Overview of HL-2A Recent Experiments

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Introduction of HL-2A

- **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

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>( R )</td>
<td>1.65 m</td>
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<tr>
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<td>( B_t )</td>
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HL-2A Tokamak—present Status

- $R$: 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
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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-angle 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

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

- LH coupling characteristic by PAM antenna studied in H-mode plasma for the first time, low RC obtained in low $n_e$.
- 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]
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Double Critical Gradients for Triggering EM Turbulence

Impurity density profile is outwardly peaked
Electromagnetic turbulence triggered by impurity density gradient

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.

Zhong W.L. PRL 2016
Zhong W.L. EPS 2016 *I5.118*
— 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.
Shallow deposition of SMBI is sufficient for ELM mitigation.

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

Shi Z.B. FEC 2016 [EX/P7-22]
Ma Q. NF 2016
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Synchronization of GAMs and Magnetic Fluctuations

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.

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

Landau damping of GAM

Zhong W.L. JINST 2015
Zhong W.L. NF 2015
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Ion ITB can be observed at the $q=1$ surface;

- Criterion for characterizing iITB: maximum $R/LT_i$ should be higher than 14.
- ITG is suppressed by the toroidal rotation shear;
- The $m/n=1/1$ internal kink mode enhances iITB.
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-locality can trigger NTMs at relatively low $\beta_N$.

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

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 enhance 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 $1.0 \times 10^{21}$.

- A toroidal alfven eigenmode (TAE) was observed during the disruption, which plays a favorable role in scattering runaway electrons, and hence, limiting the strength of runaway beam.
— RT control of NTMs by ECRH with launcher mirror steering was developed.
— An RT code solves equilibrium equation with $129 \times 129$ 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.
- Appear in the high-density Ohmic plasmas with weak magnetic shear and low pressure gradients; predicted by numerical solutions of the AITG/KBM equation;
- $f=15\text{–}40 \text{ kHz}$ which lies in KBM-AITG-BAE frequency ranges;
- Low mode number $m\sim n=3\text{–}6$;
- 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$^+$: $I_{ECCD}$/$I_P$);
- $q_{\text{min}}$ is a bit bigger than unity for NRK condition;
- $f=20$-5kHz, frequency decreasing with $q_{\text{min}}$;
- 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].
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;

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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