EAST research activities on control and data toward CFETR

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ASIPP EAST

Contents

- **Introduction to CFETR Engineering design and R&D**
- **Data management and collaboration network for CFETR design**
- **CODAC and PCS concept for CFETR**
- **EAST plasma control for CFETR**
  - Magnetic control: Z, MIMO, advanced shape,
  - Heat load control: radiation, detachment, QSF
  - Kinetic control: profile, beta, Vloop
- **Summary**

CFETR Engineering Design Started @2018

	B.1 100MW HB	B.2 200MW HB	B.2 500MW HB	B.3 1GW HB	B.4 DEMO level HB
Pf	114	250	558	1128	2192
Pinternal	190	196	202	222	75
Qplant	0.46	0.75	1.40	2.41	12.96
Qplasma	1.54	3.35	7.65	15.30	795.16
Pnetelec	-103	-49	80	312	891
Pn/Awall	0.12	0.25	0.57	1.15	2.23
BetaT	0.006	0.009	0.014	0.019	0.029
BetaN	1.00	1.20	1.50	2.00	3.0
fbs	0.40	0.40	0.40	0.50	0.75
HITER98Y2	1.01	1.09	1.18	1.19	1.54
fohm	0.30	0.30	0.30	0.30	0.24
Pcd	74	74	73	74	3
Ip	8.61	10.34	12.92	13.78	13.78
Bo	6.5	6.5	6.5	6.5	6.5
Ti(0)/Te(0)	13	17	24	24	34
n(0)	0.67	0.74	0.82	1.16	1.23
nbar/nGR	0.79	0.72	0.64	0.85	0.90
Zeff	2.45	2.45	2.45	2.45	2.45
P/R	7.58	9.33	12.63	19.11	22.97
q95_iter	8.87	7.39	5.91	5.54	5.54

Main Parameters

- R= 7.2
- a=2.2m
- Bt=6.5T
- CS magnet:≥ 480 VS
- Ip: 6-14MA

Main Features:

- More reliable Plasma targets
- DEMO validation
- Tritium sustain
- Availability: 50%
- Hybrid (30% ohmic), 480VS

~ 8 hours for 12MA, days for 6-10MA

CFETR Main Challenges

- Burning Plasma (Q =10-30, Q>30) for DEMO
- Steady-state Operation
- Particle and Heat removal
- T breeding and self-sustainment
- Plasma wall interaction
- Remote maintenance
- Materials
- Safety and license

Main CFETR R&Ds in ASIPP start @2019

SC Magnets R&D

- **SC Test**

  Material/ Conductor/Magnet
- **CFETR Magnets**
  - 1 1:1 TF Coil
  - CS Model Coil
  - Prototype CS insert with high temperature SC conductor
- **Integrated Test Facility**

Toward CFTER Magnets (TF, CS, PF (ITER PF6))

R&D on Main & Divertor

- **Material Test**
  - Φ 10 cm，SS with10^{24}/s 10MW/m^2
- **Heating and CD**
  - NBI+ECRH+RF+LH,
- Component Test (Full Size)
  - Thermal-hydraulic, EM, Plasma
- **Assemble and Maintainance**
  - Remote Handling
- **Experiments on EAST**
  - EAST Lower Divertor

Toward CFETR, Divertor and Heating & CD Key Tech.

Future R&D Area （40 hectares)

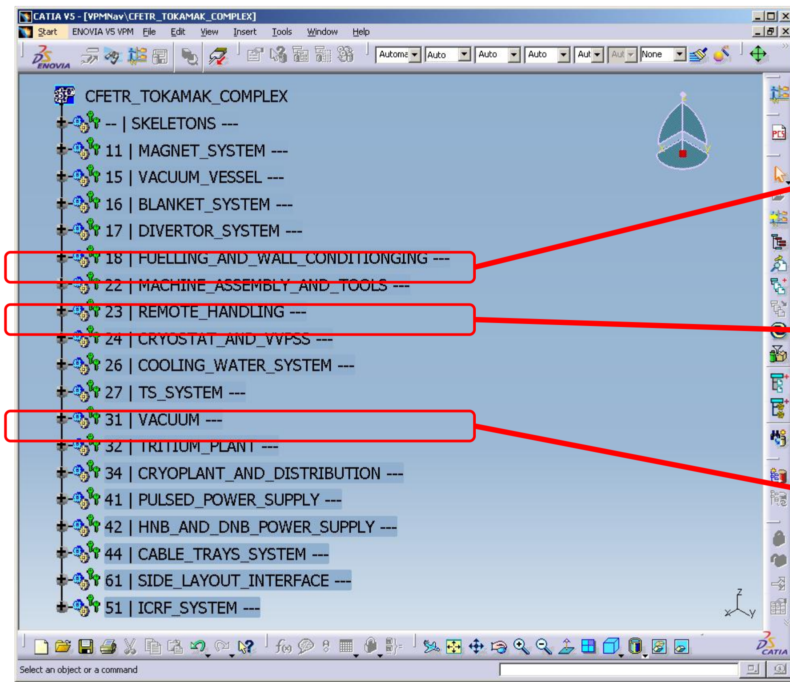
Data Management and Collaboration Network for CFETR Engineering Design

- **Main data during CFETR R&D phase**
  - 3D Models / Components ~ One Million
  - Design Documents / Reports ~ 100 Thousands
  - User Data ~ 1000

– **A data management framework has been designed to manage all the data for CFETR design:**
  - 3D Models design platform
  - Collaboration design network
  - Design documents management
  - User authentication & authorization

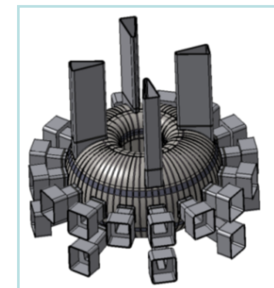
3D Models Design Platform

- The whole platform is constructed based on VPM and CATIA.
- VPM - Virtual Product Management, designers can be connected through CATIA software into this platform, and work together through collaboration network connection.

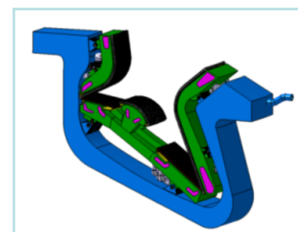


CFETR PBS

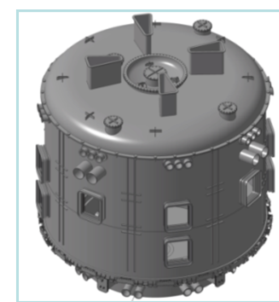
CFETR VV



CFETR diverter



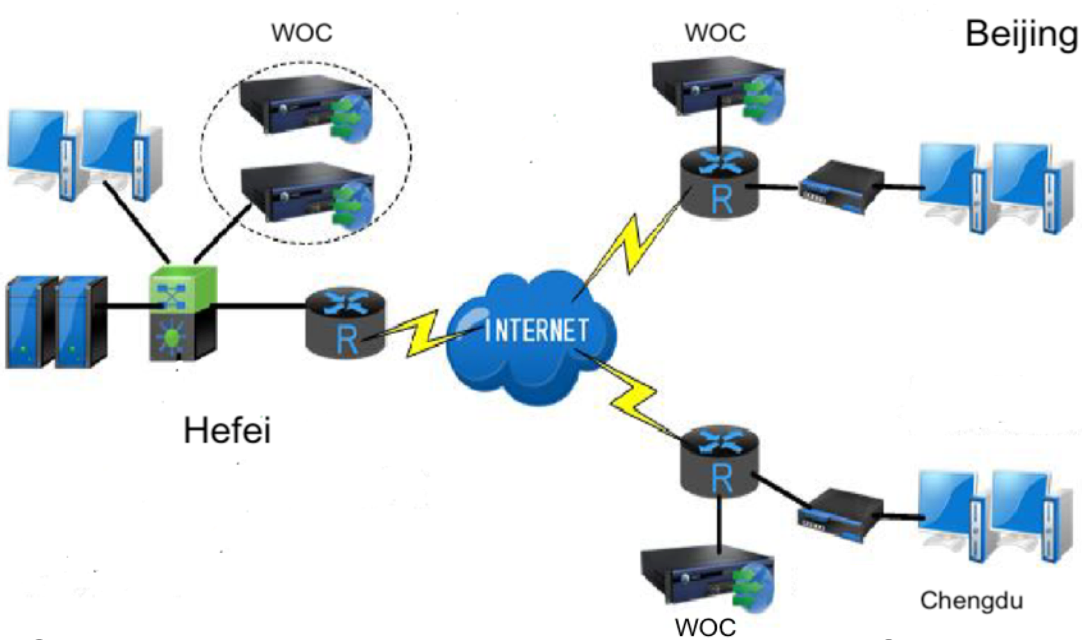
CFETR cryostat



Quickly open data

Collaboration Design Network

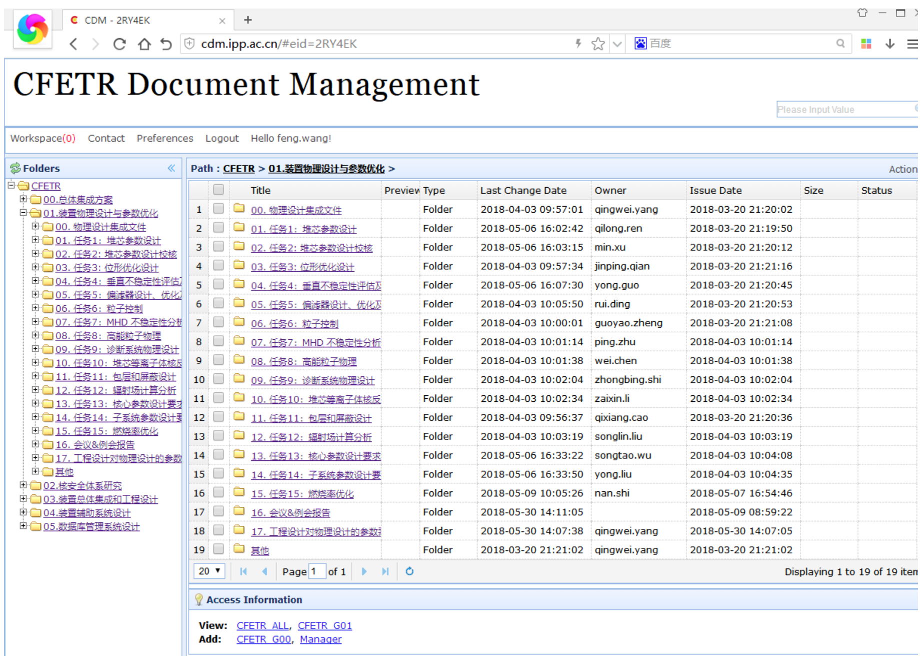
- **Based on WAN Optimization Controller (WOC) Network**
  - Virtual Private Network(VPN): To creates a safe and encrypted connection over a less secure network (current phase 100Mbps)
  - WAN Optimization: Data deduplication
  - Secure Data Transfer: File Transfer Encryption



