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

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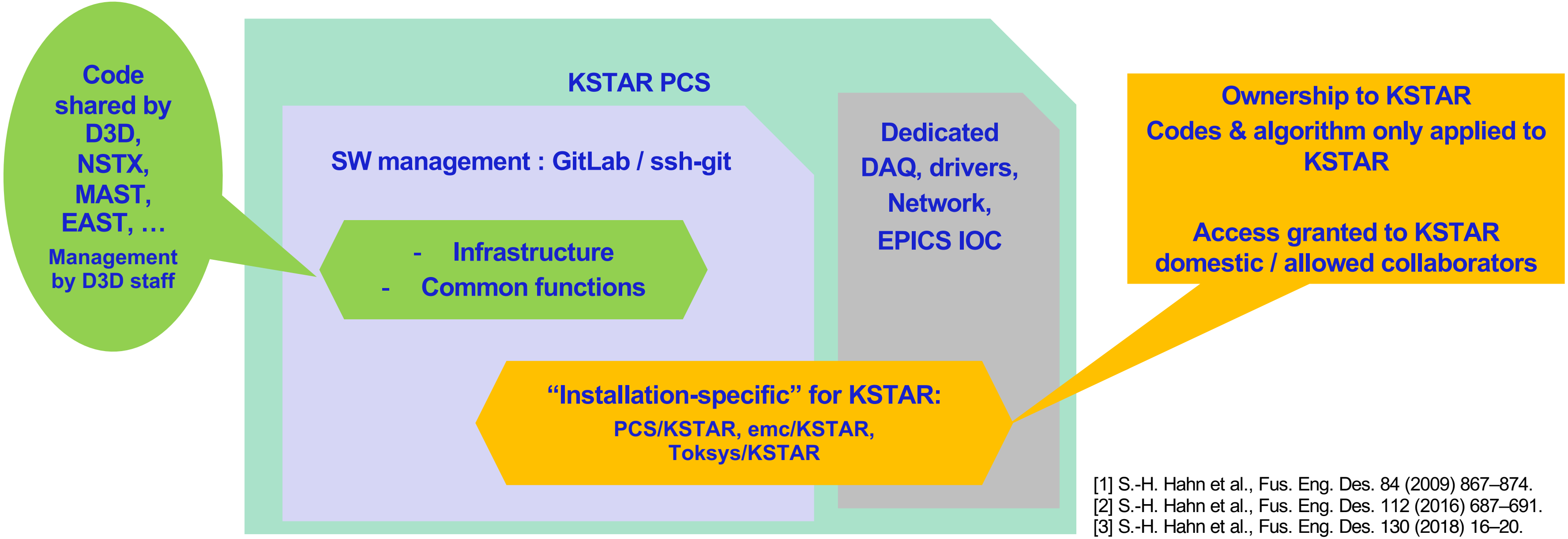
Plasma control system (PCS) in KSTAR

- 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

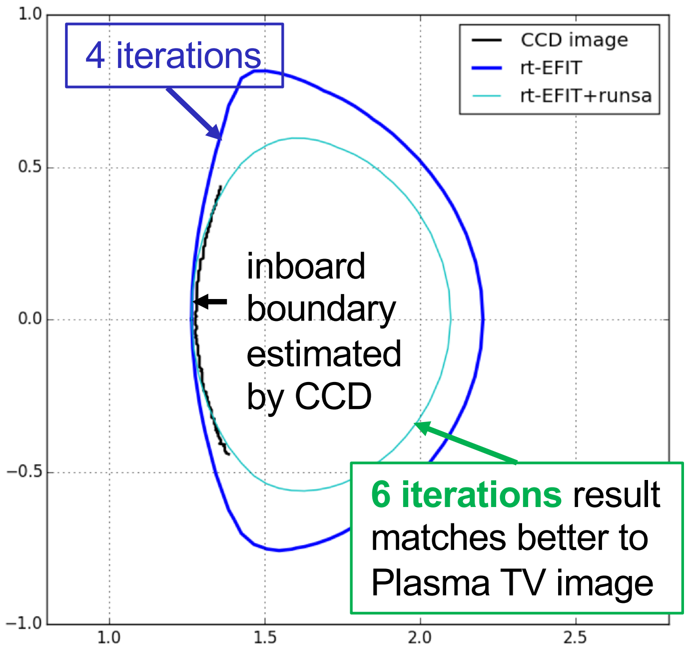


[1] S.-H. Hahn et al., Fus. Eng. Des. 84 (2009) 867–874.
[2] S.-H. Hahn et al., Fus. Eng. Des. 112 (2016) 687–691.
[3] S.-H. Hahn et al., Fus. Eng. Des. 130 (2018) 16–20.

