Achievements of actively controlled divertor detachment compatible with sustained high confinement core in DIII-D & EAST

Liang Wang\textsuperscript{1}, H. Wang\textsuperscript{2}, A. M. Garofalo\textsuperscript{2}, X. Gong\textsuperscript{1}, H. Guo\textsuperscript{2}, D. Eldon\textsuperscript{2}, Q. Yuan\textsuperscript{1}, S. Ding\textsuperscript{1}, K. D. Li\textsuperscript{1}, K. Wu\textsuperscript{1}, J. C. Xu\textsuperscript{1}, J. B. Liu\textsuperscript{1}, L. Y. Meng\textsuperscript{1}, Y. M. Duan\textsuperscript{1}, B. Zhang\textsuperscript{1}, M. W. Chen\textsuperscript{1}, B. Cao\textsuperscript{1}, Z. S. Yang\textsuperscript{1}, F. Ding\textsuperscript{1}, G. S. Xu\textsuperscript{1}, J. P. Qian\textsuperscript{1}, J. Huang\textsuperscript{1}, A. Hyatt\textsuperscript{2}, D. Weisberg\textsuperscript{2}, J. McClenaghan\textsuperscript{2}, A. W. Leonard\textsuperscript{2}, J. Barr\textsuperscript{2}, M. Fenstermacher\textsuperscript{3}, C. Lasnier\textsuperscript{3}, J. G. Watkins\textsuperscript{4}, M.W. Shafer\textsuperscript{5}, R. J. Buttery\textsuperscript{2}, D. Humphreys\textsuperscript{2}, D. Thomas\textsuperscript{2}, B. J. Xiao\textsuperscript{1}, G.-N. Luo\textsuperscript{1}, J. Li\textsuperscript{1}, B. N. Wan\textsuperscript{1}

\textsuperscript{1}ASIPP, China \hspace{1cm} \textsuperscript{2}GA, US \hspace{1cm} \textsuperscript{3}LLNL, US \\
\textsuperscript{4}Sandia National Laboratories, US \hspace{1cm} \textsuperscript{5}ORNL, US

28\textsuperscript{th} IAEA FEC, May 10-15, 2021 online
Outline

➢ Motivation & Major Progresses

➢ Active detachment control compatible with core
  ● DIII-D: fully detached high-\(\beta_p\) plasmas
  ● EAST H-mode plasmas

➢ Summary & Near-term Plans
Divertor heat load control & Core-Edge integration are critical issues for fusion reactors

- A steady-state tokamak fusion reactor: sustain fusion energy output for sufficiently long operation
  - Detachment: most promising means for SS PWI control

SS Fusion Core
- Ignition
- High fusion gain
- Non-inductive CD
- Controlled Stability
- ...

High heat flux
Long duration

Boundary/PWI
- Materials life cycle
- Pumping & He removal
- Fueling/Recycling
- T Retention
- …

Boundary condition

L. Wang / 28th IAEA-FEC, May 2021
Joint DIII-D/EAST research demonstrated active control of detachment compatible with improved core plasma

**EAST**
- ITER-like W divertor
- RF heating
- Long pulse
- ...

**DIII-D**
- High performance
- Control & Phys.
- Full diagnostics
- ...

**High $\beta_p$ scenario:** a promising candidate for ITER’s steady-state operation

**DIII-D:** Integration of full detachment + ITB + ETB in high $\beta_p$ scenario
- $T_{e,\text{div}} \leq 5\text{eV}, H_{98} \sim 1.5, \beta_N \sim 3, \beta_p > 2$ and very low divertor particle flux
- Excellent core-edge-divertor integration [L. Wang et al., Nature Commun. 12, 1365 (2021)]

**EAST:** A series of active detach. controllers compatible with H-mode
- $P_{\text{rad}}$ (2017), $J_{\text{sat}}$ (2018), $T_{e,\text{div}}$ (2019), $T_{e,\text{div}} + P_{\text{rad}}, x$-point (2019), $T_{\text{IR}}$ (2019)
- $T_{e,\text{div}} \sim 5\text{eV} & H_{98} > 1$ in standard H-mode, grassy ELMy H-mode, high $\beta_p$ scenario
Both EAST & DIII-D successfully developed active detachment controllers compatible with high-\(H_{98}\) core plasmas

