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

by

A.M. Garofalo

with

X.Z. Gong, J. Qian, J. Chen, S. Ding, G. Li, K. Li, M. Li, X. Zhai, P. Bonoli, Y. Peysson, D. Brower, L. Cao, L. Cui, H. Du, W.X. Ding, W. Guo, C. Holcomb, J. Huang, A. Hyatt, X. Jian, M. Lanctot, L.L. Lao, H. Liu, B. Lyv, Q. Ren, S. Shiraiwa, W. Solomon, Q. Zang, B. Wan

General Atomics, San Diego, California, USA
Institute of Plasma Physics, Chinese Academy of Sciences, Hefei, Anhui, China
Plasma Science and Fusion Center, Massachusetts Institute of Technology, Cambridge, Massachusetts,USA
CEA, IRFM, 13108, Saint-Paul-Les-Durance Cedex, France
Department of Physics and Astronomy, University of California at Los Angeles, Los Angeles, California, USA
Princeton Plasma Physics Laboratory, Princeton, New Jersey, USA
Lawrence Livermore National Laboratory, Livermore, California, USA

Presented at the

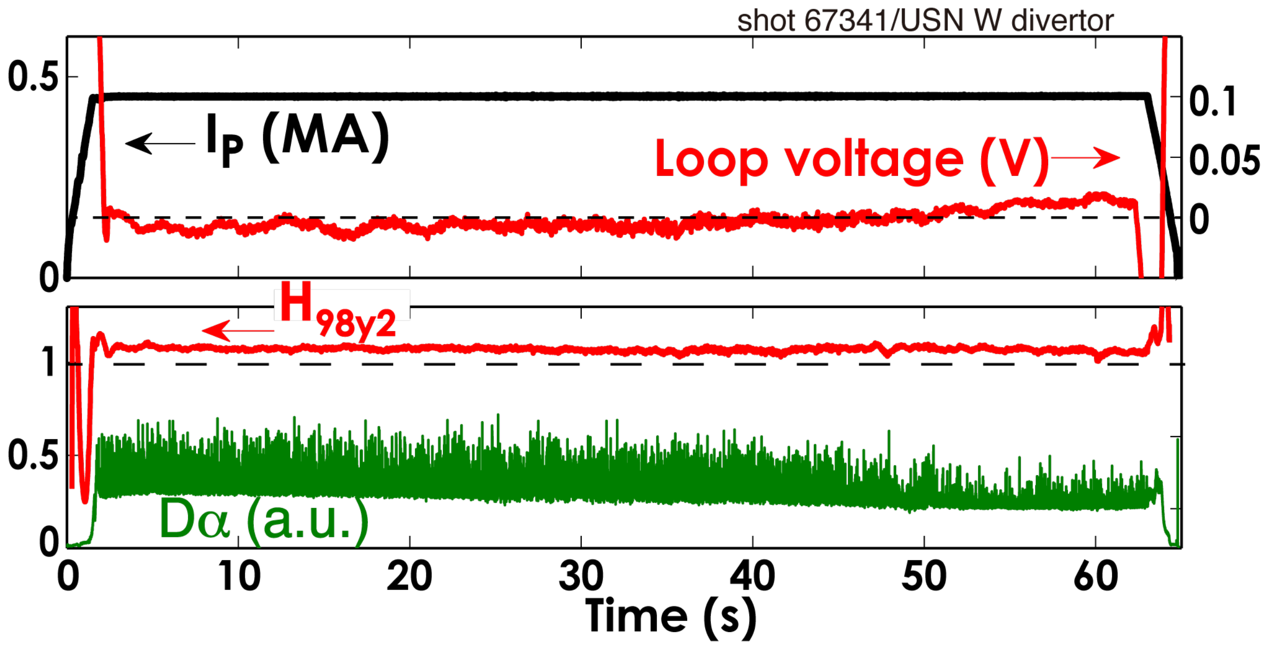
26th IAEA Fusion Energy Conference
Kyoto, Japan
17–22 October 2016

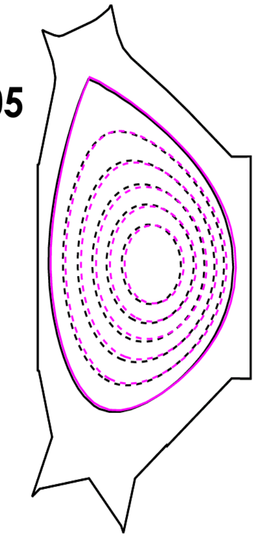
Work supported in part by the National Magnetic Confinement Fusion Program of China (No.2015GB102002), and by the U.S. Department of Energy, Office of Science, Office of Fusion Energy Sciences (Cooperative Agreement #DE-SC0010685 and Contract Nos. DE-SC-0010492, DE-FG02-01ER54615).

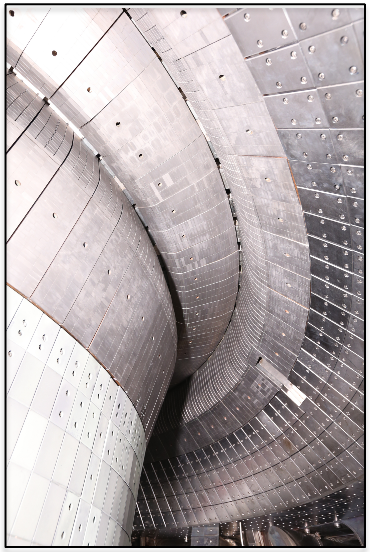
ASIPP DIII-D NATIONAL FUSION FACILITY SAN DIEGO GENERAL ATOMICS

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} ~1.1**





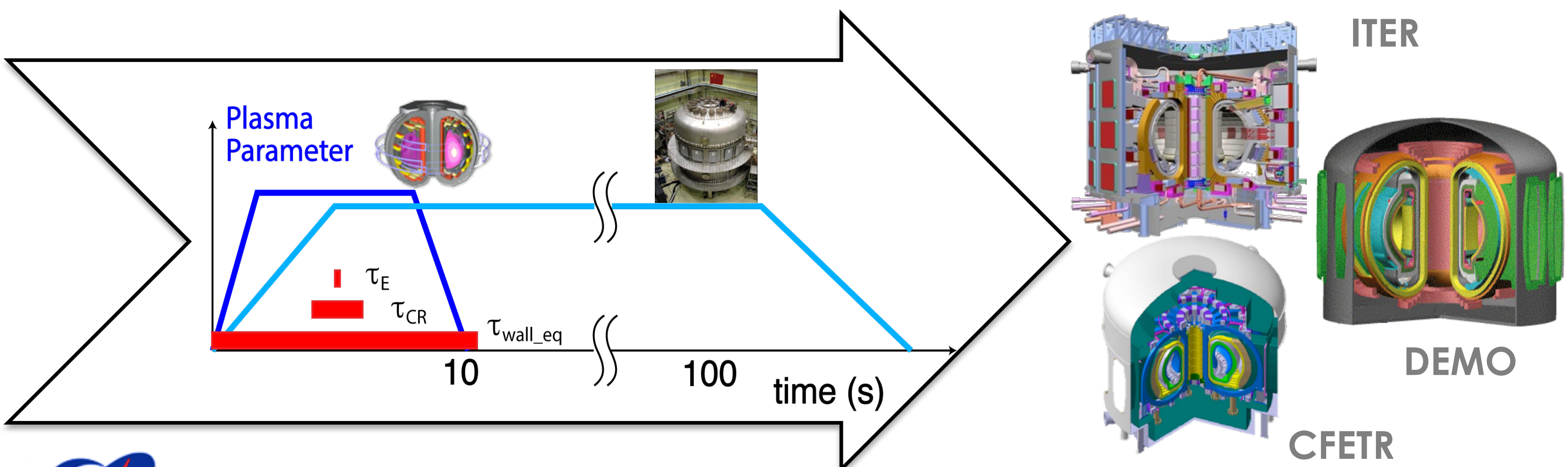


ASIPP

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 β_P → 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



ASIPP

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 β_P → 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

Demonstrate long pulse H-mode operation with tungsten divertor

Gain access to ITB

Develop tools to optimize q-profile, broaden ITB

Increase β_P toward DIII-D performance

ASIPP

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 β_P → 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

Demonstrate long pulse H-mode operation with tungsten divertor

↓

Gain access to ITB

↓

Develop tools to optimize q-profile, broaden ITB

↓

Increase β_P toward DIII-D performance

ASIPP

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 β_P → 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

Demonstrate long pulse H-mode operation with tungsten divertor

↓

Gain access to ITB

↓

Develop tools to optimize q-profile, broaden ITB

↓

Increase β_P toward DIII-D performance

ASIPP

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 β_P → large-radius ITB, excellent confinement also without rotation
- **Key challenges: long pulse, compatibility with tungsten wall**

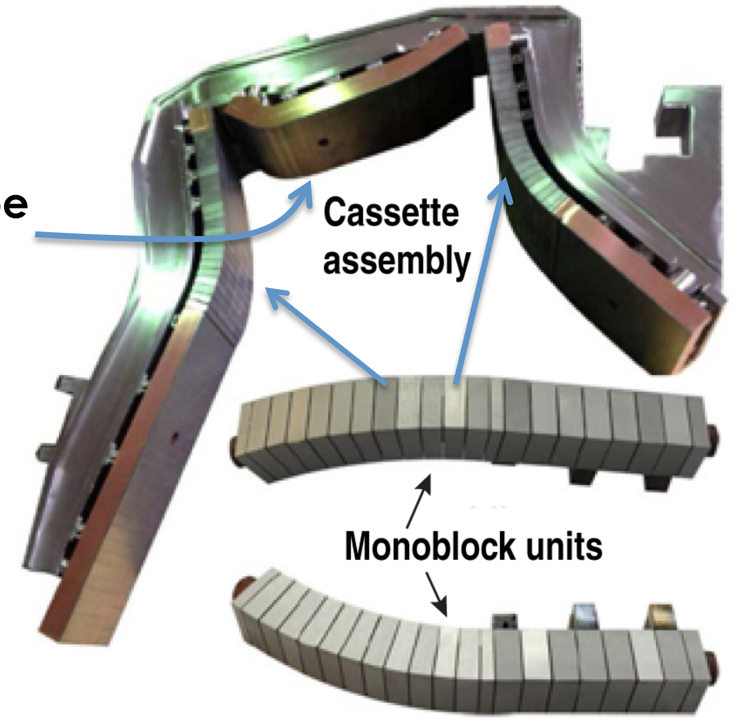
Long Pulse Initiative: extend high performance DIII-D discharges to true steady-state on superconducting EAST

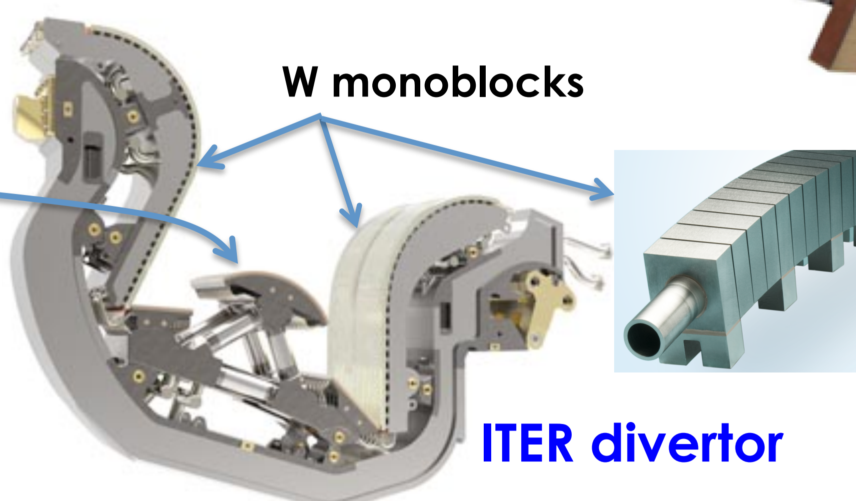
1. Demonstrate long pulse H-mode operation with tungsten divertor
2. Gain access to ITB
3. Develop tools to optimize q-profile, broaden ITB
4. Increase β_P toward DIII-D performance

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/m^2)
- **ITER-like W/Cu flat type PFCs**
  - Divertor dome and baffles (~20 MW/m^2)