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

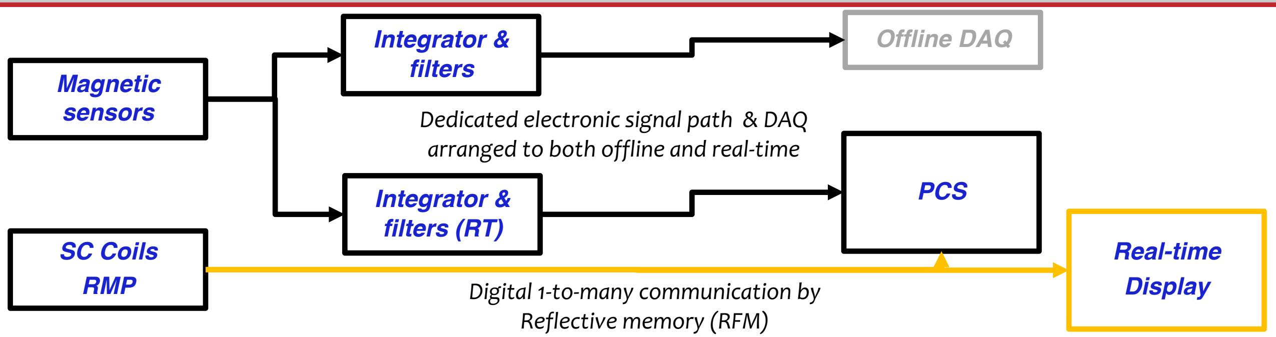
- **New Intel 64bit RT system [3]**
  - Modern Intel Xeon architecture + CERN MRG realtime
  - Reinforce feature of automated RT code generation (real-time Feedforward [4] , ONFR [5])
    - similar to planned ITER control implementations
- **Catch up with the extending requirements by the physics experiments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



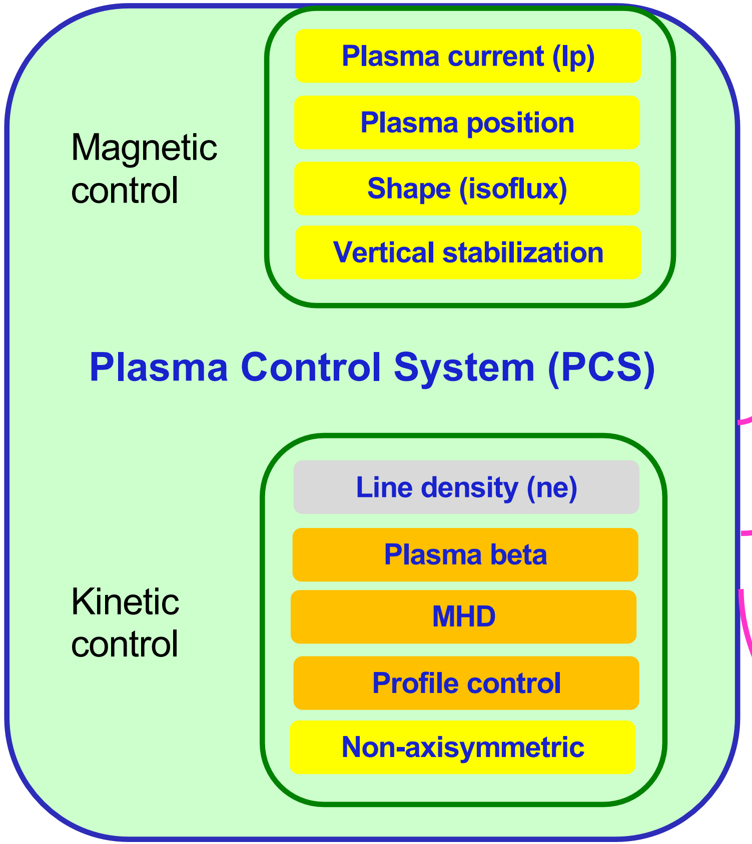
[4] M.L. Walker, M.J. Lanctot, S.-H. Hahn, 2016 IEEE Conference on Control Applications (CCA). (2016) 605–610.
[5] N.W. Eidietis et al., Nucl. Fusion. 58 (2018) 056023.

