ASIPP

The design and implementation of a new plasma control system

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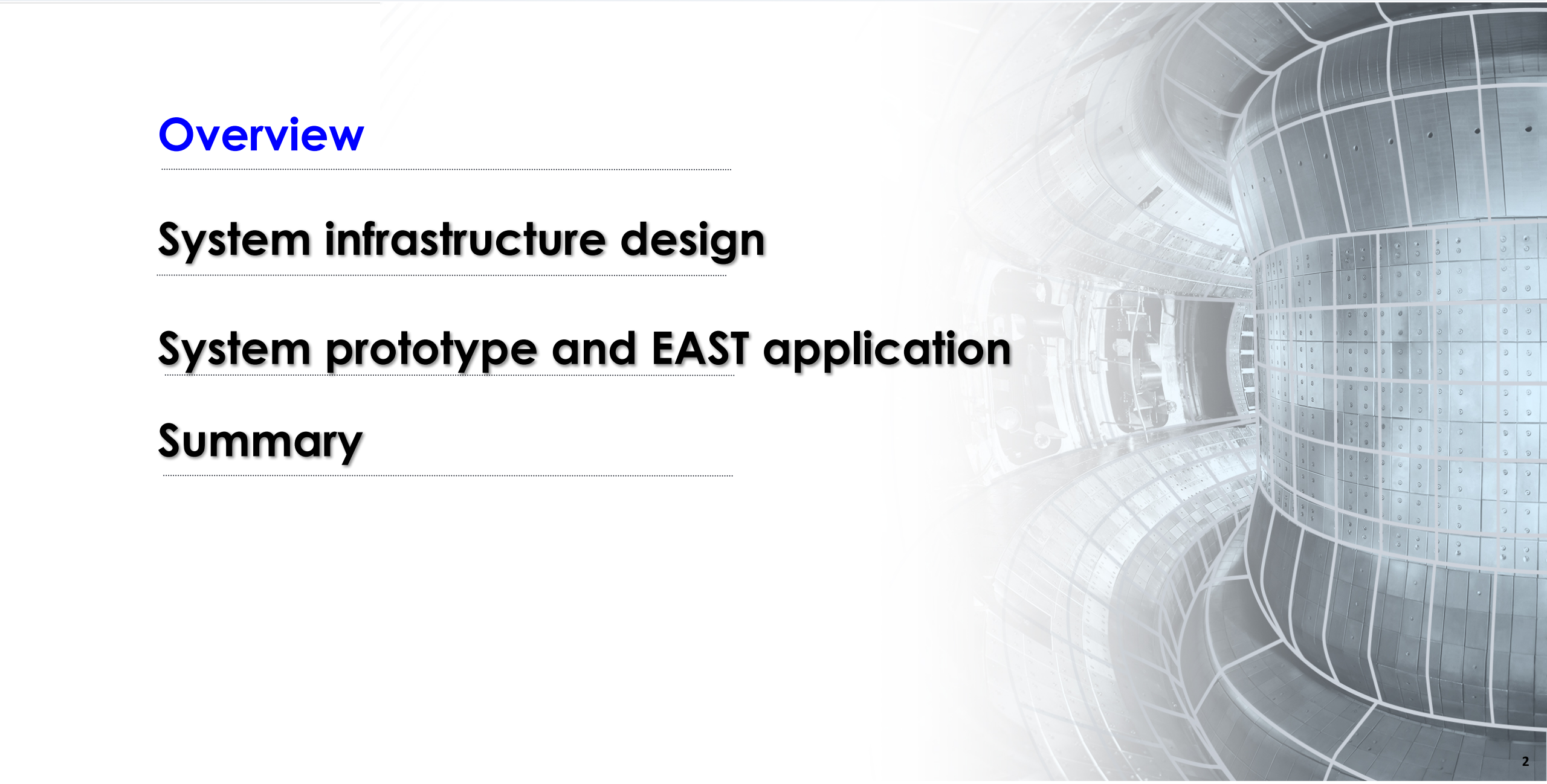
Outline

ASIPP



Overview

System infrastructure design

System prototype and EAST application

Summary

Fusion research strategy at ASIPP

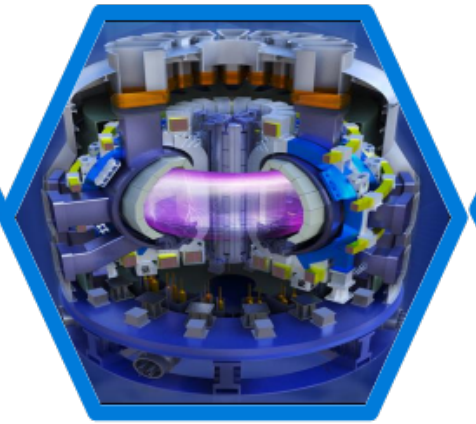
ASIPP

Operating	Constructing	Designing	Joining	Planning
Plasma physics, steady-state operation	14 key sub. sys R&D For BEST, CFETR Non nuclear	DT operation supporting ITER	DT 400s Q=10 3000s Q=5	<500MW, 5y 500MW, TBR=1, 5y 1-1.5GW, TBR>1, 5y
(2007-2030)	(2025-2040)	(2027-2045)	(2025-2045)	(2036-2050s)

FPP

EAST

CRAFT



BEST

ITER

CFETR

What needs to be done for future reactor control

For present tokamaks and future fusion reactors, the control of plasma initiation, shaping, heating, current drive, stabilization, and safe termination of discharges is required.

Infrastructure development to support steady state operation

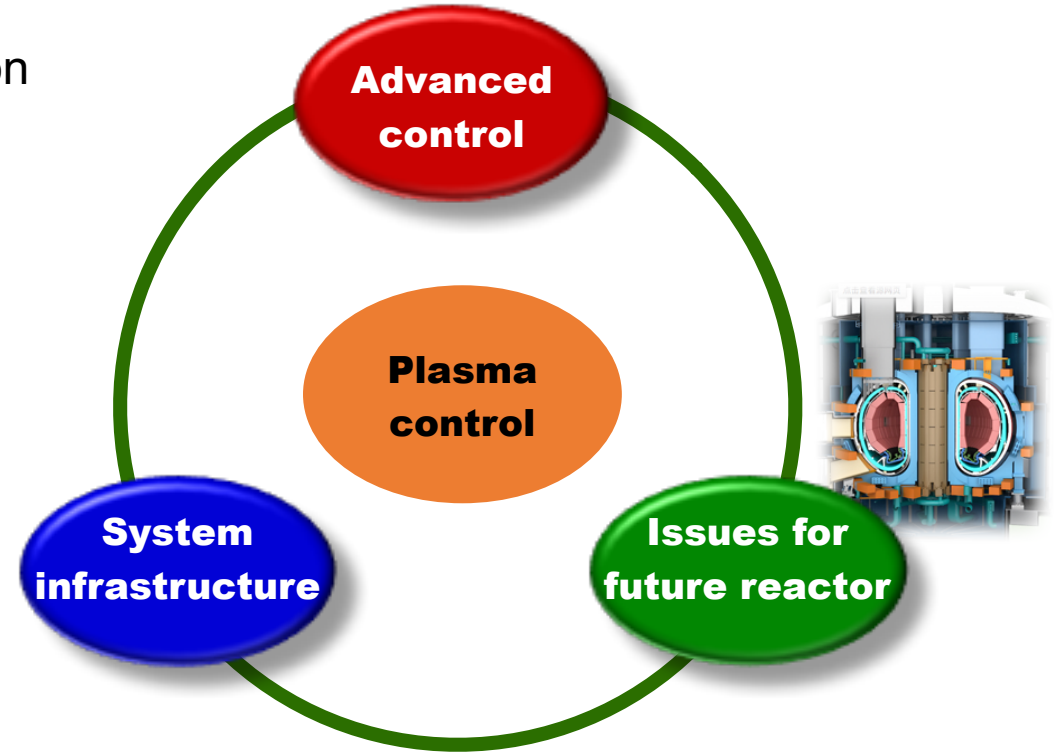
- Hardware and software infrastructure
- Assistant platforms for algorithm development and verification

Simulation for control

- Controller design and verification
- Optimization of control parameters and scenarios

Development of control algorithms

- Magnetic control
- Kinetic control
  radiation control, profile control…
- Nuclear operation
  burning control, fusion power control…
- Event handling



Outline

Overview

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System prototype and EAST application

Summary

System Infrastructure Requirement

User cases

programmer

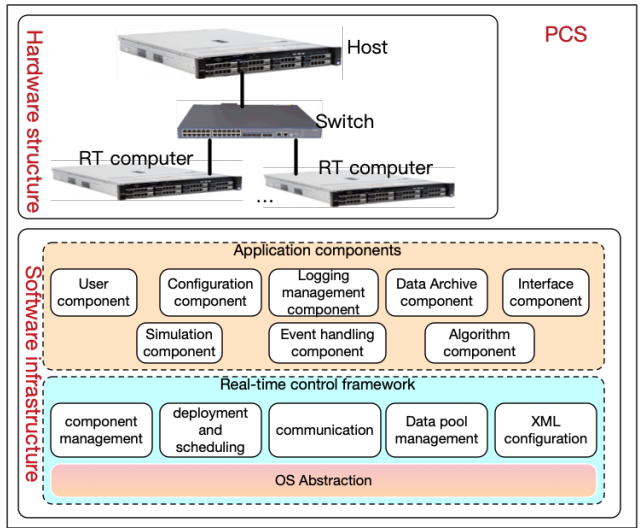
Integrate control functions

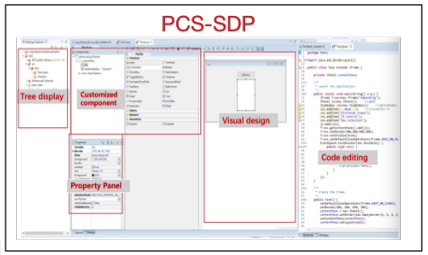
- Friendly development environment
- Module development support
- Data communication and access
- Algorithm test tool
- Code management

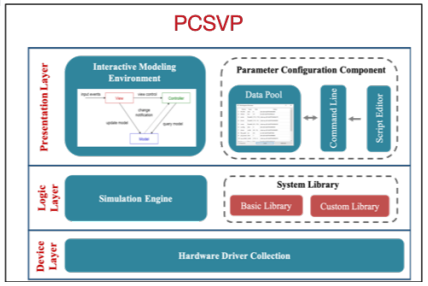
Experiment operators

Plasma control

- Discharge parameter configuration
- Workflow management
- Control schedule
- Real-time control execution
- Event handling
- Data archiving
- Log management
- Reliability assurance





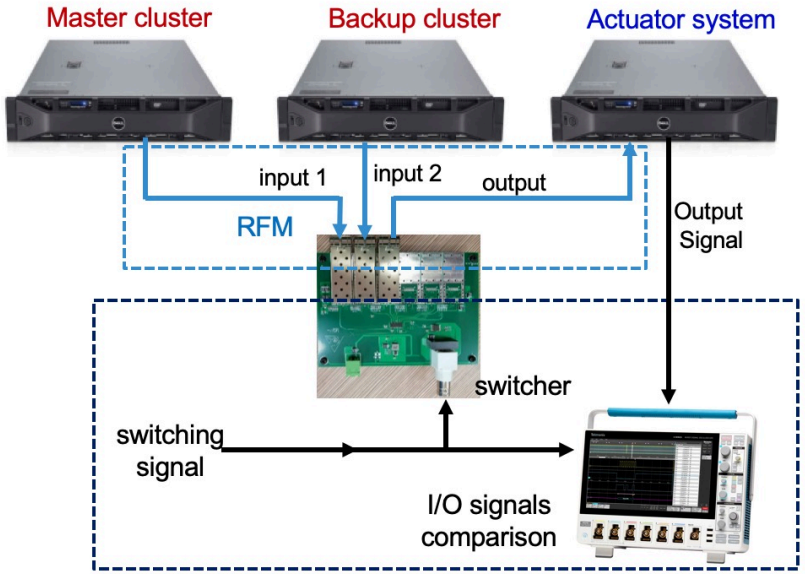


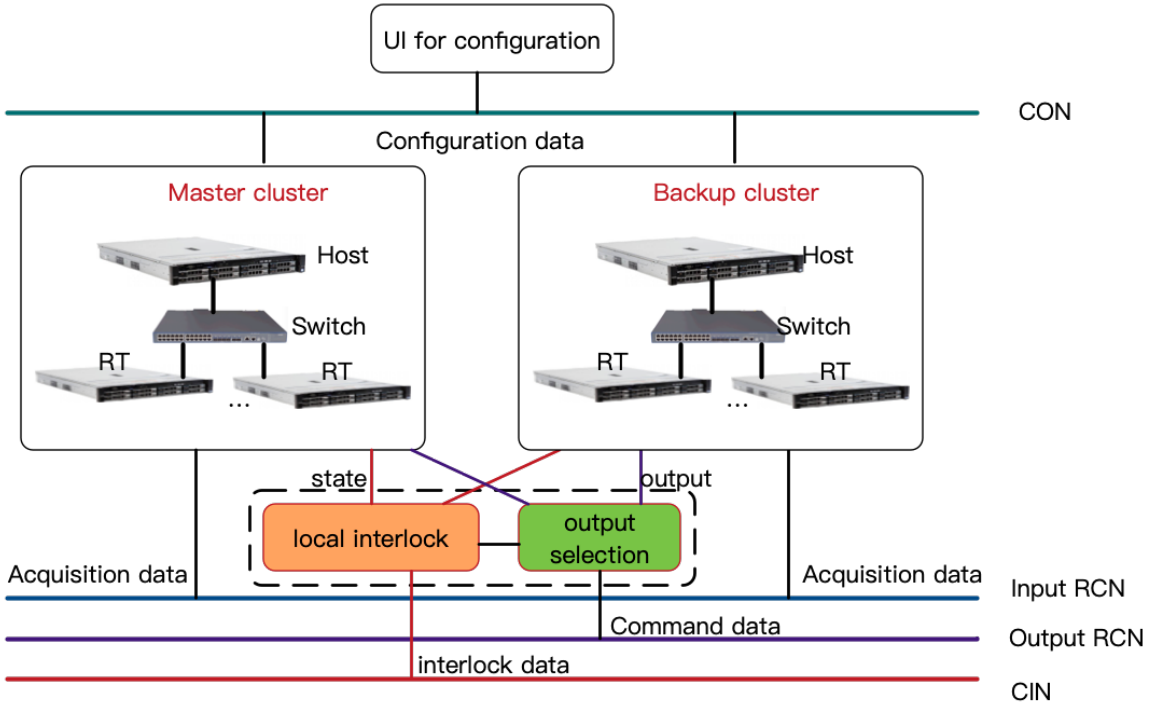
- Scalable H/S infrastructure + two assistant platforms
- Algorithm development platform (PCS-SDP) shall provide a visual and convenient programming environment.
- PCS simulation environment (PCSVP) which can be used to develop controllers and architecture, as well as to validate pulses before execution.

