Experimental studies of Low-Intermediate-High confinement transition

Presented by J. Cheng
Southwestern Institute of Physics

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School of nuclear science and Technology
University of science and technology of China, Hefei China

Outline

1. Introduction
2. Experimental setup on studying edge turbulence
3. Experimental results on HL-2A

3.1 Characteristics of limit cycle oscillation (LCO)

3.2 Role of turbulence and pressure gradient driven flows on transition

3.3 Dynamics of high-intermediate-high confinement transition

3.4 Reduction of heating power accessing H mode with a kink-like mode crash

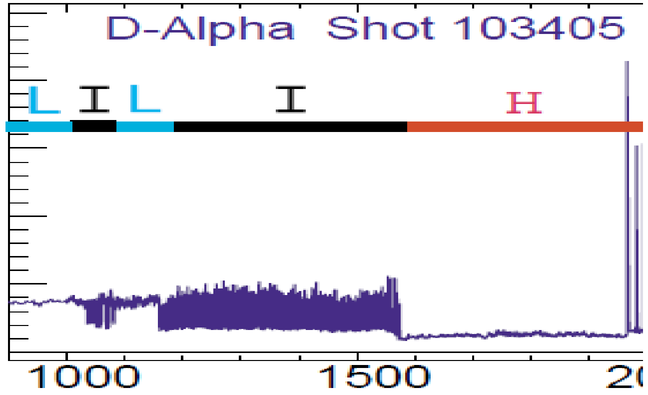
4. Summary

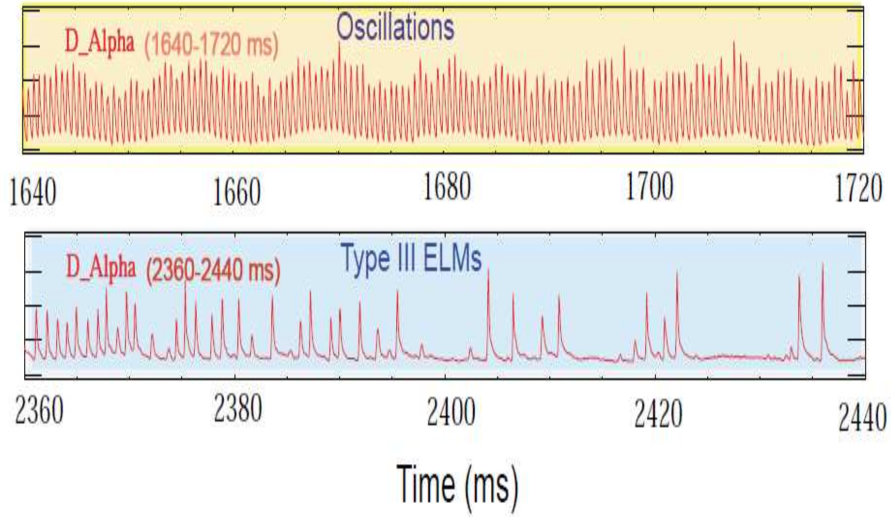
Why study I-phase?

- L-H transition physics is critical for the power threshold scaling and heating requirement in future reactors, ITER
- Usually, L-H transition happens very fast (<1ms), it needs high time-spatial resolution diagnostics to find possible relationships among turbulence, zonal flow and ∇P, etc
- Theoretical predication, heating power is near L-H transition threshold (slow L-H transition), plasma may pass by an intermediate phase or I-phase (oscillation between L and H)
- I-phase with a limit cycle oscillation (LCO, finite oscillation frequency) extends the time scale to study the causality

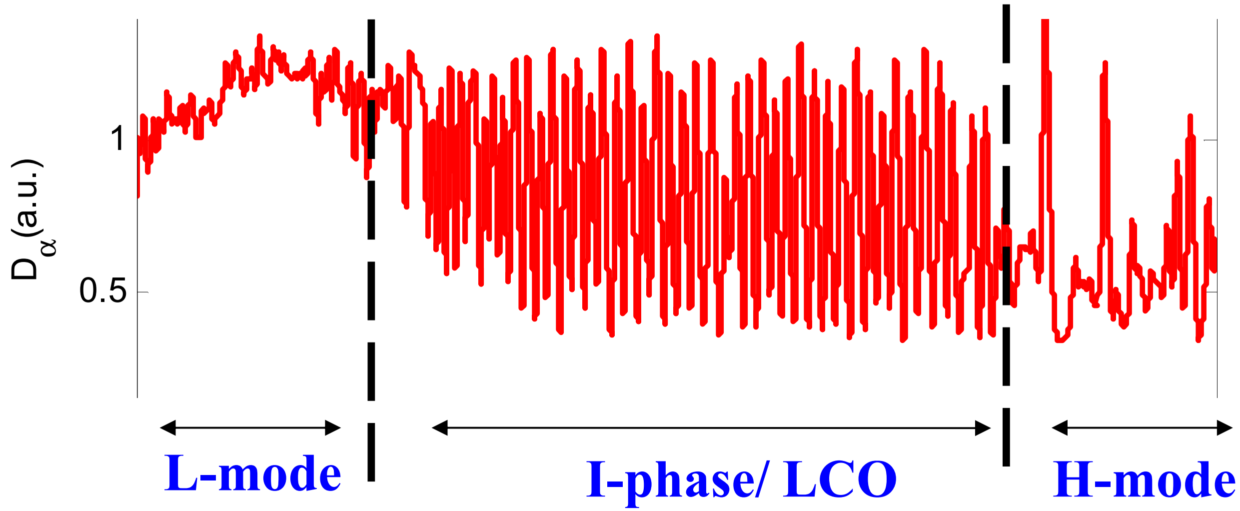
LCO: marginal power

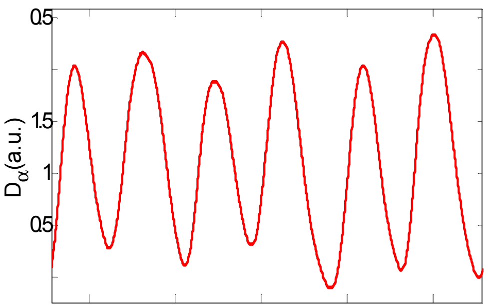
- DIII-D: NBI power=0.7 MW



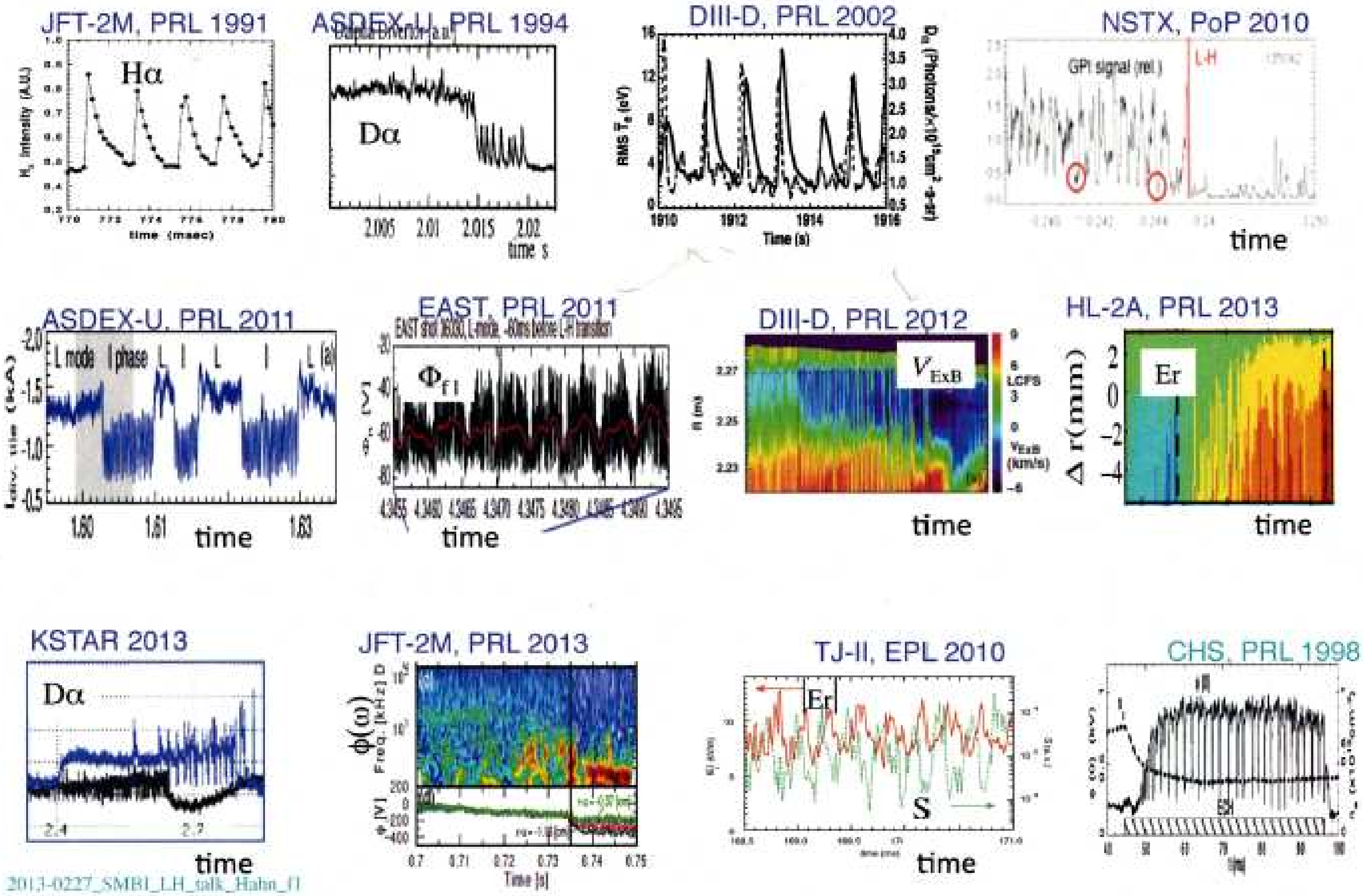


- HL-2A: NBI power=1.0 MW



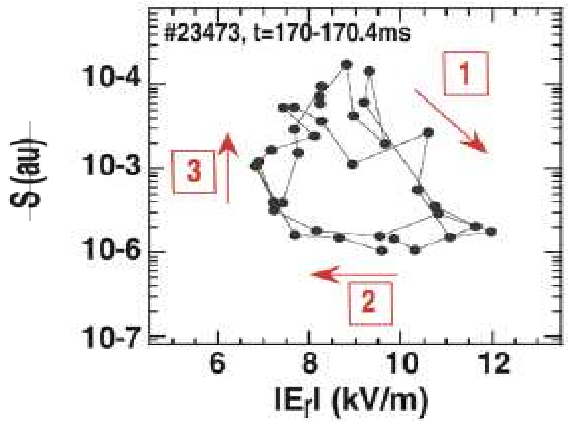


LCO provides chance to study causality

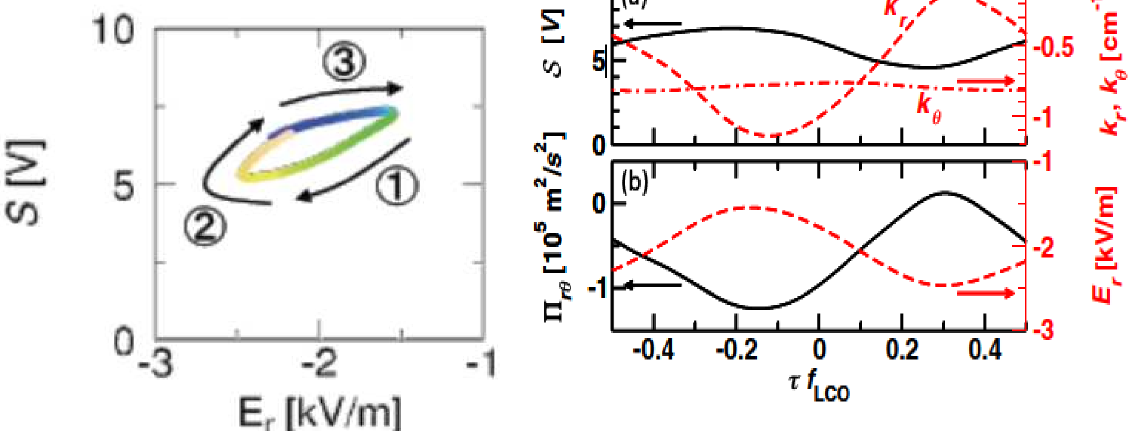


Different rotation of LCOs

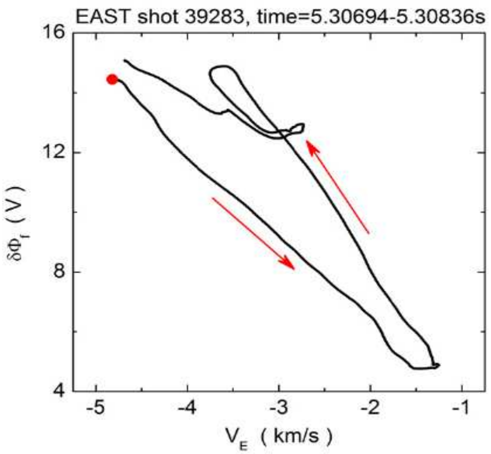
TJ-II (Estrada, PRL (2011))



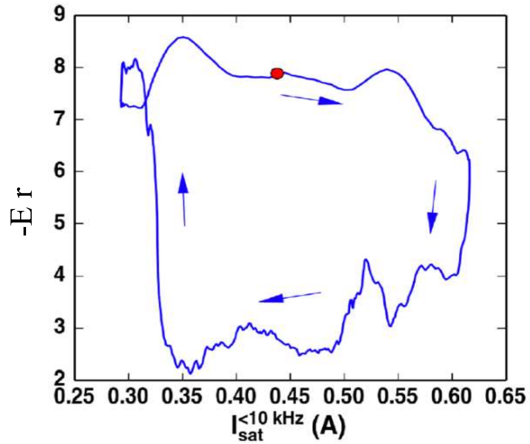
JFT-2M (PRL, 2013)



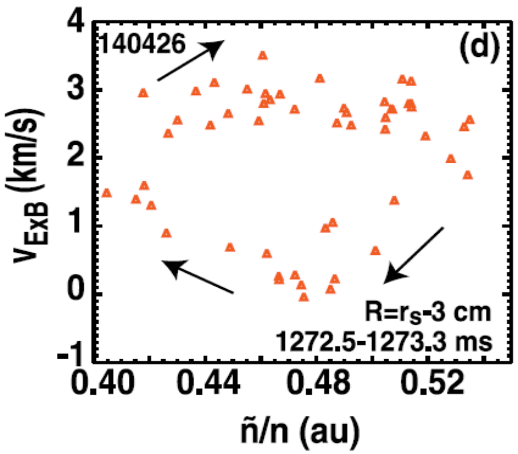
EAST (Xu, NF2014)



AUG (Mueller, PoP2014)



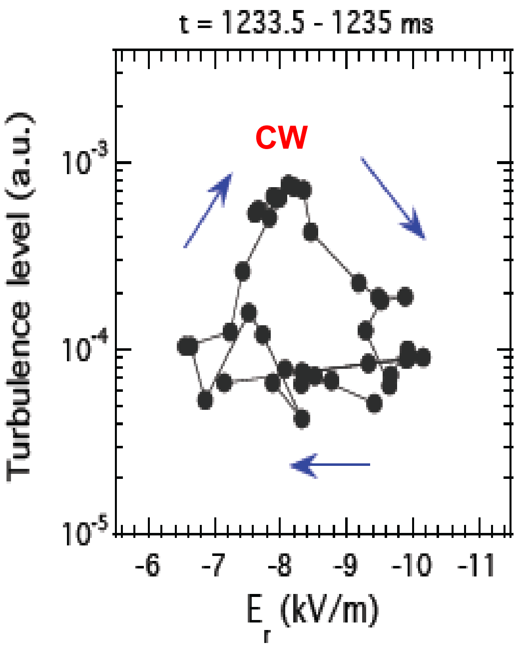
DIII-D (Schmitz, NF2014)

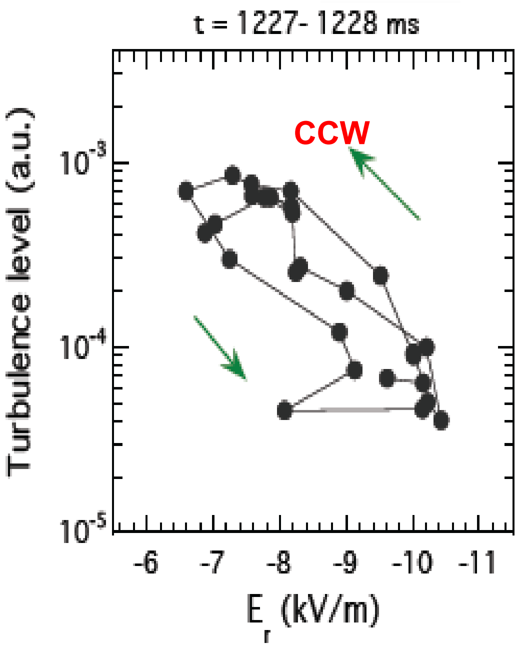


- LCO widely observed in TJ-II,AUG/DIII-D/JFT-2M (f=1-5 kHz)
- Different rotation might be correlated with the measured location (TJ-II/DIII-D)

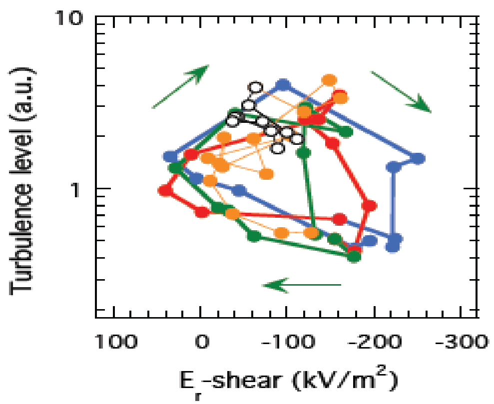
Inverse rotation (CCW) of LCOs

TJ-II DATA

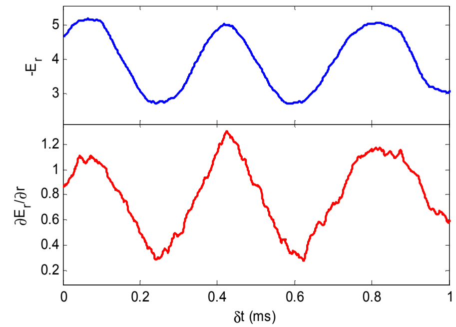




TJ-II DBS

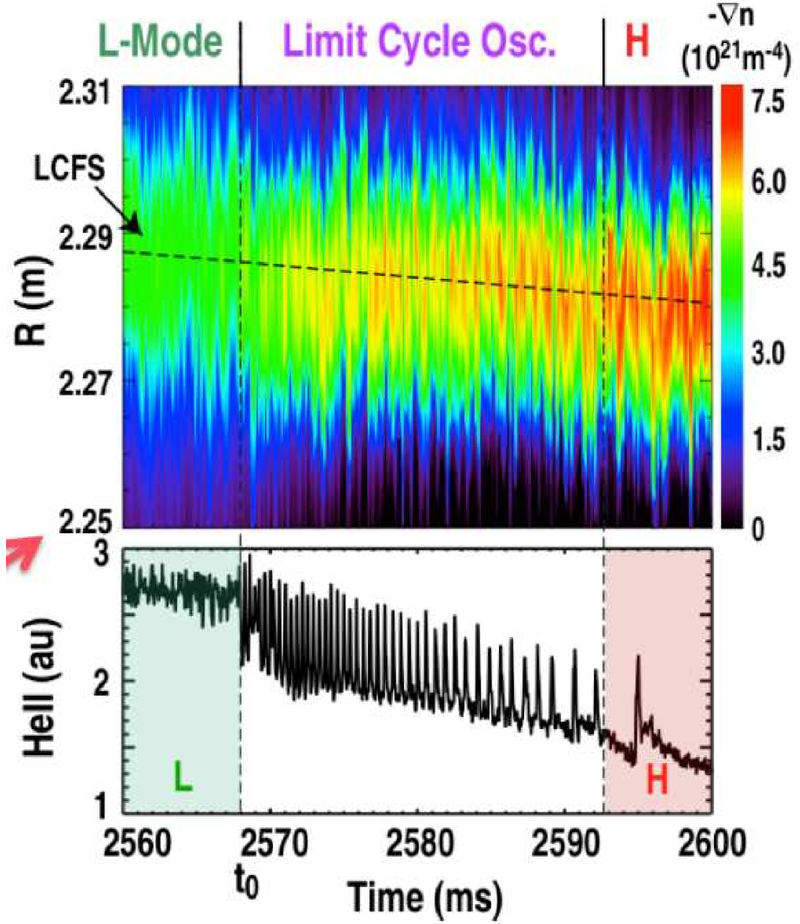


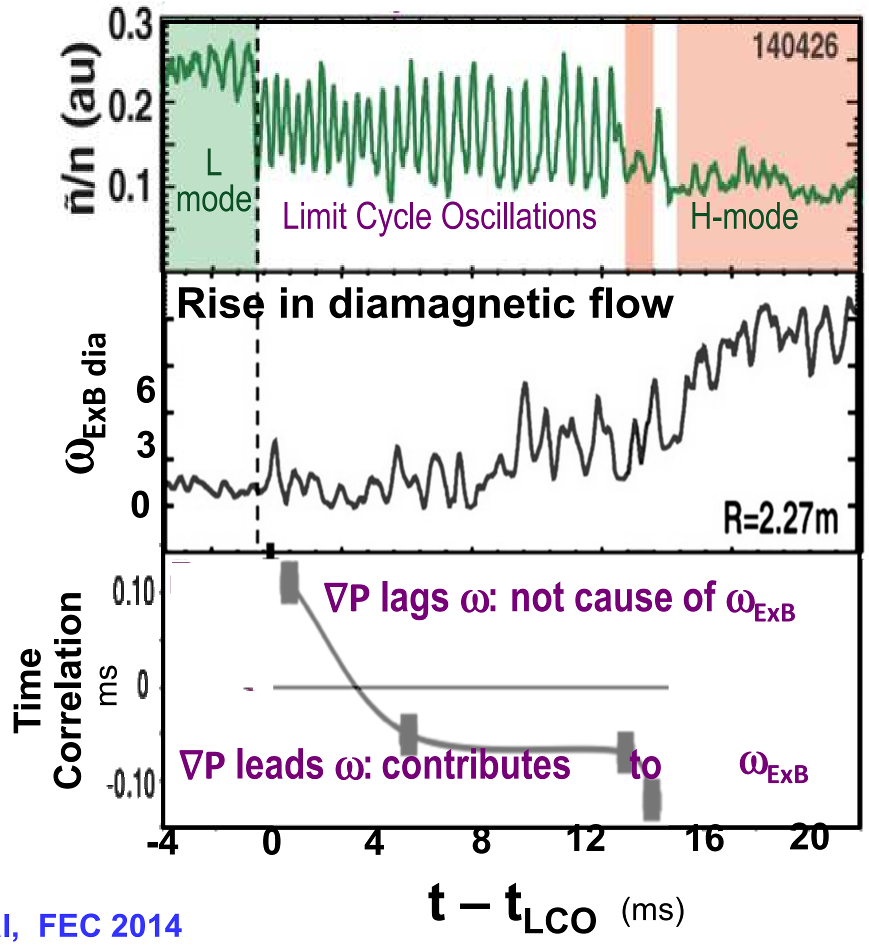
HI-2A probe



- LCO direction depending on the radial position (propagation of turbulence)
- Turbulence leads the process giving rise to an increase in the ExB flow shear
- Amplitude of Er in phase with ∂Er/∂r at this radial position

Role of Ion Diamagnetic Flow in L-H Transition

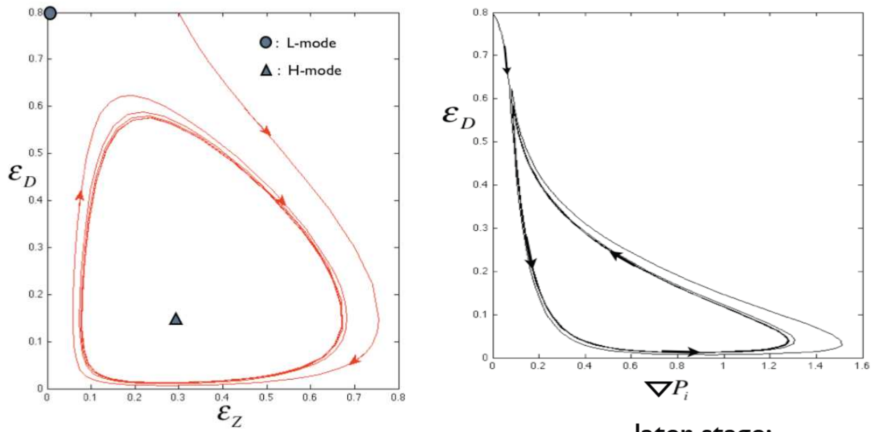




Schmitz, et al, FEC 2014

- Turbulence induced flow insufficient to sustain H mode
- H-mode locked in by rise in ion diamagnetic flow
- See ∇P term start to lead drive to $\mathbf{w}_{ExB}$ rotation

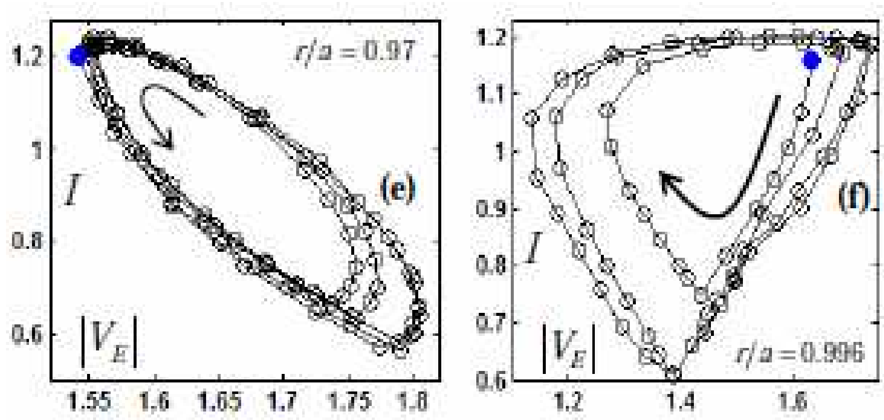
Inverse LCO at inner shear layer?



earlier stage:
clockwise LCO among turbulence and zonal flow intensities

later stage:
anti-clockwise LCO among turbulence intensity and ion pressure gradient

