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Pre-ionization Experiments in the DIII-D Tokamak Using X-mode Second Harmonic Electron Cyclotron Heating

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Pre-ionization using second harmonic resonant electron cyclotron waves with X-mode polarization (X2) has been observed in the DIII-D tokamak using both the previously installed 60 GHz gyrotrons [1] and the present 110 GHz system. Startup scenarios for future tokamaks such as ITER and KSTAR will benefit from electron cyclotron heating (ECH) simultaneous with the application of an inductive electric field for plasma initiation since thicker vacuum liners and superconducting coils limit the maximum inductive voltage to values that are marginal for plasma breakdown and burnthrough. In addition, ECH pre-ionization and startup in DIII-D can minimize runaway electron production, allow faster burnthrough and discharge reproducibility, and can be part of proposed noninductive startup experiments in DIII-D.

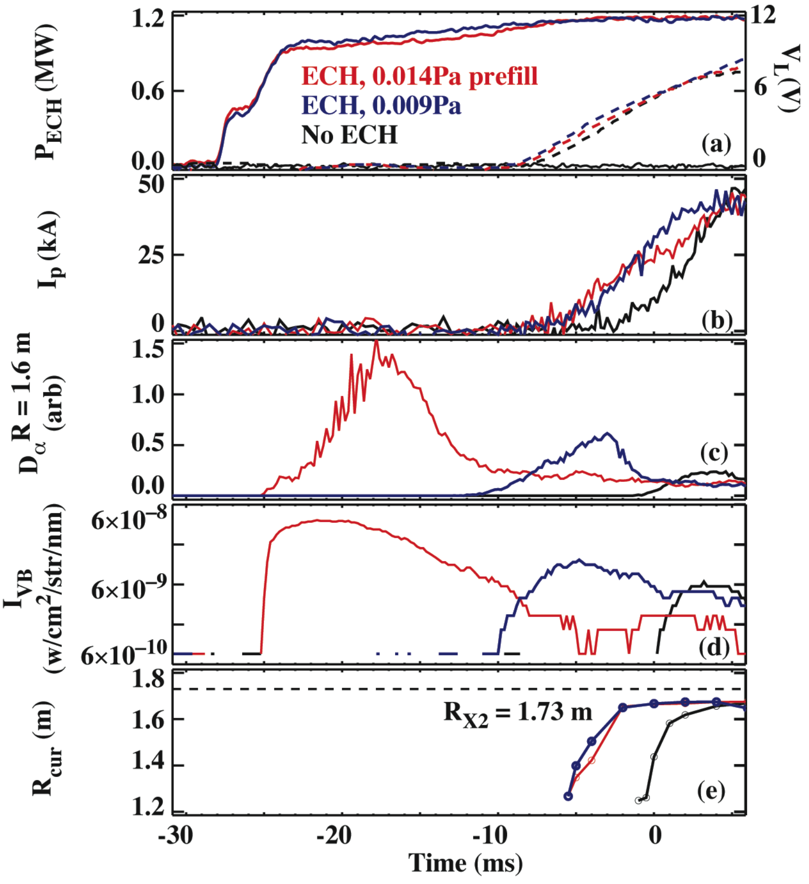

Fig. 1. ECH pre-ionization at two prefill pressures, 0.014 Pa (red) and 0.009 Pa (blue) compared with no pre-ionization at 0.009 Pa (black): (a) P_{ECH} and V_{Loop}, (b) I_p, (c) D_α intensity at floor location nearest the EC resonance location, R_{X2}, (d) VB chord whose radius of tangency is nearest R_{X2} and (e) radius of current centroid, R_{cur} calculated from a single filament model (#128489, 90, 93).

The temporal evolution for two pre-ionization discharges is compared with an ohmic discharge in Fig. 1. Prompt ionization, inferred from D_α and visible Bremsstrahlung (VB) emission, I_{VB}, is observed at high prefill pressure, 0.014 Pa (red curves), although pre-ionization has been observed in the range of prefill pressures from 0.006 to 0.027 Pa (without pre-ionization DIII-D typically operates with prefill pressures from 0.005-0.02 Pa). In addition, with pre-ionization, the start of plasma current, Fig. 1(b), begins almost simultaneously with the initiation of the inductive voltage,

Fig. 1(a). The most robust pre-ionization discharges are achieved at higher prefill pressures typically, $P_{D2} > 0.014$ Pa. For example in Fig. 1(d), ionization is detected 2.8 ms after ECH is applied for the high prefill pressure (red curves) and the rise time of the VB chord closest to the X2 resonance is also the fastest, 240 µs, where $I_{VB}\ \alpha\ Z_{eff} n_e^2 T_e^{-1/2}$, while it is significantly delayed at lower prefill pressure (blue curves). The current centroid, R_{cur}, in Fig. 1(e) is calculated from a single filament current model. The EC resonance location, R_{X2} is shown as a dashed line. Note that although the highest VB intensity occurs nearest the ECH resonance location [Fig. 1(e), dashed line] the current is initially detected (using the single filament model) closer to the inside wall (R_{wall} = 1.02 m), where the inductive electric field is highest. This is observed both with and without ECH pre-ionization.

