First experimental results with the Current Limit Avoidance System at the JET tokamak

G. De Tommasi a,⇑, S. Galeani b, S. Jachmich c, E. Joffrin d, M. Lennholm e,⇑, P.J. Lomas g, A.C. Neto b, F. Mavligia i, P. McCullen g, A. Pironti a, F.G. Rimini g, A.C.C. Sips f, G. Varano b, R. Vitelli b, L. Zaccarian j,k, JET-EFDA Contributors1

a Associazione EURATOM-ENEA-CREATE, Università di Napoli Federico II, Via Claudio 21, 80125 Napoli, Italy
b Dipartimento di Informatica, Sistemi e Produzione, Università di Roma, Tor Vergata, Rome, Italy
c Association EURATOM-Belgian State, Koninklijke Militaire School - Ecole Royale Militaire, B-1000 Brussels, Belgium
d IRFM-CEA, Centre de Cadarache, 13108 Saint-paul-lez-Durance, France
e EFDA Close Support Unit, Culham Science Centre, OX14 3DB Abingdon, UK
f European Commission, B-1049 Brussels, Belgium
g Euratom-CFTE, Culham Science Centre, OX14 3DB Abingdon, UK
h Associazione EURATOM-IST, Instituto di Plasmas e Fusione, IST, 1049-001 Lisboa, Portugal
i Associazione EURATOM-ENEA-CREATE, Via Claudio 21, 80125 Napoli, Italy
j CNRS, LAAS, 7 Avenue du Colonel Roche, F-31400 Toulouse, France
k Université de Toulouse, LAAS, F-31400 Toulouse, France

A R T I C L E  I N F O

Article history:
Received 22 October 2012
Received in revised form 4 April 2013
Accepted 4 April 2013
Available online 6 May 2013

Keywords:
Input allocation
Shape control
Nuclear fusion

A B S T R A C T

The Current Limit Avoidance System (CLA) has been recently deployed at the JET tokamak to avoid current saturations in the poloidal field (PF) coils when the eXtreme Shape Controller is used to control the plasma shape. In order to cope with the current saturation limits, the CLA exploits the redundancy of the PF coils system to automatically obtain almost the same plasma shape using a different combination of currents in the PF coils. In the presence of disturbances it tries to avoid the current saturations by relaxing the constraints on the plasma shape control. The CLA system has been successfully implemented on the JET tokamak and fully commissioned in 2011. This paper presents the first experimental results achieved in 2011–2012 during the restart and the ITER-like wall campaigns at JET.

1. Introduction

The Current Limit Avoidance System (CLA) has been recently designed and implemented at the JET tokamak to avoid current saturations in the poloidal field (PF) coils when the eXtreme Shape Controller (XSC) is used to control the plasma shape. The XSC minimizes a quadratic cost function that weights the plasma shape error in order to obtain, at the steady state, the output that best approximates the desired shape [1]. Thanks to the XSC, the session leaders can directly specify the target shape, without specifying the PF current waveforms, since the latter are automatically computed by the XSC’s model-based control algorithm. However, the XSC algorithm does not take into account the current limits in the PF coils, hence it may happen that the requested PF currents are outside the permitted ranges. This behavior could trigger a pulse stop due to current saturations.

The CLA has been implemented to solve this problem and it gives the possibility to use the XSC when the PF currents are close to their saturation values. The CLA algorithm is based on the dynamic allocator originally proposed in [2,3], and the main idea is to keep the PF currents within their limits without degrading too much the plasma shape, by finding an optimal trade-off between these two objectives. The use of CLA permits to enlarge the operational space of the XSC [4] either when the equilibrium currents in the PF coils are close to their limits and there is no margin for plasma shape control (e.g. running a discharge at higher plasma currents), or when large variations of poloidal beta βp, and/or internal inductance li push the currents requested by the XSC close to their limits (e.g. during the main heating phase).

This work discusses the CLA algorithm and presents the experimental results achieved at JET tokamak during the ITER-like wall campaigns (2011–2012). In particular, the paper is structured as follows: the next section gives a general overview of the JET plasma shape control system, and briefly introduces the XSC. Section 3...
2. Plasma shape control at JET

This section first gives an overview of the JET shape control system; afterwards the XSC control algorithm is presented. For further details the interested readers can refer to [5,1,6].

