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Advancing Fueling for Future D-T Fusion: Innovations in SMBI Technology and Physics-Based Fueling Strategies for Tritium

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Outline

- **Background**
- **Improvements of SMBI techniques**
- **Strategy for fueling via SMBI**
- **Heat load control with SMBI**
- **Summary**

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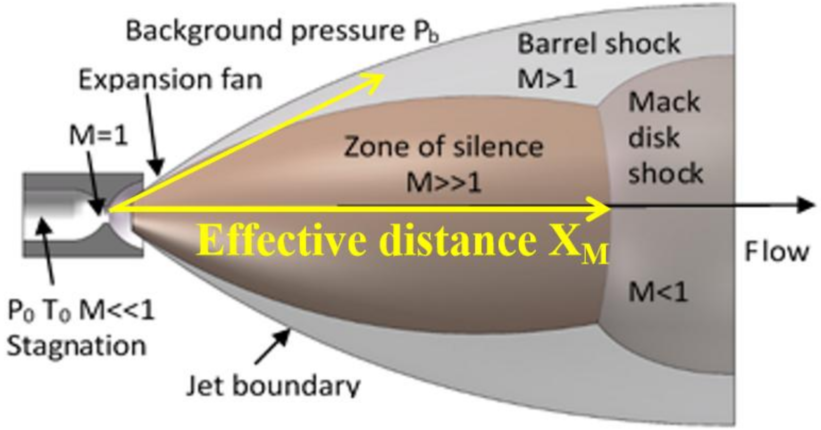
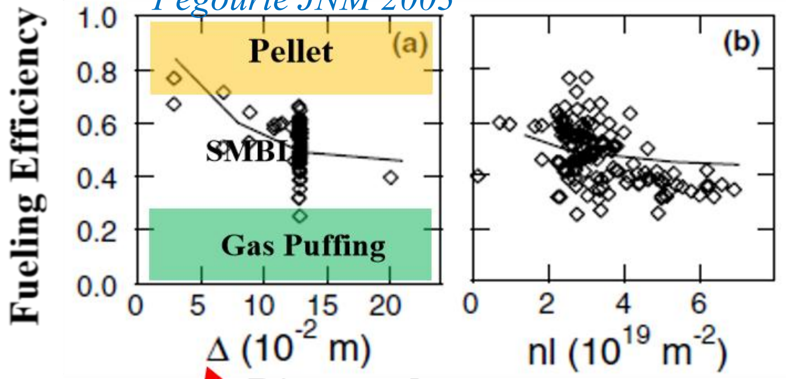
SMBI stands as the leading candidate for T_2 fueling at present

- Supersonic molecular beam injection (SMBI) was first introduced into the fusion field as a fueling technology on HL-1 and has been applied in more than a dozen fusion devices *[G.L.Xiao RMPP 2023]*

SMBI	Gas puffing
higher speed, higher fueling efficiency	slower speed, lower fueling efficiency
directivity	low directivity
lower recycling, supports long-pulse operation	higher recycling



Pégourié JNM 2003



Distance between plasma boundary and injector

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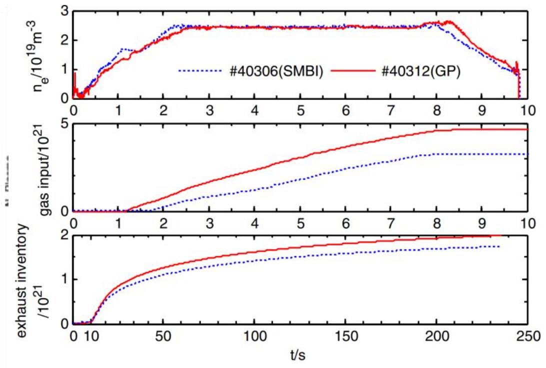

[Zheng PPCF 2013]

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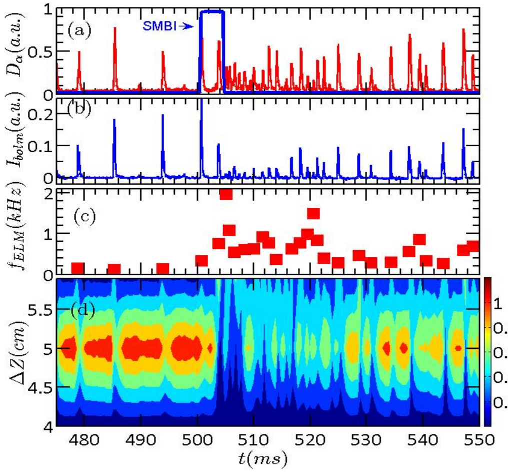
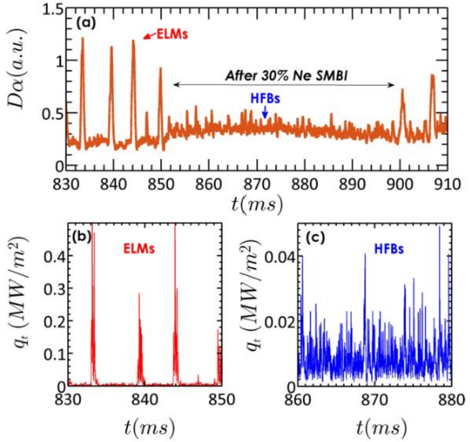
- **SMBI offers a significant benefit for heat load control**

  - **ELM control with SMBI**

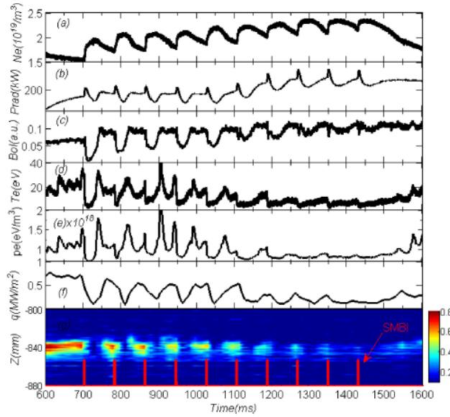
    - ✓ ELM mitigation by fueling SMBI first demonstrated in HL-2 [Xiao NF 2012], then applied in EAST and KSTAR[Zou IAEA 2012, Xiao NF 2014, Lee PoP 2015]
    - ✓ ELM suppression with impurity (or mixture) SMBI on HL-2/3 [Zhong NF 2019] and EAST [Cao PST 2025]

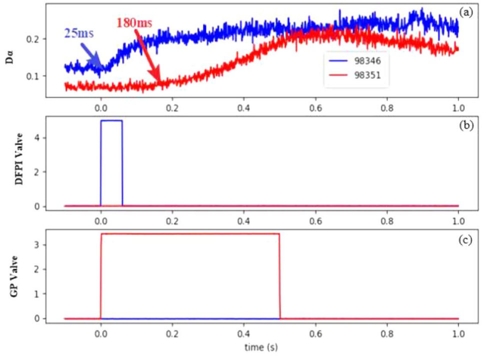




  - **Divertor detachment with SMBI**

    - ✓ Similar to GP, SMBI at midplane is applied to reduce the divertor heat on HL-2[Yan NF 2010, Gao JNM 2017] and detachment experiment on EAST [Yuan FED 2020].
    - ✓ SMBI directly installed in divertor can has good capacity, implemented on HL-2/3 and EAST [Xiao, AAPPS-DPP 2021, Cao FED 2022]





Challenges and solutions

Fuel supply → SMBI system design → Nozzle and injector → SMB characteristics → Plasma interaction

Challenges

- **low pressure for T_2 fueling**
  - ✓ SMB distribution control
  - ✓ convergent fuel
  - ✓ targeted plasma fueling
  - ✓ fueling efficiency
- **high heat load control**
  - ✓ time response
  - ✓ enhanced capacity

SMBI application

Solutions

- **techique improvements**
  - ✓ AI based distribution prediction
  - ✓ injector optimization
  - ✓ Multi-phase SMBI
  - ✓ Vector SMBI
- **experimental fueling strategy**
- **divertor SMBI for heat control**