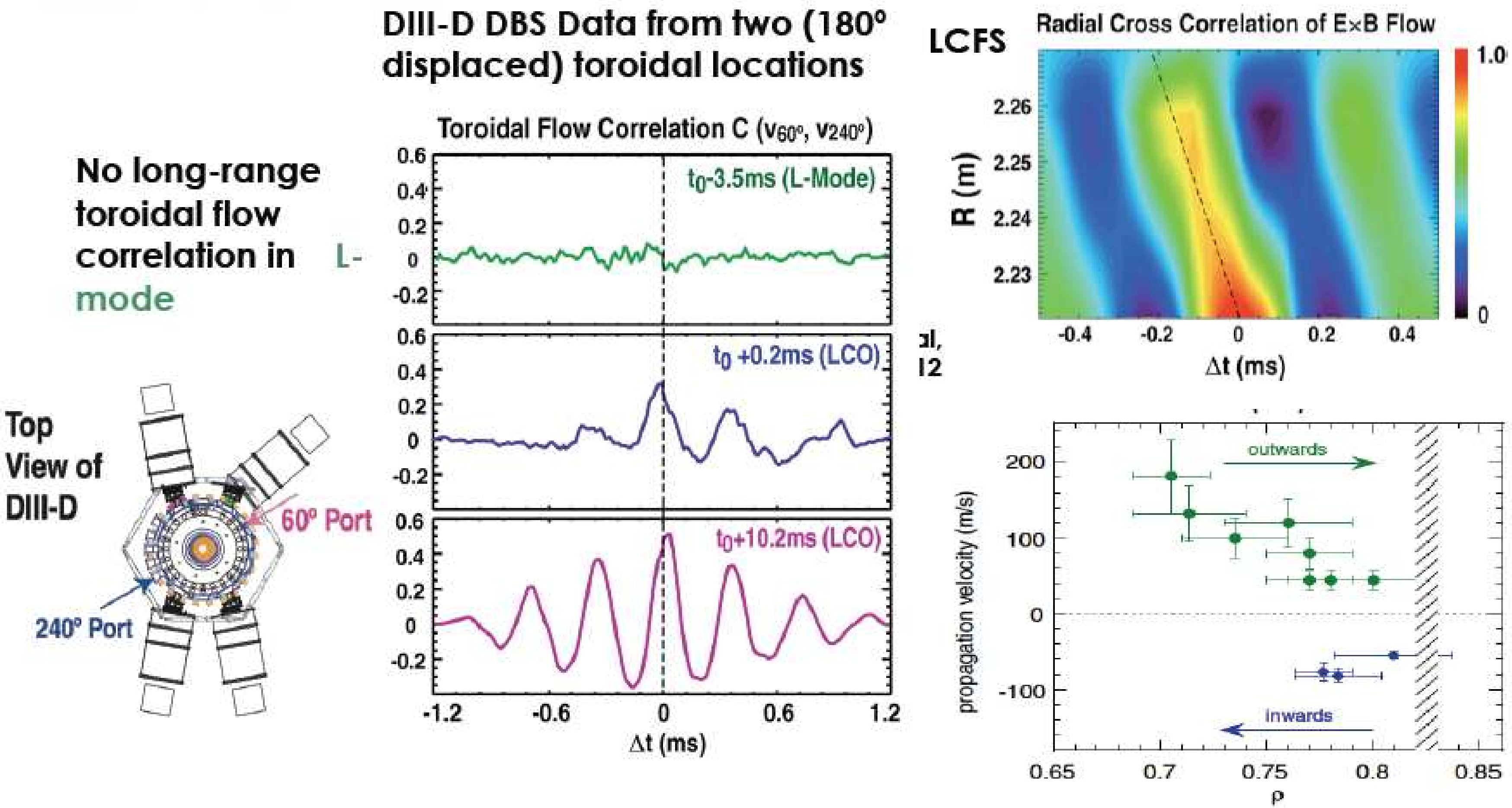
Z. B. Guo, et al., POP 21 090702 (2014)



X.Q. Wu, et al., NF 2014

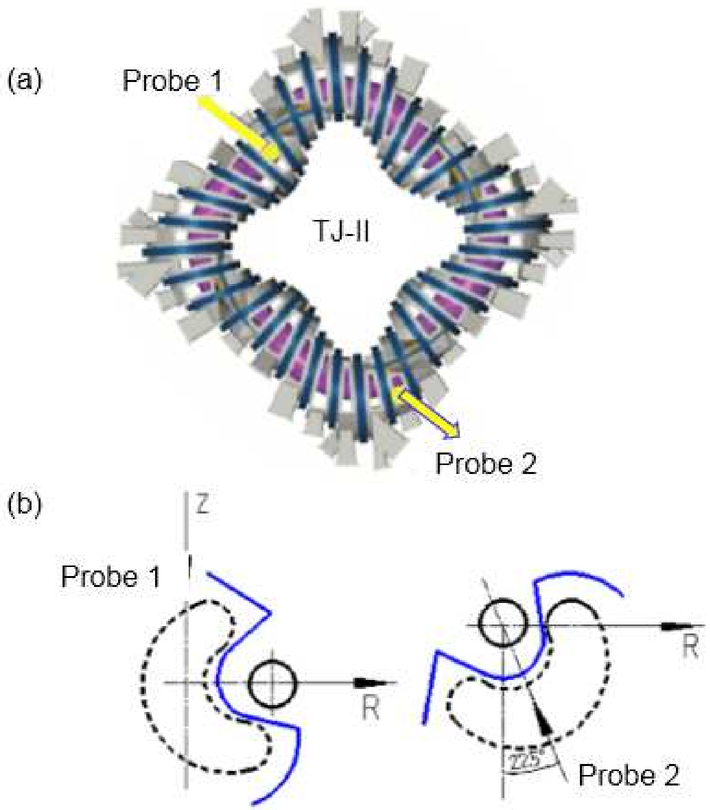
- **LCO rotation dependent on radial position**
- **The importance of LCO and its relation to the pressure gradient and turbulence stressed**

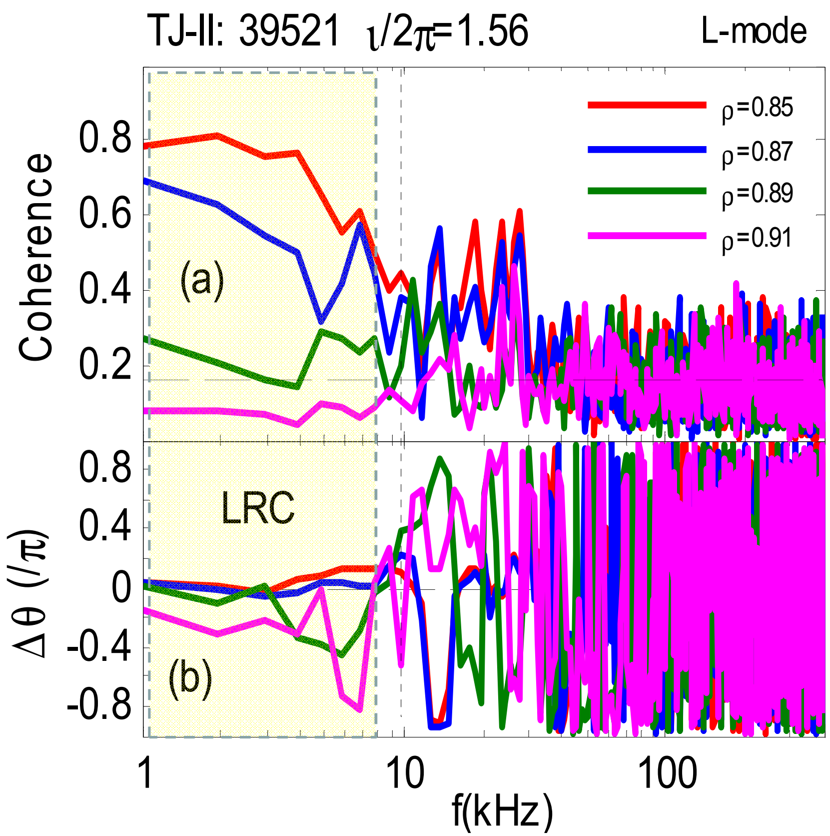
LCO has characteristics of ZF



- No LRC was observed in L mode in LCO frequency (<5 kHz)
- The LRC increases when plasma transition form L to I-phase
- LRC has a clear radial propagation (200 m/s)

Spatial structure of LFZF-like on TJ-II

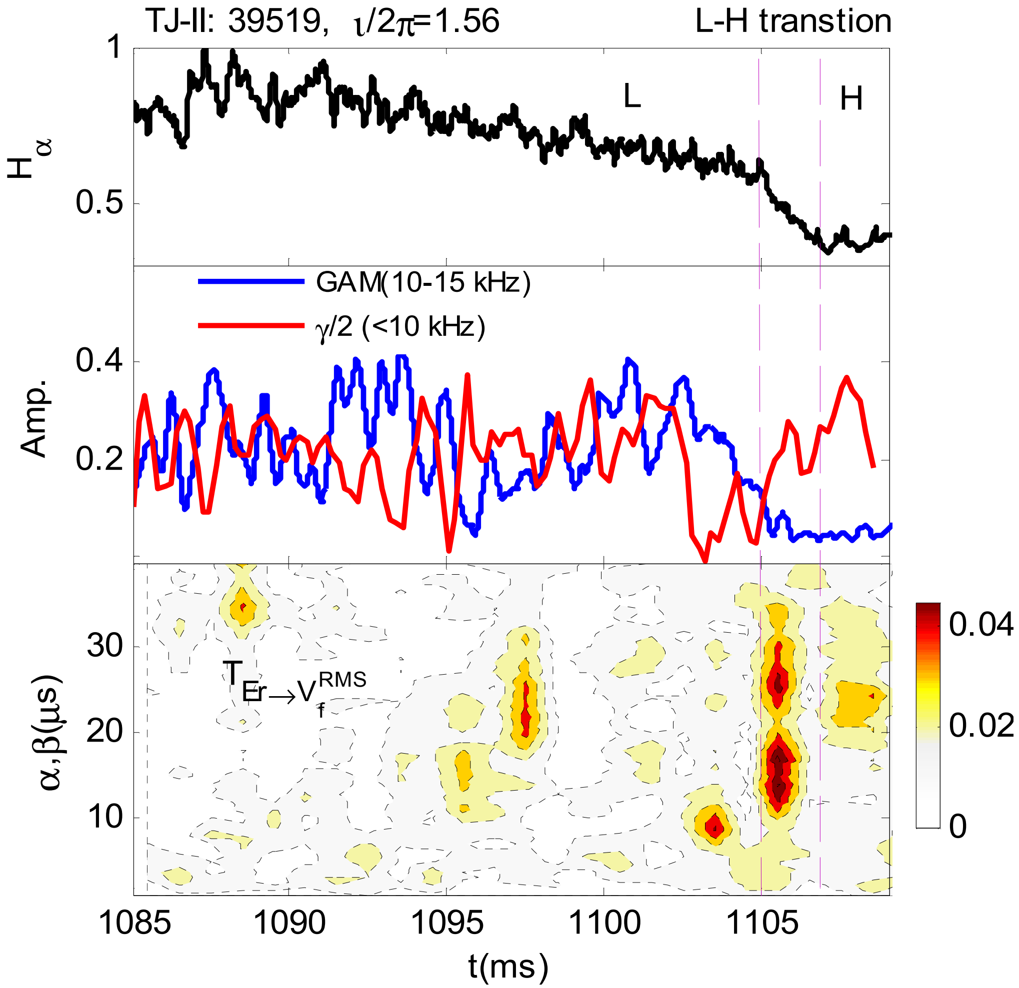


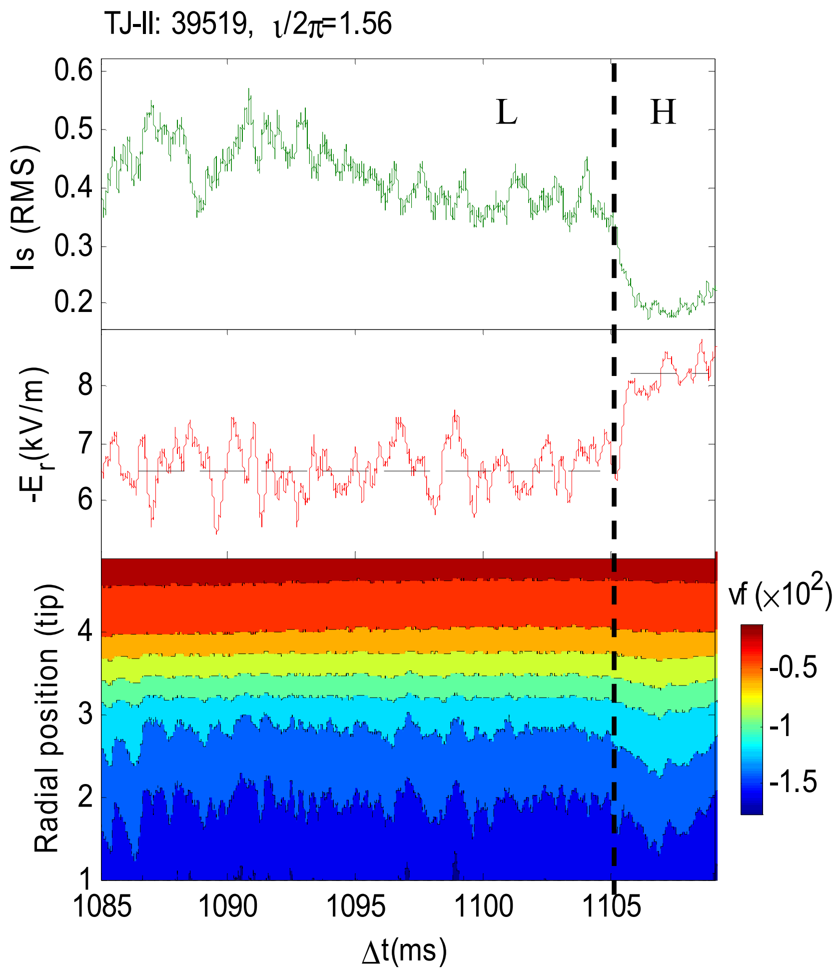


- Coherence and phase shift estimated by probe D and probe B (toroidal separation ~5 m)
- LRC (<10 kHz) has a finite radial width
- The frequency width of LRC reduces to f<3-5 kHz, in L-mode the width is f<10 kHz
- The finite wave number reduces, broadening radial width of LRC (<3-5 kHz) in H mode

J. Cheng, C. Hidalgo, et al., to be submitted to NF 2015

Transient transition to H mode on TJ-II





B.Ph. van Milligen, et al *Nucl. Fusion* **54** 023011

- L-H transition without LCO was observed in the zoomed windows ($t_{L\text{-}H}$=2 ms)
- The GAM disappears prior to L-H transition and transfer entropy rapidly increase across L-H transition
- Er has a jump rise before the L-H transition

Report on LFZF and LCO

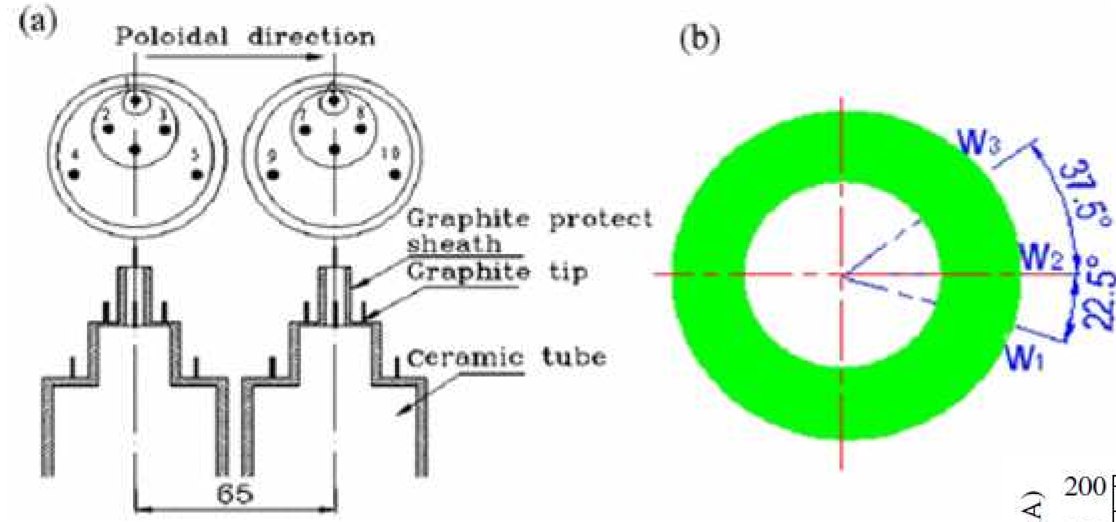
Device	Ref (year)	loca-tion	LCO freq.	Diag-nos.	mean Er	zonal flows	phase rela-tion in LCO
JFT-2M	[12] (91)	edge	0.5 kHz		perhaps	not measured	CCW
ASDEX-U	[33] (94)	edge	~ 1.5kHz		perhaps	not measured	CCW
NSTX	[23] (10)	edge SoL	~ 3 kHz	GPI	?	?	SoL density - Vp: anti corre-lation CCW?
ASDEX-U	[35] (11)	edge	~2.5kHz	DBS	Y	GAM	
EAST	[36] (11)	edge	4 kHz	Probe		ZF: energy balance	anti-correlation
DIIID	[37] (12)	edge	~ 2kHz	DBS	Y	ZF: radial wave number	CW and variations
DIIID	[38] (13)	edge	~2.5 kHz	Probe	maybe	ZF: energy balance	CW
HL-2A	[39] (13)	edge	2~3kHz	Probe	Y	perhaps No	CCW and CW
JFT-2M	[41](13)	edge	4.5 kHz	HIBP	Y	No	CCW
TJ-II	[43] (10)	r/a < 0.8	~ 2kHz	DBS		maybe	CW
CHS	[42](98)	r/a ~ 0.4	~ 0.5kHz	HIBP	leading bifurcation	not measured	
CHS	[50] (06)	r/a ~ 0.4	low freq.	HIBP	leading bifurcation	zonal flow	ZF-turb.: anti-corr.

K. Itoh, et al Plasma and Fusion Research, 8, 1102168 (2013)

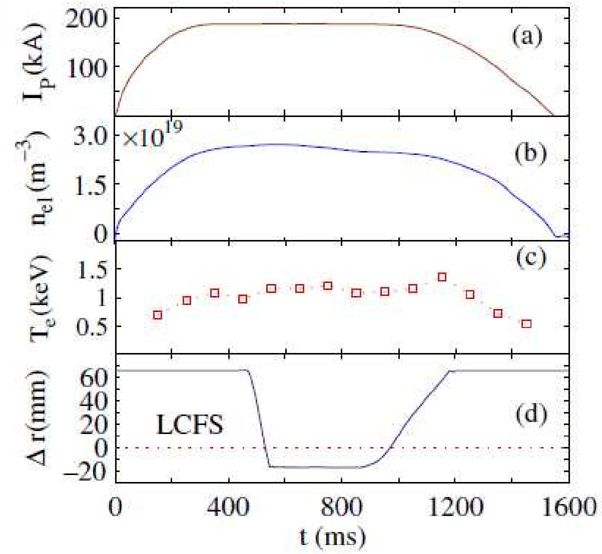
(i) Which changes first? The electric field (mean field or zonal flows) or turbulence intensity?
(ii) Are zonal flows present?
(iii) Does the turbulence Reynolds stress play a central role in driving radial electric field (mean field or zonal flows)?

Experimental setup on studying edge turbulence on HL-2A

Langmuir probe systems

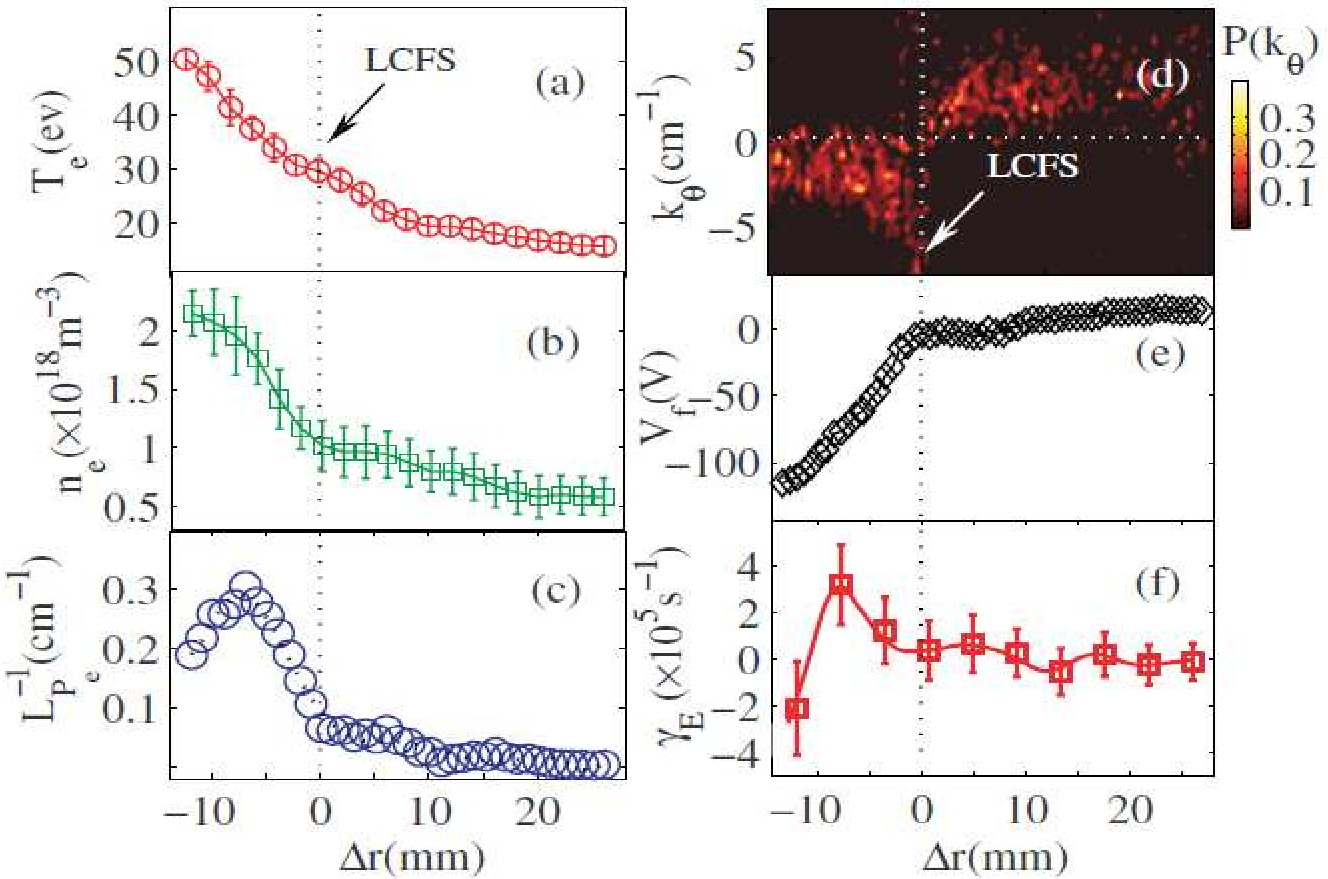


- There are two fast reciprocating probe systems (W1, W3) and a fixed probe system (W2)
- The radial scanning distance at W1 and W3 is 8 cm
- The radial reciprocating speed is 0.8-1.0m/s
- Long range correlation of floating potential can be measured by this probe array



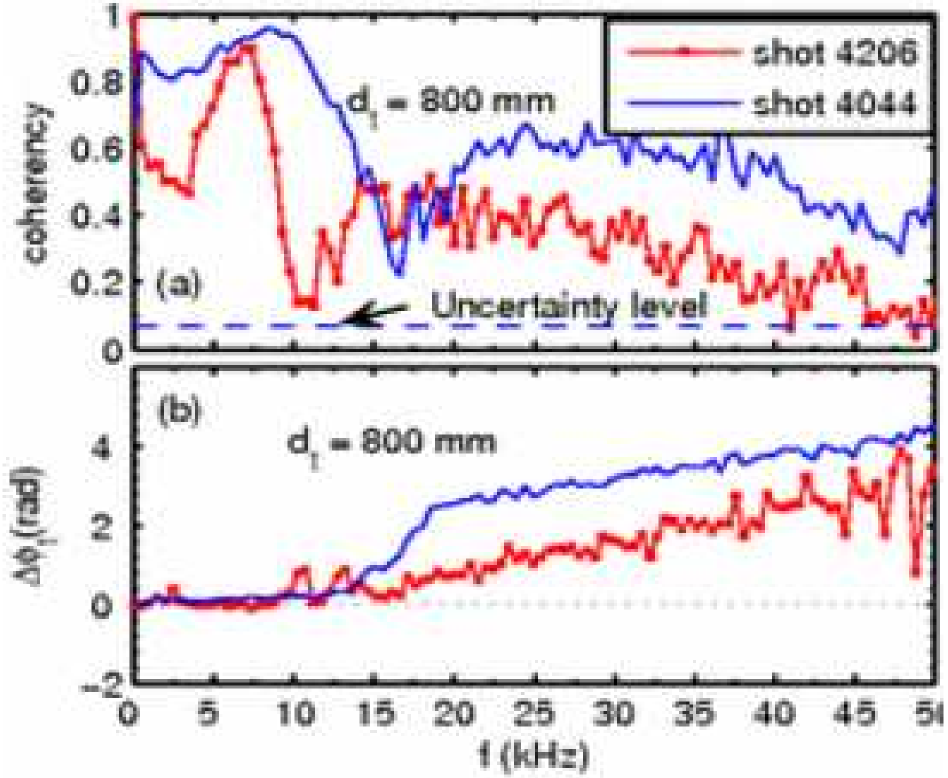
Evolution of probe reciprocating movement

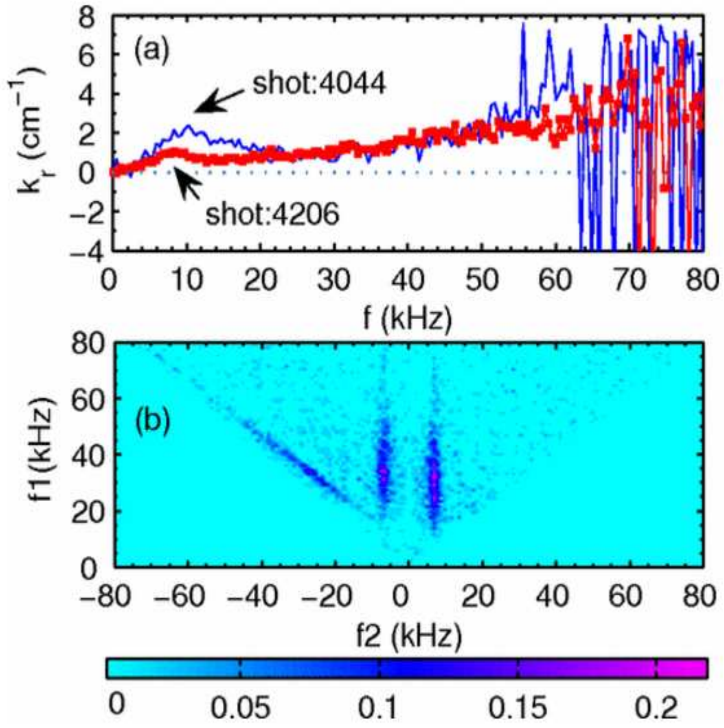
Radial profiles of edge parameters by probe



