Overview of Recent Experimental Results on EAST in Support of ITER New Research Plan

X. Gong[1*]

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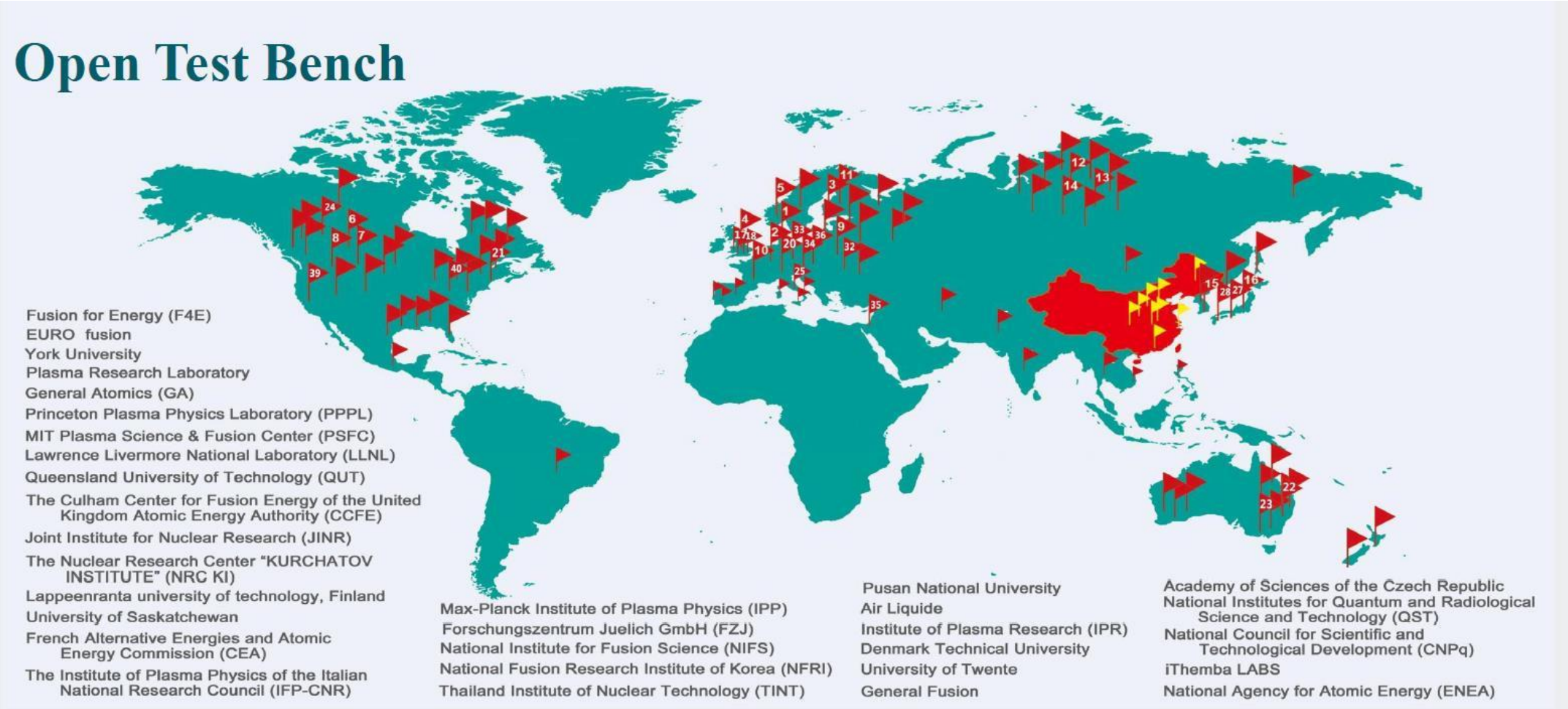
Acknowledgement

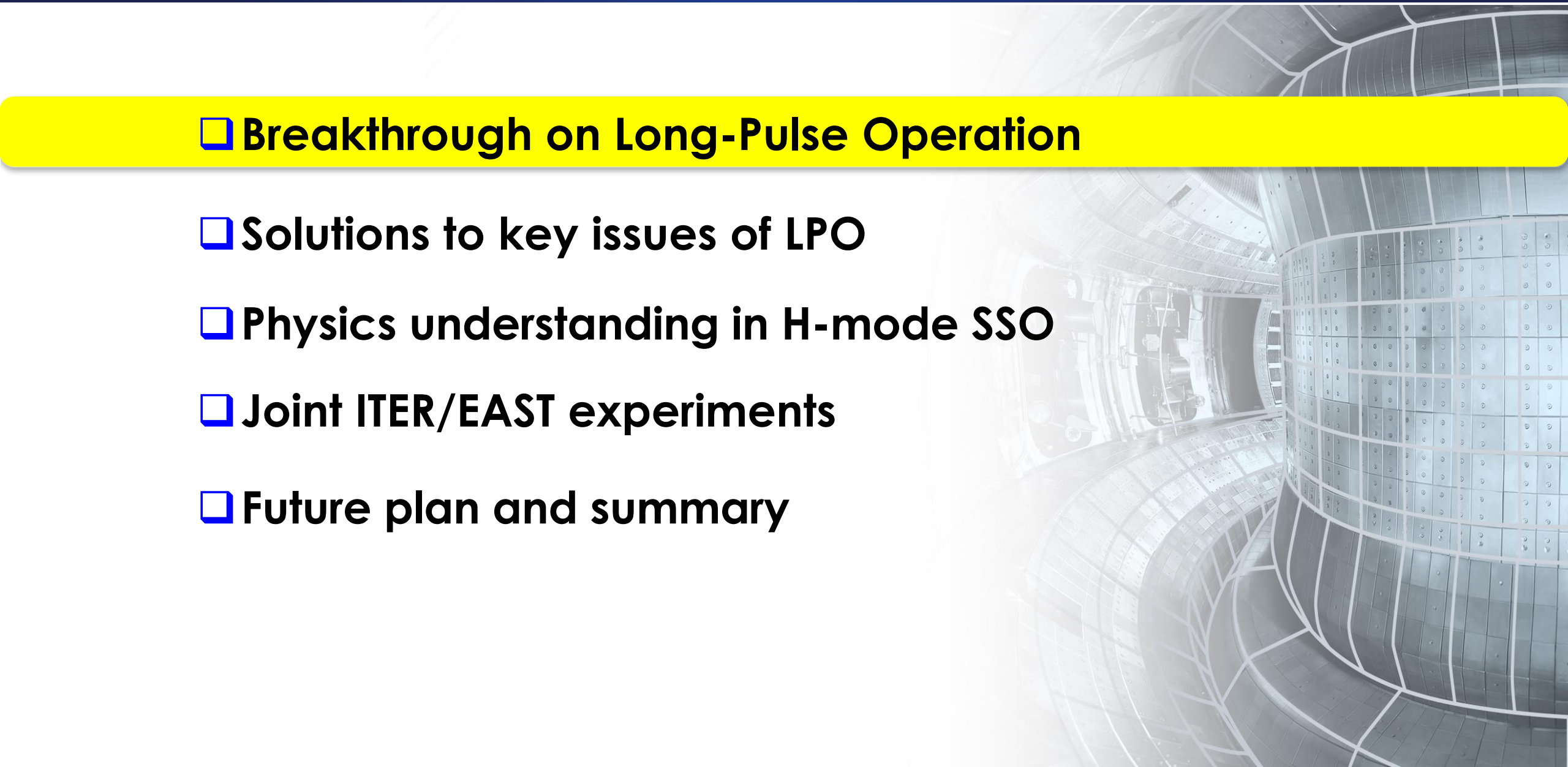


Great Progresses on EAST Benefit from Broad Domestic and Wide International Collaborations!

ASIPP

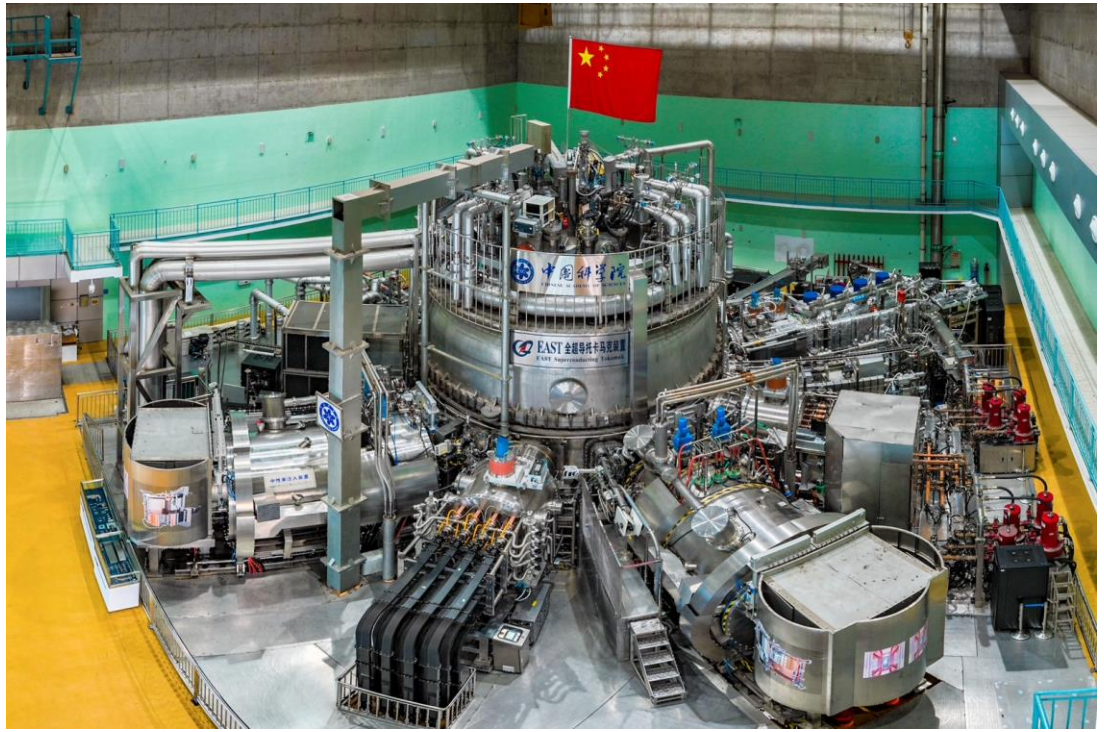
Outline

- Breakthrough on Long-Pulse Operation
- Solutions to key issues of LPO
- Physics understanding in H-mode SSO
- Joint ITER/EAST experiments
- Future plan and summary



Long-Pulse Initiative: Achieve Integrated SS High Performance Plasma and Study Related Physics and Fusion Engineering

EAST is the first fully superconducting Tokamak in the world, oriented to support the ITER new research plan and the BEST project both of scientifically and technically.



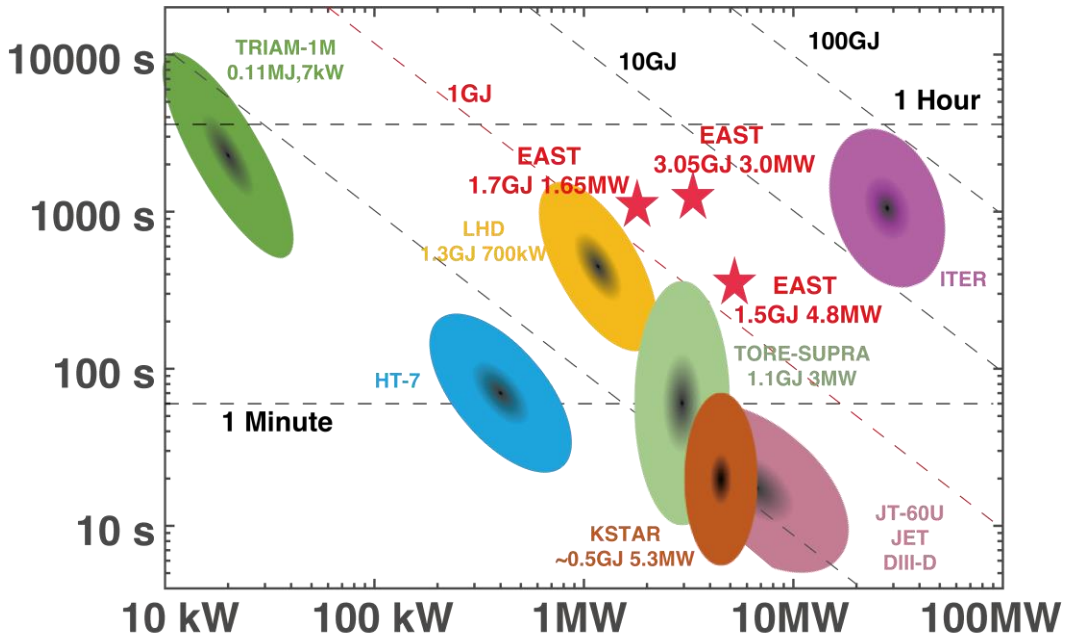
- Prof. Wan Yuanxi at 21st IAEA FEC Oct. 2006, Chengdu
- ~ 20 Years, ~160,000 Shots

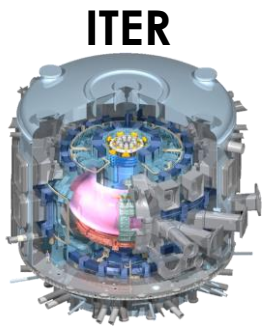
Strategies for Establishing Scientific-Based Solutions for Steady-State Operation to Support Future Fusion Devices

S1: Enhance H&CD efficiency and relevant fundamental physics understanding and key diagnostics

S2: Demonstrate long-pulse (≥400s) H-mode plasmas and develop fully non-inductive high-β scenarios

S3: Extend EAST operation regime to demonstrate high fusion performance plasmas and deliver relevant physics for ITER and CFEDR

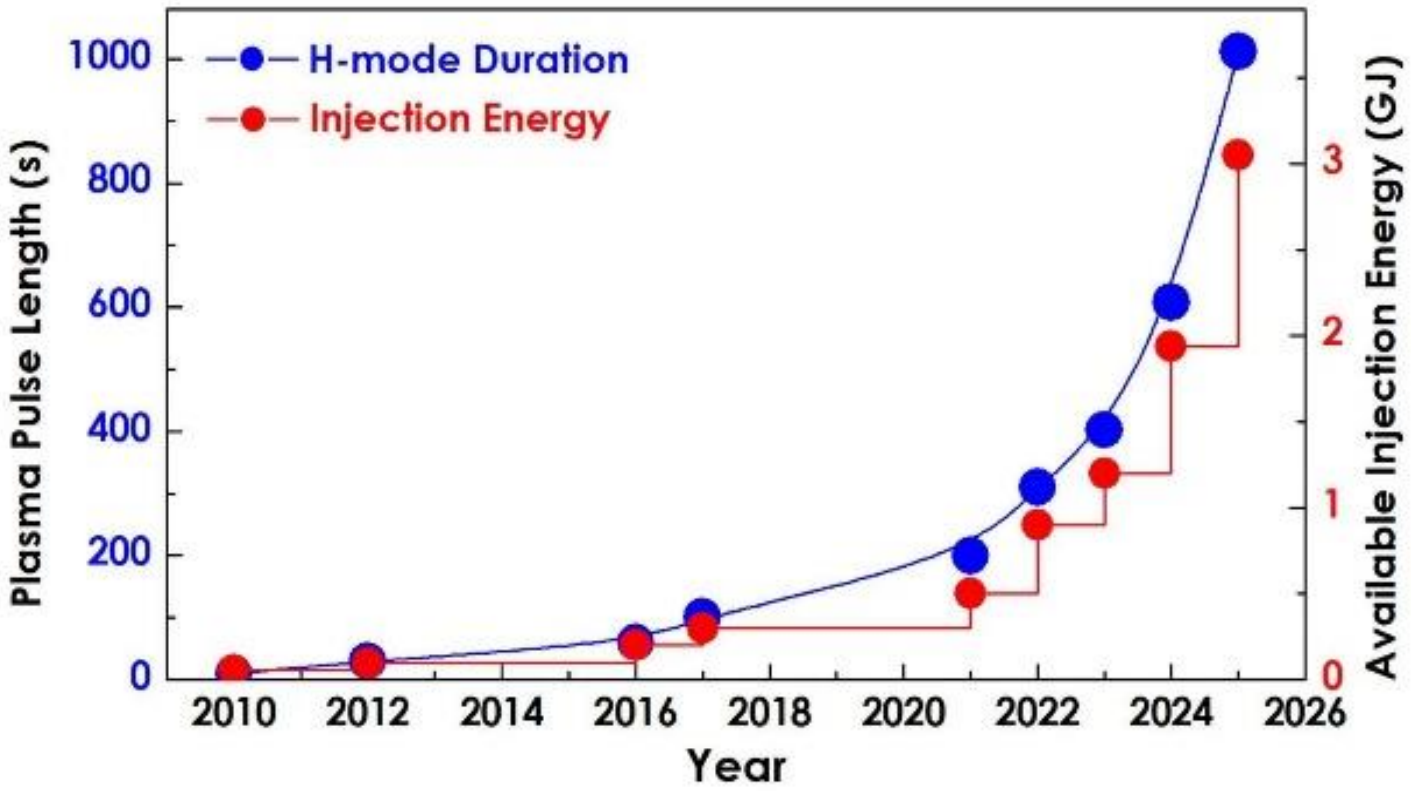




Significant Progress of Long-pulse H-mode Plasma on EAST

- **Integrated solutions of high-performance LPO**
  - High confinement and bootstrap current fraction
  - High RF current drive at high density
  - Core-edge integration
- **On time scale of particle and heat balance**
  - Particle recycling and W regulation
  - ELM mitigation and active control
  - Divertor target power exhaust

Total injected energy up to 3.05GJ



Demonstrate expertise in engineering and technical issues for LPO

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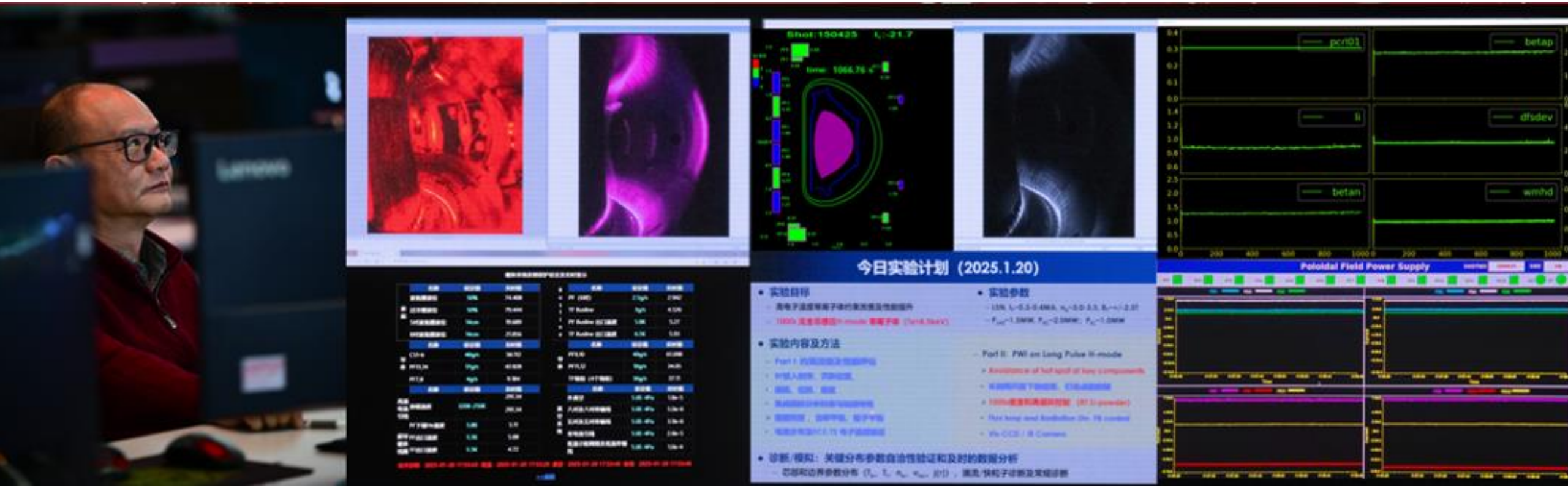
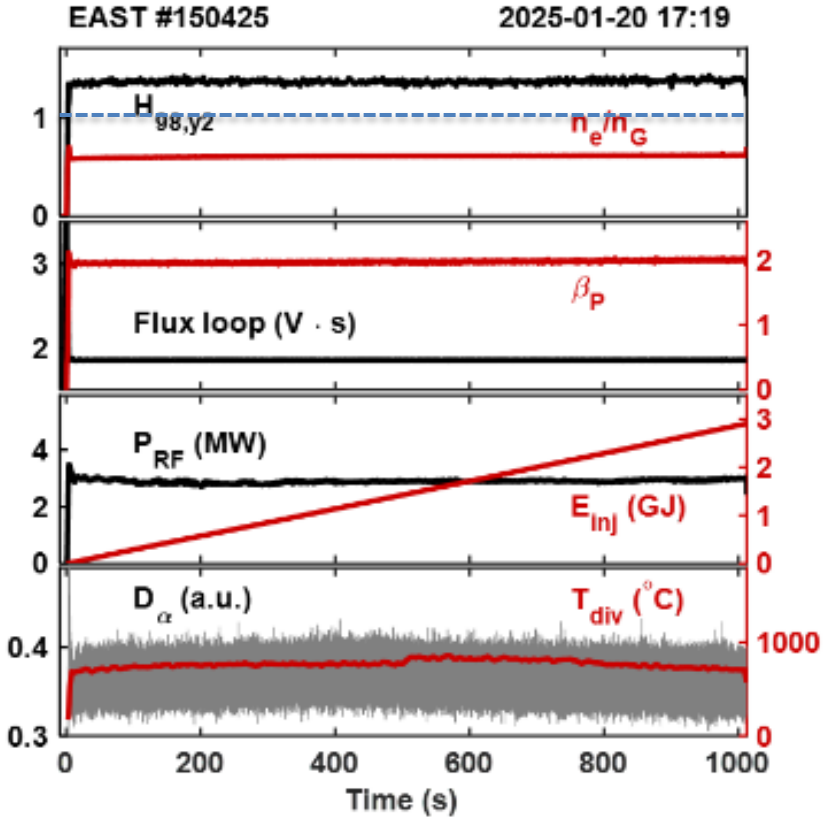
Recent Advancement and Breakthrough in Long Pulse H-mode Operation with W-Divertor on EAST

