Status and plan of KSTAR plasma control system for steady-state operations

Sang-hee Hahn
National Fusion Research Institute, Daejeon, Korea
Email: hahn76@nfri.re.kr

1. Introduction

Concept of steady-state tokamak discharge [1] has been introduced many years before: The steady-state discharge should have a pulse length that is long enough not only to satisfy demand of daily power productions, but also to sustain steady fusion performance which could reduce thermal/mechanical stress expected to the device. Even the concept was apparent, practical transition to a short pulse to a steady-state one was not achieved until a few tokamaks were equipped by full superconducting (SC) magnets, which led to great reduction of electric power requirement for the required toroidal field (TF) sustainment. In 2013 experiment, KSTAR successfully demonstrated an Ip=0.5 MA, H-mode plasma discharge over 20 seconds using SC magnet system and conventional magnetic controls existing at KSTAR. In order to sustain the plasma in better performance regime, however, 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 Te profile feedback and an integrated MHD controller using Electron Cyclotron Heating/Current Drive.

2. Status of long-pulse capable magnetic control system upgrade

In principle, Feedback control usually enables control unlimited in timescales: limitation of operating time for a feedback computer usually comes from limitation of memory, and data acquisition. For mid-size tokamaks, the required sampling on dealing with MHD-related events (VS, TM, Sawtooth, et cetera…) is more than 10 kHz, which is not a small amount of data, but downsampling is not a practical solution for post-experiment analysis for the feedback control. KSTAR plasma control system hardware uses a Linux kernel hack as the Operating system (OS) for synchronizing the system with the externally provided clock (1Mhz): the technique enabled an extendable cluster system capable of 50 kHz control cycle, but isolation from the data acquisition network during the shot inhibits extension of the maximum pulse length. Efforts of migrating the real-time OS into ITER-compatible standard

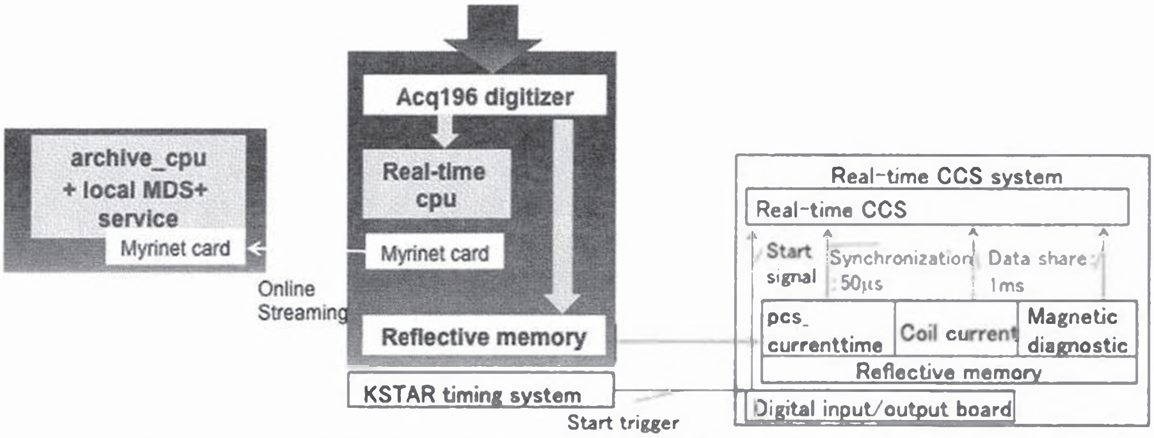

Figure 1. long-puse related system development: A dedicated MDS+ data stream archiving by Myrinet card network / an independent real-time magnetic reconstruction system using real-time data share by Reflective memory net.