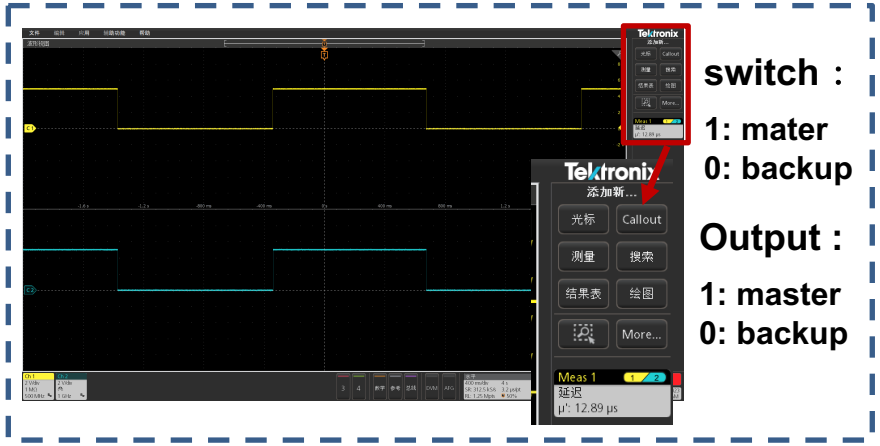
Hardware infrastructure design

Redundant clusters system

- Non real time applications and real-time control calculation will be deployed on HOST and RT computers.
- Master and backup cluster run synchronously and can be real-time switched in one control cycle.
- Transparent hardware access ensures the portability and scalability of the system.





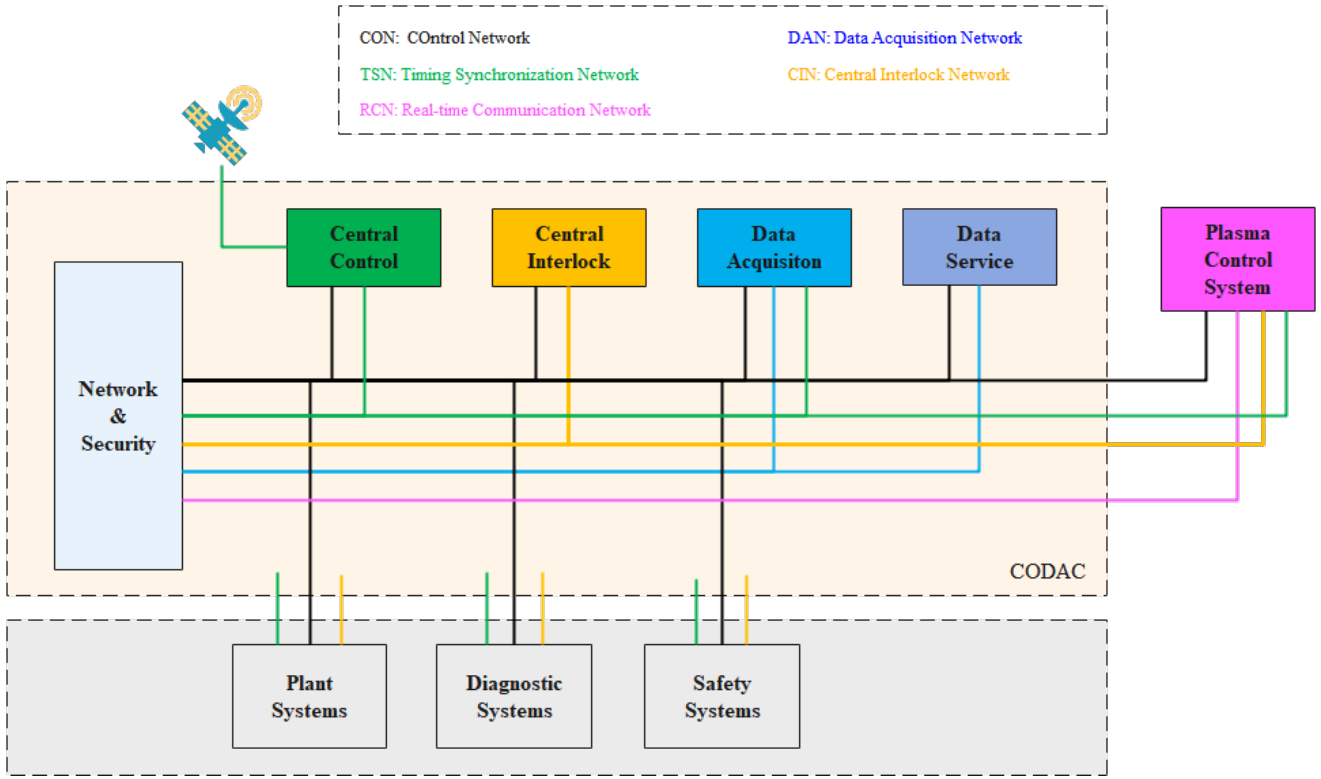


switch and output delay：12.89 μs

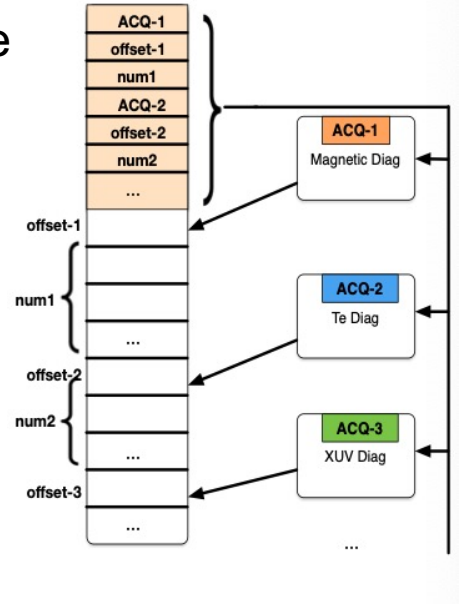
Hardware switch + RFM read + I/O output

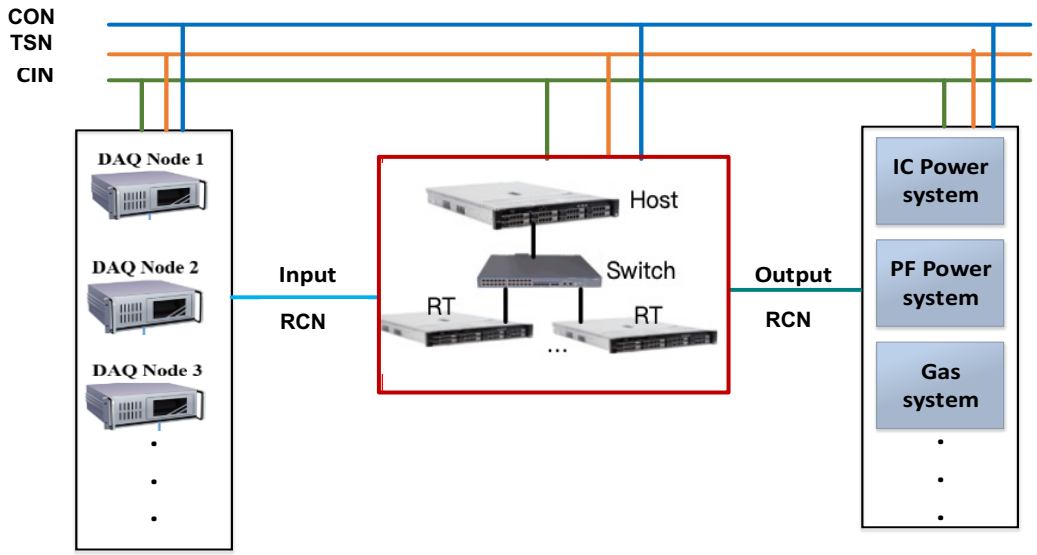
Interface design

- External systems related to plasma control include **central control system**, **central interlocking system**, distributed real-time **acquisition systems**, **actuator plants**.
- Interface to CODAC and CIS through CON, RCN, CIN



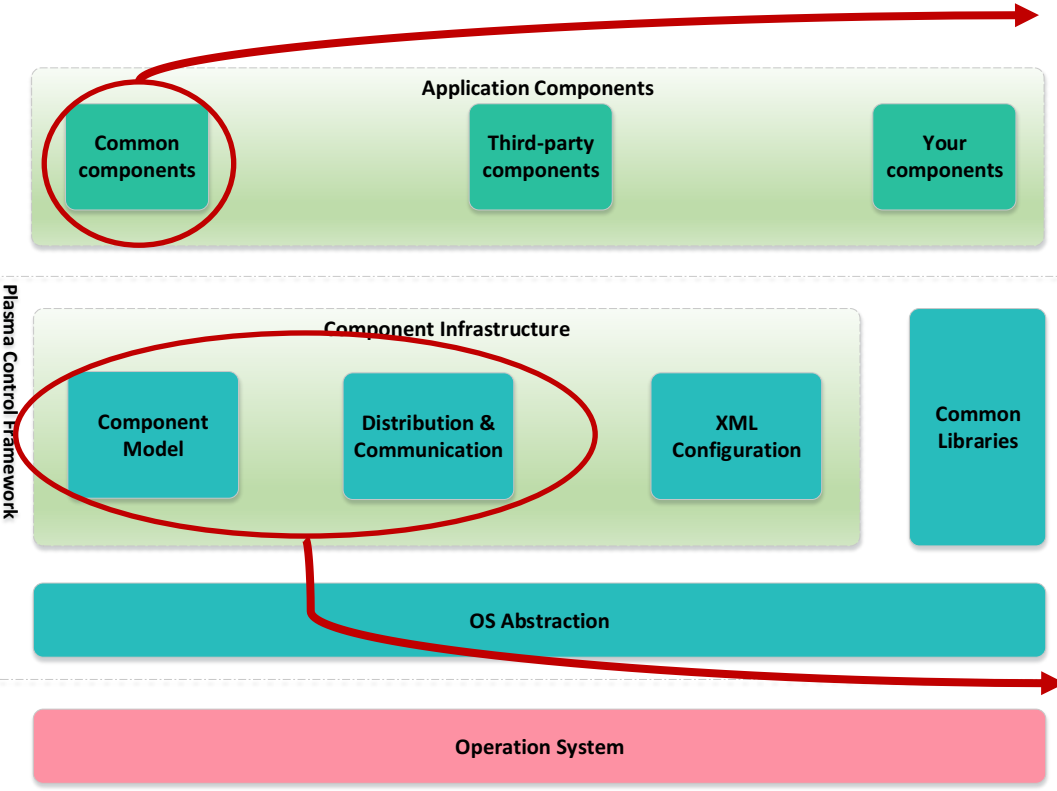
- Two separate RCNs are deployed for real-time data I/O.
- Communication head information is designed for easy extension.

