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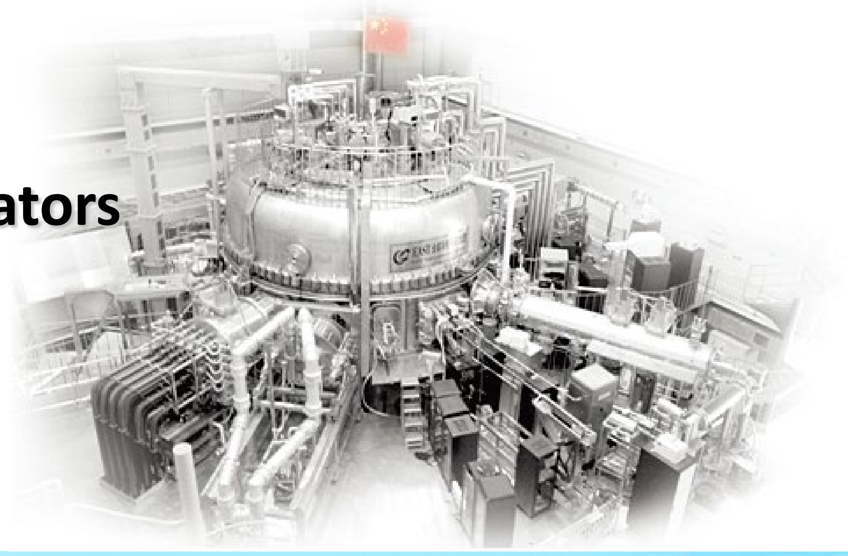
Opportunities and challenges of EAST in near future



Baonian Wan
On behalf of EAST Team and collaborators
10th US-PRC MFC workshop
2021.3.23

Institute of Plasma Physics, Chinese Academy of Sciences

EAST Positioned on Steady-state High Performance Operation in Support of ITER and CFETR

Confinement→Fusion power	**Steady-state→Burning time**
$P_{fus} \sim \langle p_{pl} \rangle^2 V_{pl}$	$I_p = I_{ohm}\ (\sim 0) + I_{cd} + I_{bs}$
$Q>1:\ n\,\tau_E\,T_i > 10^{21}\ (m^{-3}\,s\ keV)$ Heating/fueling & confinement	$I_{cd}/P_{cd} \propto T_e/n_e$ (const. effic.) $j_{bs} \propto \varepsilon^{1/2}\, p_e q f(\nabla n/n, \nabla T/T)$

Integrated solutions for Steady-state (Long Pulse) high performance operation

- ✓ Confinement (ITB)
- ✓ Bootstrap current
- ✓ Current drive at high n_e
- ✓ Instability

On time scale of particle balance

- ✓ Heat/particle exhaust
- ✓ ELM mitigation
- ✓ SOL/Divertor

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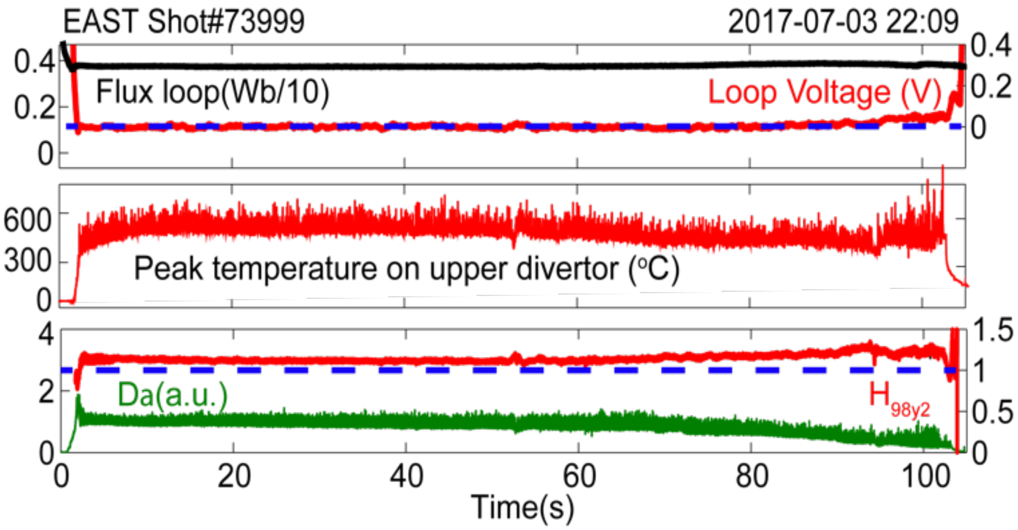
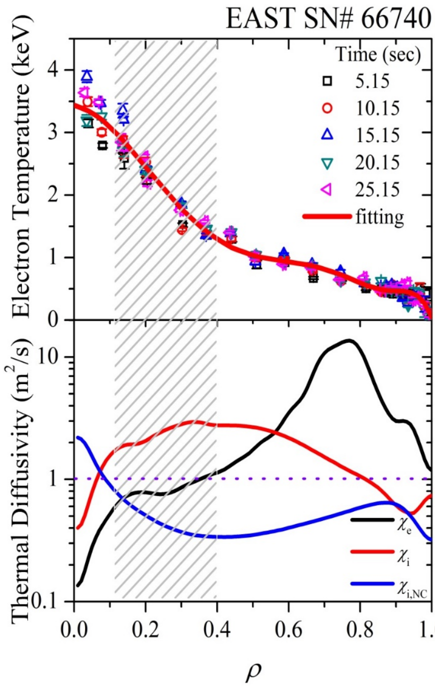
Fully non-inductive Long Pulse H-mode has been demonstrated with ITER-like Heating Schemes





- Full RF heating and current drive (zero torque input) with W divertor
- Small ELM with e-ITB, $H_{98,y2} > 1.15$
- Plasma current majorly maintained by current drive

low f_{BS}, $T_e >> T_i$ →increase f_{BS} & T_i

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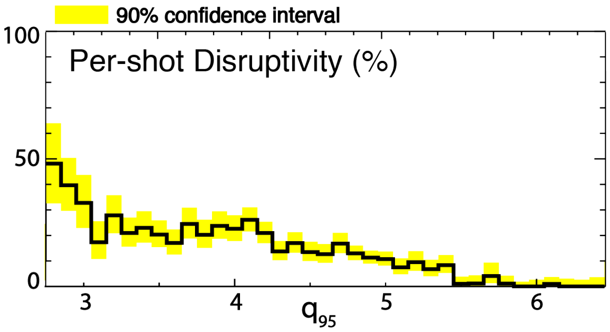
Large Efforts to Find Integrated Solutions of Steady-state Operation for CFETR on EAST in last few Years

	Q_{pl}	β_N	f_{bs}	H_{98Y2}	Ip	n_{bar}/n_{GR}	q_{95_iter}
CFETR P-1	~3	1.2	0.4	1.25	10	0.51	6.5~7
CFETR P-2	~10	2.0	0.5	1.4	14	0.57	5.5~6

$$f_{bs} \sim \varepsilon^{1/2} * \beta_p$$

High β_p Scenario is Attractive for a Steady-state Fusion Reactor with minimizing need for external current drive

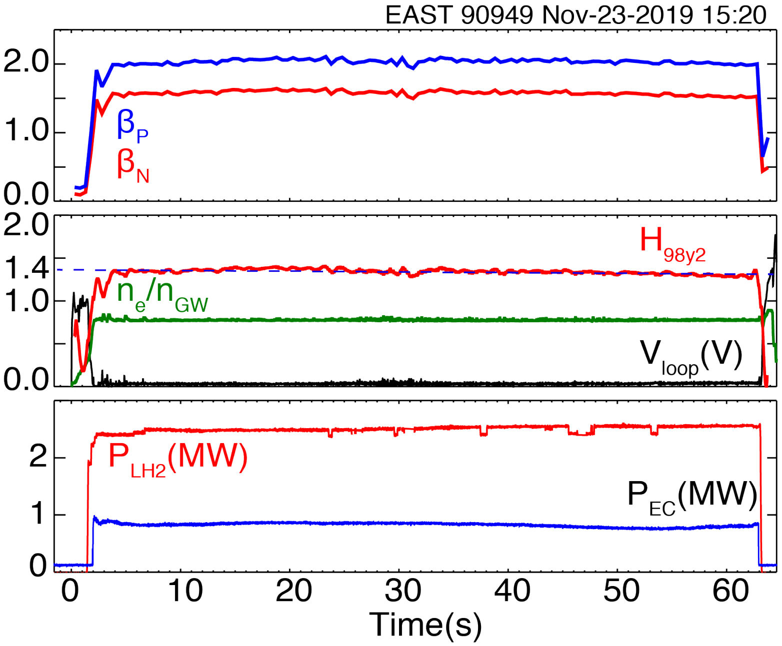
- ✓ Disruptivity decreases strongly with increasing q_{95}
- ✓ Lower the risk of damage
- ✓ Small ELM at lower Ip



