Characterization of runaway impact on instrumented sacrificial limiters on DIII-D **EX-S**

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Understanding post-disruption runaway electron (RE) impact on first wall materials is critical for ITER and FPP, as it is needed for prediction of the effectiveness of disruption mitigation systems, determining safe performance limits, and for regulator evaluations of machine safety [1]. Quantifying RE-wall damage is extremely challenging, however, and previous work has dominantly relied on post-mortem inspection of RE wall damage [2]. Instrumented sacrificial graphite dome limiters inserted into the lower divertor region of the DIII-D tokamak and struck with high current (600 kA) post-disruption runaway electron (RE) beams have allowed quantification of the RE-wall impact process at an unprecedented level.

REs impacting the limiter during the final loss instability are found to be dominantly forward-moving, with backward-moving (trapped or counter-passing) REs being low (less that of order 10% relative population), as shown in Fig. 1(c). This is consistent with the impact geometry, where forward-going REs will tend to hit the limiter, while backward-going REs will tend to hit the edge of the divertor shelf. Mean RE kinetic energies appear to be relatively moderate, of order $K \sim 2$ - 4 MeV, and pitch angles of order $\theta \sim 0.4$. Compared with pre-disruption RE estimated $K \sim 4$ MeV, and $\theta \sim 0.2$, this suggests a possible slight decrease in K and slight increase in θ during the final loss process, consistent with KORC orbit tracking simulations [3].

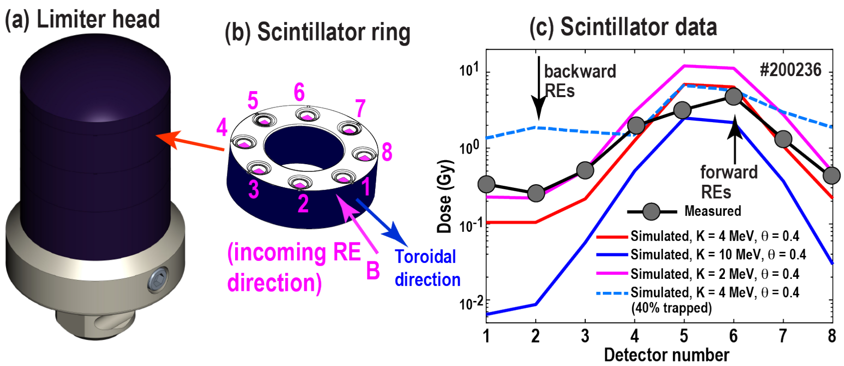

Fig. 1. (a) Sacrificial limiter head, (b) scintillator ring inserted into limiter head, and (c) matching of scintillator doses with different models, showing that forward-moving REs with moderate (~ 2 - 4 MeV) kinetic energy are needed to match the data.

Penetration depth of REs into the limiter is found to be of order 1 - 2 mm, as expected for energies $K \sim 2$ - 4 MeV, Fig. 2. The penetration depth is found to be strongly asymmetric about the incoming magnetic field direction. This asymmetry can only be explained by including the poloidally localized field perturbation caused by the RE current filament entering the limiter head. This data demonstrates that large local RE beam-wall strikes can create a local perturbation to B which can affect the local RE impact characteristics.

Shot-shot variation in RE energy deposited into the limiter is quite large (10×), ranging from 1 - 10 kJ, but is small compared with the initial RE beam kinetic energy ~ 50 kJ. This indicates that the toroidal phase of the final loss instability is not locked to one phase by the limiter but is highly variable shot-shot, consistent with magnetics measurements.

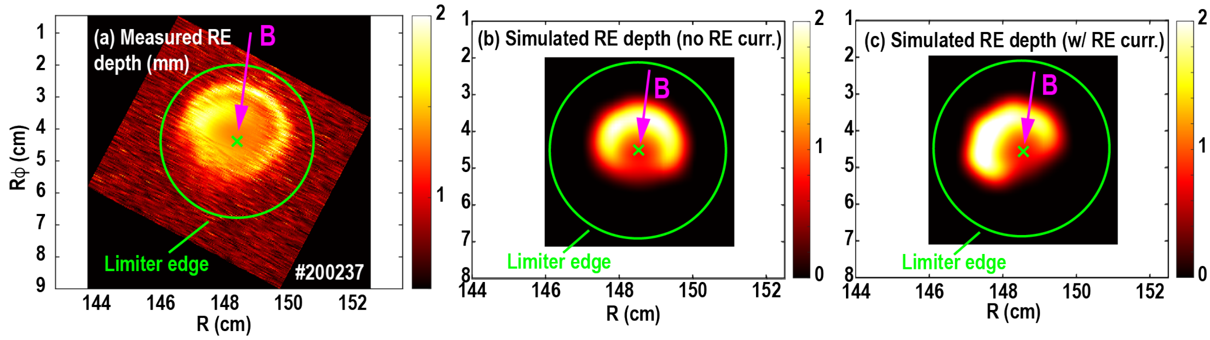

Fig. 2. (a) Measured RE impact depth (from IR time decay), (b) simulated RE impact depth neglecting RE current into limiter, (c) simulated RE impact depth including perturbation to local B field from RE current entering limiter head, showing created left-right asymmetry about B.

Current measurement into limiter head shows a narrow (100 μs) pulse of negative current when REs strike the limiter, followed by slower (200 μs) spike of positive current. The positive current pulse is observed even in lower energy impacts where limiter temperatures stay low < 500 C, indicating that the positive current pulse corresponds to ions, not thermionic electron emission. The data therefore demonstrates that the final loss of REs to the wall is followed by a pulse of cold thermal ions to preserve ambipolarity.

At higher RE heat fluences ~1000 $\mathrm{J/cm^2}$, limiter surface destruction and dust release is observed, Fig. 3. The surface temperature in these regions is found to be high, of order 3000 C, consistent with rapid volumetric material failure and gas release due to sublimation. The resulting damage depth is of order 1 mm, consistent with expected energy deposition depths. These detailed RE-wall damage measurements are enabling refinement of modeling of RE-wall impact and resulting first wall damage [4].

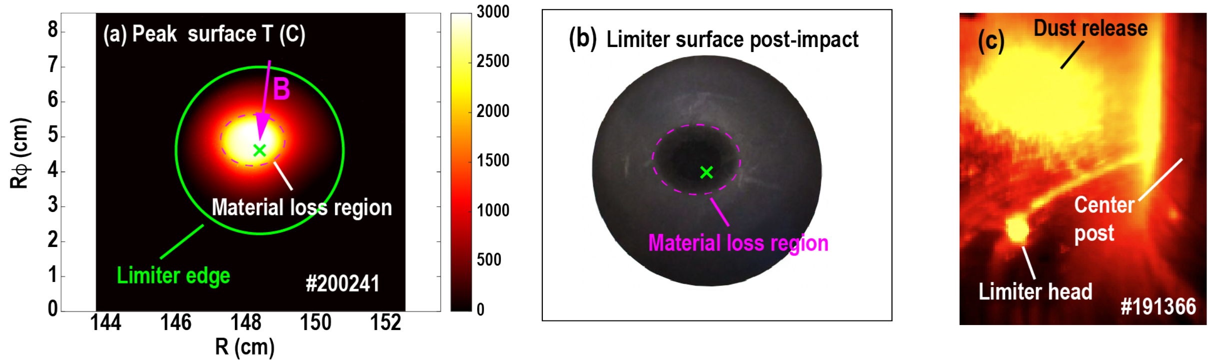

Fig. 3. (a) Surface temperature for high 10 kJ RE energy impact, (b) photo of material loss region, and (c) image of dust cloud release from limiter head.

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