Plasma integrated control: a perspective and outlook on the recent advancements at the TCV tokamak

Adriano Mele[1],

Federico Felici[1,2], Cristian Galperti[1], Alessandro Pau[1], Olivier Sauter[1], Stefano Coda[1], Daniele Carnevale[3,] Cassandre Contré[1], Luigi E. Di Grazia[4], Antonia Frank[1], Domenico Frattolillo[4], Cosmas Heiss[1], Massimiliano Mattei[4], Roberto Masocco[3], Francesco Pastore[1], Federico Pesamosca[6], Alfredo Pironti[4], Alessandro Tenaglia[3], Maria Topalova[1,5], Simon Van Mulders[1,6], Allen M. Wang[7], the TCV team[8] and the Eurofusion Tokamak Exploitation team[9]

[1] Swiss Plasma Center, École Polytechnique Fédérale de Lausanne, Lausanne (VD), Switzerland
[2] Google Deepmind, London, UK   [3] DICII, Università degli Studi di Roma 'Tor Vergata', Rome, Italy   [4] Consorzio CREATE, Napoli, Italy   [5] University of Manchester, Manchester, UK
[6] ITER organization, St Paul Lez Durance Cedex, France
[7] Plasma Science and Fusion Center, Massachusetts Institute of Technology, Cambridge (MA), USA
[7] See author list of B. Duval et al., Nucl. Fus. 2024 (https://doi.org/10.1088/1741-4326/ad8361)
[8] See author list of E. Joffrin et al., Nucl. Fus. 2024 (https://doi.org/10.1088/1741-4326/ad2be4)
e-mail (speaker): adriano.mele@epfl.ch

Over the last years, an ambitious research program involving several international partners has been actively pursued at the Swiss Plasma Center of the École Polytechnique Fédérale de Lausanne, with the overarching goal of equipping the real-time control system of the TCV tokamak with a comprehensive set of effective strategies for integrated plasma control. These developments are ultimately intended to contribute to advancing the state of the art in this field, in support of reliable operation of future devices such as ITER and DEMO.

A broad range of tools has been explored in this framework. Among these are model-based breakdown optimization techniques [1], designed to improve the reliability of tokamak start-up phases; state observers for plasma internal profiles [2,3], capable of integrating information coming from different diagnostics as well as real-time physics models to provide accurate real-time reconstruction of different quantities; and robust monitors for identifying plasma confinement states [4,5].

In addition, significant effort has been devoted to the development of effective solutions for the control of plasma shape [6]—one of TCV's natural missions—as well as advanced current limit avoidance systems [7,8] that prevent operational boundaries from being exceeded. These experiences also led to the first experimental demonstration of a MPC-based solution for plasma shape control [9] and to the development of fast plasma shape observers not based on full equilibrium reconstruction.

Finally, simultaneous control of several plasma quantities—including disruption proximity metrics—in a fully integrated fashion has been explored, with a focus on the design of optimized strategies to handle off-normal events [10] and the implementation of machine protection strategies in high-performance plasma scenarios [11]. This contribution aims to give an overview of such tools and to provide an outlook on the forthcoming experimental campaigns.

References

[1] LE Di Grazia et al., *Automated shot-to-shot optimization of the plasma start-up scenario in the TCV tokamak*, Nuclear Fusion, 2024

[2] F Felici, et al., *Integrated plasma state reconstruction, off-normal event handling and control, with application to TCV and ASDEX Upgrade*, IAEA FEC, 2021

[3] F Pastore, et al., *Model-based electron density estimation using multiple diagnostics on TCV*, Fus. Eng. Des., 2023

[4] Y Poels et al., *Robust Confinement State Classification with Uncertainty Quantification through Ensembled Data-Driven Methods*, arXiv:2502.17397v1, 2025.

[5] Y Poels et al. *Plasma State Monitoring and Disruption Characterization using Multimodal VAE*, arXiv:2504.17710, 2025.

[6] A Mele, et al., *Design and implementation of a model-based hierarchical architecture for plasma shape control in the TCV tokamak*, PPCF, 2025.

[7] D Frattolillo et al., *Implementation of an ITER-relevant QP-based current limit avoidance algorithm in the TCV tokamak*, PPCF, 2025.

[8] A Tenaglia et al. *Dynamic steady-state coil current allocation for plasma shape control: a study on the TCV tokamak*, CODIT 2024.

[9] A Mele et al., *First experimental demonstration of plasma shape control in a tokamak through Model Predictive Control*, CCTA2025.

[10] T Vu et al., *"Integrated real-time supervisory management for off-normal-event handling and feedback control of tokamak plasmas."*, IEEE Transactions on Nuclear Science, 2021.

[11] AM Wang et al., *Learning Plasma Dynamics and Robust Rampdown Trajectories with Predict-First Experiments at TCV*, arXiv:2502.12327v1