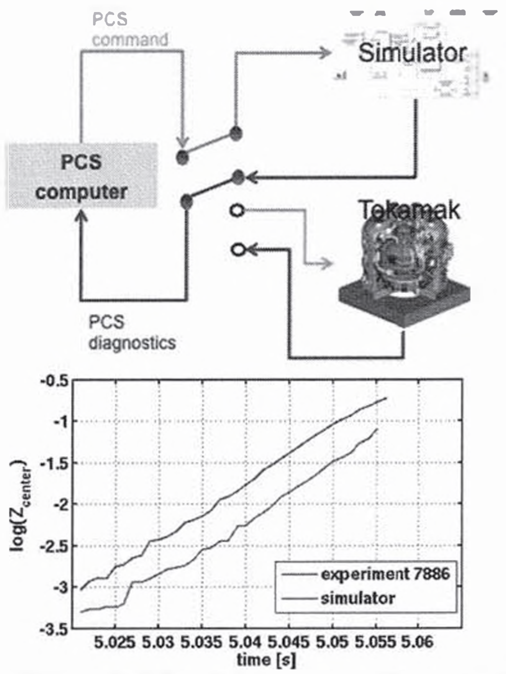

Figure 2. Closed-loop magnetic control simulator environment and its validations: KSTAR simulator provides the same virtual interface for control diagnostics as the real hardware provides (top). Comparison of open-loop vertical growth on experiment in 2012 and the simulator output (bottom).

operating system (MRG-realtime, developed by RedHat and the accelerator community) are ongoing project until 2015. Dedicated performance test showed that a real-time CPU can deal with up to 100 kHz cycle in Feb 2014 [2].

Enabling an online MDS+ data streaming via dedicated real-time network (Myrinet in Figure 1) is introduced also as an alternative way to archive data in unlimited pulse length. KSTAR hardware was confirmed to use 5 kHz to store up to +3000 MDS+ samples for ~80 seconds without missing a time stamp.

Real-time data sharing in KSTAR is achieved by customized Reflective memory (RFM) [3] network. The RFM provides a very fast, and deterministic data sharing up to 256 systems. For sharing magnetic diagnostics measurements for independent system, we implemented a direct PCI bus streaming from 2x96-channel acq196 [4] digitizers to an RFM card. The system provides 192 Channels x 4 kHz simultaneous streaming of raw digitized data to independent system hardware, and was used for implementing the real-time Cauchy Condition Surface (CCS) reconstruction system as collaboration topics with JT-60SA plasma control group [5].

Based on the analysis done in 2012, the effective plasma resistance (Rp) eventually increases as the shot extends. The Rp increase would require more loop voltage, The preprogrammed coil trajectory usually assumes constant Vloop, hence the designed gain set on Ip & shape in the earlier part of discharge may not be suitable if the deviation becomes too big.

In order to incorporate with time-varying plasma resistances for longer pulses, a PCS algorithm has been implemented in order to identify best PF currents for the Rp and the desired shape [6]. The algorithm decomposes the PF current into ohmic and shape vectors. Based on automatically calculated plasma resistance, the PCS computes best FF current values per each coil every 100 milliseconds. The logic has been confirmed by the existing magnetic control simulator, and hardware simulation tests were done under KSTAR hardware during the visit of related GA scientists. The experimental application will commence in the 2014 campaign.

Development of simulation technique and environment is especially necessary, because the tokamaks with superconducting magnets have longer preparation time, mainly due to magnet cool-down conditioning [7], and the between-shot interval cost for longer pulses that are generated by accumulation of the superconducting coil AC losses. In order to design better pulse design, a closed-loop magnetic control simulator [8] has been implemented in 2012 that can simulate virtual interface for magnetic control diagnostics. A measurement on open-loop vertical growth rate provides minimum validation on the conductor model in the simulator. As shown in Figure 2, 2012 experiment showed a very good match with the simulation result for vertical position growth rate (slope of the curve). The closed-loop PCS magnetic control simulator was updated to reflect this open-loop vertical growth rate obtained by dedicated experiments.

3. Status and plan on kinetic/profile controls

Kinetic performance can be mainly controlled by plasma heating. Until 2013, PCS did not have any control to any heating devices available at KSTAR. With dedicated organization for PCS, integration of heating power control has been initiated with the NBI and ECH for multiple purposes: the beta feedback control has been addressed as the main purpose of NBI integration into PCS in order to maintain plasma energy and to achieve reactor-relevant higher performances easier. The algorithm is a simple PID using an online plasma β_P estimator using dedicated magnetic diagnostics: The PID output gives total power required to NBI, and is divided to the individual ion source as a form of pulse width modulation (PWM) target. The first commissioning of each NB power control algorithm was done in June 2014, and the use of β_P feedback is planned in the same year.