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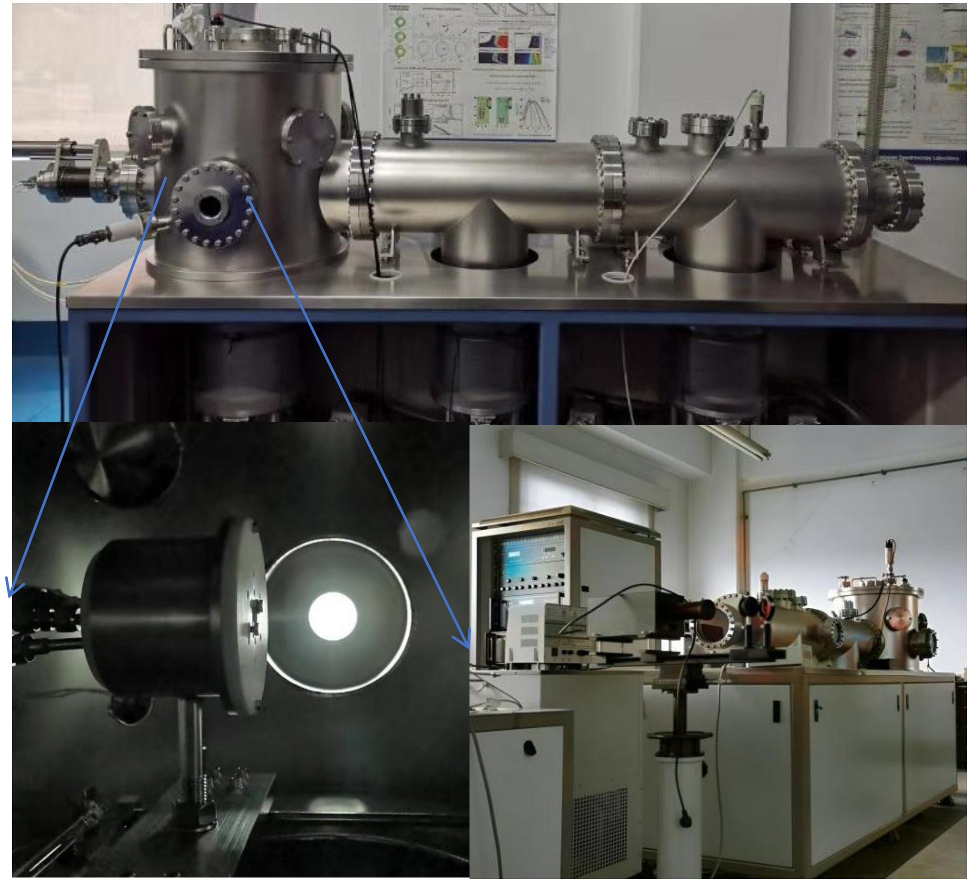
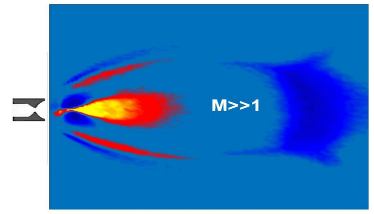
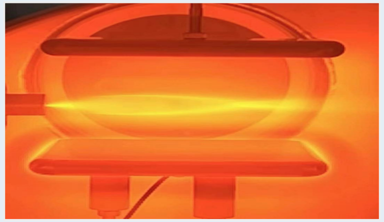
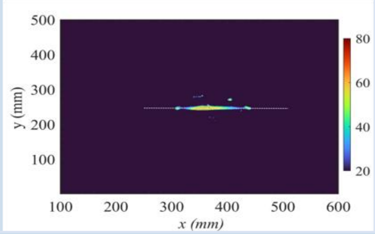
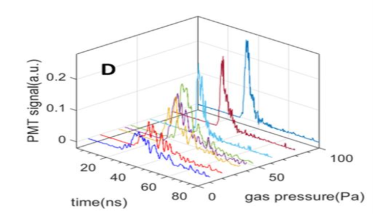
SMBI testing platform and diagnostic systems

■ **A offline SMBI testing platform with comprehensive diagnostic systems was estabished**

Offline SMBI testing platform

$>5\times10^{-5}$ Pa, $d_{max} = 0.5$ m, $L = 2.2$ m



Diagnostics	Parameters	Measurements
Schlieren system	**Beam structure, density**	
Glow discharge scanning LPs	**Beam structure, velocity**	
Laser Rayleigh scattering	**Scale of cluster**	
Laser induced fluorescence	**Atom density, velocity**	

AI-based SMBI velocity distribution

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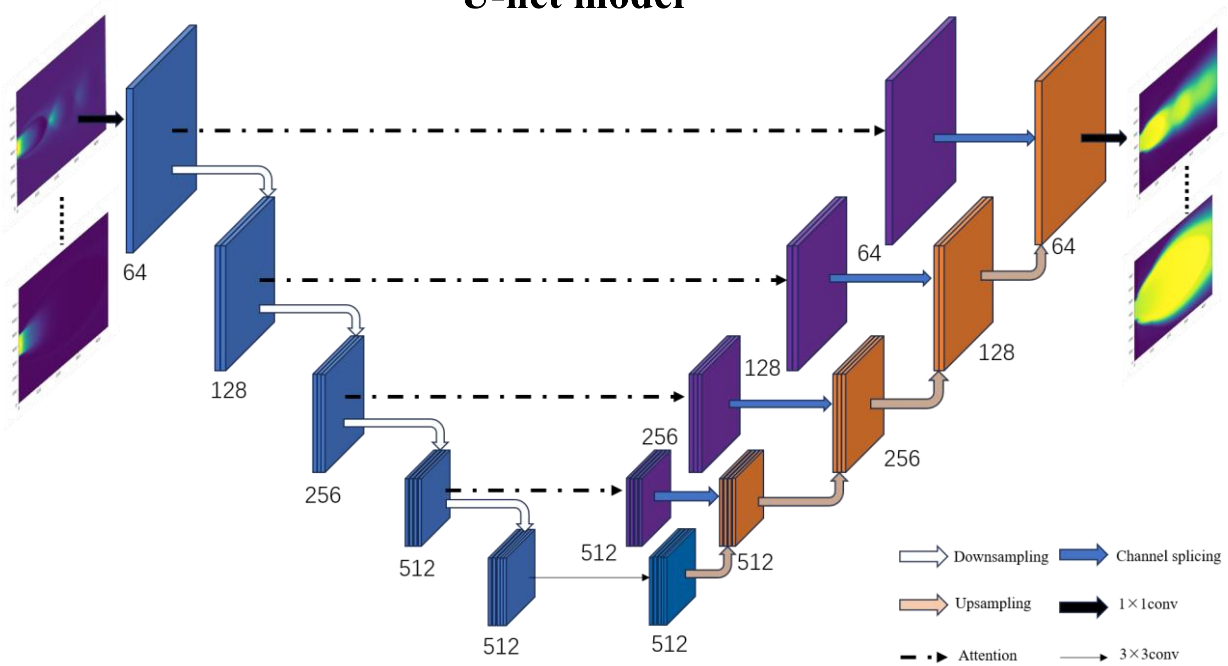
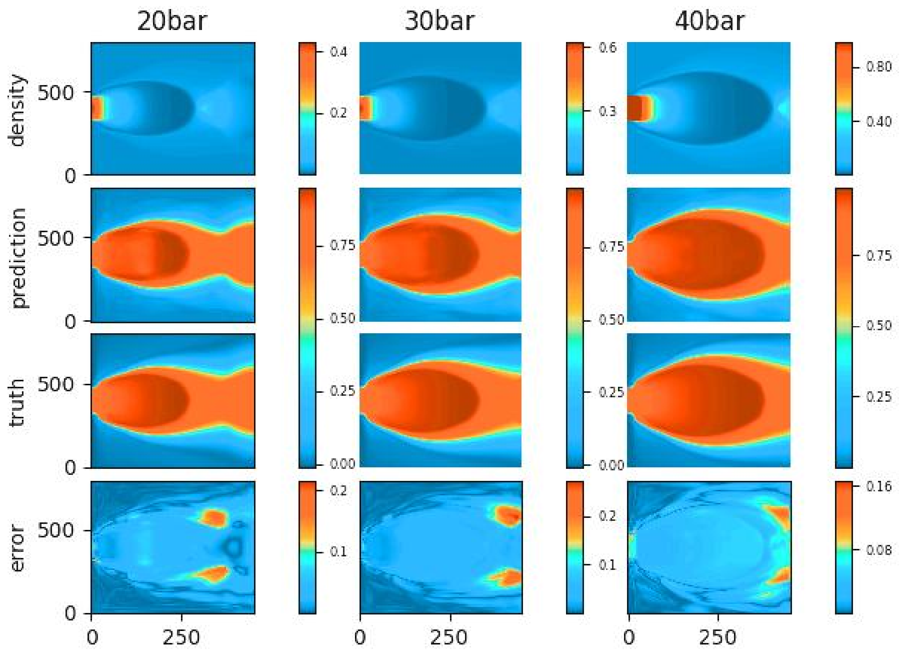
- **Obtain velocity distribution from density [$\rho(x,y) \rightarrow v(x,y)$] via U-net deep learning model**
  - ✓ Simulation data: $\rho(x,y)$ & $v(x,y)$;
  - ✓ Experimental testing data: $\rho(x,y)$ (schlieren system) & $v(x,y)$ (GD & langmiur probes)

U-net model





[Xu K. et al, China Sci: Tech. sci, 2025]

- **High Generalization Capability ✔ :** Accurately predicts unseen data.
- **Optimal Architecture ☑ :** U-net + attention @ boundary → superior beam analysis