Dedicated RT multichannel diagnostics operating for PCS

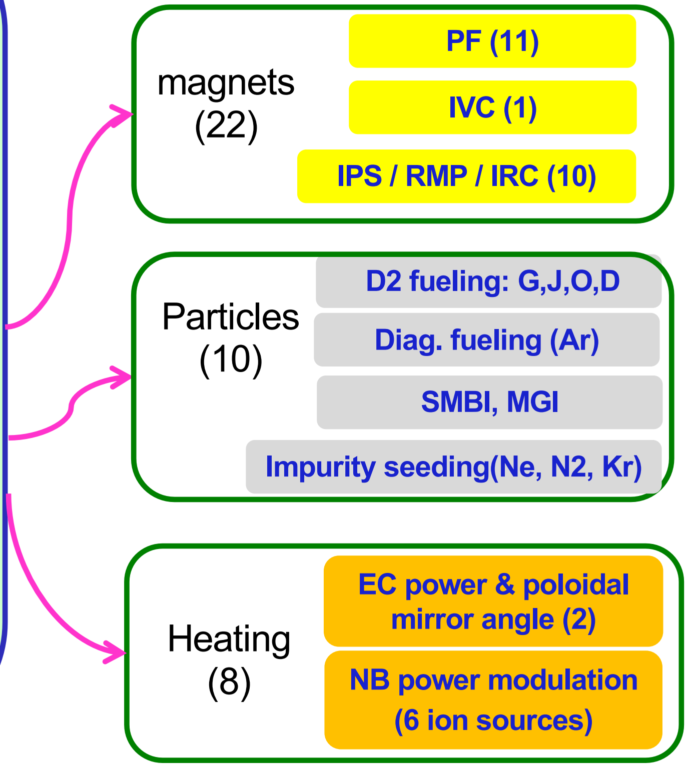


category	Status (2018)	# of channels	Plan 2019-2020
Axisymmetric magnetic diag. (MD)	RC, VCM, FL, MP, DL, LV, IVC	166	No HW installation but continues enhancements for **real-time EFIT**
3D MD	MPZ at passive plates Mirnov with bandpass	24	+ Mirnov with higher sampling [up to 100 kHz]
Kinetic / optical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

Integration of various real-time components for sophisticated plasma experiments

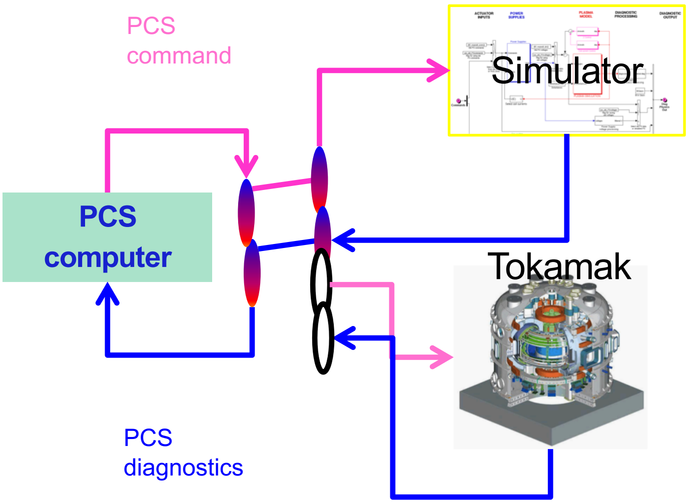


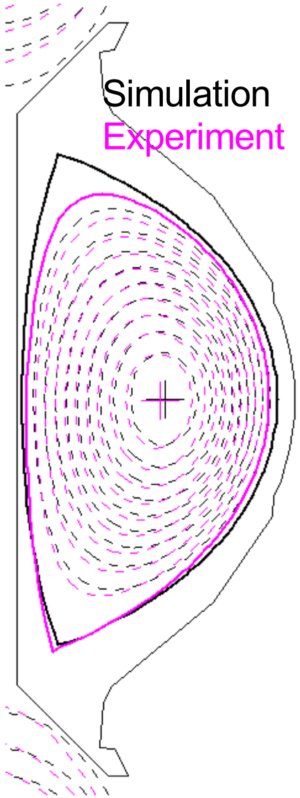
Actuator Quality controlled by component-based commissioning procedure



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



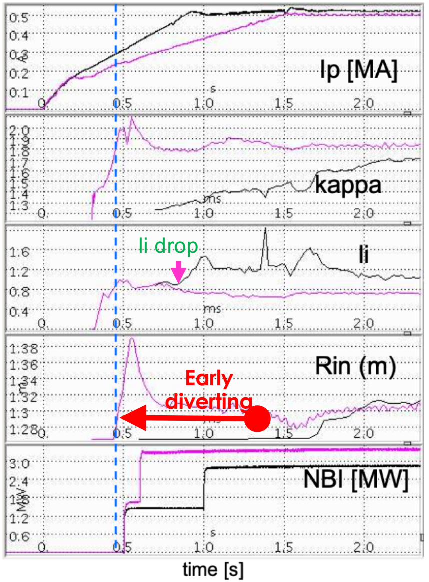


[6] A. Welander et al, Fus. Sci. Tech. 47 (2005) 763–767.

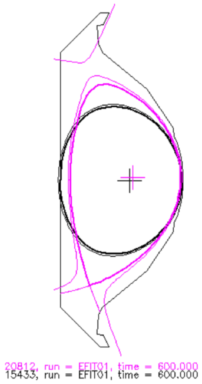
[7] S.-H. Hahn, et al., Fus. Eng. Des. 89 (2014) 542–547.

