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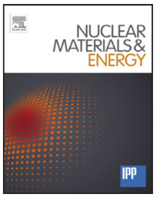

D-shaped configurations in FTU for testing liquid lithium limiter: Preliminary studies and experiments

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ABSTRACT

The feasibility of getting “D” shaped plasma configurations in FTU, with a possible X point close to the first wall, has been investigated with the aim of achieving an H-mode regime in this machine. This regime could allow both evaluating the thermal effects on the liquid lithium limiter due to the possible Edge Localized Modes and studying the L-H transition properties in low recycling conditions due to the presence of lithium.. An alternative design for the magnetic system in FTU has been also proposed, to realize an X-point inside the plasma chamber, close to the Liquid Lithium Limiter.

Preliminary experiments with elongated configurations and limited ECRH additional heating power did not allowed approaching the L-H transition but they were used to develop a proper elongation control. This controller allowed guaranteeing the vertical stability in elongated configurations despite the reduced power available for the horizontal field coils in FTU. The elongation was stably keep over 1.2, while the lithium limiter was very close to the last close flux surface. Neither limiter damages nor plasma pollution were observed in these configurations.

A possible alternative connection of the poloidal field coils in FTU is here proposed, 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. A preliminary assessment of this design allowed estimating the required power supply upgrade and showed its compatibility with the existing mechanical structure and cooling system, at least for plasmas with current up to 300 kA and flat-top duration up to 4 s.

1. Introduction

The power exhaust handling is a critical issue in the design of a nuclear fusion reactor, due to the extremely large heat loads expected on the plasma facing components for scenarios based on standard plasma configurations [1]. Liquid metals showed, in the past, noticeable capabilities in dealing with large continuous heat loads and could be a solution for this problem [2].

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[1] See the appendix of G. Pucella et al., Proceedings of the 25th IAEA Fusion Energy Conf., Saint Petersburg, Russia, 2014.

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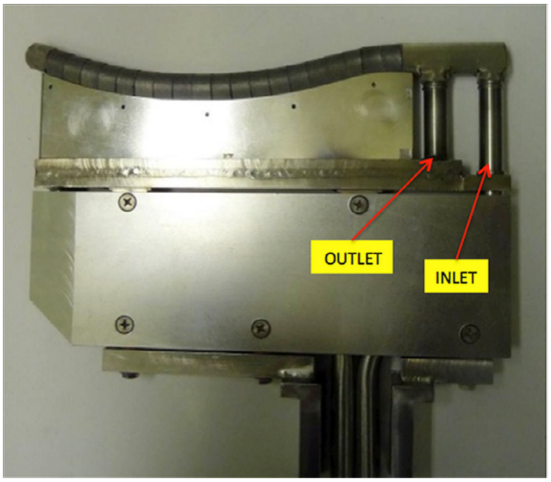

Fig. 1. Cooled lithium limiter.

With this aim, an actively Cooled liquid Lithium Limiter (CLL) has been built and installed in FTU. Recent experimental results with this CLL have provided evidence of its capability in sustaining a steady state load up to 10 MW/m^2 [3]. It is here proposed the possibility to achieve an X-point configuration in FTU with minor changes in the connections among coils and in the power supply system, allowing the study of the impact of Edge Localized Modes on this CLL.

In the following, Section 2 briefly describes the CLL and the present FTU Poloidal Field (PF) coils system; Section 3 shows the first experimental results obtained with the most elongated plasmas achievable with the current FTU configuration and heated by Electron Cyclotron Resonance Heating (ECRH); Section 4 illustrates the new configuration proposed to achieve a true X-point topology in FTU.

2. FTU and the CLL

FTU is a compact tokamak with an high toroidal magnetic field (up to 8T), a plasma current up to 1.6 MA, a circular poloidal cross-section (major radius 0.935 m, minor radius 0.30 m) and a metallic first wall [4]. The stainless steel vacuum chamber is protected by an inboard full toroidal limiter and by an outer poloidal limiter made of molybdenum tiles.

