EX/6-3Ra

ELM Mitigation by Supersonic Molecular Beam Injection: KSTAR and HL-2A Experiments and Theory

W.W. Xiao[1,2,3], P.H. Diamond[1,4], W.C. Kim[3], L.H. Yao[2], S.W. Yoon[3], X.T. Ding[2], S.H. Hahn[3], W.H. Ko[3], M. Xu[4], G.S. Yun[5], G.R. Tynan[4], L.W. Yan[2], J.W. Ahn[6], X.L. Zou[7], J.Q. Dong[2,8] Y.K. Oh[3], J.G. Kwak[3] and X.R. Duan[2], KSTAR team and HL-2A team

1) WCI Center for Fusion Theory, *NFRI, Korea* ***2) SWIP,*** *Chengdu, China* ***3) NFRI***, *Daejeon, Korea* *4)* ***UCSD,*** *California, USA*
5) POSTECH, *Pohang, Korea* ***6) ORNL,*** *Tennessee, USA* ***7) CEA,*** *IRFM, France* ***8) IFTS,*** *ZJU, China*

EX/6-3Rb

ELM mitigation with SMBI & CJI fuelling in HL-2A H-mode plasmas

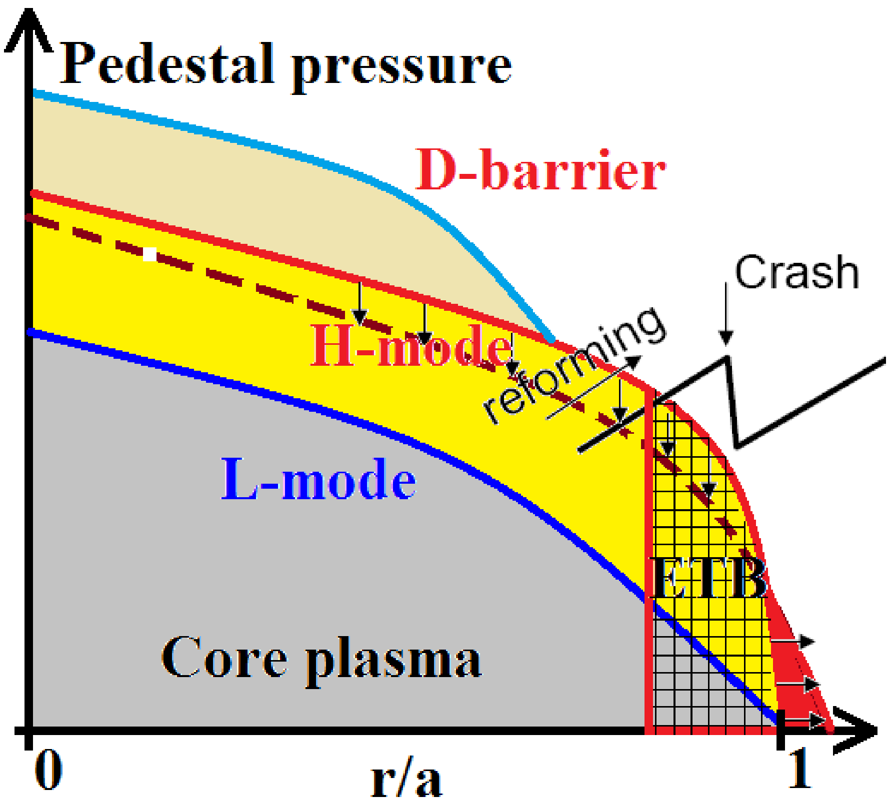
C.Y. Chen , L. H. Yao, B. B. Feng, Z. B. Shi, W. L. Zhong, J. Cheng, D. L. Yu, Q. W. Yang, X. R. Duan

Southwestern Institute of Physics, *Chengdu, China*

Introduction

Pedestal region

- Core confinement, as boundary condition
- The β-limit through p(r) and j(r)
- **Heat/particle load on facing components →transport events**



- Negative impact on the facing components.
- Reduce the ejected energy and prevent the divertors and wall surfaces [1-4].

[1] A. Loarte, PPCF (2003)
[2] A. Herrmann, PPCF (2002)
[3] T.E. Evans, GA report (2012)
[4] L.R. Baylor, GA report (2012)

Outline

We report the novel results for ELM mitigation by new method of SMBI and CJI

- **SMBI system**
- **The performance of SMBI system**
  - Particle source position in pedestal region
- **Optimized parameters of SMBI pulses for ELM mitigation**
- **The basic experimental results**
  - Density profiles
  - Fluctuation induced particle flux
  - Divertor signatures in ELM mitigation by SMBI
  - Core toroidal rotation and filaments
- **A simple model of this experiment**
- **The importance of τ_I/τ_p**
- **Conclusions, open issues and next plans**

