USTC SNST 2016 Spring Semester Lecture Series

Title: **Introduction to Research and Development in Tokamak Fusion Energy Science and Technology**

Lecture 6: Room 1617, 930-1130, **Saturday** April 22, 2016
(核学院, 西区科技实验楼东楼)

L6: Super thermal insulator “H-mode pedestal”, the suggested mechanisms that causes L-to-H transition, so far

Lecturer: 彭元凯, pengyk@ustc.edu.cn
Class assistant: 徐国梁, xudaren@mail.ustc.edu.cn
Webpage assistant: 王伸吉, dwsmile@mail.ustc.edu.cn
Up-to-date lecture PDF’s: http://www.snst.ustc.edu.cn/wdxz/

2016 spring semester class dates and topics - Updated

Work around national holidays and finals(?); add student presentations

L	1)	**03/12 –** Special features, feedback, and plan of lectures
L	2)	**03/19 –** Super thermal insulator "H-mode pedestal", the **phenomena**
S	3)	**03/26 Zero volunteer!**
L	4)	**04/09 –** Super thermal insulator "H-mode pedestal", **phenomena cont.**
S	5)	**04/16 Almost one volunteer!**
L	6)	**04/23 –** Super thermal insulator "H-mode pedestal", the **mechanisms**
S	7)	**05/07 石生宇同学; one more to go!**
L	8)	**05/14 –** Super thermal insulator "H-mode pedestal", the **instabilities**
S	9)	**05/21 ≤ 2 student presentations**
L?	10)	**05/28 – Spherical tokamak** plasma, same as tokamak plasma, or not?

Suggested Student Presentation/Discussion Goal & Procedure

1. English only, throughout
2. Goal: to train students' ability to make effective technical presentations, and enliven their R&D experience
3. Remember: true understanding is obtained only when you can express it clearly and concisely, such as in a strong PPT presentation.
4. 10 slides only, for 20-minute presentation, 30-minute additional for discussion among class
5. Sign up by sending title, 7 days in advance of class presentation, to 徐国梁 (xudaren@mail.ustc.edu.cn)
6. Send PPT of presentation, 4 days in advance of class, to me (pengyk@ustc.edu.cn)
7. I will return PPT with my suggestions 2 days in advance of presentation
8. Let's have more fun!

Main reference:

Edge radial electric field formation after the L-H transition

K. Kamiya

Japan Atomic Energy Agency (JAEA)

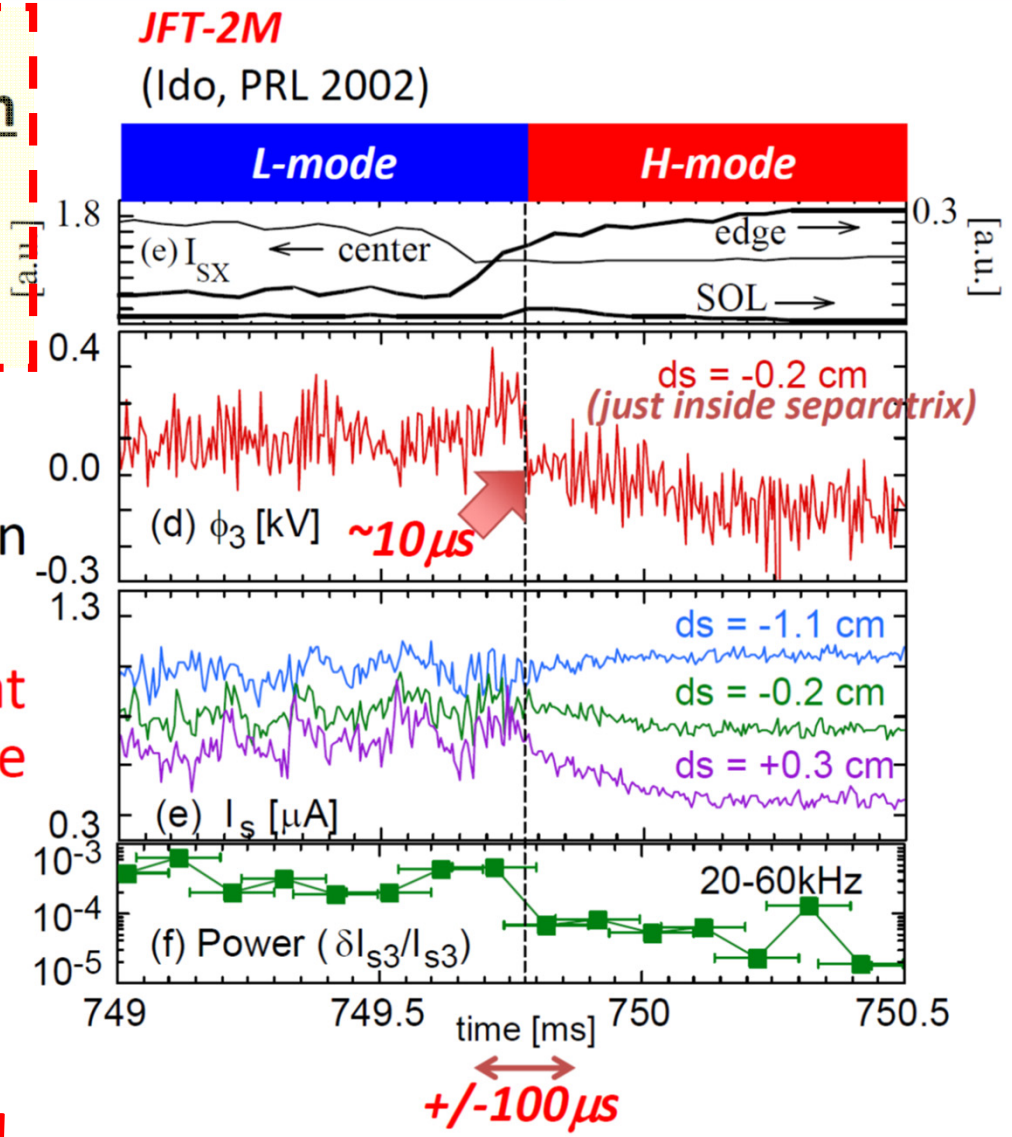
December 14 - 18, 2015 School of Nuclear Science and Technology University of Science and Technology of China, Hefei, China

8th International ITER school

Direct measurement with fast temporal resolution was performed by a HIBP in JFT-2M

- **The time-scale of the E_r formation at the L-H transition** was found to be 10-100 micro sec (<<tau_E; time-scale for global energy transport).
- Simultaneously, a significant reduction of turbulence intensity and the ETB formation were seen.
- Finally, it became no doubt that the L-H transition should be the transition of the radial electric field as predicted by a theory.
- If so, what is causality for the Er-bifurcation?