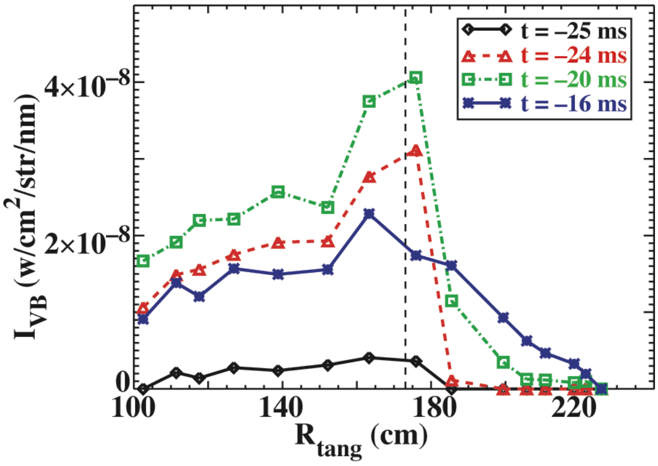

Fig. 2. VB emission at various times as a function of radius of tangency of a VB channel (#128493). ECH is applied at t = -28 ms and the inductive voltage begins at t = -8 ms. Vertical dashed line indicates R_{X2}.

VB emission profiles are shown (Fig. 2) after ECH is initiated. I_{VB} is the emission along a line of tangency, and the radius of tangency is the abscissa. Since T_e profiles were not measured during this time, Abel inversion to infer density profiles was not possible even assuming a constant Z_{eff}. Thus, only the VB intensity, integrated along the line of sight, is shown. The profiles peak near the ECH resonance location and broaden later, typical of all EC pre-ionization cases.

The radius of the EC resonance location, R_{X2}, can be varied by changing the toroidal magnetic field, B_T. Pre-ionization in DIII-D has been observed when R_{X2} is near the inside wall and extending to R_{X2} = 1.85 m, limited only by the maximum B_T available (using the 110 GHz system). The tangency radius where maximum VB intensity is initially observed correlates closely with R_{X2} (Fig. 3).

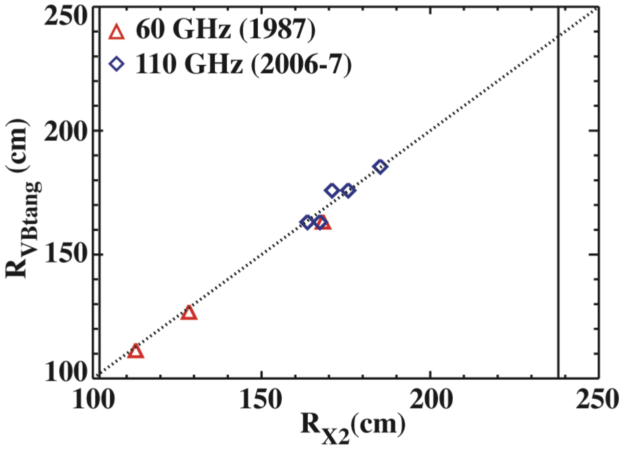

Fig. 3. Radius of tangency of the channel with maximum VB intensity as a function of R_{X2}. Solid vertical lines indicate radius of the DIII-D inner and outer wall. The discharge in Figs. 1 and 2 is represented by the point at R_{X2} = 176 cm.

A direct comparison at the same prefill pressure between 2nd harmonic X-mode (1.05 T) and fundamental O-mode (2.1 T) using the previous 60 GHz launchers showed that both achieved the same pre-ionization line-integrated density, but there was a longer time before breakdown with 2nd harmonic X-mode pre-ionization [2].