History of SMBI and its application in HL-2A and KSTAR

First report, L.H. YAO, 20th, EPS, HL-1, 1993

SMBI physics and fuelling efficiency L.H. Yao et a., HL-1M,HL-2A, 1998--

H-mode fueling and penetration V.A. Soukhanovskii, NSTX, 2006

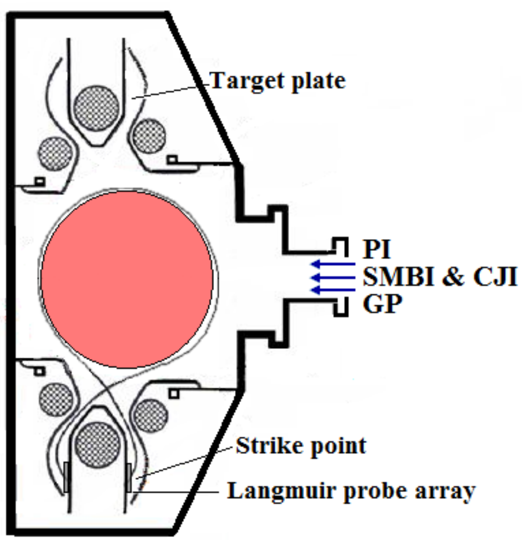
ELM mitigation, 2011-- HL-2A, KSTAR

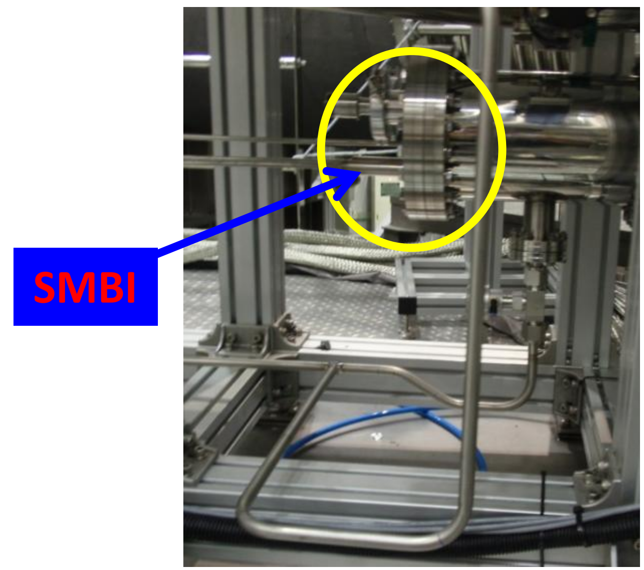
1993, 1998, 2001, 2003, 2004, 2006, 2007, 2010, 2011, 2012 ...

SMBI physics and high fuelling efficiency Pegourie B. et al., 2003, Tore Supra

Density control, Mizuuchi T et al., Heliotron J, 2010

P-ITB, HL-2A, W.W. Xiao, et al., 2010





- For the SMBI system in LFS, the backing pressure could reach 60 bars, and the duration is >0.5 ms.
- 4 ms SMBI pulse duration.
- CJI system was used in HL-2A for the first time.

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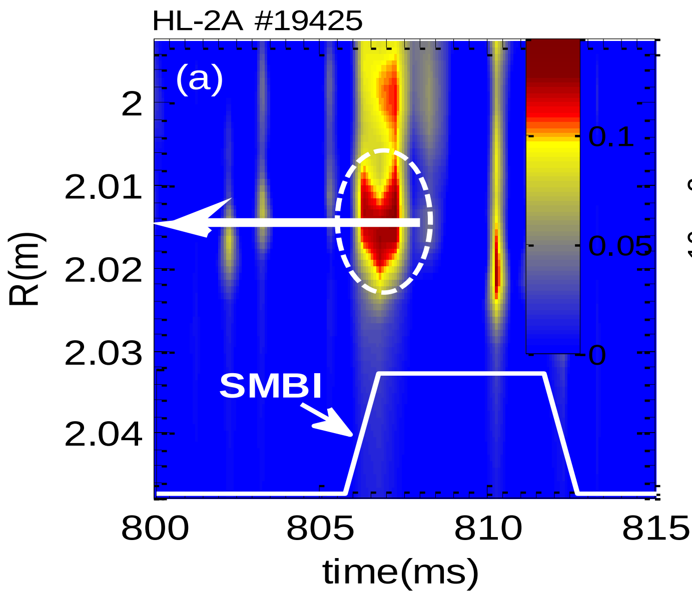
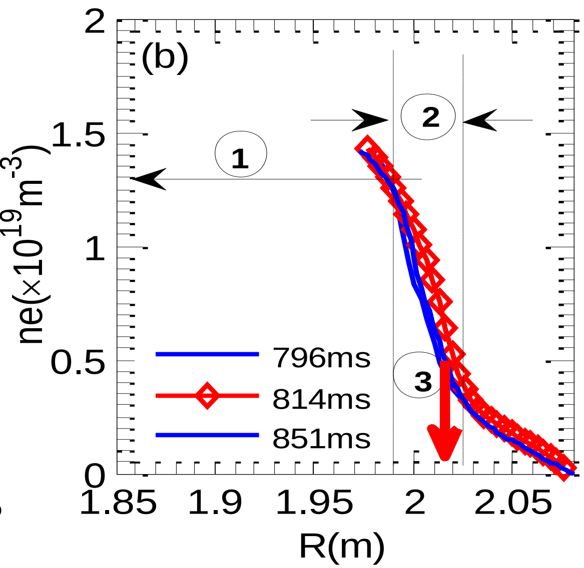
- SMBI fuelling and ELM mitigation in 2011.
- SMBI system could be operated at room temperature and at 105K.
- The gas pressure range of SMBI system is from 0.4 to 2.2 Mpa; 8 ms SMBI pulse duration.

Performance of the SMBI system

Particle source position in pedestal region [W.W. Xiao, US-TTF, 2012]





[5] W.L. Zhong, RSI, (2011)

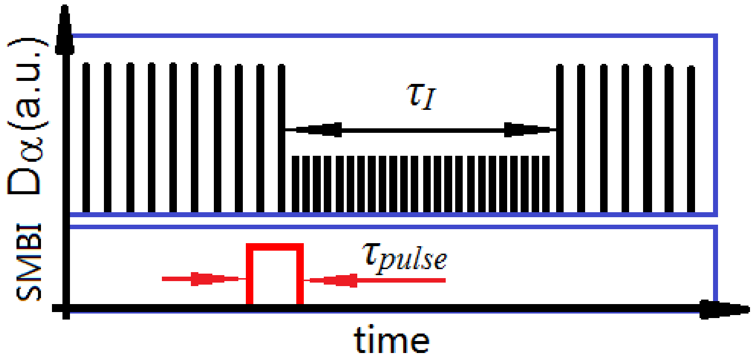
(a) the local particle source position.

(b) the pedestal density profiles [5] with and without SMBI. The red arrow indicates the particle source position in HL-2A.