Faster than all other observed behaviors!



Recent experimental results *(JFT-2M)*

JFT-2M (JAERI Fusion Torus-2M)

tokamak

R = 1.3 m, a = 0.35 m

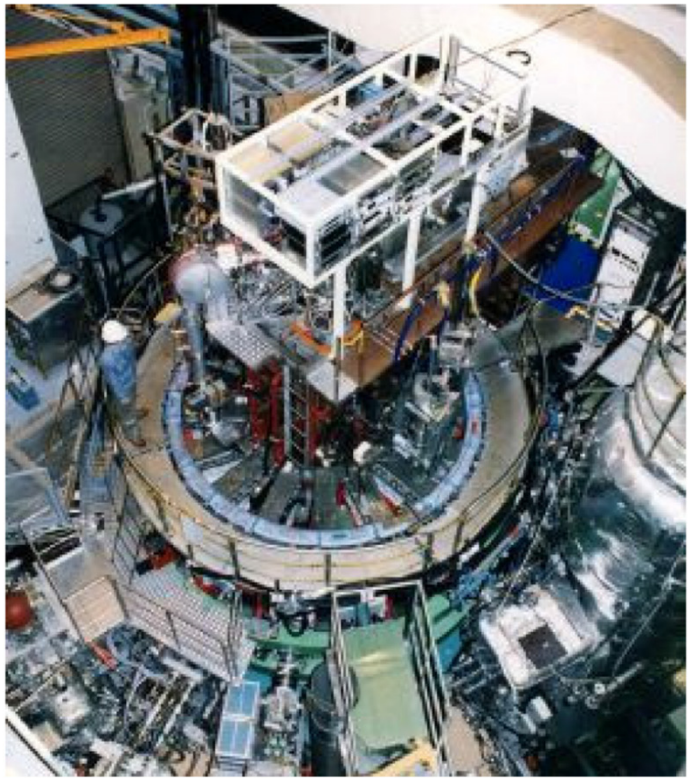
$B_t \leq 2.2$ T

$I_p \leq 0.5$ MA

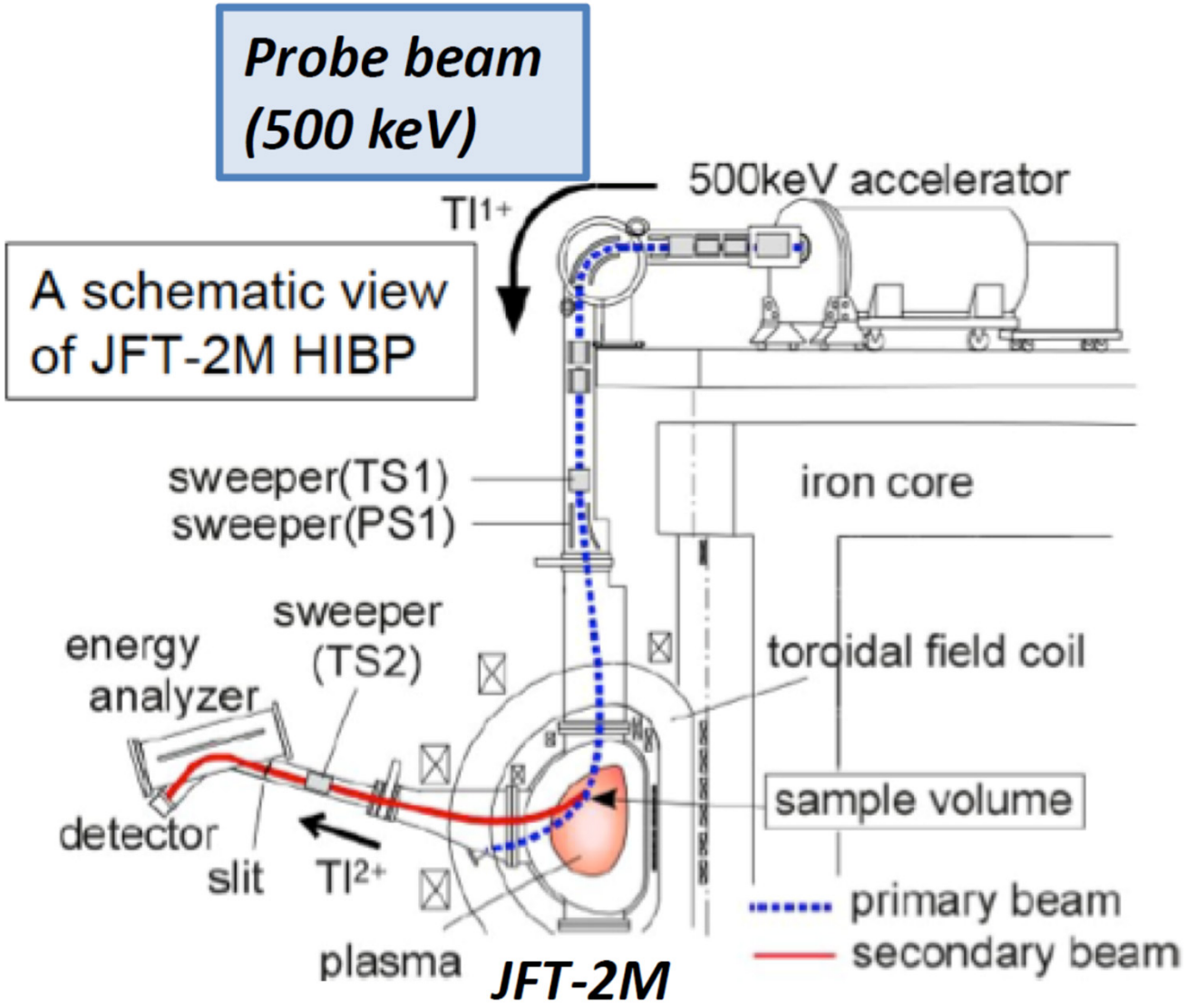
(Medium sized tokamak)

