Overview of HL-2A Recent Experiments

Min Xu on behalf of HL-2A team & collaborators

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University of Wisconsin – Madison, Wisconsin, USA
CCFE, Culham Science Centre, UK
NIFS, Japan
PPPL, USA
MIT, USA
Kyushu University, Kyoto University, Japan
ASIPP, China
USTC, HUST, Dalian UT, Beijing U, Tsinghua U, HIT, Sichuan U, China

Outline

- ❑ Present status of the HL-2A Tokamak
- ❑ Progress of physics study in H-mode plasma
  - Techniques and physics of ELM control
  - Pedestal dynamics & L-H transitions
  - ITB in H-mode plasma
- ❑ Energetic particle physics and modulation of turbulence by MHD
  - Control of fishbone by ECRH
  - Fishbone-like mode destabilized by fast ions
  - Interaction between TM and turbulence
- ❑ Summary & Outlook

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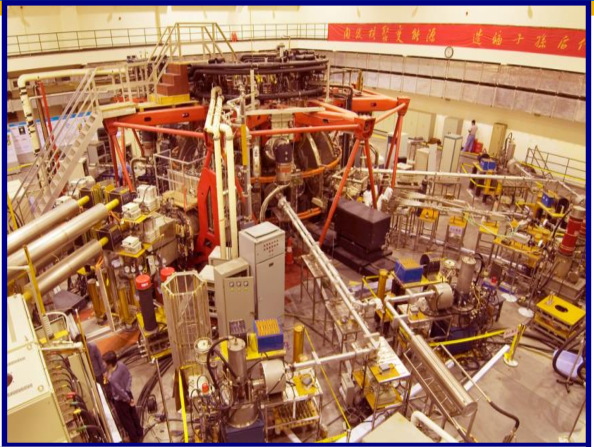
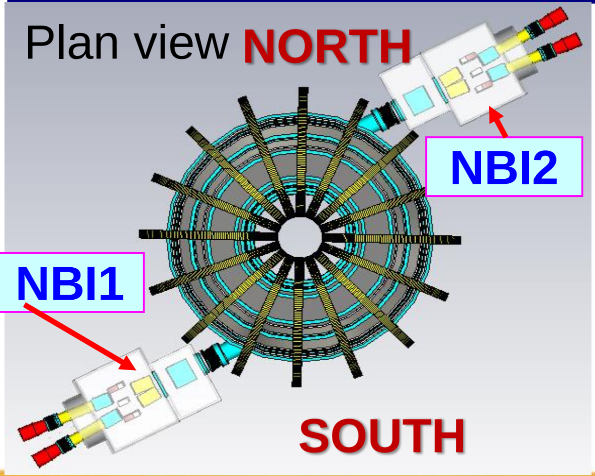
Present Status of HL-2A Tokamak





- *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 ~ 3.5 keV

Heating systems:

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

Newly developed diagnostics

- Beam Emission Spectroscopy (BES)
- Phase Contrast Imaging (PCI)
- He Gas-Puss-Imaging (He-GPI)
- Coherence Imaging Spectroscopy (CIS)
- CO2 laser collective Thomson scattering system

Mission of the HL-2A

Mission: key physics for advanced tokamaks (e.g. ITER)

- **Present stage:**
  - H-mode physics: L-H transition, edge turbulence & transport
  - MHD control: ELM, EPM, Disruption control
- **Next plan:**
  - real time control of MHD (NTM, Disruption,…)
  - development of advanced ELM control techniques
  - multi-scale physics

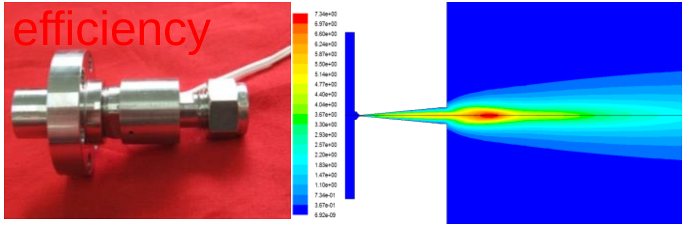
Current operation regime

- High beta： $\beta_N \geq 2.5, \beta_p \sim 2.0$
- Good confinement: $H_{98} \sim 1.2$
- Bootstrap current fraction: >30%
- Full non-inductive operation: $V_{loop} \sim 0$

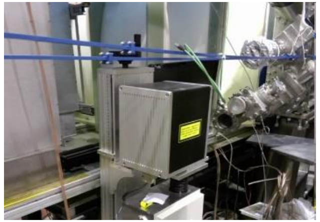
Fuelling and MHD Control Systems

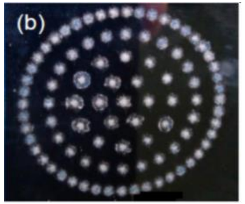
- Supersonic molecular beam injection (SMBI):
  - new skimmer, 1kHz,Max throughput :10^{22}
  - H_2,D_2, He,Ar…,with pressure: 0.1-5 MPa
- Laser blow-off (LBO):
  - Al, Fe, Ti, W,…
  - multi-pulses frequency: 30 Hz
- Shattered pellet injection(SPI)：
  - diameter: 3.5 mm, length: ~4.5 mm
  - Velocity: 0.2 to 0.5 km/s
- Pellet injection:
  - diameter: 1-1.2 mm; 0.1-0.5 km/s
- Gas Puffing: ~0.18 MPa
- Massive gas injection (MGI): max throughput :10^{23}

SMBI injector with higher fueling efficiency

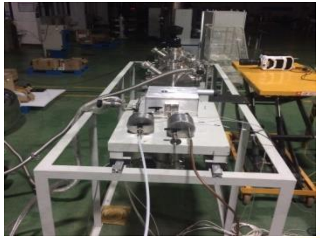


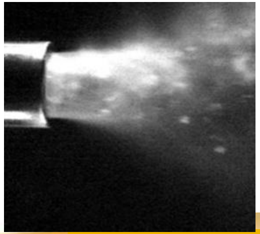
LBO system





SPI system





Main diagnostics on the HL-2A

◆ Diagnostics for transport study

- **T_e profile:** Thomson Scattering, ECE
- **T_i profile:** CXRS, CP-NPA
- **n_e profile:** Thomson Scattering, Interferometer, Reflectometer
- **rotation :** CXRS, Doppler reflectometer, Probe array
- **q profile:** MSE, Polarimeter

◆ Diagnostics for plasma fluctuations

- $\tilde{\mathbf{n}}_e$: Interferometers, Doppler reflectometers, Reflectometer, BES
- $\tilde{\mathbf{T}}_e$: ECE, ECEI, Soft-x-array, Electrostatic probe
- $\tilde{B}$: Mirnov coils

◆ Diagnostics for fast ions

- **Fast ion distribution:** FIDA, CP-NPA ,CXRS
- **Fast ion loss:** Fast ion loss probe, Fission chamber, neutron rate

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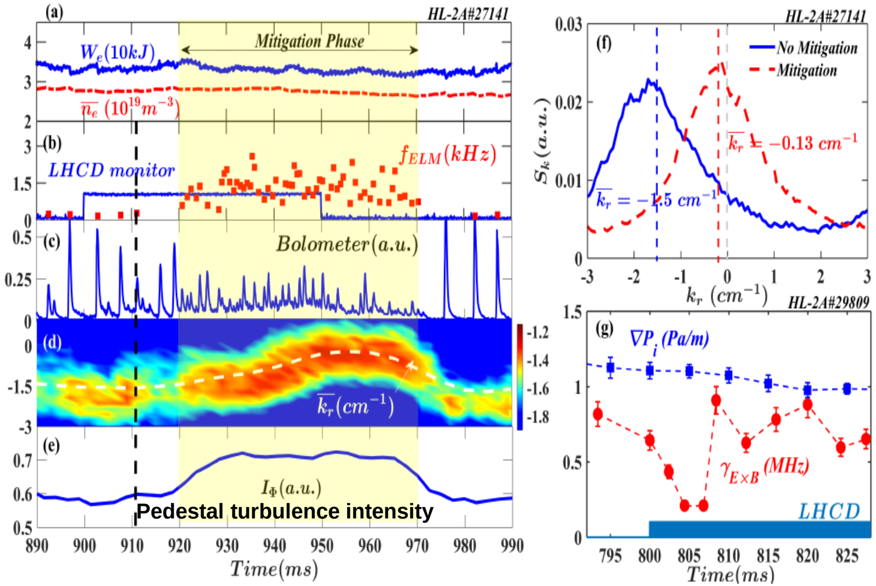
ELM Mitigation by LHCD

Mechanism: LHCD → ExB shear decrease → k_r shift → $\tilde{n}_e$ increase → ELM mitigation

