Stabilization of Energetic-Ion-Driven MHD Modes in the Advanced Helical Device, Heliotron J''

K. Nagasaki\(^1\), S. Yamamoto\(^1\), S. Kobayashi\(^1\), Y. Nagae\(^2\), K. Sakamoto\(^1\), Y. I. Nakamura\(^2\), T. Mizuuchi\(^1\), H. Okada, \(^1\), T. Minami\(^1\), K. Masuda\(^1\), S. Ohshima\(^1\), S. Konoshima\(^1\), N. Shi\(^1\), Y. Nakamura\(^2\), H. Y. Lee\(^2\), L. Zang\(^2\), S. Arai\(^2\), H. Watada\(^2\), M. Sha\(^2\), H. Sugimoto\(^2\), H. Fukushima\(^2\), K. Hashimoto\(^2\), N. Kenmochi\(^2\), G. Motojima\(^3\), Y. Yoshimura\(^3\), K. Mukai\(^3\), G. Weir\(^4\), N. Marushchenko\(^5\), F. Volpe\(^6\), T. Estrada\(^7\), F. Sano\(^1\)

1 Institute of Advanced Energy, Kyoto University
2 Graduate School of Energy Science, Kyoto University\(^2\)
3 National Institute for Fusion Science
3. University of Wisconsin-Madison, USA
5 Max-Planck Institute für Plasma Physik, Germany
6 Columbia University, USA
7 CIEMAT, Spain
Kyoto: Japan's “Heartland”
Kyoto University

As of May, 2013

Founded in 1897
Nobel Prize winners: 9 (Oct 2013)

Faculties: 10
Graduate schools: 16
Research institutes: 14
Research and educational centers: 18

Undergraduate students: 13,585 (187)
Graduate students: 9,323 (1,212)
Foreign students: 1,399
Academic staffs: 2,787
Non-Academic staffs: 2,655

Scholastic exchange agreements:
94 Institutions of 34 countries
Institute of Advanced Energy
Institute for Chemical Research
Disaster Prevention Research Institute
Research Institute for Sustainable Humanosphere
Heliotron J Laboratory
Institute of Advanced Energy, Kyoto Univ.

Energy Research with Advanced Facilities

- Bio-energy
  - Dye-sensitized solar cell
  - Ceramic nano-tube
  - High intensity fs laser

- Heliotron J
- IECF
- KFEL
- DuET
Outline

1. The Heliotron J Device and 70 GHz ECH/ECCD System
2. Energetic-particle-driven MHD modes
3. Modification of rotational transform profile by ECCD
4. Stabilization experiments of energetic-ion-driven MHD modes by ECCD
   - Stabilization of energetic particle modes by ECCD
   - Effect of magnetic shear
4. Conclusions
Heliotron J Project Aims To Develop Attractive Compact Fusion Reactor

A steady-state, compact, high-\(\beta\) helical reactor

- No disruptions (currentless operation)
- No close conducting wall or active feedback control of instabilities
  - (no serious MHD instabilities)
- High \(Q_{\text{eng}}\) (= net \(P_{\text{ele.}} / P_{\text{oper.}}\))
  - (at minimum recirculating powers)
- Wall loading
  - (3~4 MW/m\(^2\) under the development of advanced wall materials)
# Planned/Operating Helical Systems

