Progress of Long Pulse and H-mode Experiments on EAST

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24th IAEA-FEC Oct. 8-13 2012, San Diego
Collaborators

Domestic:

• SWIP, USTC, THU, PJU, DHU, ZJU, HUST, DLUT, SCU, BIT, HFUT, ICC, UBAA, ATC, AU

International:

• USA (GA, PPPL, MIT, IFS-UTA, UCSD, UCD, UM, ORNL, LLNL, SNL),

• EU (CEA-IRFM, IPP, FZJ, DTU, ENEA, FOM, IFP, DTU, CCFE, JET),

• JP (NIFS, JAEA, U. Kyoto/Kyushu/Tokyo/Chubu),

• KR (NFRI),

• ITER IO,

• CA: University of Saskatchewan
Outline

• Introduction
  • System capabilities
  • Recent progress
  • Near future plan
Introduction

- EAST as a superconducting tokamak, aims at high performance plasma for long pulse operations.

- Just after last IAEA-FEC in 2010, 1MA plasma, minute scale long pulse and stationary H-mode operations have been realized by LHCD and ICRF heating.

- The augmented capabilities in last two years allow us to extend the plasma operation into new regimes for even longer duration, and led to some new observations.
Progress in 2010

EAST missions: 1MA, high-performance steady-state operation (SSO).

1. Stationary H mode
   6.4 s H mode, $H_{IPB98(y,2)} \sim 0.9$

2. Long pulse diverted plasma
   100 s L mode, $T_{e0} \sim 1.2$ keV

3. 1MA operation
   $I_p = 1$ MA, L mode
Outline

- Introduction
- **System capabilities**
- Recent progress
- Near future plan
In-vessel components

2010: full graphite PFC
2012: Mo + graphite Div.
Lower retention; Reduced H in D plasma to 3% with intensive Li coating
System Capabilities

- PFC (tiles with 2MW/m²)
- Internal Cryo-Pump, Removable limiter
- RTEFIT/Isoflux control, limiter, SN, DN
- Plasma: Ip~0.25~1.0 MA, Bt~1.6~3T, Td~400s (0.28MA, nₘₐₓ~1.2×10^{19}/m³)
- Shaping: kappa~1.9, delta~0.65

- System Capabilities:
- LHCD: 2.45GHz, 4MW (injection 2.5MW)
- ICRF: 20-70MHz, 6.0MW (injection 2.4MW)
- Diagnostics: for key profiles and specific physics
- Multi-purpose gas injection at different location for various gas (D₂, CD₄, Ar, N₂ …)
- Fuelling: GP, SMBI, pellet injection, Li granules
Wall Conditioning

1. ICR wall conditioning (cleaning and coating).
2. HF-GDC conditioning (cleaning and coating).
3. Li conditioning for H/(H+D) ratio control:
   ✓ RF Li coating,
   ✓ Li evaporating: 2010: from 50% to <10%
   ✓ Li Droplets, 2012: down to ~3%

Reduced impurity level and Hydrogen concentration allow effective ICRF heating and easier H-mode access

Collaborated with PPPL

HF GDC Conditioning

RF Conditioning antenna
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• Near future
Demonstration of SSO

- Flux control by LHW for SSO
- Minimizing $I_{CS}$ for safety margin
- Swiping between USN and LSN configuration to spread heat
- No retention saturation

$I_p \sim 0.28\, \text{MA}/411\, \text{s}, \, \text{DN}&\text{SN}, \, n_e \sim 1.2, \, P_{LHCD} = 1.2\, \text{MW}, \, B_t \sim 2.5\, \text{T}$

EX/P5-15 Guo H.
Demonstration of Long pulse H-mode

$IP \sim 0.3 \text{MA}$, line averaged density at $\sim 2 \times 10^{19} / \text{m}^3$ with $H_{\text{PB98(y,2)}} \sim 0.8 \pm 0.1$

Pulse length is only limited by presently attainable discharge durations

Dominated small ELMs mixed with Type III ELMs $P_{\text{LH}} \sim 2 \text{MW}$, $P_{\text{IC}} \sim 0.8 \text{MW}$

EX/P5-15 Guo H.
Edge magnetic topology change induced by LHCD

Helical Radiation Belts (current sheet) lead to the splitting of divertor strike points with similar effects to RMP.

3D edge topology can be actively controlled by SMBI: increases the striated heat flux and decreases the heat flux at the outer strike area.

Alternative way for ELM control?

PD Liang Y, Zhou X
Edge topology changes ELMs

LHCD tends to generate small ELMs, compared to the H-modes with similar ICRH power.

