Real-time plasma control of fully non-inductive operation in EAST 1056s long pulse discharge

by

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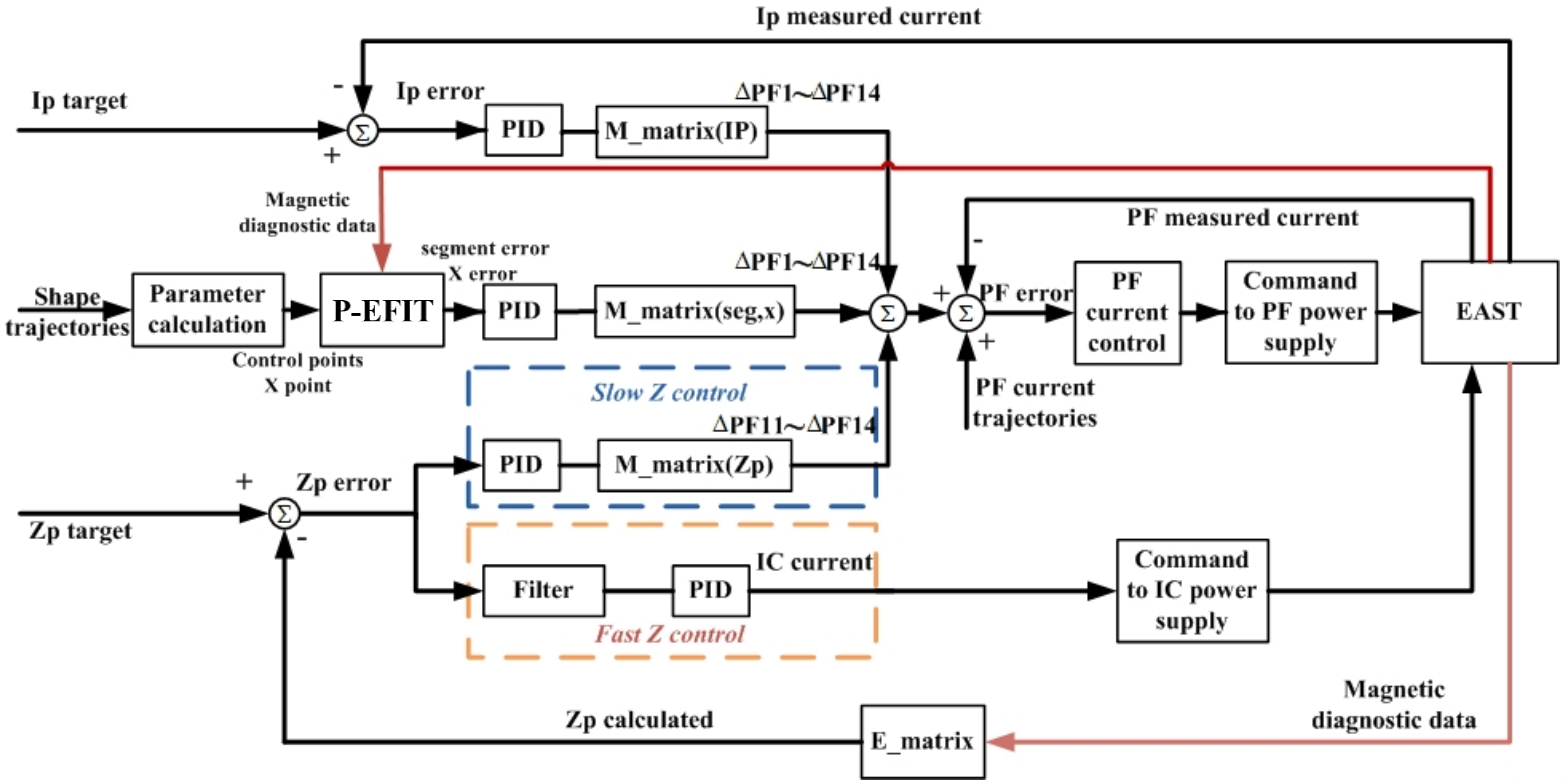
Background: Robust plasma control needed in 1000s time scale

The steady-state real-time plasma control requires integrated accurate control of plasma equilibrium, current and loop voltage in 1000s long pulse operation

Magnetic plasma control

- Plasma current
- Plasma shape (LCFS)
- Vertical instability
- Vloop



Key issues in plasma control for EAST 1000s long-pulse operation

Magnetic measurements

- Magnetic probes and flux loop calibration
- PF and plasma current measurement

Integrator

- Integrator with low zero drift
- Linear voltage offset drift correction

Shape parameter estimation

- Equilibrium reconstruction for plasma shape control
- Fast Z estimator for vertical instability control

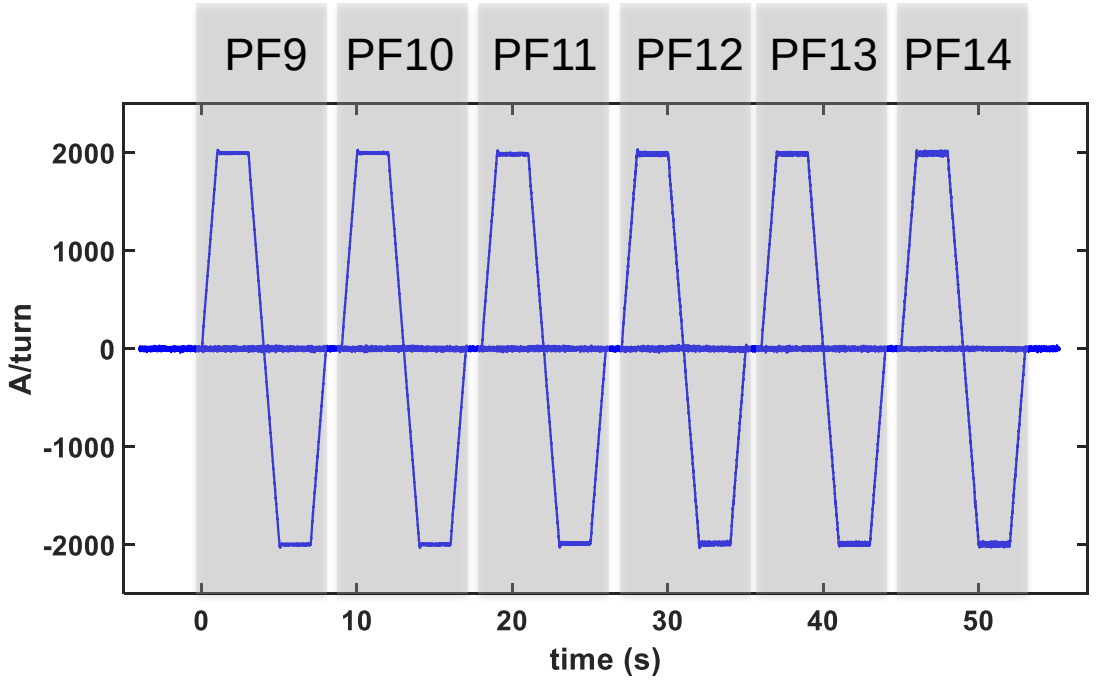
Plasma magnetic control

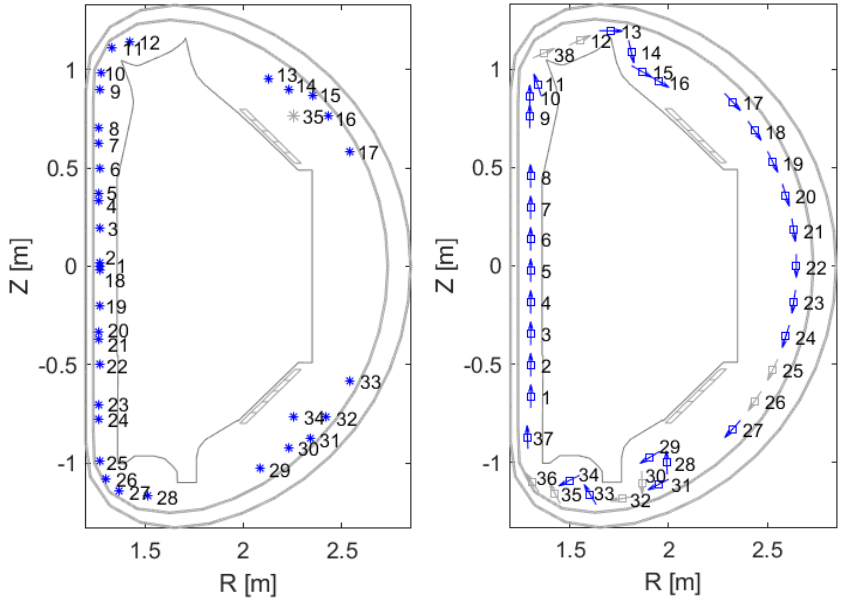
- Vloop control for fully non-inductive operation

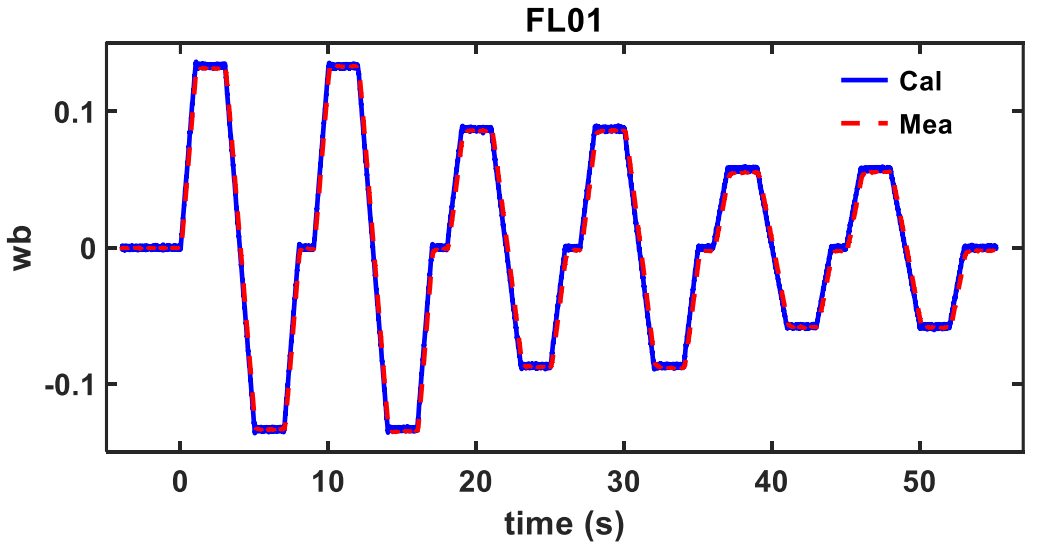
ASIPP

Electromagnetic measurement system provides precise signal input for plasma control

