Recent progress on pedestal and divertor experiments towards long-pulse H-mode operation in EAST

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for the EAST Team and Collaborators**

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** See appendix of B. N. Wan et al., Nucl. Fusion 57, 102019 (2017)
EAST aims at demonstration of SS high-performance operation under ITER-like condition and address relevant physics basis for ITER and CFETR

**Roadmap of Fusion Energy Research in China**

- **EAST**
  - Advance PFC, steady-state advanced operation
- **HL-2M**
  - Advanced divertor, high power H&CD, diagnostics
- **J-TEXT**
  - Disruption mitigation, basic plasma

**ITER**

- **(2030’s start operation)**
  - Phase II: DEMO validation, Q>10, CW, 1GW, >50dpa
  - Phase I: Q=1-5, steady-state, TBR>1, >200MW, <10dpa

**CFETR**

- **(> 2050)**
  - 1GWe, Power Plant Validation

**PFPP**

- **(2025)**
  - Phase II: Q=5, 3000s, 350MW, steady-state burning plasma
  - Phase I: Q=10, 400s, 500MW, Hybrid burning plasma

Y. X. Wan, et al, NF, 2017
EAST features strong RF H&CD, ITER-like W upper divertor and Mo first wall, balanced NBIs.

Total injection power ~ 15 MW

Water-cooled first wall
EAST Achieved the Longest Pulse Fully Non-inductive Steady State H-mode Operation with Tungsten Divertor

- **Prerequisite:** High CD&BS
  - Efficient non-inductive CD in H-mode/ High $f_{bs}$
- **Prerequisite:** Optimized PWI
  - Low peak heat load/ Tolerable transient heat shock/ Low impurity concentration/ Efficient recycling control
- **Integrated operation into long pulse H-mode discharge**
Goal of EAST in the near future for the reference of ITER & CFETR SSO

Long pulse: >400s H-mode

Current status: 100s H-mode

High performance: ~50% bootstrap current fraction
Current status (2018 campaign) towards the goal

**Relevant physics research in support of future long pulse H-mode operation with \( f_{\text{BS}} \sim 50\% \)**
- Scenarios Development: High beta SSO & Hybrid
- H&CD, T&C, pedestal & DSOL physics, dynamic control, EP physics, etc.

**Exploration of high beta regime relevant to ITER baseline with high power injection**

- **Full RF:** \( \beta_p \sim 1.9, \beta_N \sim 1.6 \)
- **RF + NBI:** \( \beta_p \sim 2.5, \beta_N \sim 2 \)
Higher $\beta_p$ Scenario Sustained over 20s

- **80933**, higher $\beta_p$ and $\beta_N$, **RF only**
  - $\beta_p \sim 1.9$, $\beta_N \sim 1.55$, $q_{95} \sim 6.5$, $f_{Gr} \sim 0.7$, $V_{loop} \sim 10$mv.

**Next goal:**
- Fully Non-Inductive, $v_{loop} \sim 0$, for $>100$s.

Validation of Active Water-cooling Capabilities for W-divertor and LHCD W-guard limiter
The challenge on edge plasma physics for EAST

- **EAST** is focusing on the development of truly steady state H-mode scenarios for ITER & CFETR.
- For very long pulse plasma operation, the key issue is particle and heat balance.
- Optimizations on edge plasma physics are necessary to achieve the SSO with high bootstrap current fraction scenario:
  - **Pedestal physics:** controlling the source
    - Suppression & mitigation of large ELM
    - Exploration and extension of the small/no ELM scenario
  - **Divertor & SOL physics:** reducing the expenditure
    - Active handling of particle and heat depositions on divertor
    - Design of the new tungsten lower divertor
Pedestal physics:

- Suppression & mitigation of large ELM
  - Li injection
  - RMP
- Exploration and extension of the small/no ELM scenario

Divertor & SOL physics: reducing the expenditure

- Active handling of particle and heat depositions on divertor
- Design of the new tungsten lower divertor
EAST has various capabilities for ELM control

- Low hybrid wave [Liang Y. et al, PRL (2013)]
- Pellet, SMBI fueling
- RMP [Sun Y. et al, PRL (2016)]
- Li injection [Hu J. et al, PRL (2015)]
- ITER-like full metal wall, low rotation, long pulse
ELM suppression by Li aerosol injection

- Reproducible ELM-free discharges with W divertor
- Same target plasma, $f_{\text{ELM}} \sim 200\text{Hz}$
- #70591, ELM gradually disappears
- ELM completely suppressed except NBI blips
- ELM suppressed, before and after Li injection

