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Advanced ECH pre-ionization model for KSTAR*

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POSTECH

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Abstract

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In previous study, we used a simple primary-secondary transformer circuit for calculating the induced voltage from primary coils. But, KSTAR will adopt 7 pairs of poloidal coils for the primary. We modified the circuit equations with the mutual inductance data of poloidal coils and with the poloidal current scenario. The mutual inductance data were given by KBSI. They also studied the poloidal current scenario. In this advanced model, we studied ECH start-up timing with some input conditions of ECH system and KSTAR plasma parameters. The effect of iron impurity is also added in addition to carbon and oxygen impurities.

Introduction

KSTAR defined target operation modes for each operation phases. The operation phases are classified into first plasma, ohmic plasma, baseline plasma, and upgrade plasma. The target operation mode for the first plasma is an ECH-assisted 5 V-inner start-up mode. In the first plasma phase, the toroidal magnetic field, B_0 is 1.5 T at tokamak center and the flatop plasma current, I_p is 100 kA. KSTAR also made the operation scenarios (poloidal field coil current scenarios) for the each operation phases.

We modified the circuit eqaution in the ECH pre-ionization code with the KSTAR PF coil current scenario for the first plasma phase and the inductances and mutual inductances of 7 pairs of PF coils. Since B_0 is 1.5 T, the corresponding first order resonant frequency is 42 GHz. But, the operating frequency of ECH pre-ionization system is 84 GHz which is the second order resonant frequency. Microwave power is coupled to the KSTAR plasma at B_0 = 1.5 T with second order heating rate. But, in the code simulation, we use first order heating rate for the inner start-up. We also added the radiation power loss term of iron impurity in addition to carbon and oxygen impurity radiation power losses. In this paper the results of the code simulations are presented.

Impurity Radiation Power Losses & Circuit Equations

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- **Impurity radiation power loss**

$P = n_e\, n_I \times 10^f \times 10^6$ [W/cm^3] [P. G. Carolan et al., Plasma Phys. 25, No. 10, 1065 (1983)]

Where,

$f = -33.93 + 4.888\,Q - 2.432\,Q^2 + 0.3697\,Q^3$ for Carbon impurity,

$f = -34.06 + 4.194\,Q - 1.827\,Q^2 + 0.2467\,Q^3$ for Oxygen impurity,

$f = -30.23 - 0.152\,Q + 0.073\,Q^2 - 0.020\,Q^3$ for Iron impurity, and $Q = \log10(T_e)$.

This form is obtained from the polynomial fit with the data in the above reference.

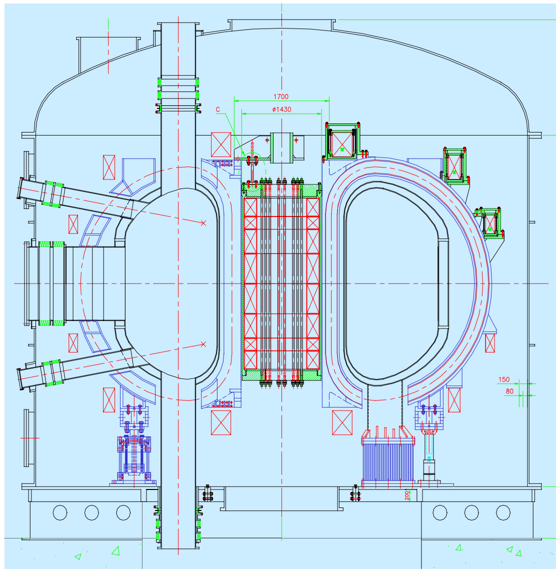
- **Circuit equations**

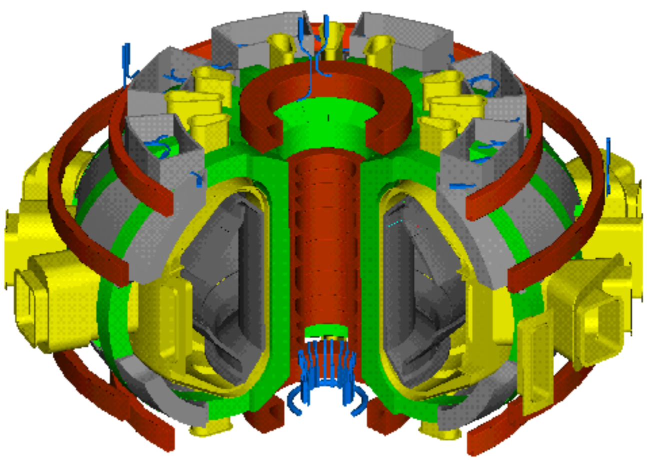
$$-\sum_{n=1}^{8} M_{n8}\frac{dI_n}{dt} - I_8 R_p = 0 \quad \Rightarrow \quad dI_8 = \frac{-\sum_{n=1}^{7} M_{n8}\frac{dI_n}{dt} - I_8 R_p}{M_{88}} \times dt$$

$$V_{loop}\,(\text{loop voltage}) = -\sum_{n=1}^{7} M_{n8}\frac{dI_n}{dt},\quad V_{resis}\,(\text{resistive voltage}) = -I_8 R_p$$

Where n = 1 – 7 for the 7 pairs of PF coil and n = 8 for the plasma, R_p is the plasma resistance, and the M_{n8} is the mutual inductances between PF coils and plasma.

