Fusion Engineering and Design xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

# Progress and plan of KSTAR plasma control system upgrade

Sang-hee Hahn [a,*], Y.J. Kim [a], B.G. Penaflor [b], J.G. Bak [a], H. Han [a], J.S. Hong [a], Y.M. Jeon [a], J.H. Jeong [a], M. Joung [a], J.W. Juhn [a], J.S. Kim [a], H.S. Kim [a], W.R. Lee [a], M.H. Woo [a], N.W. Eidietis [b], J.R. Ferron [b], D.A. Humphreys [b], A. Hyatt [b], R.D. Johnson [b], D.A. Piglowski [b], M.L. Walker [b], A.S. Welander [b], D. Mueller [c], P.G. Milne [d]

[a] *National Fusion Research Institute, Daejeon, South Korea*
[b] *General Atomics, San Diego, CA, USA*
[c] *Princeton Plasma Physics Laboratory, Princeton, NJ, USA*
[d] *D-TACQ Co. Ltd, Scotland, UK*

## HIGHLIGHTS

- Recent achievements of the KSTAR plasma control system are described.
- Requirements and results of the testbed system for the future upgrade of the KSTAR plasma control system are presented.
- An overview of the upgrade layout based is given.

## ARTICLE INFO

*Article history:*
Received 20 June 2015
Received in revised form 10 May 2016
Accepted 12 May 2016
Available online xxx

*Keywords:*
Magnetic fusion
Tokamak
Control system
KSTAR
Plasma control
Real-time control

## ABSTRACT

The plasma control system (PCS) has been one of essential systems in annual KSTAR plasma campaigns: starting from a single-process version in 2008, extensive upgrades are done through the previous 7 years in order to achieve major goals of KSTAR performance enhancement. Major implementations are explained in this paper. In consequences of successive upgrades, the present KSTAR PCS is able to achieve ~48 s of 500 kA plasma pulses with full real-time shaping controls and real-time NB power controls. It has become a huge system capable of dealing with 8 separate categories of algorithms, 26 actuators directly controllable during the shot, and real-time data communication units consisting of +180 analog channels and +600 digital input/outputs through the reflective memory (RFM) network. The next upgrade of the KSTAR PCS is planned in 2015 before the campaign. An overview of the upgrade layout will be given for this paper. The real-time system box is planned to use the CERN MRG-Realtime OS, an ITER-compatible standard operating system. New hardware is developed for faster real-time streaming system for future installations of actuators/diagnostics.



## 1. Introduction

Since its first operation in 2008, the plasma control system (PCS) of KSTAR [1,2] became one of the essential systems for annual plasma operations. Starting from a single-process version in 2008 [3], with adaptation of the General Atomics Plasma Control System software, extensive upgrades are done through the previous 7 successive campaigns in order to achieve annual goals of KSTAR performance enhancement.

In last 3 years of experiment (2012–2014), KSTAR successfully demonstrated an $I_p = 0.5$ MA, H-mode plasma discharge over 47 s using 11 superconducting poloidal field (PF) coil systems and conventional magnetic controls implemented at KSTAR PCS. In order to sustain the plasma in the better performance regime, however, more development on the real-time kinetic performance control is required. Key themes for the KSTAR include a direct kinetic output control on plasma energy, a real-time $T_e$ profile feedback and an integrated MHD controller using Electron Cyclotron Heating/Current Drive.

Recent operational space exploitation on the highest achievable $\beta_N$ [4] revealed a new demand on the upgrade of the PCS. Recent operation in 2012–2014 temporarily achieved $\beta_N$ above the $n = 1$ no-wall limit in the plot of $\beta_N$ vs $l_i$ [5]. Hence a capability of dealing with such advanced scenarios, beyond the no-wall limits, is desired to the PCS. The capability desired consists of faster real-time data acquisition hardware system, a new software scheme to deal

* Corresponding author.
*E-mail address:* hahn76@nfri.re.kr (S.-h. Hahn).

http://dx.doi.org/10.1016/j.fusengdes.2016.05.018
0920-3796/

with multiple input-multiple output (MIMO) controls, and easier incorporations with existing EPICS-based controllers in KSTAR.

In this paper a brief summary on already implemented specific controls are given, and a test result will be given for the essential system upgrades in order to match the desired capabilities.

## 2. Progress of KSTAR plasma control system upgrade

### 2.1. Hardware capabilities

At the end of year 2014, the KSTAR PCS became a complex system capable of dealing with 8 separate categories of algorithm. 26 actuators are directly controllable during the shot, including 15 control coil power supplies, 7 fueling valves, and 4 heating sources controllable in real time. It is also equipped by real-time data communication units consisting of +180 analog channels and more than 600 digital I/O through the reflective memory (RFM) [6] network. 5 independent real-time processes are installed and operated routinely. The fastest cycle is set to 50 μs regarding the vertical stability (VS) control for high elongation ($\kappa \leq 2.0$) and the RFM I/O thread.

Real-time data sharing through an RFM network enabled a very fast, and deterministic data communications up to 255 independent servers with different form factors. The RFM network connects PCS, all available coil power supplies and 1 ECCD source as primary real-time communication network during the shot. In order to match the real-time scheme given by the PCS RT kernel, the core functions of the device driver are rewritten to disable interrupts on the DMA transfer [7–9].

