Study of Current drive efficiency and its correlation with photon temperature in the HT-7 tokomak

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合肥绿岛——董铺湖与科学岛航拍

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Outline

• Introduction
• Study of Photon temperature
• Current drive efficiency and its correlation with photon temperature
• Summary
• Acknowledgements
The word tokamak is derived from Russian words, *toroidálnaya kamera* and *magnitnaya katushka*, meaning ‘toroidal chamber’ and ‘magnetic coil’. The device was invented in the former Soviet Union, the early development taking place in the late 1950s. The advantage of the tokamak comes simply from the increased stability provided by its larger toroidal magnetic field. The successful development of the tokamak was principally the result of the careful attention paid to the reduction of ‘impurities’ and the separation of the plasma form the vacuum vessel by means of a ‘limiter’.
Tokamak is a toroidal plasma confinement system. The plasma being confined by the magnetic field.

The principle magnetic field is the toroidal field. However, this field alone does not allow confinement of the plasma. In order to have an equilibrium in which the plasma pressure is balanced by the magnetic forces, it is necessary also to have poloidal magnetic field.
Typical parameters of tokamak are as follows

Maximum, magnetic field of the coils is about 12T, Since the toroidal magnetic field is inversly proportional to the major radius of the tokamak, so the resulting magnetic field at the center of the plasma is around 6-8T.

In large tokamaks current of the order of MA are available. Present tokamak plamas typically have particle densities in the range $10^{19}-10^{20}$ m$^{-3}$. This is factor of $10^6$ lower than that in the atmosphere.
Current drive refers to the production of toroidal electric current in a plasma torus, i.e., the current that encircles the torus hole.

The intended use of this current is to enable a tokamak fusion reactor to operate continuously.
Non-Inductive Current Drive Techniques

- Neutral Beam Current Drive
- Lower Hybrid Current Drive
- Fast Wave Electron Current Drive
- Fast Wave Minority Ion Current Drive
- Electron Cyclotron Current Drive
1. LHCD has proven to be a versatile and highly successful method for driving non-inductive current in tokamak plasma.
2. The effectiveness of lower hybrid waves for control of the radial profile of plasma current has been demonstrated in many tokamaks.
3. It is very effective to control the plasma density profile using LHCD.
4. More recent applications have involved localized off-axis current drive generation for controlling saw-teeth, neoclassical tearing modes and optimizing reversed shear for improved access to advanced tokamak regimes.
5. LHCD has the highest CD efficiency recorded to date compared to other CD methods.
Experimental work in LHCD

Apparatus for injecting waves into tokamaks

\[ \omega_{LH}^2 = \left( \Omega_e^2 \Omega_i^2 + \omega_{pi}^2 \Omega_e^2 \right) / \left( \omega_{pe}^2 + \Omega_e^2 \right) \]

LH frequency

\[ n_{//}^{acc} = \omega_{pe} / \omega_{ce} + \sqrt{1 + \omega_{pe}^2 / \omega_{ce}^2 - \omega_{pi}^2 / \omega^2} \]

Accessibility condition
On Alcator C tokamak, Steady state current drive efficiency at $B=8$ T. (a) Line-averaged density times current vs power (b) Efficiency vs density.
Experimental work in LHCD

History of achieved driven current by LHCD.
Experimental work in LHCD

CD efficiency versus parallel refractive index in ASDEX. Symbols show experimental data and line show theoretical CD efficiency.

CD efficiency versus volume averaged electron temperature.
LHCD efficiency based on hot electric conductivity theory.

Characteristics of reduced loop voltage versus normalized LH power with different plasma parameter on HT-7 tokamak.

Dependence of CD efficiency on lower hybrid wave parallel refractive index on HT-7 tokamak.
CD efficiency was investigated in many tokamaks based on loop voltage studies by scanning different plasma parameters.

Our investigation of current drive efficiency is unique in a way as it is based in terms of population of fast electrons generated by lower hybrid waves and we also investigated the correlation of CD efficiency with photon temperature.
HT-7 tokamak LHCD System

- Frequency: 2.45GHz
- Pulse length: CW
- Power: up to 1.2 MW
- $N_{||}^{\text{peak}}$: 1.25~3.45
Progress of long pulse plasma operation on HT-7 tokamak
More than 30 diagnostics are available on HT-7 tokamak that provide useful information during experimental campaigns.

$T_e$ was measured by a SX-PHA shot by shot in LHCD plasmas.