Inductances and Mutual Inductances





KSTAR PF coil structure

(Unit : mH)

	PF1	PF2	PF3	PF4	PF5	PF6	PF7	PLA
PF1	82.97	26.38	26.38	26.38	26.38	26.38	26.38	26.38
PF2	26.38	44.66	15.36	15.36	15.36	15.36	15.36	15.36
PF3	7.11	15.36	20.09	11.49	11.49	11.49	11.49	11.49
PF4	4.3	7.67	11.49	19.96	9.09	9.09	9.09	9.09
PF5	7.28	7.77	6.71	9.09	321.12	36.82	36.82	36.82
PF6	7.0	5.72	3.64	3.68	36.82	196.66	100.21	100.21
PF7	8.03	6.26	3.79	3.67	30.6	100.21	307.84	0.284
PLA	0.11	0.073	0.037	0.031	0.135	0.219	0.284	0.003

KSTAR Target Operation Modes for Each Phases

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Operation Phase	Target Operation Modes	
First Plasma	1.0 ECH-assisted 5V-inner start-up mode	B_o=1.5T, I_p=100 kA
Ohmic Plasma	2.0 ECH_assisted 6V-outer start-up mode	B_o=3.5T, I_p=2 MA
Baseline Plasma	3.0 Ohmic + NBI mode 3.1 Ohmic + NBI + RF mode 3.2 Ohmic + NBI + RF + MW mode 3.3 Extended mode	B_o=3.5T, I_p=2 MA P_{NBI}=8MW, P_{RF}=6MW P_{MW}=1.5MW
Upgrade Plasma	4.0 Low-beta Reverse-shear mode 4.1 Low-beta High-li mode 4.2 Low-beta H-mode 4.3 High-beta Reverse-shear mode 4.4 High-beta High-li mode 4.5 High-beta H-mode 4.6 Full performance mode	B_o=3.5T, I_p=2 MA P_{NBI}=16MW, P_{RF}=12MW P_{LH}=3MW, P_{ECH}= 3MW

KSTAR Operation Scenario (First Plasma Phase)

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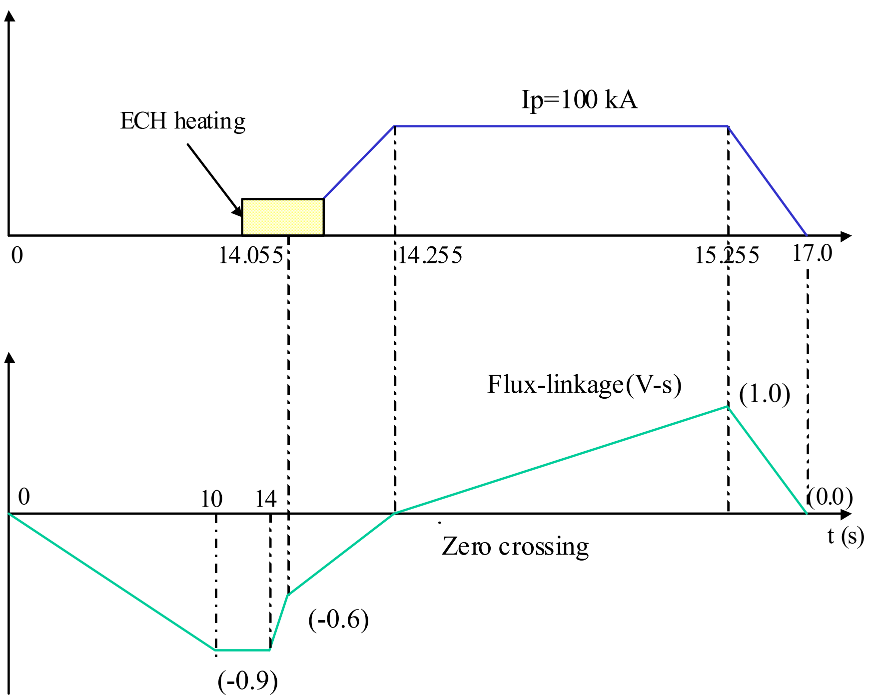