<table>
<thead>
<tr>
<th>Plasma Device (Laboratory)</th>
<th>H-1 (ANU)</th>
<th>TJ-II (CIEMAT)</th>
<th>LHD (NIFS)</th>
<th>HSX (U. Wisconsin)</th>
<th>Heliotron J (Kyoto Univ.)</th>
<th>W7-X (MPI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coil System</td>
<td>M=3 HFC+CR+TFC</td>
<td>M=4 HFC+CR+TFC</td>
<td>M=10 HFC+PFC</td>
<td>M=4 Modular Coil</td>
<td>M=4 HFC+TFC+PFC</td>
<td>M=5 SC Modular Coil</td>
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<tr>
<td>Major Radius</td>
<td>1.0 m</td>
<td>1.5 m</td>
<td>3.9 m</td>
<td>1.2 m</td>
<td>1.2 m</td>
<td>6.5 m</td>
</tr>
<tr>
<td>Minor Radius</td>
<td>0.22 m</td>
<td>0.1-0.25 m</td>
<td>0.6-0.65 m</td>
<td>0.15 m</td>
<td>0.18 m</td>
<td>0.65 m</td>
</tr>
<tr>
<td>Plasma Volume</td>
<td>0.96 m³</td>
<td>1.43 m³</td>
<td>30 m³</td>
<td>0.44 m³</td>
<td>0.82 m³</td>
<td>54 m³</td>
</tr>
<tr>
<td>Magnetic Field</td>
<td>1.0 T</td>
<td>1.5 T</td>
<td>3 T</td>
<td>1.37 T</td>
<td>1.5 T</td>
<td>3.0 T</td>
</tr>
<tr>
<td>Pulse Length</td>
<td>1 sec</td>
<td>0.5 sec</td>
<td>CW</td>
<td>0.2 sec</td>
<td>0.5 sec</td>
<td>&gt; 10 sec</td>
</tr>
<tr>
<td>Heating System</td>
<td>ECH (0.2MW) Helicon</td>
<td>ECH (0.6MW) NBI (4MW)</td>
<td>ECH (3MW) ICH (3MW)</td>
<td>ECH (3MW) ICH (2.5MW)</td>
<td>ECH (0.5MW) NBI (1.5MW)</td>
<td>ECH, ICH NBI (20-30MW)</td>
</tr>
<tr>
<td>Features</td>
<td>Flexible configuration, High beta</td>
<td>High rotational transform, Low shear</td>
<td>Moderate shear</td>
<td>Quasi-helical symmetry</td>
<td>Local quasi-isodynamicity</td>
<td>Quasi-isodynamicity</td>
</tr>
<tr>
<td>Schematic View</td>
<td><img src="image1.png" alt="Diagram" /></td>
<td><img src="image2.png" alt="Diagram" /></td>
<td><img src="image3.png" alt="Diagram" /></td>
<td><img src="image4.png" alt="Diagram" /></td>
<td><img src="image5.png" alt="Diagram" /></td>
<td><img src="image6.png" alt="Diagram" /></td>
</tr>
</tbody>
</table>
Heliotron J Device

Major Radius: R=1.2 m  
Plasma Minor Radius: a=0.1-0.2 m  
Magnetic Field: B≤1.5 T  
Vacuum iota: 0.3-0.8 with low magnetic shear  
Heating System: ECH 0.4MW  
NBI 0.8MW  
ICRF 0.4MW  

Magnetic coil system:  
one l/m=1/4 continuous helical coil  
two sets of toroidal coils  
three pairs of vertical field coils

Typical plasma parameters;  
$\mathbf{n_e}=0.2-4 \times 10^{19} \, \text{m}^{-3}$  
$\mathbf{T_e}=0.3-1 \, \text{keV}$  
$\mathbf{T_i}=150-200 \, \text{eV}$
Magnetic Field Structure of Heliotron J

Magnetic flux surfaces
straight section  
corner section

Rotational transform $\frac{1}{2\pi}$

Magnetic field along axis

- $B_{st}/B_{cor} = 1.06$
- $B_{st}/B_{cor} = 0.95$
- $B_{st}/B_{cor} = 0.82$

ECH injection port
Straight section

Toroidal Angle (deg)

B (T)
Shear Alfvén Waves

- Shear Alfvén Waves are transverse electromagnetic waves that propagate along the magnetic field
  - Dispersionless: $\omega = k_\parallel v_A$
  - Alfvén Speed: $v_A = B/(\mu_0 n_i m_i)^{1/2}$
  - $E_\parallel$ is tiny for $\omega << \Omega_i$
  - Particles move with field line
  - All frequencies below $\Omega_i$ propagate

- The damping rate of shear Alfvén waves is very large at the Alfvén resonance due to Coulomb collision and Landau damping
  “Continuum damping”
Global Alfvén Eigenmode (GAE)

- If $\omega^2 < k^2_{||} v_A^2$, the Alfvén resonance disappears, and the Shear Alfvén waves can propagate.

- Since $-k^2_{\perp}$ is not so large, the eigenmodes is excited all over the plasma radius.