NBI power ≤ 1.6 MW (Balanced)

*Already been shut down in 2004
http://www-jt60.naka.jaea.go.jp/jft2m/



So, how does a Heavy Ion Beam Probe (HIBP) work?



- Thallium (Tl^{1+}) ions accelerated to 500keV
- Carefully steered to pass through plasma edge region
- Toroidal field bends its orbit; edge potential changes its energy
- Some ions lose another electron (Tl^{2+}) while in plasma
- Energy analyzer directly measures energy change, almost instantly!

HIBP and CXRS are the most powerful tool for the physics study of edge Er formation during L-H transition

HIBP	CXRS
Direct measurements for the change of potential and fluctuation, simultaneously; $E_r = -\nabla\phi$	Indirect evaluation from radial force balance equation for impurity ions; $E_r = \nabla p_j / Z_j e n_i - V_{\theta,j} B_\phi + V_{\phi,j} B_\theta$
Fast temporal resolution up to 1 micro-sec at a few spatial points, simultaneously, being suitable for the study on causality of ETB formation	***High spatial resolution*** up to ~1 cm at multi-points simultaneously in the pedestal, achieving a better S/N by means of heating neutral beam.
Installation costs is too high (especially for larger devices), depending on the diagnostic beam.	Conventional and useful method in many devices, but time resolution (~1ms, or less) is not enough in some case.
Simultaneous measurement for plasma density fluctuation, but pedestal measurements at higher density is limited due to beam attenuation ($n_e \leq 1 \times 10^{19}$ m^{-3}, typically).	Even though, CXRS has an advantage for simultaneous measurements of pedestal information (e.g. n_i, T_i, V_p, and V_t).

(from L2-L4) Let's compare tokamak and stellarator H-modes, to sort out which plasma behavior is germane to the phenomenon

Behavior associated with H-mode	Tokamak	Stellarator
H_α line emission (edge particle recycling) drops (~ms)	Yes	Yes
Edge transport barrier (ETB) region just inside LCFS	Yes	Yes
Temperature and density profiles develop steeper gradients	Yes	Yes
Strong poloidal plasma flow with strong flow shear in ETB	Yes	Yes
Flow correlates with strong radial electric field (0.1-1.0kV/cm)	Yes	Yes
Density fluctuations in edge region disappear fast (~ms)	Yes	Yes
Need large edge magnetic shear, such as divertor	No	No
Energy confinement time increases, more for divertor than limiter plasmas	Yes	No
Heating power and density thresholds depend on configuration	Yes	Yes
Edge localized modes (ELMs) can occur during H-mode	Yes	Yes
Plasma returns to L-mode in ~30ms after heating power stops	Yes	Yes

Plasma edge ϕ and E_r appear in 10 μs, faster than these phenomena?

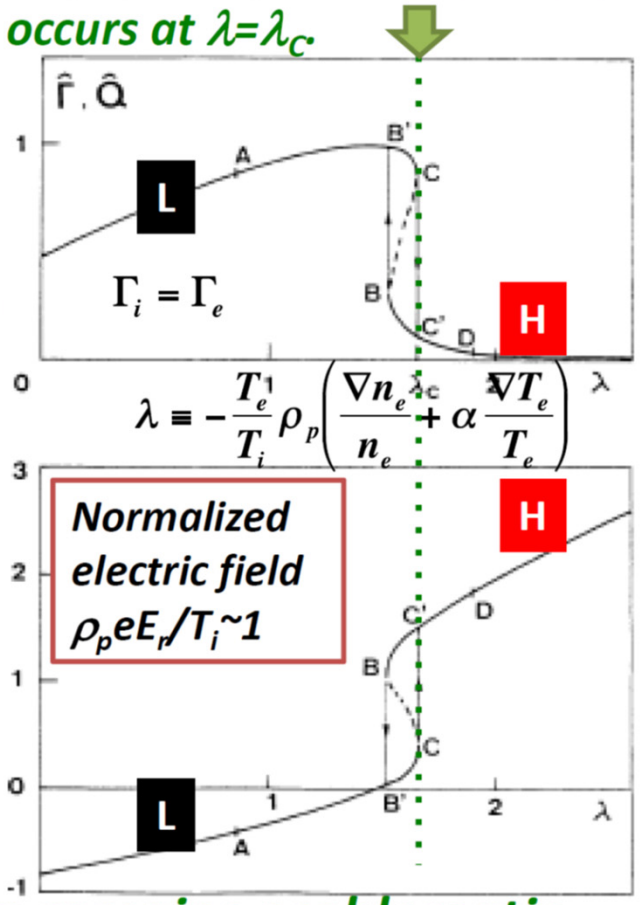
Have we answered the question:

What causes the very fast creation of large E_r at the L-to-H transition?

Ion orbit loss model near the plasma boundary was proposed *[Itoh and Itoh, PRL1988]*

- In 1988-89 (>5 years after the 1st H-mode discovery in ASDEX), *before experimental observation*, theoretical work predicted that the E_r might play an important role in the mechanism of the L-H transition.
- Experimental verifications on many devices were also performed [Burrell, PPCF 1992, PoP 1997; Ida, PPCF 1998].
- It is conventionally *believed* that the high confinement regime is achieved when the ***E ×B shear*** is sufficient to stabilize the turbulent fluctuations responsible for anomalously high transport.