AI-based SMBI distribution prediction

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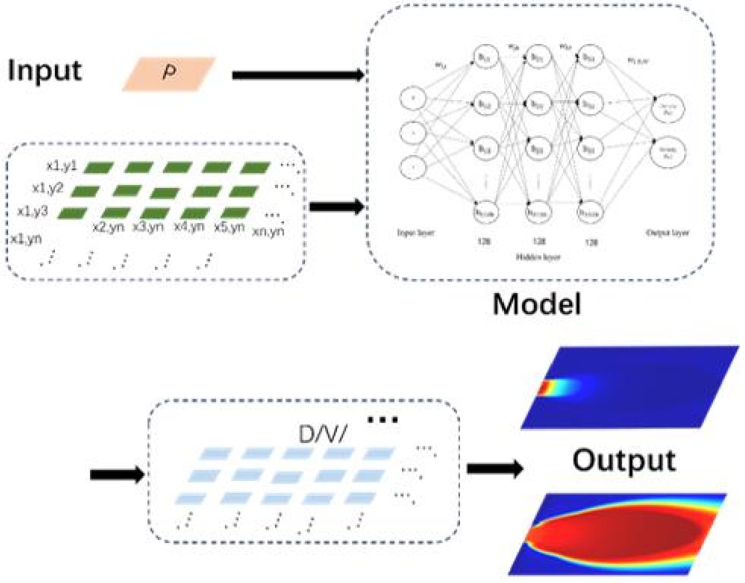
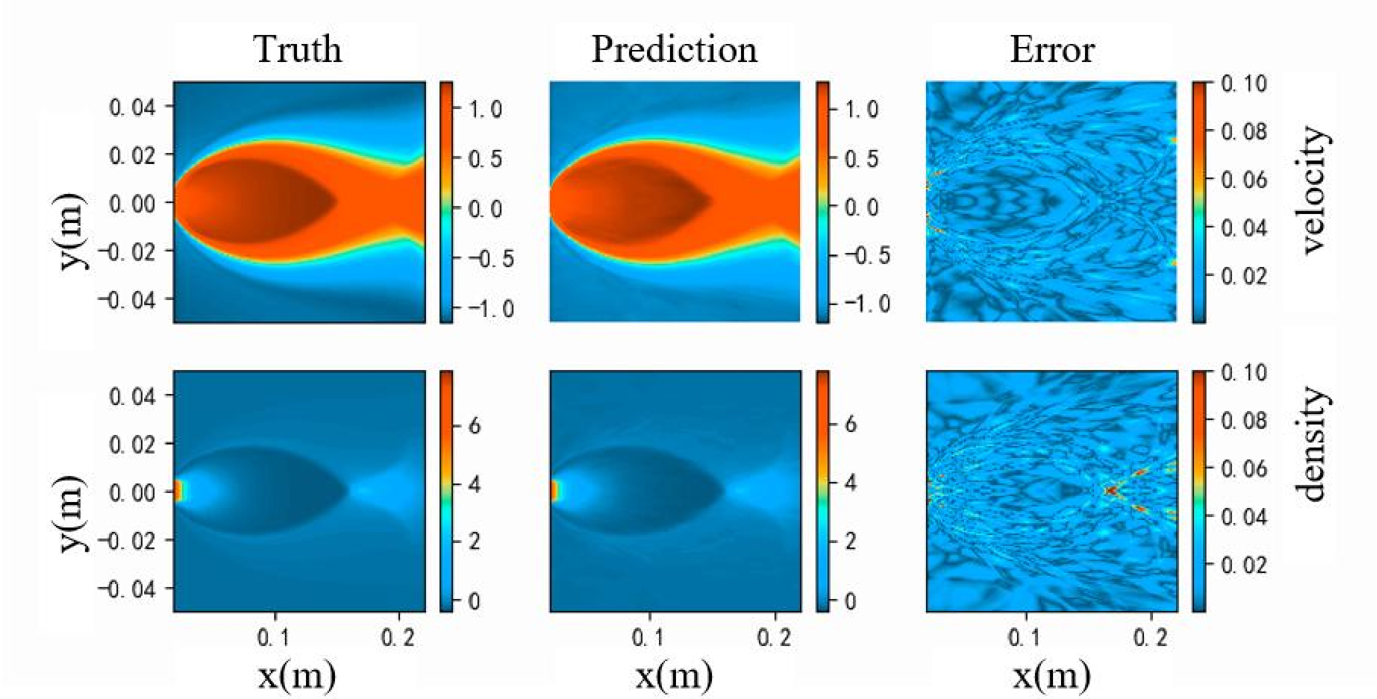
- **Realized > 1000× faster prediction of SMB distribution aiming for real-time control of plasma profiles**
  - ➢ **Key Assumption:** Beam distribution is governed only by gas source pressure P_{SMBI}
  - ✓ **Fixed:** Injector geometry (d, L, θ) & background pressure. **Sole variable:** P_{SMBI} or P_0

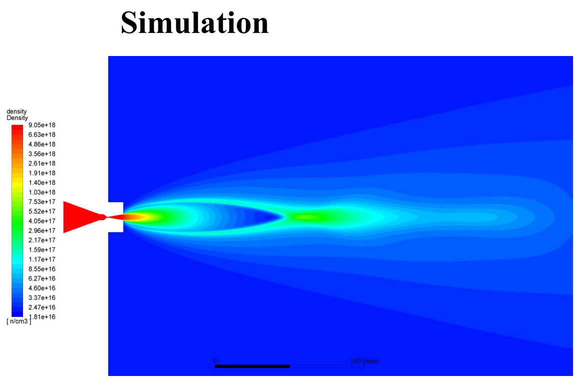


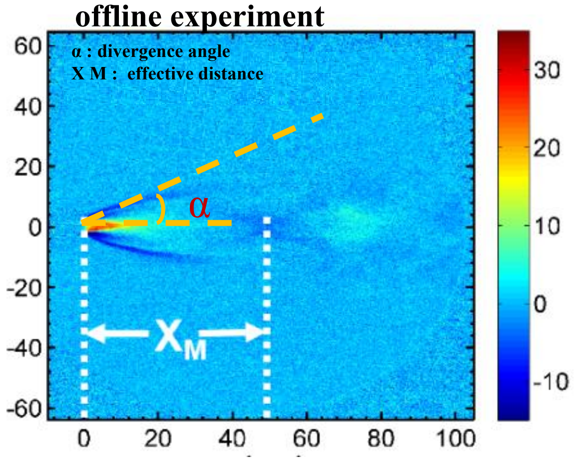


- ✓ **Baseline:** Surpasses traditional fluid simulation and beam image measurement
- ✓ **Speed:** Millisecond-level beam distribution prediction for real-time control

SMB parameter dependance

■ **Parametric dependance of SMB characteristics on injector and working condition**





➢ **Injector structure design**

L: Length of the expansion section

θ: cone angle

d: diameter of nozzle

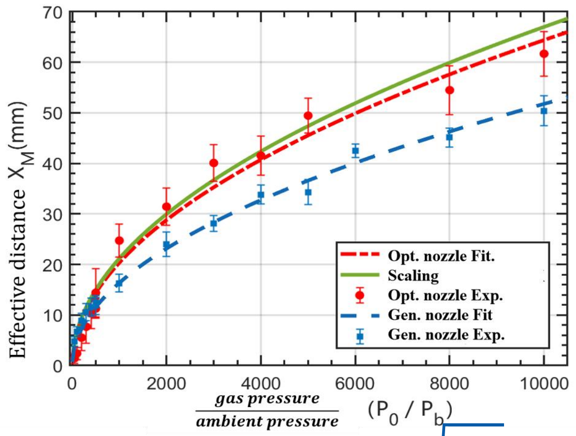
P_0: source pressure of SMBI

P_b: pressure of the background at oulet

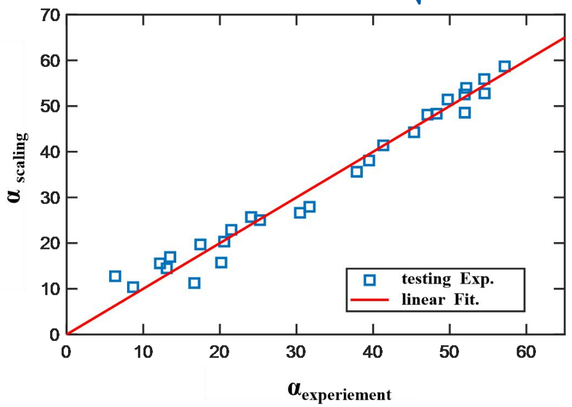
➢ **Beam characteristic parameters:**

X_M: Length of silent zone; effective distance

α: Half of the divergence angle



$$X_M = 0.67d\sqrt{\frac{P_0}{P_b}}$$

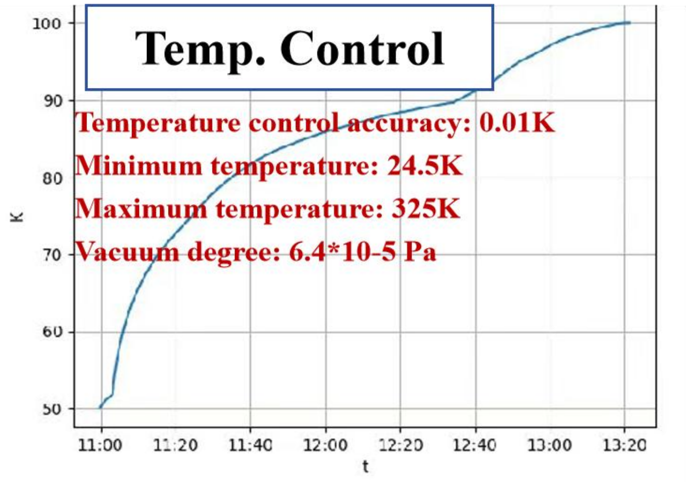


$$\alpha_{scaling} \propto d^{0.15} \times L^{-0.82} \times \theta^{-0.83} \times P_0^{0.21} \times P_b^{-0.12}$$