Extension of operational space made by improved magnetic controls

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



at t=0.6s



#15433 : typical H-mode

#20812 : new early diverted scenario

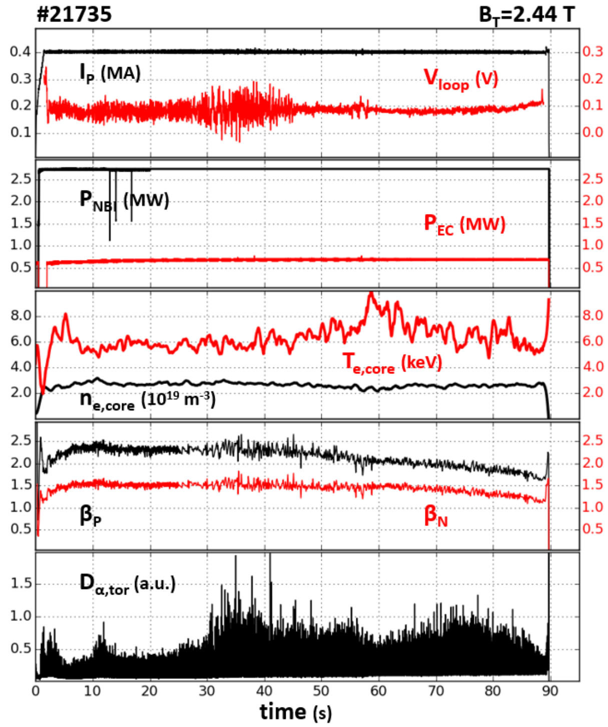
Early-diverting strategy enables diverted shape at t~0.45s:

- 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

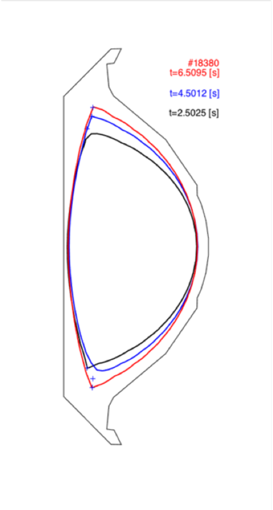
New pulse length record of ~90s by high-βp H-mode discharges (2018)



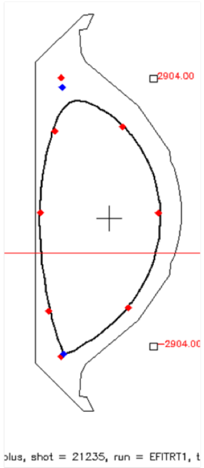
ITER shape access made easy by advanced magnetic control scheme: Improved VS + real-time Feedforward + MIMO Xpt controls

Improved vertical stabilizations (VS) enable κ =2.16 [8,9]