“Global Alfvén Eigenmode (GAE)”

“Discrete Alfvén Eigenmode (DAE)”

$r_A$: Cut-off for shear Alfvén wave
Shear Alfvén Continua in 2-D Magnetic Configuration

- In high magnetic shear configuration, shear Alfvén continua will intersect each other, then TAE and EAE gaps are formed.
- In low magnetic shear configuration, GAE can lie below and/or above the continuum instead of TAE (low-\(n\)).
In Boozer coordinate, magnetic field strength is expressed as

$$|B| = B_0 \left[ 1 + 0.5 \sum_{\mu \nu} \varepsilon_{B}^{\mu \nu} (\psi) \cos(\mu \theta - \nu N_p \phi) \right]$$

Mode coupling occurs between \((m, n) \Leftrightarrow (m \pm \mu, n \pm \nu N_p)\)

$$\omega_* = k_{||}^{\mu \nu} |V_{A*}| \equiv |\mu t_* - \nu N_p| \frac{V_{A*}}{2R}$$

$$t_* = \frac{2n + \nu N_p}{2m + \mu} \quad (t = 1/q)$$

\((\mu, \nu) = (1,0): TAE / (2,0): EAE / (1,1): HAE_{11} / (0,1): MAE_{01}\)
Energetic-Particle-Driven MHD Instabilities in Fusion Plasmas

- Energetic alpha particles are produced through deuterium-tritium fusion process and beam ions used for plasma heating
- They have a velocity comparable with the Alfvén velocity, can interact resonantly with shear Alfvén waves during slowing-down process
- Alfvén eigenmodes (AEs) are excited, resulting in enhanced radial transport of the energetic ions
- Even a small fraction of alpha power loss in a burning plasma can seriously damage plasma facing components

Energetic ion losses induced by TAE bursts in LHD.

Ogawa, Nucl. Fusio (2010)
In NBI heated plasmas, some coherent MHD instabilities are observed in the range of Alfvén frequency.

The frequencies are similar to those of the GAEs with $m=2/n=1$ (without impurity effect).
Identification of the mode as GAE

- The spatial structure of eigenmode with $f_{\text{cal}} = 101$ kHz agrees with that of the observed mode with $f_{\text{exp}} = 95$ kHz.
- Comparison of experimental result with shear Alfvén spectra indicates that the observed modes are GAEs.
- Effect of toroidal mode coupling on low-$n$ GAE with $N_f = 4$ is weak.

☆ Continua and eigenmode are calculated by STELLGAP and AE3D coded by D. Spong.
Energetic Particle Modes (EPM)

- Energetic particle modes (EPM) are excited when pressure of energetic particles (EP) is comparable to bulk pressure.
- Energetic particles create a new wave branch.
- Energetic particles resonate with mode, altering \( \text{Im}(\omega) \).
- Intense drive overcomes continuum damping.

Shinohara, Nucl. Fusion (2001)  
Briguglio, PoP (2007)
Observation of EPM

- The ratio of beam velocity to Alfven velocity is about 0.3.
- Observed mode frequency is not proportional to $n_e^{-0.5}$.
- Mode amplitude depends on electron density.

![Graph showing the dependence of b on n_e](brms_hj_eccd12_np04_ned_n02.ppc)
A Severe Impact of ECH on the AE Behavior Was Observed in DIII-D and TJ-II

- In DIII-D, ECH near $q_{\text{min}}$ suppresses RSAE and lower amplitude TAEs are unstable in DIII-D.
- In TJ-II, ECH+NBI causes steady frequency Aes to decrease in amplitude and begin chirping.

Van Zeeland, PPCF (2008)
Van Zeeland, Nucl. Fusion (2009)

Nagaoka, Nucl. Fusion (2013)
70GHz ECH/ECCD System for Heliotron J

Gyrotron (0.5MW, 0.2sec)

Transmission line using corrugated W.G.

