Development of advanced vacuum and wall conditioning technologies for extending plasma pulse duration for EAST

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Outline

- Introduction
- Upgraded PFMs and structure
- Enhanced pumping and fueling capability
- Advanced wall conditionings
- Summary and outlook

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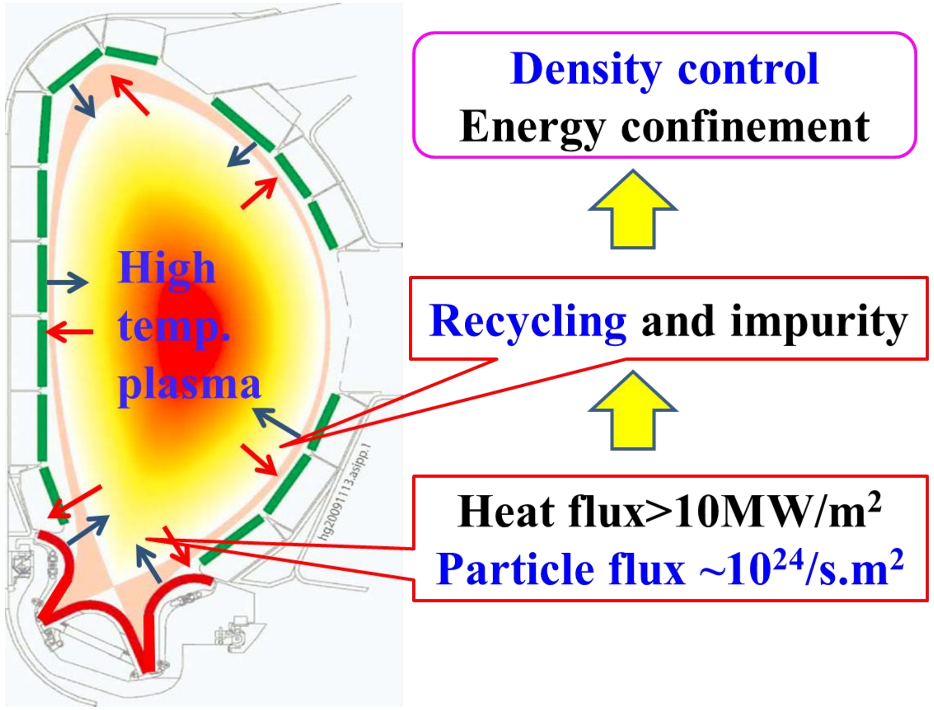
Fuel and impurity particle control of fusion device

- Control of fuel and impurity particle is very key to long pulse, high performance plasma operation.



Impurity → Degrades plasma performance due to power radiation

Fuel particle → Recycling → Plasma density control

Fuel particle → Core fueling → High density plasma

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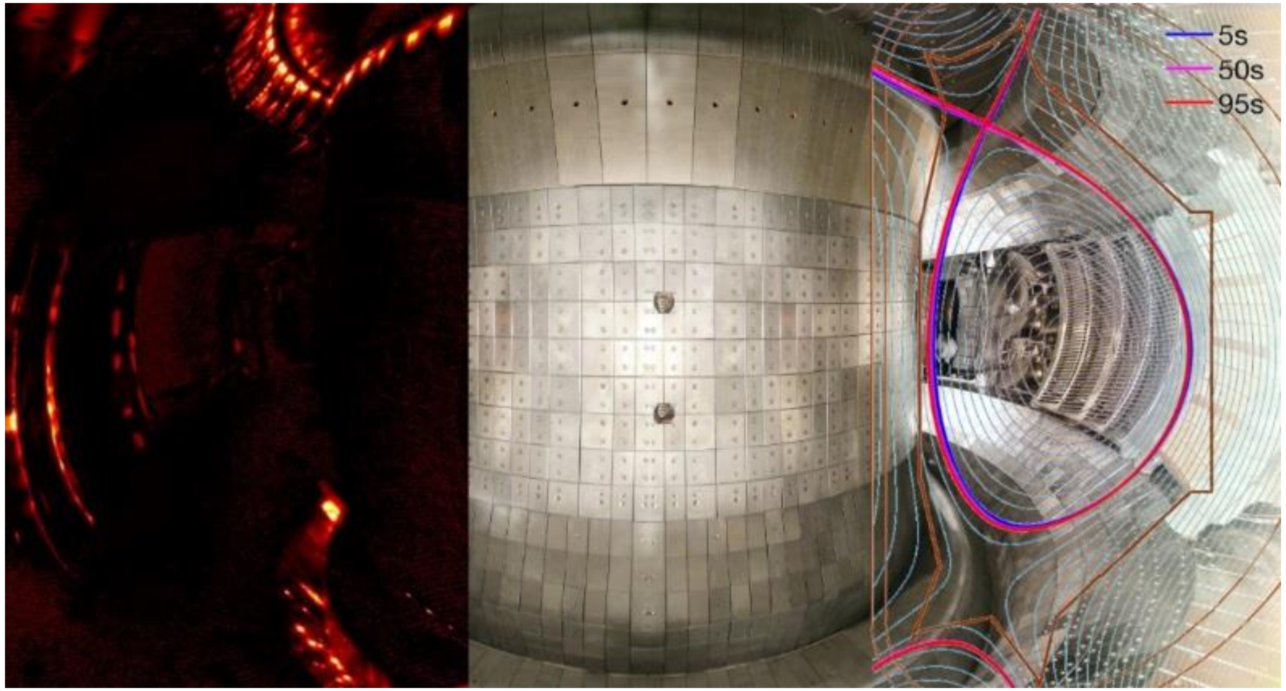
EAST towards a long-pulse SS operation



Aiming to: long pulse high-performance discharges

EAST Targets
100s&10MW
400s H mode
1000s plasma

ITER-like configuration (DN, USN, LSN)

R=1.7-1.85m, a=0.4-0.45m, B_T=3.5T

Main Missions

- Play the key role for understanding advanced SS plasma physics.
- Provide valuable data bases for ITER and DEMO under SSO condition.

Advanced vacuum and wall conditioning to reduce fuel particle recycling and impurity content, providing a valuable reference for future fusion devices.

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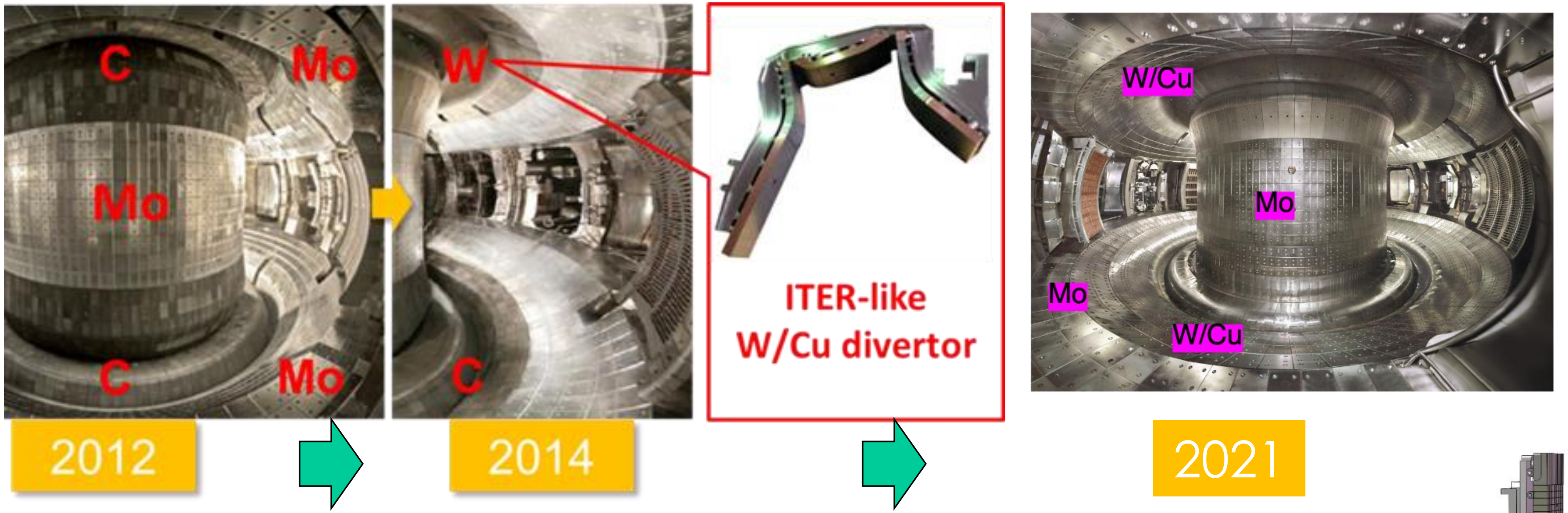
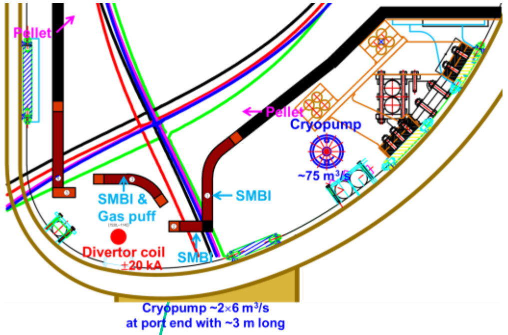
New W divertor for enhanced power & particle exhaust

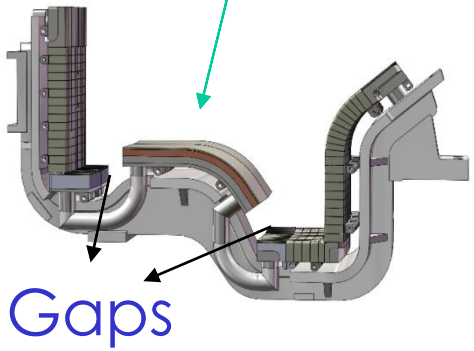
- **Enhanced particle exhaust capability：** Larger gap between targets increase conductance of tube





- **Facilitate both LSN and DN, flexible strike point**

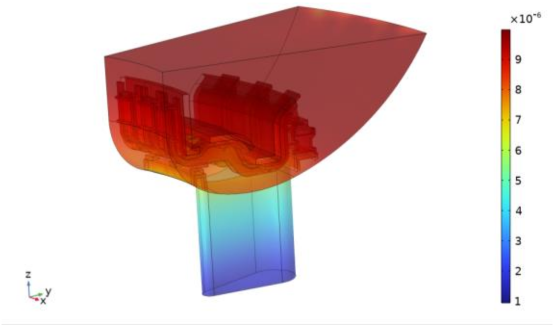
✓ Divertor target with monoblock or flat-type structure has a high capacity to handle a heat flux of up to 10 MWm^{-2} for long time

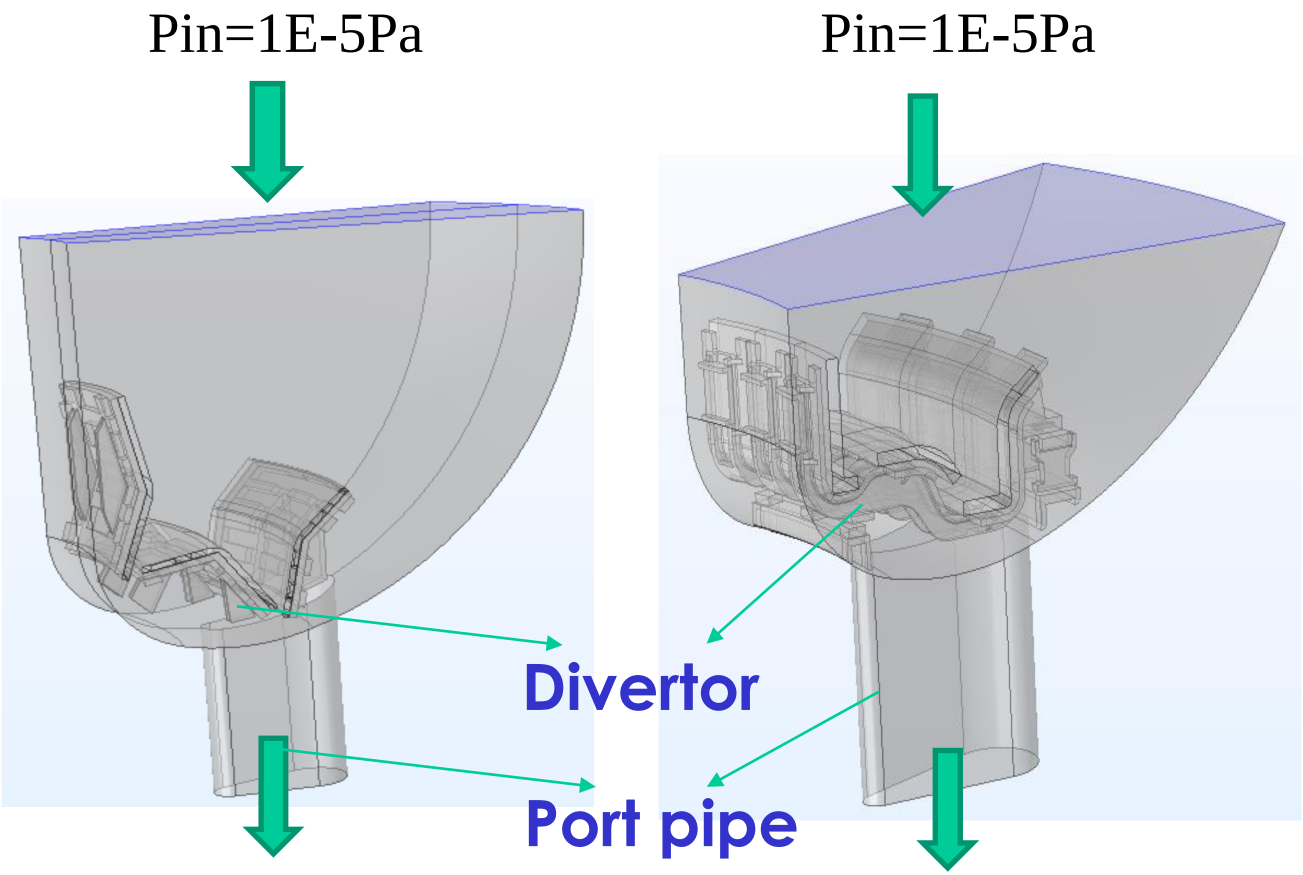


Increased flow conductance of new lower divertor

Flow conductance calculated by COMSOL

- ✓ Flow conductance calculation including divertor and pipe：
- ✓ New divertor： 13.83 m^3/s
- ✓ Old divertor： 10.14 m^3/s
- ✓ **An increase of ~36%**