- The particle source position is shallow, and just inside of the separatrix.
- **Shallow particle deposition is sufficient for ELM mitigation [6].**

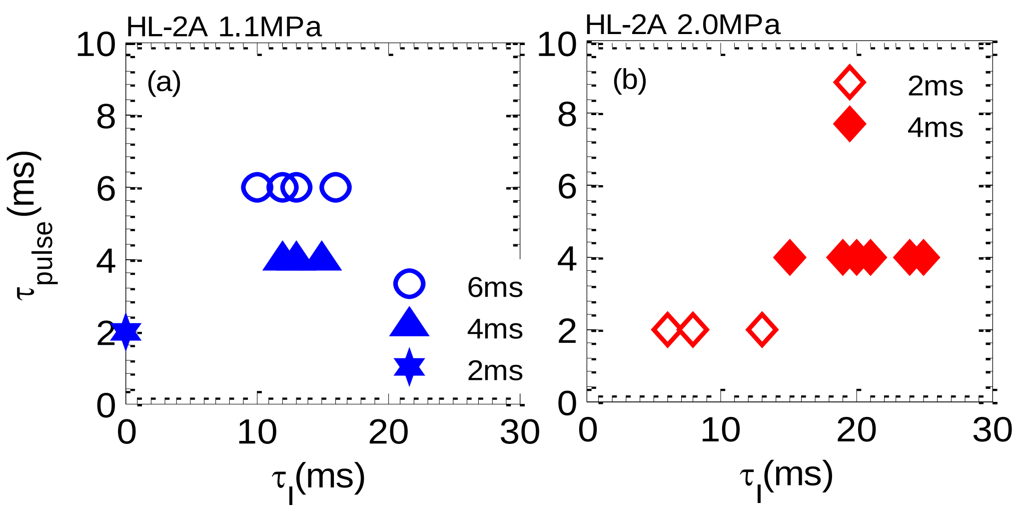
[6] W.W. Xiao, NF, (2012)

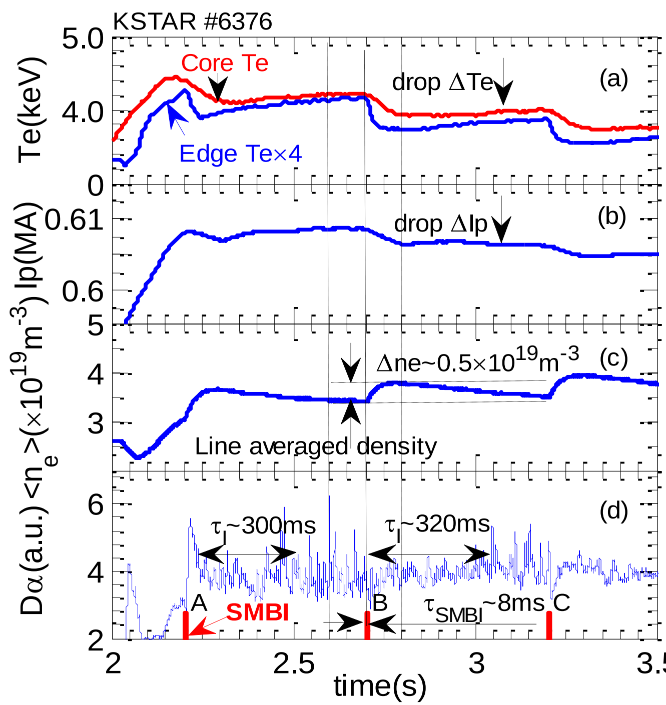
Optimized parameters of SMBI pulses



τ_I → duration for the SMBI influenced pedestal profile to refill.

τ_{pulse} → control signal of SMBI pulse.



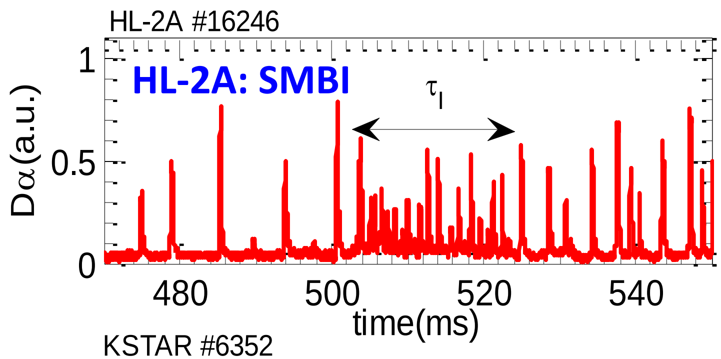


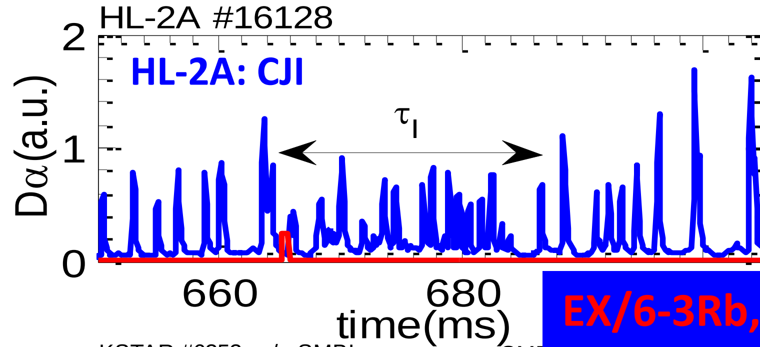
- **Too short τ_{pulse}** --- no effect by SMBI; **Too long τ_{pulse}** --- similar to normal gas puff, and density increases strongly.
- Optimized parameters of SMBI pulses:
  HL-2A → τ_{pulse} ~4ms, gas pressure~2MPa; KSTAR → τ_{pulse} ~8ms, gas pressure~1MPa.
- **Multi-pulses for continuous ELM mitigation was obtained in KSTAR ※**

Experiments on ELM mitigation by SMBI and CJI in KSTAR and HL-2A

Basic results on ELM mitigation

- $f_{ELM}^{SMBI}/f_{ELM}^{0}$ ~ 2-3.5;
- ELM amplitude decreases by half;
- $f_{ELM} \times \Delta W$ ~ const.





