Progress of ECW and Alfven Wave Experiments in the SUNIST Spherical Tokamak and Related Theoretical Research Activities

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Brief introduction to the SUNIST

- **Sino United Spherical Tokamak**
  - Managed by Department of Engineering Physics, Tsinghua Univ. and Institute of Physics, CAS
  - Close collaborated with SWIP, ASIPP and other universities.

- **Typical parameters**
  - \( R_0/a \approx 0.3 \text{m} / 0.23 \text{ m} \)
  - \( B_{T0} < 0.15 \text{ T} \)
  - \( I_P \approx 50 \text{ kA} \)
  - \( n_e \approx 1 \times 10^{19} \text{ m}^{-3} \)

- **Major diagnostics**
  - Langmuir probes /magnetic probes
  - 94GHz interferometer /26-40GHz reflectometer
  - Fast camera (5130 fps) /\( H_a \) diode array
  - Visible Spectrometers (200 ~ 1000 nm)

- **Major interests/activities**
  - Properties of ST plasmas
    - Edge plasma fluctuation
    - MHD activities and its control (by biased electrode, external coils, rf antennae)
  - Non-inductive plasma startup and CD
    - Startup by electron cyclotron waves
    - Alfven waves current drive
Outline

• Recent research progress
  – ECW startup: experiment and modeling
  – Preliminary results of AW experiments

• Efforts for further experiments
  – Improvement of Ohm discharge
  – Upgrade of rf system
  – Future experimental plans

• Some related theoretical researches
  – O-X-B conversion of ECRF
  – Nonlinear ponderomotive force and current/flow drive

• Summary
ECW startup: experiment

- **Experimental setup and results**
  - 2.45 GHz O mode/<100 kW/10 ms (loaned from SWIP)
  - ~2 kA $I_p$ last for several ms
  - $I_p$ is inversely proportional to $B_V$
  - Closed flux surface formed but no current jump observed

- **What we are interested in**
  - The spikes at the beginning of discharges ($I_P$, $H_\alpha$ and $n_e$)
  - This transient process of the plasmas during startup may dominate the efficiency of startup
  - PS: spikes are widely found on STs
ECW startup: experiment (ctd.)

- $H_a$ and the reflected microwave power are found to have connections with these scanning parameters.
- The time and spatial evolution of $n_e$ is essential to understand the physics of startup.

Y Tan, Z Gao and L Wang, Nucl. Fusion 51, 063021(2011)
Main processes
- Ionization by microwaves
- Motion of particles
- Reflection of microwaves

Coefficient estimation based on experiments
Approximations: optical launch and receive
ECW startup: modeling (ctd.)

Experimental results

One spike

Oscillating

B\textsubscript{T} scanning

Simulation results

Y Tan, Z Gao and L Wang, PST 13, 30(2011)
Preliminary results of AW experiments

- **Motivation**
  - To explore the effective current drive method in high dielectric constant (high density at weak field)
  - to verify the theory of low frequency current/flow drive [discussed later]

- **Antenna system**
  - four modules in toroidal, two straps in poloidal for each module
  - BN limiter designed

- **Experimental setup**
  - Rf generator: 20 ~ 50 kW, 0.4 ~ 1 MHz (non-continuous, only two phases stable)
  - Two of four pairs used with \( \pi \) phasing
  - \(|N|=1 \sim 60\%\), \(|M|=1 \sim 15\%\) (no shielding yet)
  - Experimental parameters
    - IP: 30~50 kA
    - \( n_e \): 0.5 ~ 3\( \times \)19 m\(^{-3}\)
    - BT: 800~1200 G

Experimental results (left) and theoretical results (right) of the impedances of antenna shows a similar trend

Y Tan, Z Gao and Y He, FED 13, 30(2009)
Runaway discharges are enhanced when:
- Low IP (~30 kA), low ne (<1E19 m⁻³)
- Accelerated by rf field rather than resonant drive?