- ELM mitigation
- Divertor detachment
- Small/no ELM

Compatible with High β_p plasma

Developed RF-only Long-pulse High β_P Plasma Close to CFETR Phase 2 Performance

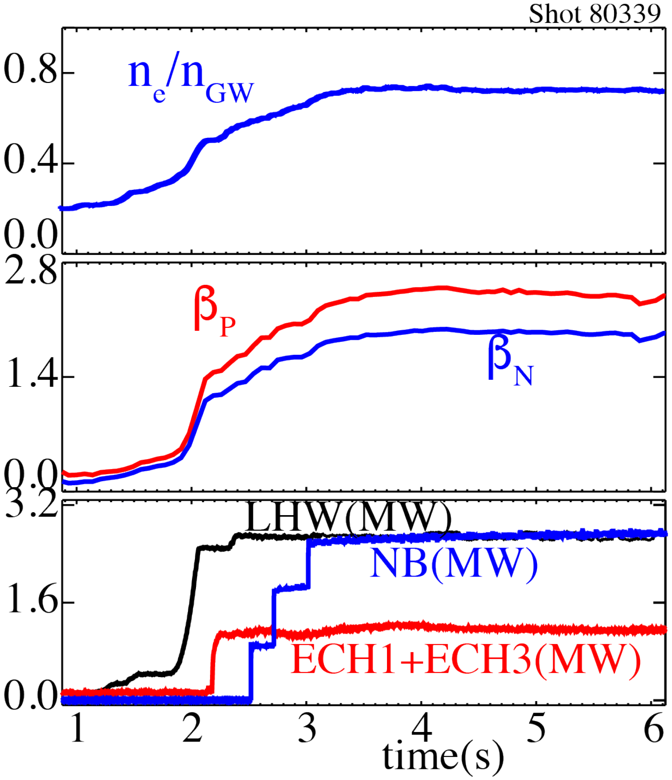


	CFETR A.3 SS	EAST SS
P_fusion	974	
β_N	2.0	1.6
f_{bs}	0.50	0.45
H factor	1.41	1.3
n_e/n_{GW}	0.57	0.8
q_{95} Iter	5.54	6.7

- Improved confinement（H_{98y2}~1.3□ , zero torque with eITB
  - β_P ~2.0, β_N ~1.6, f_{BS} ~ 45%
- RF-only fully non-inductive at high density (n_e/n_{GW}~0.8)
- Metal wall with low tungsten concentration
- Long pulse with small ELMs (f_{ELM}~1kHz)

Challenges → T_e>>T_i

Developed High β_P Plasma at CFETR Phase 2 relevant Performance



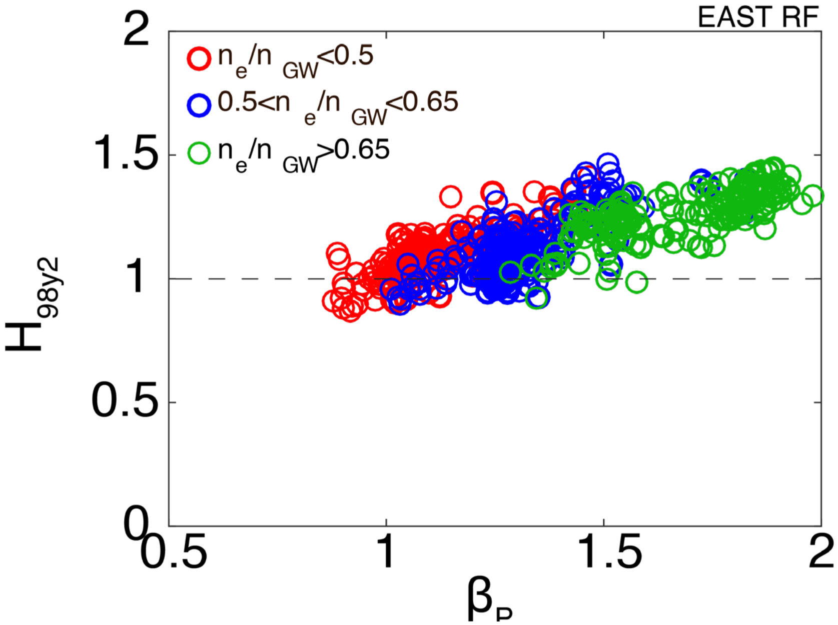
	CFETR A.3 SS	EAST SS
Fusion power	974	
β_N	2.0	~2.0
f_{bs}	0.50	0.50
H factor	1.4	>1.3
n_e/n_{GW}	0.57	>0.65
q_{95} Iter	5.54	6.7

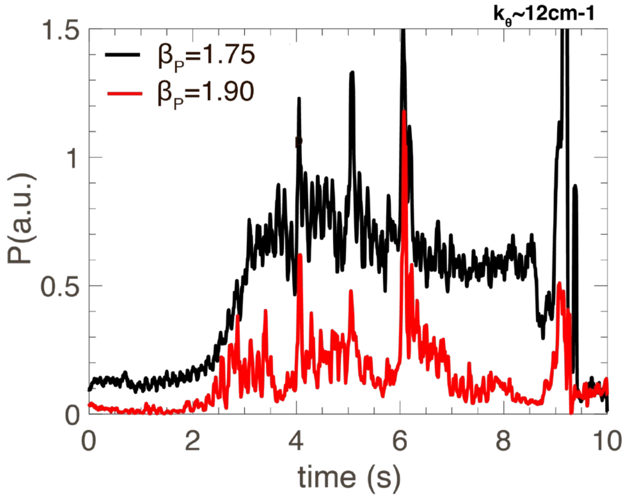
- Increased ion-heating power
- **Pulse limited by NBI**
- **Fast ion loss from counter beam**

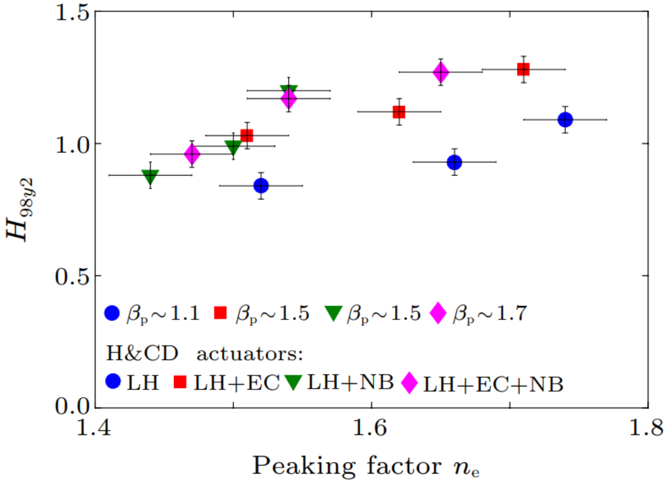
- Improved confinement（H_{98y2}>1.3□ , balanced NBI with eITB
  - **β_P ~2.5, β_N ~2.0, f_{BS} ~ 50%**
- Fully non-inductive at high density (n_e/n_{GW} >0.65) V_{loop}~0
- On-axis ECH pumps out high Z impurities from core plasma
- Small ELMs (f_{ELM}~1kHz)

Experiments Show Improved Confinement When Extending to Higher β_P

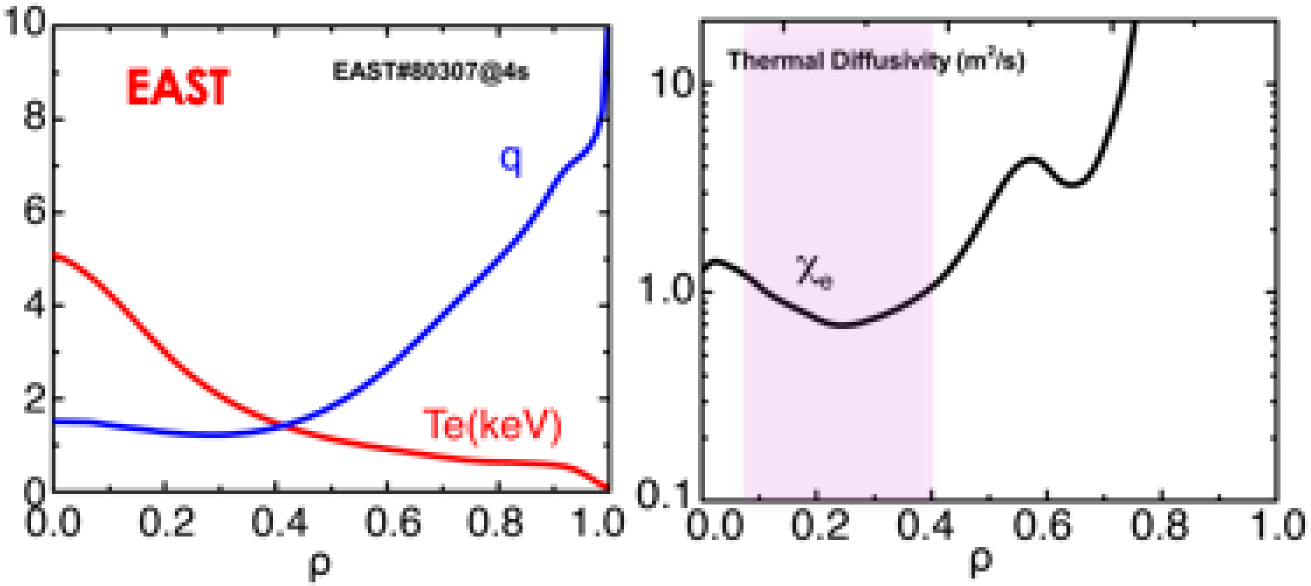
- Density gradient is a control knob to improve energy confinement
- Independent on heating schemes
- Stabilization effect of Shafranov shift plays a major role in turbulence suppression in high β_P scenarios