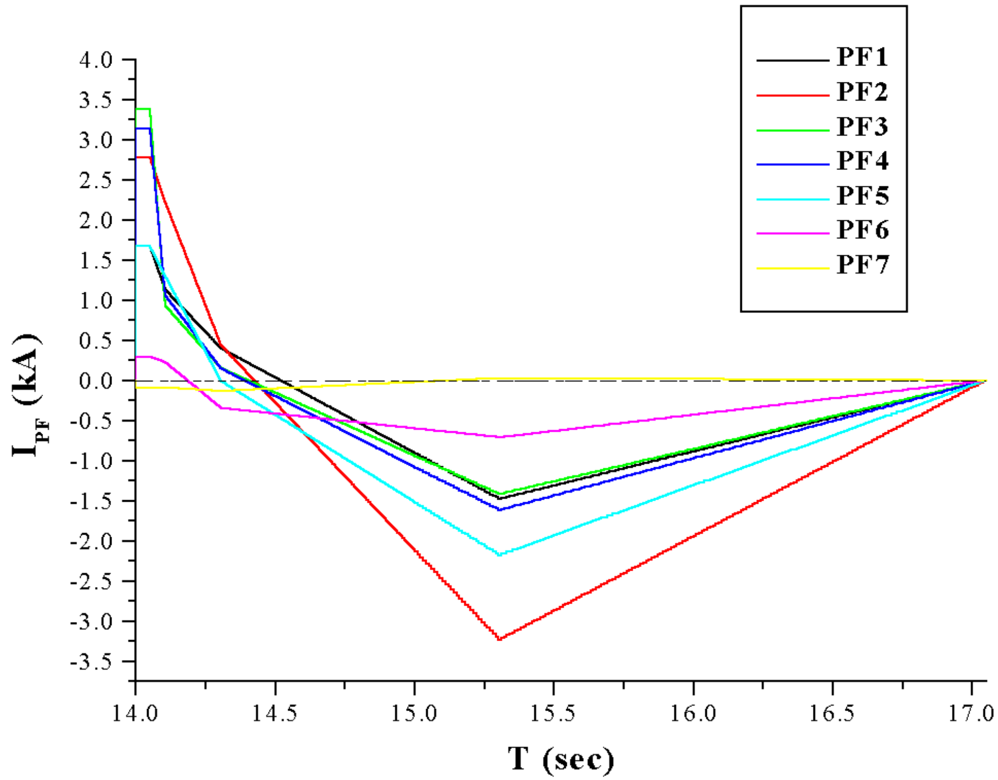

Plot I-1 – I_p and T_e

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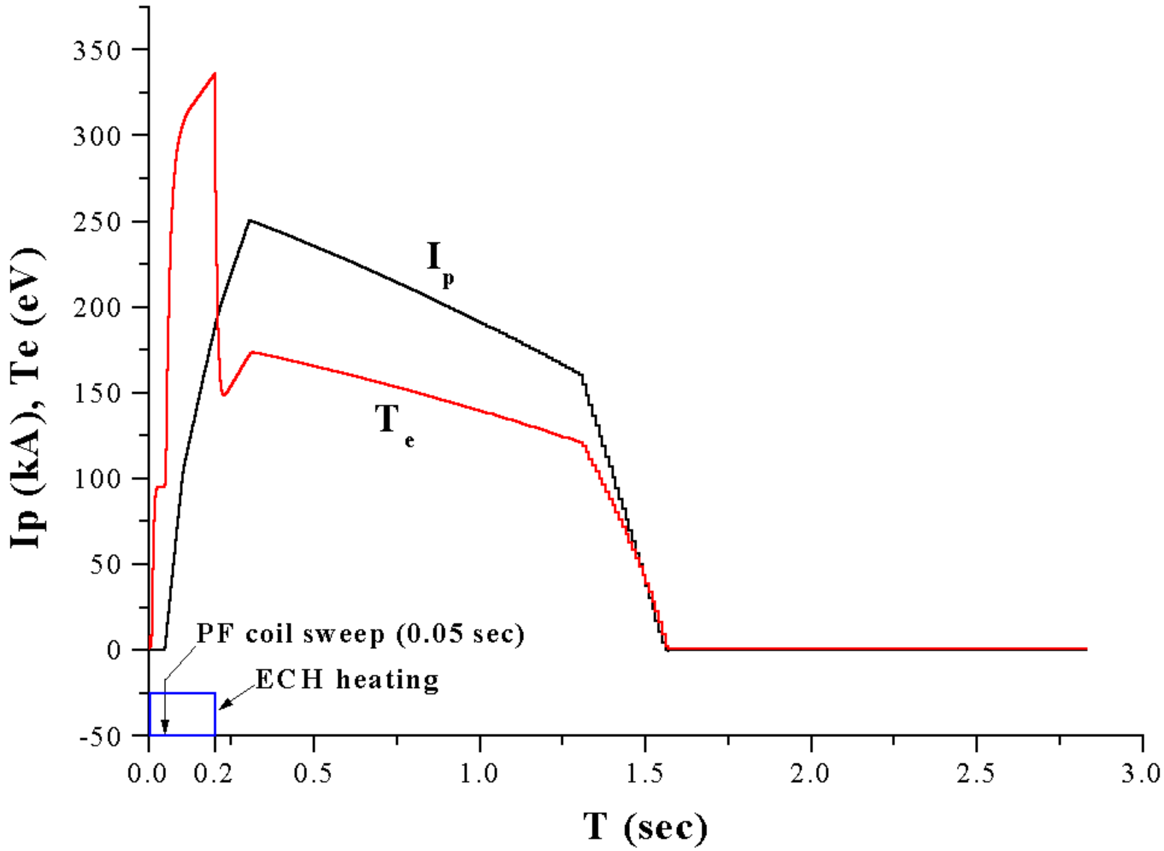