- **Evolution of edge parameters measured by the reciprocating probe system**
- **LCFS is exactly confirmed by the inverse of <k_θ>**
- **The data in the staying phase is used to analysis spectrum, correlation, etc**

First experimental identification of toroidal symmetry of GAMs

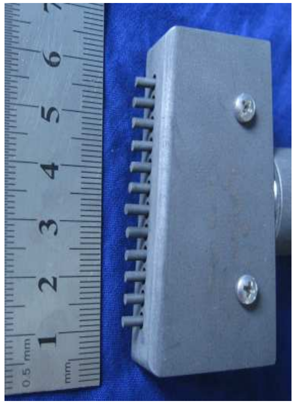


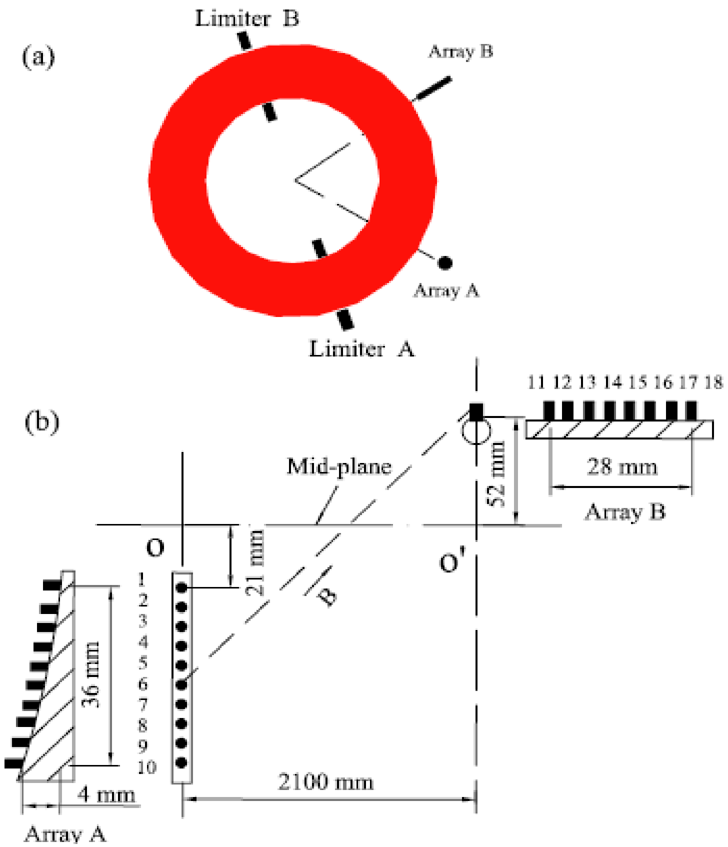


K.J. Zhao, T Lan, et al 2006 PRL 96 255004
A.D. Liu, T Lan, et al 2009 PRL 103 095002

- Toroidal symmetry of GAM (geodesic acoustic mode) confirmed on HL-2A
- The toroidal mode numbers are *n~0*
- GAM is uniform in a flux surface, which is generated by three-wave interaction

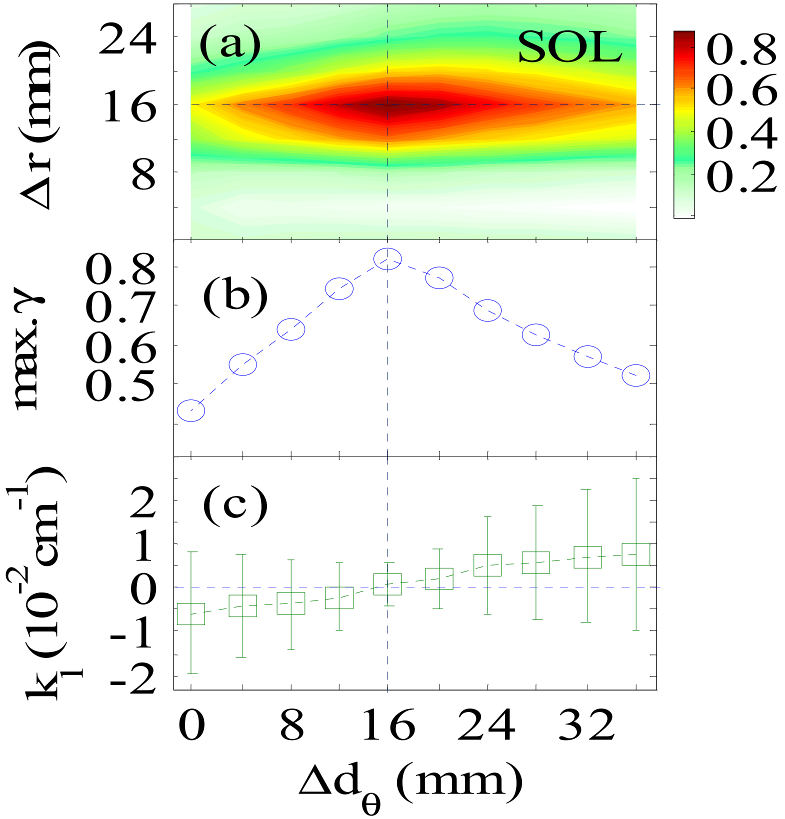
Combined probe array

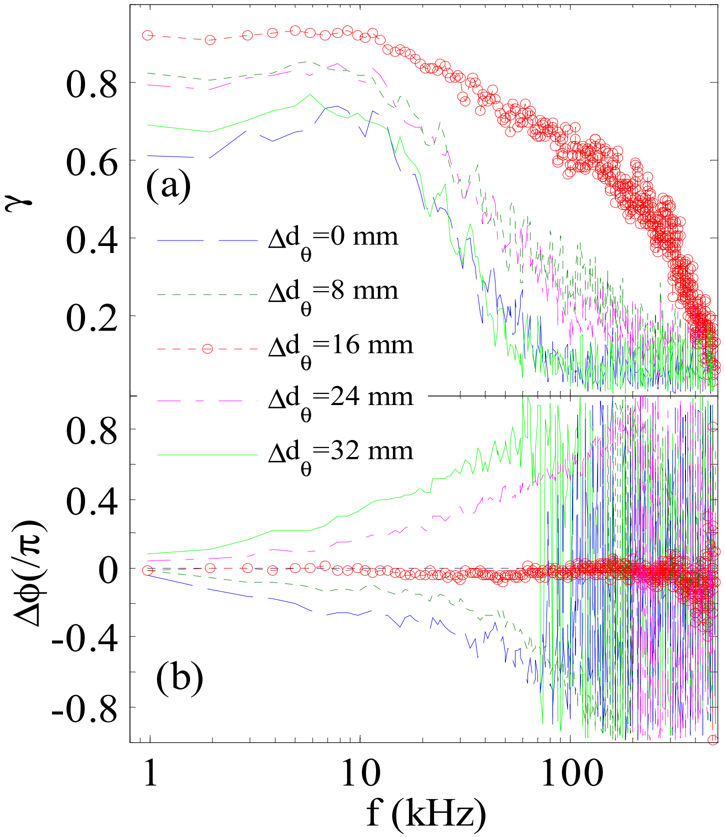




- Poloidal probe and radial probe
- Spatial resolution is 4 mm
- Measured parameters: Is and vf fluctuations

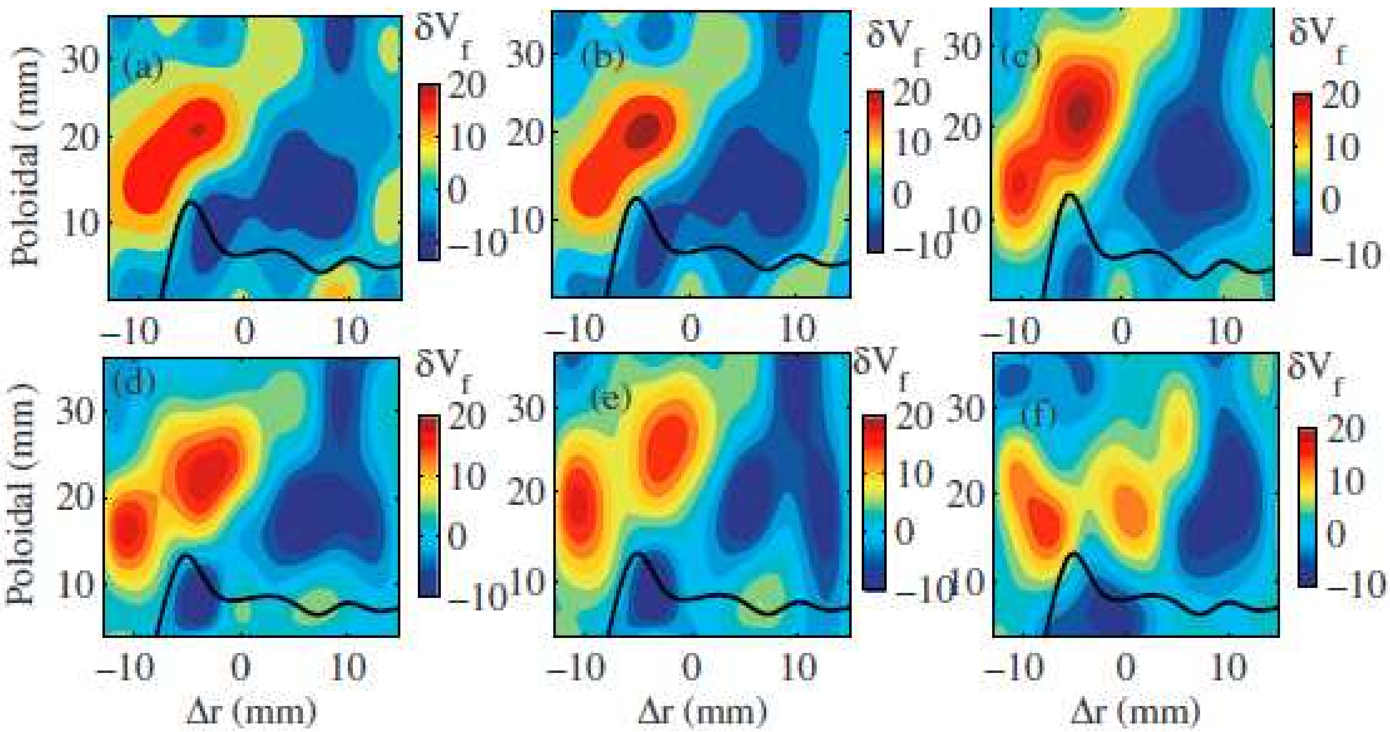
SOL Turbulence characteristics





- **Contour plot of Max. correlation between array A and Array B**
- **$k_{//}$ changes sign from negative to positive at Δd_θ~16 mm, where coherency is max**
- **Frequency spectra at five typical positions (Right Figure)**
- **Two tips in the same line: significant coherency and zero phase shift below 100 kHz**

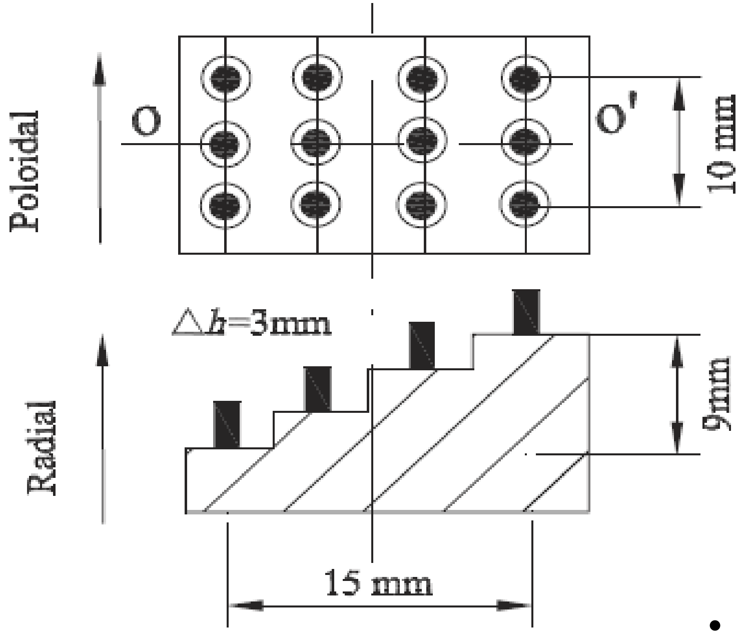
Visualization of 2D structures



- **Conditional averaged: high correlation and zero phase shift**
- **Eddies deform, titled and break**

J. Cheng, J.Q. Dong, et al 2013 NF, 53 093008

Four-step probe array



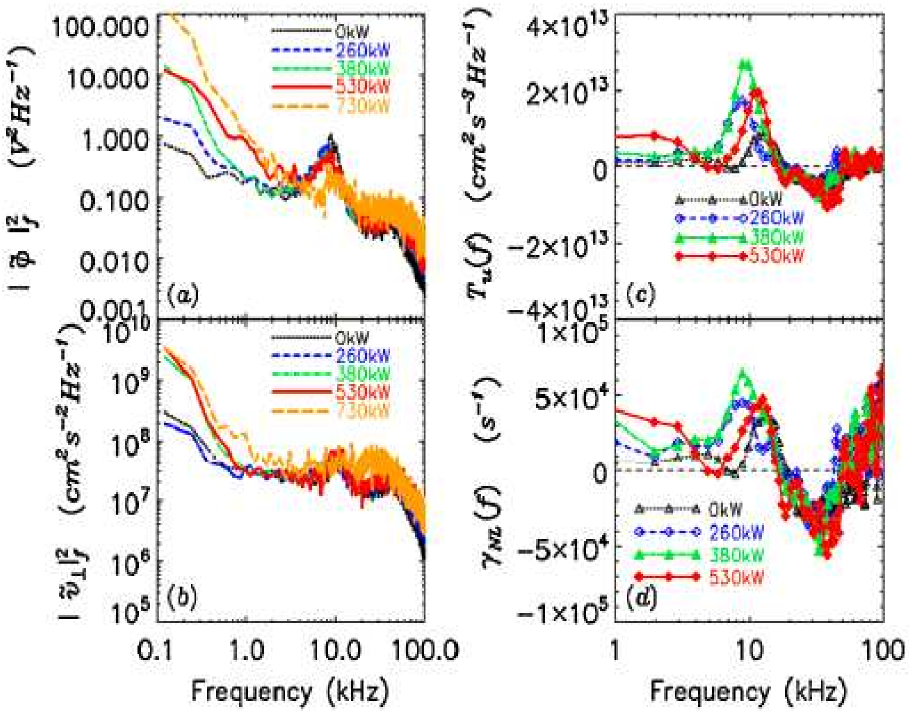
Previous probe

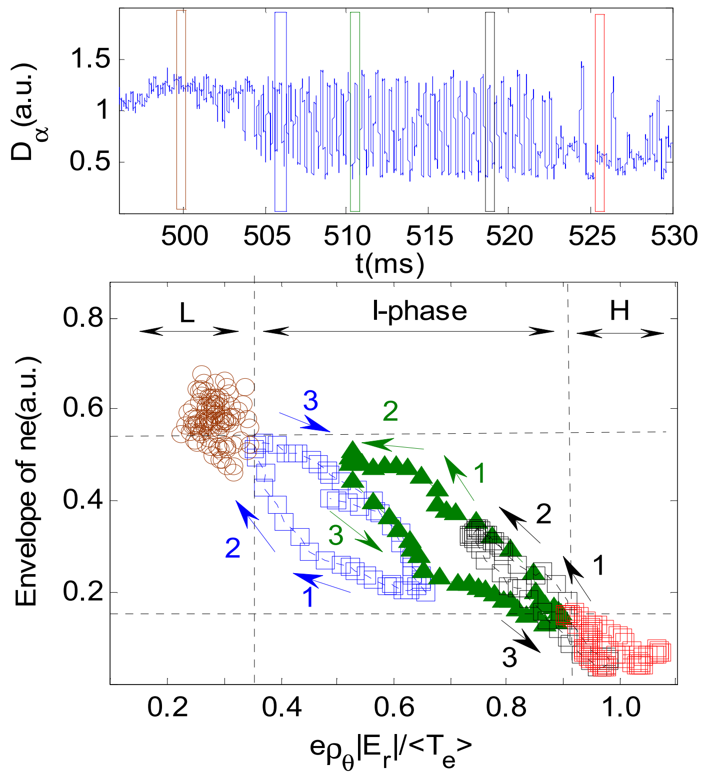
Updated probe

- **Sampling rate = 1 MHz**
- **Spatial resolution= 4 mm**
- **Diameter of tips is 1.5 mm.**
- **Height of steps is 3 mm.**
- **LCFS is identified by EFIT code**
- **Measured parameters:**

$$T_e, n_e, \phi_f, \tilde{n}_e, E_r, P_e, E'_r, P_e',$$

Energy transfer rate and LCO





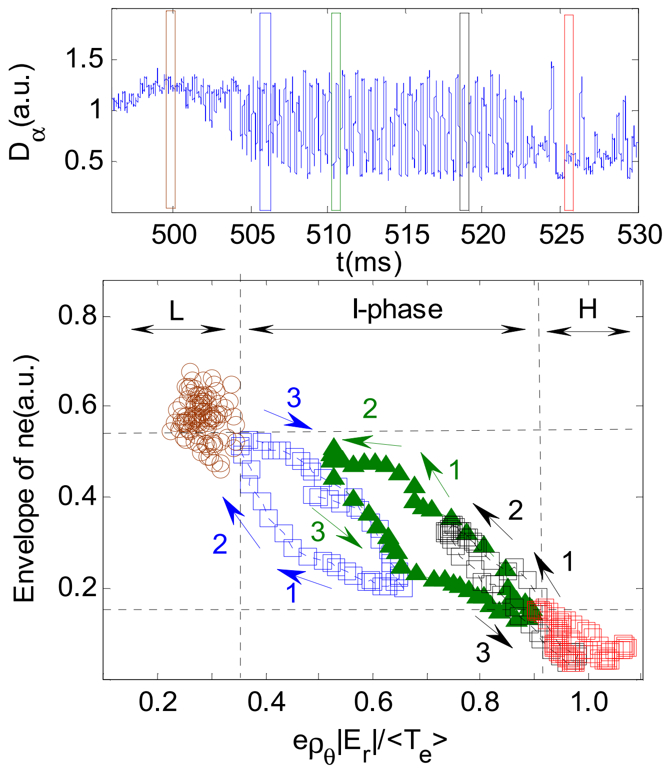
- **Energy transfer rate: more energy is transferred from turbulence to LFZF when heating power increases**
- **Dynamics of LCO in I-phase**

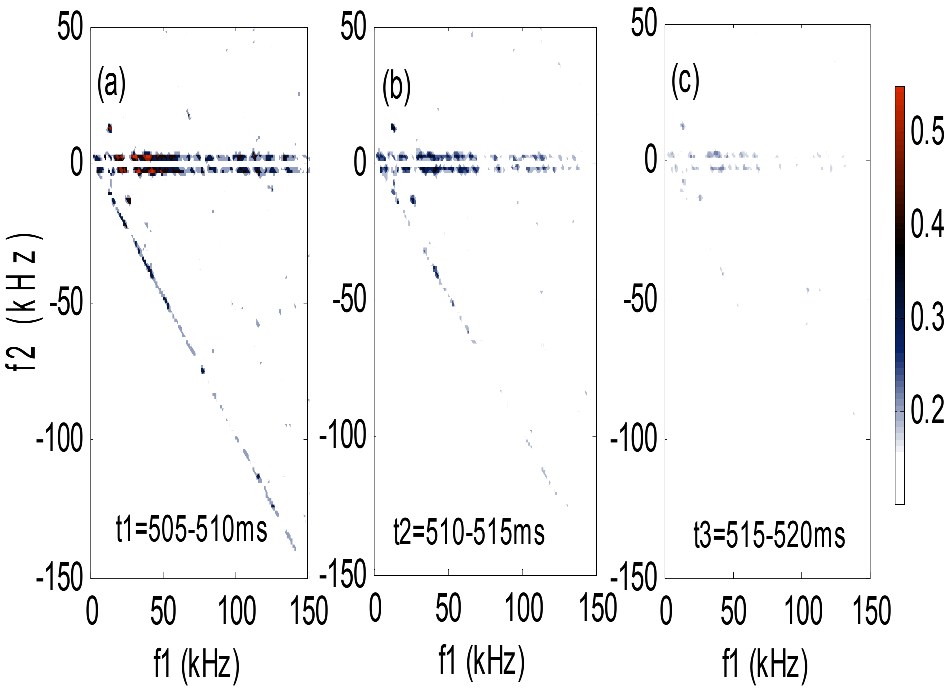
M. Xu, G.R. Tynan, et al, 108, 245001, PRL, 2012
J. Cheng, J.Q. Dong, et al, 110, 265002, PRL, 2013
K.J. Zhao, J. Cheng, et al NF, 2013

Part I

Characteristics of limit cycle oscillation in L-I-H transition

Two kinds of LCOs





Auto bi-spectrum of potential fluctuations

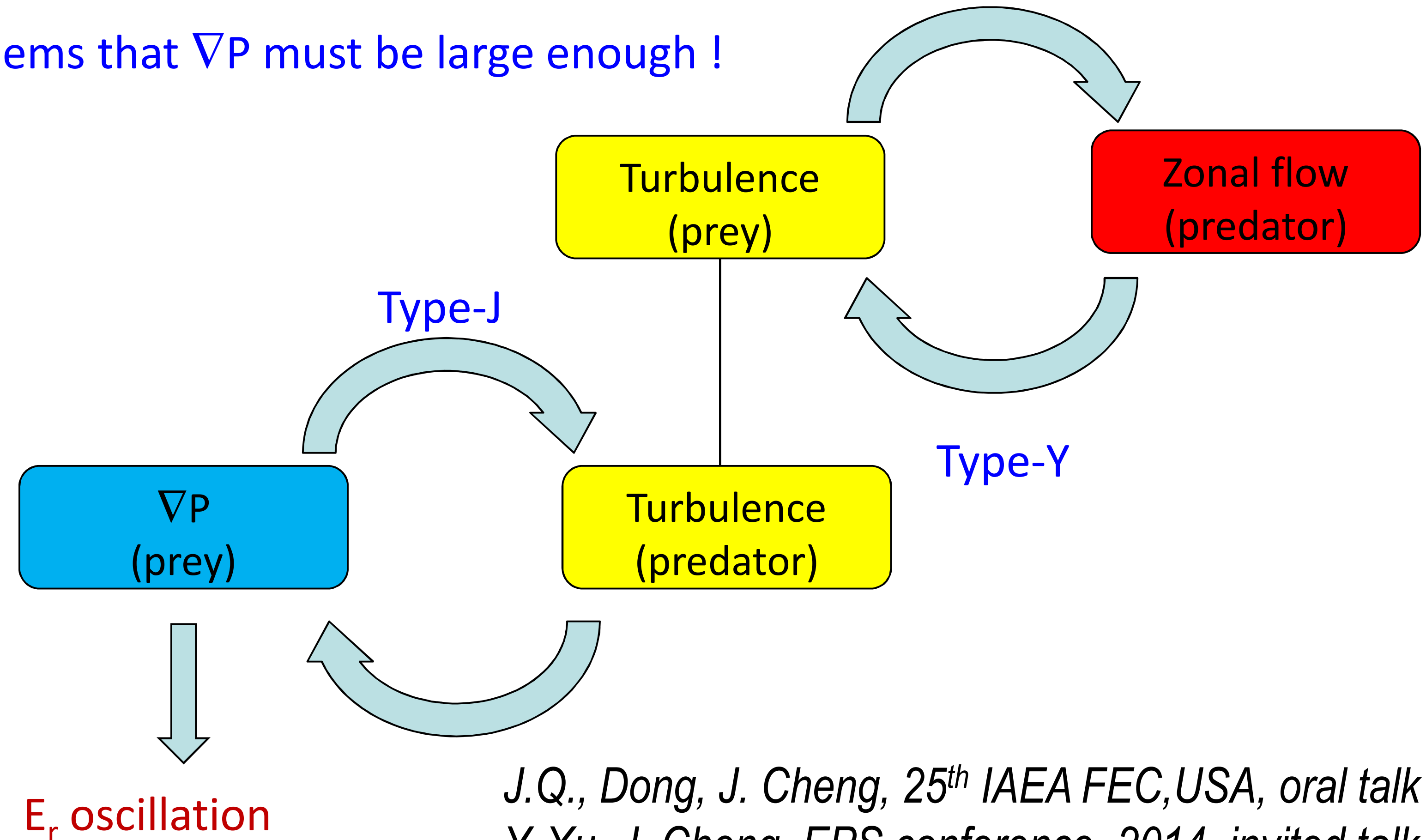
- **Two kinds of LCO: type-Y (clockwise) and type-J (counter-clockwise)**
- **Type-Y: turbulence is prior to shear flow (Predator-Prey)**
- **Type-J: turbulence lags Er, ∇Pe (∇Pi) dominant, critical for I-H transition**
- **Bi-coherence intensity reduces close to the H-mode**

J. Cheng, J.Q. Dong, et al, 110, 265002, PRL, 2013

Possible interpretation for two types of LCOs

For the transfer of type-Y to type-J,

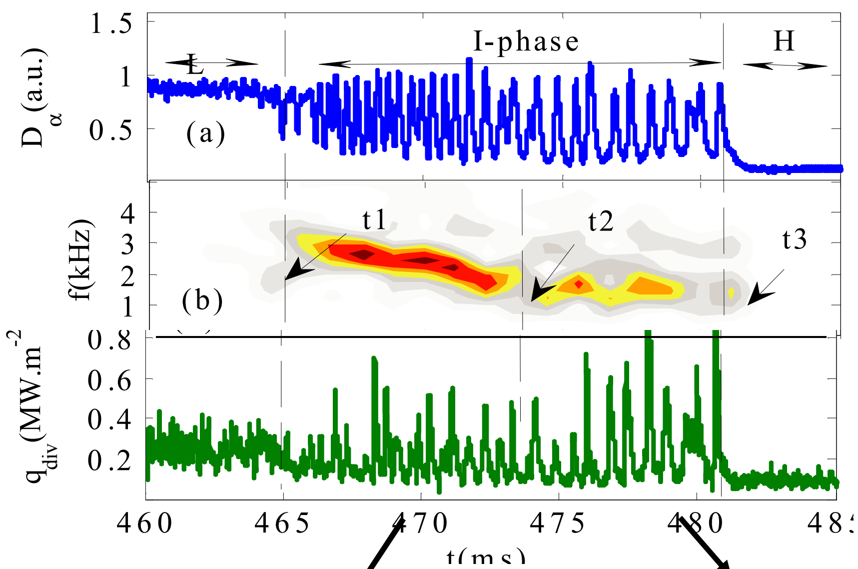
It seems that ∇P must be large enough !

