First ECRH heated elongated plasmas with an actively water cooled liquid lithium limiter on FTU

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1. Introduction

Power exhaust is one of the main issues to be tackled to achieve steady state operation of future reactors. In the last years liquid metals have demonstrated to be a possible candidate to improve the situation. Recently an actively Cooled liquid Lithium Limiter (CLL) has been built and installed in Frascati Tokamak Upgrade (FTU) that will enable sustaining up to 10 MW/m^2 [1]. The results of first elongated plasmas heated by Electron Cyclotron Resonance Heating (ECRH) with the new CLL will be given here. These discharges aim at investigating the access to H-mode without an X-point into the main chamber, as done at JET with MarkIIGB divertor by moving the X-point up to 5cm inside the septum [2]. Details on possible modifications of Poloidal Field Coil (PFC) connections and power supplies to move the X-point into the camera will be also presented.

2. Cooled lithium limiter system

FTU is a compact high magnetic field machine (toroidal field B_T from 2.5 to 8T, plasma current I_P up to 1.6 MA) with circular poloidal cross-section (major radius R_0 of 0.935m, minor radius a of 0.30m) and metallic first walls [3]. The stainless steel vacuum chamber is covered internally by a toroidal limiter made of molybdenum (Mo) tiles. Since 2006, experiments on a poloidal Liquid Lithium Limiter (LLL) have been successfully performed on FTU: heat loads of 1-2 MW/m^2 were withstood without troubles and transient phenomena, i.e. disruptions, in the order of 10-15 MW/m^2 didn't cause any damage to the limiter surface [4-5].

Table 1. Main parameters of CLL in-vessel element

Parameter	Value
Initial lithium surface temperature	≅ 200°C
Lithium surface temperature during plasma interaction	≤500 °C
Power removal capability	up to 100 kW
Plasma interacting area	~ 100 cm^2
Lithium amount (volume/weight)	up to 60 cm^3/ 30 g
Element dimensions (L × H × W)	33×20.5×3.2 cm
CLL curvature radius	29 cm

The LLL uses a Capillary Porous System (CPS) to confine liquid metal by means of capillary forces. In order to prevent the overheating of the liquid Lithium (Li) surface and the consequent strong Li evaporation for T>500°C, an advanced version of LLL has been recently realized and installed on FTU by using the same vertical bottom port of the previous limiter. This new system (CLL) has been optimized to demonstrate the lithium limiter capability to sustain thermal loads as high as 10 MW/m^2 with up to 5s of plasma discharge duration, reachable in FTU by operating at low magnetic field (4 Tesla). The main design parameters of CLL are given in Table 1. The CLL operates with an actively cooled system with water circulation at the temperature of about 200 °C, for heating lithium up to the melting point and for the heat removal during the plasma discharges [1]. To characterize the CLL under plasma discharges, a fast infrared

* *See the appendix of P. Buratti et al., Proceedings of the 24th IAEA Fusion Energy Conf., San Diego, USA, 2012*

camera and the spectroscopic signals from Li and D atom emission have been used. A picture of the CLL system is shown in Fig.1. First ohmic experiments on FTU [1], have been performed to study the behaviour of CLL in the FTU scrape-off layer in order to identify the best plasma conditions for a good uniformity of the thermal load. The CLL has been exposed to a typical reference circular plasma discharge #37789 (I_p=0.5 MA, B_T=6T and line-averaged electron plasma density $<n_e>$=0.5-1.0x$10^{20}m^{-3}$), with net power to the $P_{SOL}=P_{input}-P_{rad}\approx$300kW and progressively inserted into the vacuum chamber almost up to the last closed magnetic surface (LCMS) as defined by the main toroidal Mo limiter. Li signal was quite constant during the plasma current flat top as a clear indication that the surface temperature was below 500 °C without a strong evaporation.

