Recent advances in EAST experiments in support of steady-state operation for ITER and CFETR

by

B. N. Wan

on behalf of EAST team & collaborators
We acknowledge contributions from domestic and international partners to EAST research program.
Outline

• Introduction

• Extension of steady-state operational regime with dominant RF H&CD

• Physics studies to resolve scientific and technical issues for EAST steady state operation
  – LHW PI effect
  – ELM control
  – Particle/power exhaust control

• Summary and future Plan
CFETR and ITER aim SS or hours operation

<table>
<thead>
<tr>
<th></th>
<th>$Q_{pl}$</th>
<th>$\beta_N$</th>
<th>$f_{bs}$</th>
<th>$H_{98Y2}$</th>
<th>$I_p(f_{oh})$</th>
<th>$n_{bar}/n_{GR}$</th>
<th>$q_{95_iter}$</th>
<th>$R/a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFETR SSO</td>
<td>~10</td>
<td>2.0</td>
<td>0.5</td>
<td>1.4</td>
<td>14</td>
<td>0.57</td>
<td>5.5~6</td>
<td>7.2/2.2~3.3</td>
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<tr>
<td>CFETR HB</td>
<td>&gt;15</td>
<td>2</td>
<td>0.5</td>
<td>1.2</td>
<td>14(0.3)</td>
<td>0.85</td>
<td>5.5~6</td>
<td>7.2/2.2~3.3</td>
</tr>
<tr>
<td>ITER SSO</td>
<td>&gt;5</td>
<td>&gt;2.6</td>
<td>0.5</td>
<td>&gt;1.3</td>
<td>9</td>
<td>0.85</td>
<td>5</td>
<td>6.2/2~3.1</td>
</tr>
</tbody>
</table>

$f_{bs} \sim \varepsilon^{1/2} \beta_p \propto \beta_N \times q_{95}$; large $\varepsilon$ is favorable for confinement

- Develop physics basis for steady-state operation ($\varepsilon$, $\beta_p$)
- Extend integrated high performance results to true SSO

EAST demonstrated high $\beta_P$ long pulse H-mode operation with high $f_{bs}$ for ITER and CFETR

EAST aims to find integrated solutions of tokamak steady-state operation

- Long pulse operation with metal wall
- Bootstrap current fraction $f_{bs} \sim 50\%$

Dr. Wan

World record long pulse steady-state H-mode operation with tungsten divertor

Extension of $\beta_P$ operational regime with $f_{bs} \sim 50\%$ at CFETR relevant $q_{95}$
EAST capabilities facilitate to extend high performance to true steady-state operation

- **LHCD 4+6 MW (2.45/4.6GHz)**
  - Fast Electron Source/Edge Current Drive /Profile
- **ICRH 6+6 MW (25-75MHz)**
  - Ion and Electron Heating Central Current Drive
- **ECRH 1+1(4) MW (140GHz)**
  - Electron heating/Steering mirror, $j_\phi$ tailoring
- **NBI 4+4 MW (co/counter, 80kV)**
  - Ion heating/Variable rotation/ rot-shear
- **Fueling (gas puffing, SMBI, pellet)**
- **In-vessel cryopump**
- **Wall conditioning**
- **Active water cooling (PFC)**

New 4.6GHz LHW W guide limiter $P_{\text{in-Max}} \sim 3.5\text{MW}$
Diagnostic systems in support of steady-state long pulse operation and physics study

- **Plasma operation**
  - Magnetic measurement, visible/IR camera, thermocouples, LP, pressure gauges, RGA

- **Profile diagnostics**
  - POINT, TS, ECE, XCS, ME-SXR, HCN, Reflectometry, Recip.-LPs, He-BES, Li-BES, XCS, CXRS

- **Plasma impurities & radiation**
  - filterscope, Vis Spec, EUV, XEUV, SX-PHA, Divertor W Spec, Vis Brems., CXRS, XCS, Bolometer, AXUV