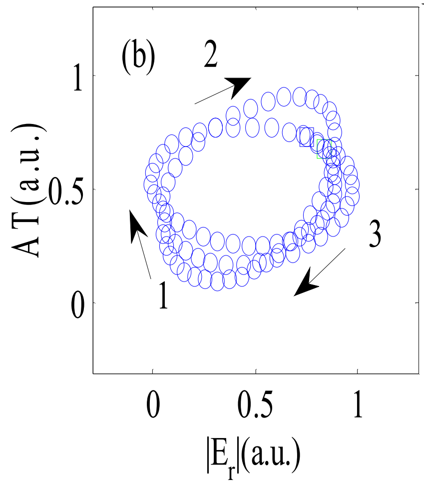


J.Q., Dong, J. Cheng, 25th IAEA FEC,USA, oral talk
Y. Xu, J. Cheng, EPS conference, 2014, invited talk

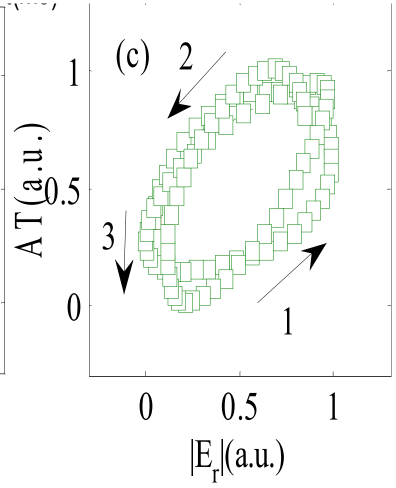
Transition from Y- to J-LCO

HL-2A DATA

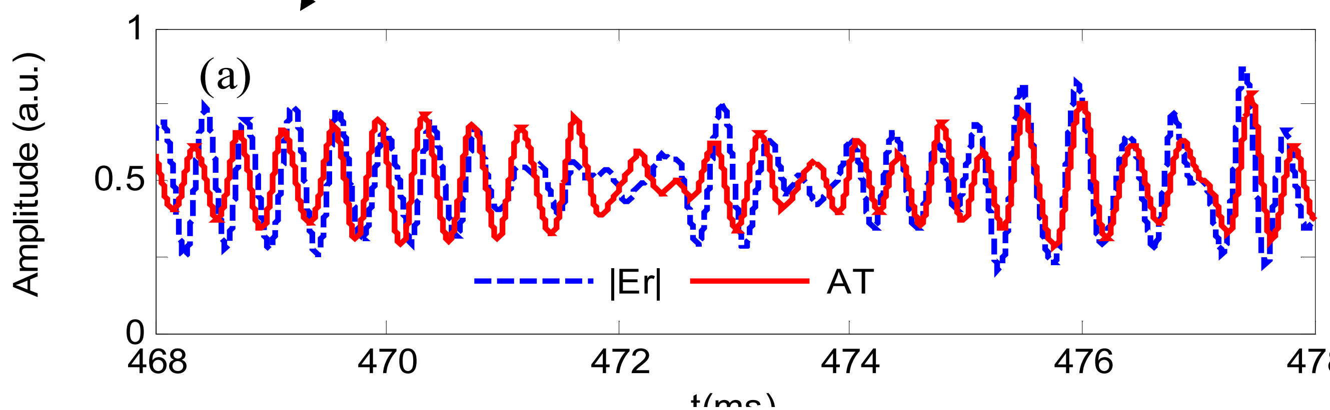




Y-LCO



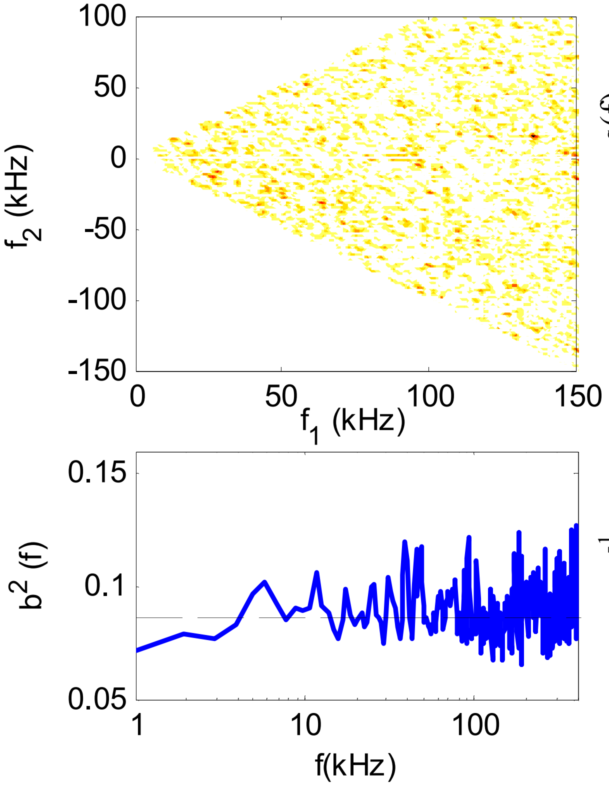
J-LCO

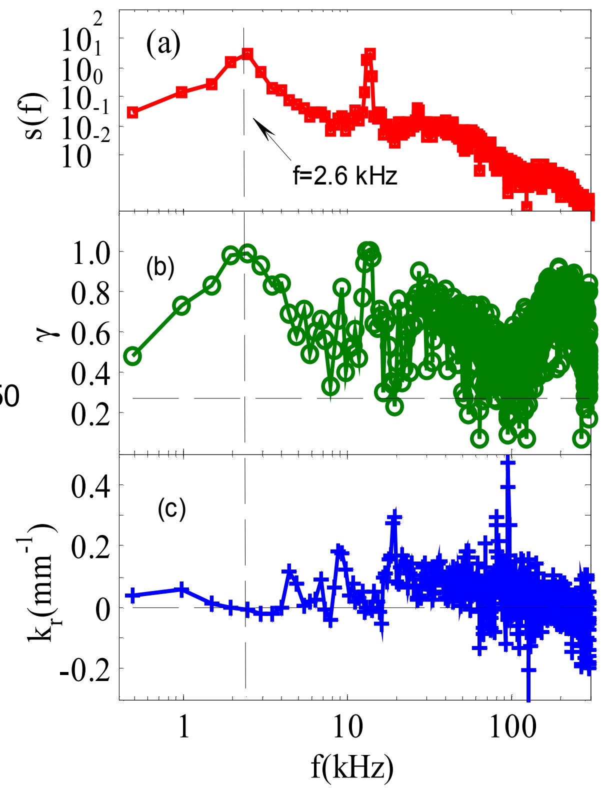


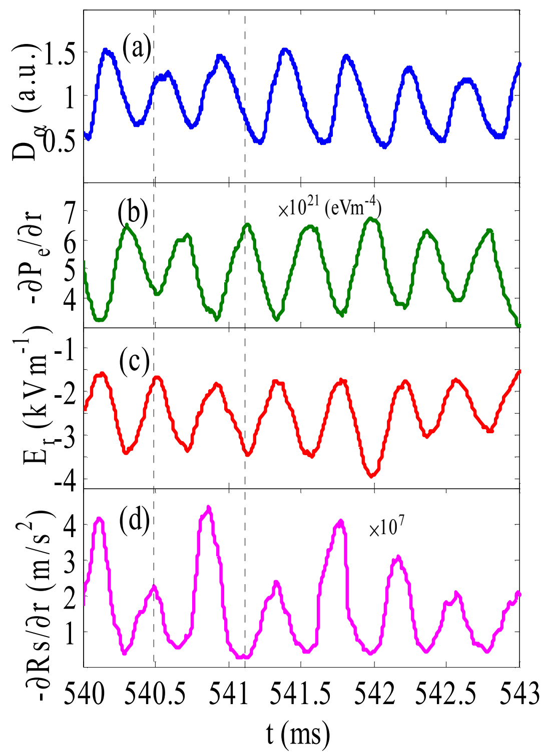
- Evolution of the magnitude of Er and turbulence in L-I-H transition
- Transition from Y-LCO to J-LCO measured at Δr=-8 mm

J. Cheng, L.W. Yan, et al, JNM 2015

Characteristics of J-LCO



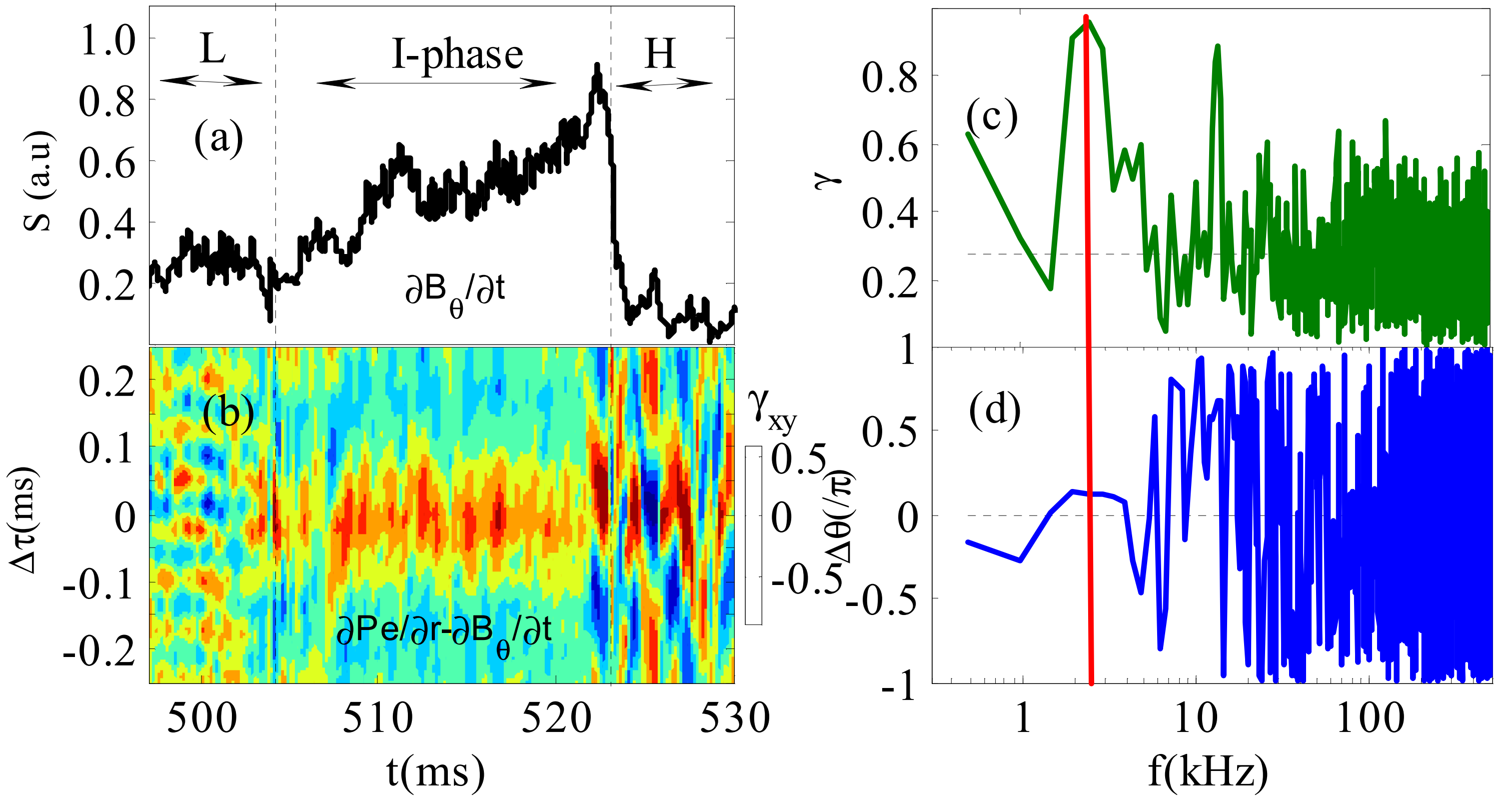




- The coupling of floating potential fluctuations (Δr=-6 mm) at LCO frequency is weak
- The -∂Rs/∂r out of phase with E_r (pressure gradient)
- Type-J LCO is different with the LFZF

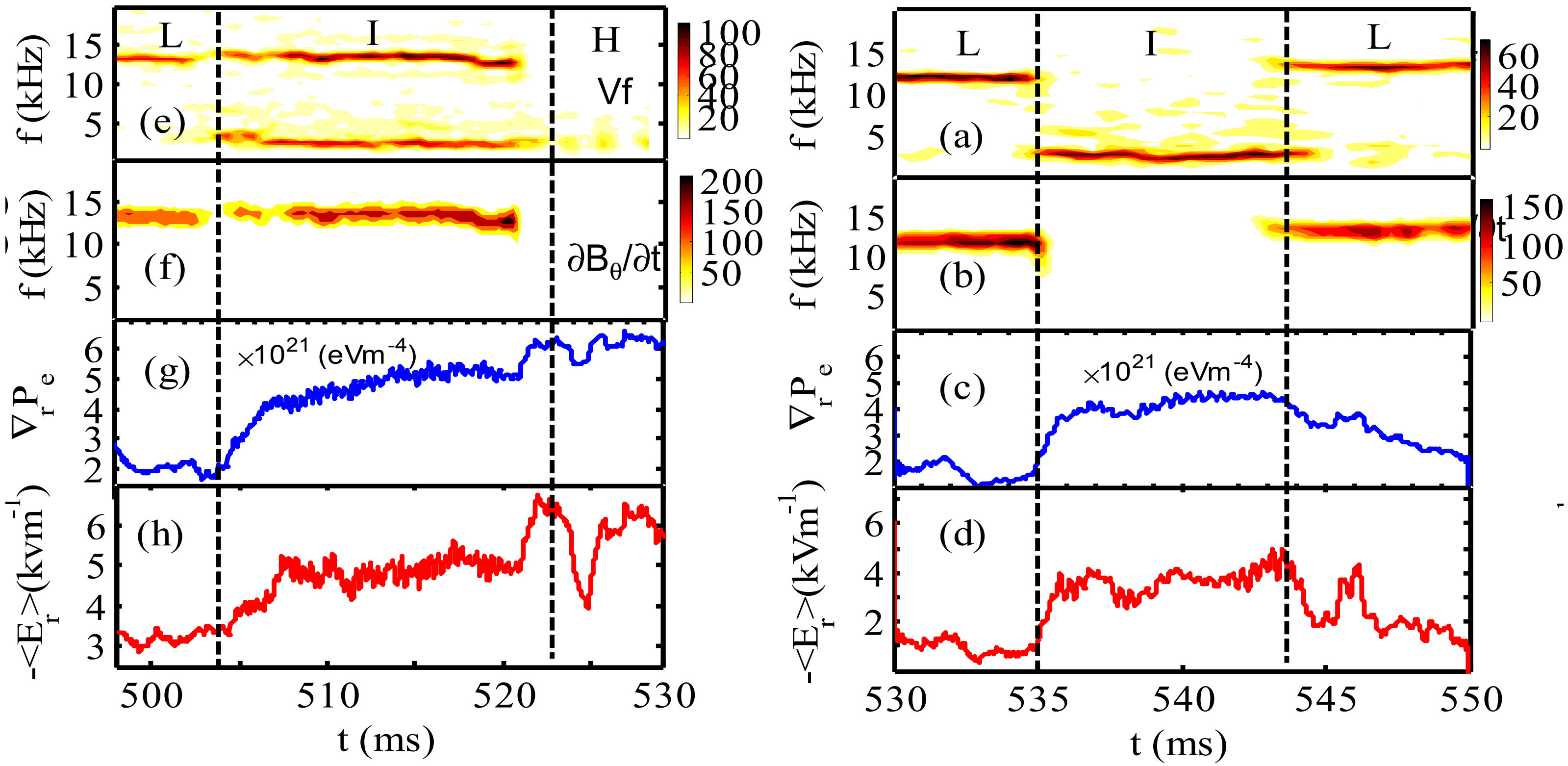
J. Cheng, J.Q.Dong, K. Itoh, et al 54, 114004 NF 2014

Correlation between ∇P_e and $\partial B_\theta/\partial t$



- **Time-frequency spectrum of $\partial B_\theta/\partial t$**
- **Correlation and phase shift of ∇P_e — $\partial B_\theta/\partial t(\Delta r$=-6mm)**
- **$\partial B_\theta/\partial t$ amplitude gradually increases in I-phase**
- **High correlation and zero-phase shift, $\nabla P=J\times B$**

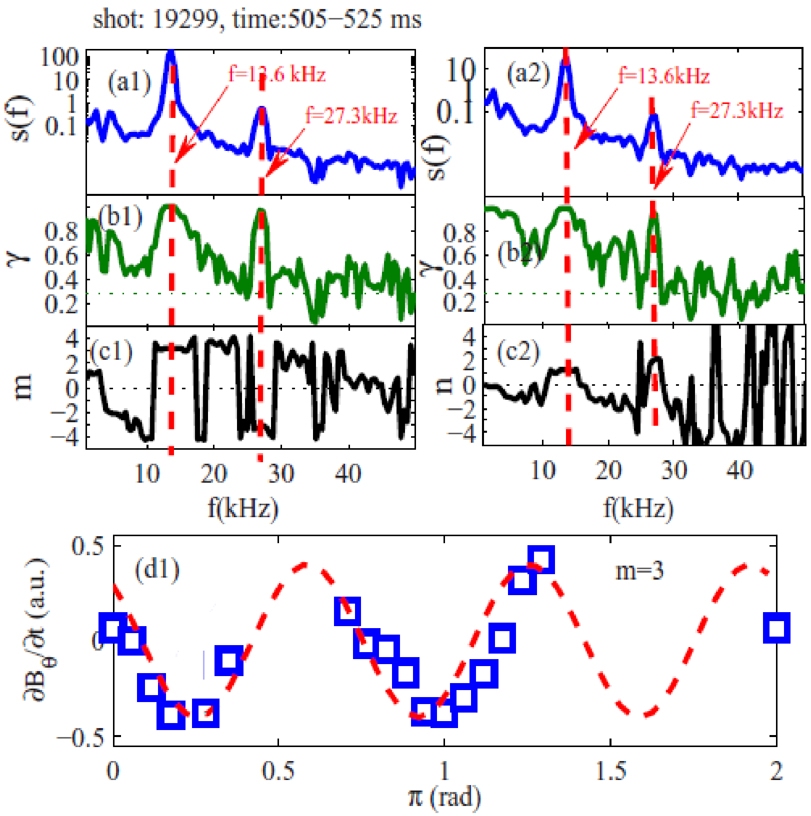
Role of ∇P_e in J-LCO phase

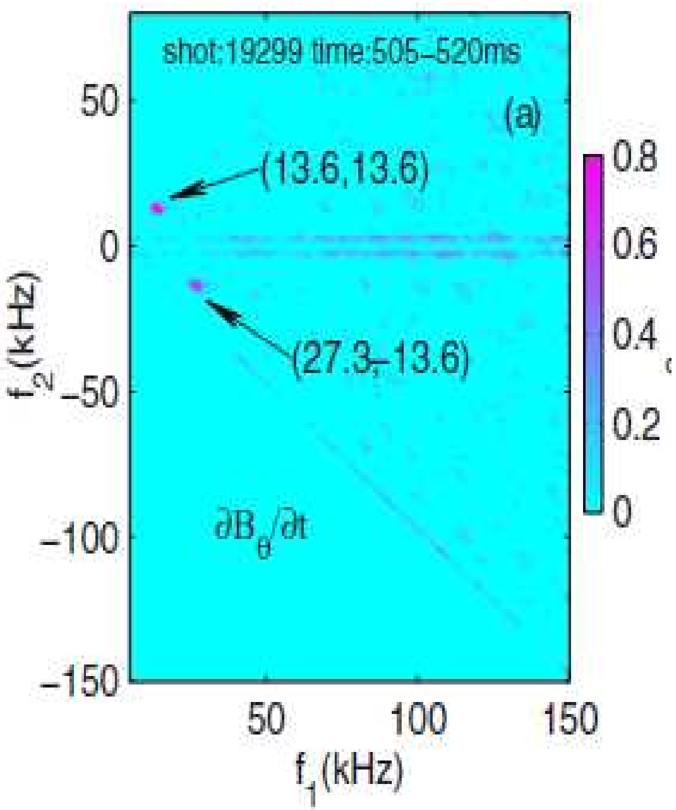


- The coherent mode with f=13.6 kHz rather than GAM
- The pressure gradient gradually increases in L-I-H , but it remains invariable in L-I-L
- A abrupt rise of shear flow in J-LCO can further reduce turbulence
- The influence of mode on turbulence is under study

J. Cheng, *et al., the25th IAEA FEC*, Russia , EXC/P7-24 (2014)

Characteristics of mode in I-phase





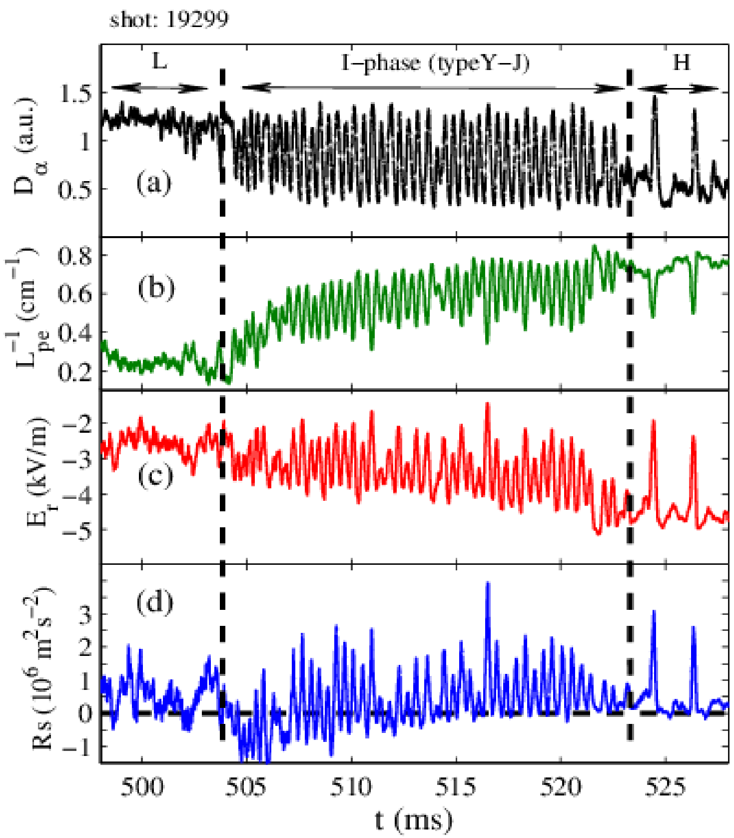
- Mode structure observed with SVD method on magnetic fluctuation signals
- This mode has electromagnetic characteristics
- No clear coupling range in bicoherence spectrum

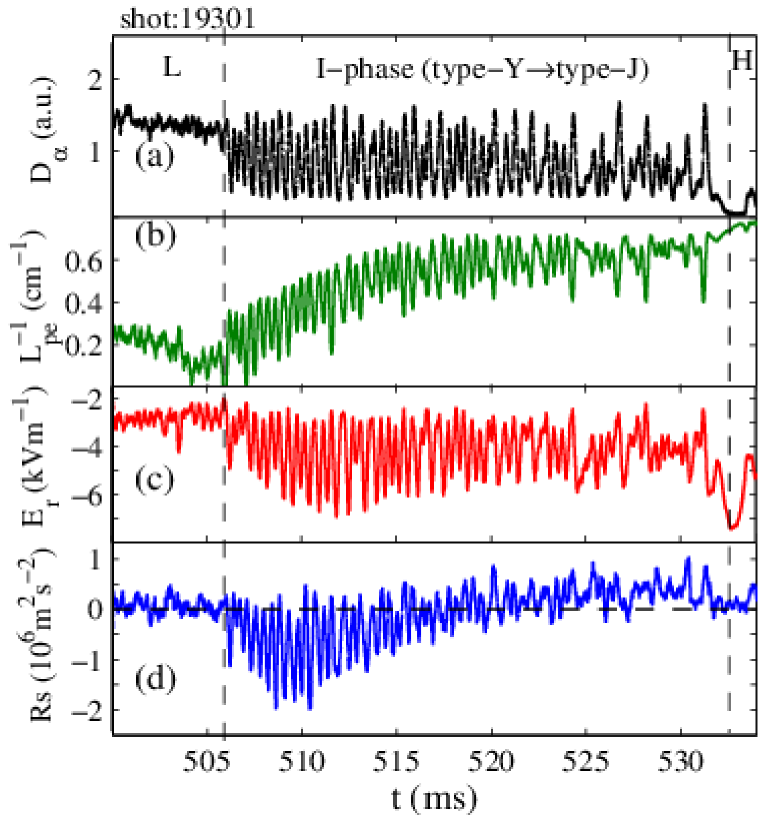
L.W.Yan, J. Cheng, *et al., Nucl. Fusion (2015)*

Part II

Role of turbulence-pressure gradient driven flow on L-I-H transition

Inversion of the Rs in I-phase

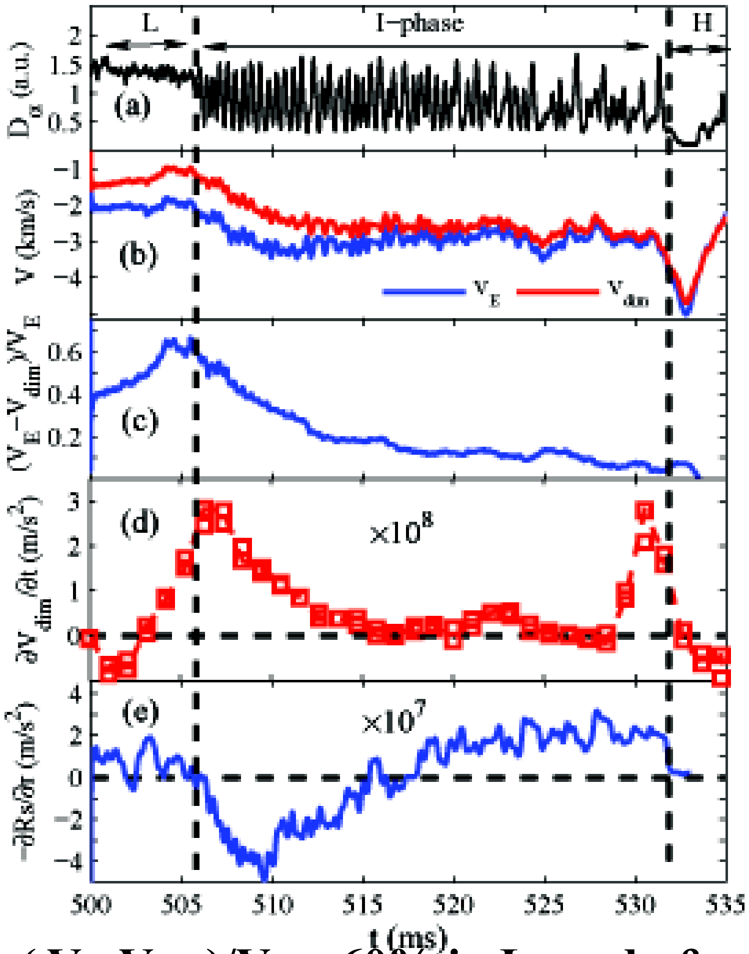




- Time-resolved evolution of L_{pe}^{-1}, Er and Rs in L-I-H transition
- The measured radial position is inside the separetrix about 6-8 mm
- The Rs reverses L-I and I-phase across Y-J LCO (f_{LCO}=2-3 kHz)
- The Lpe^{-1} gradually increase and has a rapid rise prior to the I-H transition

