Measurement of density fluctuation of ICRF waves
using a reflectometer in GAMMA 10

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Objective

ICRF waves in the GAMMA 10 central cell; externally applied and spontaneously excited ones

Fluctuation measurement in ion-cyclotron frequencies using a microwave reflectometer

Application of bispectral analysis

Evaluation of three-wave interaction between ICRF waves
  • Sum and difference interactions
  • Radial dependence

Summary
Objective

- In the GAMMA 10 central cell, high frequency (0.1M ~ 20 MHz) fluctuations are observed.

Drive force is apparent

1. ICRF waves applied for ion heating
2. ICRF wave destabilized by temperature anisotropy (AIC wave)

Not apparent

3. Other fluctuations
   (satisfy matching condition with fluctuations caused by 1. 2.)

   should be concerned primarily with nonlinear coupling

- We have evaluated the nonlinear coupling by bispectral analysis.

Signals obtained by a reflectometer show the fluctuations(3.) more clearly than signals at the edge, e.g. signal of a pick-up coil. Analysis of the reflectometer data provides assessment of the nonlinear coupling in the hot core region of G-10.
High frequency waves excited in the G-10 central cell

1. Waves excited for ICRF heating

- hydrogen plasma
- fundamental beach heating

Ω_{ci} - resonance

Fast wave (FW)
Slow wave (SW)

Location of ICRF antennas

East anchor cell  Central cell  West anchor cell
2. ICRF wave destabilized by temperature anisotropy (Alfvén ion cyclotron wave)

\[ \frac{T_{\perp}}{T_{\parallel}} = 10, \beta_{\perp} = 0.01 \]

Central cell
East anchor cell
West anchor cell

High frequency waves excited in the G-10 central cell
Microwave reflectometer

- High-frequency wave at a local point in hot plasma can be measured by a reflectometer.

Electromagnetic wave in ion-cyclotron range of frequencies accompanies the density fluctuation. (H. Hojo 1993)
• Fluctuations (③) are more clearly observed in the reflectometer signal than the edge magnetic probe signal.
Application of bispectral analysis

• Wave-wave coupling needs following matching (or resonance) condition both in frequency and wavenumber spaces.
  \[ f_1 + f_2 = f_3, \quad k_1 + k_2 = k_3. \]
  (Note: higher order couplings are neglected here)

Furthermore, certain phase relationship must be involved in the three interacting waves.

• Bicoherence, which can evaluate the degree of three-wave coupling, is defined by the following equation.

\[
b^2 (k, l) = \frac{|B(k, l)|^2}{E[|X_k X_l|^2] E[|X_m|^2]} \quad m = k + l
\]

\[
B(k, l) = E[X_k X_l X_m^*]
\]

[ ]: Expectation operator

• Bicoherence distinguishes between nonlinearily generated wave and independently excited wave.
Calculation condition

• Apply to the density fluctuation signal obtained by a reflectometer. (sampling frequency is 25 MHz)

• Use several shots with good reproducibility.

• A number of ensembles are extracted from one shot in steady state period.

• Use a total of about 900 ensembles for one calculation.

• Probing frequency of the reflectometer was varied shot-by-shot from 8 - 12GHz with interval of 1 GHz. → Evaluate the radial dependence of nonlinear coupling.

\[ f_{\text{probing}} = 11\text{GHz} \ (r/a \sim 0.5) \]
Example of the calculation

\[ b^2(k, l) = \frac{|B(k, l)|^2}{E[|X_k X_l|^2] E[|X_m|^2]} \]

\[ B(k, l) = E[X_k X_l X_m^*] \]

- Limit from Nyquist frequency: 
  \(-f_N < k, l < f_N, -f_N < k+l < f_N\)

- Symmetry of bispectrum 
  \(B(k, l) = B(l, k) = B^*(-k, -l)\)

\[ f_{\text{probing}} = 11\text{GHz} \quad (r/a \sim 0.5) \]

Reduce computation

Region of “Sum” interaction

Region of “difference” interaction
• Fluctuations with the sum freq. (RF2+AICs) are shown to be generated by three-wave interaction.
• Somewhat broad peaks appeared in AICs×2 freq. are caused by multiple sum combinations among AICs.
Bicoherence — Difference interaction

- Also for the difference freq. between RF2 and AICs, occurrence of nonlinear coupling is clearly shown.
Bicoherence — Difference interaction

\[ RF2 - (RF2 - AIC) = AIC \]
\[ AIC + (RF2 - AIC) = RF2 \]

Also for the difference freq. between RF2 and AICs, occurrence of nonlinear coupling is clearly shown.
Bicoherence — Difference interaction

- Also for the difference freq. between RF2 and AICs, occurrence of nonlinear coupling is clearly shown.
- Bicoherence remains high for RF2, AIC + f<100kHz, leading to the broadening of spectral width around peaks.
Difference frequencies between the AIC waves

Axial transport of high-energy ions of over 6 keV appears in discrete way rather than continuous. Wave-particle interaction may be related.

- Fluctuations with diff. freq. of the AIC waves are generated in the core region. Radial dependence does exist.
Radial dependence of nonlinearity

- Fluctuations with diff. frequencies between the AIC waves are strongly generated in the core region and not in the peripheral region.
- At periphery, in the low-frequency range of <100kHz, significant nonlinearity is involved. This may indicate the couplings with the background turbulence at the periphery.

Combinations which satisfy $f_3 = \text{const.}$

Integration along this line would work out as a good indication of nonlinearity included in the $f_3$. $\Rightarrow$ useful for comparison
Summary

• In the GAMMA 10 central cell, high-frequency (0.1M ~ 20 MHz) fluctuations are observed; 1. ICRF waves applied for ion heating, 2. spontaneously excited ICRF waves (AIC) and 3. others.

• Bispectral analysis is applied to the density fluctuation obtained by a reflectometer for evaluating the three-wave coupling between ICRF waves.

• Nonlinear excitation of 3. the other fluctuations is confirmed by a significant bicoherence.

• Radial dependence exists; difference frequencies of the AIC waves are strongly generated in the core region of the G-10 central cell. In the periphery, coupling with low-frequency components are noted.

In the future,
• Acquire data with higher sampling and evaluate the difference of coupling among slow and fast waves.

• Reduce the number of ensembles extracted from one shot by acquiring identical data from many shots.
  → Investigate the time evolution of bicoherence and the relation to the plasma parameters.