Advances and Challenges in KSTAR plasma control toward long-pulse, high-performance experiments

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Plasma control system (PCS) in KSTAR

- An integrated set of controllers to create, control and shut down the plasma
  - Crucial to KSTAR operations / Main control tool for experiments
  - Another successful adaptation of DIII-D PCS software (2005-present)
  - First operations at 2007-2008 [1], upgrade to 64-bit systems in 2016 [2,3]
  - Development done thru US-KSTAR collaborations & domestic researchers

KSTAR PCS

- Infrastructure
- Common functions

SW management: GitLab / ssh-git

Dedicated DAQ, drivers, Network, EPICS IOC

“Installation-specific” for KSTAR:
PCS/KSTAR, emc/KSTAR, Toksys/KSTAR

Ownership to KSTAR
Codes & algorithm only applied to KSTAR
Access granted to KSTAR domestic / allowed collaborators

Enhancement of computing capability by migrating to 64bit + MRG-realtime

- **New Intel 64bit RT system** [3]
  - Modern Intel Xeon architecture + CERN MRG realtime
  - Reinforce feature of automated RT code generation (real-time Feedforward [4], ONFR [5])
    - similar to planned ITER control implementations

- **Catch up with the extending requirements by the physics experiments proposed to KSTAR**
  - Covering up to 20 kHz cycle
  - Single box + Up to 9 real time processes
  - 36 different actuators (gas, heating, coils)
  - +200 analog inputs (AI)
  - +600 digital I/O through Reflective Memory / DO modules
  - New interface for fast interlock

- The rtEFIT boundary accuracy & speed enhanced by new system
  - within ~1 cm errors + more iterations allowed

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Dedicated RT multichannel diagnostics operating for PCS

<table>
<thead>
<tr>
<th>category</th>
<th>Status (2018)</th>
<th># of channels</th>
<th>Plan 2019-2020</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axisymmetric magnetic diag. (MD)</td>
<td>RC, VCM, FL, MP, DL, LV, IVC</td>
<td>166</td>
<td>No HW installation but continues enhancements for real-time EFIT</td>
</tr>
<tr>
<td>3D MD</td>
<td>MPZ at passive plates Mirnov with bandpass</td>
<td>24</td>
<td>+ Mirnov with higher sampling [up to 100 kHz]</td>
</tr>
<tr>
<td>Kinetic / optical</td>
<td>MMWI or TCI (selectable)</td>
<td>2</td>
<td>+ MSE for adding RT(MSE)EFIT [12x2 ch]</td>
</tr>
<tr>
<td>Coil control</td>
<td>TF, PF, IVCC</td>
<td>200 (RFM)</td>
<td>+ add dedicated coil DAQ for safety</td>
</tr>
<tr>
<td>Etc.</td>
<td>Fast interlock interfaces</td>
<td>6</td>
<td>+ additional disruption detection signals (TBD)</td>
</tr>
</tbody>
</table>
Integration of various real-time components for sophisticated plasma experiments

**Magnetic control**
- Plasma current ($I_p$)
- Plasma position
- Shape (isoflux)
- Vertical stabilization

**Plasma Control System (PCS)**
- Line density ($n_e$)
- Plasma beta
- MHD
- Profile control
- Non-axisymmetric

**Kinetic control**
- D2 fueling: G, J, O, D
- EC power & poloidal mirror angle (2)
- Diag. fueling (Ar)
- SMBI, MGI
- Impurity seeding (Ne, N2, Kr)
- IVC (1)
- IPS / RMP / IRC (10)

**Actuator Quality controlled by component-based commissioning procedure**
- PF (11)
- Magnets (22)
- Particles (10)
- Heating (8)
- NB power modulation (6 ion sources)
Simulator environment for axisymmetric magnetic control enabled more cost-effective operations

- Based on nonrigid response model [6], reflecting shape deformation
  - Validated for the vacuum, PF actuators and shape controls [7]
- Development by MATLAB/Simulink + Automatic code generation by Simulink Coder
  - Can switch/verify directly from simulation to real experiment

Extension of operational space made by improved magnetic controls

Access to high-qmin & high-Ip regime utilizing early-diverted, low-li shots

Early-diverting strategy enables diverted shape at t~0.45s:
- reduction of li
- early beam injection
- optimal flux consumption (important for long pulse)

