Overview of Recent Experiments on HL-2A

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

Southwestern Institute of Physics, Chengdu, China

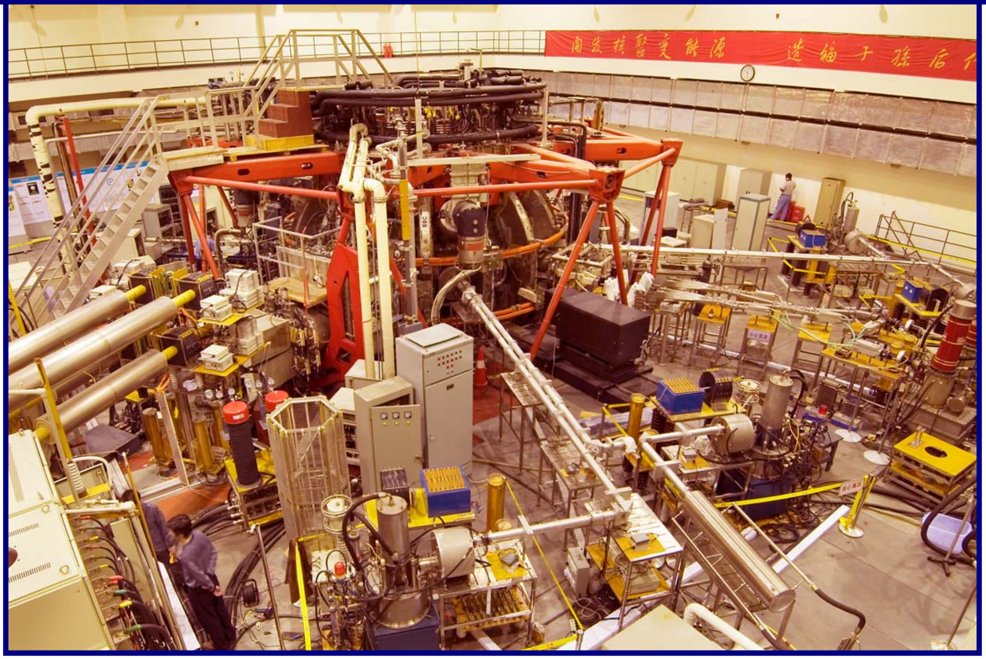
In collaboration with

University of Science and Technology of China & ASIPP, China
IRFM/CEA, Cadarache, France
University of California, San Diego, USA
NIFS, Japan
WCI/NFRI, Korea

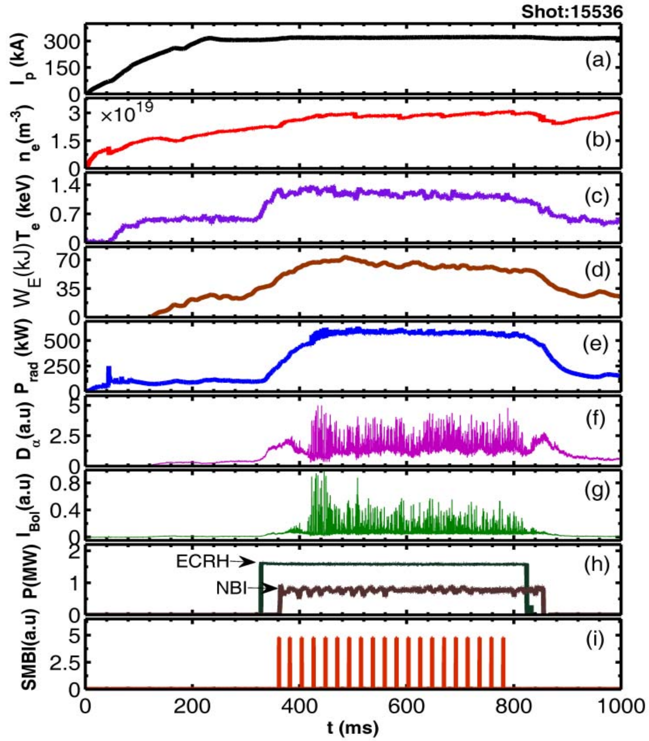
Acknowledgements

MPI für Plasmaphysik, IPP-Juelich, Germany
GA, PPPL, LLNL, UCI, UCLA, USA
JAEA, Kyoto University, Japan
ENEA, Frascati, Italy
Kurchatov Institute, Russia
Zhejiang Uni., HUST, PKU, Tsinghua Uni., China

HL-2A tokamak-*present status*



- *R/a:* 1.65 m/0.40 m
- *Bt:* 1.2~2.7 T
- *Ip:* 150 ~ 430 kA
- *ne:* 1.0 ~ 6.0 x 10^{19} m^{-3}
- *Te:* 1.5 ~ 5.0 keV
- *Ti:* 0.5 ~ 2.8 keV



Auxiliary heating:

ECRH/ECCD: 5 MW

(6× 68 GHz/500 kW/1 s, modulation: 10~30 Hz;

2× 140 GHz/1 MW/2 s)

NBI(tangential): 1.5 MW

LHCD: 1 MW

(2×2.45 GHz/500 kW/1 s)

More than 30 kinds of diagnostic systems

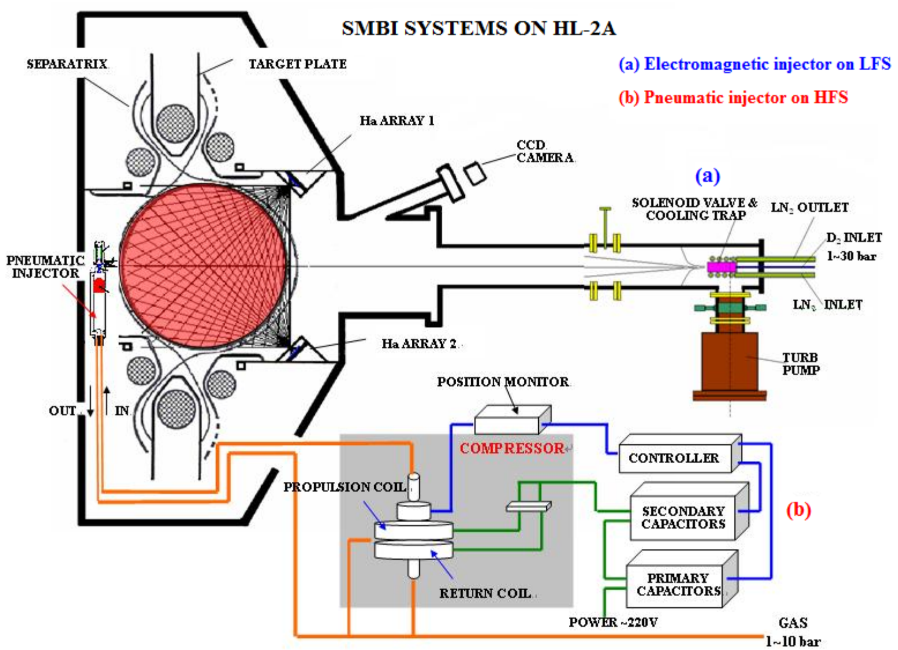
Outline

- ELM mitigation by SMBI/CJI
- Energetic particle physics and MHD activities
- L-H transition, turbulence and transport
  - *Nonlinear energy transfer and vorticity transport*
  - *Generation of large scale coherent structure*
  - *Meso-scale electric field fluctuations*
  - *L-H transition*
  - *nonlocal transport*
- Summary and outlook

SMBI/CJI System

Supersonic Molecular Beam Injection (SMBI)

Proposed by Prof. L H Yao from SWIP and applied on HL-1 in 1992
applied on HL-1M, W7-AS, ASDEX-U, Tore-Supra, KSTAR, EAST etc.



