Error-field Effects on ECH pre-ionization for KSTAR*

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Abstract

The gyrotron for the KSTAR ECH system has the maximum RF power of 500 kW with a pulse length of 2 seconds. However, the power delivered to the plasma through the waveguide and mirror-optics system will be smaller than 500 kW due to various effects such as mode conversion, resistive loss, optical loss, and others. On the other hand, the error fields require a higher power for the plasma startup. The delivered microwave energy to plasmas can be controlled by pulse-lengths. In this paper, we present the error field effect on the delivered microwave energy for the KSTAR ECH pre-ionization.

Introduction

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- Preionization is to reduce: (a) the voltage required to start the plasma current,

  (b) the startup runaway electrons,

  (c) the volt-sec expenditure.
- Previous work: (a) M. Peng et al. for voltage and volt-sec reduction

  (b) Kulchar et al. for experiments at ISX-B (ORNL)

  (c) Marloli and Petrillo for plasma radial growth

  (d) Lloyd et al. for impurity effect

  (e) C. S. Chang et al. for error-field effect
- This presents preionization simulation by advanced code for KSTAR:
- We considered 7 pairs of superconducting poloidal coils structure for circuit equations between plasma and poloidal coils. The self and mutual inductances are used in the circuit equations.
- The plasma expanding in minor radius will be the future study subject.

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** $Q = \log 10(T_e)$.

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

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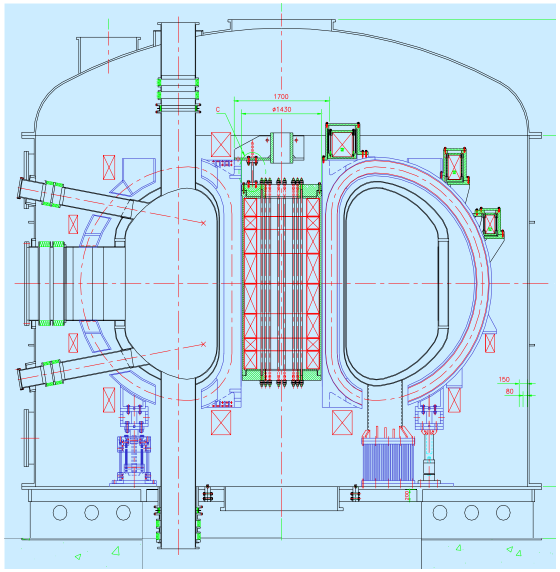

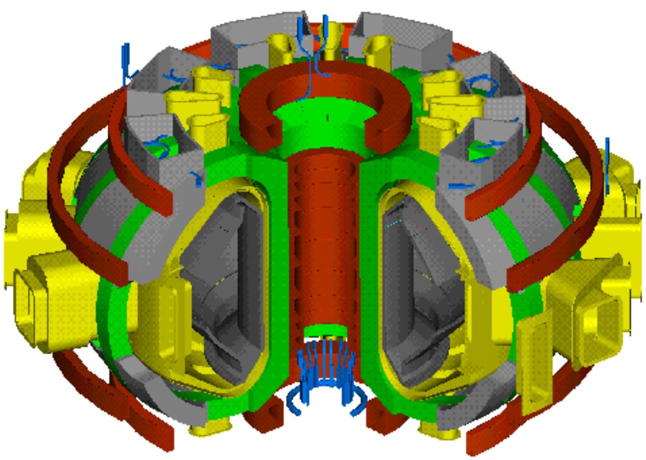

KSTAR PF coil structure

(Unit : mH)