Transition from the branch of large flux (L) to small flux (H) occurs at $\lambda=\lambda_C$.

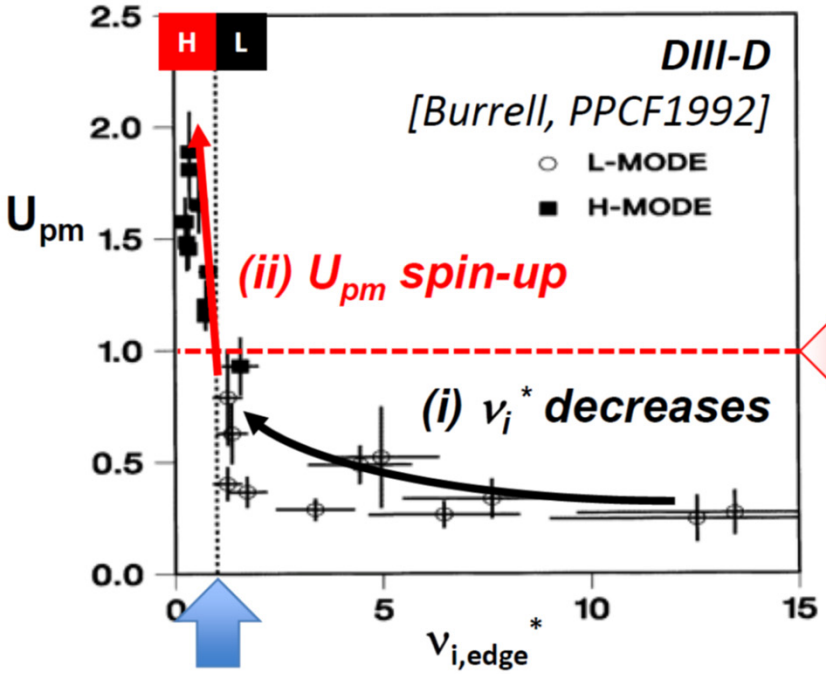


Nevertheless the transition trigger mechanism remains problematic.

Buildup time of charge?

Sequence of the physical events in the L-H transition, according to the ion-orbit loss model

[K. C. Shaing and E. C. Crume, Jr., Phys. Rev. Lett. 63, 2369 (1989).]



***A critical ν_i^* value**, depending on the details of devices (e.g. hot ion fraction, impurities, neutrals…).*

=> Indeed, larger nyu_i* (=10–50) was reported [Miura, PRL 1992, Carlstrom, PoP 1996]

i) Because of plasma heating, $\nu_{i,edge}^*$ decreases.

ii) U_{pm} makes a transition at a critical value of $\nu_{i,edge}^*$ and becomes more positive [the corresponding E_r value becomes more negative with its time-scale of $\mathbf{O}(\nu_{ii}^{-1})$].

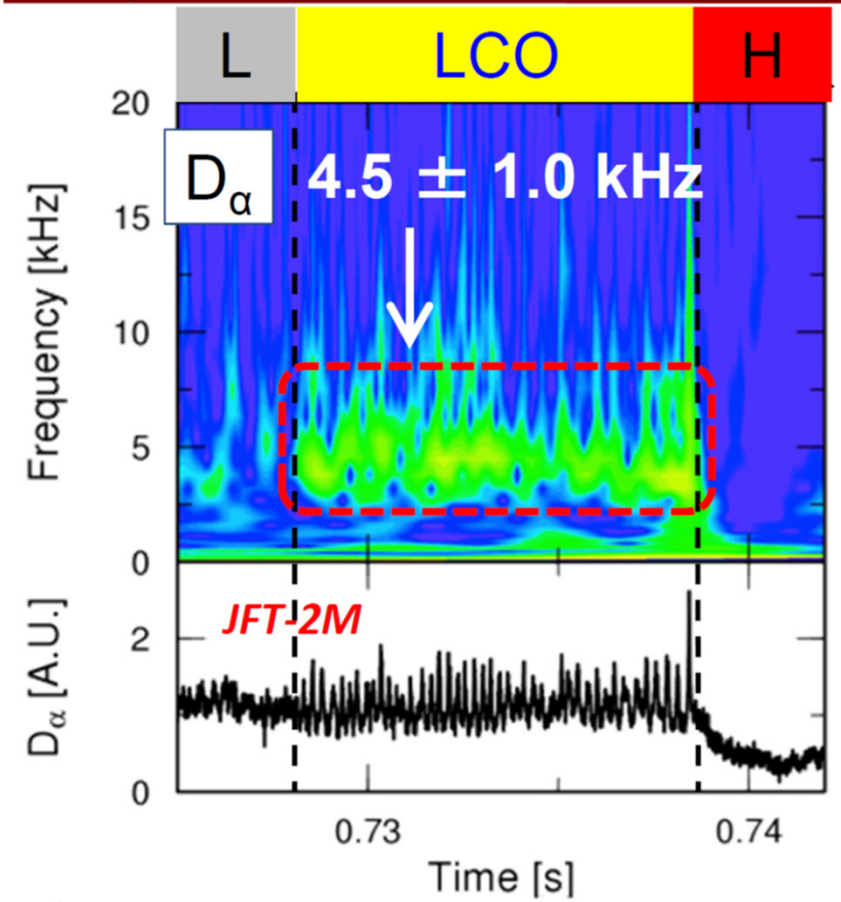
iii) When V_θ increases, fluctuations saturate at lower level due to decrease the de-correlation time for turbulent fluctuations, and the L-H transition thereby occurs.

iV) The D_α intensity drops, and the edge gradient becomes to build in the pedestal …

Buildup time of poloidal rotation?