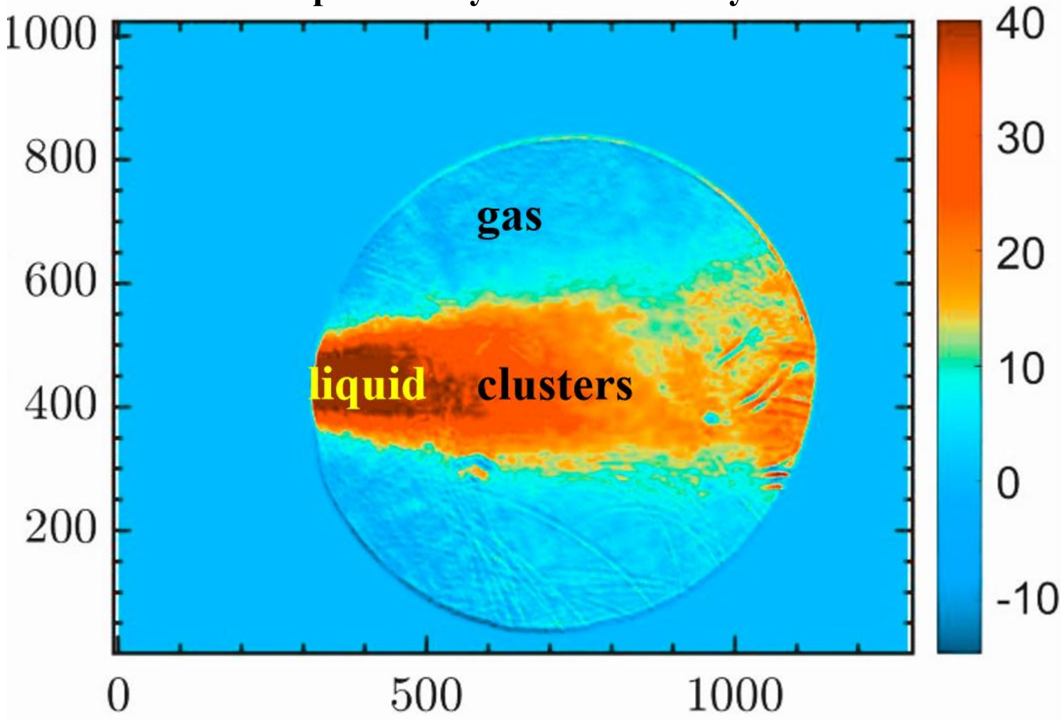
■ Optimized injectors obtained for effective fueling

Multi-phase SMB injection technology

- **Precise control of injected components via gas source temperature**
  - ✓ Approches: Adjusting gas source temperature (also the pressure)
  - ✓ Regulates component injection from gas, cluster, to liquid phases and their mixing.



An illustrative measurement of the beam composition by the Schlieren system



Vector injection technology

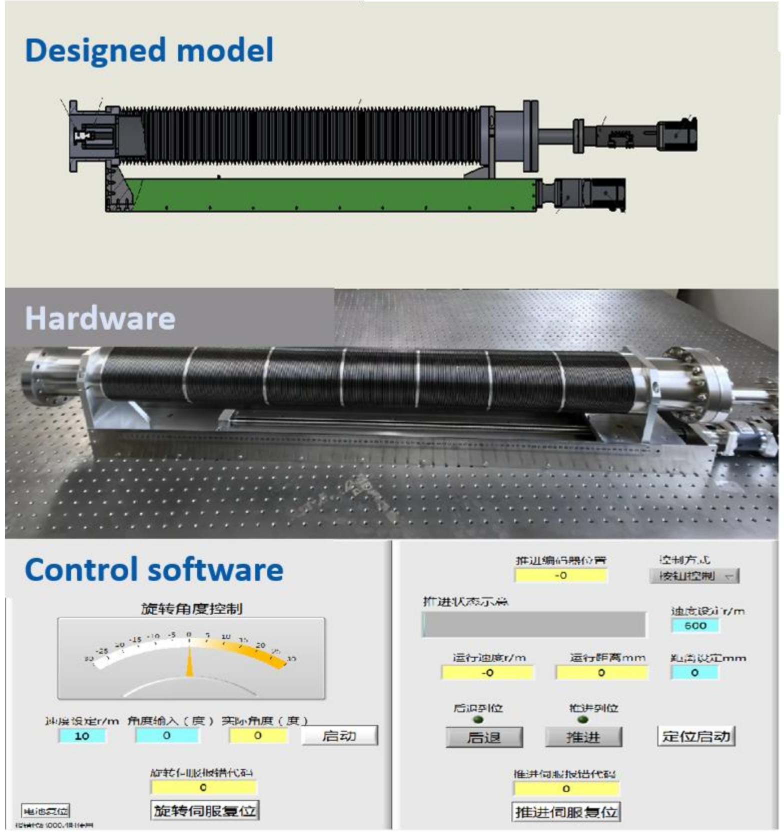
- **Vector injection SMB system: flexible beam steering before reaching plasma edge**
  - **Capabilities:** precise control of injection position and angle

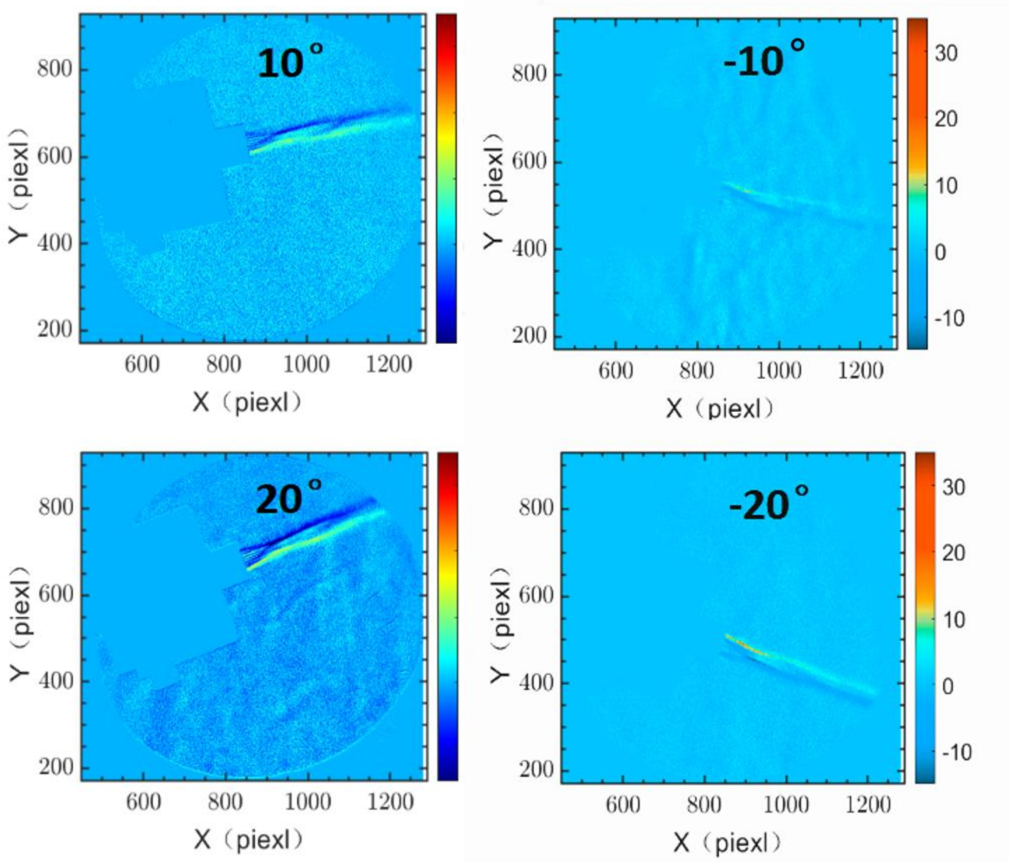
Adjustment Ranges:

✓ **Radial Position:**

0 - 0.66 m

✓ **Poloidal/Toroidal Angle: ±20°**





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Maximized SMB velocity

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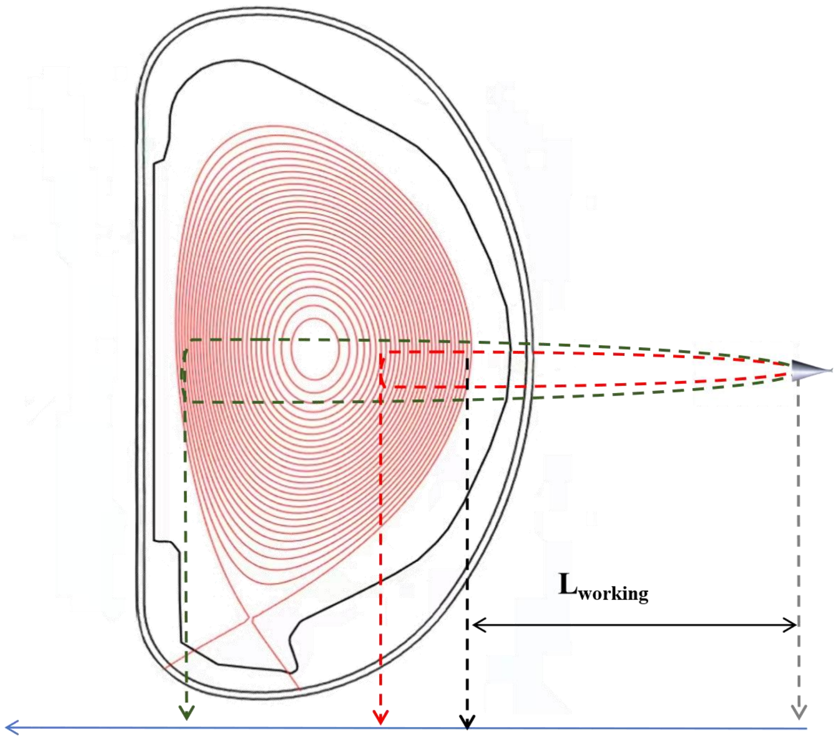
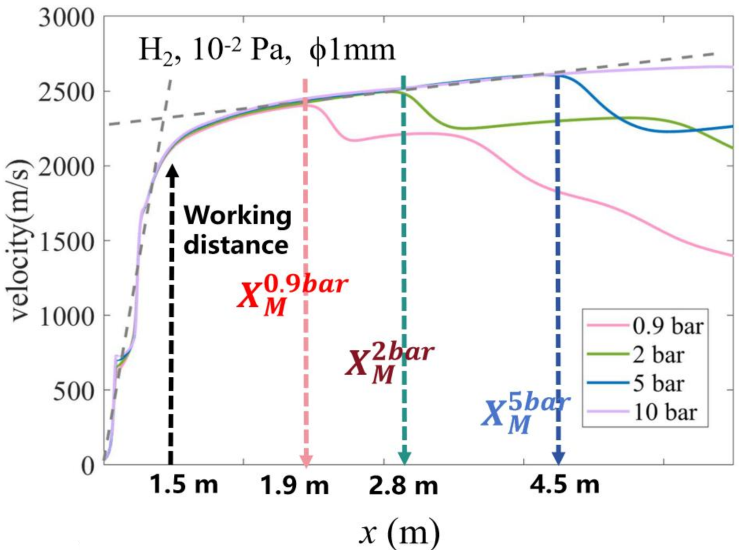
- **Simulation and experiments:** the beam velocity is independent of pressure, which primarily affects density
  - ✓ Ideal design SMB nozzle allows adiabatic expansion → $v_{max} \propto \sqrt{T_0}$ (γ, M constant)