Valve attached with conical nozzle
Orifice diameter: 0.25 mm
Gas pressure: 0.2 – 4.0 MPa
Pulse duration: 0.3 ~ 50 ms @ 1~70Hz

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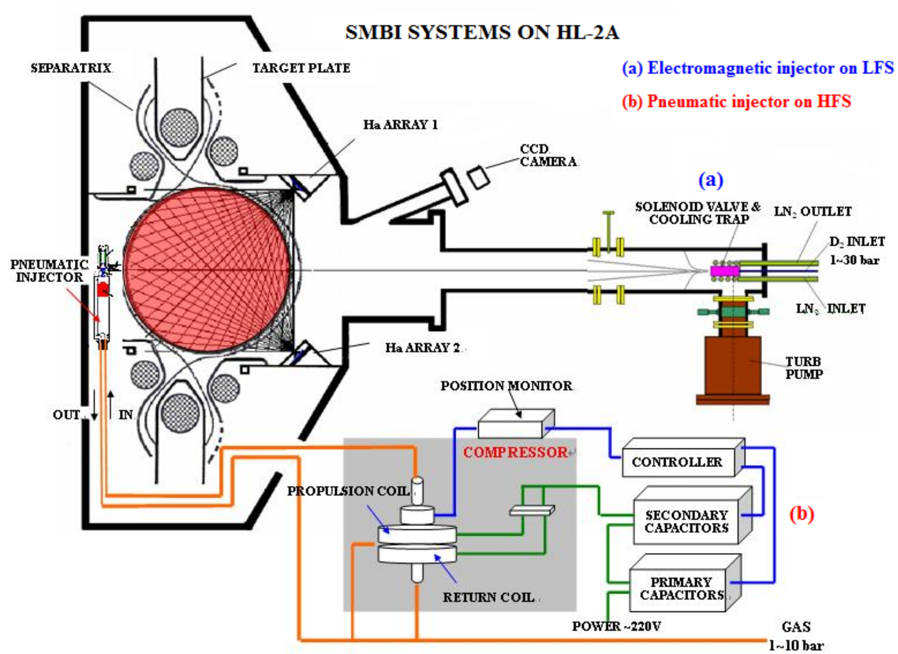

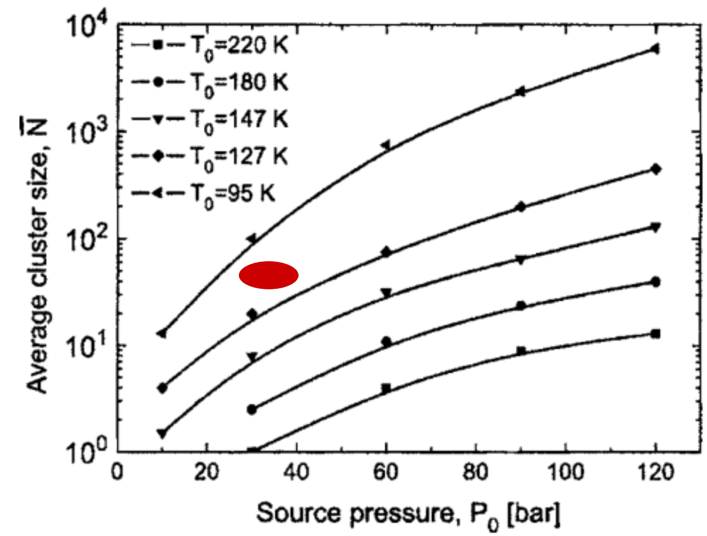

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Pulse duration: 0.3 ~ 50 ms @ 1~70Hz

Stagnation-pressure dependence of D_2 cluster sizes at different source temperatures, T_0.

Y. Ekinci et al., J. Chem. Phys. ***125****, 133409 (2006)*

if the gas is cooled by liquid nitrogen, clusters could be formed in the beam

ELM mitigation by SMBI/CJI

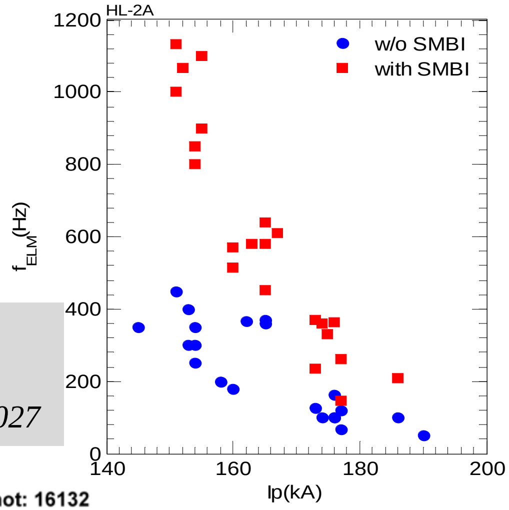
$f^{SMBI}_{ELM}/f^{0}_{ELM} = 2 - 3.5$

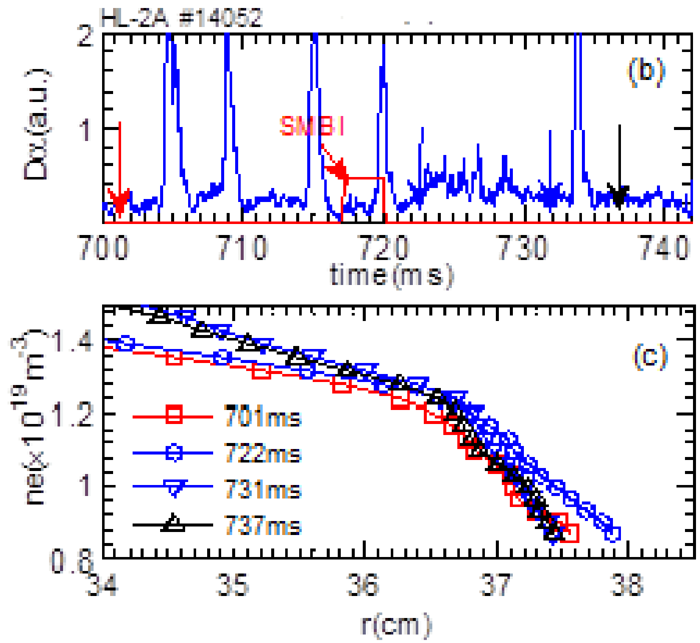
$n_e=1.8\sim2.3\times10^{19}m^{-3}$

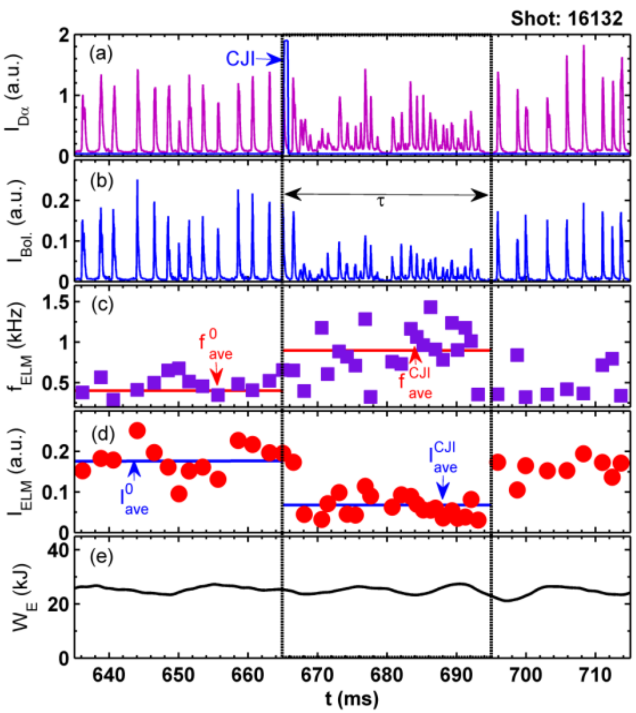
$P_{aux}=0.9\text{-}1.4$ MW

X R Duan et al., IEEE trans on Plasma Science ***40*** *(2012) 673*

W Xiao et al., Nucl. Fusion ***52*** *(2012) 114027*







$f^{CJI}_{ELM}/f^{0}_{ELM} = 2.2$

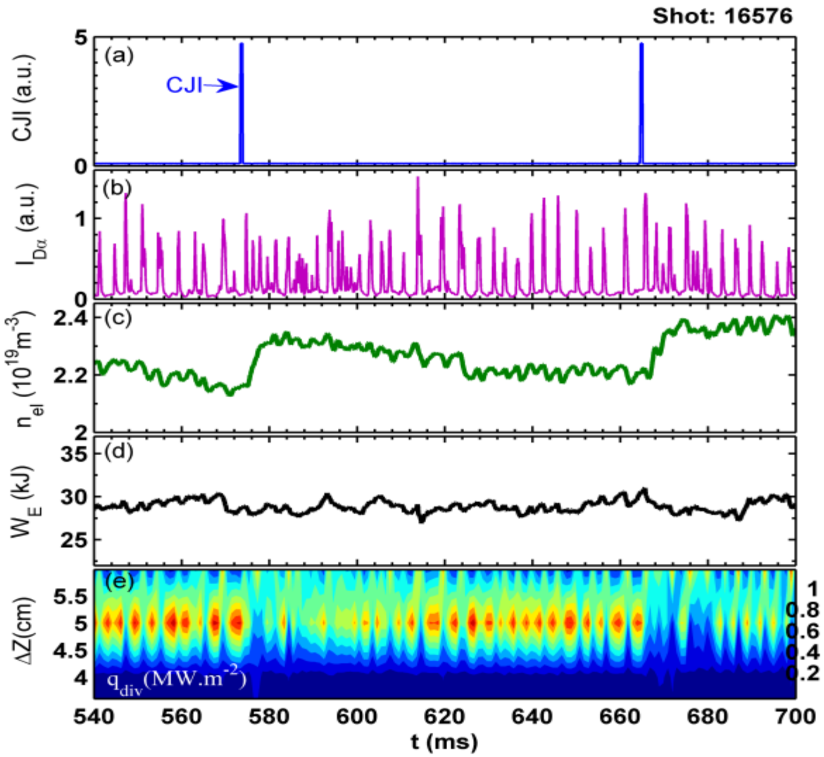
$I^{CJI}_{ave}/I^{0}_{ave} = 0.38$

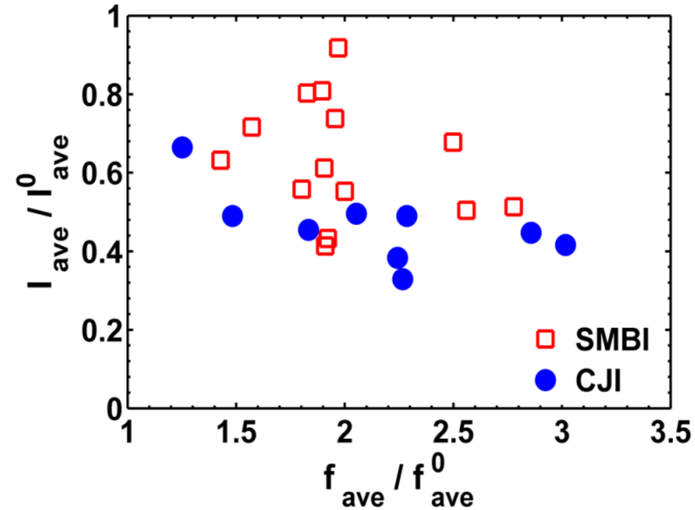
The density gradient steepness in pedestal decreaes immediately following SMBI.

