Second Harmonic ECH preionization with 7 pairs PF coil scenario for KSTAR


POSTECH

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In the initial phase of KSTAR operations, the toroidal magnetic field is planned to be 1.5 T at the tokamak center. In this case, the electron cyclotron frequency is 42 GHz., and the operating frequency of the ECH pre-ionization system is 84 GHz, corresponding to the second harmonics. We modified the pre-ionization code with 7 pairs of poloidal coils. Through the pre-ionization simulation, we obtained the dependence of the loop voltage, electron temperature, and plasma currents for several input parameters in the second harmonic ECH pre-ionization. It is compared to the results of the fundamental harmonic ECH pre-ionization.
# KSTAR Target Operation Modes

<table>
<thead>
<tr>
<th>Operation Phase</th>
<th>Target Operation Modes</th>
<th>( B_0 ) = 3.5 T, ( I_p ) = 2 MA</th>
</tr>
</thead>
<tbody>
<tr>
<td>First Plasma</td>
<td>1.0 ECH-assisted 5 V-inner start-up mode</td>
<td></td>
</tr>
<tr>
<td>Ohmic Plasma</td>
<td>2.0 ECH-assisted 6 V-outer start-up mode</td>
<td></td>
</tr>
<tr>
<td>Baseline Plasma</td>
<td>3.0 Ohmic + NBI mode</td>
<td>( B_0 ) = 3.5 T, ( I_p ) = 2 MA</td>
</tr>
<tr>
<td></td>
<td>3.1 Ohmic + NBI + RF mode</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3.2 Ohmic + NBI + RF + MW mode</td>
<td>( P_{\text{NBI}} = 8 ) MW, ( P_{\text{RF}} = 6 ) MW</td>
</tr>
<tr>
<td></td>
<td>3.3 Extended mode</td>
<td>( P_{\text{MW}} = 1.5 ) MW</td>
</tr>
<tr>
<td>Upgrade Plasma</td>
<td>4.0 Low-beta Reverse-shear mode</td>
<td>( B_0 ) = 3.5 T, ( I_p ) = 2 MA</td>
</tr>
<tr>
<td></td>
<td>4.1 Low-beta High-li mode</td>
<td>( P_{\text{NBI}} = 16 ) MW, ( P_{\text{RF}} = 12 ) MW</td>
</tr>
<tr>
<td></td>
<td>4.2 Low-beta H-mode</td>
<td>( P_{LH} = 3 ) MW, ( P_{\text{ECH}} = 3 ) MW</td>
</tr>
<tr>
<td></td>
<td>4.3 High-beta Reverse-shear mode</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4.4 High-beta High-li mode</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4.5 High-beta H-mode</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4.6 Full performance mode</td>
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</tr>
</tbody>
</table>
### PF coil structure

(Unit: mH)

<table>
<thead>
<tr>
<th></th>
<th>PF1</th>
<th>PF2</th>
<th>PF3</th>
<th>PF4</th>
<th>PF5</th>
<th>PF6</th>
<th>PF7</th>
<th>PLA</th>
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</thead>
<tbody>
<tr>
<td>PF1</td>
<td>85.6</td>
<td>26.55</td>
<td>5.96</td>
<td>5.28</td>
<td>7.45</td>
<td>7.13</td>
<td>8.3</td>
<td>0.11</td>
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<tr>
<td>PF2</td>
<td>26.55</td>
<td>44.98</td>
<td>12.56</td>
<td>9.18</td>
<td>7.85</td>
<td>5.81</td>
<td>6.47</td>
<td>0.073</td>
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<tr>
<td>PF3</td>
<td>5.96</td>
<td>12.56</td>
<td>13.43</td>
<td>10.38</td>
<td>5.3</td>
<td>2.96</td>
<td>3.13</td>
<td>0.037</td>
</tr>
<tr>
<td>PF4</td>
<td>5.29</td>
<td>9.18</td>
<td>10.38</td>
<td>26.93</td>
<td>10.96</td>
<td>4.48</td>
<td>4.52</td>
<td>0.031</td>
</tr>
<tr>
<td>PF5</td>
<td>7.45</td>
<td>7.85</td>
<td>5.3</td>
<td>10.96</td>
<td>327.4</td>
<td>37.32</td>
<td>31.21</td>
<td>0.135</td>
</tr>
<tr>
<td>PF6</td>
<td>7.13</td>
<td>5.81</td>
<td>2.95</td>
<td>4.48</td>
<td>37.31</td>
<td>199.36</td>
<td>99.1</td>
<td>0.219</td>
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<tr>
<td>PF7</td>
<td>8.3</td>
<td>6.47</td>
<td>3.13</td>
<td>4.52</td>
<td>31.2</td>
<td>99.1</td>
<td>316.45</td>
<td>0.284</td>
</tr>
<tr>
<td>PLA</td>
<td>0.11</td>
<td>0.073</td>
<td>0.037</td>
<td>0.031</td>
<td>0.135</td>
<td>0.219</td>
<td>0.284</td>
<td>0.003</td>
</tr>
</tbody>
</table>
KSTAR Operation Scenario (First Plasma Phase)