Water-cooled W divertor on EAST

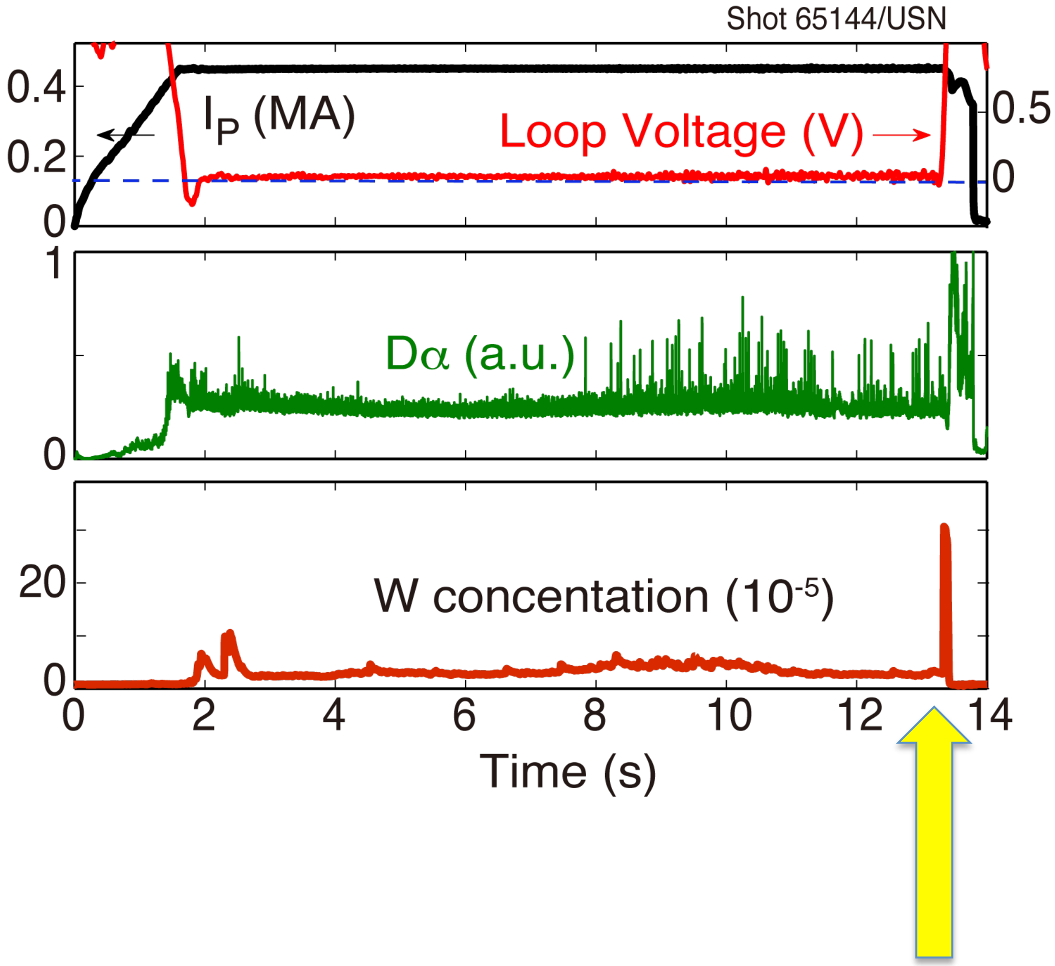




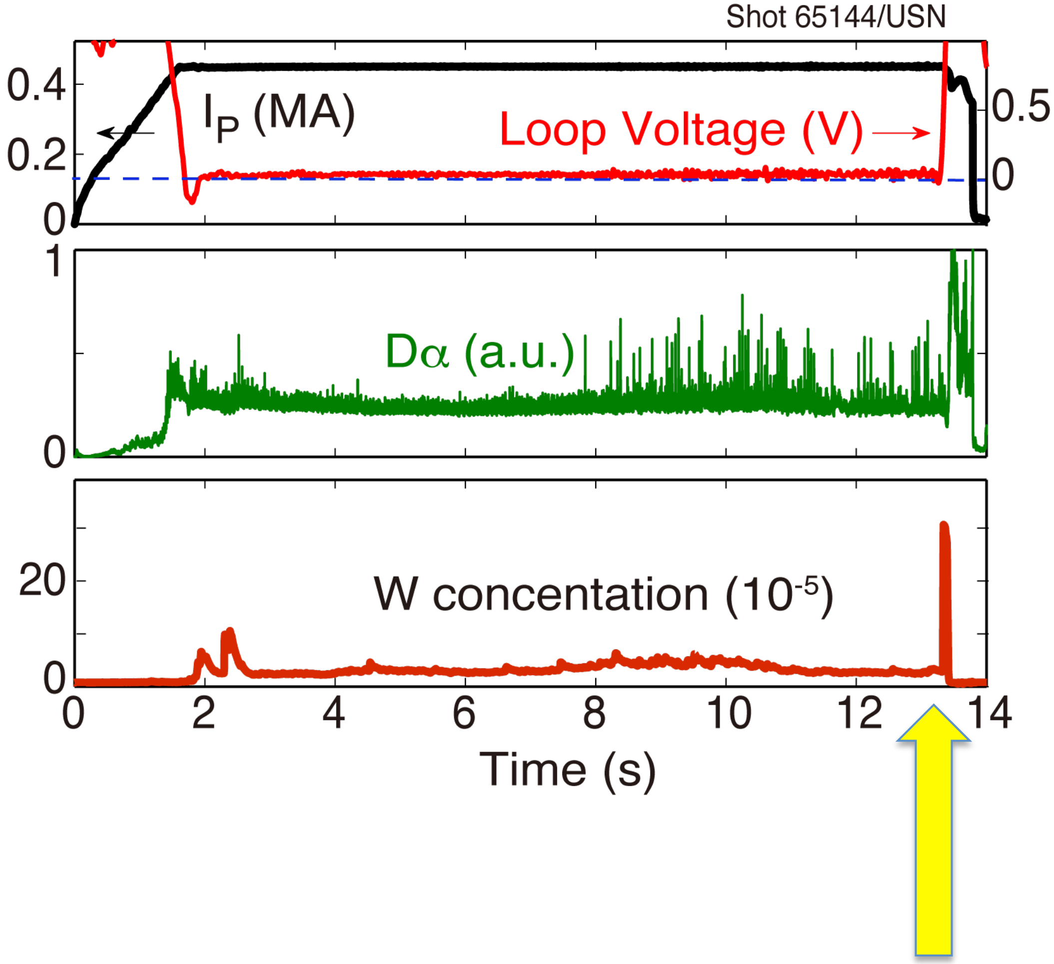
ITER divertor

See also
G.-N. Luo, MPT/1-2Ra

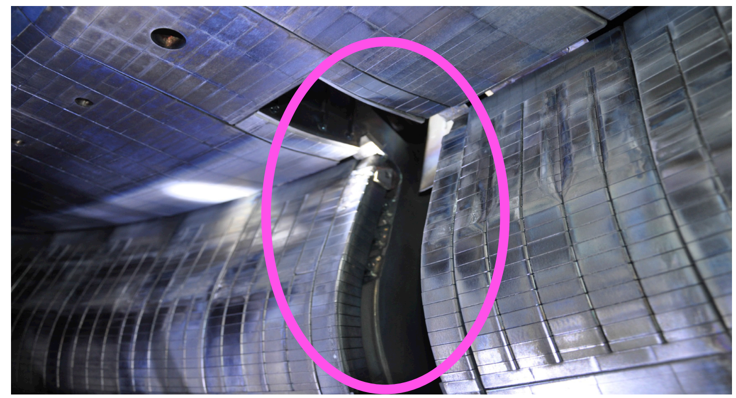
Previous Long Pulse H-modes Limited by Strong Influxes of Tungsten



Previous Long Pulse H-modes Limited by Strong Influxes of Tungsten

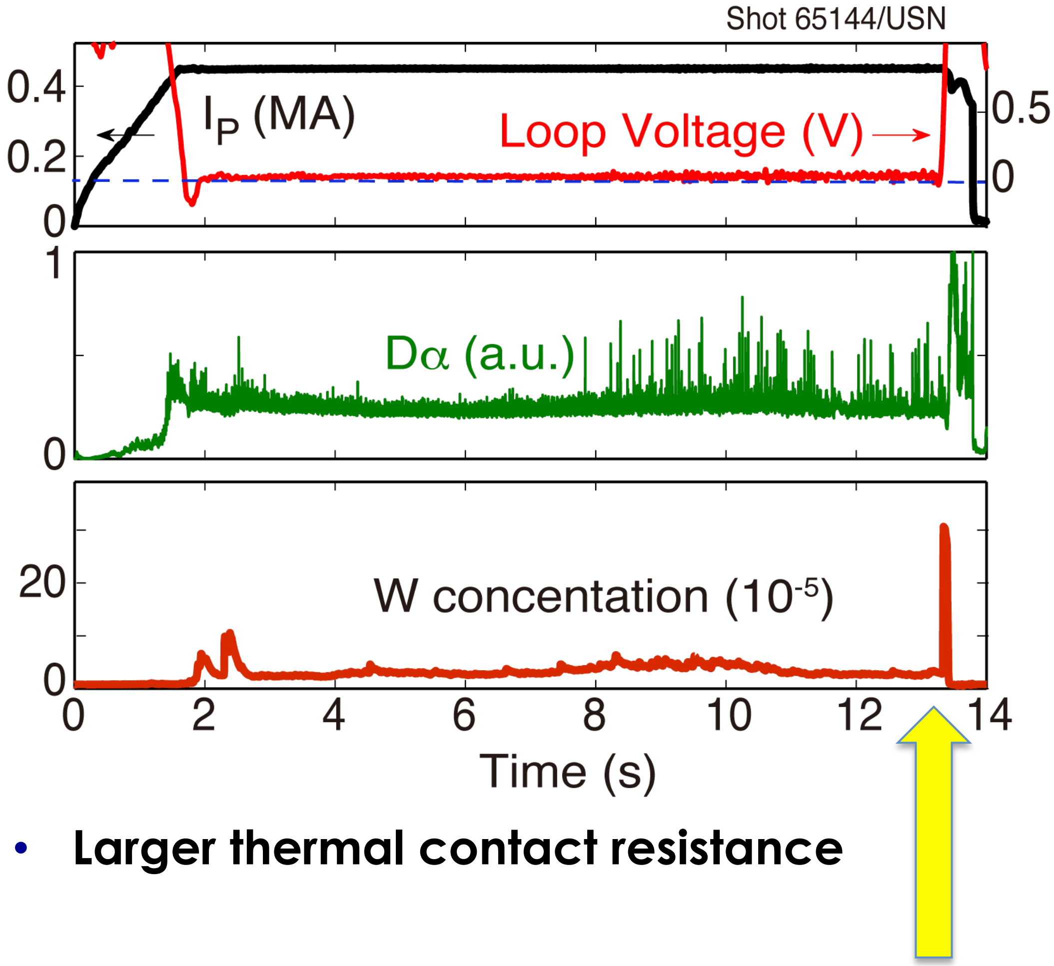


- **In one of two special locations, some armors were connected by mechanical joint (instead of Hot Isostatic Pressing)**