It suggests that particle transport increases after SMBI

ELM mitigation by SMBI/CJI

HL-2A





Intensity ratio vs frequency ratio. Ratio of averaged thermal radiation in divertor chamber induced by ELMs before & after SMBI/CJI.

The mitigation effect depends on the parameters of SMBI/CJI: a) nozzle form b)backing pressure

c) pulse duration c) temperature

ELM mitigation by SMBI has been confirmed on KSTAR & EAST in recent experimental campaign.

Heat flux $q_{div} \sim \gamma C_s n_{et} T_{et} \sin\theta$

γ : sheath heat transmission factor,

C_s: ion sound speed

θ: the incident angle

T_{et}, n_{et}: electron temperature and density at target

Heat flux on outer divertor plate q_{div} decreases ~50%

W.W.Xiao EX/6-3Ra Thurs. 15:40 Oral

X.L.Zou EX Postdeadline

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Energetic Particle Physics

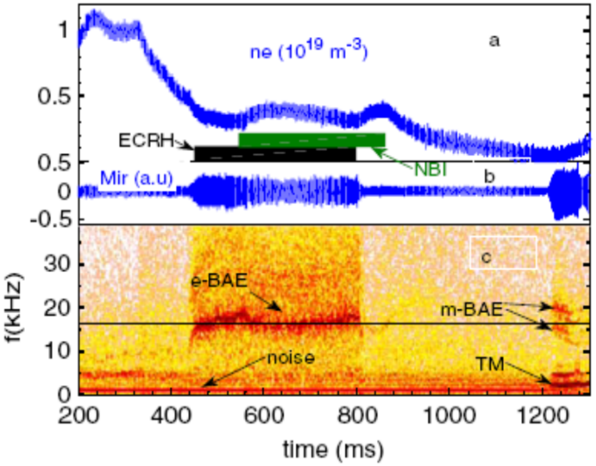
Studying energetic particle (EP) induced instabilities is important

Nonlinear wave-particle interactions enhance EP transport significantly

degrade overall plasma confinement (induce particle losses & reduce plasma self-heating)

damage PFC

First observation of e-BAE on HL-2A



W.Chen et.al. **PRL 105**, 185004 (2010)

- e-fishbone mode frequency jump during high power ECRH

  important for redistribution of energetic electrons and energetic particle losses

  L.M.Yu EX/P6-14 Thurs. PM

- multi-Alfvenic mode coexistance induced by energetic electrons

  related with LF Alfven eigenmode and affect plasma transport greatly

  X.T.Ding EX/P6-15 Thurs. PM

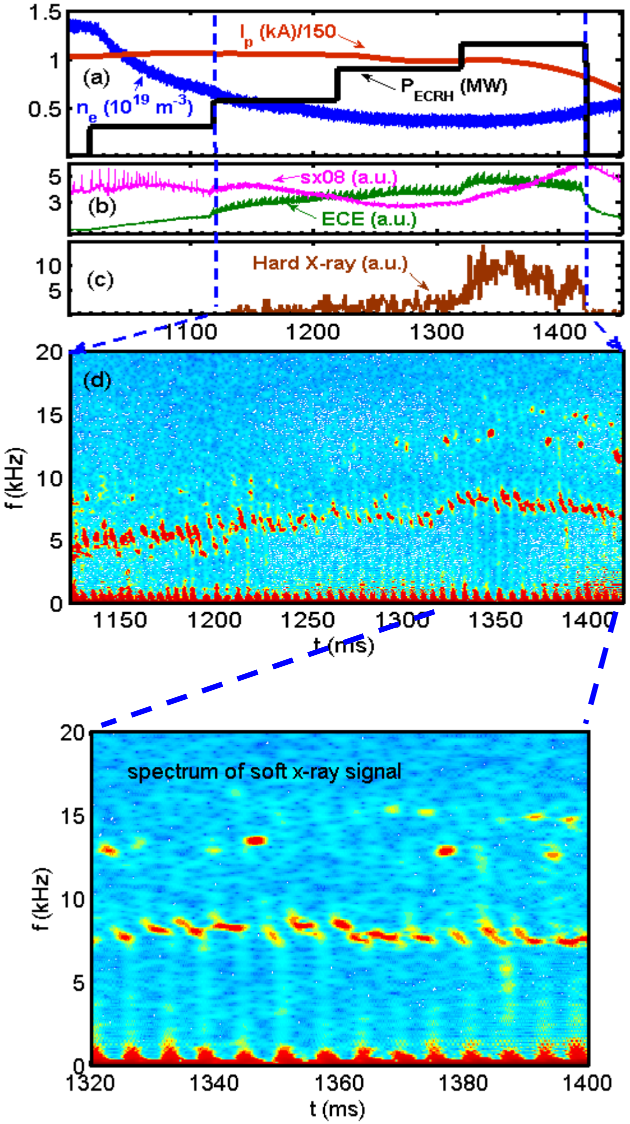
- Geodesic acoustic mode induced by energetic electrons

  to be presented in details in

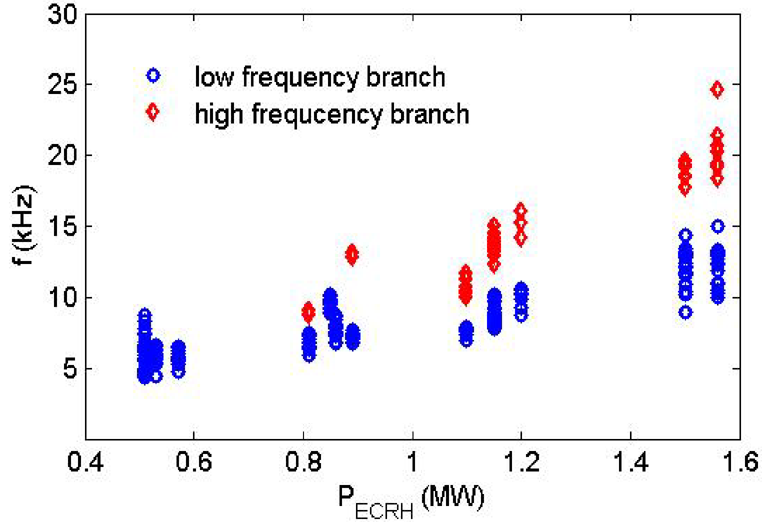
  W.Chen EX/5-3 Thurs. 12:05 Oral

Frequency jump of e-fishbone mode

HL-2A



The e-fishbone frequency jump has been observed in the low density ECRH plasmas, where the trapped particles are dominant.



