Operation of HL-2A Tokamak

planed talk for X. R. Duan

HL-2A team

Presented by

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Outline

- 1, Introduction
- 2, Heating system

  ECRH, NBI,LHW
- 3, Fuelling system

  Gas Puffing, Pellet Injection (PI),

  Supersonic Molecular Beam Injection (SMBI)
- 4, H-mode operation

  ELMy H-mode discharges, ELM-free H-mode discharges

  ELM mitigation/suppress by SMBI or PI fuelling
- 5, other physics experiments

  Transport Studies, Zonal flow and turbulence

  Energetic particle physics, MHD control with ECRH
- 6, Summary

1, Introduction

HL-2A divertor tokamak

Designed: R = 1.65m, a = 0.4m; D.Q.Liu, Fusion Engineering and Design **66/68** (2003) 147-151

Bt=2.8T, Ip=480kA ; Yong Liu, *Nucl. Fusion* **44** (2004) 372-375

Obtained: Bt=2.7T, Ip=450kA, T_{e0} ~ 4.9keV by ECRH, T_{i0} ~ 2.8keV by NBI

Achievements

The plasma discharge with divertor configuration was realized, for the first time in china, in 2004; Yong Liu, *Nucl. Fusion* **45** (2005) S239-S244

The typical ELMy H-mode operation under divertor configuration was realized, for the first time in china, in the spring of 2009;
X. R. Duan, *Nucl. Fusion* **50** (2010) 095011

Mission

L-H transition dynamics, Type-I ELM mitigation/suppress,

zonal flow and turbulence characteristics, energetic particles and MHD control,

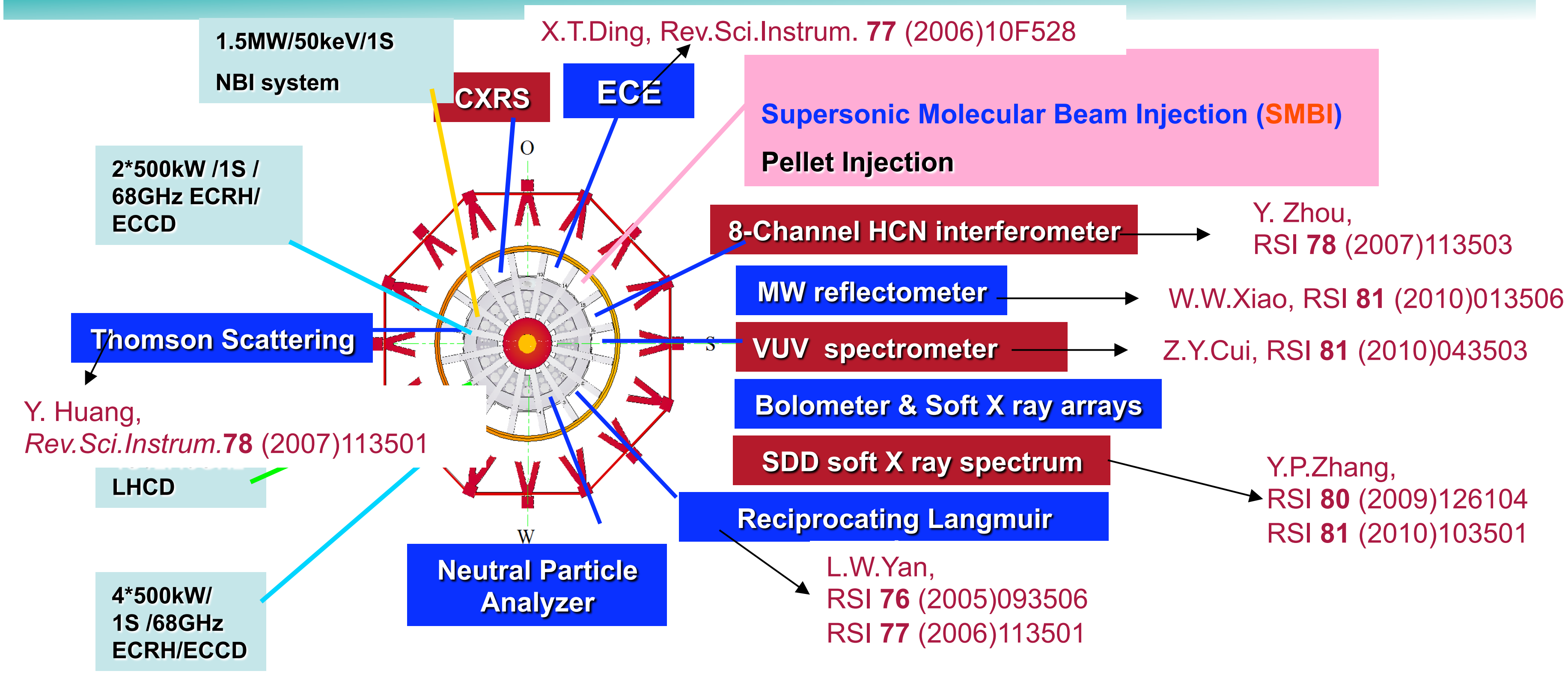
divertor and scrape-off layer physics, and so on

Yong Liu, *Nucl. Fusion* **45** (2005) S239-S244

X.R.Duan, *Nucl. Fusion* **49** (2009) 104012

1, Introduction

More 30 kinds of diagnostics



1.5MW/50keV/1S
NBI system

CXRS

ECE

X.T.Ding, Rev.Sci.Instrum. **77** (2006)10F528

Supersonic Molecular Beam Injection (SMBI)

Pellet Injection

2*500kW /1S / 68GHz ECRH/ ECCD

8-Channel HCN interferometer

Y. Zhou,
RSI **78** (2007)113503

MW reflectometer

W.W.Xiao, RSI **81** (2010)013506

Thomson Scattering

VUV spectrometer

Z.Y.Cui, RSI **81** (2010)043503

Bolometer & Soft X ray arrays

Y. Huang,
*Rev.Sci.Instrum.***78** (2007)113501

LHCD

SDD soft X ray spectrum

Y.P.Zhang,
RSI **80** (2009)126104
RSI **81** (2010)103501

Reciprocating Langmuir

4*500kW/ 1S /68GHz ECRH/ECCD

Neutral Particle Analyzer

L.W.Yan,
RSI **76** (2005)093506
RSI **77** (2006)113501

***ne*: measured by an 8-channel HCN laser interferometer, Langmuir probe and O-mode reflectometer.**

***Te*: Thomson scattering, ECE, Langmuir probe and energy spectrum of soft X-rays.**

***Ti*: charge exchange recombination spectroscopy (CXRS) and multi-channel energy spectrum of neutral particles .**

neutral gas pressure: Fast Ion Gauge

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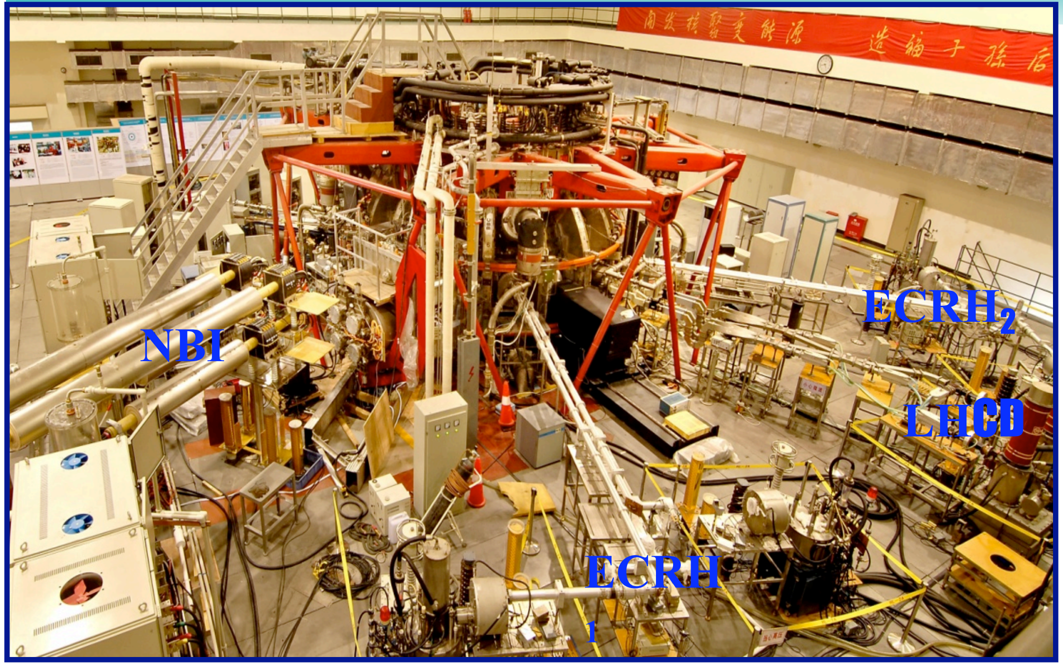
2, Auxiliary heating

ECRH system



PSM HV power supply:

50kV/22A;

using IGBT, a step of 800V;

Control of ECW power output;

fast response, fast protection;

L.Y.Yao, this meeting, **SP3-42**

ECRH/ECCD: 3.0 MW /68GHz, 6 gyrotrons, installed in low field side

M.Huang, 37th EPS Conference on Plasma Physics(2010) P5.166

Gyrotron output: horizontal linear polarization, Gaussian beam, 98% mode purity

modulation: frequency=10~50 Hz; duty cycle=10~100 %

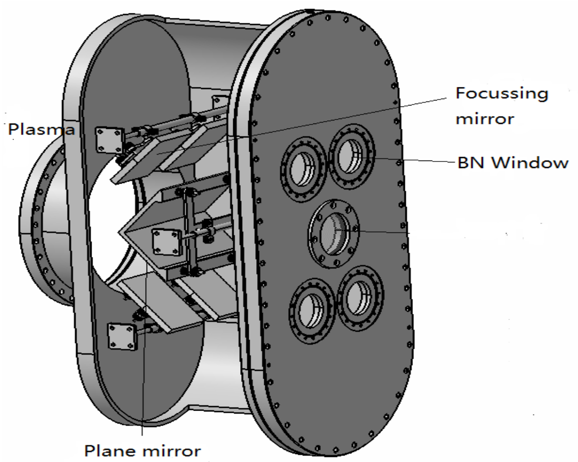
Polarizer: sinusoidal grooved polarizer was developed to realize second harmonic X2-mode ECW injection for Bt of 1.1~1.42 T.

