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Measurement of Runaway Electron Beam Composition and Estimate of Resulting Collisional Decay of Runaway Electron Currents in DIII-D

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High current (0.1–0.5 MA) runaway electron (RE) beams are created in DIII-D [1] by rapidly shutting down discharges with small (D = 2.7 mm) argon pellet injection [2]. The RE beam's position is feedback controlled to hold them centered in the vacuum vessel [3]. The ion composition of the background plasma co-existing with the RE beams is estimated to be dominantly D^+ plus approximately 10%-20% Ar^+ and <1% C^+. The co-existing neutral content of the beam is thought to be smaller than the ion content. From the beam composition, it is possible to estimate the effect of collisional drag on the runaway electron beam. The runaway electron current is observed to decay faster than expected from collisions; this excess decay, about 10/s, may be due to losses of runaway electrons to the wall, although this has not been confirmed experimentally yet.

Figure 1 shows time traces of plasma parameters from two different discharges: in one shot (red curve) an accelerating toroidal electric field is applied, while in the other (black curve) a decelerating electric field is applied. Both discharges are shut down at time t = 2000 ms by argon pellet injection, causing a rapid drop in core temperature T_e, Fig. 1(a). RE-wall strikes are seen by flashes in hard x-rays (HXRs), Fig. 1(c) [4]. Electron density n_e is

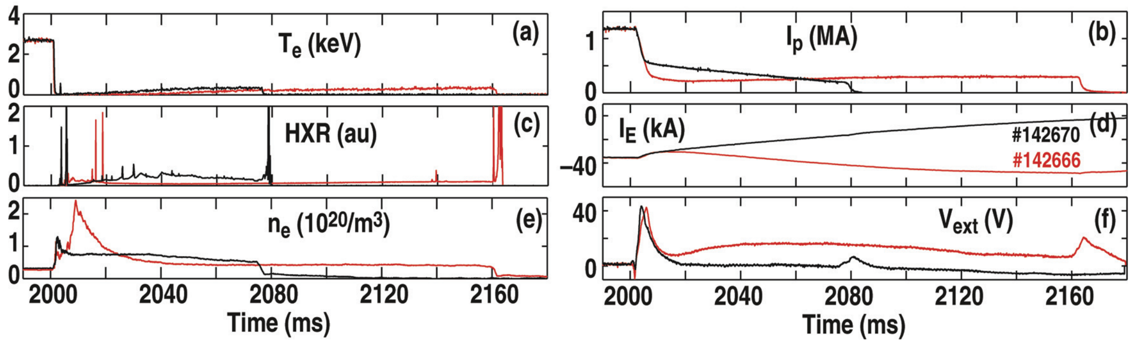

Fig. 1. Time traces from two discharges with different externally applied toroidal electric field direction during the RE plateau showing (a) electron temperature T_e, (b) plasma current I_p, (c) hard x-ray signals, (d) ohmic coil current I_E, (e) electron density n_e, and (f) toroidal loop voltage measured outside the vacuum vessel V_{ext}.

shown in trace (e) and plasma current I_p in trace (b). Times t > 2010 ms mark the "RE plateau" where the current is dominantly carried by the RE beam (not ohmic current which has <5 ms decay time). Figure 1(d) shows the ohmic coil current I_E, showing opposite toroidal field ramp directions, and Fig. 1(f) shows the external toroidal loop voltage V_{ext} measured outside the vacuum vessel.

From avalanche theory [5], the growth/decay rate of RE current in the plateau phase is expected to be given by $\nu_R \approx (dI_p/dt)/I_p \approx (\bar{\nu}_{sur} - \bar{\nu}_D)/(1 + \alpha_R)$, where $(\bar{\nu}_{sur} \approx eV_{ext}/(2\pi R m_e c\,\bar{p})$, $\alpha_R \approx I_p \ell_i/(\bar{p} I_A)$, $\bar{p} = [3(Z+5)/\pi]^{1/2} \ln\Lambda(Z)$, $I_A = 17$ kA, $\bar{\nu}_D = eE_{crit}/(m_e c\,\bar{p})$, and $E_{crit} = e^3 n_{e,tot} \ln\Lambda(Z)/(4\pi\varepsilon_0^2 m_e c^2)$. The effective total electron density $n_{e,tot} \approx n_e + 0.5 n_{bound}$ includes both free and bound electrons. Comparing the measured RE current growth rates of Fig. 1(b) to theory thus requires the RE beam self-inductance ℓ_i and the total plasma electron density $n_{e,tot}$. Determining ℓ_i is challenging, since we do not have a direct measurement of the current profile in the RE beam. In the pre-disruption plasma, $\ell_i \approx 1$; however, the current channel is then thought to expand, to $\ell_i < 1$ during the CQ and then re-compress to $\ell_i \geq 1$ during the RE plateau. EFIT gives a large range of values $\ell_i \approx 1-3$ during the RE plateau, so we simply use $\ell_i \approx 2 \pm 1$.