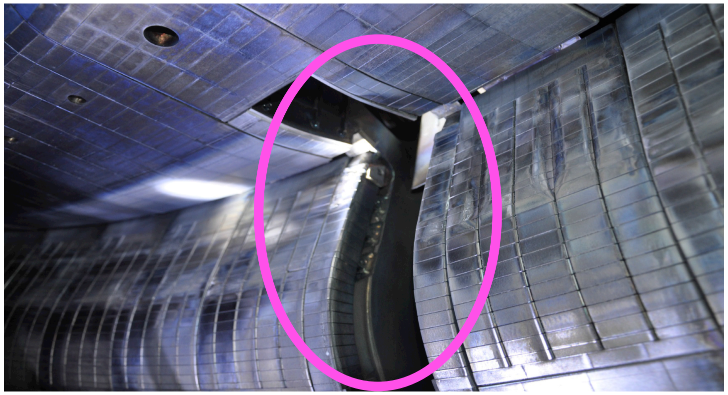
ASIPP

Previous Long Pulse H-modes Limited by Strong Influxes of Tungsten



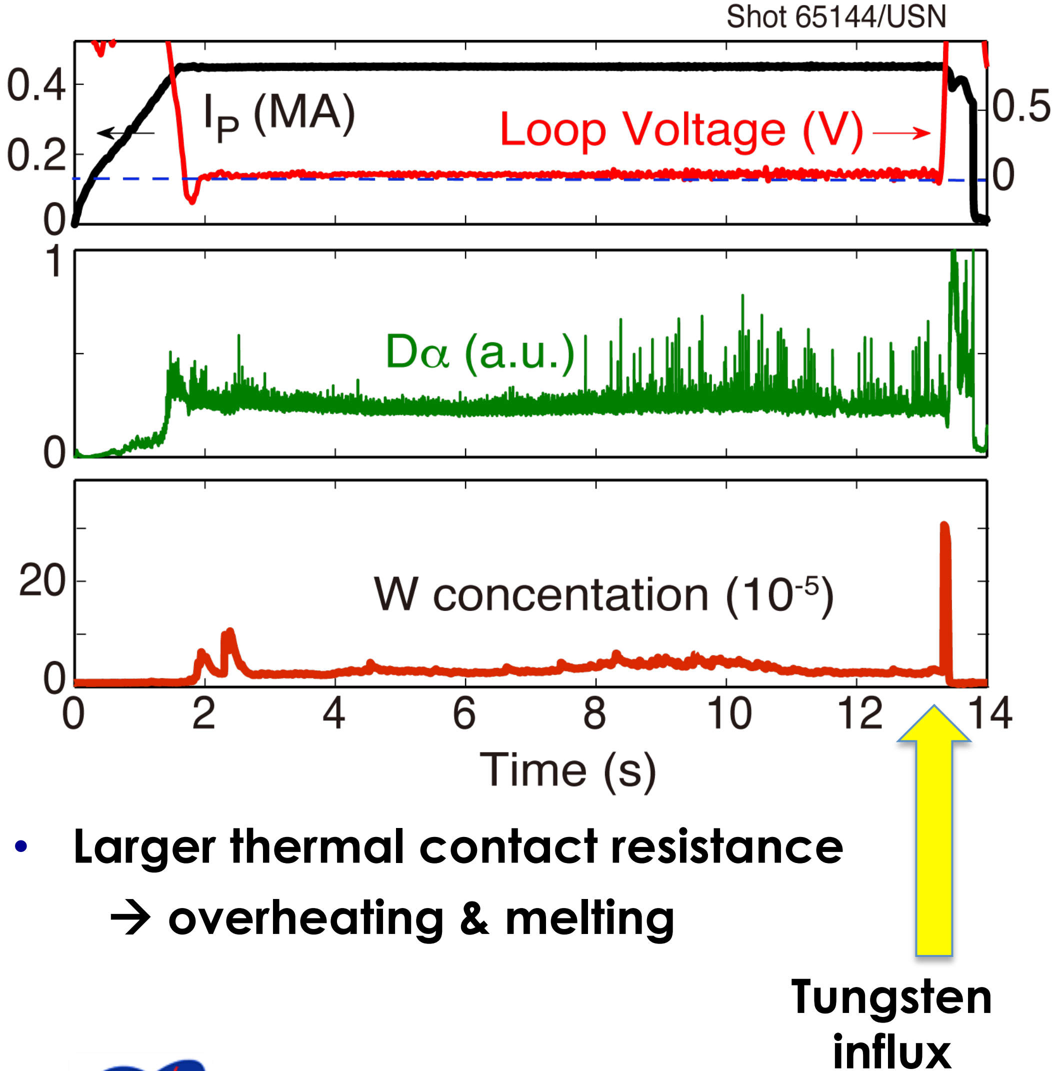
- **Larger thermal contact resistance**

- **In one of two special locations, some armors were connected by mechanical joint (instead of Hot Isostatic Pressing)**



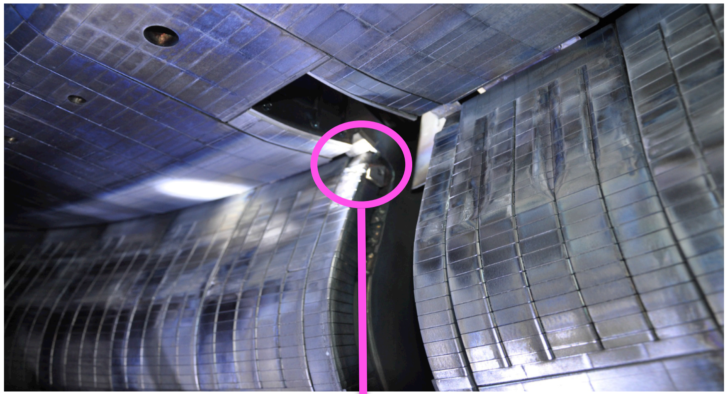
ASIPP

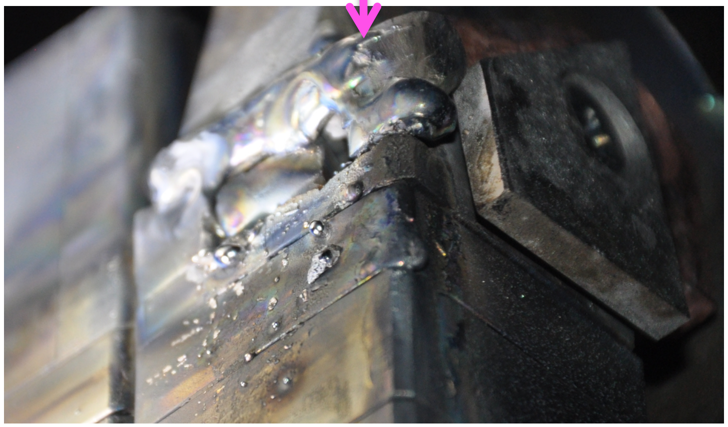
Previous Long Pulse H-modes Limited by Strong Influxes of Tungsten



- **Larger thermal contact resistance**
  → overheating & melting

- **In one of two special locations, some armors were connected by mechanical joint (instead of Hot Isostatic Pressing)**

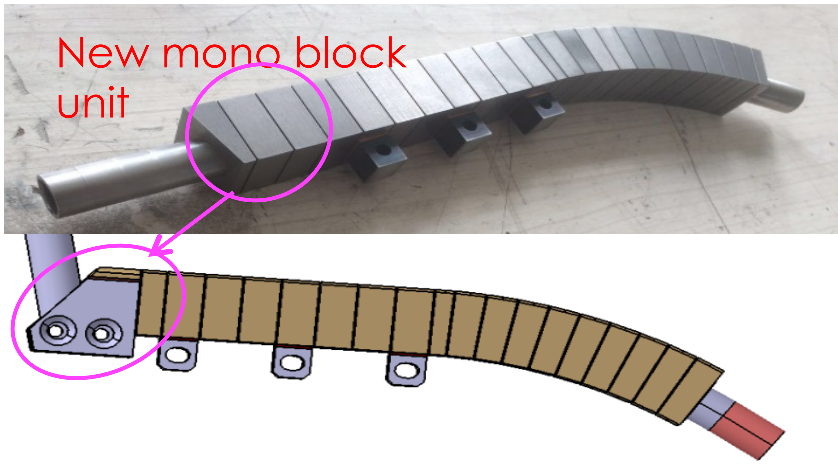




ASIPP

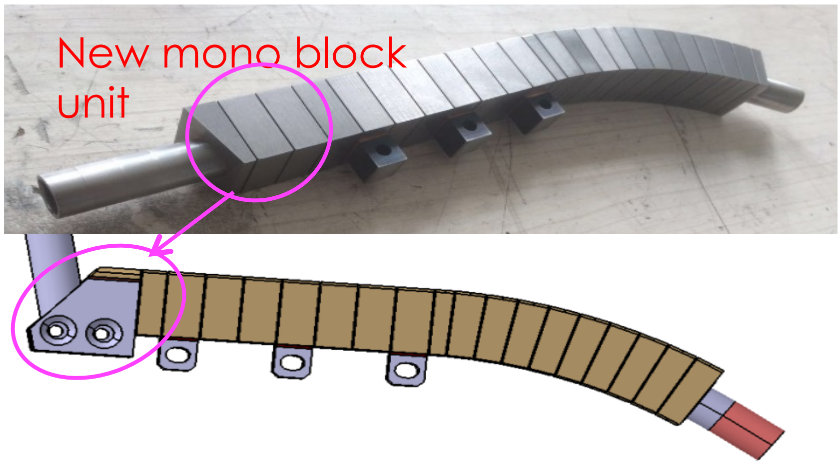
Redesigned Monoblock Units with Improved Heat Transfer

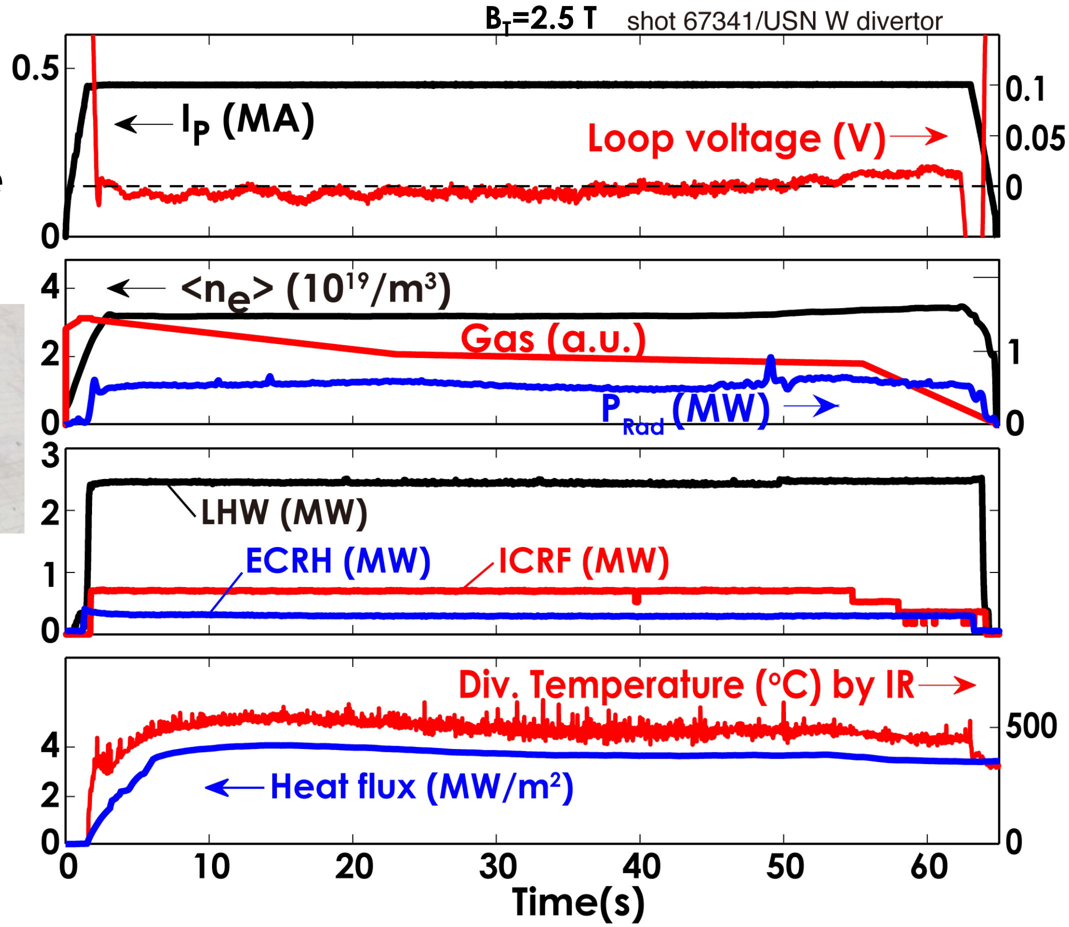
- **New monoblock units with three standard tungsten armors to replace U-shape armor have been developed and installed**



Redesigned Monoblock Units with Improved Heat Transfer Lead to Record Long Duration H-mode

- **New monoblock units with three standard tungsten armors to replace U-shape armor have been developed and installed**