In the 110 GHz DIII-D experiments, EC 2nd harmonic X-mode heating was accomplished with a circular waveguide antenna whose aperture was 60 mm, launching a HE_{11} mode. Steerable mirrors allow poloidal and toroidal positioning of the EC wave, while the polarization is adjusted to maintain X mode. In these DIII-D low-field side launch experiments, there is a strong dependence of toroidal angle on the intensity of VB radiation. Best results were obtained when the launch angle was perpendicular to the toroidal field, β_{EC} = 90 deg. Varying this angle by ±10 deg dramatically reduced the VB intensity (Fig. 4). At higher prefill pressures, the decrease in intensity with β_{EC} was not as steep, but clearly β_{EC} = 90 deg always gives the highest and most prompt pre-ionization intensity.

The power threshold for successful X2 pre-ionization in DIII-D has been observed experimentally to be: 0.38 MW (60 GHz, 2 gyrotrons) and as low as 0.25 MW (110 GHz, 1 gyrotron at reduced power) when neutral fill pressure and vacuum vertical magnetic field are optimized. Burnthrough of low Z impurity species occurred at an earlier time than for ohmic startup alone.

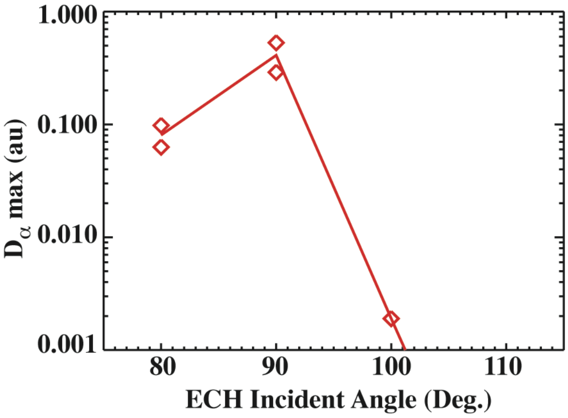

Fig. 4. Pre-ionization D_α intensity as a function of the ECH incident launch angle with respect to B_T. P_{D2} = 0.008 Pa, B_T = 1.8 T, P_{EC} = 1.0 MW.

A single particle code, including relativistic effects, was used to describe the initial collisionless electron-heating phase in DIII-D. The code shows that an electron traversing a perpendicular EC beam can be heated from room temperature, 0.03 eV, to 85 eV at the 110 GHz threshold power for pre-ionization (0.25 MW), well above the electron energy required for ionization of deuterium [2]. Second harmonic EC pre-ionization and startup may be useful for KSTAR and for ITER if experiments at reduced B_T are necessary. The results from the collisionless electron heating code are extrapolated to these devices using the geometrical scaling discussed in reference [2]. For a seed electron at 0.03 eV, the maximum heating temperatures are summarized in Table 1. We conclude that X2 heating can initially heat a cold electron to temperatures above 20 eV in both KSTAR and ITER, where ionization of hydrogenic species will occur. We note that this is only one condition required for effective pre-ionization. The model for collisionless heating assumes a coherent linearly polarized EC wave, so only the power for one gyrotron is modeled for each of these devices. Later phases of startup such as the burnthrough phase and even the avalanche may require more power. This has not been included in this discussion.

Table 1. Collisionless 2nd Harmonic EC Heating in DIII-D and Extrapolated to KSTAR and ITER

	DIII-D 60 GHz Baseline (1987)	DIII-D 110 GHz	KSTAR	ITER
B_T^{typ} for X2 pre-ionization (T)	1.07	2.0	1.5*	5.3/2
f (GHz)	60	110	85	127
P_{EC} (MW)†	0.15	0.25	0.45	1
$T_e^{initial}$ (eV)	0.03	0.03	0.03	0.03
W^{max} (eV)	60	85	174	85

*Estimated BT during the initial operations phase.

†Estimated incident power from one gyrotron, used to calculate collisionless heating.

In conclusion, ECH second harmonic pre-ionization in DIII-D has proven robust and has allowed startup at higher prefill pressures with plasma current beginning earlier than comparable ohmic discharges. Toroidal field scans show breakdown always occurring at the second harmonic EC radius as its location is varied from near the inner wall to past the center of the torus. The experimentally observed power threshold has been reduced by optimizing the prefill pressure and the vacuum vertical magnetic field. A relativistic single particle collisionless code has been used to extrapolate X2 heating to both ITER and KSTAR, showing that cold electrons can be heated to 85 eV or higher, above the threshold for ionization of deuterium and tritium. Further work is needed to demonstrate that the avalanche phase and plasma startup can be sustained, but these initial results are promising for using 2nd harmonic ECH and pre-ionization in both ITER and KSTAR when operation at reduced toroidal field is required.

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