- EAST magnetic measurement system:
  - magnetic probe: (toroidal) 3 * (poloidal) 38
  - Flux loop: (poloidal) 35
- The maximum relatively error 1% in calibration (between calculation and measurement)







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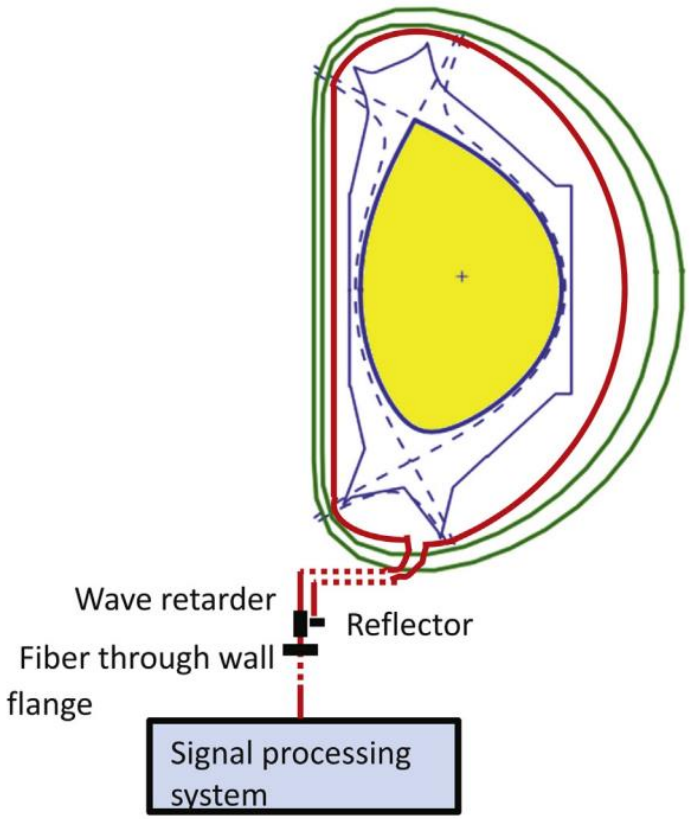
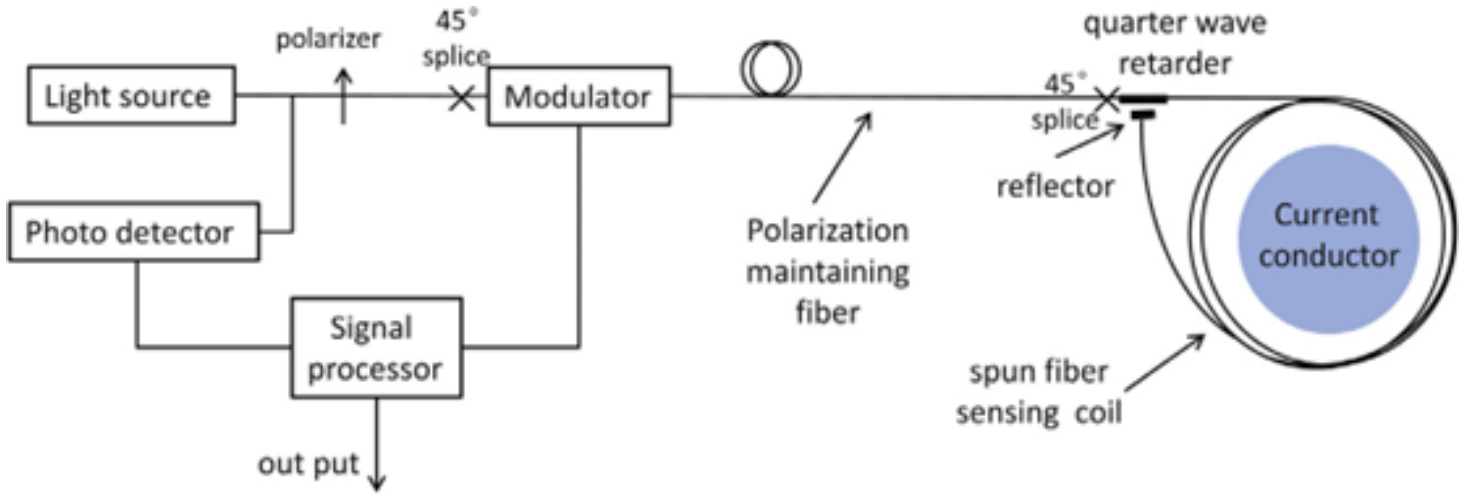
More accurate current measurement with Fiber Optic Current Sensor (FOCS) is used for feedback current control

- Multi reflective FOCS system were installed in EAST including PF and plasma current measurements.





- Fiber optic current sensors: faraday-effect with no signal drift
- PF busbars current measurement accuracy is decreased with 0.1% through reduce the magnetic field crosstalk.
- The uncertainty of current measurement is within 0.5%.

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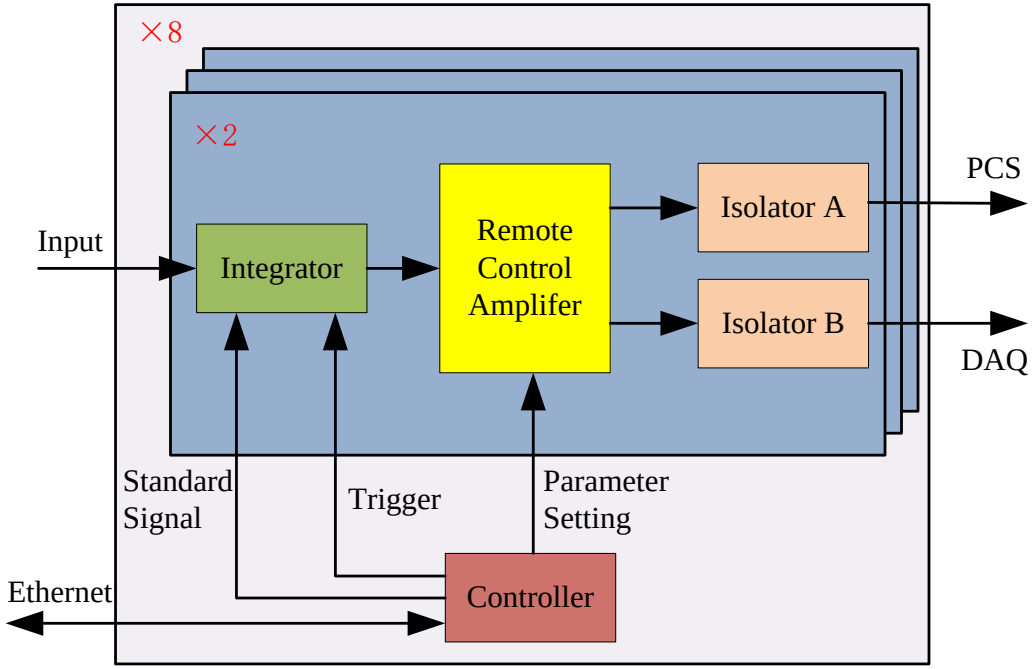
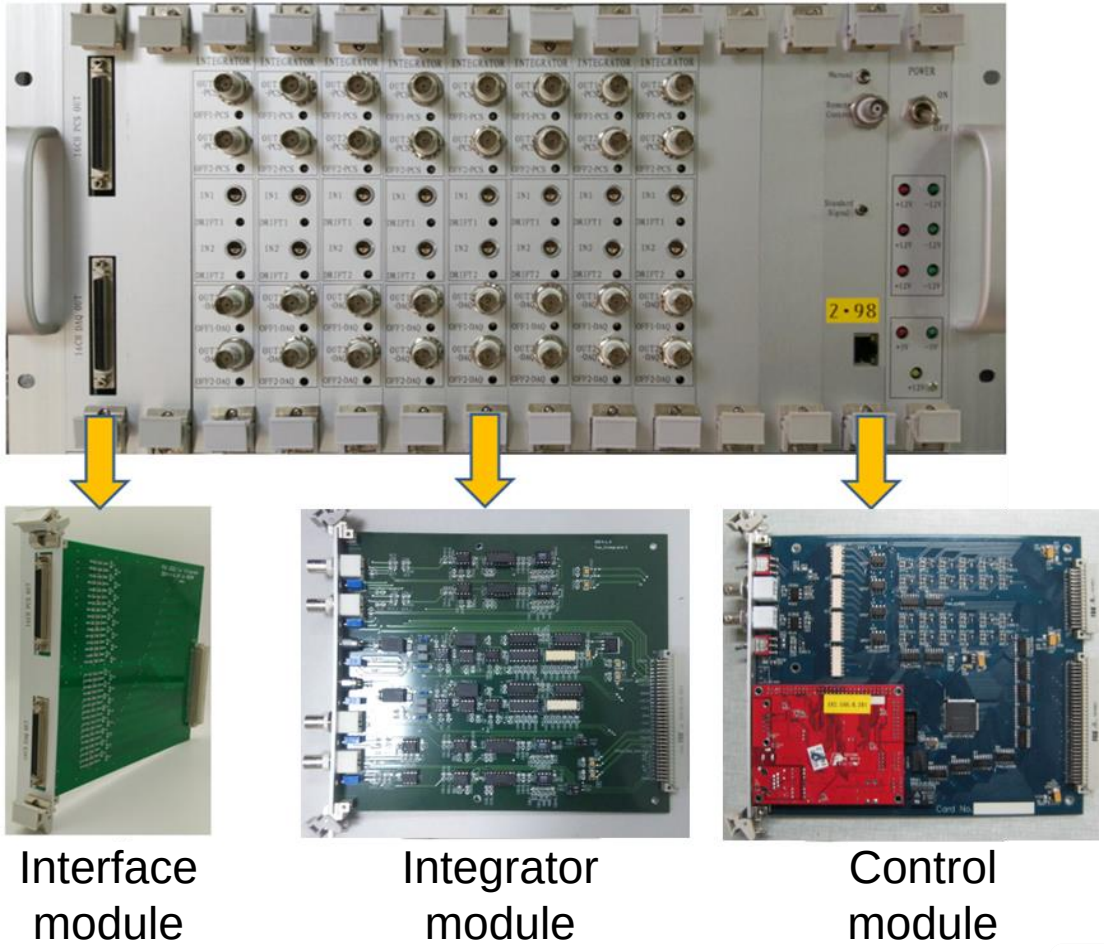
About 700 channel integrators have been used in EAST experiments