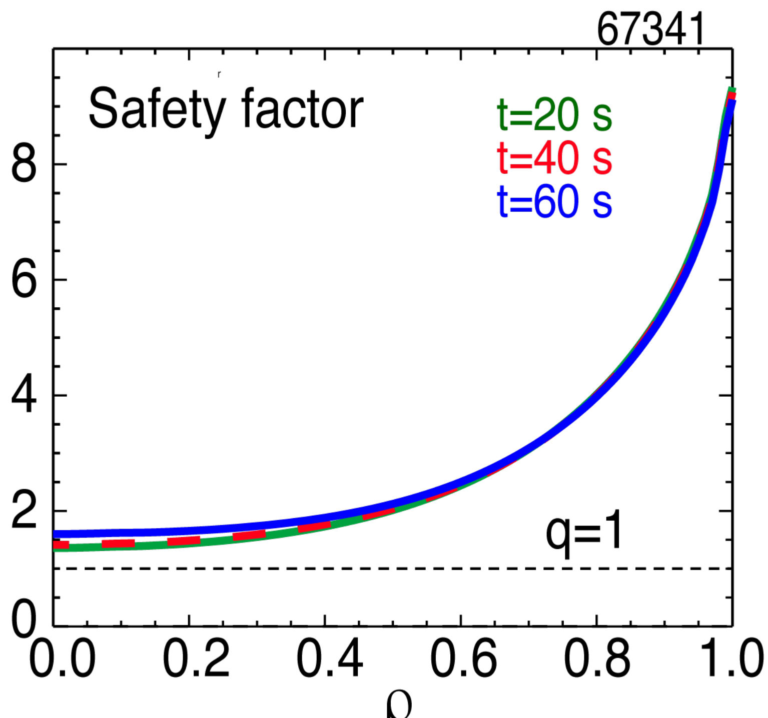


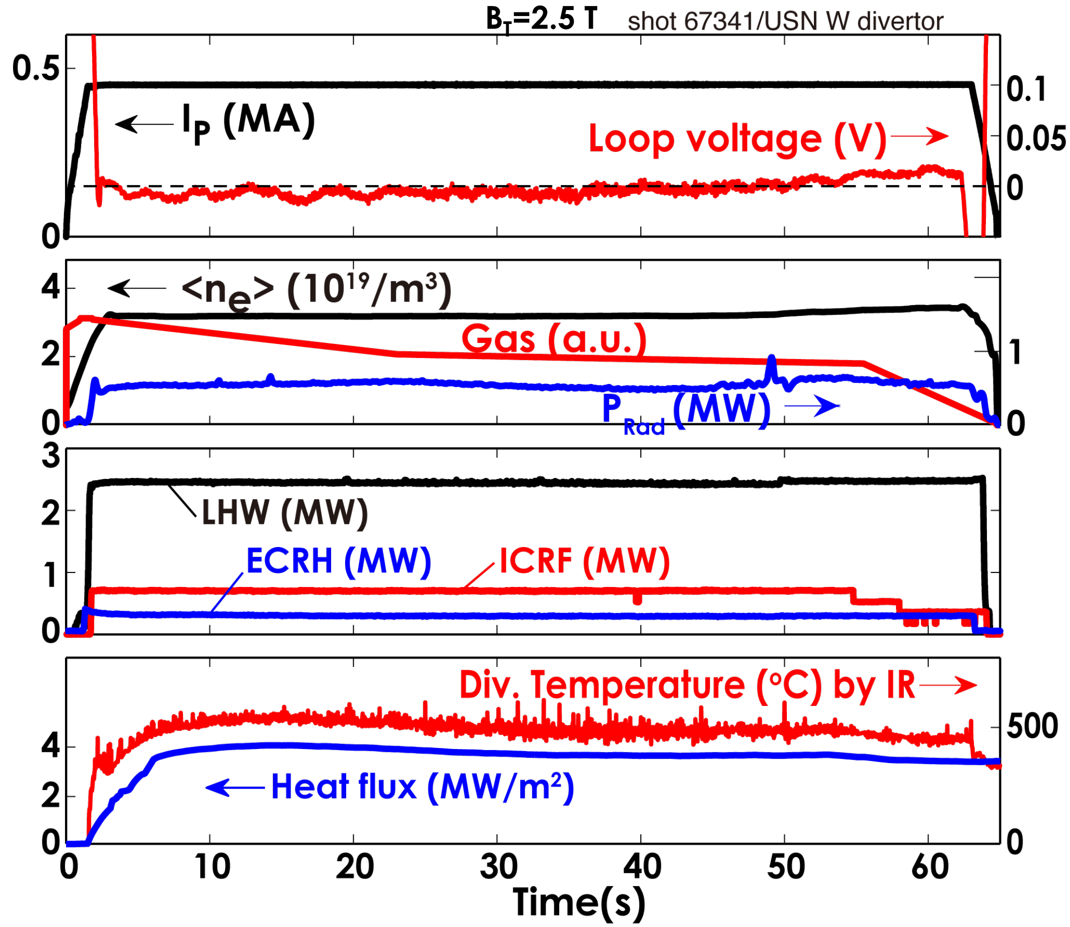


- **Duration not limited by machine capability**
- **Excellent particle exhaust**
- **Stationary W divertor temperature**

ASIPP

Redesigned Monoblock Units with Improved Heat Transfer Lead to Record Long Duration H-mode





- **Stationary current profile with q_{min}~1.5**

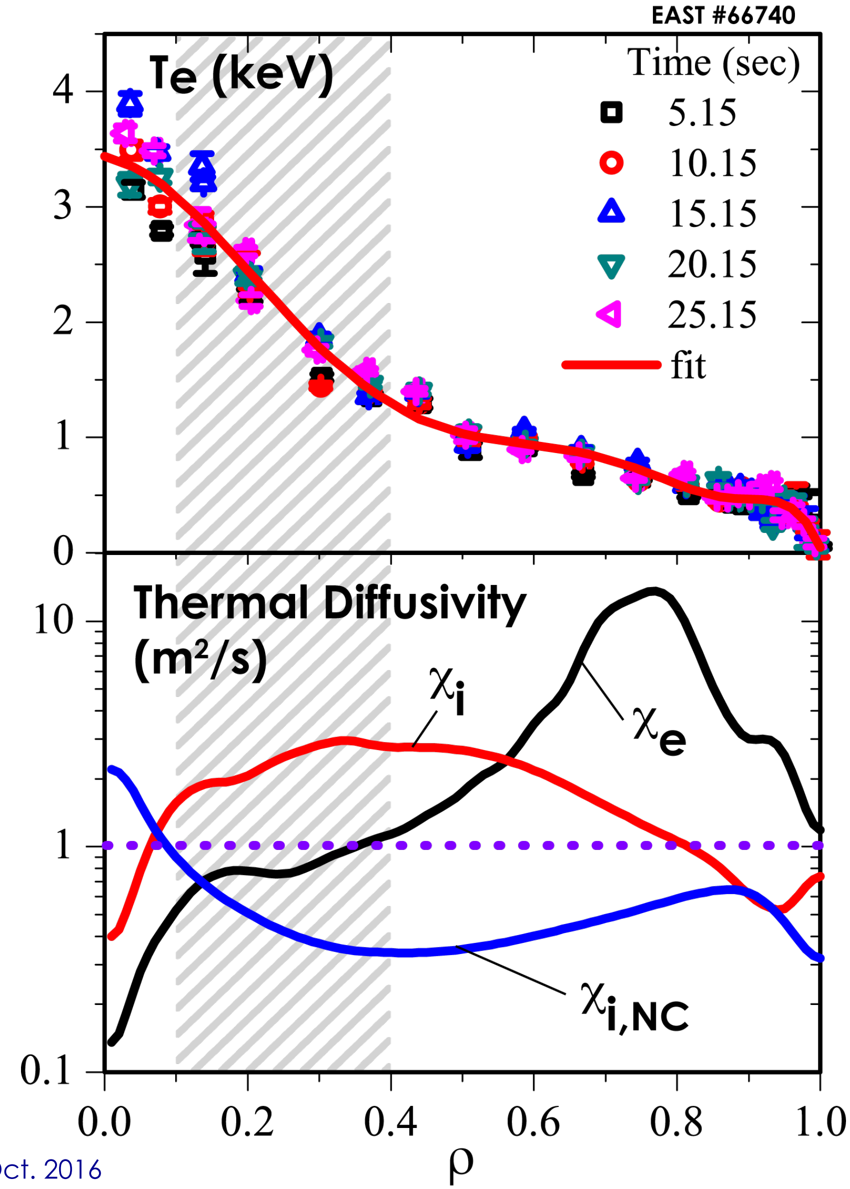
- **Duration not limited by machine capability**
- **Excellent particle exhaust**
- **Stationary W divertor temperature**

ASIPP

Steady-state eITB Features (H_{98y2}~1.1) Observed in Long Pulse H-mode Discharges

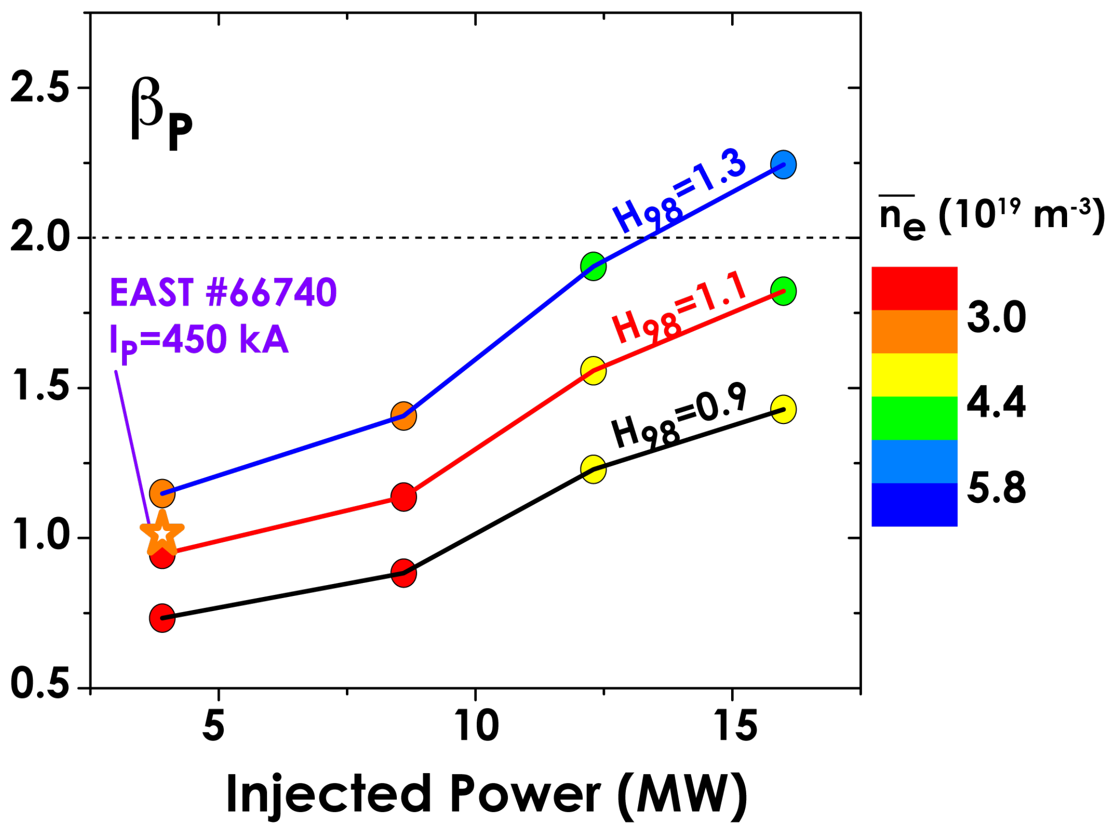
- **Peaked T_e profile and improved confinement are stationary (tens of seconds)**
- **Power balance analysis shows significantly reduced χ_e in plasma core**
- **Core T_e profile meets ITB criterion**
  - ρ^*_{Te}(max)=0.02 > ρ^*_{ITB}~0.014

    [Tresset, NF 2002]



ASIPP

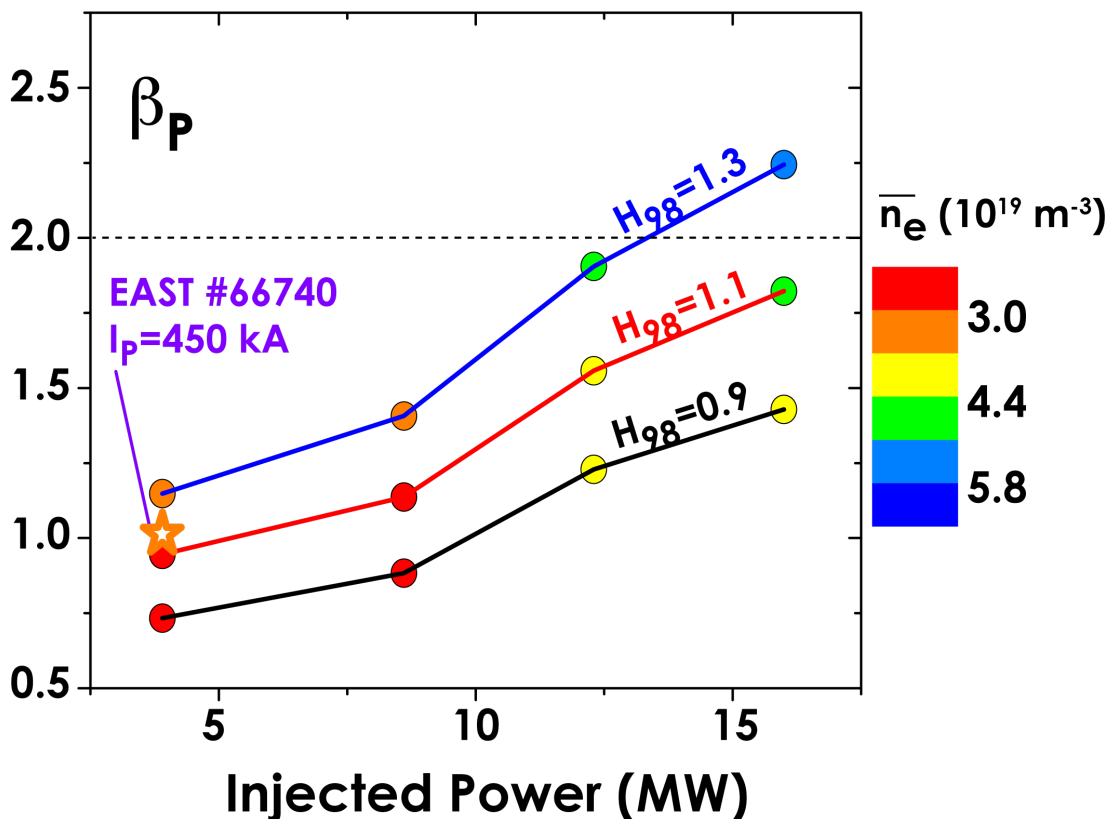
Steady-state at High Performance Requires Increased Injected Power and Improved Confinement (H_{98y2}≥1.3)



