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Integrated current profile, normalized beta and NTM control in DIII-D

A. Pajares[a,*], W.P. Wehner[a], E. Schuster[a], N. Eidietis[b], A. Welander[b], R. La Haye[b], J. Ferron[b], J. Barr[b], M. Walker[b], D. Humphreys[b], A. Hyatt[b]

[a] Department of Mechanical Engineering and Mechanics, Lehigh University, Bethlehem, PA 18015, USA
[b] General Atomics, San Diego, CA 92121, USA

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ABSTRACT

There is an increasing need for integrating individual plasma-control algorithms with the ultimate goal of simultaneously regulating more than one plasma property. Some of these integrated-control solutions should have the capability of arbitrating the authority of the individual plasma-control algorithms over the available actuators within the tokamak. Such decision-making process must run in real time since its outcome depends on the plasma state. Therefore, control architectures including supervisory and/or exception-handling algorithms will play an essential role in future fusion reactors like ITER. However, most plasma-control experiments in present devices have focused so far on demonstrating control solutions for isolated objectives. In this work, initial experimental results are reported for simultaneous current-profile control, normalized-beta control, and Neoclassical Tearing Mode (NTM) suppression in DIII-D. Neutral beam injection (NBI), electron-cyclotron (EC) heating & current drive (H&CD), and plasma current modulation are the actuation methods. The NBI power and plasma current are always modulated by the Profile Control category within the DIII-D Plasma Control System (PCS) in order to control both the current profile and the normalized beta. EC H&CD is utilized by either the Profile Control or the Gyrotron categories within the DIII-D PCS as dictated by the Off-Normal and Fault Response (ONFR) system, which monitors the occurrence of an NTM and regulates the authority over the gyrotrons. The total EC power and poloidal mirror angles are the gyrotron-related actuation variables. When no NTM suppression is required, the gyrotrons are used by the Profile Control category, but when NTM suppression is required, the ONFR transfers the authority over the gyrotrons to the NTM stabilization algorithm located in the Gyrotron category. Initial experimental results show that simultaneous control of different aspects of the plasma dynamics may improve the overall control and plasma performances. Also, the potential of the ONFR system to successfully integrate competing control algorithms is demonstrated.

1. Introduction

During all the operation phases of ITER, many different aspects of the plasma dynamics will require simultaneous, multivariable control [1,2]. Some of the control problems involved (such as current profile control, plasma beta control, NTM suppression, etc.) have very different natures and time scales. For instance, whereas the current profile evolves in a time scale within the order of seconds, electron temperature and density variations are found within the order of milliseconds. However, only a limited number of actuators will be available to achieve such variety of control objectives. As a matter of fact, most actuators affect more than one aspect of the plasma dynamics at the time. For example, in many present-day tokamaks, NBI is the main non-inductive actuator employed to heat the plasma, and therefore to control the plasma beta, but it also affects the current profile evolution as it can drive current. Moreover, control priorities may change during operation depending on the plasma state. Thus, if a magneto-hydrodynamic (MHD) instability that worsens the plasma performance develops, one of the control tasks with higher priority will be its suppression. In present-day tokamaks, one of the most common types of MHD instabilities are NTMs, some of which can be suppressed using EC H&CD [3]. Hence, the development of NTMs may restrict the use of EC H&CD for other purposes. For these reasons, the use of actuator allocation/sharing principles will be a must in future tokamak integrated PCS designs.

Therefore, this complex, coupled, plasma dynamics will require integrated control algorithms [1,2] with the capability of monitoring the plasma state by means of supervisory systems in order to determine control needs/priorities in real time. Such algorithms will also assign control authority to the available actuators or existing control

* Corresponding author.
E-mail address: andres.pajares@lehigh.edu (A. Pajares).

