Real-time control of the internal inductance and poloidal beta parameters in H-mode steady-state scenarios on EAST

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Introduction

Real-time control of the plasma current profile and pressure is essential in tokamaks for both the attenuation of plasma microturbulence and the mitigation and suppression of global magnetohydrodynamic (MHD) instabilities. Various related numerical and experimental studies have been pursued on different tokamaks such as JET [1], DIII-D [2] and TCV [3] in recent years. Nonetheless, we find that performance comparison between different feedback controllers, even in a specific scenario, rarely appears in the literature. In this work, we develop, evaluate and compare three real-time feedback control schemes, the Simple Internal Model Control with Proportional Integral (SIMC PI), the $\mathscr{H}_\infty$ robust control ($\mathscr{H}_\infty$) and the Linear Quadratic Integral (LQI) control, for the tracking of the internal inductance parameter, li, and the poloidal beta, β_p, in H-mode steady-state scenarios on the EAST tokamak. The SIMC PI and $\mathscr{H}_\infty$ are also compared experimentally. The control actuator is the 4.6 GHz Lower Hybrid Current Drive (LHCD) system with coupled powers between 1 MW and 2.5 MW. Simulations and initial experiments performed on EAST show the effectiveness of each controllers and sort out an optimal one.

Control framework, feedback design and algorithms implementation

As depicted in Fig. 1, the kinetic control framework is divided into two control layers. The inner control layer, within the purple frame, has a low sampling frequency. It contains a set of kinetic controllers, along with a switch for controller selection. The outer control layer, within the green frame but outside the purple one, has a higher sampling frequency, aiming to pre-process the measured actuations and real-time parameter estimates [4] and to track the actuator commands. Cascaded with the inner control layer, an actuator controller is devoted to actuator command tracking. Average horizon filters [5] are used to handle the high-frequency noise. An anti-windup module [6] is designed to mitigate the effects of actuator saturations.

The plasma kinetic dynamics in response to control actuations is approximated by a linear-time-invariant (LTI) state-space model, which can either be deduced from the first-principles plasma theory or identified from dedicated simulation/experimental data [2]. By adopting the balanced model reduction and the singular value decomposition (SVD) [5, 6], the LTI plasma dynamic model is then transformed into a reduced one suitable for the integrated design of the SIMC PI, $\mathscr{H}_\infty$ robust and LQI controllers.

The synthesis of the SIMC PI controller requests the model to be a stable first-order transfer function with time-delay, which can be obtained by truncating the less influential eigenmodes. A SIMC PI tuning rule [5] is then adopted to design a SIMC PI kinetic controller. A similar procedure is used for the actuator controller design. The $\mathscr{H}_\infty$ robust control design comprises two steps [5]. First, we augment the pre- and post-compensators on the reduced model to acquire the expected singular value shaping in the frequency-domain. Second, a feedback controller is synthesized to make the augmented plant robust against model uncertainties via the $\mathscr{H}_\infty$ norm optimization. For the LQI control [5], we employ the reduced model for the design of a static feedforward for the input and state references, a Luenberger observer to estimate states and a feedback via solving a Riccati equation.

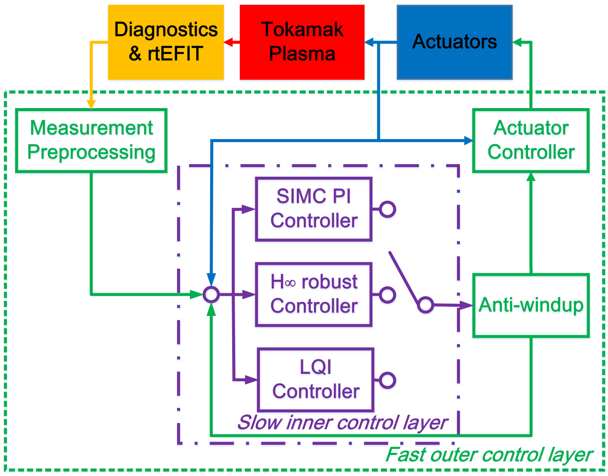

Figure 1: *Layout of the feedback control scheme.*

Once the kinetic control algorithms are implemented into the MATLAB/Simulink environment, they can directly be transformed into the C/C++ programming language using the embedded MATLAB coder (EMC) toolbox. The generated code is subsequently coupled with the EAST plasma control system (PCS) [7] and compiled for real-time application.