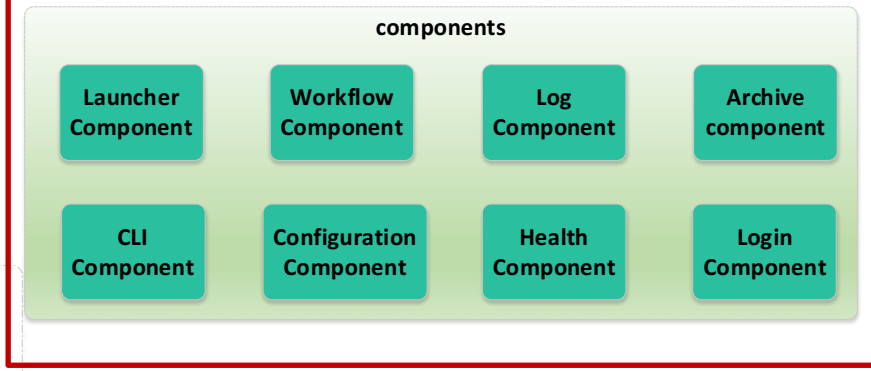




Software infrastructure design

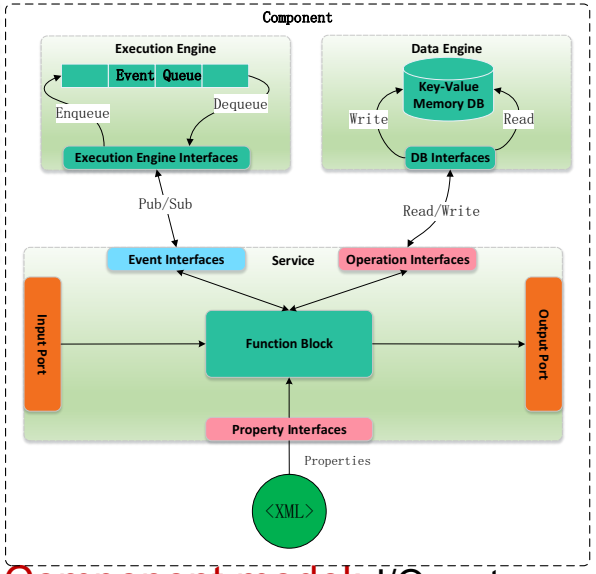
Component-based distributed real-time control framework



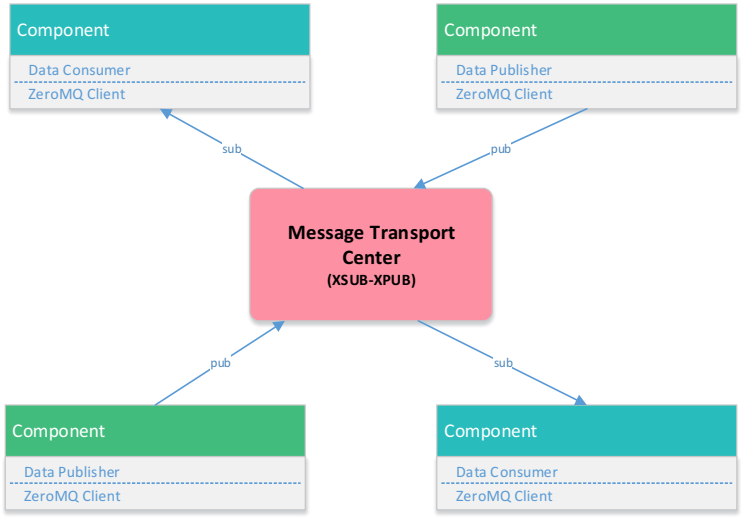


- User login
- Parameter configuration
- Deploy and workflow
- Data archiving
- Log and healthy

…



Component model: I/O port, property and operation interface

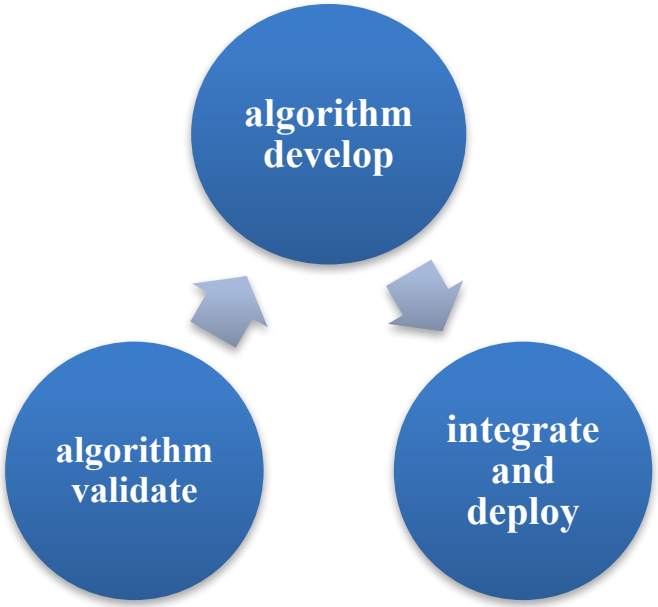


Communication : ZeroMQ (non real-time), Shared memory (real-time)

- The core framework provides communication, XML configuration, data management, etc.
- Various application components can be expanded like Lego blocks building.

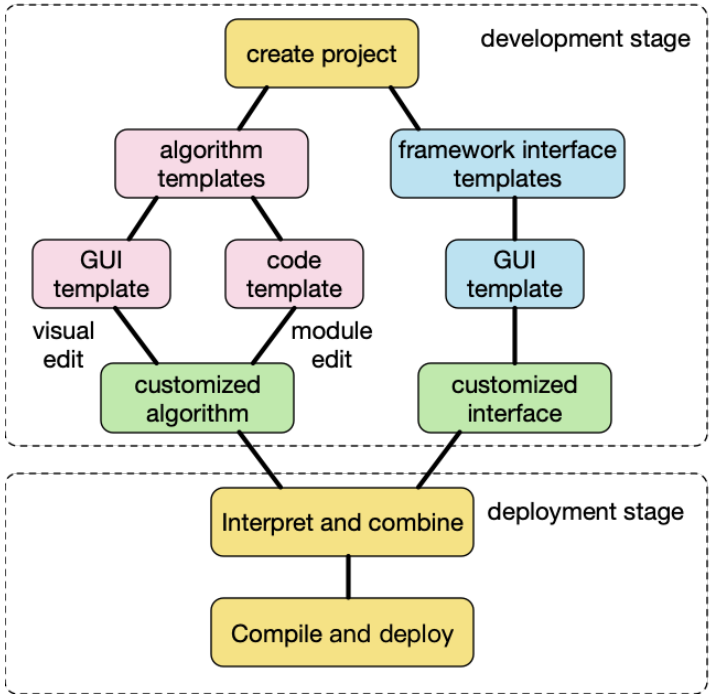
Design for algorithm development and integration

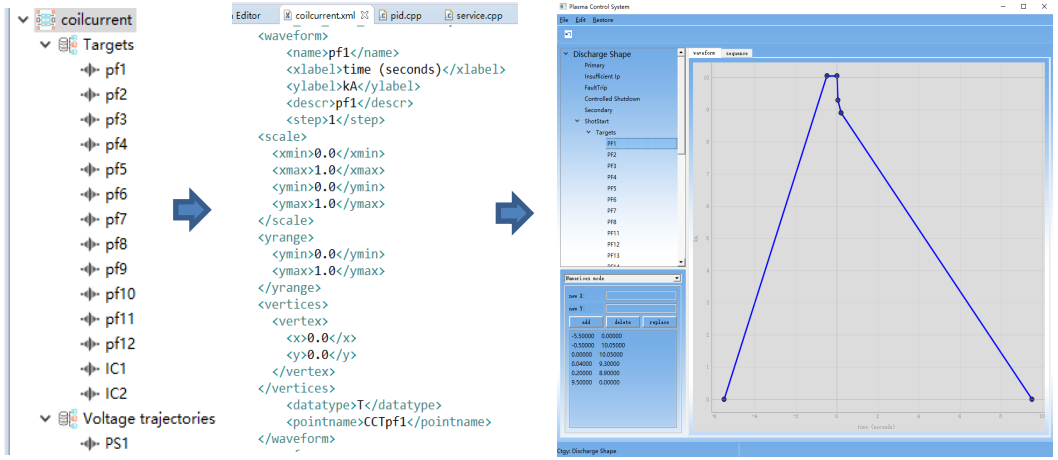
User case 1



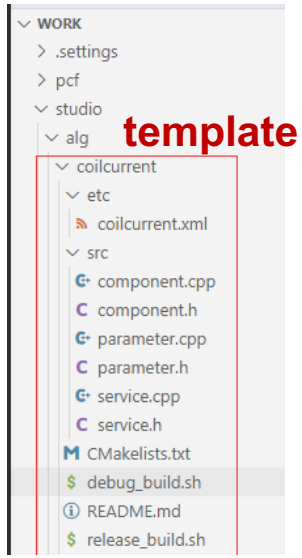
Visual algorithm development based on PCS-SDP

- Shield the difference of control framework
- Visual interface development
- Algorithm template compatible with real-time framework





Drag and drop → XML files → Embed in UI



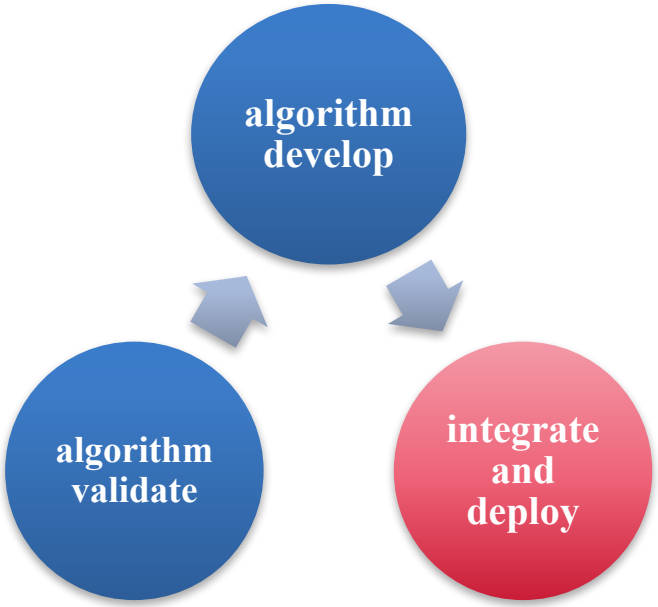
template

Automatic code generation

```
// float parameter
std::map<std::string, float*> float_params = {
    {"alg.cc.pf1", &pf1},
    {"alg.cc.pf2", &pf2}
};

for (auto iter : float_params) {
    std::string key = iter.first;
    float* value = iter.second;
    pcf::attr::add(key, *value, *this);
    pcf::attr::param::set<bool>(key, "archive", true);
}

// int parameter
std::map<std::string, int*> int_params = {
    {"alg.cc.pf3", &pf3},
    {"alg.cc.pf4", &pf4}
};

for (auto iter : int_params) {
    std::string key = iter.first;
    int* value = iter.second;
    pcf::attr::add(key, *value, *this);
    pcf::attr::param::set<bool>(key, "archive", true);
}
```

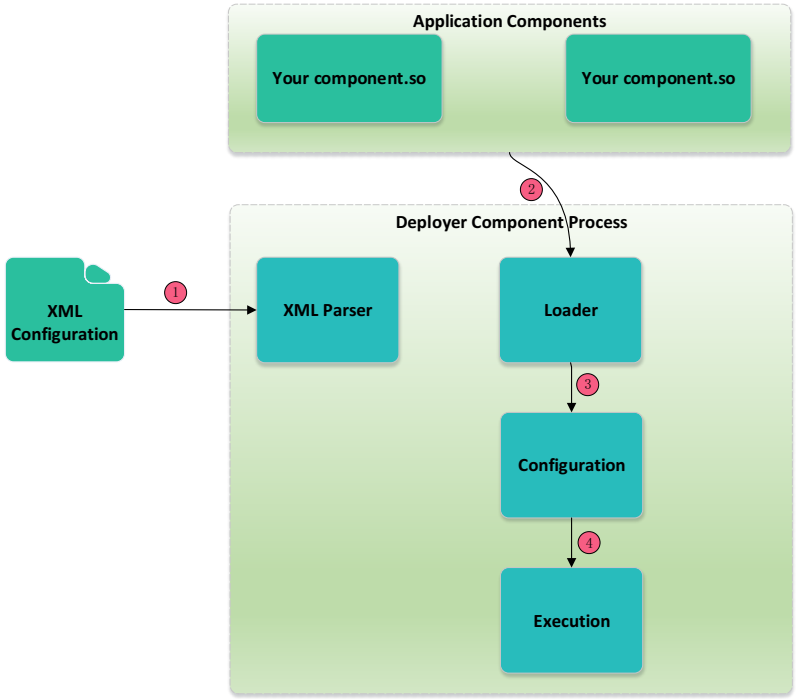
Design for algorithm development and integration

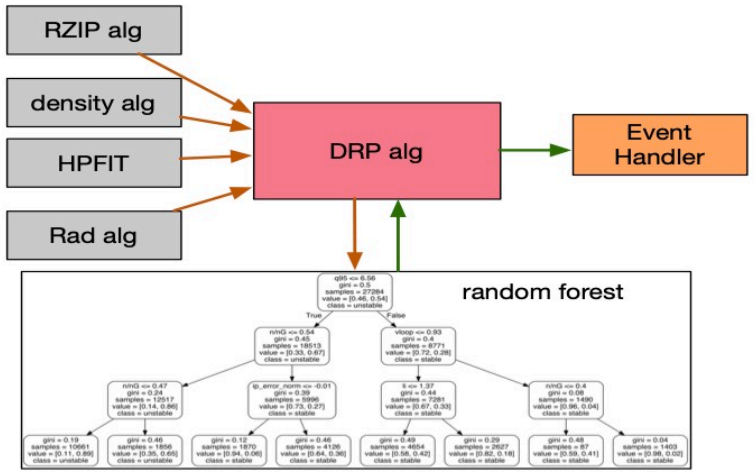
User case 1

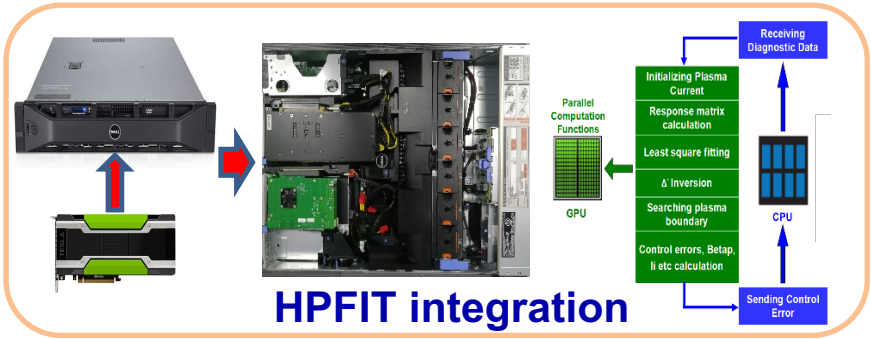


Flexible deployment based on XML configuration

- The framework supports modular development, compilation and loading.
- Support rapid integration of third-party algorithm library.
- Flexible deployment can be realized according to the XML configuration.
- Real time processes are deployed and bound on physical CPU cores.