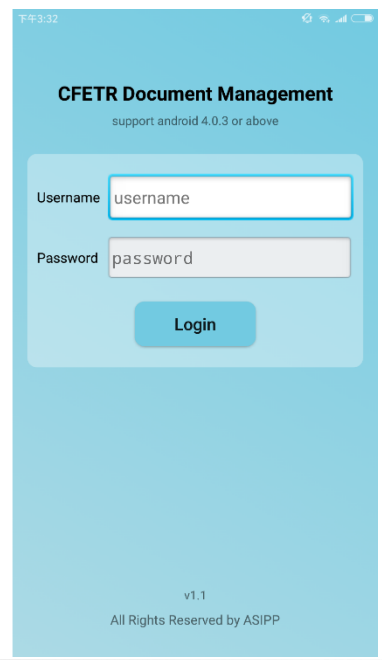
Collaboration Design Network Topology Structure

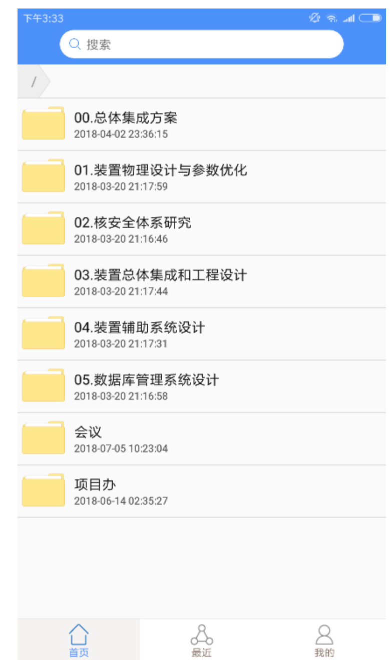
Design Documents Management

- **A web-based document management system with powerful version control and access management has been developed for CFETR design documents.**
  - 20 institutes & universities
  - 450 user accounts
  - 120 approved groups



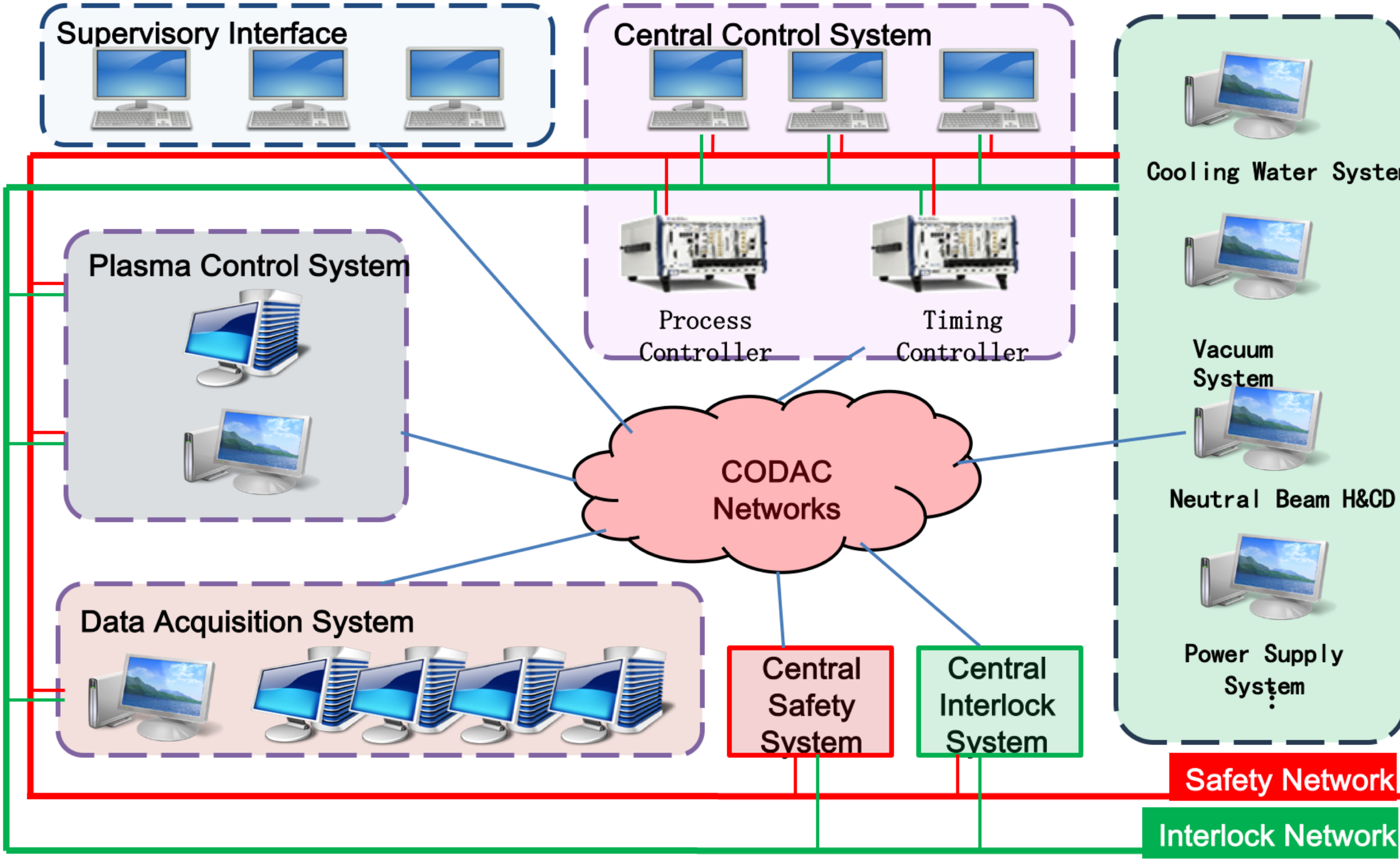
Web browser Access





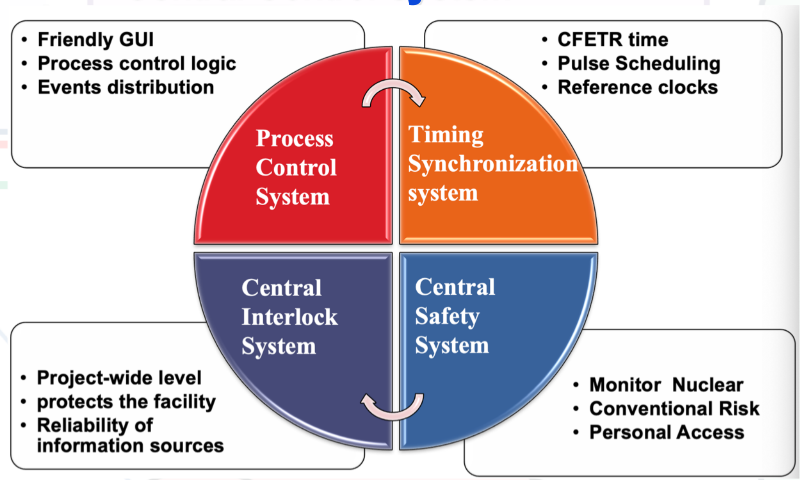
Mobile App Access

CFETR CODAC & PCS R&D Started

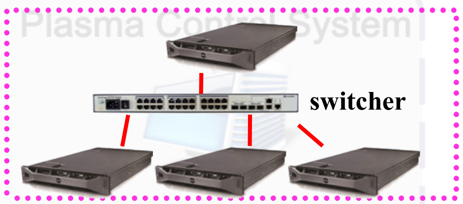


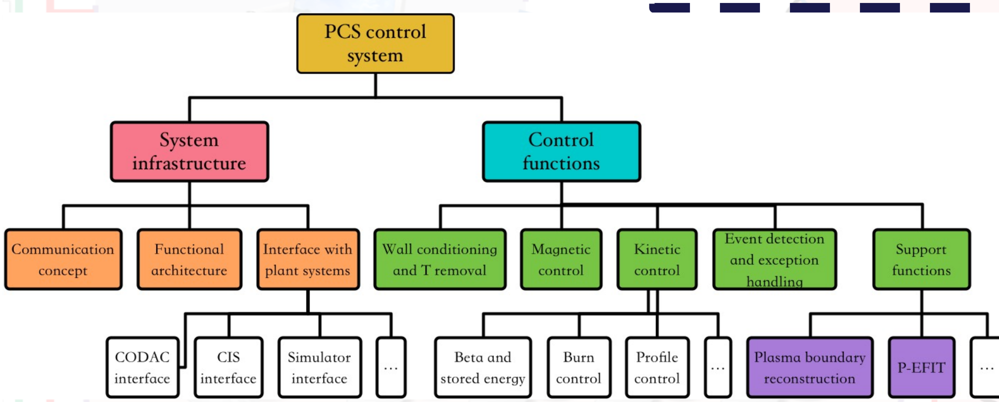
Future plan for CFETR CODAC and PCS

Central Control System

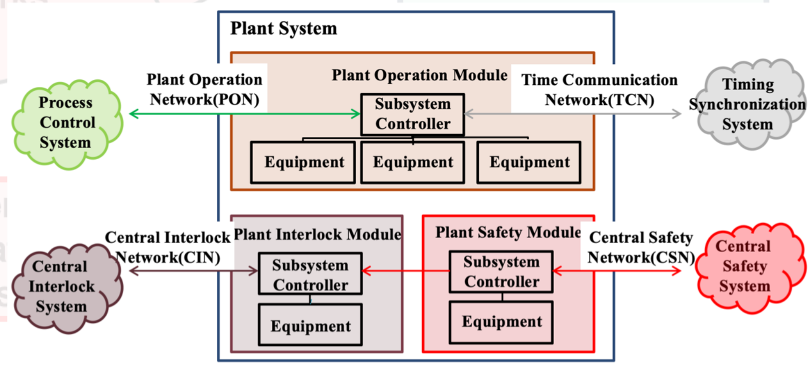


Plasma Control System





CODAC network and framework



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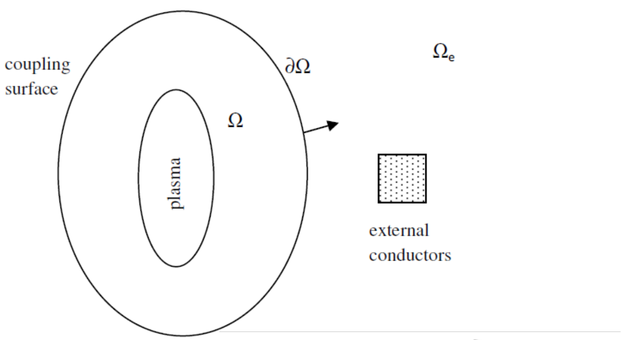
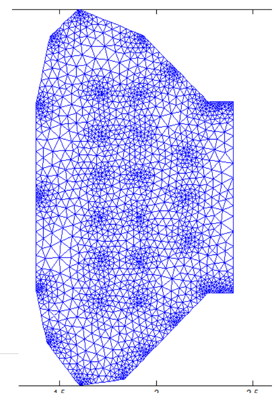
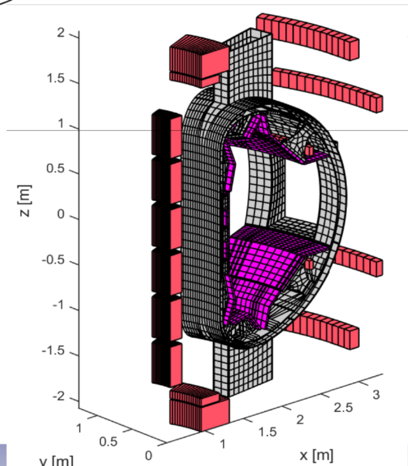
3D effects to the vertical stabilization: CarMa0 model

- CarMa0 is a linearized plasma response model, able to evaluate self-consistently the effect of 3D conducting structures on axisymmetric (n = 0) plasma evolution, using a coupling surface to describe the electromagnetic interaction between the plasma and the conductors.