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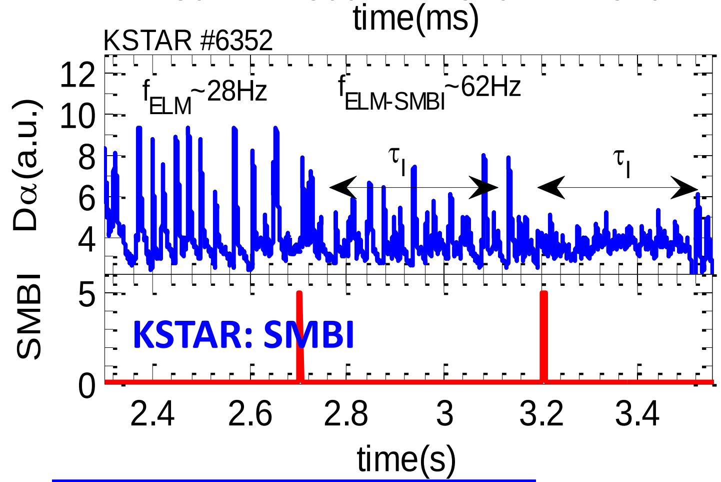

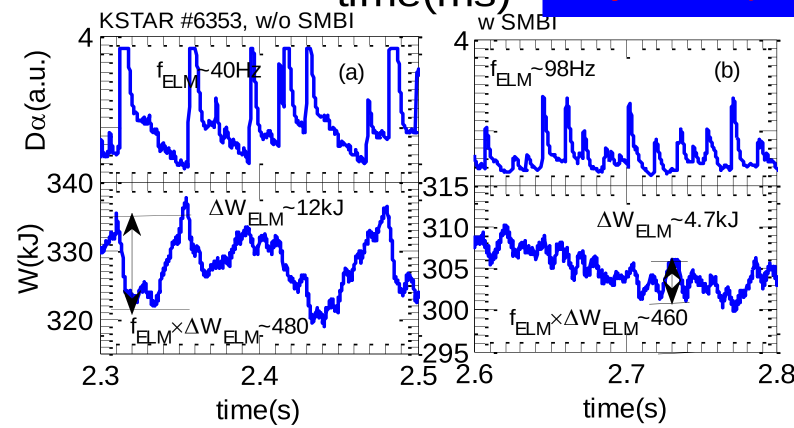

- **Physics pionts [7]:**

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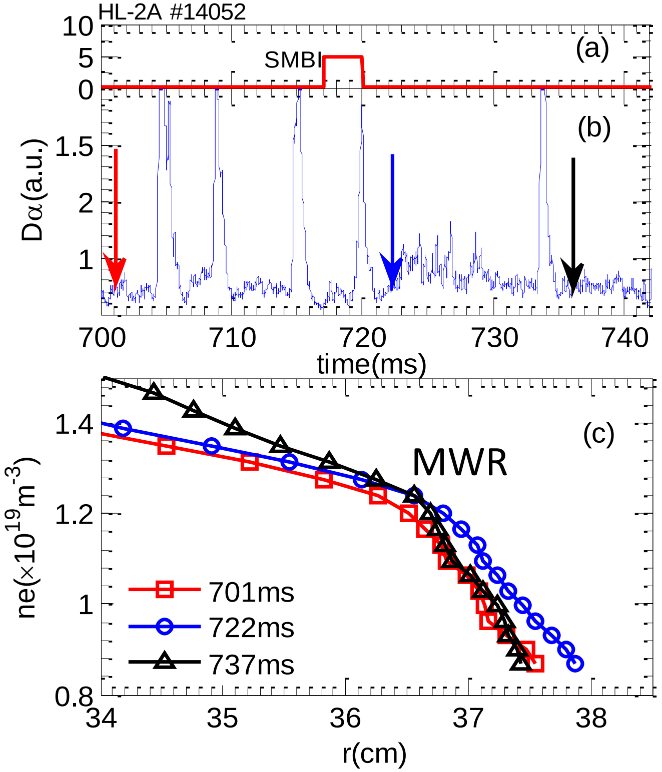
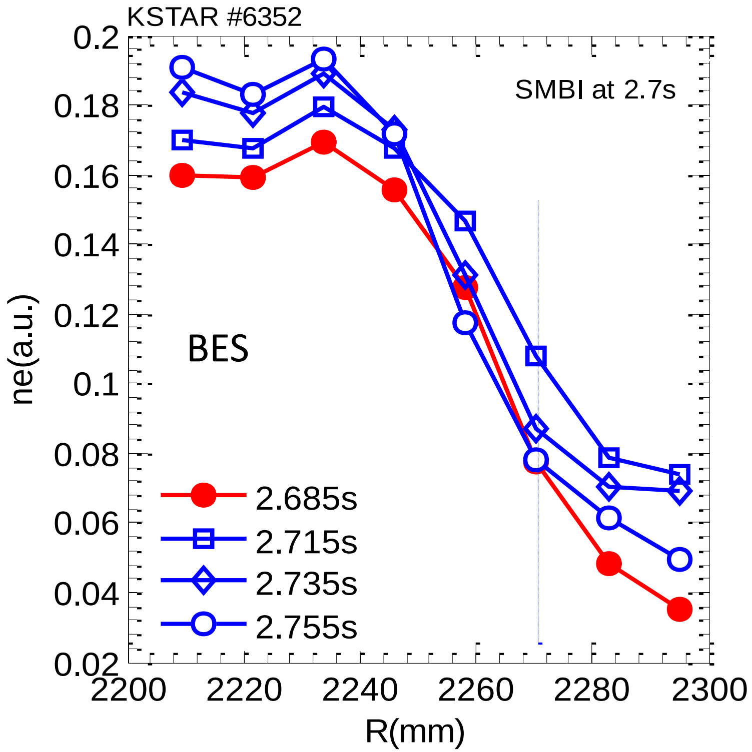
- **Density profiles soften.**
- **Edge $\Gamma \sim <\tilde{v}_r \tilde{n}_e>$ increases in high frequency region, while decreases in low frequency region.**
- **Divertor heat load decreases.**
- **Core toroidal rotation decreases during a τ_I time, then recovers.**
- **Filament spacing decreases.**