Interface module

Integrator module

Control module

- Chassis: 8 integrator and 1 control modules
- Integrator module: 2 integrator channels
- Integrator channel:1 integrator circuit, 1 amplifier and 2 isolator circuits

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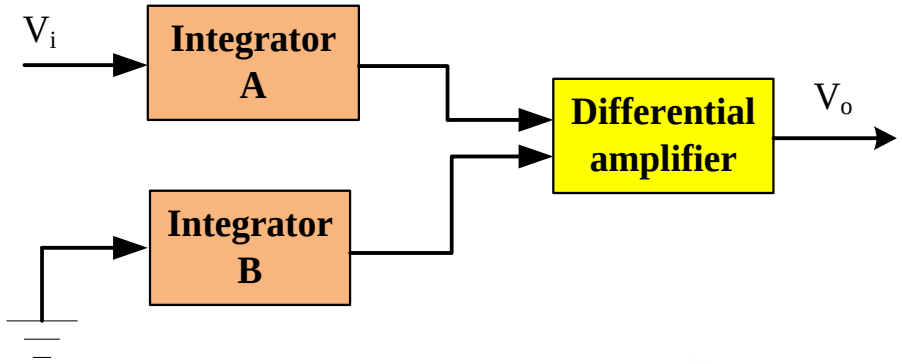
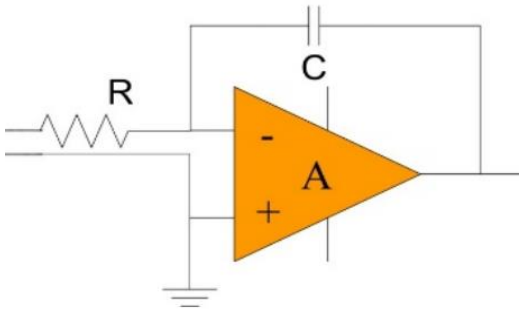
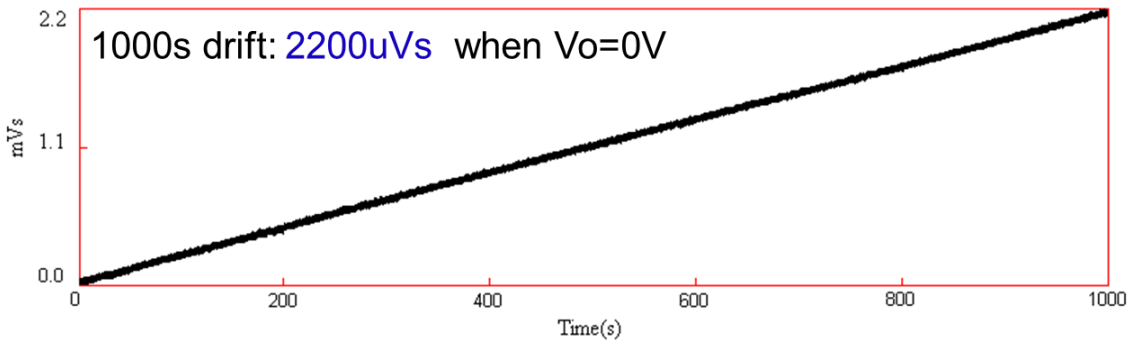
Low and stable zero drift integrator is achieved with two analog integrators and dual operational amplifier

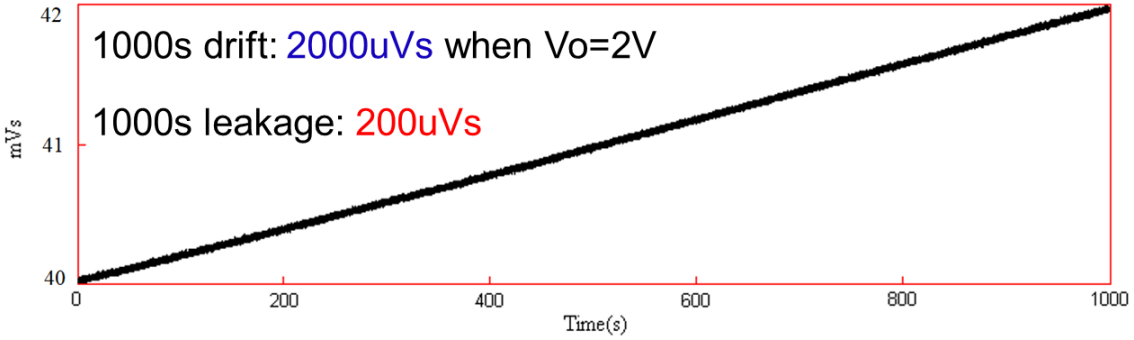




- Polystyrene capacitors
- High-precision resistors

- Input of integrator cell A: real signal
  Input of integrator cell B: shorted
- Outputs: dual integrator cell differential amplifier (integrator A subtracting B)





- Integrator zero drift**:** 2000uVs/1000s
- After linear zero drift compensation: **200uVs/1000s (10mV when RC=20ms)**

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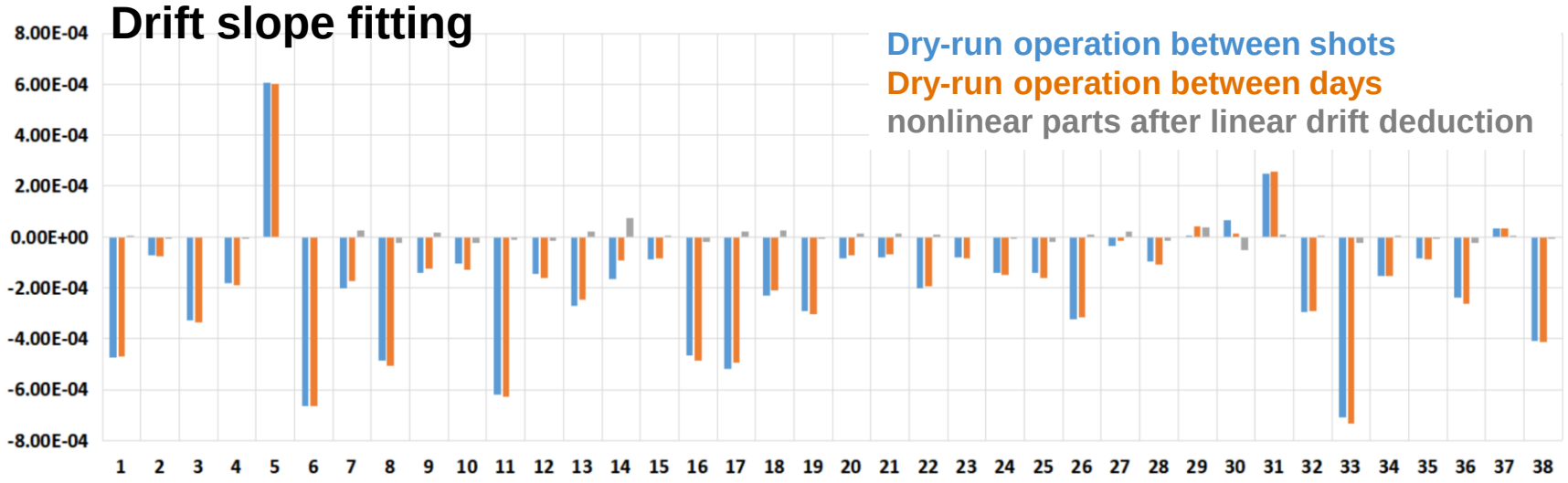
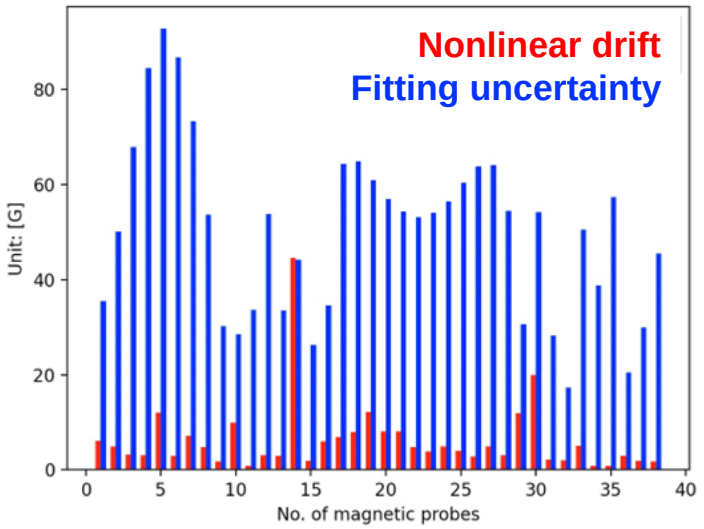
Linear deduction algorithm is used in PCS for integrated magnetic measurement signal drift