- Strong reduction in recycling due to Li accumulation and flow rate increase
- No impurity accumulations during ELM-free phase
- Non-inductive $\rightarrow$ steady-state, essential for long pulse small/no ELM H-mode
Full ELM suppression achieved with $n=1$ and $2$ RMP in RF dominant heating plasma in EAST

- A flexible RMP system has been installed in EAST since 2014
- Full ELM suppression has been achieved in EAST with RF heating ($\Omega_\phi \sim 0$) using $n=1, 2$ RMP
- Extended to long pulse ($\sim 20s$) steady state ($V_{\text{loop}} \sim 0.0V$) operation with W divertor

$q_{95} \sim 5.7$, $\beta_N \sim 0.8$, $\nu_{e,\text{ped}} \sim 1$

[Sun Y. et al., PRL (2016)]
Physical understanding of linear and nonlinear plasma response for ELM suppression

- **Linear** plasma response by MARS-F modeling determines the best spectrum for ELM suppression

- **Nonlinear** plasma response happens at the transition from ELM mitigation to suppression
Multimode plasma response directly observed in EAST tokamak

The $n=2$ plasma response was shown to be multimodal (clear phase shift) using two LFS mid-plane magnetic sensor arrays in EAST.

GPEC ideal MHD modeling captures this transition from single-mode to multimode.

Mode structure change significantly from LFS kink to dominated edge resonance, at which phasing strongest ELM mitigation observed.

[N.C. Logan et al, NF 58 (2018)]
Redistribution of divertor particle flux achieved using rotating RMP in EAST

- 3D pattern of the particle flux during the application of rotating RMP in EAST agrees well with modeling by the TOP2D code
- Plasma response modeled by MARS-F can amplify or shield the RMP, consistent with observed particle flux
Challenges for the active ELM control towards CFETR

- **Compatibility** of Li injection & FLiLi with reactors
- **The nonlinear response** of plasma to RMP
- **Compatibility** of RMP with CFETR
- **Physics understanding** of ELM control by RF
- **Engineering technology** for ELM suppression & pacing by RF
**Outline**

- **Pedestal physics:**
  - Suppression & mitigation of large ELM
  - Exploration and extension of the small/no ELM scenario
    - Grassy ELM

- **Divertor & SOL physics:** reducing the expenditure
  - Active handling of particle and heat depositions on divertor
  - Design of the new tungsten lower divertor
Grassy ELM regime obtained in EAST with metal wall

Average ELM frequency $\geq 2$ kHz
$V_{t0} \sim 10$ km/s
$H_{98,y2} \sim 1.1$
Loop voltage $\lesssim 0.005$ V with LHCD
$\langle n_e \rangle \sim 57\% n_{GW}$
$\beta_p \sim 1.8$
$l_i \sim 1.1$
$q_{95} \sim 6.8$
$\delta_u \sim 0.58$, $\delta = (\delta_u + \delta_l)/2 \sim 0.46$
$\kappa \sim 1.56$
$v_{e,ped}^* \sim 1$
$f_{BS} \sim 31$

- Compatible with low rotation
- Does not sensitive to $B_z$ direction and LHCD
- Typical profiles show wide pedestal and lower density gradient in the grassy-ELM regime

$dR_{sep} \sim 2$ cm
EAST grassy ELM has small peak heat flux and excellent control of W concentration

- $q_{95} \approx 4.8$, $\beta_p \approx 0.85$, $\delta_u \approx 0.5$
- $l_i \approx 1$, $W_{\text{MHD}} \approx 200$ kJ

- $q_{95} \approx 6.8$, $\beta_p \approx 1.72$, $\delta_u \approx 0.5$
- $l_i \approx 1.1$, $W_{\text{MHD}} \approx 190$ kJ

- $q_{95} \approx 6.8$, $\beta_p \approx 1.78$, $\delta_u \approx 0.57$
- $l_i \approx 1.1$, $W_{\text{MHD}} \approx 190$ kJ

W droplet decay

- ELM peak heat flux is reduced by more than 10 times
- Low W source due to low transient heat load
- Strong W exhaust carried by the grassy ELMs
- Strong W neoclassical transport at high $q$
The mechanism of EAST grassy ELM has been found due to less peeling drive compared with type-I ELM.

**Grassy ELMs situate near peeling boundary**

**BOUT++ nonlinear simulation**

**BOUT++ code successfully reproduce the grassy ELM.**
Fully non-inductive high-performance small-ELM regime are obtained in EAST with W divertor in **2018 campaign**

ELMs are more grassy and obtained at lower $q_{95}$ in 2018 campaign when C impurity concentration is significantly reduced by replacing the LHCD guide limiter from C to W.