The fifteen Poloidal Field (PF) coils are grouped in four sets of windings, named T, H, V, and F circuits. Five T windings, connected in series, act as a Transformer to generate the breakdown field and the poloidal flux required to control the plasma current. Two V coils generate the Vertical field required to equilibrate the plasma column. Four Feedback coils, connected in up-down anti-series, and four Horizontal field coils, connected in inboard-outboard anti-series, provide respectively the poloidal fields required to control radially and vertically the plasma position.

The actively Cooled liquid Lithium Limiter (CLL) mounted in FTU, shown in Fig. 1, exploits a Capillary Porous System (CPS) to confine liquid Lithium in a porous Tungsten mesh. The cooling circuit is realized by water flowing at temperature of about 200 °C with pressure up to 30 bar It allows heating the Lithium up to the melting point (180.5 °C) and removing the heat during the plasma discharges [3]. It has been mounted in the same bottom vertical port where it was installed the previous poloidal Liquid Lithium Limiter [5, 6].

The CLL was designed to sustain thermal loads up to 10 MW/m^2 for at least 5 s (maximum duration of a FTU plasma discharge at 4 T toroidal field), avoiding the overheating of the exposed surface and the consequent Li evaporation when $T > 500$ °C. The main design parameters of the CLL are given in Table 1.

Table 1
Main CLL design parameters.

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

Several diagnostics have been installed with the CLL to monitor its operation in FTU: thermocouples for inlet and outlet water temperatures, Langmuir probes for the edge electronic temperature and density, Li and D atomic emission spectroscopy, fast infrared camera with view of the whole limiter from the top (spatial resolution ≅1.5 mm, acquisition rate 300 full frames/s).

The performance of the CLL was evaluated with heat load up to 2.3 MW/m^2 for more than 1 s in ohmic circular plasma discharges ($I_p = 0.5$ MA, $B_T = 6$T, $\langle n_e \rangle = 0.5–1.0 \times 10^{20}$ m^{-3}, net scrape-off power $PS_{OL} = P_{input} - P_{rad} \cong 300$ kW). These experiments, with the CLL inserted up to almost touch the Last Closed Magnetic Surface, allowed to assess the regularity of Li emission and the absence of significant damage up to temperature close to 500 °C.

3. First experimental results: attempting H-mode access with outer X-point and vertical stability issues in $k \approx 1.2$ elongated FTU plasmas

To investigate the possibility of accessing H-mode regimes in partly diverted plasmas, a plasma configuration, elongated as much as possible with the existing connection among poloidal field coils ($k \approx 1.25$), was realized in FTU [7]. This configuration corresponds to the maximum elongation achievable because, in FTU, the plasma elongation depends on the ratio of the current in V and F circuits, which both produce the vertical field required for plasma stabilization but with opposite radial components. The elongated, quasi D-shaped configuration allowed with this constraint is characterized by a plasma current up to 300 kA and a discharge duration up to 4 s. The FTU integrated plasma position and elongation controller was updated with a new design allocator scheme [8] able to force the current in F circuit near to the maximum admissible value (11.5 kA) required to maximize the elongation.

The time evolution of the main plasma characteristic for the elongated shot #37869, having $B_T = 5.3$ T, $R_0 = 0.97$ m, $a = 0.25$ m, $\langle \delta_{95} \rangle = 0.18$ and without the CLL inserted is shown in Fig. 2.

In the $k = 1.2$ phase of this discharge, the X-point is located outside of the first wall but rather close to it, about 8 cm far i.e. 10 cm from the Last Closed Magnetic Surface (LCMS), as shown in Fig. 3. The flux surfaces at 1, 2 and 3λ from the LCMS (assuming an energy e-folding length $\lambda \cong 0.5$ cm in FTU) cross the CLL on the outer side, as shown in Fig. 4. In this configuration, the LCMS touches only the Mo poloidal limiter on the outboard and is detached almost 1 cm above the CLL, as shown in Fig. 3. The local magnetic shear in the LCMS near the CLL is about 40% greater than in circular plasma. These conditions are expected to be adequate to observe a transition to H-mode if enough power was provided to overcome the L-H access threshold, even when the X-point is located outside the chamber. Similar transitions were observed in JET when the X-point, outer to the first wall, was moved inside the septum of the MarkIIGB divertor [9].

