Coupling of ICRF waves and related axial transport of high-energy ions in GAMMA 10

Ryuya Ikezoe

in collaboration with

M. Ichimura, M. Hirata, T. Iimura, T. Yokoyama, T. Sato, Y. Ugajin, Y. Saito
Y. Annaka, A. Shiratani, Y. Shima, J. Kohagura, M. Yoshikawa, T. Imai

Plasma Research Center, University of Tsukuba, Japan

Japan-Korea Workshop on Physics and Technology of Heating and Current Drive
January 28-30, 2013    Hanhwa Resort, Haeundae, Busan, Korea
Outline

● Introduction:
  ➢ Anisotropy-driven Alfvén waves in the ion-cyclotron frequency range (AIC wave)
  ➢ Purpose of this study

● Measurement of internal structure of the AIC waves:
  ➢ Two-channel reflectometer
  ➢ Wave-wave coupling with the AIC waves
  ➢ Spatial correlation of the AIC waves

● Wave-related Axial transport of high-energy ions

● Summary & Proposal
Alfvén ion-cyclotron (AIC) wave is an Alfvén wave driven by strong temperature anisotropy. The frequency is slight below the ion cyclotron frequency \( \Re[\omega / \Omega_{ci}] \sim 0.9 \). In fusion plasmas it is the wave in MHz range. Theoretically derived driving force is proportional to \( \beta(T_\perp/T_\parallel)^2 \). Observed only in large-size tandem mirror mirror devices so far.
Introduction: unknown boundary condition

- In the GAMMA10 central cell, AIC waves have been observed as several discrete peaks in the frequency spectrum. ↔ as one broad peak in geomagnetism

We do not yet have conclusive idea for the mechanism that produces this difference. What determines these boundaries?

- Detailed spatial structure especially in the inner region is needed for the clarification of the boundary conditions.
Reflectometer is a useful tool for studying AIC wave

- A reflectometer can detect **local density fluctuation in the inner region of the plasma**.

It is confirmed both experimentally and theoretically that **AIC wave accompanies the corresponding density fluctuation**.

[A. Mase et al. (1995), H. Hojo et al. (1993)]

\[ V \approx \frac{a^2 + b^2}{2} + ab \cos \phi \]

\[ \approx \frac{a^2 + b^2}{2} + ab(\cos \phi_0 - \delta\phi \sin \phi_0) \]

\( a, b \) are the amplitude of the reference and the reflected waves.

\( \delta\phi \): Rapid density fluctuation at the reflection point

\( \phi_0 \): difference of light path length

- For the identification of the detailed spatial structure of AIC wave, **information at various radial and axial positions is important**.

- For radial information \( \rightarrow \) varying the incident frequency

- For axial information \( \rightarrow \) installing transmitting/receiving antennas at different positions
Two-channel reflectometer composed of two simple heterodyne reflectometers

- **In the case of line-1**
  
  simultaneous two-point measurement at two different positions  
  \(ightarrow\) measurement of axial structure

- **In the case of line-2**
  
  Two-point measurement in the same cross section (correlation reflectometer)

We can arbitrarily choose the two measuring radial positions owing to the application of two independent frequency-variable oscillators
Reflectometer system for the study of AIC wave in GAMM10

Two-channel reflectometer composed of two simple heterodyne reflectometers

- **In the case of line-1**
  
  Simultaneous two-point measurement at two different positions → measurement of axial structure

- **In the case of line-2**
  
  Two-point measurement in the same cross section (correlation reflectometer)

  We can arbitrarily choose the two measuring radial positions owing to the application of two independent frequency-variable oscillators.
Arrangement of horn antennas in the GAMM10 central cell

z = 112 cm, 137 cm

- Two horn antennas are separated by 25 cm in the axial direction.