	PF1	PF2	PF3	PF4	PF5	PF6	PF7	PLA
PF1	85.6	26.55	5.96	5.28	7.45	7.13	8.3	0.11
PF2	26.55	44.98	12.56	9.18	7.85	5.81	6.47	0.073
PF3	5.96	12.56	13.43	10.38	5.3	2.96	3.13	0.037
PF4	5.29	9.18	10.38	26.93	10.96	4.48	4.52	0.031
PF5	7.45	7.85	5.3	10.96	327.4	37.32	31.21	0.135
PF6	7.13	5.81	2.95	4.48	37.31	199.36	99.1	0.219
PF7	8.3	6.47	3.13	4.52	31.2	99.1	316.45	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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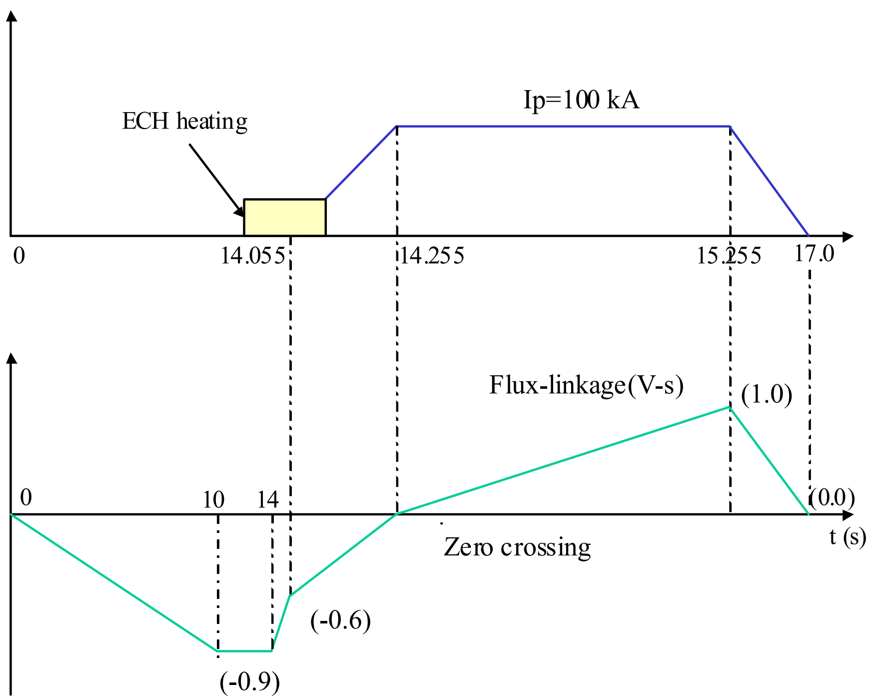

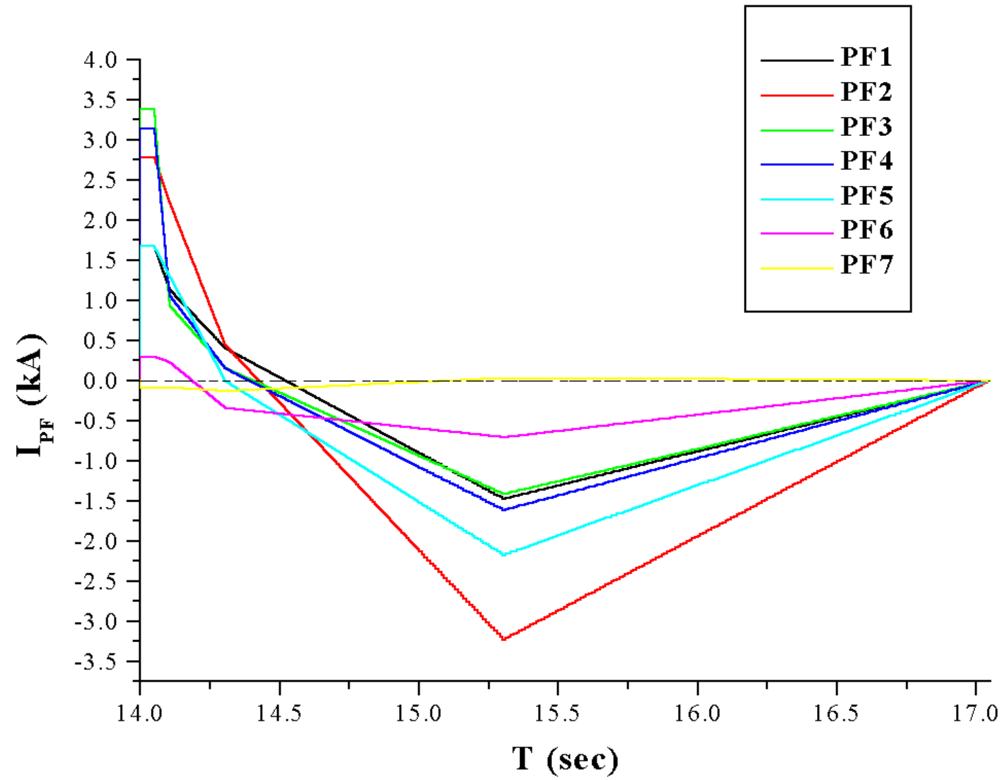

Input Conditions

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There are three kinds of input conditions.