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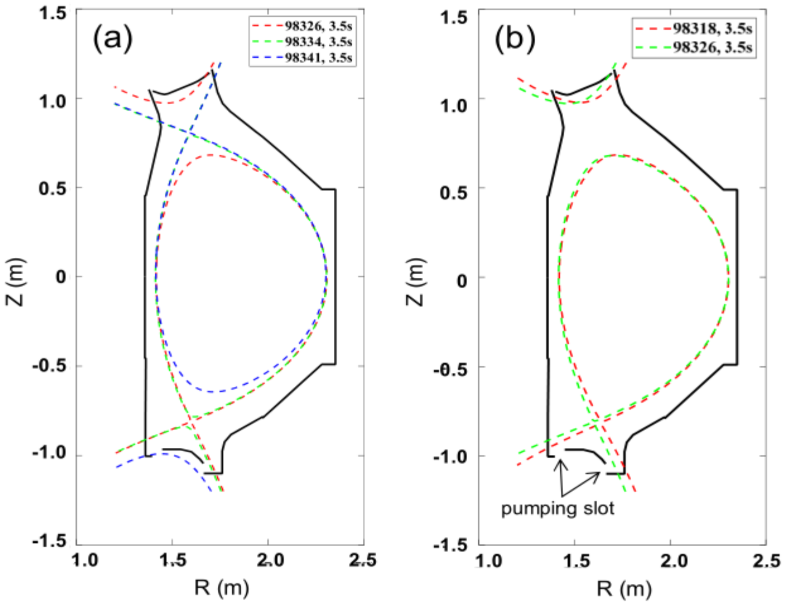
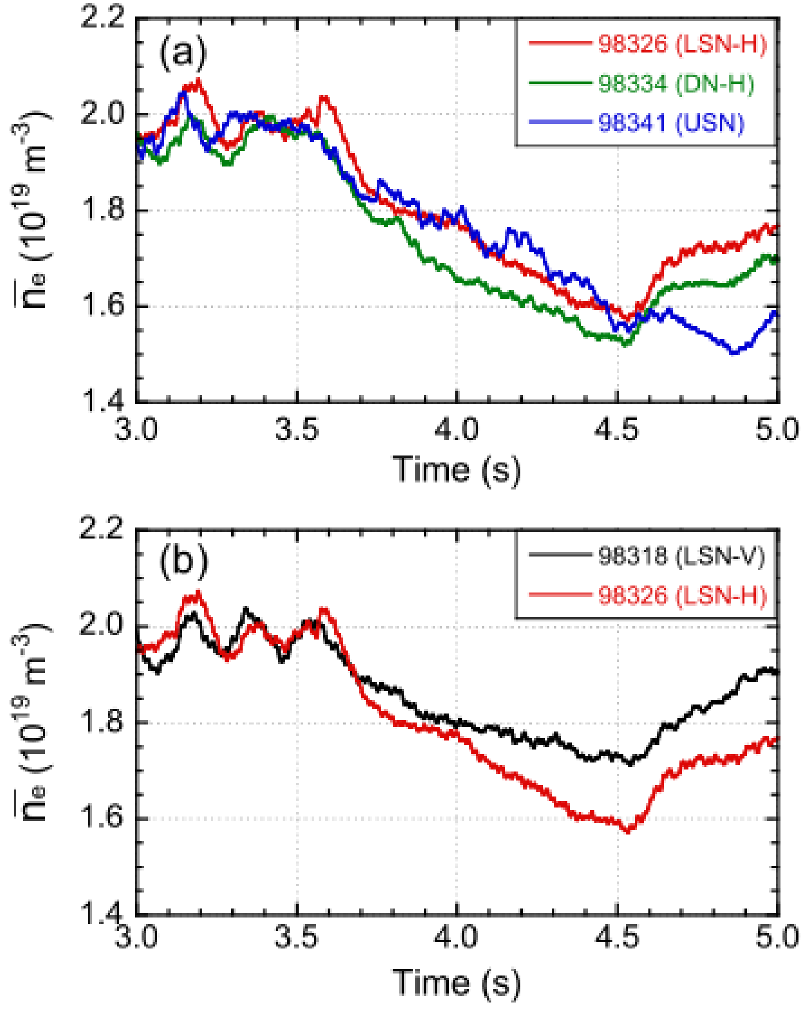
Effect of divertor structure on particle exhaust

- **Stronger particle exhaust capability with LOSP on horizontal target in both LSN and DN**
  - **Consistent with SOLPS simulation during phys. design**
- **Slightly stronger particle exhaust using DN on horizontal target than LSN and USN**

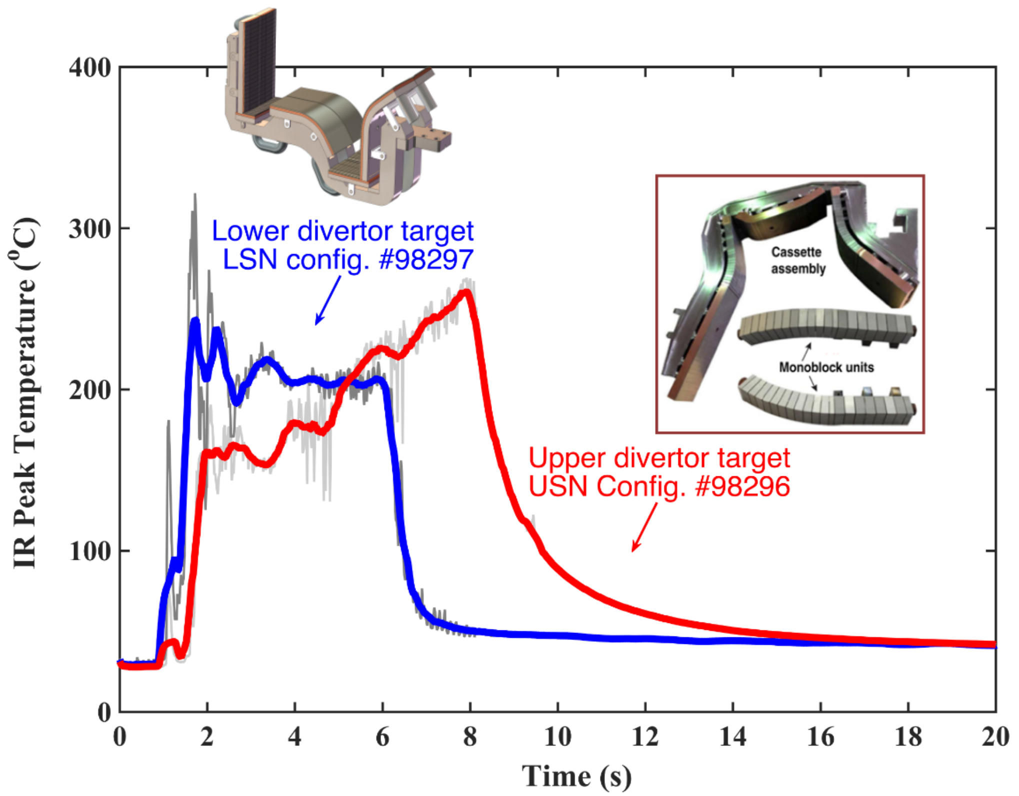


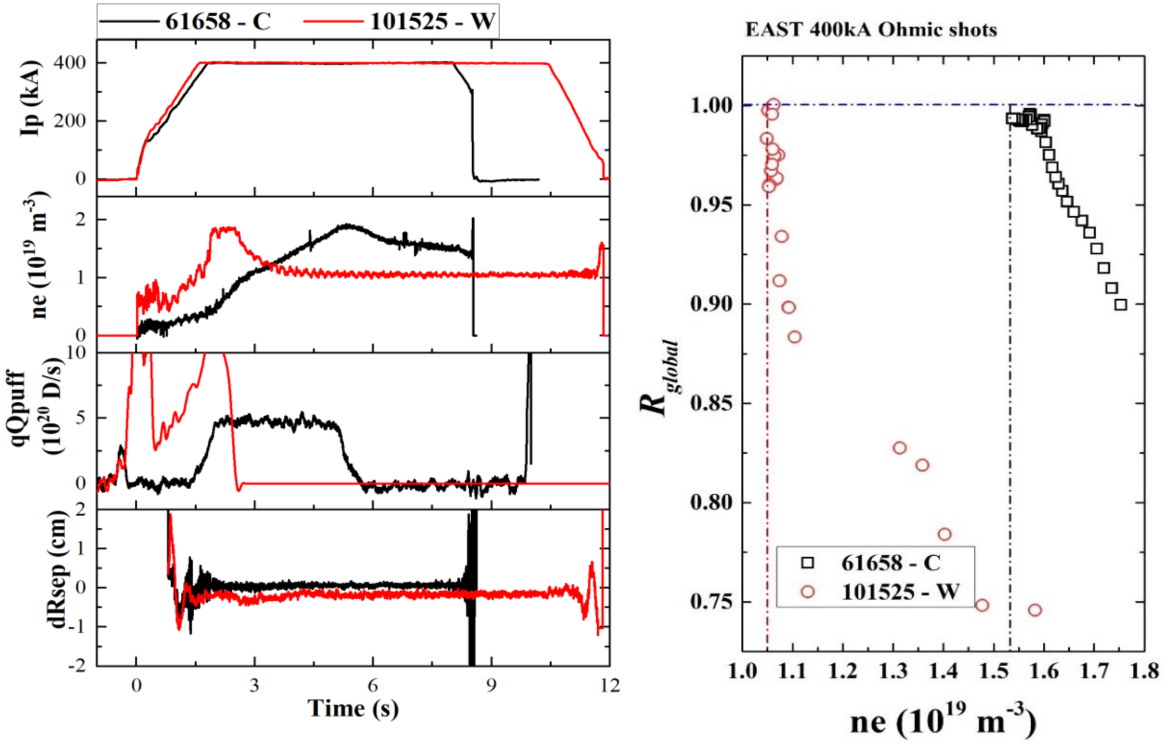


Mizuki Sakamoto, 2022 PSI poster

Effect of divertor structure on particle exhaust

- Compared with upper divertor, **new lower W divertor with larger water cooling capacity**, the wall temperature will quickly achieve balance, **less gas release from lower divertor.**





– Compared to previous lower graphite divertor, new W divertor has lower recycling