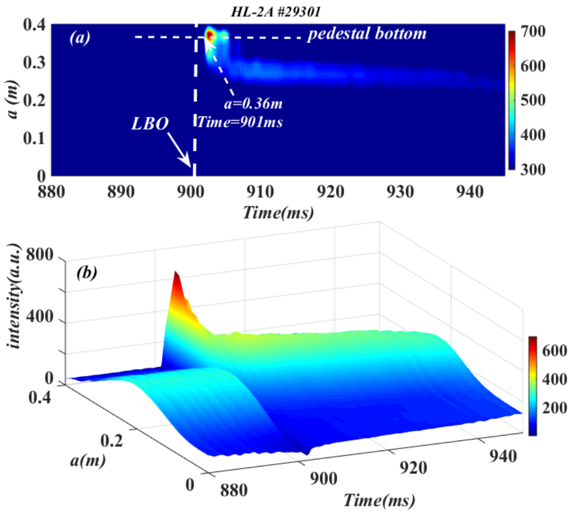


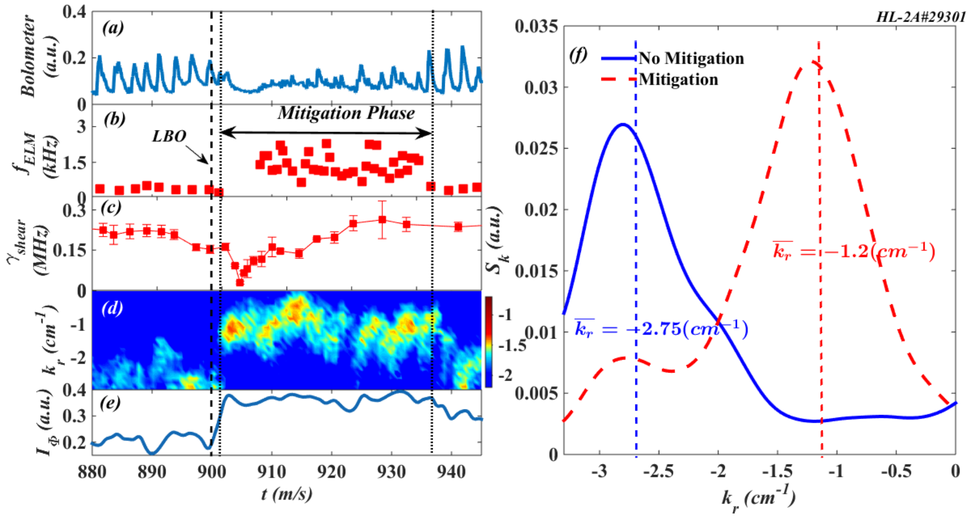
Xiao(SWIP), Zou(CEA), et al., EX/7-4

- ELM mitigation with LHCD and significantly reduction of the divertor heat load.
- A plausible mechanism : LHCD → Edge velocity shear decrease → Turbulence radial spectral shift → Turbulence amplitude → ELM mitigation

ELM Mitigation by LBO Fe impurity seeding

- ☐ **E×B Velocity shear**: severe reduction after LBO.
- ☐ **Pedestal turbulence**: Intensity enhanced. radial wavenumber spectral shift.
- ☐ **ELM Mitigation**



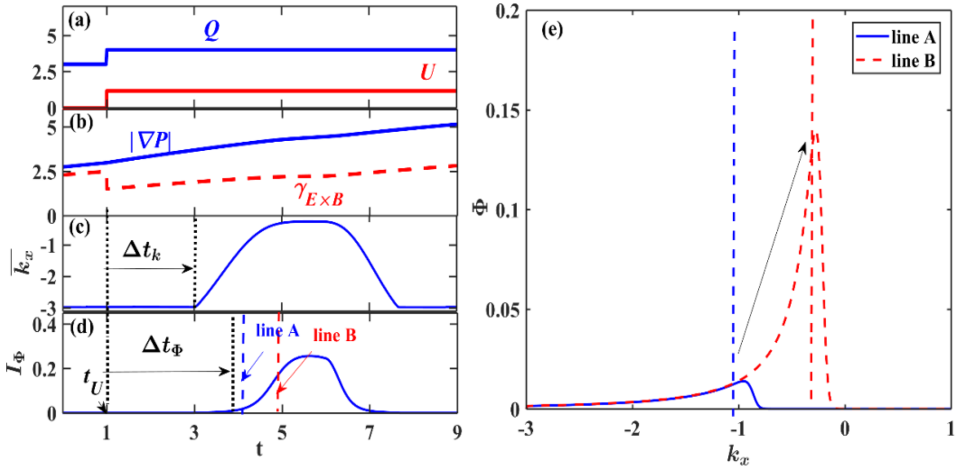


Xiao(SWIP), Zou(CEA), et al., EX/7-4

Mechanism of ELM Mitigation by LHCD/LBO

Theoretical results confirm enhancement of turbulence by shift of radial wavenumber

Theoretical results



Q: heat source
U: reduction value of ExB shear
$\overline{k_x}$:Averaged radial wavenumber
$I_{\boldsymbol{\phi}}$:Turbulence intensity

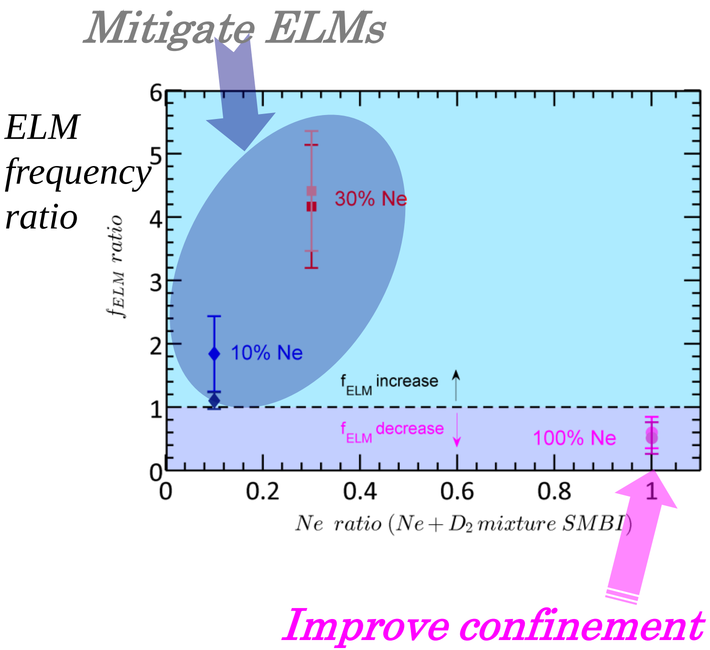
- Theory model predicts the turbulence enhancement by shift of radial wavenumber
- LHCD/LBO ➡ ExB shear decrease ➡ k_r shift ➡ $\tilde{\boldsymbol{n}}_{\boldsymbol{e}}$ increase ➡ ELM mitigation

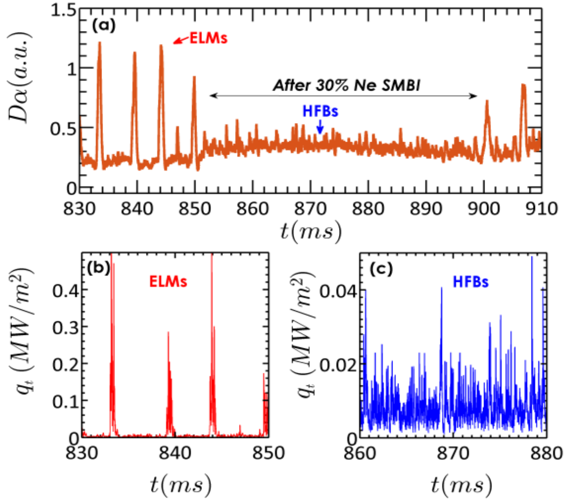
Xiao(SWIP), Zou(CEA), et al., EX/7-4

ELM mitigation with D_2+Ne SMBI

D_2 +Ne(30%) SMBI strongly mitigates ELMs

Zhong et al., EX/P5-3



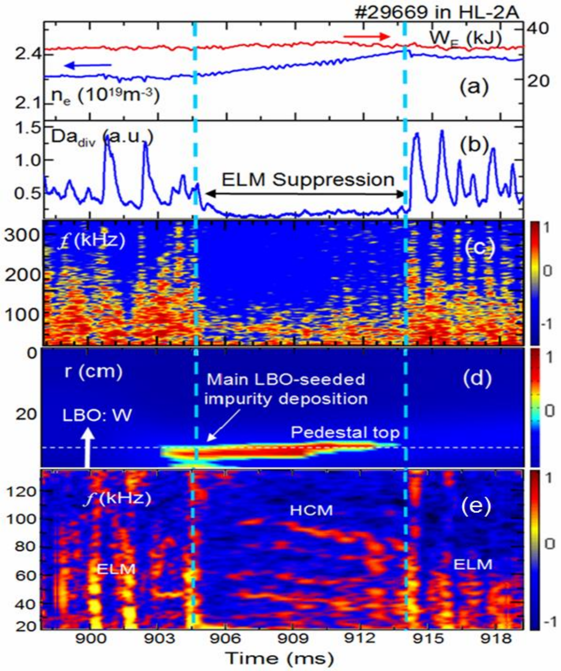


Divertor heat flux near the striking point

- Mixture SMBI mitigates ELMs & significantly reduce divertor heat flux
- Impurity ions and change of pedestal profiles lead to ELMs mitigation

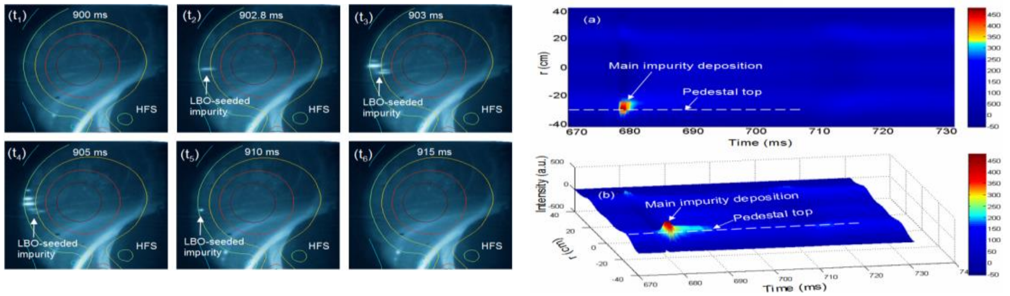
ELM control by LBO W impurity seeding

A new ELM suppression technique: LBO-seeded impurity



ELM suppressed by LBO-seeded impurity

Zhang, Mazon, et al., NF (2018)