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algorithms. Lately, some research has been carried out to develop integrated-control algorithms (e.g., [4,5]). In this paper, preliminary results are reported for an integrated-control scheme that has been implemented in the DIII-D PCS and experimentally tested in a particular hybrid-plasma scenario in which $m/n = 3/2$ NTMs normally develop, where m and n are the poloidal and toroidal mode numbers, respectively. The actuators employed are NBI, EC H&CD, and I_p modulation. The goal is to simultaneously regulate the safety factor profile, q, and normalized plasma-beta, β_N, while suppressing NTMs. The Off-Normal and Fault Response (ONFR) system [6] is utilized as a supervisor to monitor the NTM occurrence. Actuator sharing is carried out for EC H&CD, which is utilized either for q-profile + β_N control or for NTM suppression. Both NBI and I_p modulation are employed exclusively for q-profile + β_N control.

The paper is organized as follows. In Section 2, the architecture of the integrated control scheme developed for q-profile + β_N control and NTM suppression is introduced. In Section 3, the scenario chosen for experimental testing is described, the control setup is briefly presented, and preliminary experimental results are reported. Finally, a summary and possible future work are presented in Section 4.

2. Integrated control architecture

The DIII-D PCS provides an excellent benchmark for testing and development of integrated-control strategies due to its parallel architecture [1]. It is composed of different categories which allocate algorithms with a specific purpose, such as Profile control, NBI control, Gyrotron control, etc. Each category can work using multiple sequences (primary, secondary, and so on). These sequences are different preprogrammed configurations of that category which can be executed asynchronously within the same shot. Category-configuration changes that comprise each sequence may include, for example, the use of different control algorithms, saturation levels, control gains, and other control parameters. The active sequence at a given instant is the sequence that is actually being utilized within a category. This category-sequence structure allows for a flexible programming environment within the DIII-D PCS, which is very useful for integrated control development.

In this work, two categories are employed: the Profile Control category and the Gyrotron category. The Profile Control category works only with a single sequence that allocates a Model Predictive Controller [7] for q-profile control, in which a linear proportional-integral-derivative control law for β_N or energy regulation is embedded as a constraint. This MPC algorithm computes the required control signals for the individual NBI powers, $P_{NBI,(\cdot)}$ (where $(\cdot)$ is the denomination of a particular DIII-D NBI), individual EC H&CD powers, $P_{EC,(\cdot)}$ (where $(\cdot)$ is the denomination of a particular DIII-D gyrotron), EC poloidal mirror angles, $\phi_{(\cdot)}$, and I_p. On the other hand, the Gyrotron category works with two sequences (primary and secondary). If in the primary sequence, the Gyrotron category just uses the $P_{EC,(\cdot)}$ and $\phi_{(\cdot)}$ requests computed by the Profile Control category. If in the secondary sequence, the Gyrotron category computes $P_{EC,(\cdot)}$ and $\phi_{(\cdot)}$ as required for NTM suppression. In previous NTM suppression experiments [3,8], it has been customary to employ the maximum available EC H&CD power, and to aim the gyrotrons at the rational surface that requires NTM suppression, either by modifying the plasma position or by modifying $\phi_{(\cdot)}$.

The integrated-control architecture developed for this experiment is summarized in Fig. 1. As a supervisor to the Profile Control and Gyrotron categories, the ONFR system monitors the plasma state for NTM occurrence [6], and computes a signal that indicates the need for NTM suppression. This signal is sent to both the Profile Control category and the Gyrotron category, and it is an integer that determines the active sequence of the Gyrotron category (1 for the primary sequence, and 2 for the secondary sequence). If the ONFR system determines that there is no need for NTM suppression, then the active sequence of the Gyrotron category is the primary sequence, and the Profile Control category is assigned control over EC H&CD. Although they are not modified, the $P_{EC,(\cdot)}$ and $\phi_{(\cdot)}$ control requests computed by the Profile Control category must still pass through the Gyrotron category because the latter is the category allowed to send gyrotron-related commands in the current design of the DIII-D PCS. If the ONFR system determines that there is an NTM that needs suppression, then the secondary sequence is the active sequence of the Gyrotron category. In this case, the Gyrotron category takes control over EC H&CD as assigned by the ONFR system. The EC H&CD related control-requests, $P_{EC,(\cdot)}$ and $\phi_{(\cdot)}$, are fed-back into the Profile Control category, so that the MPC algorithm always has information about the $P_{EC,(\cdot)}$ and $\phi_{(\cdot)}$ requests regardless of the active sequence of the Gyrotron category.