Limit-Cycle Oscillation (LCO) was seen just before the L-H transition on many devices

Kobayashi, PRL 2013



- ✓ Theoretical models [Itoh-Itoh, PRL 1991; Kim-Diamond PRL 2003].
- ✓ Experimental observations (TJ-II, and AUG, DIII-D, EAST, HL-2A, …).

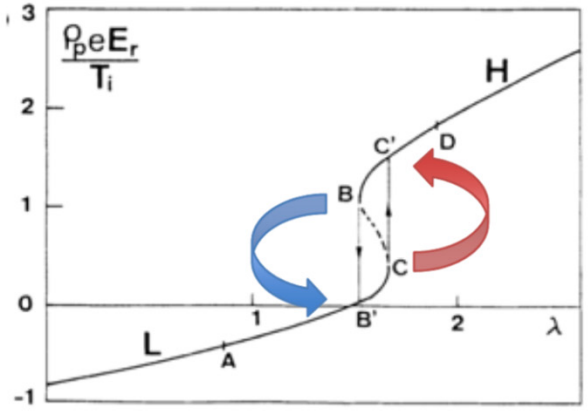
- However, understanding of the physical mechanism is still not be completed due to lack of ***direct measurements*** for the E_r,…
- Because of difficulties for simultaneously multi-channeled measurements for determination of ZF (*e.g. Analogy from Doppler reflectometory and/or floating potential measurement by probe*).
- HIBP is powerful-tool to explain the physical mechanism of the LCO, and hence we revisited this study in JFT-2M with HIBP.

LCO = "just over the hump"

Theoretical models that could explain LCO.

Model-1: E_r bifurcation

S-I. Itoh, K. Itoh et al., PRL **67**, 2485 (1991)

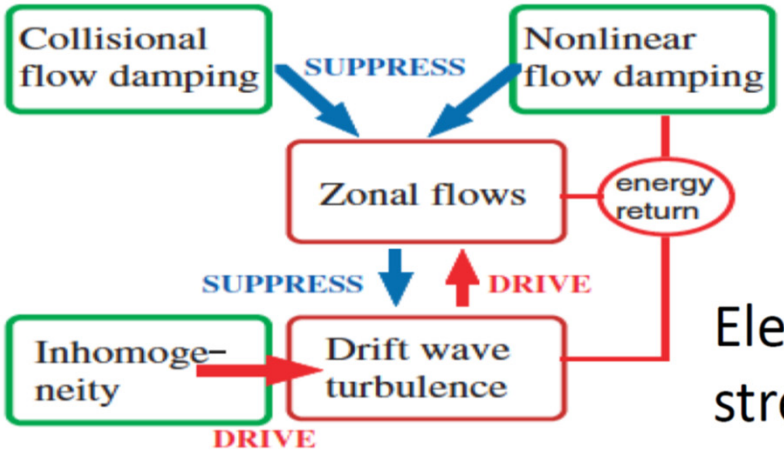


- LCO can be explained as a transition between two overlapped possible E_r values, by changing the *non-ambipolar radial flux*.
- Basically, LCO is dynamics among turbulence, mean pressure, and mean electric field.

$$\frac{\varepsilon_0\varepsilon_\perp}{e}\frac{\partial}{\partial t}E_r = \Gamma_{e-i}^{anom} - \Gamma_i^{lc} - \Gamma_i^{bv} - \Gamma_i^{v\nabla v} - \Gamma_i^{cx} - \Gamma_i^{NC} + \Gamma_e^{NC}$$

Model-2: Predator-prey model

Kim & Diamond: PRL **90** 185006 (2003)

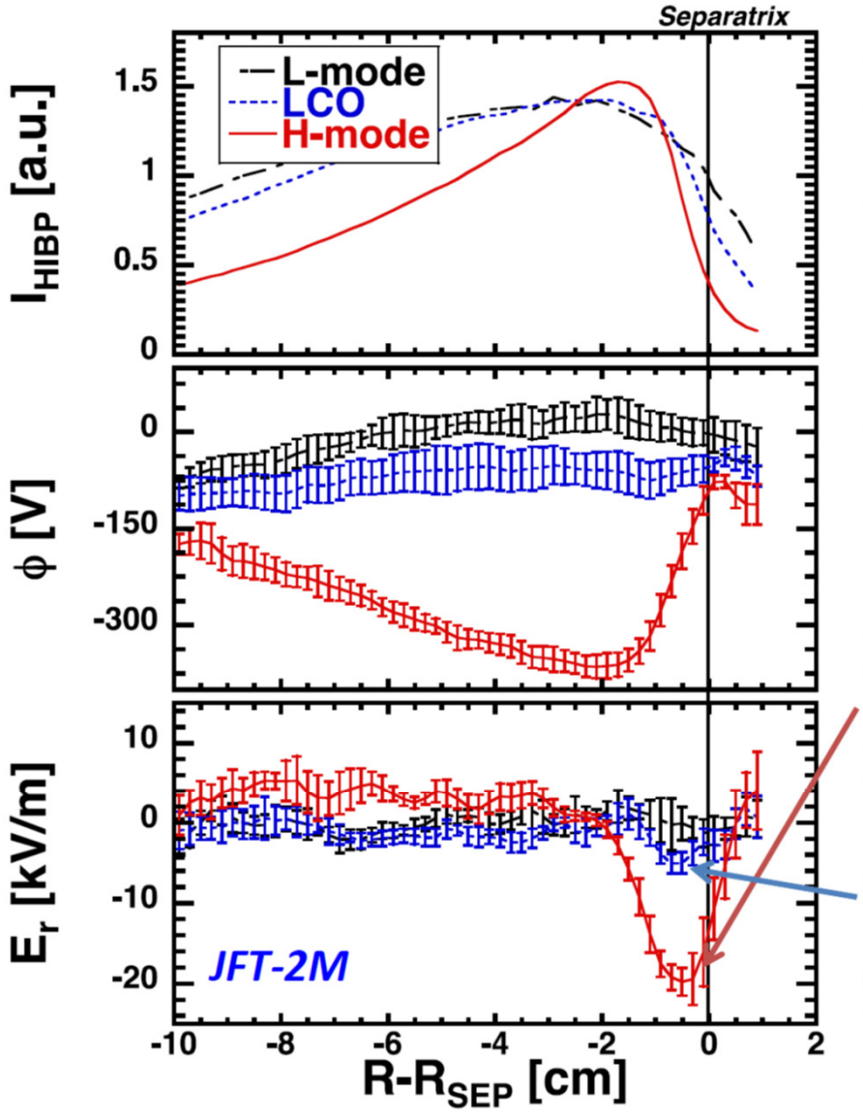


1. Turbulence intensity increases, and that excite ZF.
2. Excited ZF suppresses the turbulence.
3. ZF is also decay because the energy source (turbulence) no longer exists.