Inside Ω: linearized Grad-Shafranov equations are solved, using 2nd order triangular finite elements mesh.

Outside Ω: eddy currents equations are solved in 3D conducting structures, using volumetric hexaedral mesh of conductors only.

On ∂Ω: surface currents magnetically equivalent to the 'true' plasma perturbation.

3-D Carma0 Modeling reproduces exp. Z growth

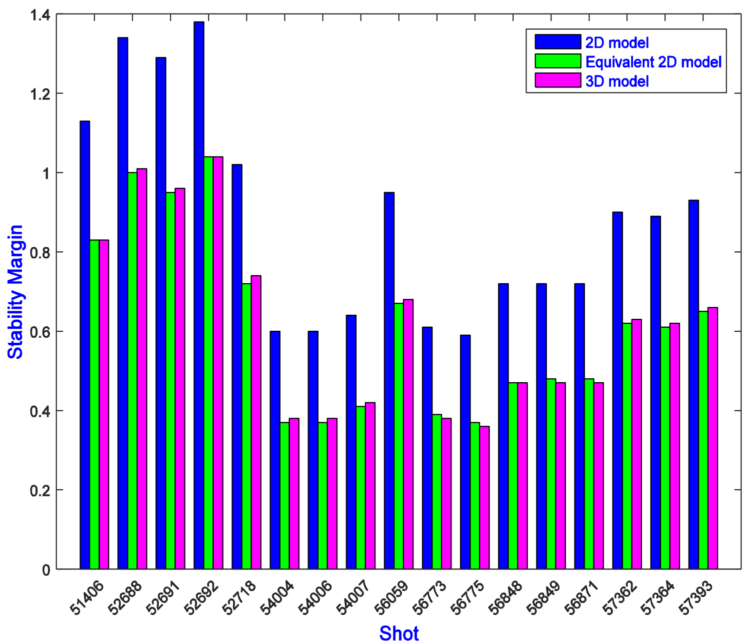
Shot#	Experimental	3D model	2D model	3D no support	2D model with only vv
35288	96	99	77	238	N.A.
35289	102	90	72	204	2952
35290	84	88	70	197	2495
36193	210	201	127	1237	N.A.

Shot#	Exp	3D	2D	3D w/o support	2D VV
36537	227	230	144	2025	N.A.
36539	316	320	178	6278	N.A.
38074	152	141	99	467	N.A.
38148	197	174	109	835	N.A.

Shot#	Experimental	3D model	2D model	3D no support	2D model with only vv
43896	136	151	105	538	N.A.
43897	152	147	103	505	N.A.
43907	194	178	115	880	N.A.
43908	241	276	150	4383	N.A.
43914	225	200	124	1241	N.A.
44003	222	221	133	1736	N.A.
44017	224	214	131	1553	N.A.
44018	243	222	134	1751	N.A.

2D model can be derived by fit to the 3D calculation

Stability margin fit by distance (4.4 cm) of PFC to plasma



- ➢ Right Eqv. 2D: 10 resistivity to the support,
- ➢ others 1.15 resistivity
- ➢ Ref: Chen SL, NF(2015), PPCF(2016), Sci Rep(2016)

Shot#	Exp	3D	3D model with no supports	Eqv. 2D	2D	2D only VV
51406	103	101	199	112	72	1293
52688	80	79	139	93	61	622
52691	81	82	151	99	65	815
52692	76	76	134	90	59	573
52718	121	116	243	135	85	N.A.
54004	314	295	2442	295	157	N.A.
54006	305	298	2557	298	158	N.A.
54007	279	262	1545	263	144	N.A.
56059	157	130	302	146	91	N.A.
56773	275	296	2531	267	146	N.A.
56775	278	318	3301	282	152	N.A.
56848	208	214	923	217	125	N.A.
56849	205	214	915	216	125	N.A.
56871	206	213	912	216	124	N.A.
57362	159	148	385	163	99	N.A.
57364	161	150	391	166	101	N.A.
57393	159	140	347	153	94	N.A.

Vertical Stability Control

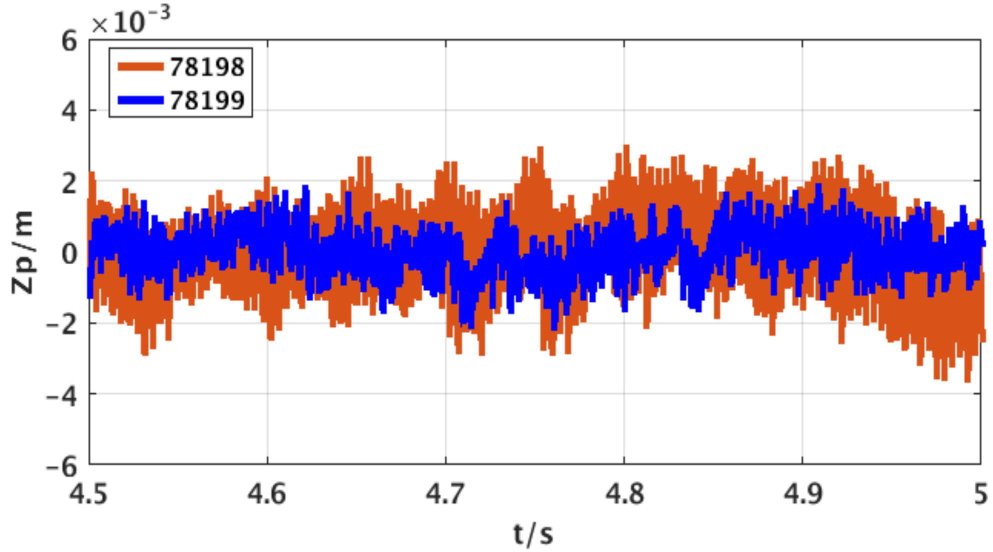
- Decoupled with shape control by not control the position directly

- Optimize the controller by considering the latency to reduce RMS

velocity

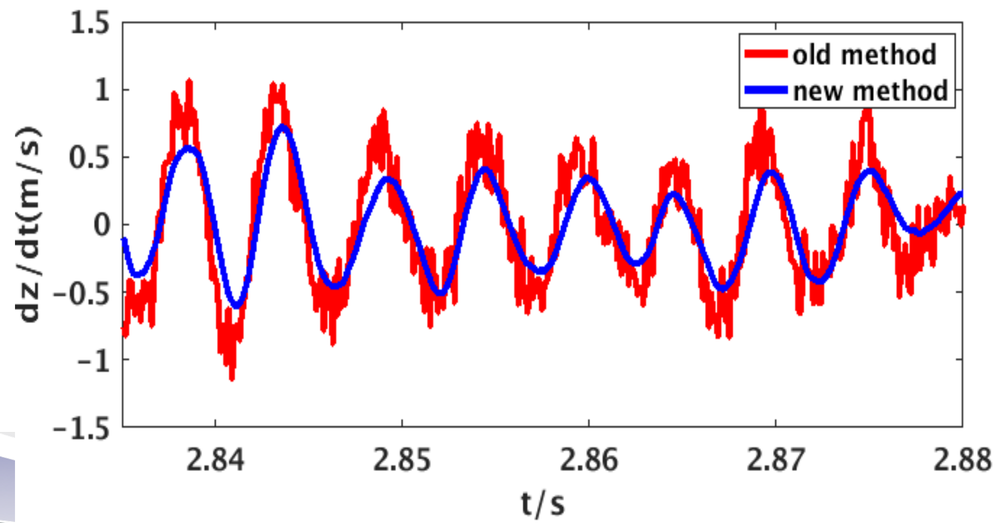
$$V_{IC} = \boxed{\frac{1+s\tau_1}{1+s\tau_2}}(K_1 \cdot I_{p_{ref}} \cdot \frac{\boxed{sz_p}}{1+s\tau_3} + K_2 I_{IC})$$

Bandpass filter for matching delay



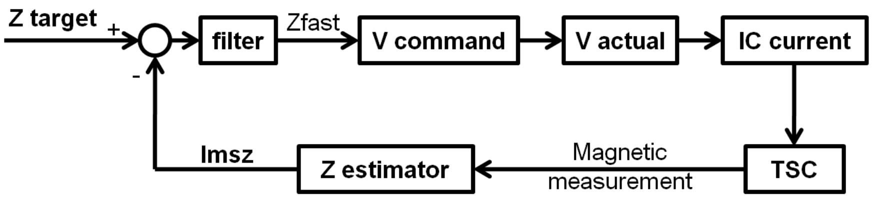
- Use Vloop to estimate dz/dt signal for better SNR