Launcher

Power monitor

Corrugated Waveguide

View of Injection System

Plane mirror

Barrier

Borehole

Miter bend

Last Flux

Polarizer

Institute of Advanced Energy, Kyoto University
70GHz ECH/ECCD Launcher System

- A launching system with a focusing mirror and a steering mirror has been installed and operated in Heliotron J since the 2009 experimental campaign
  - Maximum injection power: $P_{EC}=0.4\text{MW}$
  - Focused Gaussian beam, $w=30\text{ mm}$
  - $|N_{||}| < +0.6$
  - Possible to inject along magnetic axis
Second Harmonic X-mode ECCD

- The CD efficiency is calculated by applying the adjoint approach with parallel momentum conservation
- Good agreement was found between experimental results and TRAVIS code results in ECH-only plasmas

ECCD in ECH-only plasmas

K. Nagasaki, Nucl. Fusion 51 (2011) 103035
The bumpiness control changes the magnetic ripple structure.

The toroidal current changes its flowing direction, depending on the ripple structure.

The current direction is explained by the balance between the Fisch-Boozer effect and the Ohkawa effect.

EC Current Modifies Rotational Transform Profile, Forming a Strong Magnetic Shear in Core Region

- The TRAVIS code predicts that the total current flows 2.9 kA at $N_{||} = 0.4$, $n_e = 0.5 \times 10^{19} \text{ m}^{-3}$ and $T_e(0) = 0.8 \text{ keV}$
An Energetic-Ion-Driven MHD Mode Has Been Stabilized by Counter-ECCD

No ECCD ($N_{||}=0.0$)

- $n_e (10^{19} \text{ m}^{-3})$
- $I_p (\text{kA})$
- dB/dt (a.u.)

Counter-ECCD ($N_{||}=-0.3$)

- $n_e (10^{19} \text{ m}^{-3})$
- $I_p (\text{kA})$
- dB/dt (a.u.)

K. Nagasaki, Nucl Fusion 2013
The Observed Mode Appears to be Energetic Particle Mode

- Density fluctuation measurement using a Beam Emission Spectroscopy (BES) reveals that the mode of 80 kHz is localized at \( r/a \sim 0.6 \)
- FFT analysis of Mirnov coil signals shows that the mode number is \( m/n = 4/2 \), rotating in the ion diamagnetic direction
- This mode has high coherence with magnetic probe signals, weak \( n_e \) dependence
Radial Shift of EPM due to ECCD

- Outward movement of EPM with n=1 during the ramp-up phase of plasma current is observed in BES measurements ($n_e/\langle n_e \rangle$).
- The movement can be explained by the change of shear Alfvén continuum due to the increasing of plasma current.
Amplitude of EPM Is Reduced As EC Driven current Evolves

• The mode suppression has no transition property
Co-ECCD is Also Effective for Stabilizing Energetic-Ion-Driven MHD Modes

**No ECCD ($N_{||}=0.0$)**

- Plasma density ($n_e (10^{19} \text{ m}^{-3})$)
- Current density ($I_p (\text{kA})$)
- Time derivative of field ($\text{dB/dt (a.u.)}$)
- NBI (BL1)

**Co-ECCD ($N_{||}=0.4$)**

- Plasma density ($n_e (10^{19} \text{ m}^{-3})$)
- Current density ($I_p (\text{kA})$)
- Time derivative of field ($\text{dB/dt (a.u.)}$)
- NBI (BL1)

*Figures show time evolution of parameters with and without Co-ECCD for different $N_{||}$ values. Graphs include plots of frequency vs. time for NBI emissions.*
EPM Is Stabilized When Magnetic Shear Exceeds a Threshold Value

- For counter-ECCD, when the magnetic shear is larger than 0.12, the mode amplitude is completely suppressed to the level of ECH-only phase.
- Similar suppression is observed for co-ECCD, but the threshold shear is not clear.