### EAST Shot#80307

- **Full RF heating: LHW+ECRH**
- High $q_{95}$ ($\sim 6.7$)
- High $\beta_p$ ($\sim 1.9$)
- High density ($\sim 0.75 \, n_{GW}$)
- High $f_{BS}$ (> 45%)
- **Configuration: USN**
- $B_t$ direction: favorable
Exploration of small-ELM regime towards lower $q_{95}$

Towards lower $q_{95}$ (~5.4):
- Grassy-like small ELMs can be obtained with unfavourable $B_t$;
- Mixed ELMs appear with favorable $B_t$.

**EAST shot #79897**

- $\beta_p \sim 1.4$
- $\langle n_e \rangle / n_{GW} \sim 0.6$
- $q_{95} \sim 5.4$
- $D_a$ (a.u.)

**EAST Shot #79978**

- $\beta_p \sim 1.75$
- $\langle n_e \rangle / n_G \sim 0.6$
- $q_{95} \sim 5.4$
- $D_a$ (a.u.)
Mixed ELMs turn to grassy ELMs by impurity seeding without confinement degradation

Promising to be applied for lower $q_{95}$ exploration
Challenge: how to extend the grassy ELM regime to future facility?

Grassy ELM regime prescription:
1. High q_{95}
2. High $\beta_p + l_i/2$
3. Wide pedestal
4. Strong shaping $\delta$

It could be naturally achieved in CFETR.

Further exploring the parameter space of grassy ELM towards CFETR should concern:

✓ High bootstrap current fraction (✓)
✓ Compatible with high density (✓)
✓ Compatible with radiative divertor (✓)
✓ Integrate above in one pulse and long-pulse demonstration (to be done)
Outline

- Pedestal physics:
  - Suppression & mitigation of large ELM
  - Exploration and extension of the small/no ELM scenario

- Divertor & SOL physics:
  - Active handling of particle and heat depositions on divertor
    - Strike point splitting by LHW
    - Active feedback control
    - Quasi-Snow Flake in W divertor
    - W control
  - Design of the new tungsten lower divertor
LHW-induced strike point splitting shows toroidal asymmetry: 3D divertor footprint features

- **100s** H-mode with **strike point splitting on W divertor targets**

- good handling of heat flux and thus impurity source.

- Both divertor **temperature** and **recycling** were well maintained

- **Not sensitive to** $q_{95}$, in contrast to fixed RMP coils

- A threshold of $P_{\text{LHW}} \sim 0.9$ MW exists for 3D footprints & ELM mitigation in EAST
Active feedback control of divertor heat load in H-mode for long pulse operation

- Achievement of feedback ctr. of radiation in EAST [K. Wu, NF (2018)].
- Successful extension of divertor radiation & heat flux ctr. in high $\beta$ scenario on DIII-D [March 2018].
- Stable feedback ctr. of divertor detachment in EAST [July 2018].

Total radiation power was actively controlled by feedback of LFS neon-SMBI seeding.
QSF compatible with high performance in SSO using W divertor

QSF: Quasi-Snow Flake divertor configuration

A steady-state regime with improved confinement ($H_{98} > 1$) & high bootstrap current ($\beta_p > 2$) is obtained.

Outer strike point flux expansion: $f_{m,QSF}/f_{m,SN} \sim 3$

Peak heat flux reduced by a factor of 1.5

Collaborated with ENEA
Effect of W divertor closure on particle exhaust

- Effective particle exhaust with strike point close to the pumping slot, good for long pulse operation.
- No significant difference against ion $B_x \nabla B$ directions.

**EAST: USN, 2.5 T/0.4 MA**

Different strike point positions in reversed $B_t$

- EAST #67065

**EAST: USN, 2.5 T/0.4 MA**

Different strike point positions in Normal $B_t$

**EAST #67065**

Strike point sweeping

Time (s)

$\langle n_e \rangle \left(10^{19} m^{-3}\right)$

$SMBI$ (a.u.)