A first attempt of radial Te profile control is done in 2013 by collaboration with Seoul National University (SNU). Based on a simplified transport model in [4], a feedback system using real-time ECE data streaming and 110GHz ECH was constructed. Since KSTAR does not have any q-profile diagnostics, the feedback target was set to only ECE Te profiles at rho_pol = 0.1, 0.2, 0.3, 0.4 and 0.5. Schematic for the real-time system is shown in Figure 3, using EPICS CA for ECE streaming and real-time EFIT flux labels at midplane through the KSTAR RFM network. The control cycle was set to 0.5 seconds, and sent the EC power demand to ECH every cycle. The controller has been commissioned successfully in 2013. Result of this feedback control is shown in Figure 3 for an L-mode plasma #9386, at Ip = 0.6 MA, BT = 2.0 Tesla, PNB = 1.0 MW, Te baseline ~ 1.9 keV. In L-mode discharge, it has been verified that the controller does not have hardware problems and the Te profile seems to slowly approach to its desired target, but the available power of the actuator (EC 110 GHz) is rather limited (<150 kW) to see faster responses.

There is an ongoing activity for implementing integrated controller of MHD using ECH/CD as main actuators. Since the tearing modes (TM) and neoclassical tearing (NTM) will become a candidate of obstacles for both the high performances and the long pulses, a large plan for making active suppressions to this specific exception is ongoing at KSTAR aiming at 2015-16, as shown in Figure 4, which targets suppression of the NTM and sawtooth period controls.

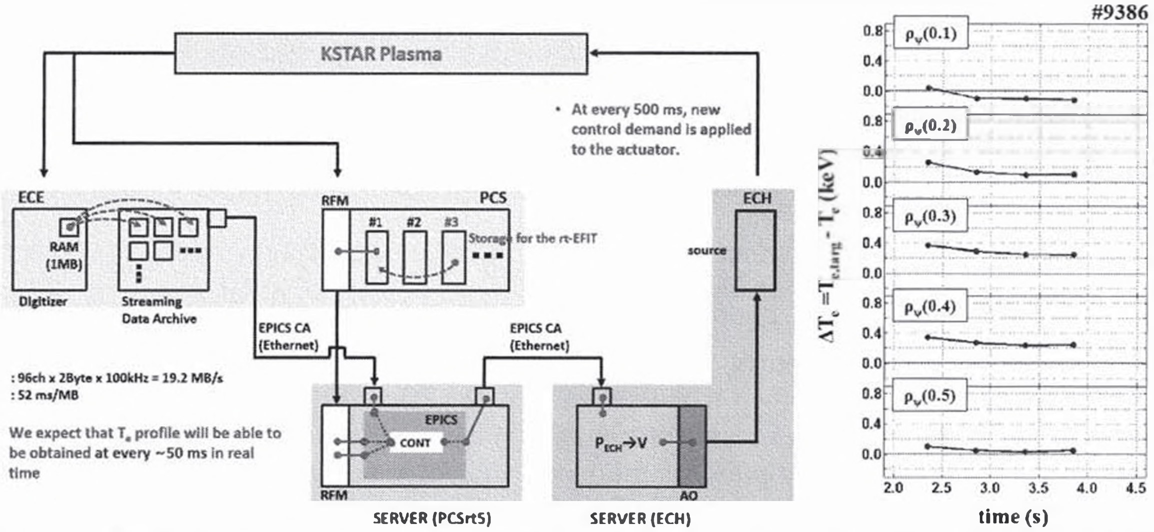

Figure 3. (left) Schematic diagram for SNU-implementation of real-time Te profile control + EC 110 GHz in 2013. (right) Time evolution of Te errors by ~100 kW EC110 at t=3.0s.

