Development of High Poloidal Beta, Steady-state Scenario with ITER-like Tungsten Divertor on EAST

by

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with


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Experiments on EAST Achieve First Long Pulse H-mode Operation with Tungsten Divertor

- Up to 65 s, sustained with loop voltage ~ 0
- ~4 MW RF heating
- $H_{98y2} \sim 1.1$
EAST/DIII-D Partnership: Sharing of Resources Accelerates Progress toward Fusion Energy

- Fully non-inductive high bootstrap scenario on DIII-D achieves performance attractive for fusion reactor
  - Broad current profile + high $\beta_P \rightarrow$ large-radius ITB, excellent confinement also without rotation
- **Key challenges:** long pulse, compatibility with tungsten wall

Long Pulse Initiative: extend high performance DIII-D discharges to true steady-state on superconducting EAST
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**Demonstrate long pulse H-mode operation with tungsten divertor**

- Gain access to H-mode
- Develop tools to optimize $q$-profiles, broaden ITB
- Increase $\beta_p$ toward DIII-D performance
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Upper Divertor on EAST Is Prototyping a Water-cooled Tungsten Divertor for ITER

- Based on cassette technology
- ITER-like W monoblocks
  - Divertor targets (10 MW/m²)
- ITER-like W/Cu flat type PFCs
  - Divertor dome and baffles (~20 MW/m²)

See also G.-N. Luo, MPT/1-2Ra
Previous Long Pulse H-modes Limited by Strong Influxes of Tungsten
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- In one of two special locations, some armors were connected by mechanical joint (instead of Hot Isostatic Pressing)
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- Larger thermal contact resistance $\rightarrow$ overheating & melting

Tungsten influx
Redesigned Monoblock Units with Improved Heat Transfer

- New monoblock units with three standard tungsten armors to replace U-shape armor have been developed and installed.
Redesigned Monoblock Units with Improved Heat Transfer Lead to Record Long Duration H-mode

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- Duration not limited by machine capability
- Excellent particle exhaust
- Stationary W divertor temperature
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Stationary current profile with $q_{\text{min}} \approx 1.5$

Safety factor

$t=20$ s
$t=40$ s
$t=60$ s

$B_T = 2.5$ T

$<n_e> (10^{19}/m^3)$

$P_{\text{rad}}$ (MW)

$LHW$ (MW)

$ECRH$ (MW)

$ICRF$ (MW)

Div. Temperature ($^\circ$C) by IR

Heat flux (MW/m$^2$)

Loop voltage (V)
Steady-state eITB Features (H$_{98y2}$~1.1) Observed in Long Pulse H-mode Discharges

- Peaked $T_e$ profile and improved confinement are stationary (tens of seconds)
- Power balance analysis shows significantly reduced $\chi_e$ in plasma core
- Core $T_e$ profile meets ITB criterion
  - $\rho^{*}_{Te}(max)=0.02 > \rho^{*}_{ITB}\sim 0.014$
  - [Tresset, NF 2002]
Steady-state at High Performance Requires Increased Injected Power and Improved Confinement ($H_{98y2} \geq 1.3$)

- 0D modeling of steady-state solutions at $I_p = 450$ kA
- Up to 16 MW of steady-state injected power to become available in near future
- $\beta_p > 2$ with higher density and higher injected power, if $H_{98y2} \geq 1.3$
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Broaden the current profile to expand ITB radius and increase $H$, similar to DIII-D experiments
Standard Techniques to Broaden the Current Profile Only Work Transiently

- Application of early heating power (with/without early H-mode transition) affects early $\ell_i$ evolution, but leads to same final state
  - Current relaxation time, $\tau_{CR} \sim 0.4$ s $\ll$ pulse length
Stationary, Lower $\ell_i$ Achieved by Increasing Density in LH Current-driven Plasmas

- L-mode discharges
- Radial penetration of LH wave slower at higher density
  - Expect wave to be fully absorbed closer to plasma edge
- Loop voltage $\sim 0$
Stationary, Lower $\ell_i$ Achieved by Increasing Density in LH Current-driven Plasmas

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- L-mode discharges
- Radial penetration of LH wave slower at higher density
  - Expect wave to be fully absorbed closer to plasma edge
- Loop voltage $\sim 0$
- Time of analysis is after $>5\tau_{CR}$ of operation at $\sim$zero loop voltage
  - Negligible Ohmic current

Time for equilibrium reconstructions
Equilibrium Reconstructions Confirm Broader Current Profile at Higher Density

- Steady-state negative central shear obtained at high density
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“High performance synergy” between broad current profile and high density
Current Profile Reconstruction Enhanced by New Polarimetry-Interferometry (POINT) Diagnostic

- POINT → line-integrated measurements of internal magnetic field and plasma density
- Provides sufficient constraint to reveal hollow current profile
  - Uncertainty estimate constructed by the Monte Carlo method of uncertainty propagation

See also W.X. Ding, EX/P7-16
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With no Ohmic current, profile of $J_{\text{Tot}} - J_{\text{BS}}$ can be compared directly to $J_{\text{LHCD}}$ simulation

See also W.X. Ding, EX/P7-16
LHCD Modeling Reproduces Trend of Broader Profiles at Higher Density

- GENRAY/CQL3D and C3PO/LUKE give similar results.

- Matching experiment magnitude requires anomalous fast electron transport, $D_r > 0$.
  - Similar to results from other tokamaks.

\[ <J_{\text{Tot}}> - <J_{\text{BS}}> \text{ (A/cm}^2\text{)} \]
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\[
\begin{array}{c|cccc}
D_r (\text{m}^2/\text{s}) & 1.15 & 1.3 & 0.8 & 0.8 \\
n_e (10^{19} \text{ m}^{-3}) & 2 & 2.5 & 3 & 3.3 \\
\end{array}
\]

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- Optimal $D_r$ is smaller at higher density
- $D_r \sim 1$ m$^2$/s consistent with $\delta B/B \leq 10^{-4}$
  
  [Rechester-Rosenbluth, PRL 1978]
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- Simulated profiles are systematically broader than experiment
  → “Tail” model may yield better agreement
EAST Achieves First Long Pulse H-mode with Zero Loop Voltage and ITER-like W Divertor

- 65 seconds, not limited by machine capability
- Steady-state improved confinement ($H_{98y2} \approx 1.1$) with low core $\chi_e$ and eITB features
- Broader current profile by increasing the density for more off-axis lower hybrid current drive
  - Modeling of LHCD has challenges, but can predict the experimental trend
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Landmark progress made toward demonstration of steady state high performance for a fusion reactor
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➢ Next step: Optimize ITB with higher $\beta_P$ and broader current profile