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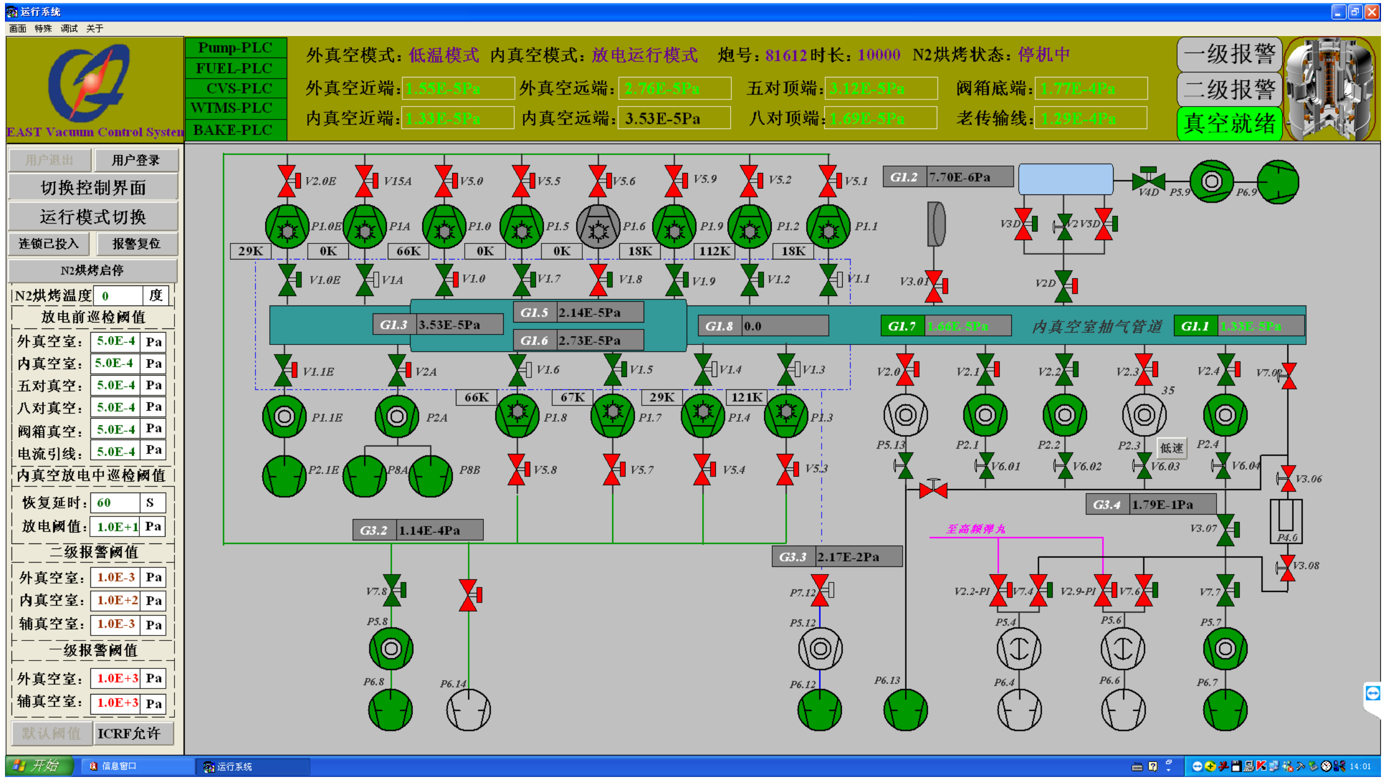
EAST pumping systems of plasma discharge VV

- Pumping system provides limit vacuum and meets the particle exhaust requirement of steady state plasma discharge with **Max.10 $Pa \cdot m^3/s$ gas feeding**
  - Impurity and fuel particle exhaust : D/He/N/Ar/Neon…
  - 13 cryopumps + 4 molecular pumps
  - 2 in vessel cryopumps



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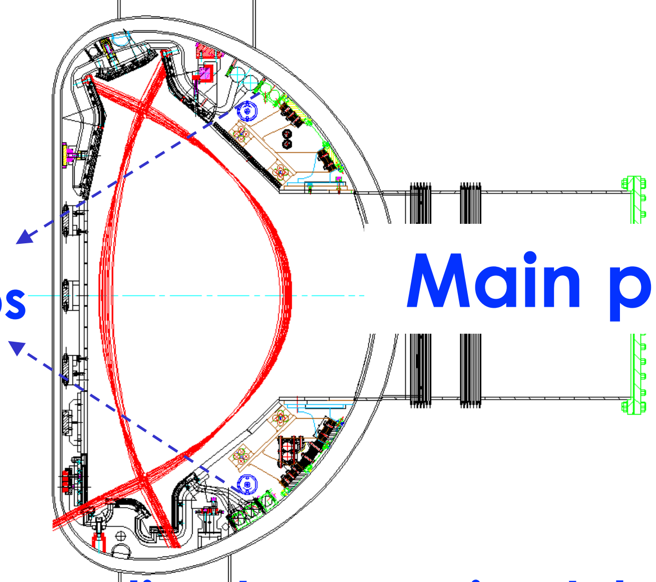
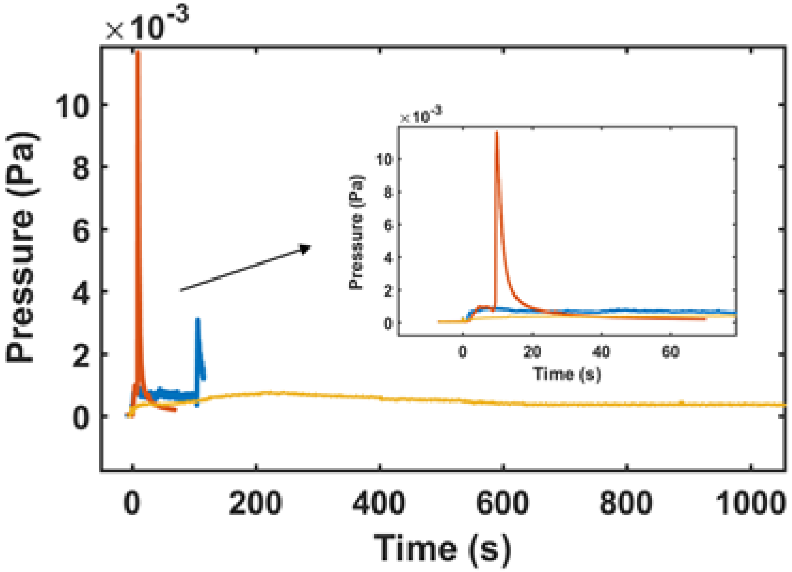
Upgrade of pumping systems for improving particle exhaust in EAST



- Design larger pumping speed and capacity cryopumps
  - Pumping speed(H_2): 11 m^3/s → 18m^3/s
  - Capacity: 25 $Pa\cdot m^3$→100$Pa\cdot m^3$

pumping system	*type*	*tot pumping speed(m^3/s)*
main pumping system	*turbo pump*	*25*
	cryo-pump	*28*
upper divertor pump	*cryo-pump(in-vessel)*	*65*
	cryo-pump(out-vessel)	*13*
lower divertor pump	*cryo-pump(in-vessel)*	*65*
	cryo-pump(out-vessel)	*4.5*

Further increasing pumping capacity for SS plasma

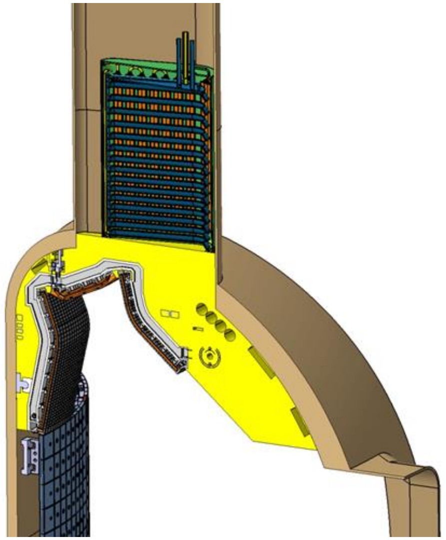


Neutral pressure kept constant during long pulse plasma

- ◻ Development of plug-in cryopumps
- ◻ Develop quickly regeneration cryopumps

provide a technologic reference for CFETR

Plug-in cryogenic pump ($6m^3/s$)



Pump No.	CFETR steady-state operation (120s per grid), 9 cryopumps alternate running											
	1	2	3	4	5	6	7	8	9	10	11	12
1	P	P	P	P	R	R	R	R	R	P	P	P
2	R	P	P	P	P	R	R	R	R	R	P	P
3	R	R	P	P	P	P	R	R	R	R	R	P
4	R	R	R	P	P	P	P	R	R	R	R	R
5	R	R	R	R	P	P	P	P	R	R	R	R
6	P	R	R	R	P	P	P	P	P	R	R	R
7	P	P	R	R	R	R	P	P	P	P	R	R
8	P	P	P	R	R	R	R	P	P	P	P	R
9	P	P	P	P	P	R	R	R	P	P	P	P

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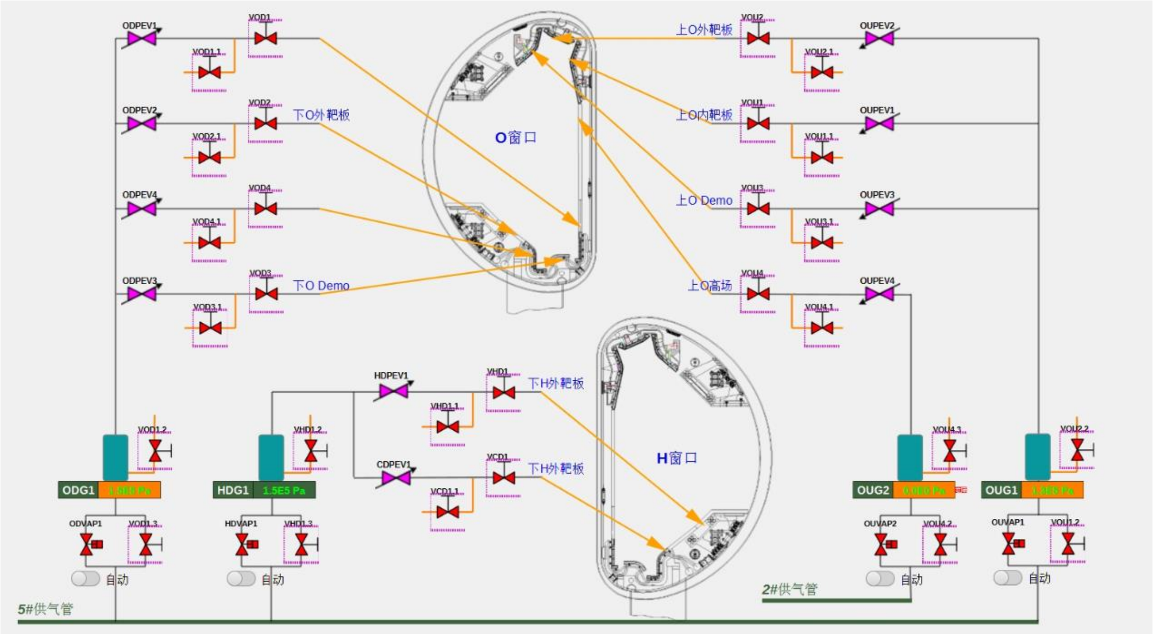
Gas puffing systems

- **Gas puffing: a basic fueling technique, provides working medium for plasma establishment, heating antenna, and divertor experiment, wall conditioning**
- **~20 gas puffing positions at high/low field side, upper/lower divertor.**
  - Response time：20-100ms；
  - Valve response time：2ms；



Divertor gas puffing systems

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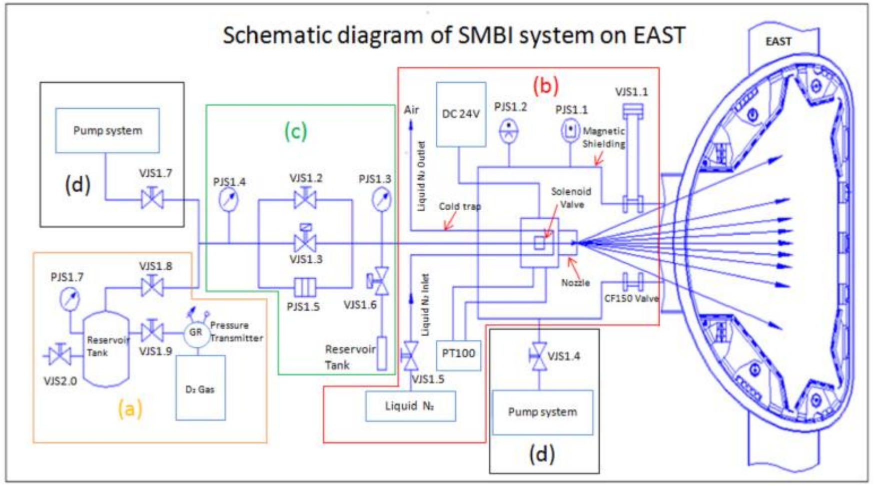
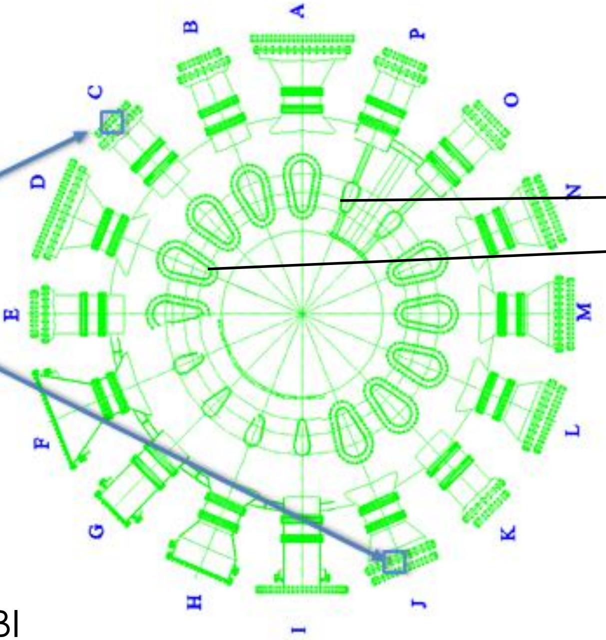
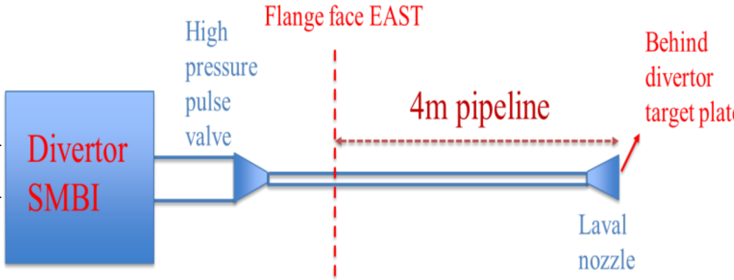
Supersonic molecular beam injection (SMBI)