- **EAST:** 5 detachment/radiation controllers achieved with core \(H_{98} > 1\)

<table>
<thead>
<tr>
<th>Control methods</th>
<th>Control parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total radiation \cite{Wu18NF}</td>
<td>(P_{\text{rad, total}})</td>
</tr>
<tr>
<td>Div. particle flux \cite{Wang19NF,Yuan20FED}</td>
<td>(j_{\text{sat}})</td>
</tr>
<tr>
<td>Div. electron temperature \cite{Eldon21NME}</td>
<td>(T_{\text{et}})</td>
</tr>
<tr>
<td>Combination of div. electron temperature and X-point radiation \cite{Xu20NF}</td>
<td>(T_{\text{et}} + P_{\text{rad, X-point}})</td>
</tr>
<tr>
<td>Div. target temperature \cite{Chen20NF}</td>
<td>(T_{\text{t, peak}})</td>
</tr>
</tbody>
</table>

- **DIII-D:** DoD controller via \(j_{\text{sat}}\) achieved with core \(H_{98} \approx 1.5\) in high \(\beta_p\) scenario

<table>
<thead>
<tr>
<th>Control methods</th>
<th>Control parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Div. electron temperature \cite{Eldon17NF}</td>
<td>(T_{\text{et, DivTS}})</td>
</tr>
<tr>
<td>Div. radiation \cite{Eldon17NF}</td>
<td>(T_{\text{et}} + P_{\text{rad, div}})</td>
</tr>
<tr>
<td>Div. particle flux \cite{Eldon21NME}</td>
<td>(j_{\text{sat}})</td>
</tr>
</tbody>
</table>
Outline

➢ Motivation & Major Progresses

➢ Active detachment control compatible with core
  ● DIII-D: fully detached high-$\beta_p$ plasmas
  ● EAST H-mode plasmas

➢ Summary & Near-term Plans
High $\beta_p$ is a promising candidate scenario for steady-state fusion core, facilitating core-edge-divertor integration

- High $\beta_p$ → Strong Shafranov shift → High confinement quality → high fusion gain → reduce reactor cost
  - Large-radius ITB + ETB → isolate hot core vs cold boundary

- High $\beta_p$: high confinement at lower pedestal $T_e$ → benefit heat exhaust
  - Full detachment with $T_{e,\text{div}} \leq 5$ eV across the entire target
  - ITB breaks core stiffness and improves core-edge integration

- Recent experiments & simulations support the possibility of high $\beta_p$ scenario for ITER reaching $Q=10$ at low $I_p$ [S. Ding, this Conf., EX/1-TH/1-3, Tue AM]

X. Gong, this conference, EX/1-TH/1-5, Tue AM
A. Garofalo, AAPPS-DPP 2019; J. Qian, APS-DPP 2019; J. McClenaghan, IAEA-FEC 2018; J. Huang, EPS-DPP 2019

L. Wang / 28th IAEA-FEC, May 2021
DIII-D: Excellent compatibility of detachment and high global performance has been achieved in N$_2$ seeded high $\beta_p$ plasmas

- $\beta_N \sim 3$, $\beta_p \sim 2.4$, $H_{98} \sim 1.5$, $f_{GW} > 0.9$, $f_{NI} \sim 0.7$

- Degree of Detachment feedback control
  - Adjust impurity puff rates [D. Eldon, this conference, EX/P1-934]
  - DoD $\sim I_{roll}/I_{sat}$, follows the control preset

- Radiation dominates the power dissipation
  - $P_{rad, tot}/P_{nbi} \sim 0.75$; $P_{rad, core}/P_{nbi} \sim 0.3$

- IR peak heat flux from 2MW/m$^2$ to $\sim$0.3MW/m$^2$

H. Wang, 62$^{nd}$ APS-DPP, 2020;  H. Wang, 29$^{th}$ ITPA-DSOL, 2020
DIII-D: Full detachment and sustained large-radius ITB + ETB are simultaneously demonstrated in high $\beta_p$ plasmas

- $T_{e,\text{div}} \leq 5\text{eV}$ across entire target plates
  - > 90% divertor pressure loss
  - DoD $>5$ with strong $J_{\text{sat}}$ reduction
  - High neutral pressure $\rightarrow$ exhaust

- ITB grows during detachment
  - ITB at a large radius
  - $n_e$ and $T_e$ ITB grows and expand

