Non-inductive Plasma Initiation and Plasma Current Ramp-up on the TST-2 Spherical Tokamak

Y. Takase, A. Ejiri, H. Kakuda, T. Oosako, T. Shinya, T. Wakatsuki, O. Watanabe\textsuperscript{3}, T. Ambo, H. Furui, T. Hashimoto, J. Hiratsuka, H. Kasahara\textsuperscript{1}, K. Kato, R. Kumazawa\textsuperscript{1}, C. Moeller\textsuperscript{2}, T. Mutoh\textsuperscript{1}, A. Nakanishi, Y. Nagashima\textsuperscript{3}, K. Saito\textsuperscript{1}, T. Sakamoto, T. Seki\textsuperscript{1}, M. Sonehara, R. Shino, H. Togashi, T. Yamaguchi

The University of Tokyo, Kashiwa 277-8561 Japan

\textsuperscript{1)} National Institute for Fusion Science, Toki 509-5292 Japan

\textsuperscript{2)} General Atomics, San Diego, CA 92186 U.S.A.

\textsuperscript{3)} Research Institute for Applied Mechanics, Kyushu University, Kasuga 816-8580 Japan

24th IAEA Fusion Energy Conference
8-13 October 2012
San Diego, CA, USA
Motivation and Goal of Research

- Economically competitive tokamak reactor may be realized at low aspect ratio by eliminating the central solenoid (CS)

• Formation of Advanced Tokamak Plasma without CS was Achieved on JT-60U

Start-up and initial ramp-up
Noninductive ramp-up (LH)
Transition to self-driven phase


• Is $I_p$ ramp-up by LHW possible in ST? → Demonstrate on TST-2
LHCD Experiment on TST-2

• LHCD experiments have started on TST-2.
  – The scenario is to ramp-up $I_p$ from a very low current ($\sim 1$ kA), very low density ($< 10^{18}$ m$^{-3}$) ST plasma.
  – Up to 400 kW of power at 200 MHz is available. 8.2 GHz ECH (20 kW) installed to enable high $B_t$ (0.3 T) operation required for LHCD.
  – Experiments using a combline antenna (FW launch) was completed, and initial experiments using a dielectric-loaded waveguide array ("grill") antenna (SW launch) have begun.

• Experimental results presented in this poster:
  – Efficiency of $I_p$ ramp-up (FW launch vs. SW launch).
  – X-ray measurements.
  – Polarization-resolved wave measurements by RF magnetic probes.

• Improved antenna for direct SW excitation is being tested.
  – Capacitively coupled traveling wave antenna.
Cold Plasma Dispersion Relation

CMA diagram

- Ion cyclotron resonance
- Electron cyclotron resonance
- Lower hybrid resonance
- O-mode cutoff
- No propagating wave
- HHFW

slow wave (SW) or LH wave

fast wave (FW)

\(R = 0.1\)
\(R = 0.6\)

\(\frac{\Omega_e}{\omega}\) vs. \(\frac{\omega_p^2 + \omega_i^2}{\omega^2}\)

\(N_x^2\) vs. \(R\) and \(n_e\)

slow wave

fast wave
TST-2 Spherical Tokamak and Combline Traveling Wave Antenna

- $R = 0.38$ m, $a = 0.25$ m ($A = 1.5$)
- $B_t = 0.3$ T, $I_p = 0.14$ MA

Combline antenna
(11 elements)

- excites traveling FW
- $I_p$ driven by SW (LHW)
  (requires mode conversion)
$I_p$ Ramp-up to 15 kA Achieved by 200 MHz RF Power
(Combline Antenna)
Hard X-ray Spectra for Co/Ctr Current Drive Directions (Combline Antenna)

- Photon flux is an order of magnitude higher in the co direction.
- Photon temperature is higher in the co direction (60 keV vs. 40 keV).
- Consistent with acceleration of electrons by a uni-directional RF wave.
Frequency Spectra Measured by RF Magnetic Probes (Combline Antenna)

- LHW excited by PDI?
  - Pump wave (f = 200 MHz ± 1 kHz) has FW polarization (|B_t| > |B_p|).
  - PDI sidebands have SW (LHW) polarization (|B_t| < |B_p|).
- Pump wave weakens when sidebands intensify.
Dielectric-Loaded Waveguide Array Antenna (Grill Antenna)

- excites traveling SW (LHW)
Comparison of Driven $I_p$
(Combline Antenna vs. Grill Antenna)

For similar $B_v$ and $P_{RF}$, driven $I_p$ is slightly lower for grill antenna.
  