Design of mid plane SMBI

Design of divertor SMBI

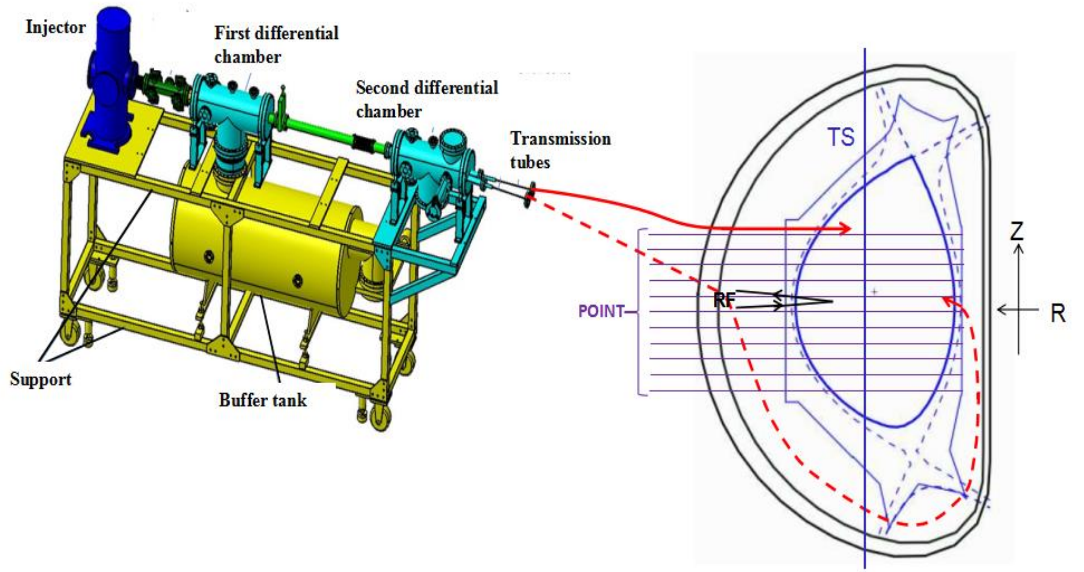
- ☐ **Supersonic beam: formed through a Laval nozzle and high pressure gas.**
- ☐ **2 located at midplane, and 2 at divertor.**
  - Theory speed: 400-2000m/s; Max. gas flux: 2.47×10^{22}/s
  - Max. injection depth in plasma: 175-350mm

- EM valve response time: 160μs
- Delay time :~5-25ms(mid-divertor)

Development of advanced Pellet injection systems

☐ Pellet injection

- ✓ Screw extrusion, propellant acceleration
- ✓ Low frequency: plasma core fueling
- ✓ High frequency: ELM pacing



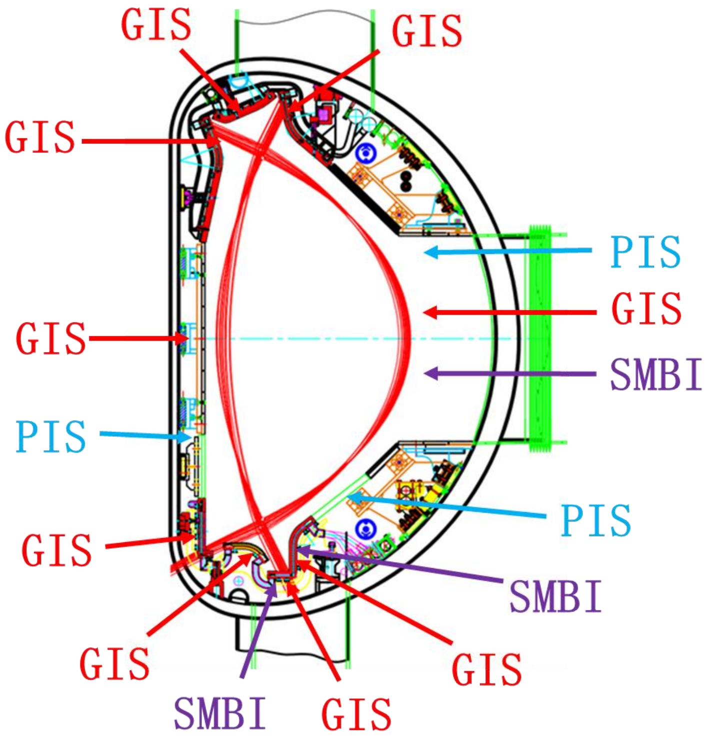
Parameters	PI-20	PI-50(new system)
Pellet size (H_2/D_2)	Diameter 2mm, length 2mm	Diameter 1.5mm, Length1.2/1.5/1.8mm
Pellet velocity	150-300m/s	200-300m/s
Pellet frequency	1~10Hz	Two modules 1~50Hz
reliability	≥95%	≥90%

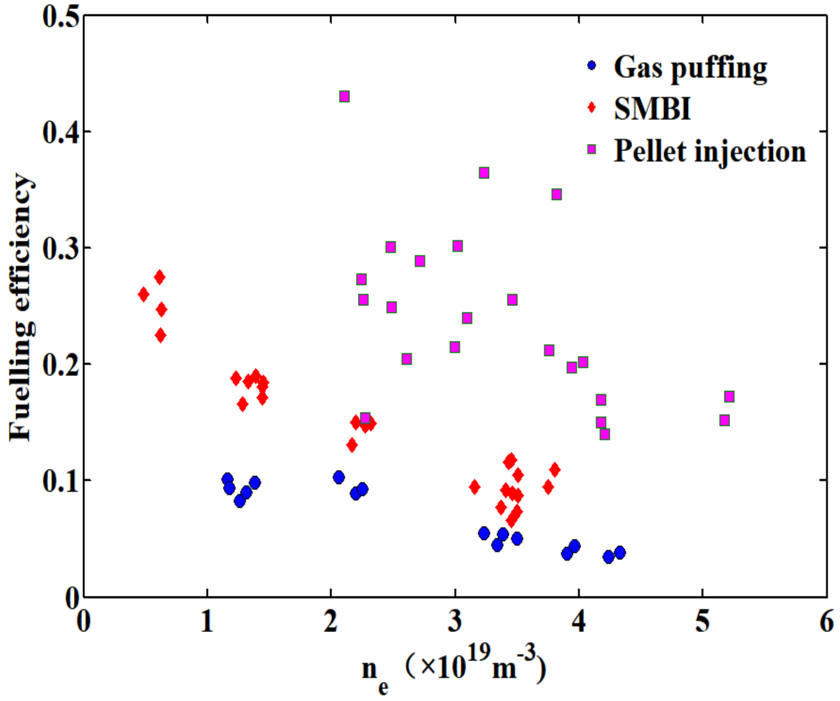
Fueling efficiency of various fueling methods

- **Pellet fueling efficiency is higher** than SMBI and gas puffing.
- **SMBI used as density feedback** due to its stability for long pulse plasma and it produces small density disturbance.

$$\eta = \frac{\Delta(n_e l)V/2a}{N_{pel}}$$

GIS: Gas puffing
PIS: Pellet injection





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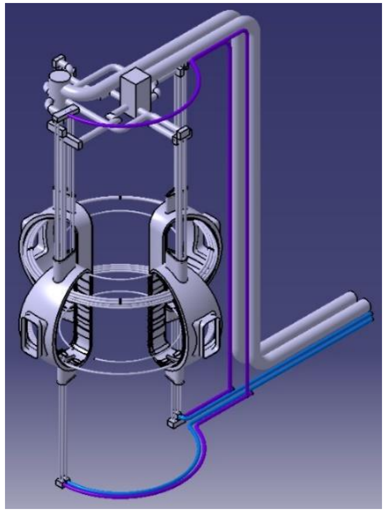
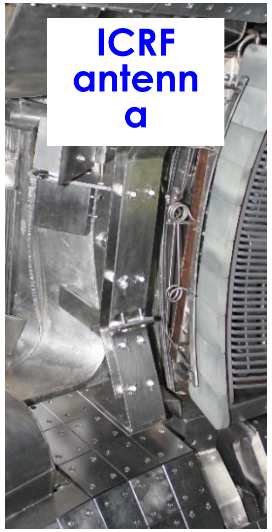
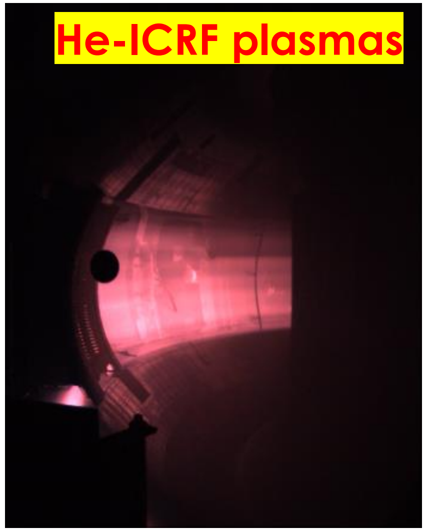
Baking and discharge cleanings

- **Baking: hot N_2, ~200 °C**
- **Glow discharge cleaning (GDC)**
  - 4 anodes inside, first wall as cathode
  - Breakdown: 1000 V, D_2/He 1 - 20 Pa
  - Operation: 100 - 500 V, 2 - 6A
- **Ion Cyclotron Radio Frequency (ICRF) discharge cleaning**
  - Dedicated belt antenna
  - 27/41 MHz (New power supply)
  - 20-30 kW (max. 50 kW)
  - **Compatible with magnetic field**







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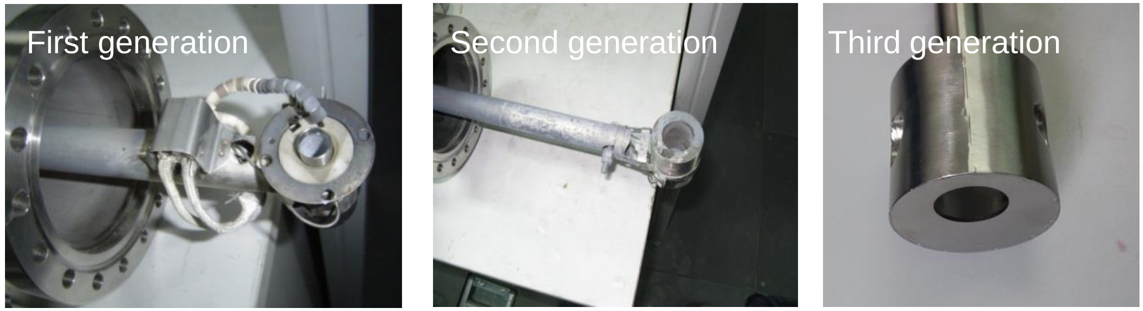
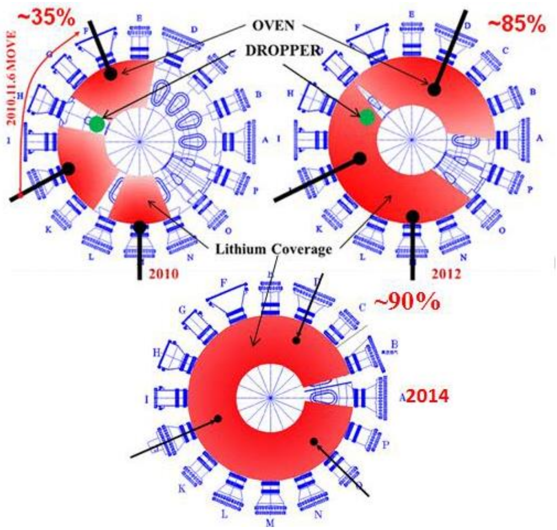
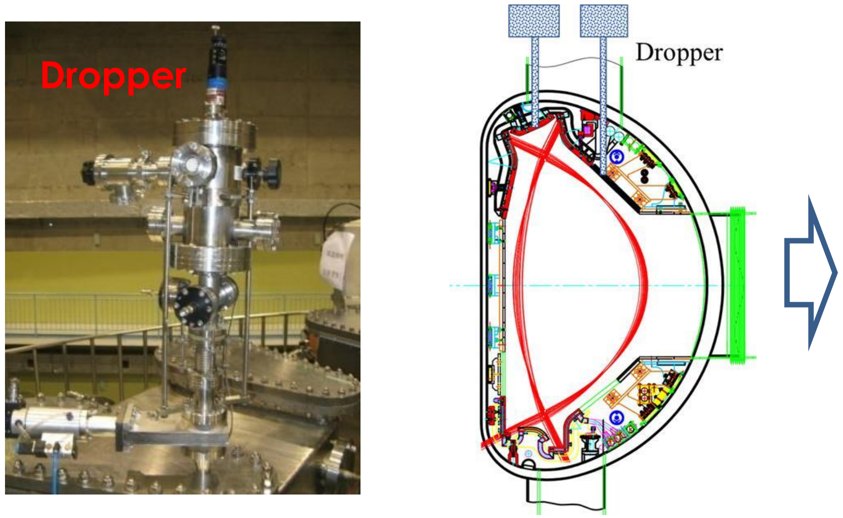
Coating and lithium injection technologies