Power modulation show that LHCD trigger small amplitude, high frequency ELMs, or even completely suppress ELMs

Current sheets induced by LHCD in edge/SOL act as perturbative source to change ELMs characteristics

PD Liang Y
ICRF heating (27MHz)

- Ip=0.5MA, Bt(0)=1.8T, H/(H+D)~3%
- Significant electron & ion heating
- Co-current toroidal rotation
- No obvious increase of impurity influx and density

Demonstration of ICRF with He3
- Ip=0.4MA, Bt(0)=3.0T, H/(H+D)~5%
- Clear ion heating
**H-mode by ICRF only**

- **ICRF at 27MHz, Bt=1.8T, Ip=0.5MA, H98≤0.8**
- **Dithering L-H transition**
- **A short ELM-free period of ~200ms, followed by type-III ELMs**

EX/P6-25 Qin C
H-mode by LHW only

In 2010
After intensive Lithium coating, LHCD+ohmic power close to $P_{\text{th}}$. $I_p \approx 500\text{kA}$, $B_t \approx 1.54\text{T}$, $n_{\text{H-mode}}/n_{\text{GW}} \approx 0.5$

Density pedestal formed after L-H transition

Profile of shot 33067

Electron temperature pedestal after L-H transition
H-mode by LHW+ICRF

- Enhanced $D_a$ emission, irregular ELMs,
- $f_{ELM}$ decreases with increased power
- $H_{98} \leq 0.8$ even for higher power ($>2P_{th}$)

High density, $n_e/n_{GW} \geq 0.6$ (2012)

$I_p \sim 0.4\, \text{MA}, \quad B_t \sim 1.85\, \text{T}, \quad \text{LSN}, \quad P_{LH} \sim 1.2\, \text{MW}, \quad P_{RF} \sim 1 \, \& \, 1.6\, \text{MW}, \quad f=27\, \text{MHz}$
Quasi-coherent mode

- A quasi-coherent mode at 25kHz with enhanced ambient turbulence in the core
- QCM at ~30kHz was also observed in pedestal region
- High frequency turbulence around 190kHz.

Account for enhanced transport?

Ip ~0.4MA, Bt~1.85T, LSN, PLH ~1.2 MW, P_{RF} ~1.6MW, f=27MHz
Mixed Type I & small ELMs

Reduced density, $n_e/n_{GW}<0.5$
$I_p\sim 400\,\text{kA}$, $B_t\sim 1.85\,\text{T}$,
$P_{\text{LH}}\sim 1.6\,\text{MW}$, $P_{\text{RF}}\sim 0.8\,\text{MW}$,
reduced density $4\to 3\times 10^{19}/\text{m}^3$
in H-phase

Mixed type I and small ELMs,
$1>H_{98}\geq 0.8$

$f_{\text{Large ELM}}\sim 20-50\,\text{Hz}$

$\Delta W/W\sim 5-10\%$ depends on inter-ELM time

What’s role of Small ELMs for confinement?

$(\delta = 0.4-0.42)$
Large ELMy H-mode with $H_{98} \sim 1$

At $I_p \sim 0.3\text{MA}$ and $n_e \sim 2 \times 10^{19}/\text{m}^3$, low density $n_e/n_{GW} \geq 0.4$--0.45

Access large ELMy H-mode regime with $H_{98} \sim 1$, normally accompanying with small ELMs
Giant ELMs

At lower density, higher power

- H98 ~1 with small ELMs
- Giant ELMs cause peak heat flux at div. plate exceed 10MW/m².
- Global energy confinement degraded by ~10%.

At $I_p \sim 0.3$MA and $n_e \sim 2 \times 10^{19}$/m³
ELMy characteristics and heat load

- **Type I ELMs:**
  \[ \frac{n_e}{n_G} < 0.5, \quad P_h > 1.5 \quad P_{th}, \quad \delta \sim 0.4, \quad \text{LSN} \]

- **Compound ELMs:**
  \[ \frac{n_e}{n_G} > 0.5, \quad P_h \sim 1.5 \quad P_{th}, \quad \delta \sim 0.45, \quad \text{DN} \]

- **Type III ELMs:**
  \[ \frac{n_e}{n_G} = 0.3 \sim 0.6, \quad P_h > 1.0 \quad P_{th}, \quad \delta \sim 0.4, \quad \text{LSN&DN} \]

- **Small ELMs:**
  \[ \frac{n_e}{n_G} < 0.5, \quad P_h > 1.5 \quad P_{th}, \quad \delta \sim 0.4, \quad \text{LSN} \]

- **Irregular ELMs:**
  \[ \frac{n_e}{n_G} > 0.6, \quad P_h > 1.5 \quad P_{th}, \quad \delta = 0.33 \sim 0.36, \quad \text{LSN} \]

EX/P5-13 Wang L. Need further studies with improved diagnostic capabilities
BOUT++ simulations show that the stripes from visible camera are consistent with ELM filamentary structures.

The experimental filament captured by CCD camera from the EAST shot #41019 at time=3034ms is consistent with the BOUT++ simulation result.