- ECH heating
- Ip=100 kA
- Flux-linkage (V-s)
- Zero crossing
- PF Coil Current (kA) vs. time (sec)

PF Coil Current (kA) vs. time (sec)

- Initial Current Charge
- Start
- End

- PF-1
- PF-2
- PF-3
- PF-4
- PF-5
- PF-6
- PF-7
- FECC
- IRC
Input parameters

1. A major radius; \( R = 180 \text{ cm} \).
2. A minor radius; \( a = 50 \text{ cm} \).
3. An error field range; \( B_{\text{err}} = 0.1 \sim 4 \text{ (mT)} \).
4. An initial neutral density; \( n_{o} = 0.2\times10^{13} \sim 3\times10^{13} \text{ (cm}^{-3}\text{)} \).
5. RF pulse duration; \( T_{RF} = 0.2\text{s} \).
6. A magnetic field; \( B_{o} = 1.5 \text{ T} \).
7. A carbon impurity fraction; \( f_{ci} = 0.01 \).
8. An oxygen impurity fraction \( f_{oi} \) is always set to 2 times \( f_{ci} \).
9. All wave propagates X-mode.
Pre-ionization code model

**Continuity equation**
\[
\frac{dn_e}{dt} = n_e v_{\text{ion}} - n_e (v_{\text{err}} + v_{\text{dr}} + v_{\text{diff}})
\]
where \(v_{\text{ion}}\) is the ionization rate,
\(v_{\text{err}}\) is the loss rate due to error field,
\(v_{\text{dr}}\) is the loss rate due to the toroidal drift and \(v_{\text{diff}}\) is the loss rate due to the diffusion.

**Particle balance**
\[
\frac{dn_e}{dt} = -\frac{dn_p}{dt}
\]
\(n_e\)

**Energy balance**
\[
\frac{dU_e}{dt} = \frac{P_{\text{ECH}} + P_{\text{eff}} - P_{\text{RAD}}}{V} - U_e (v_{\text{err}} + v_{\text{dr}} + v_{\text{diff}}) - \frac{1}{V} (P_{\text{EQU}} + P_{\text{REM}} + P_{\text{RAD}})
\]
\[
\frac{dU_i}{dt} = \frac{1}{V} (P_{\text{EQU}} - P_{\text{CX}}) - U_i v_{\text{E}}
\]
\(U_e, U_i, T_e\)

**Circuit equation**
\[
-\sum_{n=1}^{8} M_{n8} \frac{dl_n}{dt} - I_s R_p = 0 \quad \Rightarrow \quad \frac{dl_i}{dt} = -\sum_{n=1}^{8} \frac{M_{n8} dl_n}{dt} \times dt
\]
\[
V_{\text{loop}} \text{ (loop voltage)} = -\sum_{n=1}^{7} M_{n8} \frac{dl_n}{dt}
\]
\[
V_{\text{resis}} \text{ (resistive voltage)} = -I_s R_p
\]
where \(n = 1 \sim 7\) for the 7 pairs of PF coils and \(n = 8\) for the plasma,
\(R_p\) is the plasma resistance
and the \(M_{n8}\) is the mutual inducances between PF coils and plasma.