- $P_{\text{ped}}$ reduces due to detachment
  - $T_e$ pedestal reduced by 50%
  - $n_e$ pedestal increases slightly

---

H. Wang, 62nd APS-DPP, 2020; H. Wang, 29th ITPA-DSOL, 2020

L. Wang / 28th IAEA-FEC, May 2021
DIII-D: Current density increases at large radius ($\rho = 0.6-0.7$) due to reduced $P_{\text{ped}}$ during detachment access

- $D_2$ fueling detachment lowers $P_{\text{ped}}$ height, which promotes strong ITB
  - Further evidenced by neon seeding

- **Edge current density decreases $\rightarrow$ current density increases at large radius**
  - Decrease of magnetic shear around $\rho = 0.6-0.7$ triggers ITB
DIII-D: Formation of Strong Large-Radius ($\rho = 0.6-0.7$) ITB due to Reduced $P_{\text{ped}}$ Height, induced by divertor detachment

- $s-\alpha$ contour plot is produced by CGYRO scan based on experimental data
  - Large radius $\rho = 0.6$, $k_0\rho_s = 0.3$, EM

  Reduction of pedestal & its current density
  - Current density at $\rho \sim 0.6$ increases
  - Magnetic shear at $\rho \sim 0.6$ decreases
  - Plasma leaves high growth rate region
  - Pressure gradient build up
  - Plasma moves into second stability regime

S. Ding, 10th US-PRC MFC Workshop, March 2021
DIII-D: Neon seeding detachment leads to more effective $P_{\text{ped}}$ reduction and strong large-radius ITB formation

- $\beta_N > 3$, $\beta_p \sim 2.3$, $H_{98} \sim 1.4$, $f_{GW} > 1.1$, $q_{95} \sim 7$

- Neon reduces pedestal even more compared to N2 cases
  - Lower pedestal, higher ITB

- Partially detached w/ $T_{e,\text{div}} = 5$-10eV

- Steady ELM suppression + divertor detachment + high performance core
  - Reproducible ELM suppression by neon seeding

Motivation & Major Progresses

Active detachment control compatible with core

- DIII-D: fully detached high-β_p plasmas
- EAST H-mode plasmas

Summary & Near-term Plans
EAST: Achieved feedback control on degree of detachment (DoD) via $j_{\text{sat}}$ in standard H-mode

- The feedback was achieved with two separate means, $T_{e,\text{div}} < 5\text{eV}$
  - ① LFS D2 fueling using SMBI, ② Divertor neon seeding

- Excellent compatibility with core plasma, $\Delta W_{\text{MHD}} < 10\%$
  - Neon seeding compatible with core → no confinement loss
EAST: Achieved feedback detachment control via $T_{e,\text{div}} + P_{\text{rad}}$ in grassy ELMy H-mode

- A new combined control module using Div.-LP $T_{e,\text{div}}$ & X-point radiation
  - Divertor target $T_e$ near strike point maintained at 5-8 eV
  - $H_{98} > 1$ & plasma stored energy remains constant

G. Xu, this conference, EX/P2-872, Tue PM
G. Xu et al., Nucl. Fusion (2020) ; K. Wu et al., Nucl. Fusion (2018)
EAST: Achieved feedback control of H-mode detachment via Divertor-Te

- $T_{e,\text{div}}$ control is important for sputtering reduction
- For $T_{e,\text{div}} = 5eV$, neon is more compatible with core plasma, $H_{98} \sim 1.1$
- Argon seeded detachment induces slight confinement loss

D. Eldon, this conference, EX/P1-934, Tue AM
D. Eldon et al., Nucl. Mater. Energy (2021); D. Eldon, 24th PSI Conference, 2021

L. Wang / 28th IAEA-FEC, May 2021
EAST: Ne improves confinement facilitating steep-gradient core while Ar degrades core $T_e$ in standard H-mode

- $T_e,\text{div}$ control is important for sputtering reduction
- For $T_e,\text{div} = 5\text{eV}$, neon is more compatible with core plasma, $H_{98} \sim 1.1$
- Argon seeded detachment induces slight confinement loss

K. D. Li et al., Nucl. Fusion (2021, in press)
D. Eldon, this conference, EX/P1-934, Tue AM

L. Wang / 28th IAEA-FEC, May 2021
EAST: Active detachment control is used to improve core-edge integration in high $\beta_p$ scenario