The JET Plasma Position and Current Control (PPCC) system [7] is in charge of the axisymmetric magnetic control [8]. When dealing with the control of the current, position and shape of the plasma column inside the vacuum vessel, the problem is typically considered axisymmetric, and the following three control issues are considered: the vertical stabilization, the plasma shape control, and the plasma current control.

Following a common approach adopted on different fusion devices, at the JET tokamak the plasma is first vertically stabilized on a fast time scale, according to the constraints imposed by the passive structures and the actuator. The current and shape controller is then designed on the basis of the vertically stabilized system. As a result, the PPCC system has a distributed architecture that includes the following two subsystems:

- the Vertical Stabilization (VS [9]) system, which stabilizes the plasma by controlling the plasma vertical velocity;
- the Shape Control (SC [5]) system, which controls both plasma current and shape (and hence also its position).

The actuators used by the PPCC system are the Poloidal Field (PF) coils, that are shown as red squares in Fig. 1. These coils are linked together into 10 circuits driven by independent power supplies, named P1, P4, IMB, SHA, PFX, D1, D2, D3, D4 and RFA. In particular, the P1 circuit is controlled by the SC system and enables both the plasma inductive formation and the control of the plasma current. Furthermore, the SC system controls also P4, IMB, SHA, PFX, D1, D2, D3, and D4 to perform plasma shape control. The VS system stabilizes the plasma by controlling the current in the RFA circuit not shown in Fig. 1.

In the actual implementation of the SC system, the user can choose two different algorithms for plasma shape control, namely:

- the standard Shape Controller [5], which is conceived as a solution to the shape control problem for the entire discharge. During the plasma formation process, this algorithm controls the currents in the PF circuits so that they track a set of preprogrammed waveforms. Afterward, when a small plasma column is formed, only the plasma radial position is controlled. Eventually, during the main experimental phase, i.e. when the plasma becomes bounded by a separatrix [10], the control is switched to the geometrical descriptors²; in particular the standard Shape Controller gives the possibility of controlling simultaneously up to six geometrical descriptors. However, the standard way to use it is to control, by dedicated control loops, up to four of the geometrical descriptors shown in Fig. 2, while controlling the currents in the remaining PF coils.
- the XSC [1], which can be used only after the separatrix formation. This algorithm permits to perform a more precise tracking of the overall plasma shape, by simultaneously controlling, in a mean square sense, more than 30 geometrical descriptors, as described in the next section.

2.1. The eXtreme Shape Controller

The XSC controls the whole plasma shape, specified as a set of geometrical descriptors (typically 32), by calculating the correspondent current references to the PF circuits. These PF current requests are then sent to the JET Standard Shape Controller, in which the P1 circuit is set in plasma current control mode, while the remaining eight PF circuits are set in PF current control mode.

The design of the XSC is based on the CREATE plasma linearized model [11,12]. In particular, if \( g \in \mathbb{R}^{32} \) holds the \( n_C \leq 32 \) variations of the plasma shape descriptors, and \( \mathbf{d}_{PF} \) is the vector holding the PF currents normalized to the equilibrium plasma current, then

\[
\delta g(t) = \mathbf{C} \; \delta \mathbf{d}_{PF}(t),
\]

which implies that the plasma boundary descriptors have the same dynamic response as the PF currents.

The XSC design is based on the matrix \( \mathbf{C} \) in (1). It is worth to notice that the plant model is non-right-invertible, since \( n_{PF} < n_C \), i.e. the number of independent control variables is less than the number of outputs to regulate. For such a plant it is not possible to track a generic set of references with zero steady-state error. Furthermore, given a generic set of references, the best performance that can be achieved in steady-state is to control to zero the error on \( n_{PF} \) linear combinations of geometrical descriptors. Controlling to zero

² The plasma shape is usually specified via a set of geometrical descriptors that includes gaps, strike points and X-point positions (see also Tutorial 7 in [10]).
such an error is equivalent to minimizing the following steady-state performance index (see [13]):

$$J_{XSC} = \lim_{t \rightarrow +\infty} (\delta g_{ref} - \delta g(t))^T (\delta g_{ref} - \delta g(t)).$$

(2)

where $\delta g_{ref}$ are constant references for the geometrical descriptors.