1. For the microwave source;

   The microwave source for the KSTAR ECH system is a CPI gyrotron tube. The gyrotron tube can generate a maximum of 500 kW with pulse lengths up to 2.0 seconds. However the power delivered to the plasma through the waveguide and mirror-optics system is smaller than 500 kW due to various effects such as mode conversion, resistive losses, optical losses, etc. From the KSTAR ECH system design, the total power lost is 9 %, so that the delivered power to the KSTAR plasma is about 455 kW. Since the power and the pulse length can be adjusted by the gyrotron power supply, the power and the pulse length are employed as the input parameter in the simulation.

2. For the KSTAR plasma;

   For the KSTAR plasma, we consider the following input parameters: the major radius (R_0 = 180.0 cm), the minor radius (a = 50.0 cm), the initial neutral density (N_0), the error field (B_{err}), and the impurities such as carbon, oxygen and iron. The major radius and minor radius are fixed in all simulations.

3. For the poloidal field (PF) coils;

   The condition for the PF coils is already explained in the previous section. The important parameter for the PF coils is the beginning time (T_{OH}) of the current sweep of the coils after the ECH power is turned on. We call TOH as the ohmic heating delay time.

Plot I – Temporal Behaviors

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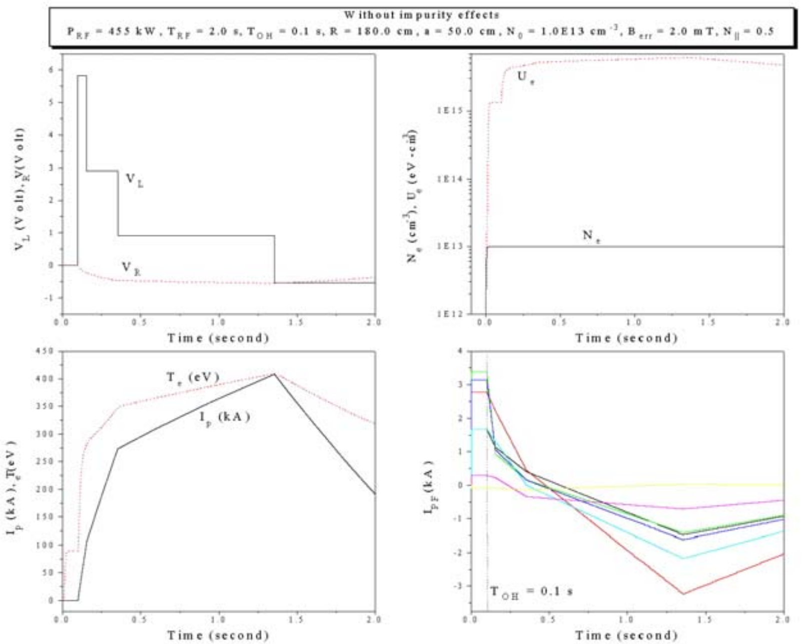

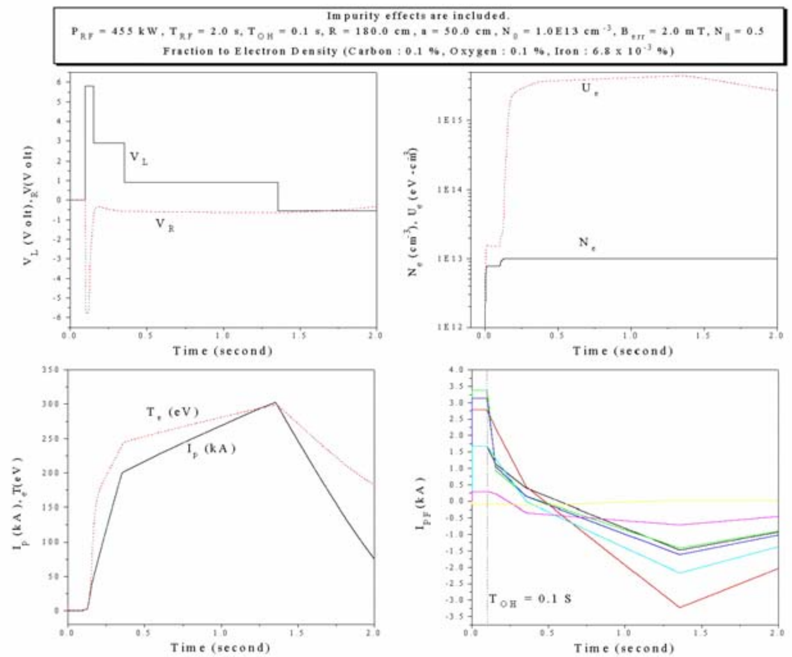

The temporal behaviors of plasma parameters with initial conditions: P_{RF}= 455 kW for duration of 2.0 seconds, T_{OH} = 100 milliseconds, R = 180.0 cm, a = 50.0 cm, N_0 = 1.0 x 10^{13} cm^{-3}, B_{err}=2.0 mT, and no impurities.

