Recent ICRF Experiments on the GAMMA 10 tandem mirror

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1. Introduction

GAMMA 10 Device

GAMMA 10 is an axisymmetrized tandem mirror with minimum-B anchors

ICRF:
- Plasma Production
- Ion Heating
- MHD Stabilization

ECH:
- Potential Formation
- Electron Heating
- MHD Stabilization

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Diagram showing the GAMMA 10 device with labeled cells and magnetic field lines. The diagram includes labels for East plug/barrier cell, East anchor cell, Central cell, West plug/barrier cell, West anchor cell, and magnetic field (B) and potential (Z) profiles.
ICRF systems in the central cell

<table>
<thead>
<tr>
<th></th>
<th>Max. power</th>
<th>Max. duration</th>
<th>Frequency range</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF1</td>
<td>300kW ×2</td>
<td>500ms</td>
<td>7.5 - 15 MHz</td>
</tr>
<tr>
<td>RF2</td>
<td>300kW ×2</td>
<td>500ms</td>
<td>4.4 - 9.6 MHz</td>
</tr>
<tr>
<td>RF3</td>
<td>200kW</td>
<td>500ms</td>
<td>36 - 76 MHz</td>
</tr>
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RF1 System (fast waves) 9.9, 10.3 MHz
RF2 System (slow waves) 6.36 MHz

Schematics near the west end of the central cell
ICRF antenna and gas puffing system

changed to 4-10MHz
Photograph near west end of the central cell

- Gas Box
- DHT Antenna
- Nagoya Type III Antenna
- Diamagnetic Loops
Three ICRF systems (RF1, RF2 and RF3) are now in operation. Principally, Type III are driven by RF1 system and are used for the plasma production in the central cell and the ion heating in the anchor cell. The frequency is adjusted to the ion cyclotron frequency at the midplane of the anchor cell.

DHT are driven by RF2 system and used for the main ion heating in the central cell. The frequency is adjusted to the ion cyclotron frequency at near the midplane of the central cell.

In near future, the frequency of RF3 will be changed to 4 – 10 MHz for plasma production and heating.
2. Higher density plasma production with phased antennas

Motivation

In the GAMMA 10 tandem mirror, the improvement of axial confinement has been attained with potential formation

Density clamping is sometimes observed in ICRF produced plasmas ~ $2.5 \times 10^{18}$ m$^{-3}$

To extend the operation region, higher density plasma production is needed.

We are trying:
- Inject of large amount of gas
- Pellet injection
- Use of high harmonic fast waves
- Use of phased antenna array

Mechanism for the density clamping is considered that the eigenmode formation

In the present parameter region, that is, small plasma size, low density and the frequency near $\omega / \omega_{ci} = 1$, one radial eigenmode is only excited.

There is a boundary in the axial direction. Axial eigenmodes have the optimum density discretely. The density clamping will be possible at such optimum value.
Experimental configuration and results

Antennas in east side are fixed. Antennas in west side are driven with the same frequency and the phase between west DHT and Type III antennas is controlled.

RF current flows

\[ \Delta \phi = 0 \text{ deg} \]

\[ \Delta \phi = 180 \text{ deg} \]
Background

Wave propagation analysis in the cylindrical plasma

Wave propagation analysis in the inhomogeneous plasma
by finite element method (FEM) (developed by Prof. A. Fukuyama, Kyoto Univ.)

The dielectric tensor is cold plasma approximation including collisions
Two dimensional code (Axi-symmetric mirror configuration)

B-field                     Density              Axial Profile of B     Radial Profile of n

1 loop antenna assumes Double Half Turn antenna
conducting vessel
**Eigenmode formation in the axial direction**

$k// \text{ increases with density}$

At first, a fast wave with a fundamental radial mode is excited.

$n=0.2$  
$n=2.0$  
$n=6.4 \times 10^{18} \text{ m}^{-3}$
Wave amplitude depend strongly on the antenna configuration

Multiple antenna is better for wave excitation

East and West TypeIII with $I_{rf} = 1$ A
West TypeIII with $I_{rf} = 1.41$ A

DHT antenna is more effective for the fast wave excitation than TypeIII antenna

Both DHT antennas with $I_{rf} = 1$ A
Both TypeIII antennas with $I_{rf} = 1$ A

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Both TypeIII antennas with $I_{rf} = 1$ A
Experimental results

Phase control

10.3 MHz

Phase shifter

RF2

RF1

Fixed at optimum phase and increased production power

Optimum phase is almost zero

could not produce plasma

Line Density \([10^{13} \text{ cm}^{-2}]\)

Time \([\text{ms}]\)

Line Density \([10^{13} \text{ cm}^{-2}]\)

RF power for production \([\text{kW}]\)

Type III + DHT antenna

only Type III antenna

201177 0 deg.
201178 90 deg.
201180 -90 deg.
201181 -45 deg.
201173 180 deg.

Fixed at optimum phase and increased production power

Optimum phase is almost zero

could not produce plasma
3. Evaluation of parametric decay of ICRF waves

**Motivation**

Saturation of diamagnetism is sometimes observed when ICRF heating power is increased. Possible reasons:

- Degradation of confinement
- Macro- and micro-instabilities

Parametric decay of ICRF waves into spontaneously excited waves:

AIC waves and Low frequency (LF) waves

In GAMMA 10, Alfvén ion cyclotron (AIC) waves are excited due to a strong temperature anisotropy.

AIC waves excited in the central cell of GAMMA 10 have several discrete peaks. The frequency of the AIC mode is just below the ion cyclotron frequency.
Conditions for the parametric decay

Frequency: \[ \omega_{ICRF} = \omega_{AIC} + \omega_{LF} \]

Azimuthal mode number: \[ m_{ICRF} = m_{AIC} = m_{LF} \]

Axial wave number: \[ k_{ICRF} = k_{AIC} = k_{LF} \]

Temporal evolution of LF waves

LF waves appear when diamagnetism becomes large. Sometimes, LF waves accompany small reduction of diamagnetism.
Azimuthal mode number

RF2 for ion heating will excite slow (m=-1) and fast (m=+1) waves. Only fast waves (m=+1) can be detected due to resonance layer between antenna and probe positions. (Slow waves (m= -1, 0 ) are damped) AIC waves are in slow wave branch. Always detected in m=-1. LF waves are detected with m=0,+1,+2.

If decay conditions are satisfied, RF2 AIC LF waves 
m= -1 -1 +2 0 -1 +1 +1 -1 0
Axial wave number

Recently, we have started to measure the axial structure of excited waves with axial probe array. Tentatively, we obtained the different axial wave numbers for different azimuthal mode numbers.

Distance between two probes is 0.77 m. Phase differences of 0 and $\pi$ will indicate standing wave formation.
4. Summary

Two topics in recent ICRF experiments on GAMMA 10 are reported.

1. High density plasma production with phased antenna has been done. Conventional Double Half Turn Antenna is effective for the fast wave excitation. Plasma production depends strongly on the phase between two antennas. Phase difference of $\phi = 0$ means both currents enhances wave excitation. (Like slot antenna in HANBIT)

2. Parametric decay of ICRF waves are evaluated. From azimuthal mode number measurement, some modes (slow and fast waves) are candidates for the parametric decay. From the axial wave number measurement, the standing wave structure will be one of the possible solutions.