doi:10.1017/S143192762200856X
Microsc. Microanal. 28 (Suppl 1), 2022
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# How Low Can You Go: Pushing the Limits of Dose and Frame-time in the STEM

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Modern innovations in the scanning transmission electron microscope (STEM) such as cold field-emission guns and aberration correctors have resulted in getting ever greater beam-currents into finer and finer probes. While this has led to many developments in the field of materials science and is of great use for quantitative studies [1], it is perhaps less appealing to those who image beam-sensitive materials such as biological specimens [2].

High-intensity probes can readily damage, if not destroy, beam-sensitive materials at doses many order of magnitude less than those typically used for high-dose imaging conditions [3]. What is needed then are techniques aimed at reducing both the electron dose, and the dose-rate, to extend the benefits of these technological improvements to a wider audience. Here we present our approaches to tackling these problems by:

- Minimising the line-flyback time to reduce unnecessary beam exposure while correcting for any artefacts introduced.
- Implementing frame-interlacing in the STEM to reduce both frame-time and electron dose, and comparing deinterlacing methods for retrieving the missing information.
- Establishing the temporal transfer function (TTF) to quantify the effect that detector decay time has on low-dose images captured with short frame-times.

Flyback time is the additional waiting time added to compensate for the hysteresis of the scan coils that can cause an appreciable lag between the intended and actual position of the beam. This manifests as a compression artefact at the start of each line which is detrimental to the accuracy of techniques such as strain measurement (**Figure 1**). Fortunately, this artefact is reproduceable for given imaging settings and so can be diagnosed and corrected for on both newly captured and previously captured data. We diagnose this compression through comparison with an undistorted reference image and can correct both single-rotation image series and rotating-scan image series. This open-source technique sees a dramatic increase in dose-efficiency (**Figure 2**) and decrease in frame-time while maintaining spatial fidelity when compared to longer flyback time, less dose-efficient images.

Video-interlacing is a method which saw wide adoption on televisions for its ability to halve the bandwidth and data rate for what was often an imperceivable loss in image quality. By implementing the same in the STEM, a corresponding reduction in dose-rate and frame-time can be achieved while minimising any loss in information as most imaging is already done well above Nyquist. Through a simulation-based study we also investigate the performance of various deinterlacing techniques for

https://doi.org/10.1017/S143192762200856X Published online by Cambridge University Press

recovering the missing scan-lines. Although overhead time introduced by some scan generators may prevent interlacing from halving the frame-time, our approach still sees an improvement of at least 30% for little loss in information, and with 90° scan-rotation advancement between successive this loss of information is even smaller.

When pushing the limits of frame-time with very short pixel-dwell times, the decay time of the detector becomes a large factor in the final image quality. This is due to the decay of the signal from each electron impact being longer than the pixel-dwell time leading to streaking in the final image [4]. Although we have developed methods to eliminate this [5], we have now also established a quantitative measure of high-speed detector performance to evaluate the effect this artefact has on image quality. This measure, which we call the temporal transfer function, is analogous to the modulation transfer function (MTF) used to describe TEM cameras. We have established this behaviour via simulations for a range of detector decay times and discuss its effect on STEM images. Furthermore, to highlight suitable detectors for high-speed imaging we have measured this TTF for a range of real detectors. As scan speeds increase so too will the significance of high-speed detector performance, and we hope the TTF will highlight areas of improvement to increase this metric on current and future detectors.

The combination of minimising flyback time and frame-interlacing requires no additional hardware while still producing images suitable for onwards processing, such as frame averaging, and is a powerful tool for low-dose microscopists. Combined with the knowledge gained from the TTF we hope not only to extend the performance and lifetime of existing equipment in a sustainable way, but also inform future purchasing decisions on the ideal detector for one's imaging needs [6].