Challenge for SC tokamak
- slow PF coils, different freq responses
- need stronger VS
- accumulation of control errors to integral gains
- changes on magnetics quality

New pulse length record of ~90s by high-βp H-mode discharges (2018)

#15433 : typical H-mode
#20812 : new early diverted scenario
ITER shape access made easy by advanced magnetic control scheme: Improved VS + real-time Feedforward + MIMO Xpt controls

Improved vertical stabilizations (VS) enable $\kappa = 2.16$ [8,9]

Reproducible ITER shape access at $I_p = 850$ kA, $B_T = 1.8$T (2017-2018)

Kinetic controls evolving for density / heating / MHD

RT Poloidal beta control [10]

Density feedbacks [11,12] (feat. PZT/SMBI)

Versatile controls for 3D magnetic perturbation coils [13] (RMP-ELM, RWM, NRMP)


Kinetic controls evolving for density / heating / MHD

Search & suppress demonstration \(^{[14]}\) (2015) using \(n=1\) TM amplitude detector

RT EC mirror controls for TM suppression

S&S triggered here by \(n=1\) amplitude detector

q-surface tracking experimentally tested

Mirror position was tracking to \(q=2.5\) surface on \(R_{\text{res}} = 1.80\) m

Categorized fast interlock scheme by “severity” provides ways to plan complex sequential actions

Severity levels determined by **plasma current (Ip) controllability:**
- Ip survivable : low → continue discharge
- Ip controllable to rampdown : med → soft stop
- Ip uncontrollable : high → hard stop

Compatible with upcoming ONFR [5] design
Connected with the KSTAR Fast Interlock System (FIS)[15]

[15] Myungkyu Kim et al., this conference P/1-1
Categorized fast interlock scheme by “severity” provides ways to plan complex sequential actions.

**Example of sequential stop [16]**

- **NB3 armor fault** triggered the forced landing[*], \( \text{Ip rampdown starts (LV3}_2, \text{ Soft Stop) } \)

- **“Beam-off” action** was added for avoiding shine-through at \( \text{Ip} < 200 \text{ kA} \)

- **Loss of NB power** leads to “Ip min fault” (LV3_1, Hard Stop)

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The path to successful fusion belongs to control advances

- Extension to Mega-Amp access
- Long pulse with high performance
- Access to scaled ITER baseline
- New RT functions integration
The path to successful fusion belongs to control advances

- Improved Vertical stabilization
- MIMO shape control
- Realtime Feedforward
- Off-Normal Fault Response
- Automated Disruption avoidance
- Extension to Mega-Amp access
- Long pulse with high performance
- Access to scaled ITER baseline
- New RT functions integration
- Particle balance controls
- ELM crash controls
- beta control
- Profile controls
- MHD control
- Automation by Machine Learning

Startup improvement

Automated Disruption avoidance
New sophisticated ideas recently tested by standalone systems for future integrated control advances

Feasibility experiment for Te profile feedback using NB / ECH [17]

Automation of real-time detection for L→H [18,19] thru Machine Learning:
: offline test accuracy above 90%


[19] G.W. Shin, this conference (P/1-4)
Developments ongoing toward more sophisticated controls for achieving advanced operational regime

- **New real-time functions planned**
  - Integrate RT controls for 6 NB sources / 6 gyrotrons / Helicon
  - Fast interlock / ONFR improvements for disruption-free operations
  - Enable multibox extension for high-freq diagnostics
  - Improve adaptive shape control for easier access of ISS/IBS
  - Control simulator (simserver) improvement with NB / VDE responses

- **New real-time diagnostics technology investigation ongoing**
  - Technology dev for real-time Profile diagnostics (ECE / TS \(^{[20]}\) / MSE \(^{[21]}\))
  - Collaboration efforts on high-freq computer system for real-time MHD analysis \(^{[22]}\)

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\(^{[20]}\) Seung-Ju Lee et al., this conference, O/8-2
\(^{[21]}\) Hanmin Wi et al., this conference, P/4-2
\(^{[22]}\) Keith Erickson et al, this conference, O/4-3