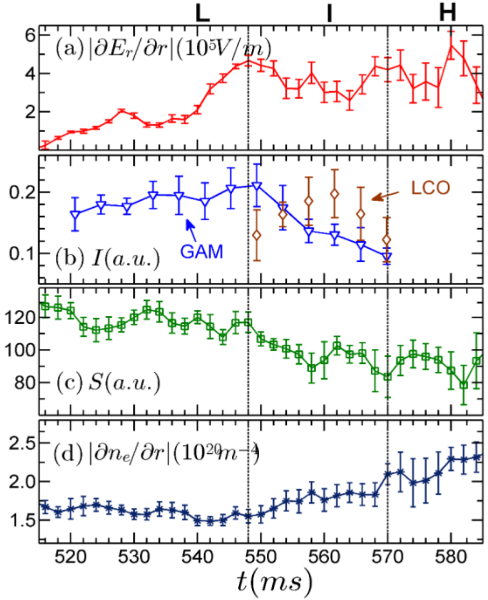


LBO-seeded impurity measured by camera and bolometer

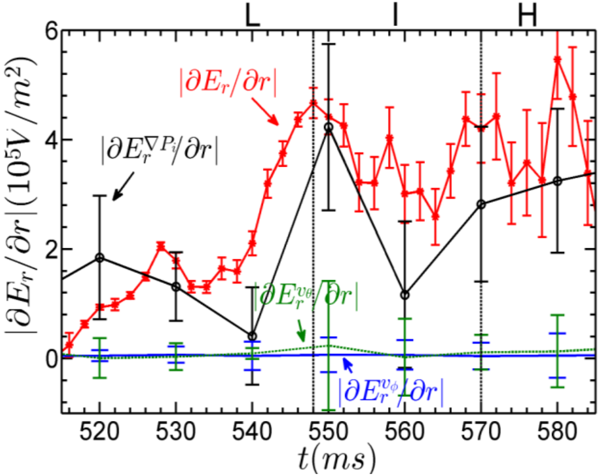
- ELM suppressed by LBO seeded impurity (W)
- In suppression phase, a new mode (Harmonic Coherent Mode, HCM) was found.

Interaction between plasma flows and turbulence

Pressure gradient → E×B flow shear increase → L-I&I-H transition



$$\frac{\partial E_r}{\partial r} = \frac{\partial E_r^{\nabla P_i}}{\partial r} - \frac{\partial E_r^{v_{\theta i}}}{\partial r} + \frac{\partial E_r^{v_{\phi i}}}{\partial r}$$

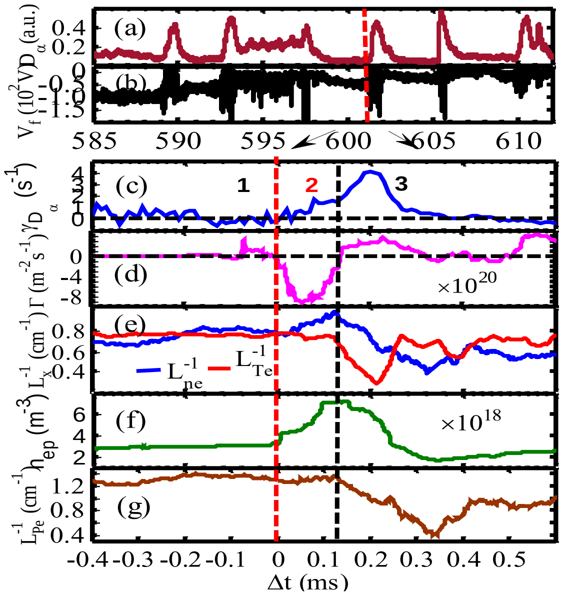


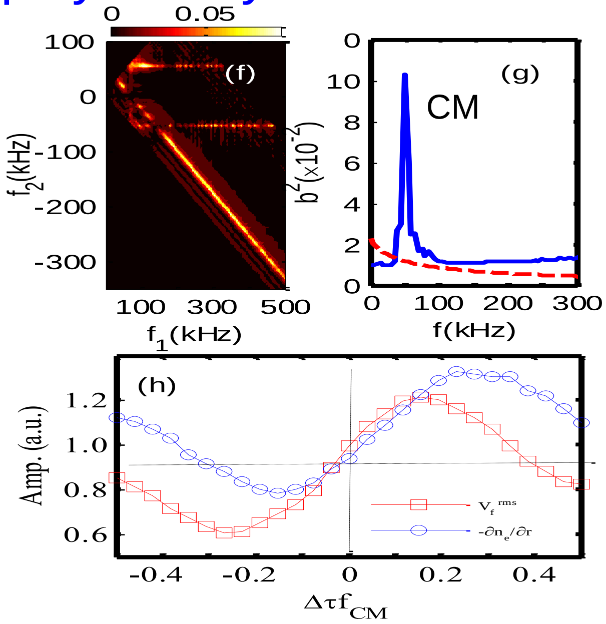
Liang et al., PoP 2017

- GAM facilitates the L-I transition with energy transfer from GAM to LCO.
- Increased mean E×B flow shear promotes the L-I and I-H transitions .
- The increment of $|\partial E_r/\partial r|$ comes from the ion diamagnetic component $\left|\partial E_r^{\nabla P_i}/\partial r\right|$

Nonlinear coupling in pedestal turbulence

Coherent mode (f=30-70 kHz, EM) plays a key role in inward particle flux



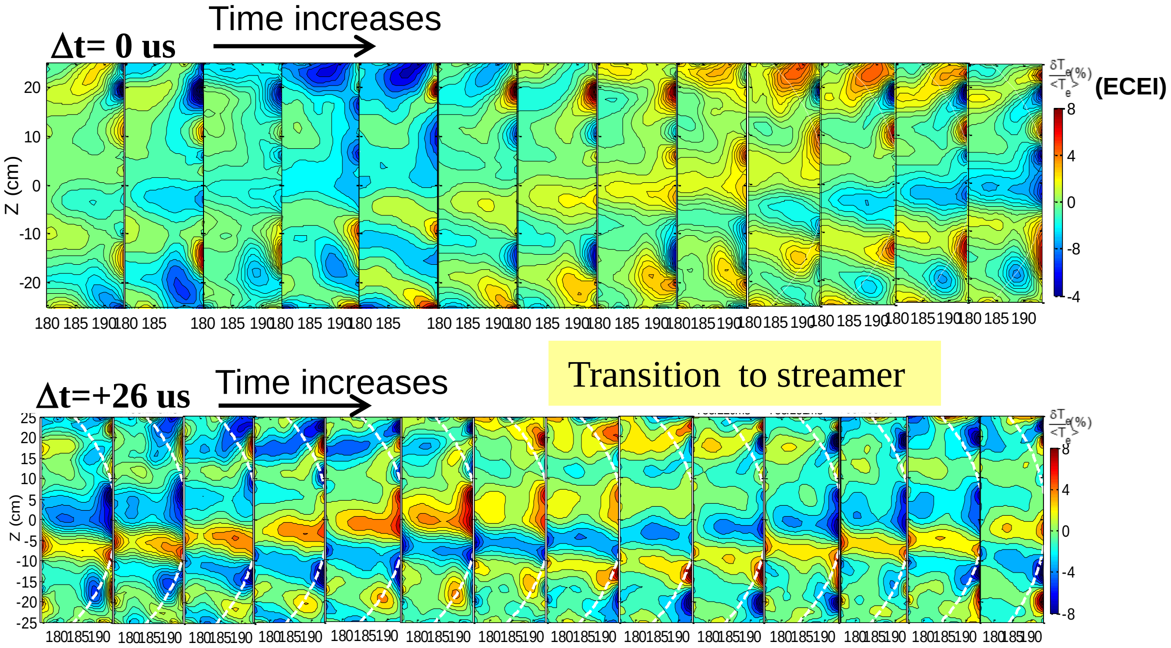


- CM: f=30-70 kHz, m=20-24,localized in pedestal (2~3cm)
- Inward particle flux induced by the coherent mode
- CM generation mechanism: nonlinear coupling of small scale turbulence

Cheng et al., AAPPS-DPP, 2017

First observation of streamer in H mode

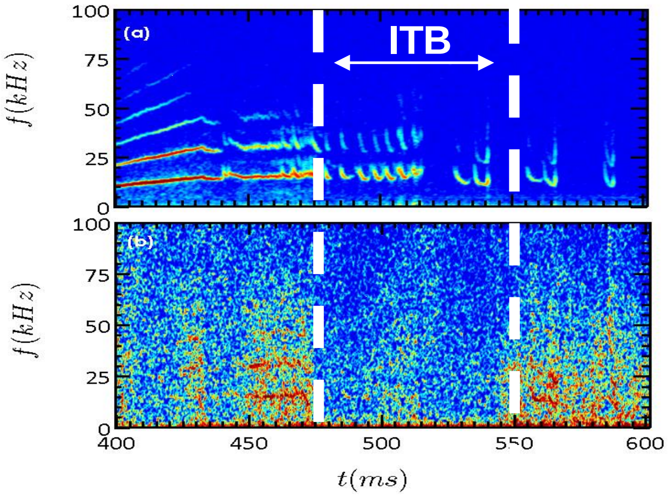
In ELM phase: streamer induces a transport channel from core to edge within a few microsecond