Closed-loop feedback control experiments on the EAST tokamak

We now evaluate the effectiveness of the implemented kinetic control algorithms on the EAST tokamak. Both simulation and experimental results are obtained. In our study, the reference plasma operation scenario in H-mode steady state has the toroidal field at 2.5 T, the plasma current at 350 kA, the central electron density at $\sim 4.2 \times 10^{19}$ m^{-3} and the central electron temperature at $\sim$ 4 keV. 0.6 MW of LHCD power at 2.45 GHz was actuated in the period [0.95, 2.25] s, while 0.9 MW of ECRH power at 140 GHz was injected in the interval [1.98, 7.91] s. The LHCD power at 4.6 GHz was allowed to vary in real-time within the range of 1.0-2.5 MW, tracked by a SIMC PI LHCD power controller. The real-time EFIT reconstruction code, P-EFIT [4], was employed to estimate plasma parameters. The ARTAEMIS [2] procedure was applied to identify an LTI plasma dynamic model. It was then transformed into a reduced model for the design of the SIMC PI, $\mathscr{H}_\infty$ robust and LQI controllers separately, with the goal of tracking li and β_p by adjusting P_{LHCD}. The outer control layer adopted a sampling time at 1 ms whilst the inner-layer one was fixed at 20 ms. A moving average filter with a time horizon of 10 ms was used to handle the measurement noise. Fig. 2 shows linear closed-loop simulation results on li and β_p tracking, in presence of simulated output disturbances. One can conclude that all the controllers achieve effective kinetic tracking, the SIMC PI performing best.

The experimental SIMC PI control of β_p was performed in EAST shot #95195. Figs. 3(a) and 3(d) show the evolution of β_p and P_{LHCD}. Both β_p and P_{LHCD} are perfectly under control, except during the period [3.6, 4.8]s, when the LHCD actuator is saturated. The control of β_p using the $\mathscr{H}_\infty$ feedback controller was carried out in shot #95197, whose results are shown in Figs. 3(b) and 3(e). Although all the targets were achieved when LHCD did not saturate, the tracking performance is not as good as in shot #95195 as the controller takes longer to recover from the saturated actuator. The SIMC PI control of li was performed in shot #95196. It was more difficult because of the unphysical linear drift of magnetic probe and li measurements, and also the achievable domain for li control was narrow. As shown in Figs. 3(c) and 3(f), the first target was achieved on average but with some oscillations. In the period [3.0, 3.5] s, the references linearly dropped from 1.07 to 0.99, properly tracked by the li controller. After 3.38 s, due to saturation, the second target is not reached.

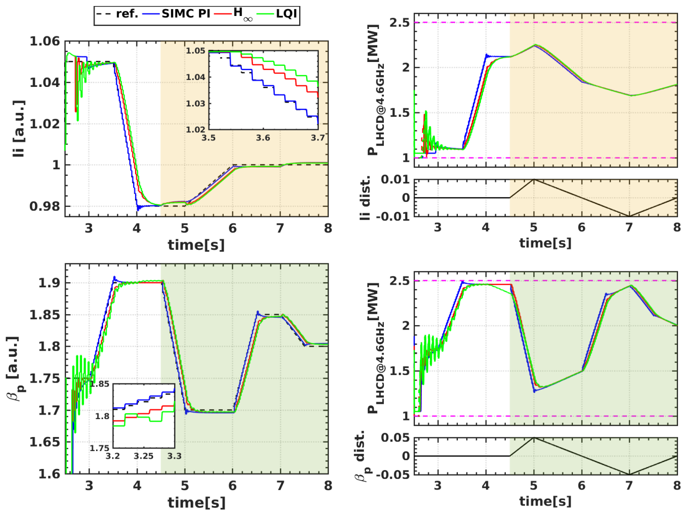

Figure 2: *Simulated tracking of li and β_p using P_{LHCD}. Left panels: time traces of li (resp. β_p). Right panels: time traces of P_{LHCD} and li (resp. β_p) disturbances (shaded region).*