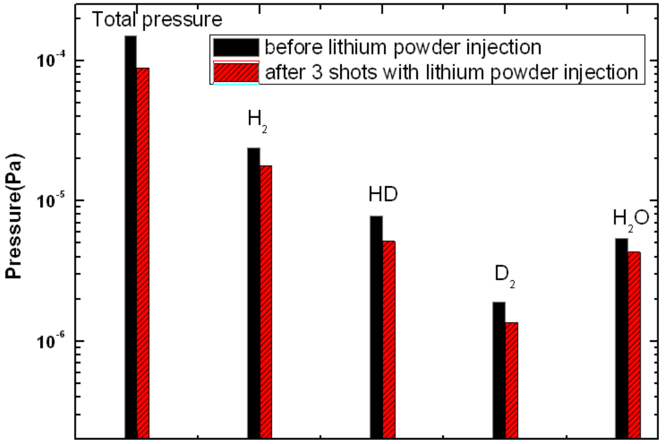
- **Lithium coating by evaporation**
  - Three ovens (500-550 °C) for uniformed coating
  - Deeply movable ovens for high coverage
  - Associated by GDC or ICRF discharge (1~3 hours/coating, 5~15 g/coating)
- **Lithium dropper for real-time active lithium coating during plasma operation**



Gradual upgrade of Li oven







EAST lithium dropper from PPPL

G.Z. Zuo, PPCF(2012)/FED(2018)

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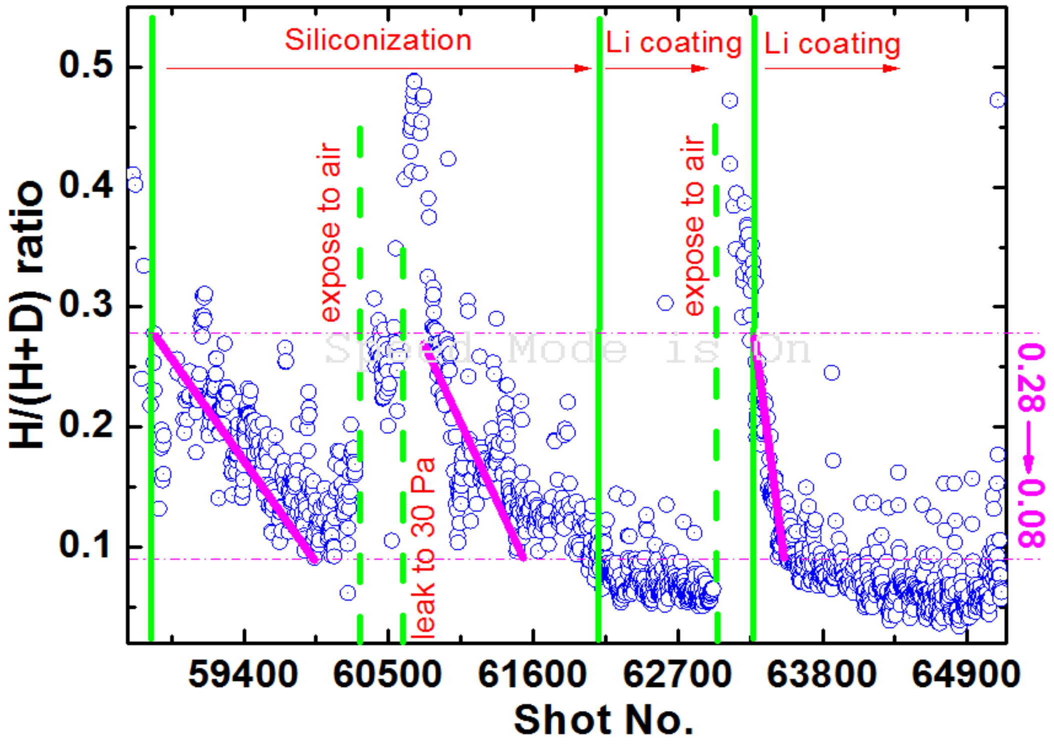
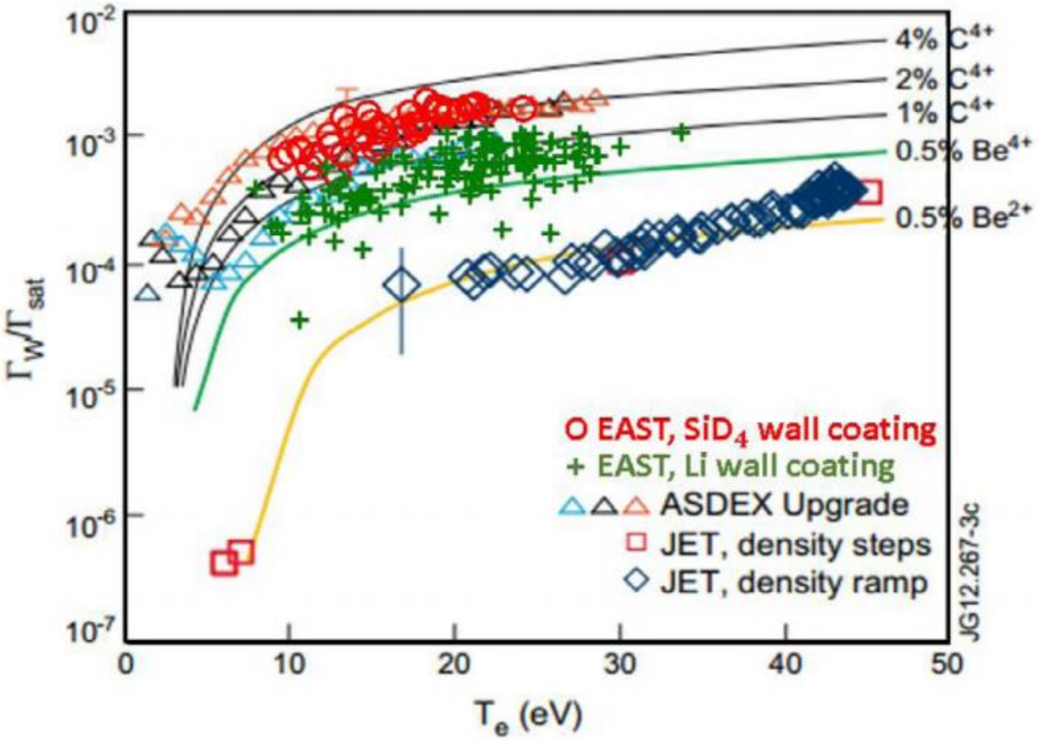
Comparison of Si and Li coatings





- Low H/(H+D) achieved by Silicon (~10%) and lithium (~5%) coating
- Lithium coating is more effective than SiD4 coating for hydrogen control and impurity control

Fusion Engineering and Design 131 (2018) 41–48

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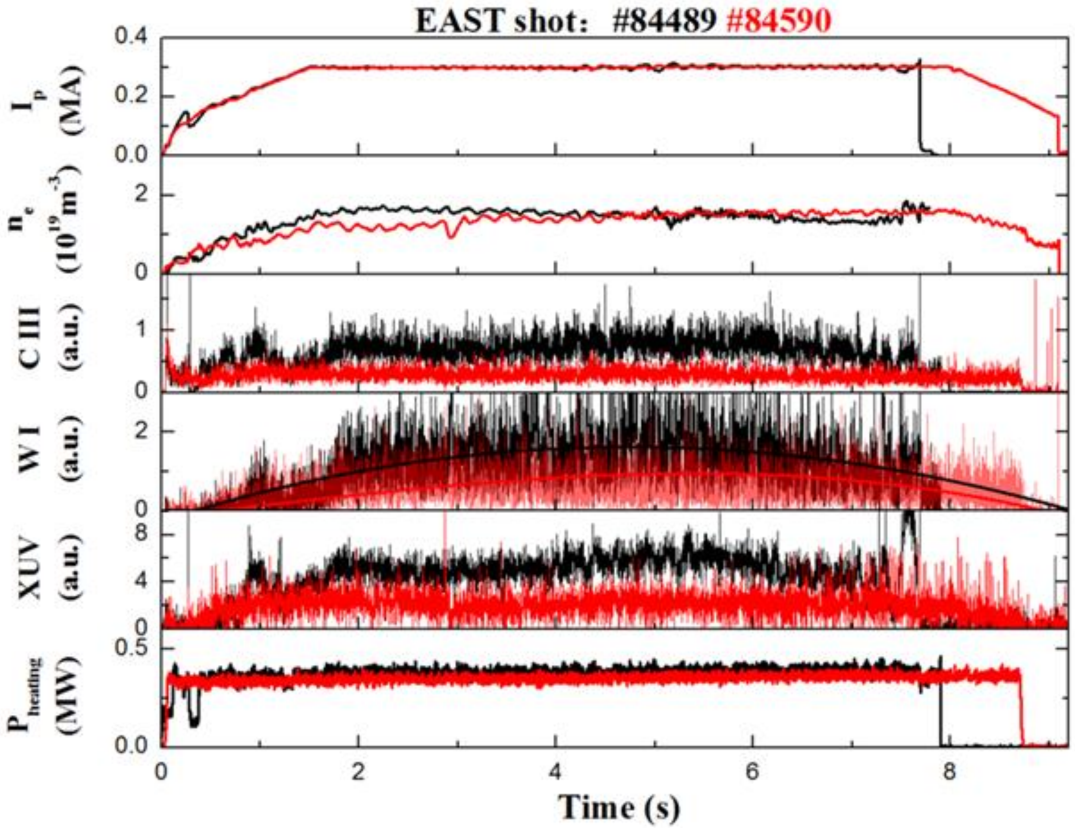
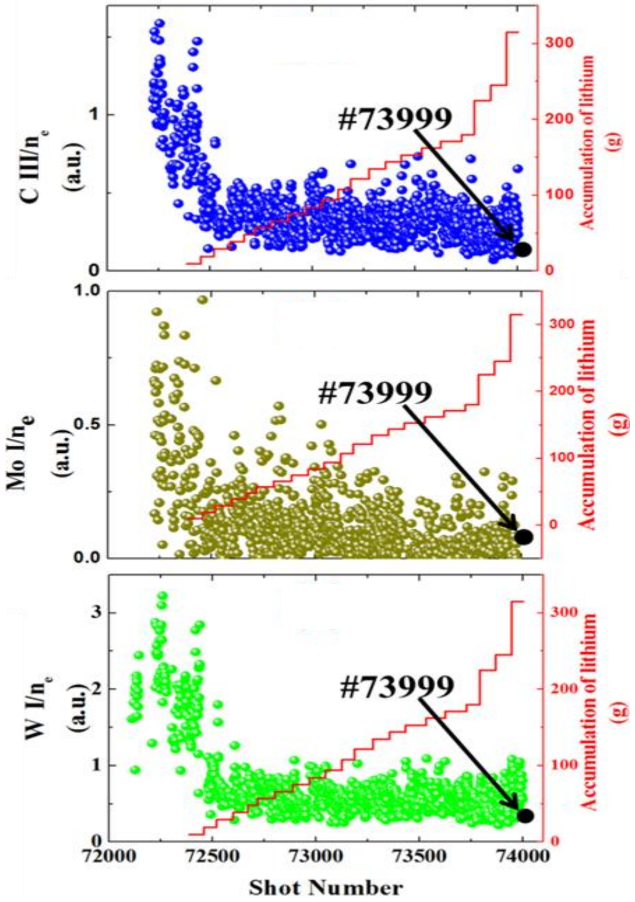
Impurities control using Li coating

