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Observation on fundamental and second harmonic mode ECRH assisted plasma startup in SST-1 experiments

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ABSTRACT

In SST-1, successful plasma startup has been achieved at very low loop voltage with the help of ECRH pre-ionization. ECRH is operated in both O mode and X mode for the purpose of pre-ionization at the pre fill pressure of 1×10^{-5} mbar. A delay in breakdown has been observed in case of second harmonic ECRH pre-ionization; where in case of fundamental mode of ECRH pre-ionization, the instant breakdown has been observed. This work has attempted at explaining the non-linear interaction of the seed electrons with the electromagnetic field of the incident ECRH wave that has led to break down of the plasma. The delay in the break down attributes to the time differential between the applications of the ECRH pulse to that of the appearance of the H-alpha signal in SST-1. The observed experimental results have been discussed in this paper from the first principles and numerically solving the electron-ECRH field interactions resulting in energy gains of the electrons leading to plasma break down in SST-1 specific discharge conditions.

1. Introduction

SST-1 is an experimental superconducting Tokamak in operation at the Institute for Plasma Research [4]. The vacuum vessel and the cryostats of SST-1 are electrically conducting. The plasma break-down in SST-1 is assisted with Electron Cyclotron Resonance pre-ionization. A 500 kW, 500 ms gyrotron at 42 GHz assists the pre-ionization after which the toroidal induced electric fields from the SST-1 central solenoid forms the toroidal plasma column in SST-1. This pre-ionization assisted plasma break-down has been discussed in this paper from first principles. The seed electrons interact with the incident microwave fields of the ECH and collisionlessly gains energy in both fundamental mode and in second harmonic modes. Once the electrons have gained sufficient energy while in transit within the SST-1 vacuum vessel, they can lead to sufficient ionization with the neutrals available from the pre-filled pressure resulting break-down of the plasma. In a pre-fill gas of hydrogen as is the case with SST-1, copious H-alpha emissions are observed at the onset of the break-down process of the plasma. Application of ECRH during plasma startup conserves the volt-seconds and creates plasma current channel at a well defined location away from the wall, which reduces the plasma wall interaction during startup phase and helps in improving subsequent energy confinement time. ECRH assisted pre-ionization also helps in faster plasma current build up. In addition to the pre-ionization ECRH also serves as initial current drive for plasma current build up. Similar experiments of using second harmonic ECRH for startup has been reported by KSTAR [8].

ECH assisted breakdown and subsequent current ramp-up has been successful in SST-1 in both fundamental modes and second harmonic modes. Appropriate O–D model has been developed in the context of SST-1 estimating the minimum ECRH threshold power required and have been bench marked with experimental results. It has been observed that second harmonic ECRH breakdown is delayed as compared to the fundamental mode in SST-1. A nonlinear cyclotron harmonic absorption model has been described in Ref. [1], which has been adopted here in the context of SST-1 to explain the ECRH assisted pre-ionization experiments in SST-1. Here, it is assumed that seed electrons are present initially at room temperature with energy of ~0.03 eV. ECRH being Electromagnetic RF waves, the seed electrons interact with the electric field of the RF wave. For resonant wave heating to happen, ECRH RF wave frequency should be equal to the electron's cyclotron frequency or in multiple of its harmonics. Whenever the electron passes through the resonance region, it receives a gain in perpendicular speed $\upsilon_\perp$. As the cyclotron resonance heating is stochastic and the particle's phase is randomized by collisions, particles need multiple pass thorough the micro wave beam to gain sufficient energy.

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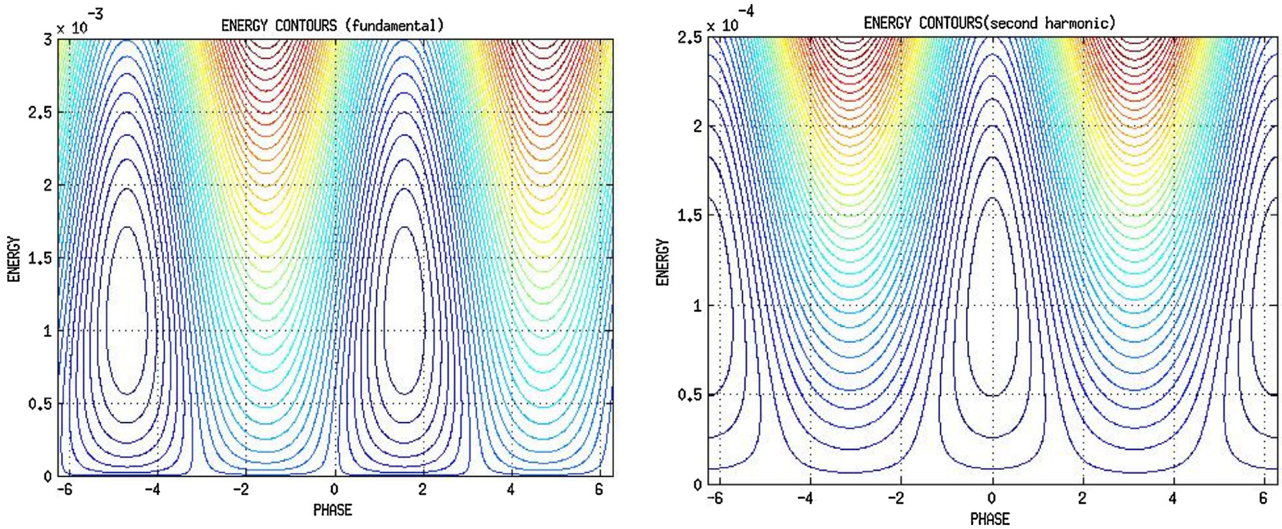

Fig. 1. Energy oscillation contours.

