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

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***Abstract*— The DIII-D Plasma Control System (PCS [1]), initially deployed in the early 1990's, 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 EAST and KSTAR. 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 PO's (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 D3D 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.

Keywords*— *plasma; control; simulation; model; conditional; digital; tokamak; algorithm

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I. INTRODUCTION

The DIII-D tokamak device was designed and built to test, among other things, the stability and confinement properties of plasmas of many different shapes [1]. Its 18 independent poloidal field (PF) shaping coils and large (12 V-s), 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 co-injected neutral beams (NB) 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 twelve 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 (MSE) polarimetry measurements of the plasma current density profiles, charge exchange recombination (CER) spectroscopy measurements of ion temperature and toroidal and poloidal velocity profiles and more.

Prior to 1993 plasma control at DIII-D was accomplished using a configurable network of individual analog computation modules: adders, multipliers, dividers, switches, etc. Plasma control was confined to the plasma current, density and plasma shape using a limited set of poloidal flux and field

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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, etc. Preprogrammed waveform generators provided the control targets. Changing the analog control network, from e.g. a lower single null to a double null, 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 many more. 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 plasma control system for several tokamaks, including the next generation superconducting tokamaks EAST and KSTAR in China and South Korea respectively, the low aspect ratio 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]. The present 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 a previous paper [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 consists of a number of physicists, the Physics Operators (POs), who confer with experiment leaders to set up 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. Physics Operators 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: (a) Hardware testing, where the PCS is cycled using fixed data and external trigger inputs that form a standard sequence; (b) a shot data sequence, where all the external data and triggering information comes from an archived, pre-existing discharge; and (c), 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 Plasma Control System (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 FDF/FNSF. 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 3D 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, neutral beam heating and rotation, and electron cyclotron current drive systems, with varying degrees of simplicity appropriate for control analysis.

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 Figure 1(a). The difficulties are associated with two observations: (1) the DIII-D poloidal field (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 Figure 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 non-zero 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. For example, the plasma boundary can be selectively distorted in some chosen location in order 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 Double Nulls (DNs), this has been sufficient to produce acceptable results. For up-down asymmetric shapes with lower single nulls (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 in order 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 Figure 2. It is useful to note that from the Physics Operator's 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 Figure 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 Physics Operators to rapidly develop new shape control approaches on DIII-D.

III. EXPANDED CHECKLISTS AND PROCEDURES AT DIII-D

We previously described [5] 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 Physics Operator, the Second Physics Operator and the Machine Console Operator (MCO). Formally, the Physics Operators 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.

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 testing during this procedure as well. The Checklist sets up the PCS for this, and won't 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 3D field correction coil systems. The Checklist loads in standardized algorithms and waveforms to accomplish these tests, and requires certification of acceptable results in order 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 neutral beam 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 Physics Operator 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 a 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 Website [5]. This Website 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 Website has built up a library of memos, diagrams, specific task checklists, troubleshooting guides, etc, that can be quickly recalled to help the PO during the experiment when needed.

IV. CONCLUSION

The DIII-D Plasma Control System 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 Physics Operators 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 Website, have proven similarly valuable in minimizing human error and maximizing physics productivity.

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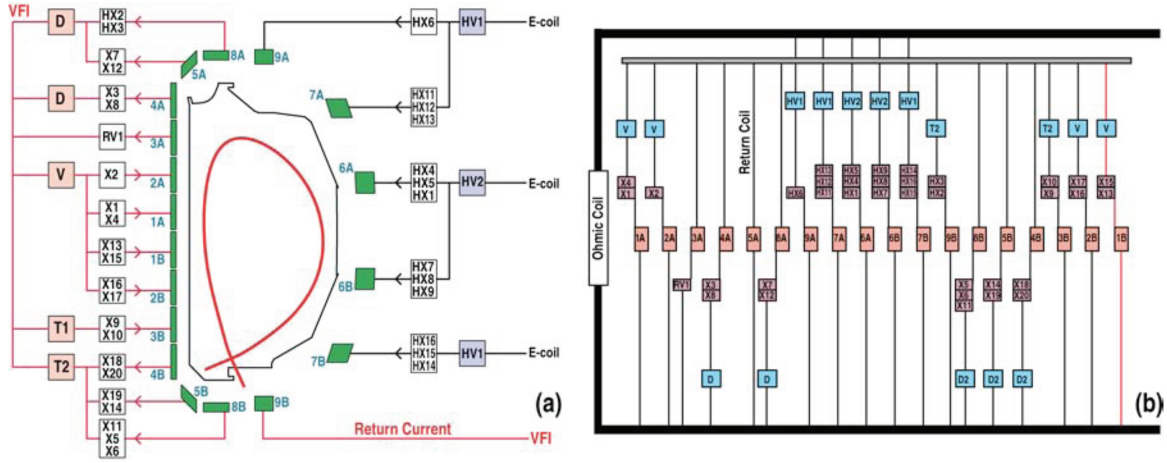

Figure 1(a). The ISS target boundary in red is shown within the DIII-D Limiter outline. The PF coils are shown in green, labeled 1A through 9B. The DC Supplies and the switching “choppers” they power are shown connected in parallel to the VFI bus (red) or across the Ohmic coil, the “E-coil” (black). 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. Figure 1(b) is a 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 Fig 1(a) is the choice of the Return Coil. This particular configuration was used to successfully produce the ISS as shown in Figure 3(a).