Calculating total plasma electron density $n_{e,tot}$ requires knowledge of the RE beam atomic composition. Plasma visible spectra indicate that the ions in the RE plateau are dominantly singly-ionized. This can be seen in Fig. 2, showing (a) ArII and CIII emission for spectra integrating over the TQ; (b) disappearance of CIII and strengthening of ArII during the RE plateau; and (c) relatively weak Dα but strong CII during the RE plateau. Fitting to the line shapes like Fig. 2(c) gives $T_i \approx 1.6$ eV for the C^+ ions.

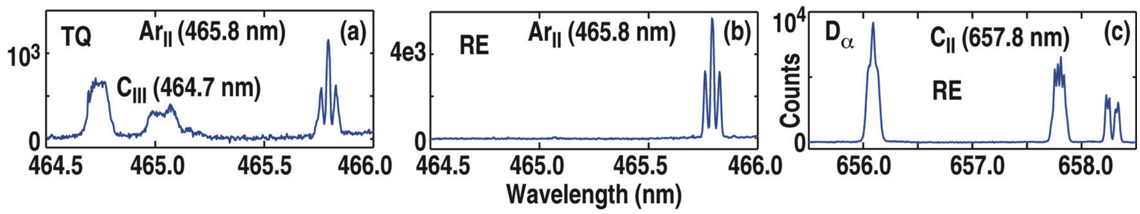

Fig. 2. Central chord visible spectra of (a) ArII and CIII in the TQ, (b) ArII in the RE plateau, and (c) D_α and CII in the RE plateau.

The line-averaged C^+ fraction in the RE beam can be estimated to be of order 0.01 or less from the CII (657.8 nm) line brightness. The thermal electron density $n_e \approx 5\text{–}15\times10^{19}$ m^{-3} in the RE beam is known from interferometry. The RE electron density $n_R \approx 4\text{–}18\times10^{15}$ m^{-3} can be estimated from the RE current and the RE beam radius a: $n_R ec \approx I_R/\pi a^2$, where a is taken as the radius of the last closed flux surface estimated from magnetic signals as shown in Fig. 3(b) for example. The thermal electron temperature in the RE plateau is expected to be well-equilibrated with the ion temperature, $T_e \approx T_i \approx 1.6$ eV. The RE temperature is assumed to be half-Maxwellian (from avalanche theory) with $T_R \approx 20$ MeV (or $\bar{p} \approx 40$) estimated from synchrotron emission brightness. We estimate that the CII (657.8 nm) line brightness is dominantly (roughly $5\times$ larger) due to thermal electron impact, rather than RE impact. A similar spectroscopic estimate can also be made for the line-averaged Ar^+ fraction using the measured ArII (465.8 nm) line brightness, giving Ar^+ fractions of order $n_{Ar^+}/n_e \approx 0.2$. We estimate that the ArII (465.8 nm) line brightness is mostly (roughly $2\times$ larger) due to thermal electron impact, rather than from RE impact. An independent estimate of the RE beam argon ion content can be made from the neutral pressure measurement, together with the known volume of the injected Ar pellet, giving argon fractions of order 0.3, i.e. around 50% higher than the spectroscopic estimate [6].

The assumption that neutral argon is excluded from the RE beam is based on measured spatial profiles of D_α emission, which show hollowing, as seen in Fig. 3(c). In contrast, ion line emission (from ArII), Fig. 3(d), can be seen to be strongly centrally peaked. Based on the D_α hollowing and on the significantly shorter ionization mean free path expected for Ar compared with D (because of the higher Ar mass and slower velocity), we expect neutral Ar to be mostly excluded from the center of the RE beam.