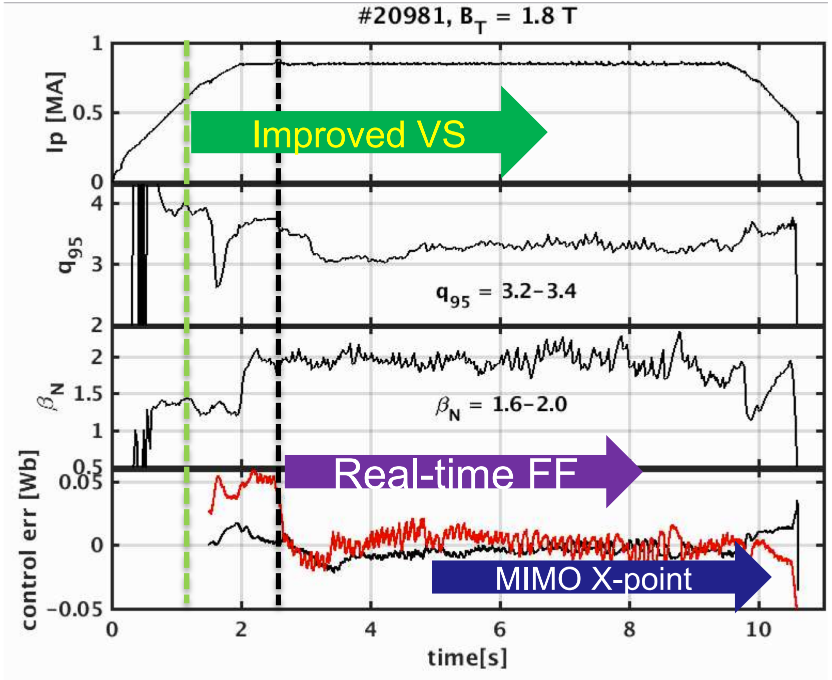
2017 shape\
#18380



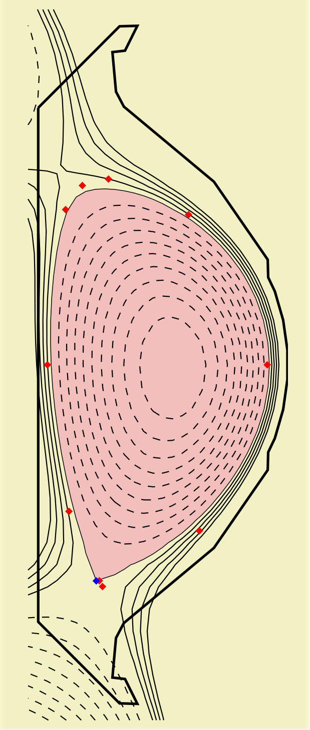
2018 shape
With 30% low βp
#21235



Reproducible ITER shape access
at Ip = 850 kA, BT=1.8T (2017-2018)



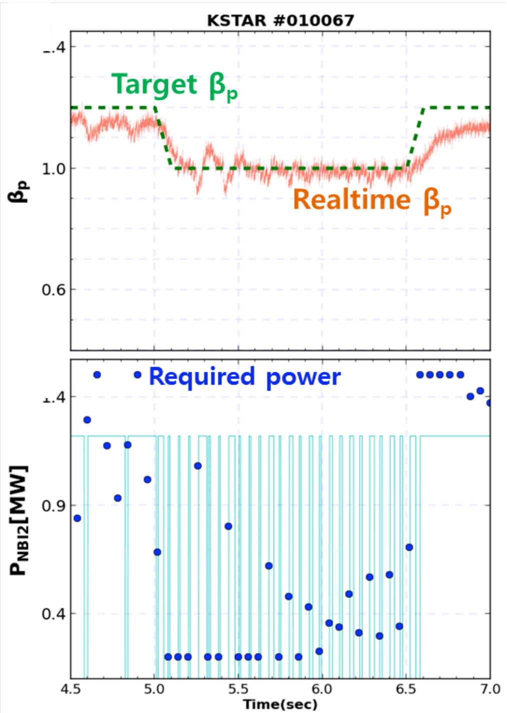
ITER Shape
at KSTAR



[8] S.Hahn et al., FEC 2016
[9] D. Mueller et al., Fus. Eng. Des. 2019

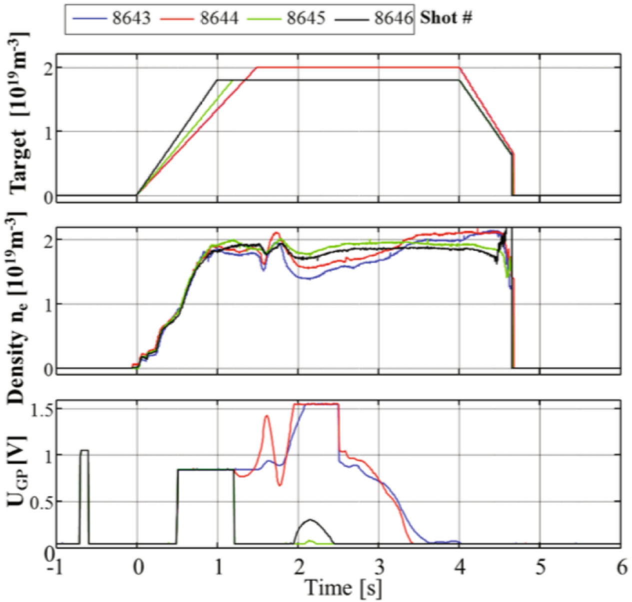
Kinetic controls evolving for density / heating / MHD

RT Poloidal beta control [10]



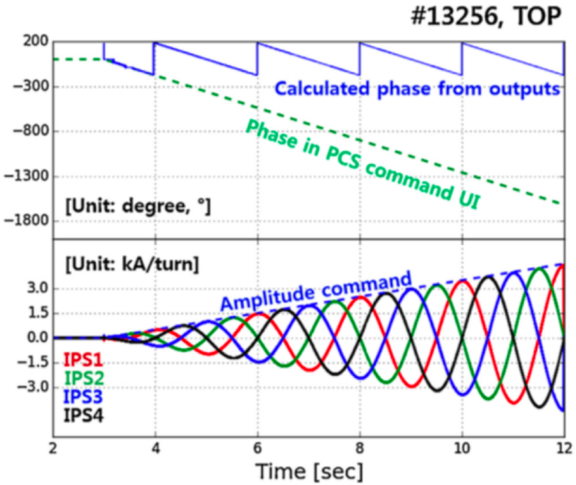
[10] H. Han et al., Fus. Eng. Des. 95 (2015) 44–49.

