EVOLUTION AND MITIGATION OF RUNAWAY ELECTRONS EMERGING DURING TOKAMAK PLASMA START-UP

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Start-up runaway electrons (REs) reaching an energy of over 30 MeV have been observed in DIII-D 1.5s after discharge initiation with first-time measurements of the time-dependent start-up RE quantity and energy spectra. Over a wide range of start-up parameters, REs with an energy of ~ 0.5 MeV are detected immediately after the burn-through phase. This is consistent with a recent hypothesis that start-up REs may emerge, in varying quantities, in all tokamak plasmas [1]. Without mitigation, the maximum RE energy continues to grow during the plasma current (I_p) flattop and can exceed the resolvable energy of the RE diagnostic. Unlike previous studies of start-up REs, which used proxy diagnostics for indirect determination of RE presence, the evolution of RE quantity and energy spectra is directly determined here using the Gamma Ray Imager (GRI) [2].

Understanding the dynamics of start-up RE and mitigating their formation are important for the development of safe start-up scenarios for ITER and future tokamaks. Like disruption-generated RE, the loss of start-up-generated RE can damage plasma-facing components. Due to the limited maximum loop voltage, V_{loop}, in ITER, plasma initiation will only succeed with a low pre-fill gas pressure [3], which increases the likelihood of a large RE population. A large RE population may also cause failure of plasma initiation.

These data were obtained in low density, Ohmic, DIII-D plasmas. The toroidal magnetic field is 1.7 T, and the line-averaged electron density, $\langle n_e \rangle$, is approximately $4.5 \times 10^{18}\ m^{-3}$ during the I_p flattop. The GRI tracks the temporal evolution of the hard-x-ray (HXR) energy spectrum (f_γ) by resolving individual bremsstrahlung photons with energies ranging from 0.5 – 30 MeV at over a 1 MHz count rate. Photons are binned together to create each spectrum. Only one GRI detector was available for this study, so the RE spatial distribution is not yet measured. Assuming spatial homogeneity of the RE distribution function (f_e), the raw experimental measurement of f_γ can be inverted into f_e using the technique described in [4].

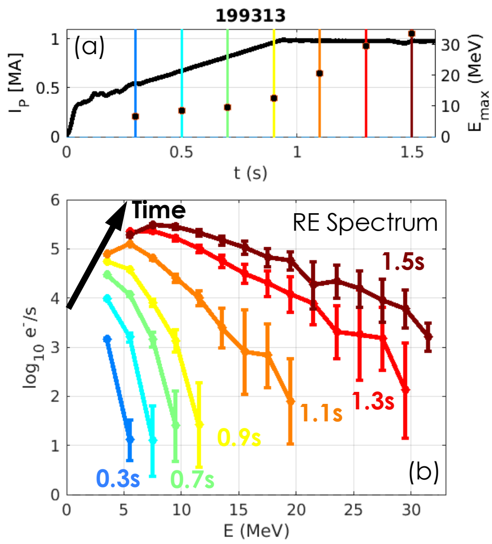

***Figure 1**: From a low density, Ohmic, DIII-D discharge (a) plasma current waveform (line) and maximum RE energy (circles on the colored lines), (b) RE energy spectra at times indicated by colored lines in (a) (integration time 200 ms). Spectra reflect number of REs per second.*

Without mitigation, the RE quantity and energy grow steadily during the I_p ramp, eventually reaching the GRI limit of about 30 MeV during the I_p flattop. With I_p evolving as shown in Fig. 1(a), the time evolution of f_e is shown in Fig. 1(b). As shown in Fig. 1(a), the growth of the maximum RE is, surprisingly, faster during the I_p flatttop than it is during the I_p ramp. This is encouraging for mitigation taking place during the ramp. In addition, extrapolation of the two highest-energy spectra in Fig. 1(b), at 1.3 s and 1.5 s, implies RE energies much higher than 30 MeV, well beyond the previously reported maximum RE energy on the order of 10 – 20 MeV in FTU and JET [5,6].