- Signal drift induced by the voltage offset caused by the thermal, radiation or other effects
- The linear drift slope is fitted with 500s long pulse dry-run operation between shots
- Several dry-run operations between days are performed to confirm drift slope consistency





- Magnetic measurement signals selection and uncertainty in equilibrium reconstruction are based on nonlinear parts after linear drift deduction

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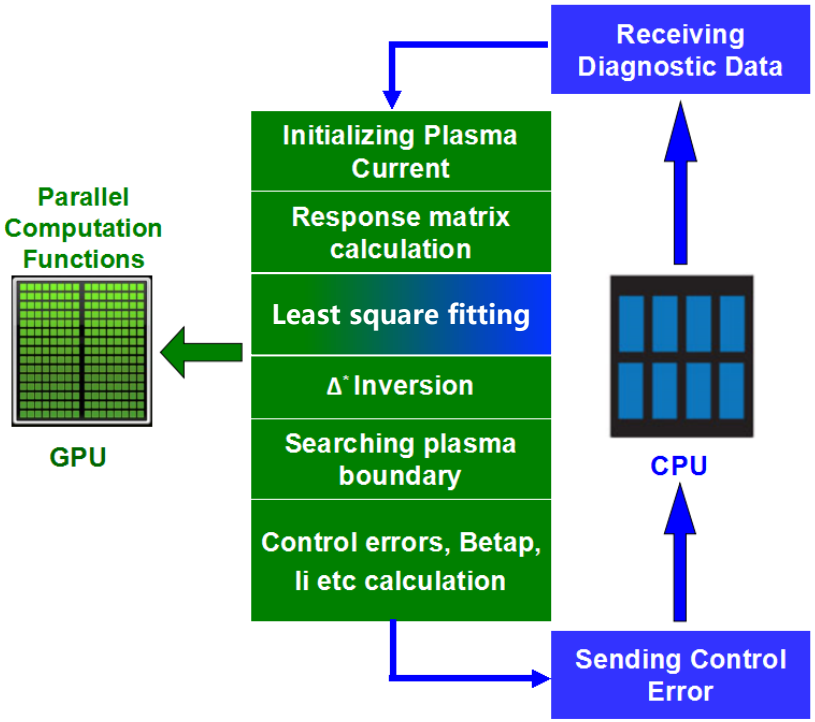
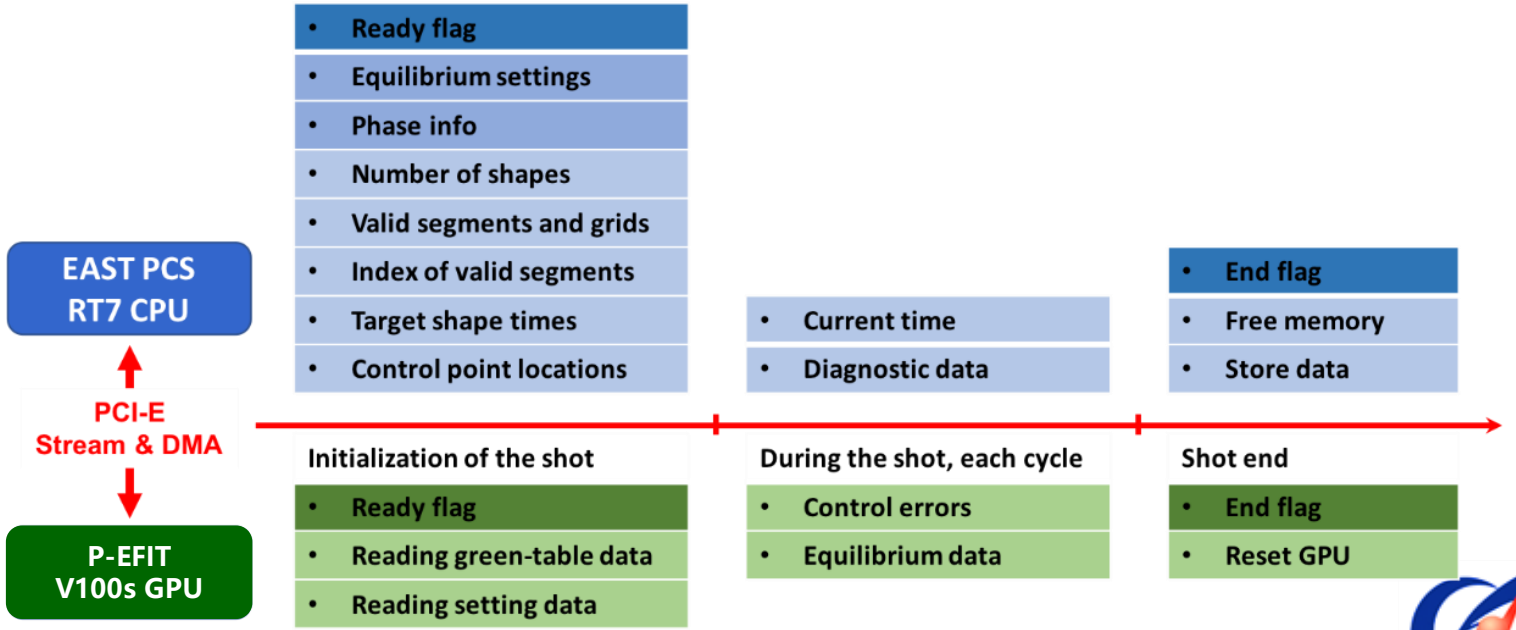
P-EFIT code routinely provides real-time equilibrium reconstruction and shape control signals in EAST plasma control system

P-EFIT code is based on the EFIT framework but using massively parallel GPU cores to significantly accelerate the computation with hundreds times.

- 300us per full equilibrium reconstruction iteration (129×129 spatial grids, Tesla V100s GPU)
- P-EFIT is integrated into PCS as a sub-algorithm and run with streaming mode in real-time.





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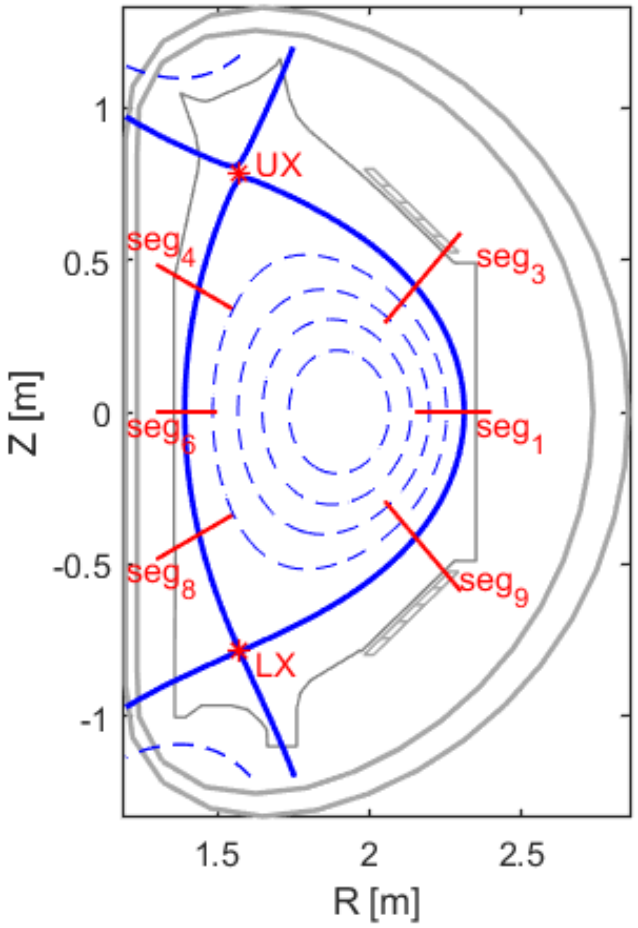
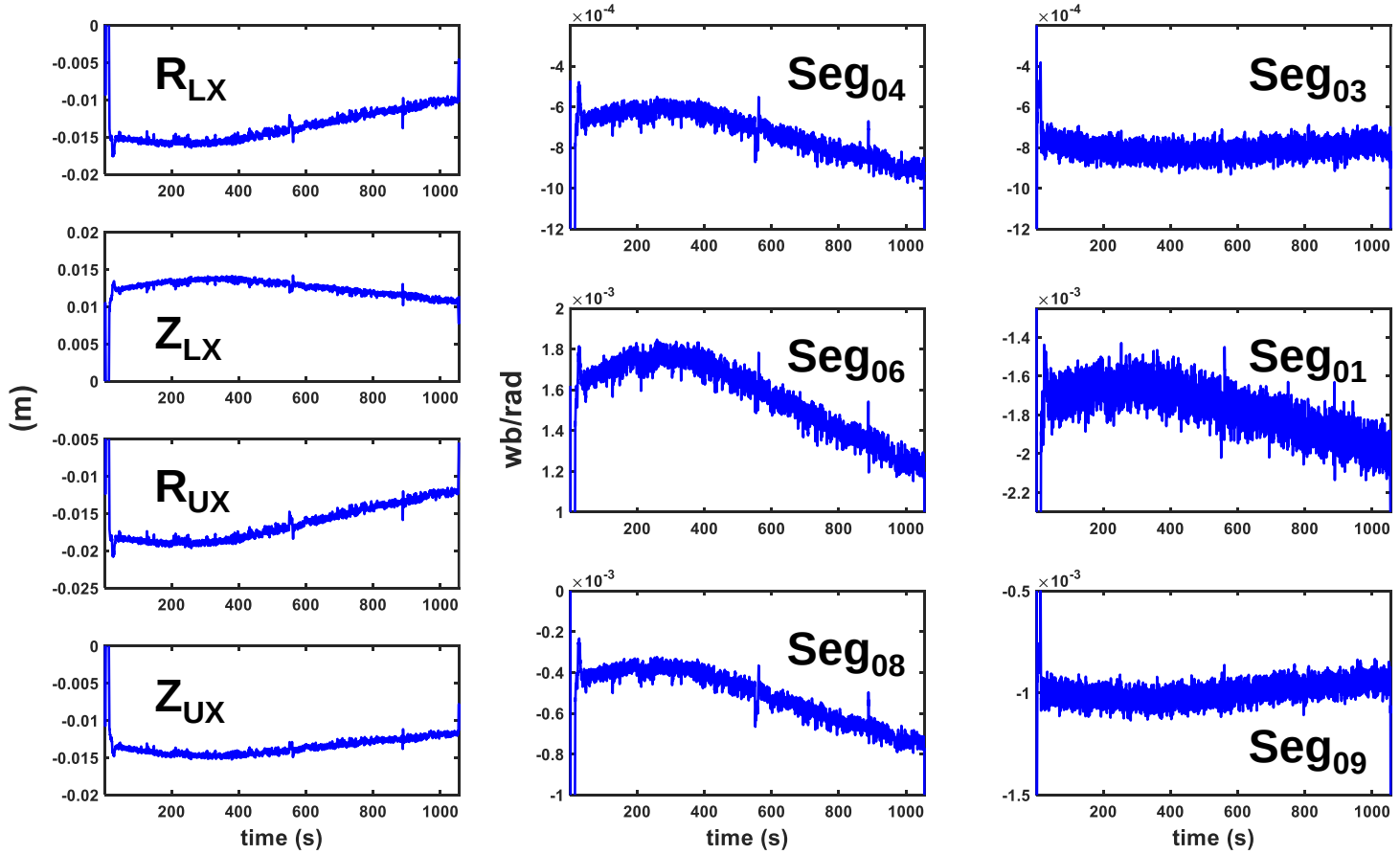
P-EFIT code routinely provides real-time equilibrium reconstruction and shape control signals in EAST plasma control system