- 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
- β_P>2 with higher density and higher injected power, if H_{98y2}≥1.3

ASIPP

Steady-state at High Performance Requires Increased Injected Power and Improved Confinement ($H_{98y2} \geq 1.3$)



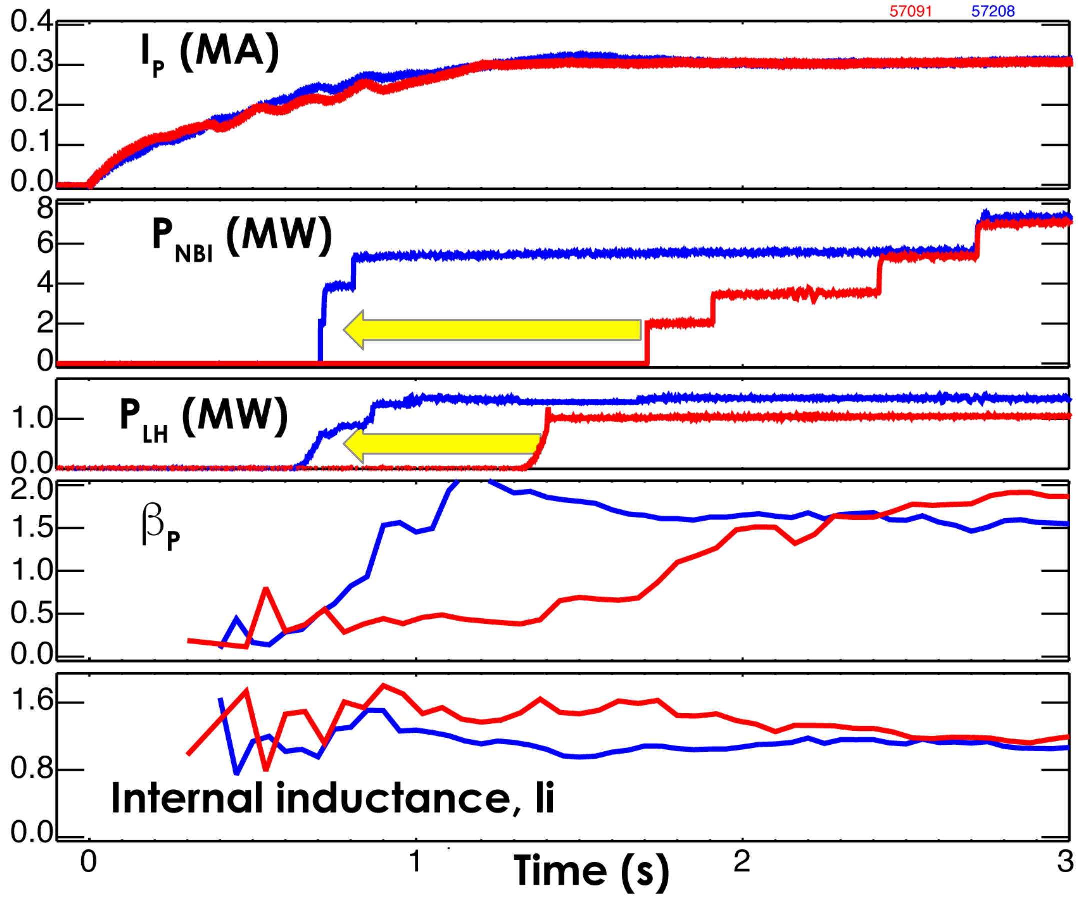
- 0D modeling of steady-state solutions at I_P= 450 kA
- Up to 16 MW of steady-state injected power to become available in near future
- β_P>2 with higher density and higher injected power, if $H_{98y2} \geq 1.3$

Broaden the current profile to expand ITB radius and increase H, similar to DIII-D experiments

ASIPP

Standard Techniques to Broaden the Current Profile Only Work Transiently

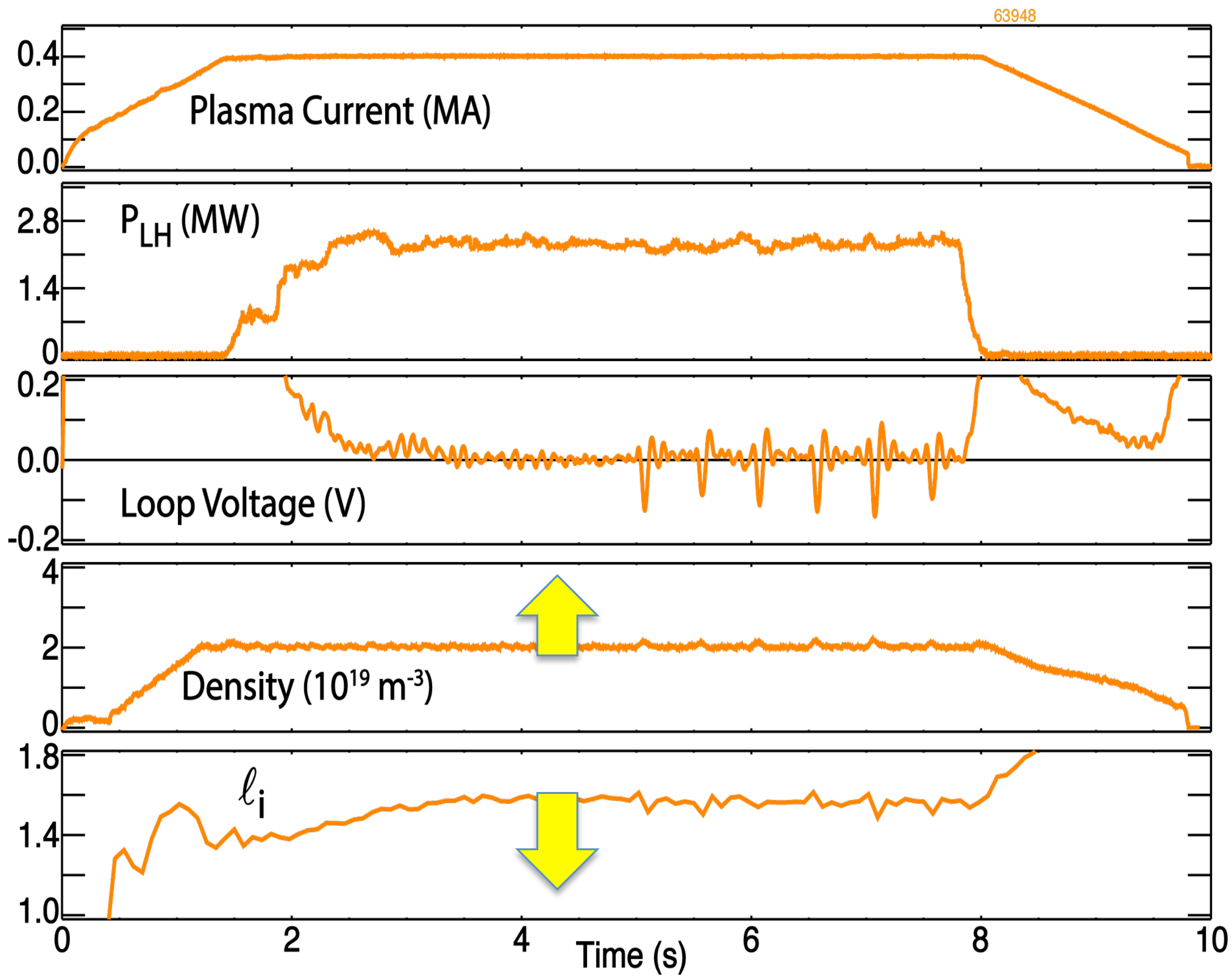
- **Application of early heating power (with/without early H-mode transition) affects early ℓ_i evolution, but leads to same final state**
  - Current relaxation time, τ_{CR} ~0.4 s << pulse length



ASIPP

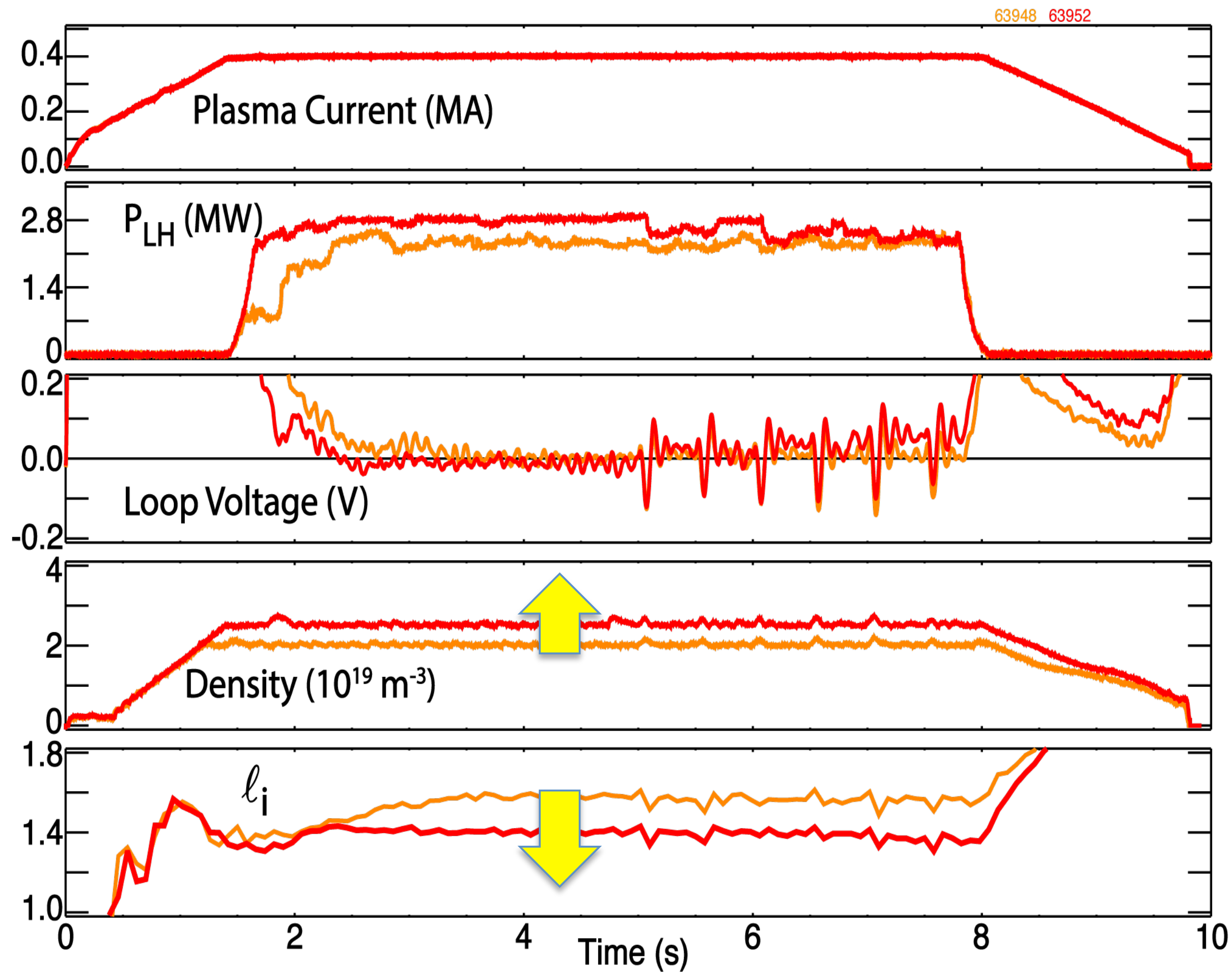
Stationary, Lower ℓ_i Achieved by Increasing Density in LH Current-driven Plasmas

- **L-mode discharges**
- **Radial penetration of LH wave slower at higher density**
  - Expect wave to be fully absorbed closer to plasma edge
- **Loop voltage ~ 0**