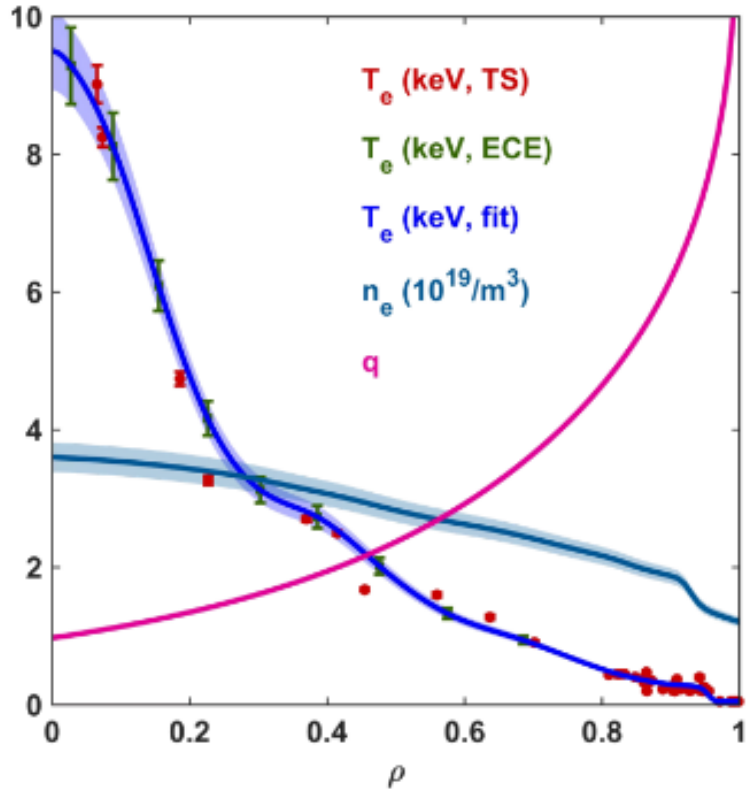


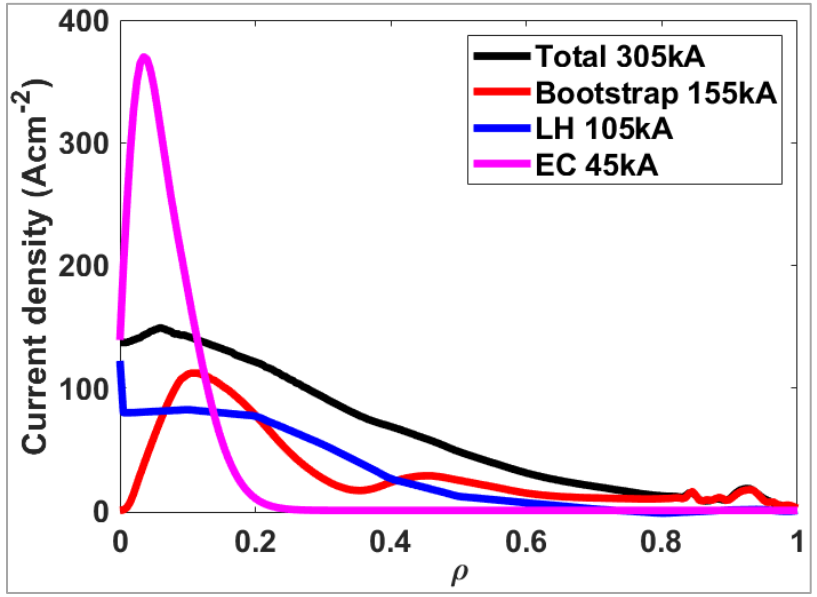
An exciting milestone in achieving a 1066.7 second steady-state high confinement plasma on January 20th, 2025

EAST Made an Important Advance by Achieving a Record H-mode Plasma over 1066-second

– Bt~2.5T/LSN, H_{98y2}~1.35, n_e/n_G ~0.6, f_{BS} ~50%, T_{e0}~10keV, E_{inj}~3.05GJ







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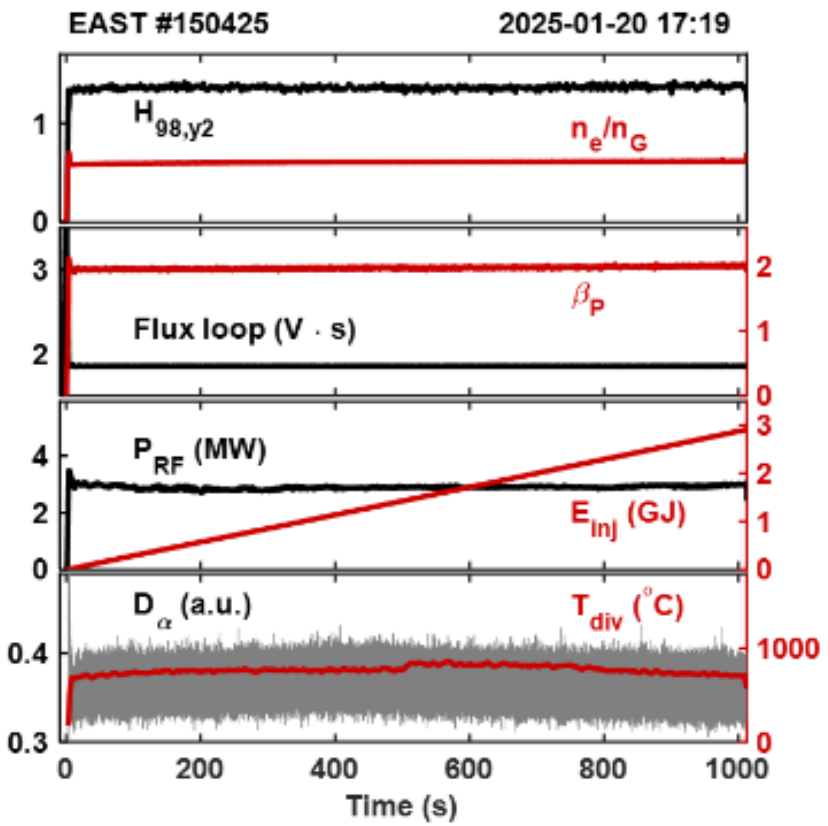

- P_{LHCD} =1.1 MW, P_{ECRH}=1.9 MW, β_P = 2.0 with e-ITB, f_{BS} ~50%, T_{div}~600-800°C
- A flux loop feedback conrol to sustain zero loop voltage, guaranteeing a fully non-inductive plasma with an electron density at 60% of the Greenwald limit.
- A grassy ELM regime with OSP on the horizontal target, facilitating efficient RF power coupling and reducing W sputtering/erosion.
- Low Z materials wall coating and real-time powder injections to improve particle control capability.

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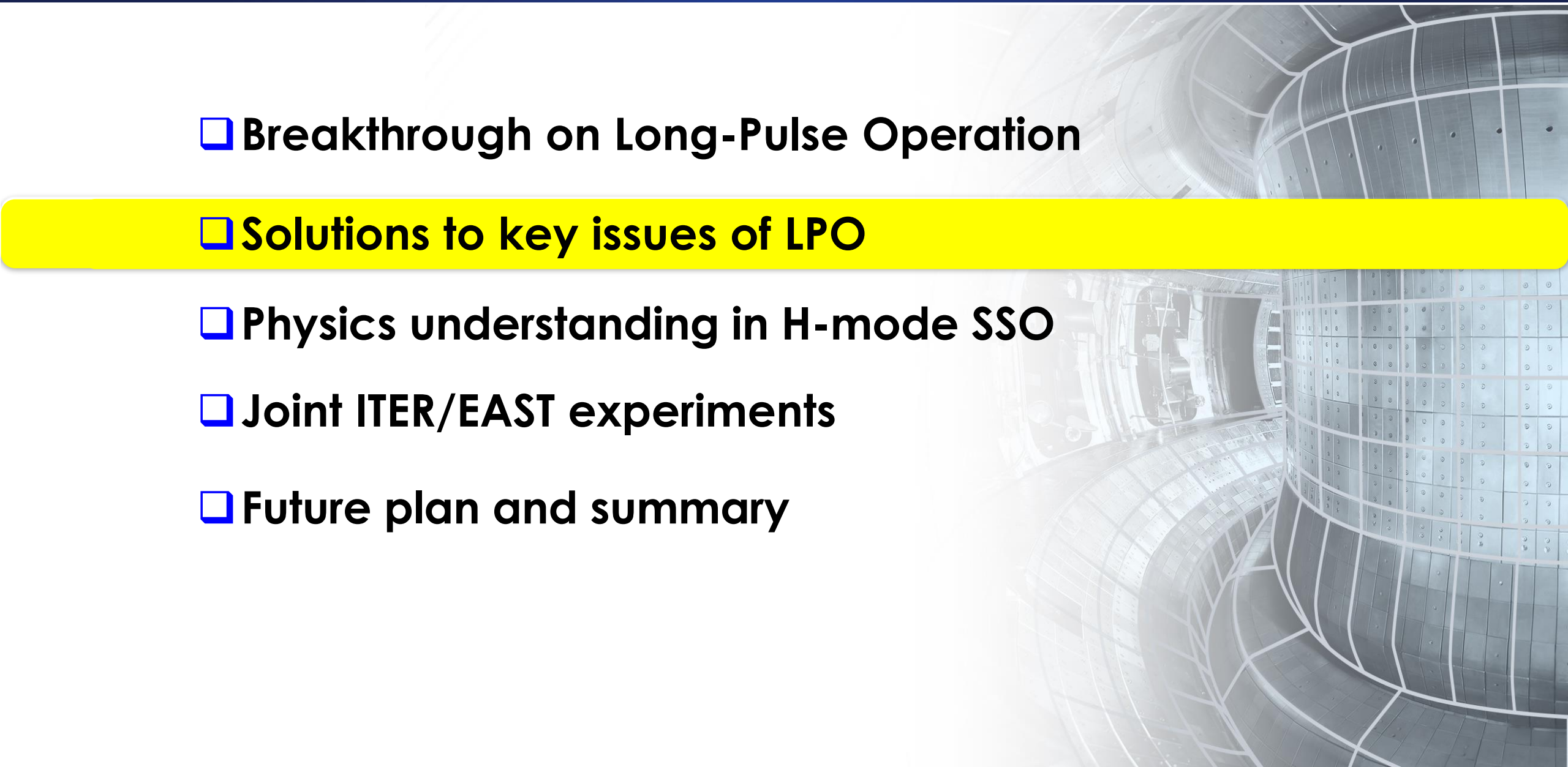
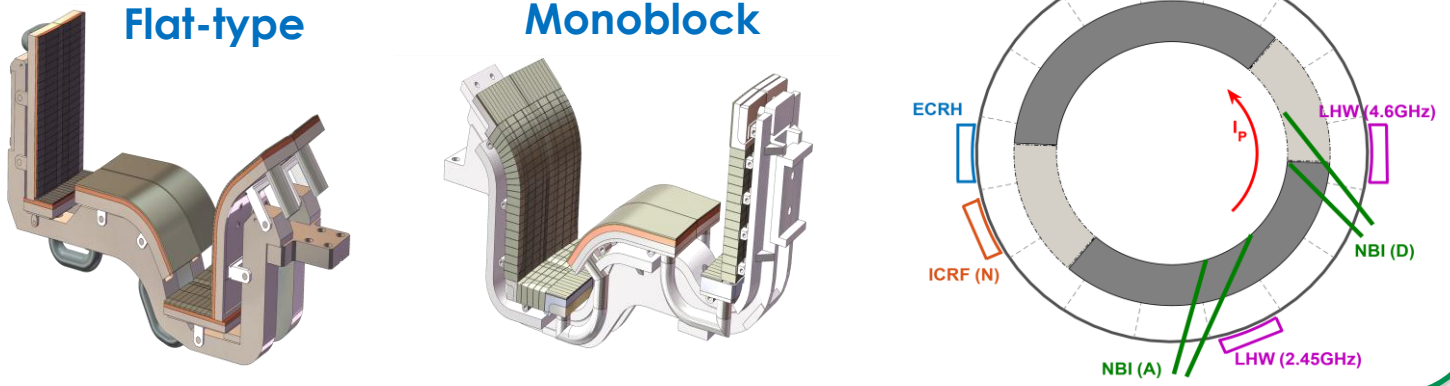
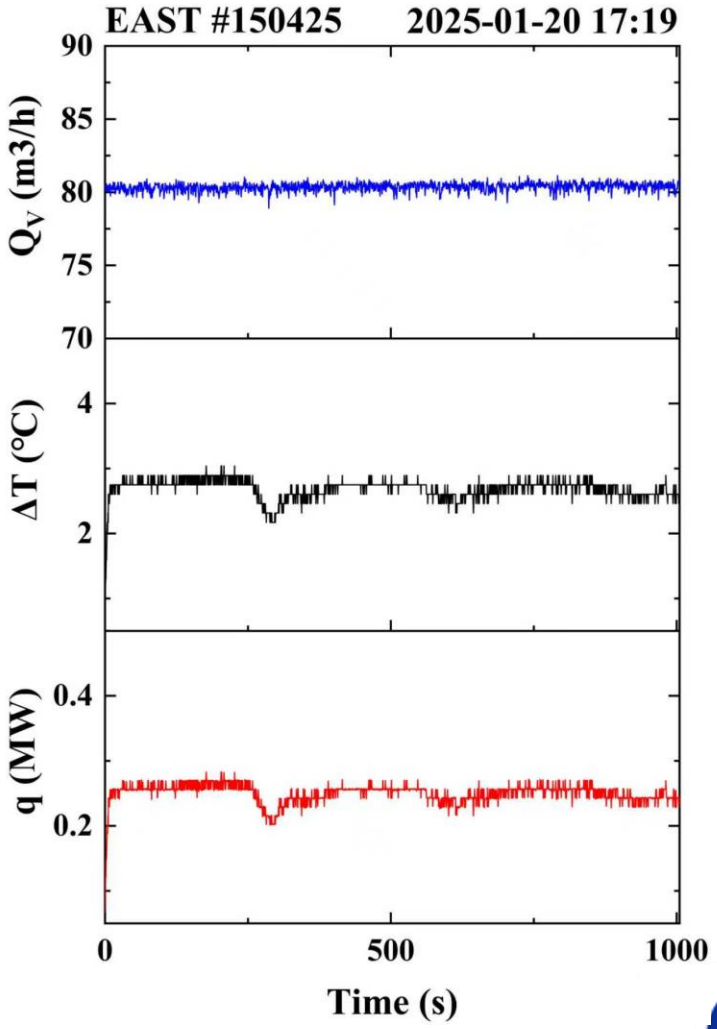


Fully Active Water-cooling Metal-Wall with W-divertors Enable Advances in SSO Research

New lower tungsten divertor





- **A new lower water-cooled tungsten divertor installed**
  - ¾ with the monoblock structure
  - ¼ with the flat-type structure
- **Enhanced particle/heat flux load and removal capability**
  - Increase steady-state heat exhaust to 10-20MW/m^2
- **Thermal equilibrium achieved quickly at new W-divertor**
  - Actively Cooling Thermal-hydraulic Behaviors: M2 Sector (1/8)

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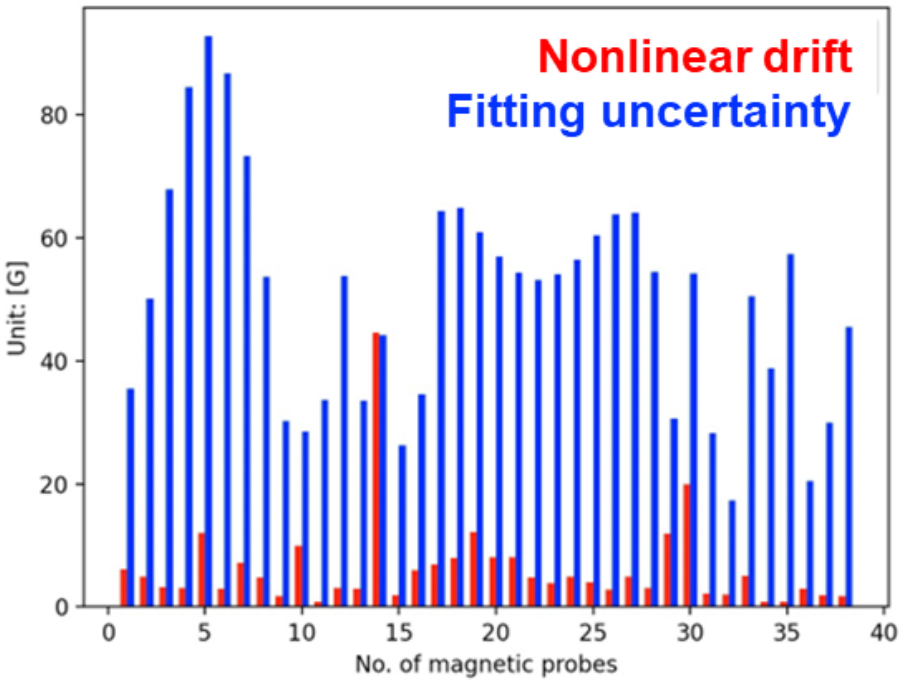
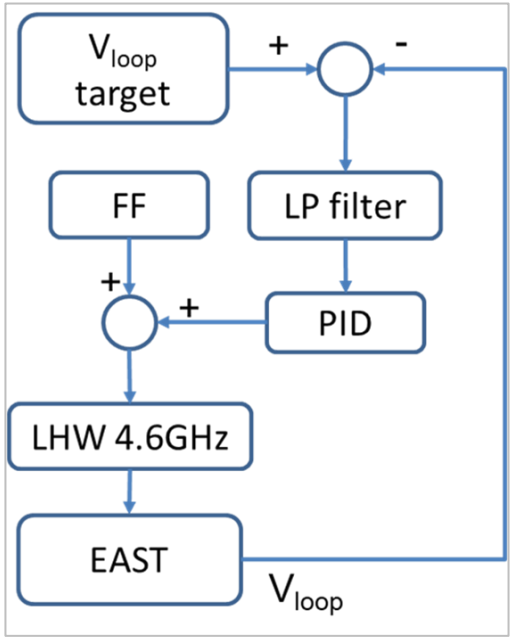
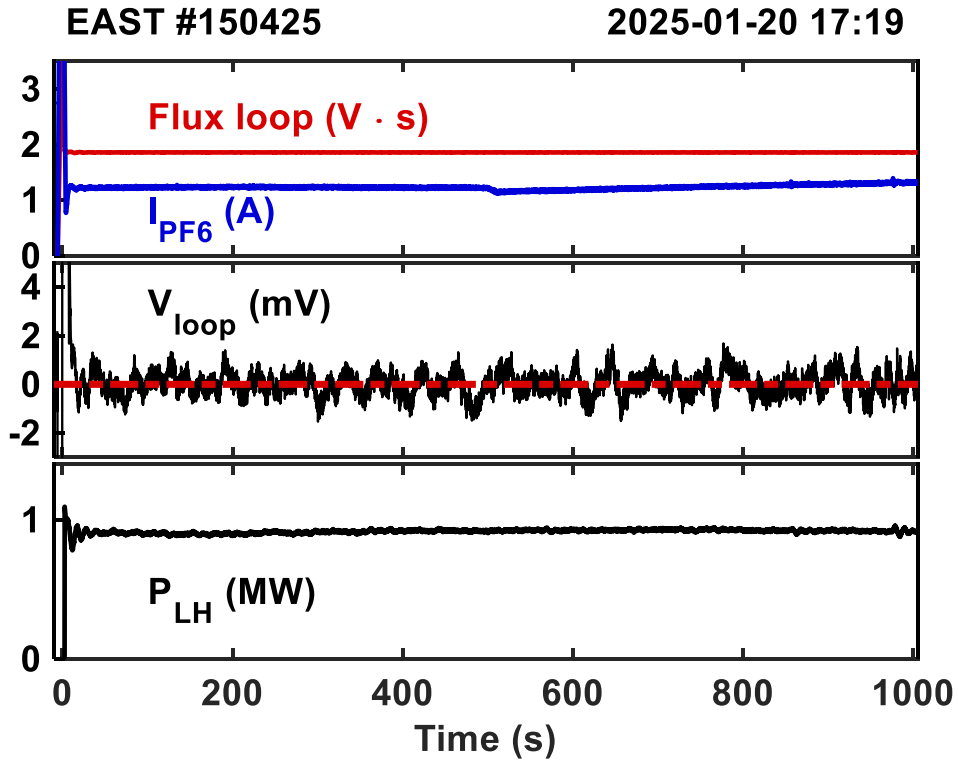
Robust Plasma Shape Control and Fully Non-Inductive Current Regime Sustainment via Innovative Loop Voltage Feedback Algorithm



