ECRH PRE-IONIZATION ON TOKAPOLE II

D.A. Shepard
S.C. Prager
J.C. Sprott

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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.

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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.

TOKAPOLE II PARAMETERS

Major radius: 50 cm

Minor cross section: 44 × 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 kV capacitors)

Base vacuum: 3×10^{-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: ~ 250 kA

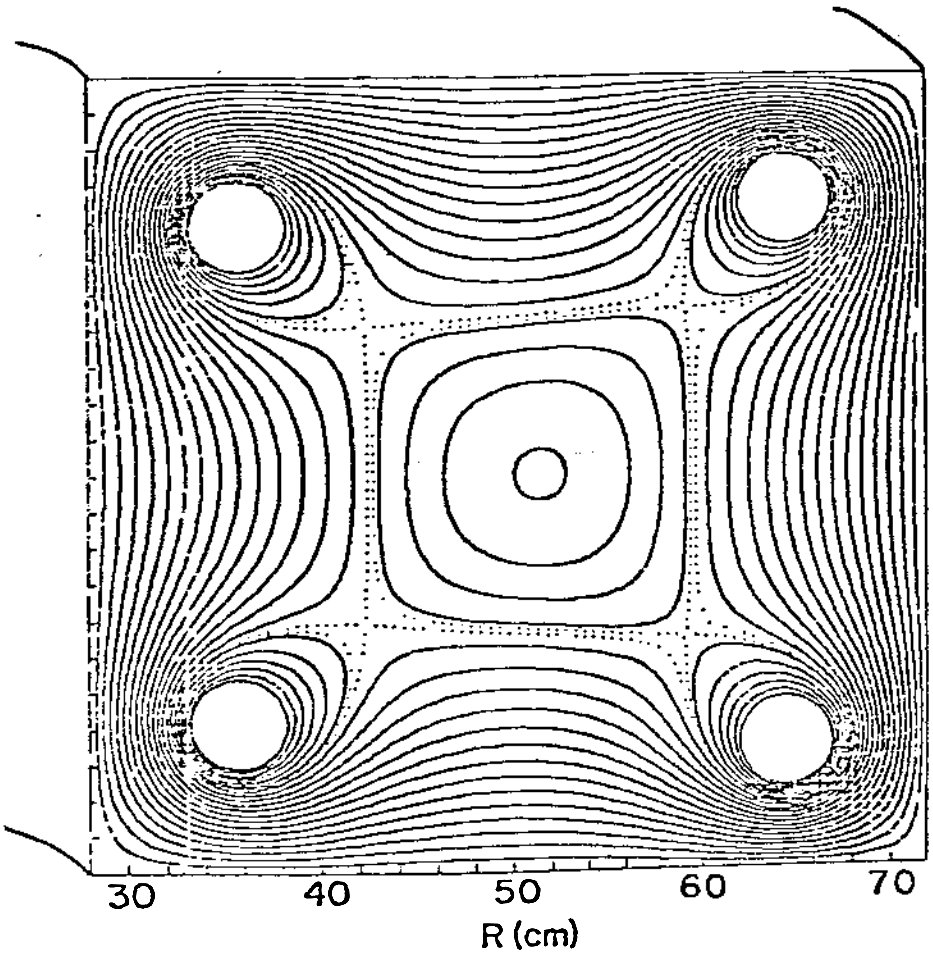
Plasma Current: 40 kA

Electron Density: 2×10^{13} cm^{-3}

Electron Temperature: 100 eV

Ion Temperature: 40 - 80 eV

Minor Radius of Current Channel: ~ 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: H_2 WAS PUFFED INTO THE TOROID.