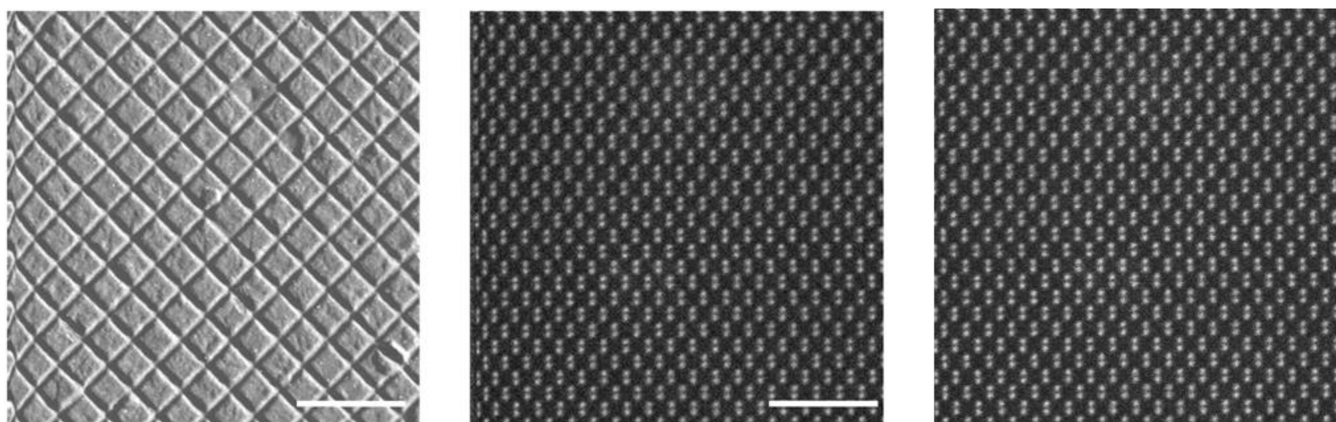

**Figure 1.** Image of a cross grating test specimen captured (left) and a single silicon crystal (middle) captured with low flyback times. Despite being captured at different magnifications (scale bars of 1 µm and 2 nm respectively) and on different instruments, a similar compression behaviour is seen on the left-hand side of the images. The rightmost image is the middle image after flyback hysteresis correction, note the regular atomic spacing across the entire image.

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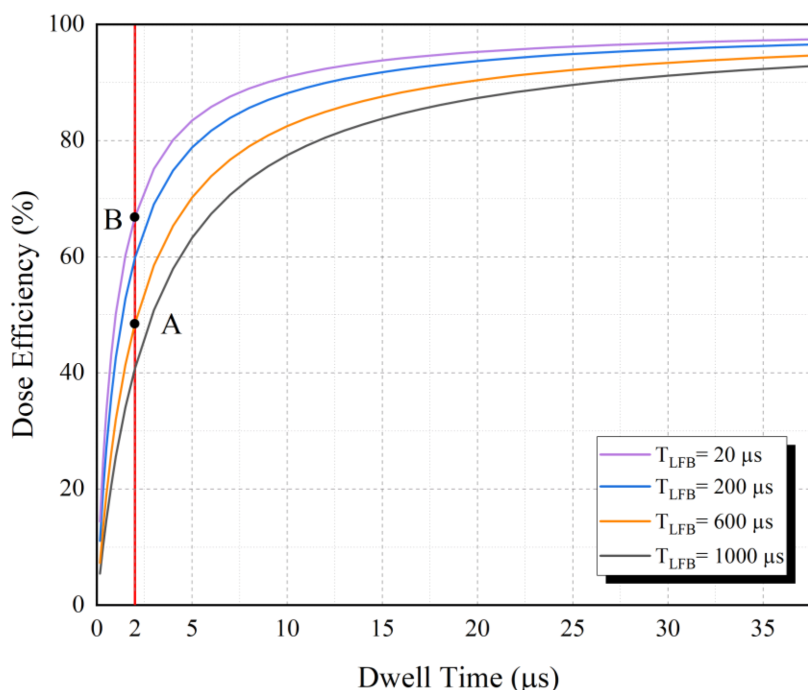


**Figure 2.** A graph of dose-efficiency vs dwell time for a range of flyback times ($T_{LFB}$) for a 512 × 512-pixel image. At a dwell-time of 2 μs (red vertical line), the dose-efficiency increases by nearly 20% (from point A to point B) when decreasing the $T_{LFB}$ from a standard 600 μs, to 20 μs, which is fully compatible with our method.

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6. The authors would like to acknowledge the Centre for Research on Adaptive Nanostructures and Nanodevices (CRANN) and the Advanced Materials and BioEngineering Research (AMBER) Network for financial and infrastructural support for this work. L.J. is supported by SFI award URF/RI/191637. J.J.P.P. and L.J. acknowledge SFI grant 19/FFP/6813, T.M. acknowledges the SFI & EPSRC Centre for Doctoral Training in the Advanced Characterisation of Materials (award references 18/EPSRC-CDT-3581 and EP/S023259/1) This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 823717 – ESTEEM3.

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