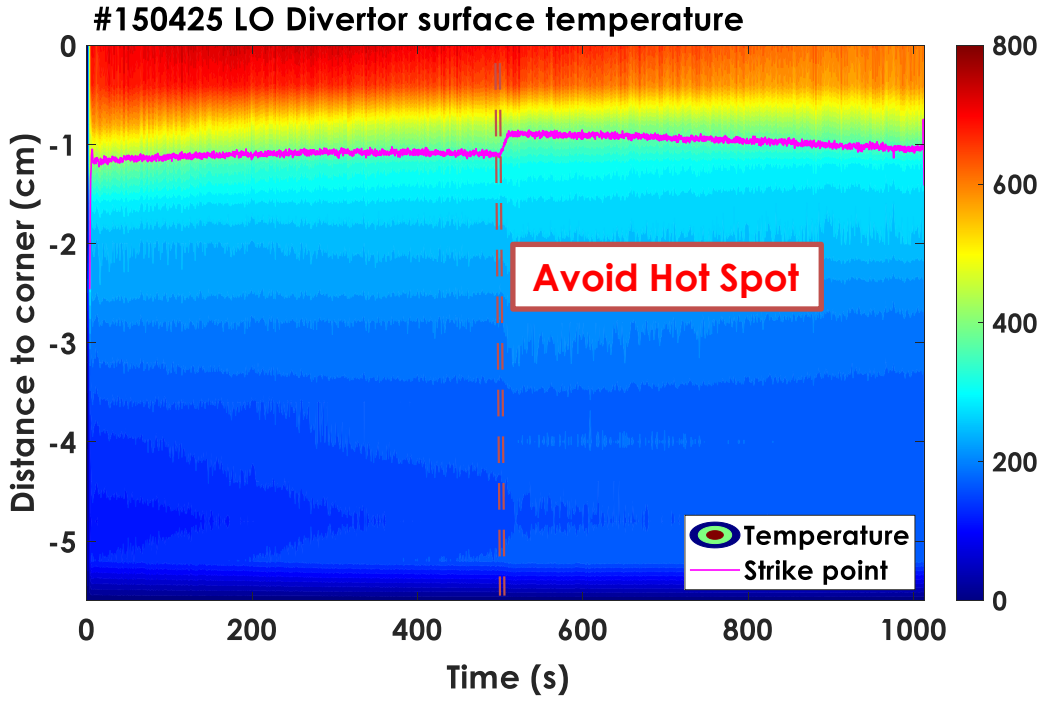


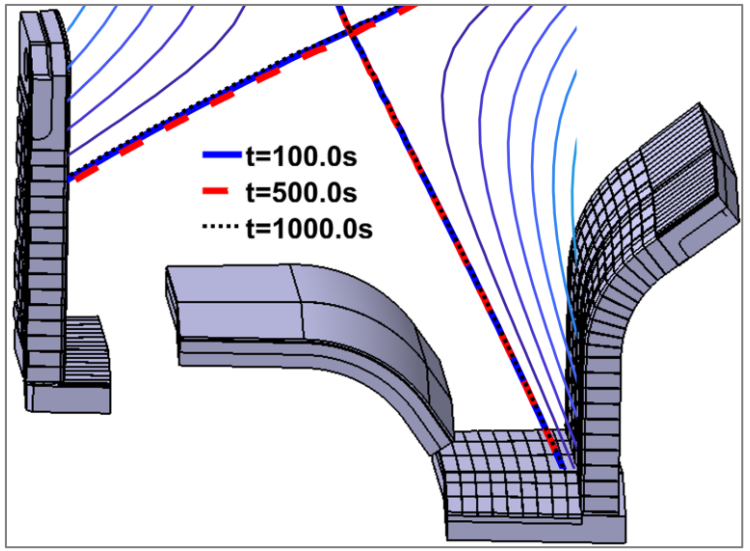


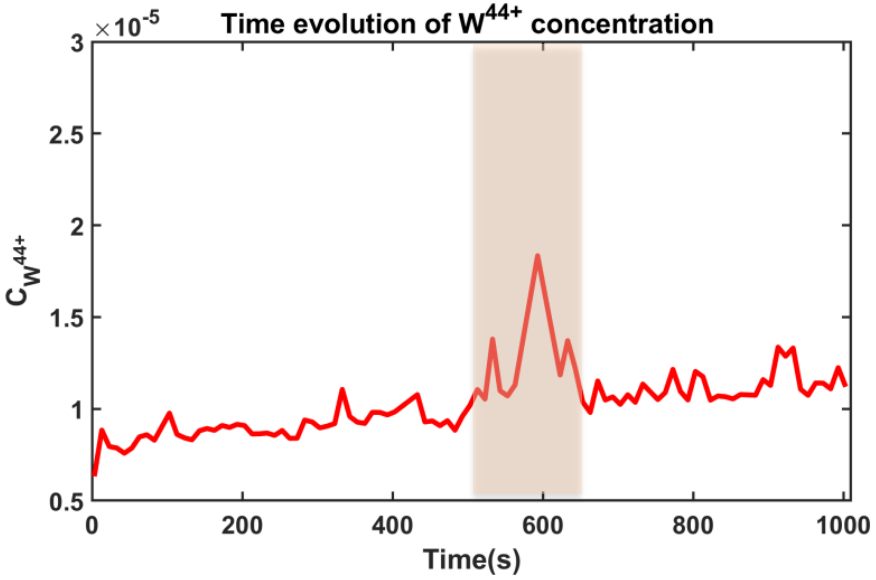
- **Good accuracy shape control with Gap < 2mm, X-point(R,Z) < 3mm**
  - Magnetic measurement for PF coil current using new fiber optic current sensors
  - Low drift of integrator with linear drift deduction by timely calibration and algorithm in PCS and nonlinear drift reduction by replacing good integrator modules
- **Optimization of Flux Loop control by LHW to minimize PF coil current**
  - All PF coil current remained stable and constant to reduce AC loss in superconducting coils

Robust Plasma Control Maintain Precise Strike Point Location And Efficient Protection of Divertor Target in Long Pulse Operation

- Precise control of strike point with Rx drift < 3 mm
- Actively water-cooled divertor target surface: 800°C
- Divertor sputtering well controlled, W-sources







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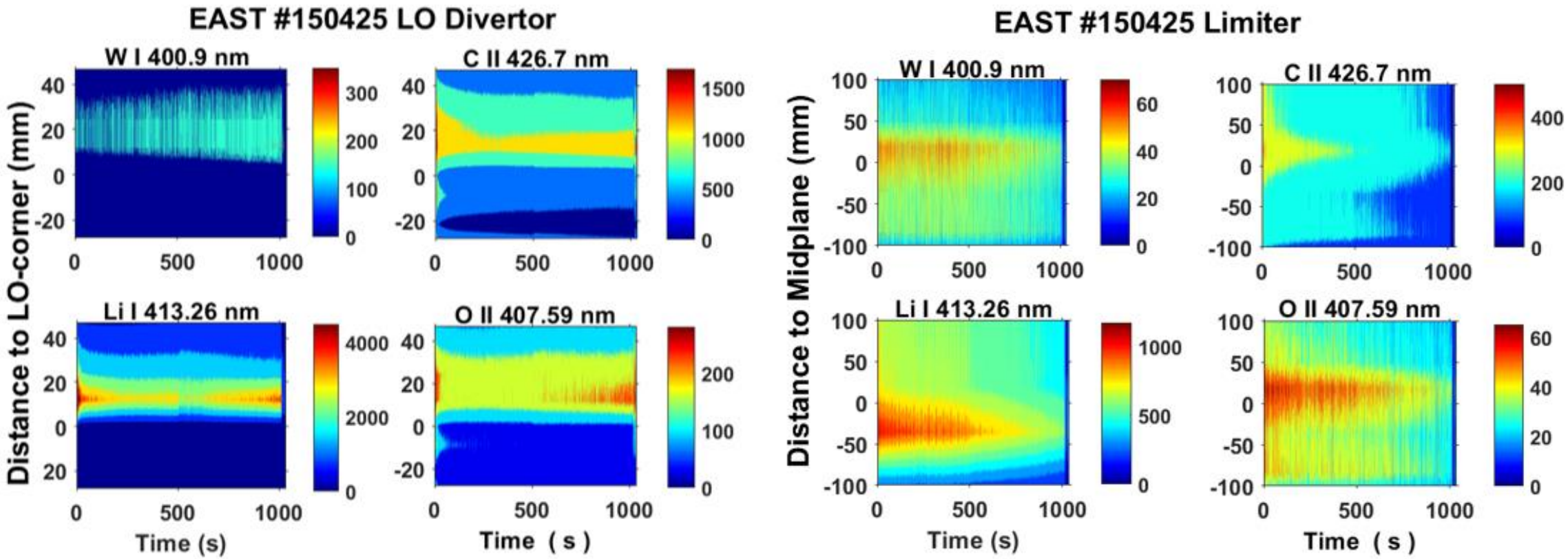
Control of Recycling and Impurity by Real Time Wall Conditioning using Lithium Powder Injection Advancing Long Pulse Operation



- **Impurity sources at both the divertor and the mid-plane limiter effectively suppressed**

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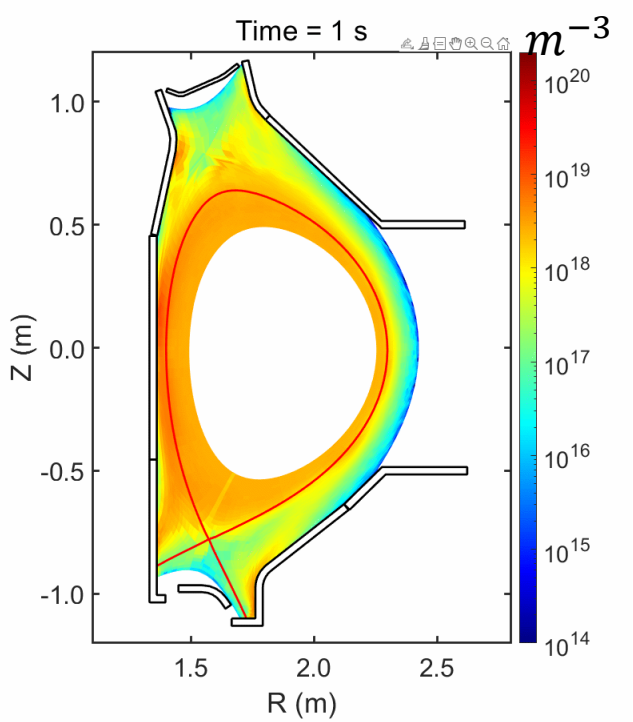
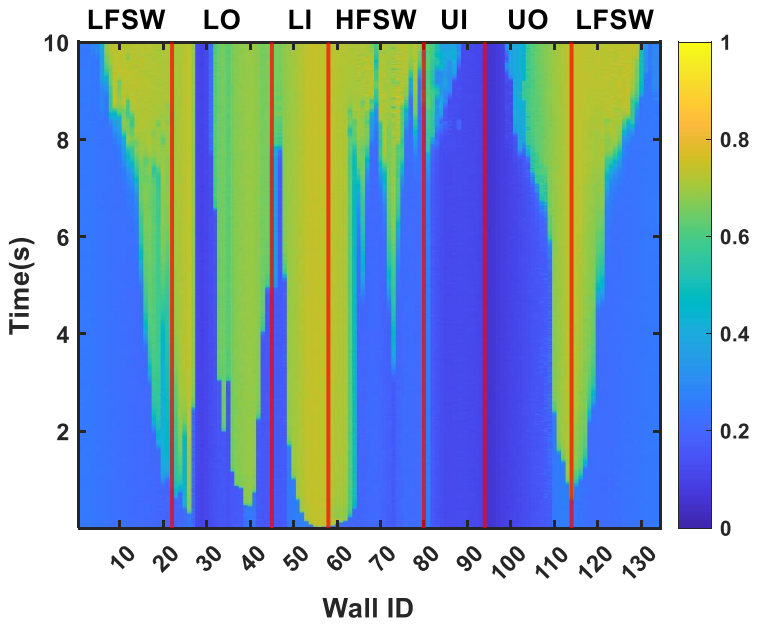
Time Dependent Modeling of Wall Materials Migration and the Related Effect on Particle Recycling

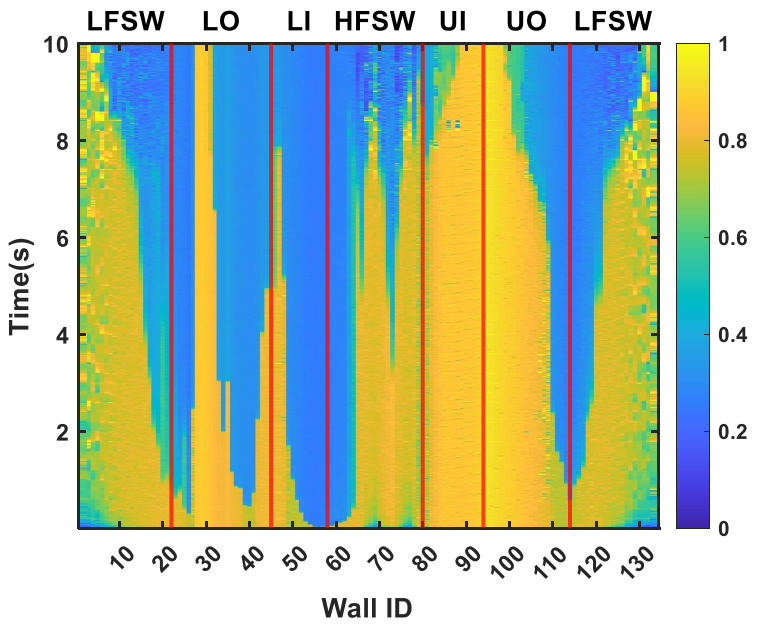
Dynamic Li distribution



D reflection rate



D reemission rate

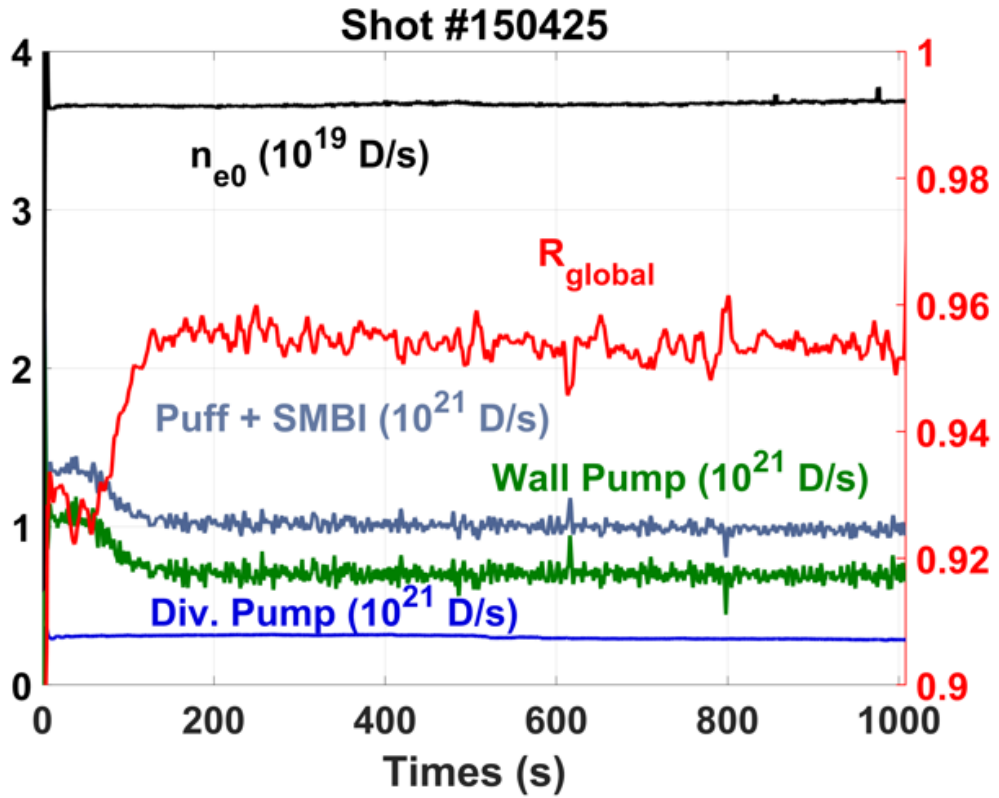


See **G.L. XU's** Poster in this meeting

- **SOLPS-SDTRIM and SP-DIVIMP integrated modeling framework has been developed for time dependent Li-W material evolution and particle recycling study;**
- **D reflection and reemission rates vary with the surface materials compositions.**

Effectively Controlled Fueling Recycling Beyond Wall Saturation Time Scale

- **More difficult on recycling control in moderate density to adapt to high-Te**
  - Higher Li-powder ➔ H&CD efficiency decreased ➔ confinement worse
  - Lower Li-powder ➔ H/H+D increased ➔ uncontrollable density
- **Modulation of lithium powder by feedback control**
  - **R_{global} ~ 0.95 and H/(H+D) ~ 3.5%**



- **Constant density sustained by SMBI fueling**
  - Wall pumping played a significant role in recycling control
  - Improved particle exhaust with larger pumping speed and fresh wall condition

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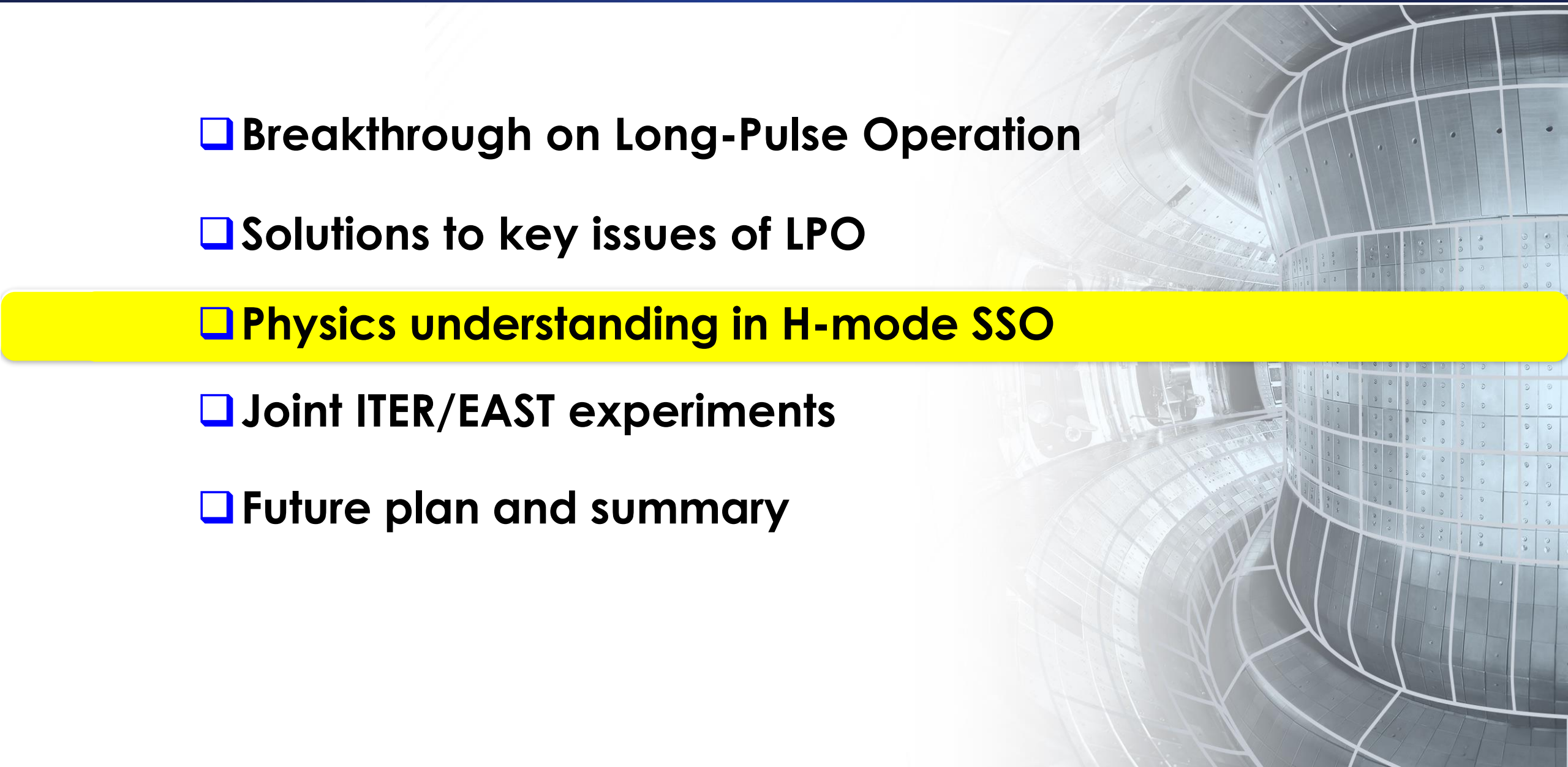
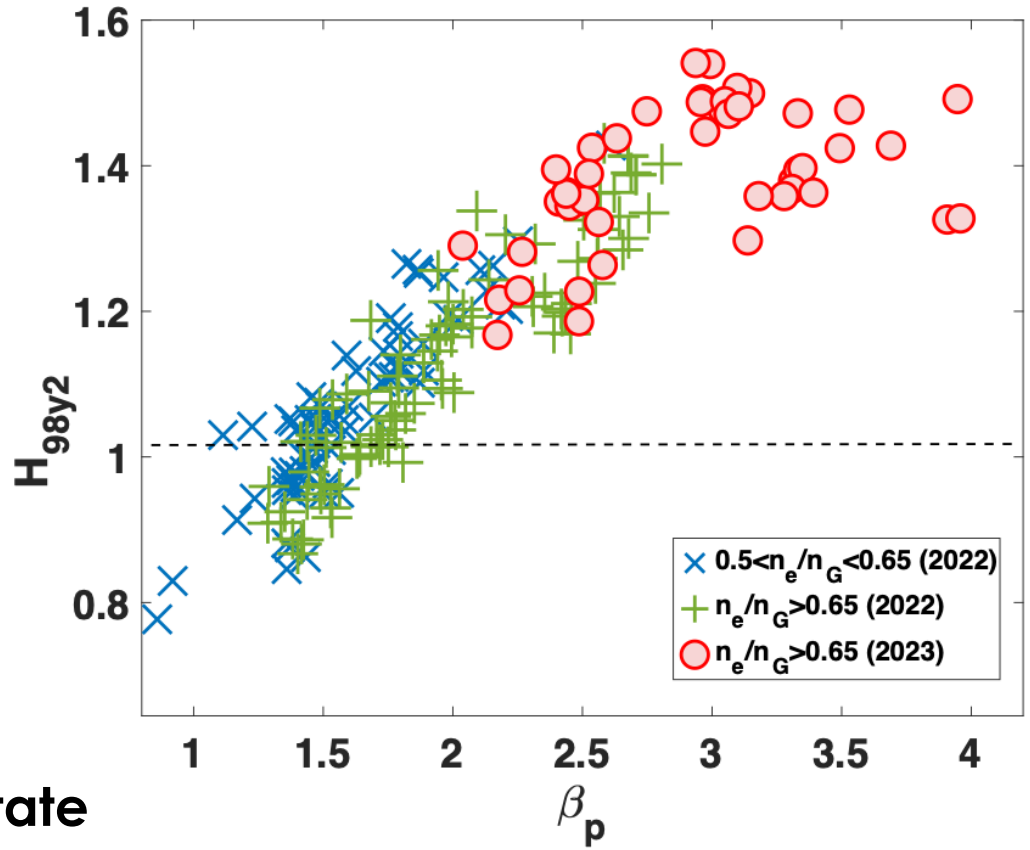