The temporal behaviors of plasma parameters with initial conditions: P_{RF}= 455 kW for duration of 2.0 seconds, T_{OH} = 100 milliseconds, R = 180.0 cm, a = 50.0 cm, N_0 = 1.0 x 10^{13} cm^{-3}, B_{err} = 2.0 mT, carbon density = 0.001 N_e, oxygen density = 0.001 N_e, and iron density = 6.8 x 10-5 N_e.

Plot II – Ohmic Heating Delay Time

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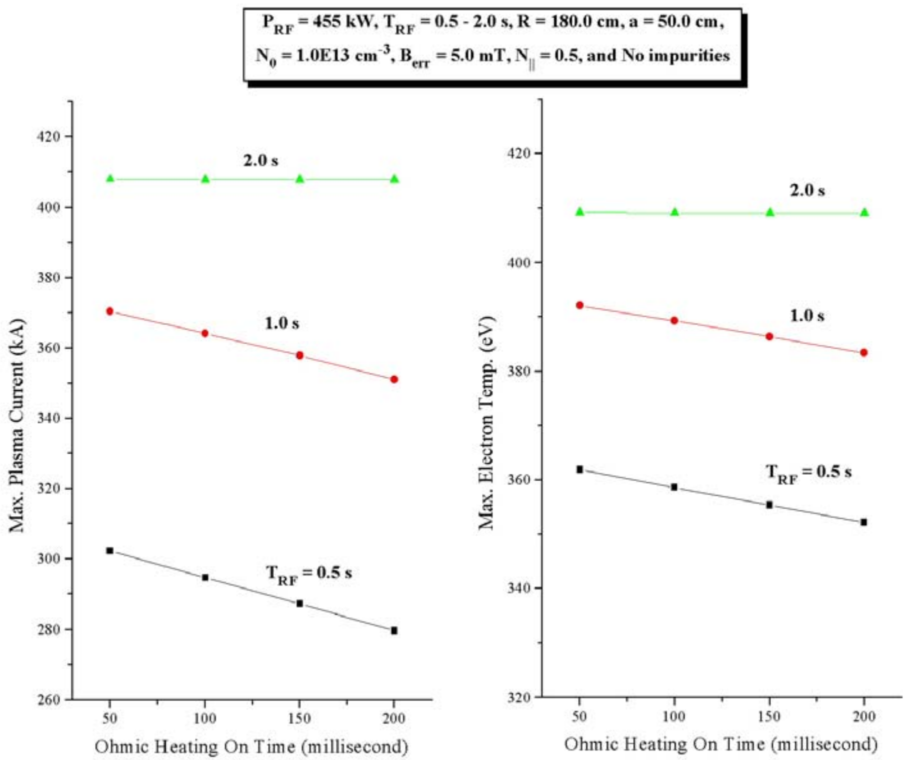

The maximum plasma current and electron temperature as a function of the ohmic heating delay time (T_{OH}) for an RF power P_{RF} = 455 kW with durations of 0.5 s, 1.0 s, and 2.0 s.

