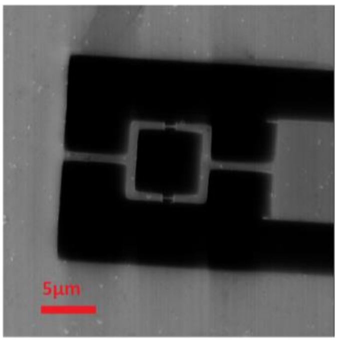

Fig. 3. Helium FIB image of a NbN phase-slip nanowire device. NbN is bright and the exposed sapphire substrate is dark.

density, $B_{local} = FB_{applied}$. At local fields higher than 30 mT the device not only retains its flux-tuneability but also the Q is flux-independent (within the noise level) and exceeds 10,000.

VI. Niobium Nitride Phase-Slip Nanowires

Fig. 3 shows a typical fabricated device structure for investigation of phase-slip physics in NbN nanowires. In what follows we report measurements of such a device containing nanowires of length 200 nm and width 35 nm at T = 300 mK. The transition temperature of the NbN was measured to be 8.5 K. Our measurements therefore are made at temperatures far below the predicted value of the crossover temperature below which the rate of quantum activation of phase slips exceeds the thermal rate [6]. The intrinsic Q for this device is 2,000 whereas, prior to the neon FIB milling stage, it was 13,000. The higher loss in the NbN devices by comparison with the Nb devices discussed above may be associated with the high level of structural disorder and low film thickness, both of which are necessary to maximise the CQPS rate. Nevertheless the Q of the neon-milled devices is two orders of magnitude larger than previously reported CPQS devices based on indium oxide films [7] and somewhat larger than other NbN CQPS devices [8].

The magnetic-field dependence of the spectral response of this device is shown in Fig. 4. We observe two effects: (i) a parabolic decrease of the resonant frequency as the field increases. This results from the field-dependence of the kinetic inductance of the "bulk" NbN film, which (unlike for the Nb devices reported above) is larger than the geometric inductance; (ii) a periodic modulation of the resonant frequency with period 4.15 mT. This arises from incoherent quantum phase-slip events occurring in the NbN nanowires, allowing a single flux quantum to tunnel into the loop. The dashed line in Fig. 5 shows a fit to the data using (2) and (3), modified to include the parabolic field-dependence parametrised by a phenomenological field-scale B*. The fitting parameters are the flux focussing factor and B*. The goodness of this fit, coupled with the absence of any signature of an avoided level-crossing, confirms that incoherent quantum phase slips are occurring in the nanowires.

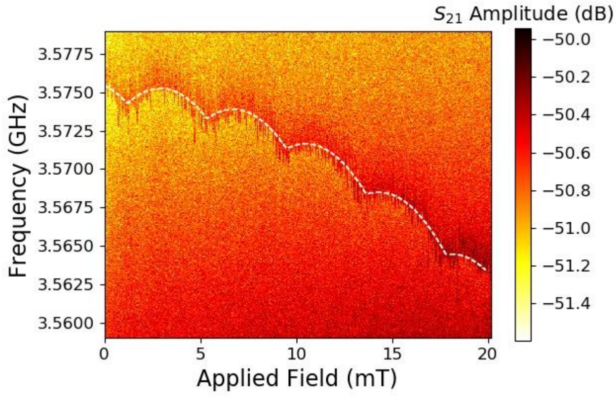

Fig. 4. Dependence of the transmission of the nanowire phase-slip device upon frequency and magnetic field applied perpendicular to the plane of the superconducting loop. The white dashed line shows the fit to the resonant frequency using (2) and (3).

VII. Conclusions

We used neon FIB to fabricate nanowires of width less than 50 nm which exhibit non-linear quantum effects whilst maintaining low loss. The field resilience of the Nb Dayem bridges (shown here up to a perpendicular local field of 60 mT) suggests that they may be useful for application as a readout technology for spin qubits [5]. Additionally measurements of incoherent flux tunnelling in NbN nanowires at 300 mK are a key milestone towards measuring coherent quantum phase slips. Future work will focus on minimising the losses at dilution-refrigerator temperatures where we expect CQPS phenomena to be observable.

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