Experiments Show Improved Confinement and Higher Bootstrap Current Fraction when Extending to High-β_P Regime

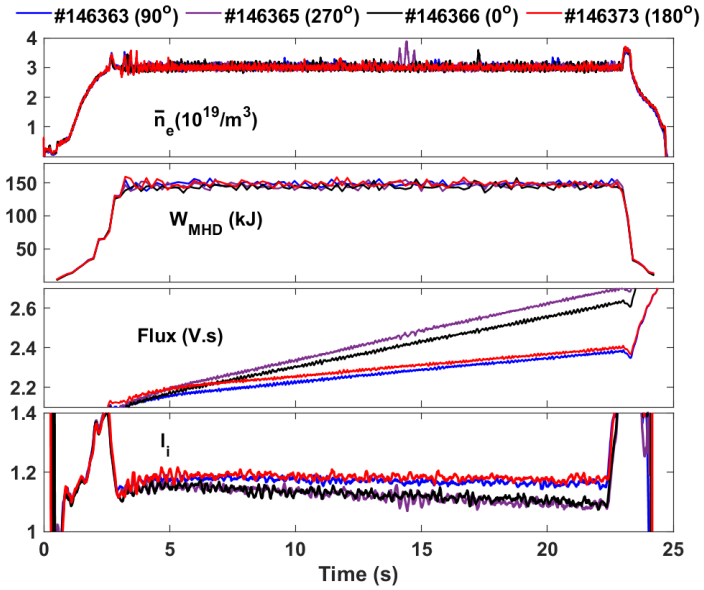
- **Demonstration of High Confinement, High Density and High f_{BS} towards Steady-state Operation**

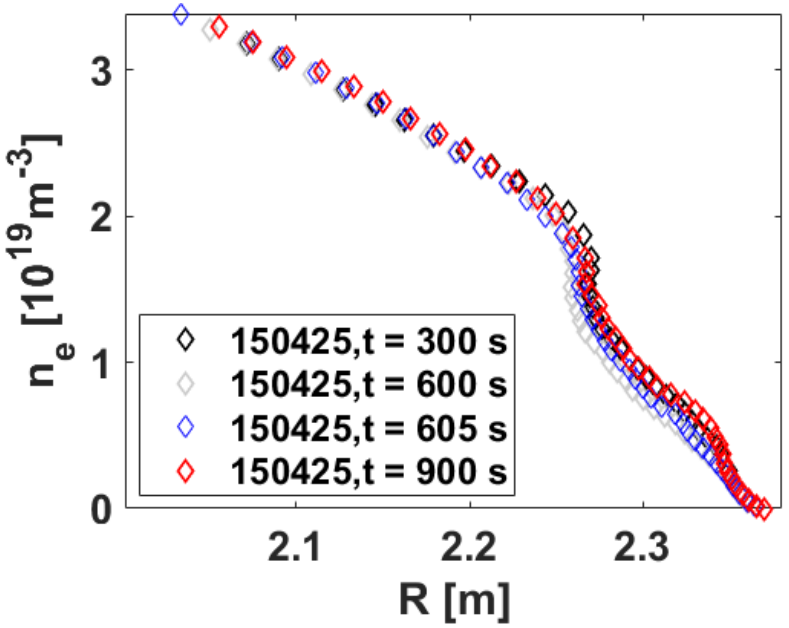
High energy confinement and high-β_p at high-n_e	Zero torque with Self-Regulating e-ITB	Electron heating dominant CD Efficiency
Small ELMs (f_{ELM}~1kHz)	Well high-Z impurity control	Compatible Core and Edge Integration

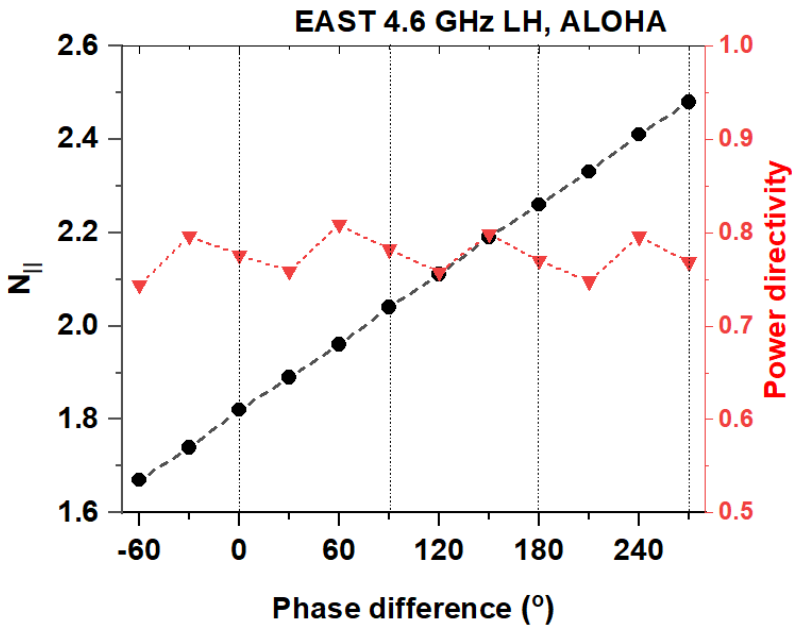


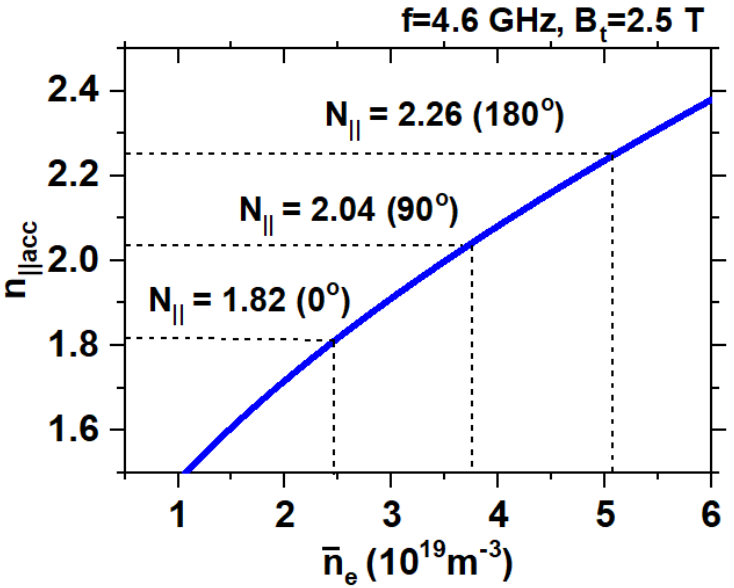
- **Normalized parameters close to ITER/CFEDR steady state**
  - β_P~4.0, f_{BS}~60%, H_{98y2}~1.5, Vloop~0, n_e/n_G~1.0, β_N~2.5~4xl_i
  - Broader q-profile (weak shear/NCS) and q_{min}>2 to avoid NTM

Improved Current Drive Efficiency by Adjusting LH Wave Phase









- **Optimal $N_{||}$ should be slightly higher than $N_{||acc}$, lower than which wave accessibility becomes worse, but too large $N_{||}$ will lead to a decrease in CD efficiency ($\propto 1/N^2_{||}$)**
- **For long-pulse H mode with $n_{e0} \sim 3.6\times10^{19}$/m^3, optimal $N_{||}$ is 2.04, corresponding to the phase of 90°.**

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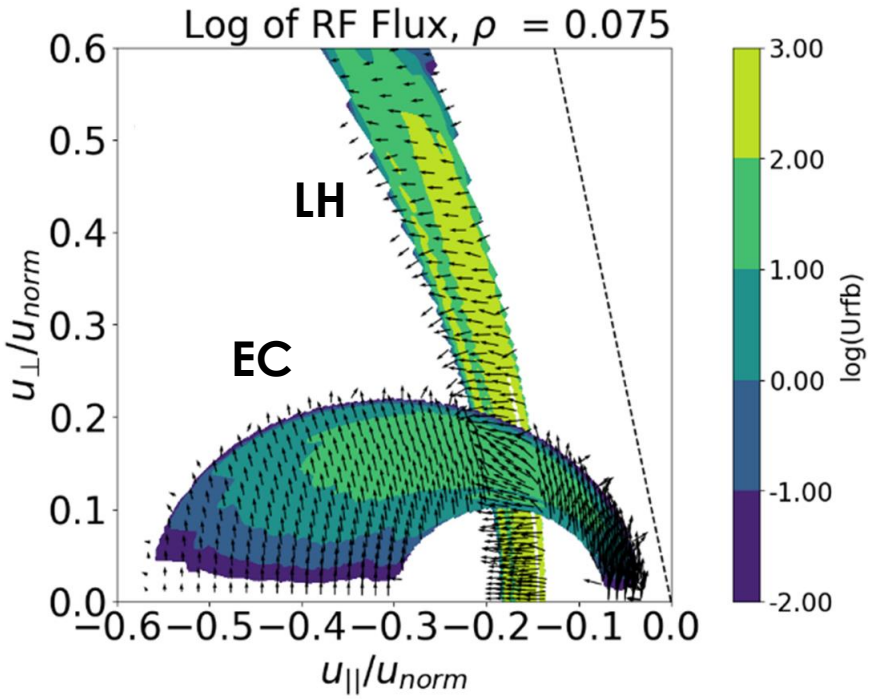
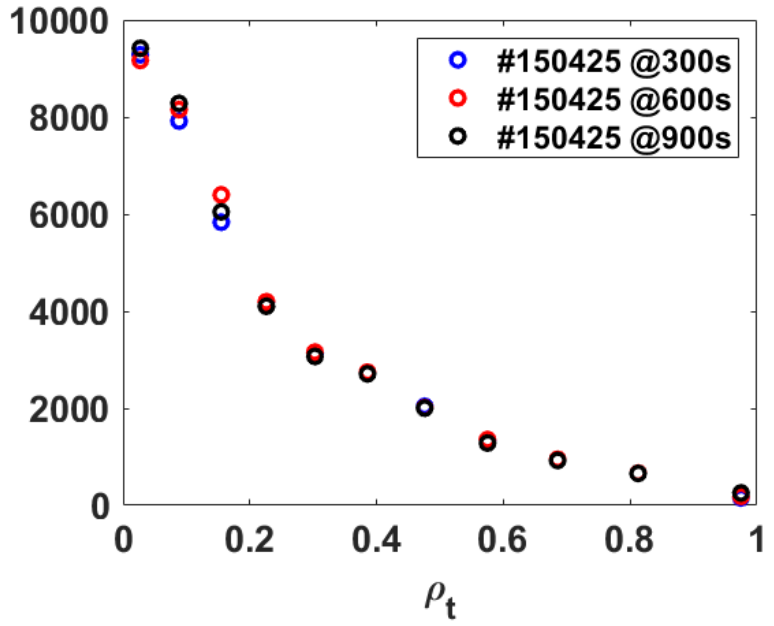
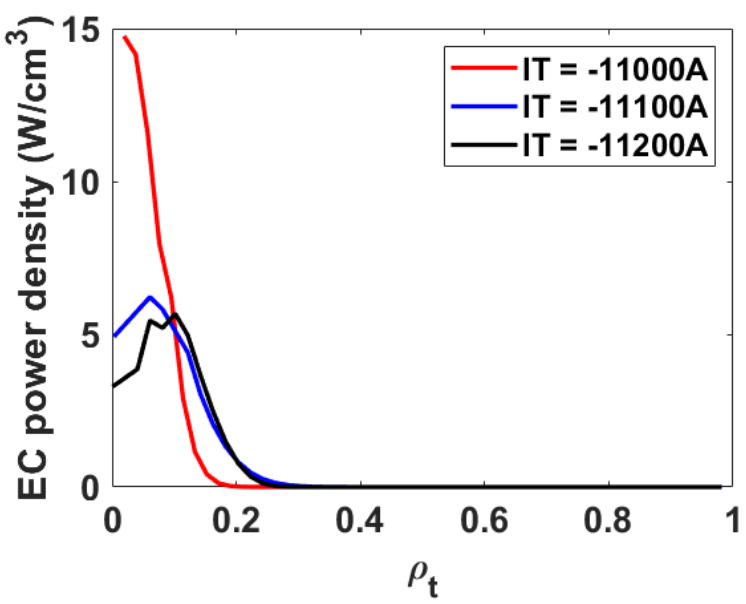
Optimizing EC Power Deposition for Higher Confinement and Enhanced Synergy Effect with LH Wave



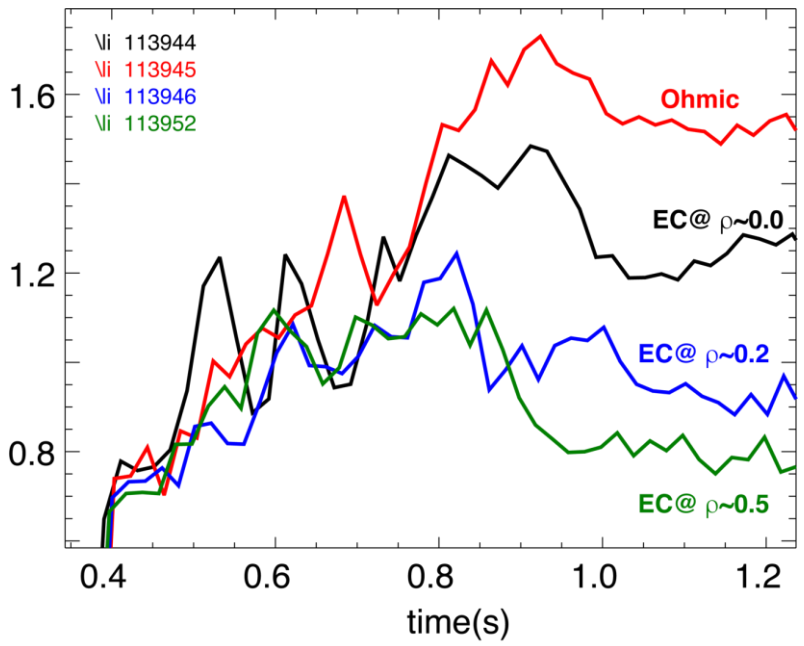


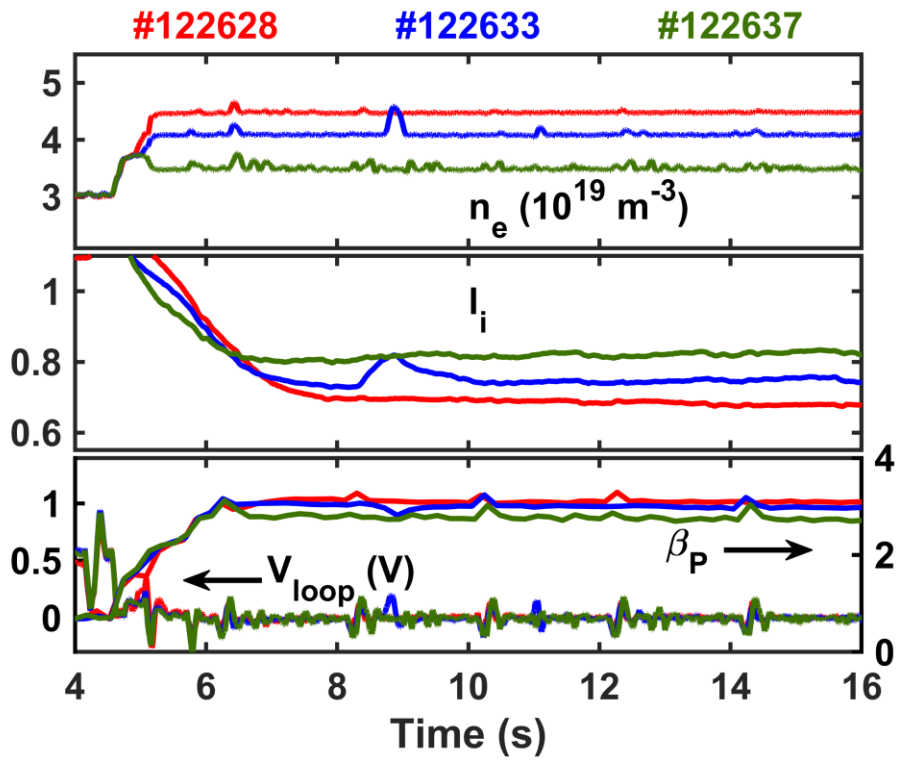
P_{EC} = 1.9 MW

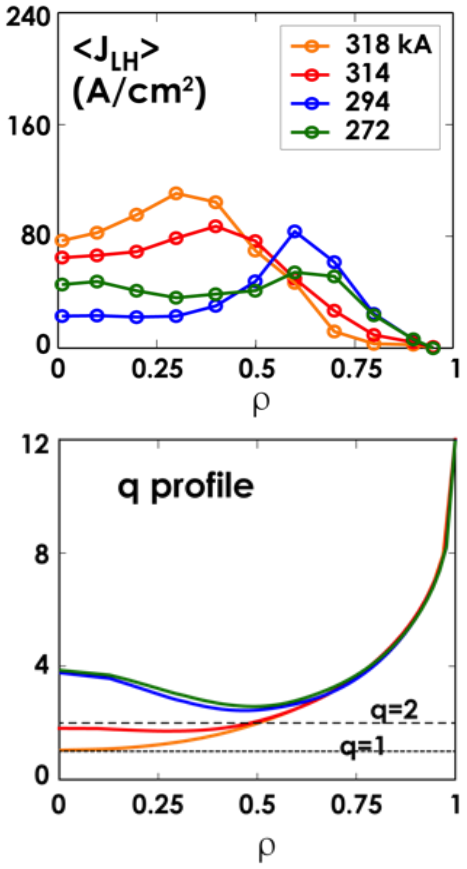


- The location of EC power deposition depends significantly on the value of magnetic filed.
- An optimal Bt (corresponding to IT = -11000A) was determined to realize high plasma confinement and synergy effect between EC and LH waves in phase space.