Ip=155-160 kA

n_e=0.3~0.7$\times 10^{19}$m^{-3}

B_T=1.2-1.22 T

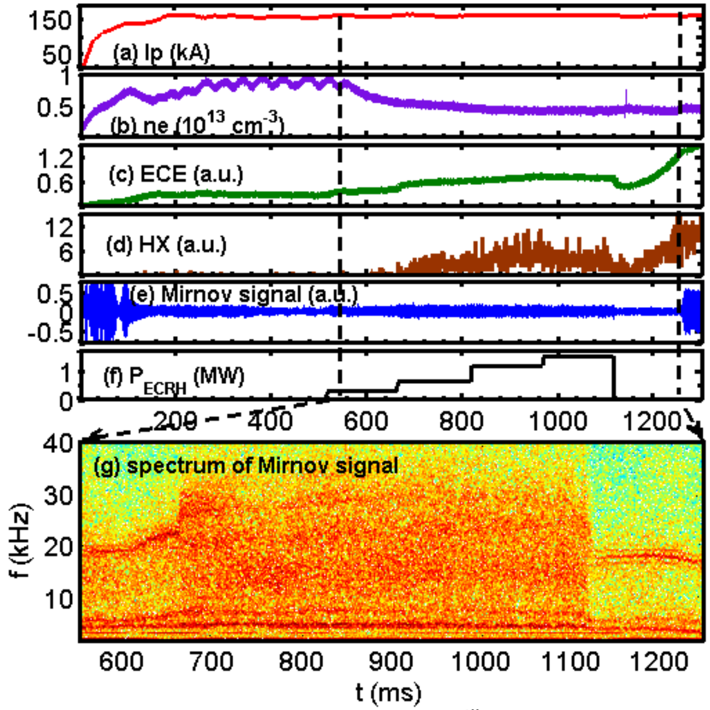
ECRH deposited Inside q=1 surface

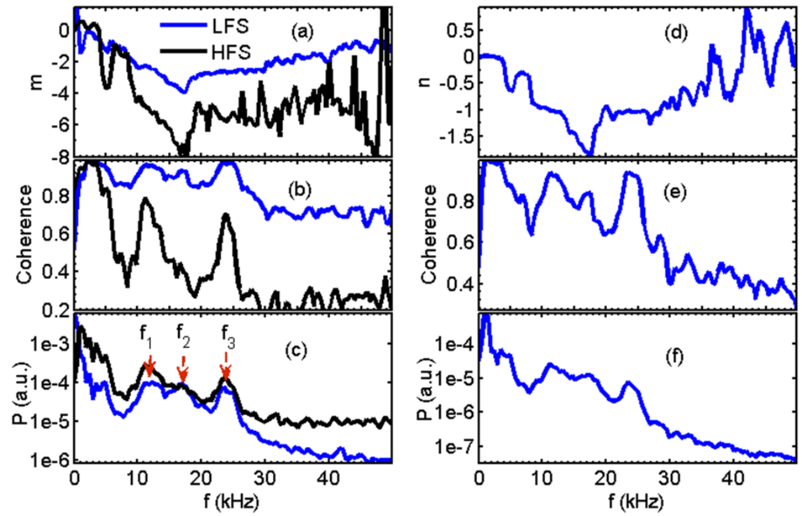
The high frequency branch could be observed only if the ECRH power is high enough (~ 0.8 MW). Frequency jump increases with ECRH power. The low & high frequency modes are m/n=1/1 and 2/2, respectively.

L.M.Yu EX/P6-14 Thurs. PM

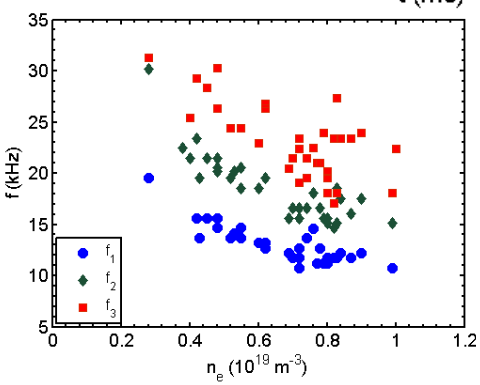
Low frequency multi-mode coexistance

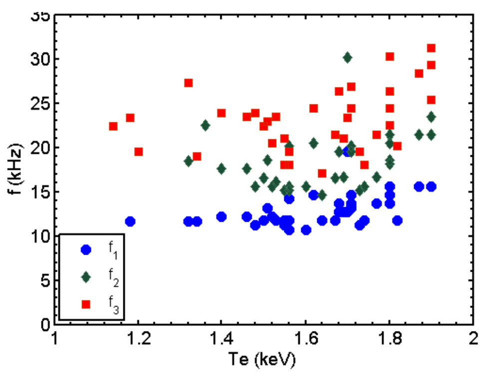
HL-2A





m/n=3/1, 6-5/2, 4/1-2





- Low frequency multi-Alfvenic mode coexistence was observed during high power ECRH.
- The mode frequencies increase with electron temperature, and overlap with each other.
- The measured wave numbers are different on the LFS and HFS.

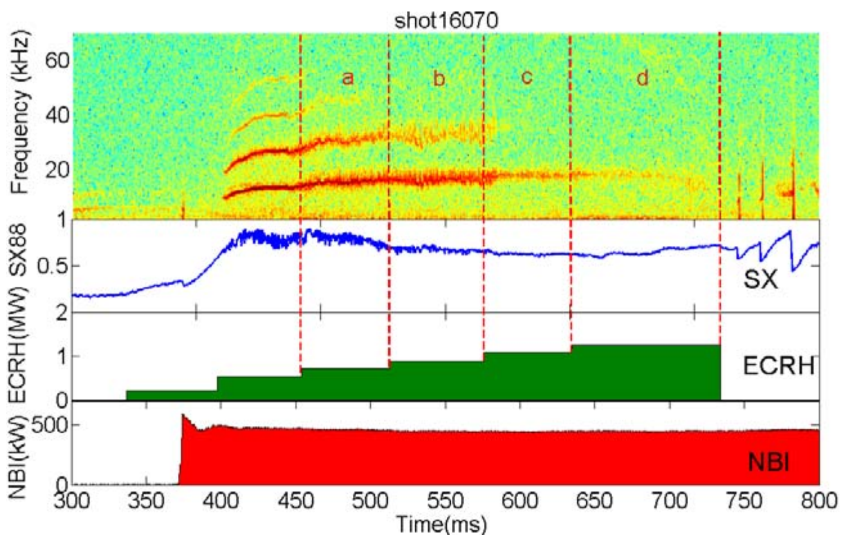
I_p: 155-160 kA *B_t: 1.2-1.4 T*

n_e: < 1.4 × 10^{13}cm^{-3} *P_{ECRH} > 0.6 MW*

X.T.Ding EX/P6-15 Thurs. PM

Long-lived mode & its control

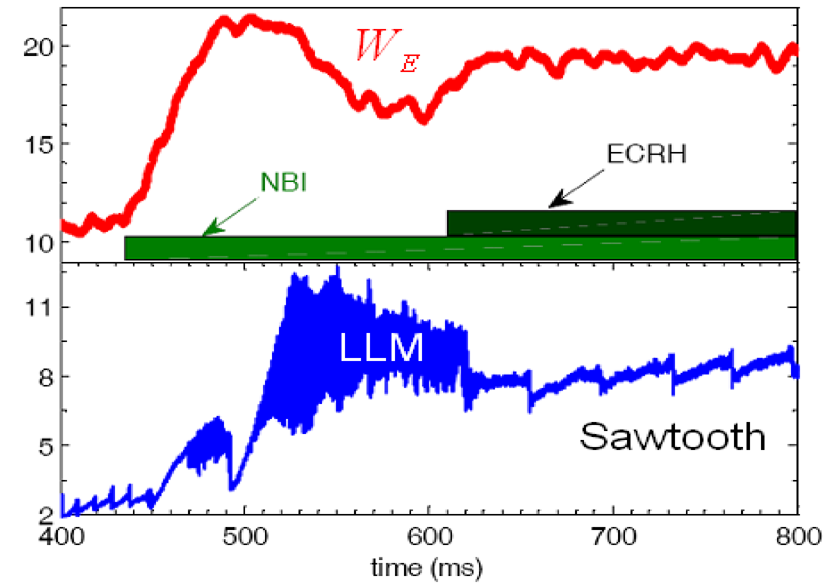
LLM observed during NBI with weakly reversed or broad low magnetic shear



- pressure-gradient driven MHD mode triggered by energetic particles;
- LLM degrade confinement of plasma and enhance loss of fast ions;
- oscillation in LFS stronger than in HFS