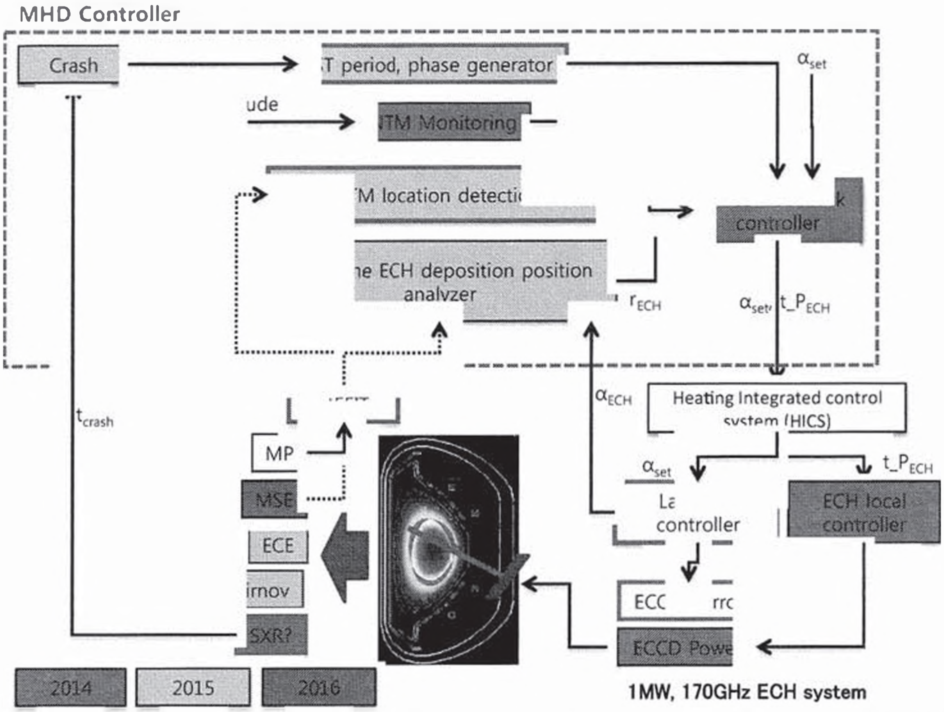

Figure 4. A 3-year plan for the real-time MHD controller featuring TM/NTM suppressions and sawtooth period-locking.

Without any real-time detection of the mode location, the first experiment was executed by a preprogrammed angle scan in 2013. Although the old PLC-based control system had big time delays (~100 ms), a partial suppression of the MHD mode is found using 0.8 MW of EC 170 GHz power at #9133 [10]. The experiment indicates that the Mirnov coil mode amplitude (dB/dt divided by frequency spectrum maxima) can be used as a primary MHD mode detection method. The speed upgrade of the motor controller system into FPGA-based one is done with the time delay ~20 ms.

In September 2014, power on/off control to the gyrotron and real-time feedback on poloidal mirror angle of EC170 GHz has been verified during the plasma commissioning. Before the package is fully implemented, a preliminary feedback system using only a single channel of the Mirnov coil is planned in 2014: The Mirnov and its mode amplitude gives a criterion of starting the suppression logic by turning on the EC power. Since we do not know the exact location, the PCS will move the mirror back and forth around a predetermined position (Z0) to search the best position where the mode amplitude starts decreasing.

A dedicated SW development contract with General Atomics is made in order to add Neoclassical Tearing Mode (NTM) control algorithm until mid 2015. The package will include a feedback algorithm that operates on mode amplitude and plasma density signals to produce on/off commands to gyrotrons and commands to mirrors that define mirror angles, active tracking logic using feedback regulation to maintain a specified alignment based on real-time (RT) q-profile estimates generated by RT EFIT, and a search-based alignment algorithm enabling automatic identification of adequate alignment in absence of direct measurement of island or q- profile.

Acknowledgement

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References

[1] Lister, J.B. et al., Nucl. Fusion, 40(6), pp.1167–1181 (2000).

[2] Y.J. Kim et al., "*Performance test of new real time plasma control system (PCS) server environment based on MRG-R*", poster presentation in 2014 KSTAR conference (2014).

[3] A product of GE Fanuc.com. For performance details, see table 2 at S. Hahn et al., Fus. Eng. Des., 84, 867-874 (2009).

[4] A product of D-TACQ co. Ltd, http://d-tacq.com

[5] Miyata, Y. et al., Physics of Plasmas, 21(3), p.032502 (2014).

[6] Walker, M.L. et al., "*On-line calculation of feedforward trajectories for tokamak plasma shape control*", In 44th IEEE Conference on Decision and Control, pp. 8233–8239 (2005).

[7] Y.-K. Oh et al., Fusion Engineering and Design, 84(2-6), pp.344–350 (2009).

[8] Sang-hee Hahn et al., Fusion Engineering and Design, 89, 542-547 (2014).

[9] S.H. Kim et al., Nucl. Fusion 52 074002 (2012).

[10] M. Jeong et al., "*Research Activity on Real-Time NTM Control in KSTAR*", presentation of the 4th A3 foresight program workshop, Nov 2013.