ZHANG Guoqing, Plasma Science and Technology **11**(2009) 619

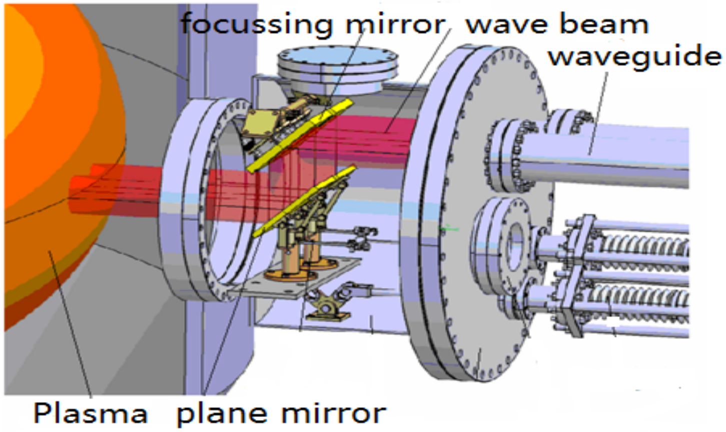
2, Auxiliary heating

ECW launcher

- **launcher 1# for 4 wave beams**
- **A fixed focusing mirror;**

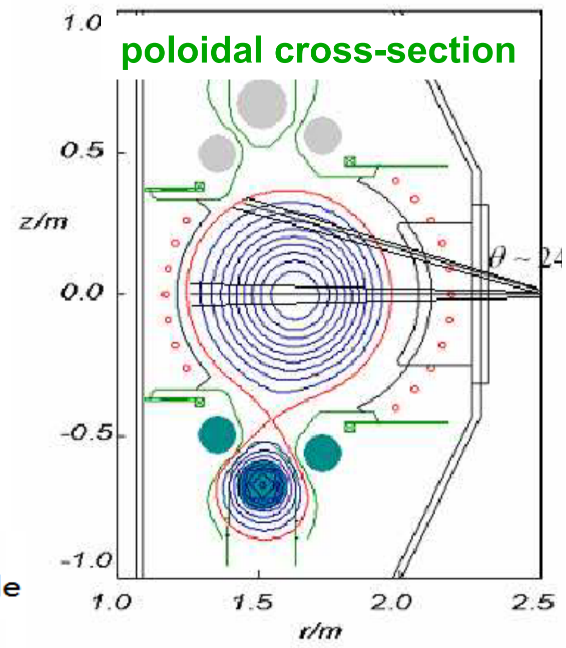


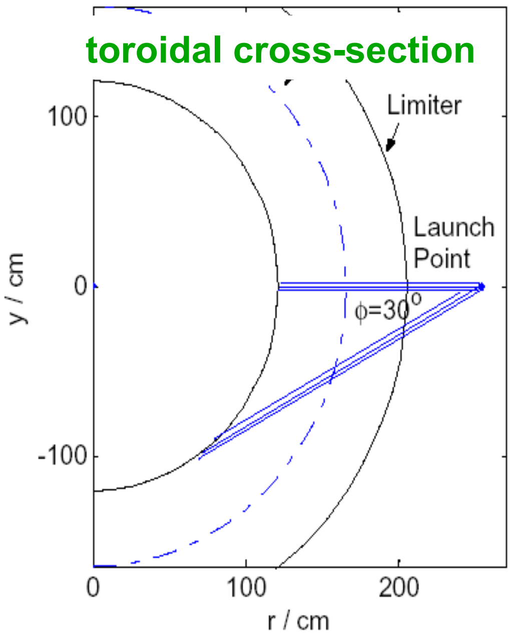
- **launcher 2# for 2 wave beams**
- **A steerable mirror.**
- **Remote controllable**



Port: 350 mm in diameter

Beam radius: 37mm in the center of plasma


poloidal cross-section

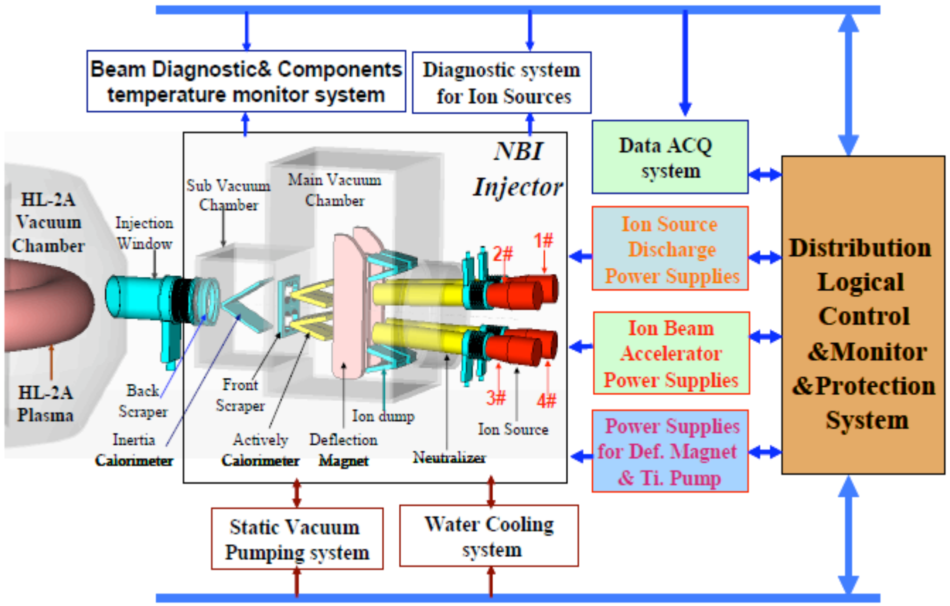

toroidal cross-section

Injection angle of launcher 2#: 0^0-30^0

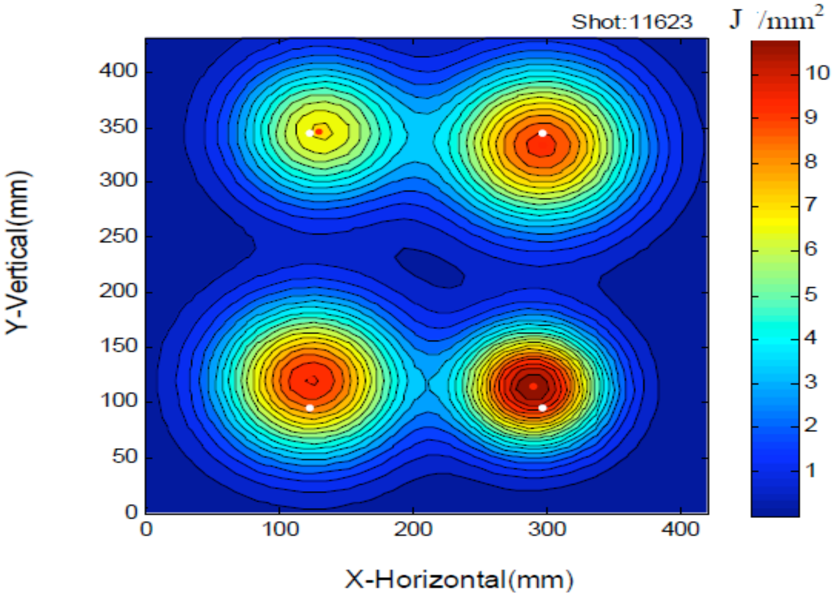
Poloidally changed for	**Toidally changed for**
On-axis / off-axis heating	**Current drive**

2, Auxiliary heating

1.0MW/45keV NBI System



Setup of 1.0 MW-beamline in the HL-2A tokamak.



Beam energy density profile on inertia target

Particle energy: ~ 35KeV, 65 % D-atom

Injection angle : 57^0 toroidally.

NBI power: ~ 800kW

Main parts: 4 positive ion sources, neutralization ducts, ion dumps, calorimeter, scrapers, calorimeter, Ti-pumps and so on.

ZOU Guiqing, Chin.Phys.Lett. **26**(2009) 082901
YU Liming, Chin.Phys.Lett. **27**(2010) 042901

calorimeter: totally 28 thermocouples. 7 thermocouples for each ion source. The beam energy density profile and beam divergence can be obtained. The minimum divergence angle is about 1.1^0 at optimized discharge conditions

calorimeter energy scaling law: obtained from extensive test experiments, which is utilized to get the NBI power injected into HL-2A plasma

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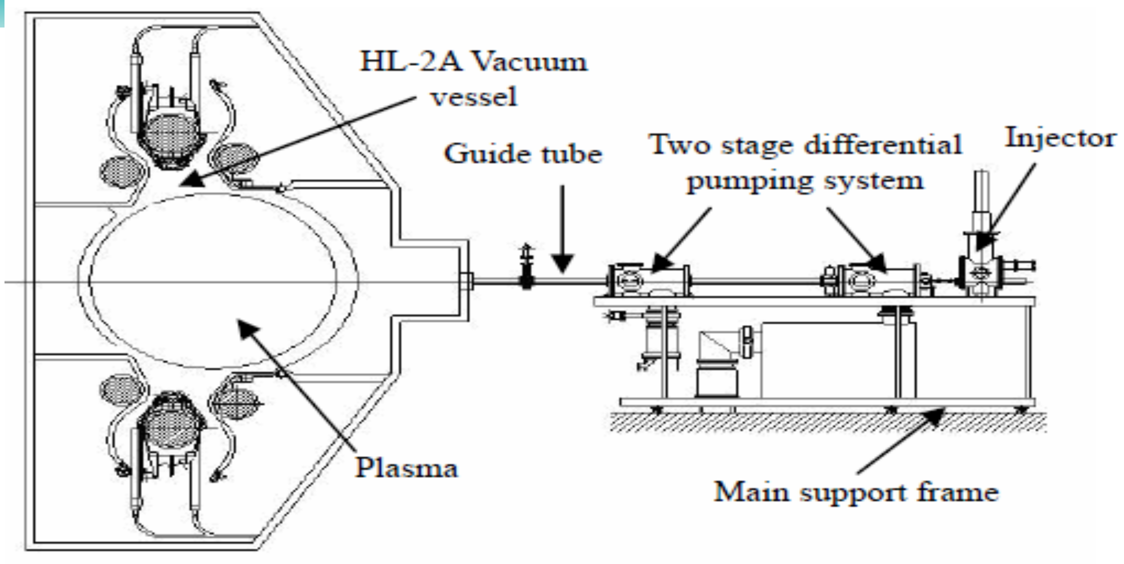
3, Fuelling System