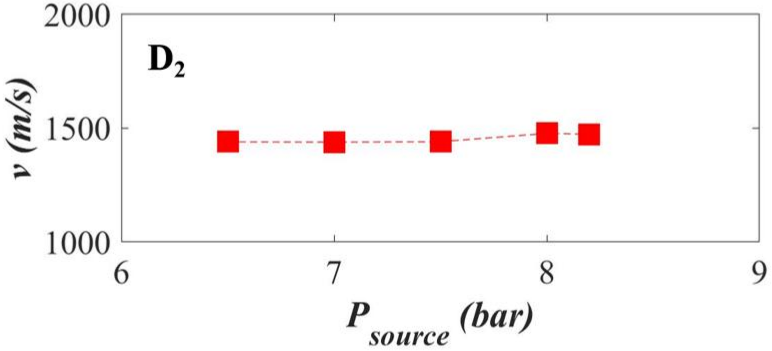
➢ **In fluent simulation:**

X_{eff} (0.9 bar) > $L_{working}$
when: $L_{working}$ = 1.5 m
⇒ v_{H2} = 2100 m/s
⇒ v_{D2} = 1500 m/s



➢ **In tokamak expriements:**

$L_{working}$ = d(plasma, injector)
$\Delta t = t_{D\alpha,onset} - t_{SMBI,start}$
⇒ v = slope ($L_{working}$, Δt)



- **Fueling analysis prioritize how SMB density distribution shapes edge plasma profiles**

Fueling efficiency analysis method

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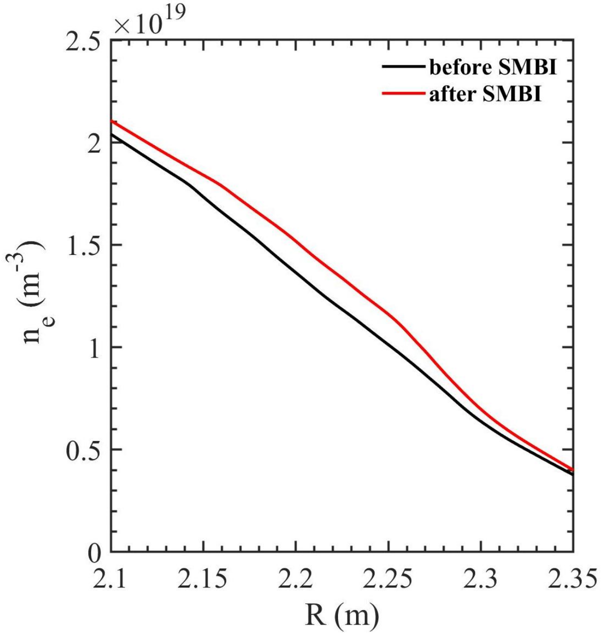
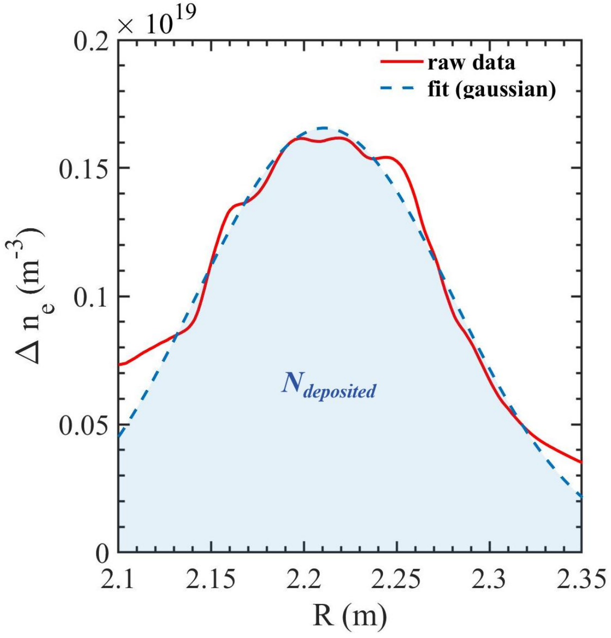
■ **Localized analysis of short-time density distributions from microwave reflectometers**





- MR: $\Delta n_e = n_{e,after}(r) - n_{e,before}(r)$
- **Local Deposition (Transport Neglected)**

  Δn_e → Gaussian Fit → $N_{deposited}$
- $N_{injected}(P_{SMBI}, t_{SMBI})$: offline calibrated, linear relation for SMBI valve)

Fueling efficiency:

$$\eta = N_{deposited} \,/\, N_{injected}$$

Effect of gas pressure on fueling efficiency

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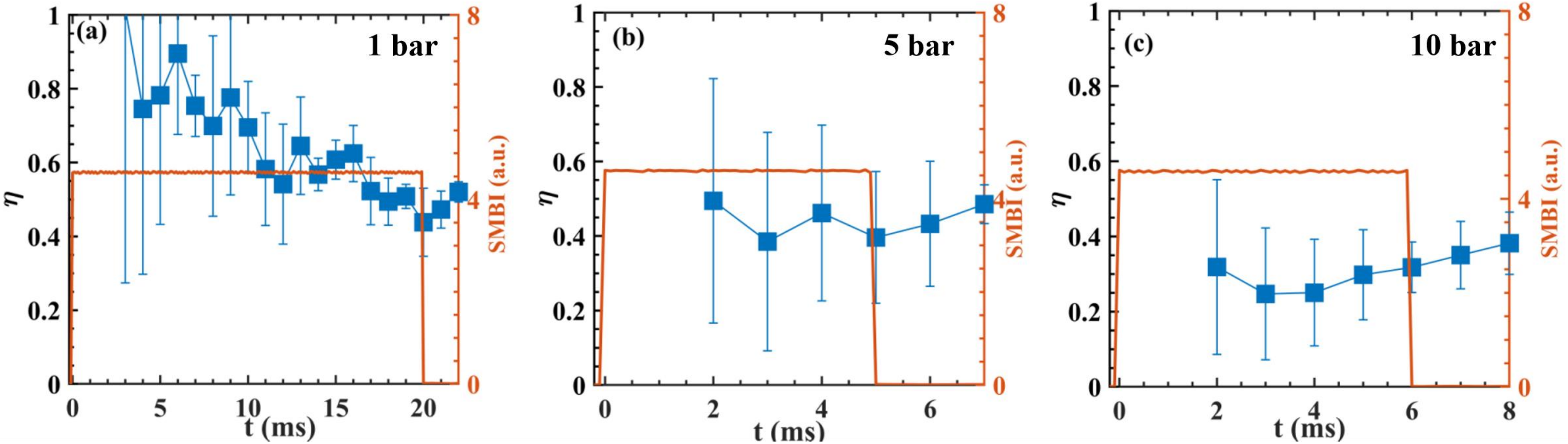
- **Fueling efficiency η decreases with increasing pulse pressure:**
  - ✓ Fueling experiments with SMBI pressure scan at fixed parameters:

$$n_e = 2.4\times10^{19}\ \mathrm{m^{-3}},\ b_t = 1.65\ \mathrm{T},\ I_p = 0.5\ \mathrm{MA},\ P_{SMBI} \sim (1 - 10\mathrm{bar})$$

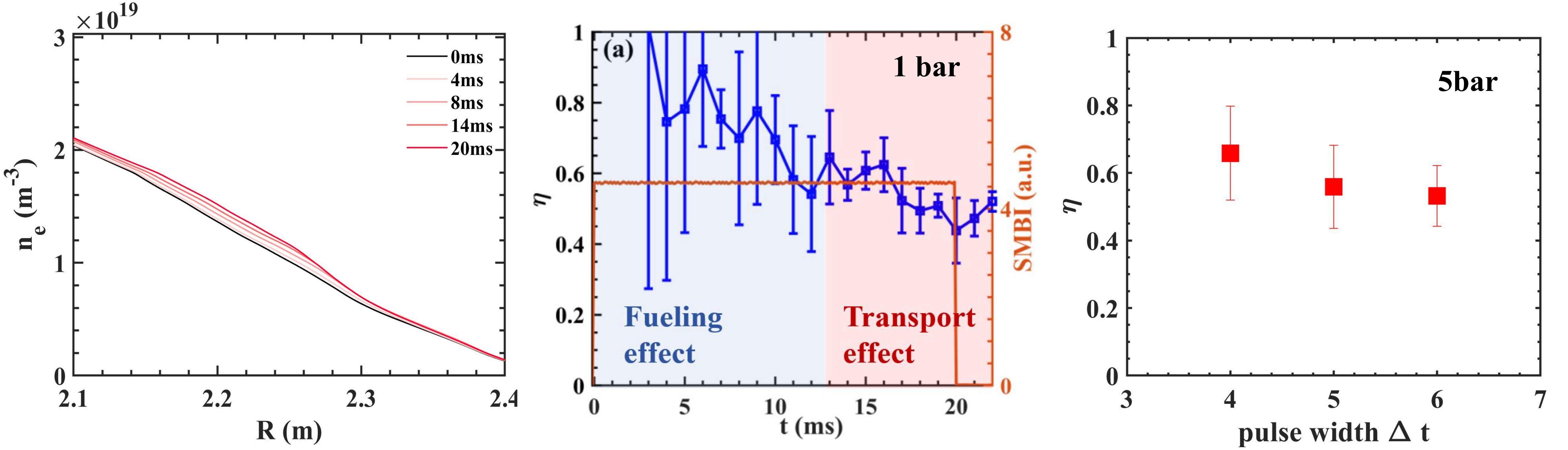


η: ~53% @ 1 bar → ~ 47% @ 5 bar → ~35% @ 10 bar

- **The use of low-pressure SMB is recommended, as it enables higher fueling efficiency while complying with tritium safety protocols.**

