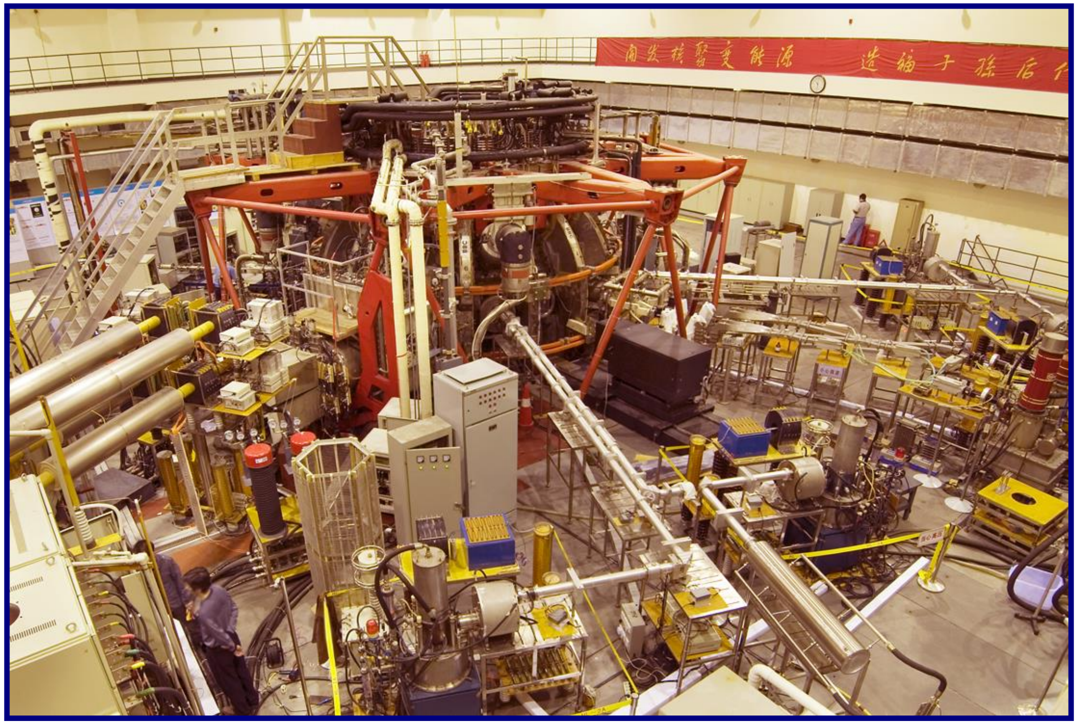
Overview of HL-2A Recent Experiments

X.R. Duan on behalf of HL-2A team & collaborators

Southwestern Institute of Physics, Chengdu, China

In collaboration with
IRFM/CEA, Cadarache, France
CASS & Department of Physics, UCSD,USA
CCFE, Culham Science Centre, UK
NIFS, Japan
Kyushu University, Japan
Harbin Institute of Technology, China
USTC, China

Introduction of HL-2A



- R: 1.65 m
- a: 0.40 m
- B_t: 1.2~2.7 T
- I_p: 150 ~ 480 kA
- n_e: 1.0 ~ 6.0 x 10^{19} m^{-3}
- T_e: 1.5 ~ 5.0 keV
- T_i: 0.5 ~ 2.8 keV

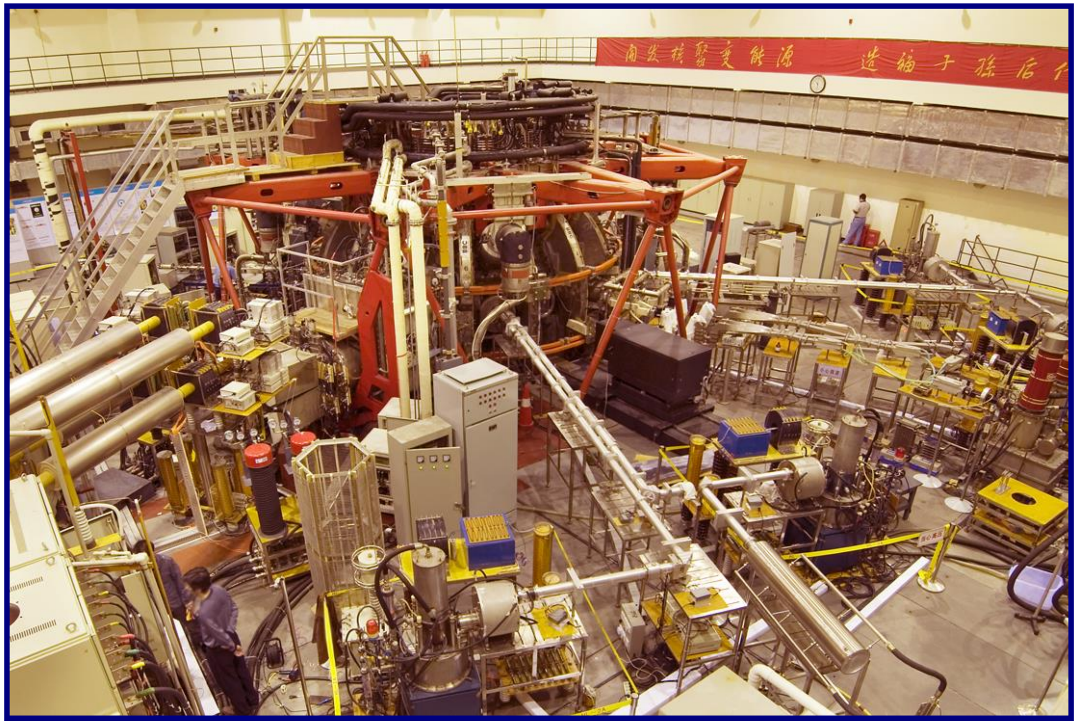
Heating systems:

- ECRH/ECCD: 5 MW
- NBI (tangential): 3 MW
- LHCD: 2 MW (PAM, 3.7 GHz/2 s)

■ Recent objectives of HL-2A

– Optimize plasma control and wall conditioning
– Improve capabilities of auxiliary heating systems
– Develop advanced diagnostics and fuelling techniques
– Investigate ITER-relevant physics

HL-2A Tokamak-present Status



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Newly developed systems since FEC 2014

- LHCD: (H-mode coupling)
- RMP (n=1), ELM mitigation
- Real-time control of NTM

- HCOOH laser interferometer/polarimeter
- ECEI (384-chs., 2.5 μs, 1cm)
- DBS (16-chs. Q-band & Ka-band)
- High frequency magnetic probe (m/n=20/30)
- Wide-angel infrared periscopes

Outline

– **First Exp. in H-mode with PAM LHCD Launcher**

– **H-mode Physics and Pedestal Dynamics**
- Double Critical Gradients of Electromagnetic Turbulence
- Roles of Quasi-coherent Mode in Pedestal Dynamics

– **ELM Mitigation and Control**
- ELM Mitigation with LHCD
- ELM mitigation with SMBI and Impurities

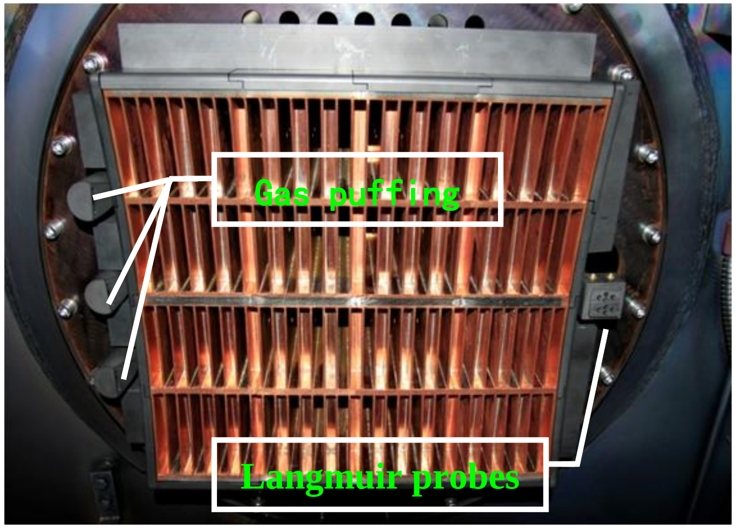
– **Edge Turbulence**
- Synchronization of GAMs and Magnetic Fluctuations
- Zonal Flows Studied by Multi-channel Correlation Doppler Reflectometry

– **Core Plasma Transport**
- Ion Internal Transport Barriers
- Impurity Transport in ECRH Plasmas

– **MHD and Energetic Particle Physics**
- Mitigation of Runaway Current with SMBI
- Real-time Control of Tearing Modes with ECRH
- Alfvenic Ion Temperature Gradient Modes and Internal Kink Modes

– **Summary & outlook**

First Exp. in H-mode with PAM LHCD Launcher



— LH coupling characteristic by PAM antenna studied in H-mode plasma for the first time, low RC obtained in low ne.

— **900kW**/400ms LH power coupled to H-mode plasma

— could give some data support for ITER LH operation

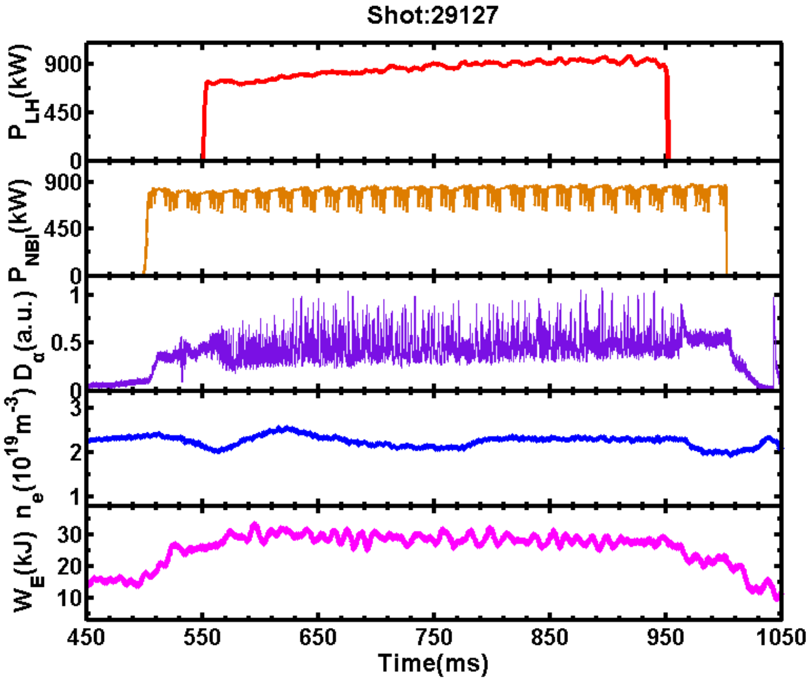
Ekedahl A. FEC 2016 [EX/P7-23]

— **Passive-active multi-junction (PAM)**

Launcher is developed in view of foreseeing a LH system for the second phase of ITER.