Pellet Injection



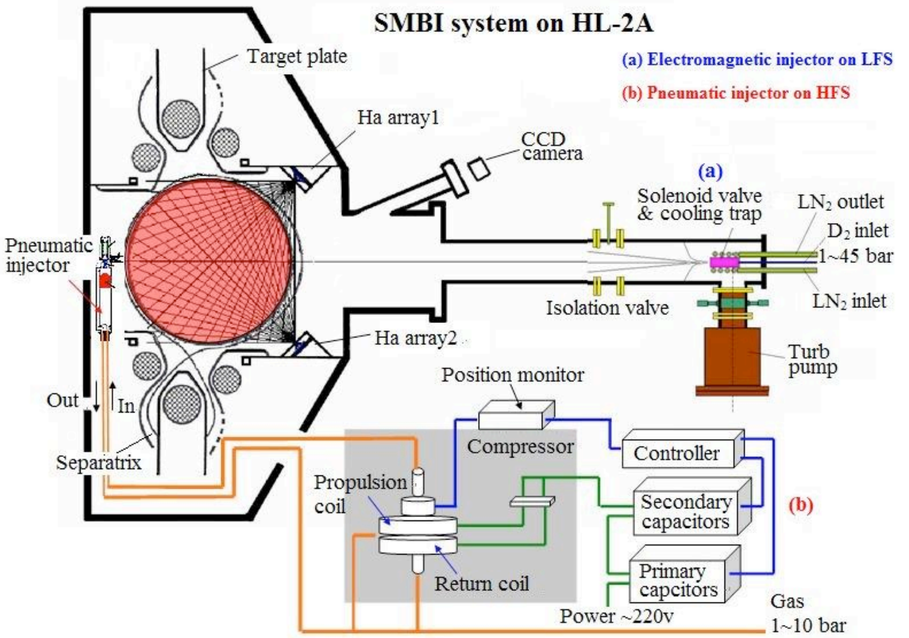
Schematic drawing of pellet fuelling system

Pellet injector:

based on the extrusion technology and injection from LFS;
working gas: H2/D2
can produce 1-40 solid pellets in one injection cycle;
frequency of 1~30 Hz;
pellet size of D= 1.3 mm and L = 1.3~1.7mm;
pellet velocity: variable in 150~1000 m/s

In recent two years, 3~5 deuterium pellets (time interval of 50~100 ms, velocity of 200~400 m/s) during a discharge were injected into L-mode or H-mode plasmas.

Supersonic Molecular Beam Injection



Experimental setup of the SMBI system with both LFS and HFS injection on HL-2A

SMBI/LFS: **using electro-magnetically driven valve with a cylindrical hole of diameter~0.2 mm to generate a supersonic molecular beam**

SMB characteristics: **measured by three Da arrays and a CCD camera**

Valve temperature: **room temperature; liquid Nitrogen cooled, cluster may be easily formed.**

Two gas tanks: **H2/D2; He/Ne/Ar**

Gas pressure: **0.2 – 4.0MPa**

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

L.H. Yao, *Nucl. Fusion* **47** (2007)1399

SMBI was first successfully developed and used on the HL-1M tokamak and then used on many other fusion devices.

L.H. Yao, *Nucl. Fusion* **41** (2001) 817

L.H. Yao, *Nucl. Fusion* **44** (2004) 420

L.H. Yao, *Chin.Phys.B* **16** (2007) 200

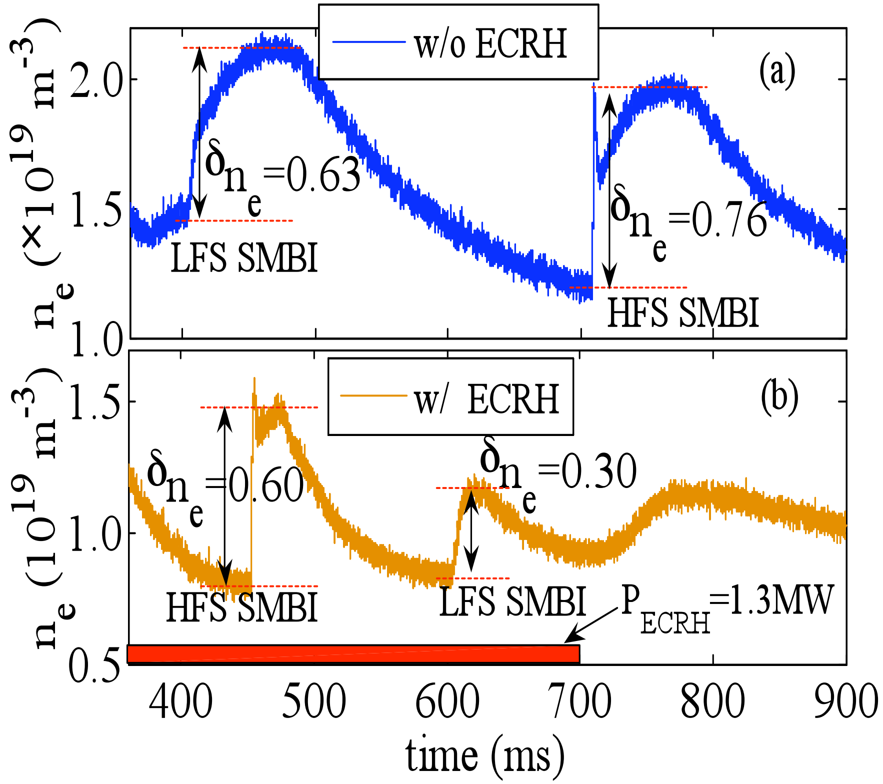
SMBI/HFS: using a pneumatic injector, in which accelerated pistons are used to compress the working gas and then open the Laval nozzle.

Gas pressure: 0.2–1.0MPa

Pulse duration: ~5 ms @5-10 Hz

3, Fuelling System

Fuelling by using SMBI



D. L. Yu, *Nucl. Fusion* **50** (2010) 035009

L.H. Yao, *Nucl. Fusion* **44** (2004)420

advantages: high fuelling efficiency and low recycling effect, enhanced penetration depth when compared with gas puffing.

fuelling efficiency:

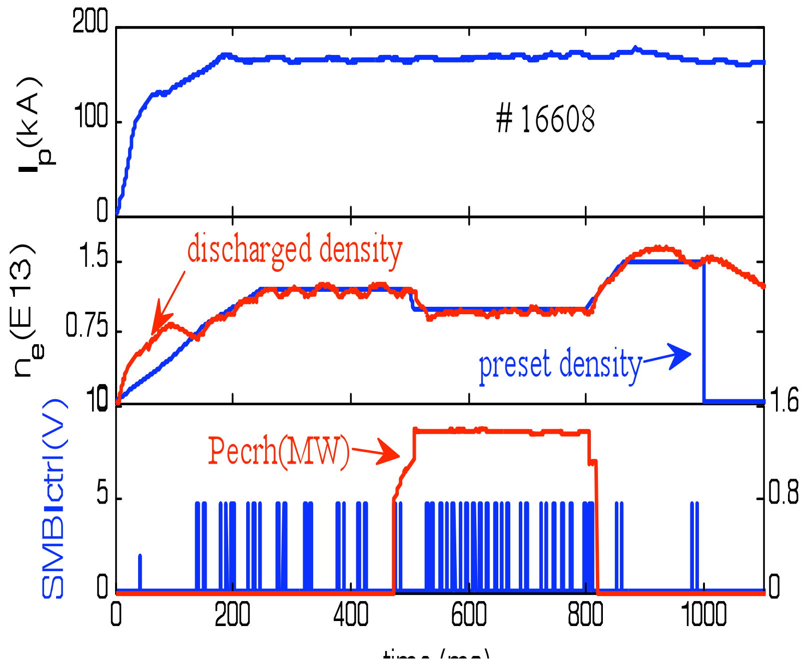
(a) SMBI fuelling is more efficient from HFS than from LFS;

(b) if fuelling for 1.3 MW ECW heated plasma, the efficiency reduces a little from HFS but drops about a half from LFS.

The fuelling efficiency of LFS-SMBI into ohmic plasma is estimated as 40~60% for a limiter configuration and 30-40 % for a divertor configuration.

3, Fuelling System

density control by using SMBI



Feedback control of decreasing density by combination of SMBI and ECRH.

- Because of high fuelling efficiency and low recycling effect, SMBI is used in feedback control of increasing and sustaining the density.
- Sometimes, the density needs to be actively decreased. The combined utilization of SMBI and ECRH is utilized to explore such experiments, due to their recent improvements on flexibly and reliably controlled output parameters.