W.Deng EX/P6-12 Thurs. PM

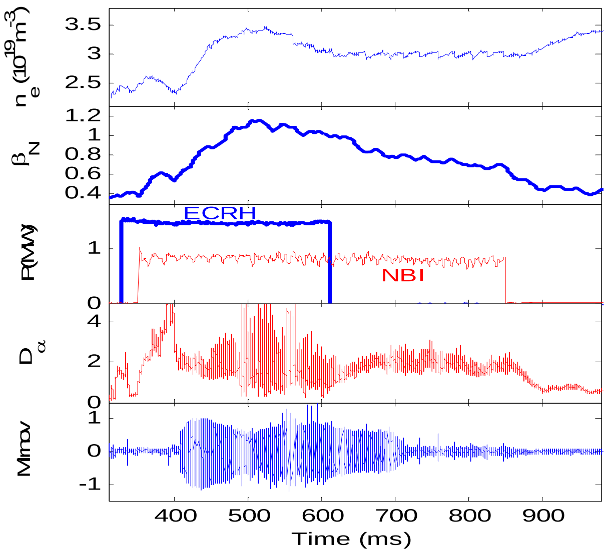
Control of LLM with ECRH or SMBI

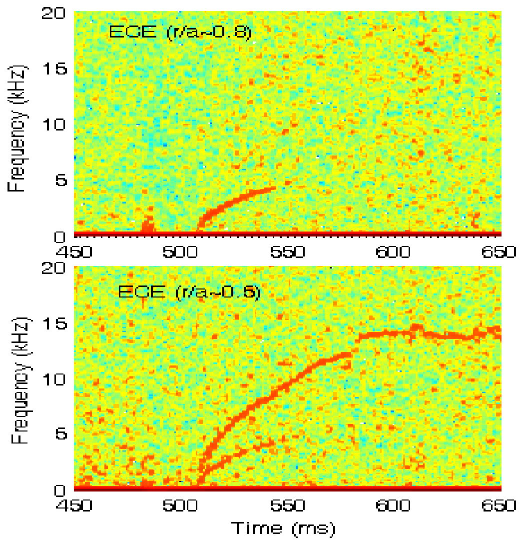


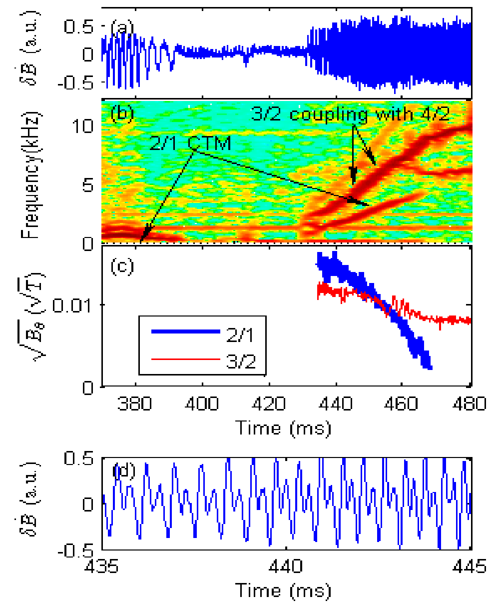
- LLMs can be suppressed by ECRH and by SMBI;
- The control of LLMs may be related to the change of the central magnetic shear or the pressure profile caused by the local heating or fuelling.

3/2 NTM during ELMy H-mode

HL-2A







I_p=300 kA, B_t=2.4 T, n_e~3×10^{19} m^{-3}

P_{ECRH}~1.5 MW, P_{NBI}~0.8 MW

m/n=3/2 mode survives

m/n=2/1 mode disappears

3/2 NTM developed due to toroidal coupling of its seed island with the 4/2 TM.

X.Q.Ji EX/P4-25 Tues. PM

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L-H transition mechanism ?

What are the roles played by

- *turbulence, flow and magnetic island in plasma confinement ?*
- *their interactions ?*
- *ZFs & GAM, mean E $\times$B flow, etc. in L-H transition ?*

L-H transition, turbulence and transport

L-H transition mechanism ?

What are the roles played by turbulence, flow and magnetic island in plasma confinement ?

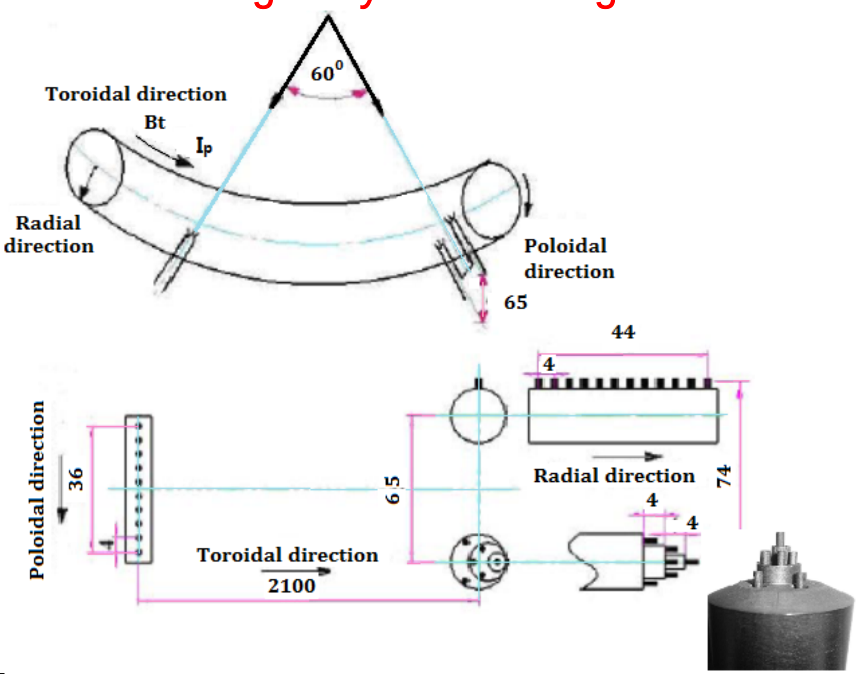
their interactions ?

ZFs & GAM, mean E $\times$B flow, etc. in L-H transition ?

Some experimental results related to the issues by means of 3D diagnostics

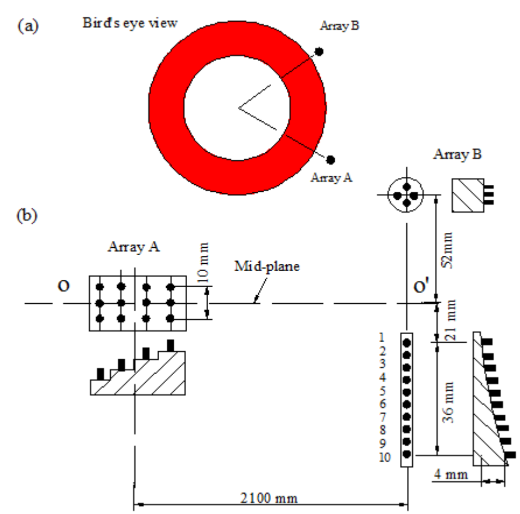
3D Langmuir Probe Arrays

3D Edge Physics Investigation

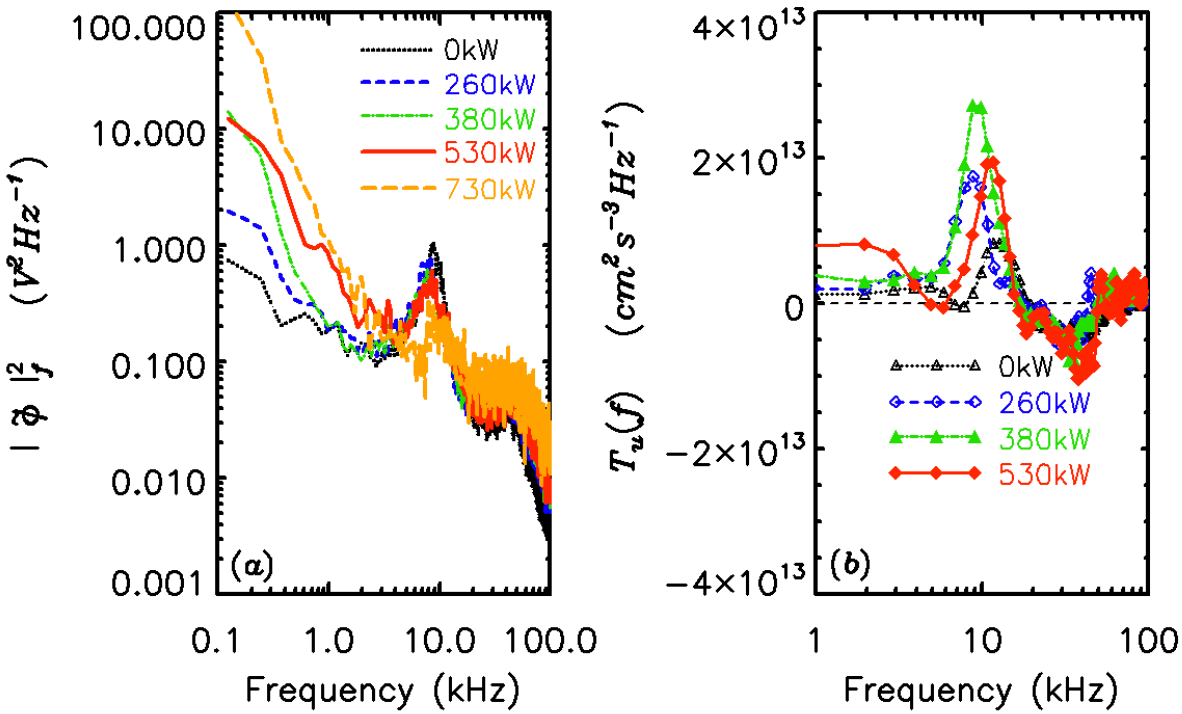


parameters measured simultaneously

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



Nonlinear Energy Transfer



nonlinear energy transfer rate

$$T_v(f) = -\mathrm{Re}\sum_{f_1}\left\langle \vec{v}^{\,*}_{\perp f}\cdot\left(\vec{v}_{\perp f-f_1}\cdot\nabla_{\perp}\vec{v}_{\perp f_1}\right)\right\rangle$$