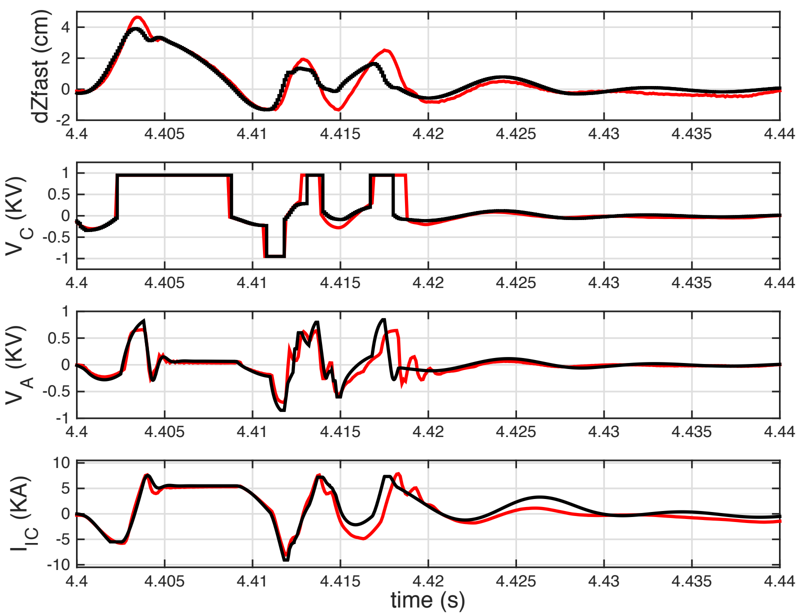
$$\frac{\mathrm{dz}}{\mathrm{dt}} = \frac{V_1 - V_2}{I_p} \frac{1}{\left(\frac{\partial M_{pl2}}{dz} - \frac{\partial M_{pl1}}{dz}\right)}$$



TSC reproduced Exp. Z control, and dzmax

Bang-bang control scheme in TSC

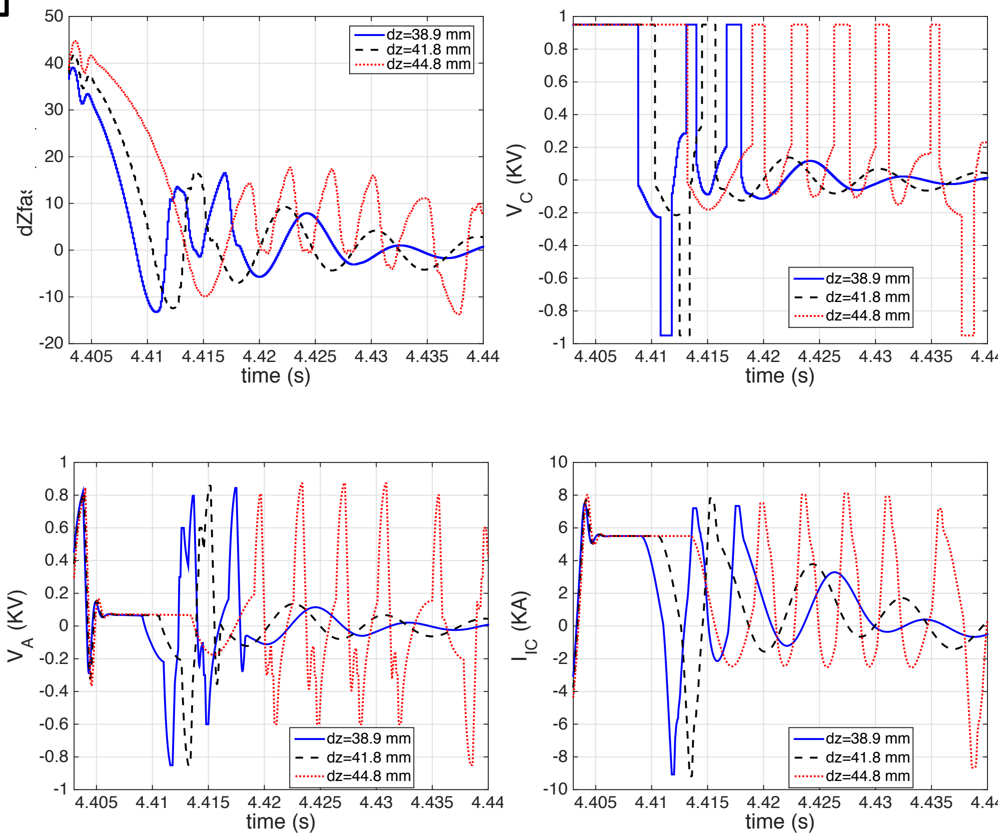




Shot 52444, the trajectories of fast Z (dZfast), IC voltage command (V_C), IC actual voltage (V_A) and corresponding IC current simulated by TSC (black line) are compared with experimental data (red line).

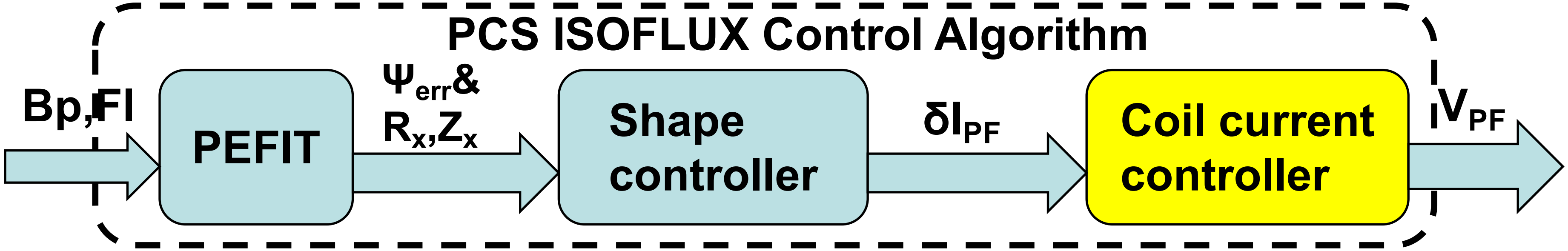
dZmax scanning:

dZmax =41.8 mm (TSC) vs. 46.4 mm (exp.)



Numerical investigation of the Bang-bang methd for dz = 38.9 mm (blue line), 41.8 mm (black dash) & 44.8 mm (red dot) by TSC

MIMO control for PF coil current



SISO: $V_{PF} = K_{PID}\left(I_{PF} - I_{PFref}\right)$

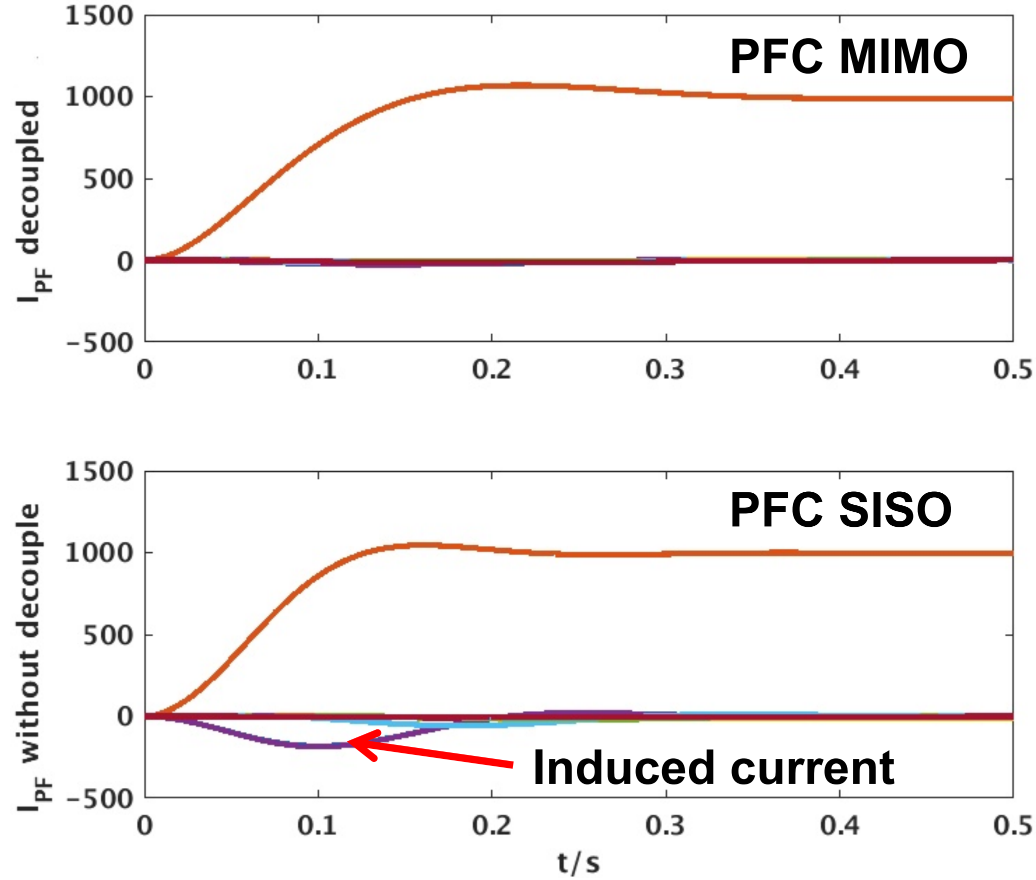
MIMO: $V_{PF} = M \cdot K_{PID}\left(I_{PF} - I_{PFref}\right) + I_{PF}R$

Decoupling matrix

$$L_{PF} = USV^T$$

$$M = VS_{Trunc}{}^{-1}U^T$$

- Using inductive matrix to decouple the coils
- Truncated the decoupled matrix to having more robust control



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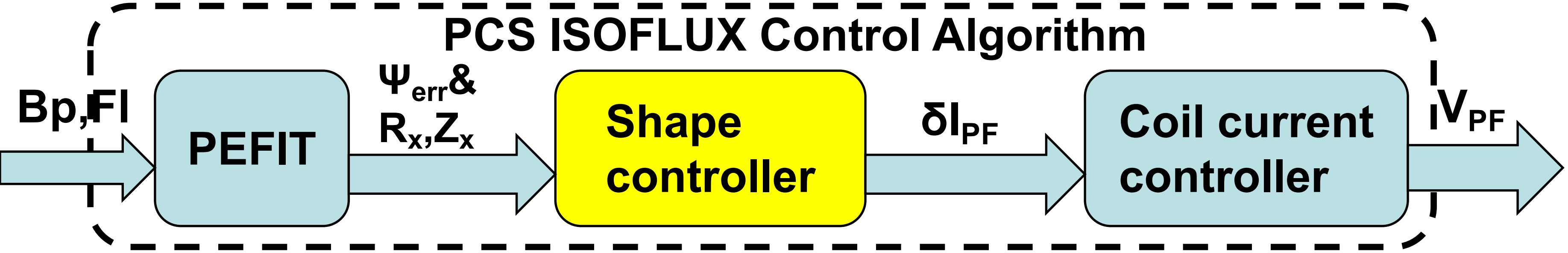
MIMO control for plasma shape



- Using plasma response matrix to decouple the control for different control points

$$\Delta\psi = C_{PF}\Delta I_{PF} \rightarrow \Delta I_{PF} = M \cdot K_{PID}\Delta\psi$$