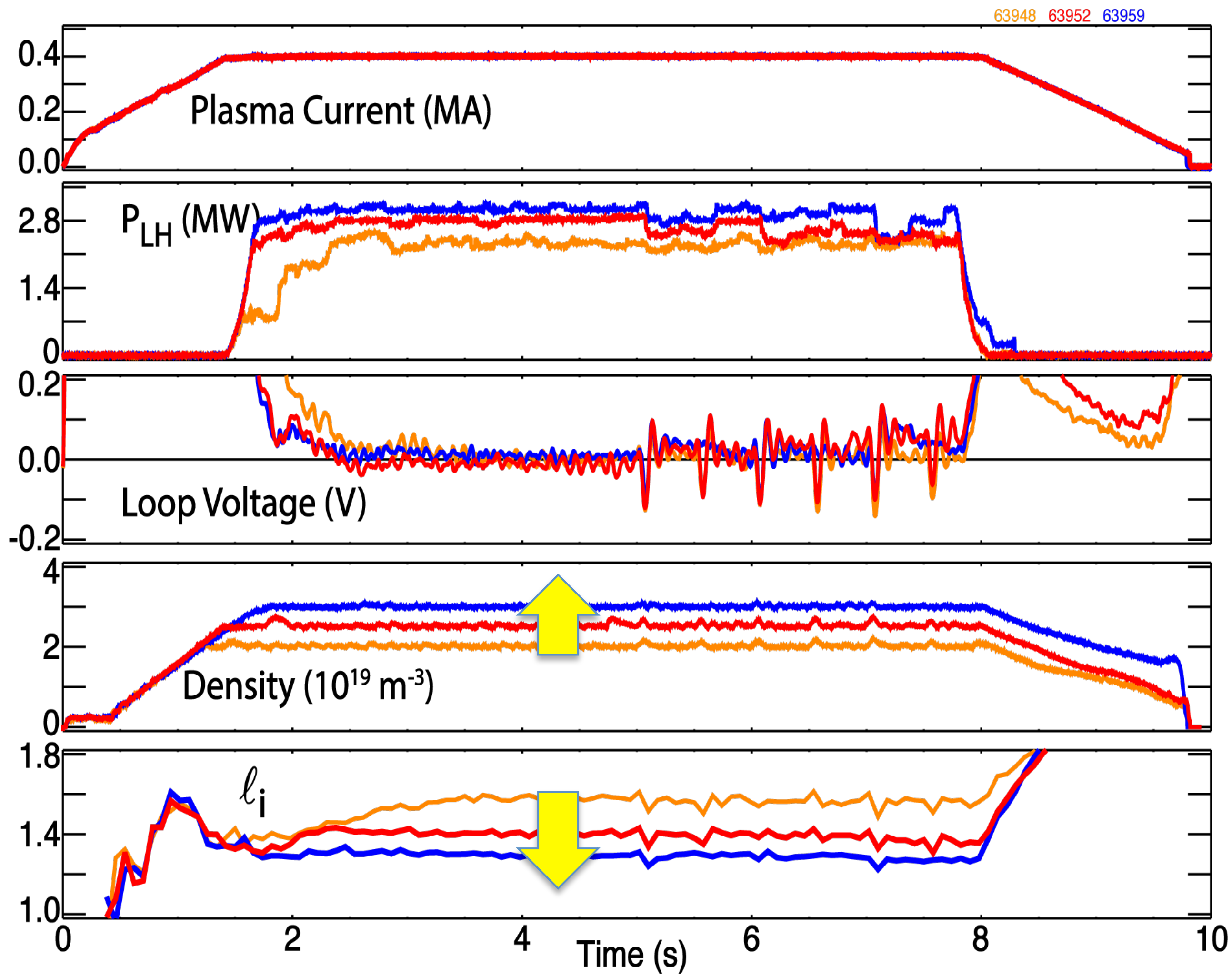
Stationary, Lower ℓ_i Achieved by Increasing Density in LH Current-driven Plasmas

- **L-mode discharges**
- **Radial penetration of LH wave slower at higher density**
  - Expect wave to be fully absorbed closer to plasma edge
- **Loop voltage ~ 0**



Stationary, Lower ℓ_i Achieved by Increasing Density in LH Current-driven Plasmas

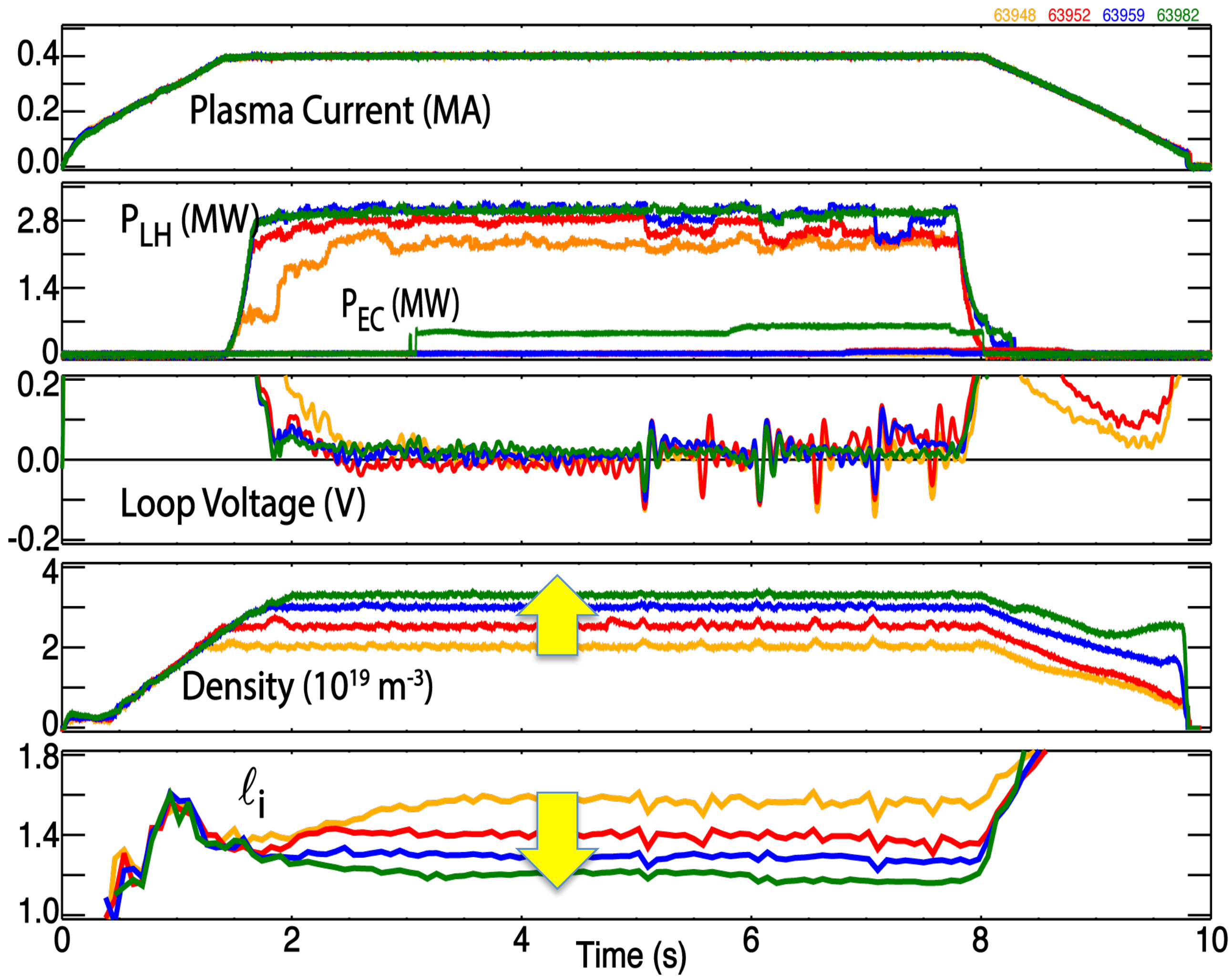
- **L-mode discharges**
- **Radial penetration of LH wave slower at higher density**
  - Expect wave to be fully absorbed closer to plasma edge
- **Loop voltage ~ 0**



ASIPP

Stationary, Lower ℓ_i Achieved by Increasing Density in LH Current-driven Plasmas

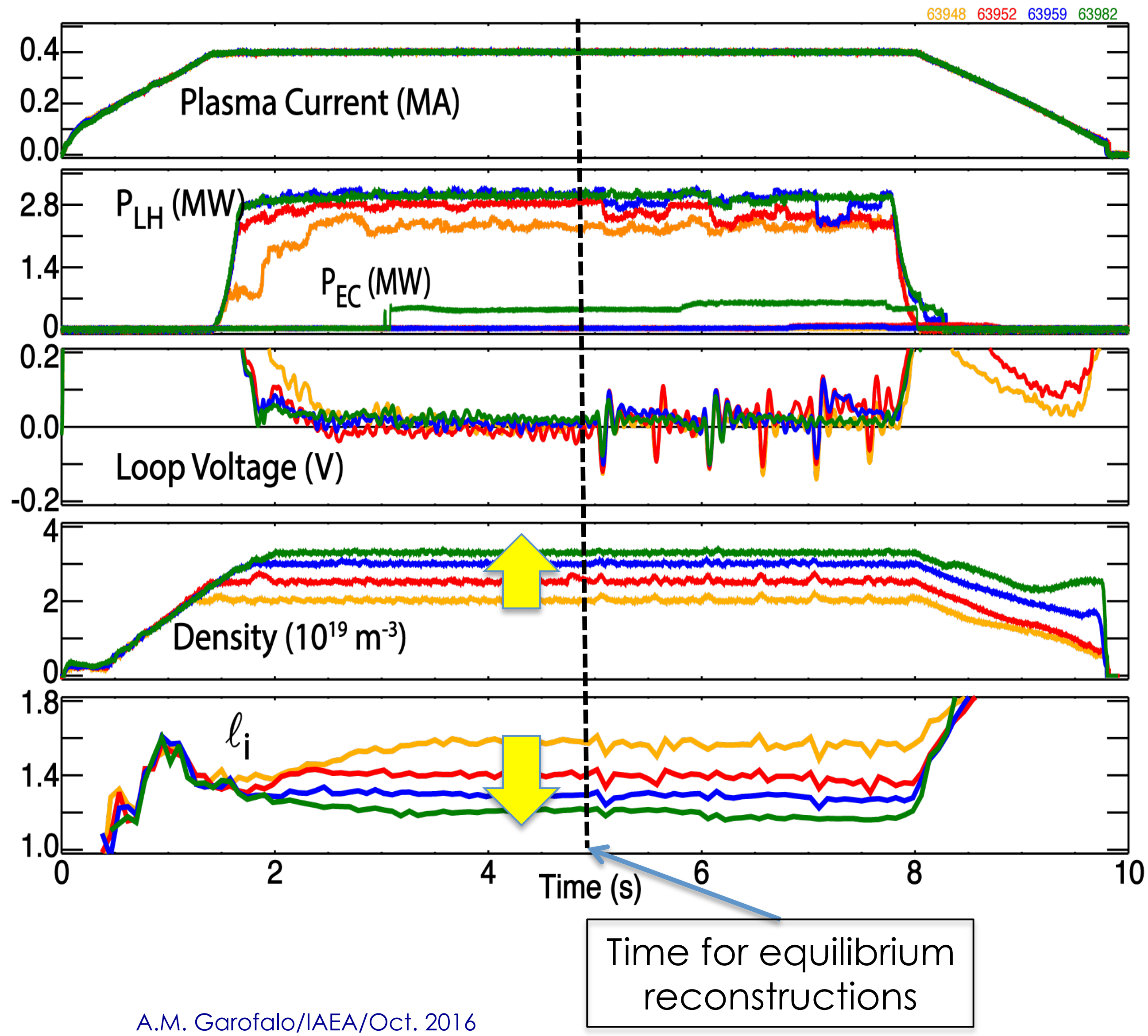
- **L-mode discharges**
- **Radial penetration of LH wave slower at higher density**
  - Expect wave to be fully absorbed closer to plasma edge
- **Loop voltage ~ 0**