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- **4, H-mode operation**

  Requirements to reduce $P_{L\text{-}H}$

  ELMy H-mode discharges

  ELM mitigation/suppress by SMBI or PI fuelling

  ELM-free H-mode discharges
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H-mode operation:

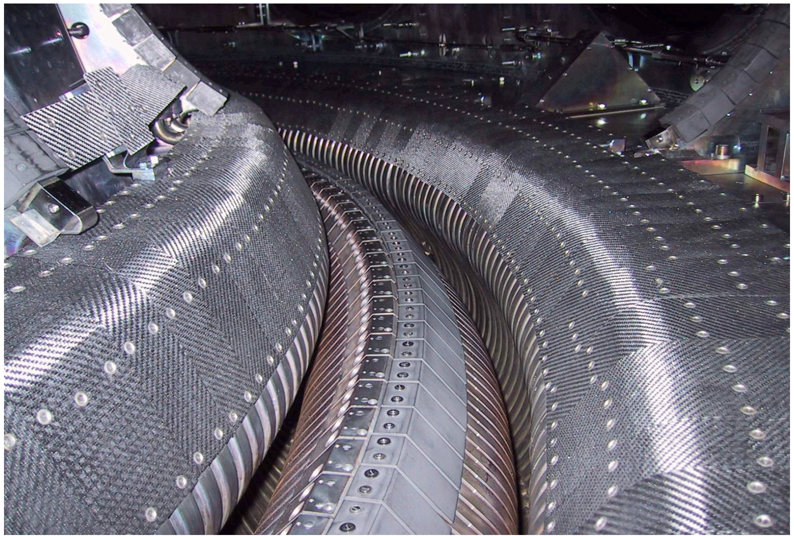
Requirements to reduce P_{LH}

$$P_{\mathrm{LH}} = 0.042 n_{20}^{0.73} B_{\mathrm{t}}^{0.74} S^{0.98}\ (\mathrm{MW})$$ (n_{20}> the n_{min})

scaling law: the power threshold for triggering an L-H transition, depends on magnetic field, density, plasma surface;

Other factors: bulk ion species, wall condition, fueling location, the direction of ion magnetic gradient drift, impurity content …

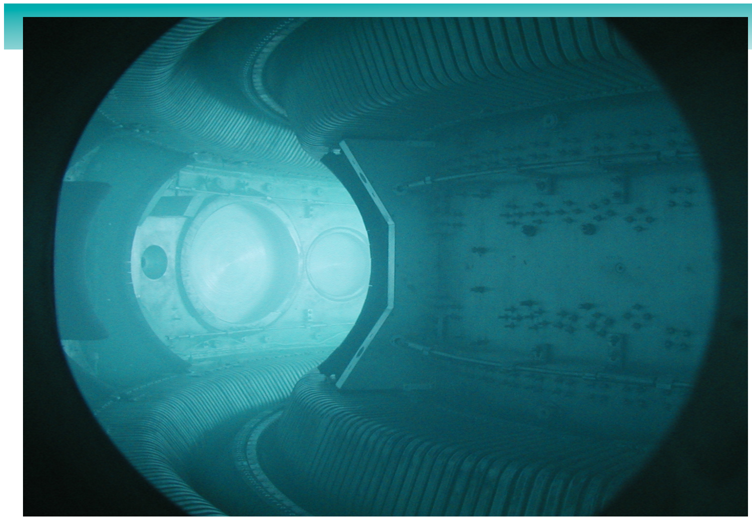
- **D2 as working gas;**
- **LSN divertor configuration;**
- **Ion Grad-B drift towards the lower X-point**
- **Wall conditioning;**
- **Discharge control**

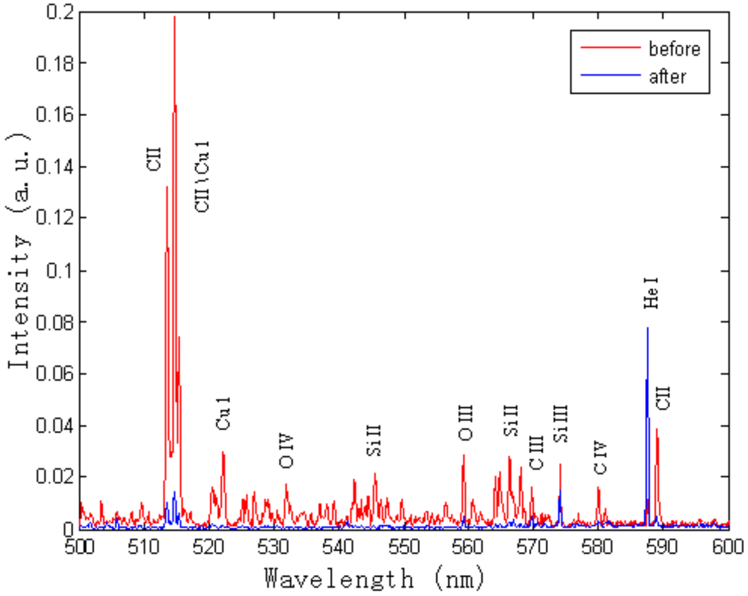


the surface of the shielding plates for the MP1 and MP2 coils are covered with carbon fibre composite (CFC), which can protect the first wall and effectively shield the splash of metal impurities.

H-mode operation:

reduce P_{LH} by Wall conditioning





D2 glow discharge cleaning is applied to remove impurities from the wall,

He-GDC for removing residual H2/D2;

Titanium gettering in the divertor region;

Siliconization by stable DC glow discharge with a gas mixture of 90% He + 10% SiD4

The impurity fluxes, released from the first wall after siliconization, are reduced, especially those of the oxygen and high Z impurities;

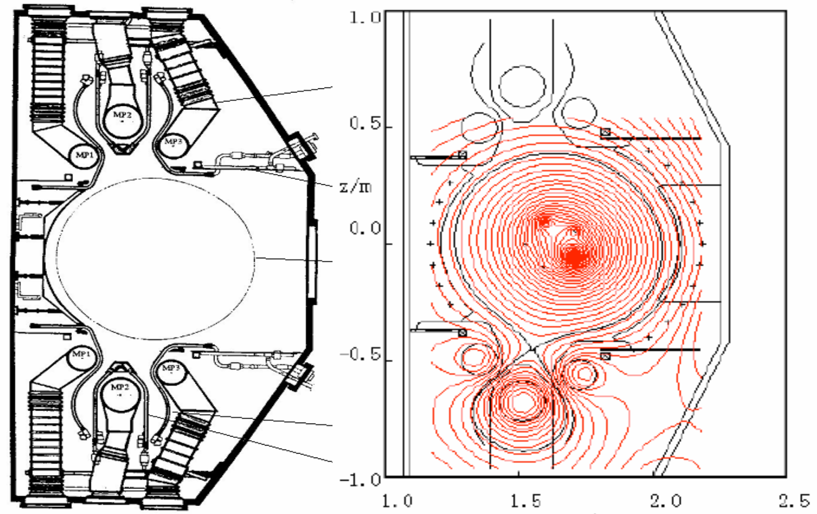
The total radiated power is decreased much.

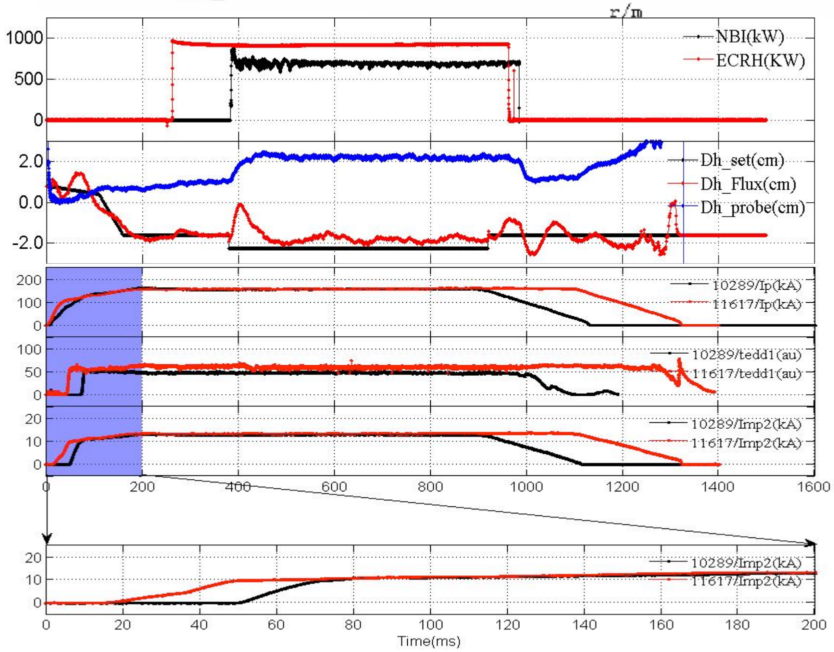
Cui. Zhengying, *Chin.Phys.B* **18** (2009) 3473

Q.W.Yang, *Nucl. Fusion* **47** (2007) S635-S644

H-mode operation:

reduce P_{LH} by Discharge control





Plasma Surface Interaction is usually strong in HL-2A due to the narrow throats(<2 cm) between the dome and the buffer plates of divertor.

Divertor configuration is formed as soon (<20 ms) after the plasma startup, in order to reduce impurity and radiation level;

Magnetic flux loop is used to guarantee the accurate measurements of plasma displacement during discharges under divertor configuration

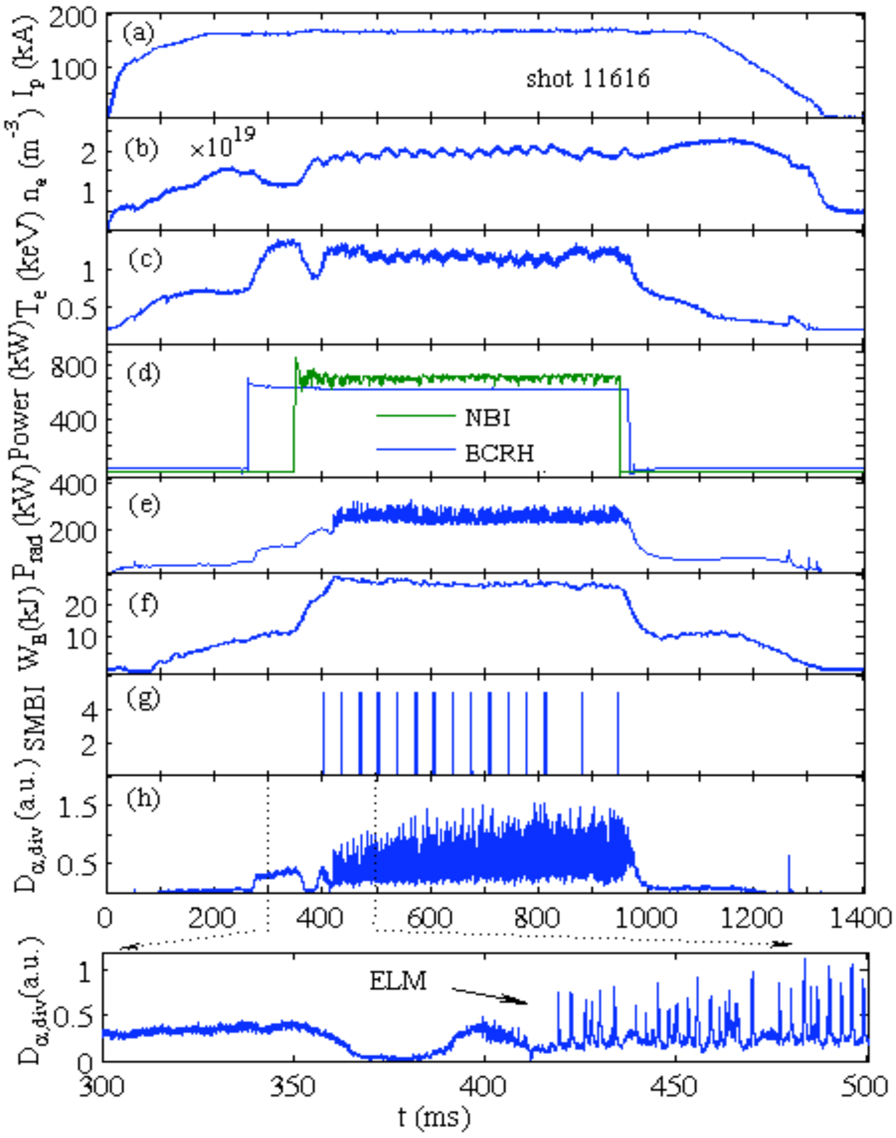
plasma displacement signal is calculated by using CF code in real time during plasma discharge , and configuration reconstruction is routinely performed by using EFIT code to monitor the variation of the separatrix for control improvement.