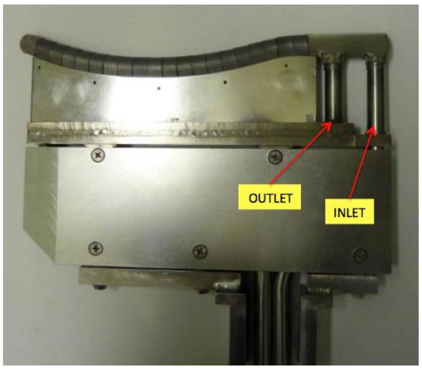

Figure 1. Photo of the FTU CLL. On the top are the Li CPS structure, the inlet and outlet vertical tubes (on the right) for the water circulation.

From the surface temperatures monitored by a fast infrared camera and the ANSYS code simulations, heat loads up to 2.3MW/m^2 have been withstood by the limiter for more than 1s.

3. Experimental setup

In 2013, first elongated FTU plasmas heated by ~500kW of ECRH have been obtained with the new CLL. The magnetic configuration (I_P=200-220kA, B_T=5.5T, $<ne>$=0.4x$10^{20}m^{-3}$, R_0=0.97, a=0.25m, elongation of k~1.2, triangularity of $<\delta_{95}>$=0.18, magnetic shear ~40% higher than in circular plasma) presents the X-point close to the first wall with the 3λ surface (λ, energy e-folding length, ~1cm in FTU) opened on the CLL. The toroidal field B_T=5.5T was chosen in order to have a B_T=5.3T at 0.935m. The new allocator scheme for elongation control, described in [6], has been used for these experiments. In FTU there are 15 PFCs connected in series to form four circuits named as: T (transformer), V and F (in feedback for radial position control) for vertical field, and H (in feedback for vertical control) for radial field. In order to achive the elongation of k~1.2, the F circuit has to work at his max value of 11.5kA limiting the plasma current to be ~200kA.

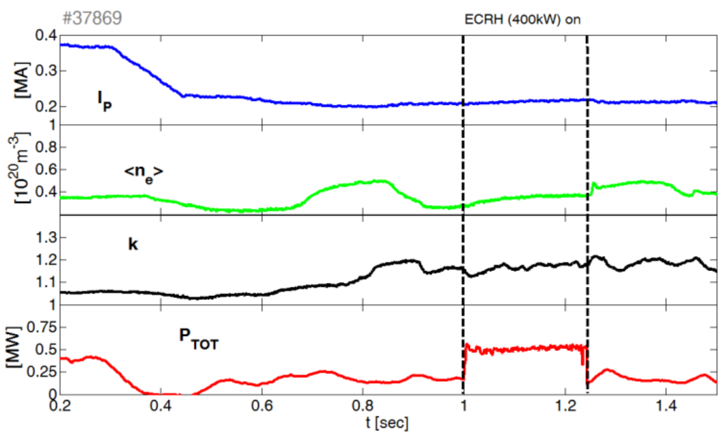

Figure 2. Time evolution of the main plasma parameters for discharge #37869 (no CLL inserted) during I_P flat-top. The total input power showed is the sum of the ohmic power dissipated in the plasma and the absorbed EC power.

The CLL has been inserted up to ~1cm from the LCMS. The D-shaped FTU plasma is indeed in contact with the outer Mo poloidal limiter. These discharges aim at investigating the access to H-mode, as done at JET with MarkIIGB divertor by moving the X-point up to 5cm inside the septum [2].

Time evolution of the main plasma parameters for discharge #37869 (no CLL inserted) during I_P flat-top are shown in Fig.2. The values for the power threshold P_{thr} for H-mode access are provided as the loss power though the separatrix, $P_{LOSS}=P_{OHM}+P_{AUX}-dW_{DIA}/dt$, where P_{OHM} is the ohmic power dissipated in the plasma, P_{AUX} is the absorbed auxliary heating and dW_{DIA}/dt is the rate of change of the diamagnetic energy W_{DIA}. The ITPA 2008 scaling [7], predicts in MW, for diverted plasmas: $P_{thr,scal08} \alpha B_T^{0.80} \cdot n_{20}^{0.72} \cdot S^{0.94}$, where B_T [T], n_{20} [$10^{20}m^{-3}$] and S [m^2] are respectively the magnetic field, line-averaged density, plasma surface area. The FTU ECRH system is composed of four gyrotrons (140 Ghz, 0.5MW, 0.5s) and operates at two magnetic field B_T=5.3T and 2.5T [7] at 0.935m. The total input power showed is the sum of the ohmic power dissipated in the plasma and the absorbed auxiliary ECRH heating power.