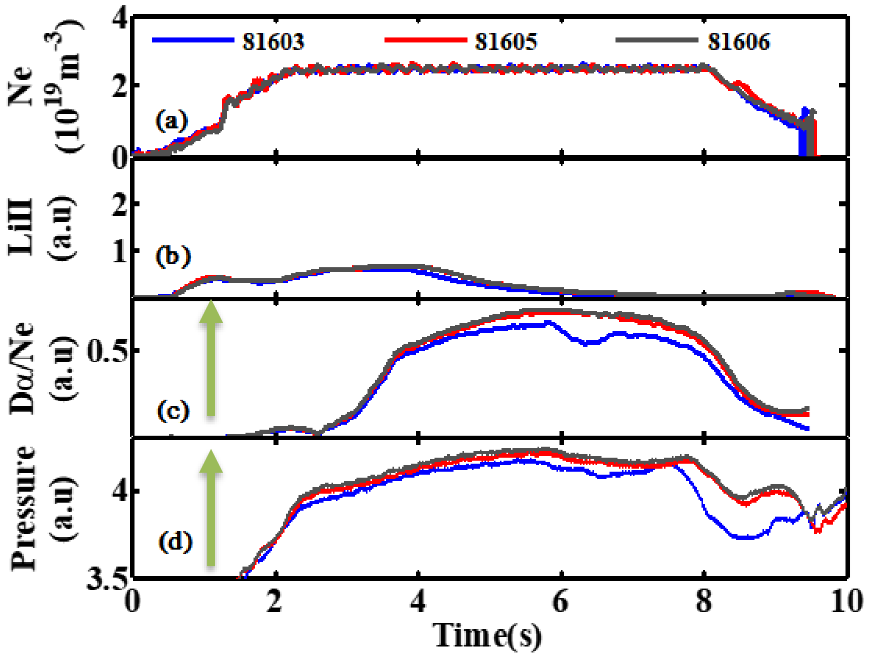


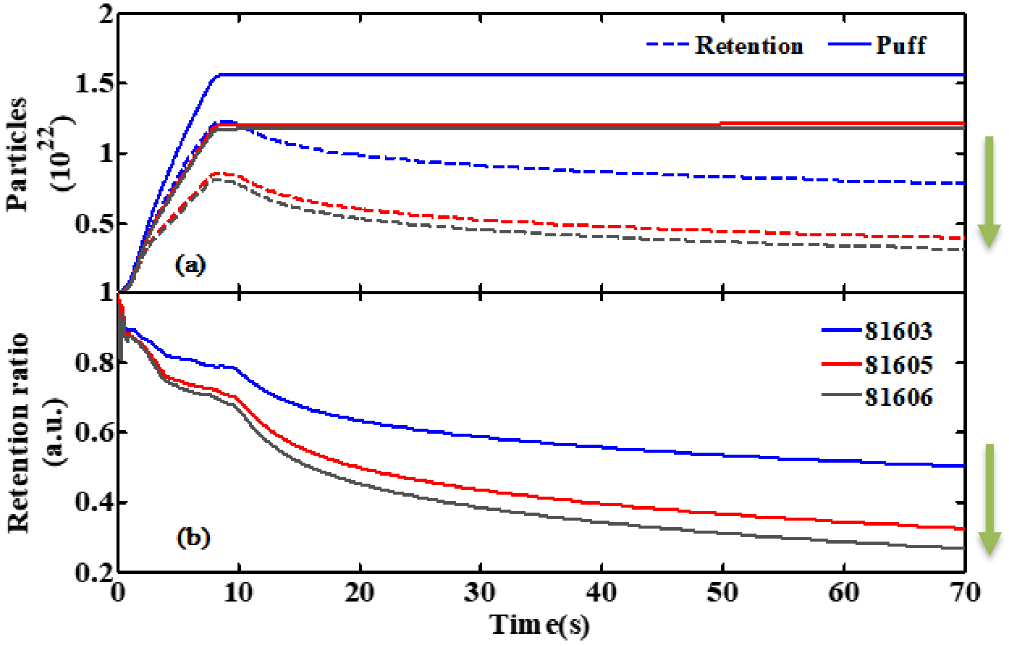


- **Both high-Z (W) and low-Z (C) impurity reduced after Li coating, and gradually decreased with the increase of Li coating times**

Fusion Engineering and Design 137, 2018, 202-208

Recycling and wall retention after Li coating





Ohmic discharge: Ip ~ 450KA, Ne ~ 2.75×10^{19}m^{-3}

C.L. Li, G.Z. Zuo, et al, PPCF(2021)

- ☐ **Particle recycling gradually increased indicated by divertor neutral gas pressure and Dα line emission;**
- ☐ **Amount of fuel particle puffing and retention ratio gradually decreased;**
- ☐ **Absorption ability can be seen to gradually become weak from shot to shot.**

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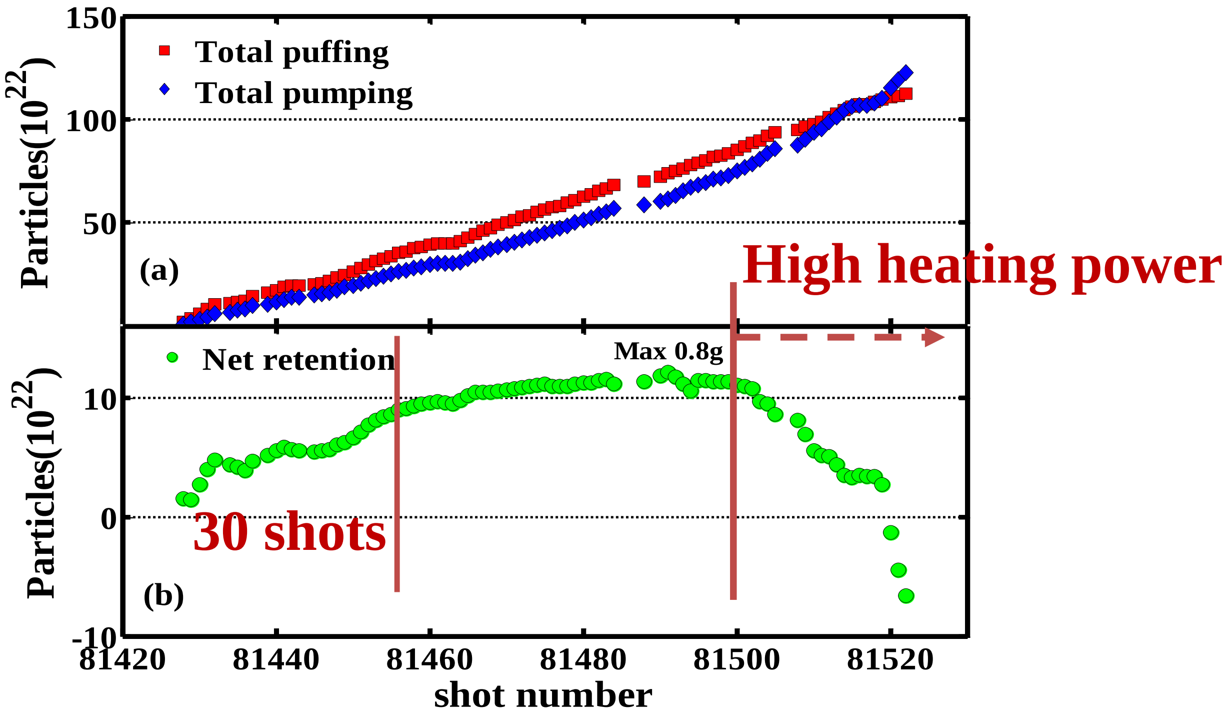
Fuel particle control gradually weakens with Li coating in successive discharges

- **Wall net retention gradually increased during the first 30 shots after Li coating;**
- **With increase of heating power, wall retention quickly decreased;**
- **The ratio of retained D particle to Li atom was ~12%;**



C.L. Li, G.Z. Zuo, et al, PPCF(2021)

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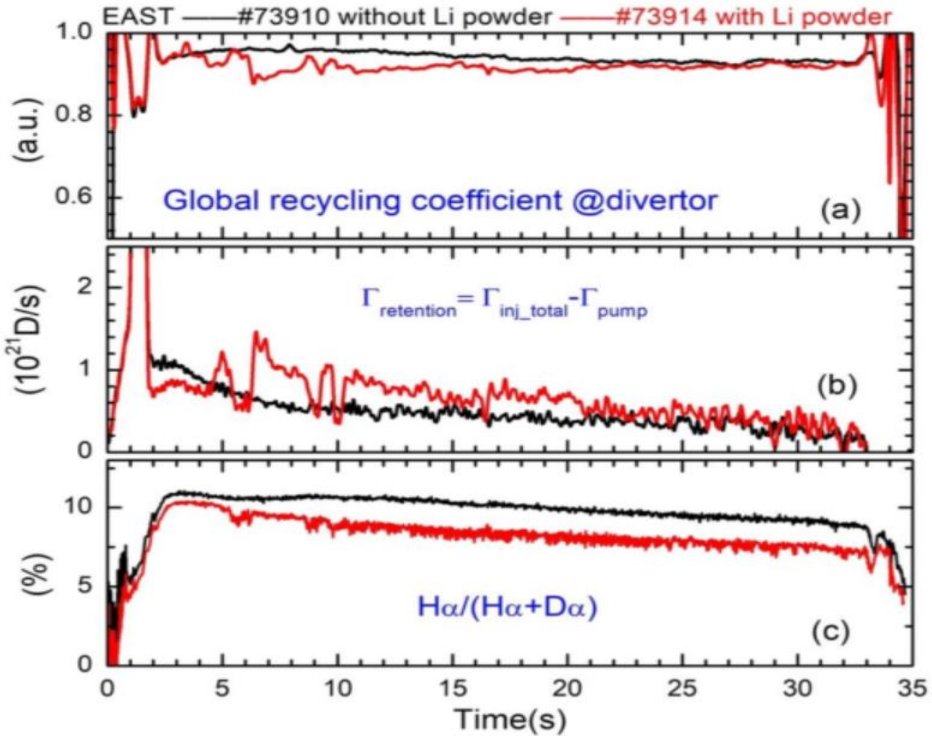
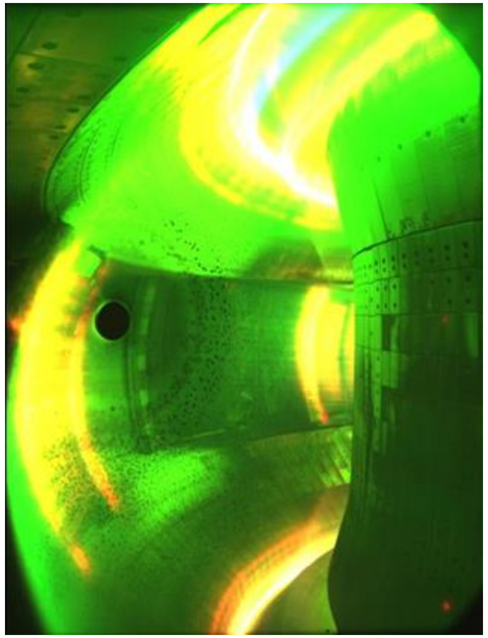
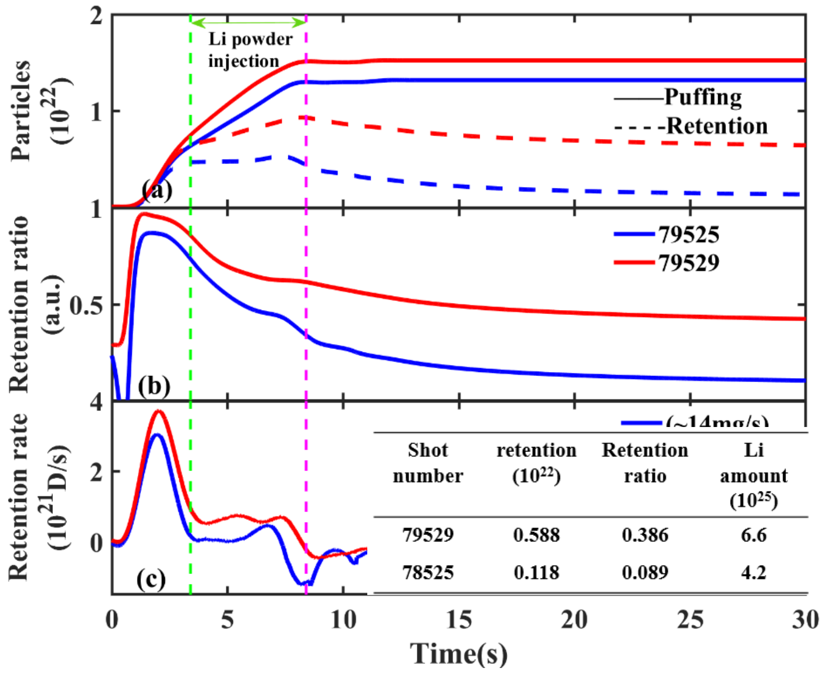
Realtime Li injection for refreshing Li film to continuously control recycling







Shot number	retention (10^{22})	Retention ratio	Li amount (10^{25})
79529	0.588	0.386	6.6
78525	0.118	0.089	4.2

- Global **recycling coefficient** and **H/(H+D) ratio** are reduced by ~**7% and 20%**
- Wall retention has a obvious increase during Li powder injection;

Z.Sun et al, 2018 PSI

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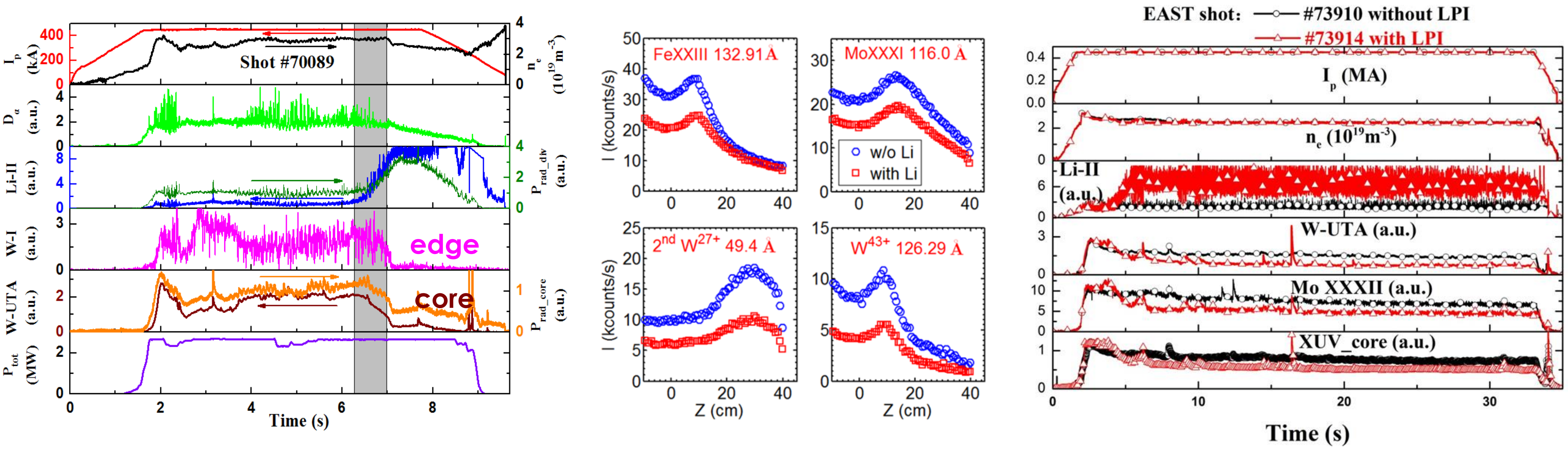
W impurity suppression using Li aerosol injection