— **PAM on HL-2A**

- 4×33, 16 active and 17 passive grills /row
- $N_{||}$=2.75, D=0.66



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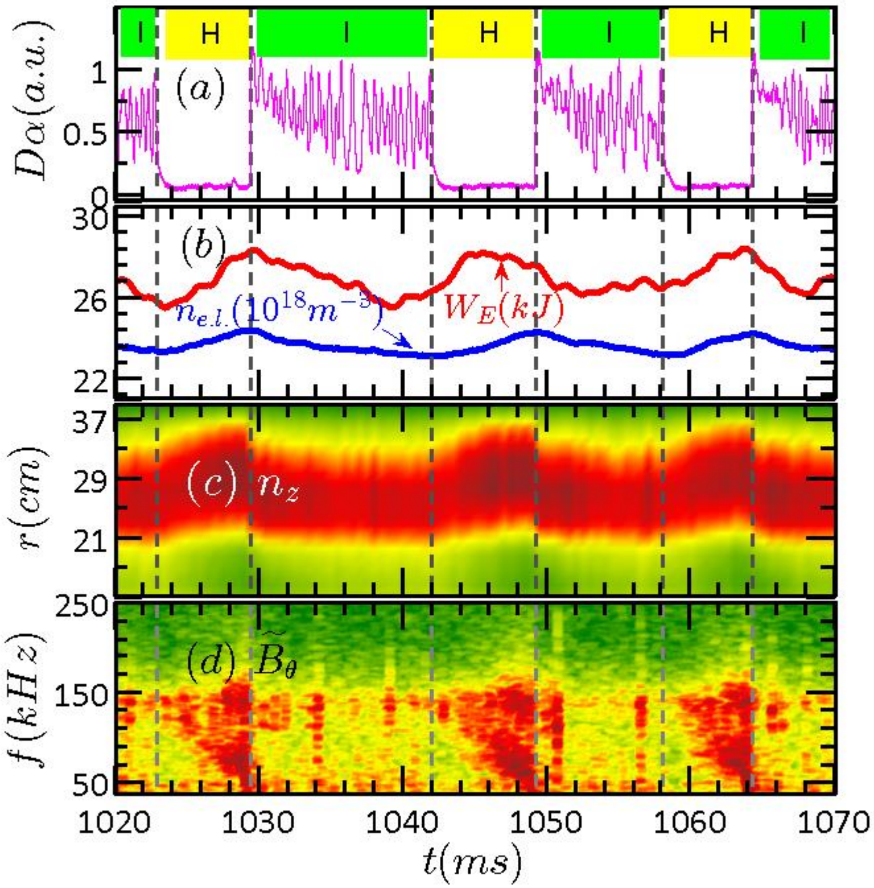
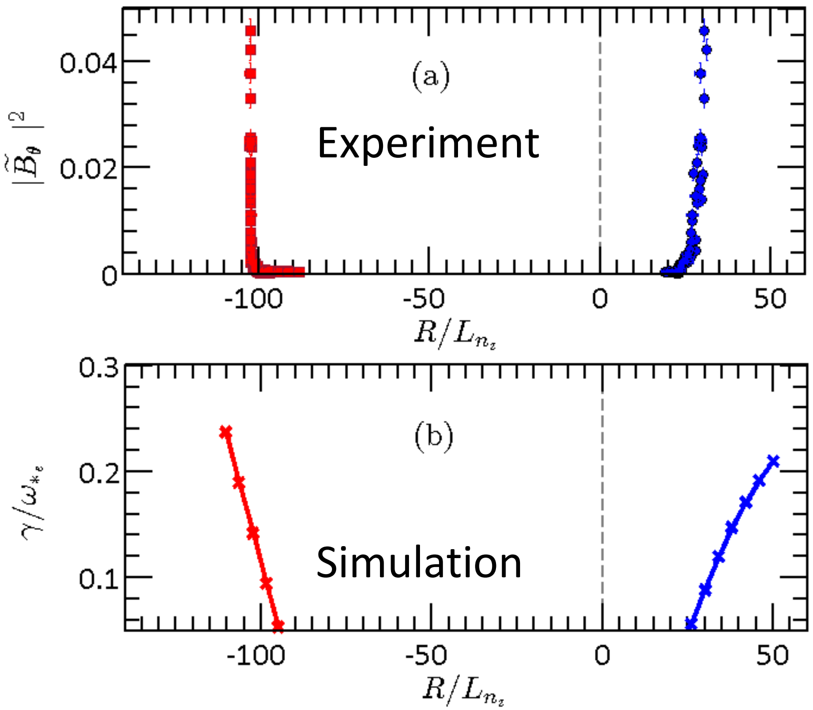
Double Critical Gradients for Triggering EM Turbulence





— Impurity density profile is outwardly peaked

— Electromagnetic turbulence triggered by impurity density gradient

Zhong W.L. PRL 2016
Zhong W.L. EPS 2016 *I5.118*

— Observation of two different critical gradients for trigging the EM turbulence .

— Key role of EM turb. in cyclic H-I transitions.

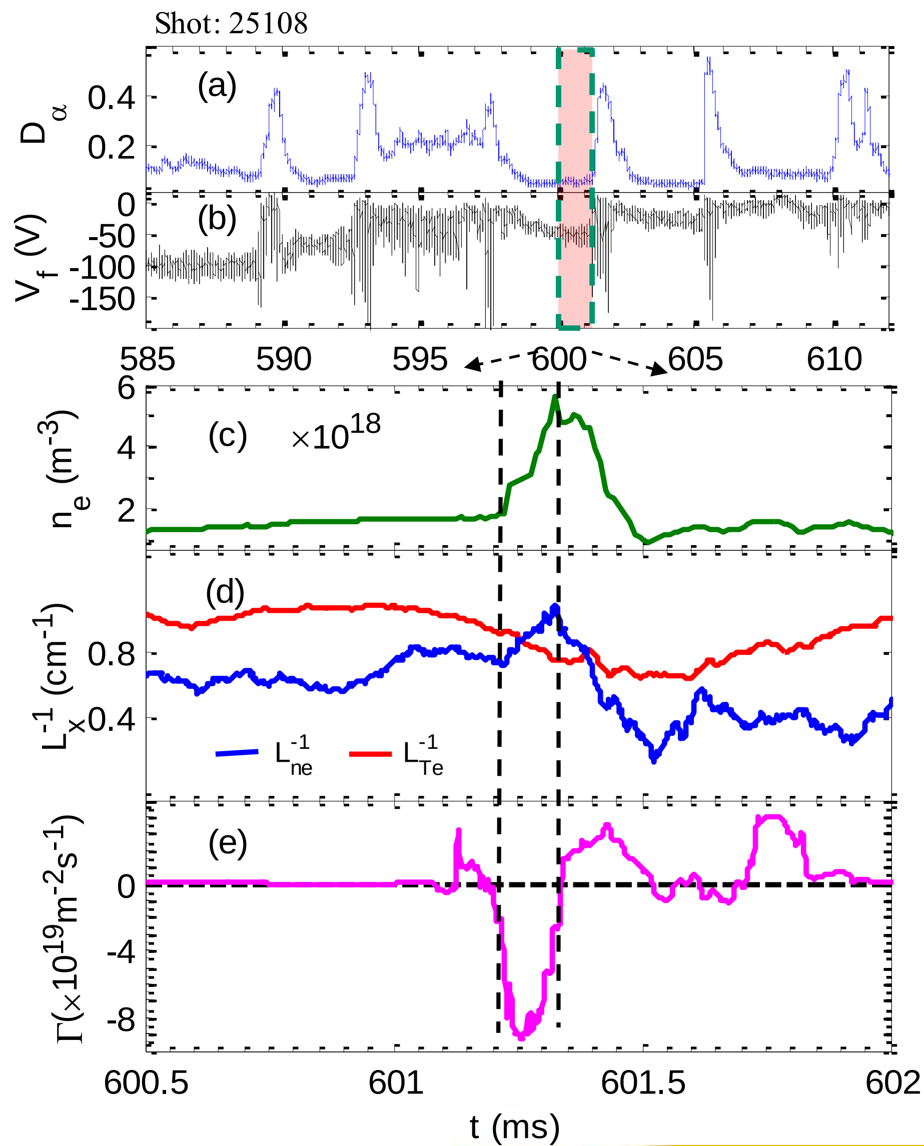
— **Positive gradient**: the mode driven by impurity density gradient.

— **Negative gradient**: the mode driven both by impurity and electron density gradients.

Roles of Quasi-coherent Mode in Pedestal Dynamics

- Dramatic increases of n_e and its gradient , and slight decrease of T_e gradient just prior to each onset of ELMs.
- A quasi-coherent mode (40-60kHz) was found to be responsible.
- The mode grows very rapidly just about 200 microseconds before each ELM .
- The mode induces inward particle flux, and also induces increases of plasma pressure and its gradient.
- The mode may play a key role in triggering of ELM onset.

