Topic: TEC

Intra-shot Tools for Plasma Scenario Optimization and Magnetic Control

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The definition and optimization of plasma scenarios is a key element for the success of tokamak research and operations. Scenarios are characterized by events applied to initiate a plasma, ramp-up the plasma current to a target value, apply some heating via auxiliary systems during the burning phase, ramp-down the plasma current and extinguish the plasma discharge safely. Scenario design has been the subject of many scientific papers: using knobs at their disposition, scientists and operators try to achieve the desired sequence of plasma states. Plasma current ramp-up rate, auxiliary heating power amount and timing, plasma shape evolution are examples of knobs that can be used in the definition of a new scenario (see for example [1], [2]).

Besides the scenario definition and optimization, the capability of controlling the plasma along the optimized target sequence of dynamic equilibria is of paramount importance. For the control of plants whose desired behaviour is known in advance, the adoption of a feedback plus feed-forward control strategy is common, where the feed-forward action is optimized using a mathematical model of the plant, and the feedback part of the control action compensates for the effects of errors and uncertainties in modelling, and for the presence of possible external disturbances.

If the controlled plant is asymptotically stable, iterative procedures such as the so-called ILC (Iterative Learning Control) can improve control performance, provided that control tasks are performed repetitively [3]. In particular, one can consider previous experimental data to correct the system behaviour over (almost repetitive) disturbances and uncertainties (see WorkFlow in Figure 1).

For plasma scenario optimization, if the correction process takes short time compared to the duration of the interval between two consecutive pulses, the iterative approach can be used to set-up a so called *intra-shot* or *shot to shot* optimization procedure.

ILC for intra-shot procedures have been formulated and solved for TCV [4] for the breakdown and early ramp-up phases. For these phases, recipes obtained by trials and errors sometimes lead to poor performance and, for future large tokamaks, the adoption of heuristics would not be a convenient strategy. In fact, trials can become more and more expensive and time consuming; moreover, the presence of large passive structures, in which relevant uncertain currents can be induced, makes the scenario design problem more difficult to cope with, increasing the need for additional information to manage uncertainties.

The procedure to design automatically the time histories of poloidal field (PF) coil currents and related power supply voltages for startup, at the basis of TCV intra-shot design procedures, is described in [5]. The user can decide the desired breakdown location, the time evolution of some magnetic quantities including the magnetic field map in the vacuum chamber, and the target evolution of the electric field, based on inductive loop voltage, at the plasma BD location. The design problem is formulated and solved as a Quadratic Programming (QP) problem with linear constraints assuming some simplifying hypotheses. Constraints include coil currents and power supply voltage limits.

After TCV, successful application of the proposed ILC procedure to MAST-U plasma initiation was achieved [6]. In fact, in view of possible application to future tokamak devices, it is important to experimentally test ILC on different kind of devices. In this regard, MAST-U is a medium size spherical tokamak, larger than TCV, with some active coils farther from the vacuum chamber and higher vacuum vessel time-constants. The reduced number of active control circuits in MAST-U (10 active circuits) with respect to TCV (18 active circuits) makes the optimization more challenging as the desired null field keeps the same target characteristics for the two tokamaks but the number of degrees of freedom for control is lower.

For larger tokamaks with superconducting coils like ITER, the problem becomes more complex because of the more important effect of the passive structures slowing down the field penetration time for active control. The authors already proved the possibility of applying a shot to shot procedure for start-up optimization for this class of tokamaks in [7].

Another important step in the application of the ILC technique to scenario design and optimization was the extension to the design of the entire ramp-up. This has been done in MAST-U under RT04 campaign in 2024 and required a substantial methodological revision to take into account elongated plasma shapes.

During 2025, with the support of EuroFusion Work Package on Tokamak Exploitation (WPTE) and WPRiO, the ramp-up ILC design procedure will be better explored on MAST-U to account for the presence of NBI and to try to clarify why the ramp-ups optimized in 2024 brought significant benefits in terms of IREs. In parallel, the plan is to test the procedure on WEST, where ICH is present and the presence of iron requires some adjustments, and on EAST, characterized by superconducting coils and by the presence of ECH.

The proposed contribution is aimed at demonstrating that future large tokamaks like ITER may benefit from the application of ILC procedures. In fact, it will focus on the application, with numerical simulations, to low plasma current ITER scenarios (see for example Fig.2 for preliminary results).

