Designing, Constructing, and Using Plasma Control System Algorithms on DIII-D

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***Abstract*—The DIII-D plasma control system (PCS), initially deployed in the early 1990s, now controls nearly all aspects of the tokamak and plasma environment. Versions of this PCS, supported by General Atomics, are presently used to control several tokamaks around the world, including the superconducting tokamaks Experimental Advanced Superconducting Tokamak and Korean Superconducting Tokamak Advanced Research. The experimental challenges posed by the advanced tokamak mission of DIII-D and the variety of devices supported by the PCS have driven the development of a rich array of control algorithms, along with a powerful set of tools for algorithm design and testing. Broadly speaking, the PCS mission is to utilize all available sensors, measurements, and actuators to safely produce a plasma state trajectory leading to and then maintaining the desired experimental conditions. Often new physics understanding leads to new or modified control requirements that use existing actuators in new ways. We describe several important DIII-D PCS design and test tools that support implementation and optimization of algorithms. We describe selected algorithms and the ways they fit within the PCS architecture, which in turn allows great flexibility in designing, constructing, and using the algorithms to reliably produce a desired complex experimental environment. Control algorithms, PCS interfaces, and design and testing tools are described from the perspective of the physics operator (PO), who must operate the PCS to achieve experimental goals and maximize physics productivity of the tokamak. For example, from a POs (and experimental team leader's) standpoint, a PCS algorithm interface that offers maximum actuator, algorithmic, and measurement configuration flexibility is most likely to produce a successful experimental outcome. However, proper constraints that limit flexibility in use of the PCS can also help to maximize effectiveness. For example, device limits and safety must be built into the PCS, sometimes at the algorithm level. We show how the DIII-D PCS toolset enables rapid offline testing of a new or modified algorithm in a simulated tokamak environment. Finally, we illustrate usage of PCS-based checklists and procedures that enhance experimental productivity, and we describe an asynchronous condition detector system within the PCS that enhances device safety and enables complex experiment design.**

***Index Terms*—Algorithm, conditional, control, digital, model, plasma, simulation, tokamak.**

I. INTRODUCTION

THE DIII-D tokamak device was designed and built to test, among other things, the stability, and the confinement properties of plasmas of many different shapes [1]. Its 18 independent poloidal field (PF) shaping coils and large (12 Vs), independently controlled Ohmic drive coil were designed to allow it to produce and control plasmas of a wide variety of poloidal cross-sectional shapes, currents, and plasma parameters. An abundance of auxiliary heating systems, including up to 14 MW from six tangentially coinjected neutral beams (NBs) and 5 MW from two counter-injected NBs, up to about 4 MW from poloidally and toroidally steerable 110-GHz gyrotrons, and up to about 3 MW from three 60–120-MHz fast wave systems, allow DIII-D to reach stability limits in all plasma shapes. Each heating system also delivers some more or less localized current drive, and the NBs also locally fuel the plasma and impart toroidal momentum. A set of six toroidally spaced window frame coils located on the midplane outside of the vessel and 12 similar coils located inside the vessel equally spaced above and below the midplane allow the imposition of static (up to $n = 3$) or rotating (up to $n = 2$) magnetic perturbing fields and some control of helicity and mode spectrum.

Together these systems to some extent offer control of the radial profiles of the plasma current, pressure, and toroidal rotation.

Complementing these actuators are a wide variety of real-time plasma measurement systems, such as poloidal flux loops and field probes, laser interferometry density measurements, Thomson scattering measurements of the electron density and temperature profiles, motional Stark effect polarimetry measurements of the plasma current density profiles, charge exchange recombination spectroscopy measurements of ion temperature and toroidal and poloidal velocity profiles, and so on.