A CdTe detector based on HX array is used as main tool in present investigations.
## Comparative performances of standard HXR detectors

<table>
<thead>
<tr>
<th>Detector</th>
<th>NaI(Tl)</th>
<th>CsI(Tl)</th>
<th>BGO</th>
<th>Ge</th>
<th>CdTe</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type</strong></td>
<td>scintillator&lt;sup&gt;a&lt;/sup&gt;</td>
<td>scintillator&lt;sup&gt;b&lt;/sup&gt;</td>
<td>scintillator&lt;sup&gt;a&lt;/sup&gt;</td>
<td>semiconductor</td>
<td>semiconductor</td>
</tr>
<tr>
<td><strong>Atomic number</strong>&lt;sup&gt;c&lt;/sup&gt;</td>
<td>46.56</td>
<td>54.02</td>
<td>62.52</td>
<td>32</td>
<td>50.12</td>
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<tr>
<td><strong>Density g/cm&lt;sup&gt;3&lt;/sup&gt;</strong></td>
<td>3.67</td>
<td>4.51</td>
<td>7.13</td>
<td>5.32</td>
<td>6.06</td>
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<tr>
<td><strong>Operating temperature (K)</strong></td>
<td>293</td>
<td>293</td>
<td>293</td>
<td>77</td>
<td>293</td>
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<tr>
<td><strong>Linear attenuation µ&lt;sup&gt;d&lt;/sup&gt; (cm&lt;sup&gt;-1&lt;/sup&gt;)</strong></td>
<td>3.70</td>
<td>5.44</td>
<td>17.38</td>
<td>1.88</td>
<td>4.51</td>
</tr>
<tr>
<td><strong>Linear attenuation µ&lt;sup&gt;0&lt;/sup&gt; (cm&lt;sup&gt;-1&lt;/sup&gt;)</strong></td>
<td>0.2</td>
<td>0.2</td>
<td>0.5</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td><strong>Stopping efficiency&lt;sup&gt;de&lt;/sup&gt; (%)</strong></td>
<td>52</td>
<td>66</td>
<td>97</td>
<td>31</td>
<td>60</td>
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<tr>
<td><strong>Stopping efficiency&lt;sup&gt;ef&lt;/sup&gt; (%)</strong></td>
<td>4</td>
<td>5</td>
<td>9</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td><strong>Energy resolution&lt;sup&gt;d&lt;/sup&gt; (%)</strong></td>
<td>15–25</td>
<td>25–30</td>
<td>35–45</td>
<td>&lt;1</td>
<td>4–10</td>
</tr>
<tr>
<td><strong>Fast neutron µ&lt;sup&gt;g&lt;/sup&gt; (cm&lt;sup&gt;-1&lt;/sup&gt;)</strong></td>
<td>0.13</td>
<td>0.09</td>
<td>0.17</td>
<td>0.13</td>
<td>0.15</td>
</tr>
<tr>
<td><strong>Thermal neutron µ&lt;sup&gt;h&lt;/sup&gt; (cm&lt;sup&gt;-1&lt;/sup&gt;)</strong></td>
<td>0.1</td>
<td>0.1</td>
<td>0.03</td>
<td>0.01</td>
<td>37</td>
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<tr>
<td><strong>Detector pulse rise time (μs)</strong></td>
<td>0.5</td>
<td>4.0</td>
<td>0.8</td>
<td>&lt;0.05</td>
<td>0.05–0.5</td>
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<tr>
<td><strong>Magnetic field shielding</strong></td>
<td>yes</td>
<td>yes&lt;sup&gt;i&lt;/sup&gt;</td>
<td>yes</td>
<td>no</td>
<td>no</td>
</tr>
</tbody>
</table>

<sup>a</sup>+ photomultiplier only.

<sup>b</sup>+ photomultiplier or Si photodiode.

<sup>c</sup>Averaged value on elements.

<sup>d</sup>At E = 122 keV, line emission of ⁵⁷Co.

<sup>e</sup>For a 2-mm-thick detector.

<sup>f</sup>At E = 1 MeV.

<sup>g</sup>From total cross-section at 2.5 Mev.

<sup>h</sup>From total cross-section.

<sup>i</sup>No with Si photodiode.
There are 11 sight lines set to observe the FEB emission in poloidal cross section from -25 to 25 cm with spatial resolution of 5 cm, and a sight line is set to monitor the wall radiation at the low field side.