- P-EFIT provides control error signals on selected control segments and x-points
- EAST plasma shape (LCFS) control: ISO-FLUX algorithm $\Delta PF = PID(M_{matrix} \times [Seg,\ X])$





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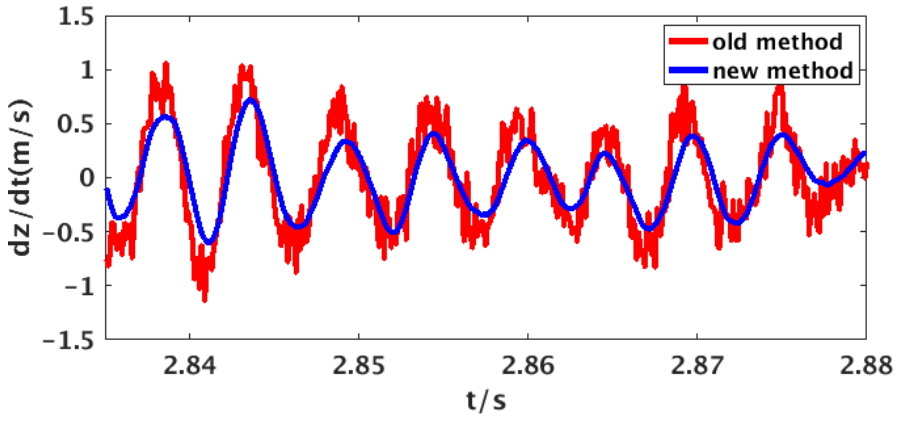
Robust plasma vertical velocity (fast-z or dz/dt) estimation in EAST vertical instability control

Plasma vertical velocity is estimated with magnetic measurements.

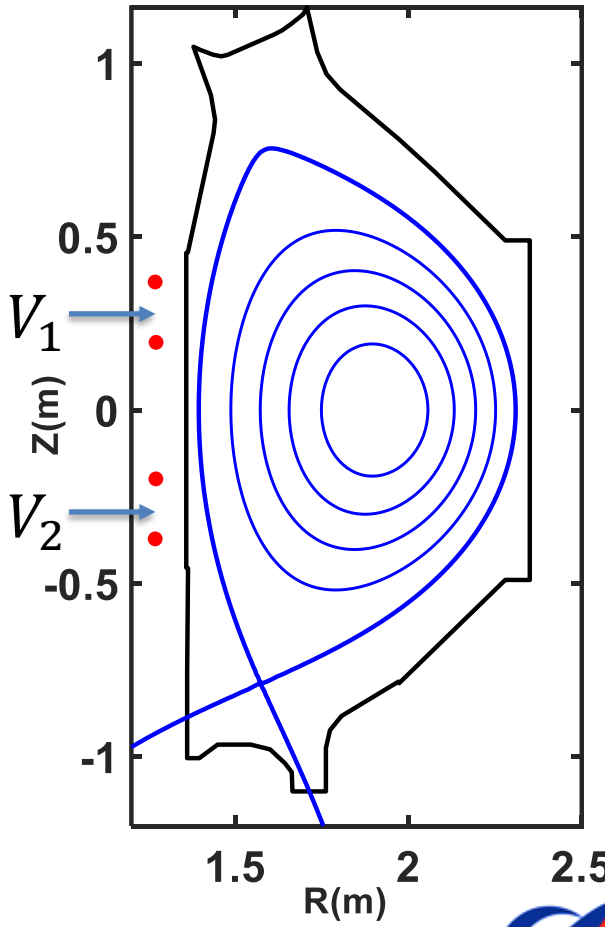
old method: $Z = E_{matrix}\begin{bmatrix} B_P \\ PF \end{bmatrix}/I_P$ fast-z = high-pass filtered Z

new method: loop voltage differential between a couple of flux loops

$$\frac{dz}{dt} = \frac{V_1 - V_2}{I_P}\frac{1}{\left(\frac{\partial M_{pl2}}{dz} - \frac{\partial M_{pl1}}{dz}\right)}$$



- Both estimation methods are not affected by magnetic measurement signal drift.



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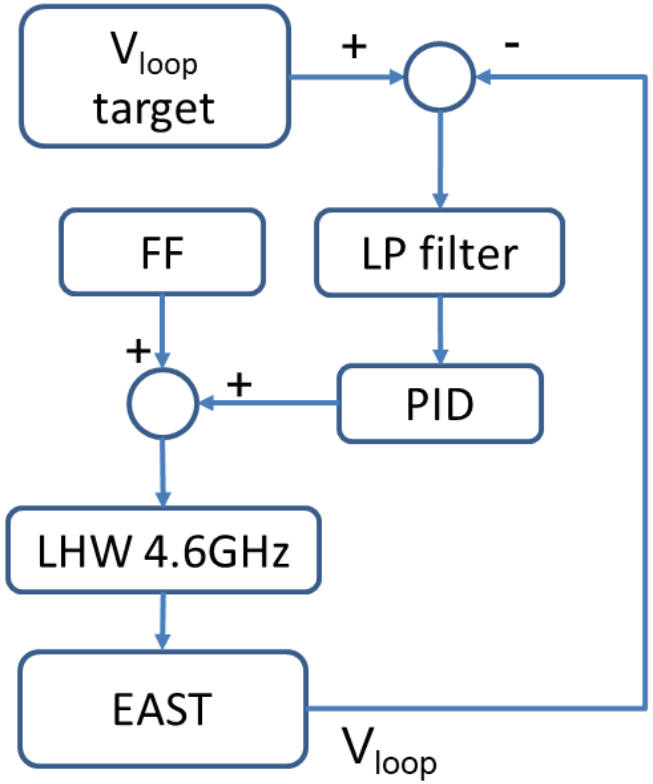
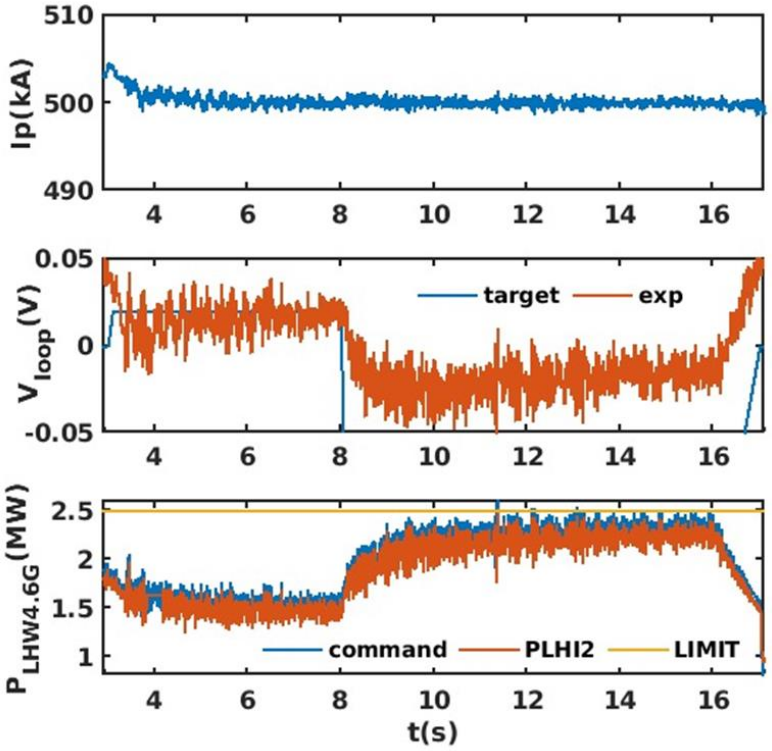
Vloop control using 4.6GHz LHW for fully non-inductive current drive

In order to realize fully non-inductive current drive operation, the plasma loop voltage control algorithm are implemented in PCS.