- $T_{et} \sim 8$ eV, $\beta_p \sim 1.8$ and $H_{98} \sim 1.1$ using Ar
  - Ar facilitates steep-gradient core and lower pedestal, different from standard H-mode in EAST
- Detachment $\rightarrow$ weaker ETB & higher core, similar to detached high $\beta_p$ scenario in DIII-D

- $\beta_p \sim 2.5$, $\beta_N \sim 2.0$, $H_{98} > 1.2$ and $q_{95} \sim 6.7$ achieved using neon seeding with more heating power [X. Gong, this conference, EX/1-TH/1-5, Tue AM]
Outline

➢ Motivation & Major Progresses

➢ Active detachment control compatible with core
  ● DIII-D: fully detached high-$\beta_p$ plasmas
  ● EAST H-mode plasmas

➢ Summary & Near-term Plans
Joint DIII-D/EAST research demonstrated active control of detachment compatible with improved core plasma

- **A series of detachment control techniques for core-edge integration**
  - DIII-D&EAST: divertor $J_{\text{sat}}$, $T_{e,\text{div}}$, $P_{\text{rad}}$
  - EAST: divertor $T_{\text{IR}}$, $T_{e,\text{div}} + P_{\text{rad}}$, $x$-point

- **DIII-D: Excellent integration of full divertor detachment with high $\beta_p$**
  - High confinement core, benefits from large-radius ITB + ETB
  - $H_{98} \sim 1.5$, $T_{e,\text{div}} \leq 5\text{eV}$ across the entire target plates
  - The synergy btw. ITB+ETB improves core-edge integration

- **EAST: Partial detachment & improved core confinement in standard H-mode, grassy ELMy H-mode, high $\beta_p$ scenario**
  - $H_{98} > 1$, $T_{e,\text{div}} \sim 5\text{ eV}$ around the strike point
  - Neon seeding is more compatible with core plasma, at present
Near-term Plans \(\rightarrow\) In support of ITER & CFETR

- **DIII-D: Detached high-\(\beta_p\) plasmas with \(q_{95} < 7\) & \(G > 0.2\)**
  - Full detachment + ITB + ETB + ELM suppression
  - More ITER-like single null shape

- **EAST: Stable H-mode detachment control > 100s**
  - New lower W divertor for enhanced heat and particle exhaust
  - Provide PWI solution for H-mode \(\geq 400s\)
Thank you for your attention!

Group photo in EAST control room

Group photo in DIII-D control room
Less Peaked Impurity Profile is Observed in High $\beta_p$ Plasma Without ECH

- A stationary, flat carbon density profile inside the ITB
- NEO predicts peaked impurity profiles
- Experiments show no metal impurity accumulation
- GK simulation shows TEM dominant inside ITB at lower $q_{95}$
  - Working hypothesis: Impurity control by self-generated TEM
- ECH can further help control impurity

Garofalo, PPCF 2018
Ding, NF 2020
Qian, APS invited 2019
2D images show the peak radiation near X-point during detachment.
DIII-D experiment was performed under favorable $B_T$ to study the compatibility of high performance core and divertor detachment

- **Upwardly Biased Quasi-Double Null with** $dR_{sep} \sim +7\text{mm} > 2\lambda_q$
  - $I_p \sim 0.72\text{MA}$

- **Ion B-gradB drift towards divertor $\rightarrow$ favorable $B_T$**
  - Beneficial for full detachment

- **Impurity: Nitrogen, Neon; from divertor or main-chamber**

- **NBI only, No ECH**

- **Several actively feedback controls**
  - $\beta_N$ feedback control $\rightarrow$ adjust the $P_{NBI}$
  - $n_{\text{oped}}$ feedback control $\rightarrow$ D gas puffing

- **Diagnostics:**
  - Divertor: Langmuir probes, Bolometer, IR camera, pressure gauge, Tangential TV, Filterscope, …
  - Core: TS, CER, SPRED, VB, …
Latest experimental progress in USN (September, 2019)