A direct PCI bus streaming is implemented from 2 × 96-channel ACQ196 digitizers to a compactPCI RFM card, in order to share raw magnetic diagnostics data with other systems. The system provides 192 Channels × 4 kHz simultaneous streaming of raw digitized data to independent system hardware, and was used for providing sample data for validating the real-time Cauchy Condition Surface (CCS) reconstruction system [10] as collaboration topics with JT–60SA plasma control group.

A quasi real-time signal display is extended to display the evolutions of plasma current and boundary information during the shot. The relevant information has been collected from the PCS measurements and reconstruction results, and the RFM I/O thread sends the information in a specific region of the RFM network every 1 ms. A dedicated host is given for converting the information on RFM into EPICS process variables (PVs) that can be easily shown at the KSTAR operation interfaces (OPI).

### 2.2. Improvement on magnetic controls

The full adaptation of isoflux/real-time EFIT algorithms [11,12] is done in 2011, and the isoflux algorithm has been utilized for the most of the pulses since 2012. The only limitation for running isoflux is the time for the first available slice of real-time EFIT slow loop, mainly due to (1) slower $I_p$ ramp rate (around 0.25–0.3 MA s) by highly inductive central solenoid coils and (2) uncertainties on the magnetic diagnostics when the plasma current is very low ($I_p < 0.25$ MA).

As described in the last section, the KSTAR PCS is able to achieve ~48 s of 0.5 MA plasma pulses with full real-time shaping controls/real-time boundary measurements by real-time EFIT. In this longest pulse, shot number #11660, a minimum set of control points were selected to minimize interactions with $I_p$ feedbacks in available SISO style shape feedback design. The corresponding control point set consists of 9 feedback targets, i.e. $I_p$, midplane inboard gap ($\theta = 180°$), 3 outboard points ($\theta = 0, \pm 45°$) and physical radial/vertical positions of upper/lower X-point. This particular shot was terminated not by the control system fail, but by the saturation of PF coil currents and available electricity.

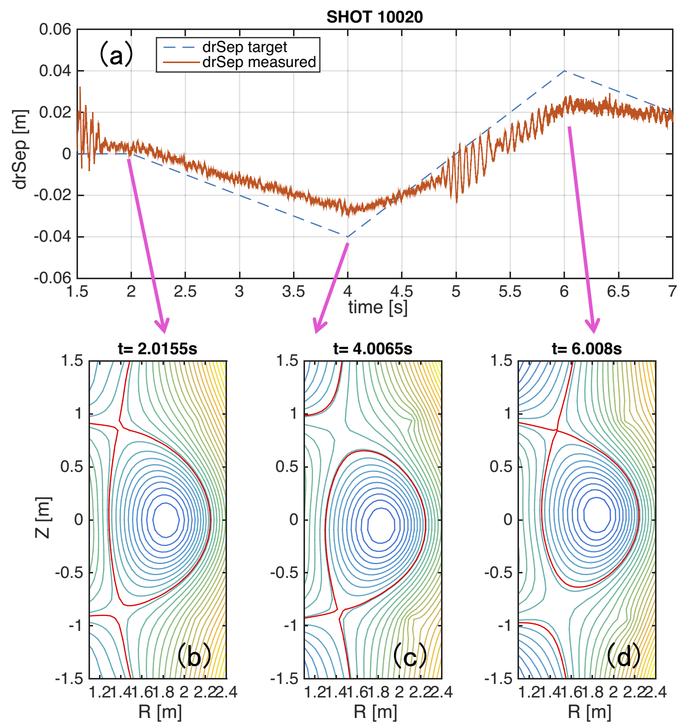


**Fig. 1.** Result of testing a multi-point isoflux drSep controller in shot 10,020. (a) Target drSep (dash blue) and measurement (solid red). (b) Shape at $t = 2.0155$ s, close to balanced DND. (c) Shape at $t = 4.0065$ s, showing lower-biased. (d) Shape at $t = 6.008$ s, showing lower-biased. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 1 shows one of particular shape control designs that enabled the up/down symmetry shape feedbacks, as known as drSep control. The drSep control aims to by maintaining the difference between the reference flux values measured at upper / lower X-point. A set of relevant High Field Side (HFS) control points was redesigned from 135/225° to 120/240°, in order to increase flux responses by the closest PF coils (PF3 and 4) and hence in order to affect significant control of the inner squareness which is essential for controlling drSep. As shown in Fig. 1(a), the measured drSep follows the target up to ±3 cm, providing balanced DND (Fig. 1(b)), lower biased (Fig. 1(c)), and upper biased plasmas (Fig. 1(d)). The plasma was terminated at $t = 7$ s due to VS control issues, which are the source of the large oscillations in dRsep at $t = 5$ s in Fig. 1(a).

The VS control is essential for elongated plasma sustainment ($\kappa > 1.1$). Since the superconducting PF coils in KSTAR have huge self-inductances and are slow in the frequency responses, the fast VS control highly relied on the dedicated anti-symmetric in-vessel vertical control coils [13]. The VS PID was independently done in the fastest loop (50 μs) in order to guarantee stabilizations for a typical KSTAR H-mode (open-loop growth rate: $\gamma_z = 60–110$ rad/s). The issue on the VS control shown at Fig. 2 is that the IVC current request is too sensitive to the noises of primary $Z_p$ estimator when its value is very close to zero. Instead of introducing more filters, we added an analog $dZ_p/dt$ measurement consisting of two up/ down symmetric loop voltage circuits that have larger signal amplitude hence the better signal-to-noise ratio. As shown in Fig. 2, the use of better SNR reduced the transient IVC current requests 5 times smaller, hence gave more margin to the controller [14].