The ITPA 2008 scaling [10] predicts an H-mode access power threshold, for diverted plasmas, given by ($0.049 \times B_T^{0.80} \times \langle n_{20} \rangle^{0.72} \times S^{0.94}$): for these discharges the threshold is then about 700 kW at 5.3 T, $\langle n_e \rangle = 0.4 \times 10^{20}$ m^{-3} or 400 kW

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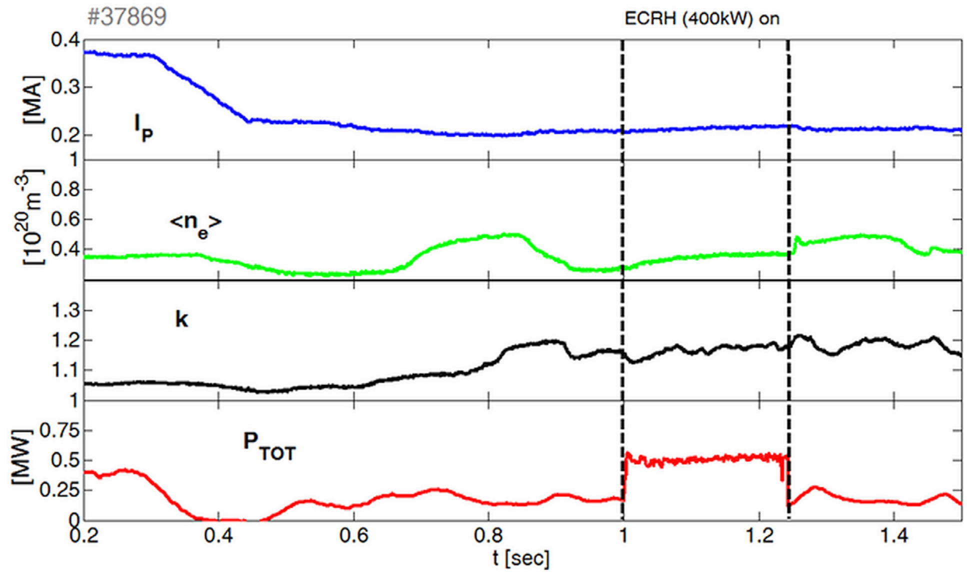

Fig. 2. Time evolution of the plasma current, electron density, elongation and total (ohmic + ECRH) input power, for the shot #37869 without the CLL.

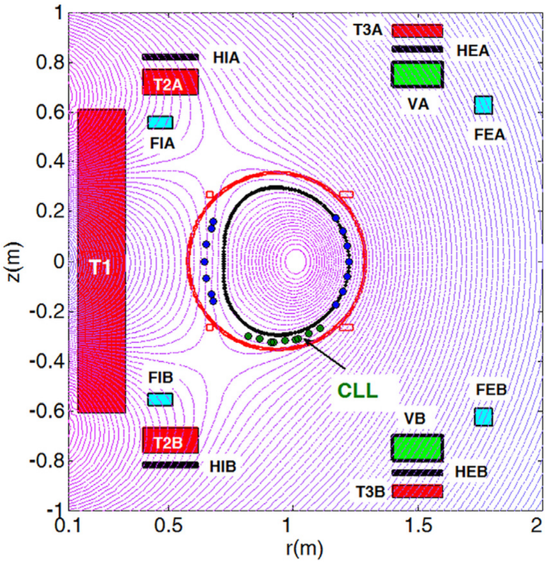

Fig. 3. Iso- magnetic flux surfaces and LCMS (black lines) for the shot #37869 at $t = 1.15$ s ($k \sim 1.2$). The profiles of vacuum vessel (red line), CLL (green points), and toroidal and poloidal limiter (blue points at inboard and outboard respectively) are shown. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

at 2.7 T, $\langle n_e \rangle = 0.3 \times 10^{20}\ m^{-3}$. The toroidal magnetic field chosen for these discharges allows having the first (at 5.3 T) or second (at 2.7 T) harmonic resonance near the plasma center (R = 0.935 m). In experiments carried out at $B_T = 5.3$ T no L-H transition was observed, since the total input power, including around 500 kW of ECRH heating, was a little lower than the L-H threshold.. In principle, the maximum ECRH power available in FTU is almost 2 MW, provided by 4 gyrotrons with 0.5 MW each, operating at 140 Ghz in a time interval up to 0.5 s.