ASIPP

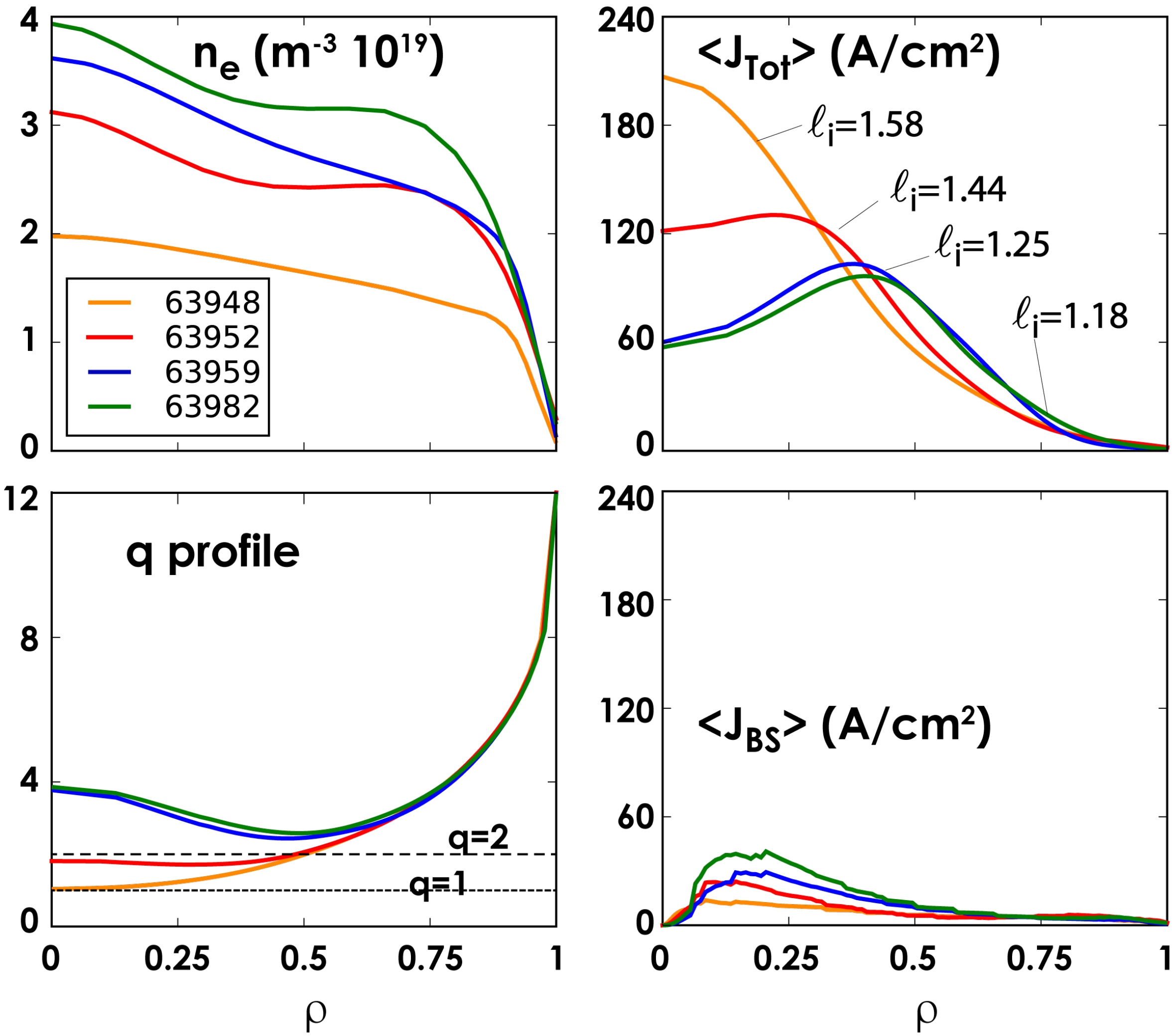
Stationary, Lower ℓ_i Achieved by Increasing Density in LH Current-driven Plasmas

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



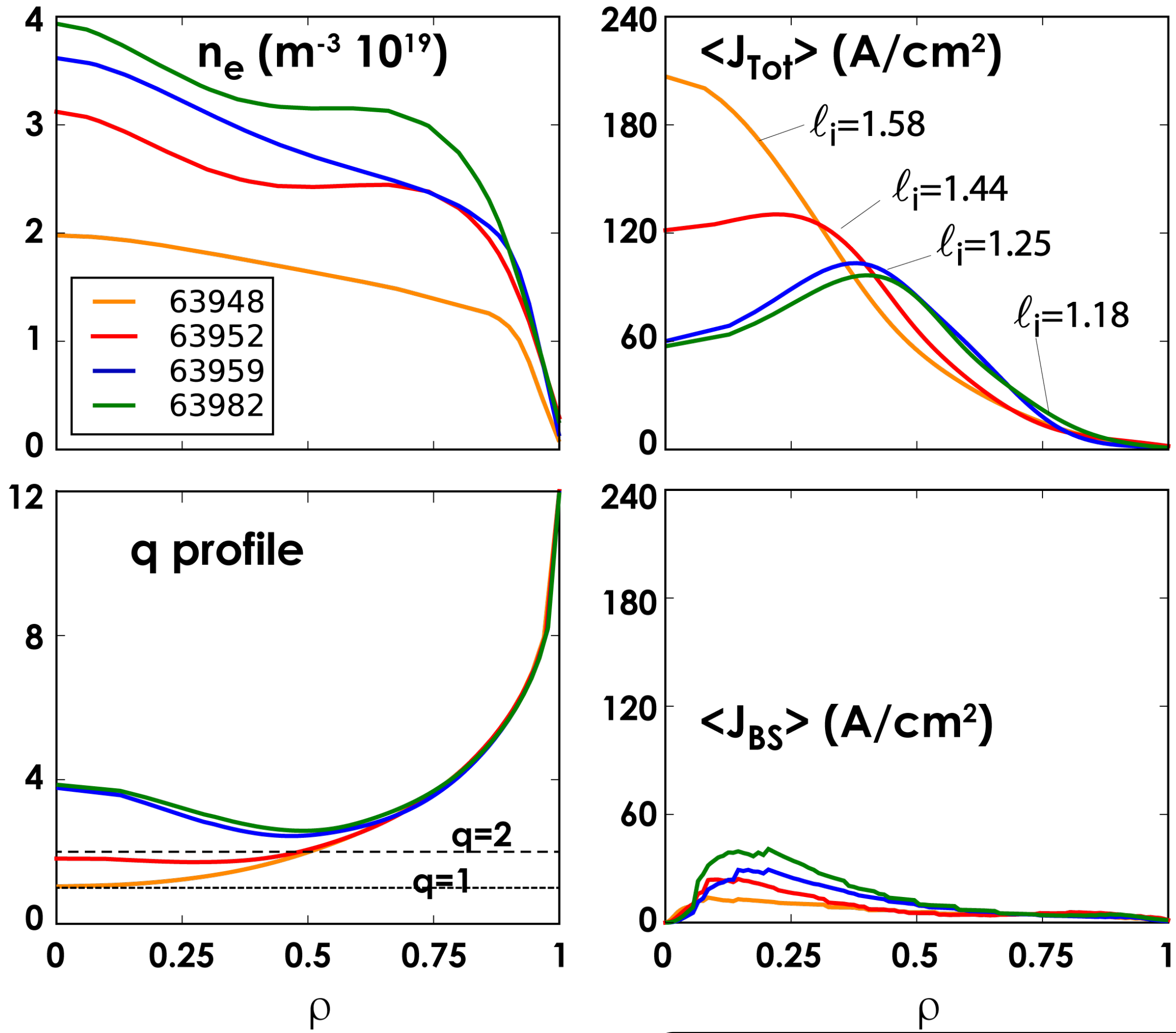
ASIPP

Equilibrium Reconstructions Confirm Broader Current Profile at Higher Density



- **Steady-state negative central shear obtained at high density**

Equilibrium Reconstructions Confirm Broader Current Profile at Higher Density



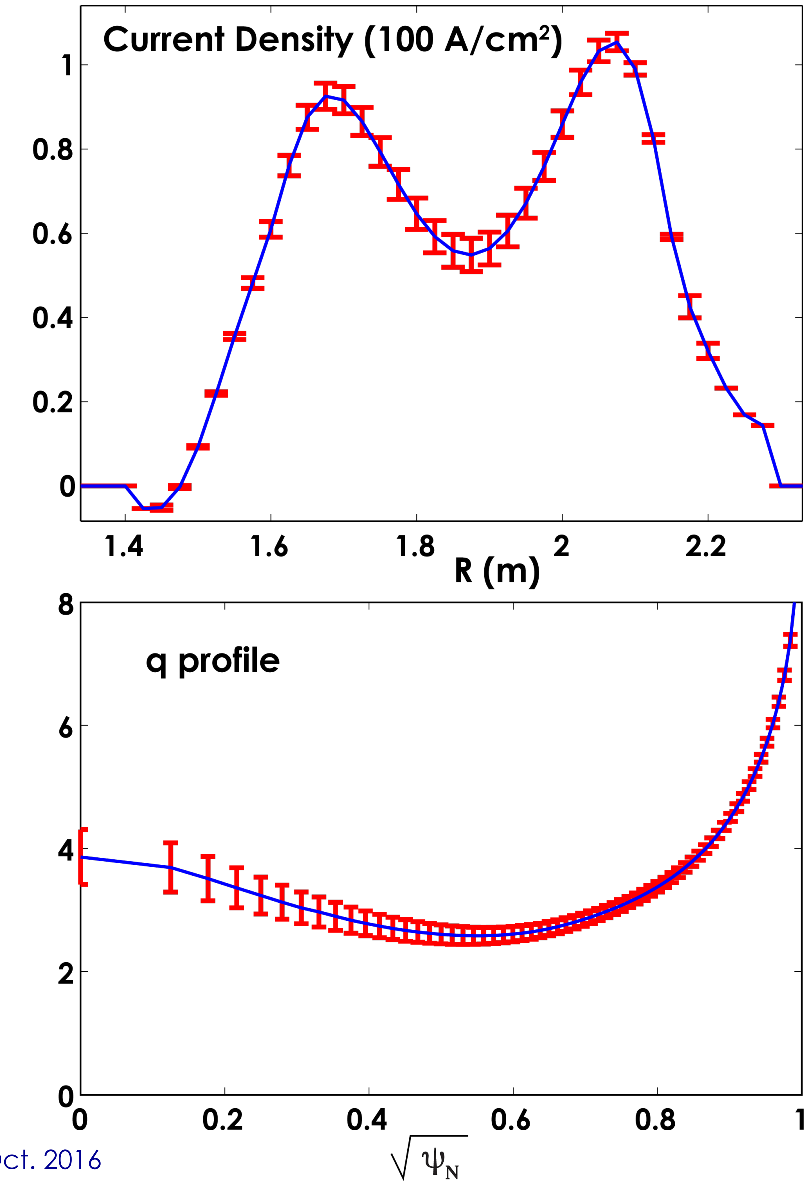
- **Steady-state negative central shear obtained at high density**

"High performance synergy" between broad current profile and high density

ASIPP

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



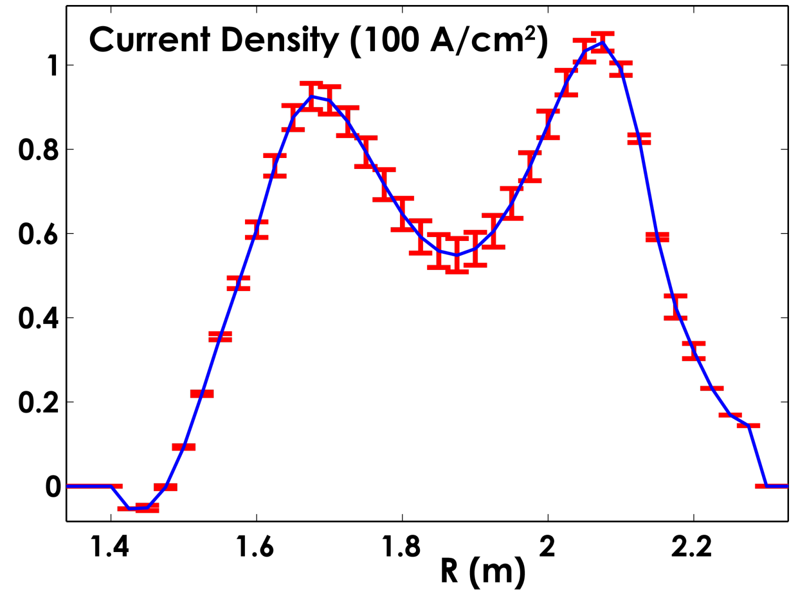
See also
W.X. Ding, EX/P7-16

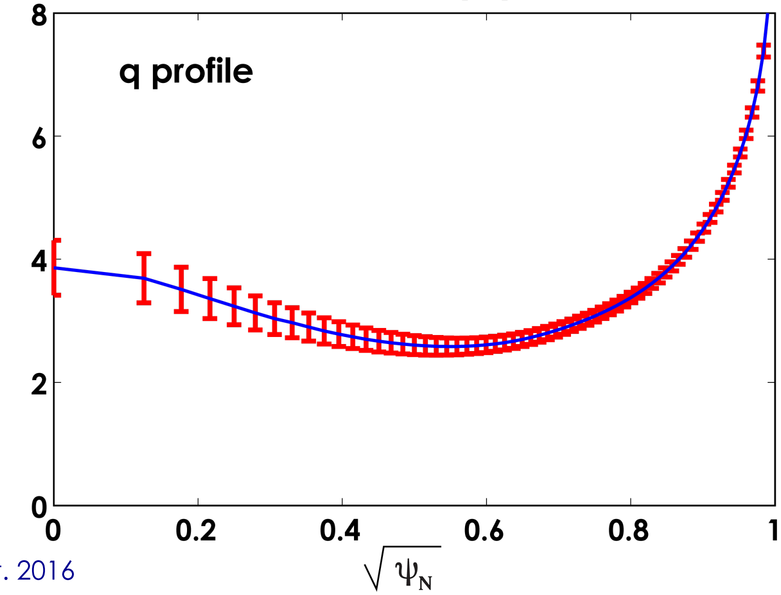
Current Profile Reconstruction Enhanced by New Polarimetry-Interferometry (POINT) Diagnostic