Weak Negative Shear Formed at High β_P Plasmas on EAST

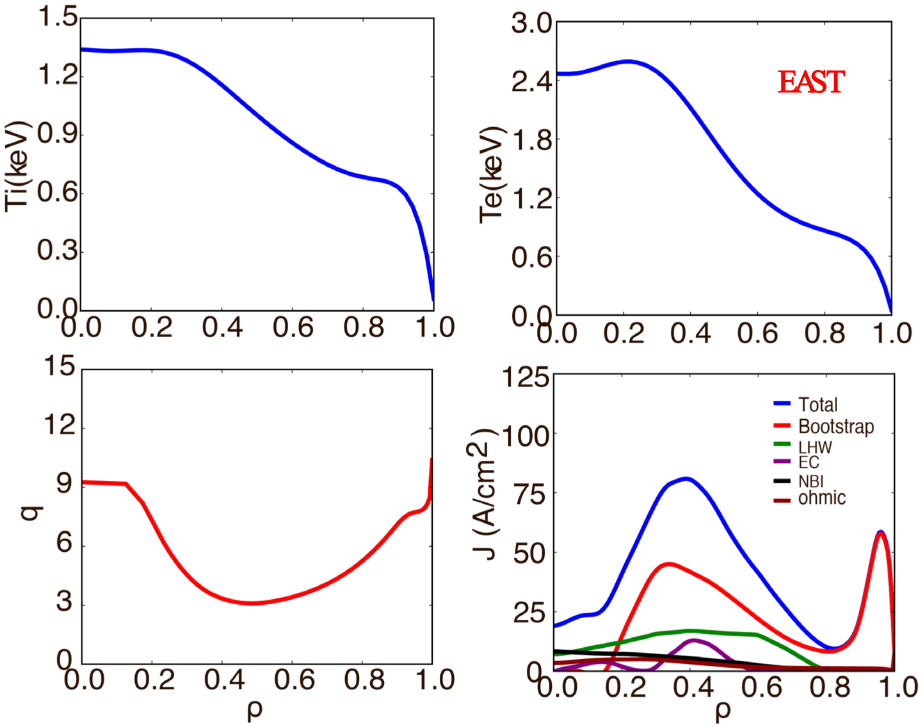


- Weak negative shear with $q_{min}>1.0$
- Sustained in fully non-inductive conditions
- eITB at $\rho\sim0.3$, $\sim \rho_{qmin}$ with significantly reduced χ_e in plasma core

Challenge-> increase ρ_{qmin} and ITB radius

Modeling Shows that Larger ρ_{qmin} and ITB Radius on EAST can be Achieved at Higher β_P

- Use integrated modeling with optimized H&CD scheme
  - ECH+LHW□ co-Ip NB & ICRF
- Large ρ_{qmin} □ ~0.5□ obtained with more off-axis f_{bs} CD
  - f_{bs} from 43% to 63% with higher β_p
- Reduced q（0）will require higher on-axis CD



Flexible H&CD mixture to tailor current profile

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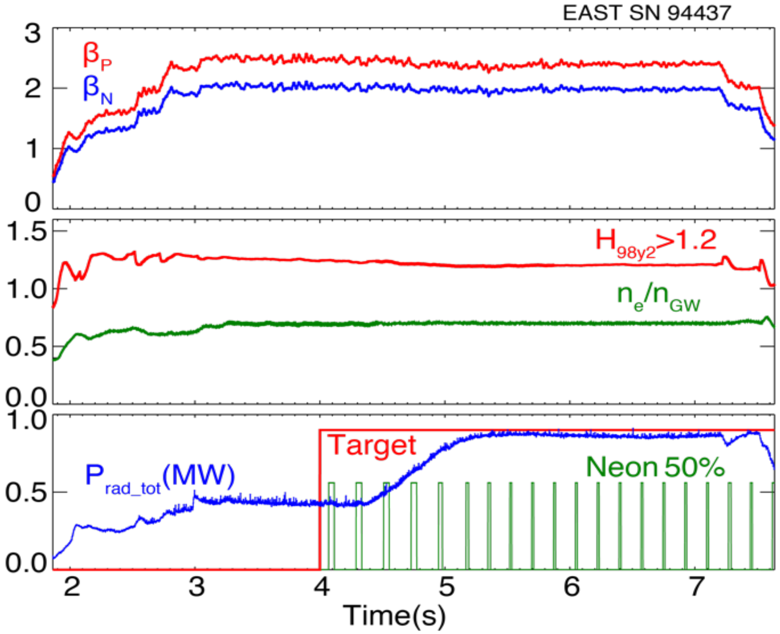
Heat Flux Control Successfully Demonstrated in EAST High β_p Experiments

- **A compatible core and edge integration in high β_p scenarios:**
  - high confinement H_{98y2} >1.2
  - β_P~2.5/β_N~2.0, f_{bs}~50%
  - n_e/n_{GW}~0.7, q_{95}~6.7



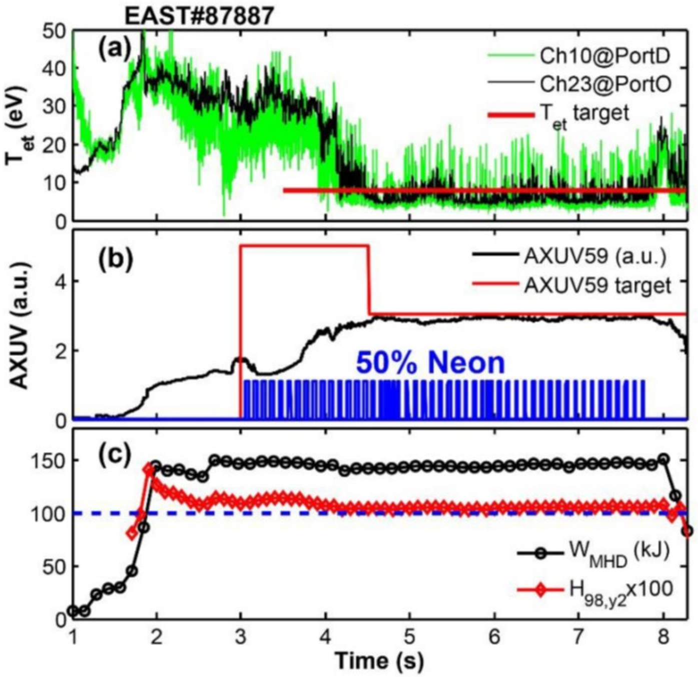
- **The peak heat flux is reduced by ~40% on the tungsten divertor**
  - Active impurity seeding through feedback control of radiation power.
  - A mixture of 50% neon and 50% D_2 is applied.

Further demonstration on time scale longer than particle balance.

Detachment-Te Feedback Control with Argon and Neon Injection

Detachment feedback control via $T_{e,div} + P_{rad}$

- A new combined feedback control using real-time divertor LP measurement and X-point radiation
- Stationary radiation and detachment
- No/small confinement degradation
- Compatible with non-inductive high $\boldsymbol{\beta}_p$



Further demonstration on time scale longer than particle balance.