X.M.Song, Fusion Engineering and Design. 66-68(2003) 815

F. Xia, this meeting, **SP1-30**

H-mode operation:

First H-mode operation was achieved in 2009 spring experiments



- **First ELMy H-mode** operation in China was realized under LSN divertor configuration.

  X. R. Duan, *Nucl. Fusion* **50** (2010) 095011

In left figure of shot #11616:

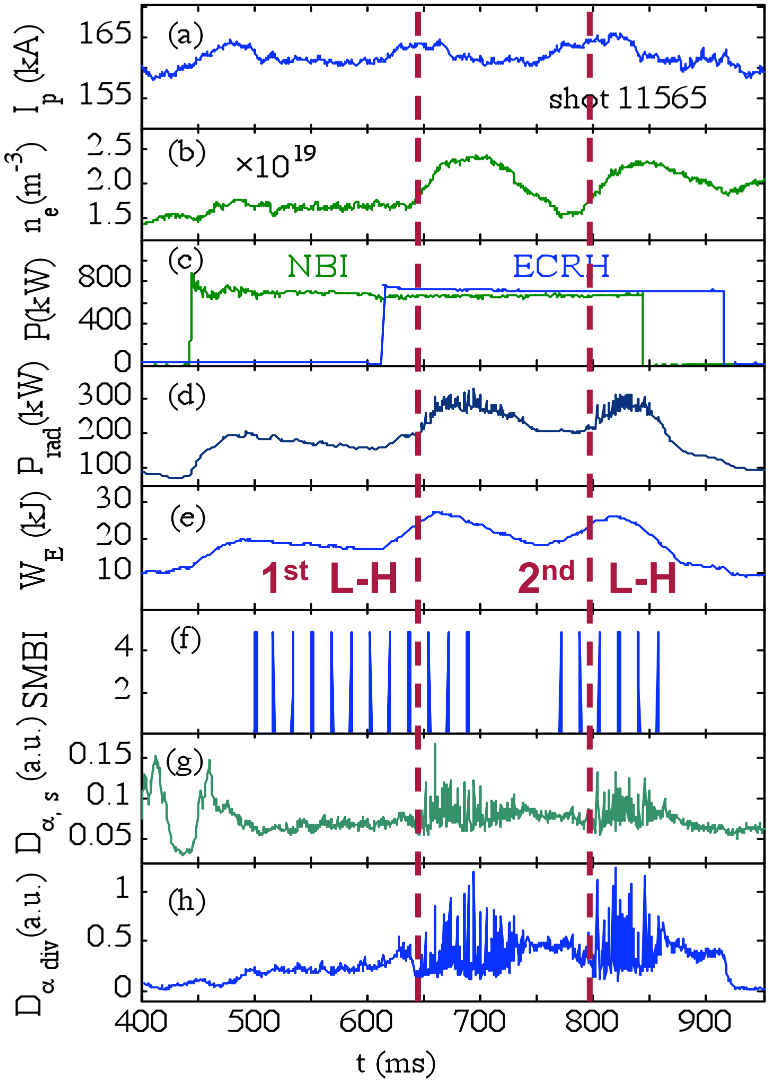
NBI and X2-mode ECRH at Bt ~ 1.3T;

- **Density control** is found being necessary, because the cutoff of X2-mode ECW at ne> 2.2×10^{13}cm^{-3};
- **Density pumping out** effect occurs obviously after P_{ECRH}=0.6 MW launched into plasma at t = 260 ms;
- **L-H transition** occurred soon after P_{NBI}=0.7 MW, at proper density;
- **ELMy H-mode** sustains ~550ms until auxiliary heating power ended;
- **Density pedestal width** is measured to be about 3 cm.

H-mode operation:

Multiple L-H transitions

induced by the SMBI fueling



- **1st L-H transition:** the ELMs appear at 640 ms with ne=1.8×10^{13} cm^{-3};

  then disappear after the SMBI is turned off, due to the cutoff of X2-ECRH power at ne>2.2× 10^{13} cm^{-3}.

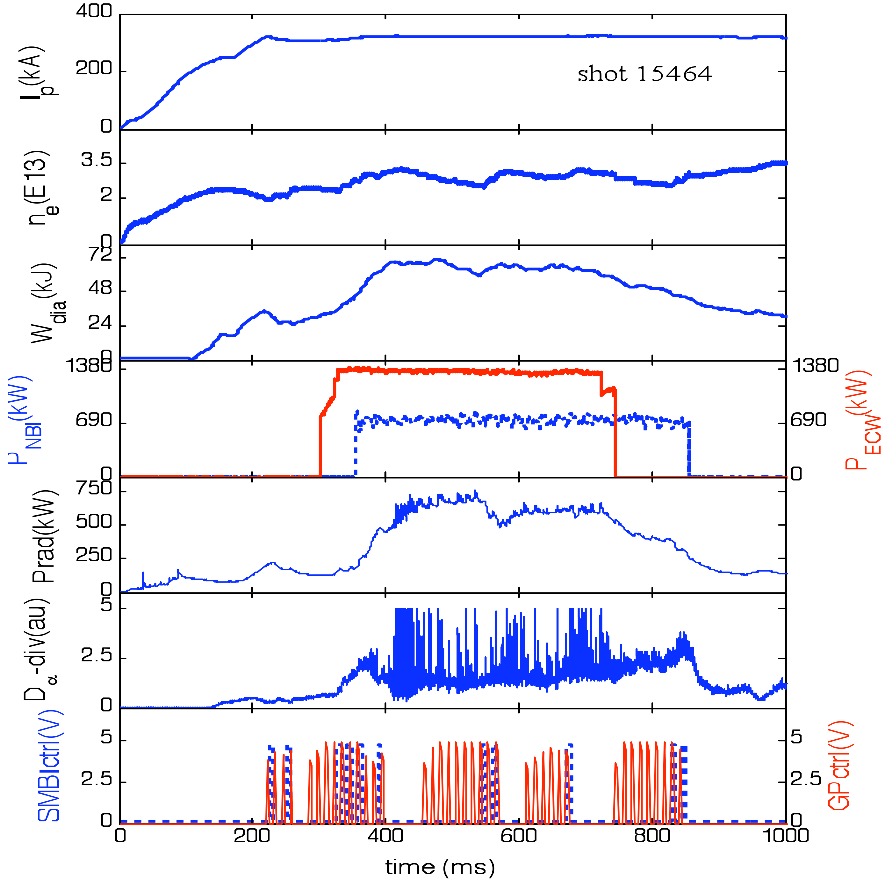
- **2nd L-H transition:** by using SMBI fuelling, the ELM appears at 793 ms with a density ~1.7×10^{13} cm^{-3}.

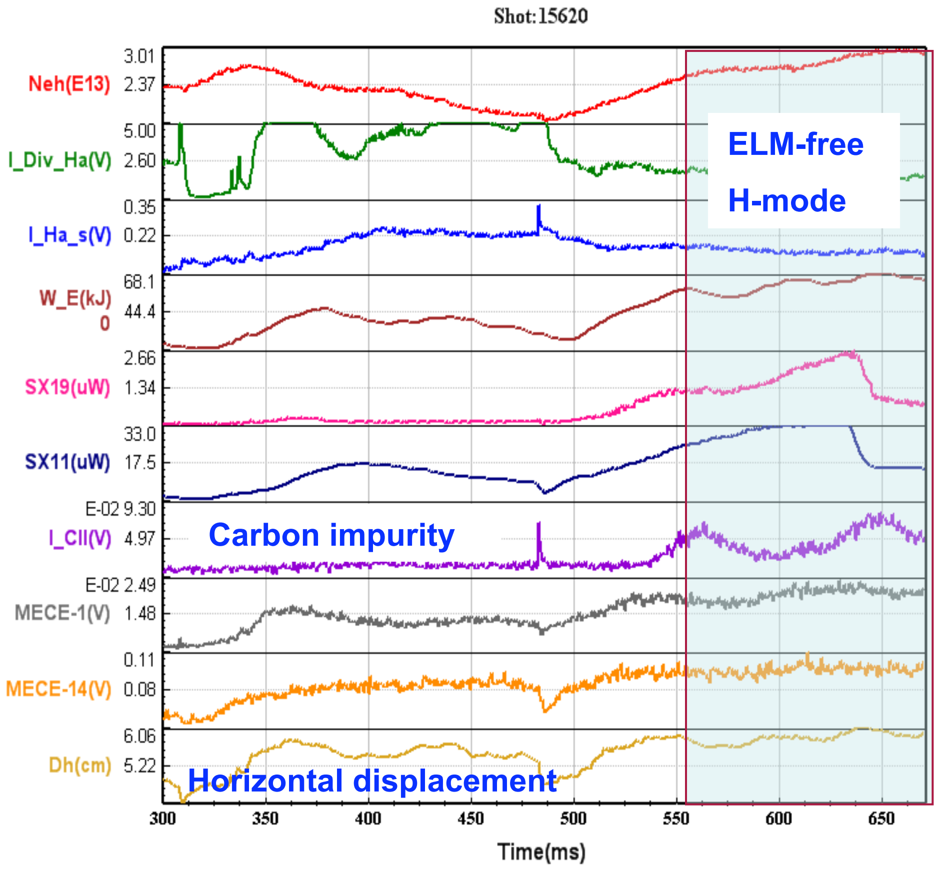
- The overall discharge exhibits a series of L-H-L-H-L transitions induced with SMBI fueling, which is interesting for the studies of L-H transition and H-L transition;

- The occurrence of 2nd L-H transition may be controllable by SMBI fuelling, as so using fast scanning Langmuir probe to study L-H transition physics.