  Due to lower directivity of the waves excited by the grill antenna?
RF Magnetic Probe Array for $k$ Measurement (Grill Antenna)

- Array can be rotated about its axis
  - to distinguish RF magnetic field polarization
    - $\tilde{B}_t$ (toroidal) and $\tilde{B}_p$ (poloidal)
  - to measure wavevector components
    - $k_t$ (toroidal) and $k_p$ (poloidal)
Measurement of $k_t$ and $k_p$ (Grill Antenna)

- Wavevector components are derived from phase differences of probes a, b, c, d relative to probe e.

SW (LHW) polarization $\tilde{B}_p (\theta = 0^{\circ})$
Radial Profiles of Pump Wave $k_t$ and $k_p$ (Grill Antenna)

- Dominant wavevector components excited by the grill antenna (for 90° phasing) are $k_t \approx 50 \text{ m}^{-1}$ and $k_p \approx 10 \text{ m}^{-1}$.
  - Measured $k_t \lesssim 10 \text{ m}^{-1}$ is much smaller (higher $k_t$ absorbed?)
Measurement of $k_R$ (Grill Antenna)

- Radial component of wavevector can be derived from radial profile of phase measured by probes relative to the injected wave.

![Graph showing phase vs. R](image)

- SW: ~ 35 m$^{-1}$
- FW: ~ 10 m$^{-1}$
Typical Values of Wavevector Components (Grill Antenna)

<table>
<thead>
<tr>
<th></th>
<th>$\tilde{B}_p$ (SW component)</th>
<th>$\tilde{B}_t$ (FW component)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>k_t</td>
<td>\equiv</td>
</tr>
<tr>
<td>$</td>
<td>k_p</td>
<td>$</td>
</tr>
<tr>
<td>$</td>
<td>k_R</td>
<td>$</td>
</tr>
<tr>
<td>$</td>
<td>k_\bot</td>
<td>$</td>
</tr>
</tbody>
</table>

$k_\parallel = 10 \text{ m}^{-1}$ corresponds to $n_\parallel = 2.4$
New Traveling Wave LHW Antenna

- Consists of 13 mutually coupled vertical bars arrayed in the toroidal direction.
- Electric field polarized in the toroidal direction (SW polarization).
- Power is fed to the outermost element. Successive elements are excited through mutual capacitance.
- Antenna is undergoing low-power testing.
Conclusions (1)

• ST plasma initiation and $I_p$ ramp-up by waves in the LH frequency range were demonstrated on TST-2.
  – Combline antenna (FW launch) and dielectric-loaded waveguide array (“grill”) antenna (SW launch) drive similar $I_p$.
  – Slightly lower $I_p$ for the grill antenna may be a result of lower directivity of the excited wave.

• Combline antenna results:
  – X-ray measurements indicate acceleration of electrons by a unidirectional wave.
  – Combline antenna excites the FW, but SW is excited by parametric decay.
Conclusions (2)

• Grill antenna results:
  – Wavevector components for FW and SW were measured by an array of RF magnetic probes.
  – Results are consistent with expectations based on dispersion relations for FW and SW.
  – Lower observed $k_t (\equiv k_{||})$ compared to $k_t$ excited by the antenna may indicate absorption of higher $k_{||}$ components.

• A new type of traveling SW antenna (capacitively coupled array) is being tested at low power.
  – Scheduled to be tested on TST-2 in early 2013.
Acknowledgments

• This work is supported by

  – Japan Society for the Promotion of Science Grants-in-Aid for Scientific Research (S) 21226021, (A) 21246137, (B) 23360409.

  – National Institute for Fusion Science Collaboration Research Program NIFS12KNWR001.

  – Japan-US Cooperation in Fusion Research and Development.