- **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

With no Ohmic current, profile of J_{Tot}–J_{BS} can be compared directly to J_{LHCD} simulation

See also
W.X. Ding, EX/P7-16

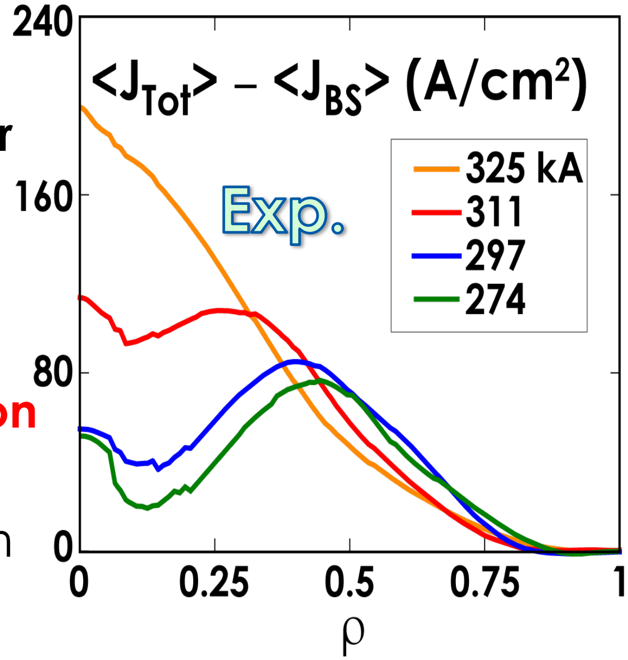


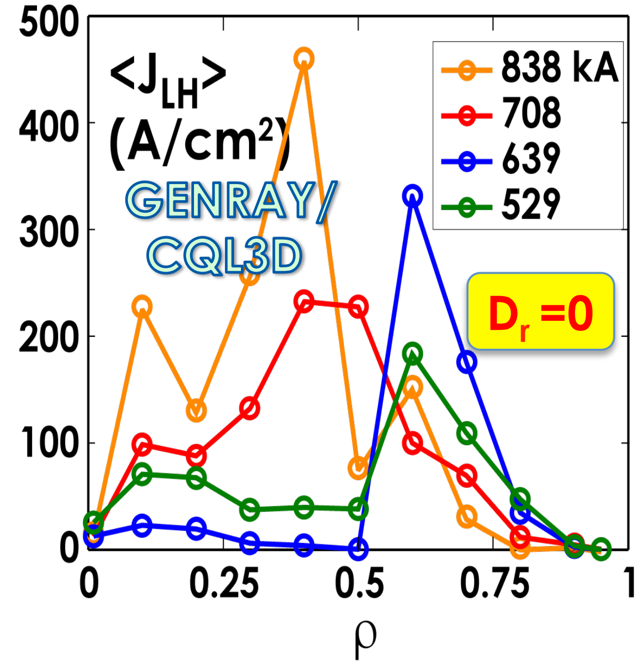


ASIPP

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

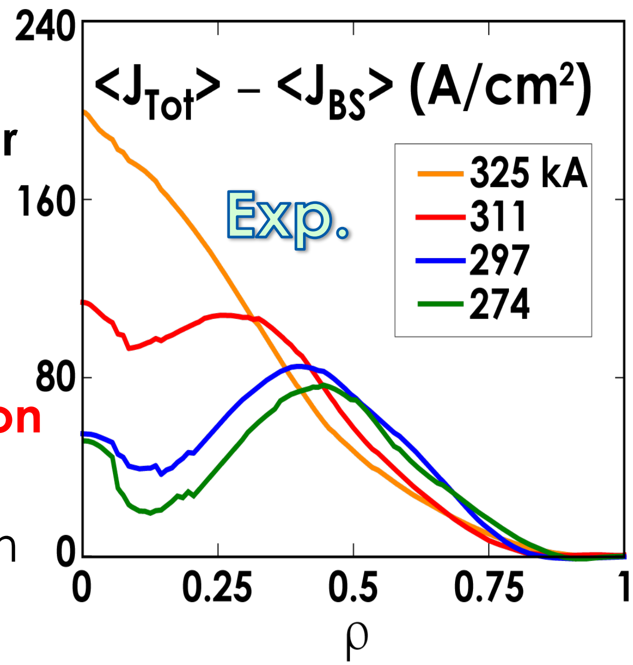


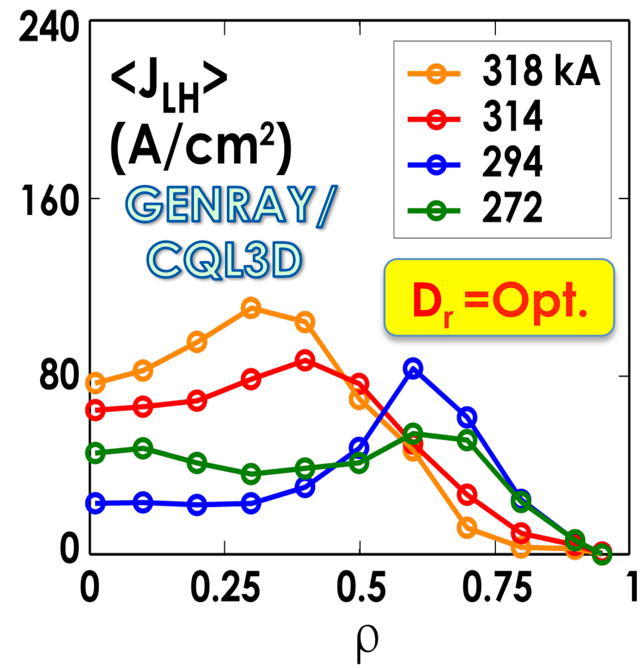


ASIPP

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





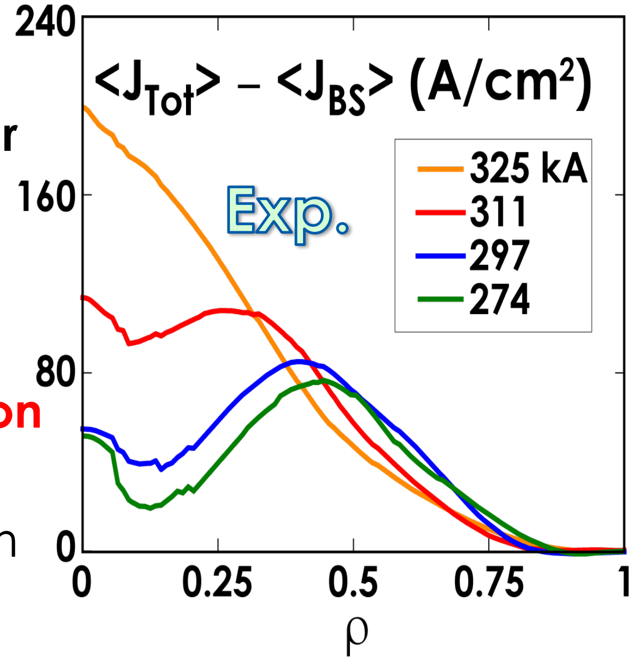
D_r (m²/s)	1.15	1.3	0.8	0.8
n_e (10^{19} m^{-3})	2	2.5	3	3.3

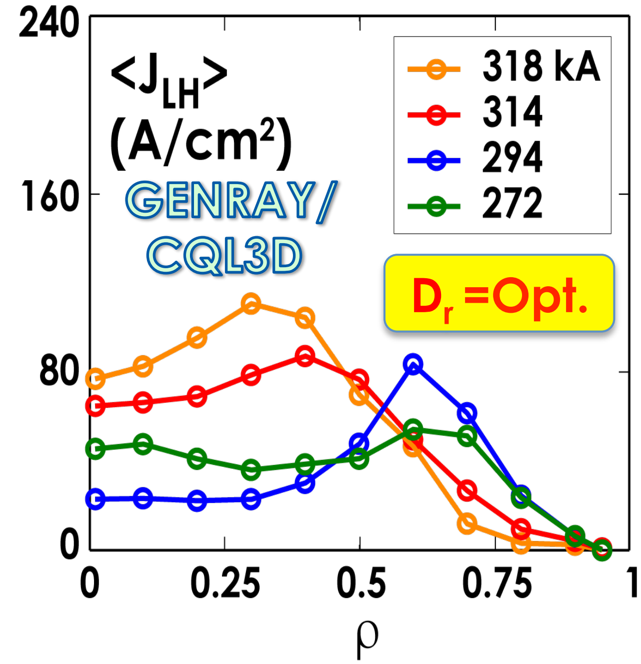
- **Optimal D_r is smaller at higher density**

ASIPP

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





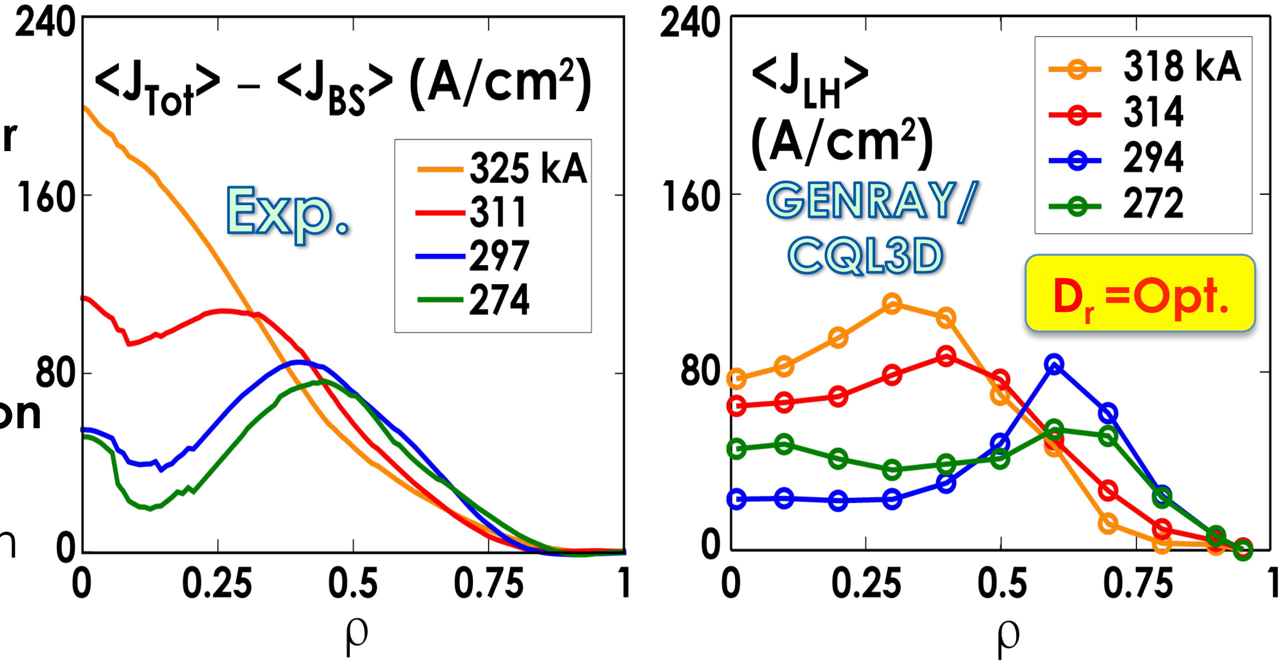
D_r (m²/s)	1.15	1.3	0.8	0.8
n_e (10^{19} m⁻³)	2	2.5	3	3.3

- **Optimal D_r is smaller at higher density**
- **$D_r \sim 1$ m²/s consistent with $\delta B/B \leq 10^{-4}$**
  [Rechester-Rosenbluth, PRL 1978]

ASIPP

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



D_r (m^2/s)	1.15	1.3	0.8	0.8
n_e (10^{19} m^{-3})	2	2.5	3	3.3

- **Optimal D_r is smaller at higher density**
- **D_r ~ 1 m^2/s consistent with $\delta B/B \leq 10^{-4}$**
  [Rechester-Rosenbluth, PRL 1978]

- **Simulated profiles are systematically broader than experiment → "Tail" model may yield better agreement**

ASIPP

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}~1.1) with low core χ_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 can predict the experimental trend

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}~1.1) with low core χ_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 can predict the experimental trend

Landmark progress made toward demonstration of steady state high performance for a fusion reactor

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}~1.1) with low core χ_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 can predict the experimental trend

Landmark progress made toward demonstration of steady state high performance for a fusion reactor

- **Next step: Optimize ITB with higher β_P and broader current profile**