H-mode operation:

Boundary of H-mode operation
is extended





ELM-free

H-mode

Carbon impurity

Horizontal displacement

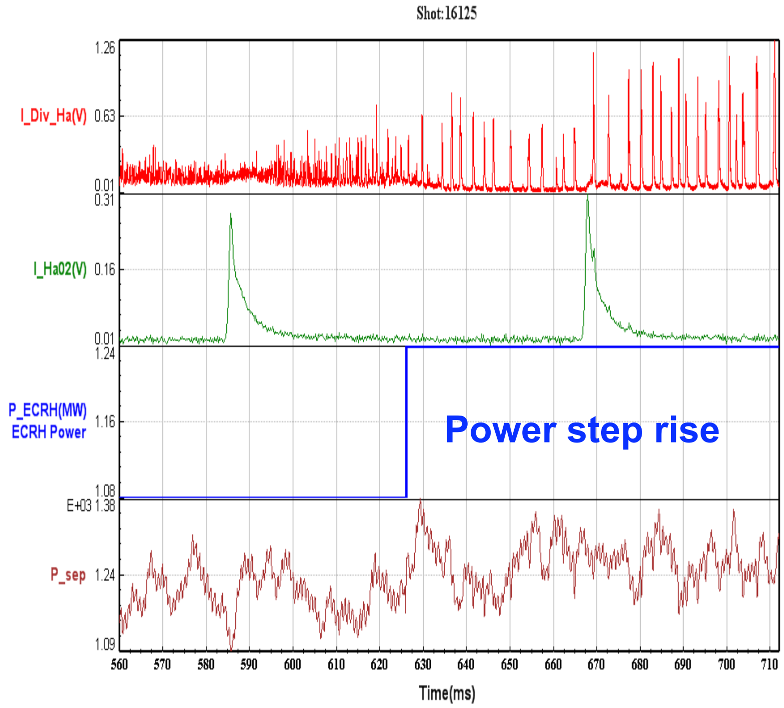
ELMy H-mode is also obtained by combination of NBI and O1-mode ECRH at Bt ~ 2.4T

ELM-free H-mode was obtained in shot #15620 by both NBI and O1-mode ECRH, its H_{89} factor is about 1.3

EHO-like characters were observed

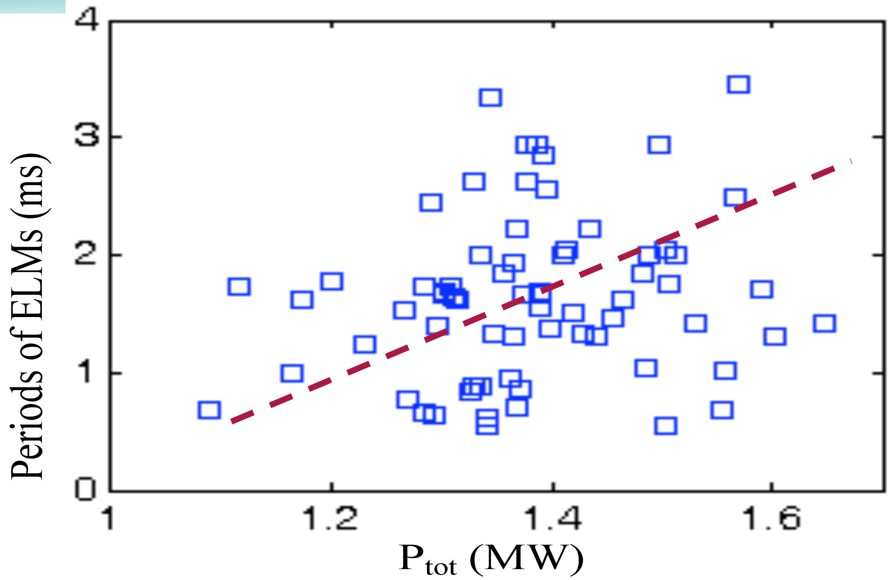
H-mode operation:

Type-III ELMs



in the shot #16125, ELM frequency decreases with heating power increasing

➢Type-III (small) ELMs



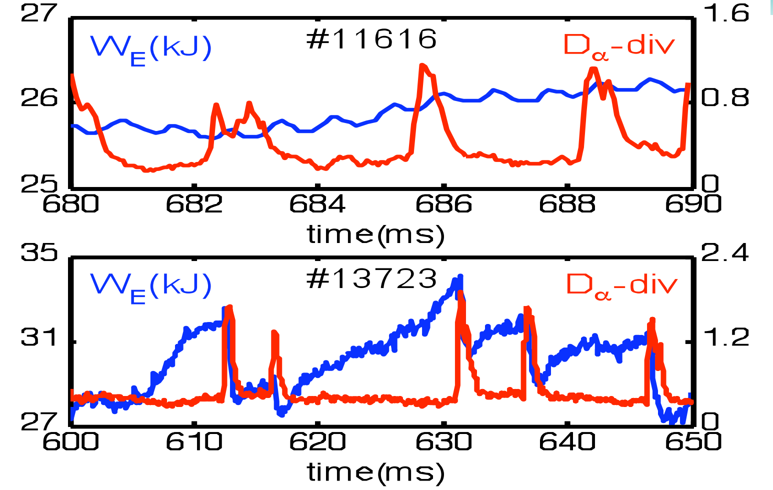
- By increase of total heating power, the time intervals of ELMs tend to increase, i.e. ELM frequency decreases.

  Type-III (small) ELMs.
- The periods should rely on edge plasma pressure and density profiles even if the heating power and line-averaged density are fixed.

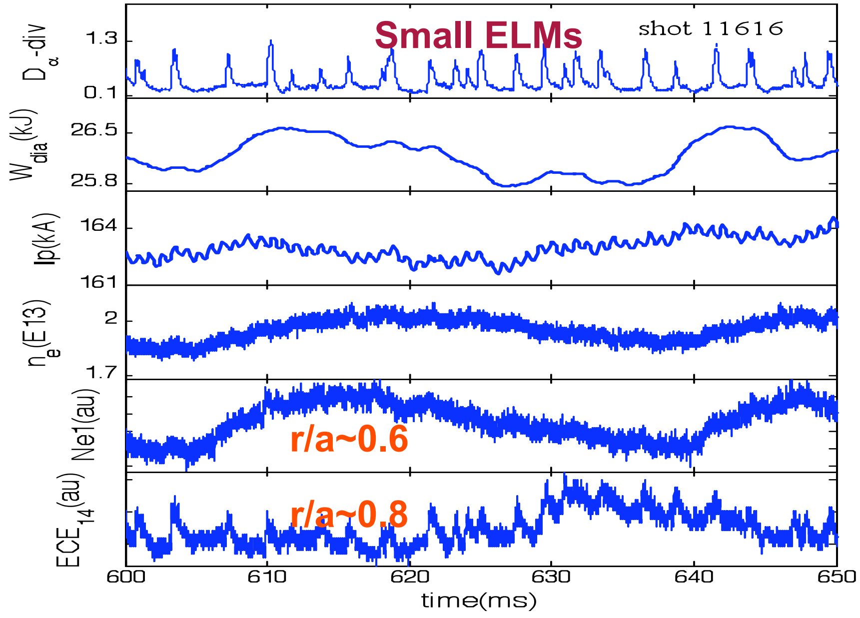
Y. Huang, *Chin.Phys.B* **20** (2011) 055201

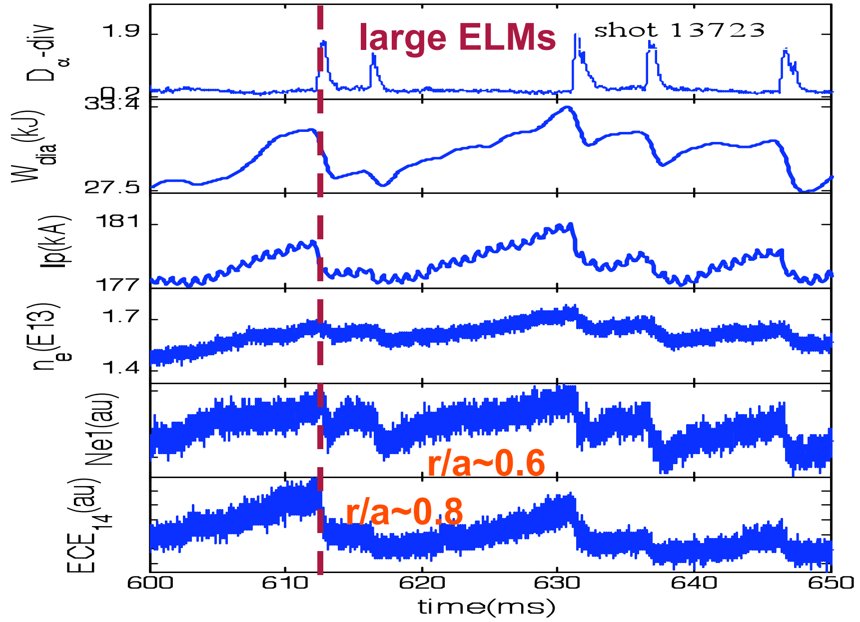
H-mode operation:

Comparison of large / small ELMs



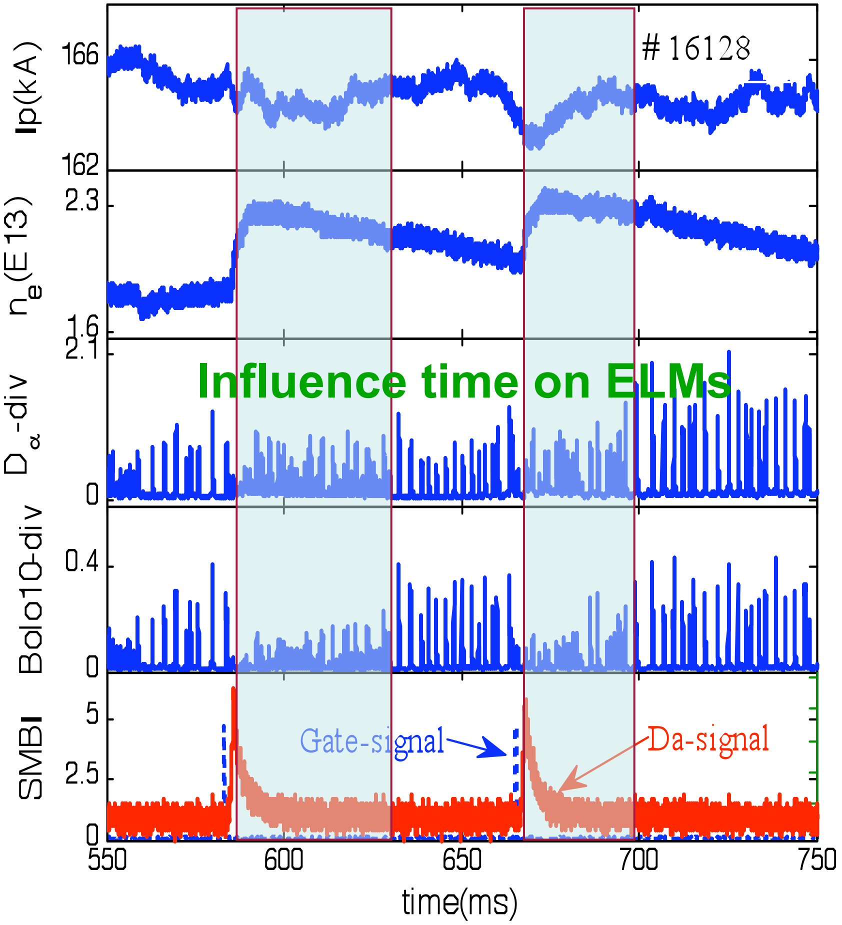
- Small ELMs have periods of 3 ms and little perturbation to plasma current or stored energy, as in #11616
- Some large (type-I) ELMs have periods of 10-30 ms with stored energy loss more than 10 % by an ELM. Large ELMs have obvious perturbation to plasma current, edge plasma Te and ne



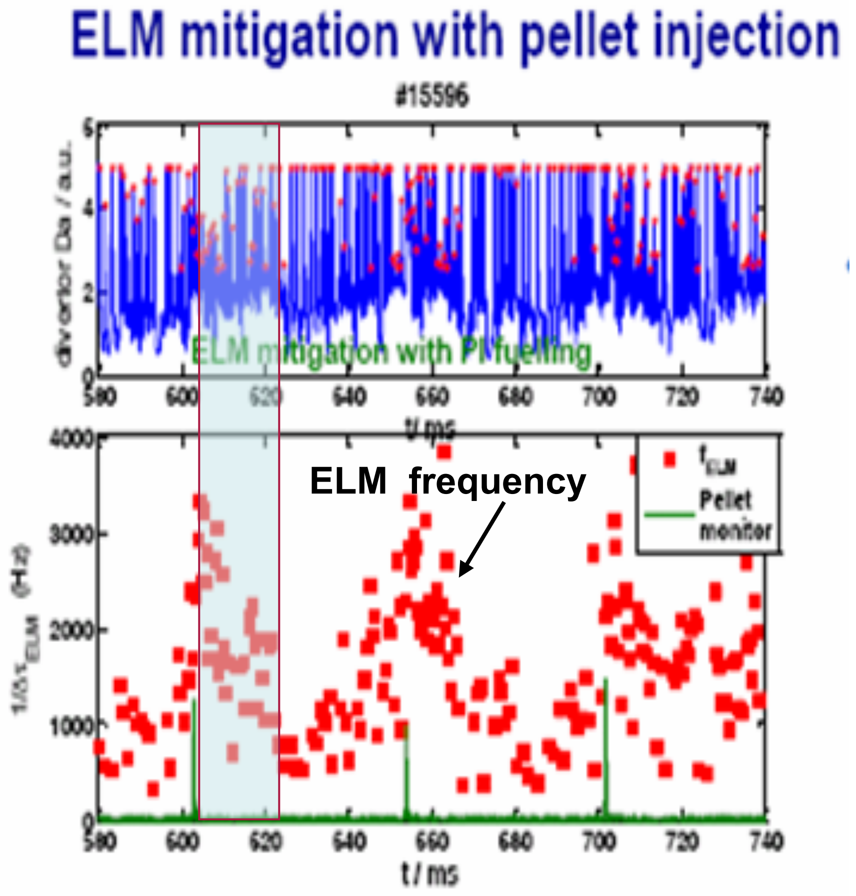


H-mode operation:

SMBI/PI effect on ELMs



SMBI(D2) influence time on ELMs depends on parameters of plasma and SMB. **W.W.Xiao, unpublished**



ELM amplitude decreasing and ELM frequency increasing after pellet injection

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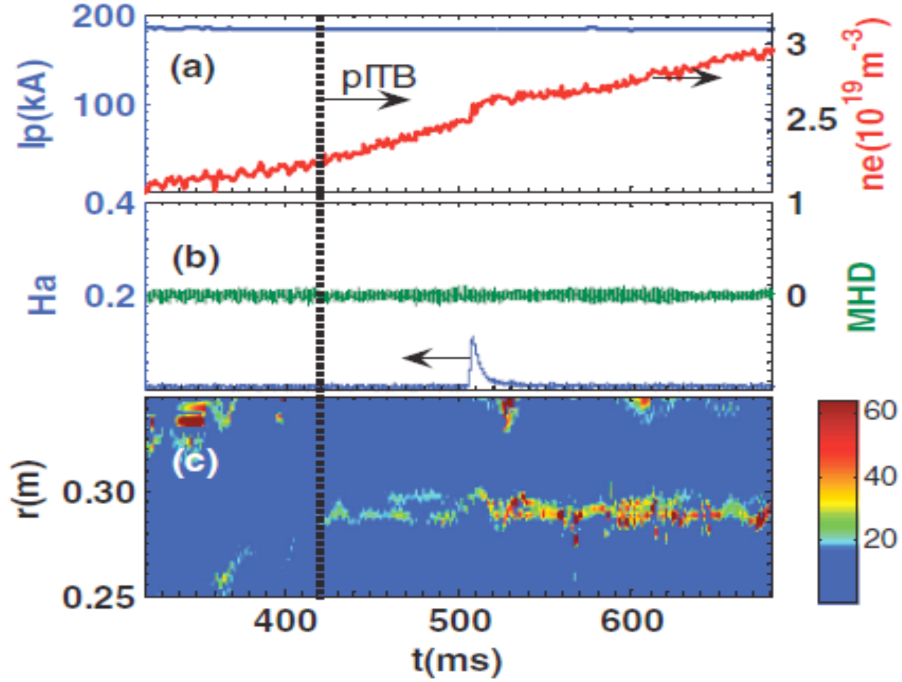
- **5, some other physics experiments**

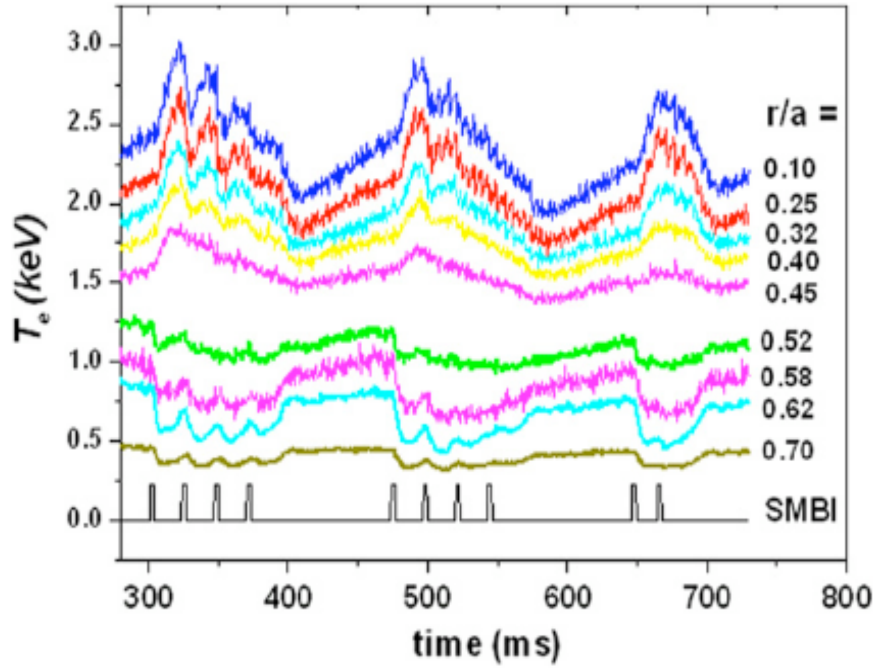
  Transport Studies, Zonal flow and turbulence

  Energetic particle physics, MHD control with ECRH

- 6, Summary

5, Operation for transport study





Spontaneous pITB: easily be observed in purely Ohmic heating plasmas without any external momentum input or extra particle sources

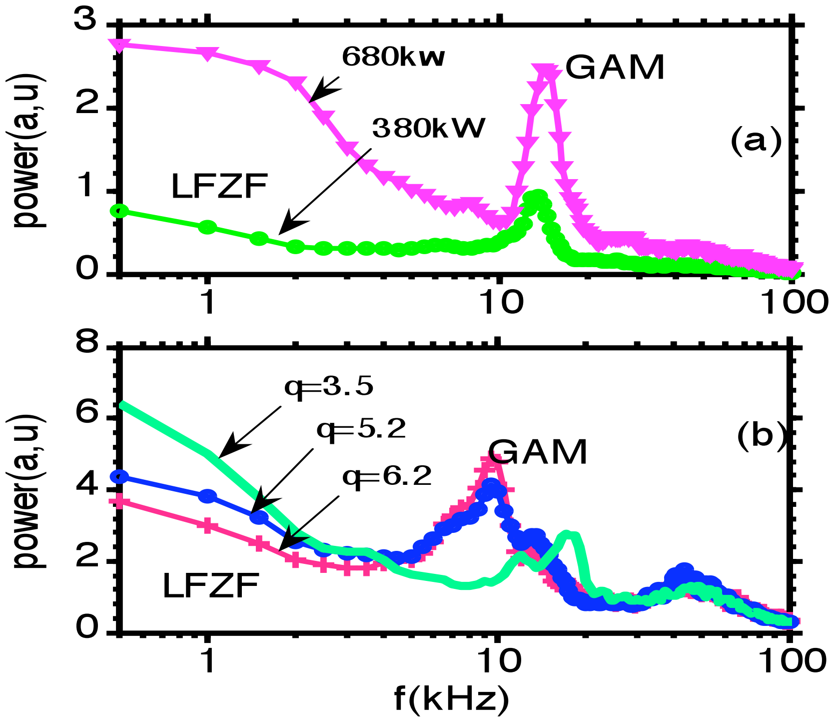
W.W.Xiao, *Phys. Rev. Lett.* **104** (2010) 215001
X.R.Duan, *Nucl. Fusion* **49** (2009) 104012

non-local transport: a strong cooling in the edge plasma immediately provokes a obvious heating in the central plasma

non-local effect by using SMBI is observed in HL-2A low density plasma, which provides a new flexible method to make such physics experiments