- **Energetic particles:**
  - FIDA, FILDs, ssNPA, neutron camera

- **Multi-scale fluctuations**
  - Mirnov, soft X-ray, ECE/ECEI, POINT, BES, DBS, ECEI, GPI, CO2 laser
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EAST long pulse steady-state H-mode operation with tungsten divertor

- Integrated plasma control
- Saturated W-Div. surface temperature (~10 sec)
- Good confinement (LHW+ICRF+ECH)
  - $H_{98y2} \sim 1.1$ with e-ITB
- Small ELM
Recent experiments extended steady-state high $\beta_p$ scenarios with $f_{bs} \sim 45\%$ using RF H&CD only

- Pure RF heating, $V_{loop} \sim 0.0$
  - $P_{LHW} \sim 3.2\text{MW}$,
  - $P_{ECRH} \sim 1.0\text{MW}$;
- Good confinement
  - $H_{98y2} \sim 1.2$, $\beta_p \sim 1.9$, $\beta_N \sim 1.5$
  - $f_{Gr} \sim 0.8$, $f_{BS} \sim 45\%$
- Good control of impurity accumulation
  - Small ELMy, on-axis ECH
- Demonstrated steady-state operations with similar $q_{95}$ and good confinement under ITER and CFETR relevant condition
  - Metal wall, zero torque, e-heating
Achieved $f_{bs}$ over 50% using RF+NB H&CD

- **RF+NB H&CD,**
  - $P_{LHW} \sim 2.5\text{MW}$,
  - $P_{ECH} \sim 1.0\text{MW}$;
  - $P_{NB} \sim 2.2\text{MW}$

- **Plasma parameters**
  - $\beta_p \sim 2.5$, $\beta_N \sim 1.9$
  - $f_{BS} \geq 50$
  - $q_{95} \sim 6.8$

- **Density and beam voltage optimized to reduce fast ion losses**
  - $f_{Gr} \sim 0.7$, $V_{beam} \leq 65\text{kV}$
Extension of operational regime towards steady-state operation for ITER and CFETR

• $\beta_p$ versus line-averaged density of low loop voltage plasmas
  – $V_{\text{loop}} < 0.05V$, $q_{95} \sim 6.0 - 7.0$

• Extended operational regime
  – High density $f_{\text{Gr}} \sim 0.8$
  – $f_{\text{BS}} \sim 45\%$ pure RF
  – $f_{\text{BS}} \geq 50\%$ NB +RF

• Good confinement
  – $H_{98y2} \leq 1.3$
  – ITB inside $\rho < 0.4$
Development of high $\beta_N$ scenarios in the low $q_{95}$ regime

- High G (>0.3) plasmas obtained with $q_{95} = 3.5 - 4.0$ and $\beta_N \sim 2.0$
  - $\beta_N \sim 3 \times l_i$
  - $B_T \sim 1.5 - 1.8$ T

- Double barrier structures (ITB+ETB) observed in different $q$ profiles
  - Montonic, central flat and weakly reversed shear
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Correlation between the parametric instability of LH waves and modification in edge current profile

- **Stronger PI was observed**
  - With reduction in source frequency
  - With increase in plasma density

- **Stronger PI with the increase of plasma edge current**
  - More LHW power dissipates in edge

- **Control of PI is essential to access higher density regimes in a steady state H-mode plasma.**
  - Lithium coating and injection
  - LHW at higher frequency

\[ \text{LHW: } 2.45 \text{GHz vs } 4.6 \text{GHz} \]

\[ \text{ne: } 2.3 \times 10^{19} \text{m}^3 \text{ vs } 2.7 \times 10^{19} \text{m}^3 \]
Effect of PI induced spectral broadening on LH current drive efficiency

- Spectral broadening has negative effect on CD efficiency and LH power absorption
- Modeling result shows ion-sound quasi-mode-driven PI can redistribute the launched parallel refractive index ($N_{||}$) spectrum