Broad Current Profile by Early EC Heating and off-axis LHCD at High Density Sustained Fully Non-inductive High-β_P Scenarios







- Lower li obtained by early EC-heating during Ip ramp-up
- Current profile becomes broader under more off-axis EC deposition
- **Broader current profile obtained at high density with more off-axis LHCD**
  - n_e ↑ ➔ η_{CD}↓; broad j(r)+ negative shear → confinement ↑ + β_P ↑ ➔ f_{BS}↑

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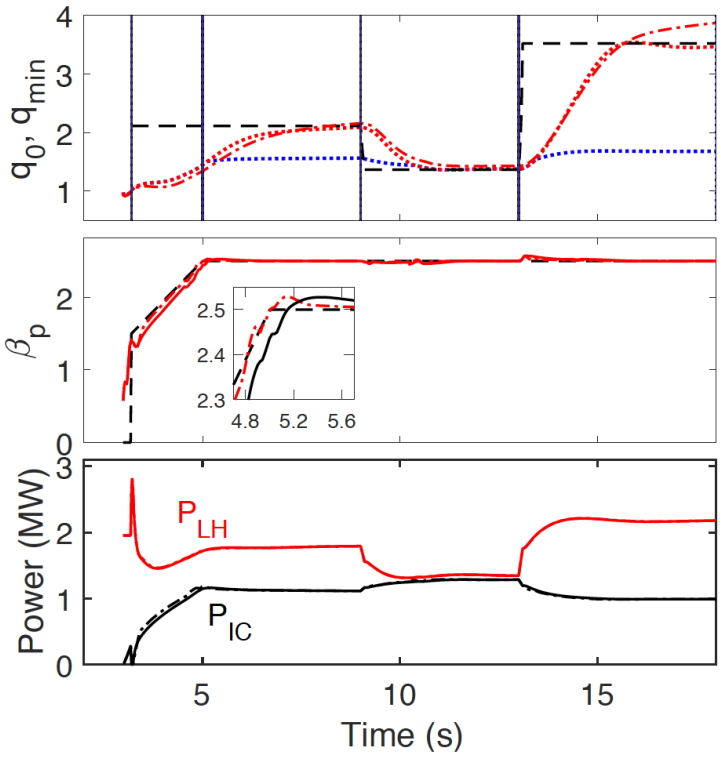
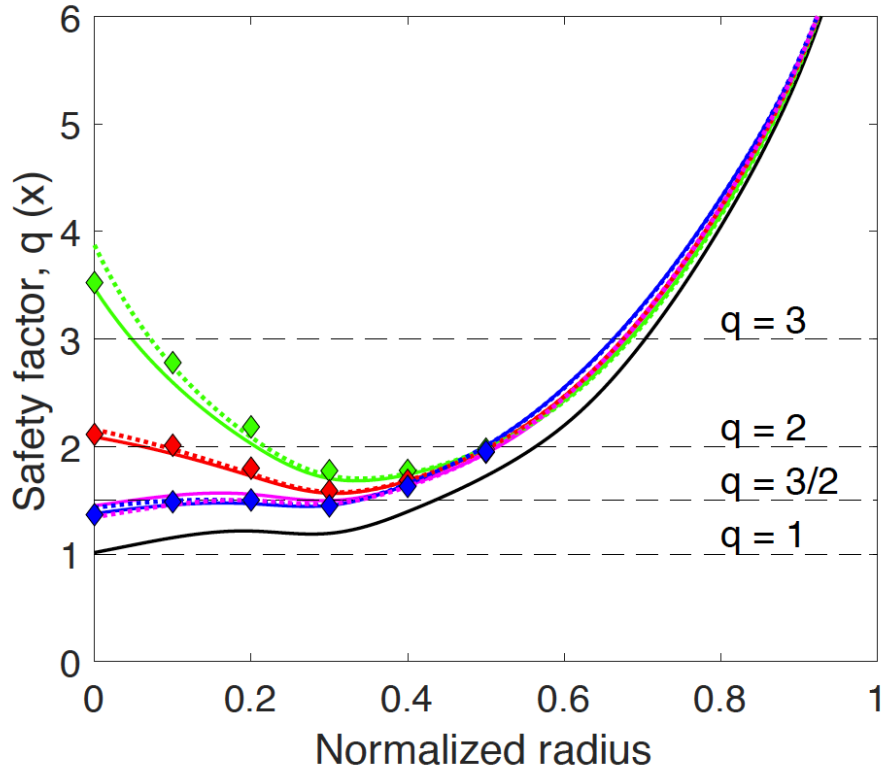
Model-Predictive Kinetic Control with Data-driven Models Developed on EAST

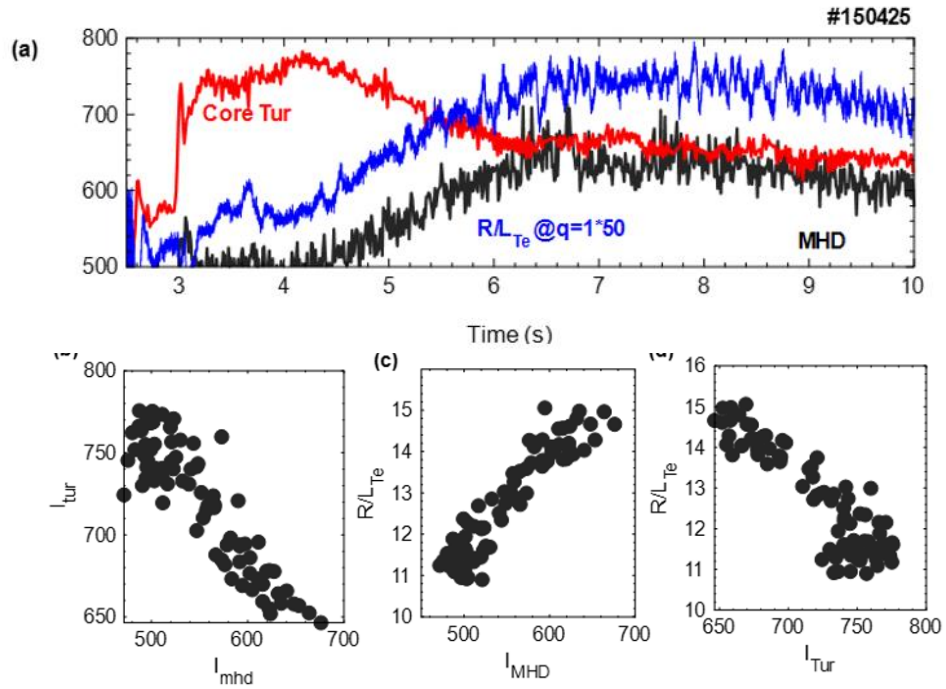


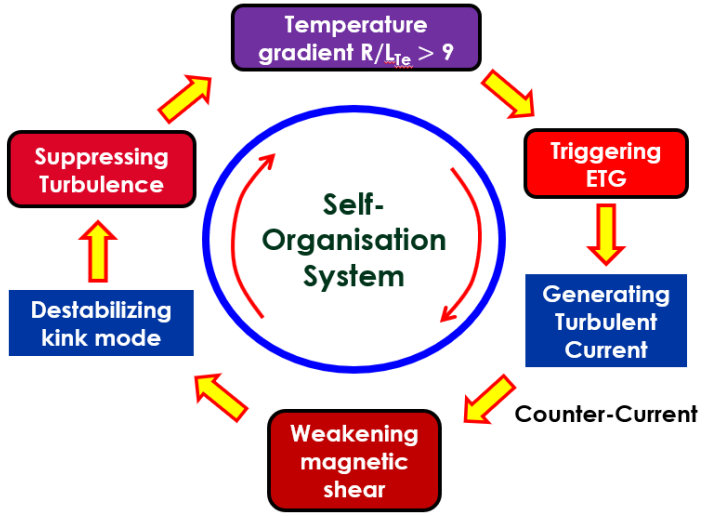


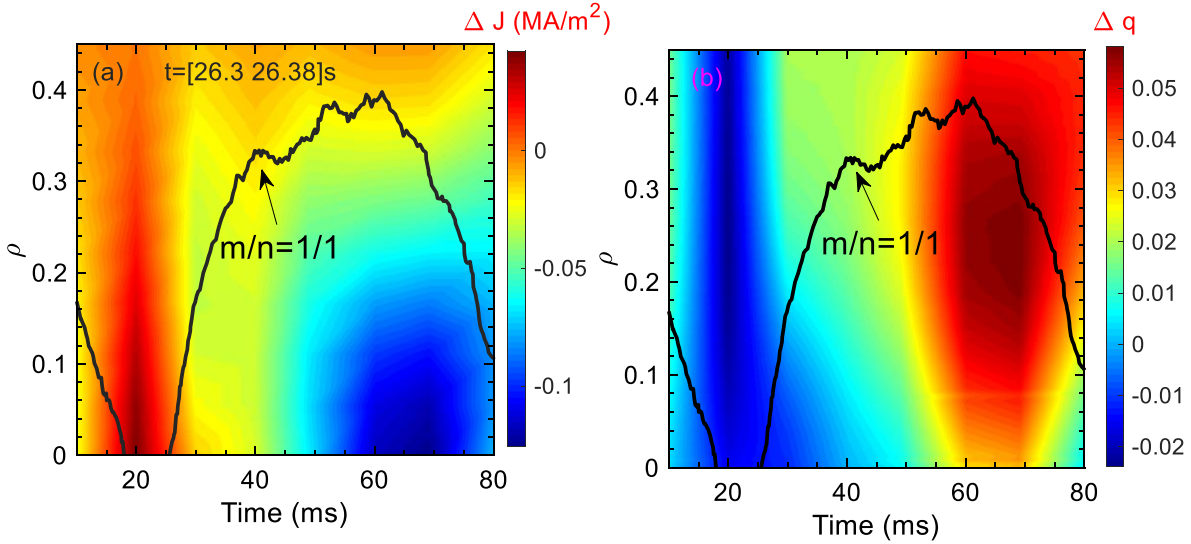
- **LHCD, NBI and ICRF were used as actuators for the kinetic control**
- **Simultaneous control of q profile, β_p and li was demonstrated for the first time in EAST**

Didier Moreau, NF 2024

Saturated m/n=1/1 Kink Mode Sustained High-T_e Plasma with Improved Confinement for Long Duration Operation







- **ETG turbulence is excited when R/L_{Te} is above a threshold (R/L_{Te} >9)**
- **ETG turbulence can be reduced by m/n=1/1 mode**
  - 1/1 mode can lead negative current
  - Increase $q_{(0)}$ >1 to form weak magnetic shear
- **The self-regulation system to sustain T_e-ITB in SS LPO**
  - The interplay among negative current, kink mode, turbulence

X. Zou, ASIPP Seminar, 2024

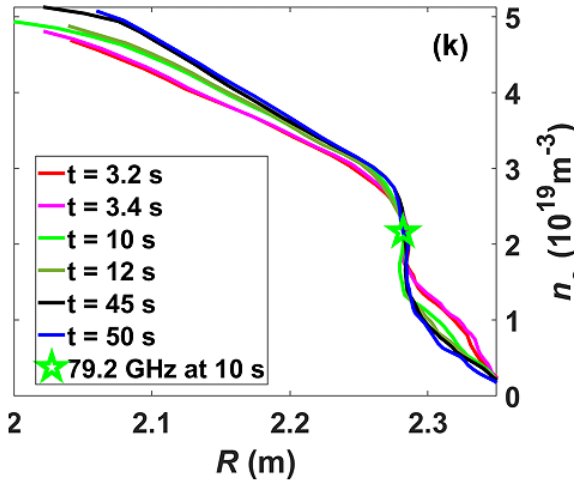
Compatible Core and Edge Integration by Active Detachment Control for Long Pulse H-mode

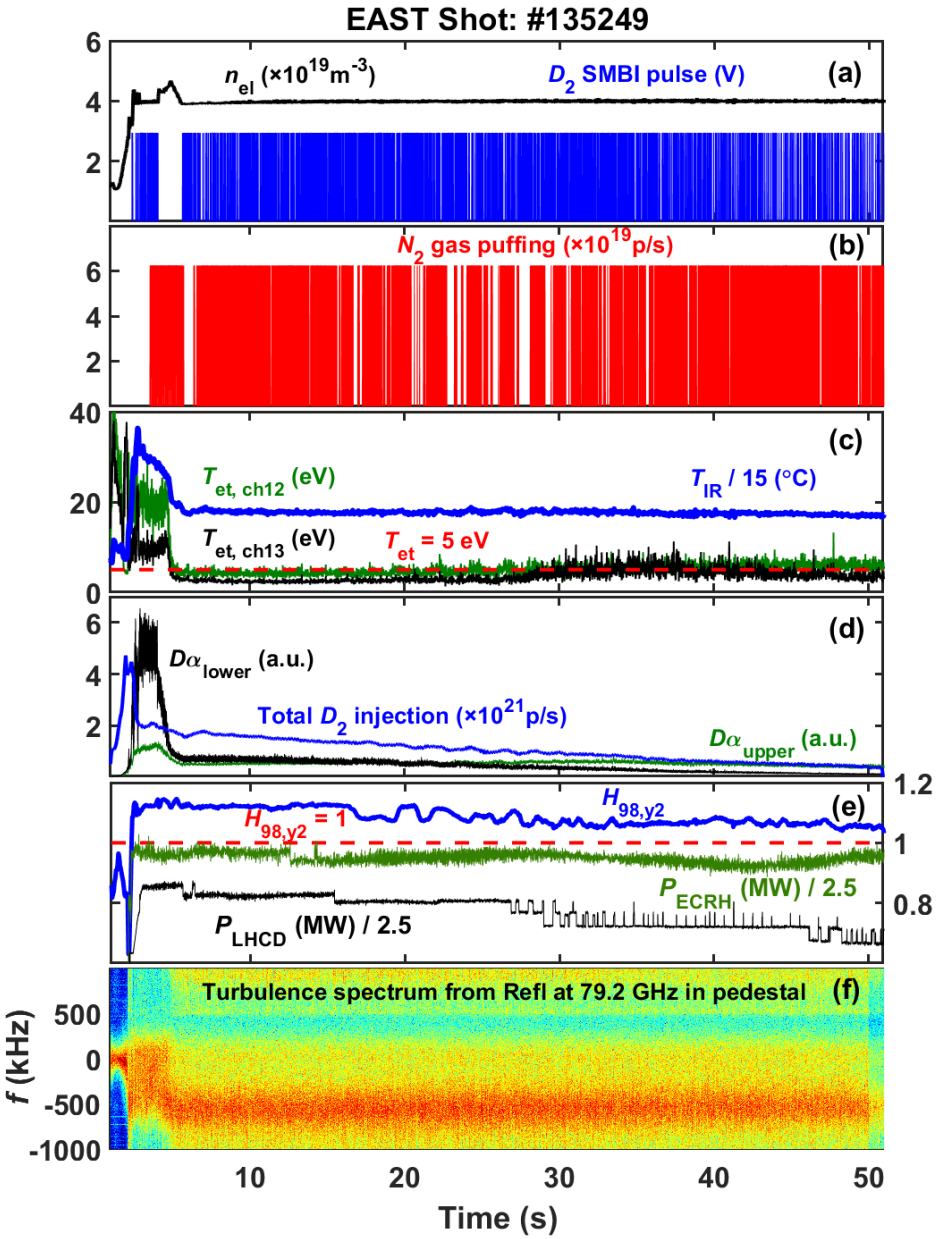
Control Parameters	Actuator
Total radiation ($P_{rad,\ total}$)	LFS and divertor impurity seeding
Divertor particle flux (j_{sat})	Divertor impurity seeding LFS D2 fueling by SMBI
Div. electron temperature (T_{et})	Divertor impurity seeding
Div. target temperature ($T_{t,\ peak}$)	Divertor impurity seeding
Div. electron temperature + X-point radiation (T_{et} + $P_{rad,\ X\text{-}point}$)	Divertor impurity seeding D2 fueling by SMBI

Demonstration of Divertor Detachment and ELM-free Long-pulse Discharge Enabled by HFBT-assisted Particle Exhaust

- P_{EC}~2.5MW + P_{LHCD}~1.9MW = 2.2 P_{L-H}
- β_P~1.55, β_N ~1.36, q_0~1, κ~1.6, δ_l~0.66
- LSN with dR_{sep}~-2 cm and dR_{out}~5.9 cm
- n_{el}~61%n_{GW}, T_{e0}~4.7 keV, T_{i0}~1.1 keV, $f_{rad}=P_{rad}/P_{inj}$ = 29%

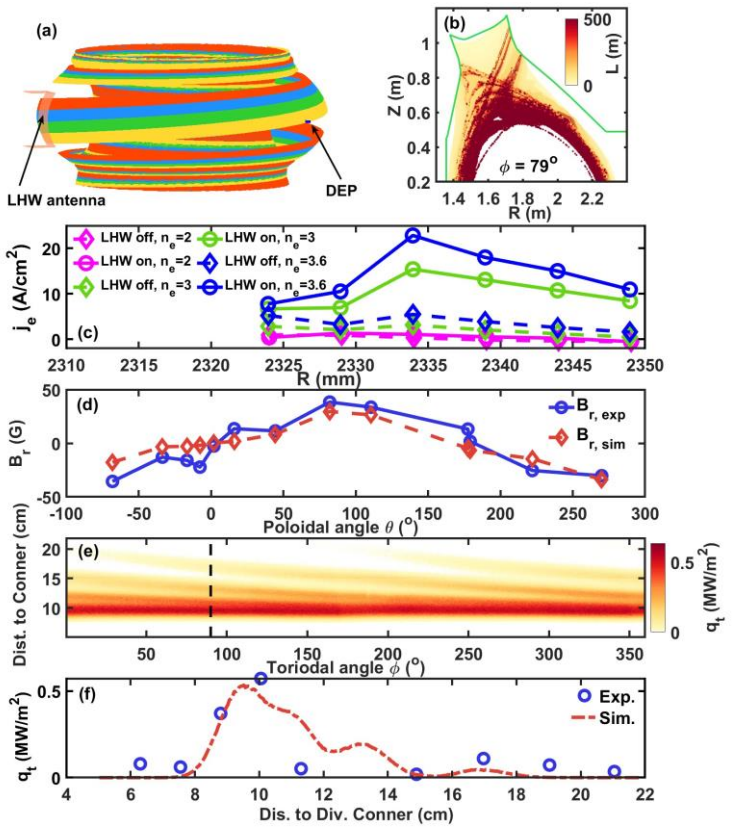
- **50-second long pulses operated without ELMs throughout the whole discharge.**
- **After nitrogen impurity injection, T_e and $T_{surface}$ of the divertor target plate decreased significantly, entering a partially detached state.**
- **A high-freq. turbulence mode of ~600 kHz existed in the steep gradient region of pedestal, assisting in particle removal and preventing impurity core accumulation and ELM bursts.**