- The plasma current and the electron temperature vs. time. The RF power, P_{RF} = 500.0 kW and the pulse length, T_{RF} = 0.2 sec. After the ECH power is turned on, the starting time of PF coil current, T_{OH} is given as 50 ms. The major radius, R = 180.0 cm, and the minor radius, a = 50 .0 cm. The initial neutral density, N_0 = 1.0 x 10^{13} cm^{-3}. The error field, B_{err} is 2 mT.

Plot I-2 – V_{loop}, V_{resis}

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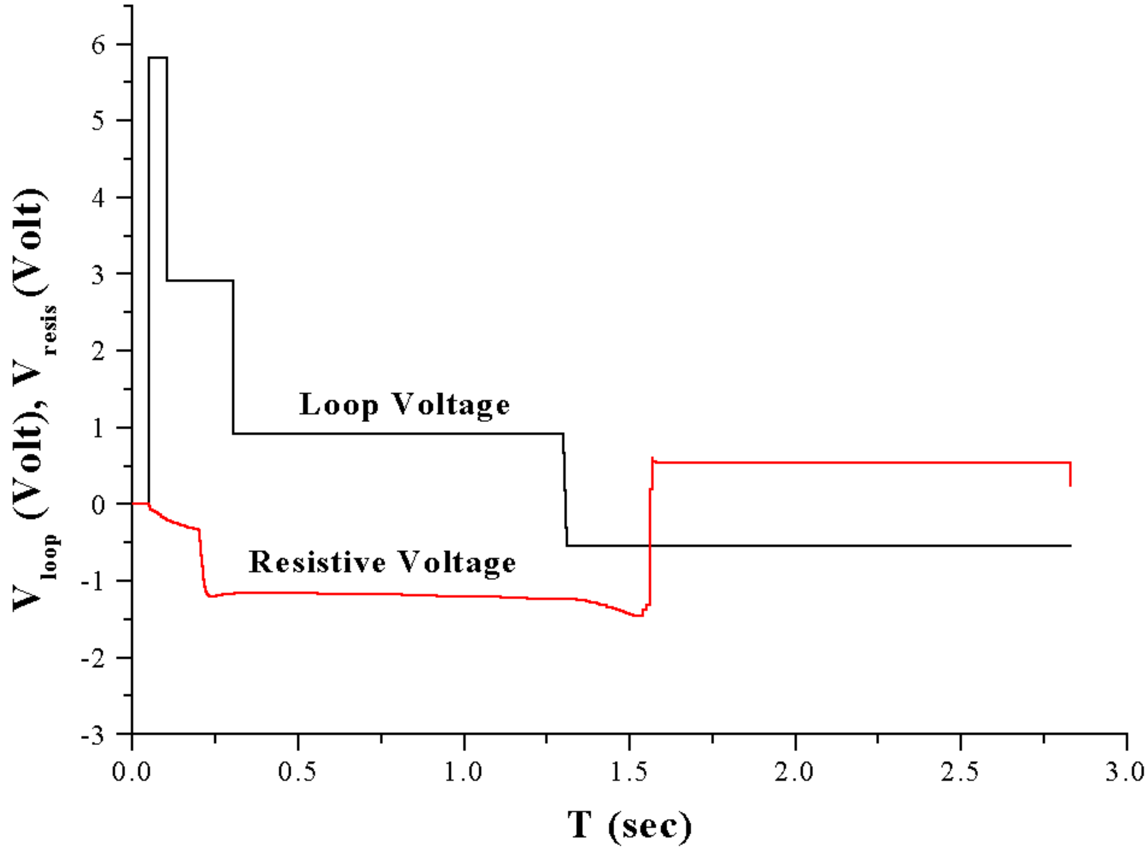

- The loop voltage and resistive voltage of plasma vs. time. The initial parameters are described in the previous view graph.