[7] W.W. Xiao, P.H. Diamond, W.C. Kim, submitted, PRL, 2012

Density profiles soften

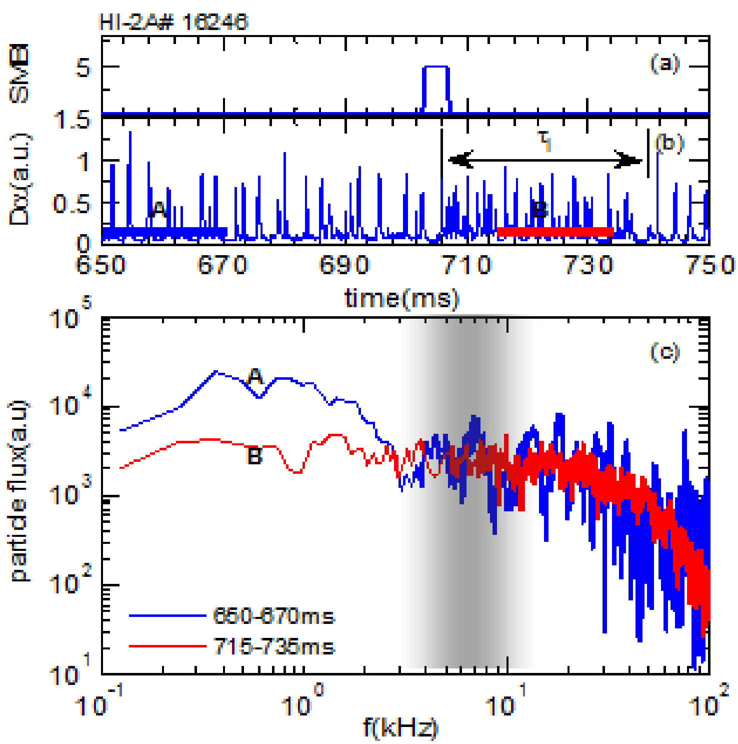
Pedestal density gradient with and without SMBI.

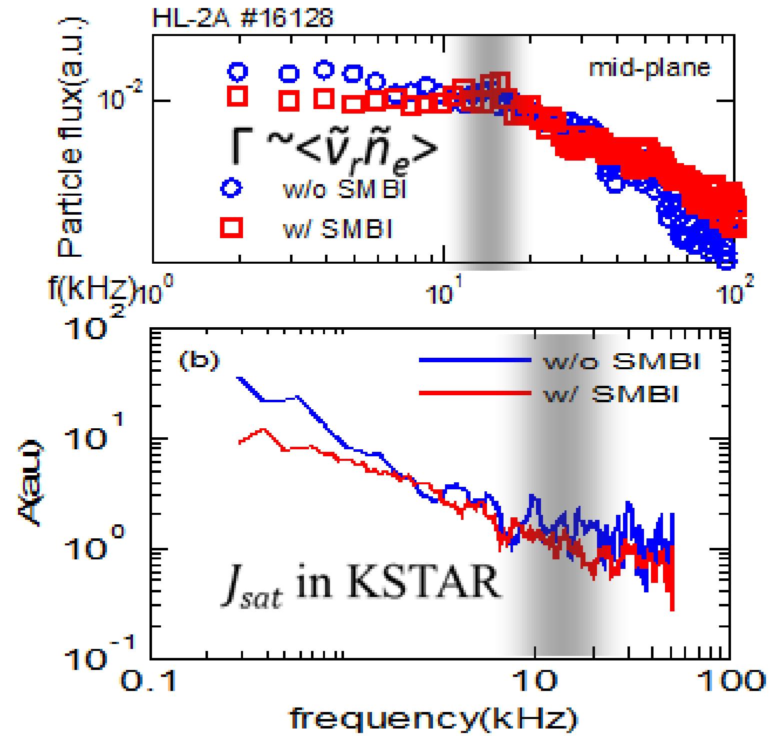




- Density profiles at different times 701 ms, 722 ms and 737 ms.
- 701ms, L_n=2.2cm; 722ms, L_n=3.3cm; 737ms, L_n=2.2cm.
- Observations → the pedestal particle confinement is slightly degraded. This point was also observed in EAST experiments. **PD8-08, X.L. Zou**