- 4.6G LHW power feedforward and feedback control
- Vloop controllable ability is limited by 4.6G LHW current drive capacity
- Maximum Vloop control ability is about -0.02V (shot 99007: Ip~500kA, Ne~$2.0\times10^{19}/m^3$)





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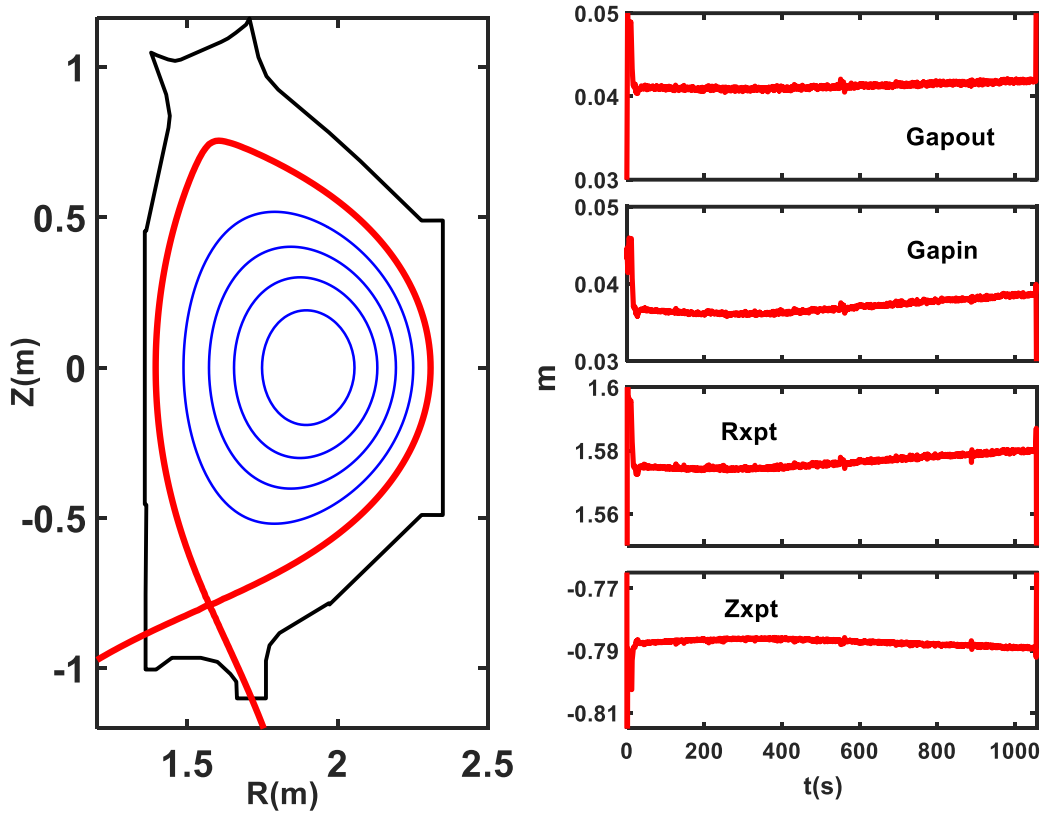
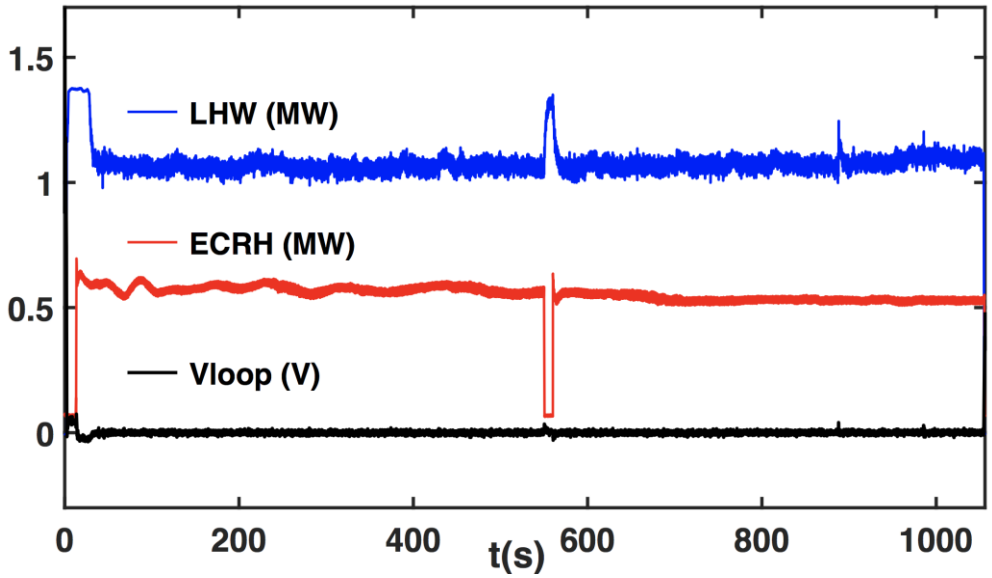
An improvement of the plasma position and shape control together with zero loop voltage control by the injected LHW power

Shape control



Vloop control



- With optimized PI controller and 4.6Ghz LHW feedforward power, loop voltage is controlled within 0.5×10^{-5} V

- Plasma shape control using upgraded magnetic measurements achieves good accuracy within a few millimeters in 1000s discharge.

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Advanced plasma control towards delicate, robust and safe fusion device operation on EAST

- Robust and flexible MIMO shape control for alternative configuration
- Advanced scenario control of q-profile, βp and li using NBI and LHCD
- Controllability of ITER-like vertical velocity and fast ramp-down
- Radiative divertor control of the advanced shape configurations and detachment
- AI application in plasma control such as disruption prediction and mitigation

Widely worldwide collaboration in EAST plasma control development

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Summary

Feedback controlled fully non-inductive plasma discharge have been sustained in EAST long-pulse operation up to 1056s with a new world record of injected–extracted energy exceeding 1.7 GJ.

Key issues solved in plasma control for EAST 1000s long-pulse operation:

Magnetic measurement

- Magnetic probes upgraded in 2021
- New fiber optic current sensors

Integrator

- Low zero drift integrator
- Linear drift deduction algorithm

Real-time equilibrium reconstruction

- Magnetic measurement signals selection and fitting weight based on uncertainty analysis in 500s long pulse dry-run operation

Fully non-inductive operation

- Vloop control by 4.6G LHW with optimized PID controller in PCS

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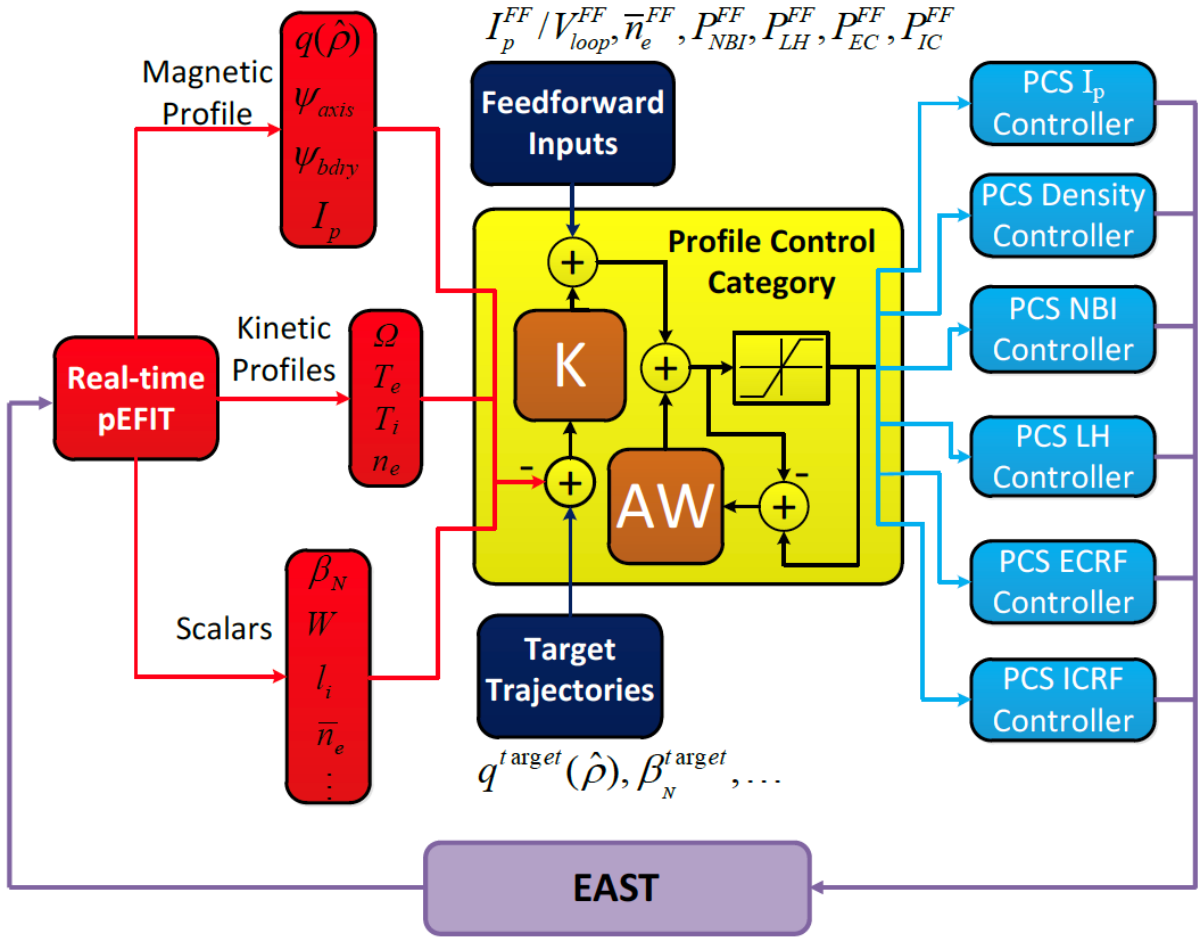
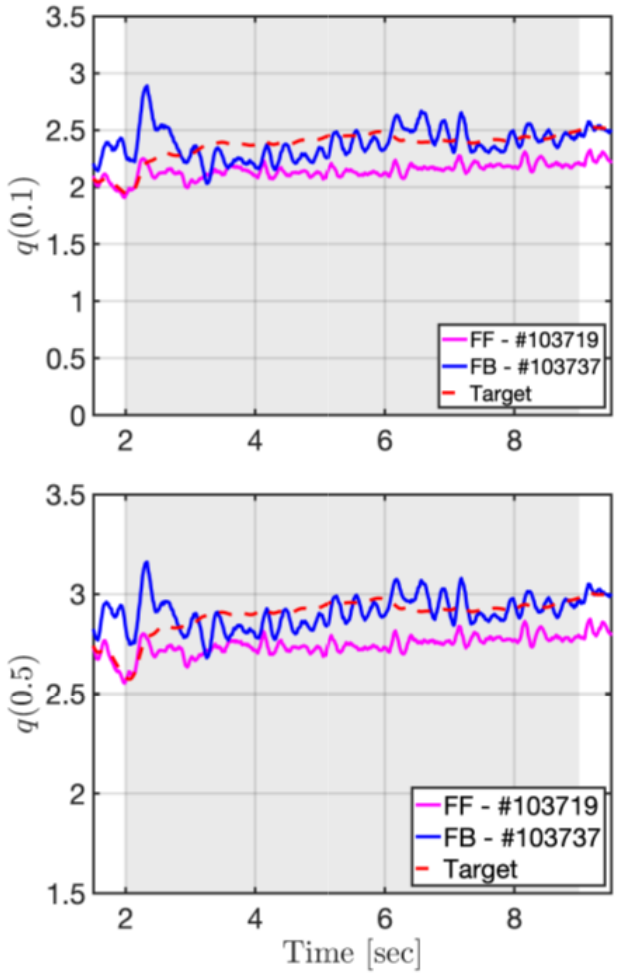
Thank you !