Plot I-3 – N_e, N_0, U_e, U_i

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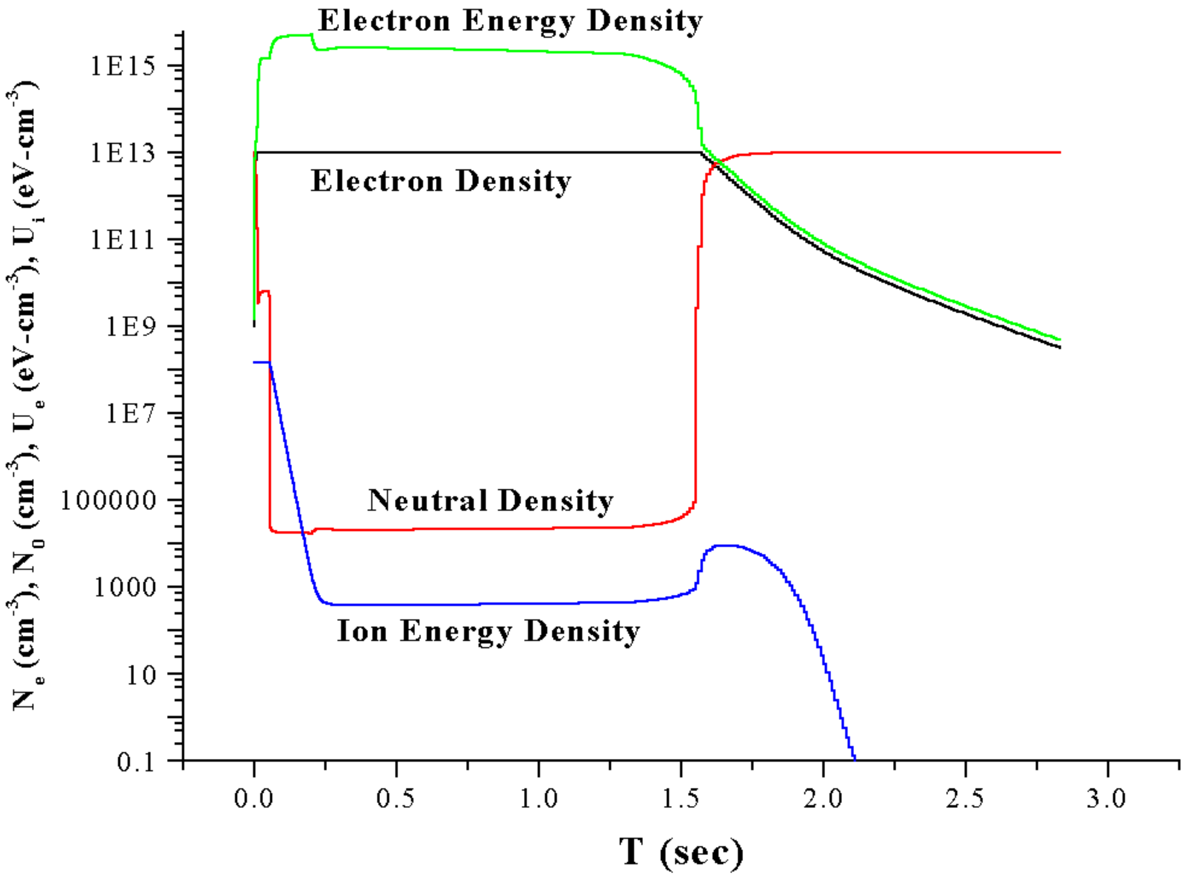

- The electron density, the neutral density, the electron energy density, and the ion energy density vs. time. The y-axis is logarithmic scale.