SST-1 plasma experiments use 42 GHz RF frequency in fundamental mode at toroidal field of 1.5 T and in second harmonic mode at toroidal field of 0.75 T. ECRH system's Gyrotron can deliver 500 kW of power for 500 ms at 42 GHz frequency [5]. In this experiment ECRH waves launched from Low field side of the SST-1 tokamak. A polarizer is used to change the polarization mode of the RF wave from fundamental mode to X mode. Experimental results for ECRH assisted pre-ionization of SST-1 plasma experiments in fundamental mode and second harmonic mode are explained in this paper. Section 2 discusses the numerical model and the associated assumptions that form the basis of the explanation for the ECRH assisted breakdown in SST-1 plasma experiments. Section 3 is devoted to the experimental results of SST-1 and related discussion.

2. Discussion of numerical model of ECRH assisted pre-ionization in case of SST-1

A theoretical model developed in Ref. [1] considers nonlinear heating of low energy electrons at room temperature for pre-ionization in ECRH assisted tokamak start-up. The primary focus is on single particle interaction with the waves at the cyclotron resonance frequency and average energy gain from the single pass through the beam. The magnetic field strength is assumed to be constant and the electric field strength is Gaussian. In Ref. [1] the Lorentz equation for electrons has been solved to demonstrate interaction between wave and particle. Here we will exploit the mathematical formulations as shown in Ref. [1] for the case of SST-1 parameters.

The phase difference and the particle's energy at the first harmonic resonance is given by following equation,

$$\Gamma^2 - \sqrt{2}\Gamma^{1/2}\epsilon \sin\Psi = C \tag{1}$$

where, C is constant and Γ represents ratio of the kinetic energy to the rest mass energy of the particle. $\Gamma = \gamma - 1$ where, $\gamma = \left(1 - \vec{v} \times \vec{v}/c^2\right)^{-1/2}$. Ψ is the phase difference between particles and the wave electric field and can be defined as

$$\Psi \equiv \psi - 1 \text{ and } \psi = \int_{t_0}^{t} dt' \Omega_{ce}\left(t'\right) + \psi_0$$

$\Omega_{ce}(t) = eB/\gamma m_0$ and ψ_0 is the initial phase of the particle.

Fig. 1 shows the energy oscillations contours versus the phase for fundamental mode and second harmonic mode ECRH for SST-1. Close contours are called the "trapped mode" and they are co-centric as expected in Refs. [1,2]. Particles energy oscillates as it passes through the resonance zone and it receives net heating effect. If the wave particle interaction time larger than the energy oscillation period, a particle will receive a net collision less heating.

For fundamental mode ECRH, nonlinear energy oscillation is given by,

$$T_{oscillation} \simeq \frac{1}{1.23\epsilon^{2/3} f_{rf}} < \tau_{passing} = \frac{L_b}{V_{||}}$$

where $T_{oscillation}$, Lb, $V_{||}$ and τ passing are the nonlinear energy oscillation period, wave beam width, particles speed parallel to toroidal magnetic field and time needed by particle to cross the wave beam respectively. In above equation $\epsilon \equiv eE_0/m_0c\omega$ is a dimensionless variable. Energy oscillation for second harmonic ECRH case is given by,

$$V_{||} < L_b \epsilon f_{rf}$$

In the startup process, a nonlinear energy oscillation occurs easily due to long stay of electron in the resonance zone. Considering L_b as 15 cm, f_{rf} as 42 Ghz and $\epsilon = 1.042E\text{-}4$, energy of the particle at the input of wave beam for second harmonic ECRH case can be approximately calculated to 4.31 eV for maximum parallel velocity. For fundamental mode ECRH the energy of the particle at the input of wave beam is 837.2 eV. So in fundamental mode electrons receives a large energy gain per passage through the wave beam as compared to the second harmonic mode.

Fig. 2 shows the consecutive energy gains by the particle in each pass through the resonance zone in fundamental mode as well as second harmonic mode. As shown in Fig. 2(a) in fundamental mode energy gain is more effective and very large as compared to the second harmonic mode ECRH and hence in fundamental mode a prompt pre-ionization happens. As shown in Fig. 2(b) for second harmonic ECRH case, low temperature electrons from room temperature take quite some time to gain sufficient energy to bring break down of the gas in the vessel and hence a delay of approximately 32 ms has been observed in SST-1. This is because after gaining approximately 4 eV of initial energy, the energy gain rate starts reducing. This is evident from Fig. 2(b).

The loss of electron inside the microwave beam is assumed to be negligible. The source of particle loss during the avalanche process