Advances in the long-pulse steady-state high beta H-mode scenario with active controls of divertor heat and particle fluxes on EAST

by

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for the EAST team & collaborators
We acknowledge contributions from domestic and international partners to EAST research program.
EAST demonstrated high $\beta_p$ long pulse H-mode operation with high $f_{bs}$

- A 60s time scale long-pulse steady-state high $\beta_p$ H-mode discharge achieved by pure RF heating with the ITER-like tungsten divertor.

Overview of the parameter space of obtained and prospective long pulse high $\beta_p$ H-mode plasmas
Outline

- Extension of steady-state operational regime
- Physics studies to resolve key issues for steady state operation
- Progress in supporting of ITER
- Summary and future Plan
Outline

• **Extension of steady-state operational regime**

  • Physics studies to resolve key issues for steady state operation

• **Progress in supporting of ITER**

• **Summary and future Plan**
A 60s scale steady-state discharge was achieved

- **Dominant electron heating by ECH & LHW**
  - $\beta_p \sim 2.1$, $\beta_N \sim 1.7$, $H_{98} > 1.3$
  - eITB ($T_e > T_i$), zero torque, low rotation
  - Flat q profile with $q(0) > 1.0$, $f_{bs} \sim f_{LHCD}$

- **Good control of impurity**
  - Small ELMy, on-axis ECH
Experiments show improved confinement and reduced turbulence when extending to higher $\beta_p$

- The higher $\beta_p$ with high energy confinement at high density.

- The electron turbulent energy fluxes decrease with $\beta_p$ increase.
  - The transport dominated by the trapped electron mode (TEM) due to the electron heating by RF power ($T_e >> T_i$).
A clear dependence of $H_{98y2}$ on the density peaking factor was observed.

- High density gradient can enhance the Shafranov shift stabilizing effect significantly in high $\beta_p$ regime.

The same trends in various Heating/CD mixtures

---A new pass for Steady-State Tokamak Fusion Reactor

Wan, CPL 37 (2020) 045202
Optimization of fast ion confinement

- **Fast-ion pressure decreased at high-density/low beam.**
  - Increase density from $4.4 \times 10^{19} \text{ m}^{-3}$ to $5 \times 10^{19} \text{ m}^{-3}$ and decrease the beam voltage from 60 to 50 kV

- **Improved plasma performance ($\beta_p \sim 2.5$ and $H_{98y2} > 1.1$) with reduced fast-ion loss**
  - A bootstrap current fraction ($f_{BS}$) up to 50% with balanced NB injection.

Huang, NF 60 (2020) 016002
Demonstration of a compatible core and edge integration in high $\beta_p$ scenarios

- A compatible core and edge integration in high $\beta_p$ scenarios
  - high confinement $H_{98y2} > 1.2$
  - $\beta_p \approx 2.5/\beta_N \approx 2.0$, $f_{bs} \approx 50%$
  - $n_e/n_{GW} \approx 0.7$, $q_{95} \approx 6.7$

- The peak heat flux is reduced by $\sim 30\%$ on the tungsten divertor
  - Active impurity seeding through radiative divertor feedback control via radiated power.
  - A mixture of 50% neon and 50% $D_2$ is applied.

Gong - EX/1-TH/1
Long-pulse Fully Non Inductive with RF only Close to 1GW CFETR Performance Achieved

- Improved confinement ($H_{98y2} \sim 1.3$)
- ~zero torque with eITB
- Electron heating dominant
- Small ELMs ($f_{ELM} \sim 1$kHz)
- Good impurity control

Close to 1GW CFETR Performance
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Divertor impurity seeding extends the grassy-ELM regime to lower $q_{95}$

- **Stationary grassy ELM regime**
  - Low heat flux
  - Strong particle exhaust capability

- **Divertor impurity seeding leads to a transition from mixed ELMs to grassy ELMs**
  - 20% Neon injected near the outer strike point of the upper divertor.

Extension of the grassy-ELM regime to lower $q_{95}$→5

Li, PPC F 62 (2020) 095025
ELM suppression by Neon seeding

- ELM suppression achieved with neon seeding.
  - Edge Coherent Mode (ECM) disappears and replaced by a Broad-Band fluctuation in the pedestal gradient region.

- Existence of a threshold of neon seeding observed for ELM suppression.
ELM suppression by boron injection

- Suppression of edge localized modes with real-time boron injection using the tungsten divertor is obtained.

- Edge harmonic oscillations appear during B powder injection.
  - Sufficient particle transport to maintain constant density and avoid impurity accumulation in ELM-stable plasmas.
ELM suppression by divertor CD4 seeding

- With divertor CD4 seeding, sustained ELM suppression and divertor detachment achieved
  - An n=1 low-frequency mode (<10kHz) near the upper X point.