Effect of pulse width on fueling efficiency

- **Fueling efficiency η decreases with increasing pulse width**
  - ✓ Analysis via single-pulse temporal evolution and multi-pulse width comparison

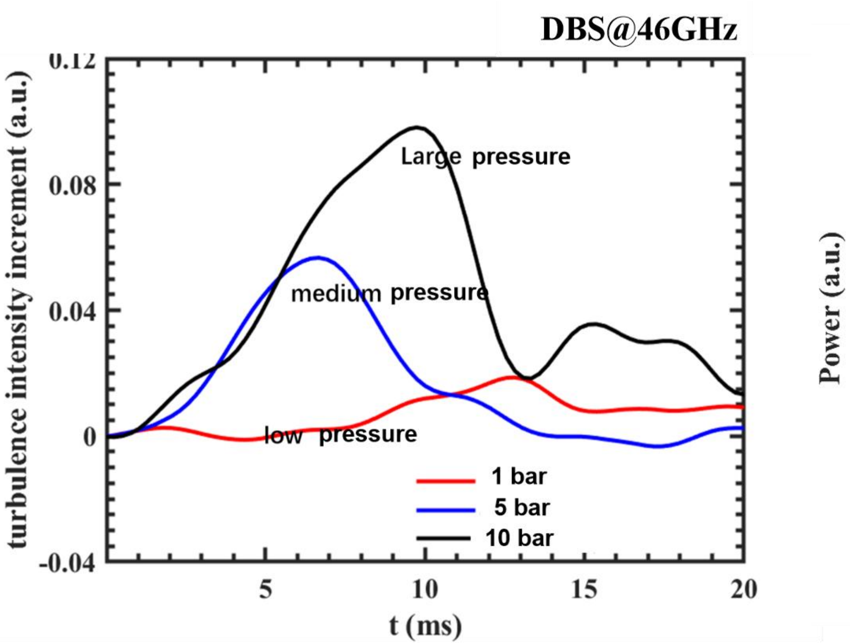


- **The use of short-pulsed, high-frequency SMBI is advised over long-pulsed SMBI for higher fueling efficiency.**

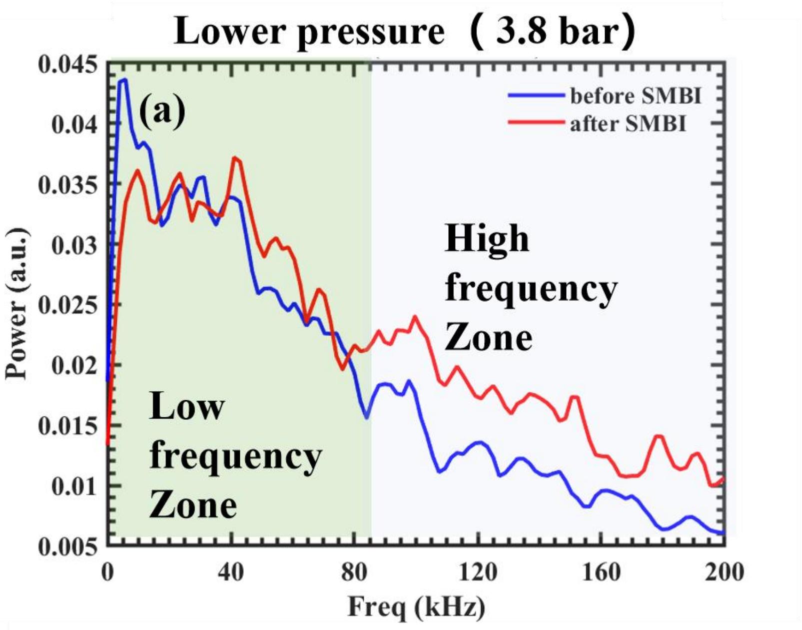
Turbulence behavior

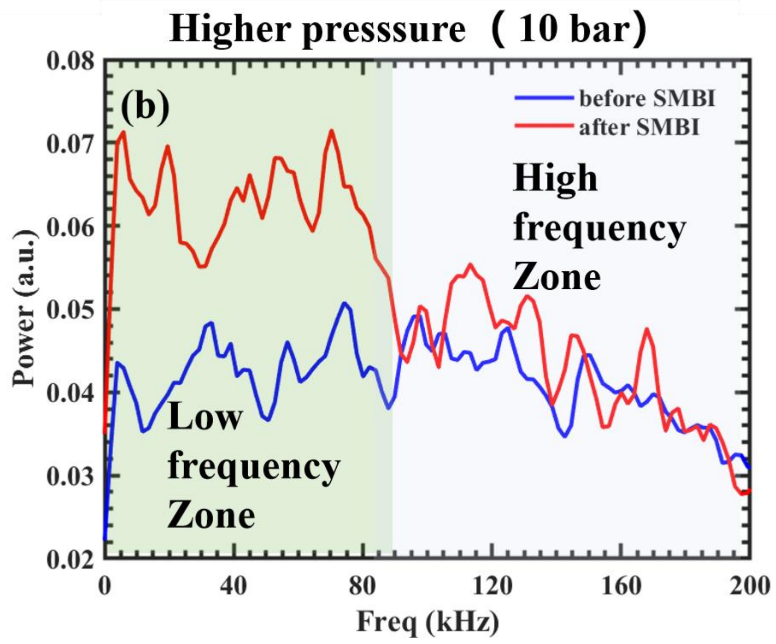
- **Higher turbulence intensity and scale for larger SMBI gas pressure**

turbulence intensity



turbulence spectrum





- **Correlation:** $P_{SMBI} \uparrow \Rightarrow \Delta I_{turb} \uparrow$ (confirmed at fixed channel)
- **Spectral Analysis:** $P_{SMBI} \uparrow \Rightarrow f_{dominant}$: High frequency zone $\rightarrow$ Low frequency zone (large scale)

Plausible physical process

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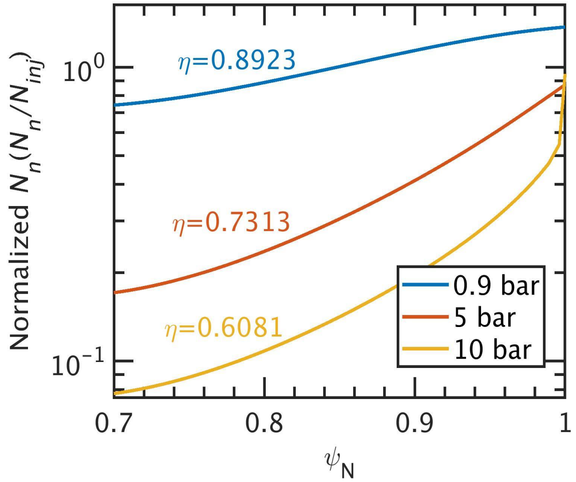
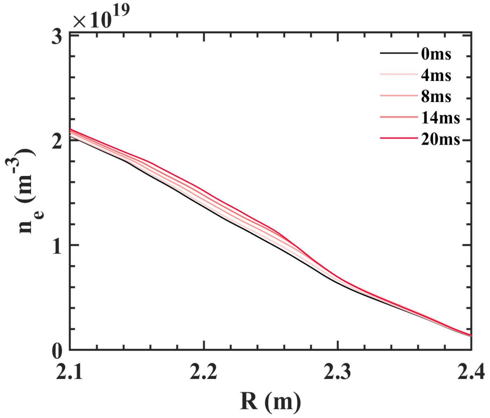
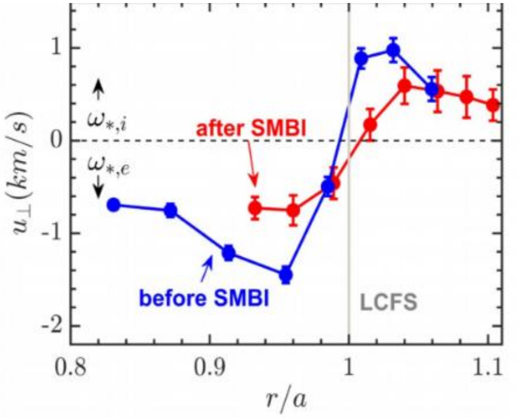
- **BOUT++ simulation:**
  - **Key Assumptions:**
    - ✓ Constant beam velocity across all P_{SMBI} cases
    - ✓ All deposited neutral particles are retained in the plasma
  - Low P_{SMBI} → high P_{SMBI}: local ∇n_e steep ↑ ⇒ Γ_{conv} ↑ ⇒ η ↓
    - ✓ **η: 89.2% @ 0.9 bar → 73.1% @ 5 bar → 60.8% @10 bar**