Dong J.Q. FEC 2016 [EX/P7-24]



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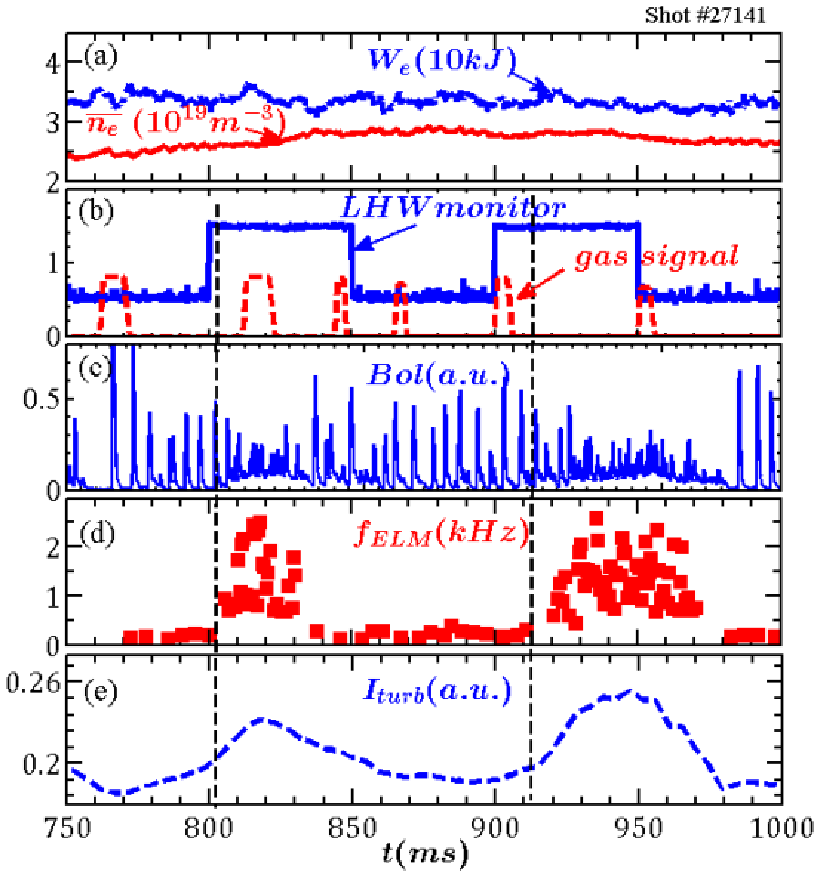
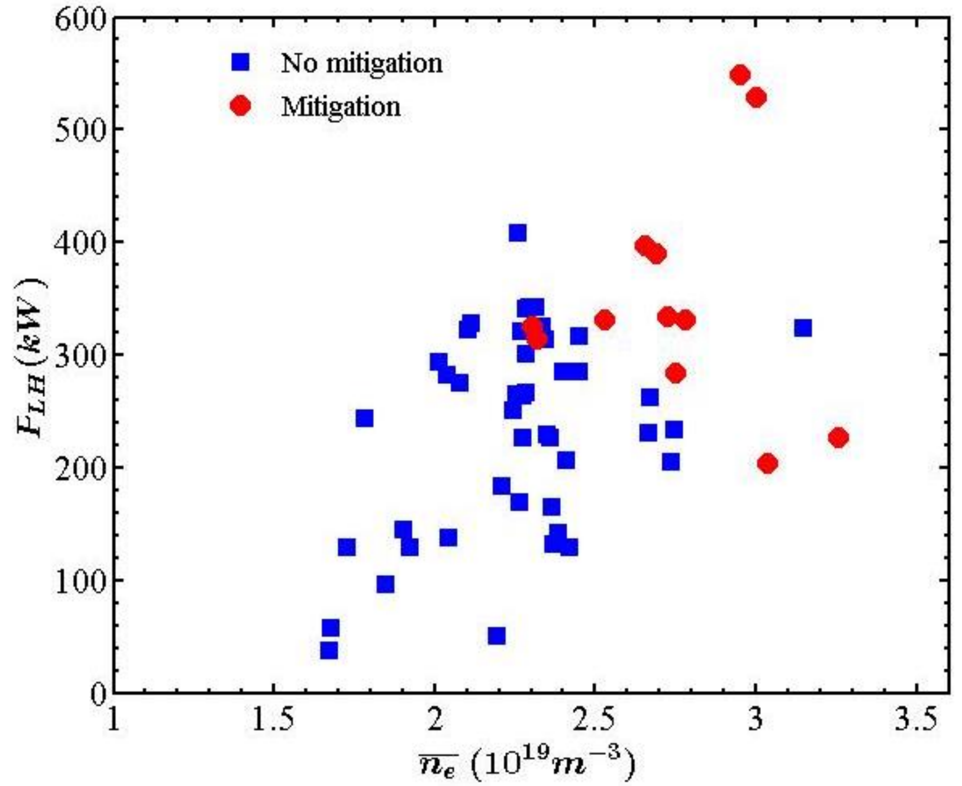
ELM Mitigation with LHCD





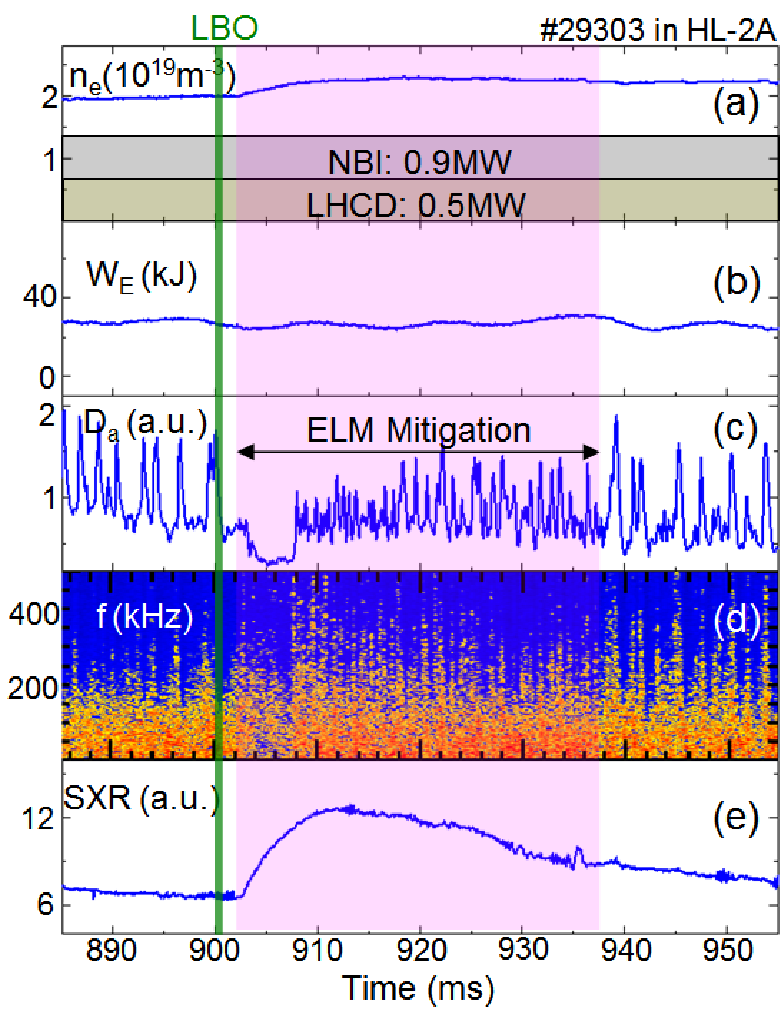
— ELM has been mitigated by using LHCD in HL-2A, divertor heat load reduced.

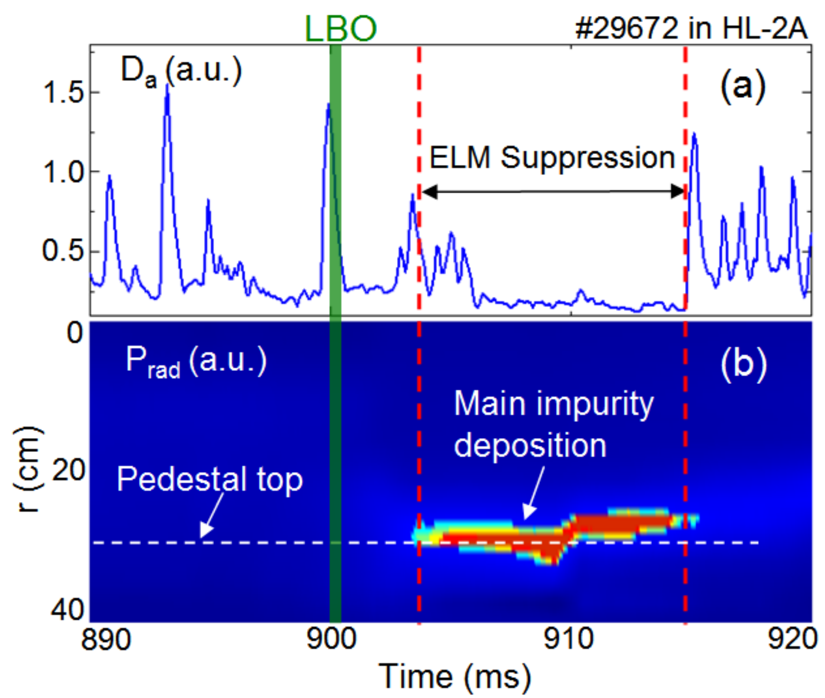
— Enhanced transport by pedestal turbulence might be the direct cause of the mitigation.

— The mitigation effect was very sensitive to the plasma density and the LHW absorbed power.