Electric field excitation process is Reynolds stress driven.

$$\varepsilon_\perp \frac{\partial}{\partial t} V_\theta = -\nabla\langle \tilde{v}_r \tilde{v}_\theta \rangle - \nu_{damp} V_\theta$$

Mean profile of E_r and density gradient in both L-mode and LCO phases are found to be similar



H-mode;

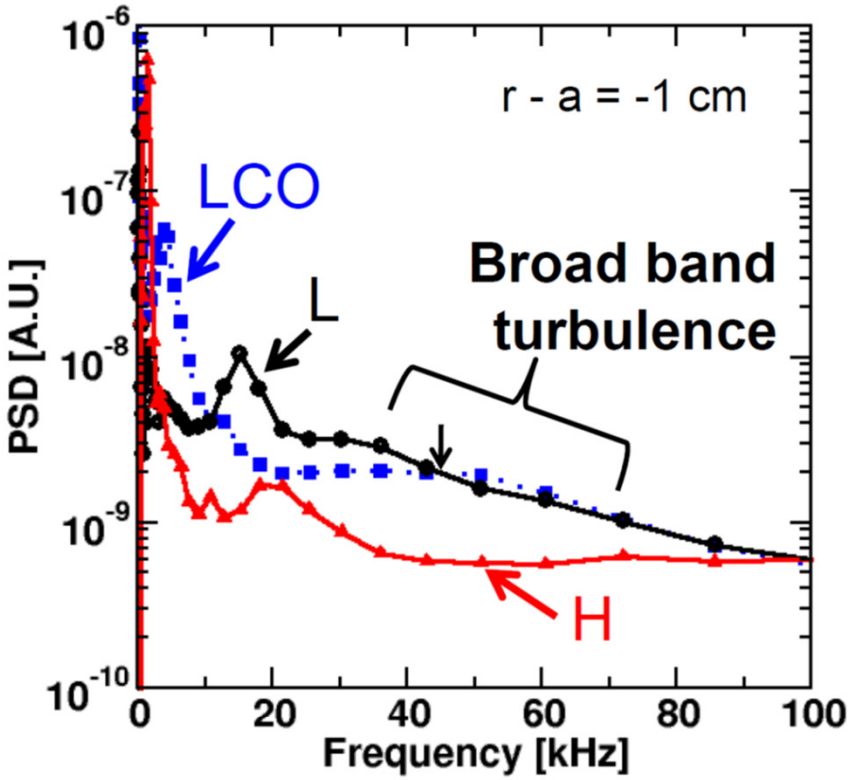
- ✓ Steep gradient in I_{HIBP} (density gradient becomes steeper)
- ✓ Strong E_r (=-dϕ/dr)

$E_r \times$ B velocity (~ 30 km/s) is quite larger, in comparison with the amplitude of the flow modulation induced by the LCO (~0.5 km/s)

Micro-scale turbulence in LCO phase was also similar to that in L-mode

JFT-2M

Power spectrum of φ



In H-mode, high frequency component is suppressed.

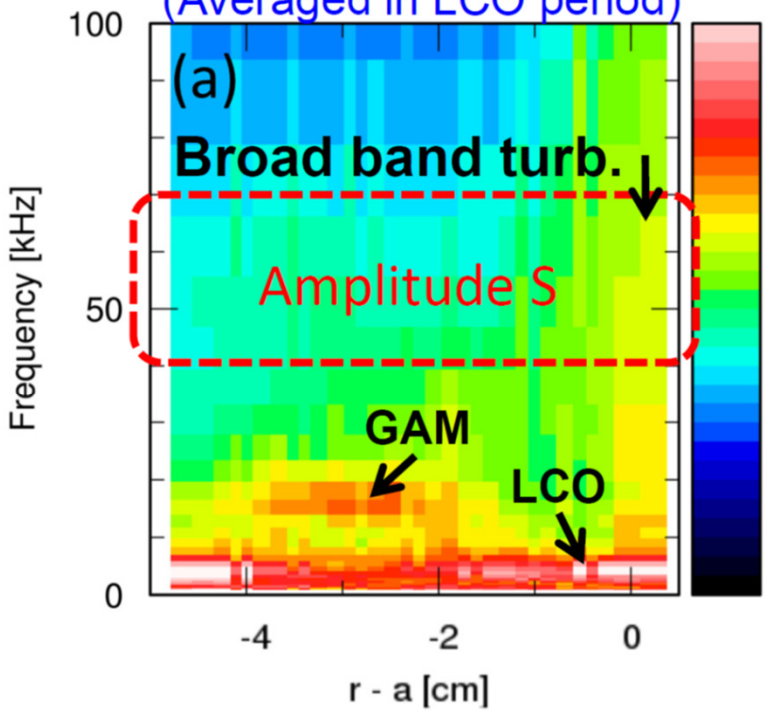
(*Kobayashi, PRL 2013, NF2014*)

⇒Family of drift wave

- m ~ -20 (electron dia.)
- Phase difference; $\tilde{N} \sim e^{-i0.4\pi e\tilde{\phi}/T_e}$
- $\omega/k_\theta \sim V_{d,e}=T_e/(eB_tL_n)$~4 km/s

