EAST Steady-state Long Pulse H-mode with Core-edge Integration for CFETR

by X. Gong

With

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Acknowledgement

Great Progress on EAST Is Benefit from Broad Domestic and Wide International Collaboration!
A Minute Time Scale Steady-state High $\beta_p$ Discharge was Achieved with Tungsten Divertor

- **61.2s H-mode sustained with enhanced RF-heating**
  - $H_{98y2}\sim 1.2$, $f_{Gr}\sim 0.7$, $\beta_p\sim 2.1$, $\beta_N\sim 1.7$, $V_{\text{loop}}\sim 0$
  - Robust iso-flux control with SP to W-divertor
- **101s H-mode achieved in 2017**
  - $H_{98y2}\sim 1.1$, $f_{Gr}\sim 0.6$, $\beta_p\sim 1.2$, $\beta_N\sim 1.0$, $V_{\text{loop}}\sim 0$

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X. Gong, Nucl. Fusion 59 (2019)
New Candidate of High $\beta_P$ Long Pulse Operation with Low Torque at High Density

- Long pulse operation with a duration of 20s by modulated neutral beam ($\sim 1.5$MW) and RF ($\sim 4.0$MW)
  - $\beta_P \sim 2.1$, $\beta_N \sim 1.8$
  - $H_{98y2} \sim 1.3$
  - $f_{Gr} \sim 0.8$
  - $T_{inj} \sim 1.0$Nm
  - $f_{bs} \sim 50\%$
Experiments Demonstrated Steady-state Scenarios with Extension of Fusion Performance

- $\beta_p$ versus line-averaged density of zero loop voltage plasmas
  - Fully non-inductive @ $q_{95}\sim 6.0-7.0$
- Extended operational regime
  - High density $f_{Gr}\sim 0.8$
  - $f_{BS} \sim 50$
- Dominant e-heating, ~zero torque
- Small ELMs with well impurity control
- Improved confinement
  - $H_{98y2}\sim 1.4$
  - eITB inside $r<0.4$

<table>
<thead>
<tr>
<th></th>
<th>CFETR A.3 SSO</th>
<th>EAST</th>
</tr>
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<tbody>
<tr>
<td>$P_{\text{Fusion}}$</td>
<td>974</td>
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<tr>
<td>$\beta_N$</td>
<td>2.0</td>
<td>2.0</td>
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<tr>
<td>$f_{BS}$</td>
<td>0.50</td>
<td>0.50</td>
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<tr>
<td>H factor</td>
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<td>1.25</td>
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<td>$n_e/n_{GW}$</td>
<td>0.57</td>
<td>0.8</td>
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<tr>
<td>$q_{95 \text{ Iter}}$</td>
<td>5.54</td>
<td>6.7</td>
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</tbody>
</table>

J. Huang et al., Nucl. Fusion 60 (2020)
J. Huang, PPCF 62 (2020)
S1: Enhance H/CD efficiency & relevant fundamental physics understanding and key diagnostics
Strategies to Establish the Scientific Basis for Long Pulse Operation in Supporting ITER/CFETR

S1: Enhance H/CD efficiency & relevant fundamental physics understanding and key diagnostics

S2: Demonstrate long-pulse (≥100s) H-mode plasmas and develop fully non-inductive high-β scenarios
**S1:** Enhance H/CD efficiency & relevant fundamental physics understanding and key diagnostics

**S2:** Demonstrate long-pulse (≥100s) H-mode plasmas and develop fully non-inductive high-β scenarios

**S3:** Extend EAST operation regime to demonstrate steady-state high performance plasmas and deliver relevant physics for ITER and CFETR
EAST Steady-state Long Pulse H-mode with Core-edge Integration

- Improved confinement
- High LHCD efficiency at high density
- Broaden current profile
- Core-edge integration
Reduced Transport in Electron Energy Channel Consistent with Te-ITB Formation

- Dominant electron heating by ECH & LHW
  - $T_e > T_i$
  - zero torque
  - low rotation
  - Flat q profile with $q(0)>1.0$

- Electron transport is significantly reduced in the plasma core ($\rho<0.4$)
  - Consistent with improved confinement
Reduced Transport in Electron Energy Channel Consistent with Te-ITB Formation

- **Linear analysis by TGLF**
  - TEM modes dominate in the low-k ($k_y<1$) region, at ITB
  - ETG modes dominate in the high-k region, outside ITB

- **The decrease of the high-k turbulence (ETG)**
  - Causing the reduction of electron transport
Modeling Shows $\beta_p$ Stabilization Effect on Electron and Ion Turbulent Energy Fluxes

- TGLF+NEO to predict transport
  - Scaled pressure profiles at fixed $q$-profile generated from experimental reconstruction

- Electron turbulent energy fluxes decreases with high $\beta_p$

- Ion turbulent energy fluxes decreases slowly with increase of $\beta_p$

J. Qian, Phys. Plasmas 2021
EAST Steady-state Long Pulse H-mode with Core-edge Integration

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- Core-edge integration

**Graph:**
- EAST #90949
- 2.5T/USN
- Time (s)
- $I_p$ (MA)
- $W_{MHD}$ (MJ)
- $\beta_p$
- $V_{loop}$ (V)
- $n_e$ ($10^{19}m^{-3}$)
- $H_{98,y2}$
- $L_{W4.6G}$ (MW)
- ECRH (MW)

**Notes:**
1. See the appendix of B. Wan et al., 25th IAEA FEC, St. Petersburg, Russia, 2014
2. See the appendix of F. Romanelli et al., 25th IAEA FEC, St. Petersburg, Russia, 2014
A Link Between the Degradation of Current Drive Efficiency and Spectral Broadening

- Spectral broadening is found to have a negative and significant effect on CD efficiency.
- The modeling results show that PI effect can redistribute the $N_{||}$ spectrum to some extent, thus leading to a pump power depletion.