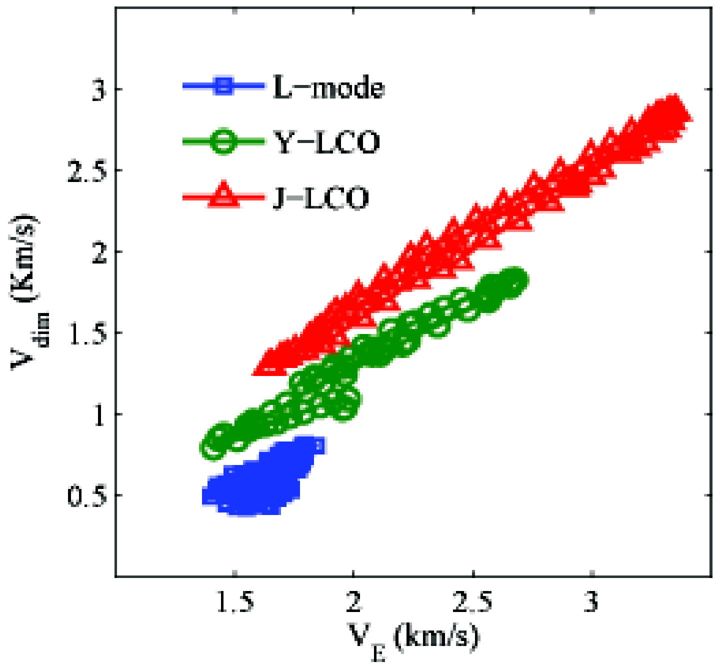
J. Q. Dong, J. Cheng, et al, 2014 FEC oral talk

Time averaged E×B and diamagnetic flows



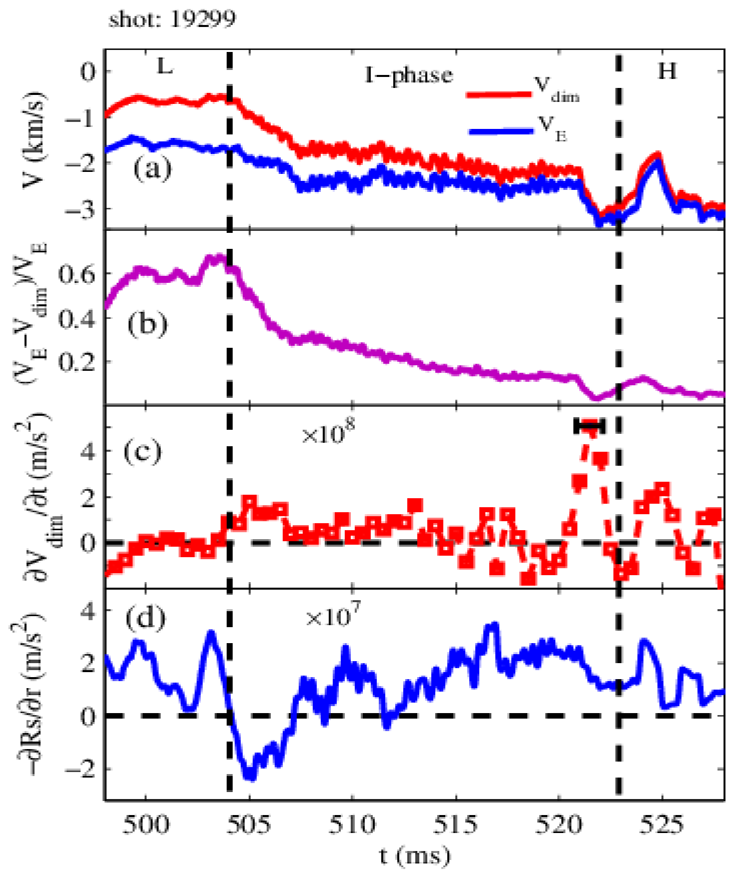
Force balance equation of ions

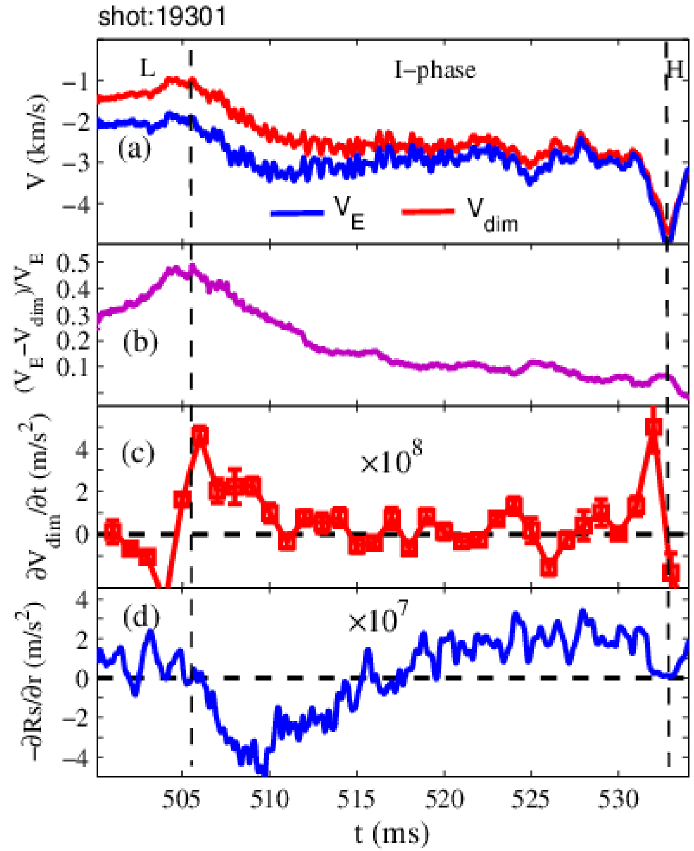
$$E_r = \underbrace{\frac{1}{n_i Z_i e}\nabla_r P_i(f)}_{E_{r,dia}} \underbrace{- v_{\theta i}B_\phi + v_{\phi i}B_\theta}_{\Delta E_r}$$



- $(V_E\text{-}V_{dim})/V_E > 60\%$ in L-mode & early I-phase but <10% prior to I-H transition.
- Evolutions of $\partial V_{dim}/\partial t$ and V_E/V_{dim} are strongly correlated.
- No evident correlations between $\partial R_s/\partial r$ and V_E are observed.

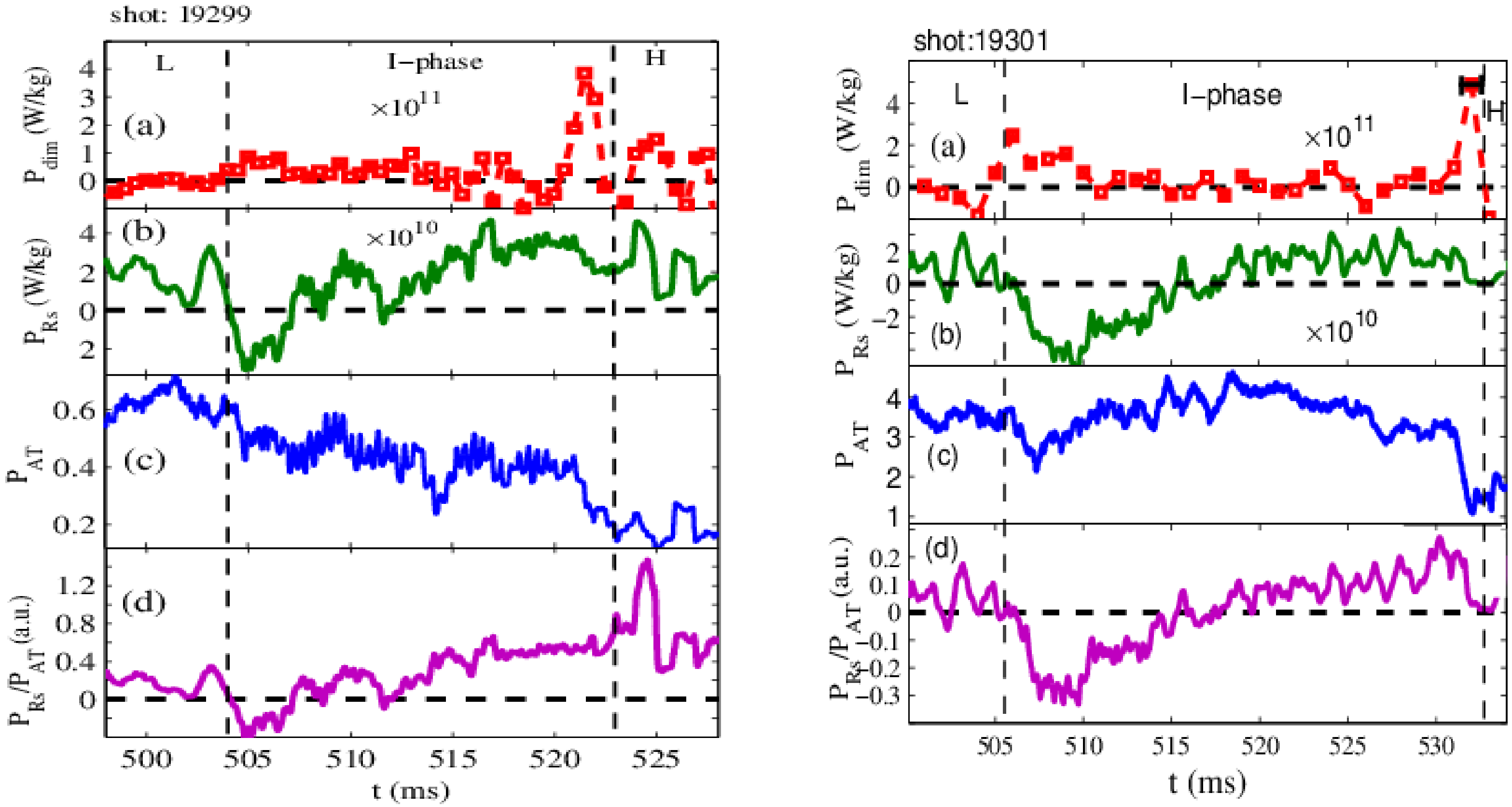
Peak of $\partial V_{dim}/\partial t$ prior to I-H transition





- Contrasting the evolution of V_{dim} and V_E in the L-I-H transition
- The ratio of rotation velocity (V_θ,V_φ) to the V_E gradually reduces towards H
- The growth rate of diamagnetic flow has a peak just prior to the I-H transition
- The gradient of Rs changes sign from positive to negative when L-I transition

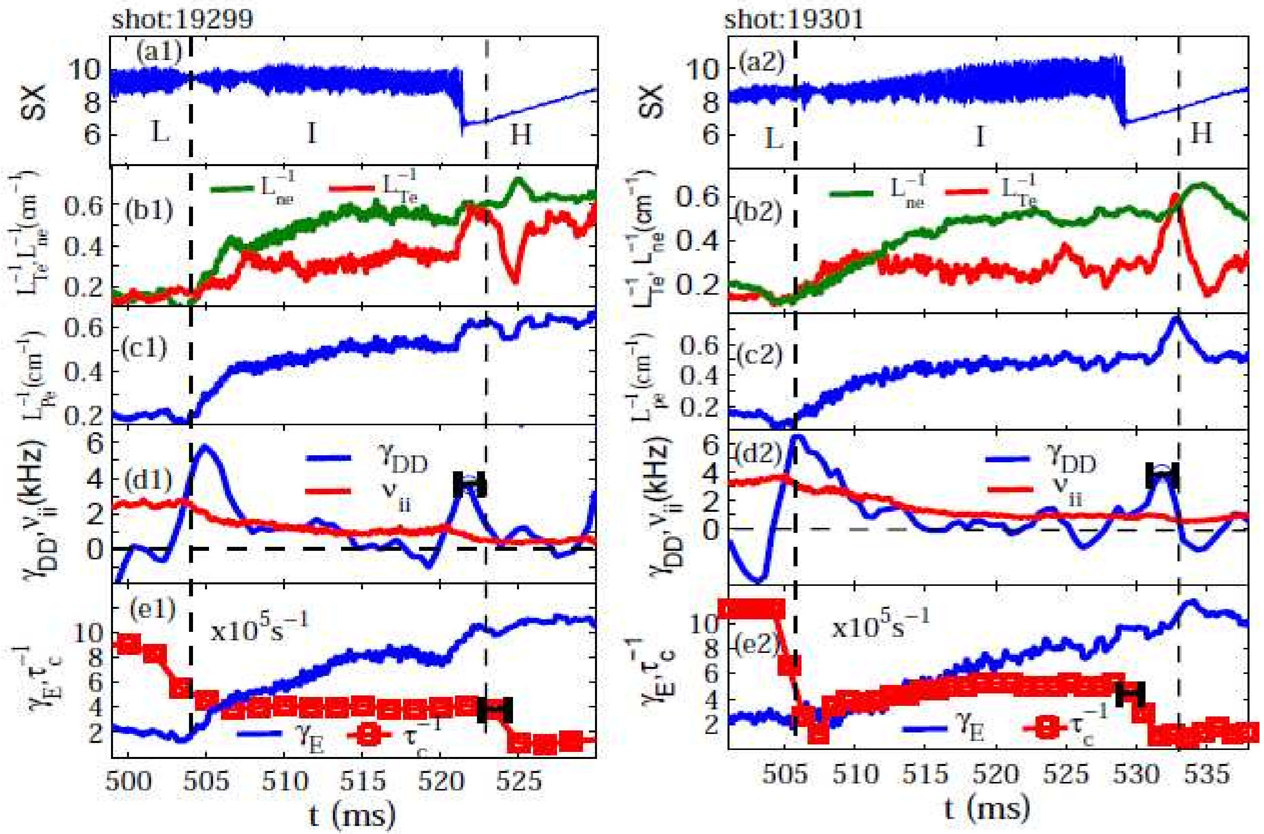
No peak of P_{RS}/P_{AT} appears prior to H



- The work done by the diamagnetic force and the Rs force are defined as $P_{dim}=\partial V_{dim}/\partial t V_E$, $P_{RS}= -\partial Rs/\partial r V_E$
- The turbulence has a rapid reduction after the peak of P_{dim}
- The ratio of P_{RS}/P_{AT} gradually increases close to the H mode

J. Q. Dong, J. Cheng, et al, submitted (2016)

The condition for I-H transition

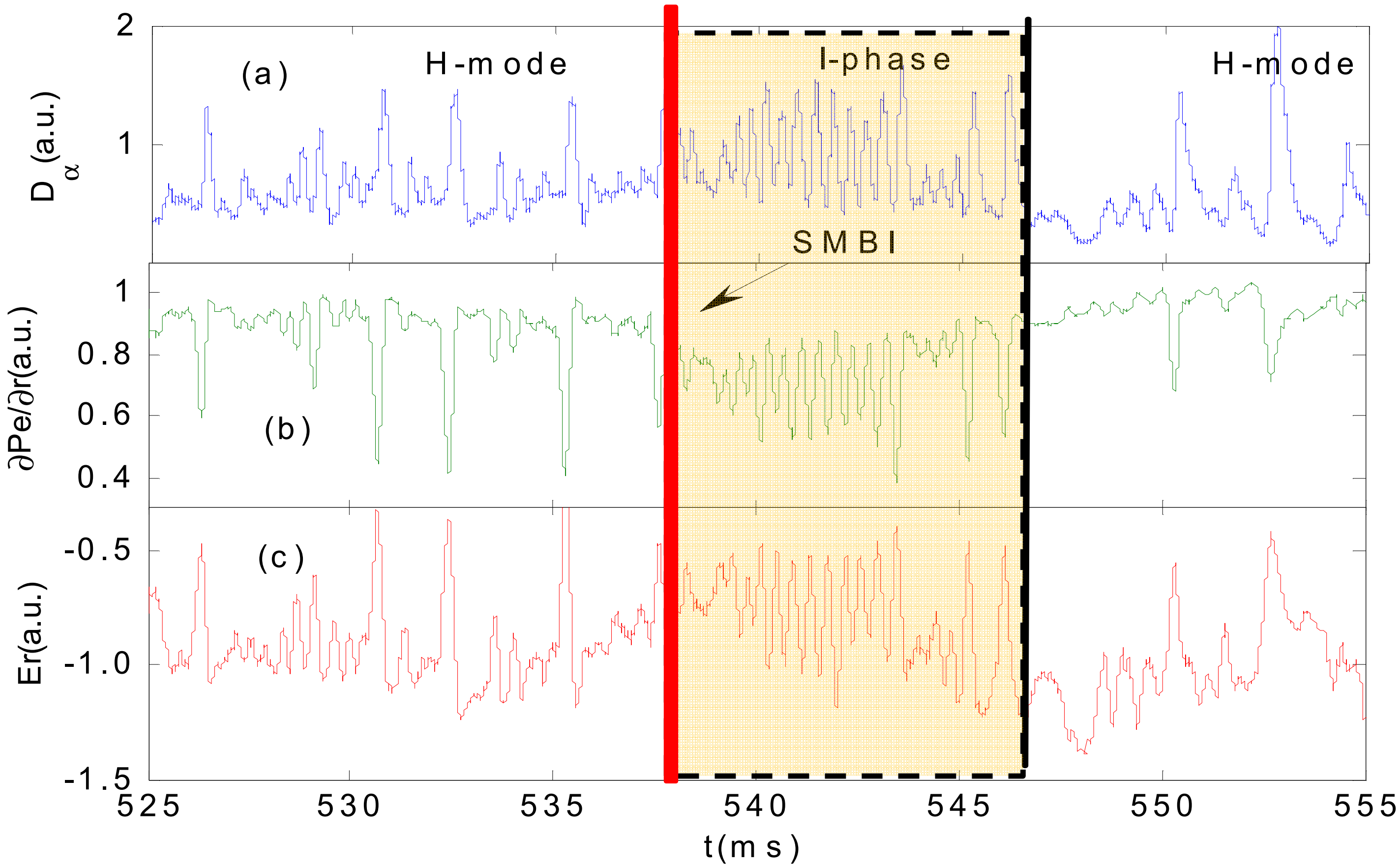


- The I-phase has type-J LCO
- The edge pressure gradient scale length L_{pe} is less than a critical value (~1.7cm), the E×B flow shearing rate is higher than a critical value (~10^6 s^{-1})
- The growth rate of the diamagnetic drift flow is equal to or higher than the ion-ion collision frequency

Part III

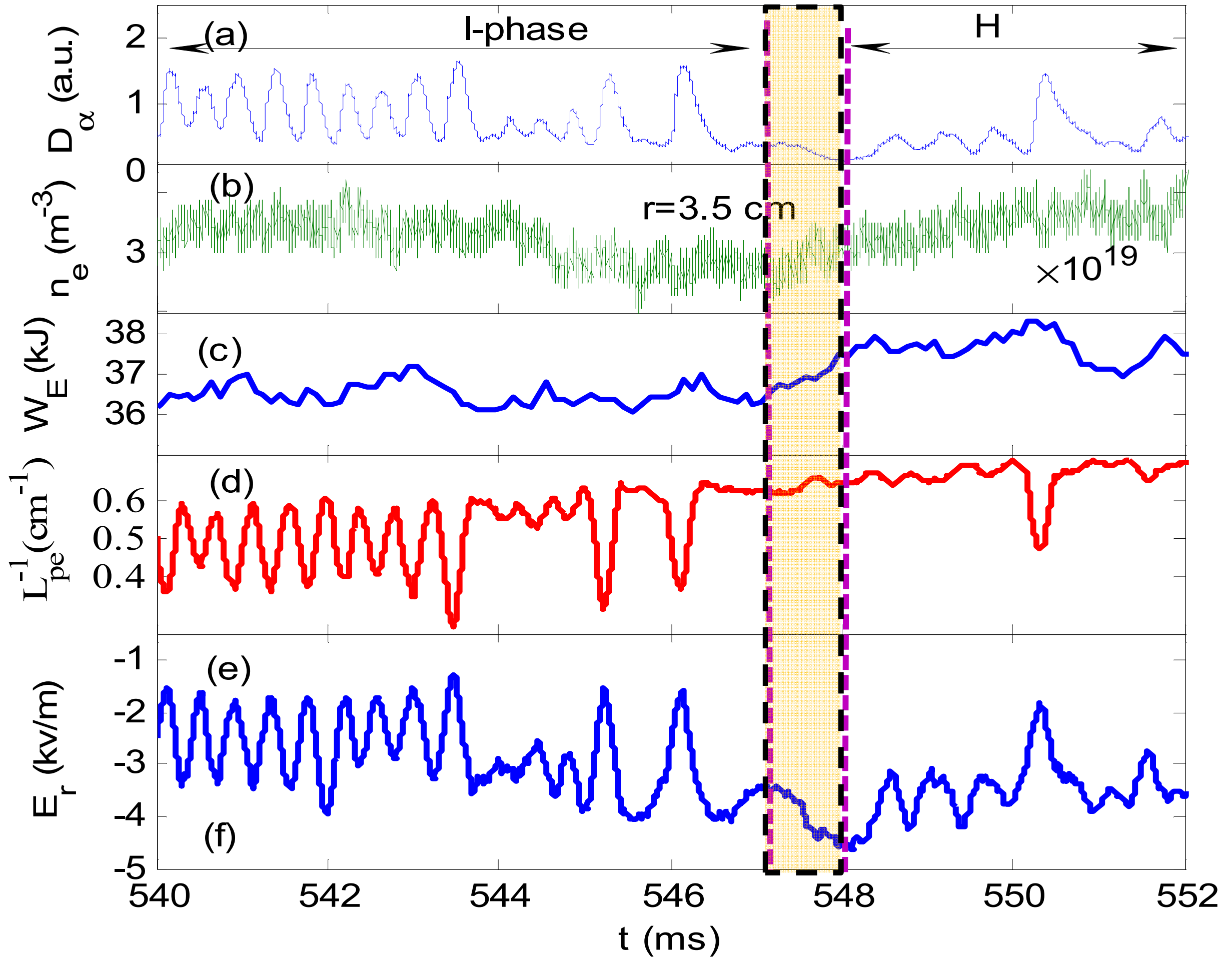
Dynamics of H-I-H transition

H-I transition stimulated by SMBI



1. Evolution of pressure gradient and radial electric field in H-I-H
2. ELM evolves into an oscillation (2.6 kHz)
3. Pressure gradient has a sharp reduction after SMBI
4. Mean pressure gradient is the key for I-H transition

Identification of I-H transition



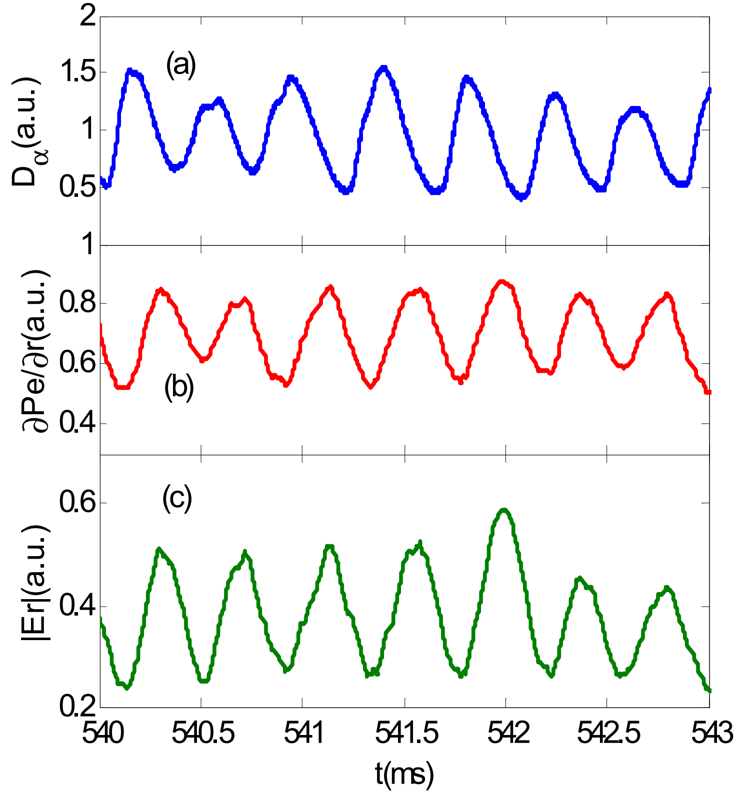
1.The I-H transition occurs during t=547.2-548 ms

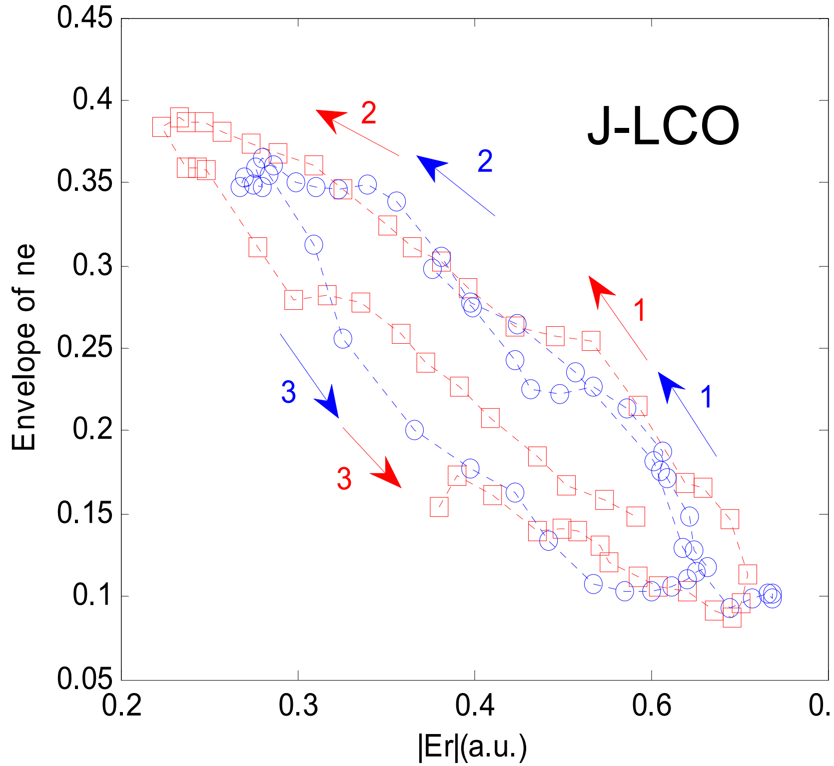
2. After t=547 ms, ne and W_E increase, D_a also starts to reduce