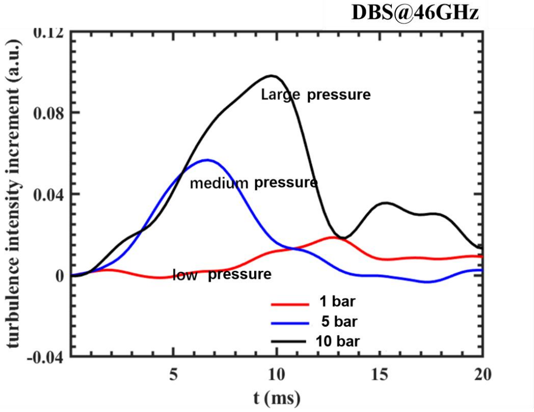


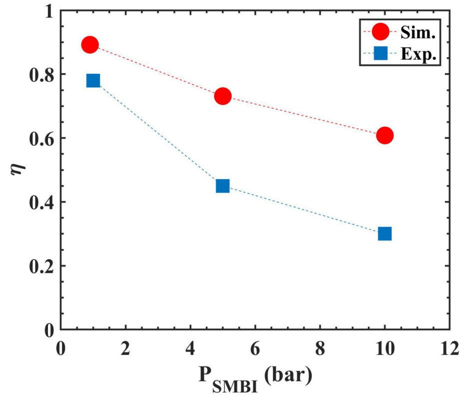
- **Plausible physical process:** P_{SMBI} ↑ ⇒ n_{SMB} ↑ (t_{SMBI}) →

→ ∇n_e (edge) ↑ → $\partial E_r/\partial r$↓ → **turbulence↑** → $\Gamma_{transport}$ ↑ → η_{fuel} ↓



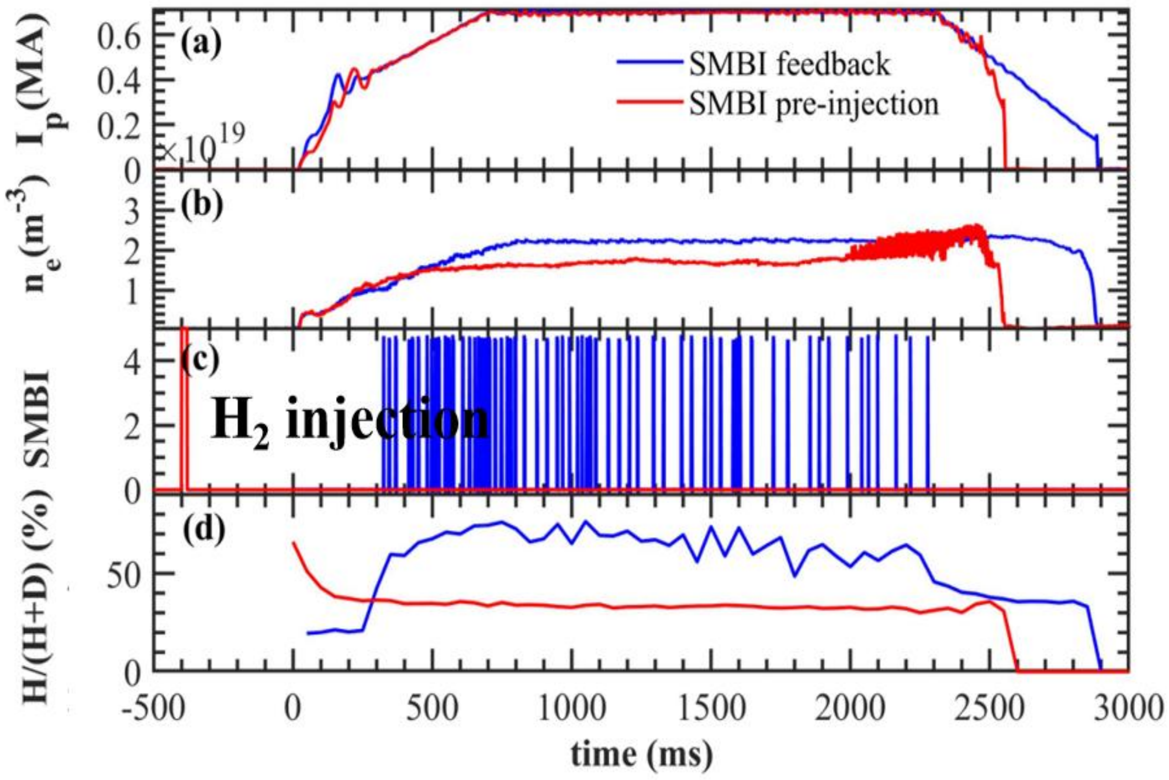






Timing for HD ratio control

- SMBI enables efficient H-D ratio control, with pre-injection providing further enhancement.



➢ For injection timing

✓ **Feedback SMBI:**

Higher H_2 consumption

✓ **Pre-injection SMBI:**

Requires only 25% of the H_2

- **The pre-injection of T_2 is recommended, with the option to follow with a combined D/T feedback**

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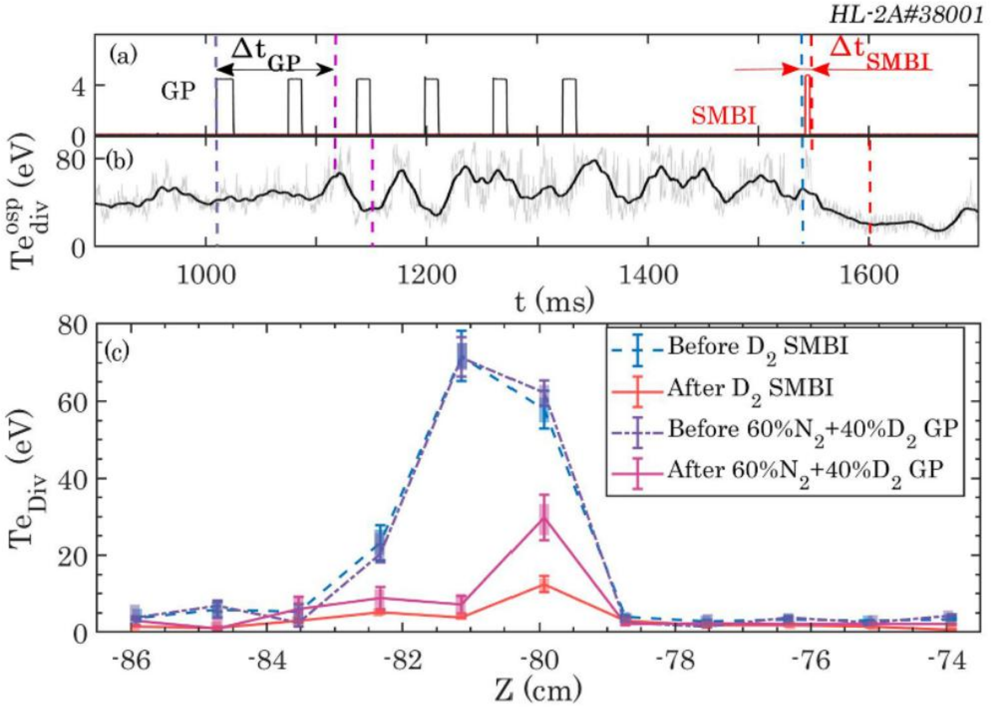
Comparison of heat load control with SMB and GP

- **Divertor SMBI is more effective than GP: faster time response, stronger heat mitigation effects**
  - ✓ Offline testing experiments show SMBI particles reach the divertor plasma in 2.7ms — 20 times faster than GP (50ms) over a 3-meter distance.

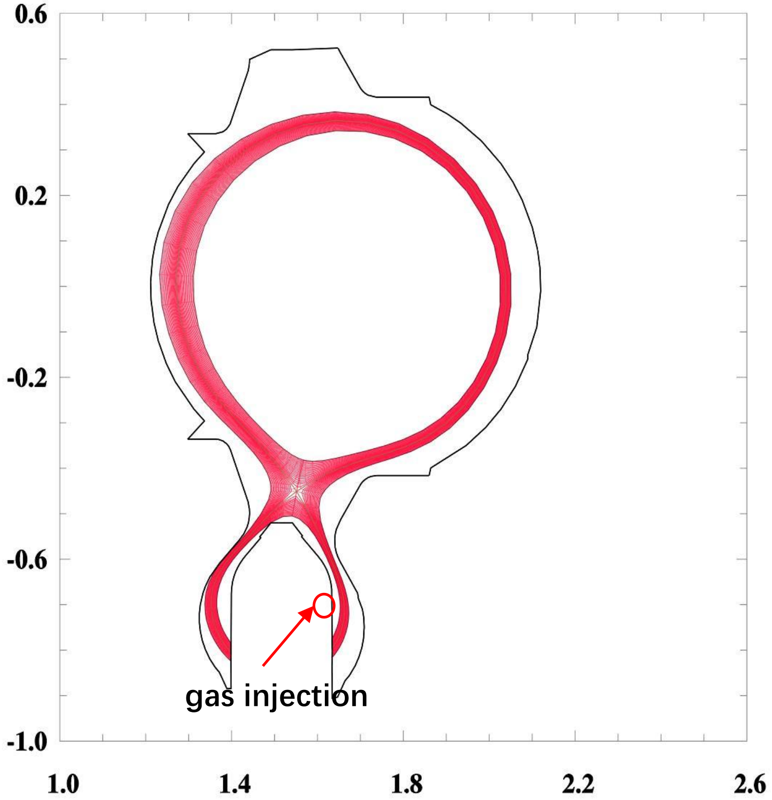


	SMBI	GP
Gas types	D_2	60% N_2+ 40% D_2
injection ratio	2e22 /s	4e21 /s
response time (velocity)	9 ms	112 ms
Te OST	9 eV	25eV