Advanced scenario control of q-profile, βp and li control using NBI and LHCD





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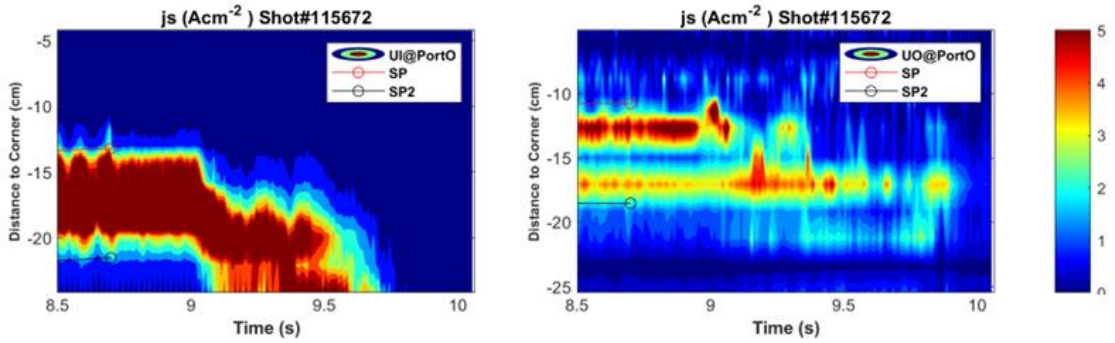
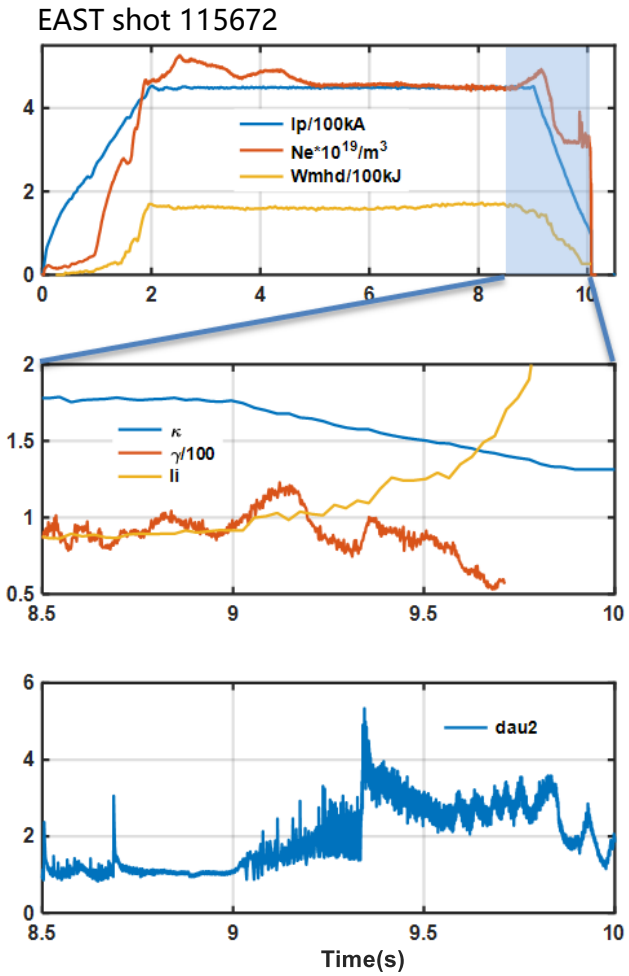
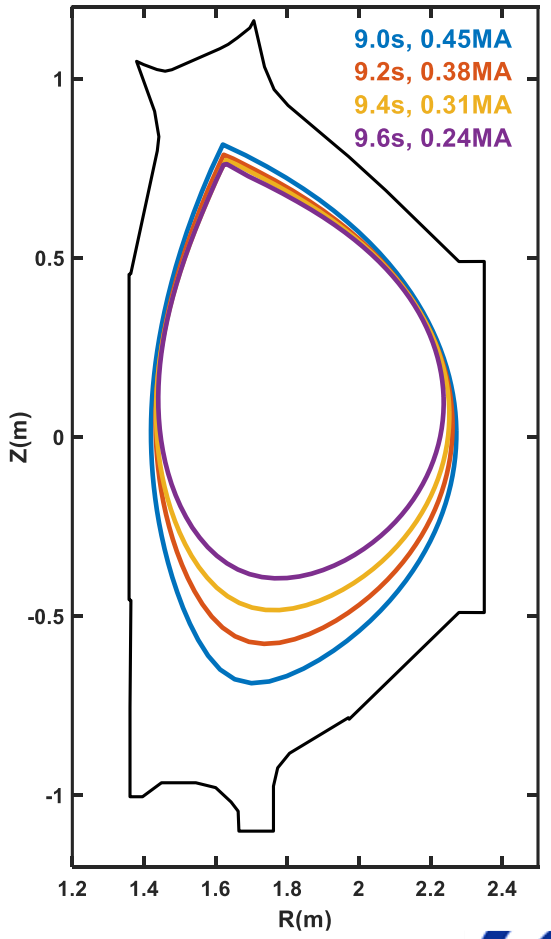
Controllability of ITER-like fast ramp-down control

EAST ITER-like ramp-down control

- H-L transition in ramp-down phase
- Keep USN and strike-points
- Reduce elongation to sustain vertical instability growth rate
- Ip ramp-down rate 350kA/s