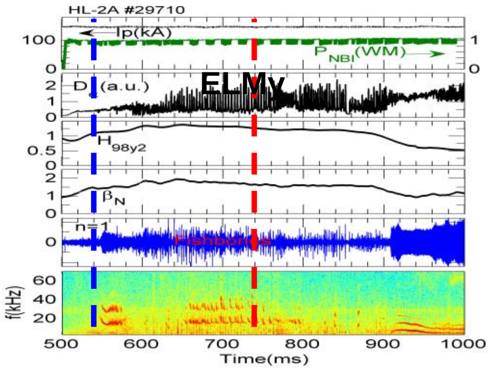


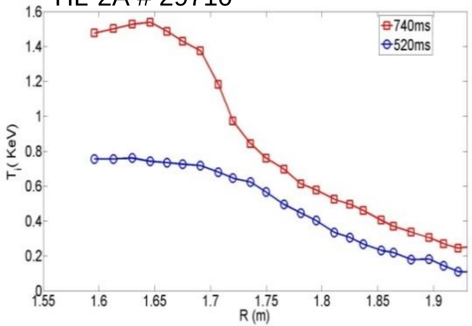
- Nonlinear coupling of turbulence → localized mode → streamer
- Streamer: life time 10 ~ 20 us, size: ~10 cm * 5 cm
- Streamer provides a fast transport channel connected the edge to core plasmas

ITB in H-mode plasma

Fishbone → fast ion redistribution→ change of q shear → affect transport → ITB formation





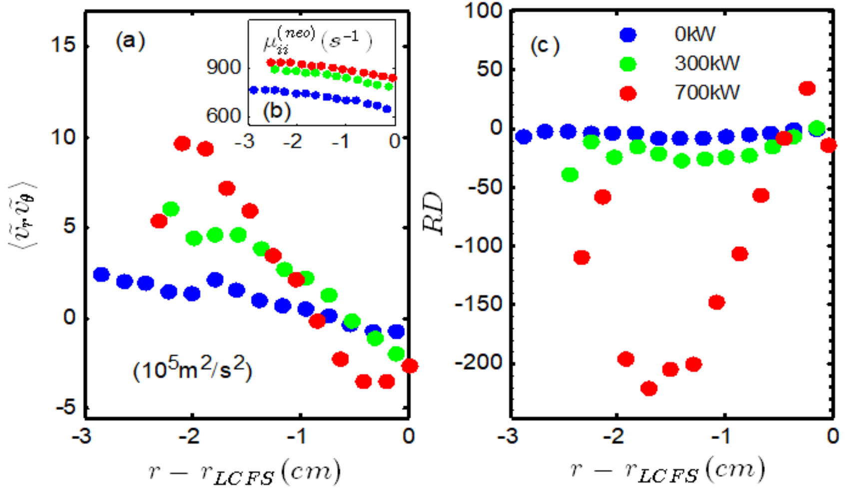


- (1/1) fishbone plays an important role in the formation and sustainment of ITB at low central shear;
- Formation of ITB in H mode plasma
- Turbulence suppressed during ITB sustainment

Liu et al., EX/P5-28

RS and Turbulent Generation of Edge Poloidal Flows

➢ Significant deviation of mean poloidal flow from neoclassical due to turbulent stresses. Shift ↑ with power.



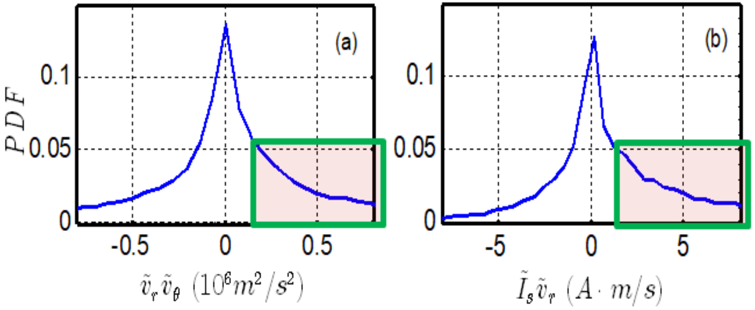


Table 1 Kurtosis for different heating power

heating power (kW)	kurtosis	
	Reynolds stress	Particle flux
0	12.2	15.0
300	15.7	13.6
700	11.5	13.9

Table 2 Kurtosis for Ohmic discharge

Fluctuation/ Intensity	$\tilde{n}/n$	$e\tilde{\phi}/T_e$	$\left\lvert\frac{\tilde{n}}{n}\right\rvert^2$	$\left\lvert\frac{e\tilde{\phi}}{T_e}\right\rvert^2$
kurtosis	3.2	3.1	11.2	9.8

- Reynold stress and particle flux PDF at 1cm inside LCFS show elevated kurtosis, which indicates fat tails;
- Deviation from Gaussian suggests the consideration of:

1. Validity of quasilinear models of edge turbulence transport
2. Phase correlations and dynamics

T. Long, P.H. Diamond et al. EX/P5-5

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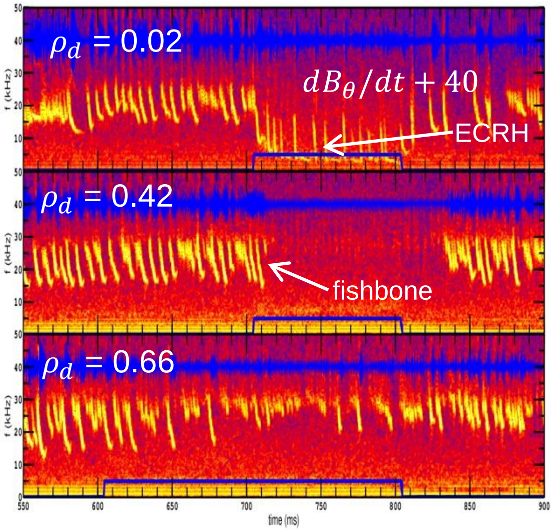
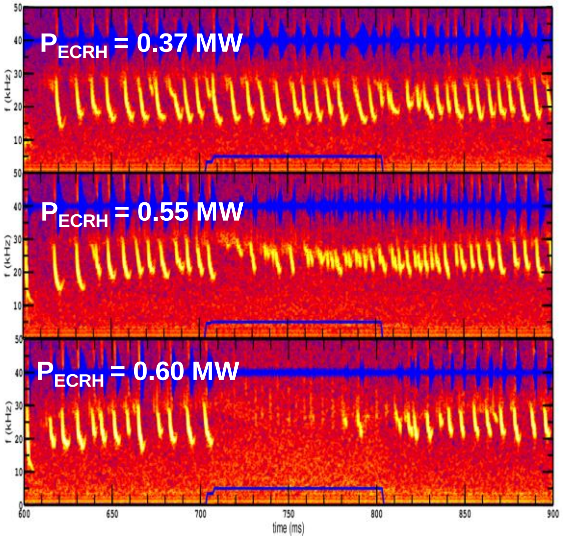
Stabilization of m/n=1/1 fishbone by ECRH

Mechanism: ECRH → Te increase → resistivity decrease → resistive fishbone stabilized