\(V_{\text{loop}}, V_{\text{resis}}, I_p\)
Results of the code calculation

1. Temporal behavior

Second harmonic case

**FIG. 1-1.** Plots of the plasma current $I_p$ and the electron temperature $T_e$ as a function of time.

The RF power 500 kW is applied for 0.2 sec, and the Ohmic heating is applied at 50 msec. The parameters are $P_{RF} = 500$ kW, $B_{err} = 1$ mT, $f = 84$ GHz, $n_o = 1.0 \times 10^{13}$ cm$^{-3}$, $n_e(0) = 1.0 \times 10^9$ cm$^{-3}$
FIG. 1-2. Plots of the plasma current $I_p$ and the electron temperature $T_e$ as a function of time.
The RF power 500 kW is applied for 0.2 sec, and the Ohmic heating is applied at 50 msec. The parameters are $P_{RF} = 500$ kW, $B_{err}$ = 1 mT, $f$ = 84 GHz, $n_o = 1.0 \times 10^{13}$ cm$^{-3}$, $n_e(0) = 1.0 \times 10^9$ cm$^{-3}$
2. Error field scan

Second harmonic case

FIG. 2-1. (a) The electron temperature $T_e$ and electron density $n_e$ at 60 ms, plotted as a function of the error field $B_{err}$.

FIG. 2-1. (b) The plasma current $I_p$ and resistive voltage $V_{resis}$ at 60 ms, plotted as a function of $B_{err}$.
FIG. 2-2. (a) The electron temperature $T_e$ and the electron density $n_e$ at 60 ms, plotted as a function of the error field $B_{err}$.

FIG. 2-2. (b) The plasma current $I_p$ and resistive voltage $V_{resis}$ at 60 ms, plotted as a function of $B_{err}$.
3. Neutral density scan

Second harmonic case

FIG. 3-1.(a) The electron temperature $T_e$ and electron density $n_e$ at 60 ms, plotted as a function of initial neutral density $n_o$.

FIG. 3-1.(b) The plasma current $I_p$ and resistive voltage $V_{\text{resis}}$ at 60 ms, plotted as a function of initial neutral density $n_o$. 
Fundamental harmonic case

**FIG. 3-2. (a)** The electron temperature $T_e$ and electron density $n_e$ at 60 ms, plotted as a function of initial neutral density $n_o$.

**FIG. 3-2. (b)** The plasma current $I_p$ and resistive voltage $V_{resis}$ at 60 ms, plotted as a function of initial neutral density $n_o$. 
4. RF power scan

Second harmonic case

**FIG. 4-1.** (a) The electron temperature $T_e$ and electron density $n_e$ at 60 ms, plotted as a function of the RF power $P_{RF}$.

**FIG. 4-1.** (b) The plasma current $I_p$ and resistive voltage $V_{resis}$ at 60 ms, plotted as a function of the RF power $P_{RF}$. 
FIG. 4-2. (a) The electron temperature $T_e$ and electron density $n_e$ at 60 ms, plotted as a function of the RF power $P_{RF}$.

FIG. 4-2. (b) The plasma current $I_p$ and resistive voltage $V_{resis}$ at 60 ms, plotted as a function of the RF power $P_{RF}$. 

Fundamental harmonic case
1. For the second harmonic case, ECH pre-ionization is not effective for initiating plasma. To make plasma initially, we must modify the central magnetic field to make fundamental harmonic magnetic field (3T) in tokamak or use mode conversion. For the fundamental harmonic case, ECH pre-ionization is very outstanding effect.

2. For the second harmonic ECH heating, the impurity effects are not significant and $T_e$ and $I_p$ maximized near 500 ~ 1000 kW RF power.
References