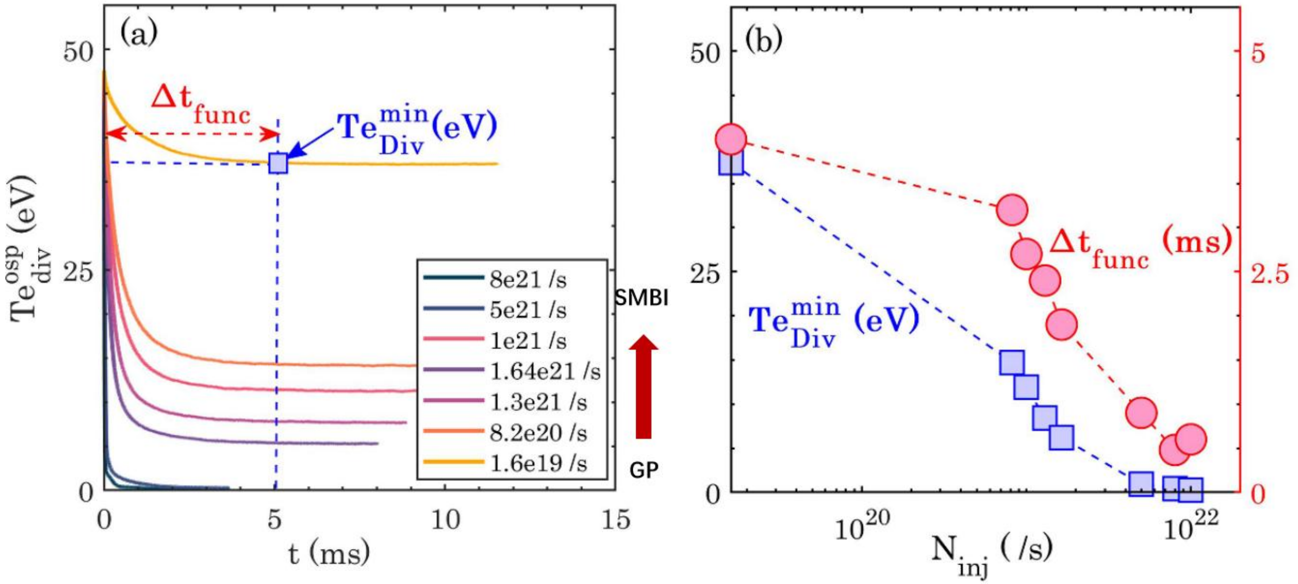
- Plasma experiments indicate particle injection rate and velocity as critical factors for heat load control

Particle injection rate effect simulation

☐ SOLPS results: a higher injection rate significantly enhances and accelerates heat load mitigation



HL-2A SOLPS grid

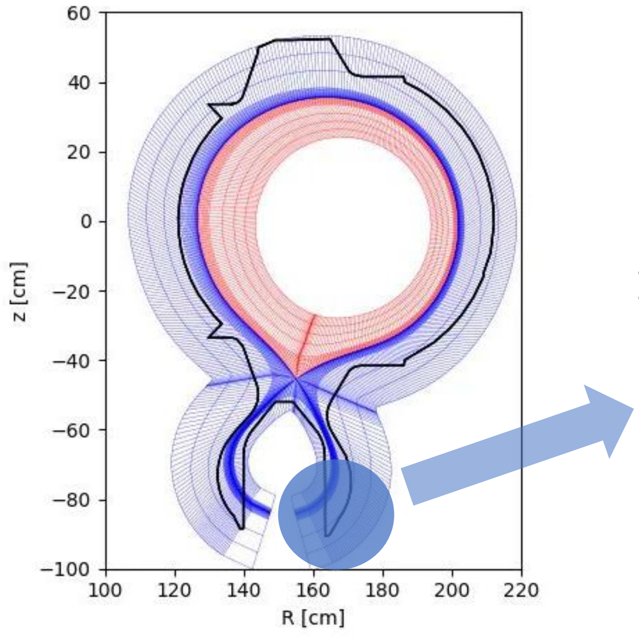


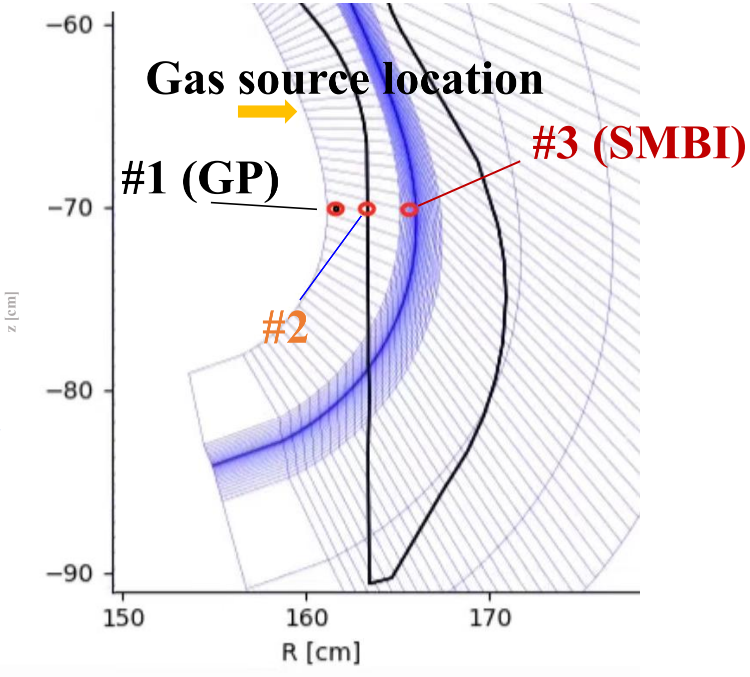
- ➢ Simulation results indicate that with increasing injection rate:
  - ✓ strong target plate temperature drops.
  - ✓ control effect decay time shortens.
- ➢ Both trends are in agreement with experimental data.

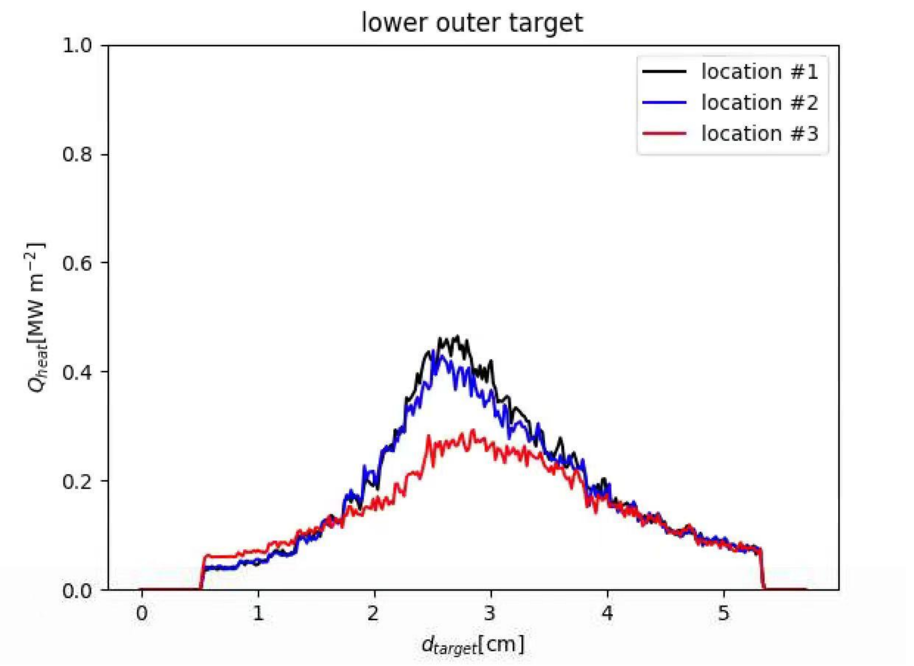
☐ Sufficient instantaneous particle flux control is adviced for enhanced, rapid heat load control

Particle velocity (deposit location) effect

- **The different neutral particle deposition depths caused by different particle velocity in EMC3-EIRENE based on experimental data**
  - ✓ Mid-plane results suggests: Higher velocity → Deeper deposition







- Superior SMBI divertor heat load control via deeper, velocity-driven penetration

Outline

Summary

■Technology Development

- **Integrated Test Platform:** Established a comprehensive SMBI test platform, integrating diagnostics including Schlieren, glow discharge, scanning probe, and laser Rayleigh scattering/induced fluorescence systems.
- **AI-Powered Analysis:** AI models enable integrated analysis of SMBI velocity distribution and rapid prediction of SMBI beam distribution including density and velocity.
- **Advanced Injection Systems:** The vector and multiphase molecular beam injection systems provide enhanced support for improving supersonic beam directivity.

■Strategy for experiments

- **Fueling Strategy**: Experimental and simulation results confirm that **low-pressure, short-pulse SMBI** is advantageous for higher fueling efficiency, and **pre-injection** is better for DT ratio control.
- **Superior Heat Load Control**: The higher injection rate and particle velocity of SMB offers better heat load control compared to conventional gas puffing, presenting a new approach for optimizing radiative divertor performance.