- Truncated the decoupling matrix matrix to having more robust control

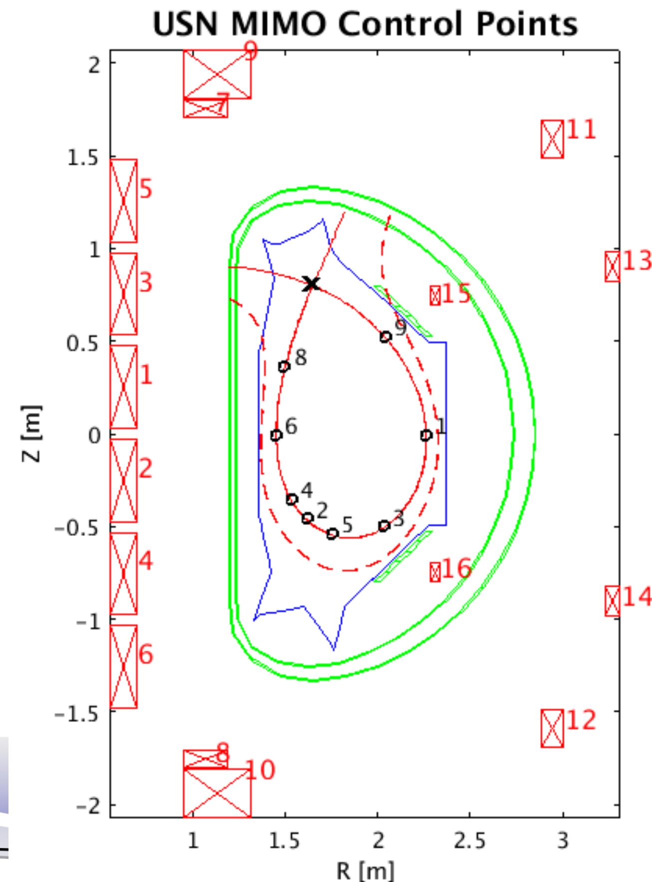
$$C_{PF} = USV^{T}$$

$$S = diag(s_1, s_2, \ldots, s_n)$$

$$s_1 > s_2 > \ldots > s_k >> s_{k+1} > \ldots > s_n$$

$$S_k = diag(s_1, s_2, \ldots, s_k, 0, \ldots)$$

$$M = VS_k^{-1}U^{T}$$



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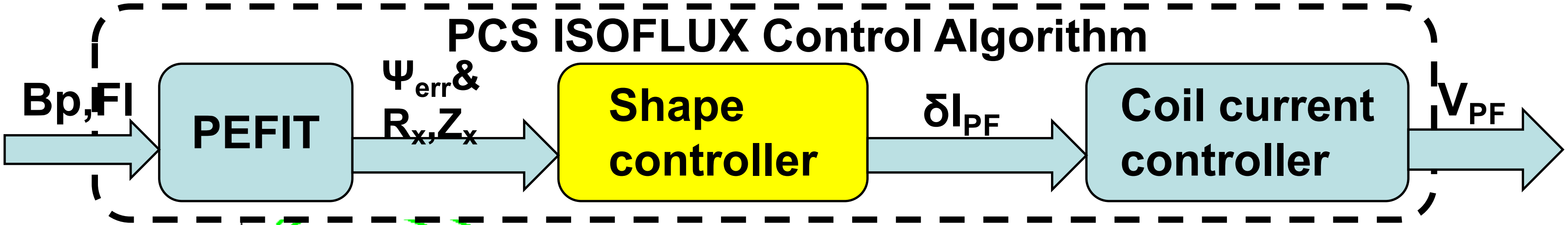
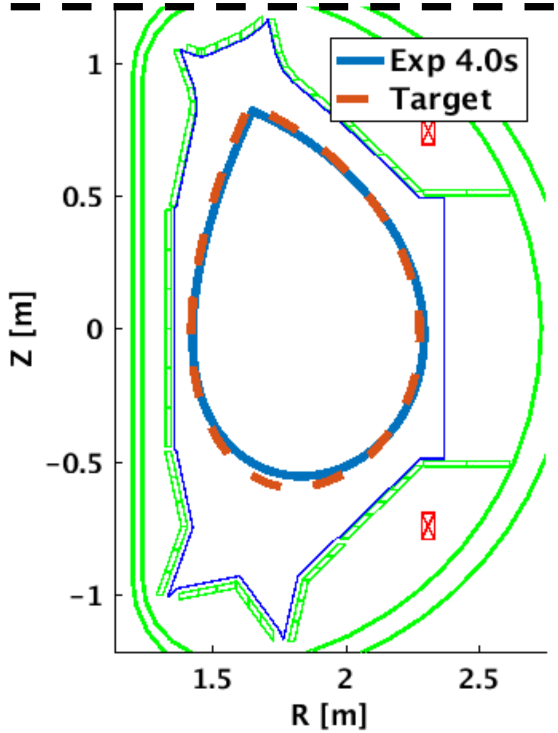
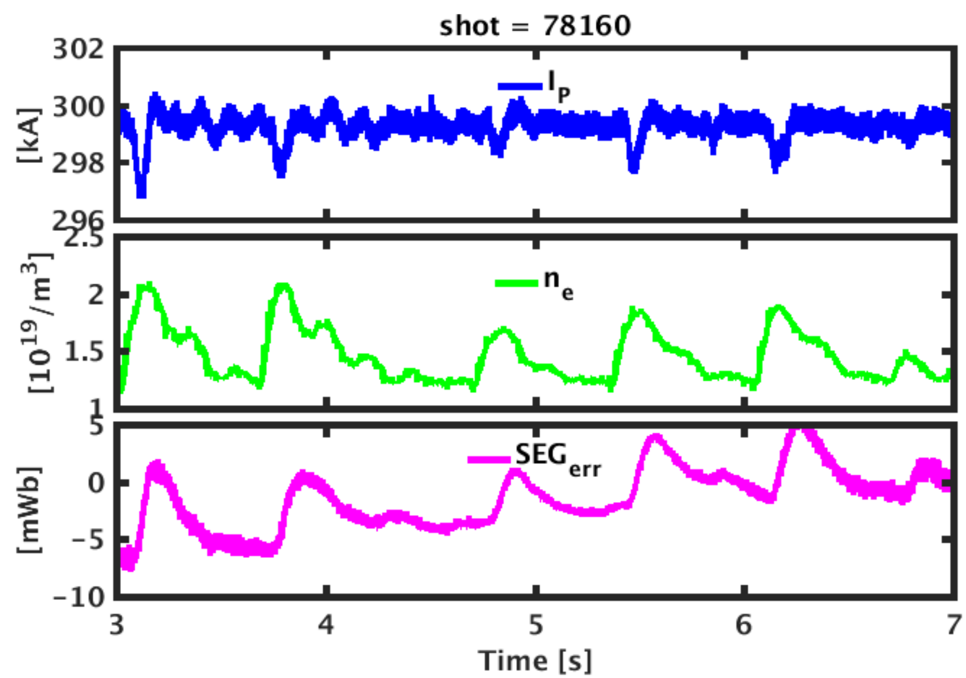
MIMO control for plasma shape