B. Ding et al NF 2018
Extension of parameter space for the EAST grassy ELM regime towards lower $q_{95}$ and higher density

Parameter space for $f_{\text{ELM}}>500$ Hz:

- $q_{95} \geq 5.3$
- $\beta_p \geq 1.1$
- $n_{\text{el}}/n_{\text{GW}} \geq 0.46$, up to 1.1
- $\beta_N$ up to 2
- $H_{98y2}$ up to 1.4
- $f_{\text{BS}}$ up to 70% (@300kA)

Overlap with CFETR 1GW scenario:

$q_{95} = 5.5-7$, $\beta_N \sim 2$, $f_{\text{BS}} \sim 50\%$, $n_{\text{el}}/n_{\text{GW}} \sim 0.7$

G.S. Xu EX/P2-4
Pedestal profiles of grassy ELM regime characterized by a wide pedestal and low pedestal density gradient

- **Characterized by**
  - Relatively wide pedestal
  - Low pedestal density gradient
  - Low pedestal bootstrap current density
  - High $n_{e,sep}/n_{e,ped}$ (up to 0.6)

- **Good compatibility with**
  - Low rotation
  - High density
  - Radiative divertor
  - High bootstrap current fraction
  - Fully non-inductive operation
  - Strong tungsten impurity exhaust capability

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G.S. Xu EX/P2-4
**E_ρxB shear has a great impact on the ELM size**

- Experimental modulation co- and ctr-lp NB;

- Smaller ELM size observed at ctr-NBI
  - stored energy and density profiles keep the same (same collisionality)

- Toroidal rotation (or $E_ρ \times B$ shear) plays an important role in modifying the ELM
Achievement of ELM suppression using n=2 RMP in a wide low $q_{95}$ window

- Achieved ELM suppression in standard type-I ELMy H-mode with low $q_{95}$ (~3.7) window
- Robust ELM suppression in a wide $q_{95}$ window 3.2-4.2 with $n = 2$ RMP achieved

$B_T \sim 1.6T$, $\beta_N \sim 1.5$, $N_{e0} \sim 3 \times 10^{19} m^{-3}$, $v_{e,ped} \sim 0.5$

$P_{NBI} \sim 2MW$, $P_{LHCD} \sim 1MW$, $\Omega_{\phi0} \sim 50$krad/s
ELM suppression achieved using a rotating n=2 + static n=3 RMP field

- ELM suppression using rotating \( n=2 \) superimposed on a static \( n=3 \) RMPs achieved in EAST

- control of 3D pattern of the particle flux on the divertor
  - Footprint of particle flux is periodically changing during \( n=2 \) RMP rotation
  - consistent with modeling by TOP2D with plasma response by MARS-F
Demonstration of radiative divertor without confinement degradation with feedback control on $J_{\text{sat}}$ or $P_{\text{rad}}$

**Target $J_{\text{sat}}$ feedback**

**Radiation power $P_{\text{rad}}$ feedback**

$T_{\text{et}}$ is sustained at $\sim 10$ eV

Promising diverter solution for long-pulse H-mode operation
ECRH is essential to alleviate accumulation of high-Z Impurities in long pulse operation

- Discharges are often terminated due to tungsten accumulation
- High-Z impurity control
  - ECRH power deposition at ρ<0.1
- Radial profiles clearly indicate the reduction of tungsten ions in plasma core regime (ρ<0.2)
RMP applied for eliminating impurity accumulation

- High-Z impurity concentration can be significantly decreased with an $Z$-dependence
  - Stronger effect on higher-$Z$ impurities

- RMP induced change significantly in transport, leading to a flattened impurity profiles.
  - Increase in diffusion
  - Larger outward pinch velocity
3D helical mode favorable to maintain advanced high $\beta_p$ operation in weak magnetic shear

- Long-lived mode was observed in high $\beta_p$ plasma with $q_{min} \geq 1$ (low magnetic shear) via flux pumping mechanism

- No large sawtooth crash in the core and no NTM

- This mode helps avoiding high-Z impurity accumulation

3-D nonlinear simulation by M3D

B.N. Wan/IAEA FEC/October 2018
New method of discharge cleanings under strong magnetic field

First successful operation of Helical Wave Plasma (HWP) and Direct-Current Glow Discharge Cleaning (GDC) in tokamaks under strong magnetic field!