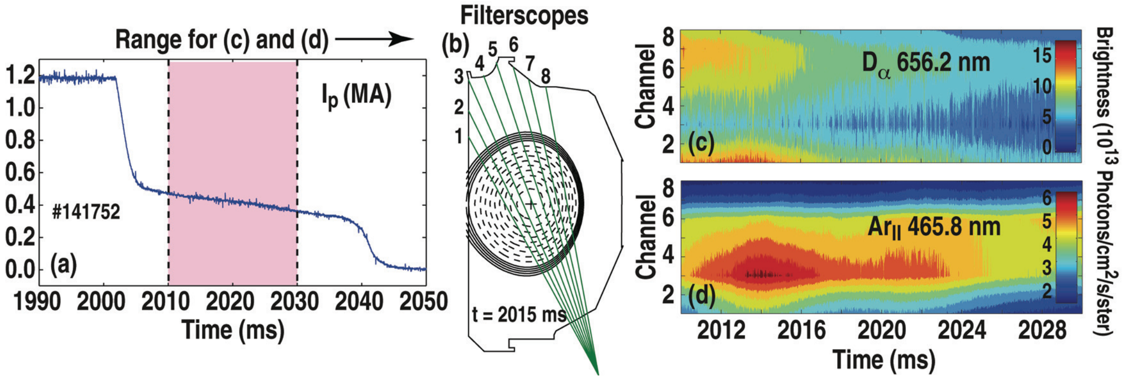

Fig. 3. Spatial profile of visible emission from RE beam showing (a) plasma current, (b) location of view chords, (c) spatial profile of Da emission vs time, and (d) spatial profile of Arii emission vs time.

In Fig. 4 we plot measured (squares) and predicted (circles) RE current growth rate ν_R as a function of surface field minus critical field, $E_{sur} - E_{crit}$. Each circle/square pair corresponds to the middle of the RE plateau in a single discharge. To calculate E_{crit}, we ignore carbon (it being much lower Z and lower density than argon) and take the average of the spectroscopic and pressure methods to calculate the Ar^+ fraction. The horizontal error bars on the squares in Fig. 4 reflect the range in E_{crit} obtained from the two different methods. These error bars are typically small even though the relative error in E_{crit} is quite large since typically $|E_{crit}| < |E_{sur}|$, i.e. $E_{crit} \approx$ 0.1–0.3 V/m and $E_{sur} \approx$ -0.2 to +1.5 V/m. The vertical error bars on the model curve come from the uncertainty in plasma self inductance, $\ell_i \approx 2 \pm 1$. It can be seen that there is a significant offset between the measured and predicted current growth rate, of order 10/s. At present it is thought that this is due to radial transport of REs to the wall. The offset could also be largely removed by assuming that the background plasma ions consist completely of argon ions, or that there is a large (comparable to the ion density) argon neutral density coexisting with the RE beam. Neither of these scenarios seems likely though, based on the analysis presented here. Another

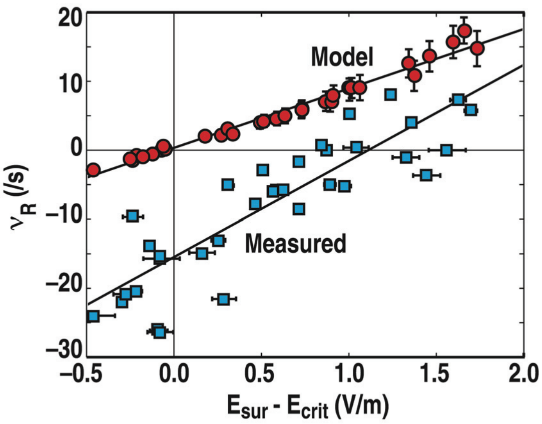

Fig. 4. Measured (squares) and predicted (circles) runaway electron growth rate ν_R as a function of the surface field minus critical field, $E_{sur} - E_{crit}$. Straight lines are linear fits to data.

possibility is RE current profile shrinking at a rate of order $(d\ell_i/dt)/\ell_i \approx 10$/s; this cannot be ruled out at present due to the large uncertainty in the RE current profile. Synchrotron and visible imaging do suggest some evolution of the plasma profile with time; however, we cannot at present separate radial variation in RE beam energy and density (current) – this will be an area of future work.

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