Plot II-1 – Initial Neutral Densities

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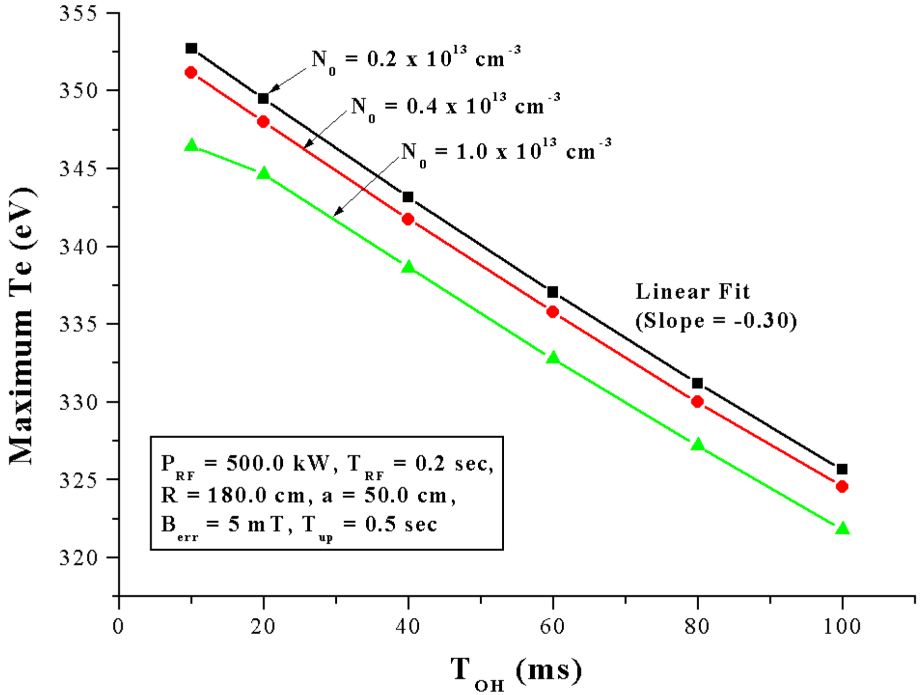
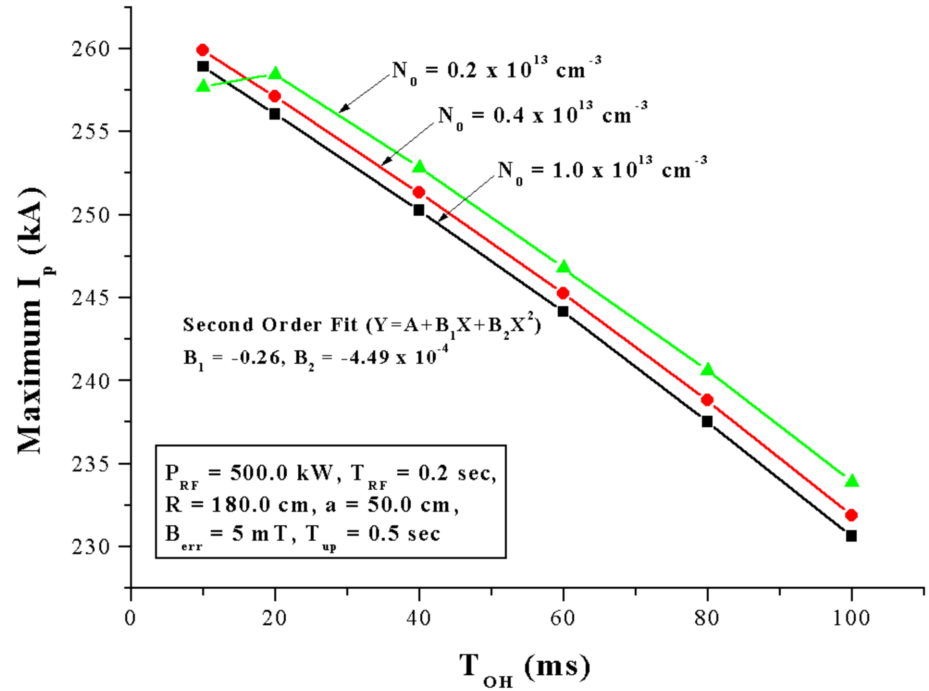
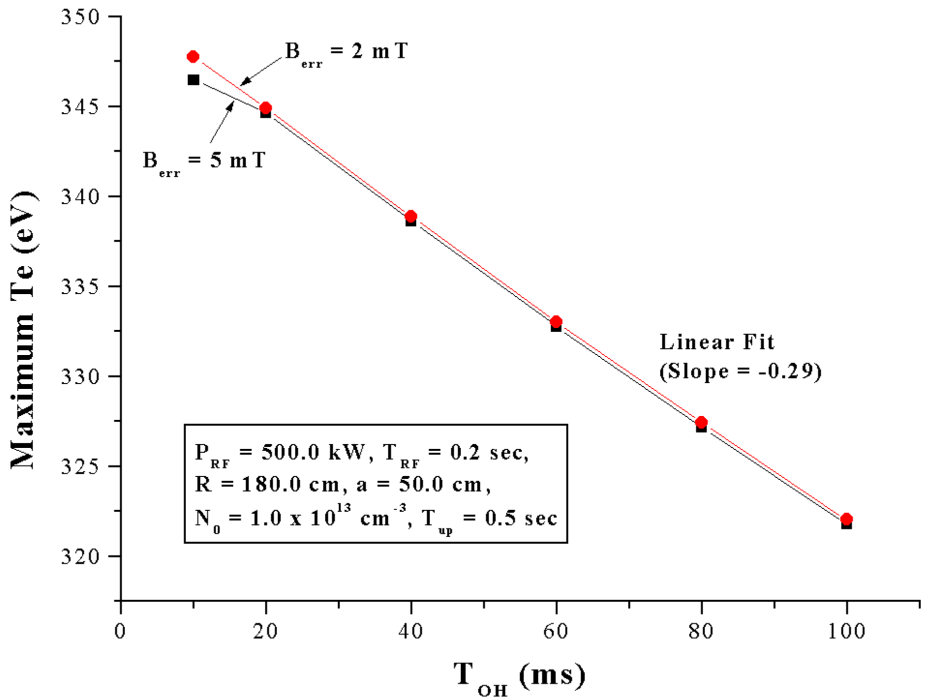
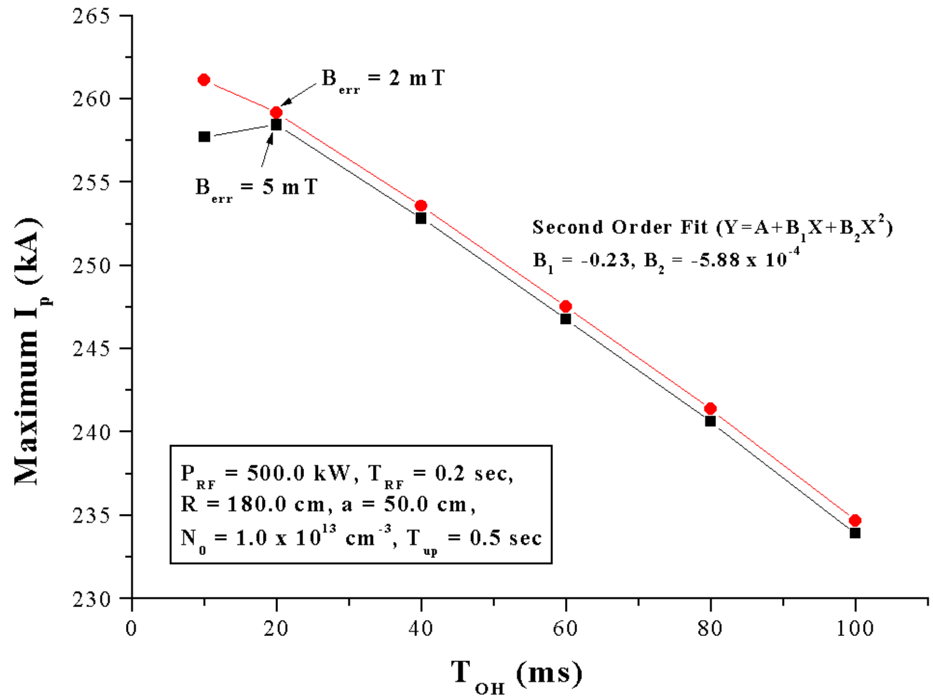