3. Experimental testing

3.1. Hybrid-plasma scenario and experiment purpose

In order to experimentally test the integrated-control scheme introduced in Section 2, a hybrid-plasma scenario is chosen. In addition to being a high-confinement scenario that may be of high interest for the development of ITER steady-state scenarios, such choice is also motivated by the fact that 3/2 NTMs normally arise, producing flux pumping, which in turn yields a high q profile that avoids 2/1 NTMs or sawtooth instabilities [8]. It has been experimentally demonstrated that 3/2 NTMs can be suppressed using EC H&CD aimed at the $q = 3/2$ surface [8]. Therefore, this scenario seems suitable for a first test on combined q-profile + β_N control with NTM suppression.

The main purpose of the experiment is to assess the EC H&CD authority transfer between the Gyrotron category and the Profile Control category as requested by ONFR in the presence of a 3/2 NTM. In order to do so, a reference DIII-D shot, 162893, is reproduced with the goal of triggering a 3/2 NTM at the beginning of the flat-top phase. The β_N and q-profile evolutions from shot 162893 are used as targets for the MPC controller allocated in the Profile Control category. The reference plasma corresponds to a double-null shape in which the machine parameters are $B_T = 1.8$ T (normal direction in 162893, but reversed in this experiment), $R_0 = 1.78$ m, $a = 0.6$ m, $I_p = 1.2$ MA, and $\beta_N = 2.6$.

3.2. Configuration of the DIII-D PCS subsystems

The ONFR system computes the strength of an NTM based on its MHD n amplitude, and allows for setting a trip level above which a particular type of NTM is detected [6]. In this experiment, the ONFR system is set up to detect 3/2 NTMs with an MHD amplitude similar to the one in the reference shot [8].

The NTM suppression algorithm is set up so that all the available EC H&CD power, P_{EC}^{max}, is employed when an NTM needs suppression. The EC toroidal mirror angles are fixed and set up so that the gyrotrons drive current in the same direction as I_p, i.e., co-ECCD is employed. Also, $\phi_{(\cdot)}$ are regulated by the NTM suppression algorithm in order to track the $q = 3/2$ surface.

Finally, the Profile Control category is configured to perform β_N + q-profile control in a feedforward + feedback scheme [7], so that it works in feedforward-only until 4.25 s, and in feedforward + feedback after 4.25 s. The DIII-D PCS is configured to allow for a maximum of 4 s of $\phi_{(\cdot)}$ control under the Profile Control category, so it is chosen that the time span during which $\phi_{(\cdot)}$ are controlled by the Profile Control category is $t \in [1, 5]$ s. Also, for q-profile control, ECCD is aimed so that its peak is found at around $\hat{\rho} = 0.5$, which corresponds to ≈ 105 degrees.

3.3. Results

Experimental results from shot 176102 are reported in this paper to illustrate the performance of the integrated-control scheme. Fig. 2 shows the time evolution for β_N, q at the magnetic axis, q_0, and q at