Xiao G.L. APTWG 2016

ELM Mitigation by Impurities Injection



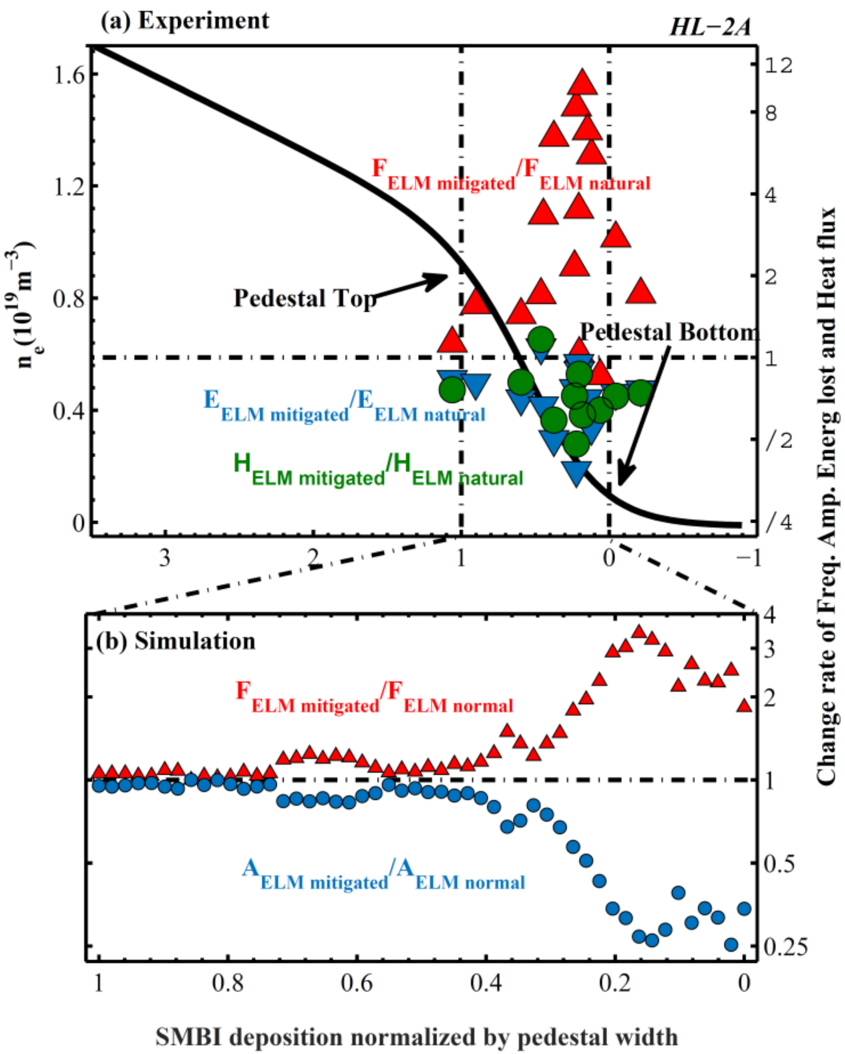


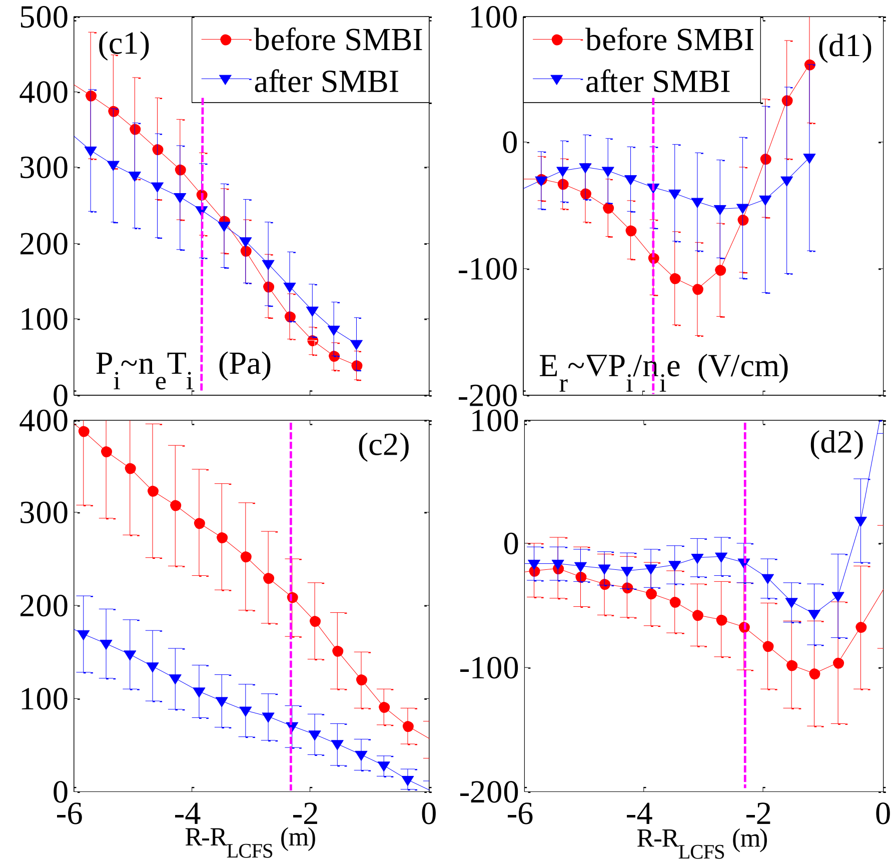
— ELM mitigation by LBO-seeded impurities has been performed recently.

— Impurities mainly deposited in pedestal top.

— Pedestal turbulence was enhanced during mitigation.

ELM Mitigation by SMBI





Shi Z.B. FEC 2016 [EX/P7-22]
Ma Q. NF 2016

— Shallow deposition of SMBI is sufficient for ELM mitigation.

— The shallower Er well may be responsible for the increase of ELM frequency.

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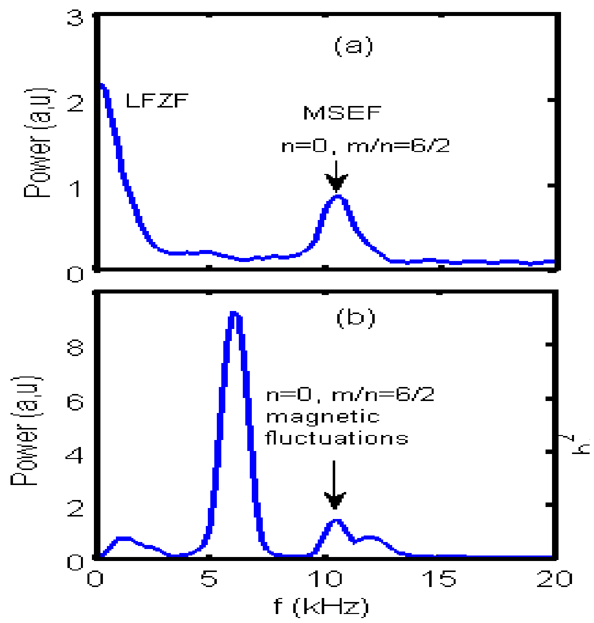
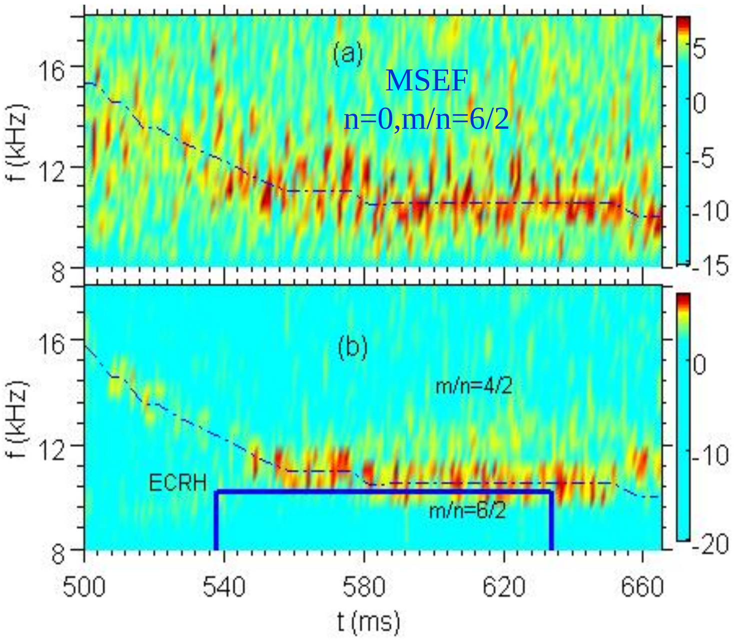
Synchronization of GAMs and Magnetic Fluctuations