M. Xu et.al. ***PRL 108****, 245001 (2012)*

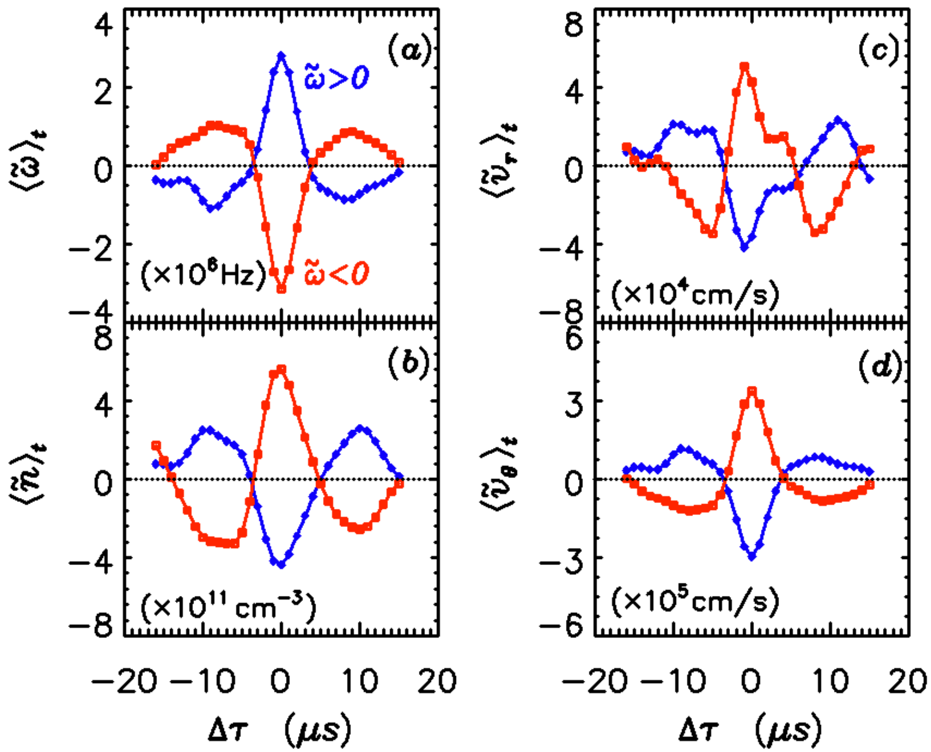
The increased energy of ZFs must come from nonlinear procceses because ZFs can not extract free energy out of the background gradient due to its' symmetry properties

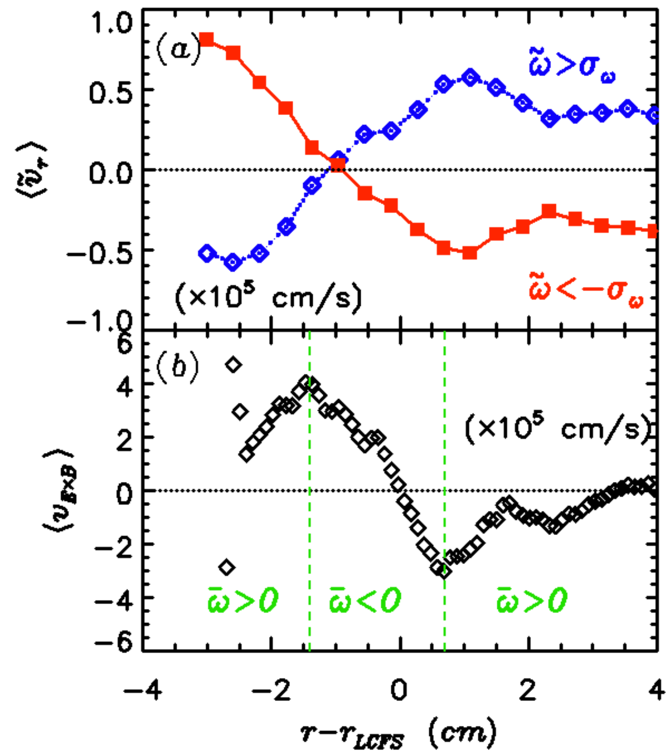
Turbulent kinetic energy was transferred into ZFs and GAMs→*the energy transfer into ZFs increases as heating power increases* → H mode with sufficient heating!

turbulence drives low frequency sheared flows

G.Tynan EX/10-3 Sat. 9:50 Oral

Vortices mediated momentum transport





Conditional average:

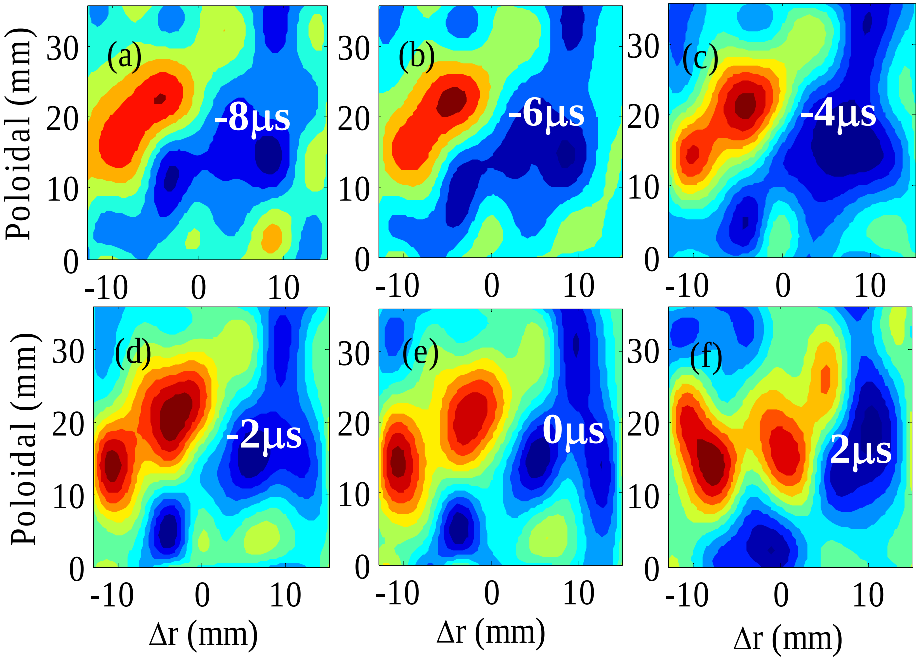
Negative eddies (i-dia., red) carry excessive positive momentum and concentrate around LCFS (at $r-r_{LCFS}$=-2.0 cm)

Vortices propagation naturally leads to a strong shear flow → *vorticity drive gets stronger as heating power increases*

→ L-H transition!

M.Xu EX/7-2Rb Thurs. 18:20 Oral

LSCS generation at the inner LCFS



dependent on the significant parallel correlation

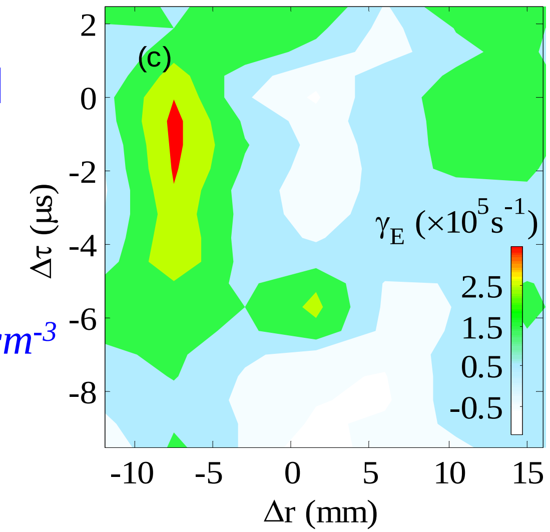
I_p: 160-170 kA

B_t: 1.8-1.9 T

n_e: 1.8-2.5 × 10^{13}cm^{-3}

q_{95}: 4.5-5.5

r/a: 0.96-1



Spatiotemporal evolution of E×B shearing rate

$$\gamma_E = (\partial E_r/\partial r)/B_t$$

Eddies amplitude increases firstly, it stretches and splits into two islands by strong E×B flow, finally blobs are ejected into SOL

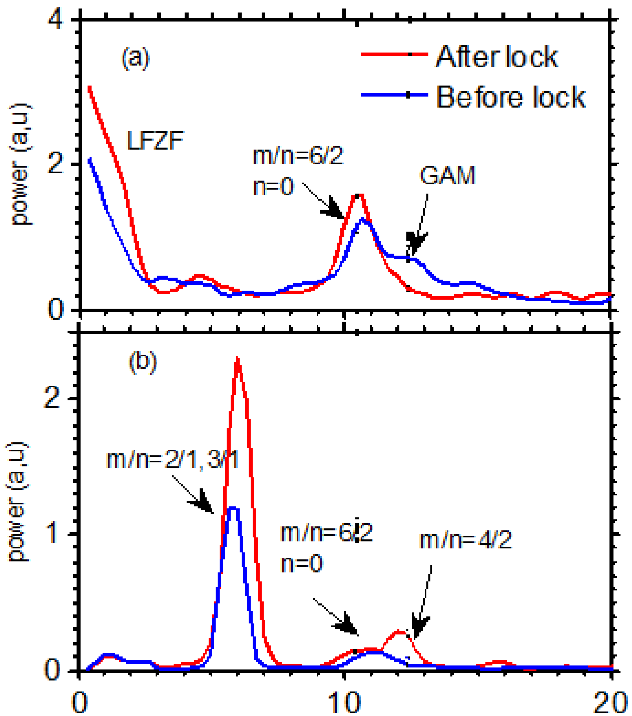
The flow shearing time at the LSCS birth place is identified to be close to the LSCS generation time (~8 μs)