Normal discharges
- 50 kA , >1E19 m⁻³
- No effects observed

The Ohm discharge is not good enough
✓ No Experiment in the first half of Year 2012

- ECR source cannot work
- Very limited duration of Ohm discharge
- Abnormal status of rf source /antenna

- Undergraduate course on fusion plasma in the Spring Semester (40 students)

Students in magnetic probe experiments @ SUNIST, Tsinghua Univ.
Recent research progress
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Efforts for further experiments
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Summary
Improvement of Ohm discharge

- **Ohmic field power supply: double swing operation**
  - IGBT switches enable +10 kA → -6 kA
    
    [+13 kA → -13 kA (60mVs) further ]
  - Pulse length of Ohmic discharge is extended to about 10 ms (20-30 ms expected )

- **Vertical field power supply: from two-step capacity discharge to arbitrarily programmable**
  - DSP + IGBT (1.5 kA) solution
Upgrade of rf system: ECR microwave source

- A 5GHz/200kW/50ms microwave system under construction
  - Deposited more inside than old 2.45GHz source
  - Under testing and tuning

The H.V. power supply

The Klystron under test
Upgrade of rf system: AW system

- **rf source**
  - Four-phase oscillator: 4x100kW / 0.4~1MHz
  - Present status: four phasing outputs are unstable/ only (0, π) phasing are stable
  - In the next stage, the following connection methods are employed rather than to build a new rf source

Antenna connections for \(|N|=1\) and \(|N|=2\)

![Diagram showing antenna connections](image-url)
Upgrade of rf system: AW system (ctd.)

- **Antenna system**
  - ✔ Shielding by BN plates (loaned from PPPL, DOE)
  - ✔ Improved Feeders
    - integrated with screening
    - increasing the impedance
    - Antenna current: 400A → 800A
Future plans

- **AW experiments**
- **Investigation of Alfven eigenmodes excited by AW antenna system**
- **ECW /EBW startup using the new 5GHz source**
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• Summary
O-X-B conversion in ECRF

- O-X-B conversion might be important for heating/CD by ECRF in ST or other high density (weak field) plasmas

\[ 5\text{GHz} \sim n_{\text{cutoff}} = 0.3 \times 10^{18} \text{m}^{-3} \]

- O-X conversion: a narrow window around the optimal \( \text{N}_z \)

\[ N_{zc}^2 = \left[ 1 - \frac{(1 - N_{zc} \beta_0)^3}{(1 - N_{zc} \beta_0 + Y)} \right] \left[ 1 + \frac{(1 - N_{zc} \beta_0) \beta_T^2}{2(1 - N_{zc} \beta_0 + Y)} \right] \left[ 3 - \frac{(1 - N_{zc} \beta_0)^2}{(1 - N_{zc} \beta_0 + Y)^2} \right] \]

\[ \frac{Y}{1 + Y} \quad \text{at } \beta_0 = \beta_T = 0 \quad \text{here, } \ Y = \frac{\omega_{ce}}{\omega} \]

- Motion of electron (current or temperature) shifts the window toward high \( \text{N}_z \) slightly.
- However, if this effect is not considered, the degeneration of O-X conversion efficiency will be 10% 

--- Jia and Gao, PoP 18, 10411 (2011)
In collisionless plasmas, all the flux-surface-in forces are depending on the resonant absorbing and none of nonresonant forces by low frequency waves can drive parallel current.

We may enhance the parallel force by increase $k_y$.

\[ F_2 = \left\langle \int d\mathbf{v} \left( \mathbf{E}_1 + \mathbf{v} \times \mathbf{B}_1 \right) f_1 \right\rangle - m \nabla \cdot \int d\mathbf{v} (\mathbf{v} f_2) \]

\[ F_{2,z} = \frac{1}{2} \text{Re} \sum_{n,m} e^{i(k_n - k_m)x} \sum_l e^{il(\theta_n - \theta_m)} E_m^* \left( \frac{k_z}{\omega} - i \delta k_x \rho_l \frac{k_y}{\omega} \right) W_l \cdot \mathbf{E}_n \]
- Parallel momentum absorbed by trapped electron may be returned to contribute the current drive in the steady status
- At the mean time, Radial electric field can be generated by resonant trapped electron pinch with rf injection, and then drive the flow
- This mechanism may partially explain the flow drive in LHCD experiment. However, it will be more clear and robust in low frequency cases (such as ICRF FW or AW)
- More self-consistent work ongoing

\[ E_r \approx \eta P_D \sum_j n_{\parallel j} \kappa_t (n_{\parallel j}) f_{Dj} \delta (n_{\parallel} - n_{\parallel j}) \]

Gao, Fisch and Qin, PoP 18, 082507 (2011)
Summary

• Research activities on ECW startup, Alfven wave experiments at the SUNIST in recent years are reviewed.
• Future experimental plans of the SUNIST and corresponding engineering efforts are introduced.
• Some related theoretical researches are briefly presented.
• Comments and potential collaborations are welcome.
backups
Conjectures from the scanning results

