How predict-first will change our approach to experimental planning

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Predictive, time-dependent, transport simulations of experiments ahead of time may become a game changer for improving the efficiency of our experimental studies. High-fidelity, validated models are critical for the success of the *predict-first* approach, which relies on these models to evolve transport and magnetic equilibrium. By using validated, reduced models, these simulations will eventually be fast enough to be used in the control room for in-between plasma discharge analysis and predictions. However, whole-device modeling is not yet at a stage where experimental planning can rely entirely on predictive simulations [1], which requires a step-wise approach where - starting from a well diagnosed plasma discharge - only perturbative changes in the external actuators are made.

We have exercised the *predict-first* approach on DIII-D [2] to demonstrate improvement of the current profile evolution for sustainment of high q_{min} at mid-radius, with a feedforward heating and current drive scheme. Starting from a well diagnosed plasma discharge with feedback control on the plasma current and on β_N, a feed-forward scheme is proposed here, with additional Electron Cyclotron heating (ECH) and current drive (ECCD) in the current ramp-up phase to retard the current diffusion and help sustaining moderate reverse shear. Time-dependent simulations indicate that a combination of ECH and ECCD for pre-heating in L-mode and Neutral Beam injection (NBI) sustain a broad and flat safety factor profile in the flattop phase, which has been verified *a posteriori* in the experiment. It is important to recognize that plasmas are highly nonlinear systems and that - in many cases - the deficiencies of the models might compensate each other resulting in fortuitous agreement. It is therefore important that - in these exercises - simulations look for qualitative variations, rather than demanding quantitative agreement.

Reference experiment and initial assessment of the limits of predictive simulations

The two reference plasmas with feedback control are shown in Fig.1. They have comparable density and temperature profiles, both relax to a monotonic safety factor profile in the flattop phase, with $q_{min} < 1.5$ and develop $n = 1$ tearing mode activity. The *predict-first* experiment is proposing to use ECH and ECCD in the early ramp-up phase to heat the plasma core and reduce the plasma resistivity to delay the ohmic current penetration, while at the same time tailoring the current profile.

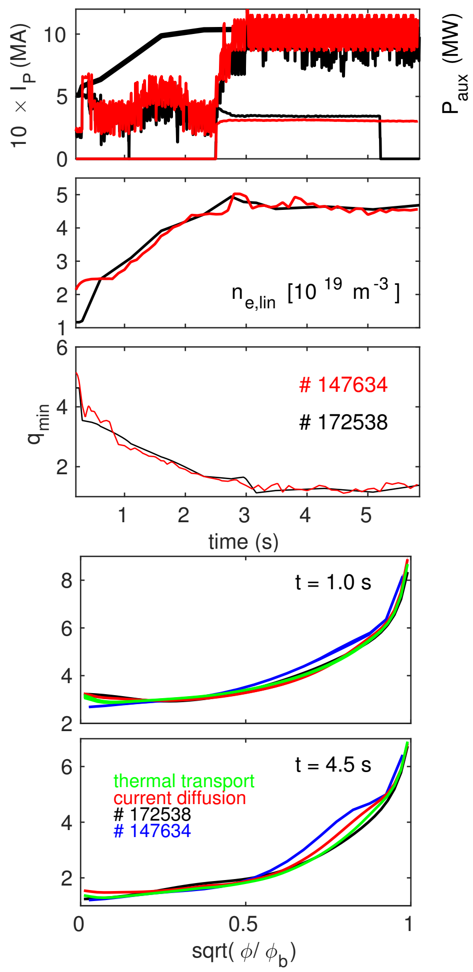

Figure 1: Top panel: time-evolution of plasma current, auxiliary power, line-averaged density and minimum safety factor in the two reference discharges. Bottom panel: comparison between the safety factor profile constrained by MSE and kinetic profiles and the predicted profile, when pressure profiles are imposed (red) and when thermal transport is included (green).

Since the only variation in the external actuators is the EC waveform, while the NBI waveform is programmed to reproduce as close as possible the input power in the reference discharge, the predictive simulation does not need to evolve the electron density. The procedure leading to the prediction of the new experiment requires two evaluations. First, an assessment of the accuracy of the calculations for the evolution of the magnetic field and current diffusion on the reference plasma discharge when the pressure profiles are fixed. Second, an assessment of the accuracy of the thermal transport when the density is fixed. Simulations have been run with the time-dependent free-boundary equilibrium and transport solver TRANSP [3]. Figure 1 compares the original and the simulated safety factor profile in the ramp-up phase and in the flattop phase, when the current diffusion is evolved with fixed temperature profiles (red) and when thermal transport is also predicted (green) with GLF23 [4, 5]. The agreement with the MSE-constrained profiles is good in both cases inside mid-radius, indicating that the predictive tools are accurate enough for our purposes. Since the goal is to modify the current profile, a rigorous validation of the thermal transport is not required here, instead it is important to reproduce the safety factor profile and the evolution of q_{min}.