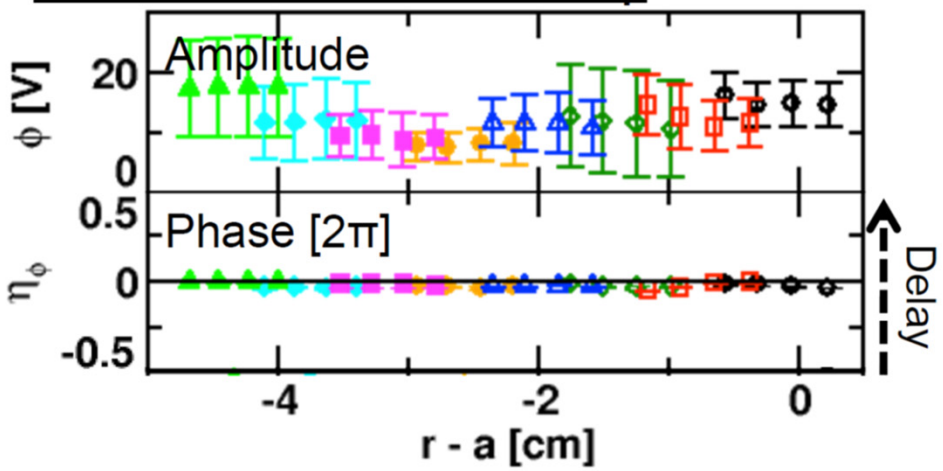
  $(\text{i.e., } k_\theta \sim -0.7 \pm 0.1\ \text{cm}^{-1})$

(Averaged in LCO period)

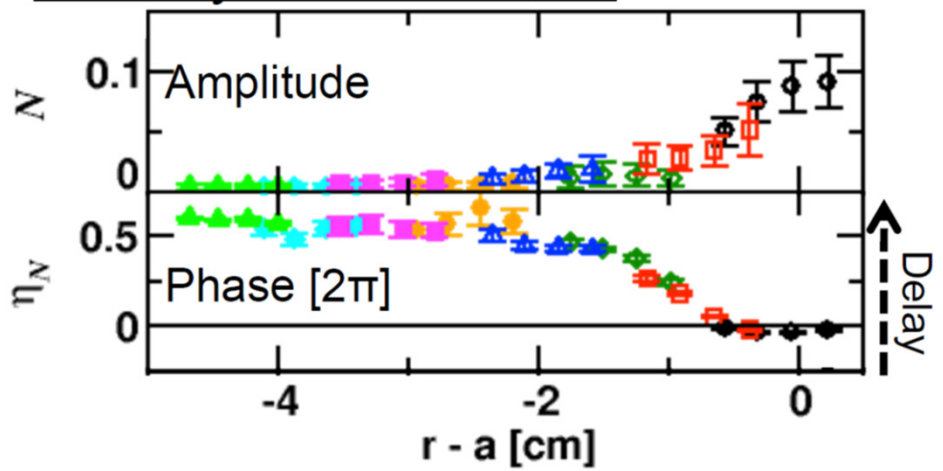


Spatio-temporal structure of φ and density fluctuations during LCO phase

Potential fluctuation: φ

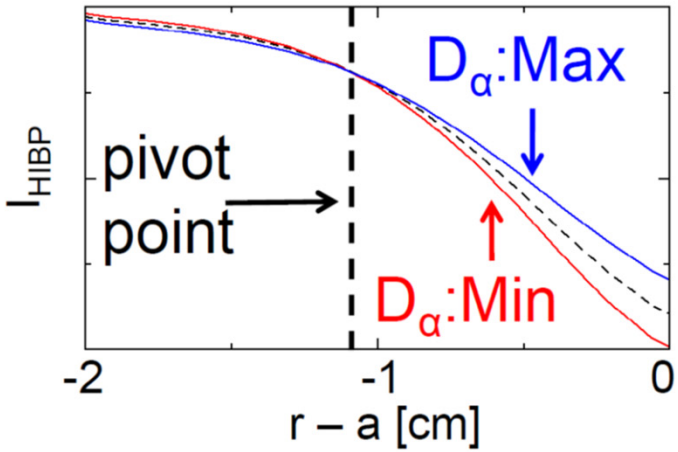


Density fluctuation: N



JFT-2M *(Kobayashi, PRL 2013, NF2014)*

- Amplitude has homogeneous profile for LCO (f~4.5 kHz)
- Phase difference ~ 0
  → k_r~0 (*Not* zonal flows)

