EAST research activities on control and data toward CFETR

B.J. Xiao\textsuperscript{1,2}, F. Wang\textsuperscript{1}, B. Shen\textsuperscript{1}, Z.P. Luo\textsuperscript{1}, Q.P. Yuan\textsuperscript{1}, Y. Huang\textsuperscript{1}, K. Wu\textsuperscript{1}, Y. Guo\textsuperscript{1}, Y.H. Wang\textsuperscript{1}, S.L. Chen\textsuperscript{1}, X.Y. Sun\textsuperscript{1}, R.R. Zhang\textsuperscript{1}, G. Calabrò\textsuperscript{3}, F. Crisanti\textsuperscript{3}, R. Albanese\textsuperscript{4}, R. Ambrosino\textsuperscript{4}, G. De Tommasi\textsuperscript{4}, A. Pironti\textsuperscript{4}, F. Villone\textsuperscript{4}, L. Barbato\textsuperscript{4}, D. Eldon\textsuperscript{5}, H.Y. Guo\textsuperscript{5}, D.A. Humphreys\textsuperscript{5}

\textsuperscript{1}ASIPP(China), \textsuperscript{2}USTC(China), \textsuperscript{3}ENEAI(Italy), \textsuperscript{4}CREATE(IItaly), \textsuperscript{5}General Atomics(USA)

bjxiao@ipp.ac.cn
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
### 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

### Table: Main Parameters

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<th>B.3 1GW HB</th>
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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**

R&D on Main & Divertor

- **Material Test**
  - Φ 10 cm , SS with $10^{24}$/s 10MW/m²
- **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 Magnets (TF, CS, PF (ITER PF6))

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.
Collaboration Design Network

• Based on WAN Optimization Controller (WOC) Network
  – Virtual Private Network (VPN): To create a safe and encrypted connection over a less secure network (current phase 100Mbps)
  – WAN Optimization: Data deduplication
  – Secure Data Transfer: File Transfer Encryption
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
CFETR CODAC & PCS R&D Started
Future plan for CFETR CODAC and PCS

Central Control System

- Friendly GUI
- Process control logic
- Events distribution

Process Control System

- CFETR time
- Pulse Scheduling
- Reference clocks

Timing Synchronization system

Central Interlock System

- Project-wide level
- Protects the facility
- Reliability of information sources

Central Safety System

- Monitor Nuclear
- Conventional Risk
- Personal Access

Plasma Control System

CODAC network and framework

Interlock Network
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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 \(\Omega\): linearized Grad-Shafranov equations are solved, using 2nd order triangular finite elements mesh.

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

On \(\partial\Omega\): surface currents magnetically equivalent to the ‘true’ plasma perturbation.
### 3-D Carma00 Modeling reproduces exp. Z growth

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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
Vertical Stability Control

- Decoupled with shape control by not control the position directly
- Optimize the controller by considering the latency to reduce RMS
  \[ V_{IC} = \frac{1 + s\tau_1}{1 + s\tau_2} (K_1 \cdot I_{p,ref} \cdot \frac{s\tau_p}{1 + s\tau_3} + K_2 I_{IC}) \]
  Bandpass filter for matching delay
- Use Vloop to estimate \( \frac{dz}{dt} \) signal for better SNR
  \[ \frac{dz}{dt} = \frac{V_1 - V_2}{I_p} \left( \frac{\partial M_{pl2}}{dz} - \frac{\partial M_{pl1}}{dz} \right) \]
TSC reproduced Exp. Z control, and dzmax

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).

Numerical investigation of the Bang-bang method 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

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

**SISO:**

\[ V_{PF} = K_{PID} \left( I_{PF} - I_{PFref} \right) \]

**MIMO:**

\[ V_{PF} = M \cdot K_{PID} \left( I_{PF} - I_{PFref} \right) + I_{PF}R \]

**Induced current:**

\[ L_{PF} = USV^T \]

\[ M = VS_{Trunc}^{-1}U^T \]

- Decoupling matrix
• 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
  \[ C_{PF} = USV^T \]
  \[ S = diag(s_1, s_2, \ldots, s_n) \]
  \[ s_1 > s_2 > \ldots > s_k >> s_{k+1} > \ldots > s_n \]
  \[ S_k = diag(s_1, s_2, \ldots, s_k, 0, \ldots) \]
  \[ M = VS_k^{-1} U^T \]
MIMO control for plasma shape

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

Latency: Gas Puff > 100 ms, SMBI ~ 1 ms
Radiation Feedback Control

EAST #71019

- Rad power target
- Rad power real
- OUPEV1 pulse
- SMBI3 pulse

- Da
- Ip
- WMHD
- Density

REF: NF(2018)
H-mode detachment by feedback control of Div-LP js with D2 SMBI

\[ W_{\text{mhd}} \text{ loss } < 20\% \]
H-mode detachment via feedback control of 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

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

IR measurements show a peak heat load reduction for QSF of a factor ~1.5 with respect the LSN
A long-pulse operation, ELM-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 \(\sim 2.7\) s, whilst the high-confinement was achieved at \(\sim 3.5\) s with \(H_{98} \sim 1.2\)

After 3.5 s, 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

Real-time Current Profile Evaluator

Profile Diagnostics

Current Profile Control Algorithm in PCS

Feedforward Inputs

Target Trajectories

PCS density controller

PCS LHW controller

PCS NBI controller

PCS ECR controller

$q(\psi_n), q(\rho), \beta_p, l_i, W_{mhd}$

$n_e, T_e, T_i$

$\bar{n}_e, P_{LHW}, P_{NBI}, P_{ECR}$

$q(\rho, t), \beta(t)$...
Preliminary Plasma current profile control in EAST

Current Profile Evaluator: \( \mu_0 J_0 \approx \frac{\text{POINT}_F5}{\text{POINT}_N5} - \frac{\text{POINT}_F7}{\text{POINT}_N7} \) \( J_{\text{Ratio}} \approx \frac{J_0}{I_P} \)

Target Trajectories: \( J_{\text{Ratio}} \rightarrow 0.26 \)

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.