Predict-first experiment

After the initial assessment of the fidelity of the predictive tools, the EC power is added during the current ramp-up phase in the simulation, with incremental steps. For the purpose of this exercise the original poloidal and toroidal aiming angles of the gyrotrons have been maintained, which provide deposition near mid-radius. Moving the EC power backward in time is a minor modification to the external actuators, but this choice increases core heating at low current,

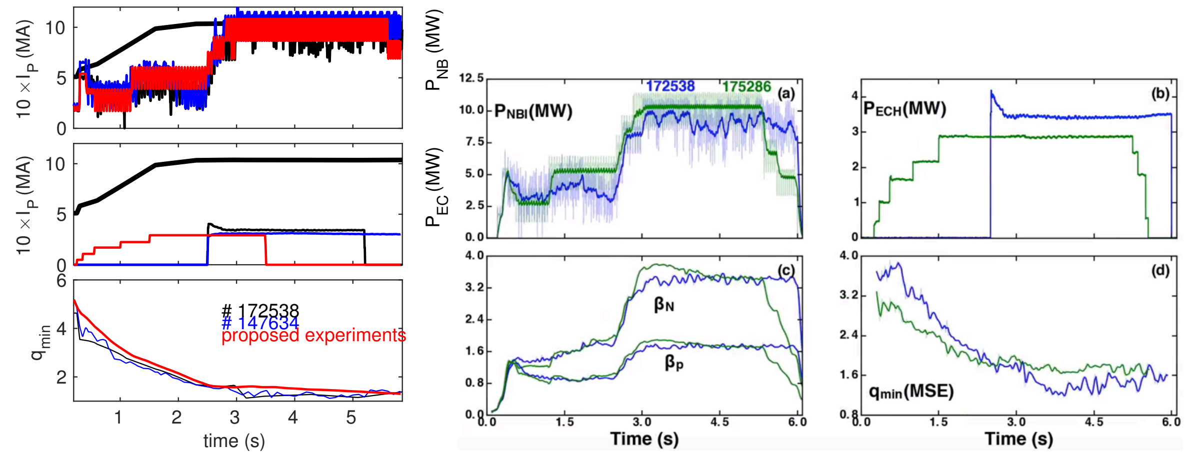

Figure 2: Left: proposed, simulated experiment (red) vs the two reference cases. Right: actual experiment (green) vs one of the references (blue).

modifies the plasma resistivity and therefore the ohmic heating and - at the same time - provides non-inductive current that modifies locally the current profile. The time-dependent simulation indicates that - even with the small variation proposed - an improvement in the evolution of the safety factor, with a minimum above unity in the flattop phase can be achieved. The predict-first experiment has been executed with these aforementioned settings and waveforms, with only the feedback on the line-averaged density, but no feedback on β_N, to ensure reproducibility and *a posteriori* validation of the time-dependent simulation. The effective experiment, shown in Fig.2, achieves sustained q_{min} in the flattop, as predicted by the TRANSP simulation. However, the evolution of q_{min} in the ramp-up is not the same. Predictive simulations in TRANSP use the input q profile as initial condition to evolve the poloidal current diffusion, and the initial condition is different in the reference plasma discharge, which does not use EC at low current. Work is ongoing to run predictive simulations on the new experiment, to separate the effect of limitations of the thermal transport and current diffusion model from the choice of the initial q profile.

As shown in the figure, the constant neutral beam input power in the feed-forward experiment results in higher β_N in the initial phase at full beam power, but β_N relaxes to the same value as in the reference case in the flattop phase, whose optimization was not targeted by this simulation. Although the main goal of this *predict-first* experiment is achieved, namely demonstrate sustained $q_{min} > 1.5$ with moderate reverse shear and reduced MHD activity in the flattop phase, with addition of ECH and ECCD in the ramp-up phase, the experiment does not reproduce the simulation. As shown in Fig.3, the safety factor profile has a minimum at radius larger than what was predicted. Differences between the simulation and the real experiment can be attributed to limits in the thermal transport model and to the lack of a self-consistent computation of fast ion anomalous transport during the high power phase and are under assessment.

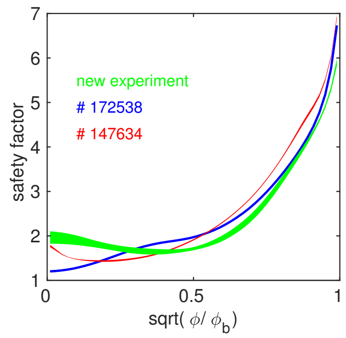

Figure 3: Comparison between the two reference discharges and the final experiment, at 5s.

In conclusion, we have shown that - when used within their limits - time-dependent simulations can be valuable to design new experiments and minimize trials and errors in the control room. It should be noted that, when predicting an experiment, no information is available apart from reference previous plasmas discharges in similar conditions. Therefore, predictive simulations should be capable of evolving the magnetic equilibrium and the thermal, momentum and particle transport, with minimum input and minimum prior knowledge. Work is in progress to demonstrate how closely our *predict-first* experiment can be reproduced with the available modeling tools in TRANSP and what steps need to be taken to improve the fidelity of the simulations.

This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Fusion Energy Sciences, using the DIII-D National Fusion Facility, a DOE Office of Science user facility, under Awards DE-AC02-09CH11466, DE-FC02-04ER54698, and DE-AC52-07NA27344. DIII-D data shown in this paper can be obtained in digital format by following the links at `https://fusion.gat.com/global/D3D_DMP`. This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

References

[1] F.M. Poli. *Physics of Plasmas*, **25** 055602 (2018).

[2] J. L. Luxon. *Fusion Sci. Technol.*, **48** 828 (1985).

[3] Hawryluk R. An Empirical Approach To Tokamak Transport. In *Physics of Plasmas Close to Thermonuclear Conditions. Proceedings, Varenna, Italy, 27 Aug-8 Sep 1979*, pages 19–46. Elsevier Ltd., (1981).

[4] Waltz R.E. *et al*. *Phys. Plasmas*, **4** 2481 (1997).

[5] Kinsey J.E. *et al*. *Fusion Sci. and Tech.*, **44** 763 (2003).