Overview of Spherical Tokamak Research in Japan

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Nationally Coordinated Research Using Various ST Devices*
*TST-2, TS-3, TS-4, UTST, TOKASTAR-2, LATE, HIST, QUEST + theory/modeling

Contents

• $I_p$ Start-up
  • RF Waves: ECW/EBW, LHW
  • CHI
  • AC OH

• Advanced Fueling
  • CT Injection

• Steady-State Operation
  • Particle Control by High Temperature Metal Wall

• Ultra-High-β Operation
  • Reconnection Heating by Plasma Merging

• Low-A Tokamak-Helical Hybrid
  • Stability Improvement by Helical Field
Non-inductive Production of Extremely Overdense ST Plasma by EBW Excited via O-X-B Method in LATE

Extremely overdense ST plasmas are produced non-inductively with EBW excited by O-X-B mode conversion when EBW is excited in the 1st propagation band (between $\omega_{ce}$ and $2\omega_{ce}$ layers). Density reaches ~ 6 times the cutoff density for 5 GHz microwave.
Density and soft X-ray emission increases when the $2\omega_{ce}$ layer is located on the outboard side of the upper hybrid resonance (UHR) layer, i.e., when EBW is excited in the 1st propagation band. Such $B_t$ dependence is observed at two different microwave frequencies.
1-D Kinetic Full-Wave Analysis of O-X-B Mode Conversion by TASK/W1

Integral-operator form of dielectric tensor to describe finite Larmor radius effects

Parameters of LATE
\( B = 0.08 \text{ T}, n_{e0} = 10^{17} \text{ m}^{-3} \)

Antenna loading resistance vs \( k_{//} \)

Perpendicular wave number vs. major radius

Peak corresponds to the optimum injection angle

\( f = 2.45 \text{ GHz} \)
\( k_{//} = 32 \text{ m}^{-1} \)

Fukuyama, et al.
Microwave power was injected at two frequencies (8.2 GHz and 28 GHz) simultaneously for fully non-inductive $I_p$, start-up and sustainment in QUEST.

Gas puff timings are indicated with $\delta P$ increments ($t = t_{g1}, t_{g2}, t_{g3}$ and $t_{g4}$).

$H_\alpha$ intensity increased at gas puff timings. Density sometimes increased spontaneously without gas puff.

Spontaneous density jumps (SDJs) were observed twice ($t = t_{SDJ1}$ and $t_{SDJ2}$) in this discharge, and the density exceeded the cutoff density for 8.2 GHz.

Equilibrium electron pressure profile was bell-shaped.

Flux surfaces are densely spaced on the low-field side.

Overdense 25 kA plasma with central high energy electron pressure was built up non-inductively and sustained for 0.4 s.
High bulk $T_e$ was observed near $2\omega_{ce}$ layer for 28 GHz, while a local $T_e$ peak was observed near $\omega_{ce}$ layer for 8.2 GHz only before the 1st SDJ at $t=1.75$ s.

Measured bulk pressure $P_e$ profile was hollow, resulting from the off-axis heating at the $2\omega_{ce}$ layer and radiation cooling after SDJs.

Current density profile and equilibrium pressure profile (EFIT) are centrally peaked.

Hard X-ray emission at high energies (>200 keV) was observed from the central overdense region, while bulk $P_e$ was larger on the high-field side off-axis region near the $2\omega_{ce}$ layer for 28 GHz.

There were abundant energetic electrons in the central overdense region.

Bulk $T_e$ and $P_e$ increased in the overdense region where there are Doppler-shifted $\omega_{ce}$ resonance layers for large $N_{//}$.
Kirchhoff integral code was used for mirror design. Mirror performance at 28 GHz was checked by 3-D full-wave simulation. Sharply focused beam with small beam size (0.052 m) was obtained. The 2nd focusing mirror can steer the beam in the toroidal direction.

Non-inductive $I_p$ of 70 kA was achieved using the new launcher.
Two capacitively-coupled combline (CCC) antennas
- Traveling LHW is excited directly
- Sharp $n_\parallel$ spectrum & high directivity

$I_p = 25$ kA achieved with outboard-launch antenna alone (improved from 16 kA)

Outboard-launch  Top-launch

(installed in March 2016)

Good core accessibility and deposition are expected even at high $n_e$.