- ☐ **Core W impurity decreased by ~50%,edge W decreased by ~45%**
- ☐ **Good compatibility of Li aerosol with long-pulse H-mode operation**

Plasma Phys. Control. Fusion 62 (2020) 085012

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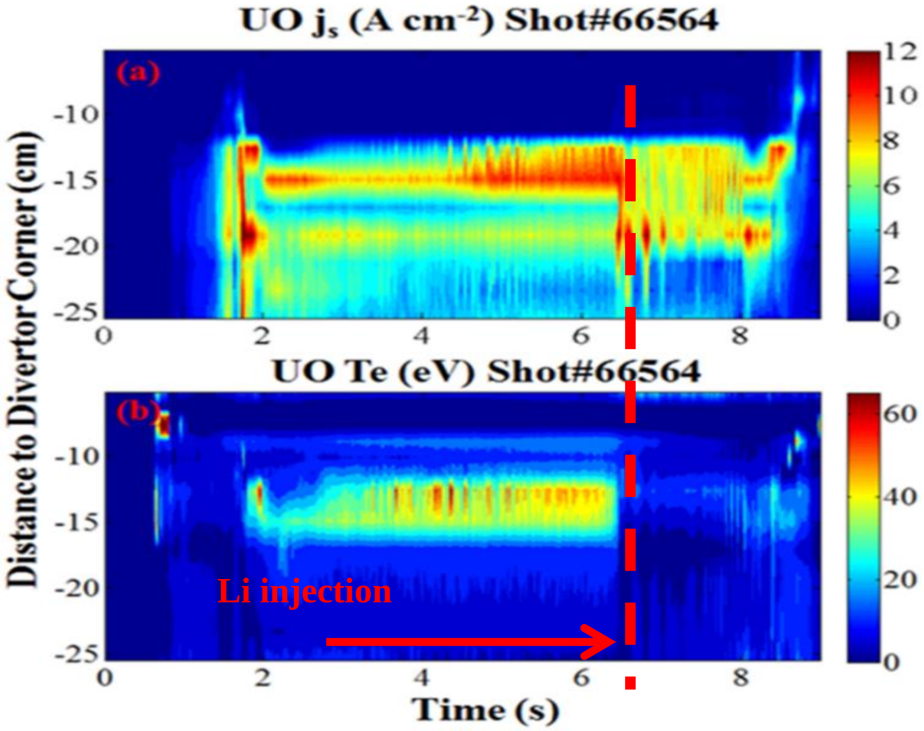
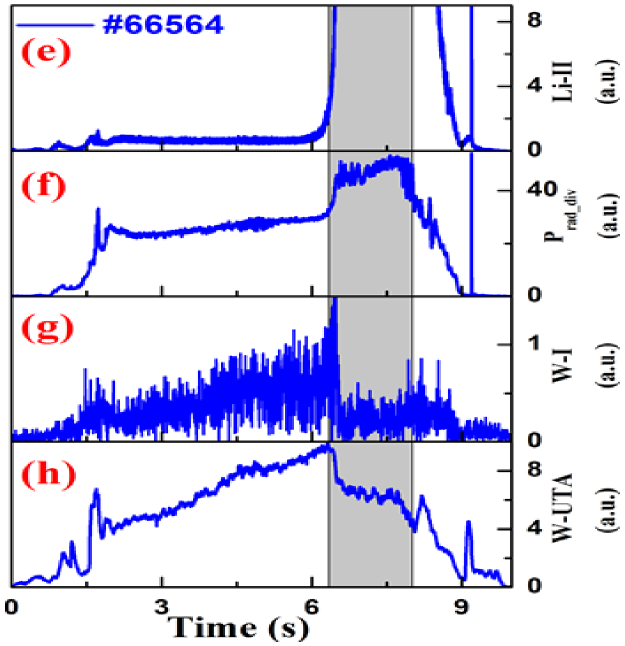
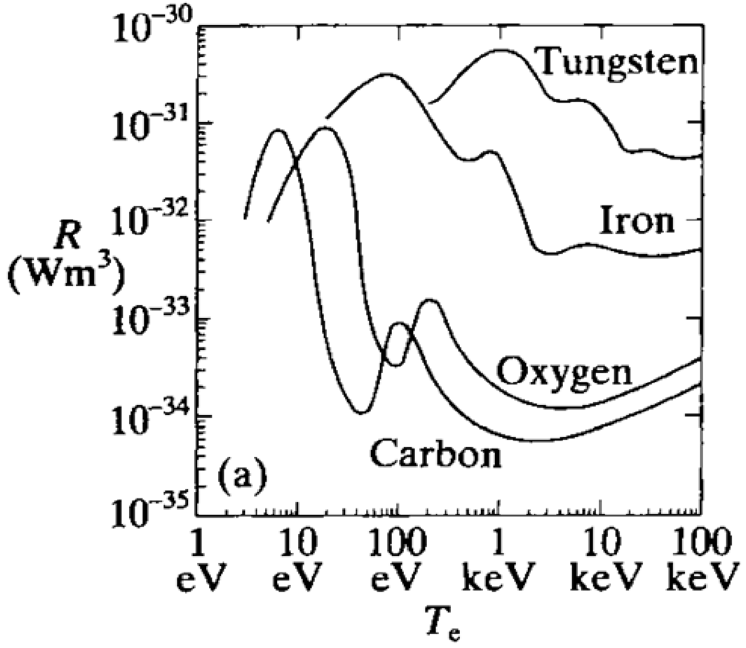
Main mechanism of W impurity reduction







- ☐ **Li power injection leads to decreased W impurity radiation**
- ☐ **Li power injection reduces divertor Te resulting in decreased W sputtering**

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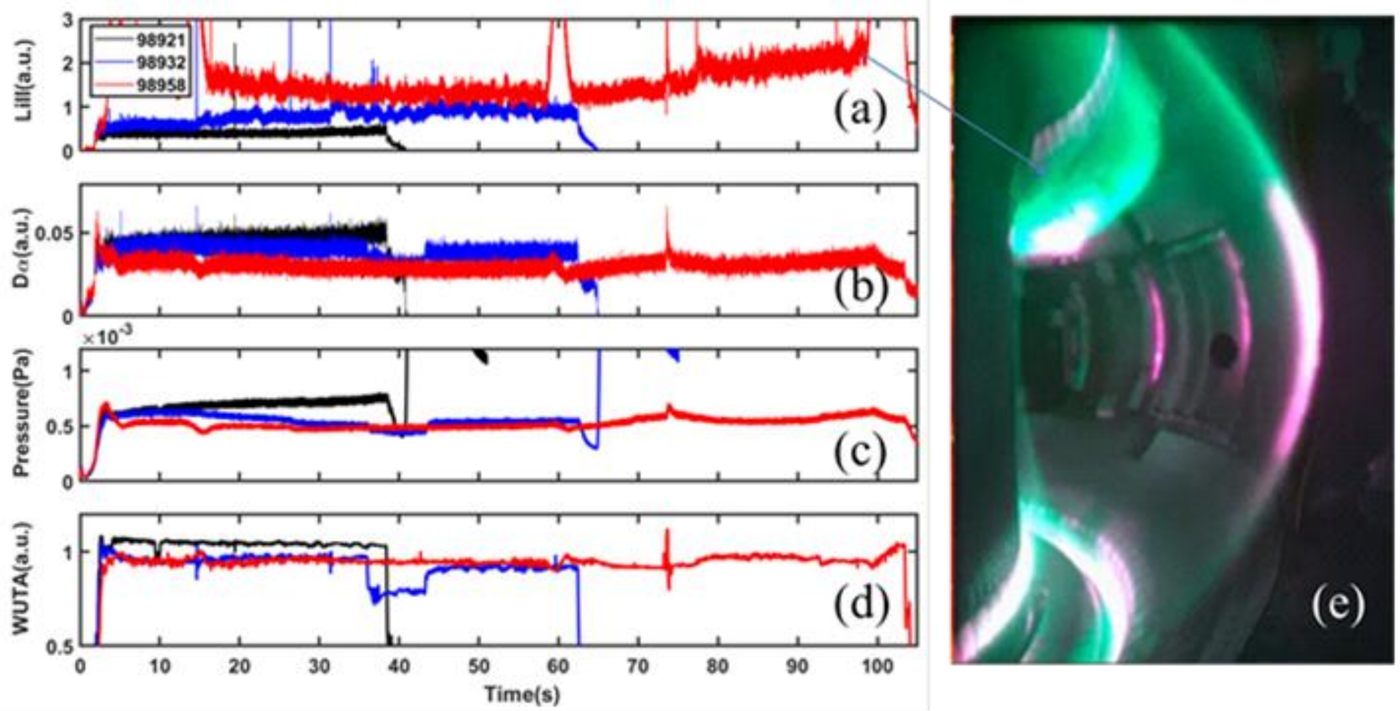
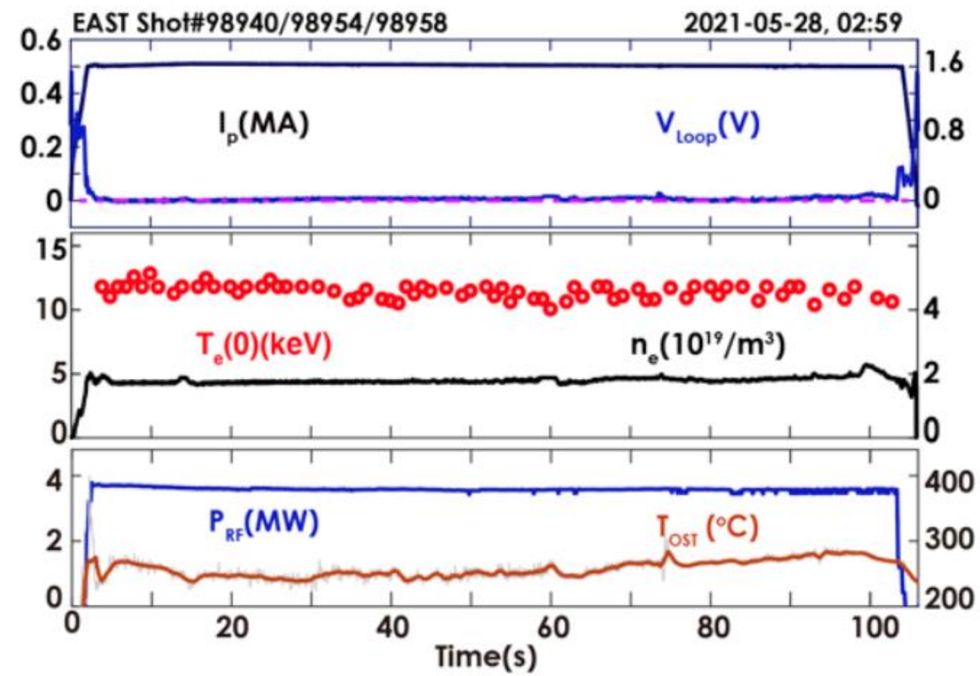
New achievement of >100s & Te > 10 keV long pulse on W divertor





LSN/Td~105s/0.5MA/ne~1.75x10^{19}/m^3，PEC~1.4MW, PLH2~2.4MW，Te0>10.5keV

- ☐ **Optimized fueling method and plasma configuration**
- ☐ **Routine Lithium coating (~10 g) + real-time Li powder injection**