![Graph showing EPM stabilization](image)

**Counter-ECCD, EPM**

- #46107-46132
- iota=0.525
- B=1.25T
- ECH 0.3MW
- NBI 0.6+0.8MW

**Co-ECCD, GAE?**

- #48085-48115
- 5to3 config
- B=1.21T (HV+86%)
- co-ECCD 0.26 MW
- NBI BL1 0.5MW

![Graph showing co-ECCD](image)
• EPM is mitigated by the change in magnetic shear due to ECCD where continuum damping is the main mechanism for stabilization

Stabilization Mechanism of EPM by ECCD

ECH

$T_e$ and $n_e$ profile

slowing down time profile

$\beta_{fast}$ profile

growth rate

ECCD

plasma current

MHD equilibrium

shear Alfvén continuum

damping rate

STABLE? or UNSTABLE?
Conclusions

- Energetic-ion-driven MHD modes such as GAE and EPM are often observed in Heliotron J NBI plasmas
- An EC current of a few kA driven in the central region modifies the rotational transform profile from a shearless flat one into a high-shear one in the medium-sized stellarator/Heliotron device, Heliotron J
- The energetic-ion-driven MHD modes have been stabilized by centrally localized second harmonic 70-GHz X-mode ECCD
- Both co-ECCD (negative magnetic shear) and counter-ECCD (positive magnetic shear) are effective at stabilizing energetic-ion-driven MHD modes
- $N_{||}$ scan indicates that an EPM is stabilized when the positive (possibly negative also) magnetic shear exceeds a critical threshold
- Comparison with AE theory is required to clarify the stabilization mechanism
Collaboration with F. Volpe (Columbia Univ.)

• $T_e$ profile measurement using EBE is under development under collaboration with Columbia Univ. and NIFS

• The cut-off density for O-mode is medium, $n_e \sim 2 \times 10^{19} \text{m}^{-3}$.

• Ray tracing calculation shows that an O-X mode conversion window is accessible

• A radiometer for 24-42GHz has been assembled and tested

Gaussian Optics Antenna
Induced Electric Field Affects Time Evolution of EC Driven Current

- The iota profile reaches quasi-steady state after 50 msec under the experimental condition, \( n_e = 0.5 \times 10^{19} \text{ m}^{-3} \) and \( T_e(0) = 0.8 \text{ keV} \)

1-D current diffusion equation

\[
\mu_0 \frac{\partial I_p}{\partial t} = 4\pi S \frac{\partial}{\partial S} \left\{ \frac{1}{\sigma} \frac{\partial}{\partial S} \left( I_p - I_{NI} \right) \right\}
\]

- \( I_p(S) \): total current
- \( I_{NI}(S) \): noninductive current
- \( S = \pi r^2 \), \( \sigma \): electrical conductivity

\[ J_{EC} (\text{MA/m}^2) \]

\[ \rho \]

- Standard configuration
  - \( I_{NI} = 3kA \)
  - \( T_e(0) = 0.8 \text{ keV} \)

\[ t=200\text{msec} \]
\[ t=100\text{msec} \]
\[ t=50\text{msec} \]
\[ t=20\text{msec} \]
\[ t=10\text{msec} \]
\[ t=0\text{msec} \]
Adjoint Approach for ECCD Calculation

- current driven by RF source,
  \[ j_\parallel = -e \int du \parallel v_\parallel \delta f_e \quad \text{with} \quad \delta f_e = f_e - F_{EM} \quad \text{and} \quad u = \gamma v \]

  can be calculated by solving DKE,
  \[ \frac{d\delta f_e}{dt} - C^{lin}(\delta f_e) = Q_{RF}(F_{EM}) \equiv -\frac{\partial}{\partial u} \cdot \Gamma_{RF} \]

- idea: exploiting the self-adjoint properties of \( C^{lin}(\delta f_e) \) to express CD through the response function formally identical to the solution of (generalized) Spitzer-Härm problem (Hirshman, 1980; Antonsen & Chu, 1982; Taguchi, 1983)

  ➢ If solution of the adjoint kinetic eq-n is known,
    \[ \frac{dg}{dt} + C^{lin}(g) = v_{e0} \frac{\parallel}{v_{th}} b F_{EM} \quad \text{with} \quad b = B / B_{max}, \]

    then with \( g(s; u, \xi) = \chi(s; u, \xi) F_{EM}(u) \) and \( \xi = \parallel / v \)

    \[ \langle j_\parallel \rangle = \frac{ev_{th}}{v_{e0}} \cdot \frac{\langle b \rangle}{\langle b^2 \rangle} \cdot \langle \int du \frac{\partial \chi}{\partial u} \cdot \Gamma_{RF} \rangle \]

- Presently, adjoint approach is most common for ray- and beam-tracing