Prior to 1993 plasma control at DIII-D was accomplished using a configurable network of individual analog computation modules: adders, multipliers, dividers, switches, and so on. Plasma control was confined to the plasma current, density,

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and plasma shape using a limited set of poloidal flux and field measurements to approximate a few of the plasma boundary's defining parameters, such as the position of the X-point, the inner and outer gaps, and the elongation. Preprogrammed waveform generators provided the control targets. Changing the analog control network, e.g., from a lower single null (LSN) to a double null (DN), required several man-hours of effort and then several more to troubleshoot, as many tens of cables needed to be moved and computational module potentiometers' settings revised. DIII-D, arguably one of the most capable and flexible tokamaks in the world, was as a practical matter far less flexible than it could be due to the limitations of the analog control system. In 1993, the first all-digital plasma control system (PCS) was installed at DIII-D. At first it just reproduced the plasma current, density, and shape control algorithms of the analog control systems, but its design allowed the setup from any previous discharge that was digitally controlled to be recalled in seconds and be executed exactly as that previous shot was. From then on the physical configuration of the PF shaping system, not the PCS, was the pacing item when a change in plasma configuration was desired. As a practical matter experiments could then change on an hourly schedule instead of weekly, as had been the case.

The digital PCS design philosophy incorporated several desired characteristics. It was designed to allow rapid change shot-to-shot between plasma configurations, to allow easy recall of past configurations, to use commercially obtained hardware, to be easily scalable and adaptable as tokamak and/or measurement systems are added/expanded/upgraded, and to provide parallel real-time control of many different systems [2]. In 1997, computational speed had risen and costs had dropped enough to enable the PCS to begin using a real-time plasma equilibrium reconstruction based on the EFIT code [3] to measure the plasma boundary and use that as the basis for shape control [4]. This choice allows measurement of many interesting plasma equilibrium properties in real-time, such as the internal stored energy, β_n, the internal inductance l_i, the identification and spatial location of interesting plasma poloidal flux surfaces like the $m/n = 2$ surface, and so on. Given suitable actuators and control algorithms these quantities may then be controlled to follow preprogrammed targets. Among other considerations, the PCS' adaptability and success in realizing these design points has led to its adoption as the PCS for several tokamaks, including the next generation superconducting tokamaks Experimental Advanced Superconducting Tokamak (EAST) and Korean Superconducting Tokamak Advanced Research (KSTAR) in China and South Korea, respectively, the low aspect ratio National Spherical Torus Experiment (NSTX) tokamak at Princeton Plasma Physics Laboratory, and others. In the present day, new algorithms are designed and deployed in the DIII-D PCS continuously to meet new experimental challenges and capabilities arising from expanding hardware systems [5]. This paper describes procedures, design tools, and systematic approaches in Physics Operations and control design that help maximize physics productivity at DIII-D and beyond.

II. PHYSICS OPERATIONS AND THE PCS AT DIII-D

In [6], we described the composition and responsibilities of the DIII-D Physics Operations group and computational support staff with regards to configuring, maintaining, operating, and expanding the PCS. Broadly speaking, Physics Operations consist of a number of physicists, the physics operators (POs), who confer with experiment leaders to setup and configure the PCS during experiments, and a group of computational specialists (CSs) who maintain, expand, and troubleshoot the PCS hardware and write much of its code. POs in consultation with the experimental staff generate conceptual designs for new or improved/expanded PCS algorithms. Together with the POs, the CSs write new code to implement the designs. Offline testing is then performed using one or more testing paradigms: 1) hardware testing, where the PCS is cycled using fixed data and external trigger inputs that form a standard sequence; 2) a shot data sequence, where all the external data and triggering information comes from an archived, preexisting discharge; and 3) a Simserver simulation, where the PCS is run with a plasma model coupled with a model of the DIII-D plant to produce a simulated discharge [7]. These testing tools are provided within the General Atomics Tokamak System Toolbox (TokSys) [8].

TokSys is a package of codes running principally under MATLAB/Simulink, which supports control design and electromagnetic analysis for tokamaks. TokSys includes generic codes for design, analysis, and simulation, as well as machine-specific codes and data enabling application of the TokSys tools to many devices. On the order of a dozen operating devices and proposed device configurations are modeled and maintained in the environment, including many of the eight devices that presently share the DIII-D PCS. These latter machines include DIII-D, NSTX, EAST, KSTAR, and PEGASUS. Machines under design or construction modeled in TokSys include ITER, NSTX-Upgrade, and Fusion Development Facility/Fusion Nuclear Science Facility. The package includes interface codes for accessing experimental data from operating devices, and programming of corresponding versions of the DIII-D PCS, where appropriate. Simserver simulations for development and verification of control algorithms are also included as part of the TokSys suite of codes [7].