<table>
<thead>
<tr>
<th></th>
<th>Slew rate of the reflected rf power</th>
<th>Delay of $H_\alpha$ peaks</th>
<th>Maximum amplitude of $H_\alpha$</th>
<th>Amplitude of the flat top of $H_\alpha$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_T$</td>
<td>+</td>
<td>-</td>
<td>0</td>
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<tr>
<td>$B_V$</td>
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<tr>
<td>$P_{rf}$</td>
<td>0</td>
<td>-</td>
<td>+</td>
<td>0</td>
</tr>
</tbody>
</table>

**Conjectured explanations**

- Drift/Formation time of the cut off layer
- Power density @ ECR
- Ionization rate and loss rate
- Microwave frequency

Summary of the scanning results
+-: positive effects, -: negative effects; 0: no effects

2012-07-11 23 SUNIST
Device upgrade: dis- and re-assembling

Mission:
• to install AW antenna and new magnetic probe system
• to open a new manhole window in vessel
• to erase the Siliconized film deposited inside the VV
• to check the CS component

✓ Completed in early 2009
Device upgrade: vacuum chamber

- A manhole window opened for convenience of in-vessel components installing and servicing and as an optical/radiant diagnostic window (CCD camera, reflectometer, spectrometer)
MHD activities: IREs

- IREs widely found on STs
- IREs and the evolution of MHD activities and equilibrium parameters during IREs observed on SUNIST
- A collapse in pressure profile may correspond to the occurrence of IREs

The appearance of IREs strongly depends on the strength of toroidal field
MHD activities: effects of n=1 magnetic field

- **Biased radial magnetic field**
  - L: 210 uH, I: 1 kA, BR max: 37 Gauss
  - Suppress the MHD oscillations
  - Change the spatial structures
  - Slightly increase electron density

The coils to produce biased magnetic field.

The discharge with magnetic field

The discharge without magnetic field

n_e slightly increases when the radial magnetic field is applied

by Prof. FC Zhong’s group in Donghua U.
通过铅屏蔽判断测量的正确性

图 1 探测器除尾部外全部被铅砖包裹，低密度的逃逸放电

图 2 同一位置，相同放电条件，移走探测器前端的铅砖

图 3 移走全部铅砖后，进气较多的放电
Parameter estimation

- **For electrons (100 eV)**
  - Lamor Radius: $\sim 0.4$ mm ($v_{\parallel} = 0, B = 875$ G)
  - $v_{\parallel}: \sim 6 \times 10^6$ m/s ($v_{\perp} = 0$)

- **For hydrogen gas (300 K, 1E-3 Pa)**
  - $v_{\text{en}}: \sim 3 \times 10^4$ 1/s (3E9 1/s for 1 torr)
  - $v_{\text{ionization}}: \sim 2 \times 10^4$ 1/s (2E9 1/s for 1 torr)
  - $v_{\text{ei}}: \sim 1 \times 10^3$ 1/s ($n_e \sim 1 \times 10^{17}$)

- **For SUNIST ($R_0 = 0.3$ m, $B = 875$ G)**
  - $< v_R + v_{VB} > = \frac{2T}{qR_cB} \frac{1}{B}: \sim 7.6 \times 10^3$ m/s (vertical)
  - $v_{E \times B} = \frac{E}{B}: \sim 1.1 \times 10^3$ m/s ($E = 100$ V/m) (radial)
  - $v_v = v_{||} \frac{B_z}{B_T}: \sim 1.4 \times 10^5$ m/s ($B_z = 20$ G) (vertical)
• 尖峰（等离子体密度、电流）的成因
  － 多次反射是否也有作用？
  － 多次反射的衡量
    • 泄漏的微波功率
  － 微波泄露在等离子体产生后迅速减少至0
  － 微波反射迅速提高
  － →多次反射几乎不存在
The triode oscillator with cables connected

The coaxial cables connected to resonant circuit

The connection between a resonant circuit and a pair of antennas.
阿尔芬波实验系统的调试

- 在等离子体击穿时，阿尔芬波天线作为外限制器存在，但在封闭磁面形成后，天线隐藏在最外层封闭磁面外
阿尔芬波天线对欧姆放电影响不大
（红线：天线安装前，黑线：天线安装后）