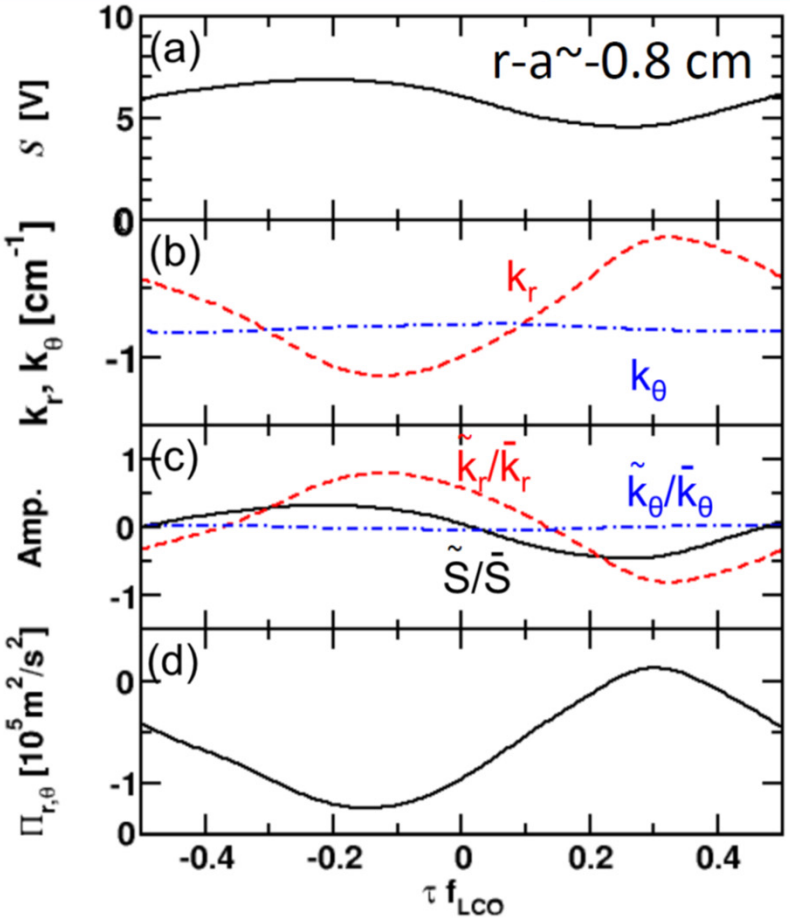


- A peak at r-a ~ 0 cm
- Phase inversion at r-a ~ -1 cm

→Small ETB formation and crash during LCO.

Reynolds stress drives only ~15 m/s of poloidal velocity modulation during LCO

JFT-2M



(conditional average of 21 oscillation periods)

Reynolds stress (f=40-70 kHz)

$$\Pi_{r\theta} = \langle \tilde{E}_r \tilde{E}_\theta \rangle / B^2$$

$$= -S^2 k_r k_\theta / (2\,B^2)$$

$$\hat{\Pi}_{r\theta} = -\bar{S}_0^2 \bar{k}_r \bar{k}_\theta \{2\hat{S}/\bar{S} + \hat{k}_r/\bar{k}_r + \hat{k}_\theta/\bar{k}_\theta\} / (2\,B^2)$$

Equation of motion

$$\epsilon_\perp \partial \hat{V}_{E\times B}/\partial t = \partial \hat{\Pi}_{r\theta}/\partial r + \cdots$$

where, dielectric constant: $\epsilon_\perp = 1 + 2q^2$ ~20

Evaluated flow modulation is:

$$\delta|\hat{V}_{E\times B}| \sim |\hat{\Pi}_{r\theta}| L^{-1} \epsilon_\perp^{-1} \omega_{LCO}^{-1} \sim 15 \text{ m/s}$$

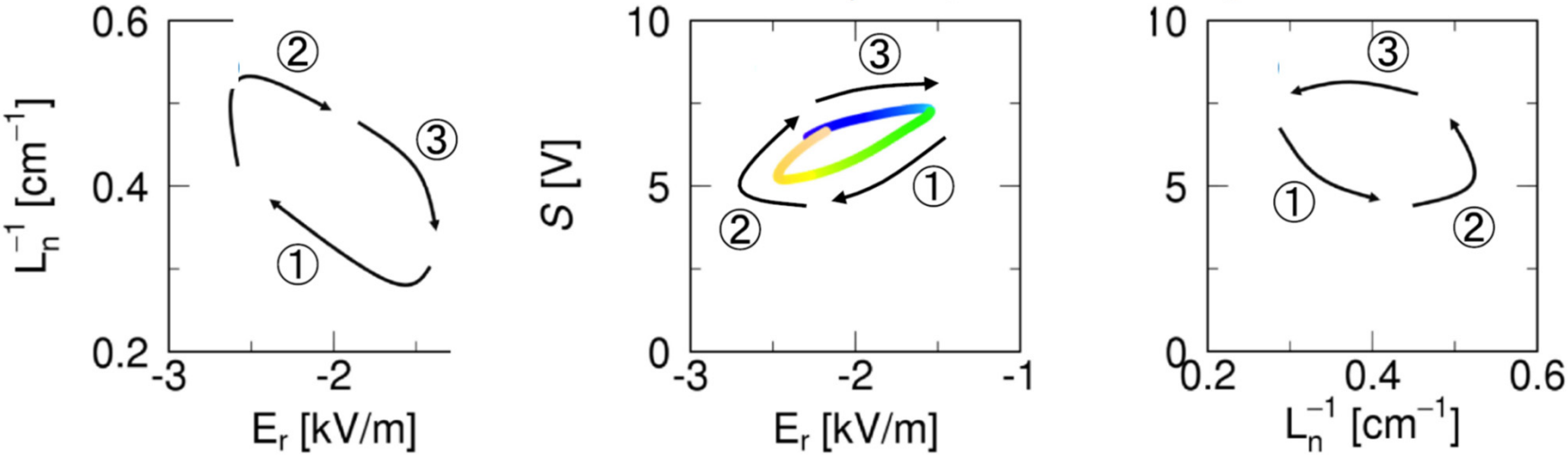
ExB flow modulation ~500 m/s.

Small role of turbulence in poloidal acceleration is consistent with the observation that the oscillatory flow in LCO is not zonal flows.

Discussion: Causal Relation among Electric Field E_r, Turbulence S and Density gradient L_n^{-1}

JFT-2M

at the location of maximal E_r amplitude during LCO.



(1) Growth of $-E_r$ suppresses S and transport, and induces the growth of L_n^{-1}.

(2) Strong L_n^{-1} excites S and transport.

(3) Transport leads to decay of $-E_r$ and following relaxation of L_n^{-1}.

Observed temporal evolution seems to be corresponds to the E_r bifurcation model [S.-I. Itoh, K. Itoh., et al., PRL (1991)],

=> Perhaps, the E_r-bifurcation model may maintain the LCO phases, rather than P-P model.

Have we answered the question:

What causes the very fast creation of large E_r at the L-to-H transition?

Not yet.

Student S5: Room 1617, 930-1130, **Saturday** April 16, 2015

1) **930-1025: 石生宇同学: 关于ETG (Electron Temperature Gradient) – delayed to L7, Saturday May 7, 2016**
2) **1030-1125: another brave soul**

Waiting for one more brave soul to step forward.
Send email to 徐国梁 (xudaren@mail.ustc.edu.cn), **today!**