A large collection of plasma response models are available in TokSys, designed to provide control level descriptions of relevant physics. Control level models represent relevant dynamics with sufficient accuracy to enable control design, but typically not so much accuracy as to require large amounts of complexity and computation time. Examples of TokSys models include rigid and nonrigid axisymmetric responses, axisymmetric resistive diffusion, nonaxisymmetric global responses based on ideal MHD calculations and 3-D conductor responses, core and divertor particle dynamics, tearing mode dynamics, and core confinement. A similar range of actuator models are also available in TokSys, including power supplies, gas valves, NB heating and rotation, and electron cyclotron current drive systems, with varying degrees of simplicity appropriate for control analysis.

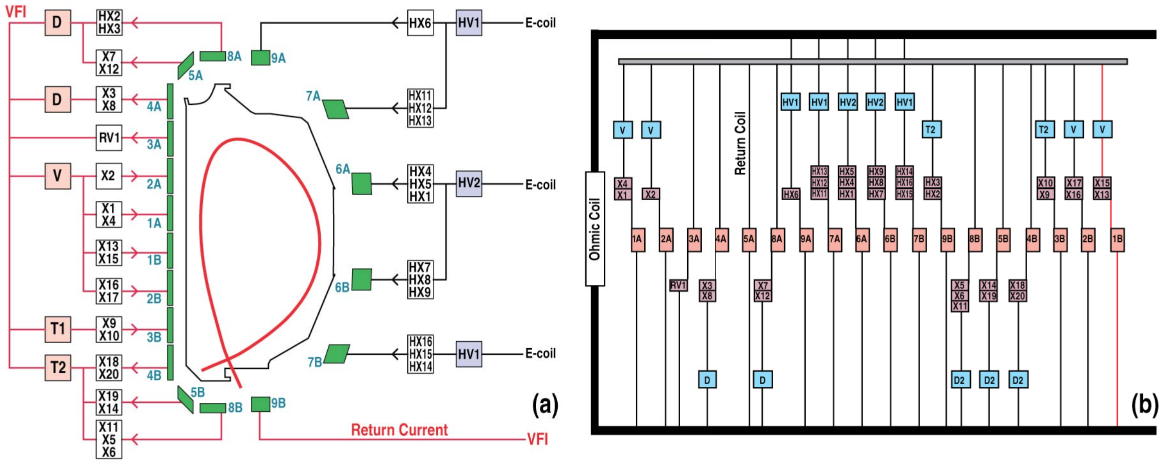

Fig. 1. (a) ISS target boundary in red is shown within the DIII-D Limiter outline. The PF coils are shown in green, labeled 1A through 9B. The dc Supplies and the switching choppers they power are shown connected in parallel to the VFI bus (red) or across the Ohmic coil, the E-coil (black). This is a standard setup for LSNs, including the ISS. The PF9B is the return current coil. The PF3A is also unpowered but is connected in series with a relatively large resistor (RV1), and thus carries little current. Choppers drive current in one direction only as indicated by the arrows. The return current is typically large and opposing the main X-point generating coil, PF8B. (b) Basic schematic of the DIII-D PF coil, power supply, and chopper system. This particular configuration shows a subset of PF coils, all connected to the common VFI bus. The rest of the PF coils are connected across the Ohmic coil. The difference between this schematic and (a) is the choice of the return coil. This particular configuration was used to successfully produce the ISS, as shown in Fig. 3(a).

Modeling codes are typically used in the large set of control design codes also available in TokSys, which extensively exploit the MATLAB suite of design toolboxes. Plasma control design codes in TokSys include tools for creation and analysis of axisymmetric equilibrium control, tearing mode control, resistive wall mode control, coil current regulation, and plasma beta and rotation. Many specialized codes are also available specialized for the needs of individual devices. For example, extensive experience applying TokSys tools to startup of new machines has produced a rich collection of specialized codes to calculate breakdown and plasma startup scenarios, and to support the needs of devices in the early phases of operation with limited diagnostic and actuator capabilities.