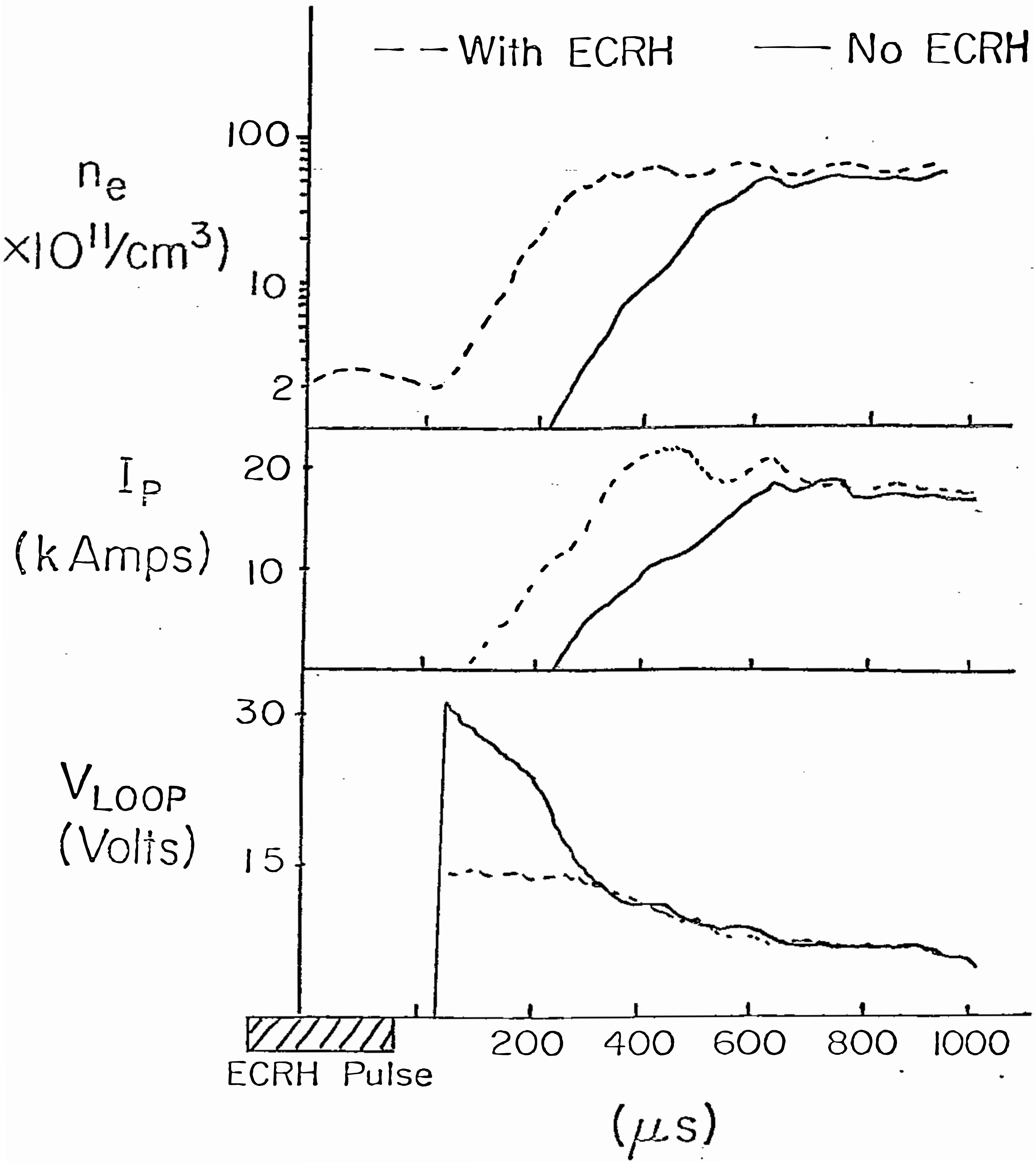
2: THE B_T BANK WAS FIRED TO CREATE A PURELY TOROIDAL FIELD.

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 ($\times 10^{11}/cm^3$)
100
10
2
I_P (k Amps)
20
10
V_{LOOP} (Volts)
30
15
200
400
600
800
1000
ECRH Pulse
(μs)