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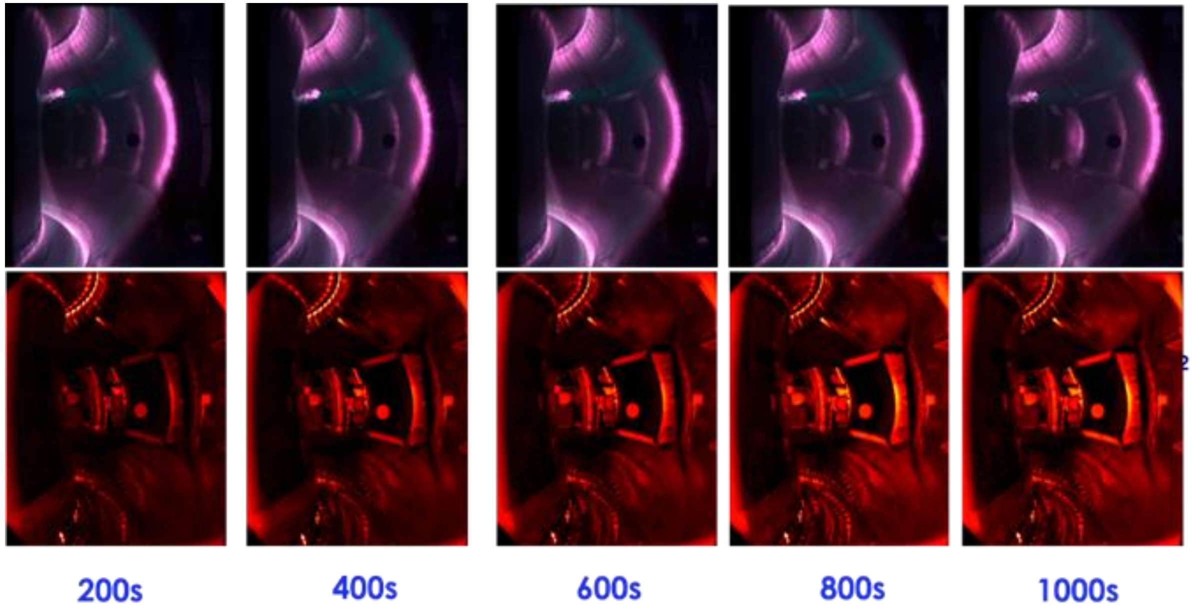
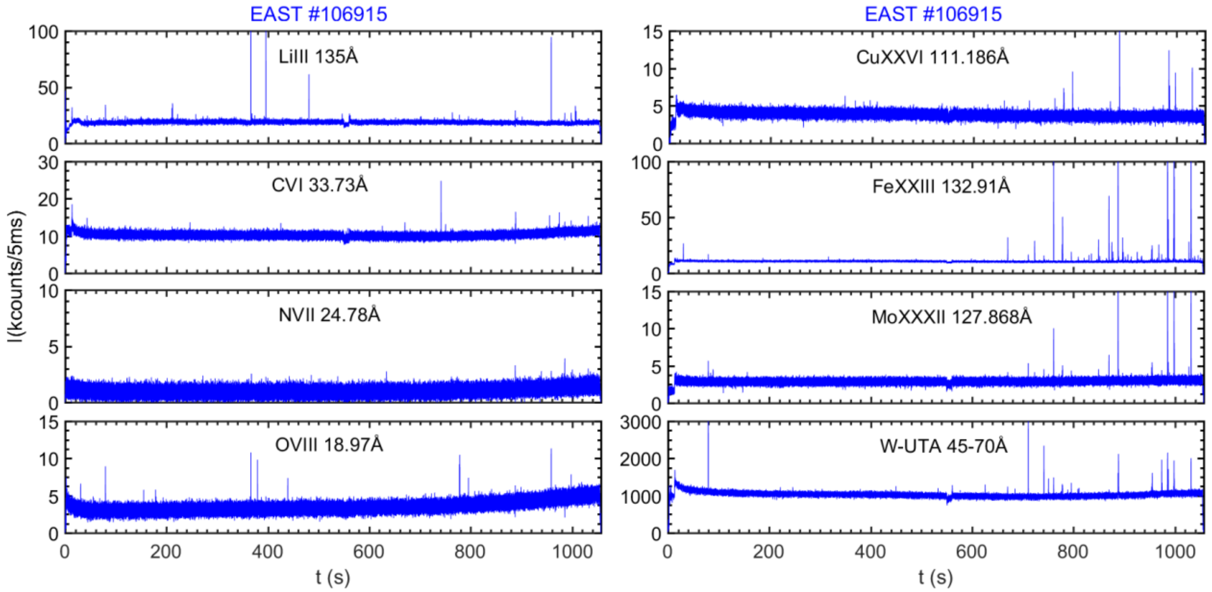
Well Suppressed Impurity Behavior in 1000s Time Scale





Intensive Li coating + Real-time Li injection **with ~1.3mg/s**

- **A stable behavior of low-Z impurity.**
- **Tungsten concentration, C_W, is estimated to be 5-6 $\times 10^{-5}$.**
- **Frequent sputter of metallic impurities (Fe, Cu, Mo, W) occurred from t=700s, which did not impact the steady-state discharge fortunately.**

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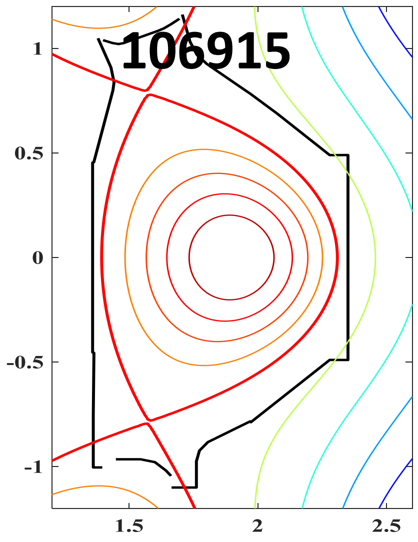
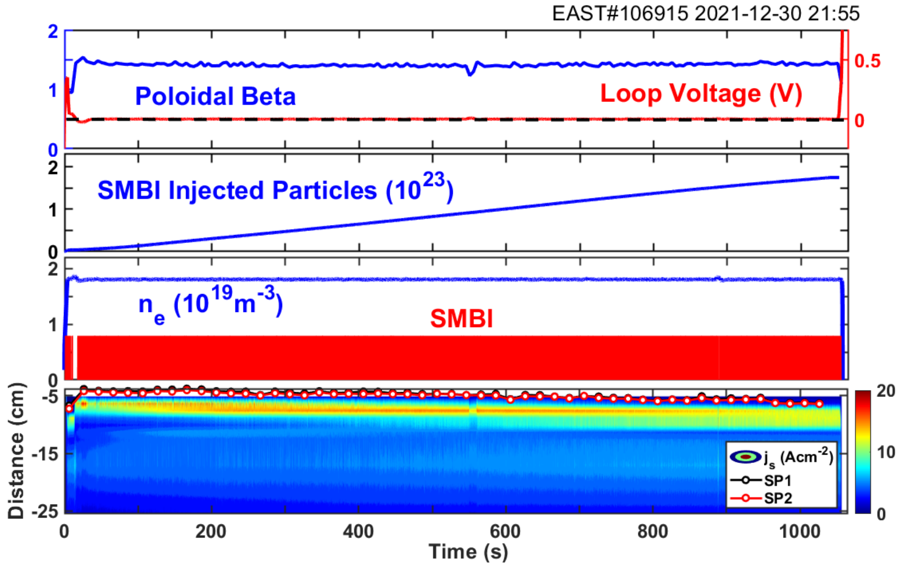
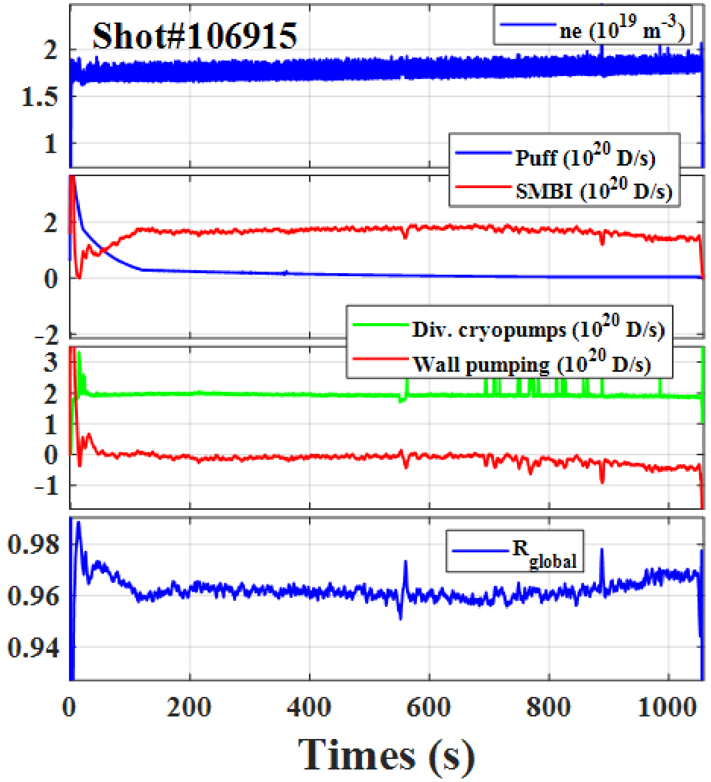
Controllable particle recycling in 1000s Time Scale







- **Enhanced particle exhaust：** new divertor structure with enlarged divertor slot and upgraded pumping system
- **Optimized configuration** for good particle control
- **High efficiency fueling** by SMBI & DOME puffing
- **Enhanced wall pumping** by real-time lithium injection

Stable fuel particle recycling ： $R_{glob.}<1$

Yu Y.W., Zuo G.Z. et al., 2022 PSI invited talk/This meeting

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Outline

- ☐Introduction
- ☐Upgraded PFMs and structure
- ☐Enhanced pumping and fueling capability
- ☐Advanced wall conditionings
- ☐Summary and outlook

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Summary and outlook

- **Advanced vacuum and wall conditioning technologies**: advanced ITER like lower W divertor structure, enhanced particle pumping and fueling capability, various wall conditionings, was **successfully developed in EAST.**
- **A record plasma of ~1056s pulse** duration with a controlled plasma density, global recycling coefficient <1 and core tungsten impurity concentration ~5.6×10^{-5} **was successfully achieved .**
- **Next step, plug in and quickly regeneration cryopumps, advanced wall conditioning technologies will be further investigated for SS plasma operation.**

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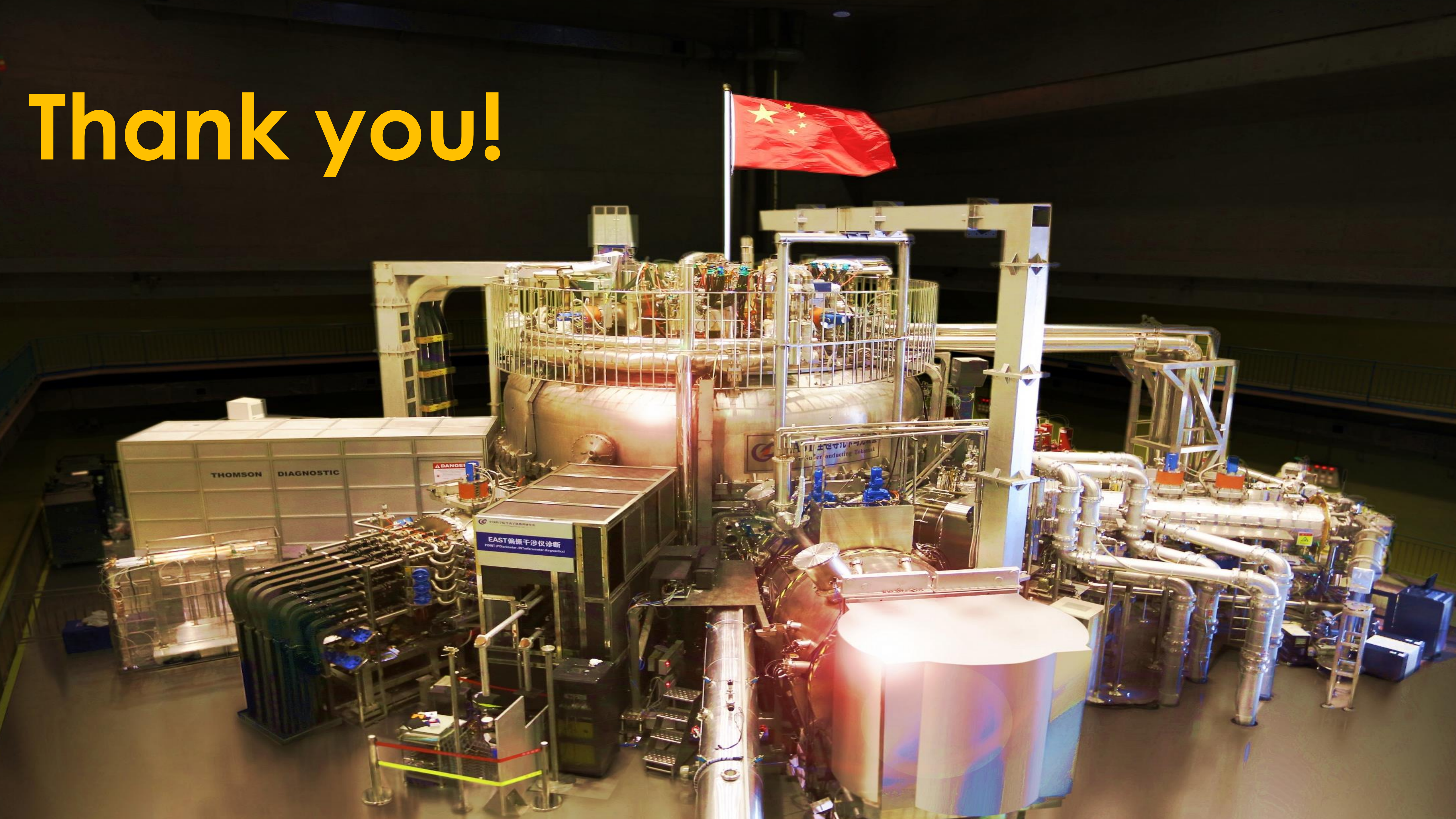
Thank you!


THOMSON DIAGNOSTIC
DANGER
EAST偏振干涉仪诊断
POINT (POlarimeter-INTerferometer diagnostics)