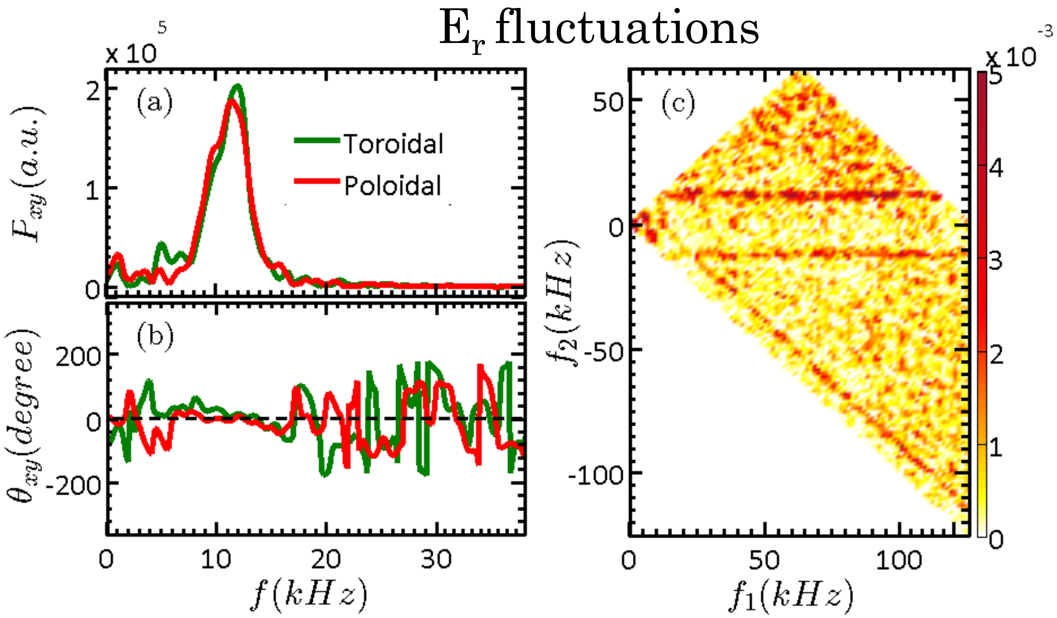


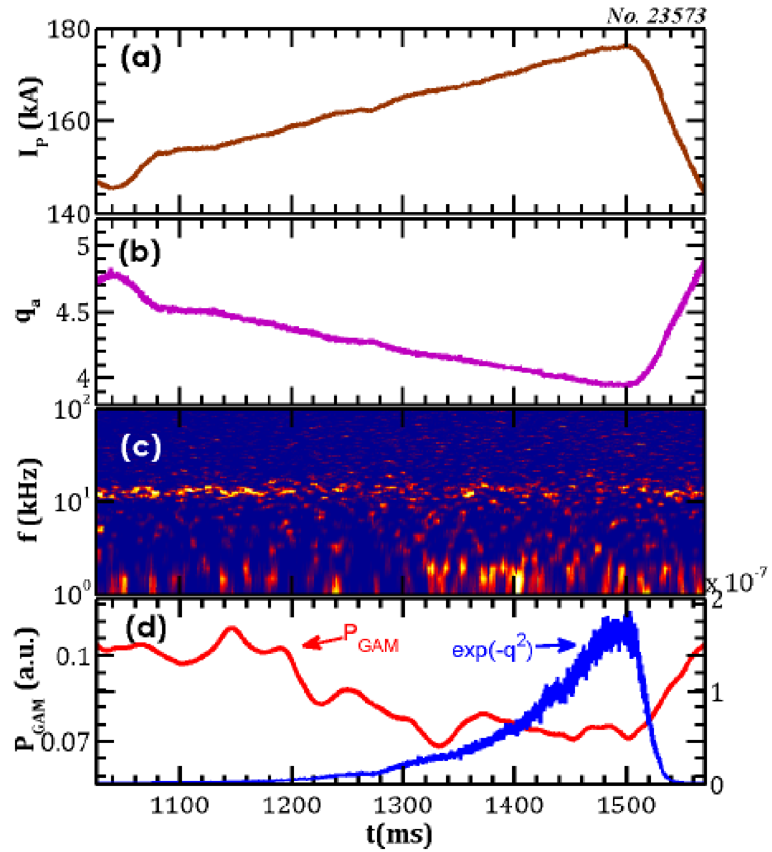
Zhao K.J. PRL 2016, Yan L.W. FEC 2016 [EX/P7-27]

– Zonal flow is synchronous with magnetic island suggests that the zonal flows see the islands, and respond to the island with sensitivity to the phase.

– Discovery of synchronization between GAMs and magnetic islands reveals a new, essential and prototypical process in nonlinear dynamics of high temperature plasmas.

Zonal Flows Studied by Correlation Doppler Reflectometry





Landau damping of GAM

– Novel multi-channel Doppler reflectometers have been developed (16 chs., high flexibility for 3-D measurement).

– For the first time, 3-D spatial structure of GAM and LFZF were measured by correlation Doppler reflectometers.

– The Landau damping and collisional damping of GAM were demonstrated.

Zhong W.L. JINST 2015
Zhong W.L. NF 2015

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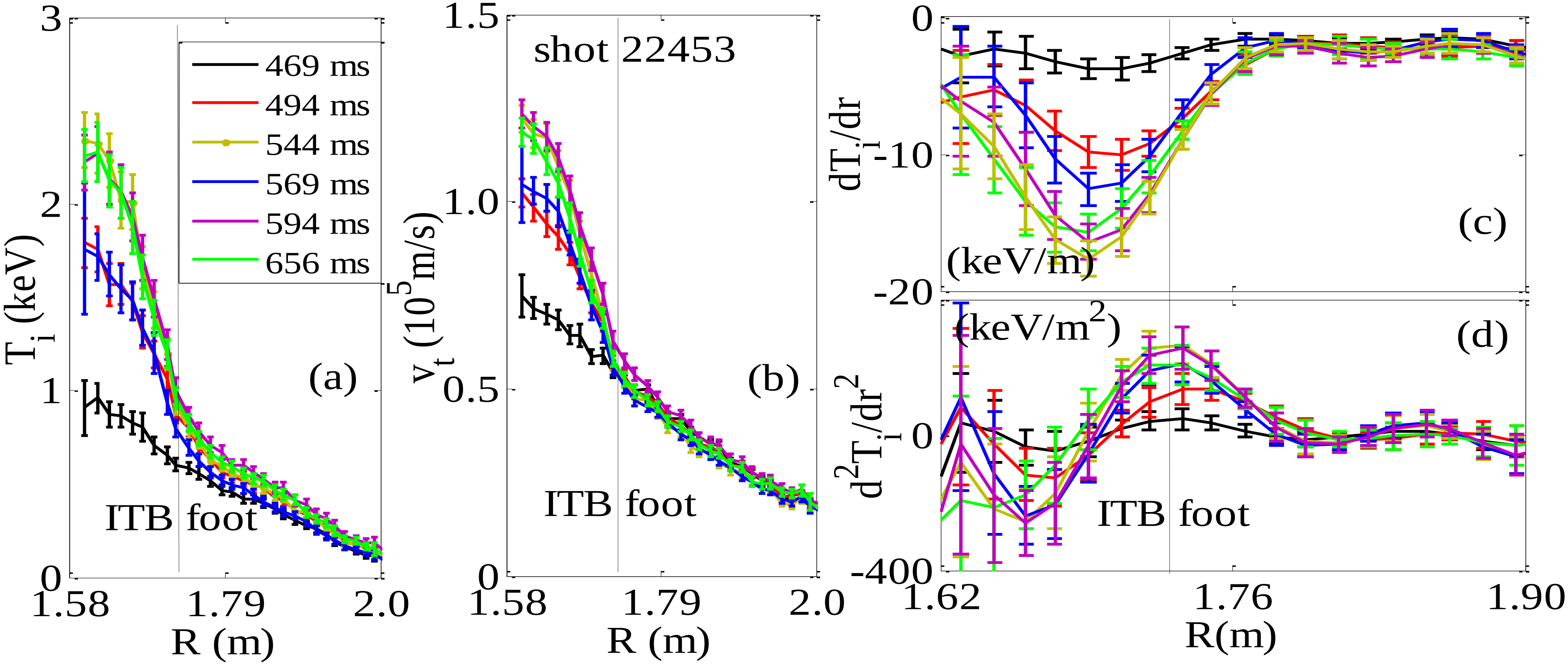
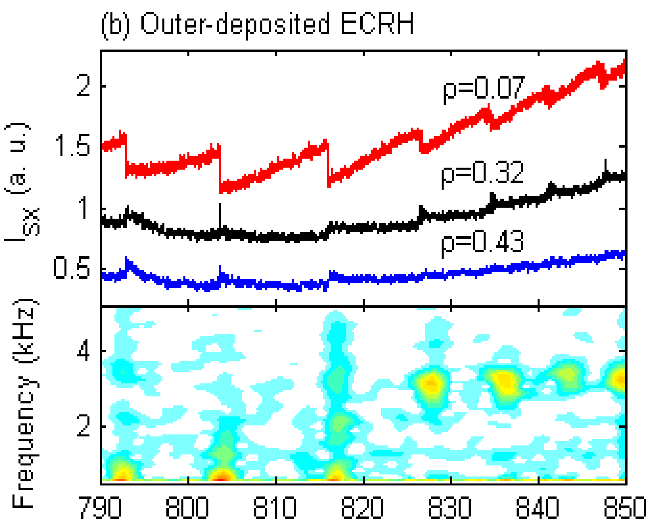
iITB Formation on HL-2A

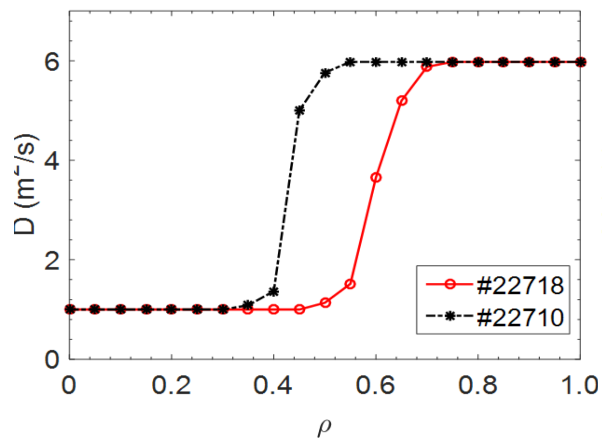


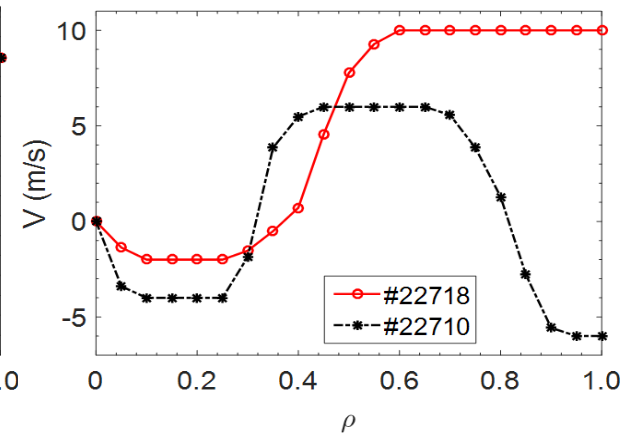
- Ion ITB can be observed at the q=1 surface;
- Criterion for characterizing iITB: maximum R/LTi should be higher than 14.
- ITG is suppressed by the toroidal rotation shear;
- The m/n=1/1 internal kink mode enhances iITB.