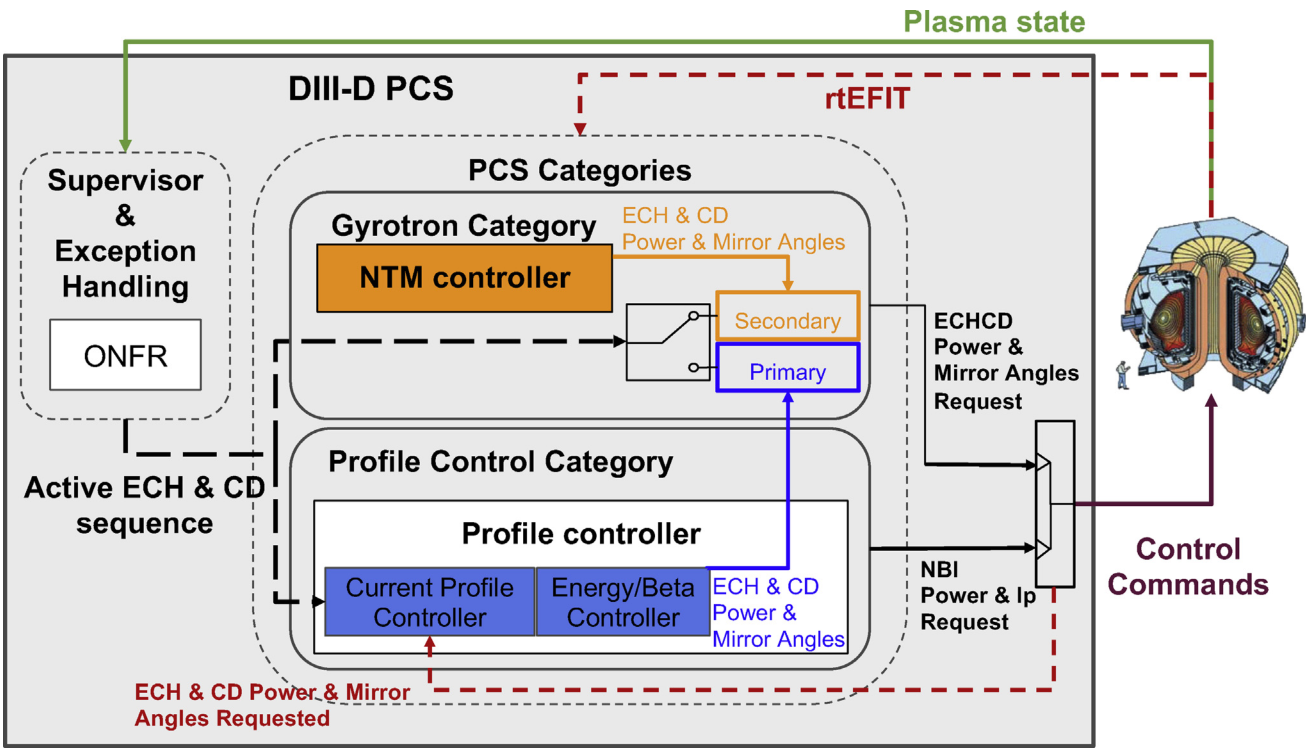

Fig. 1. Integrated-control architecture developed for q-profile + β_N control and NTM suppression within the DIII-D PCS.

$\hat{\rho}$ = 0.95, q_{95}, together with some of the controlled inputs: total NBI power, $P_{NBI} = \Sigma P_{NBI,(\cdot)}$, total EC power, $P_{EC} = \Sigma P_{EC,(\cdot)}$, and I_p. It can be seen that β_N in shot 176102 is not as constant in the flat-top phase as in the reference shot, despite using a very similar P_{NBI}: it is smaller in the early flat-top phase, higher later in the flat-top, and it is only similar to the reference shot when feedback is turned on at 4.25 s. Also, a lower q_0 is achieved in the ramp-up and early flat-top when compared to the reference shot, despite using EC H&CD earlier in the shot, which should in principle raise q_0 as it drives off-axis current. On the other hand, q_{95} evolves in a very similar way both in shot 176102 and the reference shot, as expected because I_p is also very similar. The only exception is at around 4.25 s, when I_p is increased by the feedback controller to track the β_N target at the expense of having a small deviation in q_{95}. The overall lower values of β_N and q_0 during the ramp-up and flat-top phases suggest a deteriorated confinement or a less optimal early-formation phase during shot 176102 when compared to the reference shot. The different B_T direction could also result in differences in the plasma behavior.