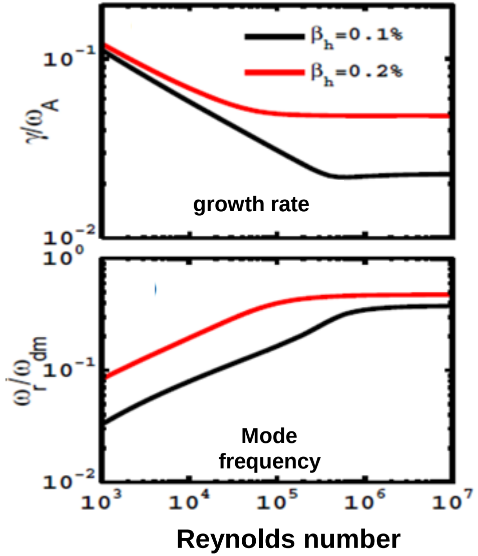
Scan ρ_d, fixed P_{ECRH}=1 MW



Scan P_{ECRH} ,fixed ρ_d = 0.42



Theoretical result

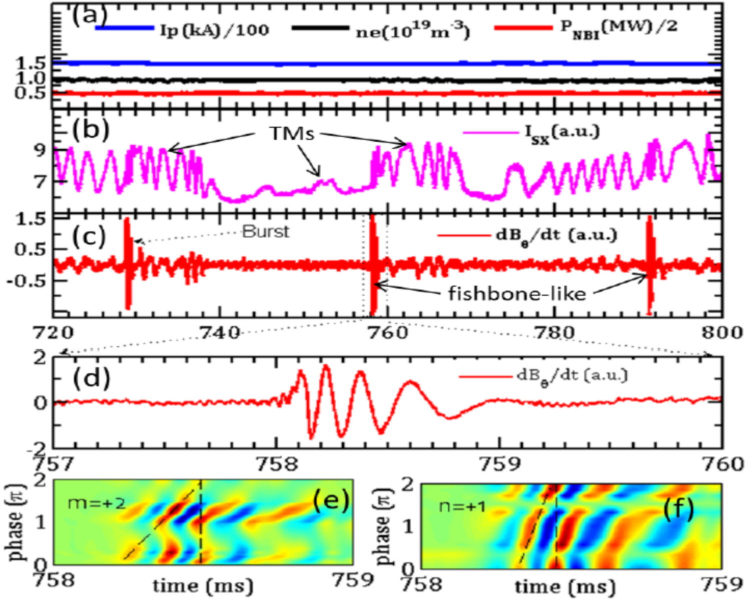


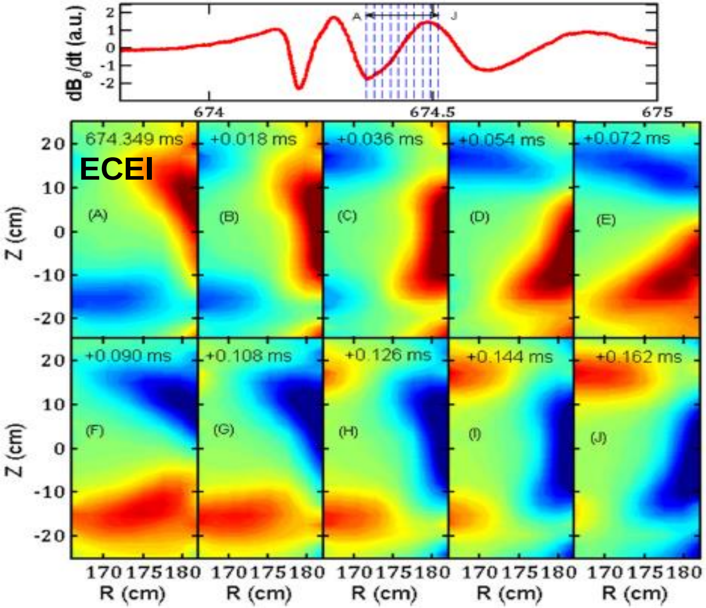
- Mode stability depends on both the P_{ECRH} and deposition location (ρ_d)
- Fishbone suppressed when P_{ECRH} exceeds a threshold.

Chen et al., EX/P5-20&NF, 2018

Excitation of m/n=2/1 fishbone by fast ions

Resonant interactions between fast ions and m/n=2/1 TM were observed



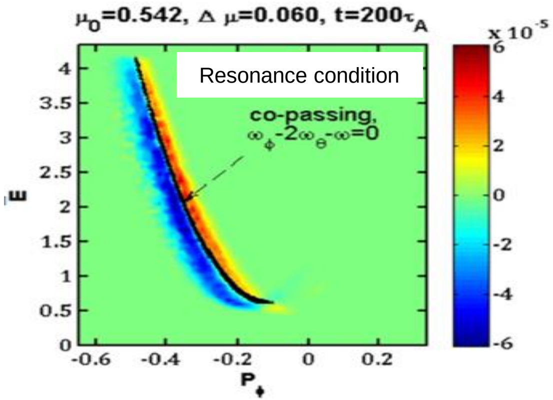


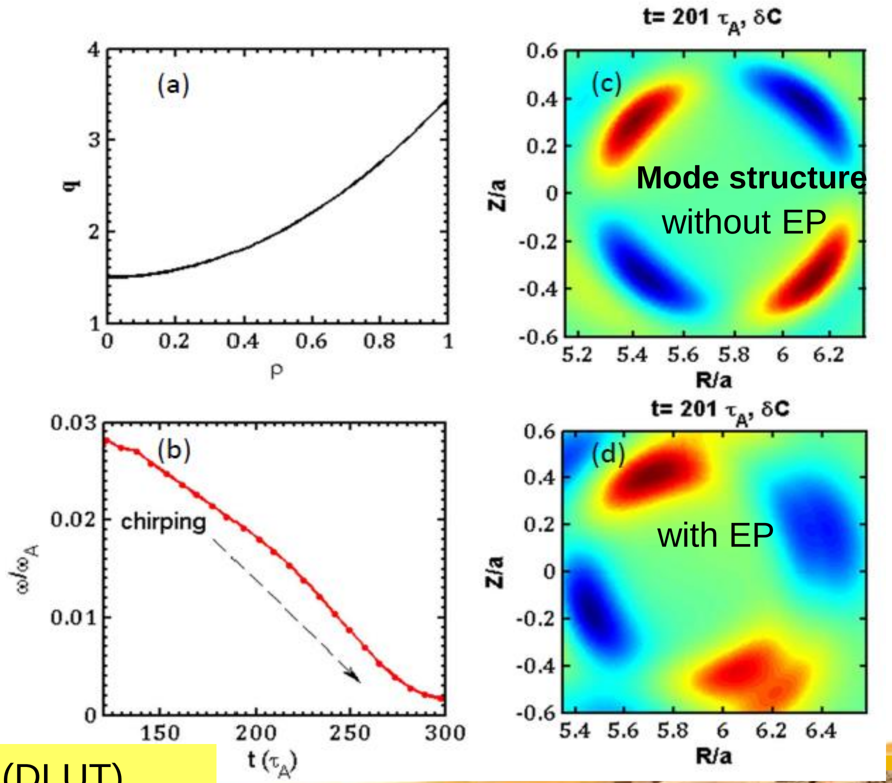
Wave-particle resonance converts unstable TM to fishbone-like mode with frequency chirping and amplitude bursting

Chen et al., EX/P5-20

Co-passing energetic-ions drive the m/n=2/1 fishbone-like mode

Co-passing energetic-ions play a key role in the fishbone-like mode drive



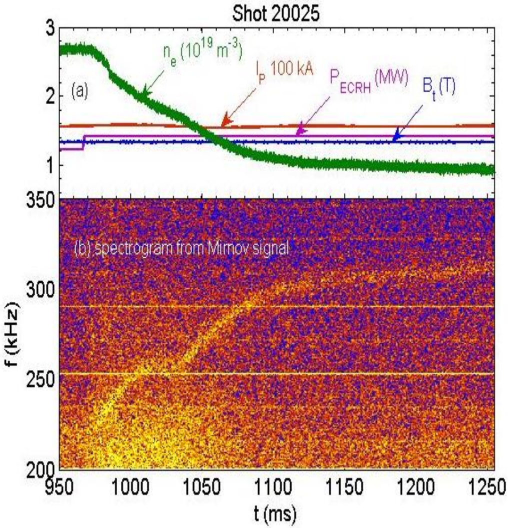


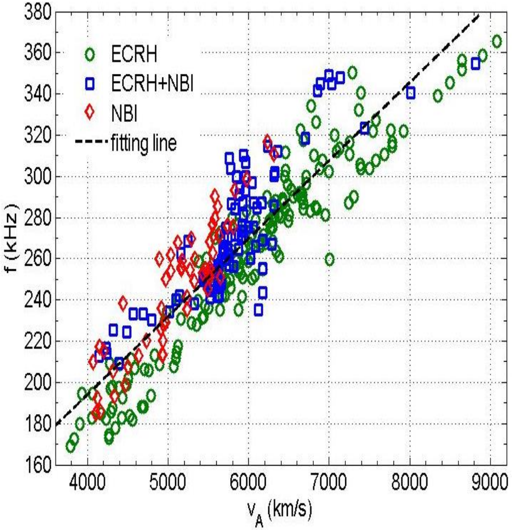
- Simulated mode structure and mode frequency chirping consistent with the measurements
- Resonance condition: $\omega_\varphi - 2\omega_\theta - \omega = 0$, and co-passing energetic-ions are responsible for the mode drive

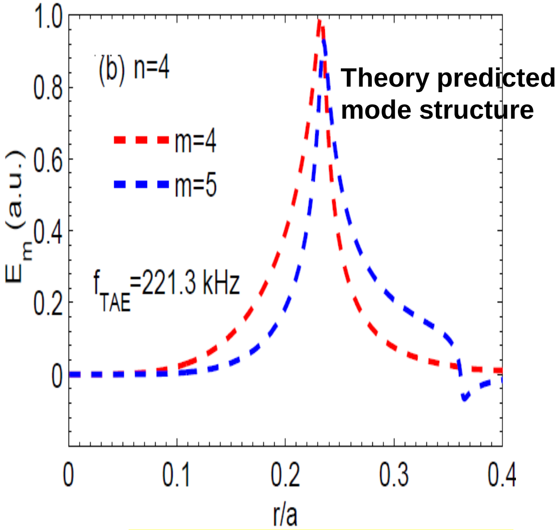
M3D-K modelling collaborates with Zhu (DLUT)