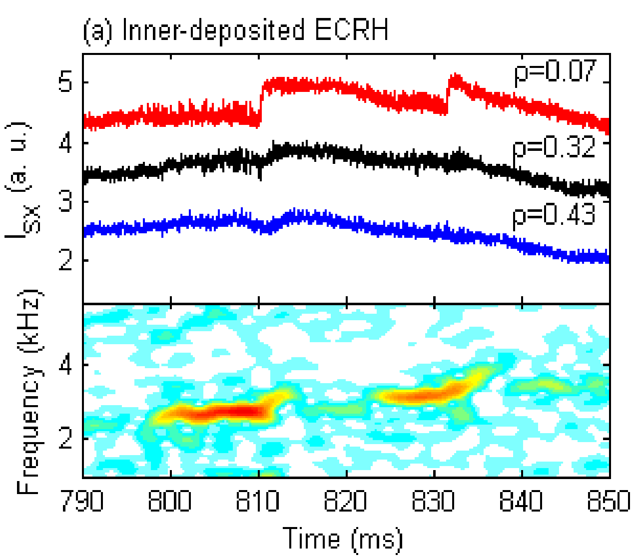
Yu D.L. FEC 2016 [EX/8-2]

Impurity Transport in ECRH Plasma with MHD instability









— Outer-deposited ECRH: normal sawtooth

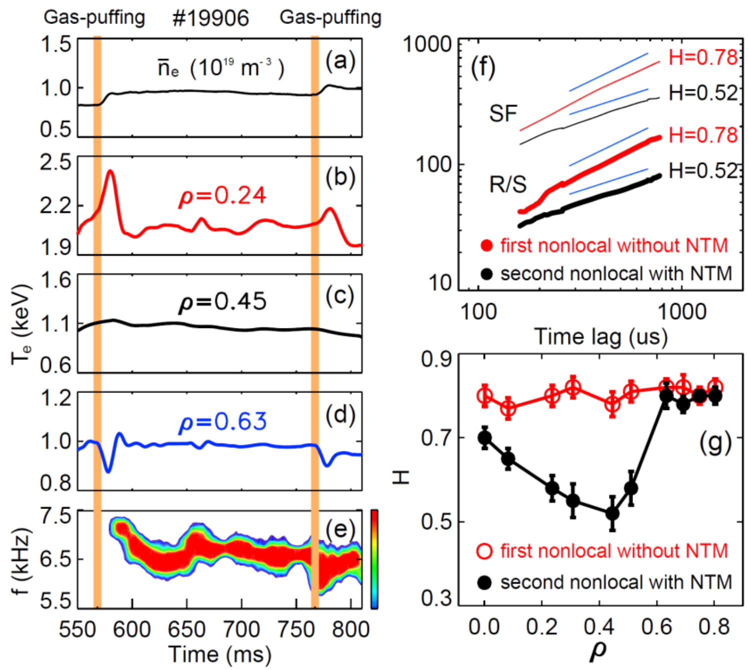
— Inner-deposited ECRH

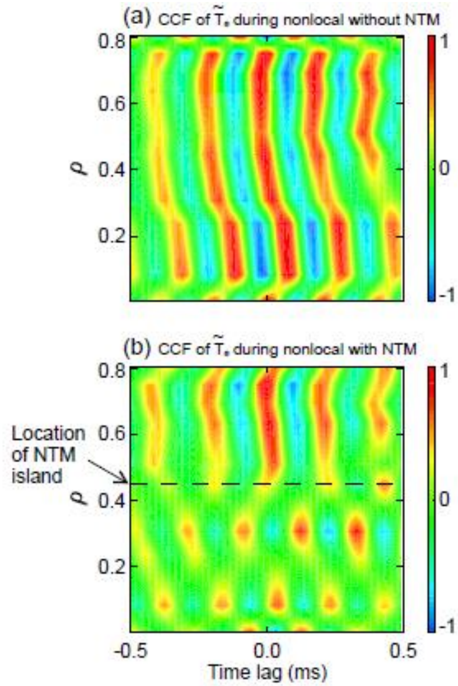
- reduction of impurity concentration;
- reversed sawtooth oscillation;
- diffusion coefficient D and convection velocity V are increased

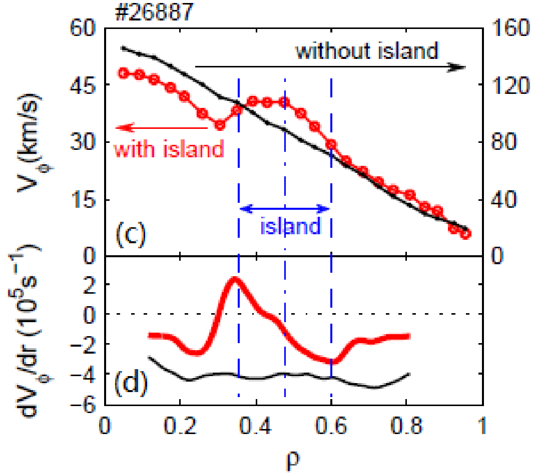
— During the occurrence of the long-lasting m/n=1/1 mode an outward heat flux was observed.

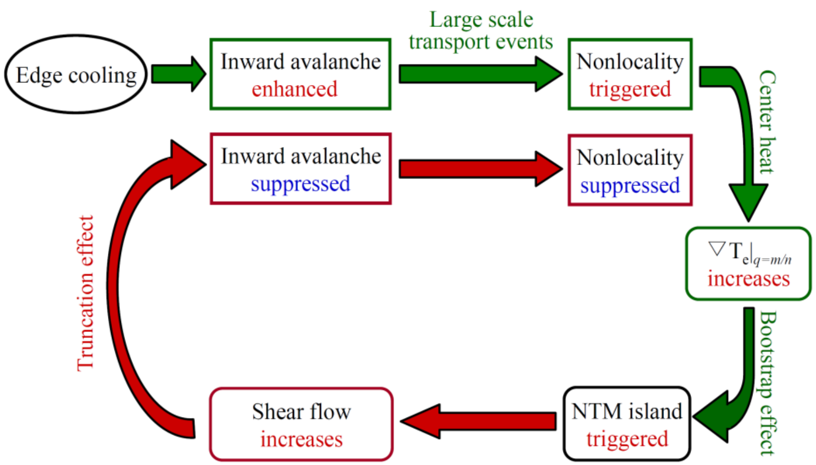
Cui Z.Y. FEC 2016 [EX/P7-21]

Interaction between Turbulence and Large-scale Mode









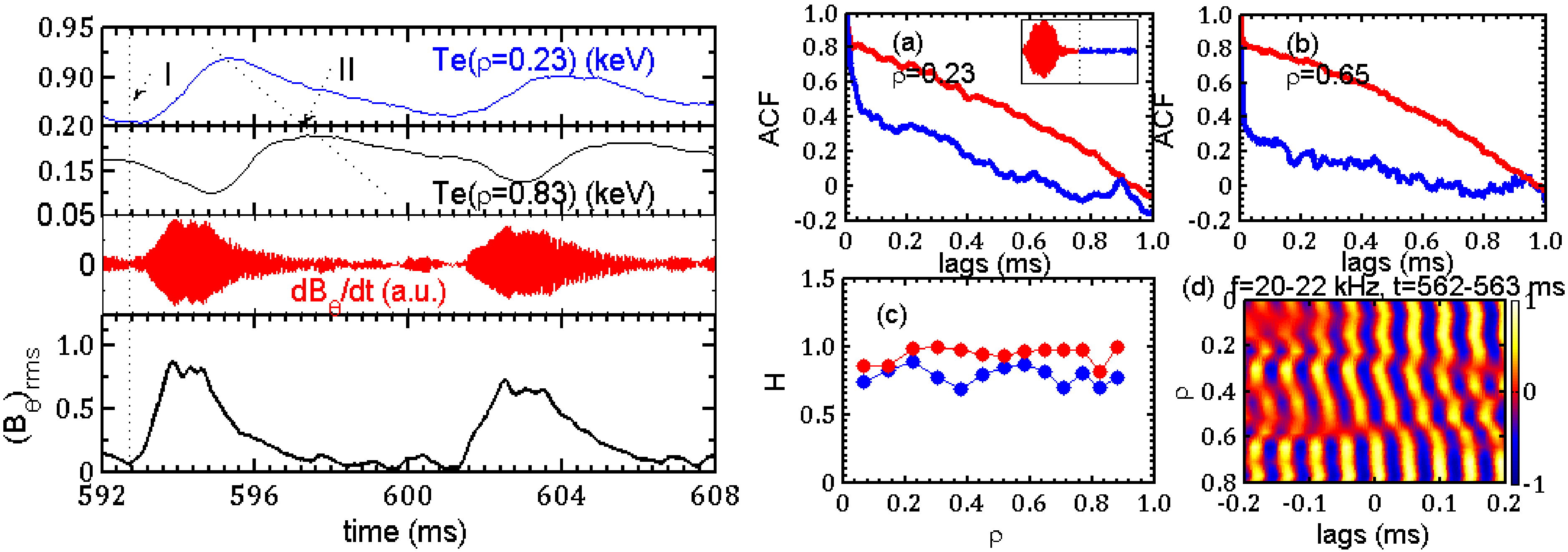
— Enhanced avalanche behavior during non-locality.

— Perturbation of local parameters by non-locaility can trigger NTMs at relatively low β_N.

— Nonlocal avalanche transport event is truncated by flow shearing developed in the magnetic island.

Ji X.Q. Sci. Rep. 2016, Pan O. NF 2015

Non-local Transport Triggered by Fishbone Mode



A new-type non-local transport triggered by a fishbone mode observed on HL-2A.

- The rapid core heating leads to a simultaneous decrease in temperature in the edge.
- I: fast time response, ~50us; II: slow time response, ~3ms.

Auto-correlation function (ACF) coefficients (a-b) of ECE signals at two radial positions and spatial profiles (c) of Hurst exponents (H, obtained by R/S method) from ECE signals.
ACFs and Hurst exponent both enhances during the fishbone and nonlocal transport. And so the new-type nonlocal transport is potentially linked to self-organized critical (SOC) dynamics.