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

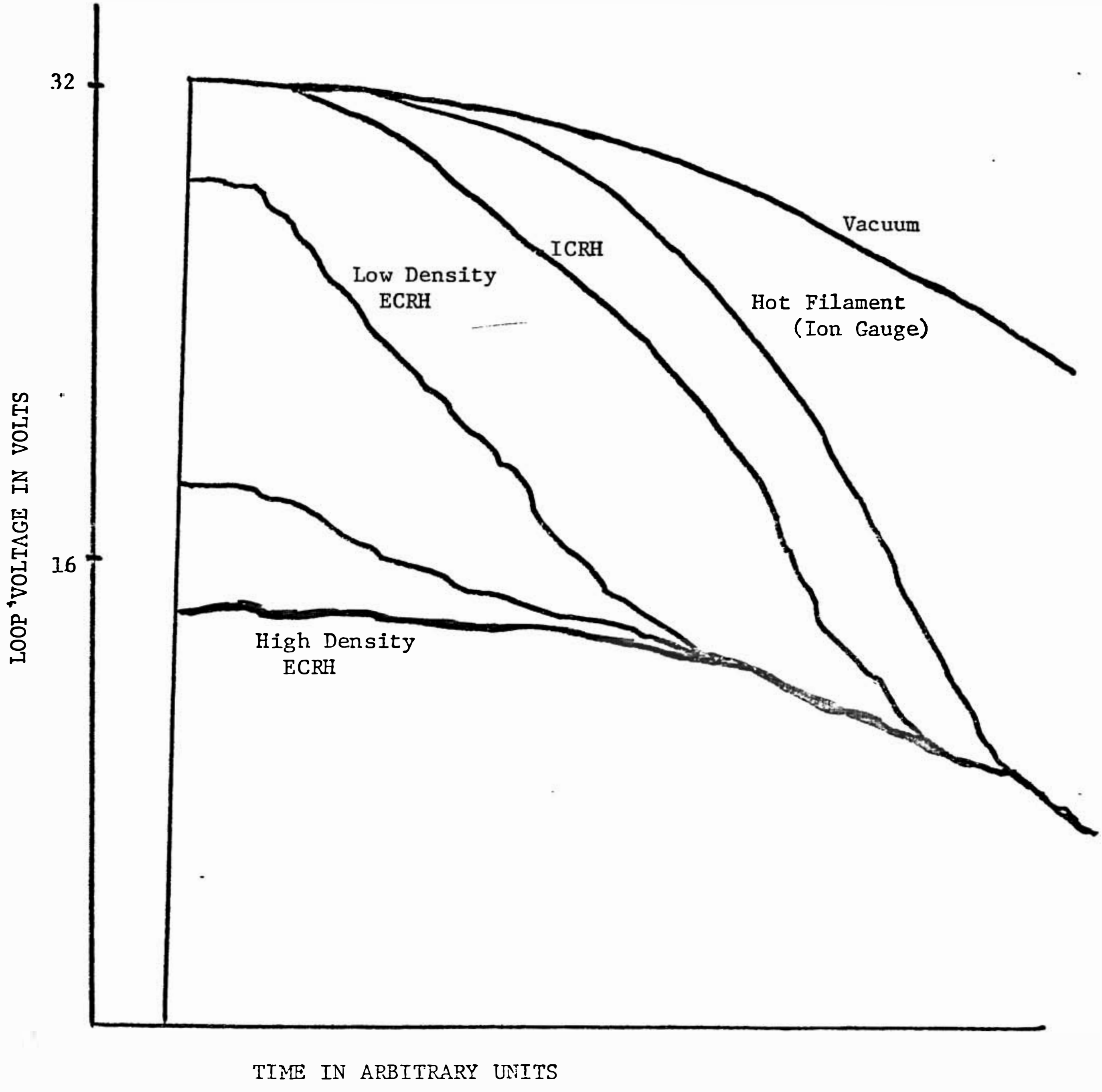
The data presented measures V_L = IR at the location of the plasma. Pre-ionization also allows a reduction in the applied voltage in the external circuitry. Preliminary measurements under non-optimized conditions gave similar discharges for:

	No ECRH	ECRH
V_L (v)	16	10
E_T (V/m)	2.5	1.6

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 ($\sim$10 KW) HAS ABOUT THE SAME BEHAVIOR. LOW DENSITY ($N_E \sim 2 \times 10^9$ 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 2×10^{11} CM^{-3}. THIS DENSITY BEHAVIOR IS PREDICTED BY OUR MODEL.