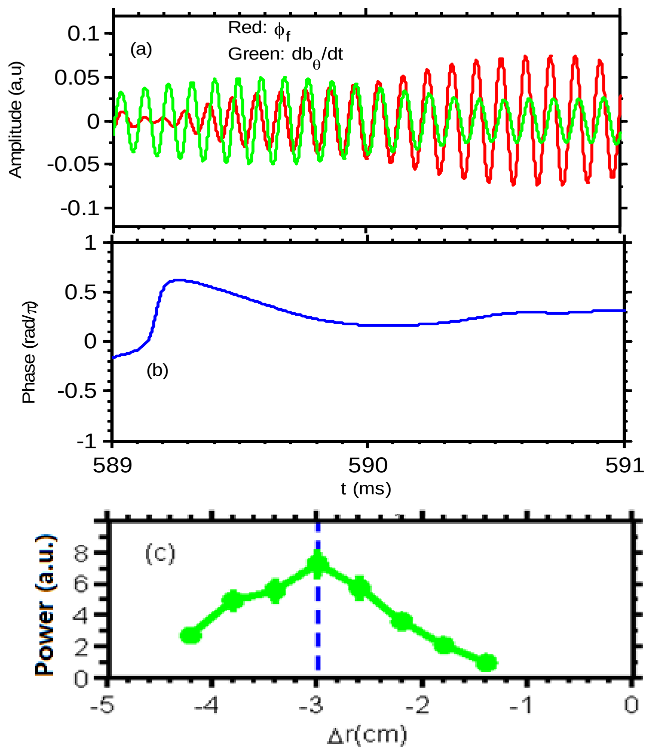
Shearing rate of GAM flow is only 28% of the mean flow shearing rate

J.Q.Dong EX/P7-07 Fri. AM

Synchronization of GAM & magnetic island

HL-2A





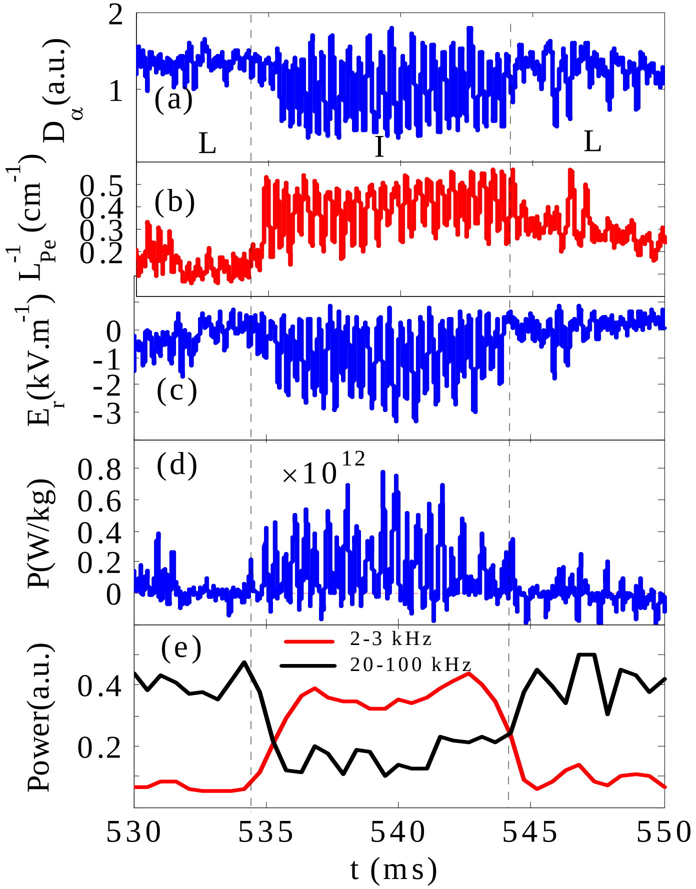
GAM frequency gradually decreases and synchronizes with magnetic island when the island width is above critical value.

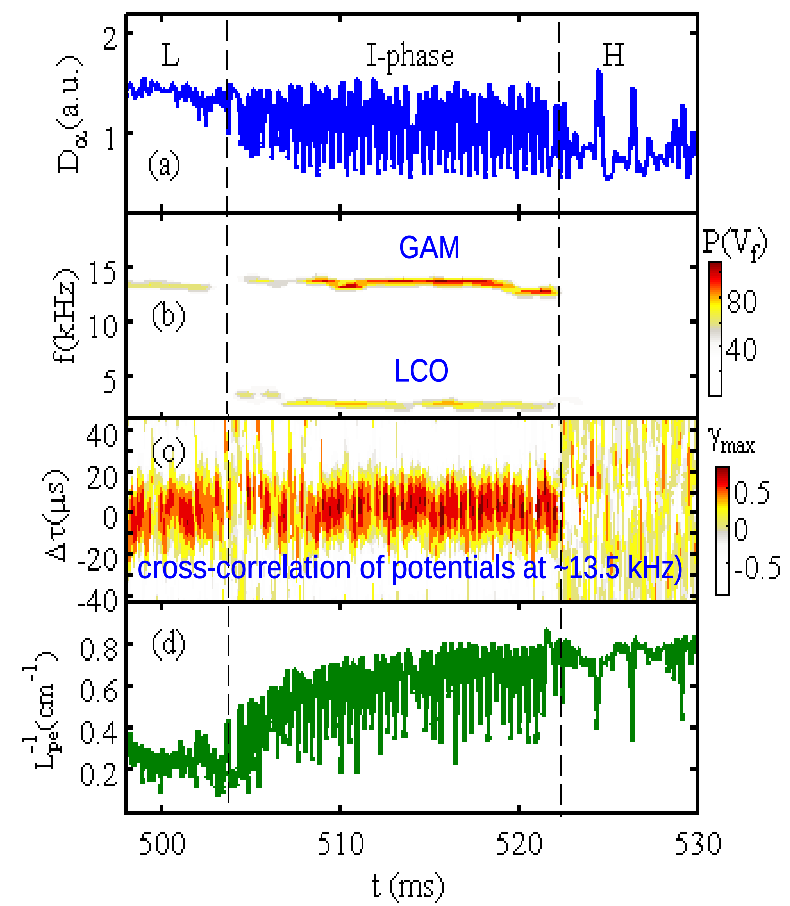
The phase lock between magnetic islands and GAM results in the generation of meso-scale electric fluctuation (MSEF), which peaks at q=3 and has both electric and magnetic field fluctuations at 10.5kHz.

Nonlinear synchronization may play an important role in energy transfer among waves

K.J.Zhao EX/7-2Ra Thurs. 18:20 Oral

Temporal evolution in L-I-L & L-I-H





Inverse scale length of electron pressure gradient: $L_{pe}^{-1} = -(\partial P_e/\partial r)/P_e$

Energy transfer rate: $P = R_s \langle \partial V_E/\partial r \rangle$

$R_s = \langle \delta V_r \delta V_\theta \rangle$

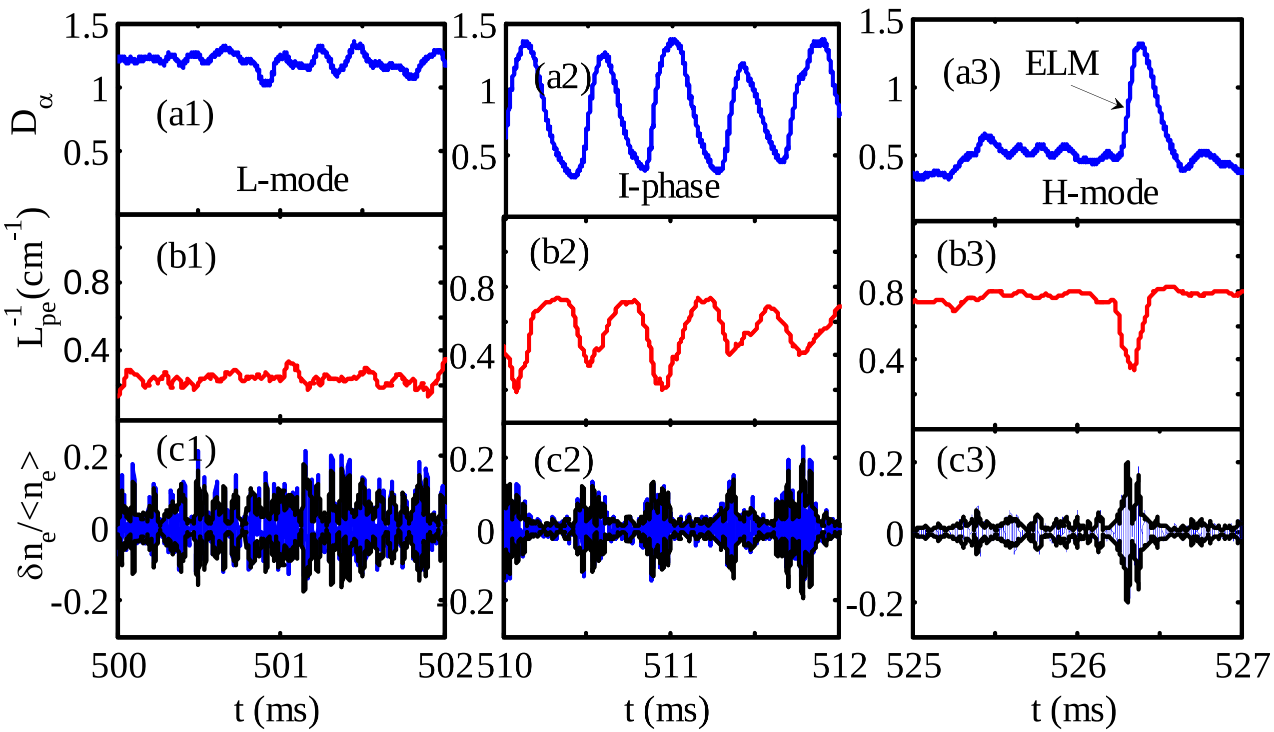
GAM can survive in I-phase, which is useful to suppress turbulence