CS-less $I_p$ Start-up by LHW
collaboration with Moeller (GA, US)
Sustained $I_p$ increases with $n_e$ and $B_t$

Comparison of discharges sustained by outboard-launch and top-launch antennas

$I_p$ of up to 13 kA is sustained by the top-launch antenna alone. However, precise plasma position and size control during the initial $I_p$ ramp-up phase is difficult.

Use outboard-launch for start-up and top-launch for ramp-up. (initial experiment in progress)
These ST devices in US and Japan aim to develop and understand non-inductive CHI start-up/ramp-up that is necessary for the viability of ST reactors.

The successful current generation up to 0.3 MA in NSTX (PPPL) validated the capability of CHI for start-up followed by inductive ramp-up to 1 MA.

A new CHI start-up experiment with an alternate electrode and insulator configuration, combined with ECH, will start on QUEST (Kyushu U.) under US-Japan collaboration.

Primary purpose of CHI experiments on HIST (U. Hyogo) is to examine the physics of flux closure and current profiles which still remain key issues of CHI.
Comparison of CHI generated plasmas between high and low bias flux operations.

- Peak $I_p$ of 80-120 kA was generated by CHI. A stable closed flux formation was achieved in the high bias case.
- In the low bias case, the toroidal current density is concentrated on the inboard side, leading to kink instabilities at a later time.
- $T_{i,D}$ during the $I_p$ rise phase in the low bias case is higher than $T_e \sim 10$ eV, indicating ion heating.
- $n_e$ was $\sim 1 \times 10^{20}$ m$^{-3}$. 

Characteristics of ST Plasmas Generated by CHI on HIST

- \( l_t \): toroidal plasma current
- \( j_t(R) \): toroidal current density
- \( T_{i,D} \): Doppler ion temperature
- \( T_e \): electron temperature
- \( n_e \): electron density
Plasmoid Formation and Flux Closure in CHI Plasmas

1. Formation of closed flux surfaces (c) was verified. The ratio of the closed flux to the total flux is 25-30%.

2. Small-scale plasmoids (a), (b) are generated in the elongated toroidal current sheet (d), (e) in the presence of a strong $B_t$.

3. The plasmoid grows in size due to inward diffusion (e), (f) of the toroidal current in the open flux region during the decay phase.

Experimental results from internal magnetic probe measurements
AC Ohmic Heating Experiments on TST-2
(for pre-ionization and DC current drive)

Resistive V.V.
Inconel 625 (t=1.57mm)
1/e frequency: 133 kHz

Small flux swing

$V_L$

$\Psi$

$I_p$

Cumulative effect to increase $n_e$ (pre-ionization)?

Heating power: $\langle I_p V_L \rangle \rightarrow$ DC current drive?
Exponential growth in emission and $I_p$

- The growth rate and saturation in $I_p$ $n_e$ can be explained qualitatively by a model based on Townsend’s $\alpha$.
- Successful pre-ionization with $|V_{\text{loop}}| \geq 0.5$ V (~0.6 V/m).

DC current drive

DC $I_p$ component (<1.9 kA) appears when $B_z$ is applied

Time averaged visible camera image shows an ST configuration.
A CT plasma with high density (up to the order of $10^{21}$ m$^{-3}$) was injected perpendicularly from the outboard midplane along the major radius at a speed $> 200$ km/s.

Compact toroid (CT) injection experiments have been conducted to develop an advanced fueling method.

UH-CT injector used in this experiment is capable of injecting a CT plasma that can penetrate to $B_t = 0.8$ T.

$B_t = 0.8$ T
$W_B = 255$ kJ/m$^3$

$B_t = 0.5$ T
$W_B = 99$ kJ/m$^3$

for pulse mode
CT Injection into OH ST Plasma

CT plasma injection:
$(V_{\text{CT\_form.}} = 17 \text{ kV and } V_{\text{CT\_acc.}} = 25\text{kV})$
- CTI has no adverse effect on $I_p$.
- $n_e$ increases just after CTI.

» Non-disruptive CTI was obtained.

Thomson scattering measurement:
- $n_e$ is observed to increase on peripheral channels 0.5 ms after CTI.

