulla Fusione, Centro Ricerche di Frascati, C.P. 65-00044, Italy
[b] Associazione EURATOM-ENEA, IFP-CNR, Via R.Cozzi, 53 20125 Milano, Italy
[c] TRINITI, Troitsk, Moscow reg., Russia
[d] "RED STAR", Moscow, Russia

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ABSTRACT

Since the end of 2005 a liquid lithium limiter has been installed on FTU. The liquid lithium is confined by capillarity in a mat of stainless steel or other refractory material and the capillary force counteracts the electromagnetic force. In this paper we review some of the most important results obtained in the experimental campaigns led on FTU. Peaked electron density profiles are spontaneously formed when the density exceeds $1.0 \times 10^{20}\,m^{-3}$. Despite to the fact that FTU is a fully metallic machine with a TZM toroidal limiter, the only impurity that is present in the plasma is lithium so that very clean plasma are obtained and the beneficial effects are discussed. Heat loads in excess of $5\,MW/m^2$ are withstood by the limiter without any damage also because the radiative losses from the evaporated lithium are able to dissipate most of the incoming heat flux.

1. Introduction

One of the most important issue for a future reactor is the material exposed to plasma. Up to now, with different motivations, two materials have been used: CFC (carbon fiber composite) and tungsten. Both of them have demonstrated in the tokamak experiments to have problems that are no easy to solve. As a consequence, plasma facing component is still an open question for DEMO. No other materials are envisaged as possible substitutes so that it is important to test in experiments new innovative concepts.

One of them is the possible use of a liquid material instead of a solid one. The suitable material should be liquid at room temperature or greater compatible with tokamak operation and with a high boiling point so that evaporation could be kept relatively low also in presence of high heat loads in the range $10–20\,MW/m^2$.

Liquid lithium meets many of these requirements but due to its good conductibility typical of metals it is mandatory to counteract the $J \times B$ force. In fact simple exposition of liquid lithium to plasma led to droplet formation causing plasma disruptions [1]. This problems has been overcome by using an innovative concept firstly proposed by Evtikhin et al. [2]

The liquid lithium is confined by capillarity in a mat of stainless steel or other refractory material and the capillary force counteracts the electromagnetic force. Of course experiment must be done in magnetic device to demonstrate its potentialities. FTU is a high field tokamak [3] ($R = 0.93\,m$, $a = 0.30\,m$, $B_t \leq 8\,T$, $I_p < 1.6\,MA$, pulse length $t_{pulse} \approx 1.5\,s$) with a TZM (an alloy 98% of molybdenum) toroidal limiter and Stainless Steel AISI 304 for the vacuum chamber. FTU can operates in a wide electron density range $n_e = 0.3–3.2 \times 10^{20}\,m^{-3}$ and with high power density so that it is possibly to test the validity of CPS configuration and the behavior of a liquid material as plasma facing component and their effects on plasma behavior.

Since the end of 2005, the liquid lithium limiter has been installed on FTU. In this article we review the experimental results obtained in these 4 years. In Section 1 a brief description of the experimental apparatus will be given, in Section 2 the experimental results will be illustrated. This section will be divided in subsection to separate different subjects and, then in Section 3 the conclusions.

2. The liquid lithium limiter (LLL)

In Fig. 1 a photograph of the three units of LLL installed on the support used for the introduction inside FTU and a quoted design of fully equipped lithium limiter unit are shown.

The lithium limiter is made of three separated and electrically insulated modules which consist for two of them of a surface layer of wire meshes of stainless steel 304 with pore radius 15 μm and wire diameter 30 μm similar to that of T-11 lithium limiter [4]. In the third one the stainless steel wires have been recently replaced

∗ Corresponding author at: ENEA, Unità Tecnica Fusione, Via Enrico Fermi 45, 00044 Frascati, Roma, Italy. Tel.: +39 0694005692; fax: +39 0694005524.
E-mail address: giuseppe.mazzitelli@enea.it (G. Mazzitelli).

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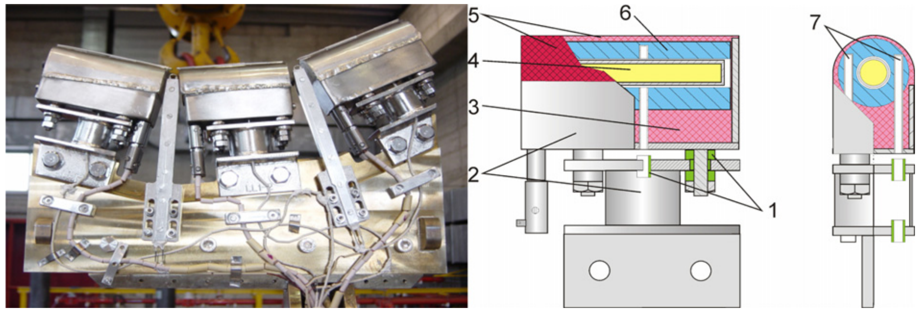