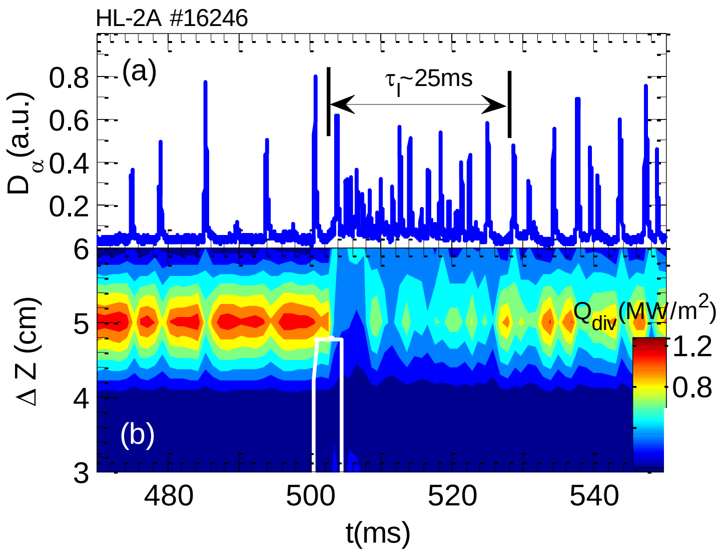
Fluctuation induced particle flux



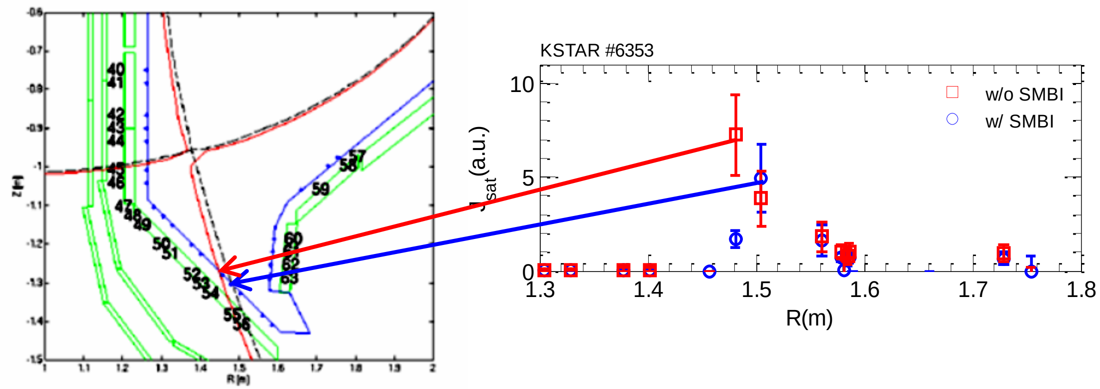


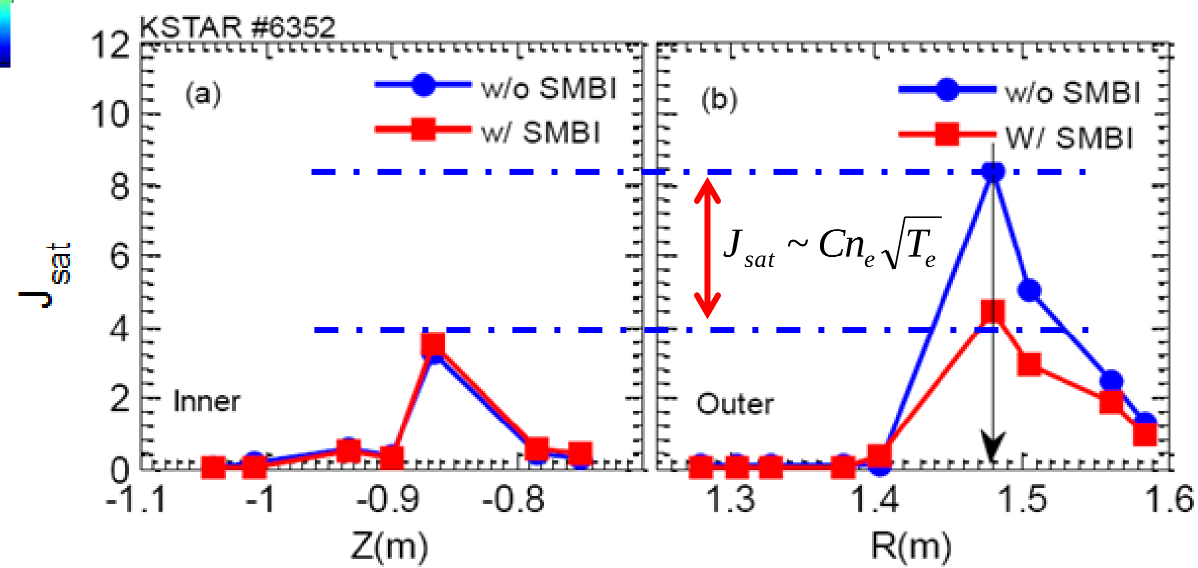
- The low frequency (f<10kHz, grey bar) content decreases, while, higher frequency (f>10kHz, grey bar) increases.
- The changes in the edge particle flux and the ion saturation current density → an increase in higher frequency fluctuations and transport events in the pedestal.
- **Key point: SMBI inhibits the formation of large (low frequency) avalanches or transport events, while triggering more small (high frequency) avalanches.**

Divertor signatures



Heat load evolution with and without SMBI for shot 16246 in HL-2A.





Heat load is estimated by Langmuir probes [8] data using following equation:

$Q_{div} \sim g\, C_s n_e T_e \sin\Theta$

g: the sheath heat transmission factor,

C_s: the ion sound speed,

Θ: is the incident angle,

T_e and n_e: temperature and density.

Inner and outer strike points [9]:

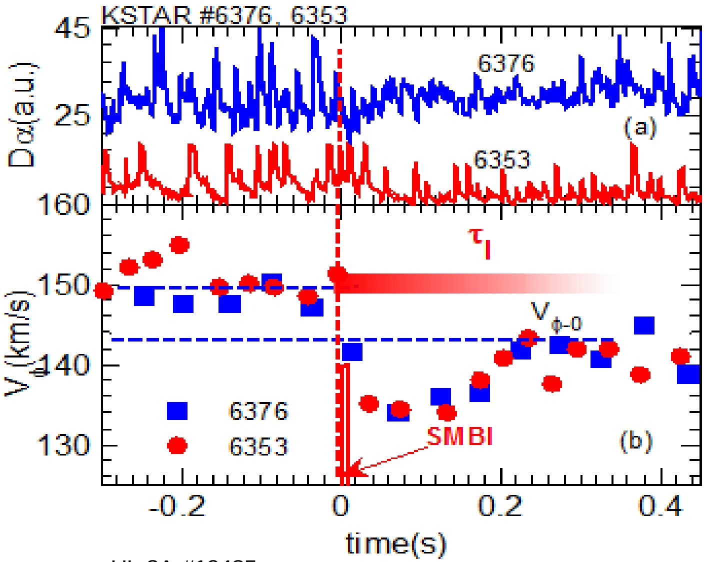
Inner → almost no change; outer → decrease by half.

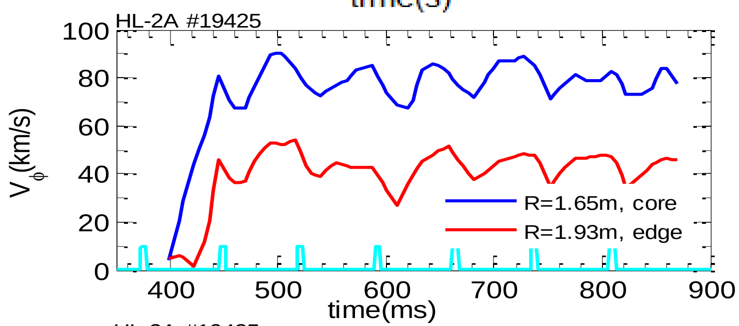
Key point: heat load and particle flux decrease during τ_I .