Minimization of (2) can be obtained by using the singular value decomposition of the matrix $C$:

$$C = U \cdot S \cdot V^T,$$

where the matrix $S$ contains the singular values, $U$ and $V$ are unitary matrices, that is

$$U^T U = V^T V = I.$$

As a matter of fact, using the JET linearized models [11,12], it turns out that some singular values (typically 2 or 3, depending on the configuration) are one order of magnitude smaller than the others. This fact implies that minimizing the performance index (2) retaining all the singular values results in a large control effort at the steady state, in terms of PF coil currents. For this reason, the XSC achieves a trade-off condition, minimizing a modified quadratic cost function that penalizes both the error on the controlled shape descriptors, and the control effort. This is achieved controlling to zero the error only for the $\Pi < P_{F}$ linear combinations related to the largest 5 or 6 singular values.

A more sophisticated version of the XSC has then been implemented introducing weighting matrices both for the geometrical descriptors and for the PF coil currents. Given a plasma equilibrium, these weighting matrices can be used to reduce the use of the coils whose currents are close to saturation.

However, the XSC design procedure does not take explicitly into account such saturation constraints. As a result, during the experiment the PF currents may saturate, triggering a safe stop procedure named (soft stop). The CLA system has been designed to avoid PF current saturations when the XSC is used to control the plasma shape.

3. The CLA system at JET

This section presents both the algorithm implemented by the CLA system and some relevant implementation details.

The current allocation algorithm implemented by the CLA system tries to keep the PF currents within their limits without degrading too much the plasma shape, by finding an optimal trade-off between these two objectives.

In particular, the current allocation aims at keeping the value of the plant inputs $u$, i.e. the PF currents, inside a desirable region, meanwhile ensuring a small tracking error $e = r - y$, i.e. a small error on the plasma shape. In order to quantify this trade-off, a continuously differentiable cost function $J_{CLA}(u^*, e^*)$ is introduced, where the superscript $^*$ on a signal denotes its steady-state value.

The CLA system corresponds to the grey shaded box in Fig. 3, which includes the current allocator. The CLA receives inputs from the XSC (block XSC in Fig. 3) and modifies the request to the plant, i.e. the plasma controlled by the JET standard Shape Controller set in PF current control mode (block AugmentedPlant in Fig. 3). Denoting by $x_e \in \mathbb{R}^{na}$ the allocator internal state, and by $B_0 \in \mathbb{R}^{na \times na}$ a suitable full column rank matrix, then the two allocator outputs read

$$\delta u = B_0 x_e,$$

(3)

and

$$\delta y = P^* B_0 x_e,$$

(4)

where $P^*$ is the steady state gain of the plant. The output (3) modifies the PF current requests generated by the XSC, while (4) hides the resulting steady-state change in the plasma shape to the XSC. Hiding the plasma shape change to the XSC is required in order to prevent the controller to react to these changes. The allocator equations are given by

$$x_e = -K_0 \left[ \frac{1}{P^*} \begin{bmatrix} I^T \nabla J_{CLA} \end{bmatrix}^T (u,e), \right],$$

(5a)

$$\delta u = B_0 x_e,$$

(5b)

$$\delta y = P^* B_0 x_e,$$

(5c)

e = r - y,$$

(5d)

where $K \in \mathbb{R}^{na \times na}$ is a symmetric positive definite matrix used to both specify the allocator convergence speed, and to distribute the allocation effort in the different directions.
The key property of the current allocator algorithm (5) is that, under suitable assumption on the cost $J_{CLA}$ (see [2] for details), for each constant current request of the XSC, it has a unique globally asymptotically stable equilibrium $x^*_u$, coinciding with the unique global minimizer of $J_{CLA}$. It turns out that $J_{CLA}(u^*, e^*)$ can be chosen in a suitable way in order to penalize the plasma shape error $e^*$ in addition to the PF currents $u^*$.

Fig. 4 shows a block diagram of the JET shape controller as it has been modified in order to deploy the CLA system. In particular, the CLA system receives as inputs:

- the PF current requests computed by the XSC;
- the reference shape for the XSC (gaps, strike-points and x-point position);
- the shape measurements (gaps, strike-points and x-point position).

and gives as outputs:

- the modified PF currents requests to be sent to the JET standard Shape Controller set in PF currents control mode;
- the additional references (gaps, strike-points, and x-point position) to be sent back to the XSC.

