Recent Results from ECH/ECCD Experiments in Heliotron J

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Outline

1. The Heliotron J device and 70 GHz ECH/ECCD System

2. Experimental results
   - Stabilization experiments of energetic-ion-driven MHD modes by ECCD
   - Production of overdense plasmas via OXB heating at low magnetic field
   - NBI plasma start-up assisted by 2.45GHz microwaves

3. Summary
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 1 MW + 1 MW
  ICRF 0.4MW

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

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

Magnetic flux surfaces

- Straight section
- Corner section

Rotational transform $i/2p$

Magnetic field along axis

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

Toroidal Angle (deg)

- Straight section
- ECH injection port
70GHz ECH/ECCD System for Heliotron J

Gyrotron (0.5MW, 0.2sec)

Transmission line using corrugated W.G.

Power monitor

Launcher

Polarizer
Stabilization of Energetic-Ion-Driven MHD Modes

- Energetic alpha particles and beam ions can interact resonantly with shear Alfvén waves during slowing-down process, and excite Alfven Eigenmodes (AEs), resulting in enhanced radial transport of the energetic ions.

- While much attention is focused on gaining a predictive capability for these instabilities in future devices through modeling and extrapolation of current experimental results, less attention has been paid to suppression and control techniques. 
  
  Van Zeeland, Nucl. Fusion 49 (2009) 065003

- ECH/ECCD is an ideal tool since it can provide highly localized EC current with a known location and good controllability.

- Research on external controllability of rotational transform (safety factor) gives us information on the characteristics of MHD modes.
ECCD in ECH-only plasmas

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

K. Nagasaki, Nucl. Fusion 51 (2011) 103035

ECCD in ECH+NBI plasmas

- Non-inductive current in ECH+NBI plasmas consists of EC driven current, NB current and bootstrap current
- EC driven current is controlled by $N_{\|}$
- Estimated NB and bootstrap current is reasonable
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 Fully Stabilized by Counter-ECCD

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

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

K. Nagasaki, FEC2012 EX/P8-10
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

• These indicate that the observed mode is energetic particle mode (EPM)
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.
- Higher magnetic shear may strengthen continuum damping.

![Graphs showing the stabilization of EPM with magnetic shear and plasma parameters.](image-url)
Electron Bernstein Wave Heating via O-X-B Mode Conversion Process

- Obliquely launched O-mode can be mode-converted into the slow X-mode if the launching angle satisfies a critical condition.
- The slow X-mode is converted into the EBW at upper hybrid resonance.
- The EBW is absorbed at electron cyclotron resonance in overdense region.

\[
C_{O-SX} = \exp \left[ -\pi k_0 L_n \sqrt{\frac{\Omega_{ce}}{2\omega}} \left\{ 2 \left( 1 + \frac{\Omega_{ce}}{\omega} \right) \left( N_{p,\text{opt}} - N_{p,\text{oc}} \right)^2 + N_y^2 \right\} \right]
\]

\[
N_{p,\text{opt}} = \cos \theta_{\text{opt}}
\]
Production of Overdense Plasmas by 2.45GHz 20kW Microwaves at B=0.1T

Bilateral collaboration with K. Toi (NIFS) and R. Ikeda (Fukui Univ.)

Neon plasma, Off axis resonance

- Te profile is hollow, and ne profile is centrally peaked with Te(0)=5eV
- Response to amplitude modulate is fastest at plasma center, and the coherence is high, indicating strong Doppler shift resonance absorption
Electron Density is 10 Times as High as Cut-off Density in Ne Plasmas

O-mode cutoff density $n_e^c = 7.5 \times 10^{16} \text{ m}^{-3}$

Electron cyclotron resonance: $B_{\text{res}} = 875 \text{ G}$

**Dependence on gas species**

<table>
<thead>
<tr>
<th>$&lt;n_e&gt;[x \times 10^{17} \text{ m}^{-3}]$</th>
<th>$B_{\text{axis}}/B_{\text{res}} [%]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ne</td>
<td>$4$</td>
</tr>
<tr>
<td>D2</td>
<td>$10$</td>
</tr>
</tbody>
</table>

- **D2**: $<n_e>/n_{ec} = 4$ (transient)
- **Ne**: $<n_e>/n_{ec} = 10$ (quasi-steady state)

Electron density is 10 times as high as cutoff density in Ne plasmas.
On-Axis and Off-Axis Heating

Power absorption measurement by power modulation in Neon plasmas
(Average injection power 14 kW, modulation 5 kW, 7kHz)