Diffusion and equilibration times of CT injected particles in the vicinity of CT deposition:
- 50~100 $\mu$s for central CT deposition
- 1.4~2 ms for peripheral deposition

» Peripheral particle deposition by CTI was observed.
Hot wall was installed in 2014

316L stainless steel coated with 0.1 mm thick APS-W, operated with $T_{\text{wall}} = 393-523$ K

**Cross-Sec. at A**
- Ion Drift
- Surface
- APS-W
- 50nm

**Cross-Sec. at B**
- Electron Drift
- Surface
- APS-W
- 50nm

**Surface of APS-W at Top Wall**
- 20µm
- 5000x, 700 Mix(L)

**QUEST**
- Top Flat Plate
- Top Conical Area
- Mid-plane Area
- Flat Divertor
- CHI electrode
- Bottom Conical Area
- Bottom Flat Plate
- Center-stack
- Vessel Cover
- Center-stack vessel
- Hot wall
- Vacuum Vessel
- Thermal Isolator
- Radiation Shield
- Heater
- Cooling panel

**Steady-State Operation**

**EX/P4-49 Hanada, et al.**
Progress Towards Steady State:
115 min Discharge Achieved with $P_{RF} = 40$ kW, $T_{wall} = 393$ K

Microwave systems:
2.45 GHz : < 50kW
8.2 GHz: < 400kW
28 GHz: 300kW
Time Evolution of Wall Pumping Rate can be Reproduced by Hydrogen Barrier Model

\[ \frac{d(H_w + H_T)}{dt} = \Gamma_{in} S - \frac{k}{Sd_R^2} H_w^2 \]

\[ \frac{dH_T}{dt} = \alpha H_w \left( 1 - \frac{H_T}{H_T^0} \right) - \gamma H_T \]

- \( dH_w/dt \): wall pumping rate for \( H \)
- \( H_w \): number of \( H \) dissolved in wall
- \( H_T \): number of \( H \) trapped in defects
- \( H_T^0 \): upper-limit of \( H \) trapped in defects
- \( S \): surface area
- \( \Gamma_{in} \): net influx per unit of area into wall
- \( k \): surface recombination coefficient of \( H \)
- \( d_R \): thickness of deposition layer
- \( a \): \( H \) trapping rate
- \( g \): \( H \) de-trapping rate

\[ \#32737 \ (T_{wall} = 393 \text{ K}: \text{blue dots}) \]
\[ \#32700 \ (T_{wall} = 473 \text{ K}: \text{red dots}) \]

Solid lines indicate calculated results predicted by the hydrogen barrier model.
A fusion reactor can maintain reaction, once D-T plasma with \( n\tau > 10^{20} \text{ m}^{-3} \text{ s} \) is heated to > 10 keV.

The key is how to increase \( T_i \) to over 10keV.

In conventional tokamaks:
1. **Ohmic heating**
   \[ W = \eta I_t^2 \propto T_e^{-3/2} I_t^2 \]
2. **Additional heating** (NBI or RF)

Merging of two toroidal plasmas can increase their \( T_i \).
\(B_{\text{rec}}^2\) Scaling of Reconnection Heating Indicates Direct Access to \(\alpha\)-heating without NBI, Leading to New High-\(B_{\text{rec}}\) Experiments: ST-40 & TS-U

\[V_{\text{outflow}} \sim V_{\text{pA}} \propto B_p / n^{1/2}\]

\[\Delta W_{\text{th}} \sim \Delta W_{\text{ion}} \propto \Delta (nT_i) \propto \Delta T_i \quad (n \sim \text{constant})\]

\[\Delta W_{\text{rec}} \propto B_{\text{rec}}^2 \propto B_p^2\]
Tokamak discharges with and without helical field were compared.

Suppression of horizontal position oscillation by helical field application was observed by a magnetic probe inserted to the plasma core under a weak vertical field condition.

• The radial movement of tokamak plasma was studied without probe insertion by a high-speed camera.
• The plasma touched the outer wall repeatedly in a discharge without helical field. In a discharge with helical field, the plasma position was stable and touched the inner wall during the discharge.
• The stabilization effect of the external helical field on the tokamak plasma horizontal position was confirmed in the TOKASTAR-2 experiment.

For Further Details (at FEC2016)

• $I_p$ Start-up
  – ECW/EBW (EX/P4-45 Tanaka, et al., EX/P4-50 Idei et. al.,)
  – LHW (EX/P4-48 Ejiri, et al.)
  – CHI (EX/P5-21 Nagata, et al.)
  – AC OH (EX/P4-48 Ejiri, et al.)

• Advanced Fueling
  – CT Injection (PD/P-16 Fukumoto, et al.)

• Steady-State Operation
  – Particle Control by High Temp. Wall (EX/P4-49 Hanada, et al.)

• Ultra-High-$\beta$ Operation
  – Reconnection Heating (EX/P3-38 Y. Ono, et al., PD/P-11 Inomoto, et al.)