2 cm of lead homogeneously cast in one piece between 0.5 cm of stainless steel provide shielding to prevent non-plasma X ray radiation from entering the detector.

Aperture size of pin hole is 4x4 mm.

The system is installed in front of aluminum vacuum window which is transparent for photon with energy greater than 20 keV.
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HT-7 Tokamak

**HT-7 typical range of operating parameters:**

- $I_p = 100\sim 250 \text{ kA} (250)$
- $n_e = 1\sim 8 \times 10^{19} \text{ m}^{-3} (6.5)$
- $T_e = 1\sim 5 \text{ keV} (4.5)$
- $T_i = 0.2\sim 1.5 \text{ keV} (1.5)$

**HT-7 wave heating systems:**

**ICRF:**
- $f = 15\sim 30 \text{ MHz}$,
- $P = 0.3 \text{ MW} (0.35)$
- $f = 30\sim 110 \text{ MHz}$, $P = 1.5 \text{ MW}$

**LHCD:**
- $f = 2.45 \text{ GHz}$, $P = 1.2 \text{ MW} (0.8)$
Questions

- What is photon temperature?
- How Photon temperature varies with plasma current, plasma density, lower hybrid power and parallel refractive index?
- What is the correlation of photon temperature and CD efficiency?
The photon temperature is just a parameter to characterize the level of anisotropy of the fast electron tail, which is determined by the exponential-like decrease of the FEB energy spectrum.

The photon temperature indicates the “hardening” of the x-ray spectra, resulting from the interaction of fast electrons with residual loop voltage.

The $T_{ph}$ is a function of many plasma parameters (e.g., plasma density, loop voltage, LH wave parallel refractive index and so on).
The Photon temperature gives the energy distribution of fast electrons driven by the LH waves, which is also affected by different aspects like slowing down time, residual loop voltage and parallel refractive index.

Radiative distribution for different energies
A typical waveform of the LHCD discharge

Waveforms of LHCD discharge no. 87655

- The plasma current is kept constant by the feedback control system that adjusts the input power from ohmic transformer.
- In HT-7 tokamak, the plasma is first built up by the ohmic discharge and then the lower hybrid wave is applied to sustain the plasma current.
- The loop voltage is decreased on the application of LHW, which means that part of plasma current is sustained by LHW power. This loop voltage drops to the value required to keep the sum of LH driven current and ohmic current unchanged.

(a) is the plasma current, (b) the loop voltage, (c) the center line–average density, (d) the LH power, (e) the center line-integrated FEB emission intensity.
The FEB emission spectrum

FEB emission spectrum from center sight line at 0.6 ± 0.05 s for discharge no. 87655.

For higher photon temperature the fraction of energetic fast electrons population is larger, which means more plasma current is carried by the fast electrons.
Photon temperature increases with the increase of plasma current. As the Plasma current increases, it needs more ohmic power to drive the plasma current at constant LHW power so the loop voltage increases.

Distribution function of electron versus normalized parallel velocity for fixed density and LH power.
Photon temperature decreases as the plasma density is increased.

Distribution function of electron versus normalized parallel velocity.
Photon temperature is weakly dependent on the parallel refractive indices of LHW.

Distribution function of electron versus normalized parallel velocity.
Summary

• The photon temperature increases with increasing plasma current at constant LH power and plasma density due to increased loop voltage.

• The $T_{ph}$ decreases with increasing plasma density at constant LH power and plasma current although the loop voltage increased.

• In LH wave phase scan and power scan experiments, no appreciable change in the $T_{ph}$ is observed.

• The results in current, density and phase scan experiment are quantitatively in good agreement with the simulation results.

• $T_{ph}$ depends mainly on global effects of the fast electron population, synergy between the fast electron and the loop voltage and the coulomb slowing down.
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Lower hybrid current drive efficiency is a very important parameter. The experimental current drive efficiency is defined as

$$\eta_{\text{exp}} = \frac{I_{rf} n_e R}{P_{\text{LH}}}$$

where $I_{rf}$ = current driven by the lower hybrid waves,

$n_e$ = central line average density,

$R$ = major radius of the plasma,

$P_{\text{LH}}$ = Injected LH wave.