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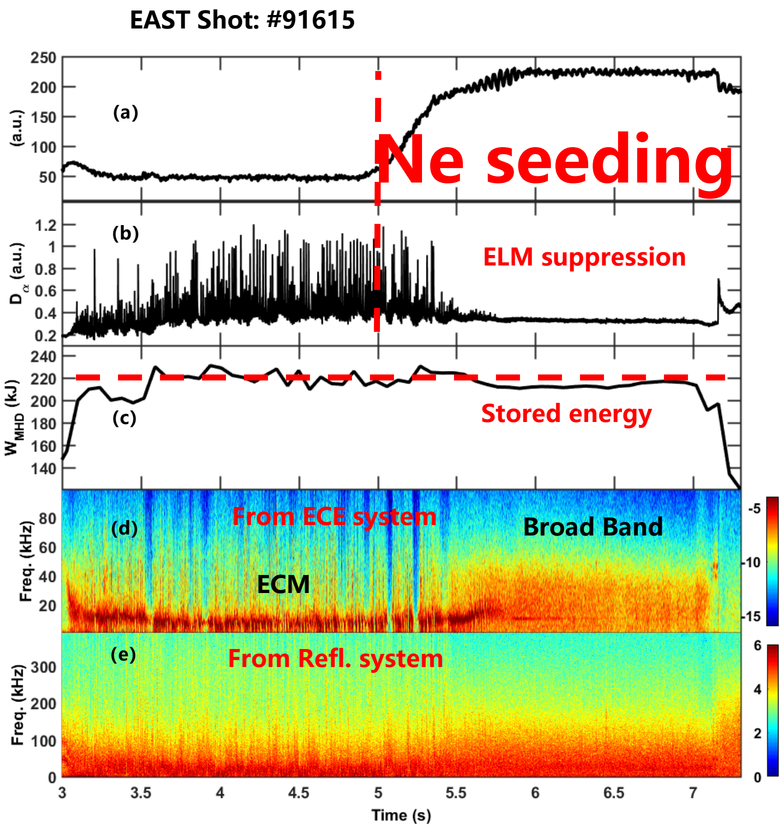
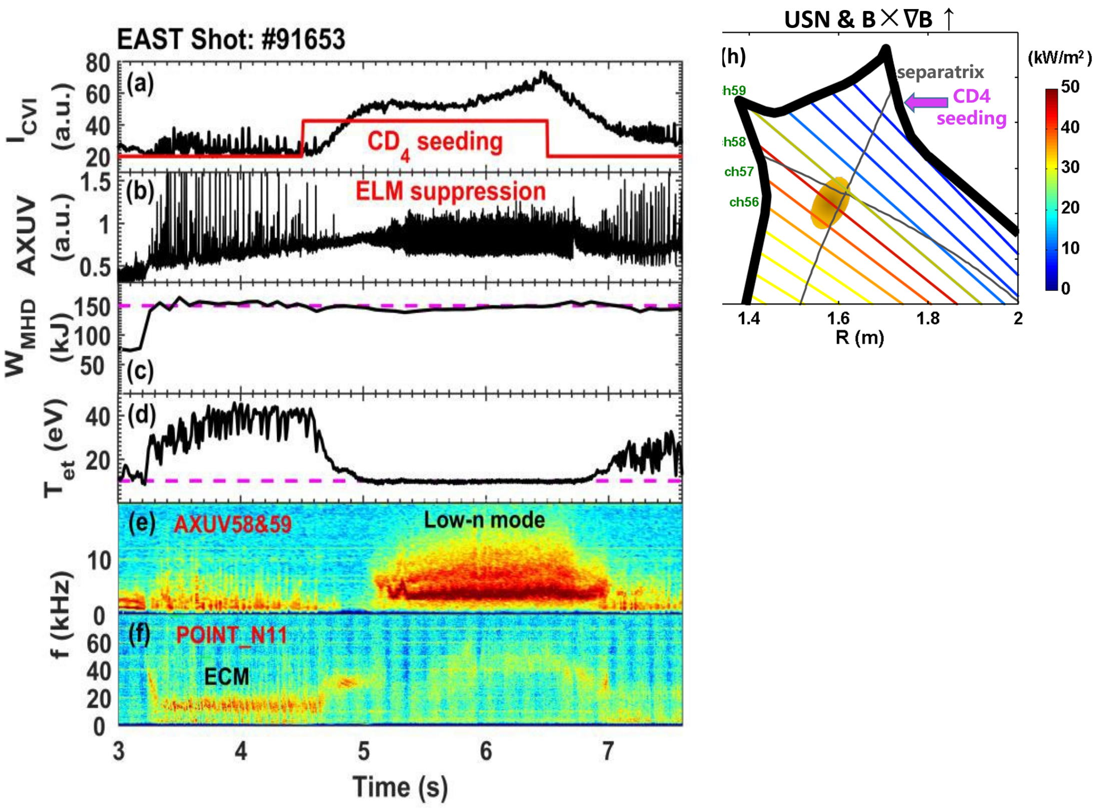
ELM Suppression by Divertor Ne or CD4 Seeding in High β_p Plasmas



Edge Coherent Mode in the ELMy phase replaced by a Broad-Band fluctuation in the pedestal gradient region.



ELM suppression and divertor detachment achieved with an n=1 low-frequency mode (<10kHz) near the X point

Further demonstration on time scale longer than particle balance.

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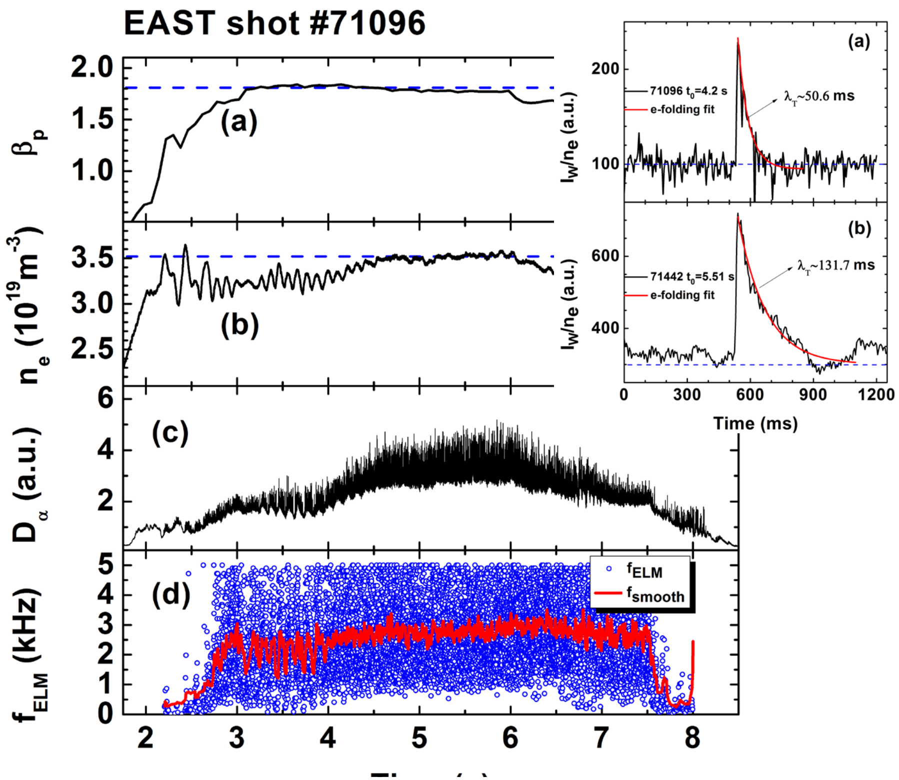
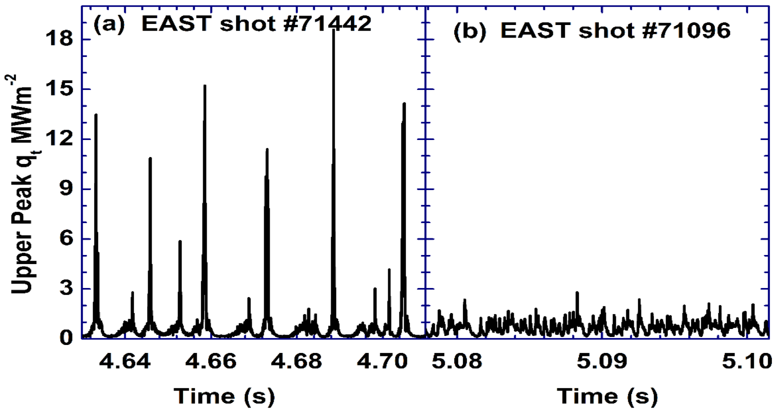
A Highly Reproducible Stationary Grassy-ELM H-mode Regime has been Achieved

- **Heat flux of grassy ELMs:**
  - 1/20-1/10 of large Type-I ELMs
- **Strong particle exhaust capability**
- **Compatible with high β_p**
  - $\beta_p \geq 1.1$, up to 3.3 with f_{BS} up to 70%
- **The regime extended to q95→5**
- **Sustained performance by divertor Neon seeding**



The regime seems to be in operation windows compatible with the steady-state (SS) operation scenarios



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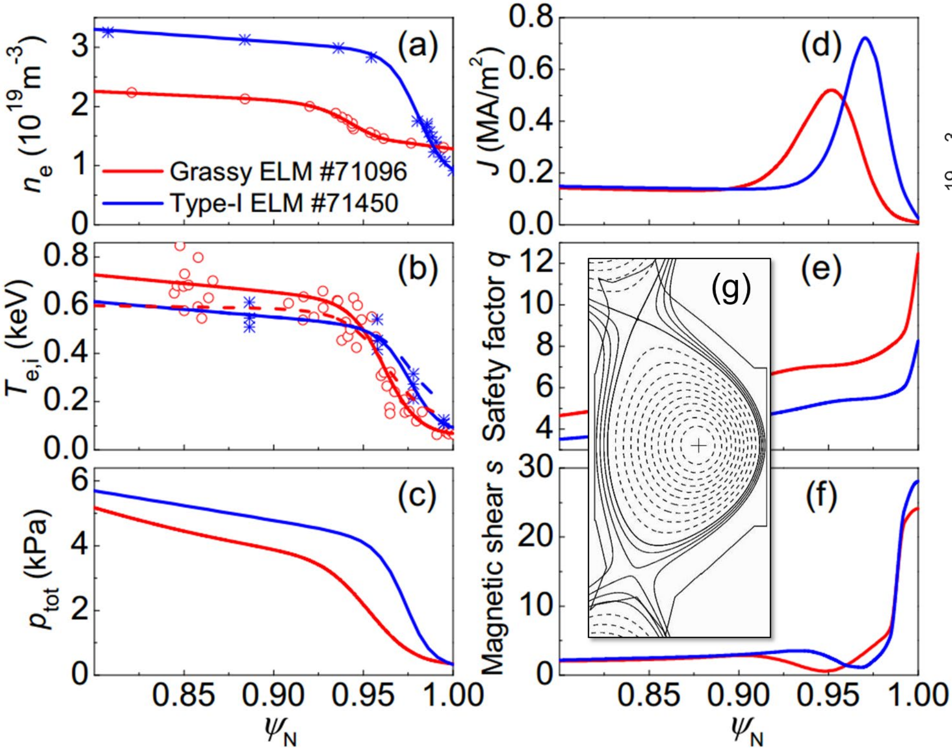
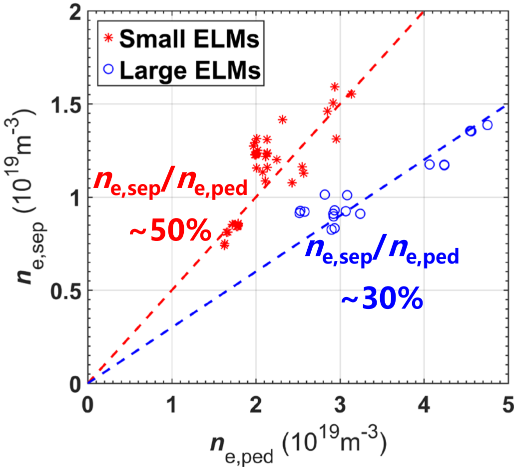
The Regime Characterized by a Low Pedestal Density Gradient and a Wide Pedestal