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



[11] J.W. Juhn et al., J. Korean Phys. Soc. 65 (2014) 1304–1311.
[12] J.W. Juhn, this conference (P/1-3)

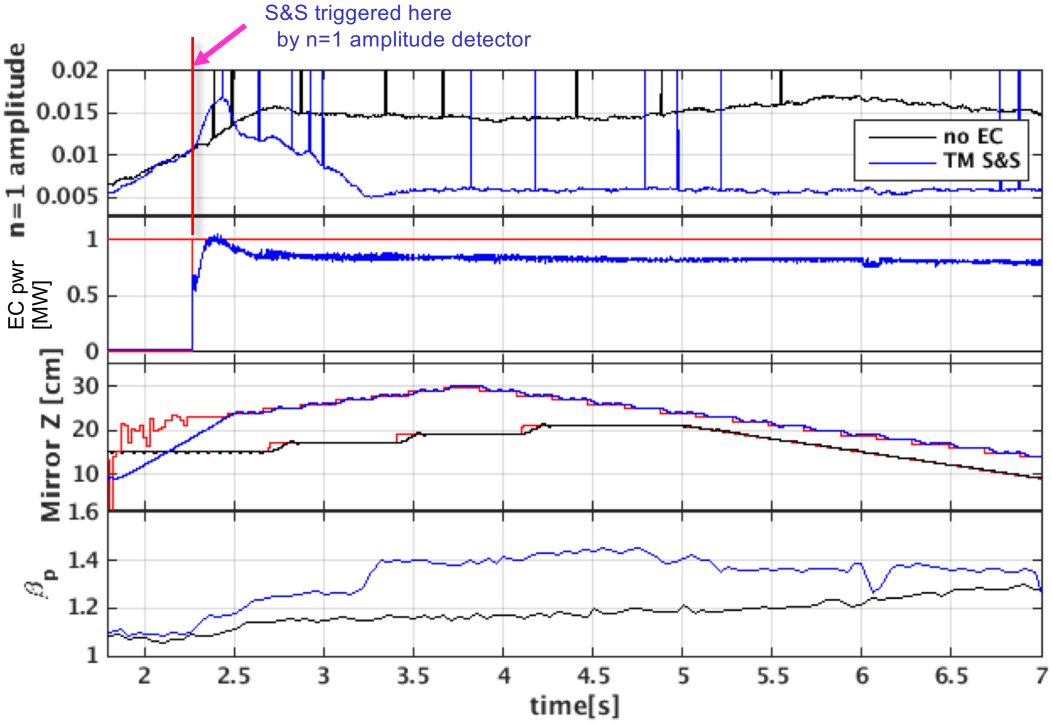
Versatile controls for 3D magnetic perturbation coils [13] (RMP-ELM, RWM, NRMP)



[13] H. Han et al., Fus. Eng. Des. 108 (2016) 60–66.

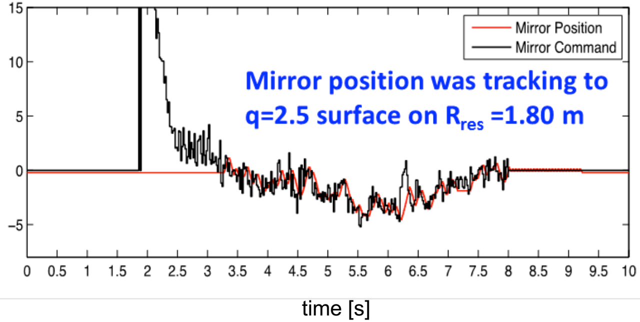
Kinetic controls evolving for density / heating / MHD

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



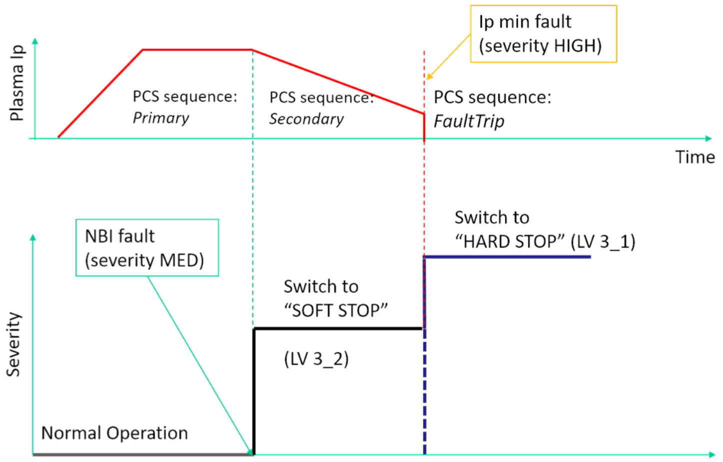
RT EC mirror controls for TM suppression