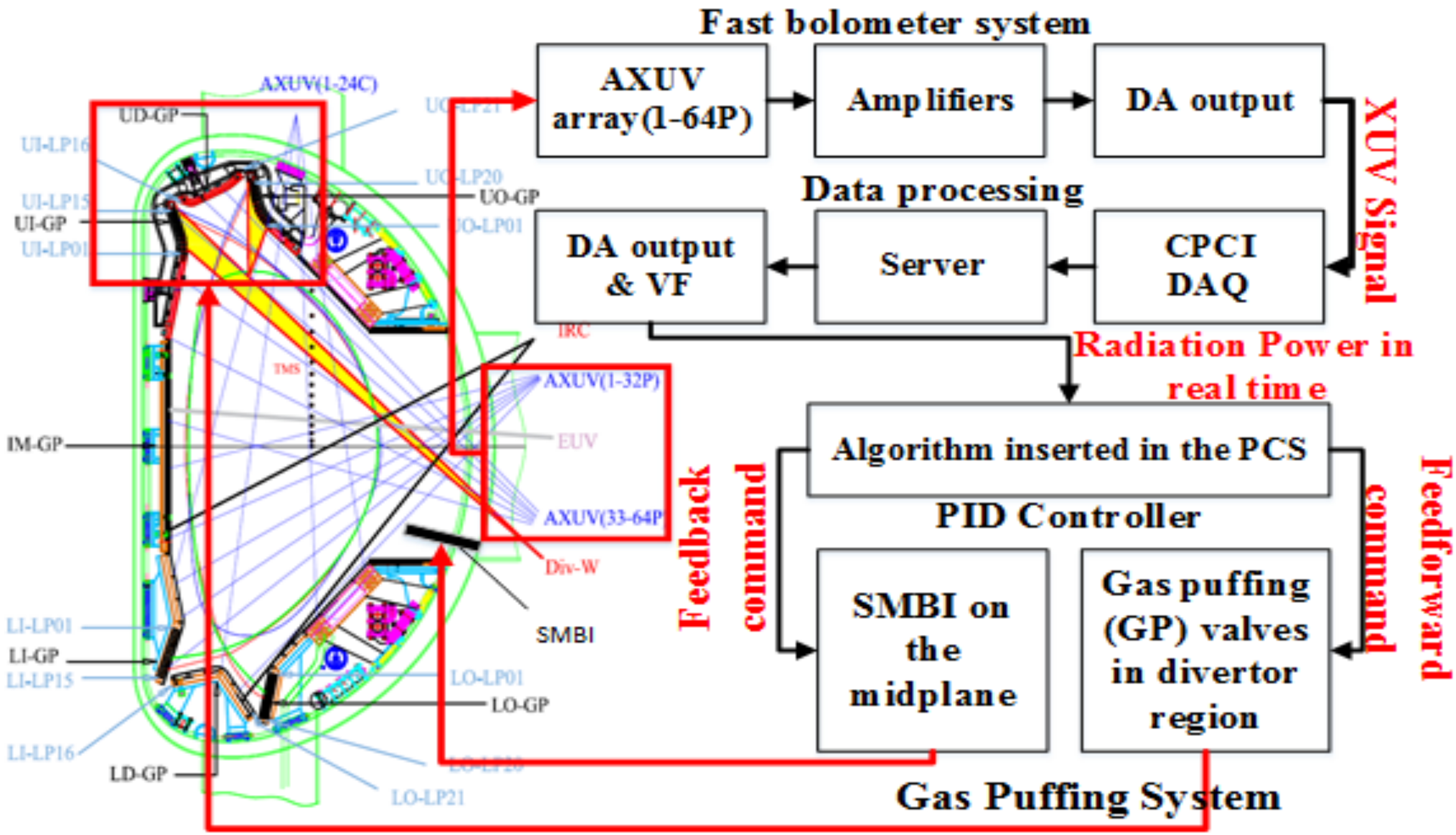






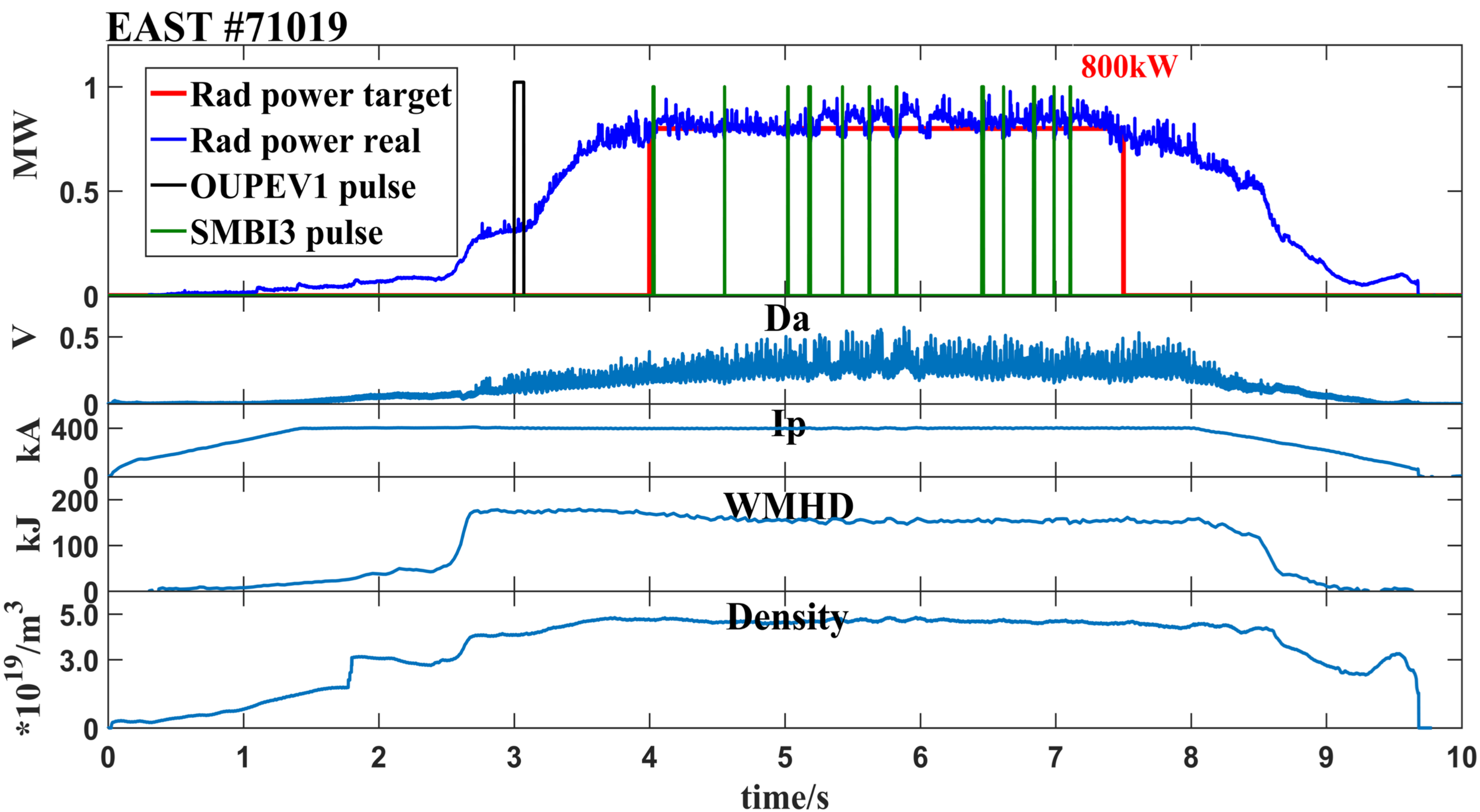
- Accuracy control: $\delta\Psi_{err}$ <1mWb
- Stable under density disturbance

Radiation Feedback control



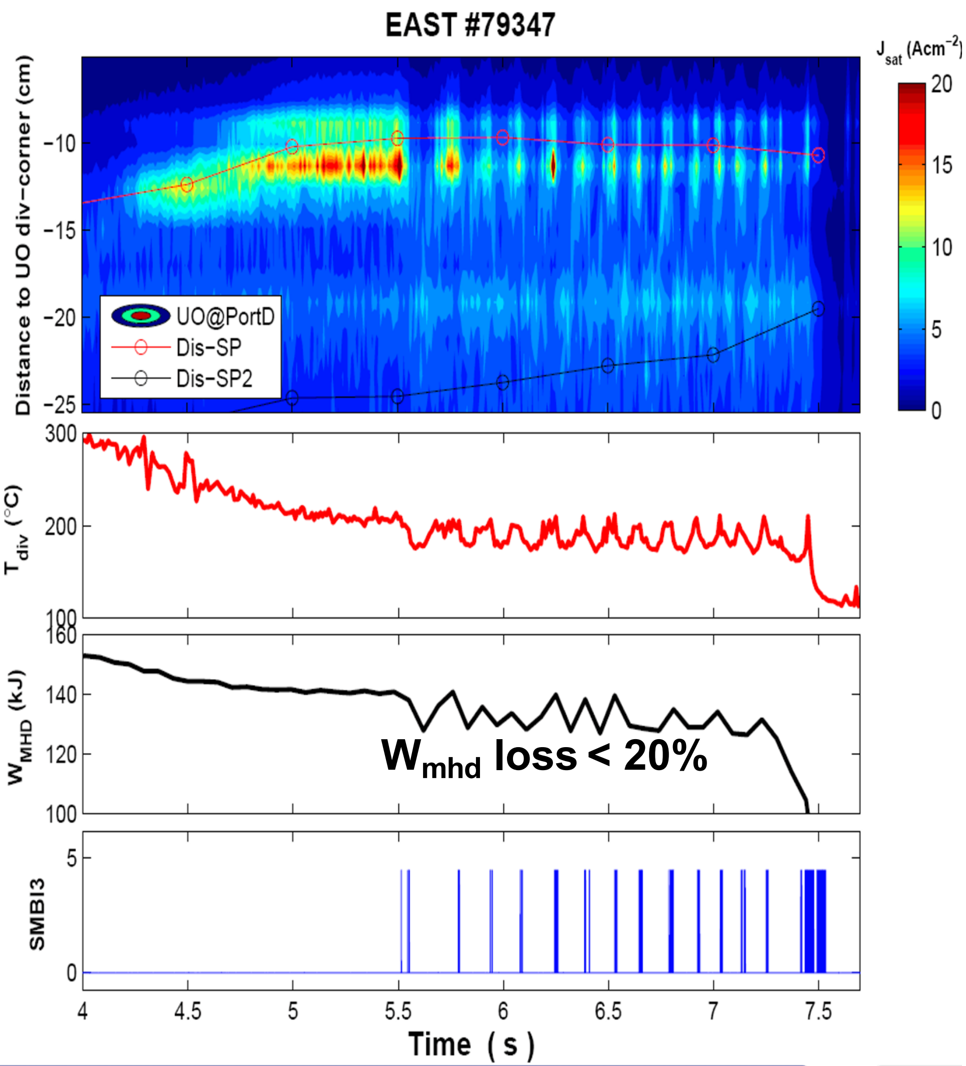
Latency： Gas Puff > 100 ms, SMBI ~ 1 ms

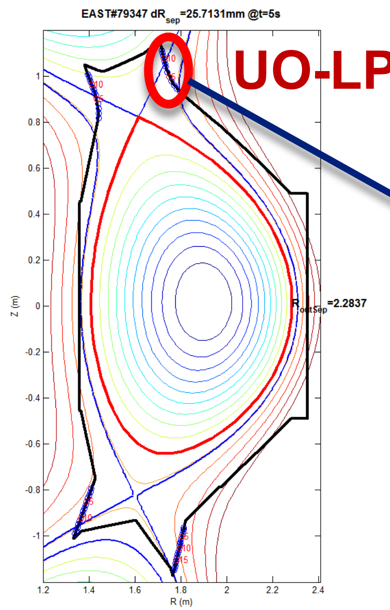
Radiation Feedback Control

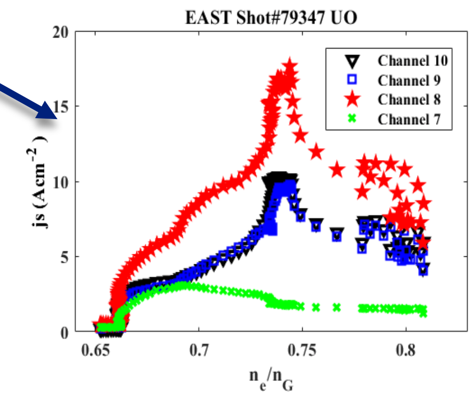


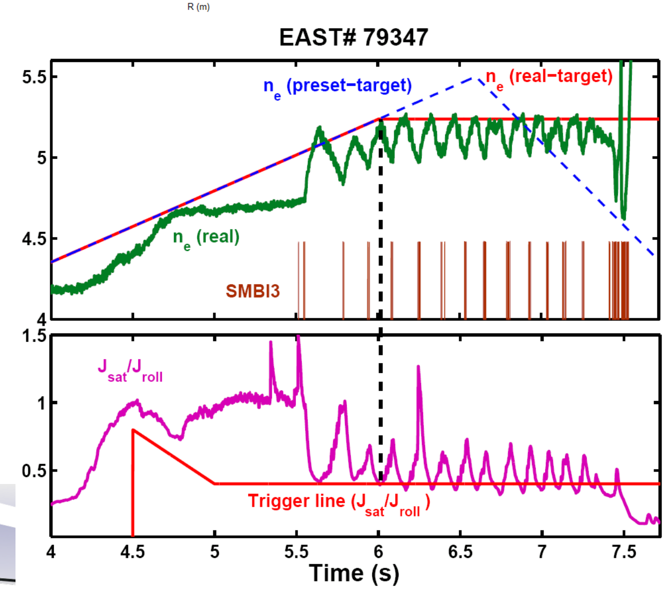
REF: NF(2018)