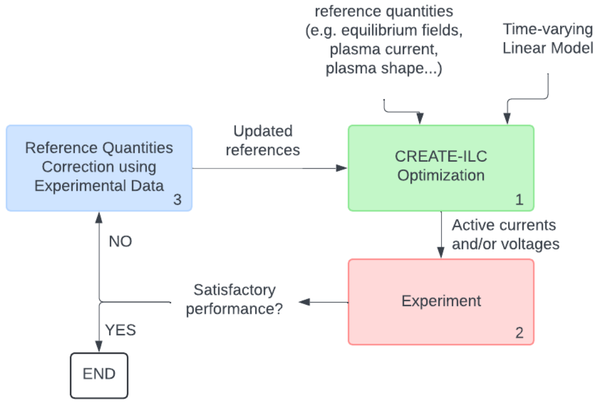

Figure 1: Workflow of the ILC intra-shot procedure

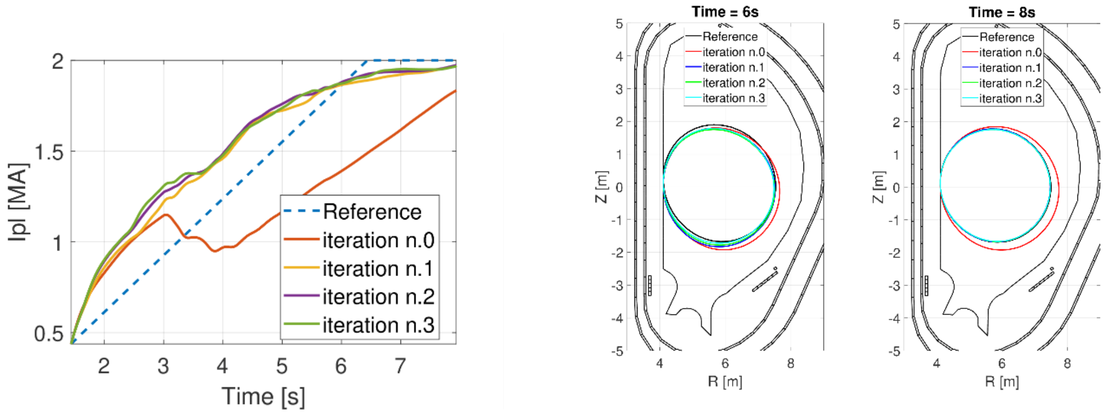

Figure 2: Plasma current evolution and plasma boundaries for the different ILC iterations. Example of application to ITER 2MA Ohmic scenario

It is finally worth to note that ILC has been also adopted in other plasma control problems such as electron density control [8, 9]. Future applications can consider ILC for integrated magnetic-kinetic control problems.

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References

[1]: S. V. Mulders, et al. *Plasma Phys. and Contr. Fus.*, vol. 66 (2023), n. 2, p. 025007.
[2]: Mitchell, A. et al., *Fusion Eng. and Des.*, vol. 192 (2023), p. 113777.
[3]: E. Rogers et al., “Iterative Learning Control - Algorithms, Applications and Future Research Directions” in *Proc. of the 63rd IEEE CDC* (2024), Milan.
[4]: L. E. di Grazia, et al, *Nucl. Fusion*, vol. 64 (2024), no. 9, p. 096032.
[5]: L.E. di Grazia and M. Mattei, *Fusion Eng. and Des.*, vol. 176 (2022), p. 113027.
[6]: L. E. Di Grazia, et al, “Iterative Learning Optimisation and Control of MAST-U Breakdown and Early Ramp-up Scenarios,” 10th CoDIT (2024), La Vallette, Malta.
[7]: L. E. di Grazia, et al., “Magnetic control strategies for the breakdown and early ramp-up in large tokamaks,” in 2022 IEEE CCTA (2022), pp. 837–844.
[8]: T. Ravensbergen, et al., *Nucl. Fusion*, vol. 58 (2017) p. 016048.
[9]: F. Felici and T. Oomen, “Enhancing current density profile control in tokamak experiments using iterative learning control,” in *Proc. 54th IEEE CDC* (2015), pp. 5370–5377.