q-surface tracking experimentally tested



[14] S. Hahn et al., APS 2015

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



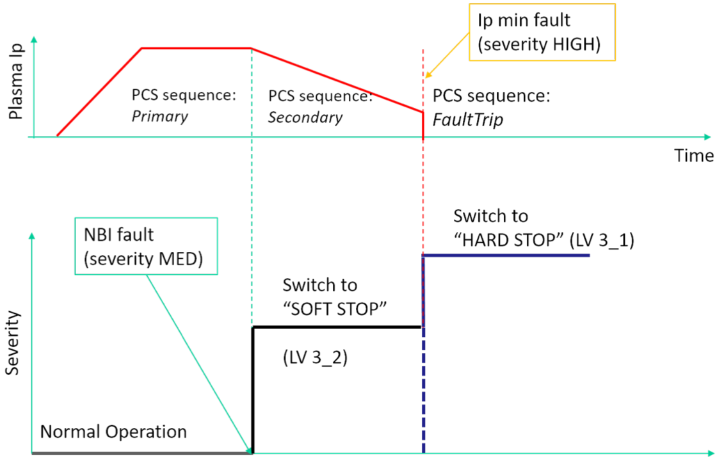
Severity levels determined by
plasma current (Ip) controllability:

- Ip survivable : low → continue discharge
- Ip controllable to rampdown : med → soft stop
- Ip uncontrollable : high → hard stop

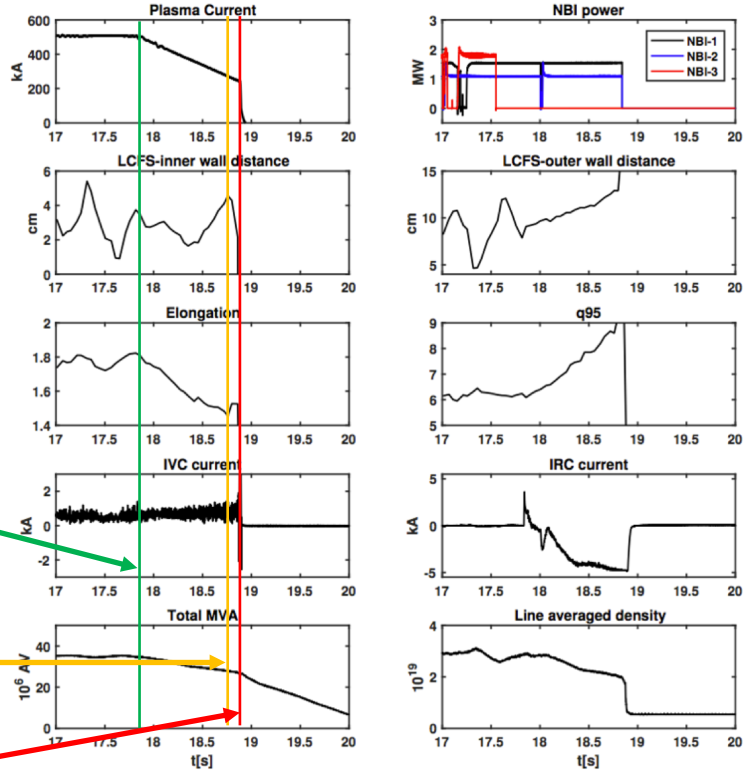
Compatible with upcoming ONFR [5] design
Connected with the KSTAR Fast Interlock System (FIS)[15]

[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[*], Ip rampdown starts (LV3_2, Soft Stop)

“Beam-off” action was added for avoiding shine-through at Ip < 200 kA

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

[16] M.H. Woo et al., Fus. Eng. Des. 128 (2018) 168–174.