The CLA block reported in Fig. 4 has been implemented as an independent and isolated plug-in by using the JETRT real-time framework [14], which was adopted to originally develop the XSC in 2003. This facilitated the test and validation phase, reducing to the minimum the operational time requested for commissioning on the JET tokamak. As conclusion of this section, it is worth to remark that the current allocation algorithm is independent from the choice of a specific algorithm for plasma shape control, as far as the control scheme relies on the presence of a PF current controller (which is the case of the XSC at JET). Hence, the only requirement that needs to be satisfied in order to deploy the CLA system on a tokamak is to have a plasma shape control scheme based on a current control inner loop, as reported in Fig. 4. Such a solution is also convenient to specify the desired scenario in terms of feedforward currents (see [8, Section III.B]). As far as the optimality is concerned, since at steady state the CLA minimizes the cost function $J_{CLA}$, the behavior of the overall system depends on the choice of this cost function (see also the discussion in the next section).

### 4. Experimental results

This section presents the first results obtained with the CLA during the JET experimental campaigns in 2011–2012. In particular, we

---

*Fig. 4. Block diagram of the JET shape controller, including the XSC and the CLA system.*

*Fig. 5. Currents in the PF coils during the CLA commissioning pulse 81179. This pulse was aimed at checking the D4 lower limit. The shared area correspond to the region beyond the limit enforced by the CLA.*
first discuss the CLA commissioning procedure that has been carried out during the JET restart, at the end of 2011. Afterwards some experiments executed in 2012 during the ITER-like wall campaigns are presented.

The JET commissioning procedure for the CLA involves the simulation of the two saturation levels in the 8 PF circuits used by the XSC. The simulation of the saturation is obtained by changing the corresponding CLA limits.

As a matter of fact, the commissioning has been performed parasitically in 17 JET pulses; during each commissioning pulse the CLA has been enabled at the end of the discharge (before the plasma current ramp-down) for 1.5 s.

The extra pulse (with respect to the ones strictly needed) was due to a software problems that occurred during the CLA initialization.

Fig. 5 shows the currents in the PF coils for the commissioning pulse 81079, during which the lower limit for the D4 current was tested. In particular, the limit was set equal to 4.5 kA and the CLA was switched on at \( t = 25 \) s. It can be noticed that at steady state the current in D4 reaches the desired value, while the other PF currents slightly change in order to keep the plasma shape, as shown in Fig. 7.

Further on, during the commissioning pulse 81081, the lower limit for the P4 current was set equal to 7 kA, but the CLA was not able to enforce the desired value, as show in Fig. 6. Indeed in this case, the error on the plasma shape due to the P4 current change is not negligible as it is shown in Fig. 8; this behavior was the expected one for the chosen CLA parameters.

As stated in Section 3, the behavior of the system when the PF currents get closer to their saturation values depends on the choice of the cost function \( J_{CLA} \), which weights both the shape control error and the control effort in terms of PF current requests. During the commissioning the shape error in the top region has been weighted more than the divertor and the radial outer regions.
After the successful commissioning, the following experiment has been carried out, aimed at producing a severe limitation for the plasma shape control, and hence to prove the effectiveness of the CLA system. In order to do that, up to four out of the eight PF currents available for plasma shape control have been limited.

The following strategy has been adopted to carry out the experiment: first the reference pulse was run (pulse 81710), where the XSC without CLA has successfully controlled the plasma shape between 20 s and 23 s.

The CLA has been then enabled starting from 21 s, in order to limit the currents in the four divertor coils D1–D4 within a range smaller than the one actually available. In particular the following steps have been considered:

- in pulse 81712 both the currents in D2 and D3 have been limited between [−31.5, −10] kA and [−11, −2] kA, respectively;
- in pulse 81713 the limit on the current on D1 has been added; the considered allowable range was [−16.5, −4] kA;
- finally in pulse 81715 the limit on D4 has been added, by limiting this current within [0, 6] kA.

When a PF current is outside its saturation limits, the CLA tries to bring it back in the permitted range, by using the redundancy of the JET’s coils system to obtain almost the same plasma shape (see Fig. 9).

In pulse 81712, when the currents in D2 and D3 are limited, the CLA changes also the current in D1 in order to minimize the shape control error, as shown in Fig. 10. The new equilibrium currents computed by the CLA are such that the shape control error is negligible, as shown in Fig. 9(a), where the shapes at 22.5 s for the two pulses 81710 and 81712 are compared.