On-axis power deposition
\[ \frac{n_e}{n_{ec}} = 10, \quad \left( \frac{n_{e\text{ axis}}}{n_{ec}} = 27 \right) \]

Off-axis power deposition
\[ \frac{n_e}{n_{ec}} = 3, \quad \left( \frac{n_{e\text{ axis}}}{n_{ec}} = 4 \right) \]

\[ \frac{B_t}{B_{res}} = 86\% \quad P_{abs} = 12\% \]

\[ \frac{B_t}{B_{res}} = 74\% \quad P_{abs} = 66\% \]

Strong Doppler shift?
Collisional damping?
NBI Plasma Startup w/o ECH Assisted by 2.45GHz Microwaves

- No ECH is applied for plasma production

Before NB turn-on
- 2.45GHz microwaves is injected 0.6s before NBI turn-on
- Intense ECE signal is observed

After NB turn-on
- Balance injection of NB (27kV, ~1MW)
- Initial plasmas ($n_e \approx 0.2 \times 10^{19} \text{m}^{-3}$) appears 10 ms after NBI
- Additional gas fueling increases line-averaged density over $2 \times 10^{19} \text{m}^{-3}$
- This plasma has almost the same performance as that produced by ECH
Seed plasma produced by 2.45GHz microwaves

STD config. B=0.8T (#41068)

- Slender seed plasma is produced along magnetic axis
- It appears that the peaked density profile is produced
- The line emission intensity increases with an increase in seed plasma density

70GHz ECH plasma

STD config. B=1.25T

(Exposure; 250FPS)
Successful Plasma Startup Depends on B and Microwave Power

• Microwave power and magnetic field strength (B) is scanned with keeping gas condition constant

• There is a threshold in 2.45GHz microwave power and magnetic field strength

• Higher microwave power is required at lower magnetic field

• Microwave power of 2 kW is enough for B=1.25T, and the power more than 5kW is needed at B<0.7T
• Lower hybrid wave heating?
  − Maybe not, $w_{LH} \sim 0.7$ GHz
• Landau damping ($w = k_v ||, N || > 1$) ?
• Production of high-energy electrons

• Results from WEGA Stellarator
  − Broad X-emission (>10 keV)
  − Very intense ECE signals (>1 keV)
  − Finite gamma ray signal

Plans in FY2013 Experimental Campaign

ECH/ECCD related experiments

1. Upgrade of 70GHz ECH/ECCD system
2. Stabilization experiments of energetic-ion-driven MHD modes by ECCD
3. Study of high-beta NBI plasmas
4. Measurement of Te profiles in overdense plasmas via BXO mode conversion process

Other experiments

1. Confinement improvement by Super Molecular Beam Injection (SMBI)
2. Turbulence study by Langmuir probes,
3. Study of MHD instabilities (AEs, Interchange)
4. Production and confinement of high-energetic ions by ICRF
New Plasma Diagnostics

Developed
✓ TV-Thomson scattering system for Te profile
✓ AM reflectometer provides detailed density profile in edge region
✓ Ti and VT profile measurement by CXRS
✓ Measurement system for magnetic islands
✓ Multiple Langmuir probe to investigate long range correlation for meso-scale structure
✓ Beam emission spectroscopy for density fluctuation

Under development
✓ HCN interferometer is under construction for high density plasma.
✓ Suprathermal electron measurement with tangential PHA
✓ Reflectometer for density fluctuation under development.
✓ SX tomography for plasma 2D profile
✓ Nd:YAG Thomson scattering system investigate time evolution of plasma profile.
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.
Summary

• Energetic-ion-driven MHD modes have been stabilized by 70GHz second harmonic X-mode ECCD
  - Both co- and ctr-ECCD are effective for the stabilization
  - Formation of magnetic shear may be a key factor
• Overdense plasmas has been produced and sustained by 2.45GHz ECH at low magnetic field.
  - The achievable density is 10 times and 4 times as high as cutoff density in Neon plasmas and deuterium plasmas
  - Placement of electron cyclotron resonance at edge regions makes on-axis heating probably due to strong Doppler shift resonance or collisional damping
• NBI plasmas have been successfully started up in Heliotron J by assistance of 2.45 GHz 5 kW microwaves
  - The successful start-up depends on gas pressure (neutral particles), magnetron power (electron heating) and NBI power (fast ions)
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: $P_{EC}=0.4$MW
  - Focused Gaussian beam, $w=30$ mm
  - $|N_|| < +0.6$
  - Possible to inject along magnetic axis