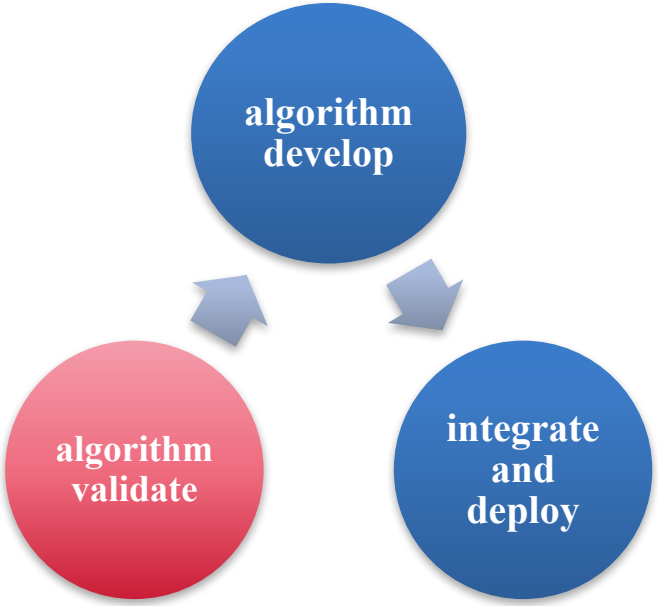






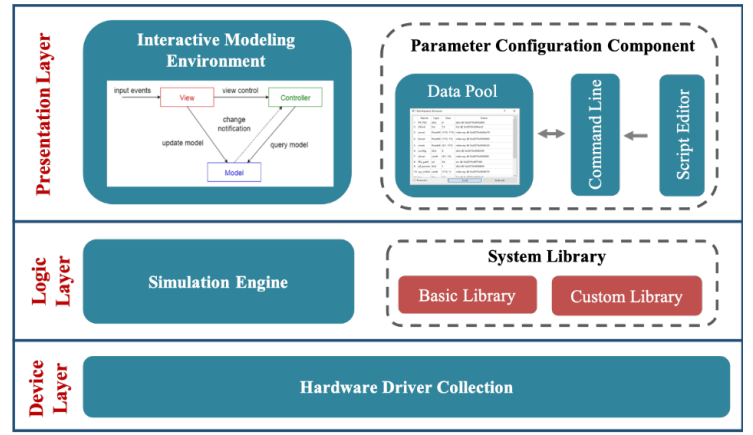
Design for algorithm development and integration

User case 1

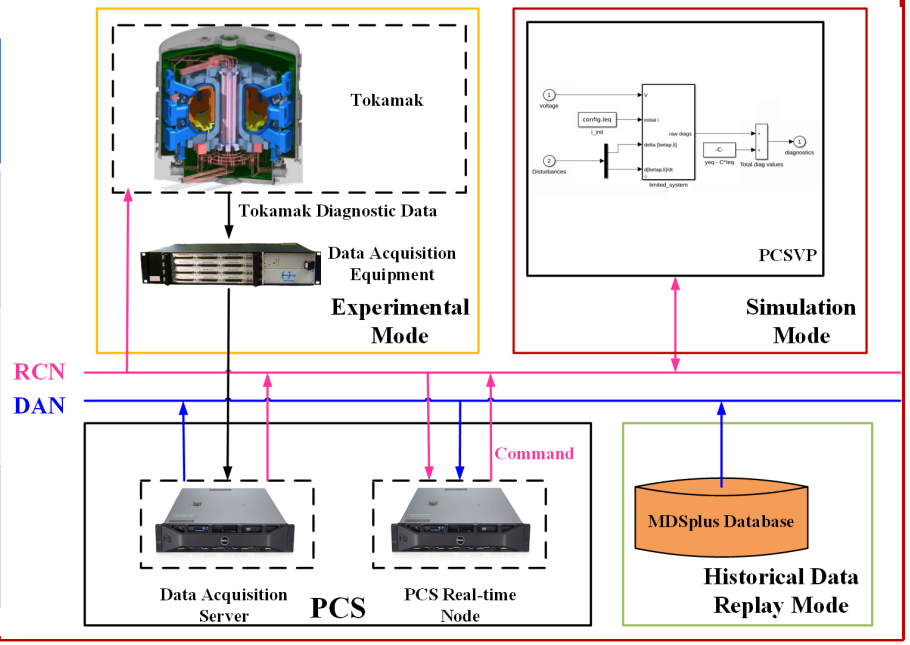


Support multiple operation modes

- The algorithm needs to be fully validated by simulation test.
- PCS supports multiple operation modes including normal experimental mode and simulation test mode.
- Python based verification platform PCSVP supports visual modelling and similar functions as Simulink.

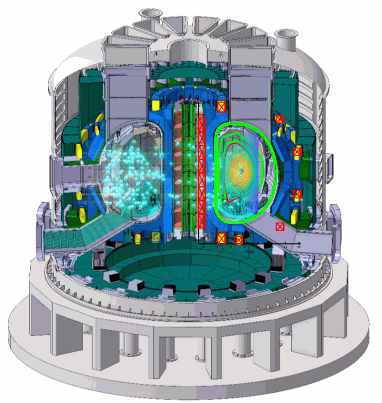


Mode	Data source	Command to go
Normal	Real-time data acquisition	Actuators
Simulation based on **data**	Historical data	/
Simulation based on **model**	Model calculation	Model



Design for control operation

User case 2

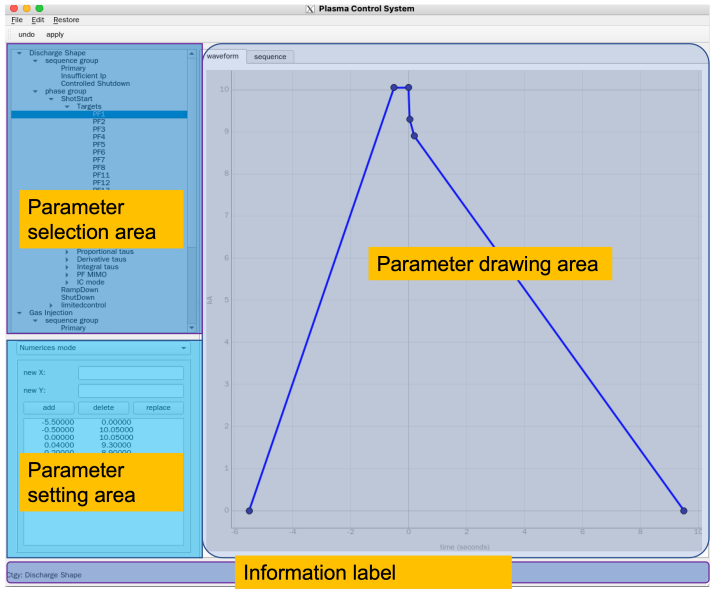


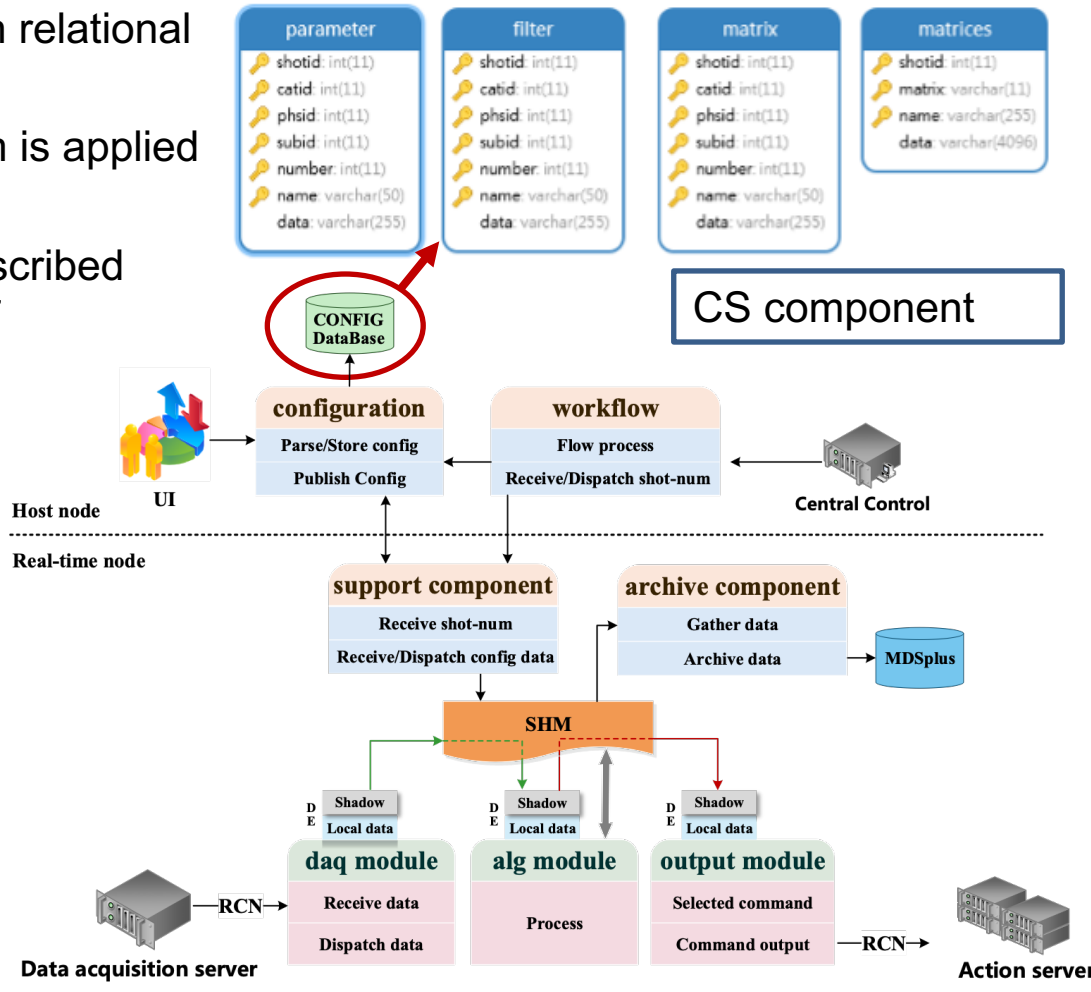
- parameter configuration management
- discharge workflow management
- schedule and control execution
- data archiving

Parameter configuration management

- Parameters are configured with XML, configuration datasets are stored in relational database.
- Subscription publishing mechanism is applied between UI and CS component.
- Data in different components is described through IDL to shield differences of programming languages.