3. I-H transition happens after t= 546 ms

4. The pulse at t=545-546 ms is LCO rather than the ELM.

Type-J LCO with high ∇P_e

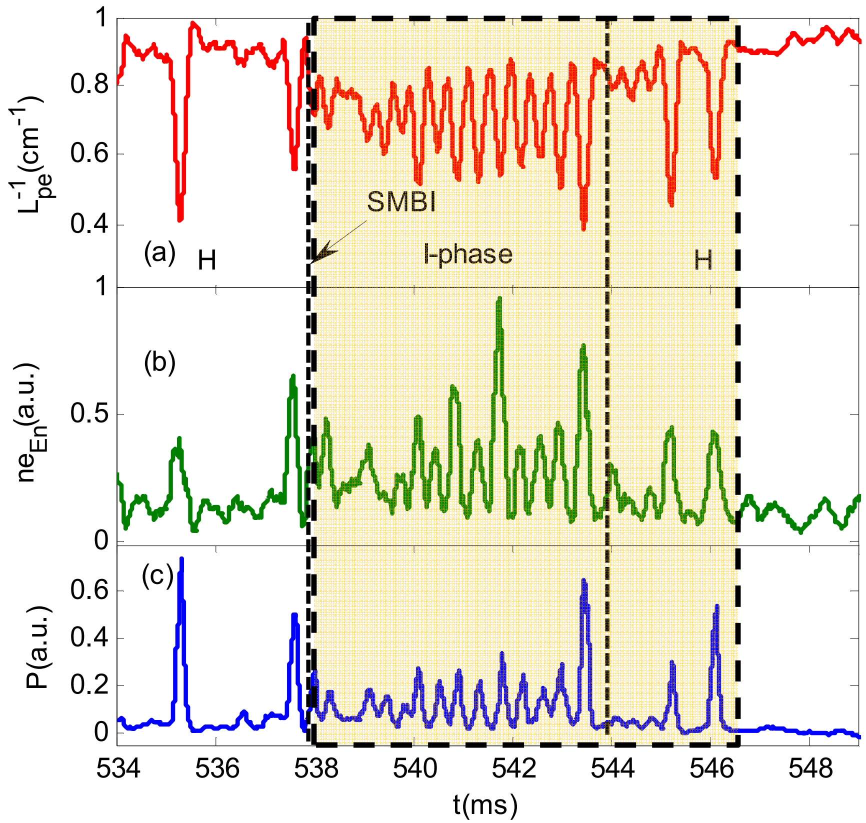


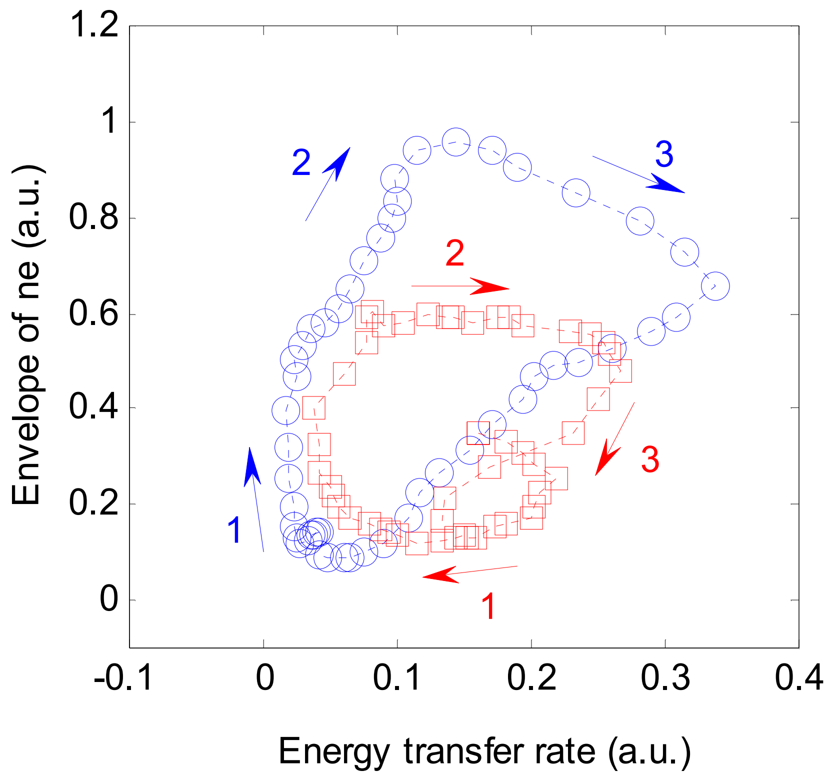


1. Temporal evolution of Da, pressure gradient and |Er| in LCO phase
2. LCO is a finite frequency oscillation (center frequency is 2.6 kHz)
3. The pressure gradient is in phase with |Er|
4. In H-I-H phase, Er leading turbulence, type-J LCO

J. Cheng, J.Q. Dong, K. Itoh, et al, PRL, 2013

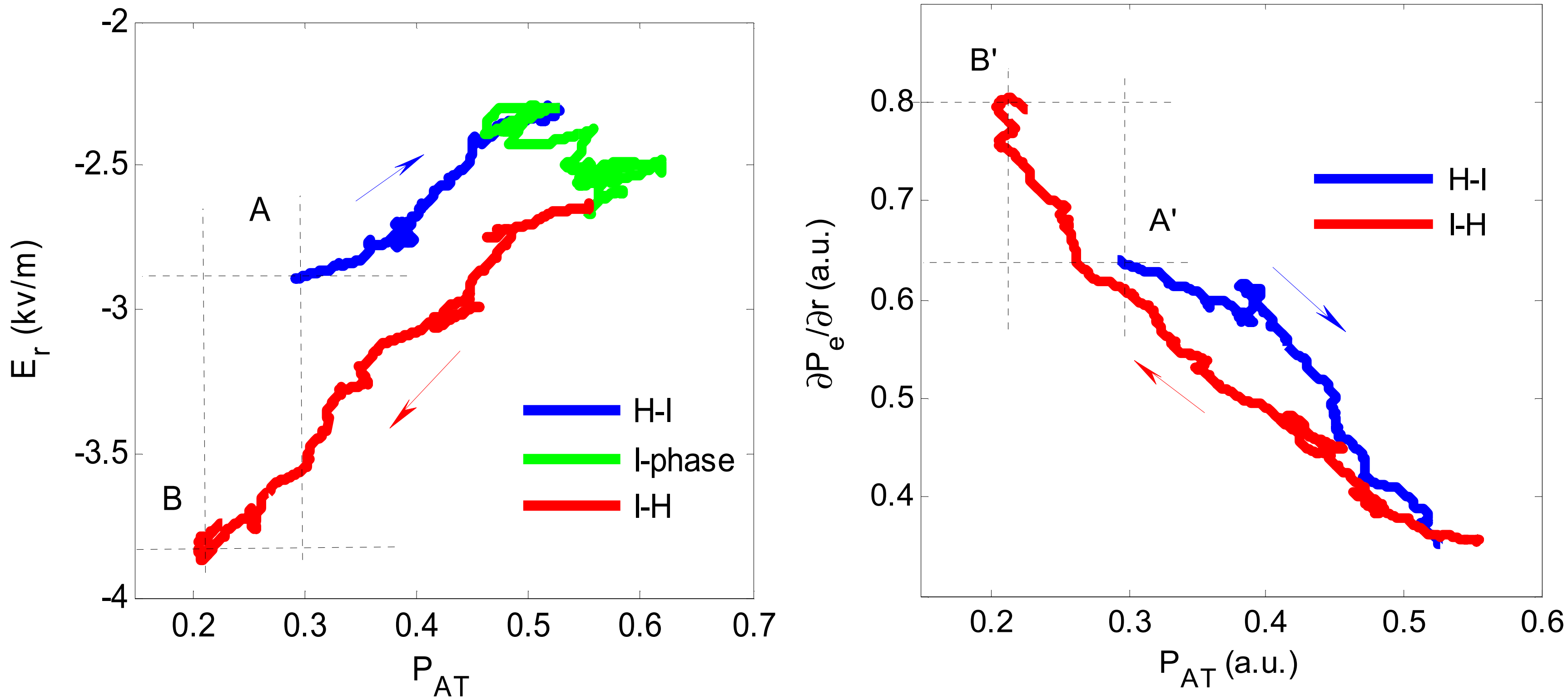
LCO between turbulence and energy transfer rate





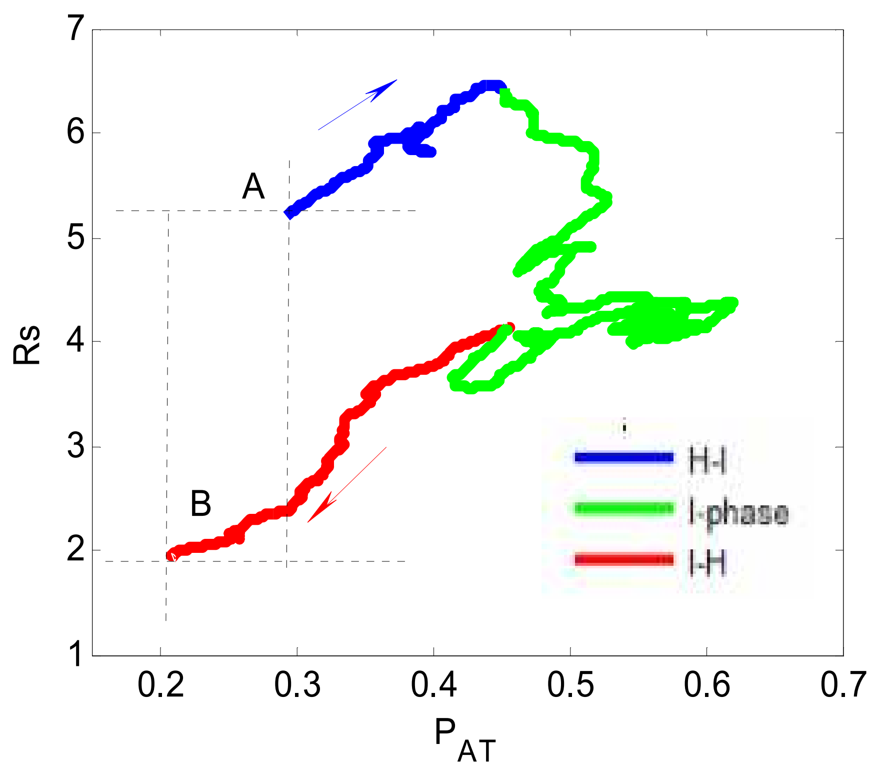
1. P means energy transfer rate: $P=Rs\partial V_{\theta}/\partial r$
2. SMBI induces H-I transition and LCO belongs to J-LCO (high pressure gradient)
3. The cycle between turbulence and energy transfer rate is clockwise rotation
4. The direction is not dependent on the time segment

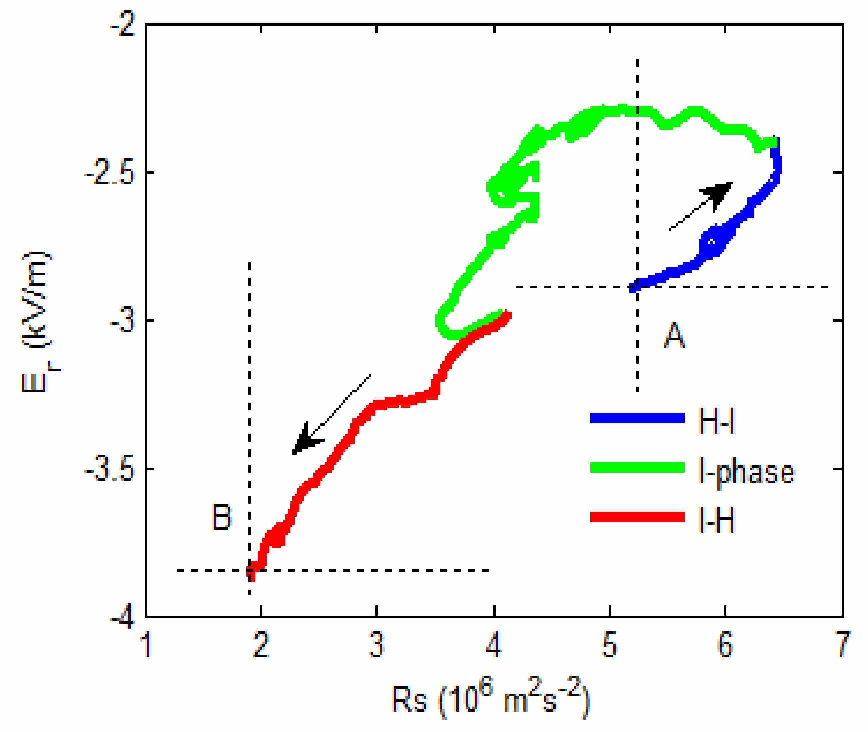
Hysteresis in H-I-H transition



1. Hysteresis appears in H-I and I-H transition
2. Er and turbulence or pressure gradient and turbulence show the similar results
3. |Er| for I-H transition is larger than that for H-I transition

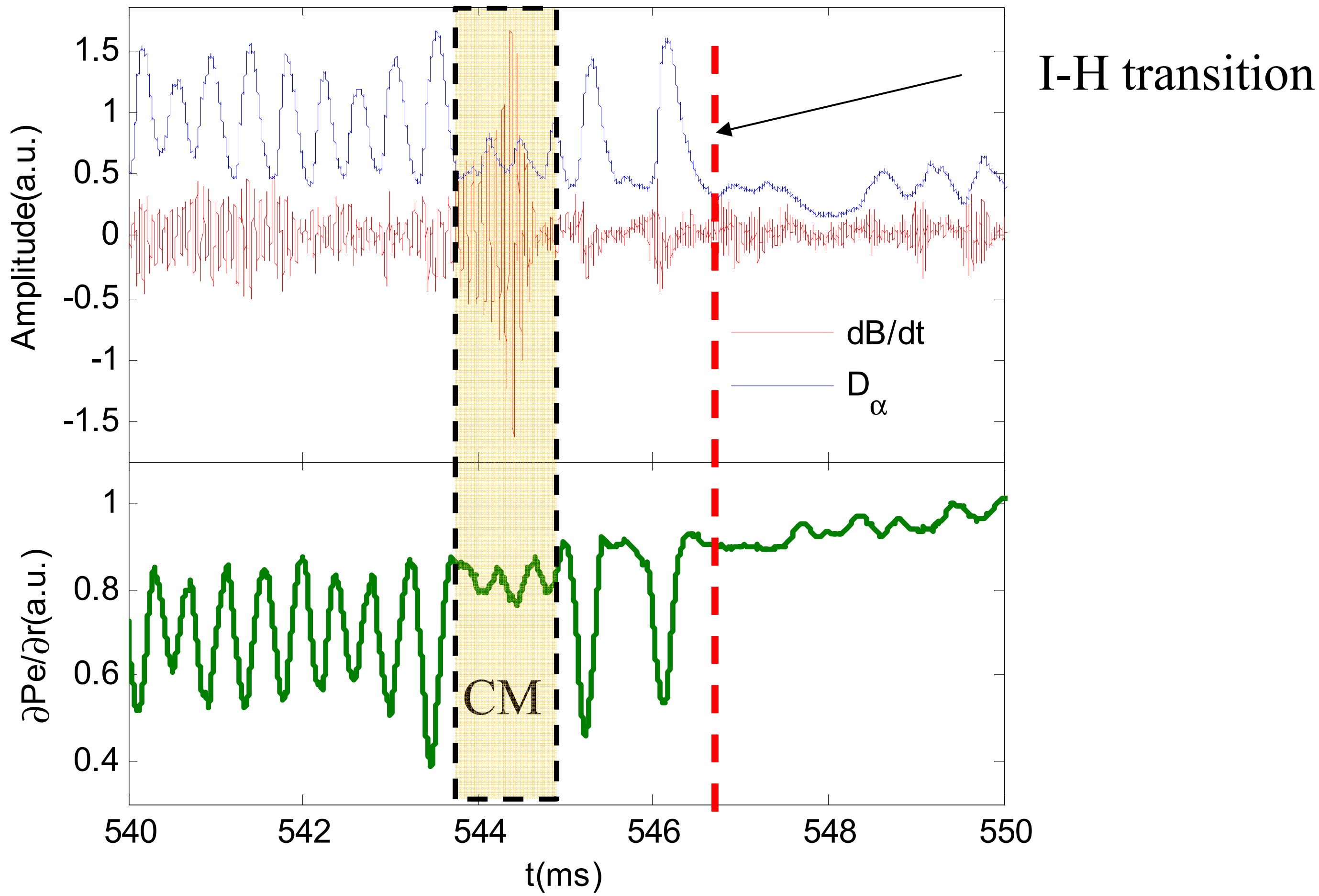
Rs out of phase with Er for I-H transition





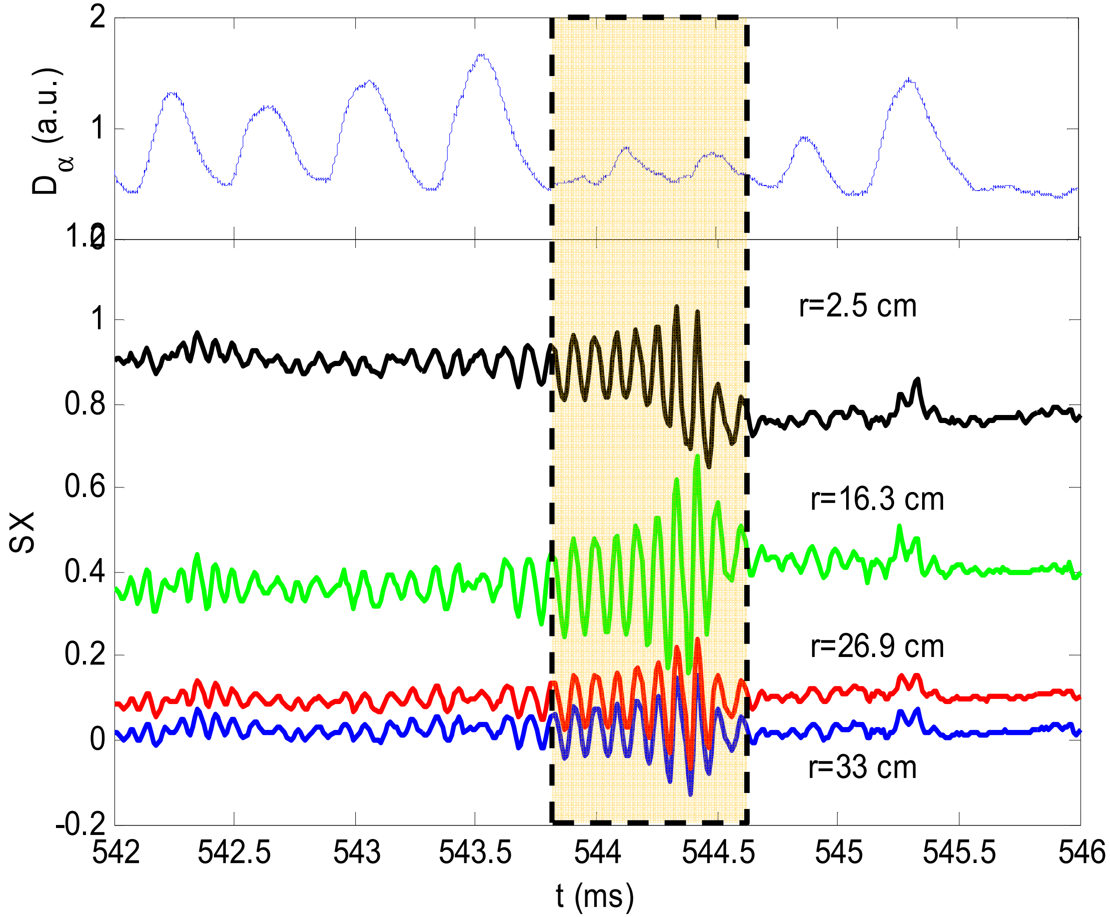
1. For H-I and I-H transition, Rs is in phase with turbulence
2. For H-I and I-H transition, Rs is out of phase with Er

Coherent mode appearing before I-H transition



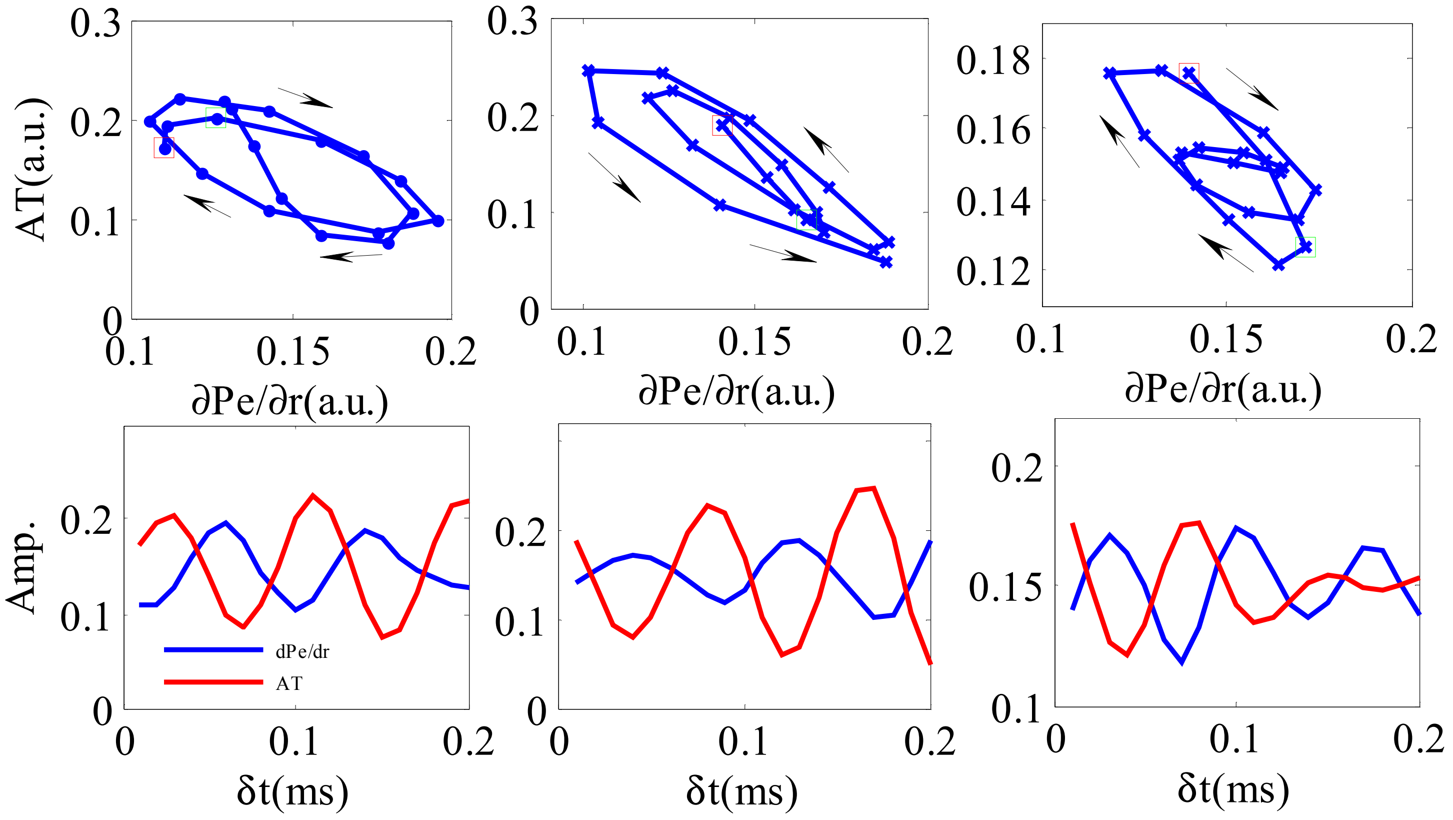
1. A coherent mode appears with f=12 kHz
2. The mode appears, meanwhile its radial particle loss reduces (D_α)
3. The role of a CM on reducing fluctuation amplitude of LCO

Spatial structure of CM



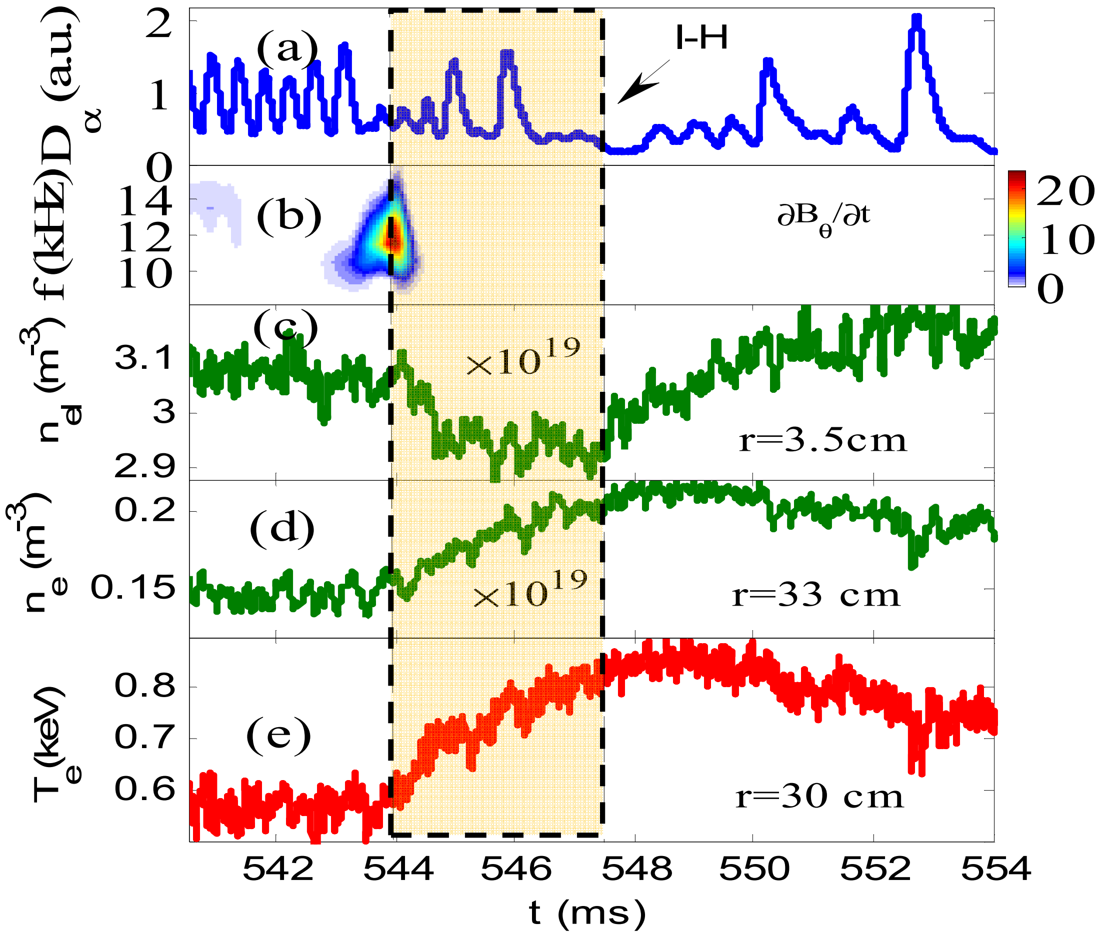
1. The coherent mode appears in SX signals at different radial positions
2. The mode is localized at core plasma and has kink mode characteristic