- Tungsten impurity concentration is significantly reduced when the mode appears, suggesting that the low-frequency mode enhances the impurity exhaust.
Simulation suggests ELMs can be mitigated by pedestal coherent mode

- The pedestal coherent modes (PCM) is always accompanied with the ELM mitigation and suppression on EAST.
- Simulation by BOUT++ shows pedestal coherent mode (PCM) decreases the ELM size by ~45%.
  - ELM mitigation by PCM is related with the three-wave nonlinear interactions
- PCM leads to the wider mode spectrum →stronger mode coupling →lower energy loss of ELMs
EAST successfully develop active detachment controllers

<table>
<thead>
<tr>
<th>Control parameters</th>
<th>Actuator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total radiation ((P_{rad, total}))</td>
<td>LFS and divertor neon seeding</td>
</tr>
<tr>
<td>Divertor particle flux ((j_{sat}))</td>
<td>Divertor neon seeding</td>
</tr>
<tr>
<td>Divertor particle flux ((j_{sat}))</td>
<td>LFS D2 fueling by SMBI</td>
</tr>
<tr>
<td>Divertor neon seeding</td>
<td>Divertor neon/argon seeding</td>
</tr>
<tr>
<td>Divertor target temperature ((T_{t, peak}))</td>
<td>Divertor neon seeding</td>
</tr>
<tr>
<td>Divertor electron temperature + X-point radiation ((T_{et} + P_{rad, X-point}))</td>
<td>Divertor neon seeding</td>
</tr>
</tbody>
</table>
A new detachment feedback control scheme, combining divertor radiation near the X point and target plate Te signals, is demonstrated.

- Divertor target Te near strike point maintained at 5-8 eV.
Feedback control of H-mode detachment via Divertor-Te

- $T_{e,\text{div}}$ control is important for sputtering reduction
- Neon is more compatible with core plasma for $T_{e,\text{div}} = 5\text{eV}$.
  - Argon seeded detachment reduces confinement slightly.

![Graphs showing temperature and other parameters for Ne and Ar](image)
Development of flowing liquid Li limiters (FLiLis)

- Liquid Li is being studied as an alternative PFM for better handling of particle and heat flux.
  - Four generations of FLiLi have been successfully in EAST.

- D retention increases gradually during FLiLi operation.
  - FLiLi can well solve the problem of the saturation of Li coated wall.

Zuo, Nucl. Fusion 59 (2019) 016009
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ELM suppression by n=4 RMP in low torque plasmas

- **Type-I ELMs are suppressed by n=4 RMP with upper-lower odd coil phasing, but not for the even one.**
  - W concentration decreased with RMP
  - Significant density pump-out (20%) happens during ELM suppression, but less drop (5%) in stored energy

- **The target plasma is close to ITER type-I ELMy H-mode operational window**
  - $T_{\text{NBI}} = 1.1 \text{ N} \cdot \text{m} \ (0.9 \text{ N} \cdot \text{m ITER equivalent torque in EAST})$
  - $q_{95} \sim 3.65$, $v_{e,ped}^* \sim 0.5$, $\beta_N \sim 1.4$
Helium plasmas demonstrated under pure RF-heating and ITER-like tungsten divertor

- Concentration of helium ($C_{\text{He}}$) in the plasma is confirmed to play a critical role in H-mode operation.
  - higher concentration raises the H-mode threshold power and deteriorates the energy confinement in H-mode.

- ELMs suppression by $n=1$ RMP is achieved in helium plasma.
  - Strong density pump-out effect during ELMs suppression, but less drop in plasma confinement.

Zhang -EX/P2-927
Divertor Detachment Achieved with Density Ramp-Up in He Plasmas

- A clear particle flux rollover occurs with favorable $B_T (B \times \nabla B \uparrow)$, similar as the D plasmas.
- $T_e$ at strike point decreases with the density ramping up.
- Higher detachment threshold density in He than D.
W Erosion is more serious in He plasmas

- W erosion rate in He plasmas is more than 3 times that in D plasmas.

- The intra-ELM W sputtering source increases linearly with the ELM frequency.
  - similar to the deuterium plasmas from DIII-D and JET.
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EAST augmented capabilities provide flexibility to continue long-pulse H-mode scenario development

- **Heating/CD systems upgraded**
  - PAM launcher for LHW (2.45 GHz)
  - Lower K spectrum for ICRF (N)
  - A new gyrotron for ECRH (1 MW)
  - Two co-current NBI systems

To optimize profiles for scenario development and instability control
EASTaugmented capabilities provide flexibility to continue long-pulse H-mode scenario development

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  To increase the steady-state heat exhaust to 10 MW/m²

- **A new lower water-cooled tungsten divertor installed**
  - ¾ with the monoblock structure
  - ¼ with the flat-type structure
Summary

• **Significant progress has been made in the long-pulse steady-state high $\beta_p$ H-mode scenario**
  - A minute time scale H-mode discharge ($\beta_p \sim 2.0$, $f_{bs} \sim 50\%$, $H_{98(y2)} > 1.3$)
  - A compatible core and edge integration in high $\beta_p$ scenarios

• **Key advances on the developments of long pulse operation, delivering steady state operation in ITER and CFETR**
  - Active controls of radiative divertor, ELM suppression, He plasmas etc.

• **A new lower tungsten divertor is installed and the H/CD systems are upgraded for achieving**
  - $\gtrsim 400s$ long-pulse H-mode operation with $\sim 50\%$ bootstrap current fraction;
  - Demonstration of power exhaust at $\sim 10$ MW power injection for $>100s$. 
Thank you!