Chen W. NF (Lett.) 2016

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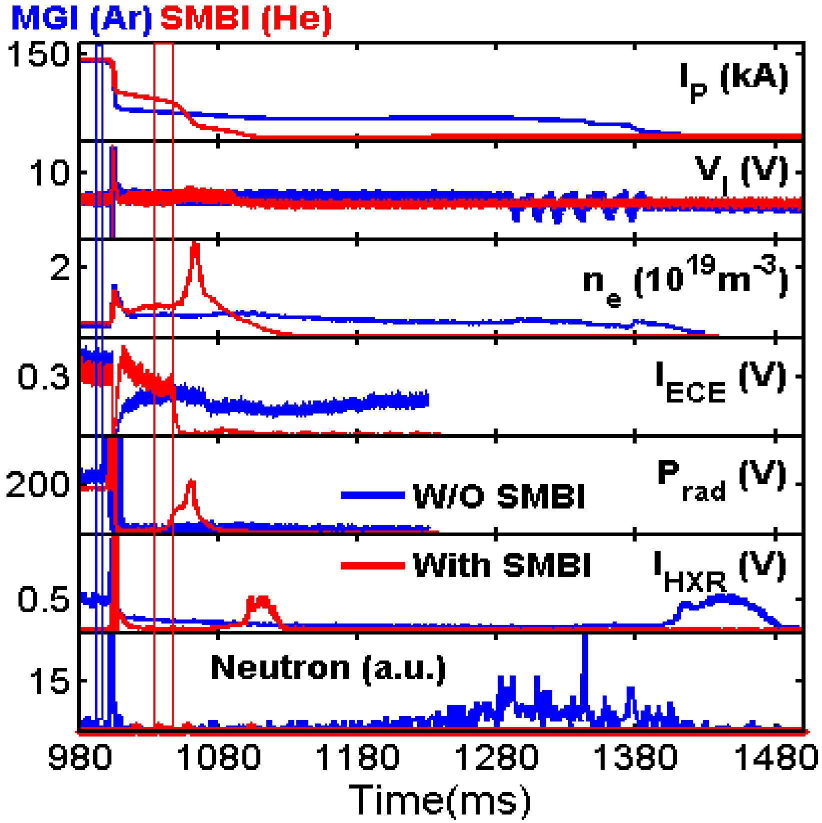
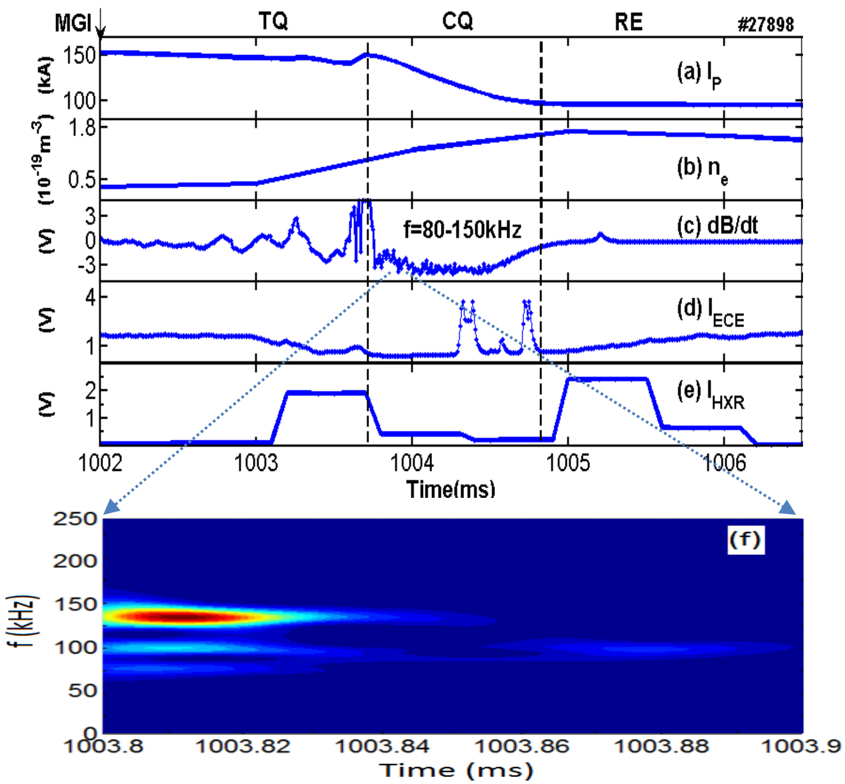
Mitigation of Runaway Current with SMBI

— Runaway current caused by argon injection with MGI was successfully suppressed by SMBI with a number of injected helium atoms of about 1.0×10^{21}

— A toroidal alfvén eignmode (TAE) was observed during the disruption, which plays a favorable role in scattering runaway electrons, and hence, limiting the strength of runaway beam.

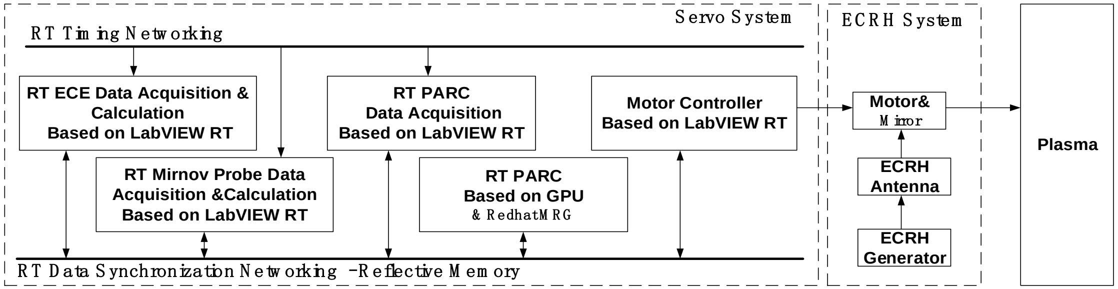


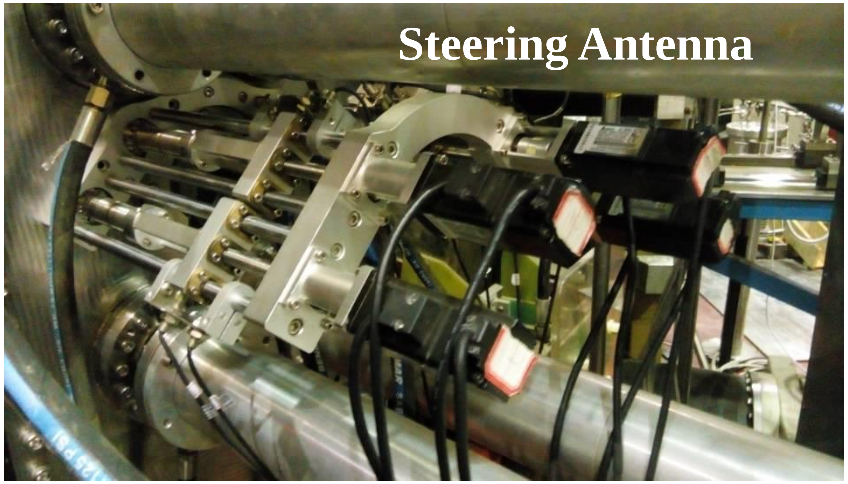


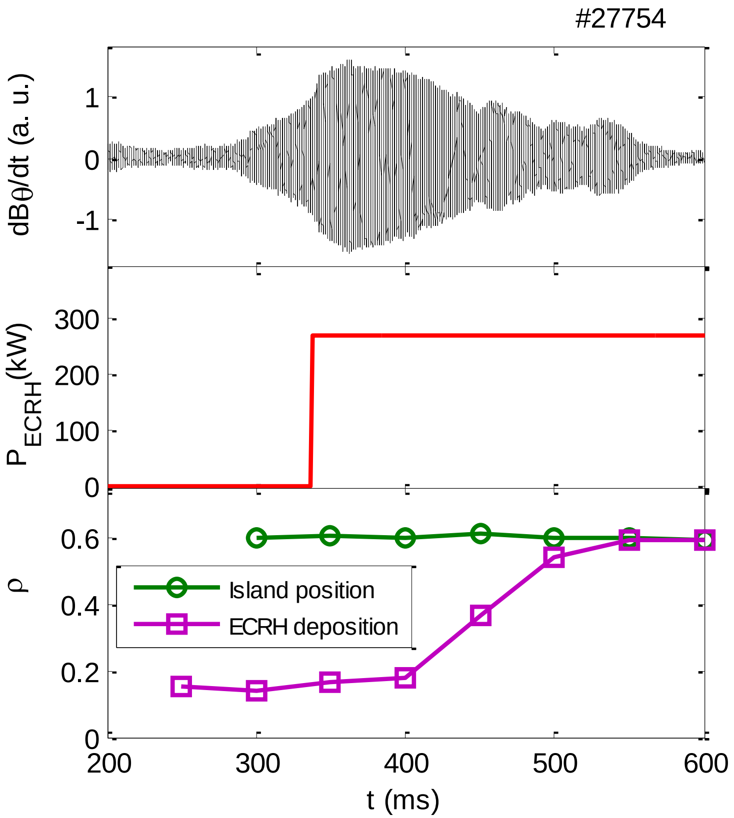
Liu Yi FEC 2016 [EX/9-3]