H-mode detachment by feedback control of Div-LP js with D2 SMBI









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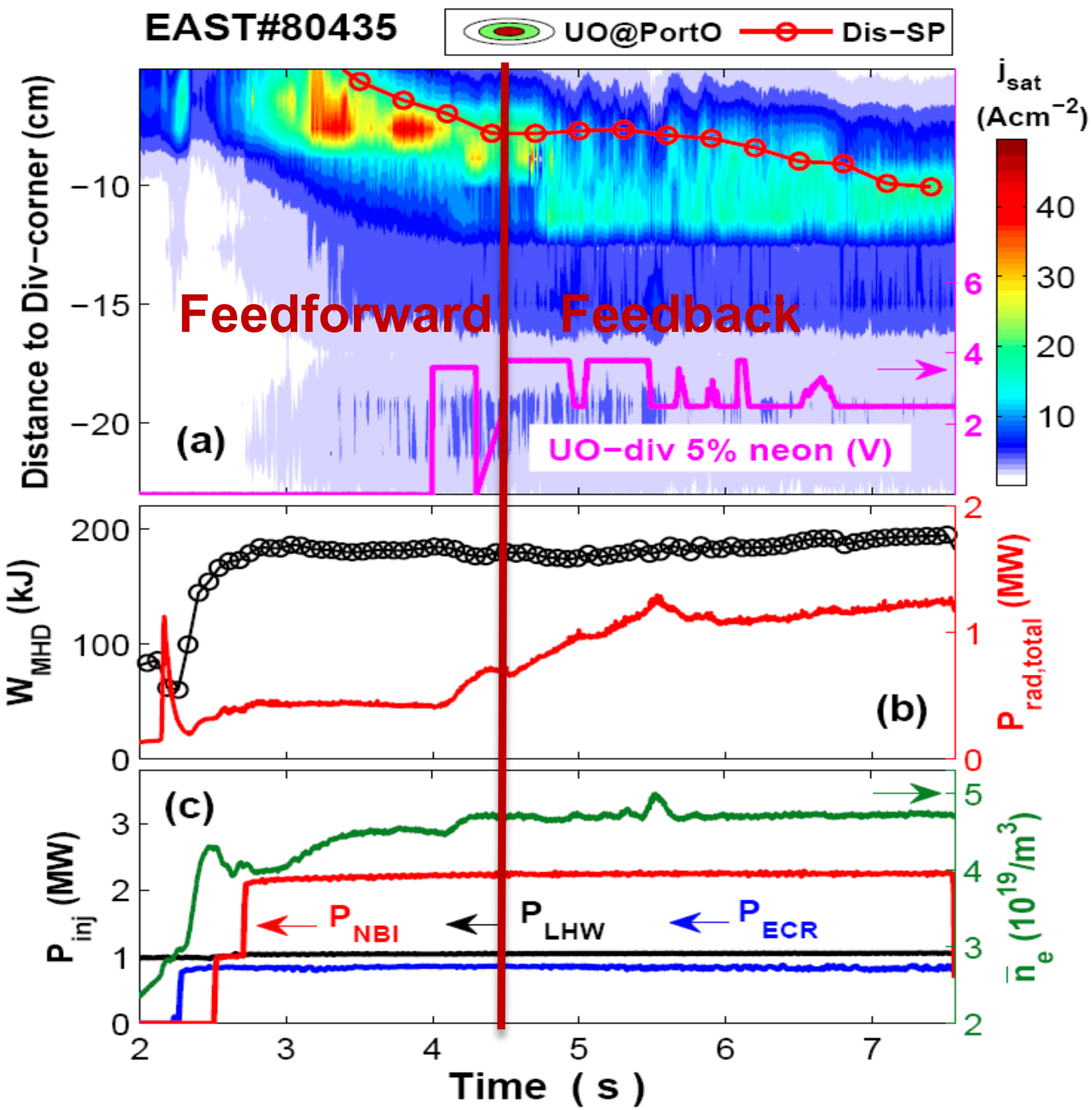
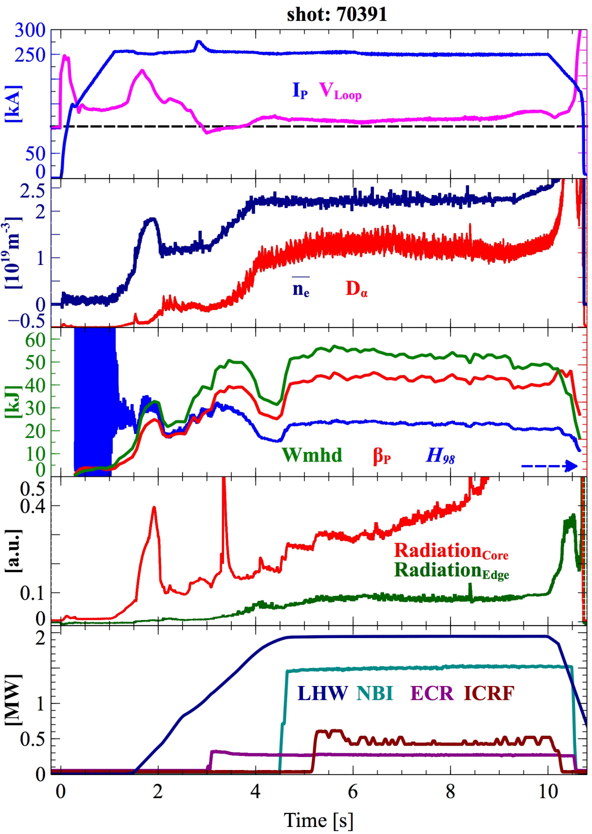
H-mode detachment via feedback controlof Div-LP js module with divertor neon seeding



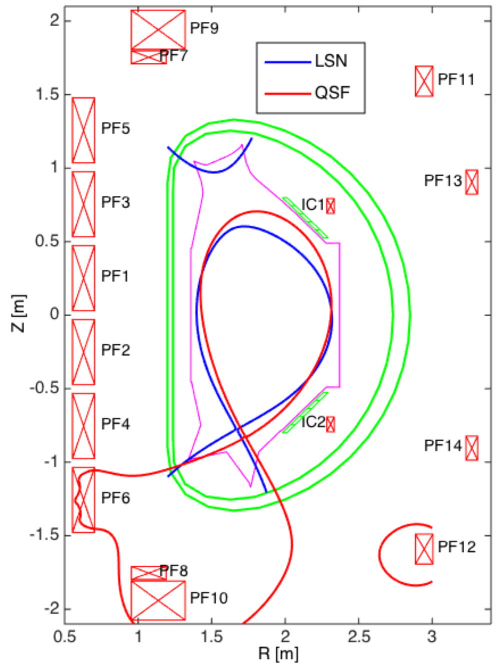
- the particle flux reduced
- the plasma stored energy slightly increases rather than decreases
- the plasma line-averaged density was maintained quite stably

QSF effectively reduces heat load to Div. Target

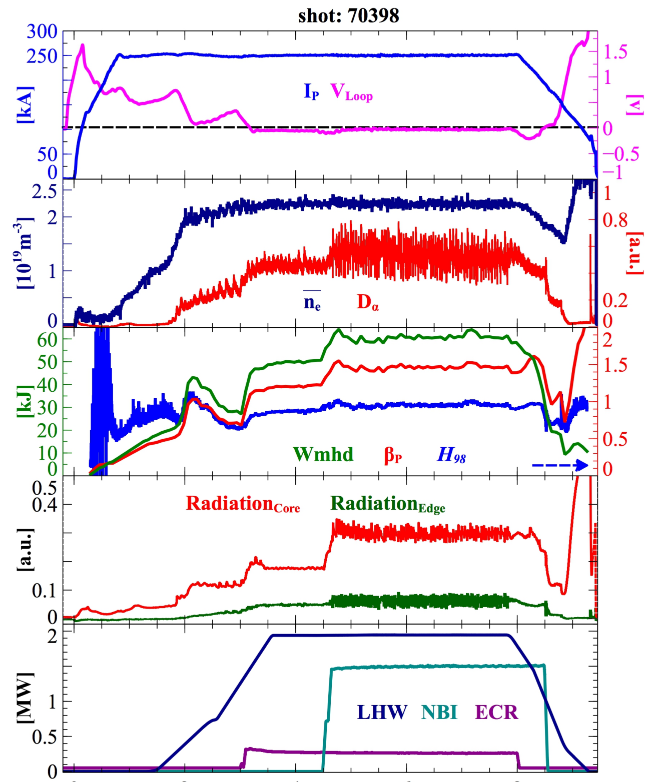
LQSF



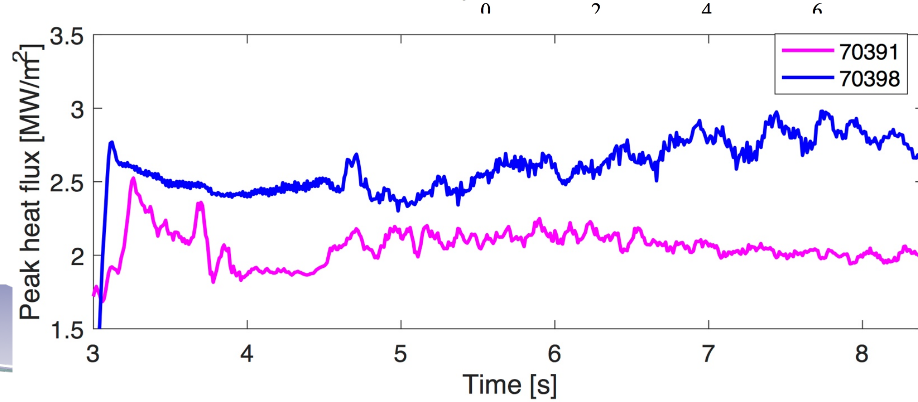
✣Flux expansion of QSF at out strike point is factor ~3 than LSN



LSN



- ✦ IR measurements show a peak heat load reduction for QSF of a factor ~1.5 with respect the LSN