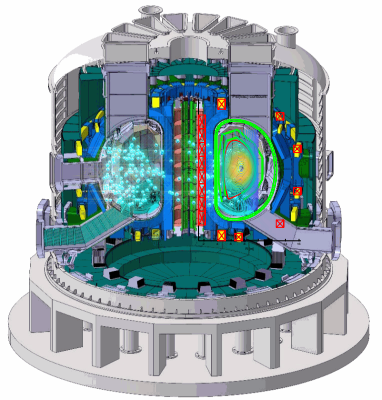
PCS#2: Design of Data Management for New Plasma Control System (87)





Design for control operation

User case 2



- parameter configuration management
- discharge workflow management
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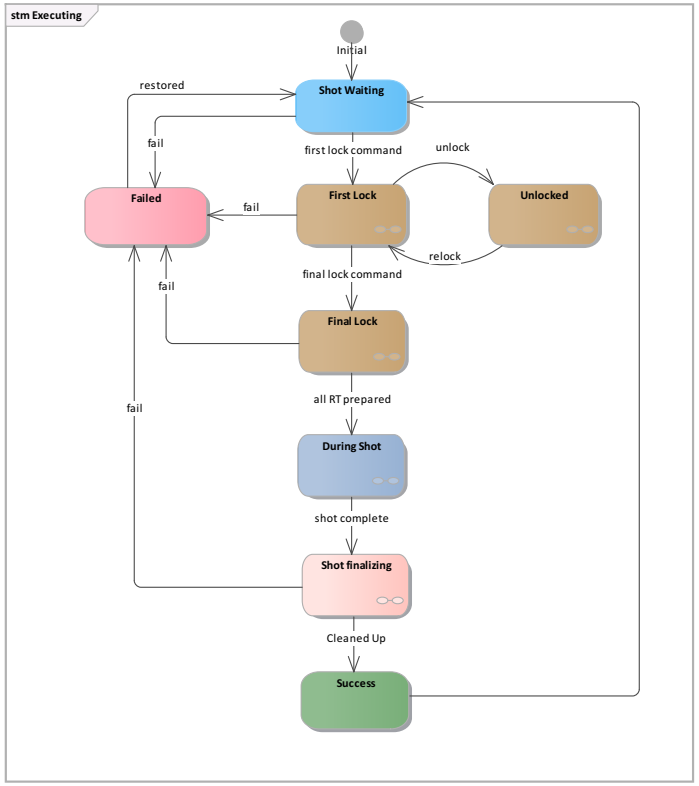
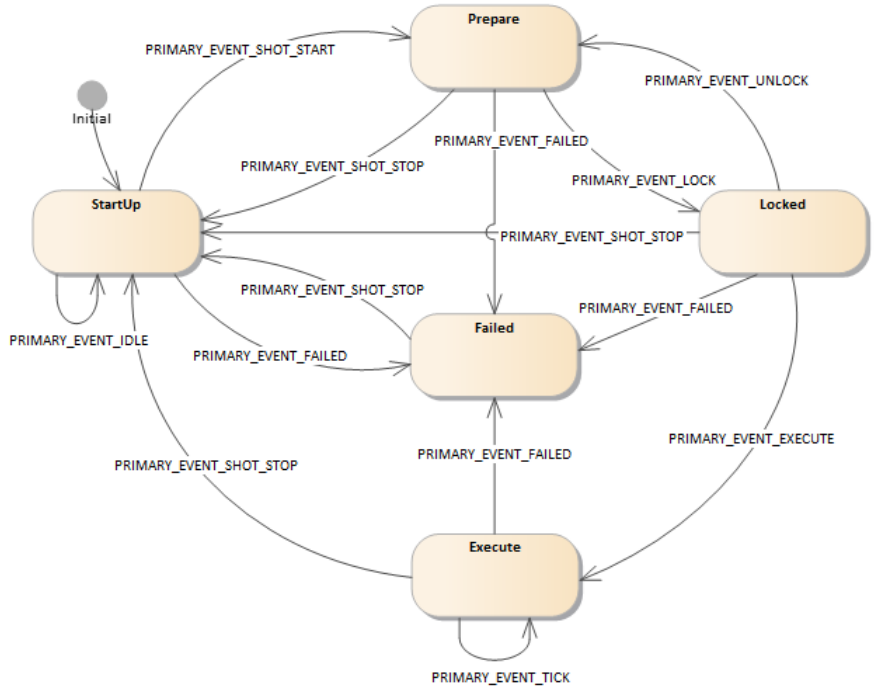
Discharge workflow management

Workflow component

- The whole plasma control workflow is controlled by workflow component which is a state machine.
- Each real-time process is managed by the local state machine.
- Key information during operation will be recorded in the log.

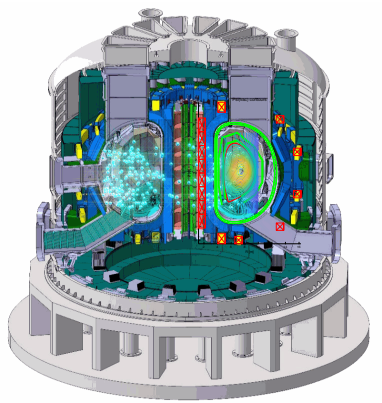




Local state machine

Design for control operation

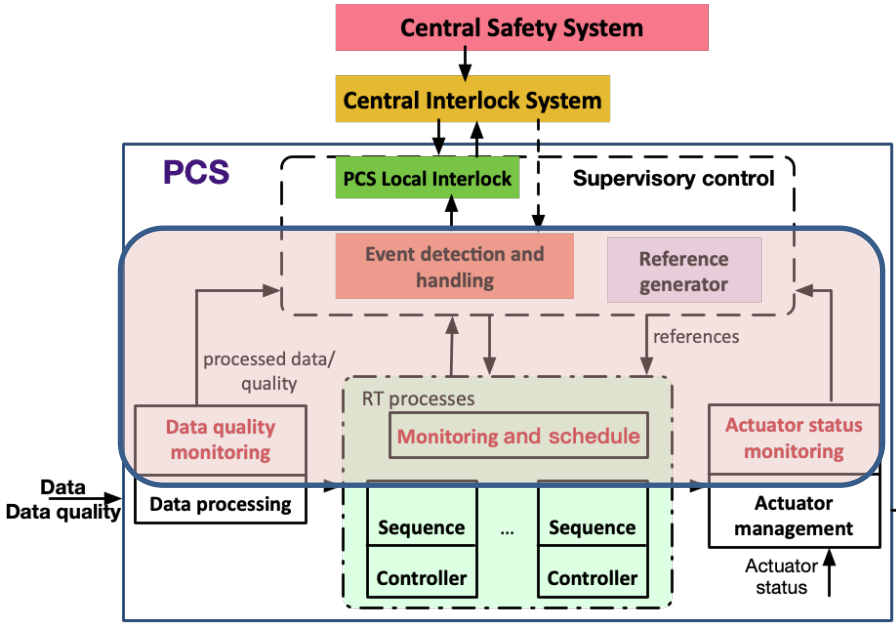
User case 2



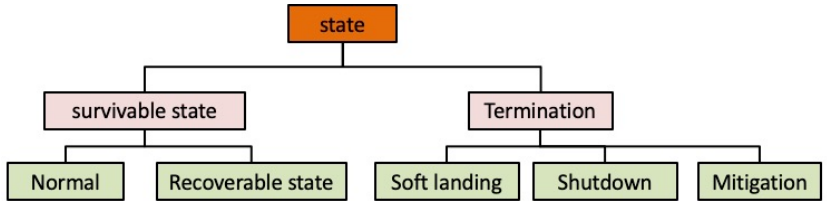
- parameter configuration management
- discharge workflow management
- schedule and control execution
- data archiving

Schedule and event handling

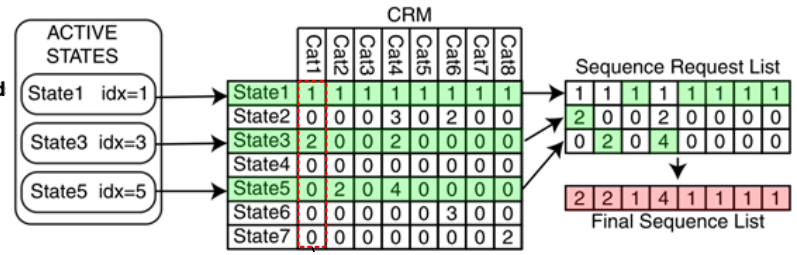
- PCS supports event detection and handling.
- The plasma discharge process is described by several limited states, and event triggers state migration.
- The execution sequence is determined according to the priority if multiple parallel states are triggered.



Status classification

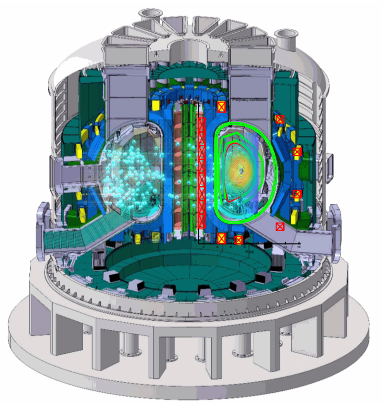


Event handling decision



Design for control operation

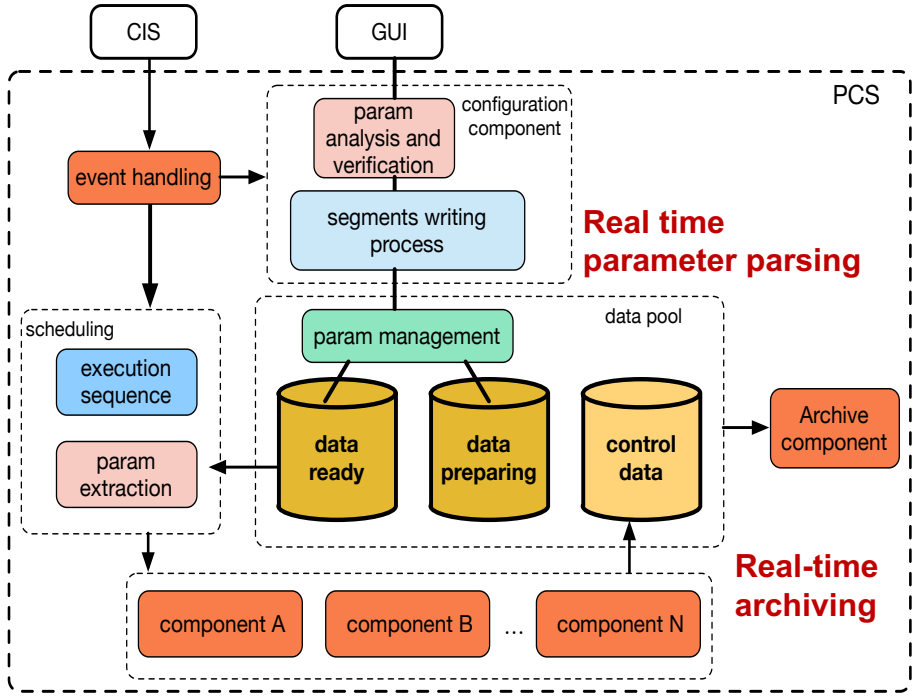
User case 2



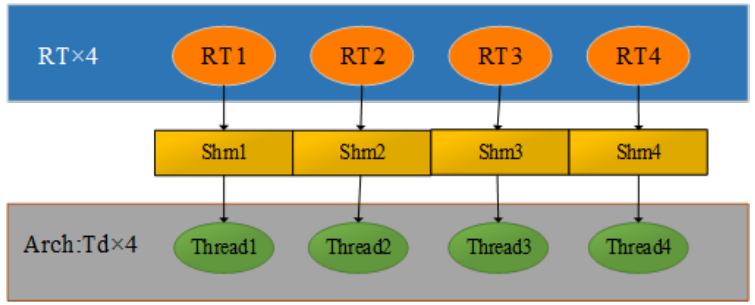
- parameter configuration management
- discharge workflow management
- schedule and control execution
- data archiving

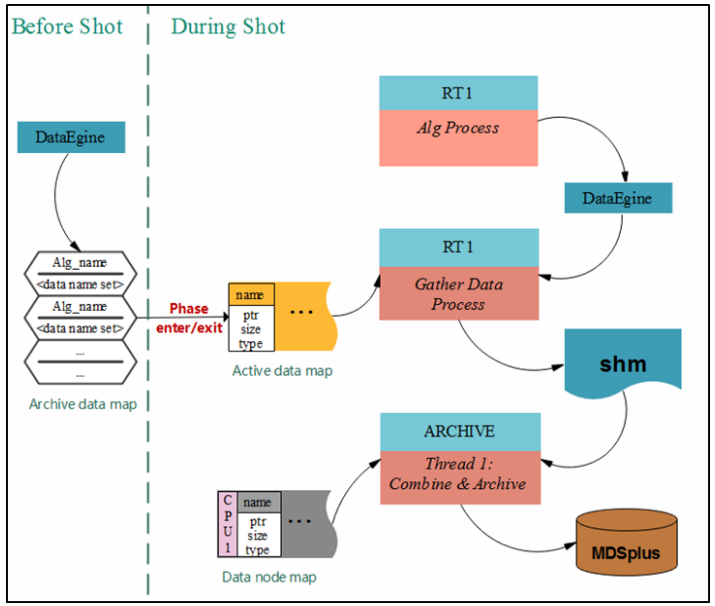
Real time data archiving

- There are archiving processes corresponding to each real time process.
- All data are stored and accessible in real-time.
- The stored procedure is independent from the storage medium.