Real-Time Control of Tearing Modes

Closed loop feedback system for NTM control





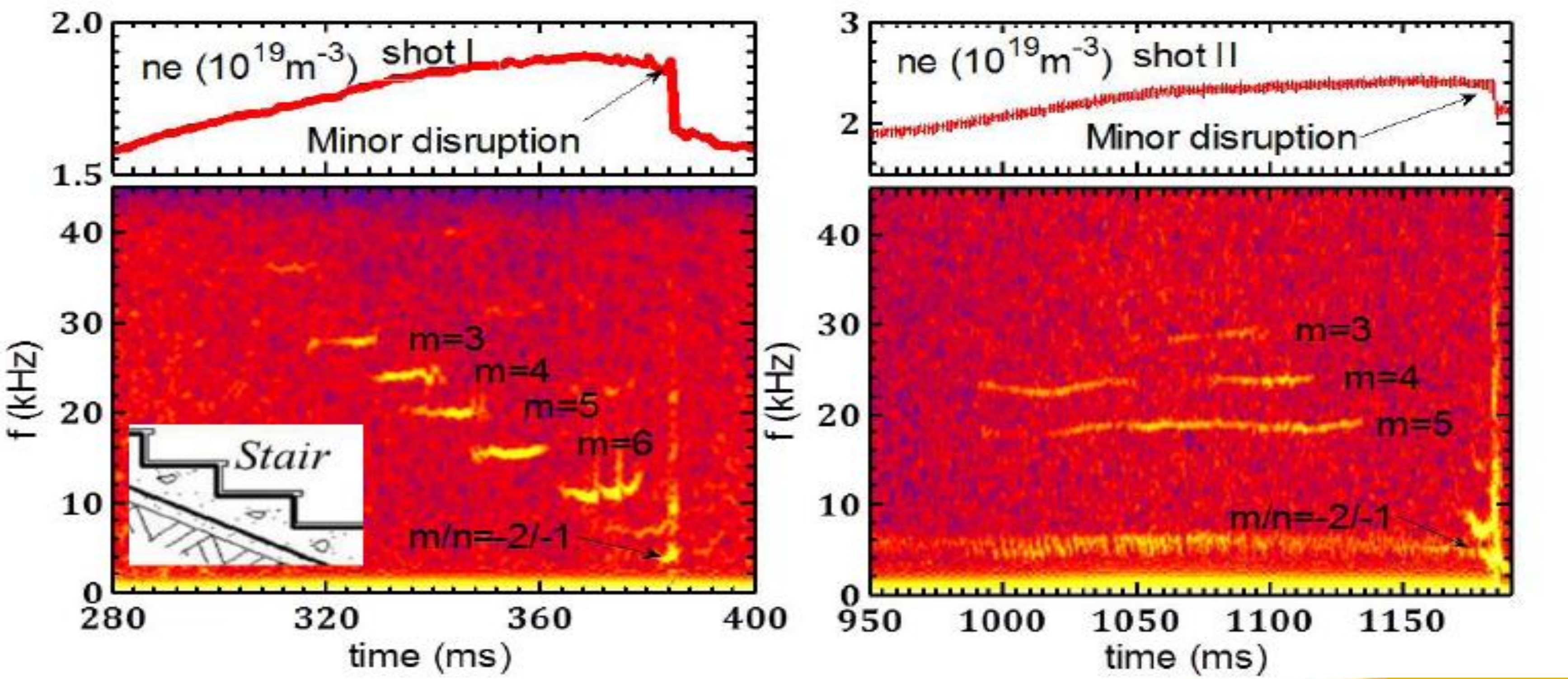


- RT control of NTMs by ECRH with launcher mirror steering was developed.
- An RT code solves equilibrium equation with 129×129 grid scale in 1 ms.
- The magnetic island location has the high spatial resolution less than 1 cm.
- Tearing modes were stabilized with the RT mirror steering.

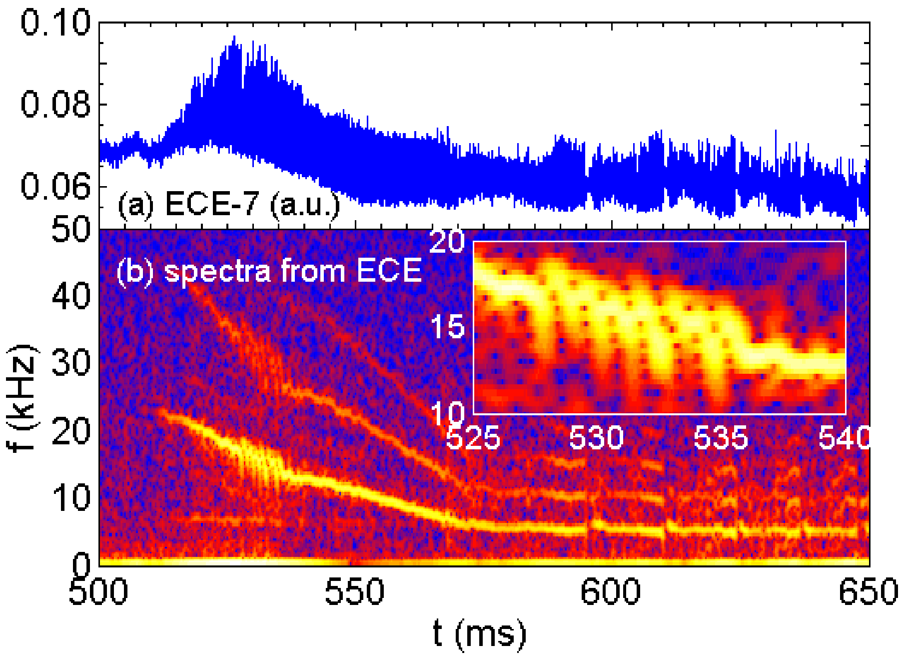
Alfvenic Ion Temperature Gradient (AITG) Mode

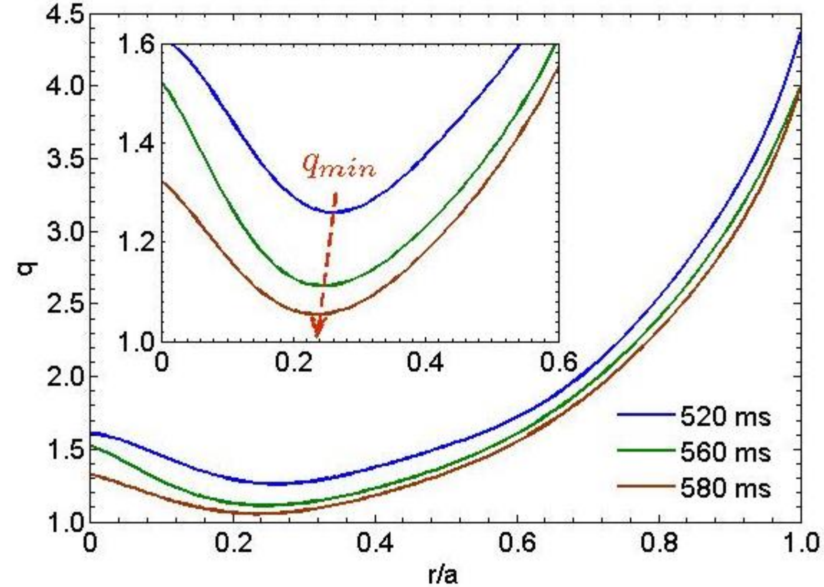
- Appear in the high-density Ohmic plasmas with weak magnetic shear and low pressure gradients; predicted by numerical solutions of the AITG/KBM equation;
- f=15-40 kHz which lies in KBM-AITG-BAE frequency ranges;
- Low mode number m~n=3-6;
- Propagate in the ion diamagnetic drift direction;
- Link to the minor disruption of plasma.

Chen W. FEC 2016 [EX/P7-17]

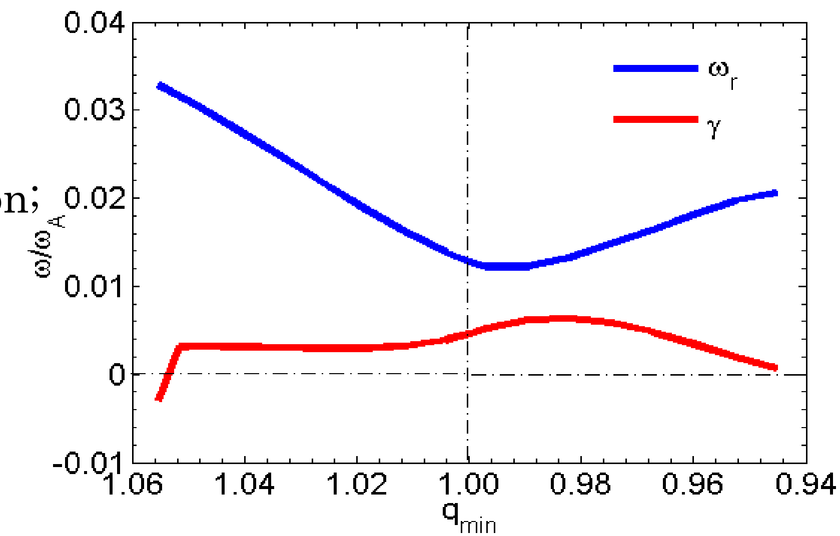


Non-resonant Internal Kink Mode





- NRK excited by energetic electrons is found firstly with ECRH+ECCD$^+$ (ECCD$^+$: I_{ECCD}//-I_P);
- q_{min} is a bit bigger than unity for NRK condition;
- f=20-5kHz, frequency decreasing with q_{min};
- multi-harmonics; Low mode number m=n=1,2,3,…;
- Propagate in the electron diamagnetic drift direction;



Yu L.M. NF 2016, submitted

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Summary

– First experiment in H-mode with PAM LHCD launcher has been performed in HL-2A *[FEC 2016 EX/P7-23].*

– EM turbulence was excited by either edge self-accumulated or externally seeded impurities. Double critical gradients observed and reproduced by theoretical simulation *[PRL 2016, EPS 2016].*

– For the first time, the synchronization of GAMs and magnetic fluctuations was observed in the edge plasmas. The frequency entrainment and phase lock were also elucidated. *[PRL 2016, FEC 2016 EX/P7-27].*

– ELM mitigation and control has achieved by SMBI, impurity seeding, RMP and LHW. *[NF 2016, PoP 2016, FEC 2016 EX/P7-22]*

–The ion internal transport barrier was observed in the NBI heated plasmas. The results suggested the importance of flow shear on ITB sustainment. *[NF 2016, FEC 2016 EX/8-2].*

– The runaway current was successfully suppressed by SMBI. In addition, a TAE-like instability was observed during disruptions deliberately triggered by MGI. *[FEC 2016 EX/9-3].*

Outlook

◆ **HL-2A**

- Heating upgrade: 2MW LHCD, 5MW ECRH, 3MW NBI,
- Diagnostics development: ECEI, MSE, BES, GPI, DBS, CXRS …
- Transport: H-mode physics, impurity transport, momentum transport
- MHD instability (RWM, NTM), NTM & saw tooth control by ECRH;
- 3D effects: on ELM control, plasma flow, ZF and turbulence, L-H transition threshold, plasma displacement;
- Energetic particles: EP driven mode identification, EP loss and control of EP induced instabilities.

◆ **HL-2M (upgrade of HL-2A)**

- Parameters: R=1.78m, a=0.65m, Bt=2.2T, Ip=2.5MA, Heating~ 25MW, triangularity=0.5, elongation=1.8-2.0
- Mission: advanced divertor (snowflake, tripod), PWI at high heat flux, high performance, high beta, and high bootstrap current plasma.

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