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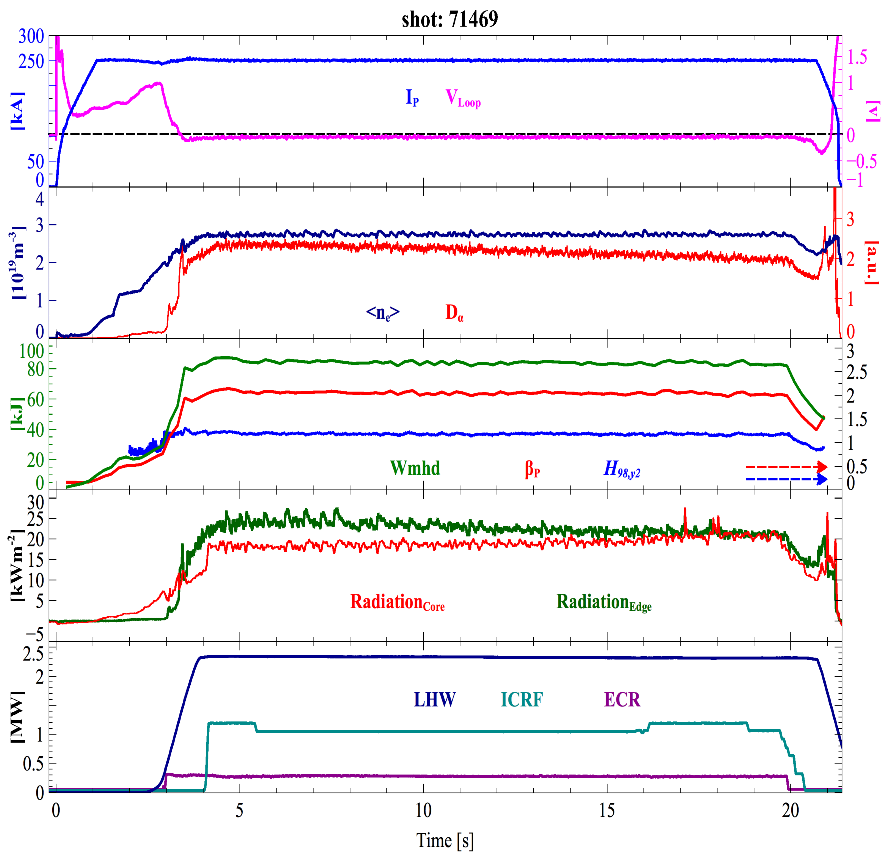
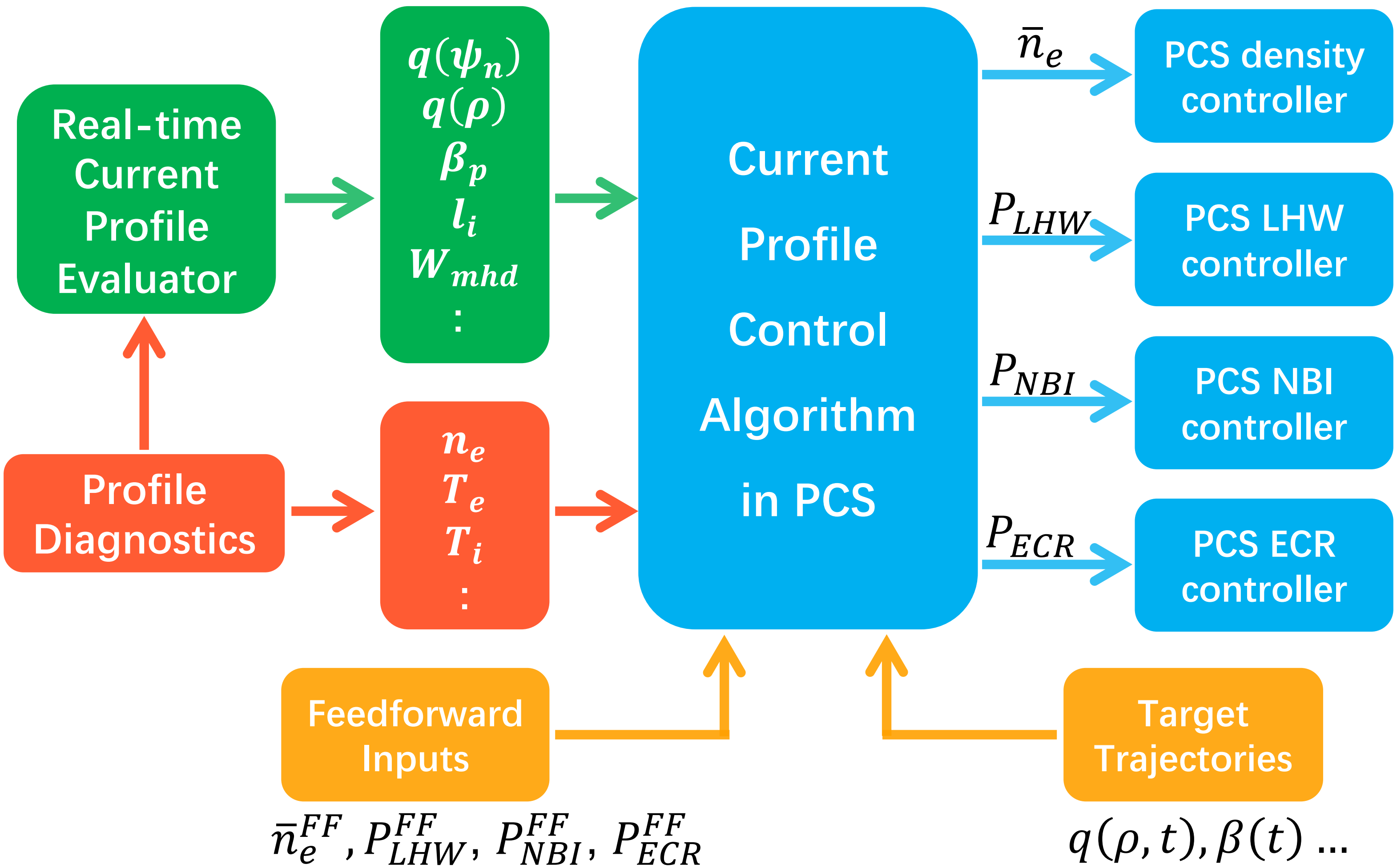
Long-pulse high-confinement ELMy-free UQSF discharge



✓ $V_{Loop} \leq 0.$ $H_{98} > 1,.$ $\beta_P \sim 2$

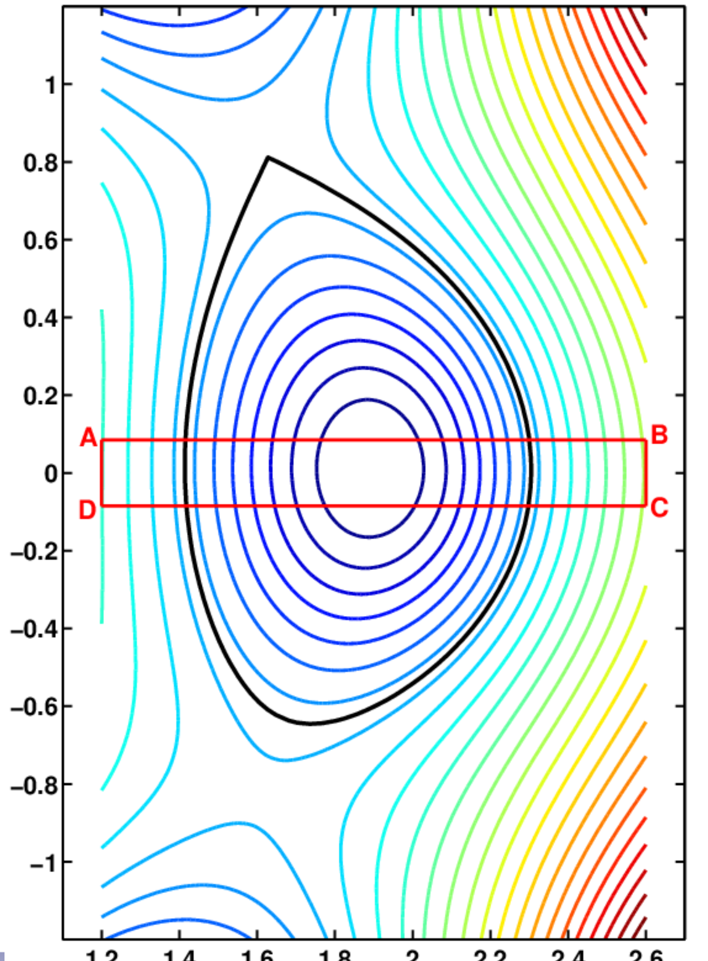
- ✓ A long-pulse operation, ELMy-free high-confinement steady-state pulse, lasting up to 21s, is achieved and limited only by the imposed technical scenario constraints.
- ✓ A stable QSF configuration reached at ~2.7s, whilst the high-confinement was achieved at ~3.5s with H_{98} ~1.2
  - ✓ After 3.5s, until plasma ramp-down, the loop voltage is kept at 0 indicating full non-inductive current drive.
- ✓ Stable plasma parameters are maintained through whole discharge until the plasma ramp-down
  - ✓ Radiation either in the core or in the edge is kept constant, a good particle control & no impurity accumulation.

Framework of plasma current profile control in EAST



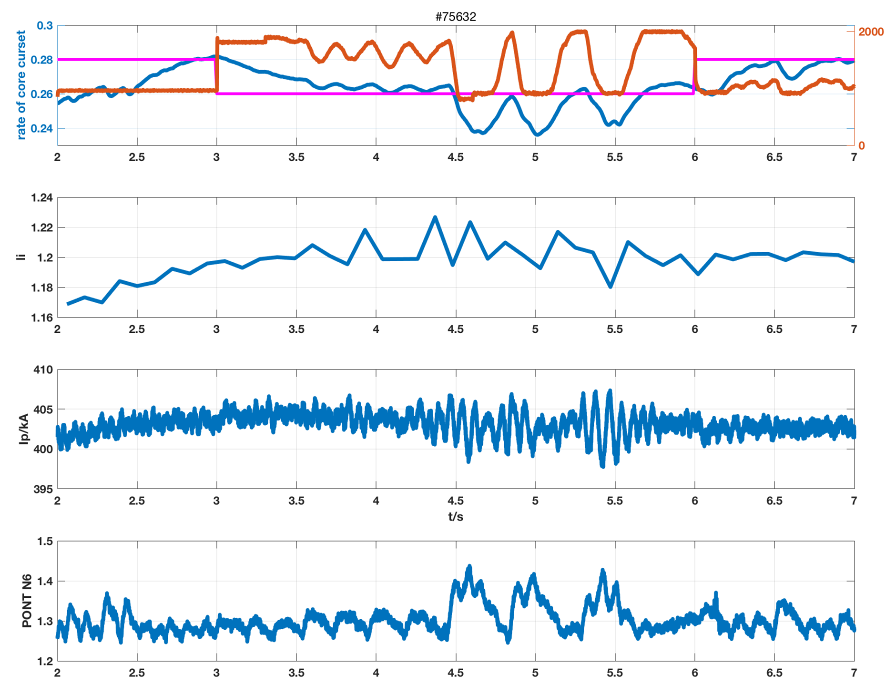
Preliminary Plasma current profile control in EAST

Current Profile Evaluator: $\mu_0 J_0 \approx \dfrac{POINT\_F5}{POINT\_N5} - \dfrac{POINT\_F7}{POINT\_N7} \quad J_{Ratio} \approx \dfrac{J_0}{I_P}$



Target Trajectories: $J_{Ratio} \to 0.26$

Actuator: 4.6G Low Hybrid Wave



Summary

- For CFETR engineering design, a collaborative network, design platform and database, and document management have been built.
- CFETR CODAC and PCS development started.
- A series of plasma control researches have been conducted aiming at more robust magnetic control and controllability, kinetic control and heat load control and demonstration of future CFETR plasma controls.