Higher LHW Frequency and Lower Recycling Wall Allows High LHCD Efficiency at High Density

- Consistent with Parametric Instability (PI) modeling:
  - Growth rate is smaller with higher LH source frequency, thus to enhance CD efficiency;
  - Low recycling wall, producing higher temperature at the plasma edge, can reduce PI intensity.

EAST Steady-state Long Pulse H-mode with Core-edge Integration

- Improved confinement
- High LHCD efficiency at high density
- Broaden current profile
- Core-edge integration
• Low $l_i$ obtained at high density, high $\beta_P$
  - Higher $\beta_P$ generates more off-axis $f_{BS}$
  - High density operation allows LH off-axis deposition

• Equilibrium analysis confirms a higher q0 for low $l_i$ case
Modeling Shows that Larger $\rho_{q_{\text{min}}}$ and ITB Radius on EAST can be Achieved at Higher $\beta_p$

- Use integrated modeling with optimized H&CD scheme
  - ECH+LHW, co-Ip NB & ICRF

- Large $\rho_{q_{\text{min}}} (~0.5)$ obtained with more off-axis $f_{bs}$ CD
  - $f_{bs}$ from 43% to 63% with higher $\beta_p$
EAST Steady-state Long Pulse H-mode with Core-edge Integration

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Well Controlled High Z Impurity in High $\beta_p$ Plasmas

- Small ELMs and high density ($n_e/n_G \approx 0.8$) reduced tungsten sputtering

- On-axis ECH pump out high Z impurities from core plasma
  - W in good control within a low level ($C_w \approx 0.3 \times 10^{-5}$)
Modeling Shows that Strong Diffusion of TEM in the Central Region Prevents W to Accumulate

- W modeling by QuaLiKiz and NEO
- TEM dominates and its strong diffusion prevents W to accumulate at r/a<0.4, including TEM and ITG
- The large modelled R/L_{Nw} at ρ~0.5 can be explained by the overestimation of stabilization effect on TEM by collisionality in QuaLiKiz.
Demonstration of a Compatible Core and Edge Integration in High $\beta_p$ Scenarios

- Radiative divertor feedback with a mixture of 50% neon and 50% D$_2$
- Peak heat flux reduced by 20-30% (IR)
- Confinement maintained $H_{98}>1.2$
ITG is Stabilized During Neon Seeding, Leading to a Higher Ion Temperature

- After Neon seeding, ITG is stabilized due to the dilution of main ions, which is consistent with the increase of $T_i$.

<table>
<thead>
<tr>
<th>$\rho$</th>
<th>$R/L_{Te}$</th>
<th>$R/L_{Ti}$</th>
<th>$T_e/T_i$</th>
<th>$\hat{s}$</th>
<th>$q$</th>
<th>$Z_{eff}$</th>
<th>$u^*$</th>
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</thead>
<tbody>
<tr>
<td>0.4</td>
<td>13.3</td>
<td>6.5</td>
<td>1.5</td>
<td>0.54</td>
<td>1.27</td>
<td>2.2</td>
<td>0.24</td>
</tr>
</tbody>
</table>

$\rho$, $R/L_{Te}$, $R/L_{Ti}$, $T_e/T_i$, $\hat{s}$, $q$, $Z_{eff}$, $u^*$ are parameters used in the analysis.
Larger Reduced Divertor Temperature with Divertor Heat Flux Splitting

- **Core**: High $\beta_p \sim 2.5 / \beta_N \sim 2.0$ with $H_{98y2} > 1.2$, $f_{Gr} \sim 0.8$, $q_{95} \sim 6.7$;
- **Pedestal**: ELM controlled by RMP $n=1$;
- **Divertor**: Radiation and splitting.
Summary

- Steady-state long pulse (>60s) demonstrated with extension of fusion performance
  - High $f_{BS}\sim50\%$ with improved energy confinement ($H_{98,y2}>1$)
  - Improved confinement at higher $\beta_p$ due to broader q-profile, Shafranov shift, e-ITB
  - W accumulation prevented by TEM with on-axis ECH
- The Radiation feedback control is compatible with good core confinement in high $\beta_p$ discharges
  - $H_{98y2}>1.2$
  - heat flux reduced by 20-30% with 50% neon
- Further research on integration of core performance and edge-divertor plasma for scenarios will be addressed

Thank You For Your Attention
Your Suggestions and Comments Will Be Appreciated