Let now consider the two pulses 81713 and 81715. In these cases three and four control currents are limited, respectively, and the shape error increases, as expected (see Fig. 9(b) and (c)). Fig. 11 shows a comparison between the divertor currents for pulses 81710 and 81715. Taking into account that the limitation of more

**Fig. 8.** Plasma shape at \( t = 27 \) s during the CLA commissioning pulse 81081. The red shape is the desired reference while the blue shape is the actual plasma shape at \( t = 27 \) s; in this case the error due to the CLA is not negligible, hence the CLA does not enforce the current in P4 to the desired value.

**Fig. 9.** (a–c) Shape comparison at 22.5 s. The black shape is the one obtained in pulse 81710 when the CLA is disabled, while the red shape is the one obtained when the CLA is enabled.
than two control currents represents already a challenging scenario for the CLA, the performance is satisfactory for both pulses 81713 and 81715.

Furthermore, it is important to note that the CLA parameters used in the considered experiment included a hard constraint on the x-point position. Indeed, when computing the new equilibrium currents, the CLA prefers to increase the shape error on the top-outer region of the plasma, rather than to change the position of the x-point, as shown in Fig. 9(b) and (c). The CLA behavior can be tuned by choosing different parameters. This task can be performed also by non-expert users by means of a set of dedicated design tools (more details can be found in [15]).

Finally, we present the behavior of the CLA when the XSC is used to control the plasma shape during the plasma current ramp-down, a phase during which the PF currents get closer to their lower bounds (which are typically set equal to zero).

Fig. 12 shows the plasma current $I_p$ during the ramp-down of the JET pulse 83014 (note that, at JET, $I_p$ takes negative values), while Fig. 14 shows some plasma shape snapshots obtained by using the XSC with CLA. In particular, the XSC achieves good tracking overall shape. The increase of the control error on the top region is mainly due to the CLA. Indeed, the CLA tries to prevent the PF currents from reaching their lower saturation limits by relaxing the plasma shape control. This is clearly shown by the CLA outputs shown in Fig. 13. In particular, the CLA outputs start to affect the plasma shape at $t \sim 16$ s, and this effect becomes relevant at $t \sim 18$ s. However, when the $I_p$ ramp-down is considered, reaching the saturation limits is unavoidable; indeed, as envisaged by the standard JET procedure, the soft stop is triggered at $t \sim 18.49$, causing XSC and CLA to lose the control (as shown by the sudden change of $\delta u$ in Fig. 13).

Fig. 10. Currents in the divertor circuits. Comparison between pulse 81710 (reference pulse) and pulse 81712. The shared areas correspond to regions beyond the current limits enforced by the CLA parameters.

Fig. 11. Currents in the divertor circuits. Comparison between pulse 81710 (reference pulse) and pulse 81715. The shared areas correspond to regions beyond the current limits enforced by the CLA parameters.

Fig. 12. Plasma current during the ramp-down of the JET pulse 83014. The red markers show the time instants where the plasma snapshots shown in Fig. 14 have been taken.

Fig. 13. Outputs of the CLA. This plot shows the PF current variations $\delta u$ computed by the CLA and added to the XSC outputs during the JET pulse 83014.
5. Conclusions

The CLA system has been recently deployed at JET. This system permits to achieve safe operations when using the XSC to control, since it prevents the plasma shape control algorithm to require currents in the PF coils that are outside the permitted range. This paper describes the first experimental results achieved with the CLA at JET.

As a final comment, it is important to remark that in 2012 the XSC has been used for more than 200 pulses during the ITER-like wall campaigns. This has been possible thanks to the CLA, which acts as a safety system giving more confidence when using the XSC. Furthermore, having proved to be beneficial for the control of plasma shape during both the plasma current ramp-up and ramp-down, the XSC with CLA has controlled the shape during the ramp-down of the last 151 pulses during the JET 2012 experimental campaign.

Acknowledgements

This work was supported by EURATOM and carried out within the framework of the European Fusion Development Agreement. The views and opinions expressed herein do not necessarily reflect those of the European Commission. The work has been also partially supported by the Italian MIUR under PRIN grant #2008E7J7A3.

References