Archiving component

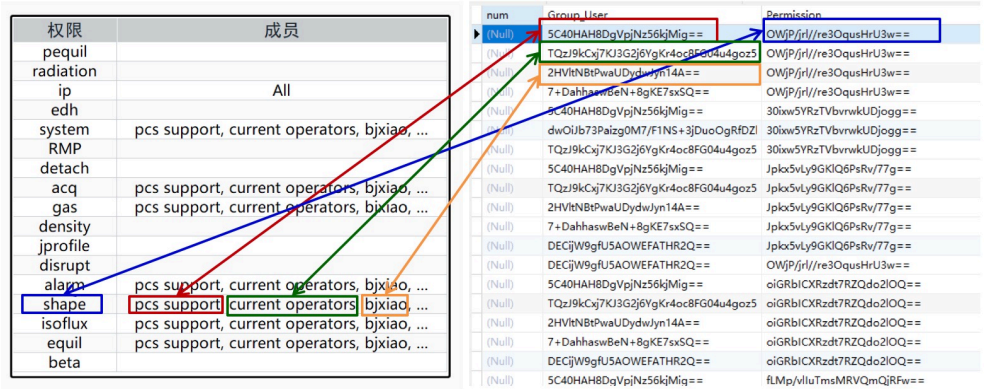




Design for system safety and reliability

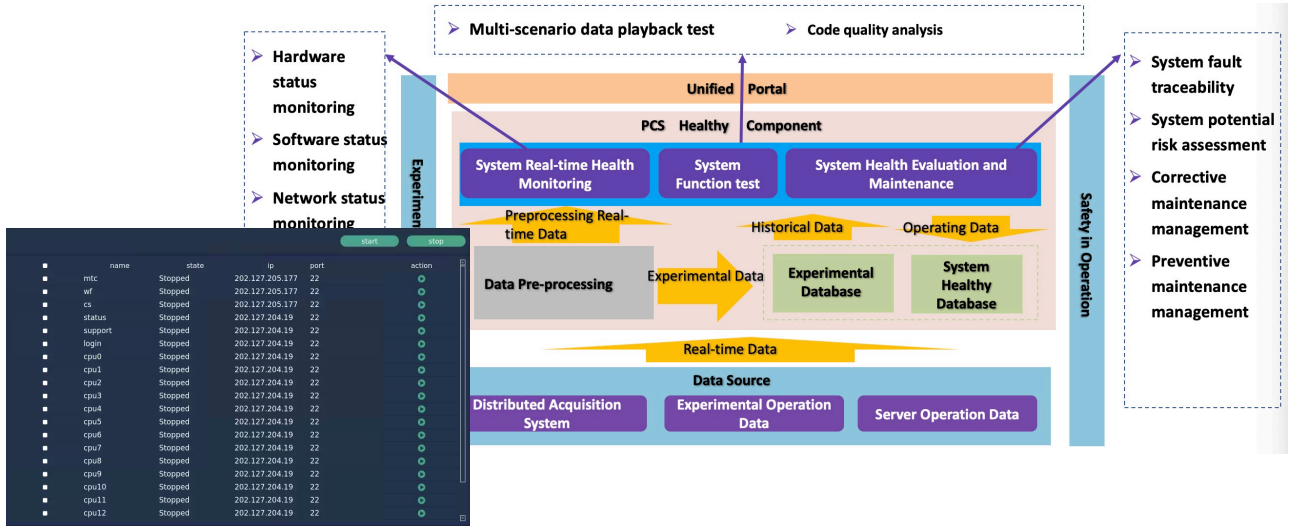
Data and transmission security

- Manage user permissions, verify user's identity, only authorized users can modify parameters.
- Check the rationality of setting parameters.
- Store user information and parameter data in encryption way.
- Ensure data transmission security through redundant networks.



Logs and health monitoring

- Record user operation and key information during shot in the log.
- Log component communicates with other components through subscription publishing mechanism.
- Real-time monitor the hardware status and processors' heartbeat.
- The processes are monitored and managed on the web-based platform.



Outline

Overview

System infrastructure design

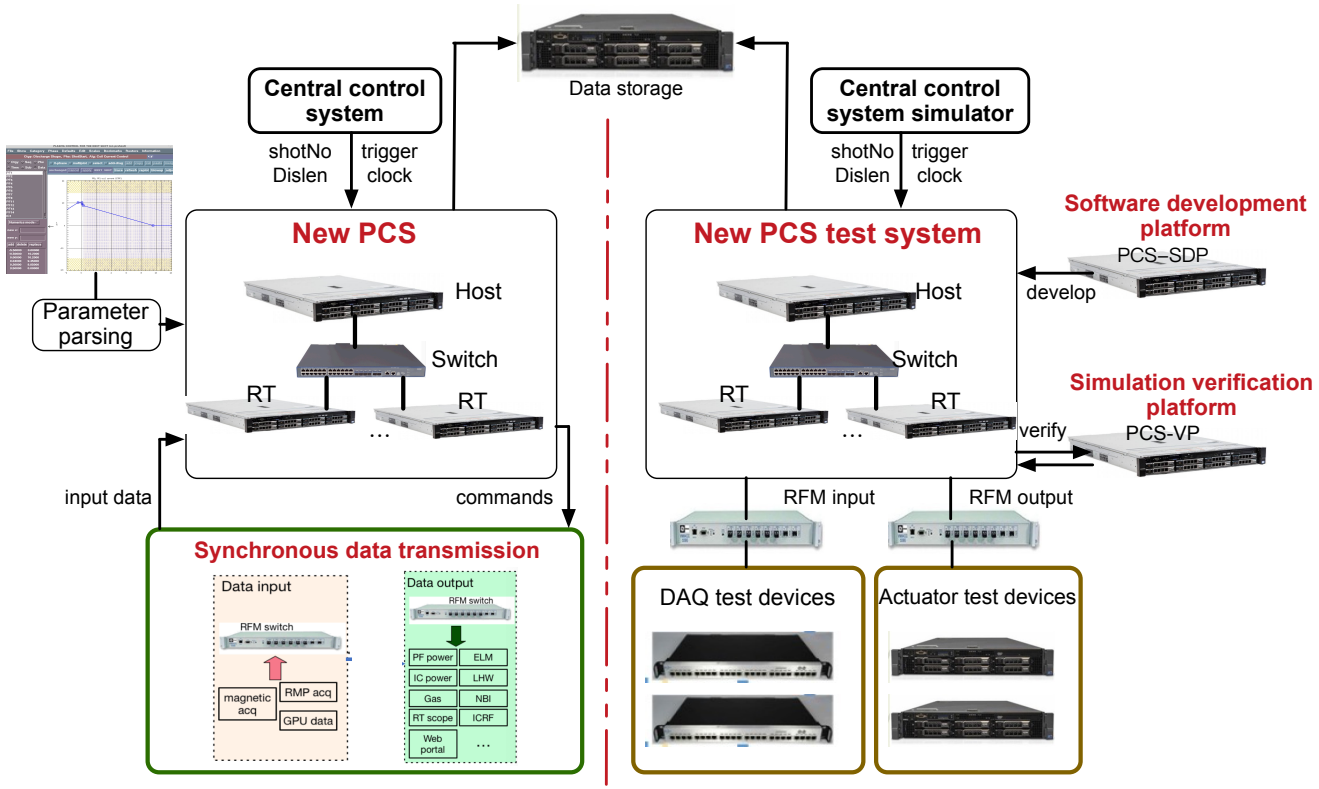
System prototype and EAST application

Summary

Deployment of new PCS prototype on EAST

Infrastructure deployment

- Two sets of clusters are deployed. One for operation and the other for testing and backup.
- The real-time communication is through RFM.



Algorithms integration

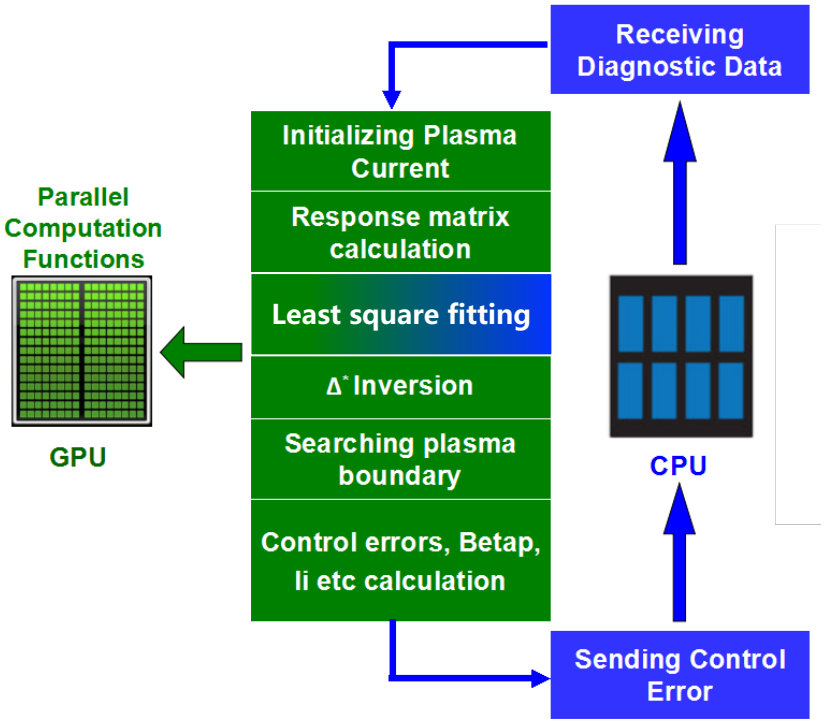
- 13 categories and almost 20 algorithms have been integrated in the prototype system for EAST.

Category	Algorithms	Description
Discharge Shape	Coil Current	Coil current control
	Limited control	Plasma position control
IP control	Ip current	Plasma current control
Density	Density feedback	Plasma density control
Gas	Gas Injection	Open loop gas puffing
HPFIT	pequil	Parallel equilibrium code
ISOFLUX	isoelong	Limited shape control
	isodnull	Double null shape
	isosnull	Single null shape
DAQ	Acq	Data acquisition
System	sysmain	Actuator management
Event Detection	edh	Event detection & handle
Profile control	beta	Plasma vloop & profile
RMP	RMP coil current	RMP coil current control
Radiation	Radiation feedback	Radiation control
Disruption	Disruption prediction	AI based prediction

High performance equilibrium reconstruction

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

- HPFIT/ISOFLUX has been applied for EAST plasma shape control. It also provides profile information for kinetic control.
- HPFIT shows good performance for DIII-D offline reconstruction and ITER discharge simulation.

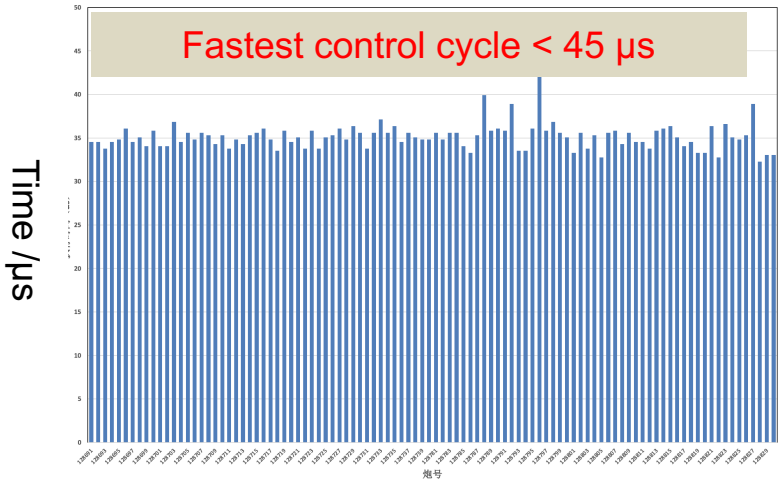


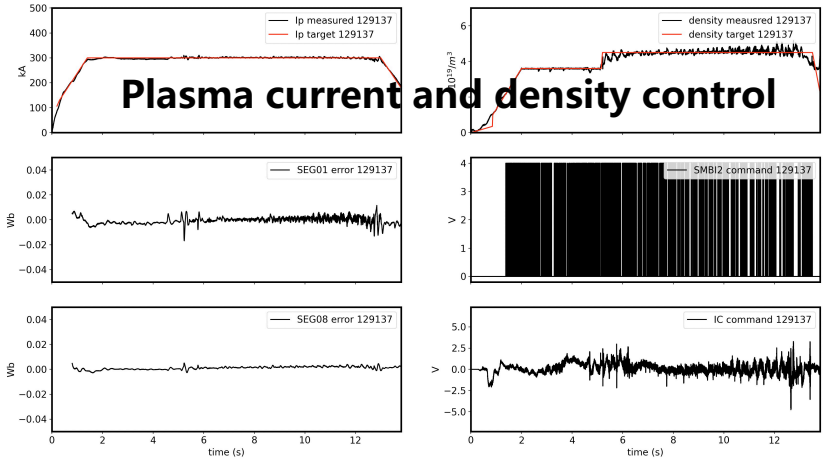
	RTEFIT	HPFIT
Current profile reconstruction	✓	✓
Kinetic reconstruction	✘	✓
Space resolution	33x33	129x129
Time resolution	2ms	300μs

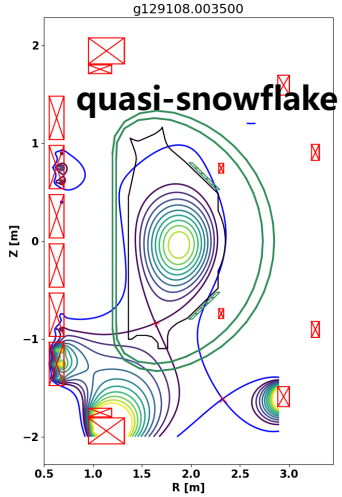
Promising reconstruction tool for ITER, BEST, CFETR…

New PCS applied on EAST

- The new PCS was successfully applied in the 2023 EAST summer operation campaign.
- Plasma current, position & shape, and density were controlled in **total 286 shots with no system failure**.