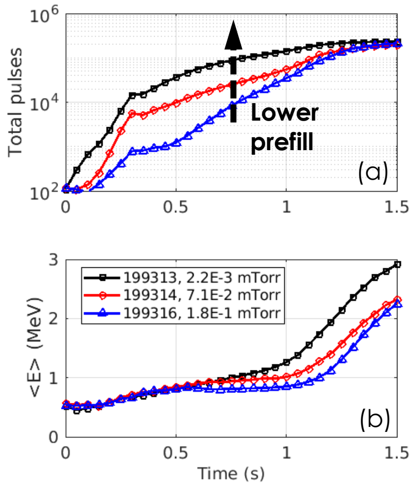

***Figure 2**: Time evolution of HXR (a) quantity and (b) mean energy in three discharges with the same I_p waveform but an overall 80-fold variation in pre-fill pressure (integration time 50 ms).*

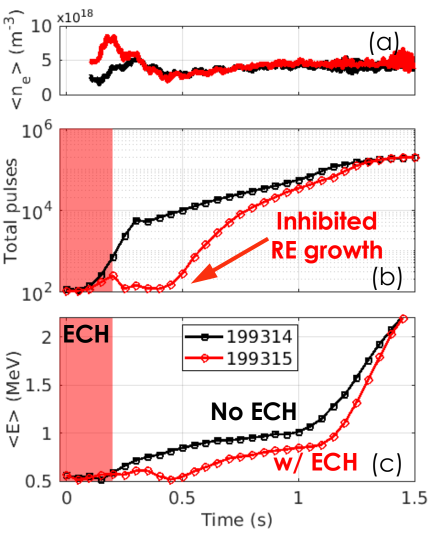

***Figure 3**: Time evolution of (a) line-averaged electron density, $\langle n_e \rangle$, HXR (b) quantity and (c) mean energy in two discharges with (red) and without ECH (integration time 50 ms). In discharge 199315, 2 MW of ECH is applied in the shaded region, from -0.03 to 0.2 s.*

Over the entire parameter space explored here, including an 80-fold variation in pre-fill pressure at plasma initiation, REs with energy on the order of 0.5 MeV are detected immediately after the burn-through phase. For a series of discharges with pre-fill pressure from 0.0022 to 0.18 mTorr, Fig. 2 shows the time history of HXR quantity and mean energy, which are directly related to RE quantity and mean energy. The HXR mean energy is calculated over the measurable spectrum at each time point. The presence of REs shortly after plasma initiation is indicated by the nonzero HXR quantity early in time in Fig. 2(a). Furthermore, Fig. 2 shows that both RE quantity and average energy are lower in the discharge with higher pre-fill pressure. The variation in RE dynamics suggests that RE characteristics depend nonlinearly on pre-fill pressure and the resultant n_e during start-up.

One potential method of mitigating start-up REs without disrupting plasma initiation is the application of ECH prior to and during the I_p ramp, which suppresses the generation and energy growth of REs. Fig. 3 shows the time evolution of HXR quantity and mean energy for a pair of discharges with and without ECH. In the case with ECH, 2 MW is injected from −0.03 to 0.2 s. During ECH, $\langle n_e \rangle$, Fig. 3(a), is almost doubled, resulting in a lower E/E_c, the ratio of applied electric field to critical electric field for runaway generation, so primary generation is reduced. Interestingly, the RE quantity and average energy with and without ECH eventually grow to similar levels during the I_p flattop despite both discharges having nearly identical $\langle n_e \rangle$, T_e and V_{loop} after 0.5 s. This implies that mitigation is required for a longer time during start-up.

This experimental study significantly advances our understanding of RE dynamics during tokamak start-up. The continuous growth to very large RE energies during non-disruptive plasma operation highlights the importance of minimizing RE seed generation during start-up and avoiding RE damage to ITER. The suppression of both RE quantity and energy during and after ECH injection establishes ECH as a potential method of start-up RE mitigation. These findings have implications for future studies on start-up RE dynamics and have already motivated a new modeling and validation effort for the development of safe start-up scenarios for ITER.

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