Further experiments are planned with lower electronic density and $B_T = 2.7$ T (in second ECRH resonance), to benefit of the lower L-H threshold.

To study the behavior of the lithium target with this elongated configuration, the CLL was inserted up to 1 cm from the LCMS. A first analysis allowed evaluating a not uniform thermal load on the lithium surface, with a maximum of ≅1 MW/m^2 for 1.5 s. This analysis was carried out by ANSYS code, using the fast infrared camera temperatures on the lithium surface as input data, offline corrected for the liquid lithium emissivity established by calibration with the temperature measured by thermocouples in the CLL.

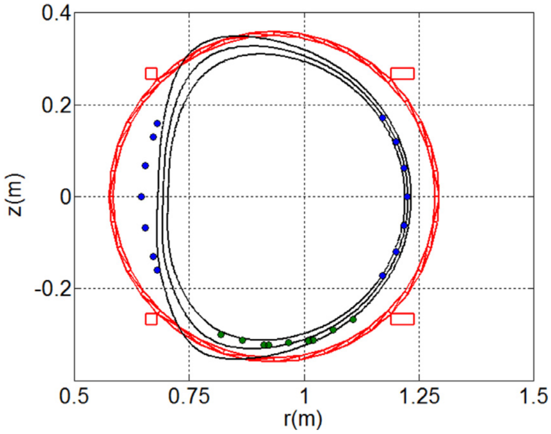

Fig. 4. Flux surfaces at 1, 2 and 3λ (from inner to outer of plasma) crossing the CLL (green points on the bottom of the plasma chamber) for the shot #37869 at $t = 1.15$ s ($k \sim 1.2$). Vacuum vessel (red line) and limiters (blue points at inboard and outboard) are also shown. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Moreover, the experiments showed that, as expected, the plasma in FTU is no more intrinsically stable in the vertical direction when the elongation is greater than $k = 1.17$. In fact, the first elongated discharges were always disrupted by a Vertical Displacement Event (VDE), due to the inadequate capability of the slow power converters in the H circuit producing the radial field, designed for circular plasmas.

This limitation in the available power provides a challenging vertical displacement stabilization problem: avoiding that the vertical position oscillations increase up to the loss of control using a slow actuator. The classical, two scale, approach to the vertical stabilization implies a first fast control loop to reduce the displacement speed and a second slow loop to stabilize the vertical position. The alternative approach suggested for the highly elongated discharges in FTU is based on an adaptive control scheme. With

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this scheme, the effect of the actual controller output is forecast at the *n*th step ahead, to select the time at which the ramp added to the PID controller should be switched off to minimize oscillations. This approach is then equivalent to a fast control loop subject to conditions resulting from plasma position acceleration. With this new vertical position controller, the amplitude of the oscillations is significantly reduced and the VDE is avoided in discharges elongated up to $k = 1.25$.

4. Design of a true X-point configuration in FTU

Achieving in FTU A true X-point magnetic configuration, with a single null inside the plasma chamber just above the CLL, could ease the robust access to H-mode, provided enough additional power was available. Actually, the existing Poloidal Field (PF) system is optimized to achieve almost circular plasmas in FTU: a magnetic topology with a null inside the plasma chamber cannot be pursued with the present PF coils system. Other barriers to this achievement are the limits in maximum current and sign of the actual Power Supply (PS) converters that restrict the accessible magnetic configurations and the maximum plasma current. On the other hand, the aim of achieving an X-point configuration is not an increase of the heat load delivered on the CLL but rather the study of transient thermal loads on it given by Edge Localized Modes (ELMs) in H-mode. This goal allows accepting plasma scenarios with a reduced plasma current. A first rough estimation of the expected transient power load due to ELMs in FTU provides a value around 50 kW, for a 300 kA plasma heated by additional 500 kW by ECRH. In this evaluation, 40% of the total plasma power is esteemed being in the pedestal and 15% of the pedestal power is supposed going in ELMs.

