ECRH PRE-IONIZATION ON TOKAPOLE II

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ABSTRACT

Reduction of the start-up voltage on large tokamaks is desirable to relax design constraints and cost. Pre-ionization at the electron cyclotron resonance is a candidate for reducing the initial loop voltage. The present experiment demonstrates that relatively little microwave power (1-10% of ohmic heating power) is required to lower start-up voltage requirements by 50%. Solutions of zero dimensional start-up equations indicate the effect is due to the high start-up density which increases the conductivity time variation (generating a back EMF) and not just due to an initially low conductivity. Comparison of the code with other experiments will be presented. Supported by U.S.D.O.E.
INTRODUCTION

MUCH OF THE MATERIAL IN THIS POSTER IS TO BE PUBLISHED IN NUCLEAR FUSION. PREVIOUS WORK BY HOLLY AND WITHERSPOON WAS PUBLISHED IN NUCLEAR FUSION VOL. 19 No. 11 (1979). THE UNIQUE FEATURES OF THIS NOTE ARE:

1: NEW DATA WITH $V_L$ REDUCTION OF 53%.
2: AN EXPLANATION OF TOKAPOLE II's PROBLEMS WITH REDUCED CAPACITOR BANK VOLTAGE.
3: A COMPARISON OF THE ZERO-DIMENSIONAL CODE WITH OTHER PUBLISHED RESULTS.
4: AN UPDATE ON THE DIRECTION OF FUTURE RESEARCH.
Major radius: 50 cm

Minor cross section: $44 \times 44$ cm square

Toroid walls: aluminum, 3 cm thick with poloidal and toroidal insulated gaps

Vacuum volume: 600 liters

Vacuum surface area: 6 square meters

Number of internal rings: 4 (copper, 5 cm diameter, supported at 3 points)

Ports: 2 - 19 cm diam, 5 - 11.5 cm diam, 22 - 4 cm diam, 13 - 0.6 cm diam

$B_T$ on axis: 5 kG (extendable to 10 kG by the acquisition of additional capacitors)

L/R time of $B_T$: 20 msec

Available OH voltage: 125 volts

Poloidal flux: 0.15 webers

Available energy (poloidal + toroidal fields): 216 kJ (72 - 240 μF, 5 kW capacitors)

Base vacuum: $3 \times 10^{-8}$ torr

Pumping system: 1500 l/sec turbomolecular pump

1200 l/sec, 10° K cryopump

Preionization: 5 kW, 2.45 GHz; 10 kW, 8.8 GHz; 10 kW, 16.0 GHz

Hoop Current: $\sim 250$ kA

Plasma Current: 40 kA

Electron Density: $2 \times 10^{13}$ cm$^{-3}$

Electron Temperature: 100 eV

Ion Temperature: 40 - 80 eV

Minor Radius of Current Channel: $\sim 7$ cm

(To Separatrix)
POLOIDAL MAGNETIC FLUX PLOT AS CALCULATED BY AN MHD EQUILIBRIUM CODE. THE FOUR CURRENT-CARRYING INTERNAL RINGS PROVIDE THE DIVERTOR FIELD. THE FLUX PLOT HAS BEEN EXPERIMENTALLY VERIFIED THROUGH INTERNAL MAGNETIC PROBE MEASUREMENTS.
THE SEQUENCE OF EVENTS FOR A TYPICAL TOKAPOLE II DISCHARGE WAS AS FOLLOWS:

1: H₂ WAS PUFFED INTO THE TOROID.
2: THE Bₜ BANK WAS FIRED TO CREATE A PURELY TOROIDAL FIELD.
3: ECRH PRE-IONIZATION PRODUCED A NEUTRAL DOMINATED PLASMS.
4: THE POLOIDAL BANK WAS FIRED, DRIVING CURRENT IN THE INTERNAL RINGS AND THE PLASMA.
ECRH can reduce loop voltage by as much as 50%.