- O-mode microwave ($f_0 = 8 - 12$ GHz, X-band) covers wide radial region ($r/a \sim 0.8 - 0$) for the typical GAMMA10 plasma.
Successful measurement of ICRF waves by the reflectometer

Wave-wave coupling between the AIC waves and the ICRF wave for heating is more clearly observed in density fluctuation than in magnetic fluctuation.
Characteristics of the wave-wave coupling observed in GAMMA 10

- The coupling is abruptly enhanced while the powers of pump waves are not so varied. → some plasma parameters should affect on the process.

- The bandwidths are extended with enhancement of the coupling.
Good correlation exists between signals measured at different positions

Coherence (reflectometer – magnetic probe)

Statistical noise level is about 0.5

- W-ICRF1 (10.3 MHz)
- E-ICRF1 (9.9 MHz)
- ICRF2 (6.36 MHz)
- AIC (5.6 – 6.0 MHz)

- Good correlations of well above the statistical noise level are obtained at the AIC frequencies and applied ICRF frequencies.

Evaluation of the phase differences is meaningful.
The phase differences of the AIC waves between two radial positions become 0 or $\pi$ according to the radial positions. → AIC waves have phase reversal point in radial direction.
AIC waves become standing waves in axial direction

- The phase differences between axially separated positions change to zero in the early period just after the excitation.

This behavior is the same as the observation with edge magnetic probes. [M. Nakamura et al., RSI 72, 394 (2001)]

→ Excited AIC waves become standing waves in the GAMMA10 central cell.

\[ f = 8 \text{ GHz}, \quad r/a \sim 0.8 \]
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● Summary & Proposal
Additional loss mechanism is needed for satisfying the energy balance.

To satisfy the experimental condition for the calculation of the energy balance, "additional loss" is needed. (H. Hojo et al., J. Plasma Fusion Res. 75, 1089 (1999))

- Pitch angle scattering caused by the AIC waves is a potent mechanism.

Pitch angle scattering

Saturation of the temperature anisotropy was observed when the AIC waves were excited. (M. Ichimura et al., PRL 70, 2734 (1993))
High-energy ions of above 6 keV are detected at the end (Axial transport)

- High-energy ions of above 6 keV have been observed at the end of the machine by using a semi-conductor detector.
- Such high-energy ions are initially generated by ICRF heating and confined in the central mirror field.
- The intensity of the signal rapidly increases when the AIC waves are excited.

Some wave-particle interaction should cause the pitch angle scattering of the confined high-energy ions in the central cell.
Not continuous but discrete-like transport of ions

Experimental fact

Axially transported high energy ions (> 6 keV) are detected rather discretely with the difference frequencies of the AIC waves, 70 - 100 kHz.

What is the underlying process which links the wave and the axial transport?

- **Large-angle scattering by the wave** → Is the E-field strong enough?
- **Bounce resonance** → The bounce frequency of high-energy ions (\(T_\perp/T_\parallel \sim 6/0.4\) keV) is the same order as the frequency of the wave. However, does it really make enough amount of losses because the resonant region in the velocity space is small.
- **Other non-resonant scattering mechanisms**

The details are now Under consideration...
We have investigated the internal structure of the AIC waves by using a two-channel reflectometer, and found follows:

- **Density fluctuation demonstrates wave-wave coupling process more clearly than magnetic fluctuations;**
  The coupling is enhanced abruptly while the powers of pump waves are not so increased.
  → Some plasma parameters should concern in the process.

- **The density fluctuation of the AIC waves has phase-reversal point in radial direction.**

- The phase differences between axially separated positions vary from finite value to zero during the early period just after the excitation.
  → **The AIC waves become the standing waves and those region extends to the axial direction.** (The behavior indicating the pass of the node of the standing wave has also been measured.)

We have measured the axially transported high-energy ions by using a semi-conductor detector.

- **The axial transport of high-energy ions (> 6 keV) does occur in not continuous but discrete-like manner;** the amount of detected ions is modulated with the difference frequency of the AIC waves, 70 – 100 kHz.
  → Some wave-particle interaction should be considered as the mechanism.