Decay time (s)
Control of W source with various methods

- LHW, high $f_{ELM}$ for relief of W, compatible with RF scenarios in EAST
- Reduce divertor heat flux by enhancing DSOL radiation via lithium aerosol

Neon/ D$_{2}$-SMBI assisted impurity injection from LFS mid-plane

$\rightarrow$ lower $T_{e,b}$ and thus reduced W sputtering significantly.
- **Pedestal physics:**
  - Suppression & mitigation of large ELM
  - Exploration and extension of the small/no ELM scenario

- **Divertor & SOL physics:**
  - Active handling of particle and heat depositions on divertor
  - Design of the new tungsten lower divertor
    - Limitations of current C divertor
    - Design of the new W divertor
Current PFCs in EAST W-shape graphite lower divertor

Pumping capability of the ITER-like W upper divertor is limited due to very narrow pumping channels through the cassette body.
The current lower divertor cannot fulfill the requirements of the near future goal

**Current limitations:**

- **Hot spots** on the lower graphite divertor is currently the **main problem** limiting heating power to < 3 MW for ~100 s long-pulse H-mode operations in EAST.
- Heavily rely on **lithium** to reduce H concentration, recycling and impurity.

**Key targets:**

- Steady-state operation of a **dissipative divertor** with low tungsten sputtering and strong divertor pumping.
- Power and particle exhaust and tungsten impurity control is the key to achieve this global target.
- Tungsten sputtering by light impurities \( T_{el} < 10 \text{ eV} \)
- Cooling capability of the PFCs \( q_{et} < 10 \text{ MW/m} \)

61s long H-mode in 2016
New divertor design for high-power steady-state H-mode operations in EAST

- Vertical inner target (VIT)
- Horizontal outer target (HOT)

**Dome:** Improve pumping

**Baffle:** trap neutral, protect the end box

**Cryopump**

**End box:** protect against downward strike point excursions

**Reflection end box:** trap neutral

**Water-cooled internal coil ~10 kAt**
High neutral pressure near the corner facilitates detachment across the entire outer target.

End box nearly parallel to field lines to avoid high heat load on the end box.

Local particle circulation Trap recycling neutrals

Optimized projection distance $\sim \lambda_n > \lambda_q < 1\, \text{cm}$
Other requirements of the new lower divertor

- Two kinds of *water-cooled tungsten* PFC tech:
  - **Flat-tile** (2mm thickness) PFCs: Dome and baffles (~5 MW/m²)
  - *ITER*-like monoblock PFCs: Divertor targets (~10 MW/m²)

- Main engineering constraints for the water-cooled tungsten PFCs in EAST:
  - **Dome**: Curvature radius limit ~9 cm
  - **End box**: flat-tile ~5 MW/m²
  - **Cryopump**: 75 m³/s on the low field side; 2*10⁶ m³/s at port end ~3m long

- **High triangularity** should allow access to the small-ELM H-mode regimes & advanced core scenarios

- Compatible with **double-null operation**
## Schedule

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Summary: The long-pulse operation of EAST are focusing on the physics design of CFETR

Pedestal physics of EAST:
- Small/no ELM
  - $\gamma(\omega \cdot \beta) - $ diamagnetic stabilization
  - Kink/Peeling
  - Unstable
  - Stable

ELM suppression
- Call on EAST

Long-pulse steady-state
- Type-II
- $n_e$

DSOL physics of EAST:
- 3D footprint
- Active feedback control of radiation
- Lower W divertor upgrade
- Lithium injection

CFETR
EAST near-term plan

Main targets:

Demonstration of long-pulse high-performance H-mode plasma operation in support of ITER and CfETR

• 400s high-performance H-mode $H_{98y2} > 1$ with $f_{BS} > 50\%$ at $q_{95} = 6-7$
• Heat & particle exhaust for 100s with 10MW heating power
• Robust ELM solutions potentially used in CfETR

Main upgrades:

• New W lower divertor (metal wall coverage > 95%)
• ECRH injection power 1→2MW (synergy between ECRH and LHCD is the key for good core confinement, NF 066011 2018)
• Diagnostics upgrade (MSE, more divertor diagnostics, etc.)

Main requirements:

• Improve ICRF absorption power
• NBI long-pulse operation
Advanced magnetic configuration and MIMO control
Challenges of edge plasma physics from EAST to CFETR

Two main challenges:
• Particle balance: only physics solutions
• Heat load: physics & engineering solutions

Pedestal physics: control the heat and particle into SOL
• Exploration the compatibility of small/no ELM regime
• Understanding ELM dynamics: active control of ELM
• Particle confinement time
• Fueling depth

Divertor physics: particle and heat exhaust
• Active control of particle and Heat flux depositions
• ITER-like full metal wall & W divertors
Thank you!
Advanced geometry and divertor are designed on CFETR

Radial scale of CFETR

L-mode High triangularity L-mode Snowflake H-mode Snowflake

ITER-like divertor SAS divertor