- Maximum electron temperatures and plasma currents within 0.5 sec vs. T_{OH} for initial neutral densities of 0.2 x 10^{13} cm^{-3}, 0.4 x 10^{13} cm^{-3}, and 1.0 x 10^{13} cm^{-3}. Fitting results are shown in the figures. The linear fit is performed for the electron temperature and second order fit for the plasma current.

Plot II-2 – Error Fields





- Maximum electron temperatures and plasma currents within 0.5 sec vs. T_{OH} for error fields of 2.0 mT and 5.0 mT. Fitting results are shown in the figures. The linear fit is performed for the electron temperature and second order fit for the plasma current.

Plot II-3 – Impurity Effects

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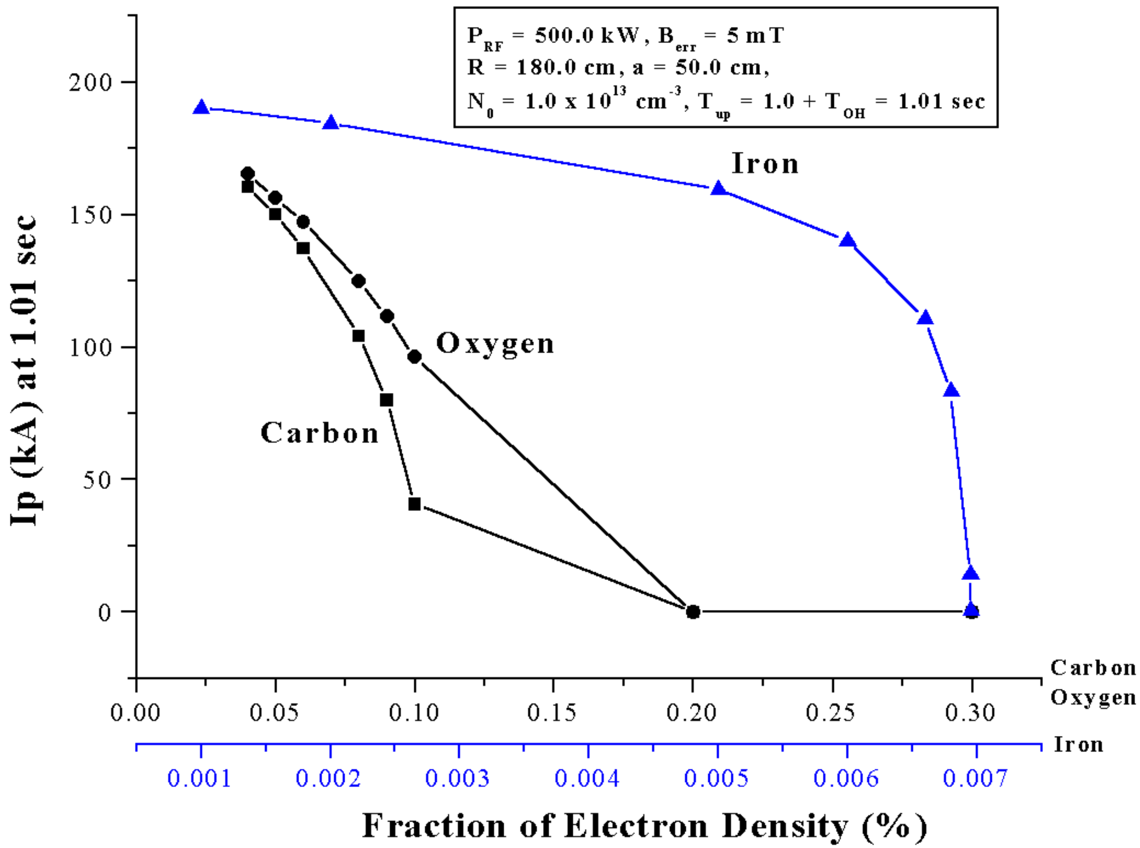