We now describe the process used to design and implement a new plasma shaping control algorithm on the PCS. We begin with some history and background. DIII-D has had some difficulty reproducing with high accuracy the ITER Scenario 2 plasma shape scaled down to fit within the vessel while preserving the details of the poloidal cross section and the aspect ratio. This ITER similar shape (ISS) is displayed in Fig. 1(a). The difficulties are associated with two observations: 1) the DIII-D PF coil set is not ideally configured to produce this ISS; note that the X-point lies between two coils and 2) a large subset of the DIII-D PF shaping coils are typically required to be connected to a common bus that features one or more nominally unpowered PF coils (known as return coils), as shown in Fig. 1(b). It is the unpowered coil(s) current (return current) that one way or another causes noticeable shape distortion and difficulty producing the X-point at desirable ISS plasma currents of 1.5 MA or so.

This bus connection—named the VFI bus for historic reasons—provides three benefits. The first is that one or more unpowered PF coils can and do carry current driven by a nonzero bus voltage which is generated by all the other bus coils' supplies in a complex fashion. The VFI bus thereby extends the number of coils that can be driven by the limited number of supplies available. The second benefit is that this bus provides an overall hardware constraint on the bus coils' currents—they must sum to zero. This in effect constrains the PF coils' contribution to the plasma boundary flux for any given boundary and plasma equilibrium, and thus selects one PF current distribution from an infinite possible set. The third benefit is that this constraint tends to produce the smallest PF coil currents required to make the equilibrium in the sense of minimizing the sum of the squares of the individual PF coil currents. This minimizes the requirements of PF supplies and reduces their cost. DIII-D does not have sufficient PF supply capability to independently power all 18 of its PF coils, and in fact the VFI bus constraint helped set the requirements for the PF supplies, so almost all plasma shaping algorithms incorporate the benefits and issues presented by the VFI bus constraint.

All of the production plasma shaping algorithms in use at DIII-D are dominantly single input–single output (SISO) in nature. In effect the PCS controls a point on the plasma boundary to a target location by increasing or decreasing the current in a nearby PF coil. More precisely, the PCS uses the real-time equilibrium solver to measure the poloidal flux at the target location and at the plasma boundary defining X-point location and controls the target location flux to match the X-point flux value. The SISO nature of the control algorithm combined with the VFI return current is prone to local shape distortion in the plasma boundary near to the return current coil(s). Consider a VFI connected control coil positioned next to a return current coil. If the control algorithm decides that coil must increase its current to move the boundary closer to the target, this increase in current tends to show up in the return coil but with the opposite sign. This tends to move the plasma boundary near the return coil closer to the coil and partially negates the effect of the controlled coil's outward push. This effect is a positive feedback that often needs to be specifically addressed by the shaping algorithm.