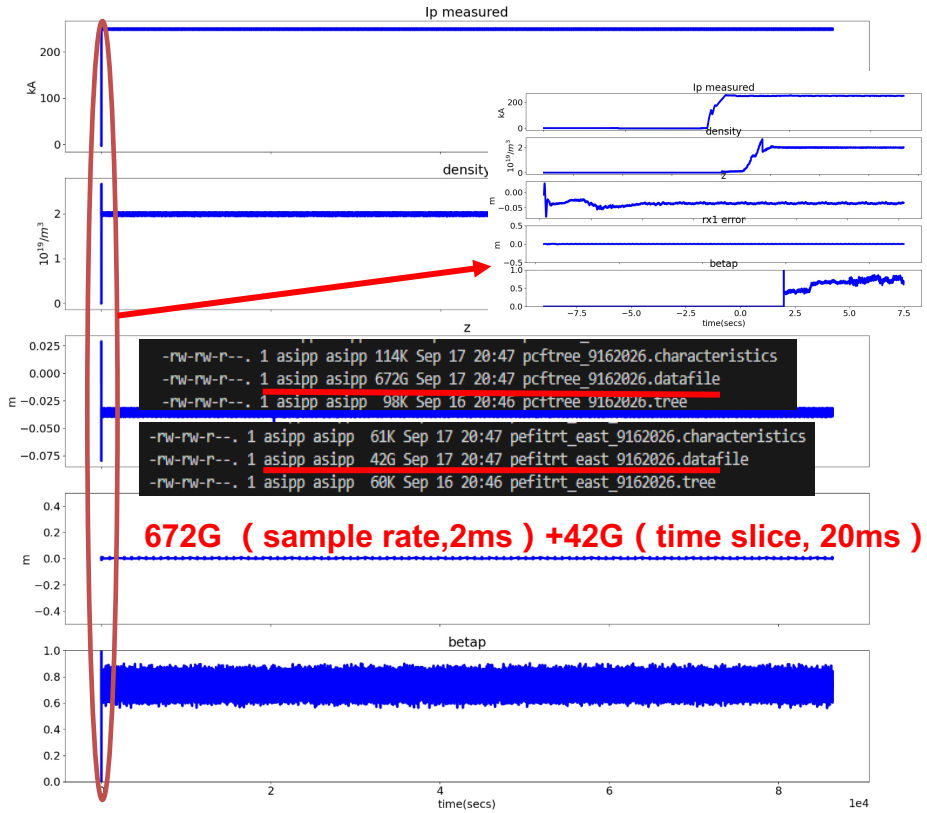




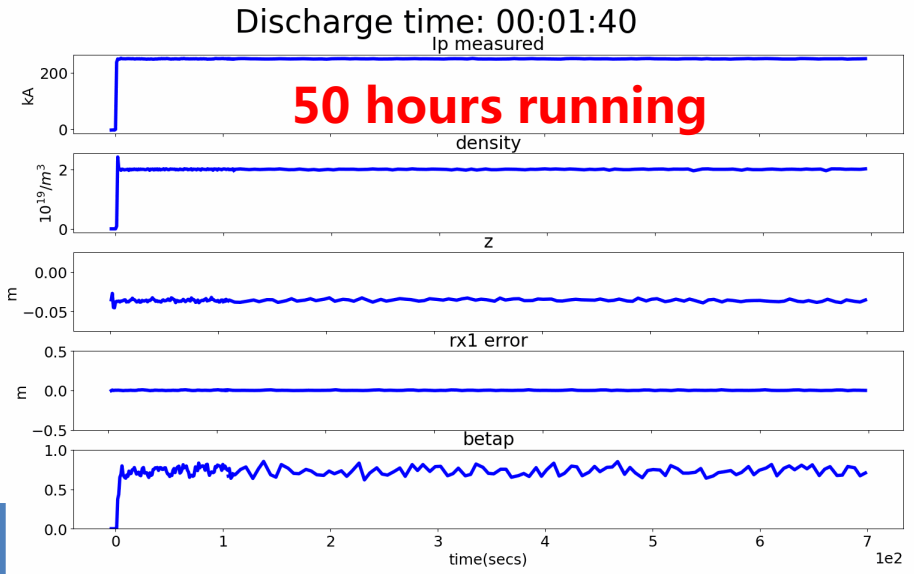
Date	Aug.2	Aug.3	Aug.4	Aug.5	Aug.6	Aug.7	Aug.8	Aug. 10
Shots	9	7	7	3	53	53	100	54
Topic	**Communication,** and Verify **CC, RZIP and density** control	**Routine exp test** shots and RZIP, density control	Repeat	Verify **plasma shape** control	Serve the physics experiment	Verify the **vloop control** and system reliability	Serve the physics experiment	Verify the **quasi-snowflake shape control** and serve the experiment
Success rate	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**

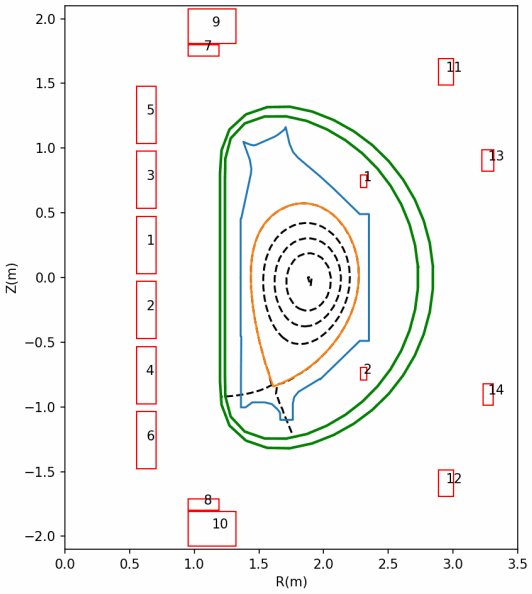
New PCS supports steady-state operation

- More than 24 hours continuous running has been tested with **real hardware** and **all algorithms** based on the extended historical data.
- The data are saved at the preset sample interval, and all data at the time of the exception is saved.



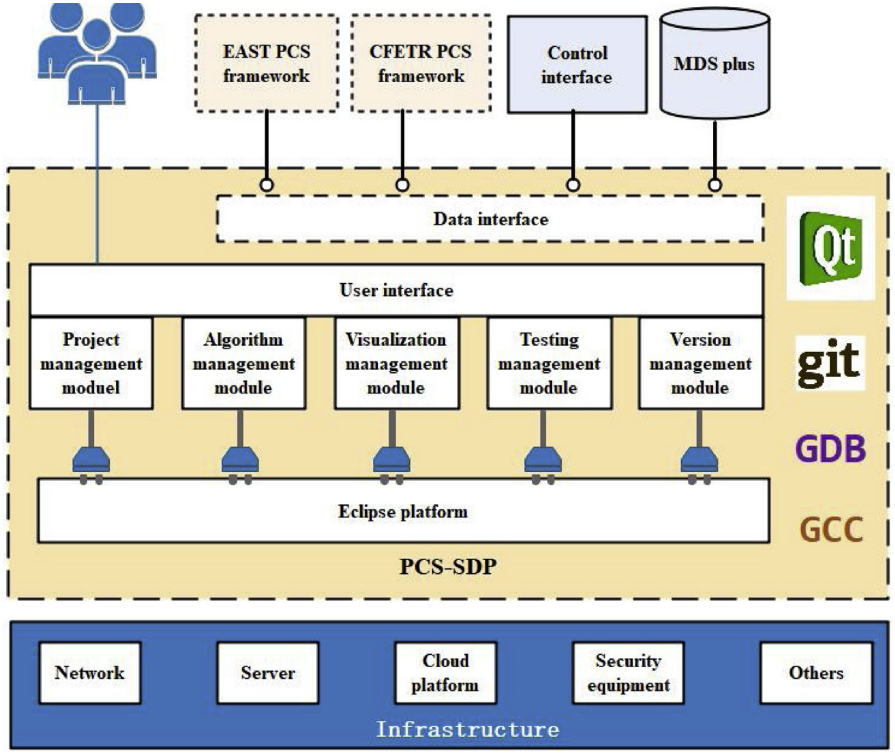
shot	Length (h)	Data
9162026	24	714G
9181415	26.8	797G
9230029	24	714G
9281601	50	1488G
10021807	25	744G

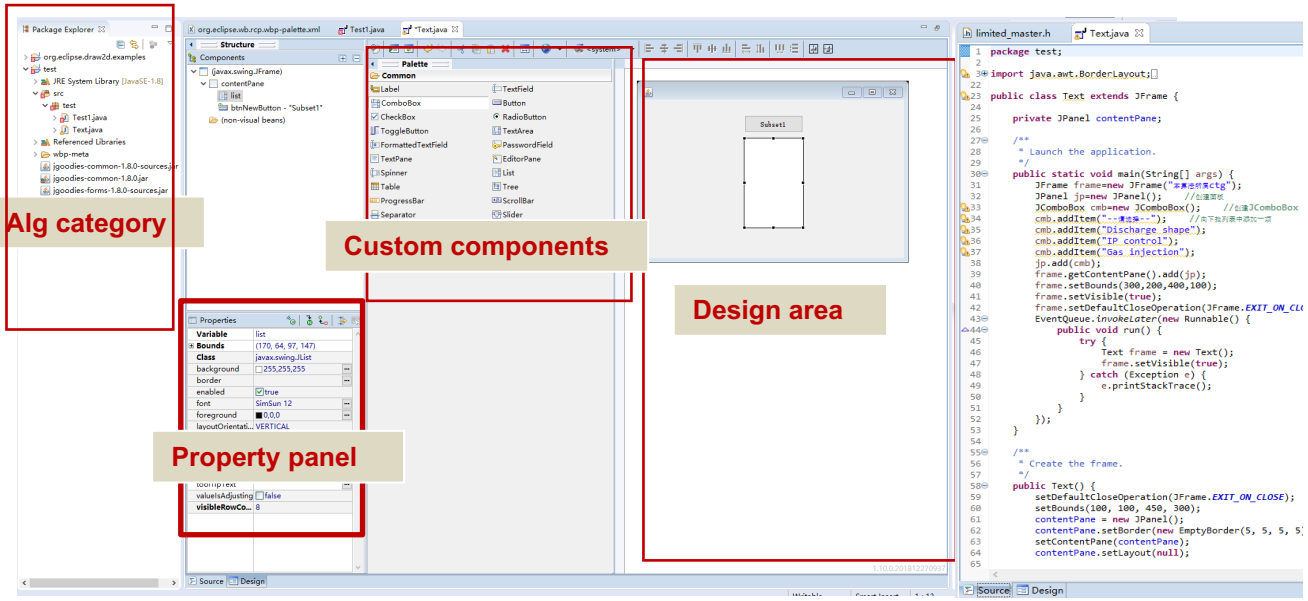


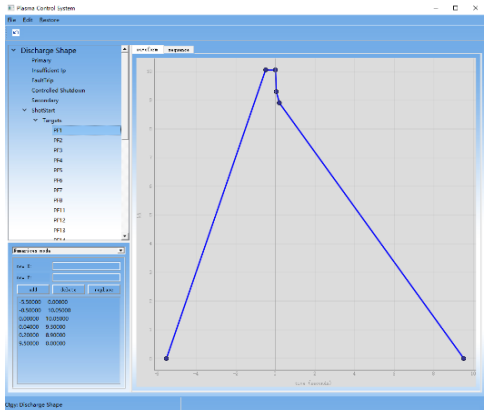


Software development platform is applied on EAST

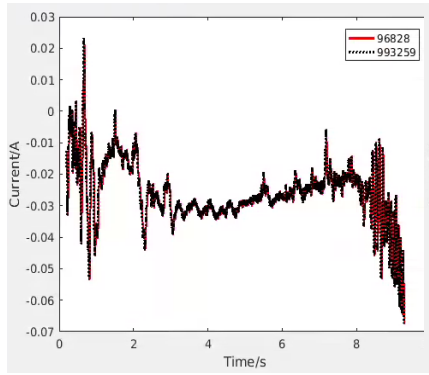
- Shield the difference of control framework
- Visual interface development
- Plasma current, position and density control algorithms have been developed and verified.