TAEs driven by energetic electrons

High-frequency TAE driven by energetic electrons was observed





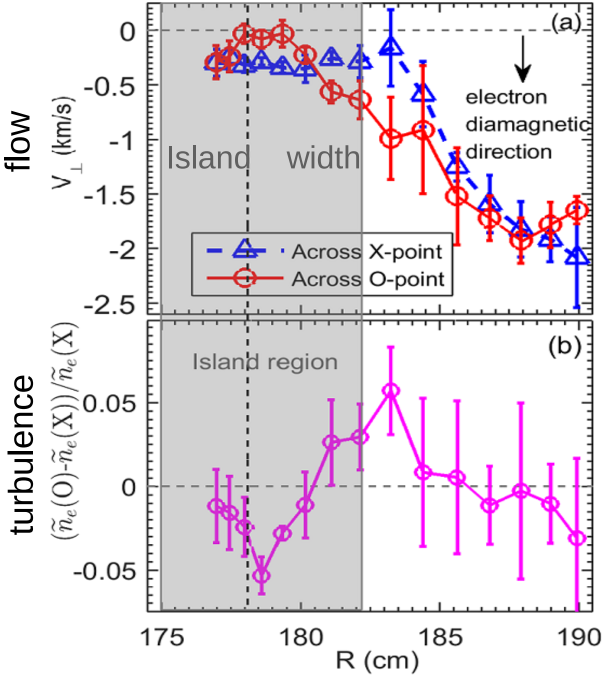


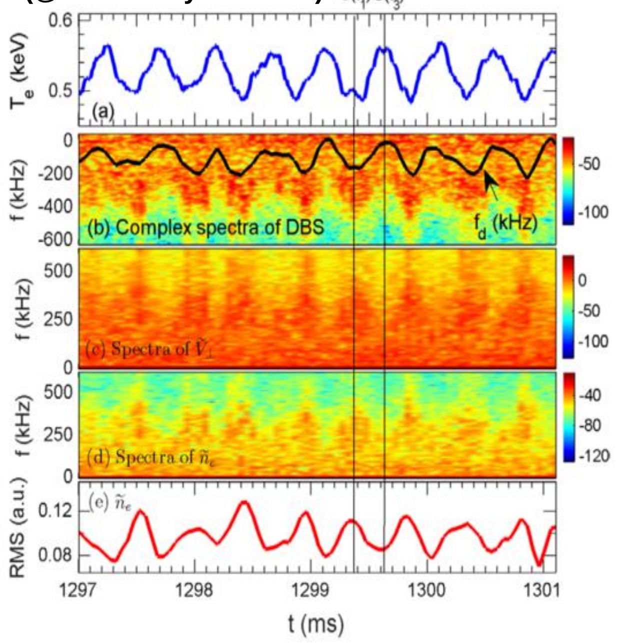
Yu et al., PoP, 2018

- Mode propagates in electron diamagnetic drift directions
- TAE locates in the core(ρ=0.35), with n=4, m=4 and 5
- f_{TAE}=224 kHz by theory close to experimental results (235 kHz);

Interaction among island, flow and turbulence

Pressure gradient plays a key role in modulation of turbulence by TM





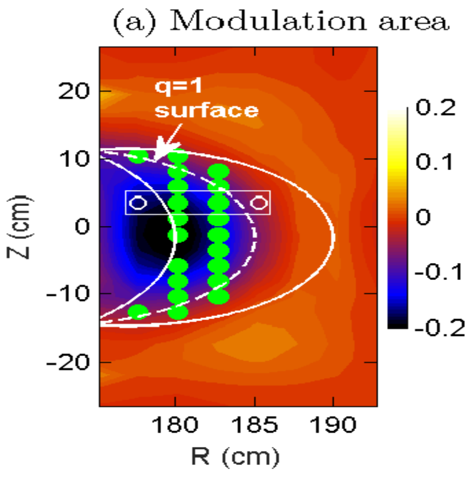
Turbulence reduced inside island while elevated at island boundary, consistent with gradient-driven turbulence

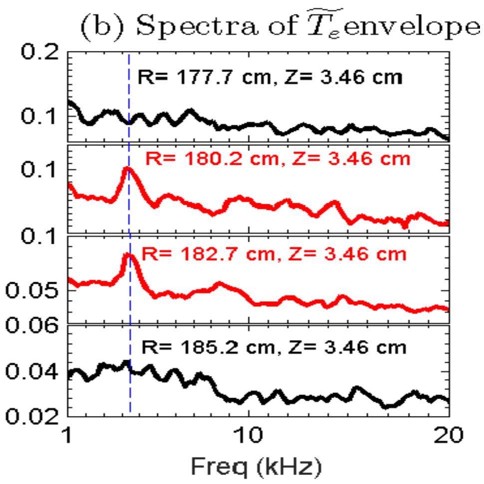
Perpendicular flow, flow fluctuation and density fluctuation were modulated by island rotation.

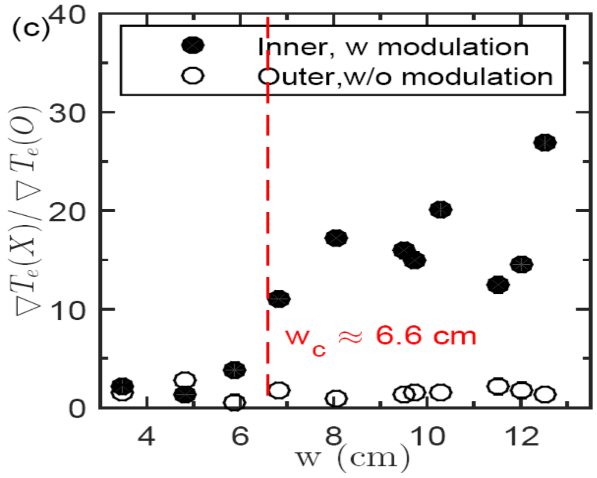
Jiang et al., NF, 2018

Localized modulation of $\tilde{T}_e$ by large island

Large ∇T_e difference between X- and O-point in inner half island → Modulation of $\tilde{T}_e$ by island only appears in the inner half island (marked by green dots in (a))







Jiang et al., EX/P5-4

An island-width threshold (6.6 cm) was found in the turbulence modulation.

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Summary of research highlights

- ELM control techniques were developed:
  - LHCD were achieved
  - LBO seeded impurity,
  - impurity mixture SMBI
- In ELM phase: streamer induces a transport channel from core to edge within a few microsecond
- Control of resistive fishbone by ECRH realized on the HL-2A. Wave-particle resonance converts unstable TM to fishbone-like mode.
- Found island-width threshold for turbulence modulation. Modulation of $\tilde{T}_e$ by island only appears in inner half island.

Outlook

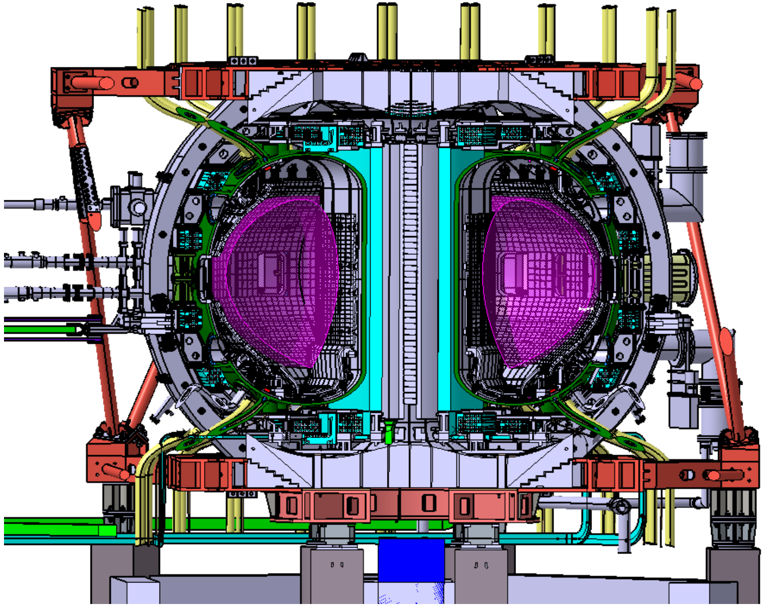
◆ HL-2M

- Mission: In support of ITER & CFETR: high performance, high beta, and high bootstrap current plasma; advanced divertor configuration (snowflake, tripod), PWI at high heat flux, etc.

- Parameters: R=1.78 m, a=0.65 m, B_t=2.2 T, I_p=2.5 MA, Heating~ 25 MW, triangularity=0.5, elongation=1.8-2.0

- **Status: Start the assembling before the end of this year.**

HL-2M tokamak



List of HL-2A Contributions

- OV/5-1 Xu: Overview of HL-2A recent experiment
- EX/P5-20 Chen: Suppression and destabilization of ion fishbone activities on HL-2A
- EX/P5-28 Liu: Development of the q=1 Advanced tokamak Scenarios in HL-2A
- EX/P5-6 Cheng: Pedestal dynamics in inter-ELM phase on HL-2A tokamak
- EX/P5-4 Jiang: Localized modulation of turbulence by magnetic islands on HL-2A tokamak
- EX/P5-19 Shi: Energetic-ion Driven Toroidal and Global Alfvén Eigenmodes on HL-2A
- EX/P5-3 Zhong: Plasma confinement and pedestal dynamics responses to impurity seeding in HL-2A H-mode plasmas
- EX/P5-8 Zhang: Effect of LBO-seeded Impurity on ELMs in the HL-2A tokamak
- EX/P5-12 Xu: Experimental evaluation of electron energy probility function and sheath potential coefficient of HL-2A
- EX/7-4 Xiao: ELM Control Physics with Impurity Seeding and LHCD in the HL-2A Tokamak

Welcome to the poster session for further discussions!