- Detachment feedback control algorithm
- More closed USN configuration
  - Constant Ip~0.72 MA & Bt w/o ramping
  - Increase $\beta_N \sim 3$ & dRsep to > 5mm
- Feedforward N2 seeding $\rightarrow T_{e,\text{div}} < 5\text{eV}$
  - N2 seeding through PFX1
- Feedback detachment control with N2 seeding, GASB/PFX1
  - Target $j_{\text{sat}}/j_{\text{roll}} = 0.3$ ( $T_{et} < = 5\text{eV}$)
  - Target $j_{\text{sat}}/j_{\text{roll}} = 0.6, 0.3$ in one shot
- Neon seeding for USN detachment access, & feedforward control

Stagnation point
Both impurity and D₂ fueling show the synergy between ITB and ETB

Extra bonus for core-edge integration
- Weaker ETB → benefits small ELMs → less intermittent events
- Strong ITB → high confinement → reduced $P_{\text{heat}}$ for feedback control
- High $\beta_p$ → wide pedestal → larger space between radiation cooling and pedestal top
D2+Neon puff, feedback control
EAST demonstrated **IR surface temperature control** for detachment

- IR surface temp. more directly addresses hardware limit
- Requires real-time processing of IR camera data by PCS
- RT signal used to modulate gas puff

M. W. Chen et al., *Nucl. Fusion* (2020)

L. Wang / 28th IAEA-FEC, May 2021
Active feedback control of $P_{\text{rad}}$ to reduce heat flux

- Radiation power was actively controlled by feedback of LFS neon-SMBI seeding.
  - slight loss of plasma stored energy: 7 - 11%
  - $f_{\text{rad}}$ extended to 41% in 2018.
- Divertor seeding exhibits much better in ctd. Expts
  ✓ Demonstration in DIII-D high $\beta_p$ scenario with ITB+ETB

K. Wu et al., Nucl. Fusion (2018)

Bottom divertor upgrade (C → W, finished)

- Mission
  - H-mode ≥ 400s; 10 MW*100s
  - Divertor & PWI control Physics
  → Core-edge integration for ITER/CFETR

- W/Cu divertor with water-cooling
  - Monoblock in the strike point region (10MW/m²)
  - Flat-type structure for the dome plates (5MW/m²)

- Enhanced particle exhaust capability

- Closed outer divertor and open inner divertor for balanced detachment

- Facilitate both LSN and DN, flexible strike point

- A new divertor coil for X-divertor operation

- Plasma configuration with $\delta_L = 0.4-0.6$

- SMBI for impurity seeding feedback control

L. Wang / 28th IAEA-FEC, May 2021
Upgrade of div.-diagnostics & gas puff systems

- **1st Priority:** safety & operation oriented
- **2nd Priority:** physics oriented

<table>
<thead>
<tr>
<th>Categories</th>
<th>Div-diagnostics</th>
<th>Plasma parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Heat &amp; Particle Fluxes</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IR camera</td>
<td></td>
<td>Heat Flux, $T_{\text{target}}$</td>
</tr>
<tr>
<td>Divertor probes</td>
<td></td>
<td>ne/Te/Particle &amp; Heat fluxes/3D</td>
</tr>
<tr>
<td>Thermal Couplers</td>
<td></td>
<td>Temperature</td>
</tr>
<tr>
<td>Neutral pressure</td>
<td></td>
<td>Neutral pressure</td>
</tr>
<tr>
<td><strong>Impurities</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Visible spectroscopy</td>
<td></td>
<td>Visible spectroscopy</td>
</tr>
<tr>
<td>Bolometer</td>
<td></td>
<td>Absolute measurements of total radiation losses</td>
</tr>
<tr>
<td>EUV/VUV</td>
<td></td>
<td>High-Z impurity emission</td>
</tr>
<tr>
<td>Divertor LIBS/LIAS</td>
<td></td>
<td>Retention &amp; wall analysis</td>
</tr>
<tr>
<td><strong>Phys. &amp; PMI</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reflectometry</td>
<td></td>
<td>ne profile &amp; turbulence</td>
</tr>
<tr>
<td>Edge Current Actuator</td>
<td></td>
<td>SOL current filaments</td>
</tr>
</tbody>
</table>

- **Div-gas puff locations**
  - Normal fast valves
  - New div-SMBI
  - Impurity, Fueling

L. Wang / 28th IAEA-FEC, May 2021
Joint DIII-D/EAST research on core-edge-divertor integration

- **EAST**: ITER-like tungsten divertor for long pulse operation, RF heating, FB
- **DIII-D**: High performance plasma, **bottom open & top closed** divertors