Several alternative connection schemes among PF coils and PS system were investigated, taking into account these constraints. This study was carried out by using the MAXFEA code, exploiting its capability to ease the modeling of different magnetic configurations. The most promising schemes were then preliminarily analyzed with regard to their compatibility with the overall load assembly and the existing subsystems. The main issues analyzed were the EM loads in the coils, the PS requirements and the compatibility with the overall plant layout.

4.1. Alternative PF coils connection scheme

The best alternative connection option allows achieving the magnetic configuration shown in Fig. 5. This configuration has a magnetic single null just above the CLL and strike points on it. It is not possible a further displacement of the X-point toward the outboard, due to the inboard-outboard symmetry of the position of the PF coils in FTU.

Few changes in the PS system and in the PF coils connection are required to realize this new configuration, as summarized below (coil names correspond to the labels given in Fig. 3):

- A new booster PS to increase the current in T2, without changing the current in T1 and T3 coils;
- Connection with bus bars through the cryostat between T2 coils and the booster PS;
- A new switch able to short-circuit on request the FEB coil, reducing the current through it by the insertion of a proper resistor;
- Connection through the cryostat between FEB coil and the short-circuit switch;
- Inversion inside the cryostat of the sign of the current flowing in FEA.

The inversion of the sign in FEA and the reduction of the current in FEB makes compulsory a redesign of the plasma position controller. Specifically, with this design all the F coils have the same current direction except for FEB: this means that the F circuit provide both the vertical and radial control field. Then, in this configuration, it must be used both for radial and vertical position control. The decoupling of these two functions can be made acting on the pure vertical field circuit V or on the pure radial field circuit H. The radial field allows also the vertical displacement of the plasma in the required position. A first assessment of this new position control scheme allowed satisfying the request of maintaining the achievability of circular plasma even with this configuration, without affecting the machine performance in terms of maximum plasma current and pulse duration. Circular and X-point configurations can be realized during the same plasma discharge.

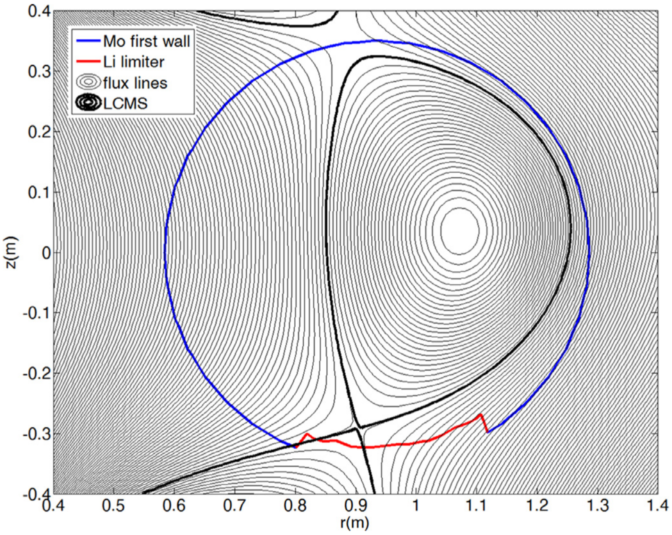

Fig. 5. Reconstruction of the magnetic equilibrium for the FTU true X-point configuration with the most promising alternative scheme. The Vacuum Vessel (blue line) and the Lithium Limiter (red line) are also shown. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Preliminary considerations on the vertical stability showed the advantages in reconnecting the outer passive stabilizing coils in a saddle configuration. These coils will ease the plasma vertical position control increasing the vertical instability growth-time without a significant rise of the poloidal flux consumed at the start-up.