Plot III – Initial Neutral Density

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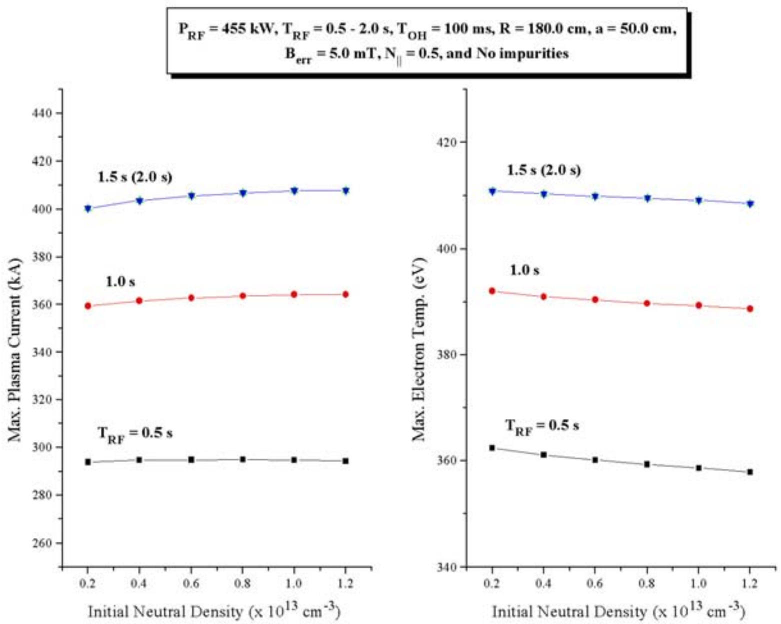
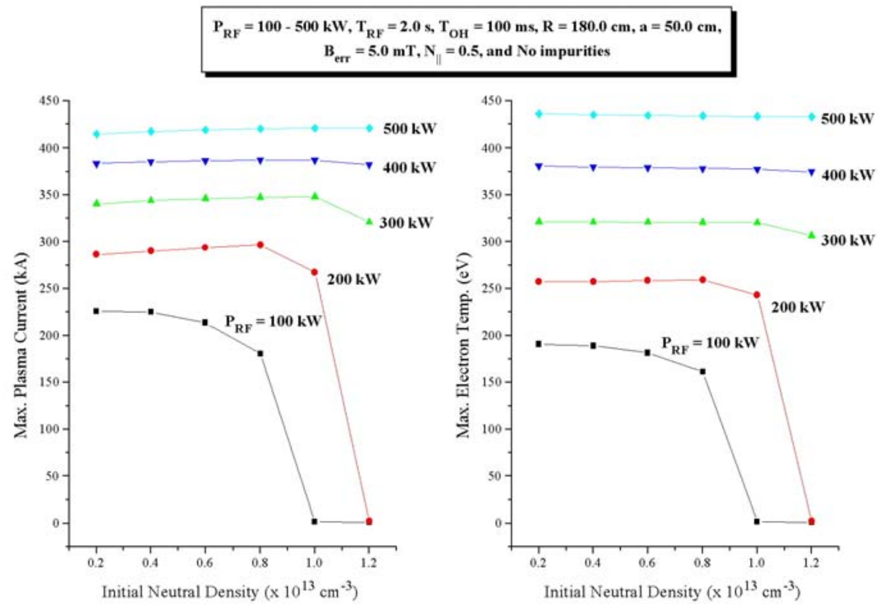


The maximum plasma current and electron temperature as a function of the initial neutral density (N_0) for an RF power P_{RF} = 455 kW with durations of 0.5 s, 1.0 s, 1.5 s, and 2.0 s.



The maximum plasma current and electron temperature as a function of the initial neutral density (N_0) for RF powers of P_{RF} = 100 kW - 500 kW with a duration of 2.0 s.

Plot IV – Error Field

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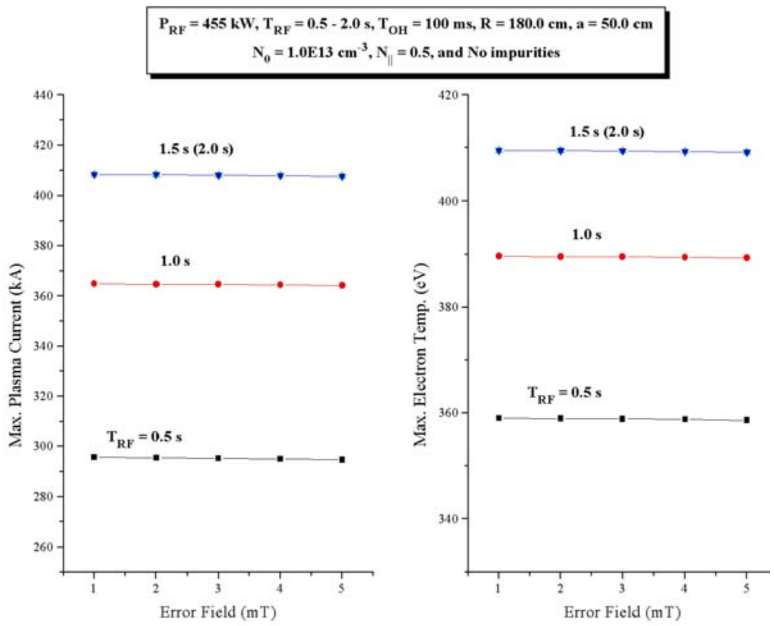
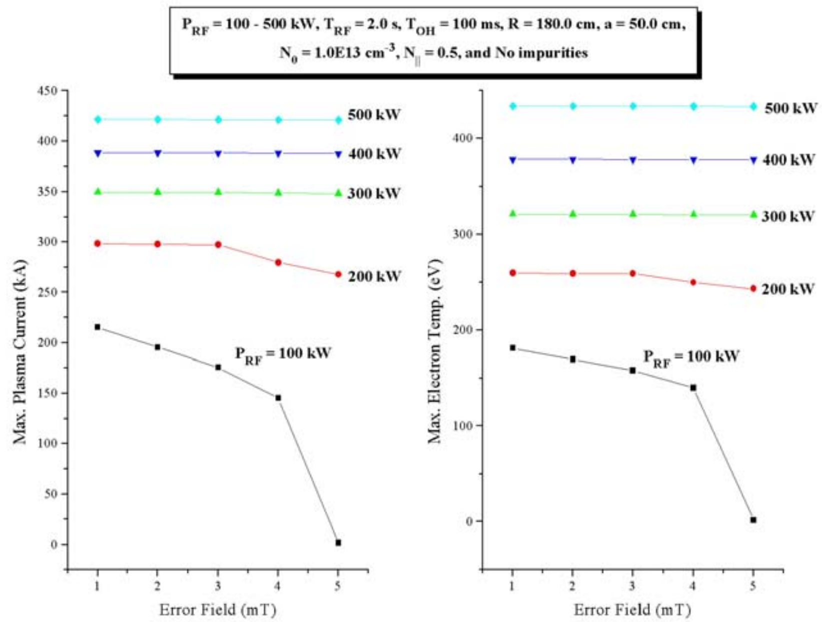