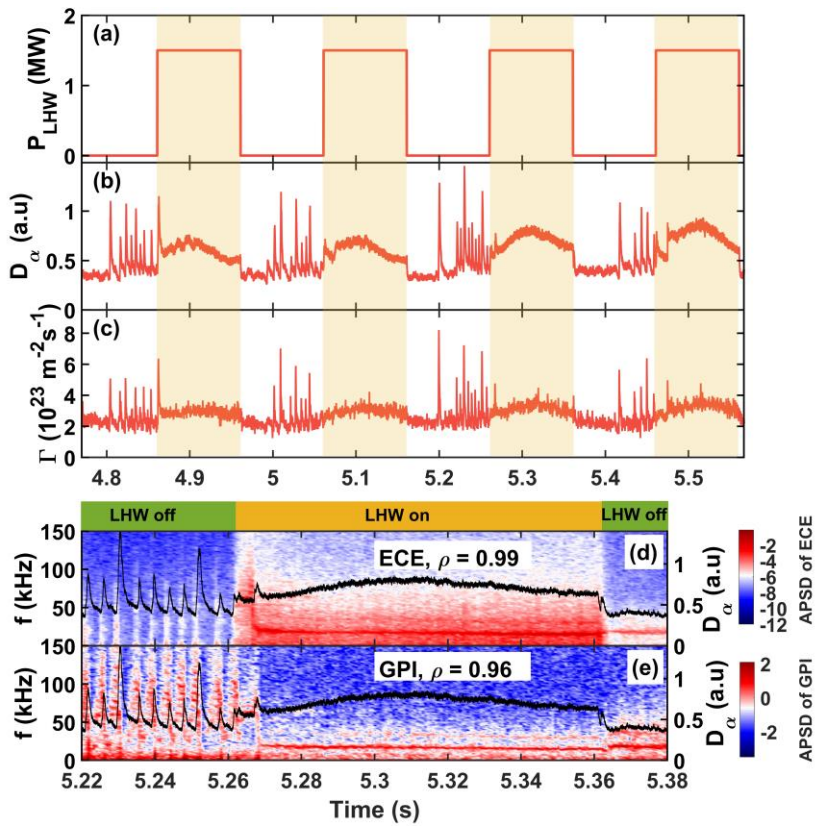


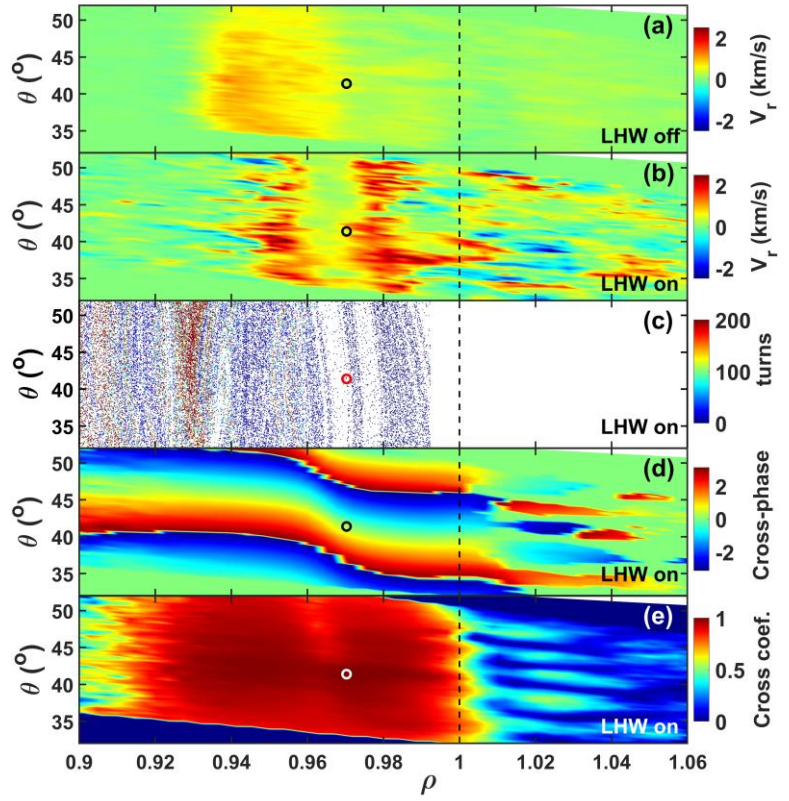


See **G.S. Xu's Oral** in this conference

First ELM Suppression by Helical Current with LHW Modulation





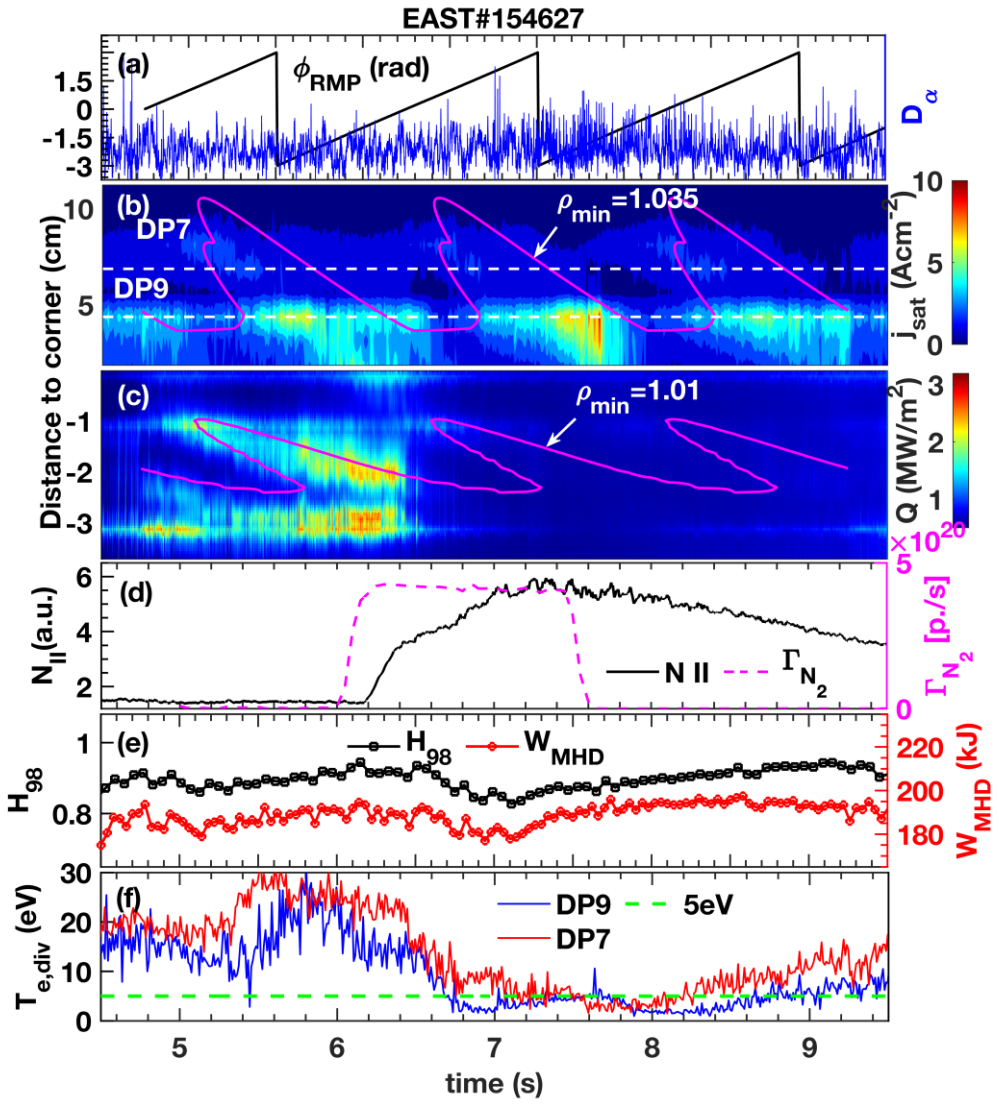


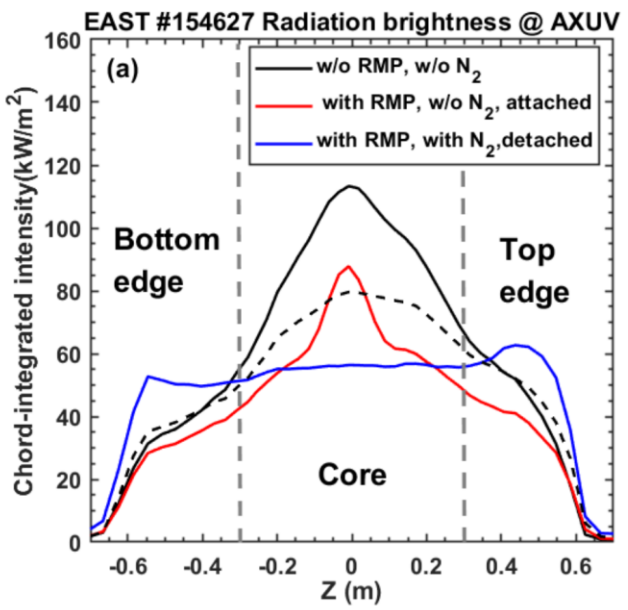
- **Achieved first ELM suppression with LHW modulation on EAST.**
  - Developed physical model of helical current filaments.
  - Sheared turbulence structures observed during LHW-on phase.

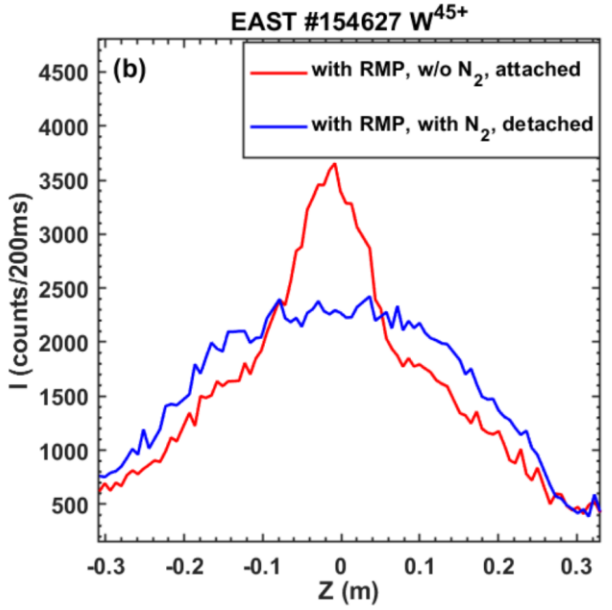
P_{ECRH} = 1.4-2 MW
P_{NBI} = 1.5-2.5 MW
P_{LHW} = 1.2-2 MW
$\bar{n}_e$ = 4.0-5.5×10^{19} m^{-3}
q_{95} = 4.6-6.2

See **S.C. Liu's Oral** in this conference

Divertor Detachment Achieved in 3-D Magnetic Geometry by RMP Being Applied for ELM Control







***Sheng**, et al., Nuclear Fusion 65 (2024) 016009*

- With rigidly rotated n=2 RMP field, spiral pattern of particle and heat fluxes clearly observed on divertor
- Detachment achieved on both original and splitting strike lines
- Core W concentration and radiation reduced during RMP application and the detachment state

See **M.N. Jia's** Poster in this meeting

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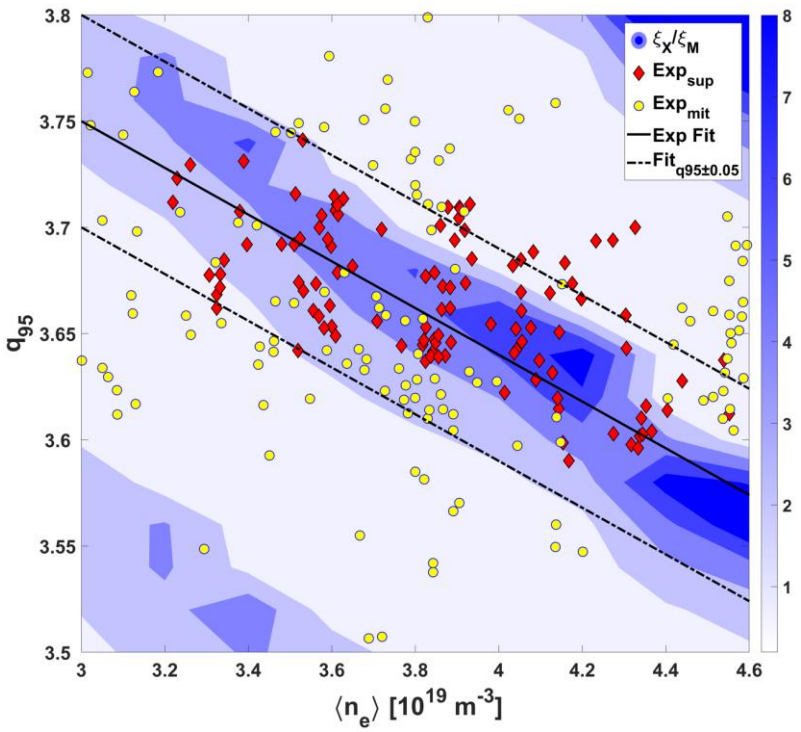
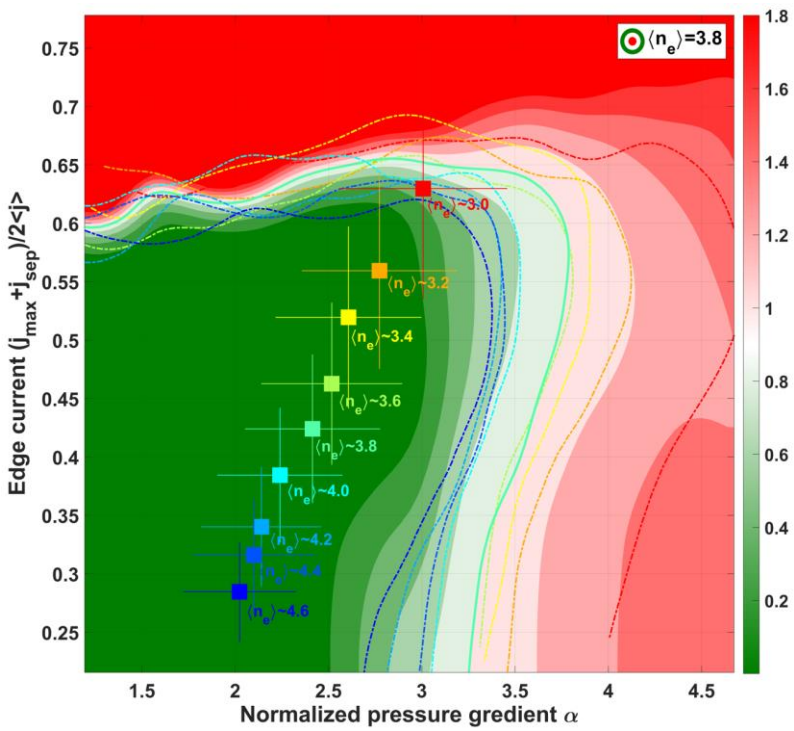
Density Windows for ELM Suppression with n = 4 RMPs

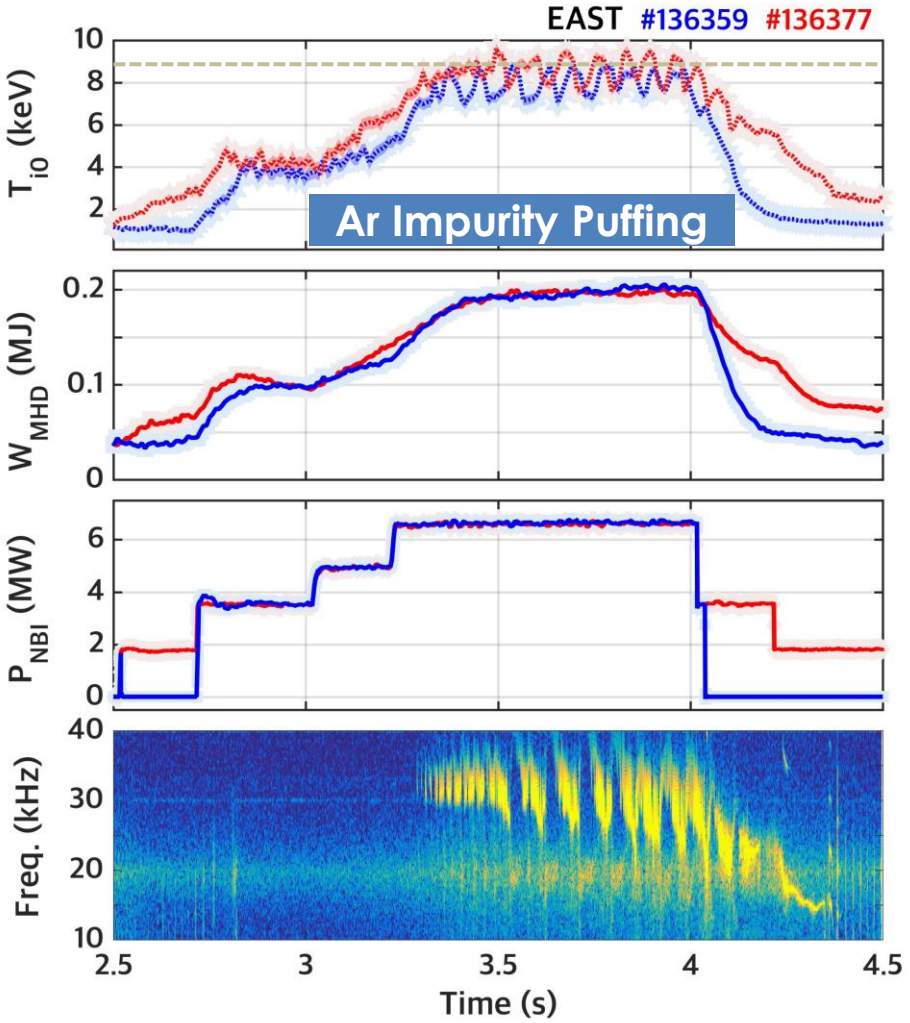




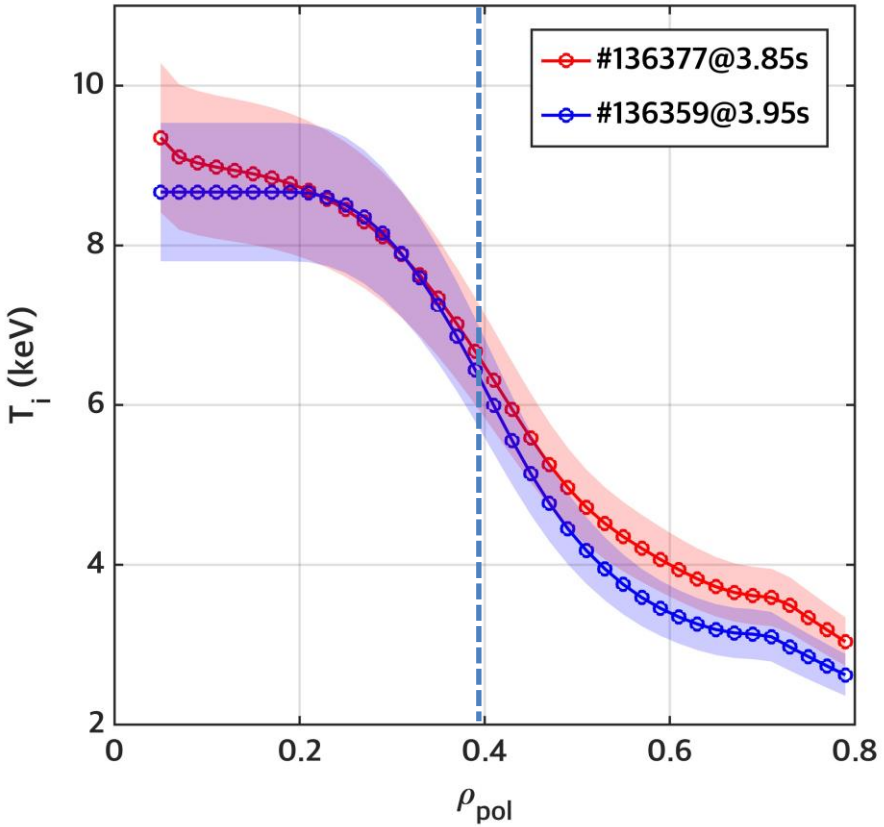
- **ELM suppression is primarily associated with peeling response and resonant component**
- **Peeling dominant at low density and ballooning dominant at high density**

See **X.M. Wu's** Poster in this meeting

Development of High Ion Temperature Scenarios

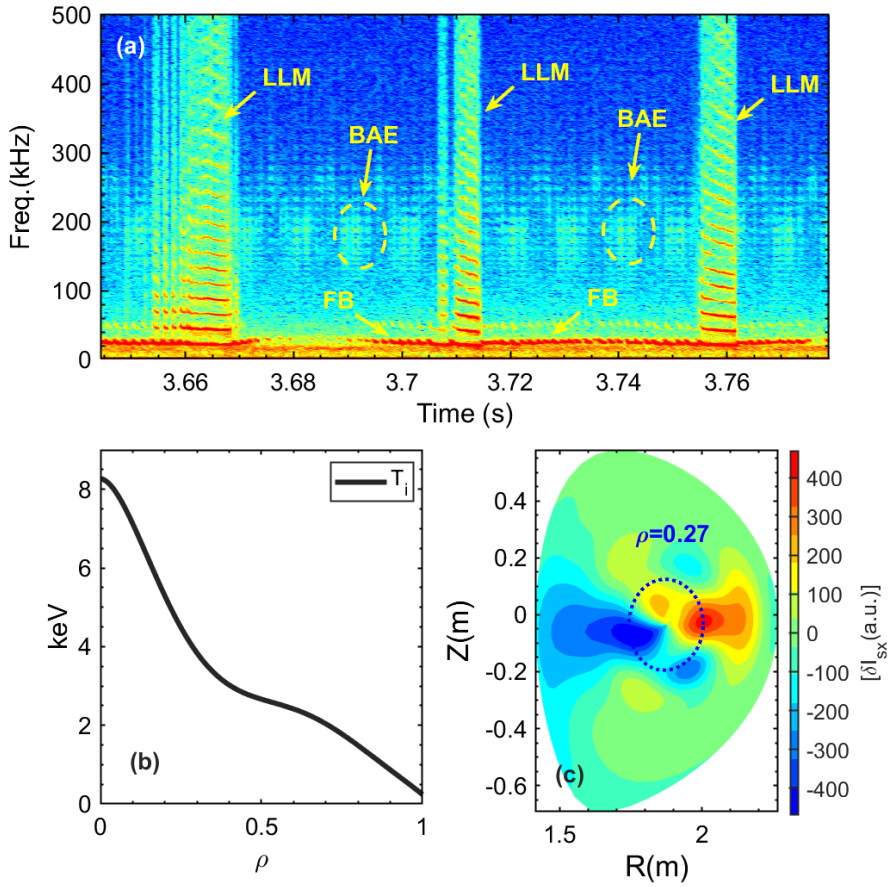


- Bt=2.5T/LSN/Ip=0.5MA/nel ~$1.6\times10^{19}/m^3$
- Fishbone & Ion-ITB, $T_{i(0)}$>9.0keV/$T_{e(0)}$~3.5keV



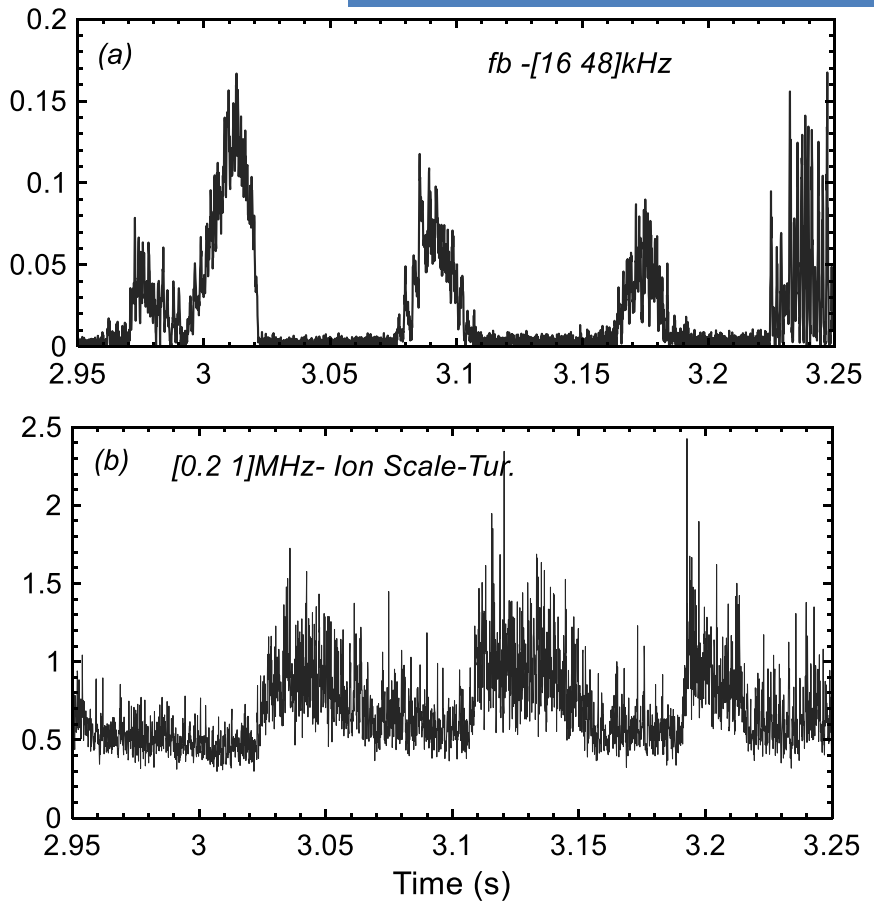
- Total store energy ~217kJ, thermal energy ~ 51%
- The neutron yield ~2.5×10^{14}