EAST#41019@3034ms
Visible camera shows bright ELM structure

BOUT++ simulation shows that the ELM stripe are filamentary structures

Z (m)
R (m)

EX/P7-11 Z. Liu
Demonstration of ELM control

SMBI Injection into type I ELMy H-mode:
ELMs: amplitude reduced,
Frequency increased by 5 times
Confinement degraded little

Li granule injection at v~45m/s
with f=25Hz
triggering ELMs, at nearly 100% efficiency

PD Zhou X

PD Mansfield
H mode threshold power

Threshold power of EAST H modes is aligned with predictions of the international tokamak scaling

2010 LHCD only with the favorable $B \times \nabla B$ direction

2012 LHCD + ICRF with the unfavorable $B \times \nabla B$

Dominant divertor (LSN) with internal cryogenic pump provide strong particle control might promote H-mode access, since H-mode was not accessed with USN without ICP at even higher power

Low density for H-mode access
Role of neutral particle in H-mode

G.S. Xu et al., NF(2011)
Evidence of Zonal Flow Limit-Cycle Oscillations during L-H Transition

- By using two GPI and two reciprocating Langmuir probe systems near the transition power threshold.
- The pressure gradient near the separatrix accumulates and triggers a series of outbursts, which drive zonal flows through the Reynolds.
- Turbulence is periodically suppressed as its kinetic energy has been released and its driving force - the local pressure gradient - has been weakened, thus allowing the equilibrium E×B flow shear to increase and lock in the transition.

EX/11-1 G.S. Xu
Small-amplitude dithering prior to L-H transition

Near the transition conditions, zonal-flow limit-cycle oscillations with much smaller amplitude compared to those during I-phase could exist well before the L-H transition or the occurrence of the I-phase, behaving like a transition precursor.

Fluctuations are periodically suppressed when the $E_r$ shearing rate transiently exceeds the turbulence decorrelation rate.

G.S. Xu et al., PRL 107 (2011) 125001
Observation of a new cycle state at H-mode pedestal

- A turbulence-flow cycle state appears shortly after the L-H transitions or in the inter-ELM phase.
- Probe measurements at ~1cm inside separatrix show zonal-flow modulation of a high-frequency-broadband turbulence in the steep-gradient region of H-mode pedestal.
- Leading to intermittent transport events across the edge transport barrier, and therefore a modulation in the recycling neutrals near the divertor targets.
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2013-2014 new capabilities and Targets

Mo wall+C(low)+W(up) divertors
lithized wall operation
Fuelling: pellet, SMB

- 4MW LHCD @ 2.45GHz √
- 6MW LHCD @ 4.6GHz
- 6.0+6.0MW ICRF @ 25-75MHz √
- 2~4MW NBI @ 50~80keV (2nd 2015)
- 4MW ECH/ECCD @ 140GHz(2014)

RMP coils (2014)

Diagnostics enhancement:
- All key profiles from core to edge
- Specific diagnostics for turbulence, MHD instability, and energetic particles

Aim to extend operation regimes:
H-mode, hybrid, AT, high β plasmas
Long pulse 0.5MA, 100s

More research opportunities in:
- Scenarios developing
- MHD instabilities
- Energetic particles
- P-I-wall interaction
- …
Target of W/Cu Project

**Divertor:**
ITER-like
Monoblock targets and W Flat type or CVD-W dome
Max. heat flux capability of divertor targets ~10MW/m²

**First wall:**
CVD-W or W flat type
Max. heat flux capability 3~5MW/m²

2013: W monoblock or flat tile
FW: CVD-W or W flat tile
Dome: W flat tile or CVD-W
Target: W monoblock

2013: Carbon
RMP coil configuration on EAST

8 coils can produce the spectrum with $n = 1-4$. $I_{\text{coils}} \sim 10$ (kA*turns).

8(U) + 8(L) = 16 coils near the passive plates.

A flexible system covers both resonant and non-resonant dominant regimes, producing $n=1-4$ RMP field.

- $n=4$ even
- $n=4$ odd
- $n=3$
- $n=2$
- $n=1$
EAST new capability will open more research opportunities

The available powers (>20MW) in next 2 years could:

• Provide flexibility for regulating current density and pressure profiles
• Realize fully non-inductive plasmas in high performance regimes
• Enhanced diagnostics allow specific physics study in more aspects

In experiments of 2012, NTM and TEA have been observed in H-mode plasmas generated by LHCD+ICRF
Major challenges for next step

EAST aims steady-state high performance operation

- How can sufficient power be injected into plasma to create stable high performance plasma? (technologies and scenario development by considering features of SC magnets)
- How can we extend these plasmas toward to steady-state? (physics in different time scales and technologies for plasma control and machine safety)
- How can we find the solutions for power and particle handling with ITER-like full-metal wall, and integration with core plasma? (plasma and wall interaction, and machine safety)
Summary

• EAST has achieved significant progress toward to long pulse and higher performance plasma operation.
• The augmented capabilities led to some new observations in physics front, particularly in:
  - 3D edge magnetic topology induced by LHCD
  - L-H transition physics near threshold power
  - H-mode access with full RF powers at $P_{in} \sim P_{th}$
  - ELM control by SMBI and Li granules injection
• Next step with high power density and high plasma performance for steady-state operation is our common challenge, which has significant importance for ITER.

Thank you for your attention!