The maximum plasma current and electron temperature as a function of the error field (B_{err}) for an RF power P_{RF} = 455 kW with durations of 0.5 s, 1.0 s, 1.5 s, and 2.0 s.



The maximum plasma current and electron temperature as a function of the error field (B_{err}) for RF powers of P_{RF} = 100 kW - 500 kW with a duration of 2.0 s.

Plot V – Carbon Impurity

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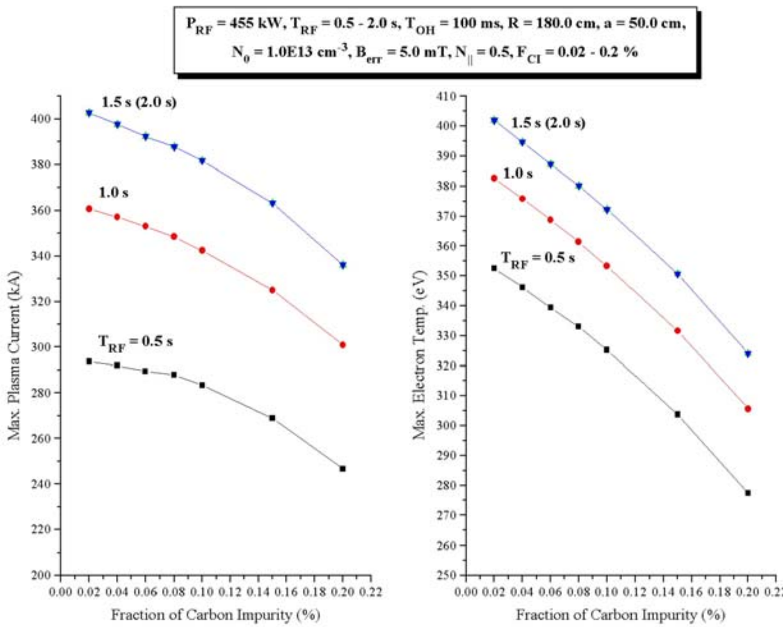