Multi-scale Instabilities in High Ion Temperature Discharges



- T_{i0}~9 keV, β_{pi}~2.2
- **Modes: LLM, FB, BAE**
- **FB: broaden radial location and n=2 component**

See **L.Q. Xu's** Poster in this meeting



- **Ion scale turbulence (f= [200-1000]kHz) suppression in FB phase**

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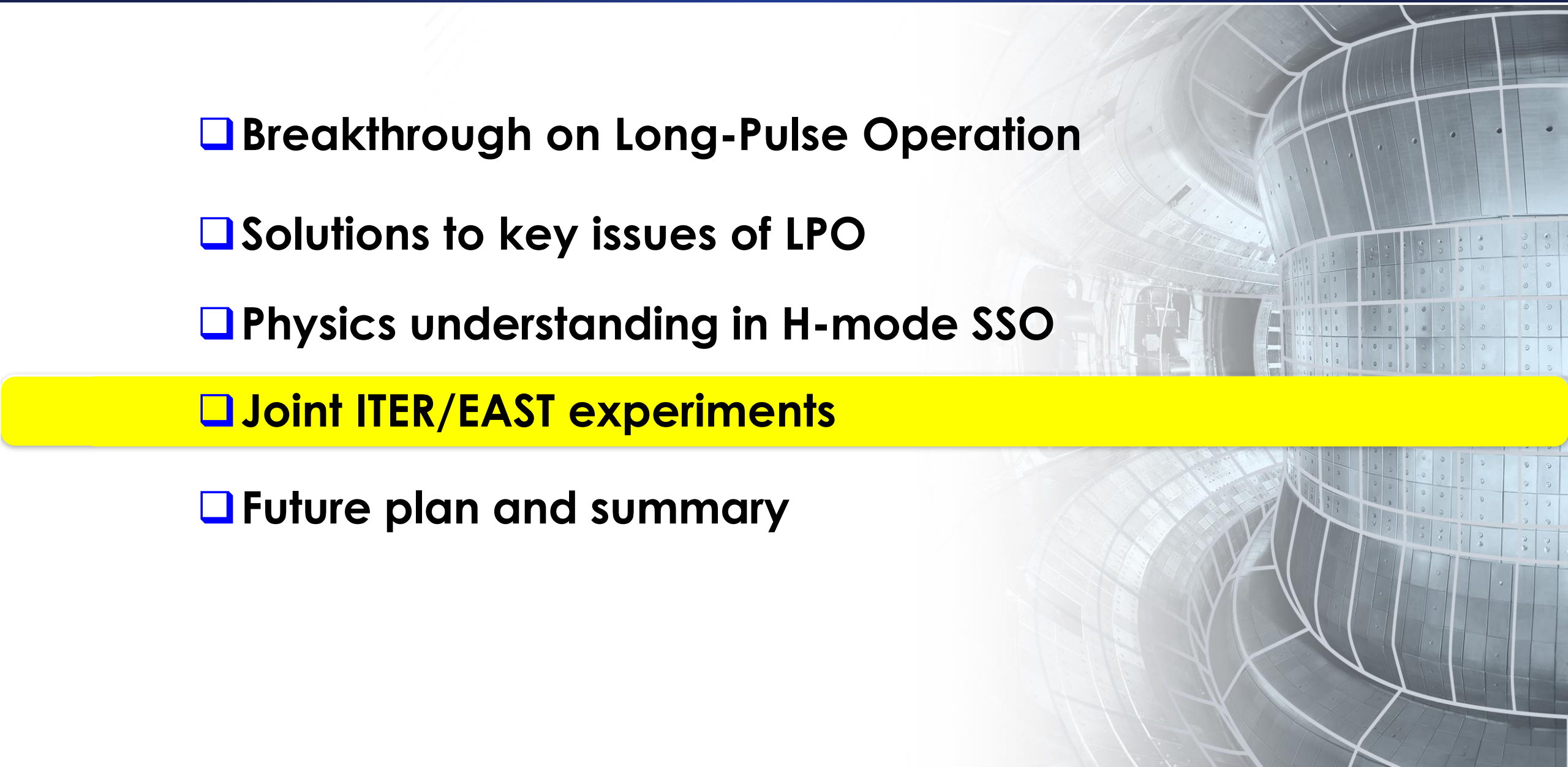
Outline

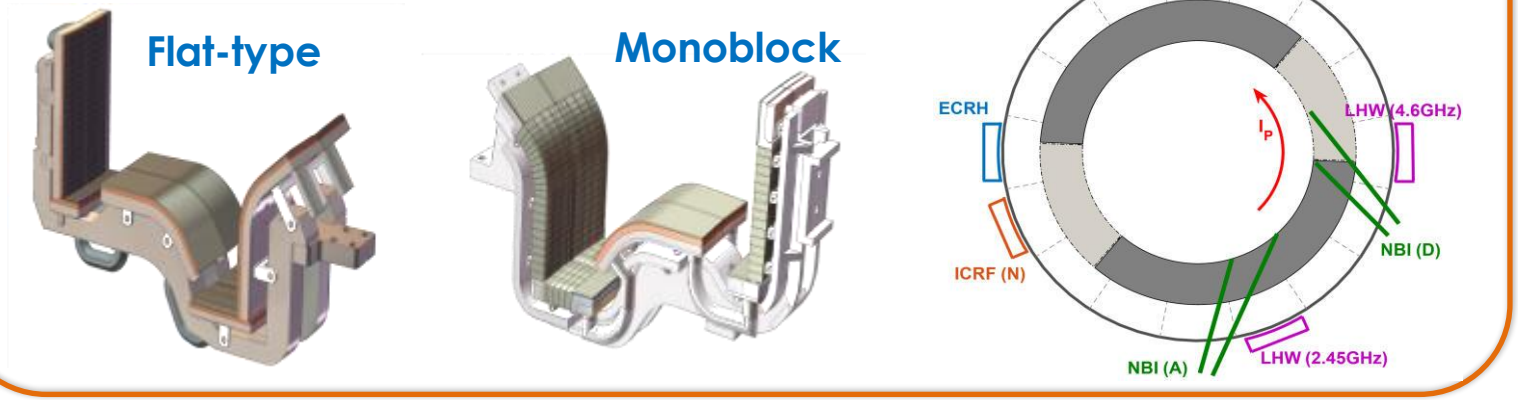
- Breakthrough on Long-Pulse Operation
- Solutions to key issues of LPO
- Physics understanding in H-mode SSO
- Joint ITER/EAST experiments
- Future plan and summary



Dedicated EAST Mini-Campaign was Performed in Support of ITER New Research Plan

- **EAST experiments with full W-limiter and W-divertors**
  - Boronization studies （**T. Wauters**）
  - H-mode operation with W wall （**A. Loarte**）
  - W Limiter start-up experiments （**R.A. Pitts**）

New Tungsten Lower Divertor

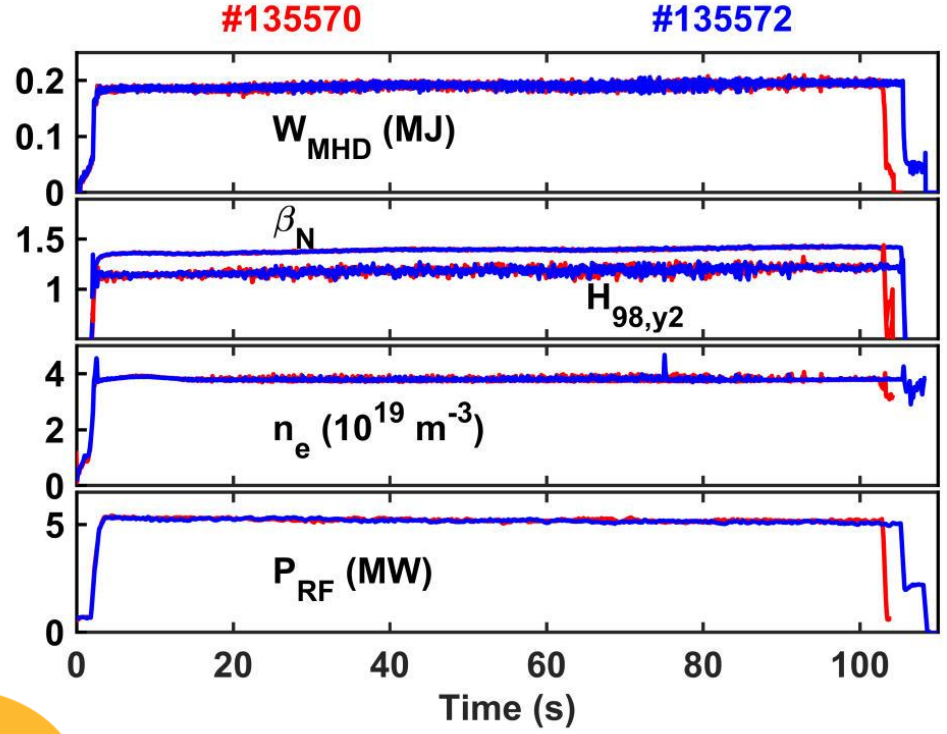


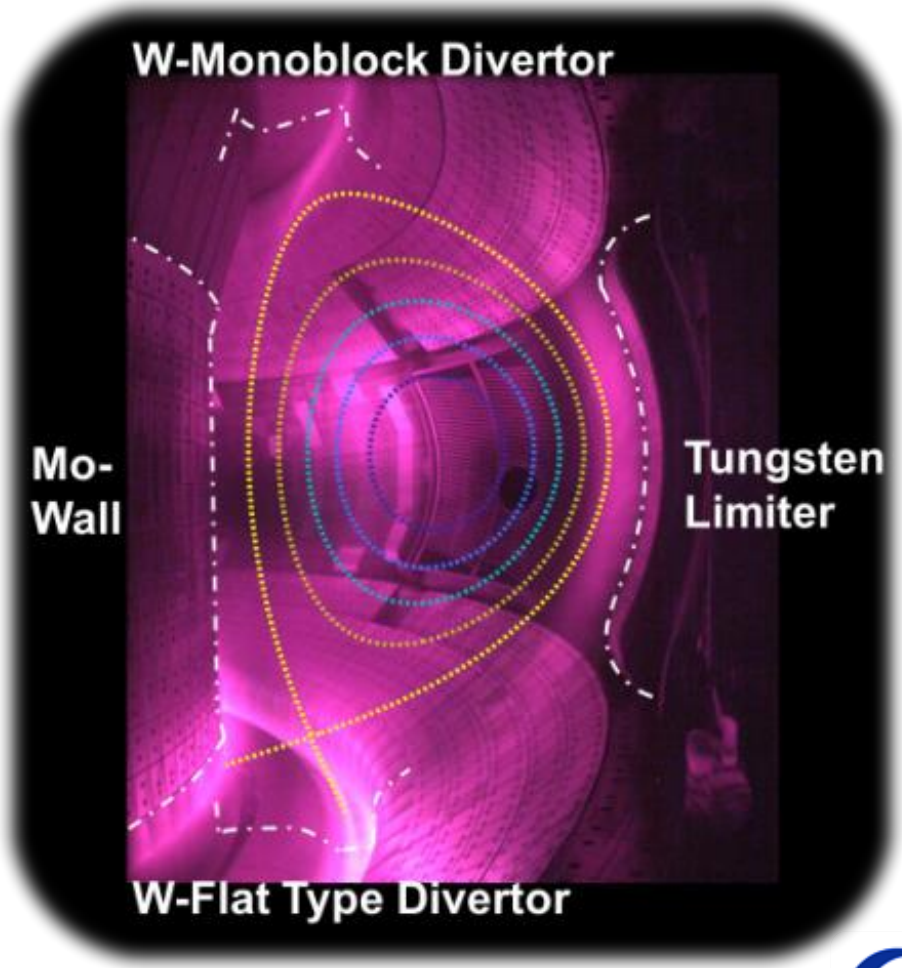
W-Limiter on EAST

See **J. Huang's Oral** in this conference

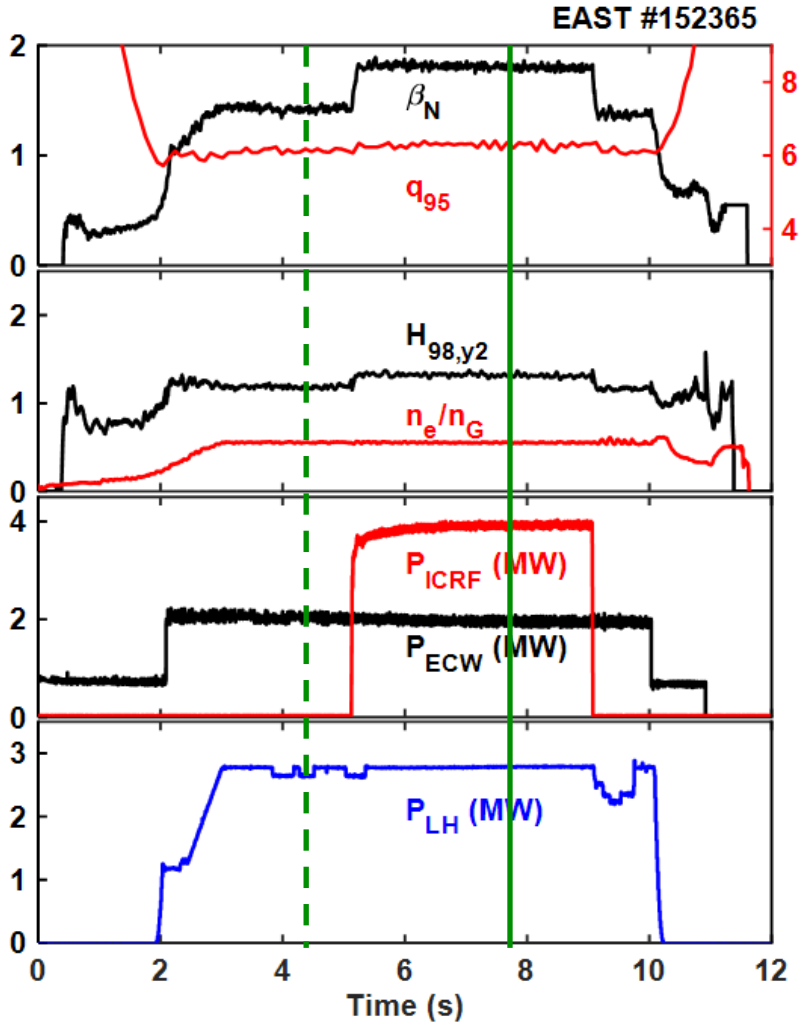
Demonstration of Long Pulse H-mode Plasmas on Full Metal Wall in Support of ITER New Research Plan

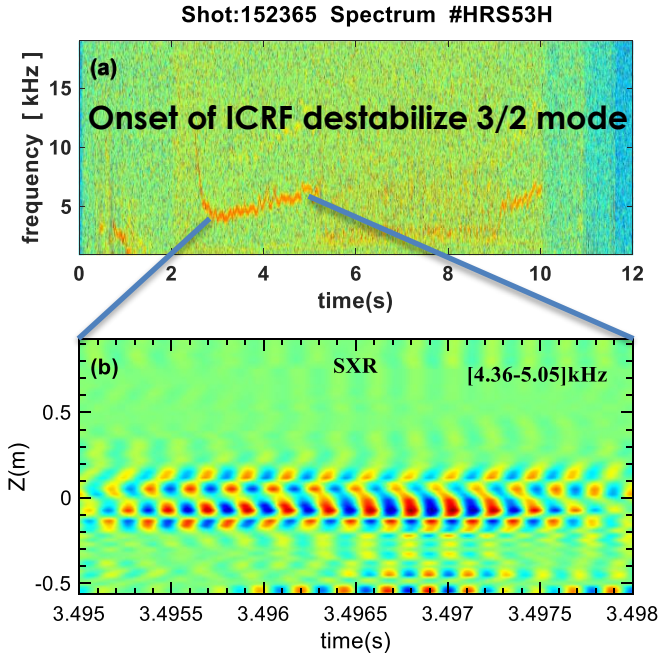
- **Stationary ~100s H-mode plasmas achieved with Boronization**
  - q_{95}~6.0, n_e~4.3/ $H_{98y,2}$~1.1, P_{EC}~ 3.0MW, P_{LH}~2.2MW
- **Optimization of the H&CD coupling**
  - Separatrix W-limiter gap ~6cm and using gas puffing
- **Well controlled high Z impurity**
  - Small ELMs and high density reduced W-sputtering
  - Avoid impurity accumulation by on-axis ECH

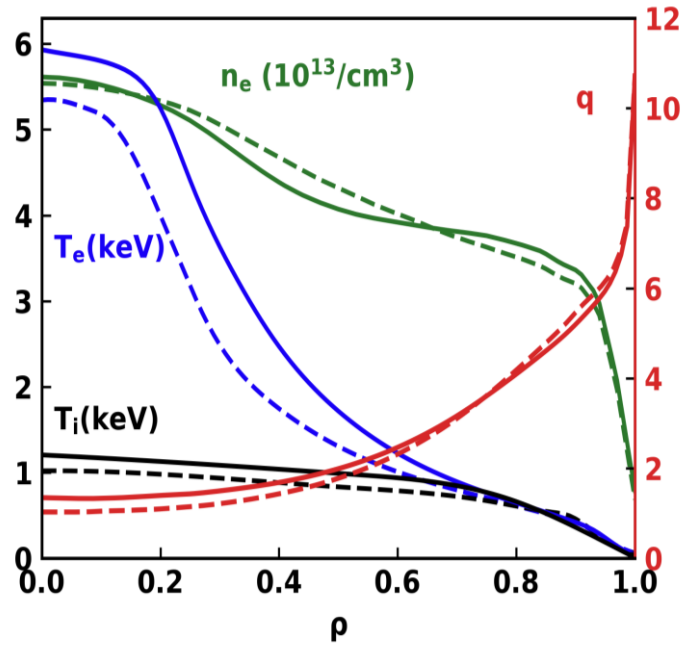




Development of High-β Steady-sate Operation Scenarios with W-Divertor in ITER-relevant Configuration towards High-Q





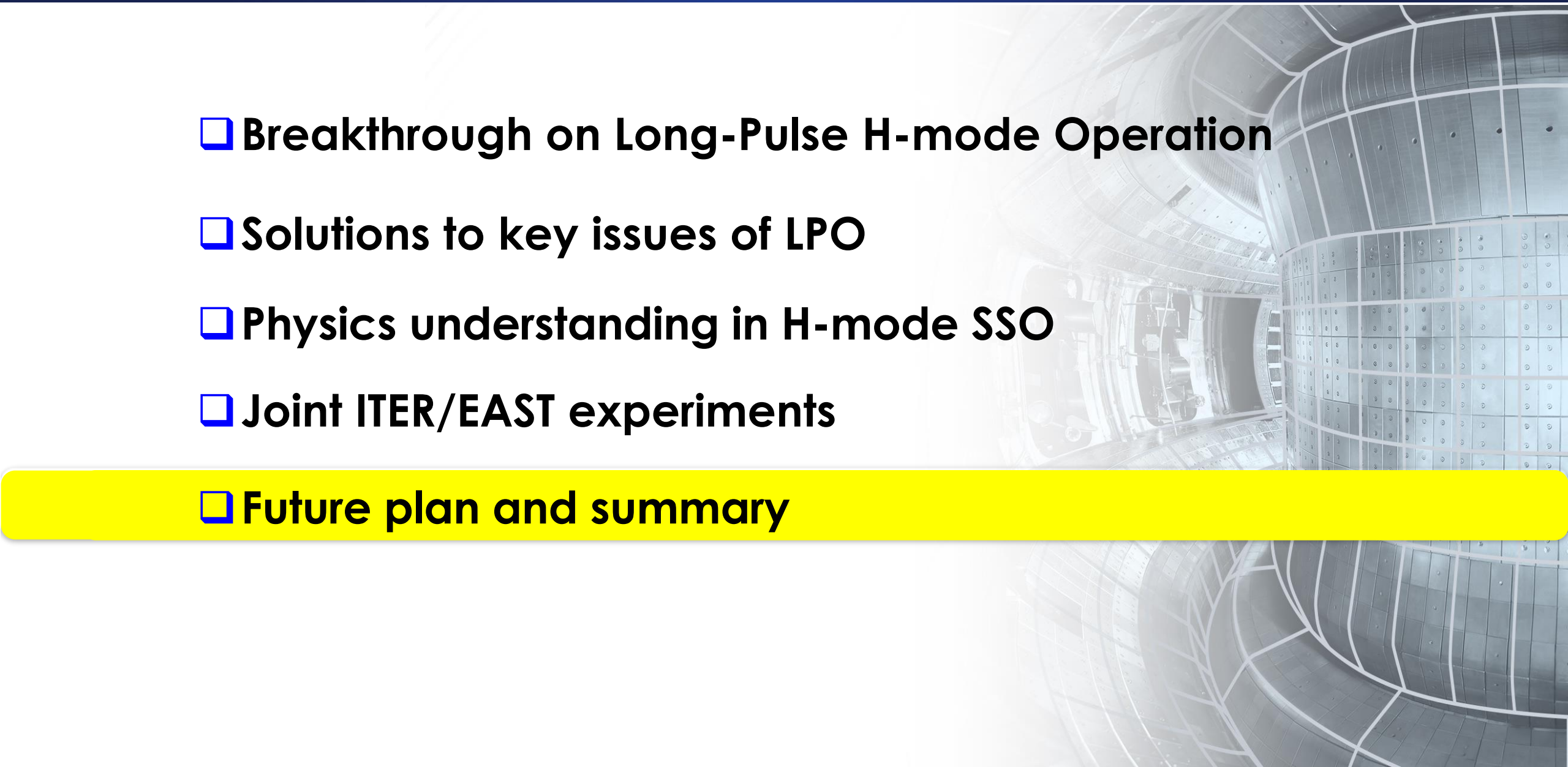


- **High-β plasmas by RF heating at high Bt~2.5T**
  - P_{LHW}~2.7MW, P_{EC}~2.0MW, P_{IC}~4.0MW
  - **n_{Gr}~0.7, β_P~2.1/β_N~1.85, H_{98y2} ~ 1.25, q_{95}~6.0**
  - **Boronization wall**
- **Broader current profile via ICRF heating**