List of SWIP Contributions

- OV/5-1 M.Xu : Overview of HL-2A recent experiments
- FIP/2-1 J. Chen:Progress in Developing ITER and DEMO First Wall Technologies at SWIP
- FIP/1-6 X. Wang: Current Design and R&D Progress of CN HCCB TBS
- EX/7-4 G. L. Xiao: ELM Control Physics with Impurity Seeding and LHCD in the HL-2A Tokamak
- EX/P5-20 W. Chen: Suppression and destabilization of ion fishbone activities on HL-2A
- EX/P5-28 Y. Liu: Development of the q=1 Advanced tokamak Scenarios in HL-2A
- EX/P5-6 J. Cheng: Pedestal dynamics in inter-ELM phase on HL-2A tokamak
- EX/P5-4 M. Jiang: Localized modulation of turbulence by magnetic islands on HL-2A tokamak
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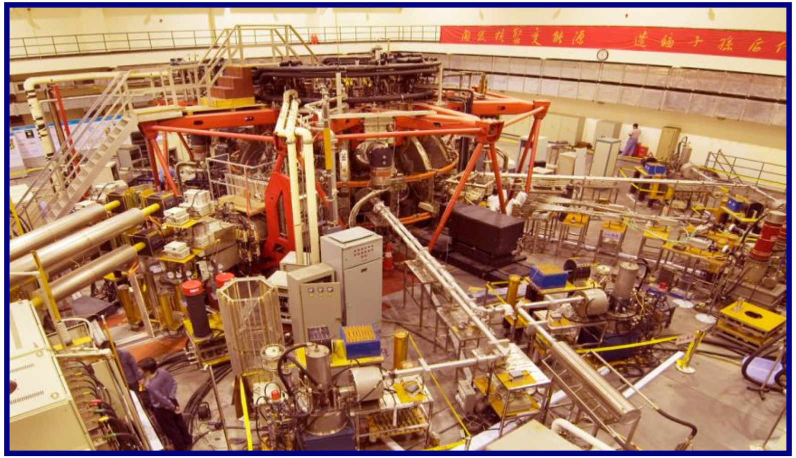
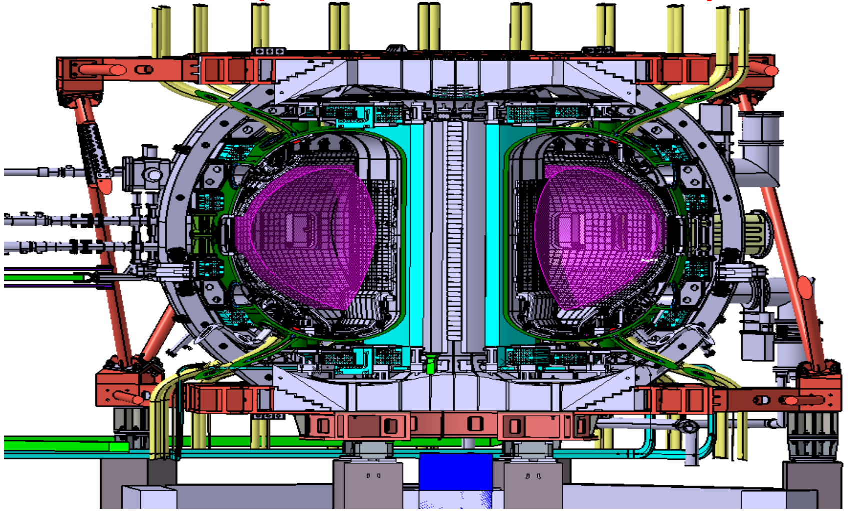
- EX/P5-12 M. Xu: Experimental evaluation of electron energy probility function and sheath potential coefficient of HL-2A
- FIP/P1-38 L. Cai: Preliminary development on a conceptual first wall for DEMO
- TH/P2-3 H. He: Simulation of Toroidicity-Induced Alfven Eignenmode Excited by Energetic Ions in HL-2A Tokamak Plasmas
- FIP/P3-22 H. Liao: Recent progress of R&D activities on Chinese reduced activation ferritic/martensitic steel (CLF-1)
- FIP/P3-11 Z. Xu: Splashing Effect of Liquid Metal Divertor Due to ELMs Crashing
- EX/P5-15 X. Q. Ji: Nonlinear evolution of multi-helicity neoclassical tearing modes in HL-2A low rotation plasmas
- EX/P5-29 Y. B. Dong: Study of disruption and runaway electrons mitigation using multipulse supersonic molecular beam injection on HL-2A
- EX/P5-30 X. M. Song: First Plasma Scenario Development for HL-2M
- EX/P5-27 L. W. Yan: Real-time control system of neoclassical tearing modes in the HL-2A tokamak
- TH/P5-13 G. Z. Hao: Centrifugal force driven low frequency modes in spherical tokamak
- TH/P6-22 Z. H. Wang: Physics of fast component of deuterium gas jet injection in magnetized plasmas
- TH/P8-13 Y. Li: Nonlinear turbulent parallel momentum transport due to blobs
- FIP/P8-13 P. Y. Li: Recent Progress of ITER Magnet Supports Package in SWIP

Thanks for your attentions!

HL-2A



HL-2M (under construction)



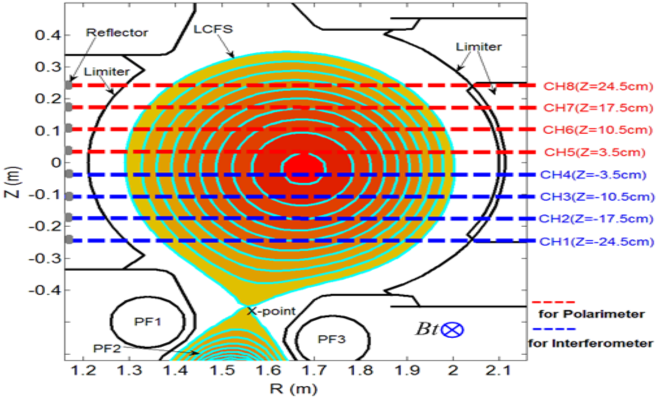
Back-up slides

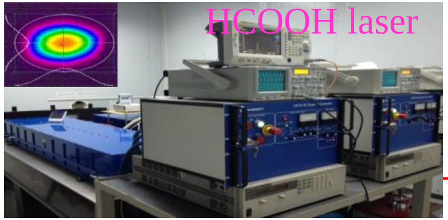
- Highlights of recently upgraded/developed diagnostics on the HL-2A
- Introduction of HL-2M

FIR laser Interferometer and Polarimter on the HL-2A

■ Multi-channel FIR laser Polarimeter-Interferometer has been commissioned on HL-2A for electron density and Faraday rotation angle measurements.

- Laser source: HCOOH laser (λ=432.5um)
- Composition: 4-chord Polarimeter + 4-chord Interferometer
- Time resolution: 1.0us, spatial resolution: 7.0cm





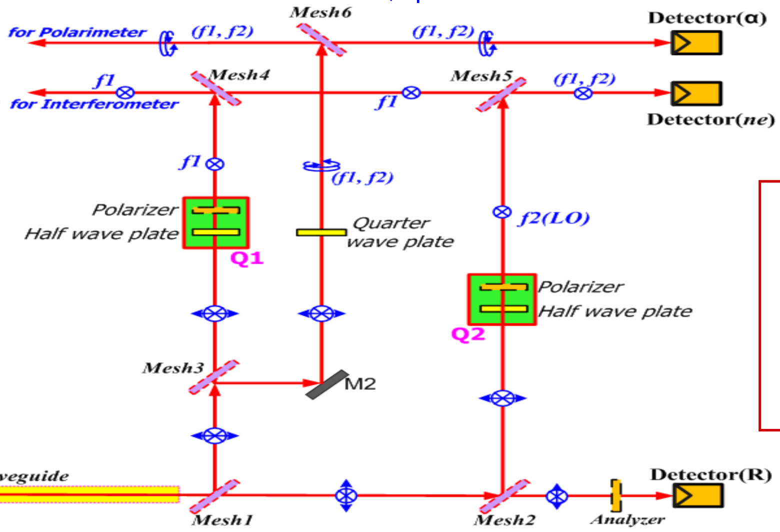


Figure:

Schematic layout of

HL-2A Polarimeter

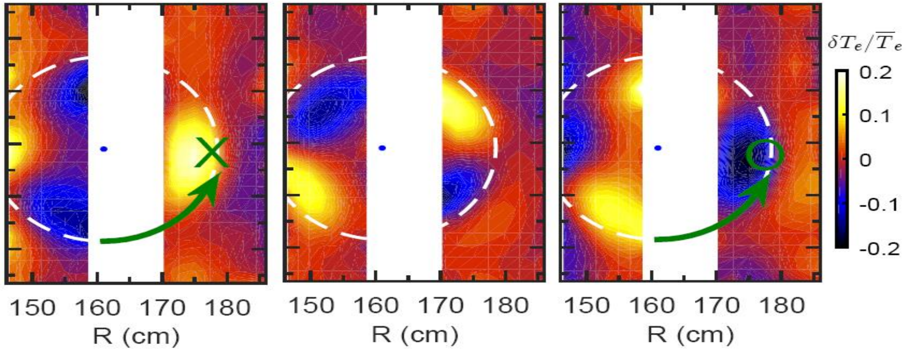
and Interferometer.

1). Y.G. Li, et al., RSI. 88, 083508 (2017)
2). Y.G. Li, et al., JINST. 12, C11004 (2017)
3). Y.G. Li, et al., FED 137, 137 (2018)

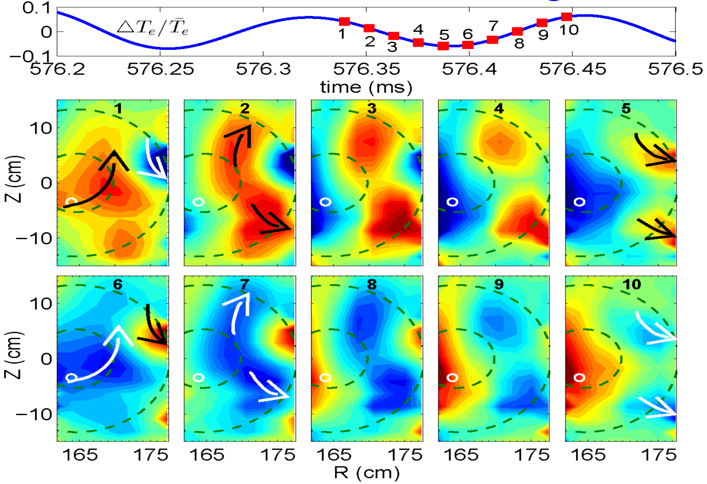
24×16 Electron Cyclotron Emission Imaging (ECEI) on the HL-2A

Optics of ECEI system

Tearing mode images



Double e-fishbone images



— 24(vertical)× 16(radial)=384 channel, with a coverage of 53 cm (vertical) × 30 cm (radial).