Fig. 1. Photograph of three units of lithium limiter installed on the support used for the LLL introduction inside. The two Langmuir probes are visible in the interspace between units. (1) Ceramic break, (2) stainless steel case, (3) lithium filled-capillary structure, (4) heater, (5) Li evaporating surface (6) Mo heat accumulator and (7) thermocouples.

by tungsten wires that should be more suitable for future application. The surface faced to the plasma is refilled through capillary forces by a liquid lithium reservoir placed on the bottom of this structure. This self-regeneration capability is a very important feature for ITER divertor plates that are expected to operate in the presence of frequent small disruptions (ELMs) that are responsible for enhanced erosion of solid plate. The limiter is inserted from one vertical port at the bottom side of the machine and its radial position can be varied shot by shot from 4 cm outside the last closed magnetic surface (LCMS) up to the LCMS position with the TZM toroidal limiter acting as main limiter. The toroidal limiter is in the high field side and starting from the midplane the poloidal extension is $\pm 35^\circ$. After plasma exposure lithium limiter can be extracted in a separated volume where an optical window permits to observe the Li surface.

The liquid lithium limiter is equipped with two thermocouples for each module and two Langmuir probes placed in the intermediate space between modules to characterize the scrape-off plasma near the limiter surface. Infrared detectors look at the three modules to monitor the lithium surface temperature during the shot [5] and the Li III (13.5 nm) line is used to monitor the lithium content inside the plasma.

The liquid lithium limiter is inserted into the vacuum chamber and preheated at about 220 °C (melting point T = 186 °C). Two different operational conditions for liquid lithium limiter have been explored: (a) physical sputtering of LLL in the scrape-off layer at the shadow of the LCMS for the whole duration of the discharge and (b) sputtering plus evaporation obtained by shifting for a short time (Δt = 0–05 s), the plasma towards the liquid lithium limiter to increase the thermal load. It was found, in order to have a good control of Li production, that the Li surface temperature must not exceed the value of 550 °C. This requirement fixed a limit, for the case (a), to the shorter distance of LLL from the LCMS (≅2 cm)

3. Experimental results

The main results obtained in the first experiments performed with the LLL are therein summarized and more details can be found in Ref. [6]. Lithization of the first wall is a powerful method to get very clean discharges comparable or even better than boronization. Recycling is strongly reduced by the Li pumping capability and in addition MHD activity is almost suppressed. These deeply modified edge conditions lead to an increase of edge electron temperature by a factor 2. In the following subsections we report in detail more recent experimental results get on FTU.

3.1. Peaked electron density profiles

One of the main characteristics of plasma operations with lithium is the spontaneously peaking of the electron density profile. When the density is greater than 1.0×10^{20} m^{-3} and in presence of a well developed MARFE, peaking factor ($n_e(0)/\langle n_e \rangle_{vol}$) up to 2.5 are obtained. This effect is shown in Fig. 2 for two following discharges in which the electron density, as measured by the central chord of the interferometer, is increased after t = 0.7 s only by gas puffing up to 2.8×10^{20} m^{-3} while the periferical chord at r = 0.235 m does not show any increase. This core peaking effect is still more evident if we look at the behavior of the electron density radial profiles in the scrape-off-layer. In Fig. 3 the electron densities as measured by the Langmuir probes, are plotted versus the distance from the last closed magnetic surface for the same discharges of Fig. 2 at t = 1.3 s. No significant differences both in value as well as in the radial pro-

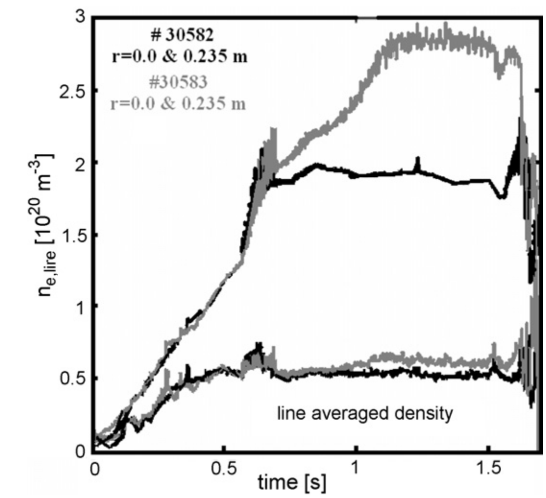

Fig. 2. Time evolution of the central and peripheral electron density for shot 30582 in blue and shot 30583 in red. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

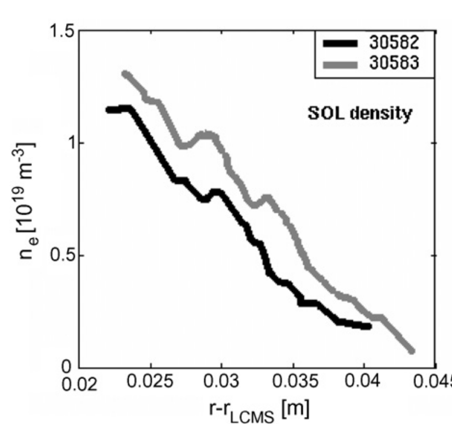

Fig. 3. SOL density profile for the shots of Fig. 2.