Fig. 3 shows the time evolution for the radiative power, P_{rad}, the line-average electron density, $\bar{n}_e$, the MHD $n = 2$ amplitude, the confinement H-factor, $H_{98(y,2)}$, the total power $P_{tot} \triangleq P_{NBI} + P_{EC}$, and the ONFR-related signals (which are the “NTM Strength” and its corresponding “NTM Trip Level”) together with P_{EC} from 0.5 to 3 s. The $\bar{n}_e$, P_{rad}, and $H_{H98(y,2)}$ evolutions confirm a lower confinement during the ramp-up and early flat-top than desired. Also, it can be noted that the MHD activity starts sooner in shot 176102, as reflected by the MHD $n = 2$ amplitude. Thus, EC H&CD is employed about a second earlier than in the reference shot, substantially increasing P_{tot} at approximately

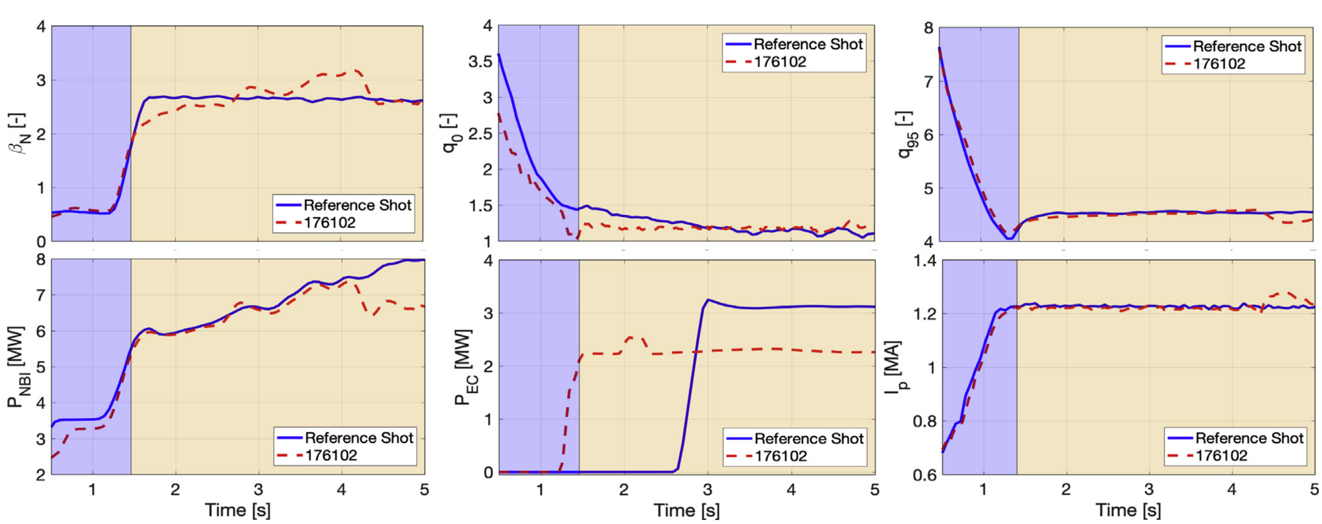

Fig. 2. Time evolution for β_N, q_0, q_{95}, P_{NBI}, P_{EC}, and I_p for the reference shot (target) and shot 176102. The blue/(orange) shaded area indicates authority of the Profile Control Category/(NTM Control Category) over EC H&CD (for interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