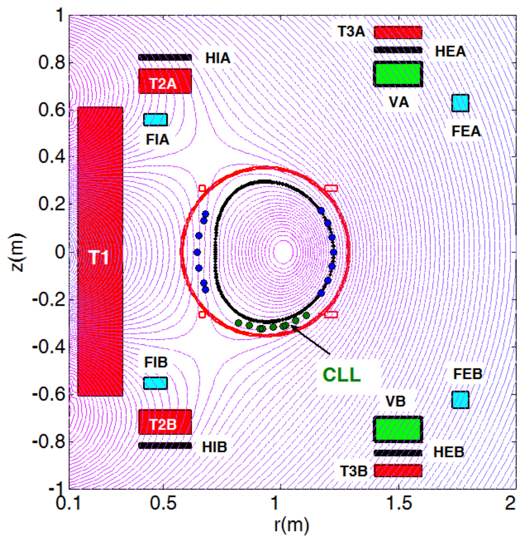

Figure 3. Flux map and separatrix for FTU discharge #37869 at 1sec. Also the PFCs, passive stabilizing coils (not actually fed) vacuum chamber, Mo (blue filled circles) and CLL limiter points (green filled circles), when inserted by 1cm, are shown.

In Fig.3 the flux map for discharge #37869 at t=1.15s is shown. Also the vacuum chamber, PFCs, Mo and CLL limiter points are shown.

4. Experimental results with the CLL

With the experimental setup described in Section 3 the CLL has been inserted from 1cm up to +3.8cm. No L-mode to H-mode transition was observed, consistent with the threshold $P_{thr,FTU@5.5T} \approx 700kW$ being above the injected power. For these discharges the radiated power was $P_{RAD,TOT}=0.4P_{TOT}$. The fast infrared (IR) camera looking at the CLL supported by the thermal analysis with ANSYS code has been used for a preliminary heat load estimate of the discharge #37931 (CLL=+3.8cm). In Fig. 4 the IR image (at t=0.3s) of the lithium limiter as seen by the infrared camera is shown. The temperature scale is not corrected for the emissivity factor of the liquid lithium and then the CLL temperature results underestimated. Thermal load is not uniform on the surface as shown in Fig.4. The highest temperatures have been reached at 0.3s (see Fig.5) when I_P=360kA, but the plasma still circular-shaped (see Fig.2). Point 1, 3 and 5 in Fig.4 are relative to the joint points on CLL.

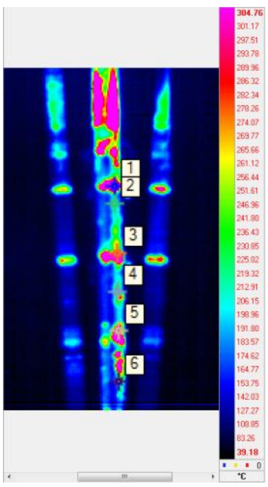

Figure 4. IR image of the CLL as seen by the infrared camera at t=0.3s. Lateral bands are due to the limiter radiation reflected by the lateral sides of the port.