Higher $n_{e,sep}$

- **enhance boundary impurity screening**
- **facilitate divertor detachment**

BOUT++ nonlinear simulations show:

- ☐ **Grassy ELM:** expansion of PBM boundary after initial pedestal collapse ;
- ☐ **Type-I ELM:** pedestal stays in unstable region after initial pedestal collapse

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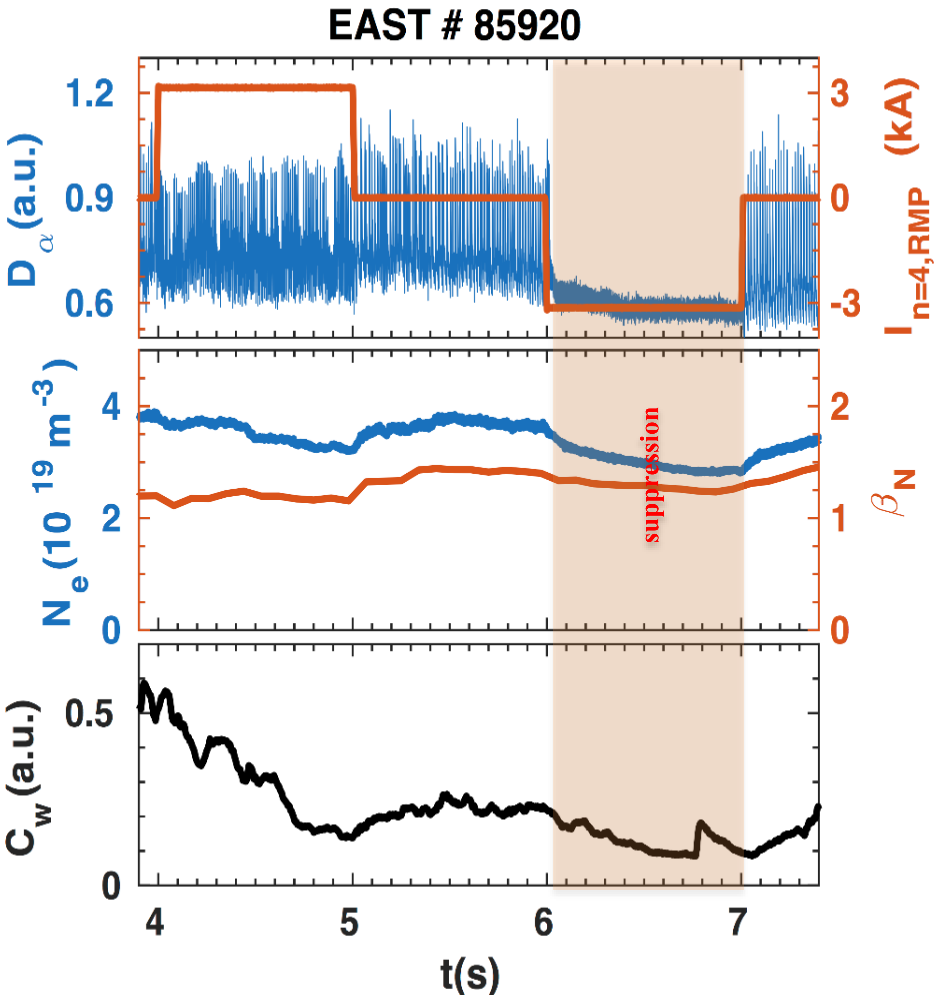
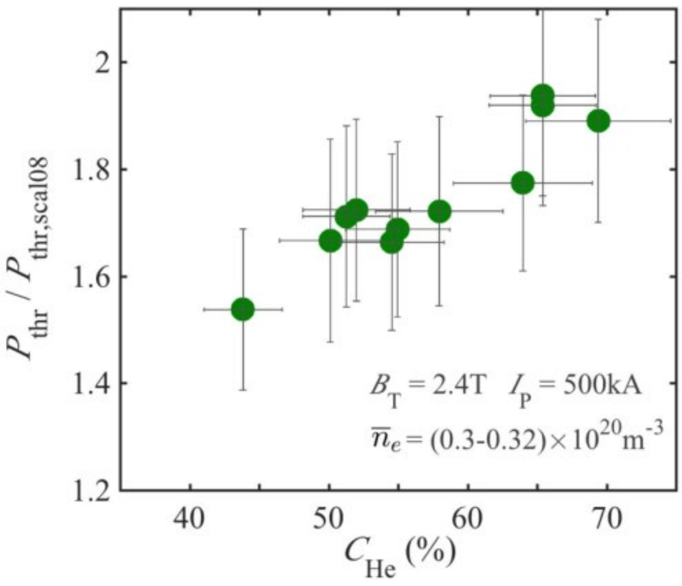
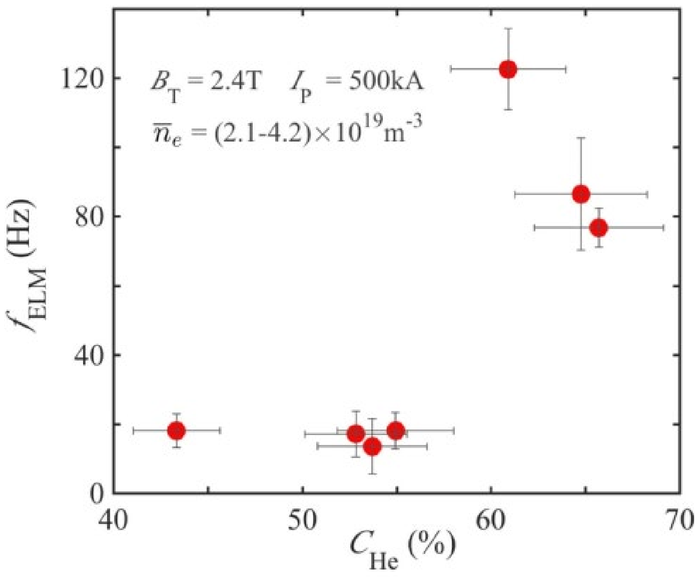
Demonstration of ELM suppression by n=4 RMP in low torque plasmas to Support ITER BL

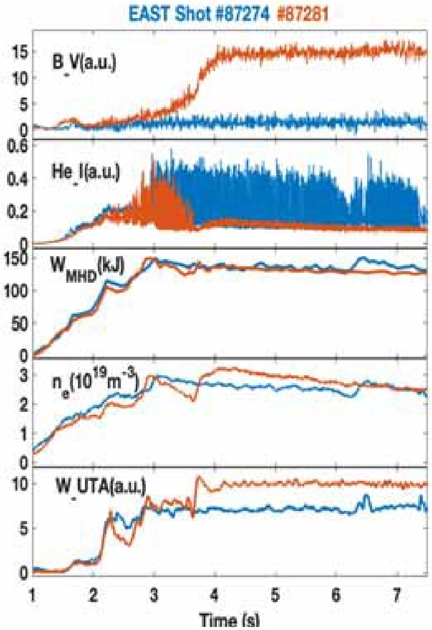
- Type-I ELMs are completely suppressed by ***n*=4 RMP** with upper-lower **odd** coil phasing, but not for the even one.
- The target plasma is close to **ITER type-I ELMy H-mode** operational window
  - **T_{NBI} = 1.1 N· m (0.9 N·m ITER equivalent torque in EAST)**
  - **$q_{95} \sim 3.65$, $\nu_{*e,ped} \sim 0.5$, $\beta_N \sim 1.4$**
- **W concentration decreased** during the application of RMP
- Significant **density pump out （20%）** happens during ELM suppression, but **less drop (5%) of stored energy**

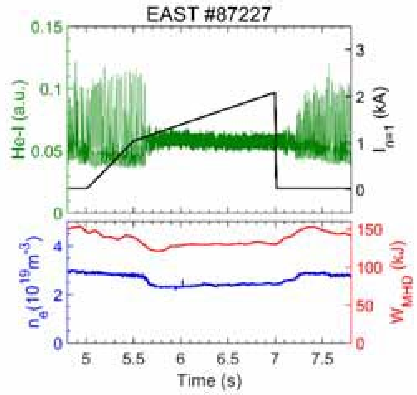


Helium Plasma Experiments in Support of ITER Operation









- **H-mode power threshold** increases with He ratio and can be twice as high as in a D plasma
- **High-frequency small ELMs** more readily accessible at high He ratio
- **ELM suppression by Boron powder injection** achieved in both He and D plasmas
- **ELM suppression by RMP** achieved in He plasmas