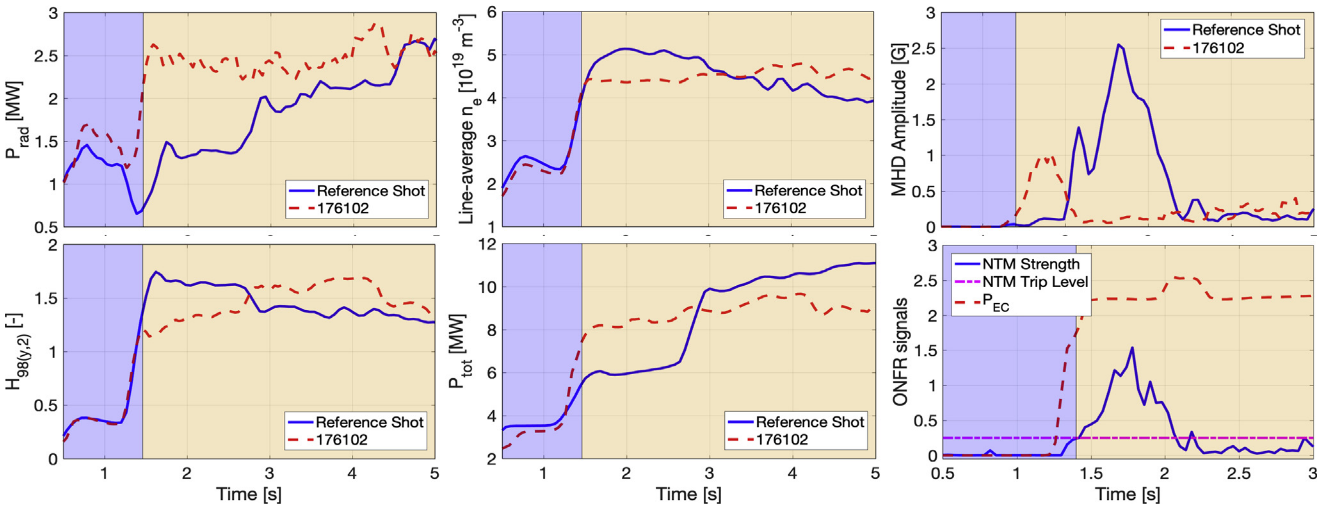

Fig. 3. Time evolution for P_{rad}, $\bar{n}_e$, MHD $n = 2$ amplitude, $H_{98(y,2)}$, P_{tot}, and ONFR signals for the reference shot (target) and shot 176102. The blue/(orange) shaded area indicates authority of the Profile Controller/(NTM Controller) over EC H&CD (for interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

1.4 s, when the NTM strength exceeds its trip level. This is when the EC H&CD authority is transferred from the Profile Control category to the Gyrotron category. In hybrid plasmas, q_0 may decrease when co-ECCD is employed to suppress 3/2 NTMs [9], as opposed to the intuition from previous q-profile control experiments [7]. These facts (poorer confinement, different early-formation phase, co-ECCD injection) may be the reason why β_N and q_0 are lower. After NTM suppression, both β_N and q_0 recover and get closer to their targets. Also, $\bar{n}_e$ and P_{rad} remain approximately flat until the end of the shot, whereas $H_{98(y,2)}$ increases. The MHD amplitude decreases due to the NTM suppression. The EC H&CD authority could have gone back to the Profile Control category once the NTM strength had become lower than its trip level (at $t \approx 2.1$ s), but the ONFR system was not configured to allow such transfer.

Finally, Fig. 4 shows the time evolution of $\phi_{(\cdot)}$ for two gyrotrons (the other $\phi_{(\cdot)}$ evolutions for the available gyrotrons are very similar). At $t = 1$ s, when the Profile Control category starts controlling $\phi_{(\cdot)}$, they are driven from their initial condition towards 105 deg for q-profile control. When EC H&CD is transferred to the Gyrotron category at 1.4 s, they are steered towards the $q = 3/2$ surface (whose position varies in time and is tracked until the end of the shot) for NTM suppression.

4. Summary and possible future work

A preliminary integrated-control architecture for q-profile + β_N control and NTM suppression has been implemented and tested in DIII-D. This scheme makes use of the ONFR system as a supervisor to monitor the plasma state and manage control authority over EC H&CD. Future work may include integration of more DIII-D PCS categories and/or control objectives.

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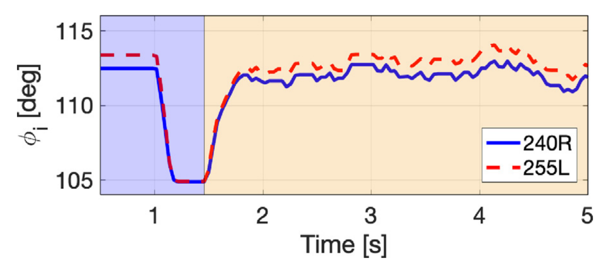

Fig. 4. Time evolution for ϕ_{240R} and ϕ_{255L} for shot 176102.

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