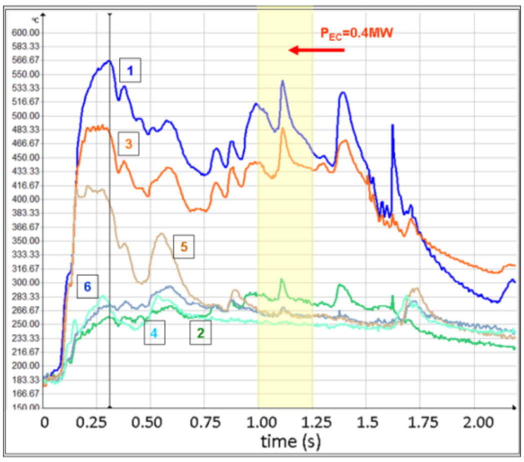

Figure 5. Temporal evolution of Li temperature, corrected for the liquid lithium emissivity by using the temperatures given by the thermocouples close to the Li surface, relative to the points of CLL shown in Fig.4.

No significant variation is observed during the ECRH phase. The oscillations of Li temperature observed with IR camera are associated to the effects of plasma vertical movements. Hot spots on the Li surface and Li evaporation (500 -550°C), as monitored by visible spectroscopy (not reported here), account for the vertical plasma movements. Despite of the deep CLL insertion, no plasma disruption has occurred and no damage has been observed on the CLL surface. A thermal analysis of the heating dynamics has been carried out by applying the ANSYS code, adapted to the real geometry of the CLL and using the experimental data. In the simulation, the shape and the position of the FTU plasma as reconstructed by the equilibrium code, the net power to the SOL (~350kW) and the energy decay lenght λ have been taken into account. Preliminary analysis has shown a maximum heat load of ~1MW/m^2 for 1.5sec. Further experiments are planned, considering discharges with a lower value of the toroidal magnetic field (2.7T) to reduce the power requirement ($P_{thr,FTU@2.7T}$≈400-500kW) [2] for accessing H-mode, thus having the possibility to study the impact of Edge Localized Modes (ELMs) on the CLL used as first limiter.

Possible modifications on FTU PFC connections

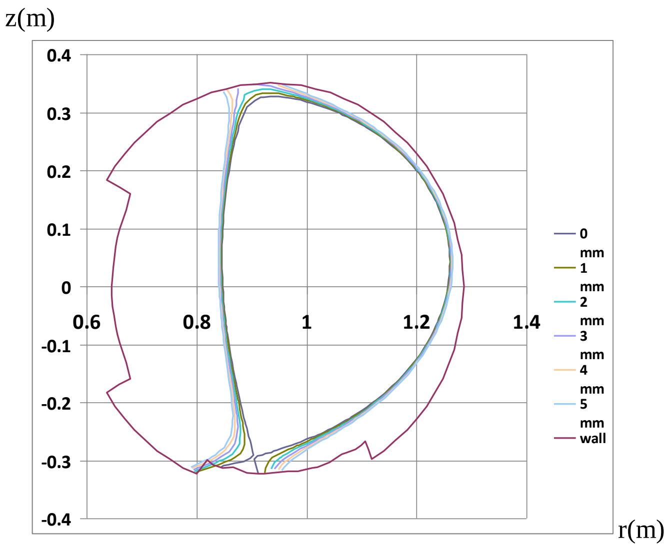

Figure 6. MAXFEA equilibrium calculation for FTU diverted plasma with an alternative connection scheme for PFCs.

An alternative connection scheme for the poloidal field coils in FTU has been preliminarily analyzed, with the aim of achieving a true X-point configuration with a magnetic single null well inside the plasma chamber and strike points on the lithium limiter [8]. The hardware upgrade required to make possible this configuration possible includes new busbars through the cryostat to independently supply some of the transformer and feedback coils, a new booster power supply, the reconnection of the passive stabilizing coils in a saddle configuration to increase the vertical instability growth-time. X-point plasma scenarios, described in [8], with current up to 300 kA and duration up to 2.5s have been studied. In Fig.6 the configuration during I_P flat-top, as calculated by MAXFEA equilibrium code, is shown. A first engineering analysis has been also carried out, showing the structural, thermal and electro-magnetic compatibility of this alternative connection scheme with the load assembly structure and with the existing power supply and cooling plants.

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