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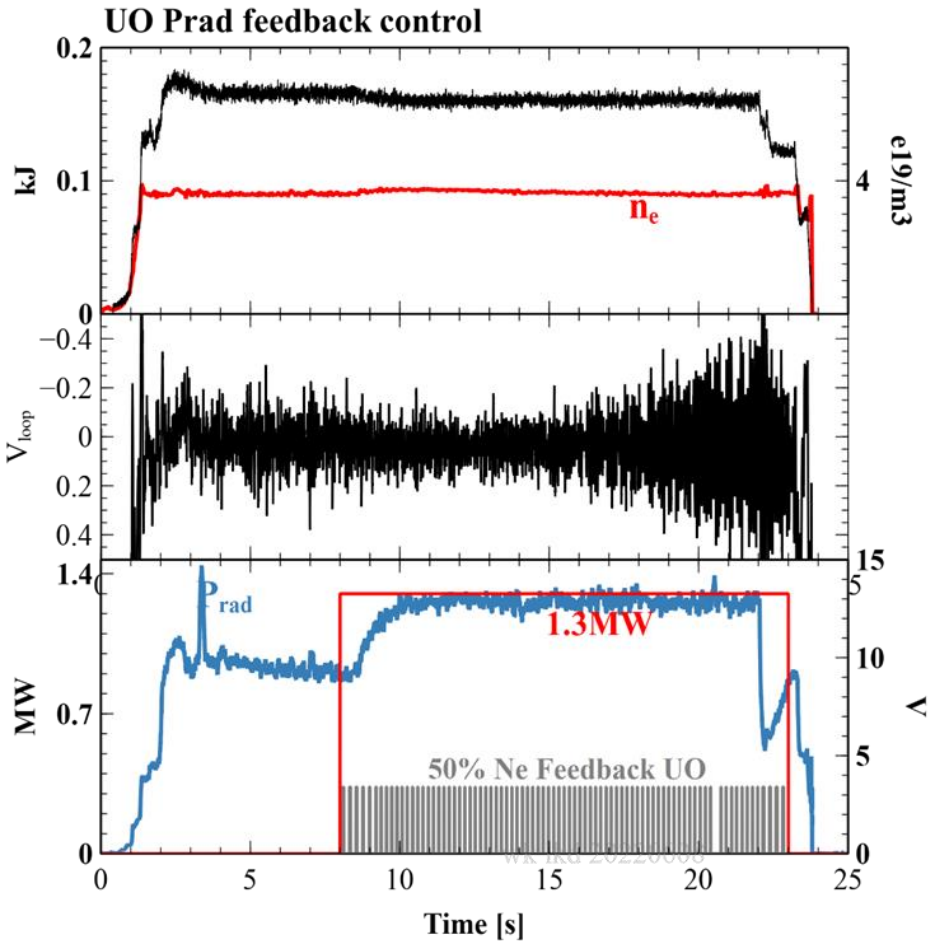
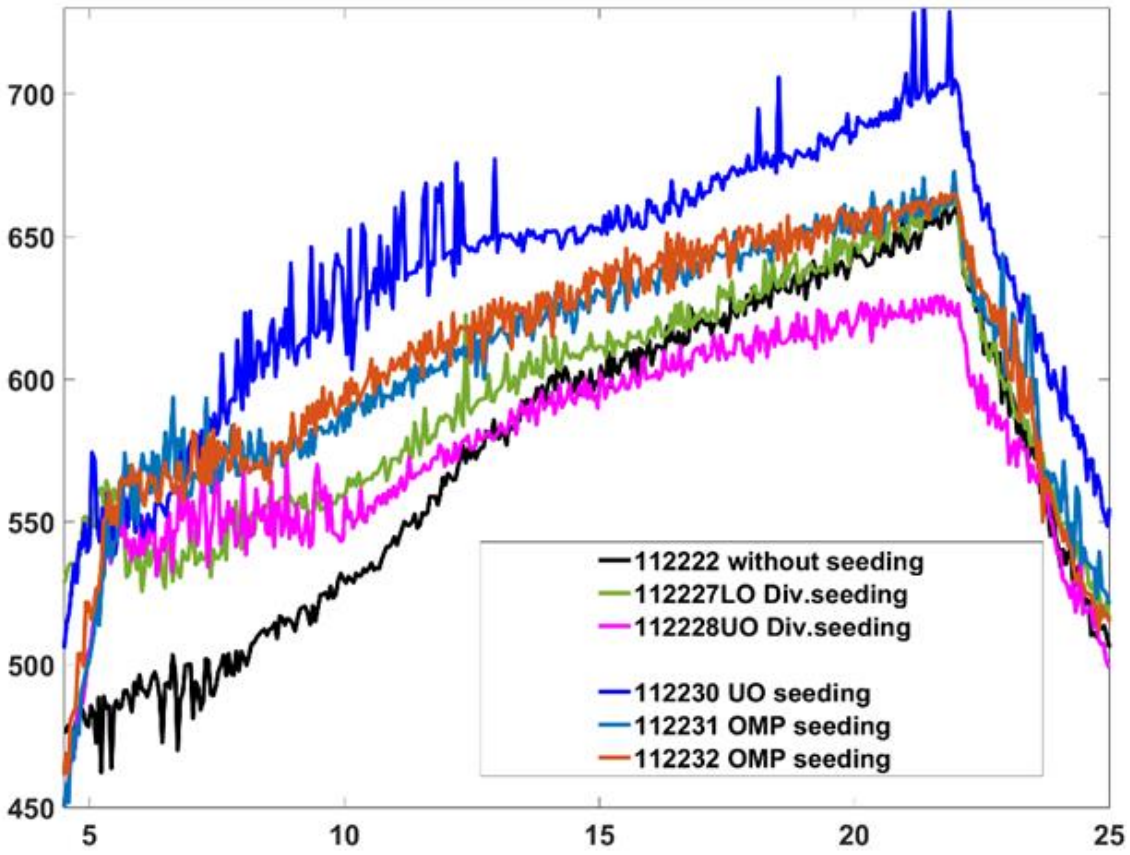
Radiative divertor control of the advanced shape configurations and detachment



Controlled radiative power with Ne impurity



Reduce heat load of limiter and divertor in long pulse H-mode discharges

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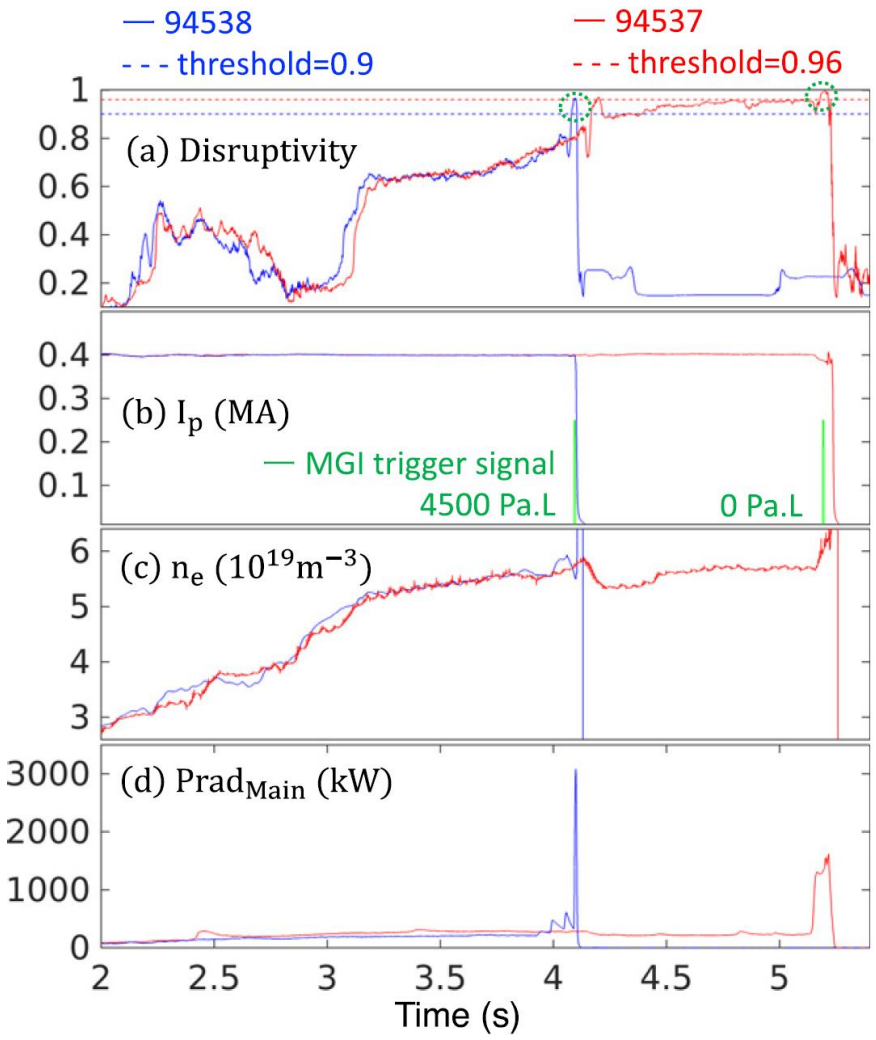
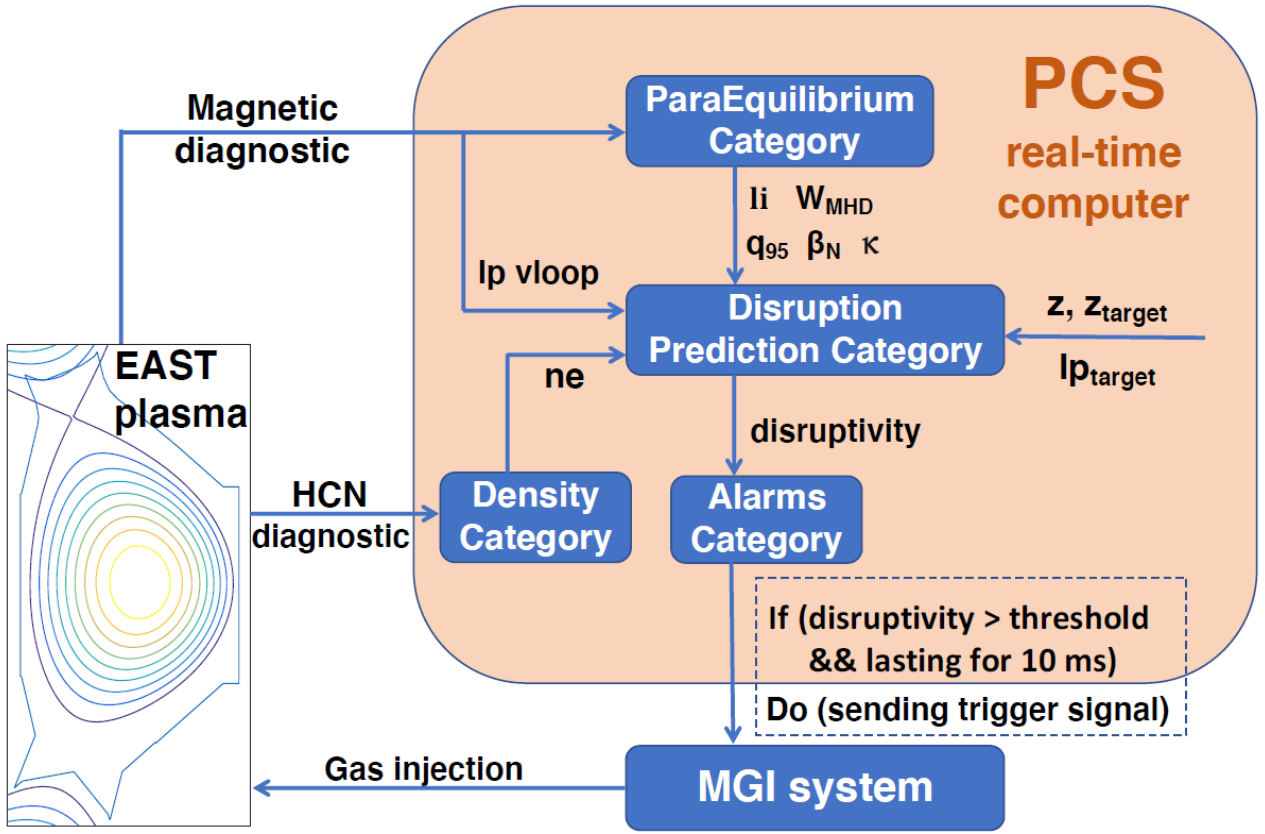
EAST real-time prediction of high-density disruptions using random forest





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