The path to successful fusion belongs to control advances

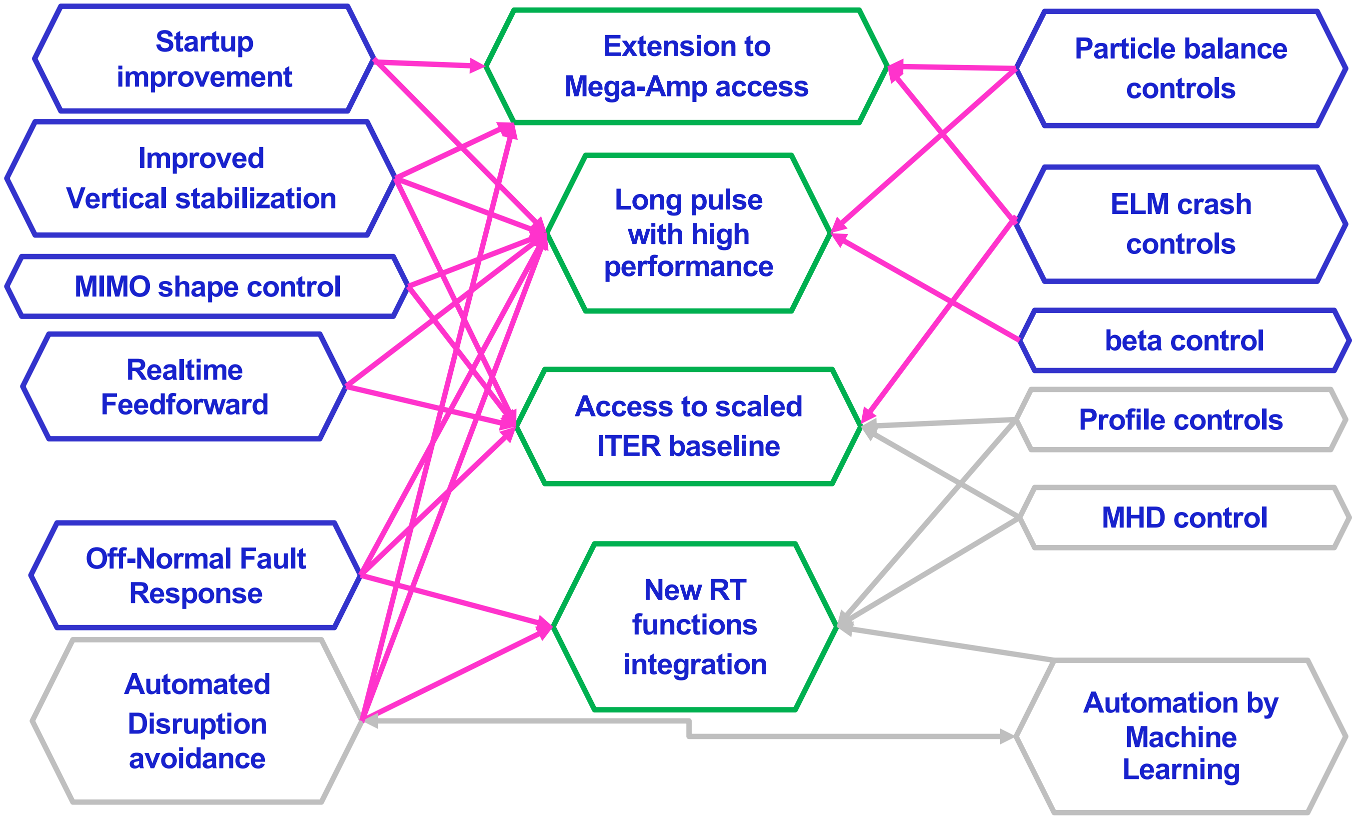
Extension to Mega-Amp access

Long pulse with high performance

Access to scaled ITER baseline

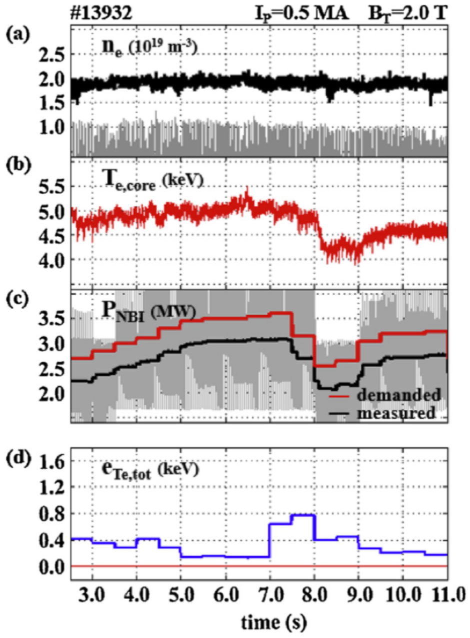
New RT functions integration

The path to successful fusion belongs to control advances



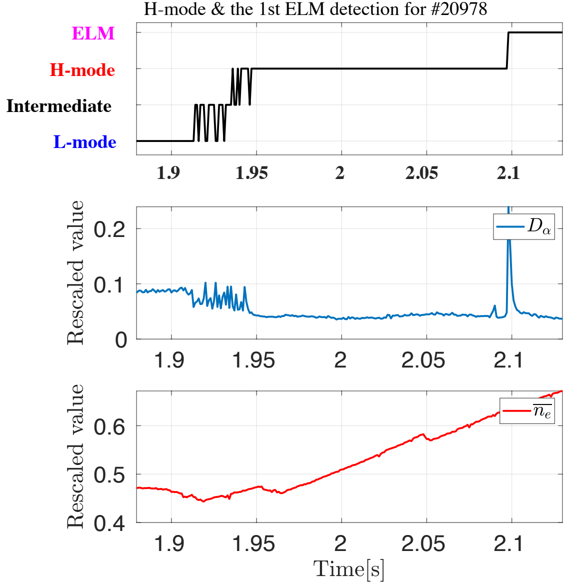
New sophisticated ideas recently tested by standalone systems for future integrated control advances

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



[17] H.S. Kim et al., Fus. Eng. Des. 2018

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



[18] G.W. Shin, Fus. Eng. Des. (2018)
[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]

[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