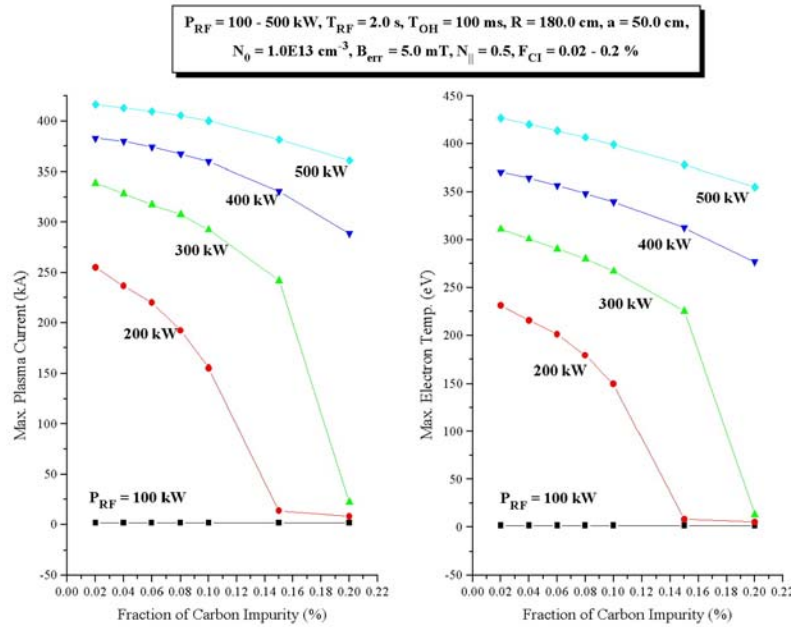

The maximum plasma current and electron temperature as a function of the fraction of the carbon impurity (F_{CI}) to the electron density for an RF power P_{RF} = 455 kW with durations of 0.5 s, 1.0 s, 1.5 s, and 2.0 s.

The maximum plasma current and electron temperature as a function of the fraction of the carbon impurity (F_{CI}) to the electron density for RF powers of P_{RF} = 100 kW - 500 kW with a duration of 2.0 s.

Plot VI – Oxygen Impurity

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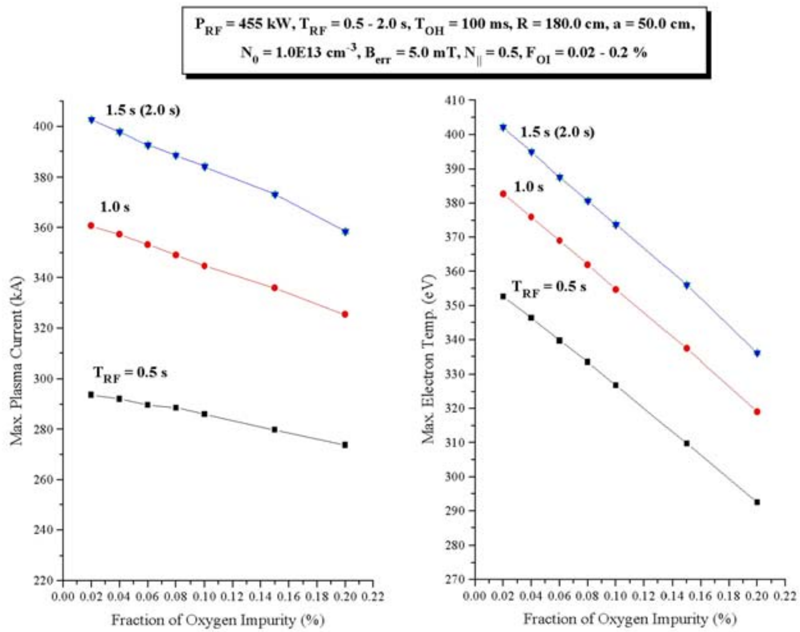
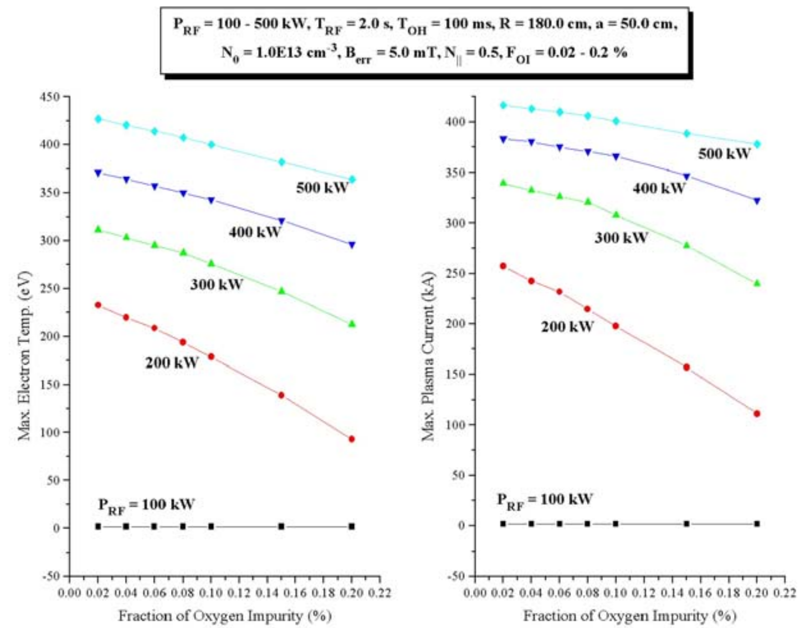
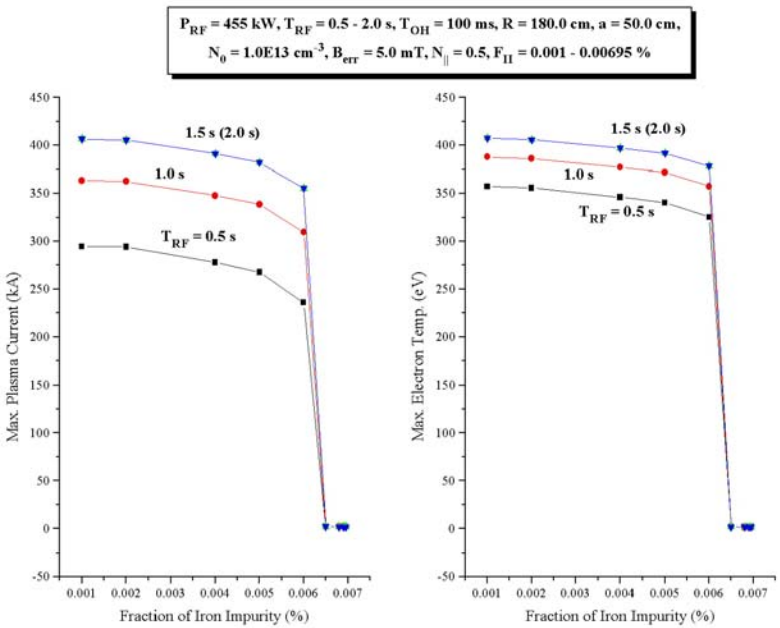