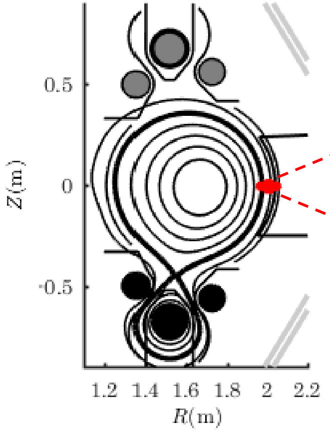
— Tempo-spatial resolution: 2μs, 1-3 cm.

— Abundant physics have been captured, such as TM, fishbone, ELM crash and multi-scale physics.

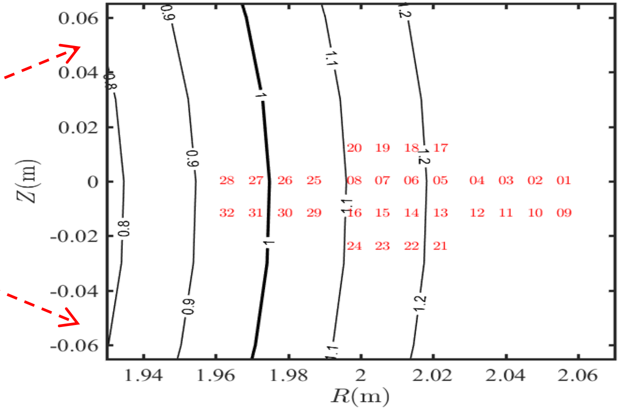
M. Jiang, NF 2018; PoP 2017; RSI 2013&2015;
Z. B. Shi, RSI 2014; PST2018
P.W. Shi, POP2017&2018. W. Chen, NF2018;

Recent process of BES on the HL-2A

- 32-channel BES array has been installed on the outer mid-plane of HL-2A tokamak, focusing on the edge and SOL region.
- Spatial resolution: Δ*r* ≈ 0.8 cm； Δ*Z* ≈ 1.2 cm, covering *r* = 34.5 ~ 40.5 cm.
- High SNR has been achieved in the experiments last ye



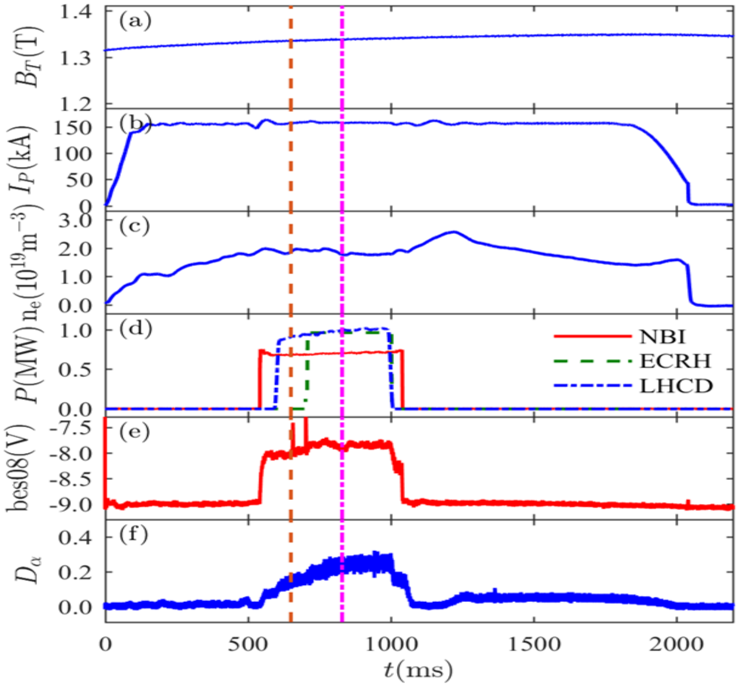
shot # 33103, 640 ms



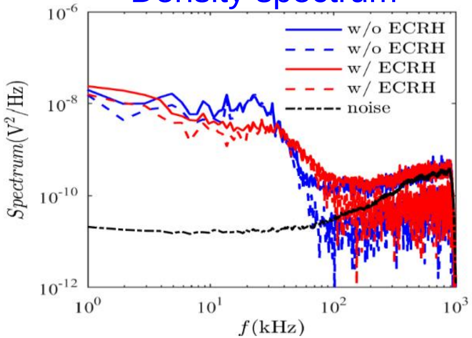
BES applied on turbulence studies

- Turbulence density spectrum is broadened when ECRH is applied.
- Poloidal velocity and shear increased with ECRH.

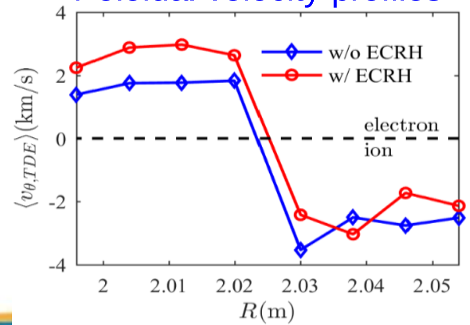
HL-2A # 33103



Density spectrum

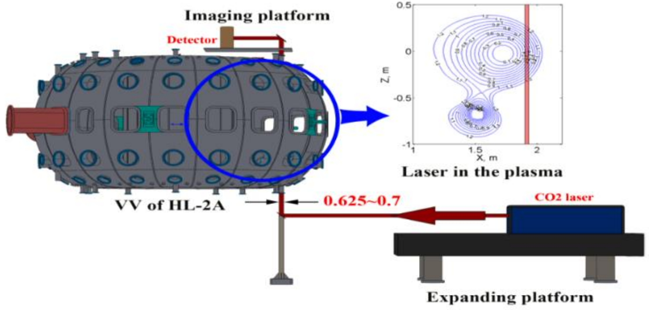


Poloidal velocity profiles

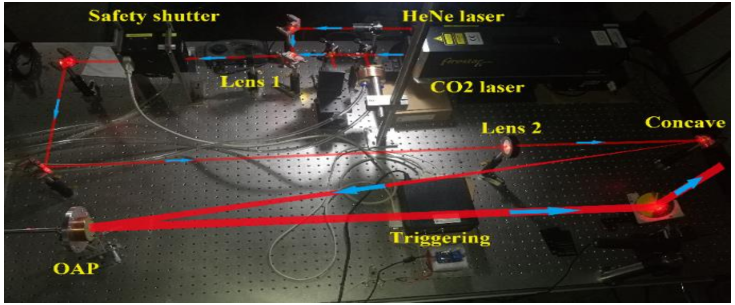


Preliminary results from Phase Contrast Imaging: $\int \tilde{n}_e dl$

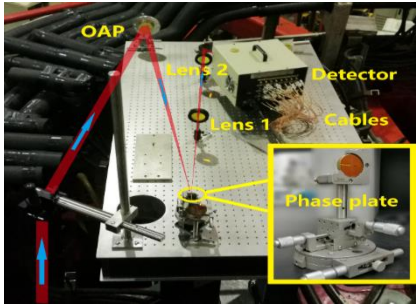
➢ Experimental Setup



System design



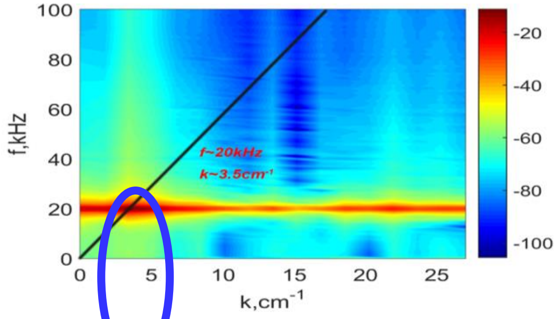
Expanding platform



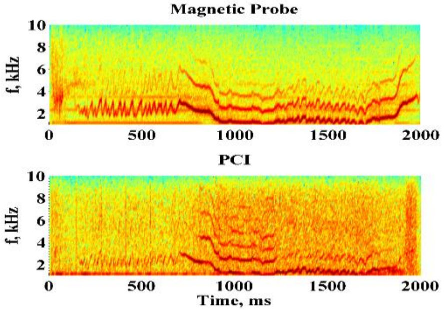
Imaging

- **Systematic Parameters**
  Time resolution: 1 us
  Spatial resolution: ~1mm
  Detector array: 32 channels
  Wavenumber: 2~15cm^{-1}

- **The consistent experimental results obtained from magnetic probe and PCI data confirm the reliability of this diagnostic.**



Calibration by Sound Wave



Observation of MHD instabilities

Introduction of HL-2M

Mission: **In support of ITER & CFETR: high performance, high beta, and high bootstrap current plasma; advanced divertor configuration (snowflake, tripod), PWI at high heat flux,etc.**

Main parameters

Plasma current	**I_p = 2.5 (3) MA**
Major radius	**R = 1.78 m**
Minor radius	**a = 0.65 m**
Aspect ratio	**R/a = 2.8**
Elongation	**K = 1.8-2**
Triangularity	**δ > 0.5**
Toroidal field	**B_T = 2.2 (3) T**
Flux swing	**ΔΦ= 14Vs**
Heating power	**25 MW**