We measure $V_L = IR$ at the plasma center with a probe. The pre-ionized plasma has $T_E \sim 1 - 5$ eV and $N_E \sim 2 \times 10^{11}$ cm$^{-3}$. 
- - - With ECRH  - - - No ECRH

\[ n_e \times 10^{11}/\text{cm}^3 \]

\[ I_p \text{ (kAmps)} \]

\[ V_{\text{LOOP}} \text{ (Volts)} \]

ECRH Pulse: 200 400 600 800 1000

(\mu s)
The applied voltage can be reduced with ECRH.

Tokapole II has internal rings which produce a four node poloidal divertor configuration. The current in these rings is driven by the same transformer as the ohmic plasma current. The rings take one half the flux produced at any setting on the capacitor banks. Consequently, when the bank voltage is reduced our vertical field is reduced and hence the discharge characteristics are changed.

Despite this difficulty we can reduce the applied voltage from a non-ECRH case and generate a like discharge at the lower voltage when ECRH pre-ionization is used.

At the lower voltage, when no ECRH is used the initial loop voltage is slightly higher and the discharge is very sub-standard.
AN ALTERNATIVE PERSPECTIVE

The data presented measures $V_L = IR$ at the location of the plasma. Pre-ionization also allows a reduction in the applied voltage in the external circuitry. Preliminary measurements under non-optimized conditions gave similar discharges for:

<table>
<thead>
<tr>
<th></th>
<th>No ECRH</th>
<th>ECRH</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_L^{(v)}$</td>
<td>16</td>
<td>10</td>
</tr>
<tr>
<td>$E_T^{(%)}$</td>
<td>2.5</td>
<td>1.6</td>
</tr>
</tbody>
</table>
ECRH pre-ionization is qualitatively different than pre-ionization by ICRH or hot filament.

The following schematic distorts the time development of the loop voltage for several cases. Our ion gauge helps the discharge begin but leaves the initial \( V_L \) at the vacuum value. A small amount of ICRH (~10 kW) has about the same behavior. Low density \( (N_E \sim 2 \times 10^9 \text{ cm}^{-3}) \) ECRH seems to prevent \( V_L \) from reaching its vacuum value but there is an initial spike. The spike is reduced as the pre-ionization density approaches \( 2 \times 10^{11} \text{ cm}^{-3} \). This density behavior is predicted by our model.
Schematic Loop Voltage Behavior

Loop Voltage in Volts

Time in Arbitrary Units

High Density ECRH

Low Density ECRH

ICRH

Vacuum

Hot Filament (Ion Gauge)
The following equations are solved by a second order Runge-Kutte routine.

\[ v = IR = V_v - L \frac{dI}{dt} \]

\[ \frac{d}{dt} \left( \frac{3}{2} n_T \right) = \frac{I^2 R(n, n_e, T_e)}{V_{\text{vol}}} - \left( \frac{3}{2} \right) n_T \frac{P_{\text{mf}}}{\varepsilon_i} \]

\[ \frac{dn}{dt} = \frac{n}{\varepsilon_i} \]

with

\[ L = \mu_0 R, \left( \ln \frac{BR}{a} - \frac{7}{4} \right) \]

\[ R(n, n_e, T_e) = \frac{10^{-5}}{a \sqrt{n_e}} \left( \frac{160}{T_e^4} + \frac{1.3 n_e}{n_e} \right) \]

\[ \varepsilon_i = n_e < \sigma v > \]

\[ \frac{dR}{dt} \] is the important parameter

**Physical Explanation**

**The time variation of the resistance due to the initial plasma density results in a large change in the current with time. This makes the back EMF of the plasma large and reduces the loop voltage.**

**Schematically**

**Initial**

- \( n_e \) = \( \frac{a}{e} < 0 \)
- \( \frac{a}{e} > 0 \)
- \( n_e \) back fill \( < 0 \)
- \( n_e \) increased

Theory predicts favorable scaling to reactors.

Theory and experiment agree well.

Softcopy: Theory and experiment agree well.

**Without Preionization**

**With Preionization**

**Experimental Points**

**Theory**

**Maximum Loop Voltage during Startup, versus density of the preionized plasma.**

**Without Preionization**

**With Preionization**

**Loop Voltage versus time with and without preionization using the code for a device of reactor proportions.**

- \( R = 5.2 \) m
- \( H_0 = 1.5 \times 10^{13} \) cm\(^{-3}\)
- \( \alpha = 1.3 \) m
- \( H_e = 2.0 \times 10^{13} \) cm\(^{-3}\)
- \( B = 5.5 \) T
Theory compares well with other experiments.