$\eta_0 = \frac{I_p n_e R}{P_{\text{LH}0}}$ is fully non-inductive CD efficiency obtained when loop voltage approaches zero. $P_{\text{LH}0}$ is the required LH power to attain zero loop voltage.
Lower hybrid current drive efficiency and ratio of intensity of hard X-ray emission to density of fast electron versus photon temperature at $n_e = 1.6 \times 10^{19} \text{m}^{-3}$, $P_{LH} = 230 \text{kW}$, $n_{//} = 2.35$, (square and triangle represent CD efficiency and ratio of intensity of hard X-ray emission to density respectively).
Photon temperature and current drive efficiency in plasma current scan experiments

\[ n_e = 1.6 \times 10^{19} \text{m}^{-3}, \ P_{LH} = 230 \text{kW}, \ n_{\parallel} = 2.35 \]

\[ I_{rf} \text{ and } V_{LH} \text{ (loop voltage during LH phase) versus plasma current,} \]
\[ \text{(square and triangle represent } I_{rf} \text{ and } V_{LH} \text{ respectively).} \]

\[ V_{th}/V_{res} \text{ versus plasma current.} \]
Photon temperature and current drive efficiency in plasma density scan experiments

\[ I_p = 150\text{kA}, \quad P_{LH} = 500\text{kW}, \quad n_{//} = 2.35 \]

Lower hybrid current drive efficiency and ratio of intensity of hard X-ray emission to density of fast electron versus photon temperature, (circle and triangle represent CD efficiency and ratio of intensity of hard X-ray emission to density respectively).

\( Z_{eff} \) and \( n_{acc} \) versus plasma density (square and triangle represent \( Z_{eff} \) and \( n_{acc} \) respectively).
Lower hybrid current drive efficiency versus lower hybrid Power at $I_p = 150\,\text{kA}$, $n_{\parallel}=2.35$, for $n_e = 1.5 \times 10^{19}\,\text{m}^{-3}$.

$\Delta T_e n_e$ versus lower hybrid Power at $I_p = 150\,\text{kA}$, $P_{\text{LH}} = 500\,\text{kW}$, $n_{\parallel}=2.35$, for two different plasma densities i.e. $n_e = 1.0 \times 10^{19}\,\text{m}^{-3}$, and $1.5 \times 10^{19}\,\text{m}^{-3}$. 
EAST tokamak

Model of East tokamak

Toroidal field coil of East tokamak
A Bird view of the EAST tokamak

The main parameters of the EAST tokamak

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toroidal field, $B_0$</td>
<td>3.5 T</td>
</tr>
<tr>
<td>Plasma current, $I_p$</td>
<td>1 MA</td>
</tr>
<tr>
<td>Major radius, $R_0$</td>
<td>1.7 m</td>
</tr>
<tr>
<td>Minor radius, $a$</td>
<td>0.4 m</td>
</tr>
<tr>
<td>Aspect ratio, $R/a$</td>
<td>4.25</td>
</tr>
<tr>
<td>Elongation, $K_x$</td>
<td>1.6–2</td>
</tr>
<tr>
<td>Triangularity, $\delta_x$</td>
<td>0.6–0.8</td>
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<tr>
<td>Heating and driving</td>
<td></td>
</tr>
<tr>
<td>ICRH</td>
<td>3 MW</td>
</tr>
<tr>
<td>LHCD</td>
<td>3.5 MW</td>
</tr>
<tr>
<td>ECRH</td>
<td>0.5 MW</td>
</tr>
<tr>
<td>Pulse length</td>
<td>1–1000 s</td>
</tr>
<tr>
<td>Configuration</td>
<td>Double-null divertor; single-null divertor; pump limiter</td>
</tr>
</tbody>
</table>
Current drive efficiency in the EAST tokamak

Relative drop in loop voltage versus normalized LH power at $I_p = 250\text{kA}$ and $n_e = 0.9\times10^{19}\text{m}^{-3}$.

LHCD efficiency versus LH power.
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Summary

• The current drive efficiency is increased with the increase of the plasma current, mainly due to the increments of both population density and $T_{ph}$ when other parameters are such as LH power and plasma density are fixed.

• The current drive efficiency is increased with the increase of the plasma density in fully accessible condition of LHCD, with the decreased photon temperature and increased population density of fast electrons at fixed plasma current.

• The slowing down via collision is responsible for the energy transferring to bulk electrons from the fast electrons.

• LHCD efficiency decreases with increasing the LHW power due to the significant decrease of loop voltage at higher LHW powers leading to weak effect of hot conductivity hence lowers LHCD efficiency.
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Thanks