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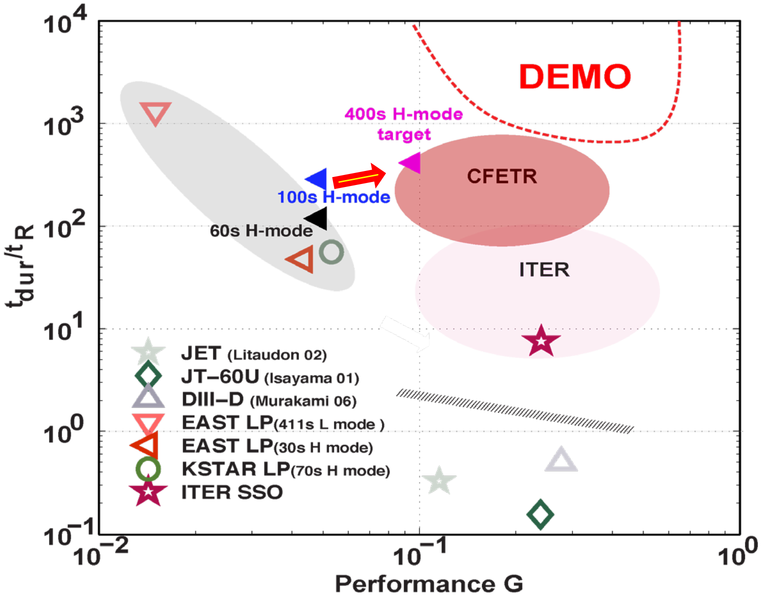
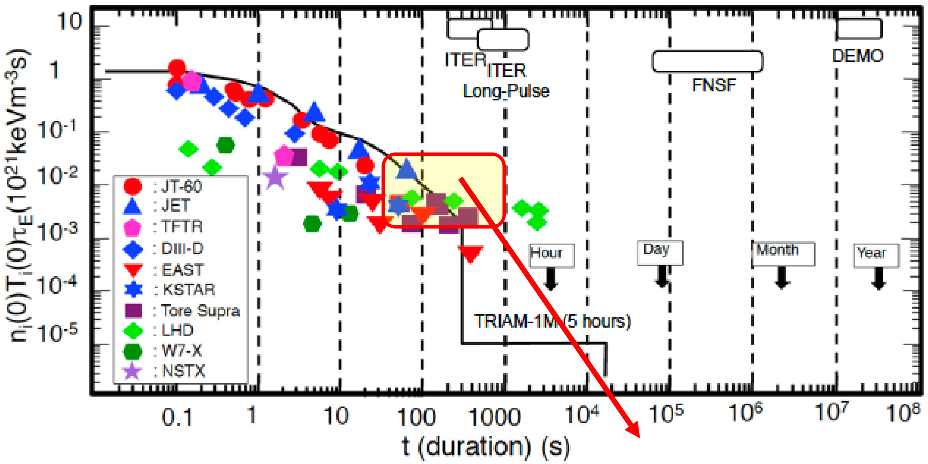
Goals of EAST in near future

1. Demonstration of H-mode long-pulse operation (≥ 400 sec) with H_{98} □ 1, f_{BS} ~50%
2. Demonstration of long-pulse power exhaust (>1GJ @10MW) for 100s
3. Demonstration of 1000s long pulse operation with T_{e0} > 8.5keV



Plasma regimes

- ➢ q_{95}=3~5~6.5
- ➢ ν^*_{vol}~0.01， ν^*_{ped}<0.5
- ➢ $T_e/T_i \leq 1.5$
- ➢ $\beta_p \geq 2.5$; $\beta_N > \beta_{no\text{-}wall}(\sim 4l_i)$
- ➢ P_{div}~10MW/m²
- ➢ …



EAST goal: $n\tau_E T_i$ half order higher

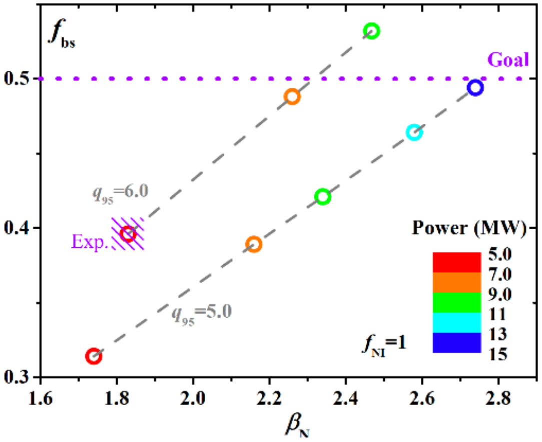
Key Physics Issues

- Physics in near reactor relevant regime (non-dimensional) and conditions (dominated e-heating, low torque input, full metal wall)
- Integrated Steady-state scenarios for long pulse operation (compatibility among confinement, Div/SOL, instability control…)
- Extending physics research:
  - stability beyond no-wall limit,
  - energetic particles (NBI+ICRF)
- Integrated modeling and experiment validation

To Access Targeted SSO Regimes

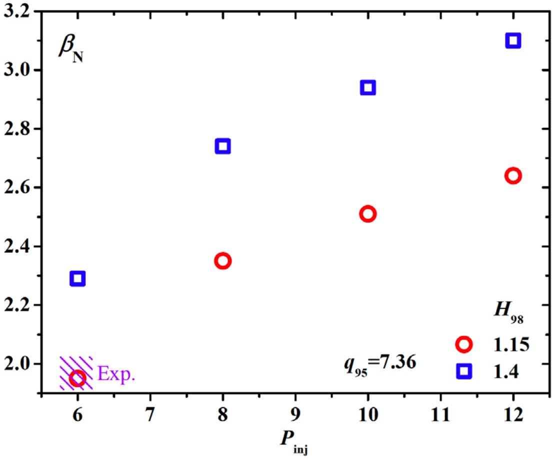
Need more power for long pulse operation:

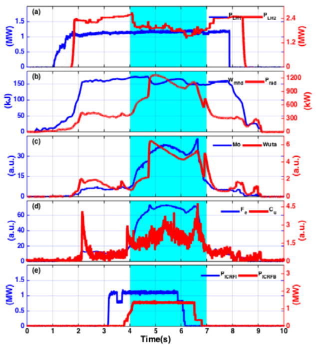
- To access higher beta and bootstrap current
- To optimize profiles for scenario development and instability control
- To regulate Ti/Te with H&CD mix for confinement and transport study

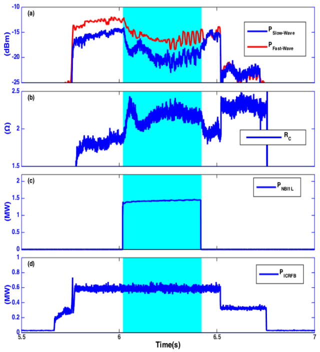


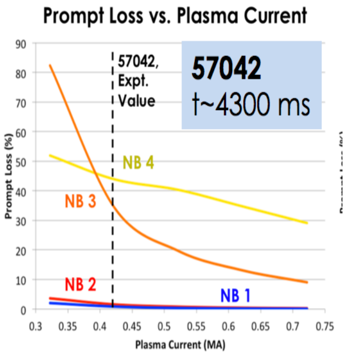
Presently, available power limited by

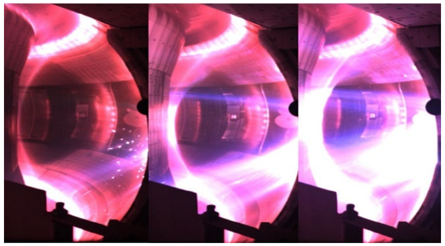
- ICRF magnetically connected to LHW
- Coupling of ICRF on port B affect by co-NBI
- Prompt loss of counter NBI, short pulse NBI
- Heat on guard limiter of launchers











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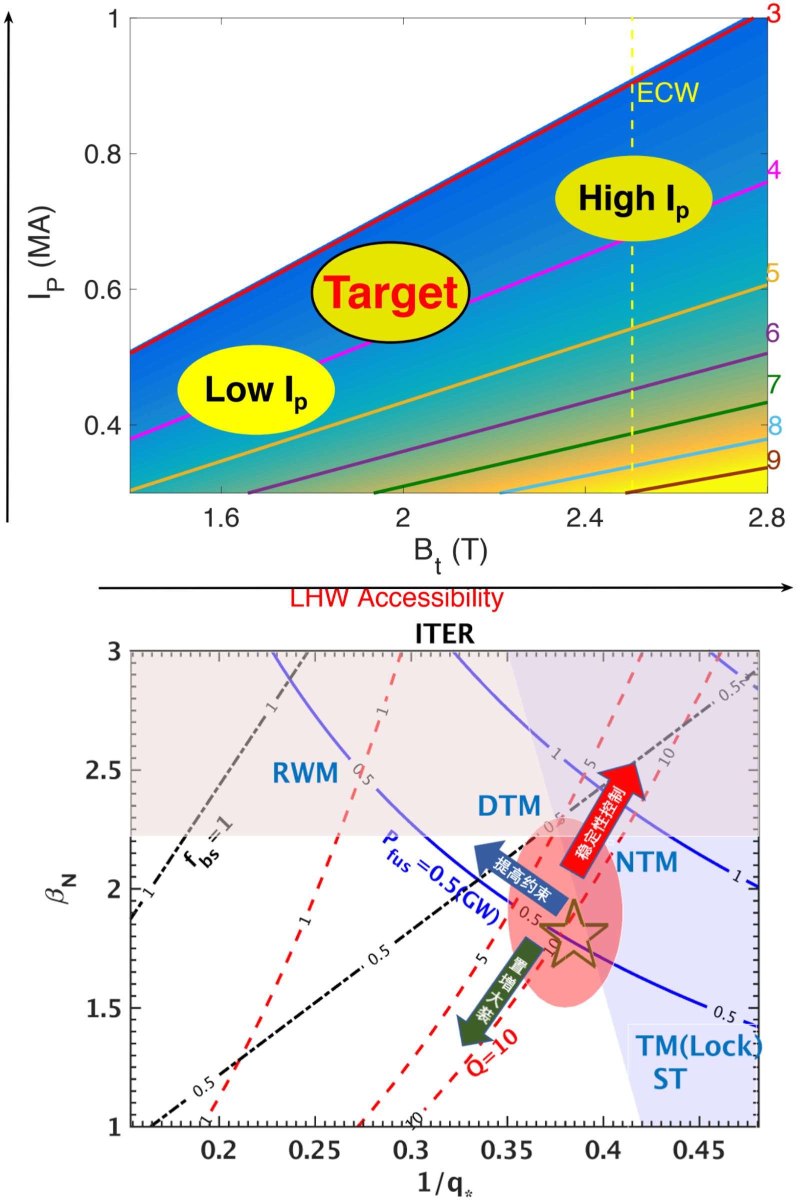
To Extend Scenarios to lower q_{95}