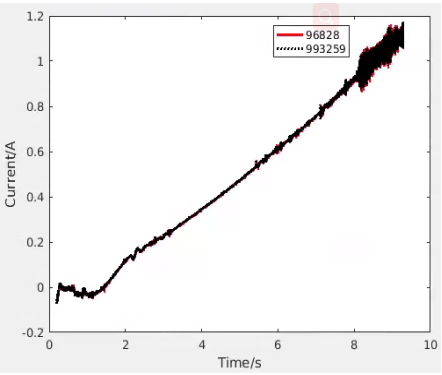




User interface



R_error compared with historical data

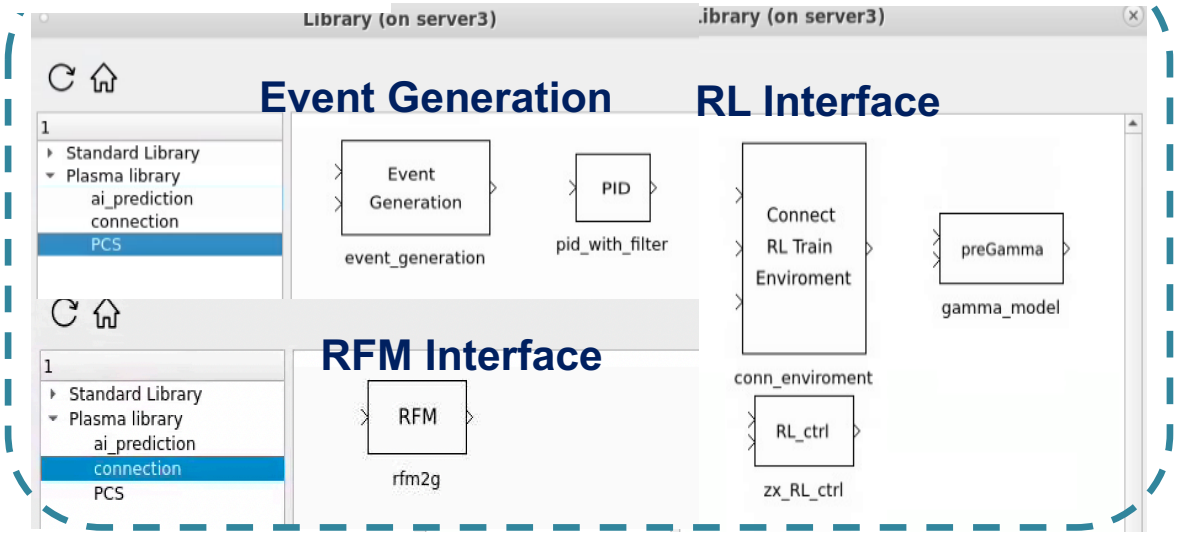


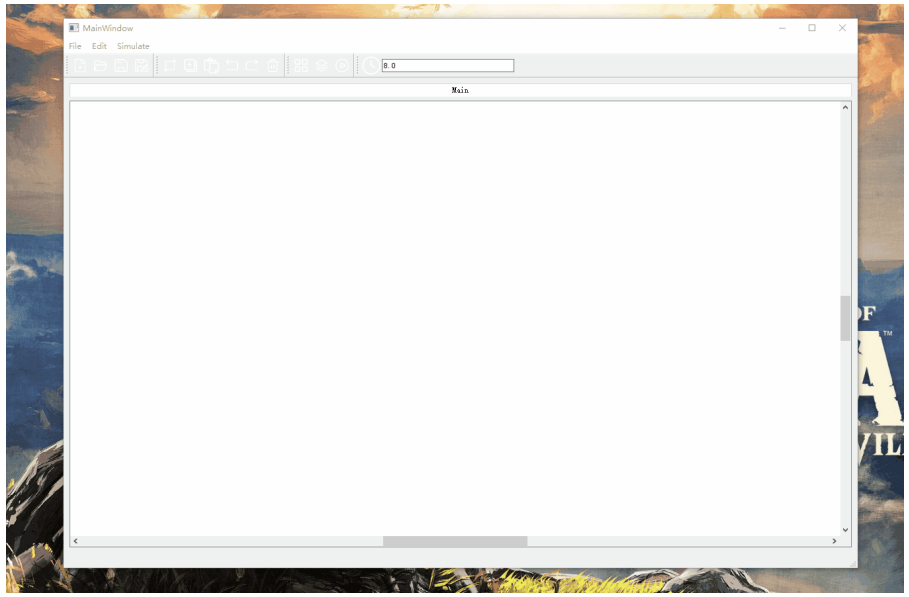
PID calculation result of Z compared with historical data

Python based prototype of PCSVP

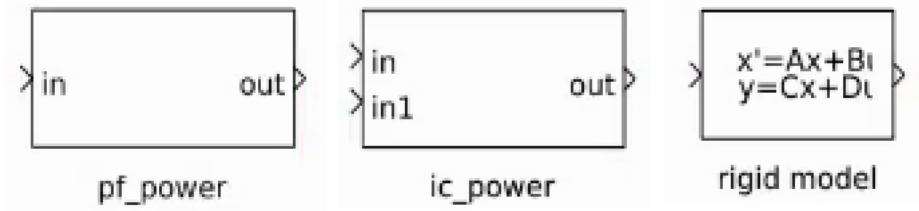
- **Python** based framework
- Visual modelling
- Support customized modules, **hardware interface**, **AI interface**

Custom libraries

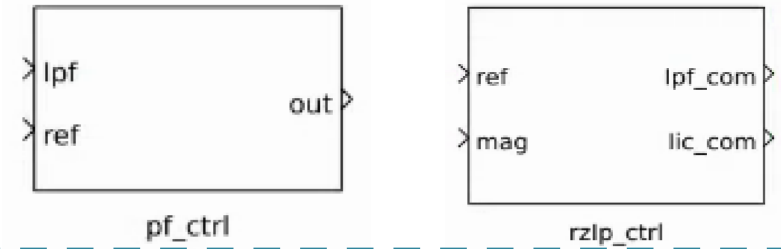




Device subsystem models



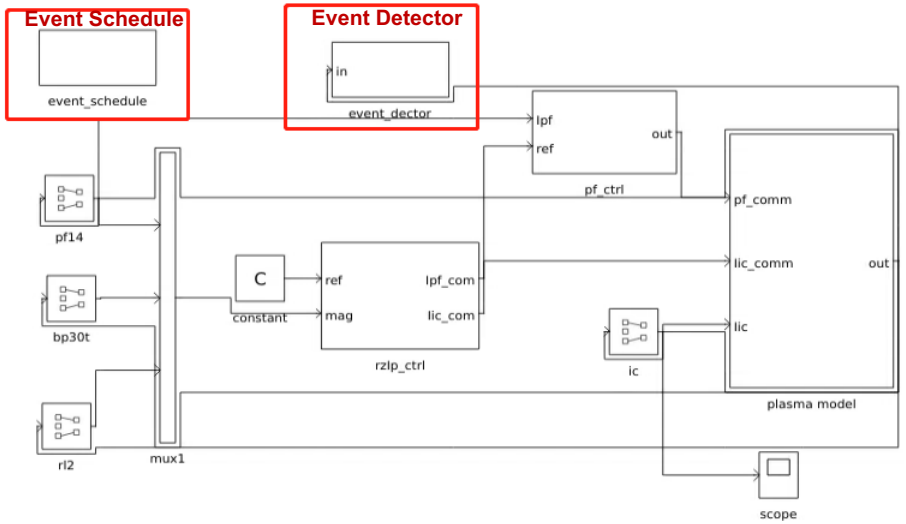
Algorithm models

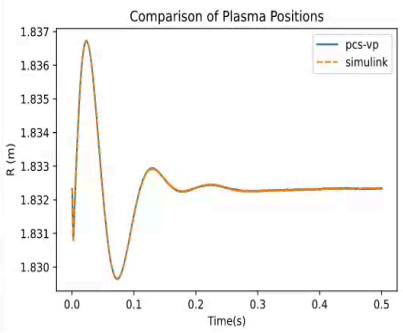


PCSVP is successfully applied on EAST

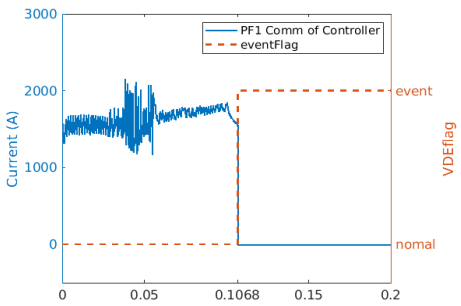
Plasma control and event simulation

- RZIp Control and actuator failure event were simulated.
- The results are consisted with the MATLAB Simulink.





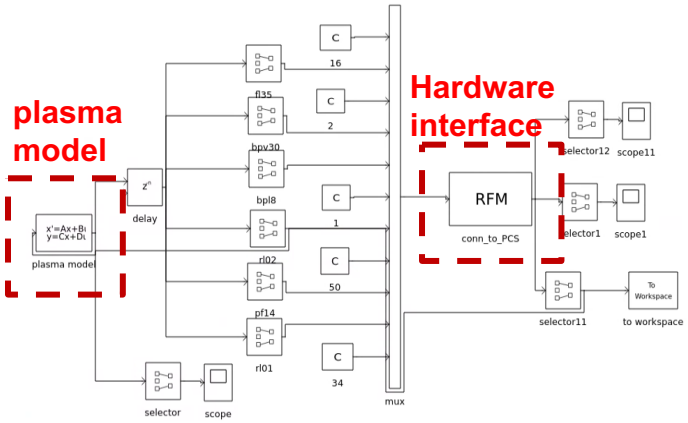
R position control result

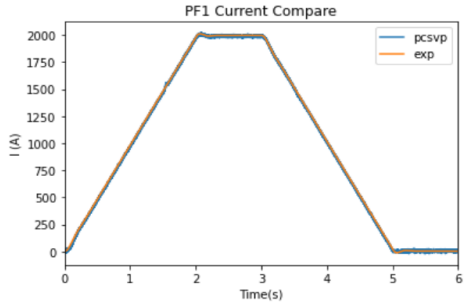


IC failure detection and handling

Hardware in loop test with PCS

- The communication delay is less than 100 μs.
- Control results are consisted with the experiment.



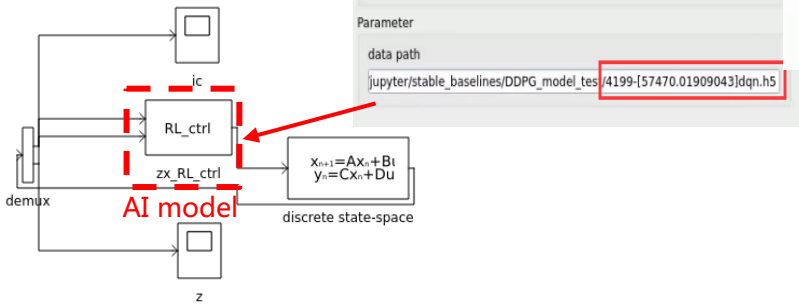


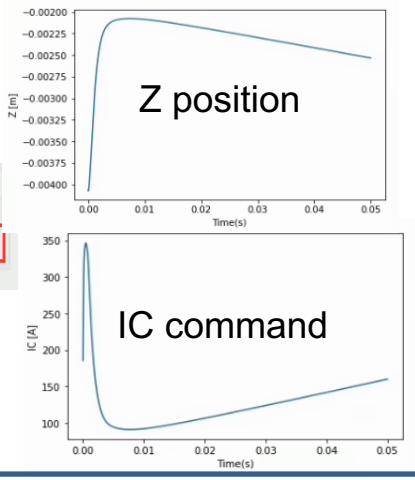
blue line - simulated I_{PF}

orange line - experimental I_{PF}

RL interface module test

- Vertical control policy was trained and tested with the plasma model.





Outline

Overview

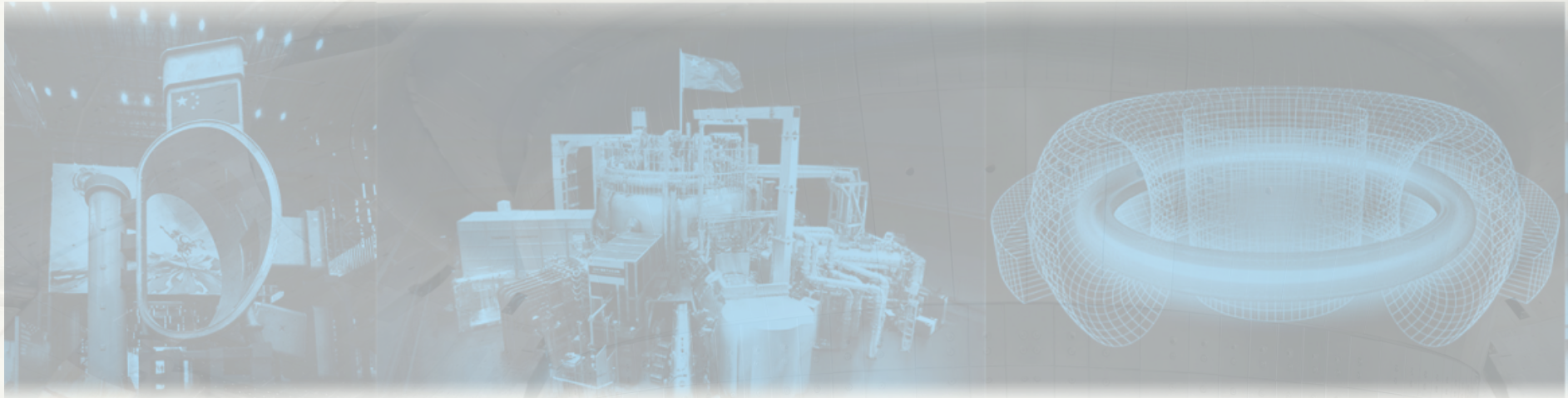
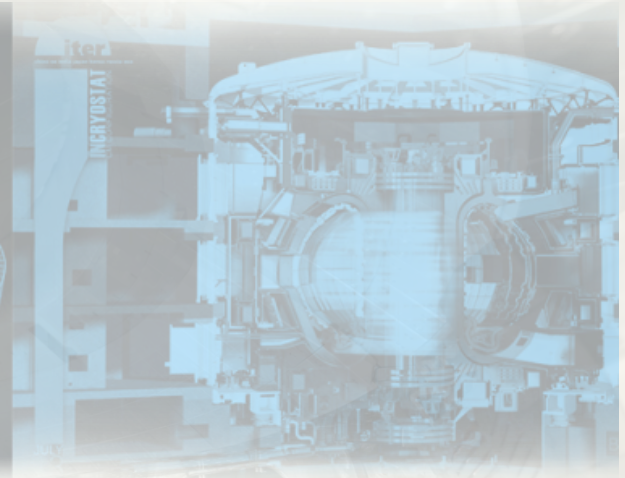
System infrastructure design

System prototype and EAST application

Summary

Summary

	New PCS
Real-time performance	The fastest control cycle: 50 μs
Reliability	On-line switching mechanism, command output switching time<13 μs, system reliability >99%
Reconstruction	HPFIT: 300 μs
AI support	Disruption prediction, parameter identification, and control optimization
Steady-state support	Support >24 hours continuous running
Usability	With the assistance of the PCS-SDP, visual algorithm development can be achieved.
Testability	With the assistance of the PCSVP+SPACE, drag & drop modelling and simulation can be realized.

Thank you !