- DC-GDC @ 2T is more efficient for retention removal
- Uniform plasmas & high current density (0.4 A/m²)
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EAST new W lower divertor upgrade scheduled in 2019 for radiative divertor feedback control and X-divertor

- Simple flat targets to reduce installation error and thus leading edges
- Closed outer divertor and open inner divertor for balanced detachment
- A water-cooled internal coil for X-divertor operation
- SMBI for impurity seeding feedback control
Summary

- Significant progress has been made in steady state long pulse operation
  - 101.2 s H-mode with $H_{98y2}>1.0$ achieved with pure RF powers and W-divertor
  - Extended pure-RF scenarios with $\beta_p \leq 2$, $f_{BS} \leq 40-50\%$, $f_{Gr} \sim 0.6-0.8$ at $q_{95} \sim 6.0-7.0$ relevant to CFETR, demonstrated for longest 20s
  - High performance SSO scenarios have been developed for further long pulse operation

- Physics research has been conducted to resolve scientific and technical issues for EAST long pulse operation, delivering steady state operation in ITER and CFETR
  - LHW PI effect, ELM suppression, radiative divertor, high Z impurity control etc.

- ≥400s Long pulse & high performance operation are planned with more gyrotrons (2019-2020) and upgrade in lower divertor (2019)
**Contribution to 27th IAEA FEC from EAST team and collaborators**

**[Overview & operation]**
- OV/2-2 B. N. Wan EAST overview
- EX/3-1 X. Z. Gong Integrated operation
- EX/3-2 G. Calabro ELM-absent H-mode
- EX/P2-26 D. Moreau Model-Predictive control
- EX/P2-16 A. Ekedahl RF heated H-mode
- EX/P5-1 Z. X. Liu I-mode
- EX/P6-21 J. Barr Low-disruptivity rampdowns

**[ELM&RMPs]**
- EX/7-2 Y. W. Sun RMP control
- EX/P2-4 G. S. Xu Grassy ELM regime

**[PSI&Divertor]**
- MPT/2-2 R. Ding High-Z material erosion & migration
- TH/P1-5 F. Schluck PSI 3D modeling
- EX/P2-8 L. Wang PSI control for H mode
- EX/P2-3 L. Zhang Tungsten control
- FIP/3-5Ra R. Maingi Li limiter and conditioning

**[Transport & turbulence]**
- EX/P2-12 P. J. Sun Microturbulence & MHD modes
- EX/P2-2 Y. Yu Anisotropic turbulence
- TH/P4-2 T. Y. Xia Particle & heat fluxes
- TH/P6-2 S. Y. Ding Gyrokinetic Simulations on H-mode
- TH/P6-1 G. Q. Li integrated modelling of transport
- TH/P7-21 X. Q. Xu Boundary turbulent transport

**[MHD&EP]**
- TH/1-1 W. Shen EP instability & redistribution
- EX/P2-15 J. Huang EP studies
- EX/P2-14 L. Q. Xu Kink mode study
- TH/P5-14 X. Q. Wu Magnetic Coherent Mode

**[CFETR]**
- OV/3-2 G. Zhuang CFETR Design
- TH/P5-16 R. Han RWM Stabilization
- FIP/P7-27 H. L. Chen Vertical Displacement
- TH/P7-3 M. Y. Ye Impurity Radiation

**[Machine learning]**
- EX/P6-20 R. Granetz Distruption warning
Thank you!