Nonlinear interaction between CM and turbulence



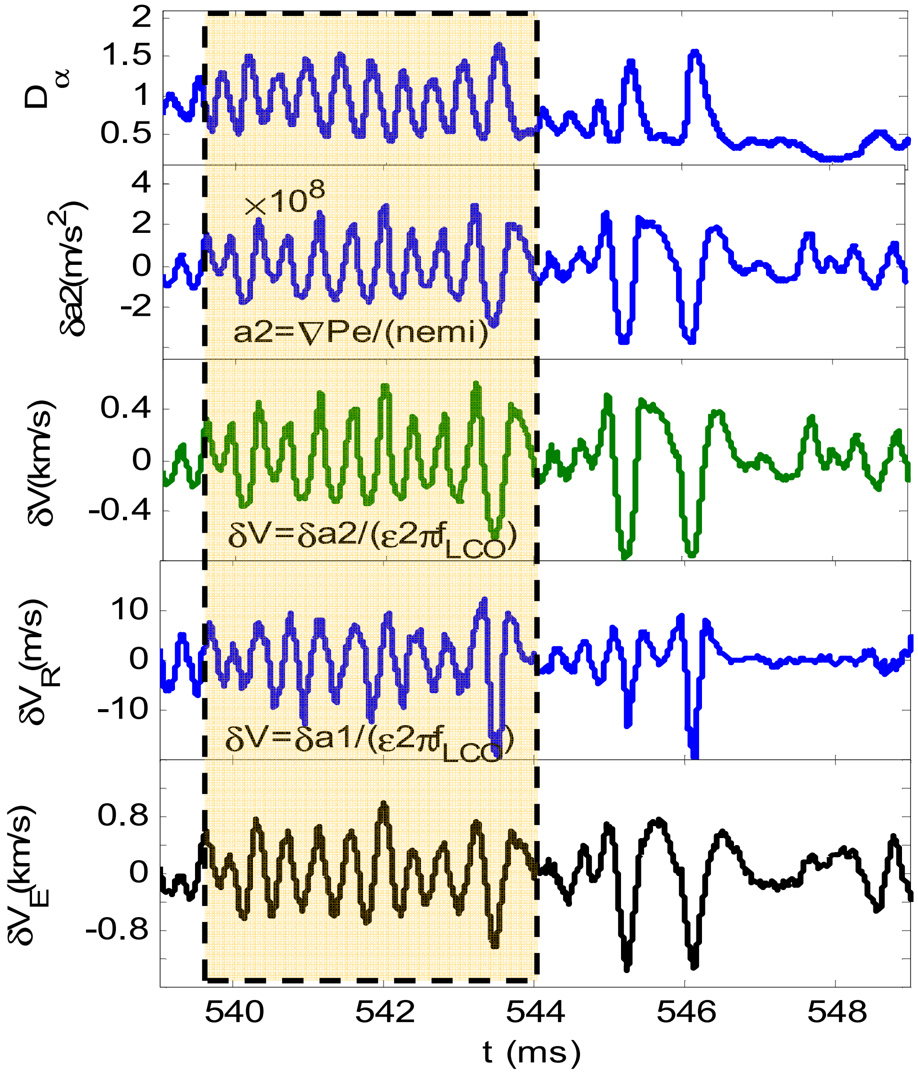
1. The turbulence is estimated with density fluctuation in 20-200 kHz
2. Pressure gradient has a strong fluctuation in CM frequency
3. Different rotations were found at different time segments
4. The phase between pressure gradient and turbulence is 0.7π

Density profile modulated by coherent mode



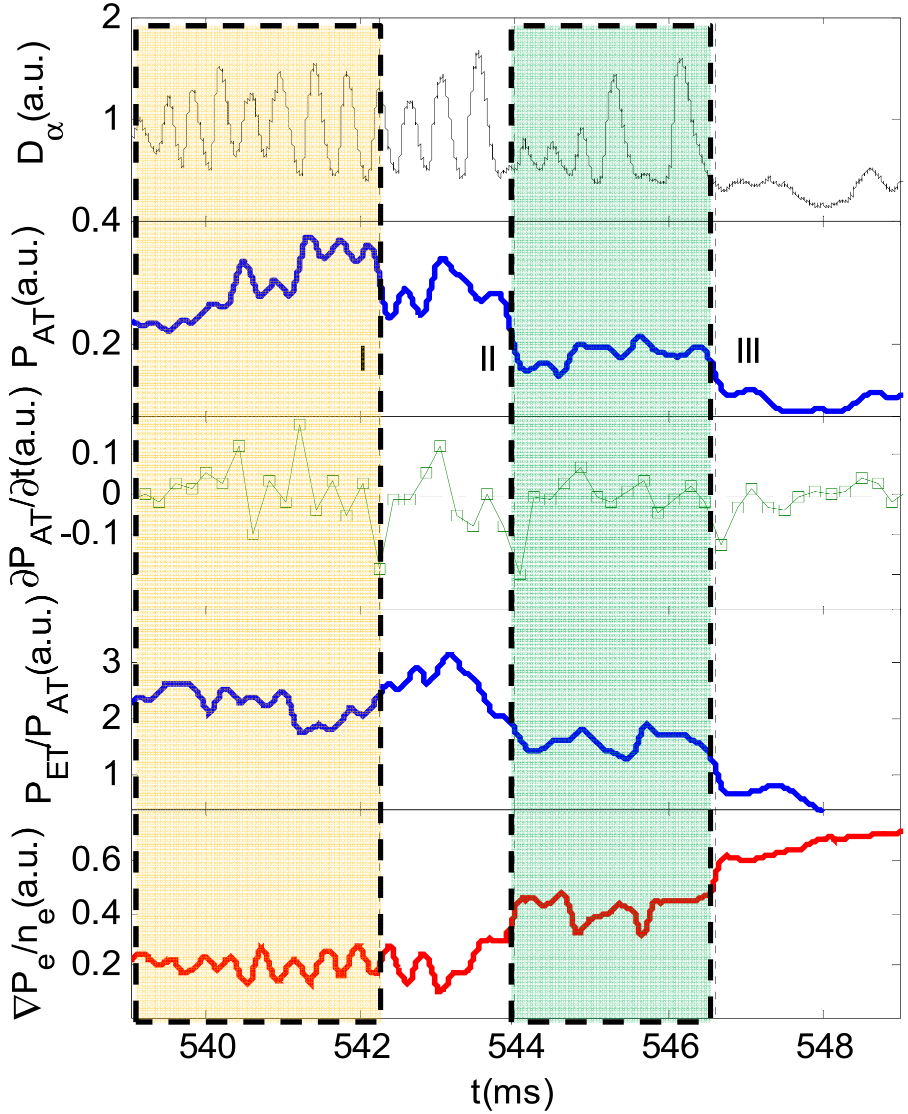
1. The coherent mode crash can reduce the core density and enhance the edge density
2. It is found that Da amplitude reduces when the CM appears

Comparison of flows driven by RS and ∇Pe



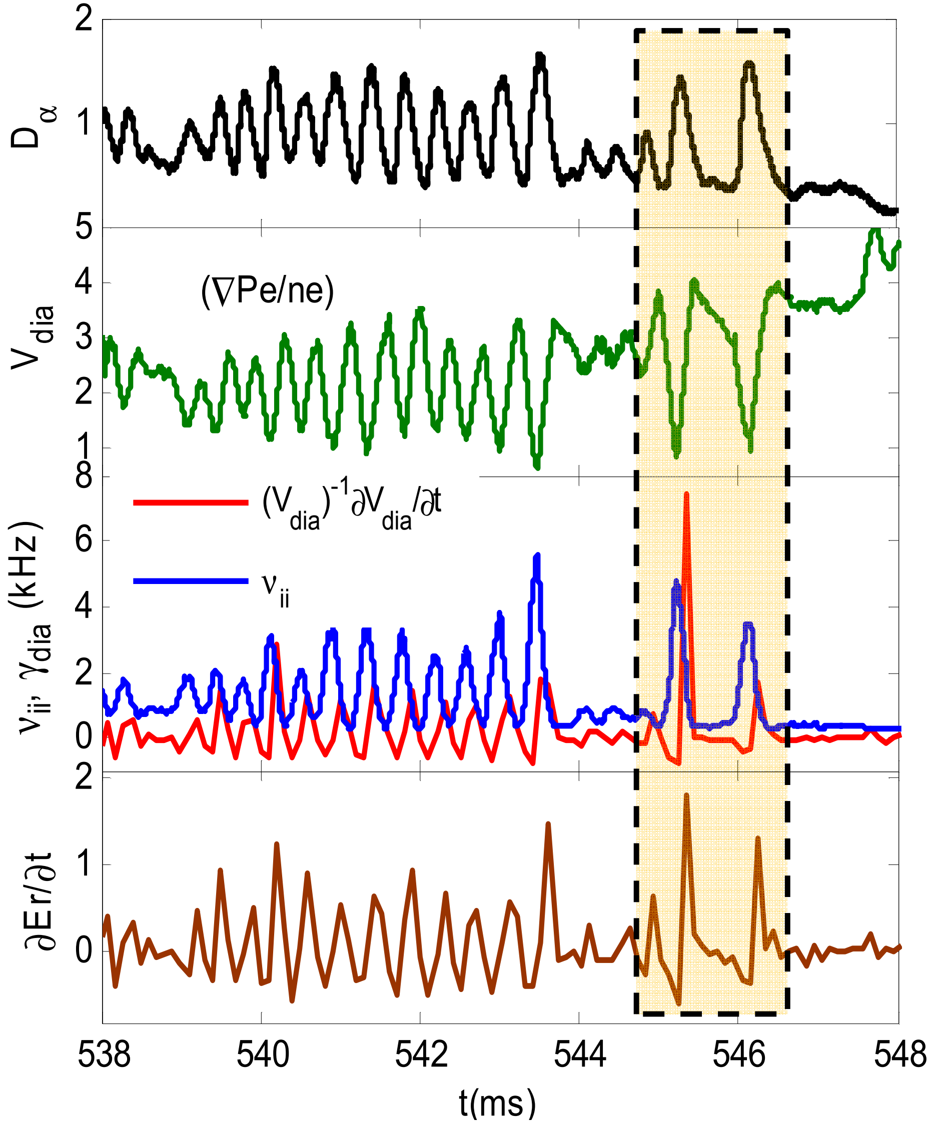
1. The acceleration driven by RS is expressed as a1=∇Rs
2. The fluctuation amplitude of flow driven by RS is 0.01 km/s, that of diamagnetic flow is 0.4 km/s (assuring Pi=Pe)
3. The amplitude of LCO is about 0.8 km/s, measured at Δr=-8 mm
4. The amplitude of poloidal flow driven by RS is really smaller than LCO
5. The diamagnetic force might be one of candidates

Role of diamagnetic flow on I-H



1. Evolution of turbulence magnitude across I-H transition measured with probe
2. The negative value of $\partial P_{AT}/\partial t$ means turbulence crash
3. P_{ET} was estimated by $P_{ET}=Rs\partial V_\theta/\partial t$, which is not correlated with turbulence crash
4. The diamagnetic flow suddenly rises, consistent with the turbulence crash

Conditions for I-H transitions

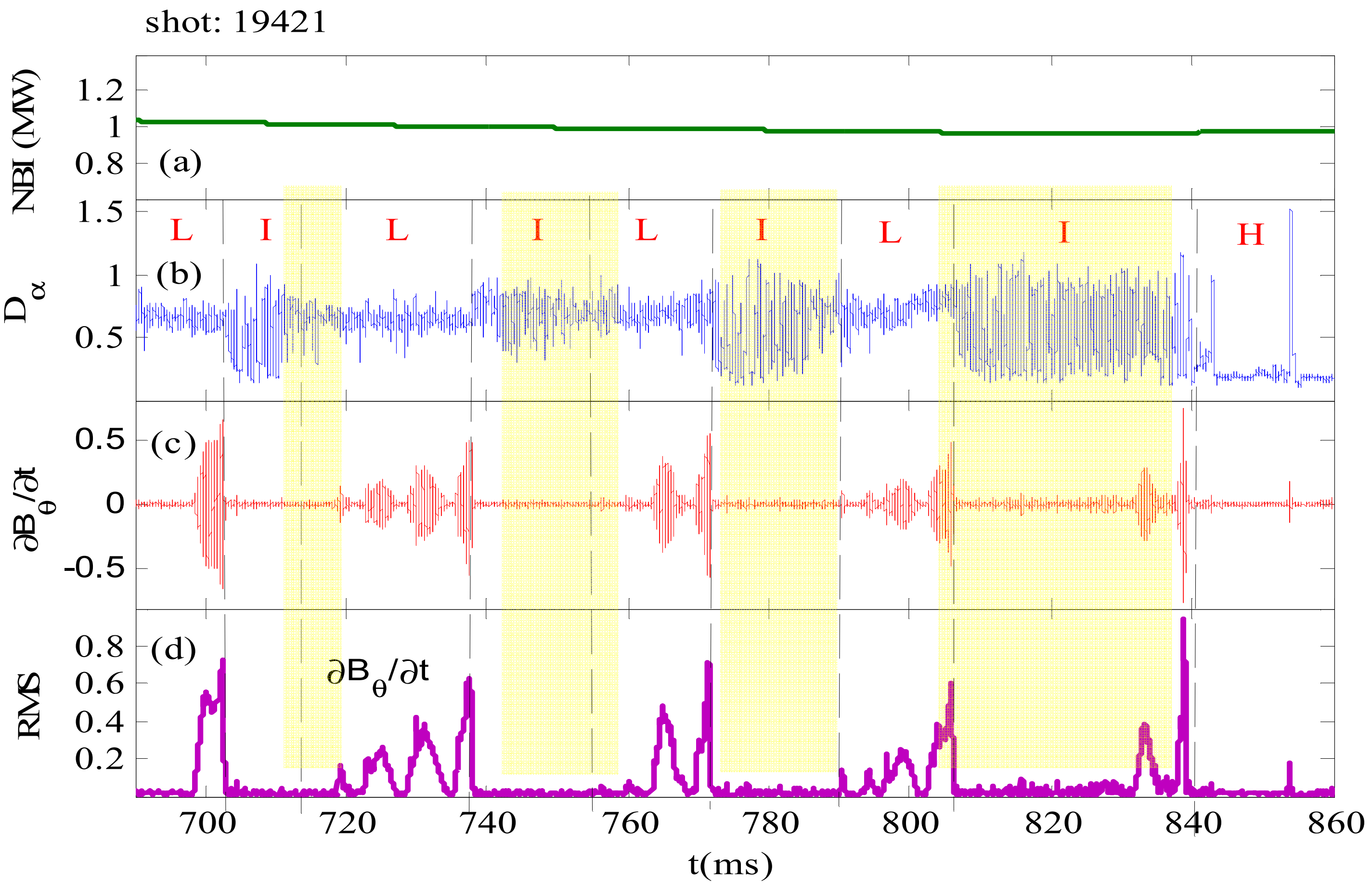


1. Evolution of diamagnetic flow measured with probe
2. The growth rate of pressure gradient is comparable with ion-ion collisionality
3. dEr/dt is in phase with the growth rate of ∇Pe/ne
4. There is a possible link between the diamagnetic driving and the LCO flow
5. The growth rate of diamagnetic flow is comparable with ion-ion collisionality

Part IV

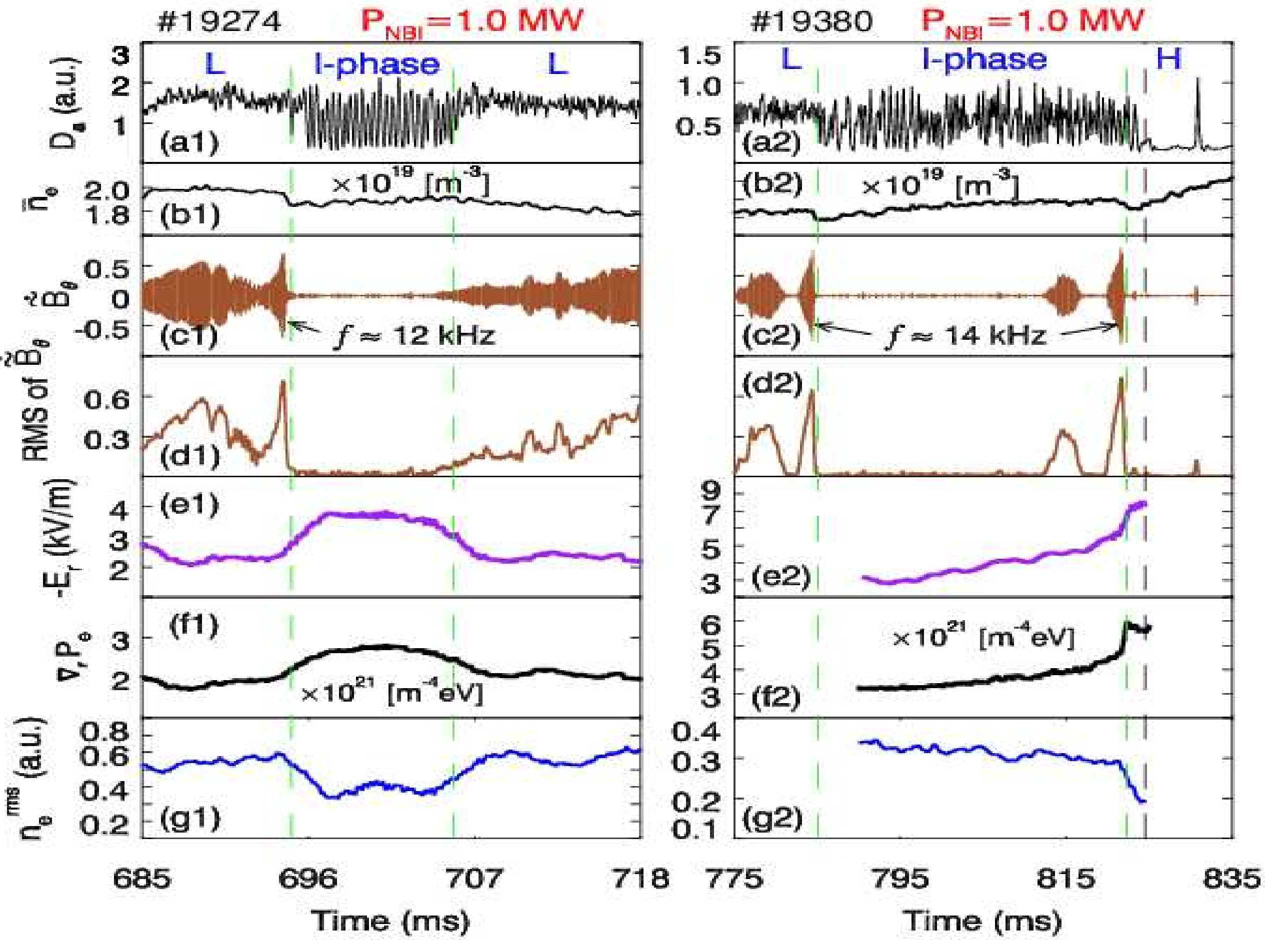
Reduction of heating power for accessing the H mode with a kink-like MHD crash

Example of L → I → L & L → I→H transition



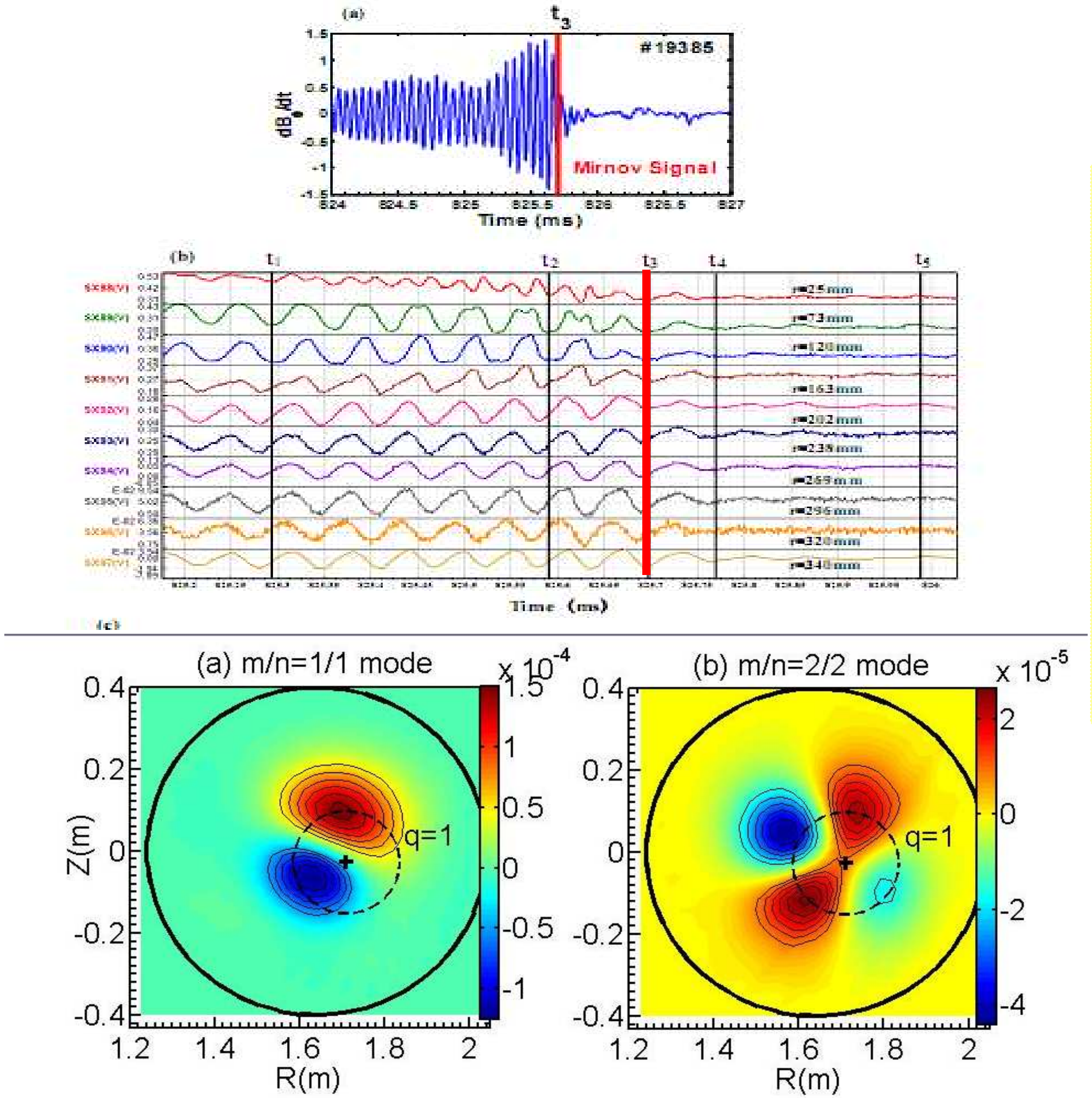
- With marginal heating power (PNBI=1 MW), I-phase appears frequently
- An MHD mode crash is often seen before L → I and I → H transition
- It seems that the I → H transition needs a MHD crash (in the I-phase)

Increasing E_r and $\partial Pe/\partial r$ induced by a MHD crash



- The coherent mode appears before the L-I or the I-H transition
- The mode frequency is 10-15 kHz and it has electromagnetic characteristics
- The time scale of mode crash is about 0.2-0.3 ms, close to $1/\nu_{ii}$
- The increasing edge E_r and $\partial Pe/\partial r$ induced by a MHD crash before L-I or I-H

Properties of the mode — internal kinky mode



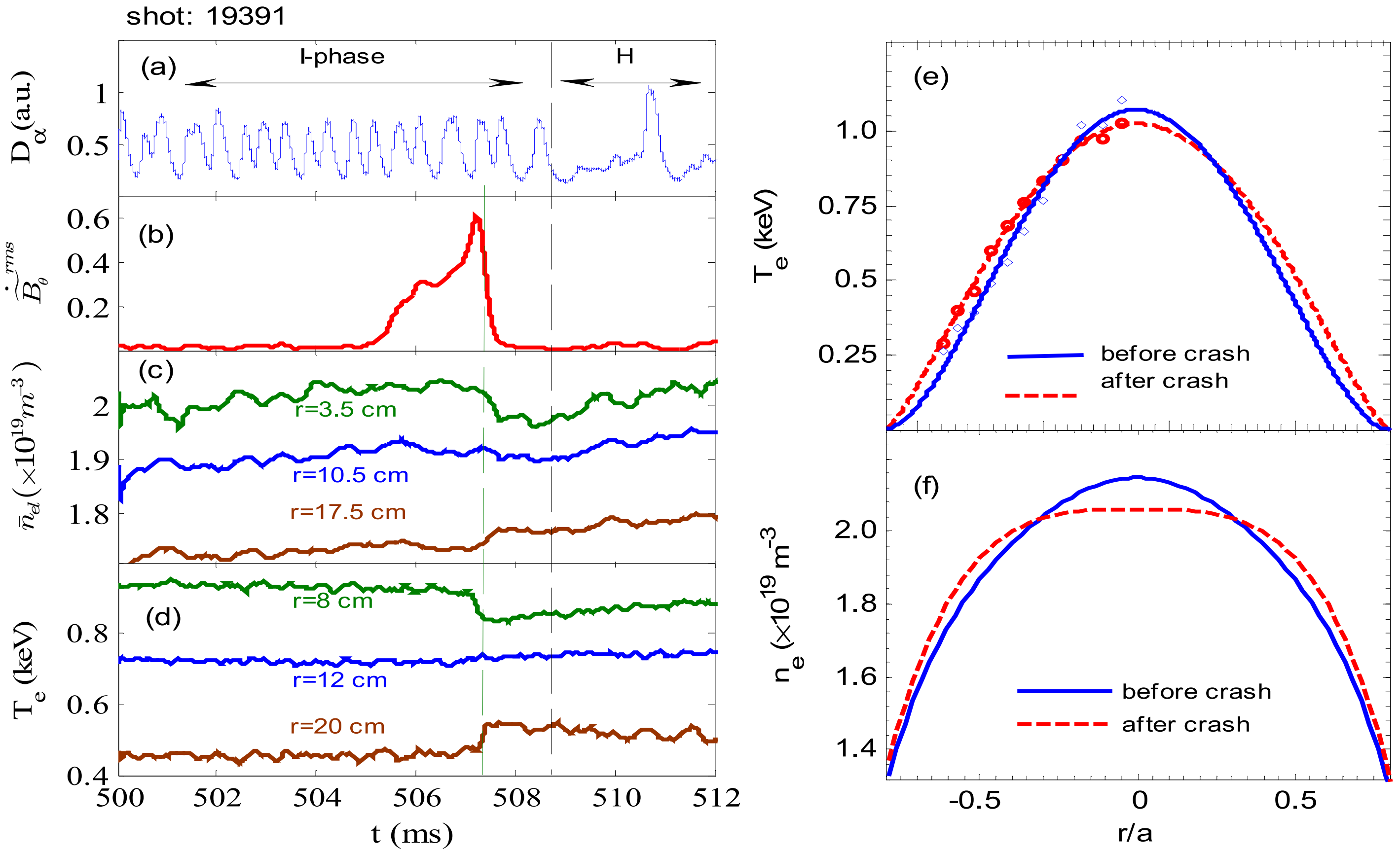
No phase inversion seen in the SXR signals, suggesting a kink mode.