4.2. FTU X-point scenario

The X-point scenario, made possible by this alternative scheme, has plasma current up to 300 kA and discharge duration up to 2.5 s. The time evolution of the currents in the PF circuits are shown in Fig. 6.

The evaluation of the EM forces on the PF coils during this scenario produced values below the maximum loads assumed in the design assessment of FTU, and then no further mechanical analysis was carried out. Fig. 7 shows the vertical forces acting on the PF coils in three different times identified by the currents in T1, T3 and T2 at maximum, around zero and minimum. A critical point in the FTU load assembly is the inner ring which hold precompressed the assembly including FI, T2 and HI coils. The sum of the forces acting on these coils is always below the preload: anyway, a careful assessment of the assembly will be performed in the future.

4.3. New booster PS for T2

Fig. 8 shows the new connection of the T coils with the PS system, including the new AL-T2. A preliminary characterization

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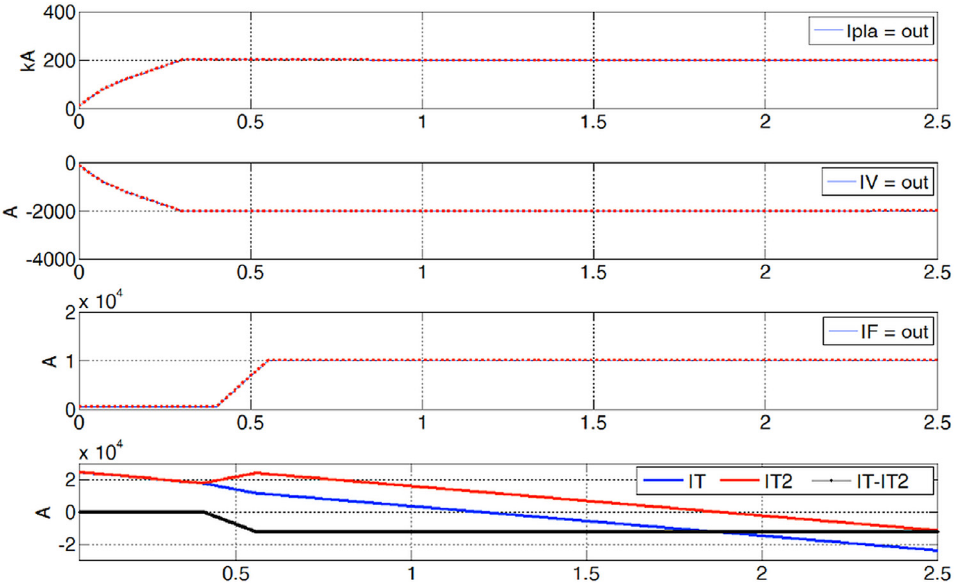

Fig. 6. Time evolution of the plasma and Poloidal Field coils currents, for the FTU X-point scenario with the alternative connection scheme.

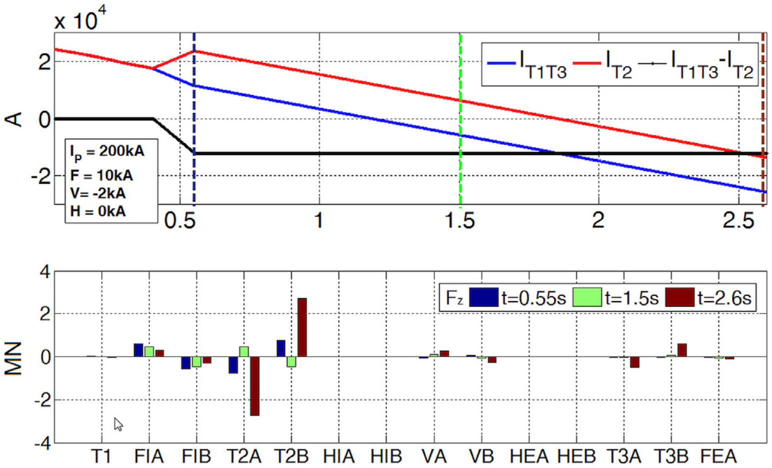

Fig. 7. Vertical forces on the PF coils (on the bottom of the figure) at three typical times of the X-point scenario (shown on the top of the figure).

