Overview of HL-2A Recent Experiments

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*In collaboration with*

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University of Wisconsin – Madison, Wisconsin, USA
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Kyushu University, Kyoto University, Japan
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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
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
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Summary & Outlook
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: $V_{\text{loop}} \sim 0$
Fuelling and MHD Control Systems

- **Supersonic molecular beam injection (SMBI):**
  - new skimmer, 1kHz, Max throughput : $10^{22}$
  - $\text{H}_2, \text{D}_2, \text{He}, \text{Ar}…$, 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 : $10^{23}$
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
  • $\tilde{n}_e$: Interferometers, Doppler reflectometers, Reflectometer, BES
  • $\tilde{T}_e$: 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

- 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

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

- Theory model predicts the turbulence enhancement by shift of radial wavenumber
- LHCD/LBO $\rightarrow$ ExB shear decrease $\rightarrow k_r$ shift $\rightarrow \bar{n}_e$ increase $\rightarrow$ 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

Mitigate ELMs

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

Improve confinement

Zhong et al., EX/P5-3
A new ELM suppression technique: LBO-seeded impurity

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

LBO-seeded impurity measured by camera and bolometer

Zhang, Mazon, et al., NF (2018)
Interaction between plasma flows and turbulence

Pressure gradient $\rightarrow E \times B$ flow shear increase $\rightarrow$ L-I&I-H transition

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

Liang et al., PoP 2017
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 (2~3 cm)
- Inward particle flux induced by the coherent mode
- CM generation mechanism: nonlinear coupling of small scale turbulence

Cheng et al., AAPPD-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 $\rightarrow$ localized mode $\rightarrow$ streamer
- Streamer: life time $10 \sim 20$ us, size: $\sim10$ cm $\times$ 5 cm
- Streamer provides a fast transport channel connected the edge to core plasmas
ITB in H-mode plasma

Fishbone $\rightarrow$ fast ion redistribution $\rightarrow$ change of q shear $\rightarrow$ affect transport $\rightarrow$ 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
• 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

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**Table 1** Kurtosis for different heating power

<table>
<thead>
<tr>
<th>Heating Power (kW)</th>
<th>Reynolds Stress Kurtosis</th>
<th>Particle Flux Kurtosis</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>12.2</td>
<td>15.0</td>
</tr>
<tr>
<td>300</td>
<td>15.7</td>
<td>13.6</td>
</tr>
<tr>
<td>700</td>
<td>11.5</td>
<td>13.9</td>
</tr>
</tbody>
</table>

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**Table 2** Kurtosis for Ohmic discharge

<table>
<thead>
<tr>
<th>Fluctuation/Intensity</th>
<th>( \bar{n}/\bar{n} )</th>
<th>( e\Phi/T_e )</th>
<th>( \bar{n}^2 )</th>
<th>( e\Phi^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kurtosis</td>
<td>3.2</td>
<td>3.1</td>
<td>11.2</td>
<td>9.8</td>
</tr>
</tbody>
</table>
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Stabilization of m/n=1/1 fishbone by ECRH

Mechanism: ECRH $\rightarrow$ Te increase $\rightarrow$ resistivity decrease $\rightarrow$ resistive fishbone stabilized

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

Chen et al., EX/P5-20&NF, 2018
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: \( \omega - 2\omega_\theta - \omega = 0 \), 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

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

Yu et al., PoP, 2018
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 $\nabla T_e$ 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 & Outlook
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.
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.
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 probability 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
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- EX/P5-8 Y. P. Zhang: Effect of LBO-seeded Impurity on ELMs in the HL-2A tokamak
- EX/P5-12 M. Xu: Experimental evaluation of electron energy probability 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 Alfvén Eigenmode 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
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=432.5μm)
- Composition: 4-chord Polarimeter + 4-chord Interferometer
- Time resolution: 1.0us, spatial resolution: 7.0cm

2). Y.G. Li, et al., JINST. 12, C11004 (2017)

Figure: Schematic layout of HL-2A Polarimeter and Interferometer.
24×16 Electron Cyclotron Emission Imaging (ECEI) on the HL-2A

Optics of ECEI system

Double e-fishbone images

Tearing mode 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
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: \(\Delta r \approx 0.8 \text{ cm}; \quad \Delta Z \approx 1.2 \text{ cm},\) covering \(r = 34.5 \sim 40.5 \text{ cm}.
- High SNR has been achieved in the experiments last year.

![Diagram showing spatial resolution and high SNR](image)
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

- **Systematic Parameters**
  - Time resolution: 1 μs
  - Spatial resolution: ~1mm
  - Detector array: 32 channels
  - Wavenumber: $2 \sim 15 \text{cm}^{-1}$

- 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: $\kappa = 1.8-2$
- Triangularity: $\delta > 0.5$
- Toroidal field: $B_T = 2.2 \ (3) \ T$
- Flux swing: $\Delta \Phi = 14 \text{Vs}$
- Heating power: 25 MW