- Plasma current at 1.01 sec vs. impurity densities. The impurity densities are given by the fixed fraction of the electron density, so that the impurity densities increase as much of the fixed fractions of the increasing electron density. Figure shows the iron impurity effects are larger than carbon and oxygen impurities effects.

Plot II-4 – Minimum RF Pulse Lengths

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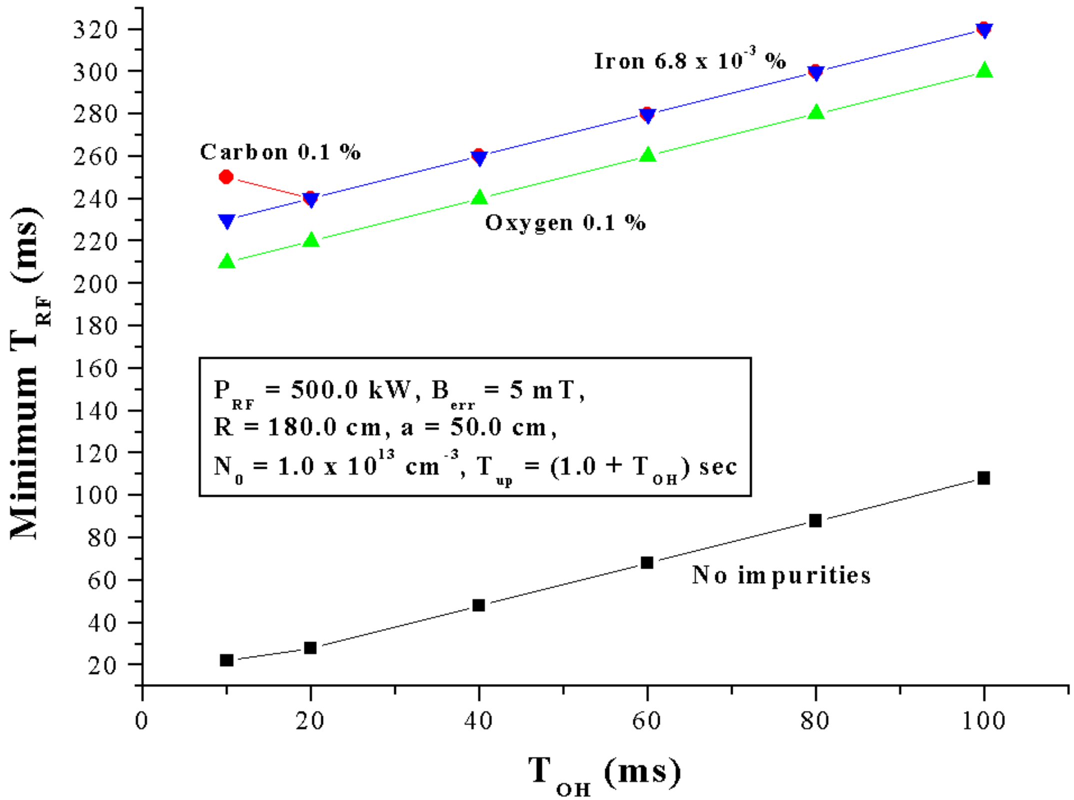

- Minimum RF pulse lengths vs. TOH in case of no impurities, carbon impurities of 0.1 %, oxygen impurities of 0.1 %, and iron impurities of 6.8 x 10^{-3} %. The minimum RF pulse length is found for the plasma current ≥ 100 kA at (1.0 + T_{OH}) sec.

Summary

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- **Maximum T_e and I_p decrease as the T_{OH} increases.**
  - Linear fit for T_e
    - Neutral density scan : slope = -0.30
    - Error field scan : slope = -0.29
  - Second order fit for I_p
    - Neutral density scan : first order coef. = -0.26, second order coef. = -4.49×10^{-4}
    - Error field scan : first order coef. = -0.23, second order coef. = -5.88×10^{-4}

- **Impurity effects**
  - Carbon effects < 0.1 %
  - Oxygen effects < 0.1 %
  - Iron effects < 6.5×10^{-3} %

- **Minimum RF pulse length (T_{OH} = 10.0 ms – 100 ms)**
  - No impurities : 22 ms – 108 ms
  - With impurities (Carbon 0.1 %, Oxygen 0.1 %, Iron 6.8×10^{-3} %) : 210 ms – 320 ms