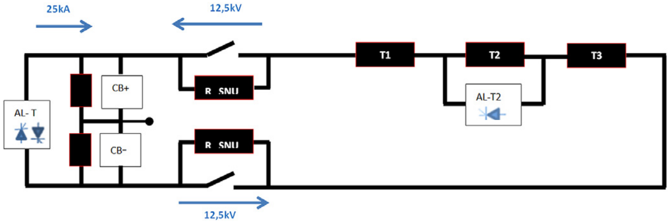

Fig. 8. Alternative connection scheme for the Transformer circuit, with the new AL-T2 booster PS.

and design of this booster PS envisages an AC/DC thyristor converter (twelve pulses operated and current controlled with unidirectional output at 12 kA, 675 V, output current distortion <5%). This converter could be directly connected, through a 9 MVA resin-insulated voltage transformer, to the ENEA-Frascati substation on the high voltage national grid.

The maximum active power required on the grid side for the X-point scenario is about 3.6 MW, with a 5 MW step as shown in Fig. 9. The maximum reactive power is about 7.2 MVAr and the maximum power required to the grid is almost 7.4 MVAr. A first as-

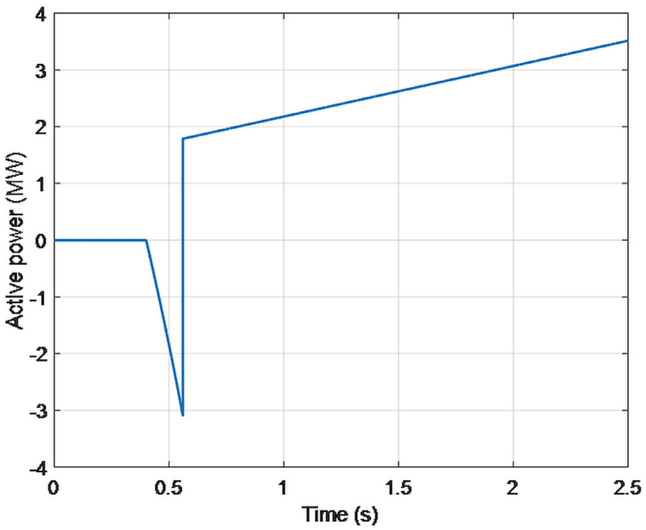

Fig. 9. Maximum active power required to AL-T2 booster PS.

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sessment showed that a local compensation of the reactive power is required because the PS operate providing few (hundreds of pulses for year) short pulses (2.5 s every half hour at most). The current harmonics injected to the national grid have been preliminarily assessed to a level lower than that tolerated by the grid operator. A preliminary layout of the converters hall has also been drawn, including the new AL-T2 booster PS and the bus bars connections from the FTU hall.

4. Conclusions

The actively water Cooled capillary liquid Lithium Limiter (CLL) is a promising solution to deal with high continuous heat loads in future fusion reactors. Preliminary experiments were carried out to investigate the possibility of gaining H-mode access in FTU, allowing the study of the impact of transient loads due to ELMs on the CLL used as target.

Elongated, quasi-D shaped and locally diverted near the CLL, plasma configurations were successfully achieved and controlled at the desired elongation ($k \approx 1.25$ at maximum) during these experiments. No L-H transition was observed until now because the available heating power did not allow overcoming the L-H transition threshold. VDEs were systematically observed in FTU when operating at relatively high elongation and required a redesign of the vertical control approach to deal with them.

An alternative connection scheme of the poloidal field coils, feasible with minor upgrades in FTU and here discussed, could allow the attainment of a true X-point configuration. This new configuration could ease the access to H-mode regimes and allow the study of the impact of transient loads on the CLL due to ELMs.

Acknowledgments

FTU Team is defined in the appendix of G. Pucella et al., Proceedings of the 25th IAEA Fusion Energy Conf., St. Petersburg, Russian Federation, 2014.

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