Sun Hongjuan, *PPCF* **52** (2010) 045003

5, Operation for Zonal Flow and turbulence study



(a) **Intensities of the LFZFs and GAMs rise with increasing ECRH power**

(b) **The LFZF intensities increase but the GAMs decrease when the edge safety factor q decreases from 6.2 to 3.5**

(c) **ZFs may regulate turbulence**

L.W.Yan, *Nucl. Fusion* **47** (2007) 1673–1681
K.J. Zhao, *Phys. Plasmas* **14** (2007)122301
T. Lan, *Phys. Plasmas* **15** (2008) 056105
K.J.Zhao, *Nucl. Fusion* **49** (2009) 085027
J. Cheng, *Nucl. Fusion* **49** (2009) 085030

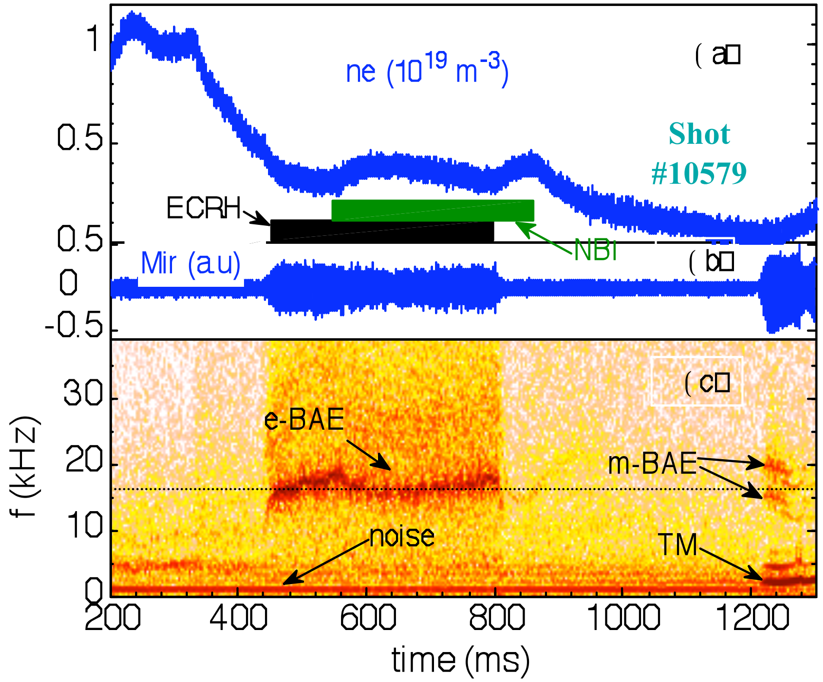
Zonal flows (ZFs): low frequency zonal flow (LFZF) and geodesic acoustic mode (GAM);
ZFs are self-generated coherent large scale structures in ZF-turbulence systems;
The toroidal symmetry of LFZF was confirmed for the first time on HL-2A tokamak;

K.J. Zhao, *Phys. Rev. Lett.* **96** **(**2006) 255004; A.D. Liu, *Phys. Rev. Lett.***103** **(**2009) 095002

During L-H transition, it is expected that turbulence decreases and ZFs increase; while in L-mode plasma with high power auxiliary heating, the turbulence and ZFs increase.

K.J. Zhao, *PPCF* **52** (2010)124008; J.Cheng, *PPCF* **52** (2010) 055003

5, Operation for study of energetic particle physics



The Alfvenic instabilities driven by energetic particles, may lead to significant loss of energetic particles and harm the first wall of ITER.

The Beta-induced Alfven eigenmode (BAE) excited by energetic electrons (termed as e-BAE) is observed during ECRH for the first time.

W. Chen, *Nucl. Fusion* **49** (2009) 075022
W. Chen, *Phys. Rev. Lett.* **105** (2010)185004

The e-BAE has mode number of m/n = -3/-1, propagating poloidally in the electron diamagnetic drift direction and toroidally opposite to the plasma current in the laboratory frame.

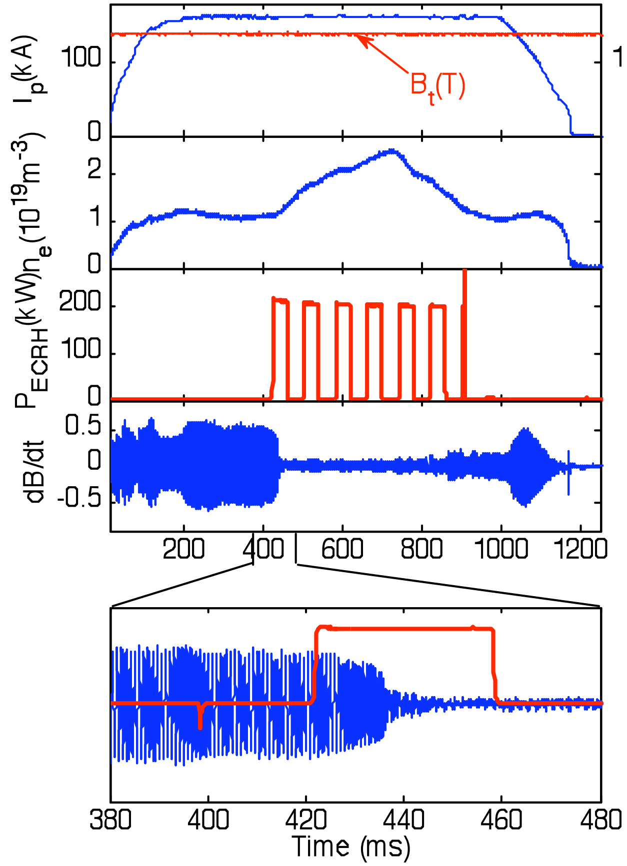
The m-BAE excited by large magnetic islands with mode numbers of m/n = 2/1 and -2/-1 propagate poloidally and toroidally in opposite directions. Large magnetic island induces m-BAE at t = 1220 ms

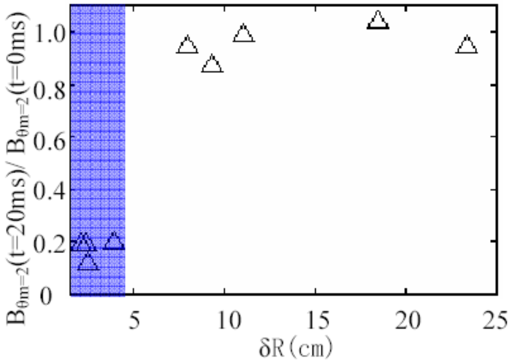
5, Operation for tearing mode suppress by ECRH

$I_p \sim 160kA, n_e \sim 1\times10^{19}\, m^{-3}, q_a \sim 3.5-4.5\text{£}\;\; \overset{\neg}{P}_{ECRH} \sim 100\text{-}300kA$

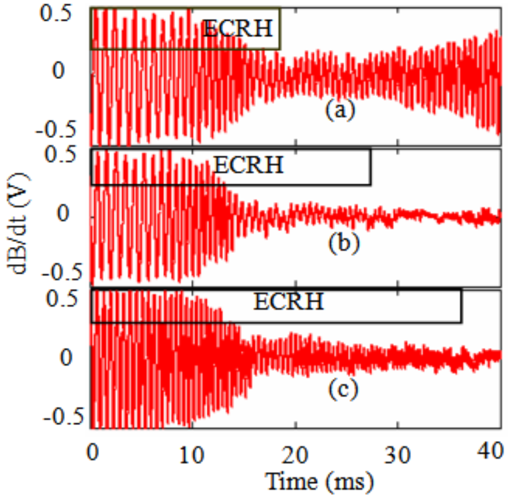
Location scan of ECR power deposition by changing toroidal field

$B_t \sim 1.2T - 1.4T \Rightarrow r_{dep} / a \sim 0 - 0.75$





Toroidal field scan



Length of ECRH pulse scan

1. **Effectiveness of 2/1 mode suppression by ECRH in HL-2A.**
2. **The necessary for mode suppression**
   - **EC power deposited near the islands.**
   - **Mode completely stabilized by long ECRH pulse.**
3. **Mechanism of mode stabilization.**
   - **The direct island heating by ECRH in HL-2A**
   - **The change of global profile caused by long pulse ECRH is the important factor on mode stability.**

Summary

- Operation conditions, were improved in recent years: NBI, ECRH, Wall conditioning and discharge control etc
- ELMy H-mode operation are realized by combination of

  NBI and X2-mode ECRH at Bt~1.3T,

  NBI and O1-mode ECRH at Bt~2.4T
- The minimum power for L-H transition is about 1.0 MW.
- ELM behaviors were studied
- ELM control/mitigation experiments performed by using SMBI/PI
- Operation regimes for transport study, zonal flow and turbulence, BAE and MHD control by ECRH, and so on, were also performed.

Plans in near future

- 2 MW ECRH at 140GHz, 2 MW LHCD at 3.7GHz
- Another NBI beamline with 2MW power
- Wall conditioning by Lithium vaporization
- L-H transition by sole Paux of NBI/ECRH/LHCD
- Type-I ELM control/mitigation by
  SMBI, PI, RMP coil
- Energetic particle physics and MHD control in H-mode phase
- L-H transition physics
- Steady state ELM-free H-mode/QH-mode exploration
- Upgrade of HL-2A tokamak

Thanks for you attention !