Conclusion and outlook

A generic kinetic control framework and alternate feedback algorithms have been developed and implemented for li and β_p tracking of an H-mode plasma on the EAST tokamak. Linear simulations suggest that, by adjusting the LH@4.6GHz power command in real-time, the three linear controllers can all achieve li and β_p tracking with robustness, among which the SIMC PI controller performs best. Initial experiments on EAST show that the SIMC PI and $\mathscr{H}_\infty$ ki-

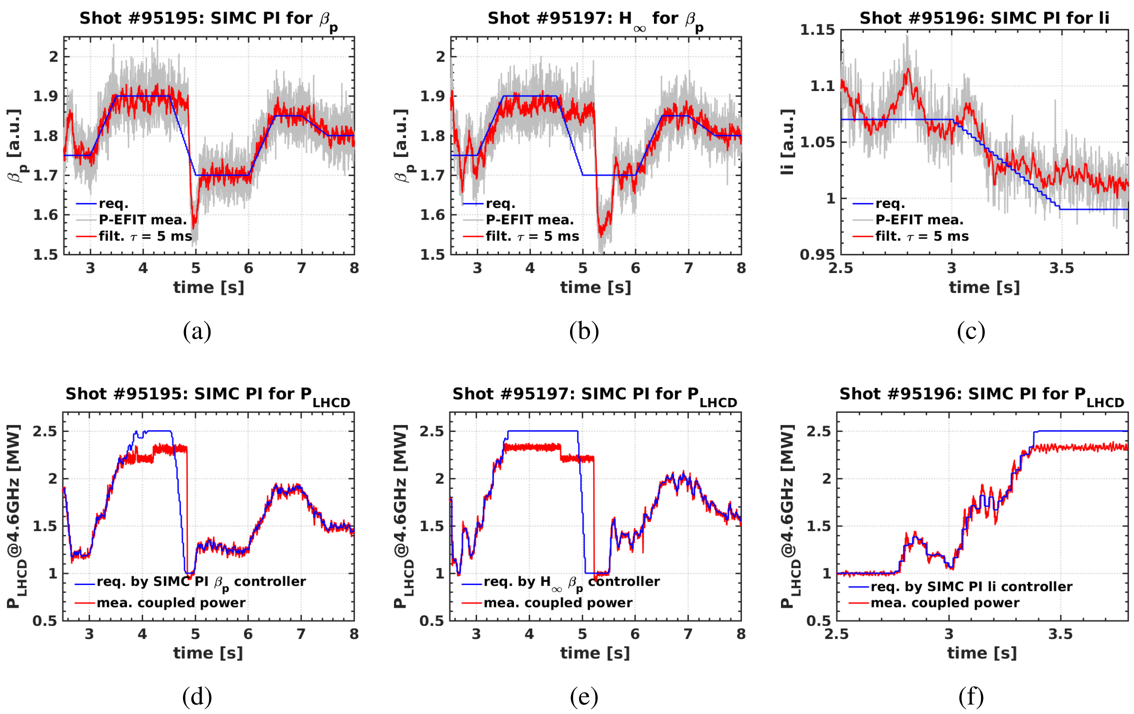

Figure 3: *Experimental tracking of β_p, li and P_{LHCD}. Upper panels: time traces of β_p (resp. li) references (blue solid), P-EFIT estimates (gray solid) and the filtered P-EFIT estimates (red solid); Lower panels: time traces of the requested LHCD power (blue solid) and of the measured LHCD power (red solid).*

netic controllers can both track β_p and the coupled LH power $P_{LHCD@4.6GHz}$ to different targets successfully, but the SIMC PI outperforms $\mathscr{H}_\infty$. Reasonable li control has been achieved with the SIMC PI scheme. Future work entails more experimental tests with the inclusion of more control actuators, e.g. co-current NBIs, and more control variables on the EAST tokamak.

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