See **J. Huang's Oral** in this conference

Joint Experiments & Actives for ITPA IOS-3.2

Outline

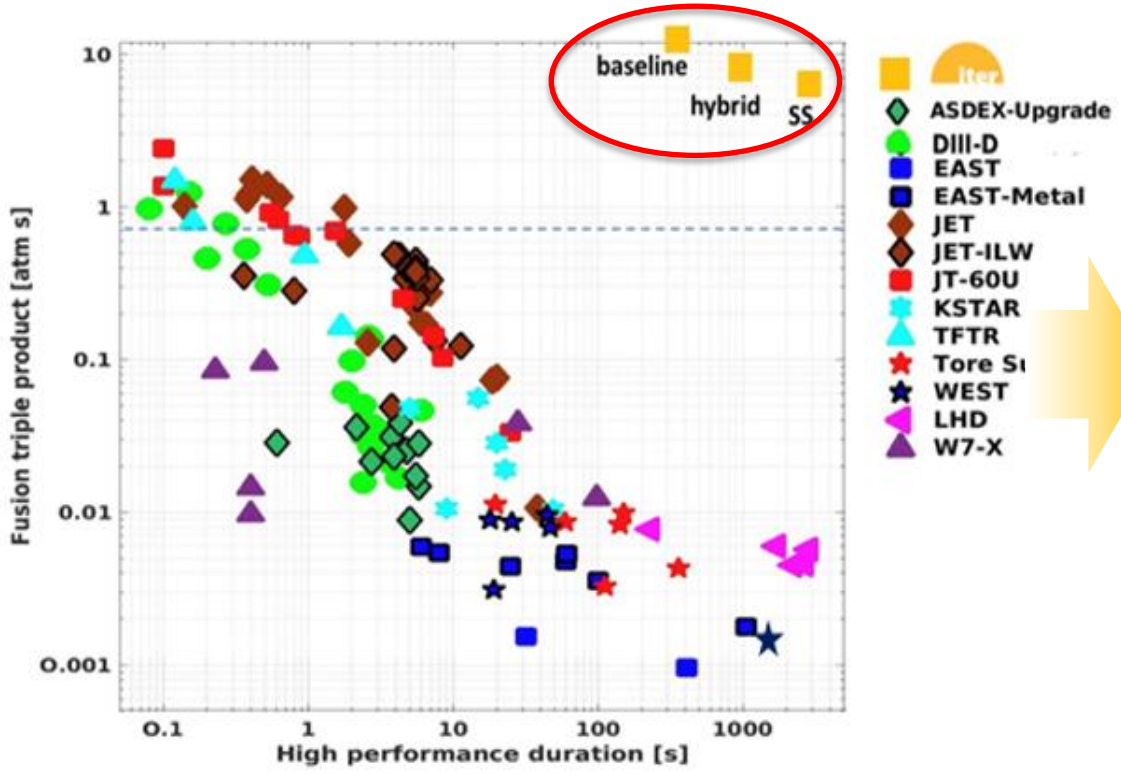


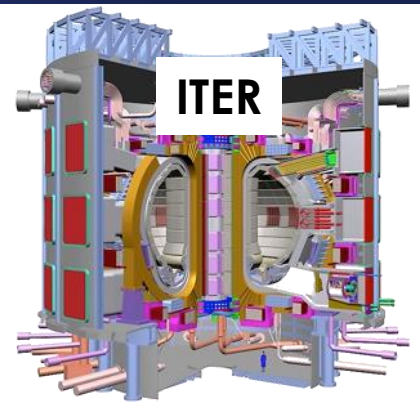
- Breakthrough on Long-Pulse H-mode Operation
- Solutions to key issues of LPO
- Physics understanding in H-mode SSO
- Joint ITER/EAST experiments
- Future plan and summary

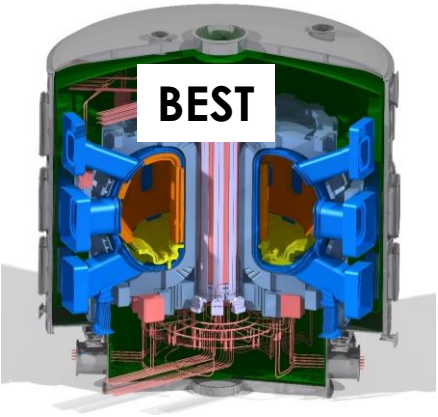
Integration of High-fusion Performance and Long Pulse Operation is the Fusion Energy "Grand Challenge"

The Integration Challenge
Reduction of fusion performance by **2-3 orders of magnitude** when increasing duration from ~1 s to 1000 s

Xavier LITAUDON, NF(2024)
Xavier LITAUDON, IAEA FEC, 2025

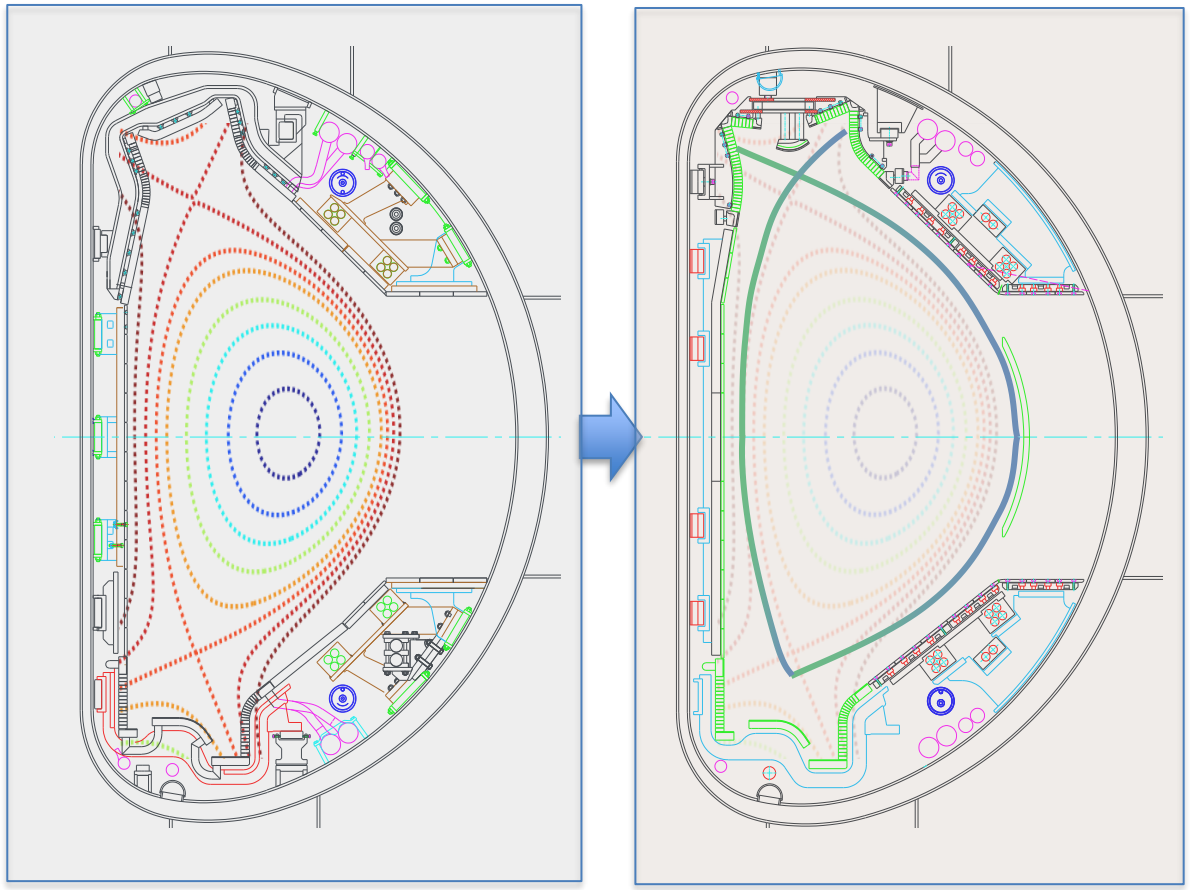






- **Scientific gaps for the development of LPO combined with high-fusion performance**
  - **Machine/engineering limits:** operate at higher power compatible with power handling capacity; Sustain a fully detached/semi-detached regime for LPO compatible with core performance; … etc.
  - **Plasma physics limits:** MHD stability; core/pedestal confinement; RF H&CD efficiency at high density; plasma radiation with W;… etc.

Major Upgrade of EAST to Extend Operation Regime to Close the Gaps towards ITER and BEST



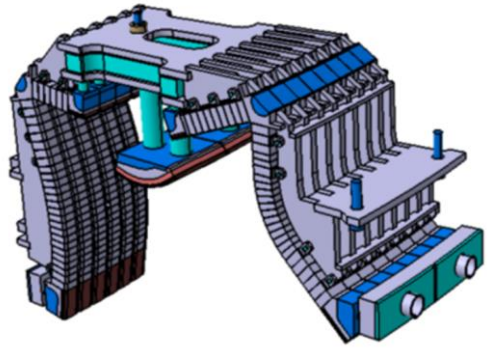
EAST Upgrade Strategies

- Enlarged plasma volume in LFS for plasma current up to **1.0 MA**
- Increased plasma radius **a ~ 0.4-0.55m** and cross section **R/a ~ 4.3→3.6**
- Enhanced the **coils current limitation** for PF&IC
- Upper divertor re-designed for BEST-like cooling structure with **12MW/m^2** power handling capability
- Total available injected power will be increased from **12 MW to 18 MW**

Hardware Enhancements Propel EAST Forward to Bridge Gaps to ITER and BEST in Steady State Operation Studies

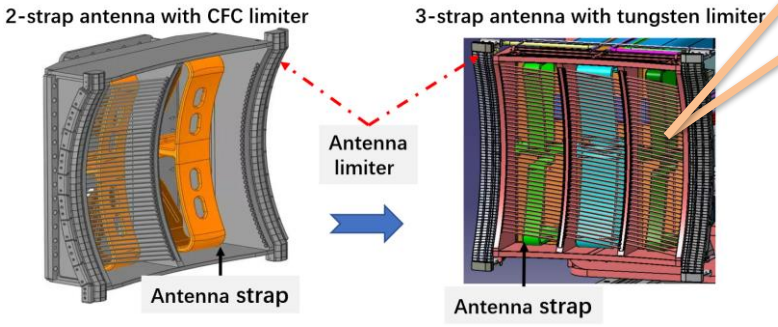
- **New BEST-like Divertor**

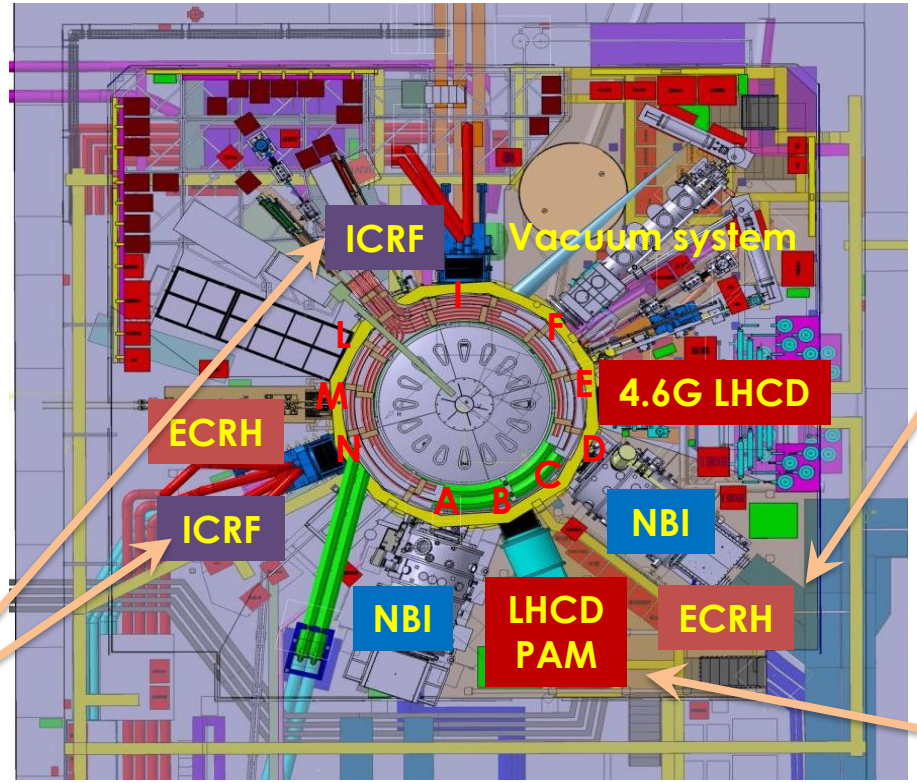
→ Enhance power handling capability



- **3-strap ICRF antenna**

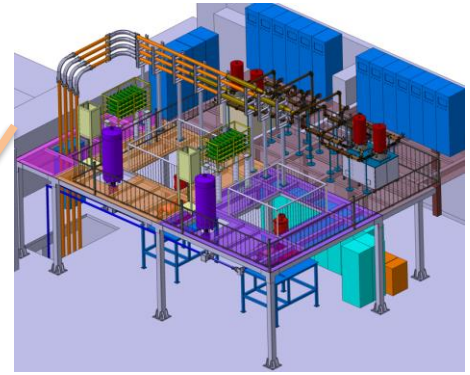
→ Decrease electric field





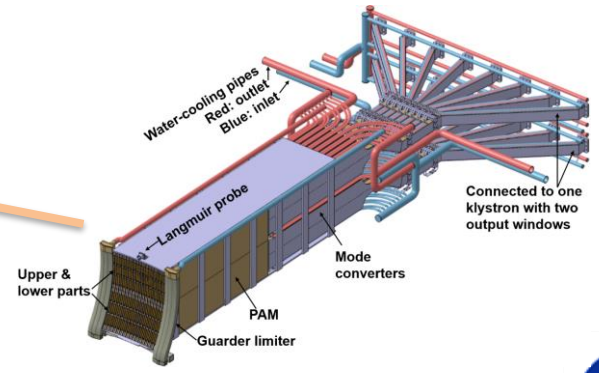
- **New two Gyrotrons dual freq.**

→ Flexible j(r) control



- **4.6GHz/4MW LHW: PAM**

→ Improve long-distance coupling



ASIPP

Summary

- **Significant progress has been made in long-pulse SSO on EAST**
  - Demonstration of high performance long pulse H-mode plasmas with a reactor-like metal wall, low momentum input, and electron dominated heating scheme
  - A series of solutions to mitigate the challenges faced by long pulse H-mode plasmas are recently addressed

- **Advances on the key issues essential for long pulse SSO, providing supports to ITER and BEST steady state operation**
  - Improved confinement with high bootstrap current, and interaction with MHD and turbulence
  - Active controls of wall conditioning, fueling recycling, plasma wall interaction and W accumulation

- **Dedicated set of joint ITER-EAST experiments have been performed in support of the ITER new researcher plan**

- **Near-term plan with upgrade of inner components and augmented H&CD systems**
  - Demonstrate SSO with **extended fusion performance** at 12-18 MW power injection

Contributions to 30th IAEA FEC from EAST Team

OV2-3	OV	Xianzu Gong	Overview of recent experimental results on EAST in support of ITER new research plan
EX3-2	Orals	Juan Huang	Development Of Steady-Sate Operation Scenarios With Full Tungsten Limiter/Divertor In ITER-Relevant Configuration On EAST
EX3-3	Orals	Guosheng Xu	Long-Pulse Elm-Free H-Mode Regime With Feedback-Controlled Detachment Under Boronized Metal Wall In EAST
EX5-1	Orals	Shaocheng Liu	First Edge-Localized Mode Suppression With Lower Hybrid Waves On The EAST Tokamak
EX4-2	Orals	Long Zeng	Thermal Quench Dynamics And Heat Flux Distribution During Massive-Impurity-Injection Triggered Disruption In EAST
2676	Posters	Shengyu Shi	Tungsten (W) Impurity Reduction By ICRH In A High Power And High Performance H-Mode Discharge On EAST
3233	Posters	Manni Jia	Divertor Flux Control By RMP Elm Suppression And Radiative Divertor Operation In EAST H-Mode With Tungsten Plasma Facing Components In Support Of ITER New Research Plan
2925	Posters	Zhen Sun	Simutaneous ELM Suppression And Divertor Detachment Combined Boron Powder And Ne Gas Injection In EAST
3145	Posters	Cong Li	Endoscope Laser-Induced Breakdown Spectroscopy (Libs) For In Situ Elemental Distribution Diagnosis On The Surface Of Divertor In EAST
2923	Posters	Pengjun Sun	Experimental And Numerical Study Of Broad Wavenumber Turbulence And Transport In Ion Internal Transport Barrier Plasmas On EAST
3226	Posters	Pan Li	Turbulence And Transport Dependence On Temperature Ratio With Te/Ti 1-1.5 In EAST H-Mode Plasma
3342	Posters	Jiayi Zhang	The Establishment Of The Synthetic Diagnostic Modeling Specifically For The Imaging Neutral Particle Analyzer On The EAST
2701	Posters	Weiye Xu	Design Of The Electron Cyclotron Heating Expansion System On EAST
2889	Posters	Shouxin Wang	Particle Transport Of Ohmic Discharges With Different Plasma Current In EAST Tokamak
2895	Posters	Yongliang Li	Improvement Of Plasma Performance By Edge ECRH Power Deposition In EAST
2968	Posters	Gongshun Li	Impact Of The Temperature Ratio On Turbulence And Impurity Transport In The EAST Plasma Core
2673	Posters	Francesco Orsitto	Physics Basis Of Discrepancies Between Temperature Measurements By ECE And Thomson Scattering In High Performance Plasmas On JET, EAST And DIII-D
2894	Posters	Ming Xu	Experimental Study Of EPM Instability In The EAST Off-Axis Region With Elevated Safety Factor (Q)Value
2981	Posters	Youwen Sun	Lower Density Limit For Accessing To Elm Suppression Using N=4 RMP In EAST
3006	Posters	Wei Shen	Investigation Of Double Frequency Fishbone In EAST With Neutral Beam Injection
3147	Posters	Miaohui Li	Progress Of Lower Hybrid Current Drive Experiment Towards Long-Pulse Operation On EAST
3207	Posters	Yifeng.Wang	Natural Small Elms Achieved At Low Pedestal Collisionality (<1) In A Metal Wall Environment On EAST
3307	Posters	Zixin Zhang	Impact Of Neutral Particles On Beam-Ion Losses In EAST Tokamak
3358	Posters	Andong Xu	Analysis Of Fast Ion Distributions Using Neutron Emission Spectroscopy In NBI-ICRF Synergistic Heating Plasma On EAST
2672	Posters	Ilya Senichenkov	Modelling of H-Mode EAST Edge Plasma With Impurity Seeding By SOLPS-ITER 3.2.0 On Wide Grid
2879	Posters	Liqing Xu	Investigating Of Multi-Scale Instabilities In EAST Ion Temperature Central Peak Discharge
2893	Posters	Zihao Gao	Simulations Of RMP Configurations For Tungsten Impurity Control In EAST Tokamak
2967	Posters	Huihui Wang	Overview Of Error Field Scaling Studies In EAST And implications For ITER
3162	Posters	Jiaxing Liu	Validation Of Plasma -Wall Self-Organization Theory By High Density Limits Achieved On EAST
3276	Posters	Yunhu Jia	Plasma Instability Events Detection And Disruption Prediction In EAST Tokamak Via Heterogeneous-Feature Multi-Task Learning
3309	Posters	Guoliang Xu	Modeling Of Wall Material Evolution And The Impact On Edge Particle Recycling For Long Pulse Discharges In EAST
2920	Posters	Zhengshuyan Wang	Sawtooth Crashes Prediction Using A Convolutional Neural Network On EAST
3123	Posters	Ling Zhang	Progress Of Core-Edge Integrated Tungsten Transport Study In EAST With ITER-Like Tungsten Divertors Using Advanced Impurity Diagnostics
3161	Posters	Zhihao Zhao	Investigation Of Transient Transport Dynamics Induced By Compact Torus Injection In The EAST Tokamak
3297	Posters	Yahao Wu	Experimental Research On The Penetration Behavior Of Compact Toroid Fueling On EAST
2883	Posters	Guizhong Zuo	Application Of Low-Z Materials For Enhancing H Mode Plasma Performance And Pulse Duration In EAST With Full Metal Wall
2878	Posters	Binfu Gao	Modeling Of Heat Flux On The Main Limiter In EAST

Thank You For Your Attention
Your Suggestions and Comments Will Be Appreciated