<table>
<thead>
<tr>
<th>DEVICE</th>
<th>EXPERIMENTAL LOOP VOLTAGE</th>
<th>THEORETICAL LOOP VOLTAGE</th>
<th>INITIAL $N_E$ (cm$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WT - 1</td>
<td>26.4</td>
<td>18.5</td>
<td>$10^{11}$ ?</td>
</tr>
<tr>
<td>TOKAPOLE II</td>
<td>29</td>
<td>30.2</td>
<td>$10^9$</td>
</tr>
<tr>
<td></td>
<td>14.6</td>
<td>16</td>
<td>$2 \times 10^{11}$</td>
</tr>
<tr>
<td>FT - 1</td>
<td>15</td>
<td>16</td>
<td>$3 \times 10^{12}$</td>
</tr>
<tr>
<td>ISX - B</td>
<td>9</td>
<td>8.2</td>
<td>$5 \times 10^{12}$</td>
</tr>
</tbody>
</table>
LAUNCH SITE COMPARISON AND
MULTIPLE SOURCE EXPERIMENT

1. PRESENTLY MICROWAVE PORTS ARE
AVAILABLE ON THE VERTICAL MID-
CYLINDER AND THE LOW FIELD SIDE.
THERE ARE NO DETECTED DIFFERENCES
IN THE LOOP VOLTAGE REDUCTION
FOR EITHER LAUNCH SITE.
PLANS FOR FURTHER STUDY INCLUDE
A) A LAUNCH SITE ON THE HIGH FIELD
SIDE.
B) A MICROWAVE ABSORBER TO REDUCE
REFLECTION ISSUES.

2. A SECOND K-BAND MAGNETRON HAS BEEN
OBTAINED AND SOME PRELIMINARY
RESULTS INDICATE:
A) THUS FAR \(N_e \approx 2 \times 10^{11}\) WITH BOTH SOURCES
FROM THE TWO LAUNCH SITES BUT
THE DENSITY CONTRIBUTIONS ADD
LINEARLY.
B) MOVING THE RESONANCE ZONES APART
DIDN'T ALTER THE DENSITY ADDITION.
A PLASMA GUN AS AN ALTERNATIVE SOURCE

A PLASMA GUN WILL SOON BE MOUNTED ON TOKAPOLE II FOR PRE-IONIZATION AND REFUELING STUDIES. DEPENDING ON THE PARTICLE TRAPPING, A WIDER RANGE OF DENSITIES AND TEMPERATURES MAYBE AVAILABLE.

EXPECTED GUN PARAMETERS ON INJECTION

\[
\begin{align*}
T_e & \quad 30 \text{ eV} \\
T_i & \quad 100 - 300 \text{ eV} \\
N_e & \quad 2 \times 10^{11} - 3 \times 10^{14} \text{ cm}^{-3} \\
N_0 & \quad 10^{-5} - 10^{-4} \text{ Torr}
\end{align*}
\]
There are plans to modify our applied voltage waveform to study any improvements in machine operation which might result. Presently we apply an abrupt voltage at the maximum value of a quarter sine waveform. Under consideration is a voltage waveform which gradually increases from zero, coupled with ECRH pre-ionization; this may be useful for further breakdown studies.
CONCLUSIONS:

1. A MODEST AMOUNT OF ECRH POWER APPLIED JUST BEFORE THE ONSET OF OHMIC HEATING IN A TOKAMAK CAN SIGNIFICANTLY REDUCE THE INITIALLY REQUIRED LOOP VOLTAGE.

2. COMPARISON WITH A ZERO-DIMENSIONAL CODE INDICATES THAT THE EFFECT ARISES FROM THE INCREASED INITIAL ELECTRON DENSITY WHICH ENHANCES THE TIME DERIVATIVE OF THE PLASMA CONDUCTIVITY IN THE NEUTRAL DOMINATED START-UP PLASMA.

3. THE CODE PREDICTS A FAVORABLE EXTRAPOLATION TO LARGER MACHINE SIZE.