To access ITER BL at B_t<1.8T and Ip>0.4MA need EC @ 105 GHz

- EC power @140 GHz does not apply
- IC power @25~70 MHz is very marginal NBI
- Low power absorption efficiency

To access ITER BL&HB at B_t≳2.0T and Ip>0.6MA need more power

- Great challenges for high β_p β_N and f_{BS}
- Heat and particle exhaust for long pulse
- Limit of PF currents for Ip>0.8 MA with low li and high β_p
- Machine safety issues



H&CD system

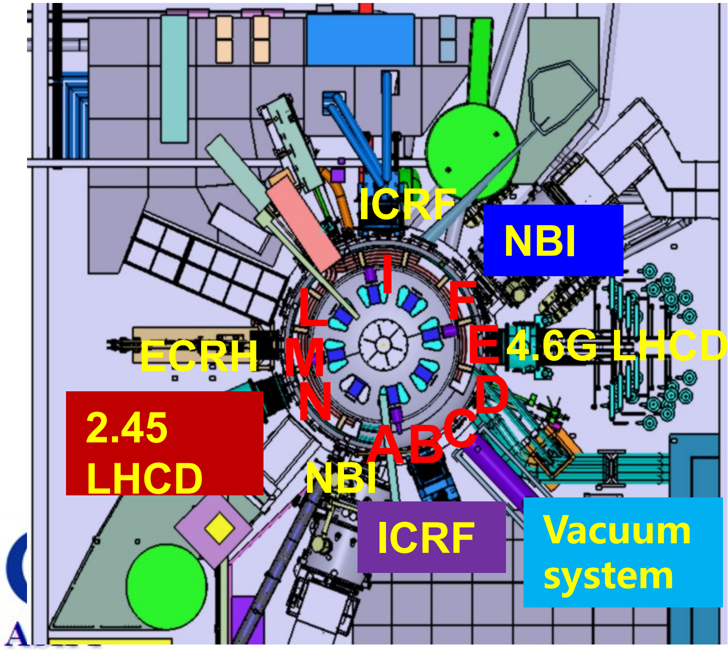
Improving the heating system for $P_{H\&CD}$>10 MW integrated long pulse and $P_{H\&CD}$>15 MW short pulse operation

✓ Re-allocation of H&CD system ports to minimizing inter-influence among them

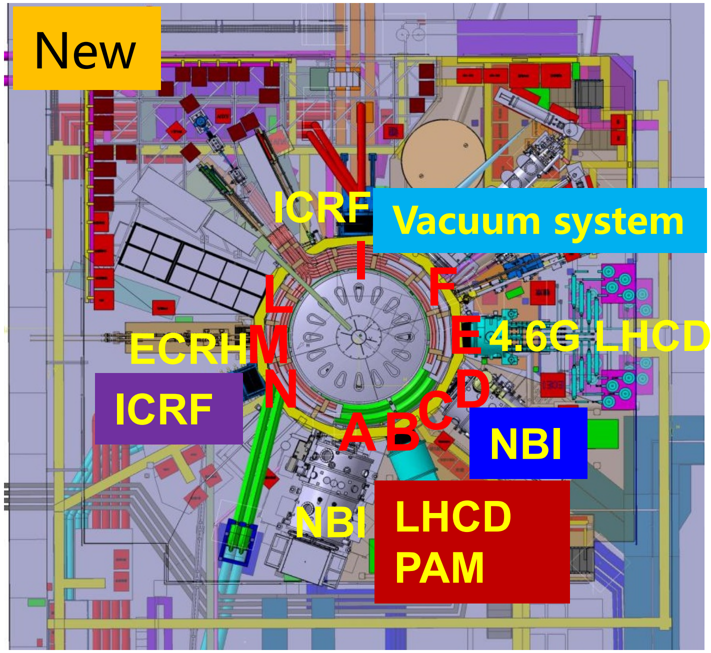
✓ New PAM launcher of 2.45GHz LHW and low $k_{||}$ ICRF antenna

✓ Counter NBI re-direction to CO-Ip

- Two Gycom Gyrotrons @140GHz upgrade to 105/140GHz
- New long pulse RF ion sources and 2 CPI gyrotrons



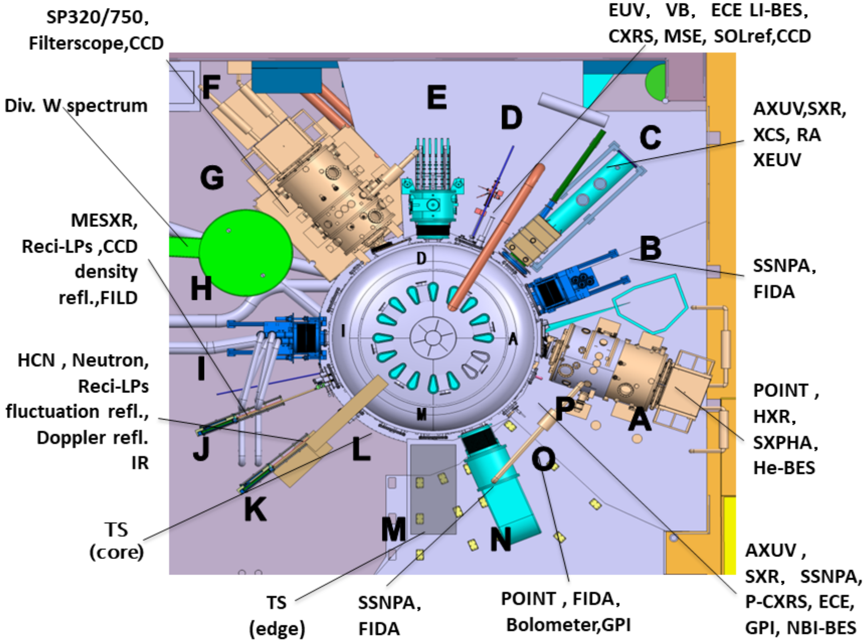
System upgrade and ports re-allocation



Deliver physics basis for ITER and CFETR

Diagnostics:

- Reallocate ports to meet measure demand
- Highly integrated design for more new diagnostics
- Reliable profile measures covering from core to SOL to meet modeling needs
- Emphasize divertor and PSI issues and key physics understanding

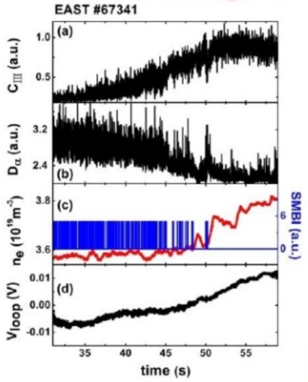


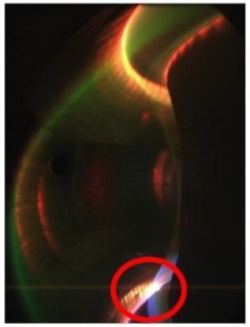
Integrated Modeling and simulation to mitigate physics risks:

- Validation of physics models and extrapolation to CFETR performance
- Guidance of scenario development on EAST
- Simulation to support prediction of plasma performance of CFETR

New lower Divertor

61s long H-mode in 2016

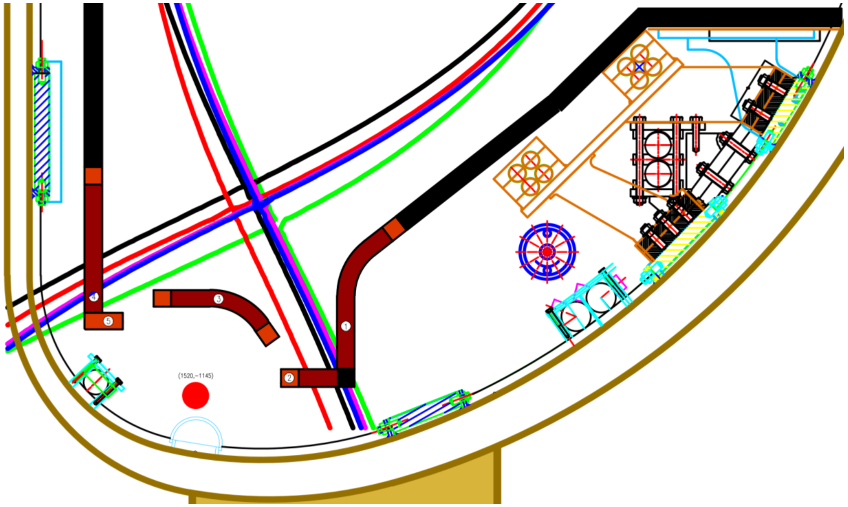




Hot spots on lower graphite divertor

Present lower graphite divertor:

- SS heat exhaust capability ~2MW/m^2;
- High particle recycling;
- Guide-limiters、leading-edge，leakage…

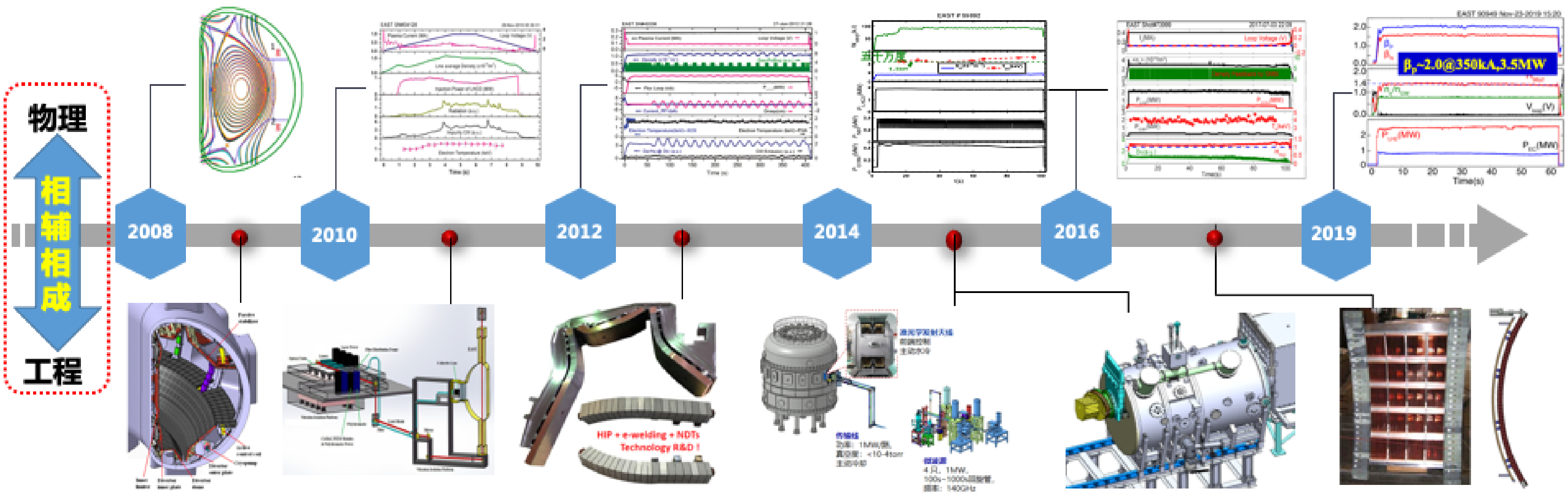


Full metal wall and new divertor:

- SS heat exhaust 10MW/m^2 ;
- Flexible configuration:
  - ➢ Vertical target: more close, detachment at lower density;
  - ➢ Horizontal target: access 10MW/m^2 power density for physics study and control technology development

Machine Maintenance for safe Machine Operation in next 10 years

13 years, 14 experimental campaigns, >90000 shots



偏滤器等离子体

1MA等离子体

411s低约束与 32s高约束等离子体

5千万度100s 低约束等离子体

101s高约束 等离子体

60s高β_p 等离子体

C in vessel

diagnostics

W divertor

ECRH@140GHz

NBI&LHW @4.6GHz

Guide limiter

In next few years, EAST would be operation at:

- Higher power, longer pulse
- Higher plasma current, broader range of toroidal field

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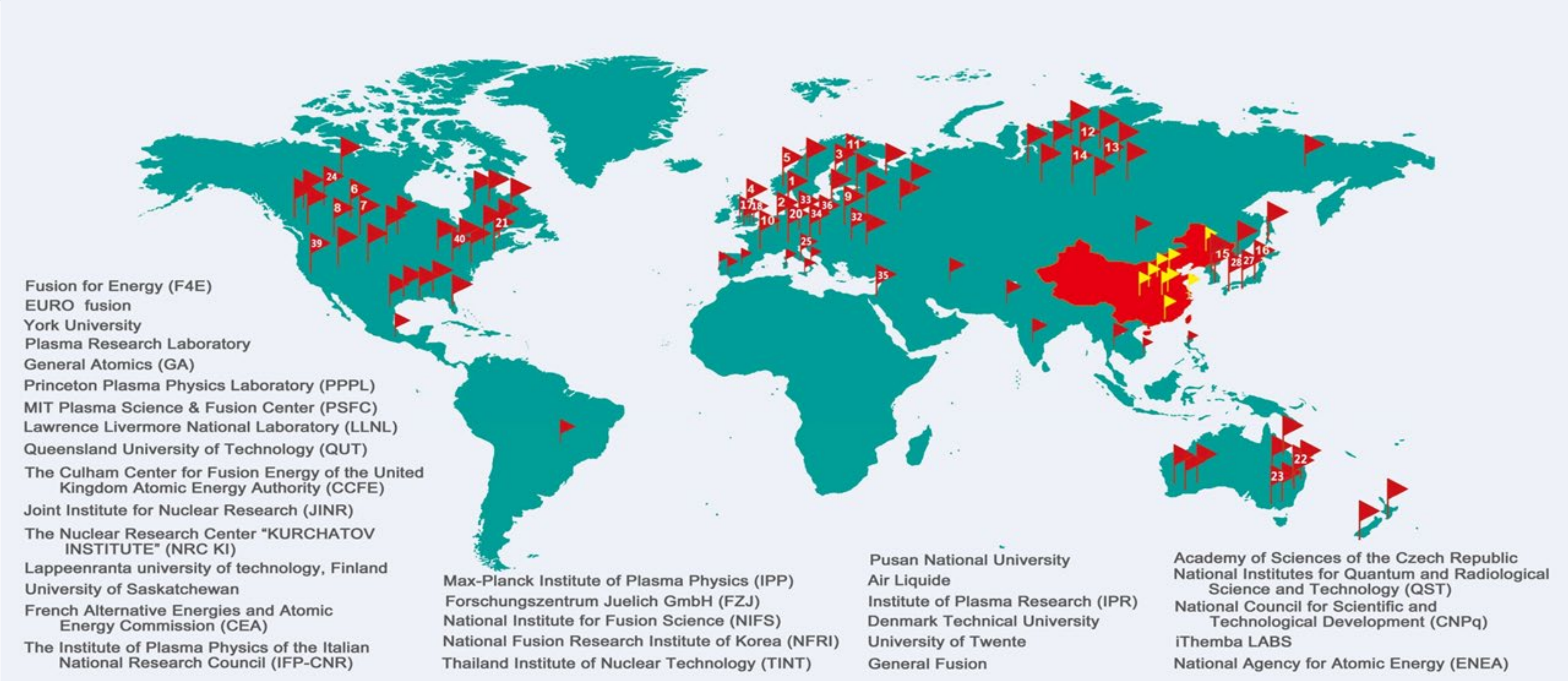
Broad collaboration network



Fusion for Energy (F4E)
EURO fusion
York University
Plasma Research Laboratory
General Atomics (GA)
Princeton Plasma Physics Laboratory (PPPL)
MIT Plasma Science & Fusion Center (PSFC)
Lawrence Livermore National Laboratory (LLNL)
Queensland University of Technology (QUT)
The Culham Center for Fusion Energy of the United Kingdom Atomic Energy Authority (CCFE)
Joint Institute for Nuclear Research (JINR)
The Nuclear Research Center "KURCHATOV INSTITUTE" (NRC KI)
Lappeenranta university of technology, Finland
University of Saskatchewan
French Alternative Energies and Atomic Energy Commission (CEA)
The Institute of Plasma Physics of the Italian National Research Council (IFP-CNR)

Max-Planck Institute of Plasma Physics (IPP)
Forschungszentrum Juelich GmbH (FZJ)
National Institute for Fusion Science (NIFS)
National Fusion Research Institute of Korea (NFRI)
Thailand Institute of Nuclear Technology (TINT)

Pusan National University
Air Liquide
Institute of Plasma Research (IPR)
Denmark Technical University
University of Twente
General Fusion

Academy of Sciences of the Czech Republic
National Institutes for Quantum and Radiological Science and Technology (QST)
National Council for Scientific and Technological Development (CNPq)
iThemba LABS
National Agency for Atomic Energy (ENEA)

- EAST is open for world fusion community since its day-one operation.
- So far, collaboration is bi- multi-lateral benefit and has made great contribution to world fusion program.
- EAST will face new scientific challenges, which are critical to fusion community
- Upgraded capability opens new collaborative opportunities in searching physics and technologies for integrated solution of ITER and reactor steady-state operation

Thank you !