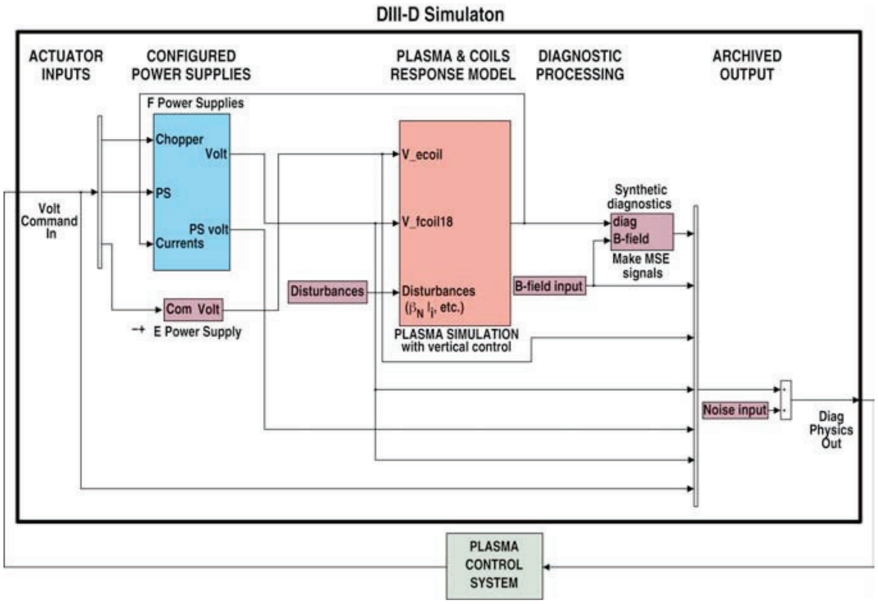

Figure 2. The DIII-D model based simulation takes the place of the actual device in the plasma shaping control loop. The model provides plant actuator responses to PCS commands, plasma equilibrium response to those actuators, and diagnostic response to that equilibrium. The plant model incorporates the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

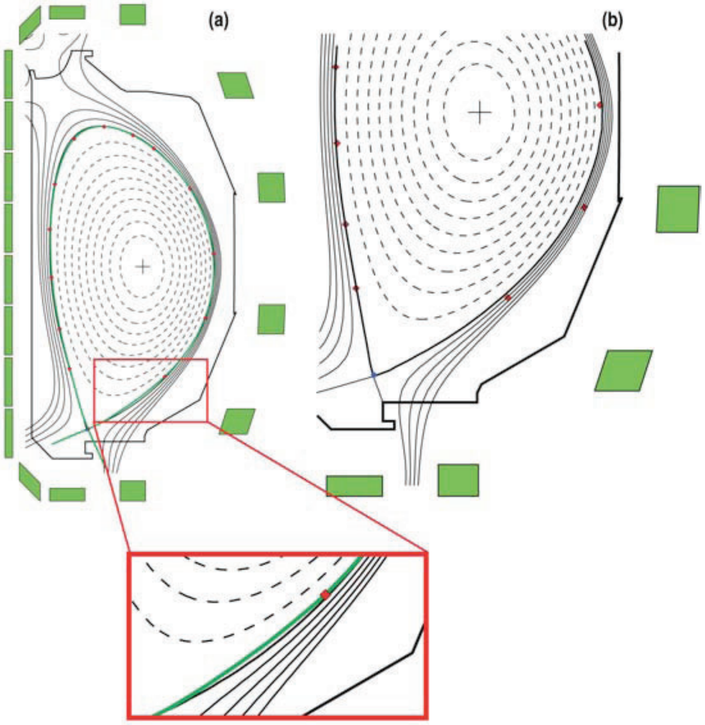

Figure 3(a). Displays the result of the simulation developed shaping algorithm in a real discharge. For reference the target ITER Similar Shape target is overplotted in green. The boundary target locations are shown as red diamonds. The blue dot is the measured X-point location. There is no applied shape distortion to control the return current. This is not the case in Figure 3(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