The mean EXB flow is crucial to L-H transition

J.Cheng EX/P7-24 Fri. AM

Comparison of parameters in L, I and H phase

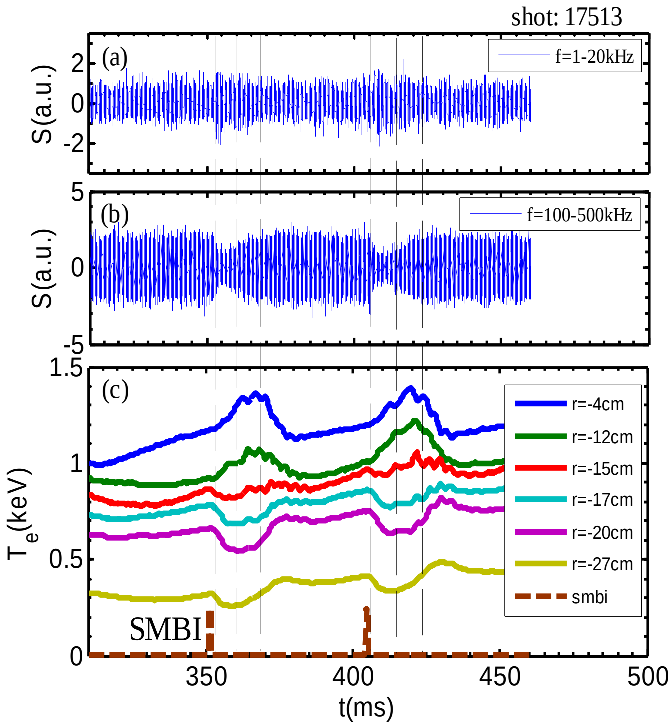
HL-2A



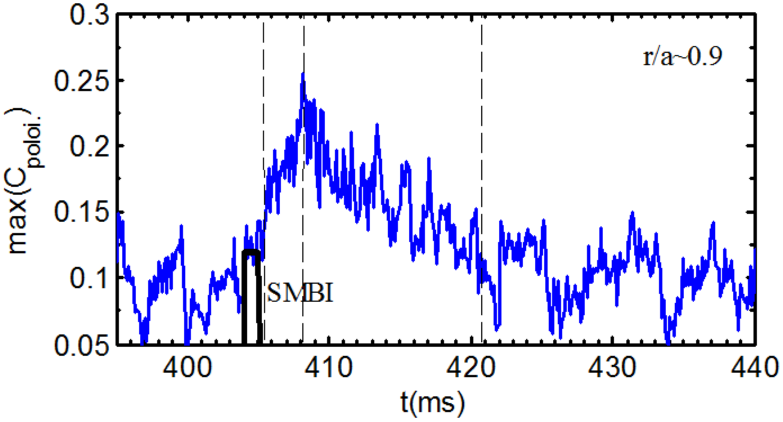
- *L-mode:* $\delta n_e/<n_e>$ is large (~20%)
- *I-mode:* $\delta n_e/<n_e>$ and GAM are modulated by 2-3 kHz oscillation
- *H-mode:* $\delta n_e/<n_e> < 5$ %, $\partial P_e/\partial r$ collapse is prior to ELM eruption
- *In H-mode*, 2-3 kHz oscillation and GAM disappear and another high frequency oscillation (f=50-60 kHz/m=15) appears in inter-ELM

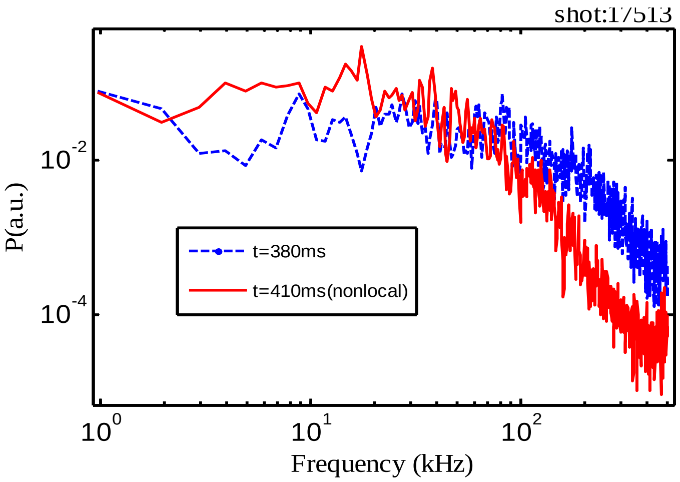
Turbulence suppression during nonlocal

HL-2A



The high frequency fluctuation (>100kHz) is obviously reduced with slightly increase of the low frequency fluctuation after SMBI is injected.





A clear increase of the poloidal cross-correlation (CCF) is observed during nonlocal central temperature rise.

B.Z.Shi EX/P7-13 Fri. AM

K.Ida OV/3-4 9:45

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Summary & Outlook

Since the last FEC, the experiments on HL-2A tokamak have been focused on the investigations on H-mode related physics including ELM mitigation and L-H transition mechanism, energetic particle physics and MHD instabilities, and L-H transition relevant turbulence and zonal flows, etc.

- ELM mitigation by SMBI/CJI

For the first time SMBI/CJI has been applied successfully to mitigate ELMs

- Energetic particle physics and MHD activities

1) LF multi-Alfvenic mode coexistance could be induced by energetic electrons

2) The e-fishbone frequency jump is observed in ECRH plasmas, where trapped particles dominate

3) Long lived-mode in NBI heated plasma could be suppressed by ECRH or SMBI

- L-H transition, turbulence and transport

Turbulent energy is transferred into ZFs & GAM, that increases with heating power.

Vortices propagation naturally leads to strong shear flow, which could lead to L-H transition

E$\times$B flow shearing is important for blob generation

The electron pressure gradient and energy transfer rate during L-I-H transition are investigated in detail.

Summary & Outlook

Recent development of diagnostics on HL-2A

- **FIR laser polarimeter for Faraday rotation measurement** (rotation angle: < 1° , temporal resolution: 0.1 ms)
- **MSE system for the magnetic and current profiles measurement** : temporal resolution: 3-5 ms
- **FM reflectometers** for density profile: 33-110GHz, X-mode, 10μs
- **Doppler reflectometers** for poloidal rotation and turbulence: 26-40 GHz, 40-60 GHz, hopping frequency, X-mode. 5ms one step.
- **Sweeping frequency ECE radiometer** (50-110 GHz, resolutions: 1 ms/3 cm)
- **EUV spectrometer** for the impurity line emissions (2-50 nm, temporal resolution: 6 ms),
- **Fast electron radiation measurement system** (9 channels, 20-200 keV)

Auxiliary heating systems on HL-2A

7.5 MW in use, *11 MW under development*

- ECRH: 68 GHz/ 1 s/ 3 MW
  140 GHz/ 2 s/ 2 MW
- NBI: 40 kV/ 20 A/ 1 s/ 1.5 MW
  55 kV/ 26 A/ 2 s/ 2 MW
  80 kV/ 45 A/ 5 s/ 5 MW
- LHCD: 2.45 GHz/ 1 MW
  3.7 GHz/ 4 MW

The improvement and development of the auxiliary heating and diagnostic systems will enhance the ability for plasma physics study and make contribution to the ITER related physics such as H-mode and energetic particle physics

Other experimental results not included in the Overview could be found in the following presentations

EX/P2-05 Sun, Aiping *(Plasma rotation)*

EX/P3-20 Zhong, Wulu *(ELM free H-mode)*

EX/P4-11 Yu, Deliang *(fueling)*

EX/P6-13 Liu, Yi *(BAAE)*

EX/P8-15 Zhang, Yipo *(runaway electrons)*

EX/P2-15 Song,Xianming *(ECRH assisted startup)*

EX/P3-21 Cui,Zhengying *(impurity transport)*

EX/P4-29 Huang, Yuan *(ELM features)*

EX/P7-08 Liu, Chunhua *(L-H triggering)*

Thank you !