m/n=1/1, 2/2 developed

m/n=1/1,2/2 grew/ crash

H-mode w/o MHDs

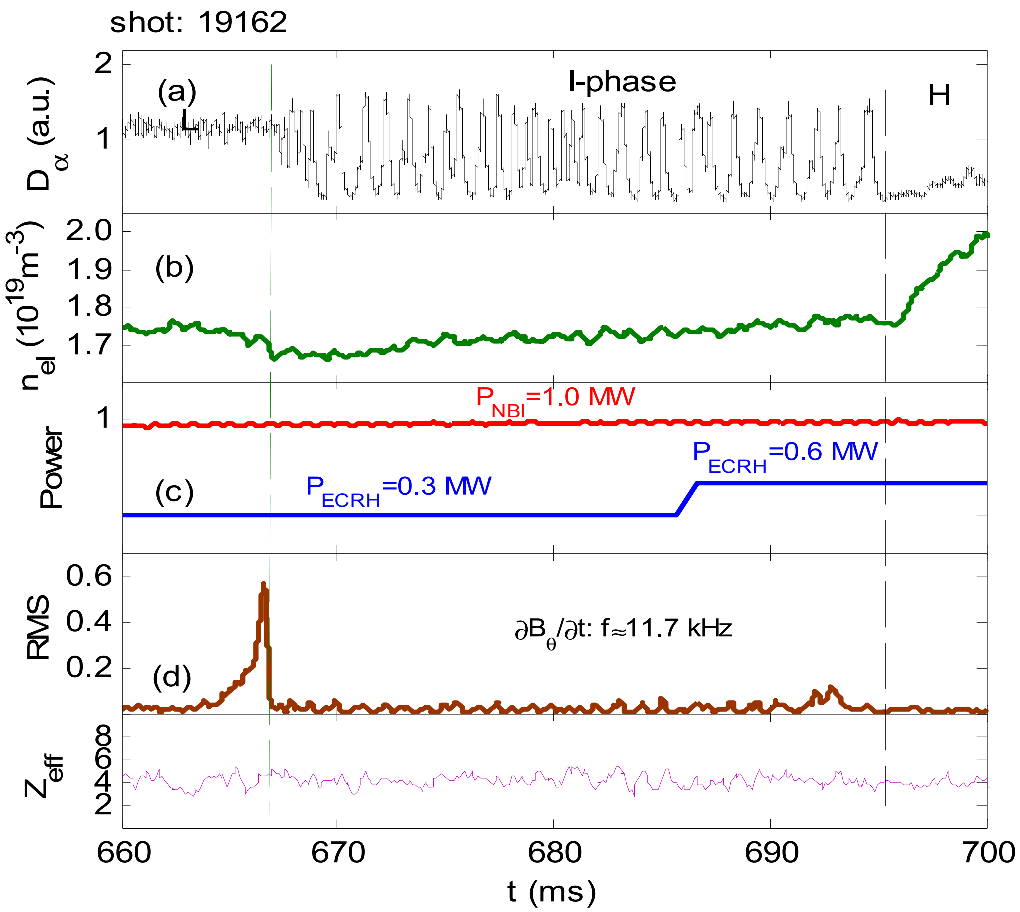
Modification of T_e/n_e profiles by the mode crash



- The mode crash prior to the H mode about 1-2 ms
- The core Te/ne reduces, meanwhile the edge Te/ne rises (ECE and HCN)
- It is clear to see the plasma profile becomes flat after a mode crash
- Edge pressure gradient over a threshold and the mean shear flow increase largely to suppress turbulence, then trigger the H mode

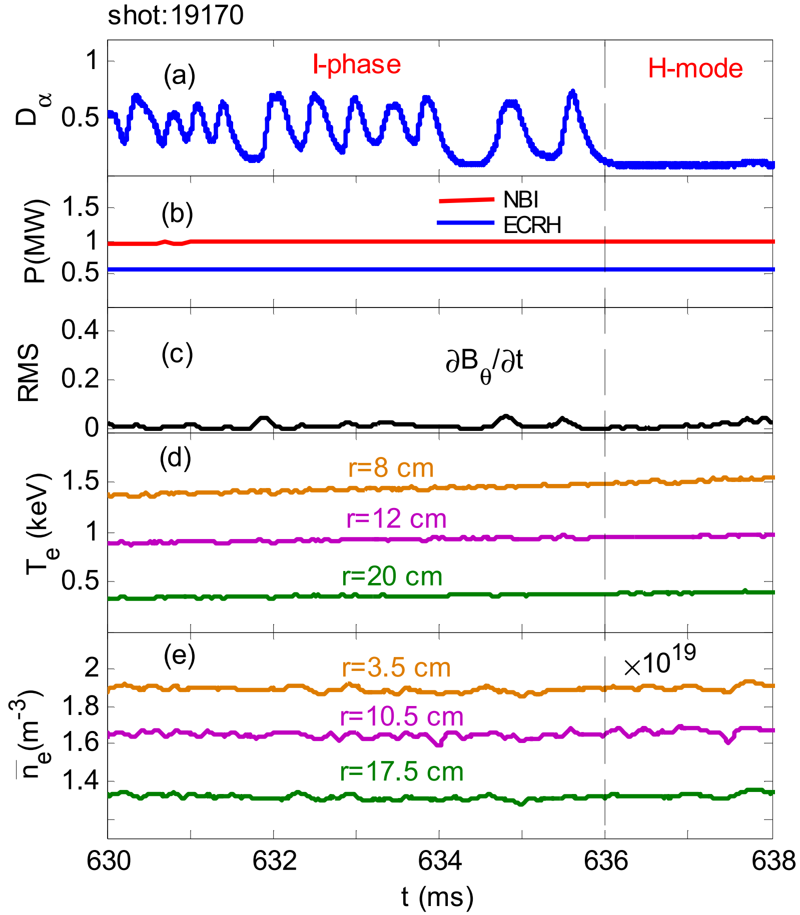
Y. Xu, J. Cheng, et al PPCF 57 014028 (2015)

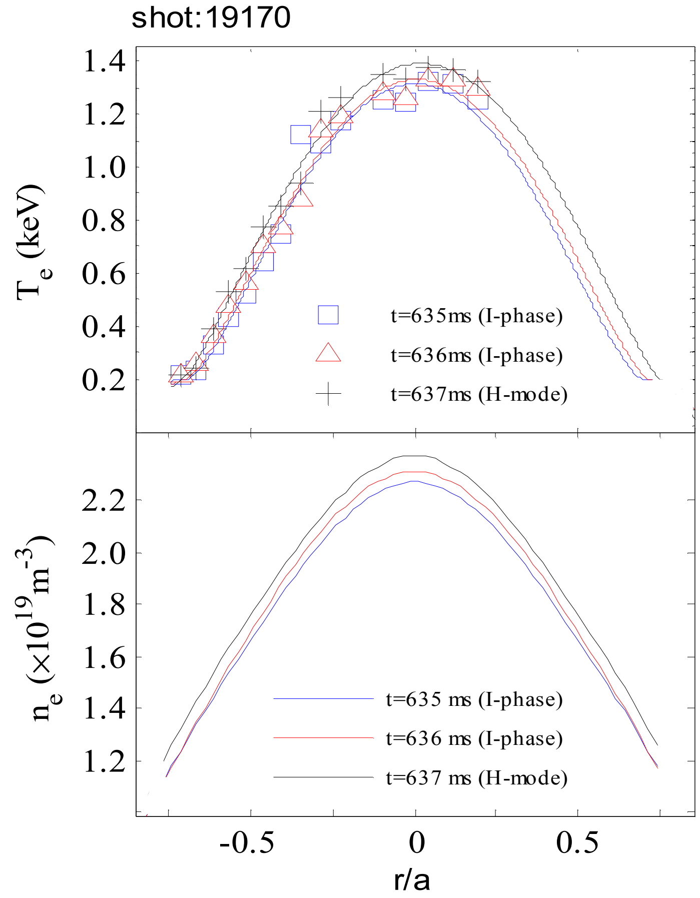
Mode disappears with increasing power



- The mode appears at L-I transition under the NBI and ECRH heating
- The mode disappears with increasing ECRH heating added to the same NBI power
- The higher heating power can cause the I-H transition without a MHD crash

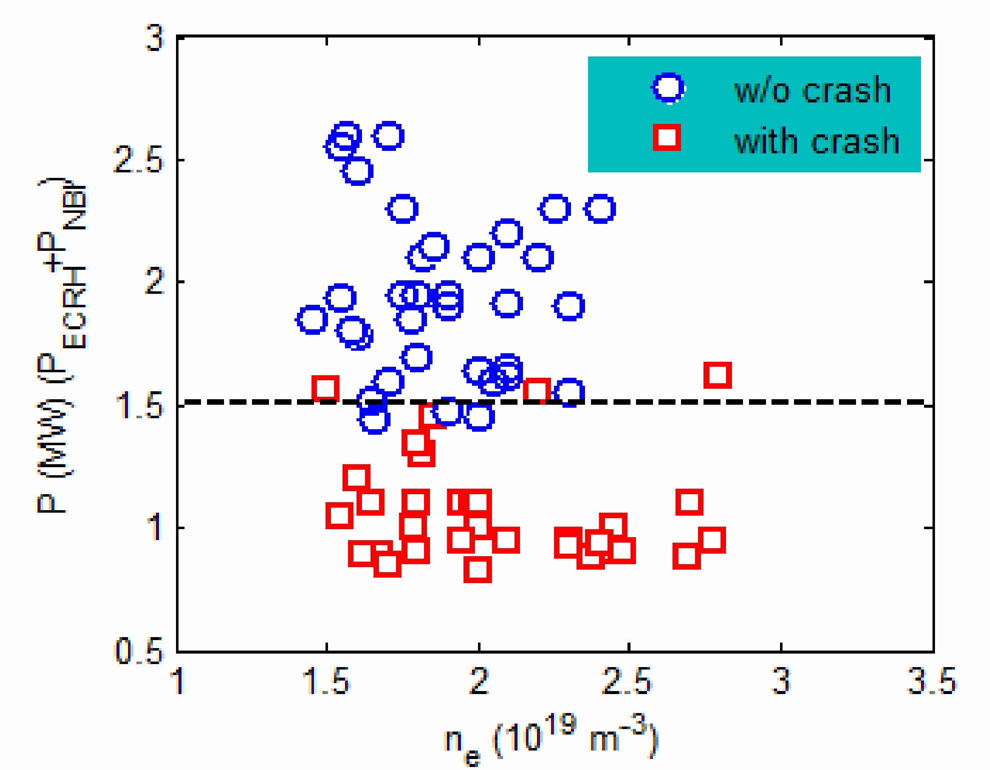
Evolution of T_e/n_e profiles without mode crash





- Mode disappears in the higher heating power (ECRH+NBI=1.5 MW
- The core and edge simultaneously rises approaching the H mode phase
- Edge pressure gradient maybe have a threshold value, over which the strong mean flow driven by pressure gradient directly deform eddy structure to trigger H mode
- The role of edge pressure gradient (ion pressure gradient) on the I-H transition

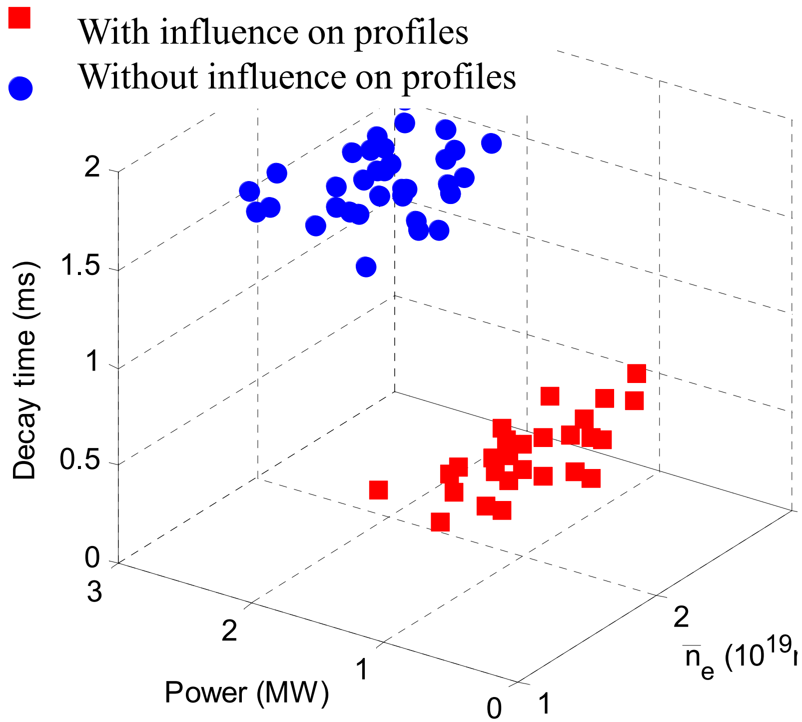
Reduction of heating power by the MHD crash

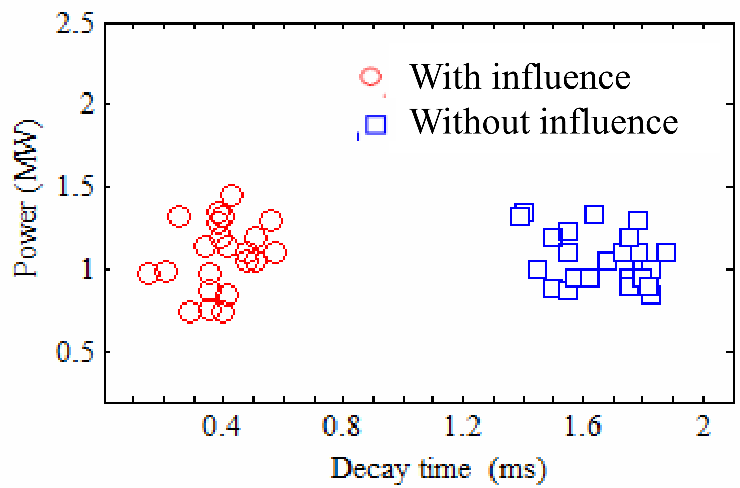


- Statistics results over 50 shots with and w/o mode crash
- In low heating power, the additional energy released by the MHD crash plays a critical role on the I-H
- This fact enlightens us to use the additional energy released by the internal kink mode to trigger H mode in the limited heating power case, such as in ITER

J. Cheng, Y. Xu, C. Hidalgo, et al will be submitted (2016)

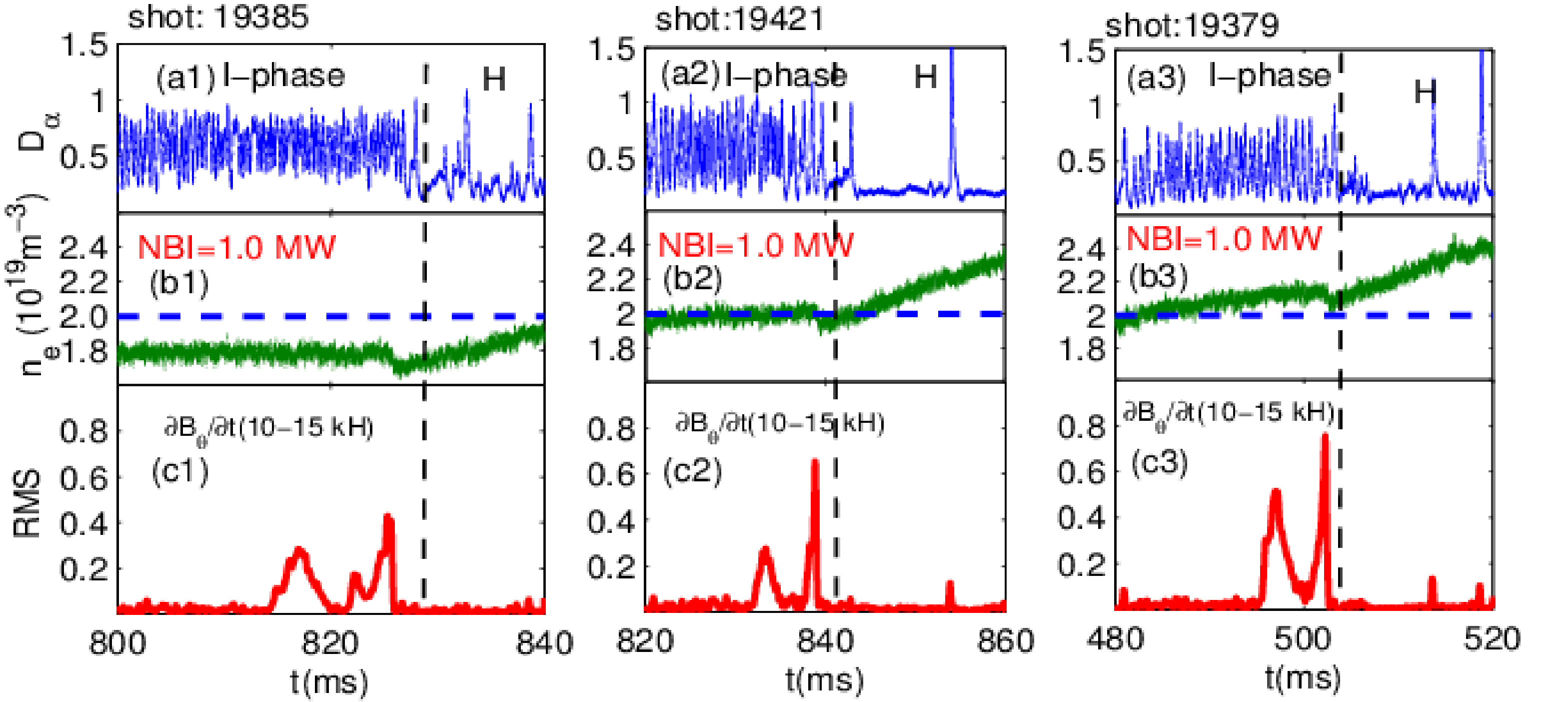
The role of decay time on I-H transition





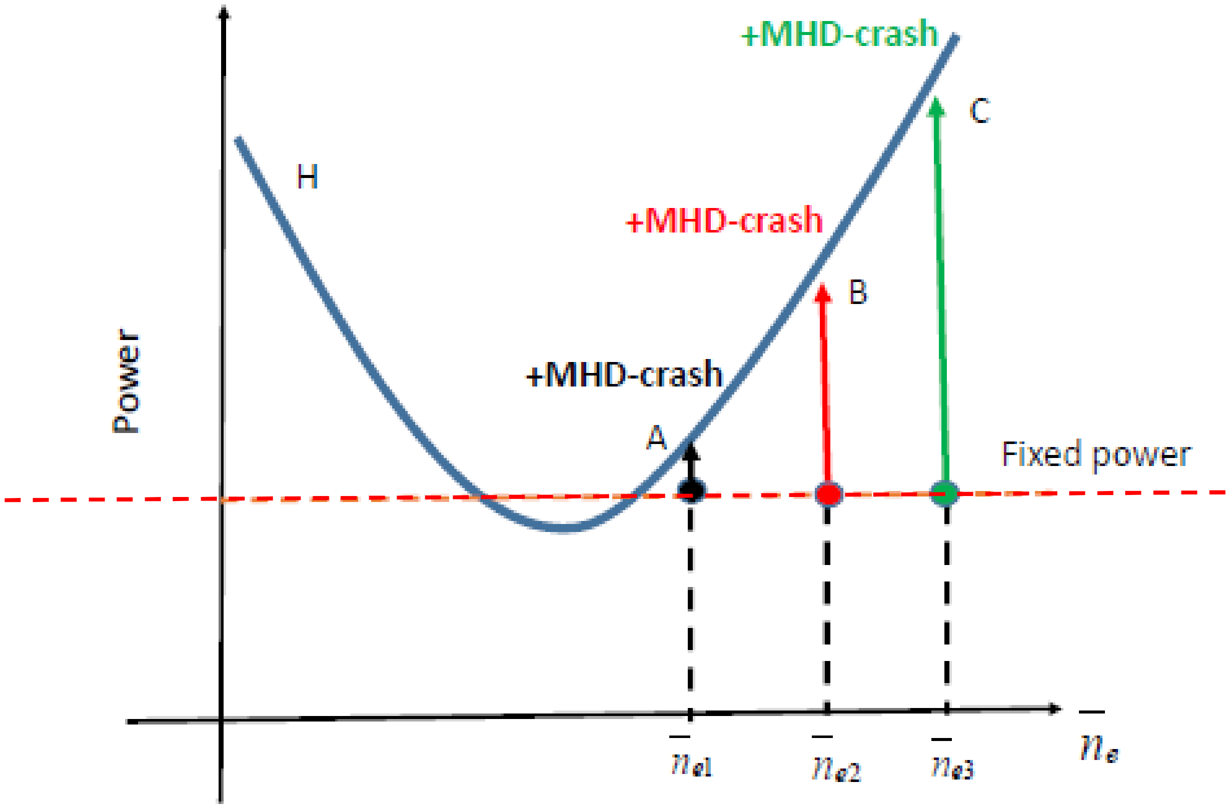
- Statistics results between decay time of mode and the heating power with and w/o mode crash
- The decay time is defined as 1/e of magnitude
- The time scale of mode crash is in the range of 0.2-0.6 ms for I-H transition
- The fast crash can evokes substantial energy release from the core to plasma boundary, increasing edge gradient and ErxB flow shear

Larger MHD contributes to I-H at higher n_e



- Under the same power NBI (P_{NBI}=1.0 MW, no ECRH)
- The line-averaged density in the range of (1.8-2.2) $\times 10^{19} m^{-3}$
- The mode routinely appears prior to the I-H transition
- The effect of mode crash on the line-averaged density, but the slower crash of the mode has no significant effect on the line-averaged density and edge pressure gradient
- The larger MHD crash helps the I-H transition at the higher density with the same heating power (limited power)

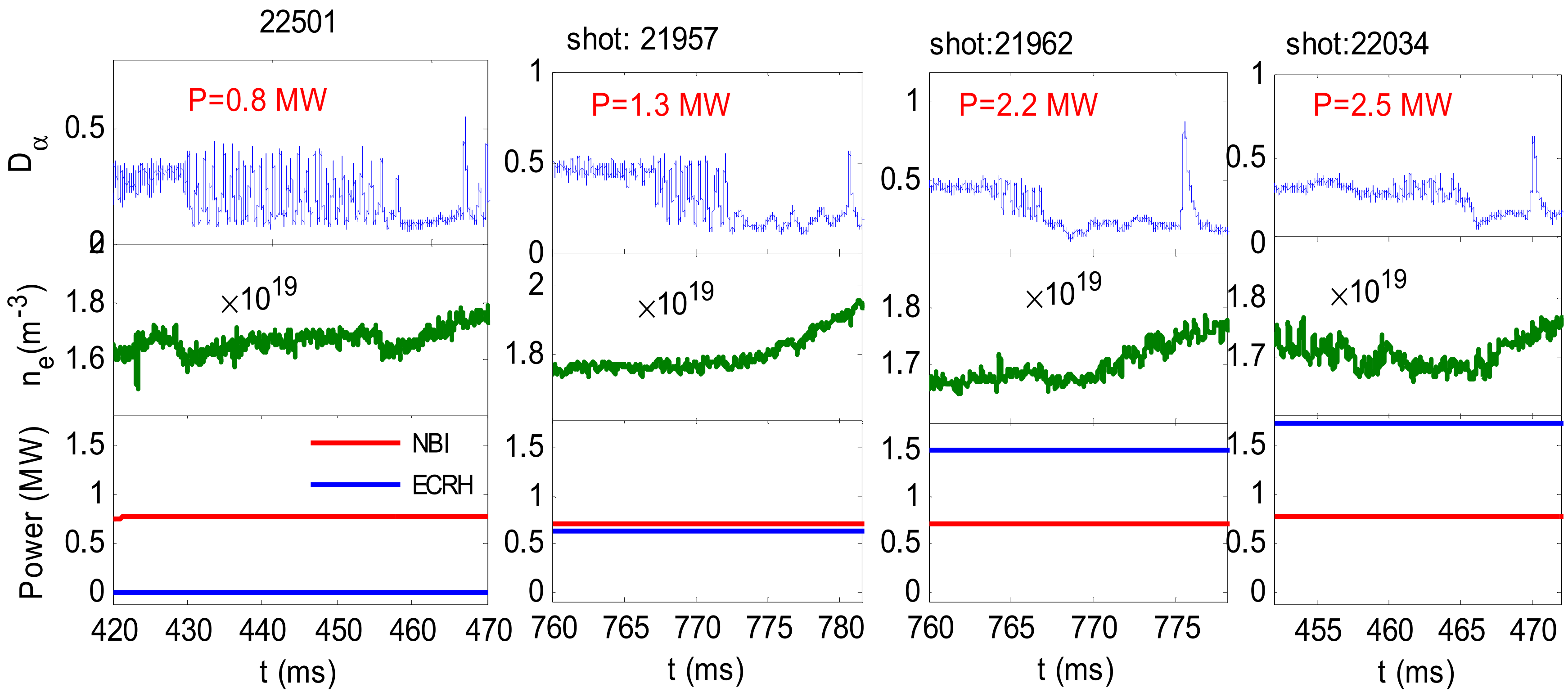
Change of MHD amplitudes with increasing n_e



Possible interpretation:

For high density plasmas, at fixed heating power the higher the plasma density, the more additional power (from MHD crash) needed to trigger the I $\rightarrow$ H transition, consistent with scaling of H-mode threshold power (Ryter, NF2013, Ma, NF2012).

LCO weaker with higher heating power



- Under the different heating power (P=0.8-2.5 MW), the similar ne (n_e=1.6-1.8x$10^{19}m^{-3}$)
- LCO lasting time reduces with the higher heating power
- Heating power over the threshold, there should be no LCO appearing
- How to evolution of the edge parameters, Te/ne profile in the high heating case?

Summary

- The toroidal symmetry of GAMs and LFZF was identified on HL-2A
- Energy transfer rate increases when heating power increases
- Two types of LCO was observed on HL-2A, J-LCO is different from LFZF
- The pressure gradient induced diamagnetic drift is a dominant contributor to the radial electric field in the I-phase of type-J LCOs-H transitions
- The conditions for the observed I-H transitions are identified
- The rapid rise of edge pressure gradient and E×B shear induced by the mode crash is responsible for the I-H transition
- The additional energy excluded by kink-like mode crash can help to stimulate I-H tarnation

Thanks for your attention