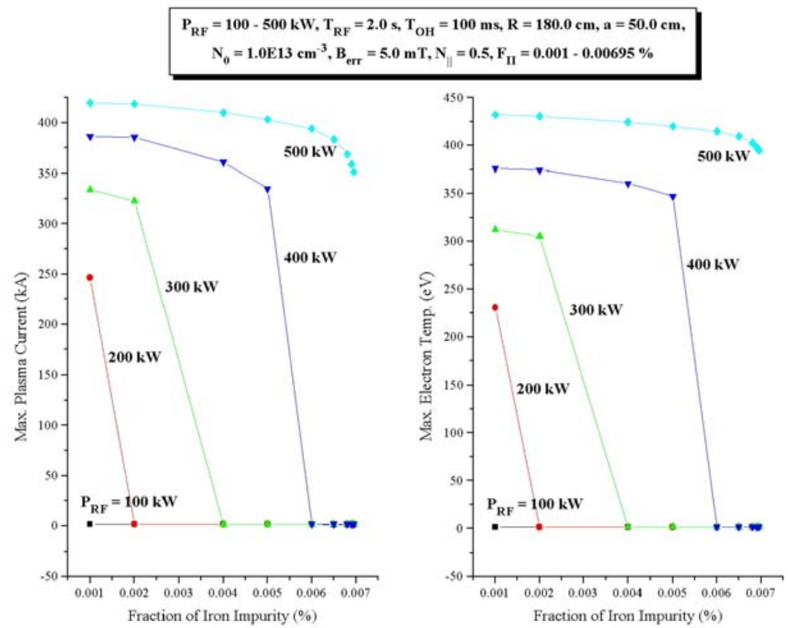


The maximum plasma current and electron temperature as a function of the fraction of the oxygen impurity (F_{OI}) to the electron density for an RF power P_{RF} = 455 kW with durations of 0.5 s, 1.0 s, 1.5 s, and 2.0 s.

The maximum plasma current and electron temperature as a function of the fraction of the oxygen impurity (F_{OI}) to the electron density for RF powers of P_{RF} = 100 kW - 500 kW with a duration of 2.0 s.

Plot VII – Iron Impurity





The maximum plasma current and electron temperature as a function of the fraction of the iron impurity (F_{II}) to the electron density for an RF power P_{RF} = 455 kW with durations of 0.5 s, 1.0 s, 1.5 s, and 2.0 s.

The maximum plasma current and electron temperature as a function of the fraction of the iron impurity (F_{II}) to the electron density for RF powers of P_{RF} = 100 kW - 500 kW with a duration of 2.0 s.

Summary

In the first phase KSTAR operation, the current scenario adopts seven pairs of poloidal field coils, and there will be no auxiliary heating except the ECH assist startup. The preionization effects are investigated by a zero-dimensional code.

As the RF pulse length and its power increase, the dependence is smaller for maximum electron temperature and plasma current on the initial conditions, such as the ohmic heating delay time, the initial neutral density, the error field, and the impurity density.

With the gyrotron RF power of 500 kW and 2.0 sec, the preionization will minimize the dependence on KSTAR initial conditions except for very high impurity densities.