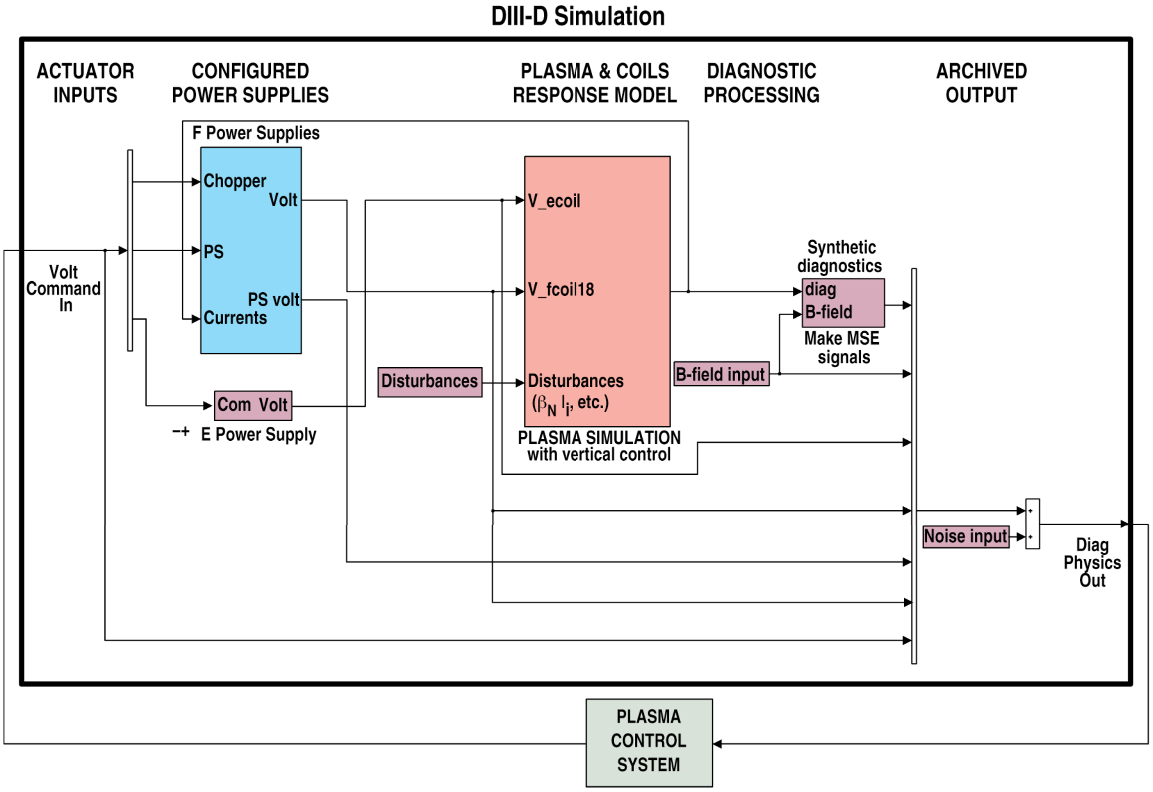

Fig. 2. DIII-D model-based simulation takes the place of the actual device in the plasma shaping control loop. The model provides plant actuator responses to PCS commands, plasma equilibrium response to those actuators, and diagnostic response to that equilibrium. The plant model incorporates the PF coil VFI configuration and must be recalculated for every change in PF coil configuration.

For example, the plasma boundary can be selectively distorted in some chosen location to modify the required return current. Production shaping algorithms have typically dealt with this effect by selecting a return coil that is both far away from the plasma boundary and next to a coil that is not connected to the VFI bus. For up–down symmetric plasma shapes, primarily DNs, this has been sufficient to produce acceptable results. For up–down asymmetric shapes with LSNs, like the ISS shape, additional control from deliberate boundary distortion was required. In the ISS shape, this distortion was applied on the outside lower boundary by adding a control loop that applied more or less current to the PF coil closest to this part of the plasma boundary to keep the return current near a chosen target value. This approach is gives generally acceptable results, with two caveats. One is that the amount of lower outer boundary distortion will, all else being equal, depend on the plasma current distribution, so that changes in plasma beta, β, and internal inductance, l_{i}, result in noticeable changes in the plasma shape unless subsequent shots adjust the return current target accordingly. More of an issue is that the details of the outer shape can significantly affect the plasma's pedestal stability and thus its ELMing behavior. Maintaining the outer shape is therefore important for many ITER relevant experiments. The other caveat is that the return coil chosen naturally opposes radially outward X-point movement; the current required from the X-point controlling coils to move outward rapidly exceeds the power supply limit before the desired location is reached for higher ranges of desired plasma currents.

In past years several attempts were made to overcome the need for shape distortion control of the VFI return coil, to move the X-point to the ISS target location, and to do these at high plasma current. These attempts were made using the actual device, consuming many hours of valuable experiment time, and all more or less failed. Different choices for the return coil location, different choices of coils connected to the VFI bus, and different SISO control loops for various boundary and/or X-point controls were tried. Recent model-based DIII-D simulations have made it possible to try many different approaches in depth, without taxing DIII-D's limited experimental time. A schematic of the DIII-D model-based simulation used in the present study is shown in Fig. 2.