SCHEMATIC LOOP VOLTAGE BEHAVIOR



The following equations are solved by a second order Runge-Kutte routine.

$$V_L = IR = V_v - L\frac{dI}{dt}$$

$$\frac{d}{dt}\left(\frac{3}{2}nT_e\right) = \frac{I^2 R(n, n_o, T_e)}{Vol.} - \frac{(3/2)nT_e}{\tau_i} + P_{rad}$$

$$\frac{dn}{dt} = \frac{n}{\tau_i}$$

with

$$L = \mu_o R_o \left(\ln\frac{8R_o}{a} - \frac{7}{4}\right)$$

$$R(n, n_o, T_e) = \frac{10^{-5} R_o}{a^2}\left(\frac{160}{T_e^{3/2}} + \frac{1.3n_o}{n}\right)$$

$$\tau_i = n_o \langle \sigma v \rangle$$

$\frac{dR}{dt}$ 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

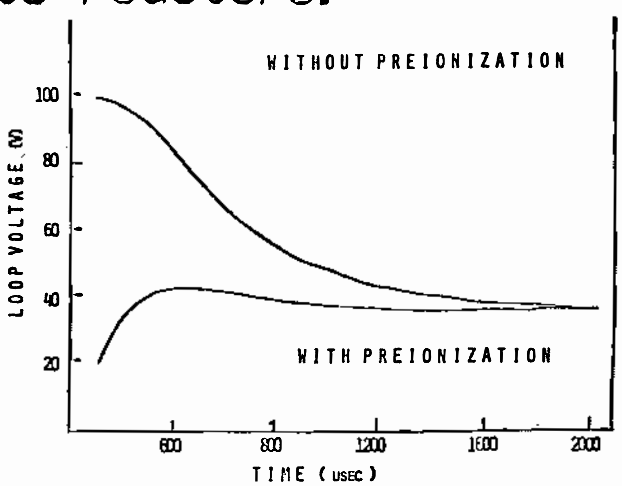
$\Rightarrow \frac{dR}{dt} < 0$

$\Rightarrow \frac{dI}{dt} > 0$

$\Rightarrow$ Back EMF > 0

$\Rightarrow V_L$ Lowered

Theory predicts favorable scaling to reactors.



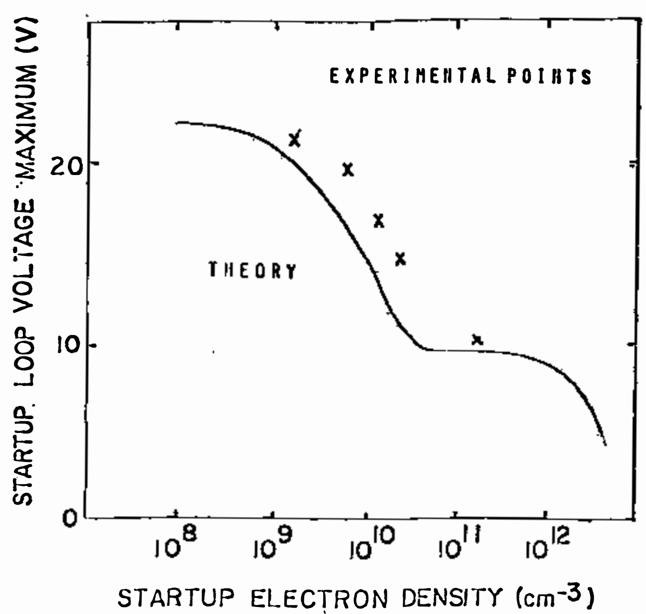
LOOP VOLTAGE VERSUS TIME WITH AND WITHOUT PREIONIZATION USING THE CODE FOR A DEVICE OF REACTOR PROPORTIONS.

R = 5.2 M $\quad N_0 = 1.5 \times 10^{13}\ cm^{-3}$

A = 1.3 M $\quad N_E = 2.0 \times 10^{10}\ cm^{-3}$

B = 5.5 T

Theory and experiment agree well.



MAXIMUM LOOP VOLTAGE DURING STARTUP, VERSUS DENSITY OF THE PREIONIZED PLASMA.

Theory compares well with other experiments

DEVICE	EXPERIMENTAL LOOP VOLTAGE	THEORETICAL LOOP VOLTAGE	INITIAL N_E (CM^{-3})
WT - 1	26.4	18.5	10^{11} ?
TOKAPOLE II	29	30.2	10^{9}
	14.6	16	2×10^{11}
FT - 1	15	16	3×10^{12}
ISX - B	9	8.2	5×10^{12}

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 $N_E \sim 2 \times 10^{11}$ 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

T_E	30 eV
T_I	100 - 300 eV
N_E	$2\times10^{11} - 3\times10^{14}$ cm^{-3}
N_O	$10^{-5} - 10^{-4}$ torr

ALTERING THE APPLIED VOLTAGE AVEFORM

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.