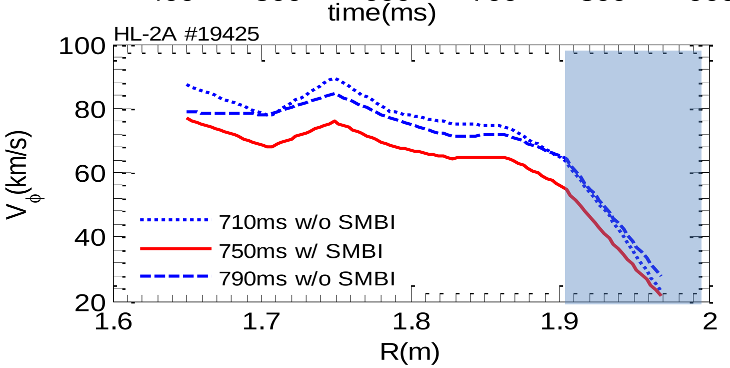
[8] L.W. Yan, RSI, (2005)

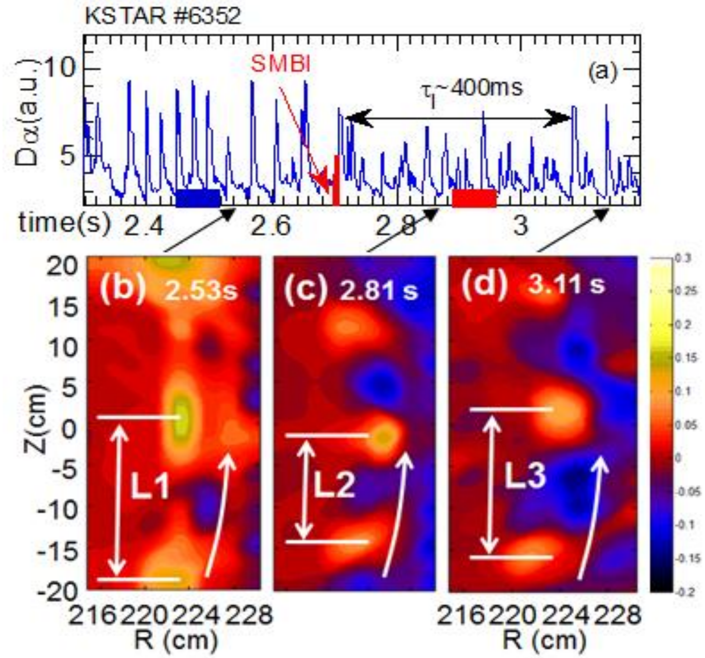
[9] J. G. Bak, Contrib. Plasma Phys. (2010)

Core toroidal rotation and filaments





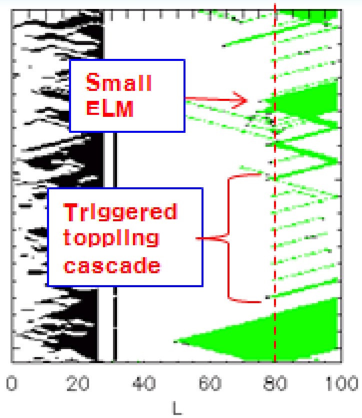


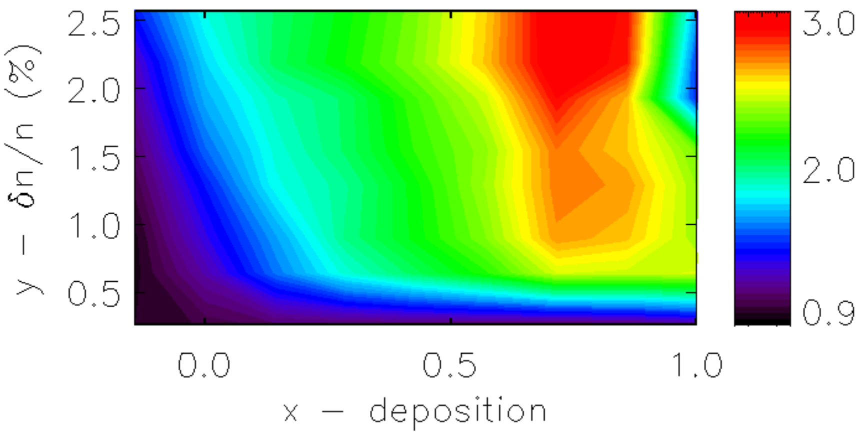


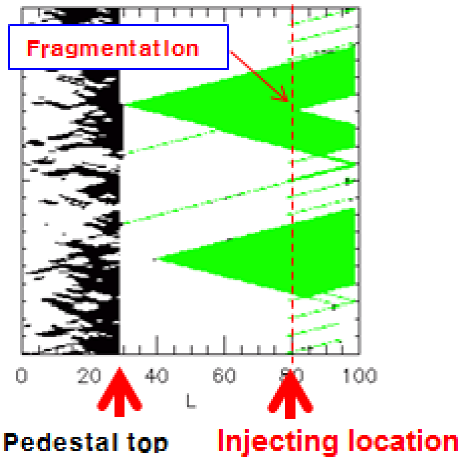
- Core toroidal rotation change during a τ_I time → softening of pressure gradient (as shown in shadow region)??