The DIII-D simulation is constructed using Simulink for MATLAB. The box at the bottom of Fig. 2 called PCS is an interface that communicates with a standalone version of the actual PCS. The commands from the PCS are sent into a simulation of the power supplies for the PF coils. The PF coil power supply model can easily be reconfigured to simulate different VFI bus configurations. The outputs from the power supply models are the voltages applied to the coils and these are inputs to the system plasma and coils. This second part of the simulation is based on a linear plasma response with the arbitrary but reasonable assumption (on typical control simulation timescales) that β_{p} and l_{i} are unaltered by changes in the external field and that the plasma resistance is constant. In order to simulate variations in β_{p}, l_{i}, and plasma resistance, the effect of such changes can be fed into the simulation as disturbances. The use of a linear plasma response provides a good approximation in simulations where the plasma is well controlled and therefore always close to the plasma shape used for the linearization. The treatment of β_p, l_i, and plasma resistance as disturbances is driven by the typical need to study control robustness to subtle changes in the transport properties of the plasma, and therefore to study control response to a variety of such disturbances. In the third and last part called diagnostic processing the signals from flux loops, magnetic probes, and Rogowski coils are calculated. Arbitrary levels of noise can be added for testing purposes. The diagnostics are then fed to the communication interface and sent to the PCS to complete the control loop.

The DIII-D simulation also provides options for modeling of neoclassical tearing mode or resistive wall mode dynamics to support design and testing of control algorithms for such MHD modes. In recent years different versions of the DIII-D simulation have also been applied to design and testing of profile control algorithms [9], as well as debugging of observed problems in fundamental equilibrium control.

It is useful to note that from the POs standpoint this simulation simply replaces the DIII-D plant and device and provides responses similar enough to the actual device response for those results to provide useful guidance. After several hundred simulated discharges, the equivalent of about a month of DIII-D experimental time, a candidate SISO algorithm approach was identified as a good choice for development on DIII-D.

This candidate approach has the return current coil placed at the top of the plasma, far away from the X-point. It also features a modified approach to setting the voltages of the PF dc supplies in a way that tends to bias the VFI bus voltage to a more favorable outcome, and hence influence the return current globally instead of locally using selected shape distortion. At this point it is not clear how this biasing is accomplished, but it appears that in effect it applies a small amount of shape distortion to all of the VFI connected coils. In other words, a noticeably large locally applied shape distortion has been replaced with smaller more globally applied shape distortion. The candidate algorithm was recently applied essentially intact for real discharges, with excellent outcome. The result is displayed in Fig. 3. Although work remains to be done qualifying this new shape control for general ISS plasma production, especially in challenging it with a broader range of plasma parameters, it can already be considered a success. Prior to this new solution, it was impossible to produce any ISS plasmas at any acceptable plasma current. Previous applications of TokSys simulations for DIII-D algorithm development have typically been done by control design specialists. This success validates the use of TokSys simulations by POs to rapidly develop new shape control approaches on DIII-D.

III. EXPANDED CHECKLISTS AND PROCEDURES AT DIII-D

We previously described [6], a set of procedures and checklists that enhance physics productivity and increase safety at DIII-D. In this paper, we will focus on significant improvements and additions to the PCS checklists and procedures.

There are several tasks that must be successfully completed to get the device and the PCS properly configured, checked, and tested before the first discharge devoted to the day's experiment can be initiated. Many of these tasks are now under the control of the PCS-based morning checklist software or program. The tasks this checklist covers are now split into three discrete groups with three discrete user interfaces all coordinated within the PCS, each the responsibility of three different operators: The first PO, the second PO, and the machine console operator (MCO). Formally, the POs are part of Physics Operations in the experimental science organization, while the MCO is part of the Tokamak Operations organization. For the purposes of this discussion, the job of the POs is to specify the device configuration and program the PCS to perform the experiments. The job of Tokamak Operations is to physically configure the device per the POs instructions, test that configuration for operations, and to insure personnel and plant safety.

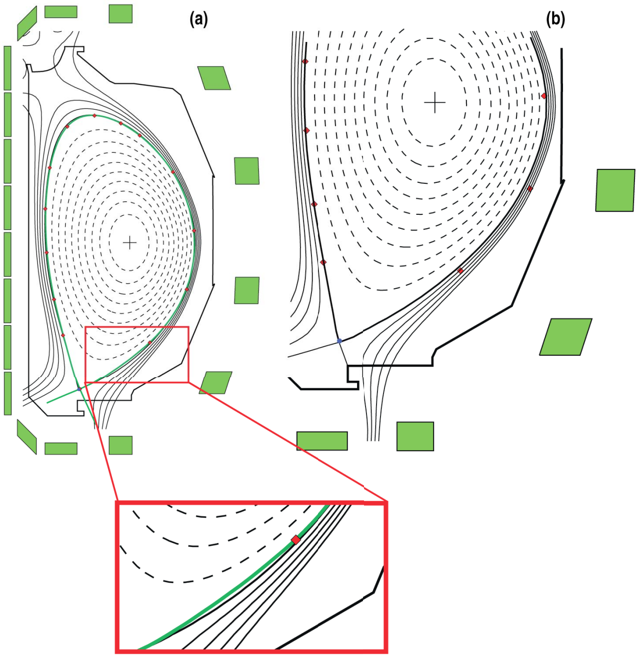

Fig. 3. (a) Displays the result of the simulation developed shaping algorithm in a real discharge. For reference the target ISS target is overplotted in green. The boundary target locations are shown as red diamonds. The blue dot is the measured X-point location. There is no applied shape distortion to control the return current. This is not the case in (b) on the right, where the production shape control algorithm forces a noticeable deviation of the lower outer plasma boundary that can be clearly seen.

There are three levels of testing performed using the checklists. When they are successfully completed, the checklist then aids in configuring the PCS for the first experimental discharge. The three levels of testing start with waveforms driving the PF coils to test the shape control algorithm sensors: the PF magnetic field probes and flux loops, and PF and Ohmic coil current sensors. In DIII-D these sensors are all integrated signals, and are tested by applying a standard square wave to each integrator and comparing the digitized output with the expected results. All programmable gas valves are tested during this procedure as well. The checklist sets up the PCS for this, and would not allow further progress until this test has passed inspection and if necessary repair and repetition. The next level of testing is to verify operability of all of the device coil systems' power supplies and configuration at low current levels, i.e., the toroidal, poloidal, and 3-D field correction coil systems. The Checklist loads in standardized algorithms and waveforms to accomplish these tests, and requires certification of acceptable results to proceed to the last level of testing. This final test level is the setup and execution of a standard plasma reference shot using standardized NB auxiliary heating and gas fueling. DIII-D now has a library of several years' worth of these nominally identically prepared and executed plasma discharges. This library has proved invaluable for tracking long-term changes in device conditions. Each day's reference shot also provides a timely test of the entire systems' capability to reproduce a known plasma. Finally, after the reference shot, the checklist guides the PO in reconfiguring the PCS to begin the day's experimental program.

Prior to the introduction of this parallelized morning checklist, progression though the test levels and final PCS setup for the day's experiment was the sole responsibility of the first PO using a less comprehensive single checklist. Dividing responsibility among three persons allowed the checklists to become more comprehensive while also speeding up the procedures. The morning's experimental program now typically begins about an half hour earlier than previously while reducing the frequency of human errors during the testing procedures.

In a previous paper, we described early implementation of the Physics Operations web site [5]. This web site has since been expanded to cover more areas of interest to POs. Notably, added have been links to web-based tools of direct interest to the PO, such as the electronic logbook used by POs, experiment leaders, tokamak operators, systems operators, and interested members of the experiment team; a countdown timer that uses device engineering calculations to determine when the next shot can safely be started; a web-based machine setup form that lets the tokamak operations staff know how the device is to be configured for the next morning's experiment, and others. In addition, the PO web site has built up a library of memos, diagrams, specific task checklists, troubleshooting guides, and so on, that can be quickly recalled to help the PO during the experiment when needed.

IV. CONCLUSION

The DIII-D PCS continues to expand to satisfy control requirements for the advancing DIII-D experimental program. Many tools and procedures have been developed to support use of the PCS, including daily Physics Operations and longer-term design and development of control algorithms. Use of model-based TokSys toolbox simulations by POs has proven highly successful in developing challenging shape control approaches with minimal use of machine time. Other advances in Physics Operations procedures and resources, including an expanded morning checklist and PO web site, have proven similarly valuable in minimizing human error and maximizing physics productivity.

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