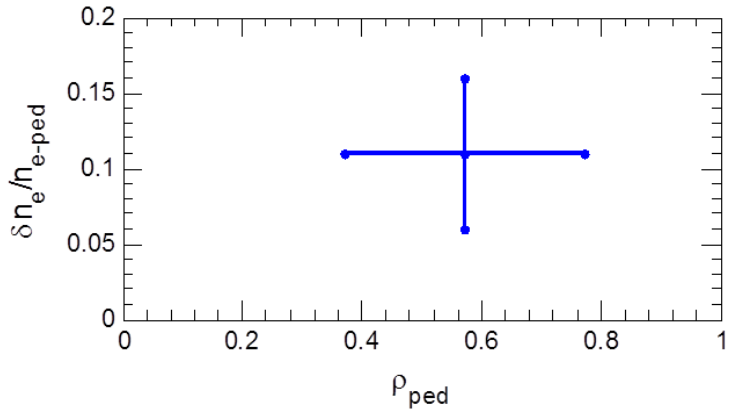
- Filament spacing indicates SMBI inhibits the formation of large MHD events, while triggering more small transport events during τ_I time.

Comparing a simple model to experiment









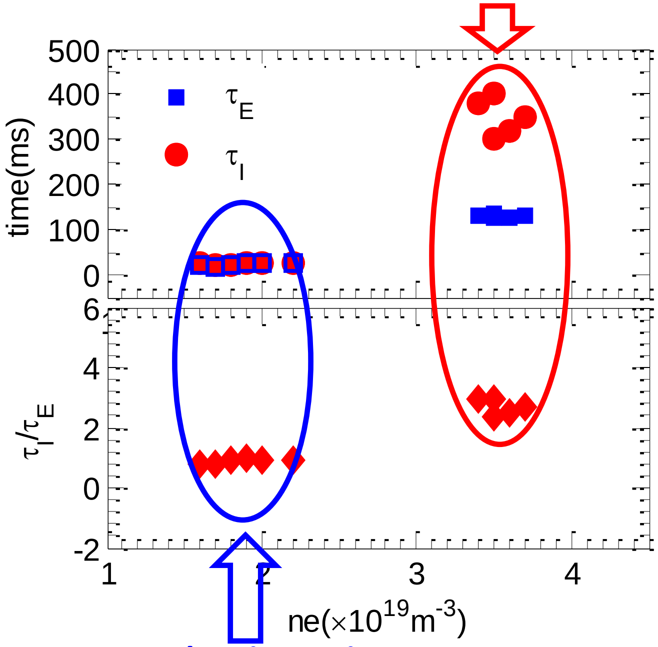
[10] T. Rhee, J.M. Kwon, P.H. Diamond and W.W. Xiao, PoP, (2012)
[11] I. Gruzinov, P. H. Diamond and M. N. Rosenbluth, PRL, (2002)

Experiments and theory support an important conclusion [10,11]:

It is not necessary to deposit particles at the pedestal top, and indicates that the ITER requirement for LFS fuelling injection to reach the top of the pedestal may be overly conservative.

Importance of τ_I/τ_P

High density regime



Low density regime

Machines	τ_E	τ_I	τ_I/τ_E
HL-2A	25+/-5ms	15-25ms	~1
KSTAR	150+/-20ms	250-400ms	~2-2.8

- τ_I is quite different in both machines.
- τ_I is close to τ_E in HL-2A (τ_E~20-25ms) [12].
- but much larger than τ_E [13] in KSTAR.

[12] X.R. Duan, NF (2010)
[13] S.W. Yoon, NF (2011)
[14] P. Staib, J. Nucl. Mater (1982)
[15] H. Takenaga, NF (1995)

- H_p factor ($H_p = \tau_p/\tau_E$) [14], for the H-mode case, the relationship τ_p VS τ_E: the ratio of τ_p to τ_E is about 1 in the low density regime; this ratio is about larger than 2 in high line averaged density regime [15].
- τ_I *vs* τ_p in ELM mitigation by SMBI.
  low density → τ_p/τ_E ~ 1 in HL-2A → an estimated ratio of τ_I/τ_p~1.
  High density → τ_p/τ_E is about 2.4 in KSTAR → τ_I/τ_p~1.1 with a averaged τ_I of 330 ms in KSTAR.

→ Particle transport events play important roles during a τ_I time.

Conclusions

Basic results:

- ELM mitigation by **SMBI** and **CJI** into the pedestal region was achieved in HL-2A and KSTAR.
- An increase in $f_{ELM}^{SMBI}/f_{ELM}^{0}$~2-3.5 and a decrease of the energy loss per ELM were achieved.
- The particle source position is shallow and just inside of the separatrix → **Shallow particle deposition is sufficient for ELM mitigation.**

Physics analysis:

- The characteristic slopes of the pedestal density are softened.
- v_{Φ} drops, then recovers at the end of τ_I .
- Edge Γ with and without SMBI→ the low frequency (f<10kHz) content decreases, while the higher frequency (f>10kHz) content increases.
- The changes of Γ and J_{sat} → increase fluctuations in higher frequency and transport events in the pedestal.
- The divertor heat load decreased in HL-2A, similar results was observed in KSTAR via J_{sat} . Also a reduction of the filament spacing during a τ_I time.
- An interesting phenomenon→ τ_I/τ_E and τ_I/τ_p ~ 1.

Turbulence and transport events play important roles during a τ_I time.

Open issues and next plans

Open issues

- What sets τ_I / τ_p ? How about τ_I / τ_p scaling?
- Another mechanism? $n_{neutral} \rightarrow \gamma_{ZF} \approx \gamma_{collis} + \gamma_{CX} \Rightarrow$ zonal flow damping. Does SMBI increase pedestal transport by damping ZF?
- Is there an intrinsic critical profile for pedestal?

Next plans

- **Edge particle transport (n_e profiles).**
- **Edge turbulence at mid-plane.**
- **What is the relation to other parameters in pedestal region? I_p, T_e…**
- **Rotation measurements.**

Finally → how to increasese the ratio of $f_{ELM}^{SMBI}/f_{ELM}^{0}$ by SMBI to more than 10 ?

Acknowledgements

This work was supported by:

- **WCI Program WCI 2009-001, WLI program, NRF Korea No. 2012-4836**
- **China National Fusion Project for ITER 2009GB104007, NSFC Nos. 11175056 and 10975049**
- **China-Korean joint foundation under the Grant No. 2012DFG02230**