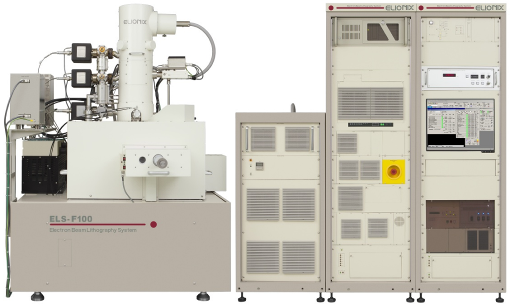
IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), September 2019.
Invited presentation 2-FA-I-8 given at ISEC, 28 July-1 August 2019, Riverside, USA.

Focussed Ion-Beams for Nanofabrication of Superconducting Devices:

Josephson Arrays, Nanowires and Flux-Tuneable r.f. Resonators

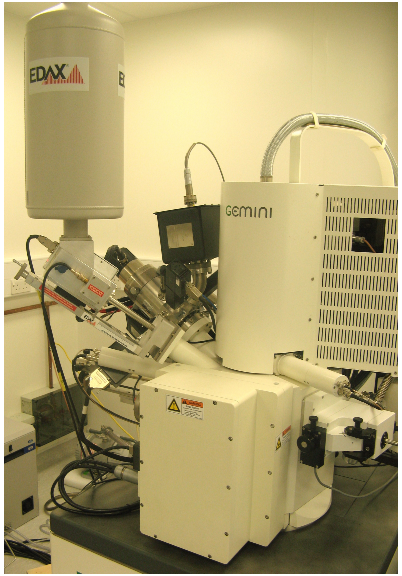
Paul Warburton
University College London

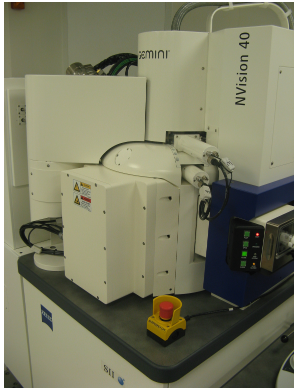
Nanofabrication at UCL



- Two Zeiss "cross-beam" Ga FIBs
- Zeiss Ne / He FIB

- Raith 150^{TWO} 30 kV EBL
- Elionix 100 kV EBL





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Which Beam to Use?

UCL

	Neon FIB	Gallium FIB	Helium FIB	E-Beam Lithography	EUV Optical Lithography
Cost (order of magnitude, £)	**10^6**	10^6	10^6	10^6	10^8
Minimum feature size (nm)	**6**	30	6	10	20
Sample poisoning	**Acceptable**	Bad	Acceptable	Excellent	Excellent
Fabrication throughput	**Good**	Very good	Poor	Very good	Excellent
Ease of 3-D fabrication	**Good**	Good	Good	Limited	Limited
Cost of process	**Minimal**	Minimal	Minimal	High	High
Compatability with silicon	**Yes**	Yes	No	Yes	Yes

Conventional mantra for Ga-FIB:
"Always use EBL *unless* there is a compelling reason not to!"

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e.g.: Three-Dimensional Nanofabrication

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Does the mantra change for Neon-FIB?

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Format of this Talk

- Three-dimensional nanofabrication with Ga-FIB

  process variability, sample damage…

- Neon-FIB

  (i) Tuneable niobium r.f. resonators for spin qubit readout

  (ii) NbN coherent quantum phase-slip nanowires

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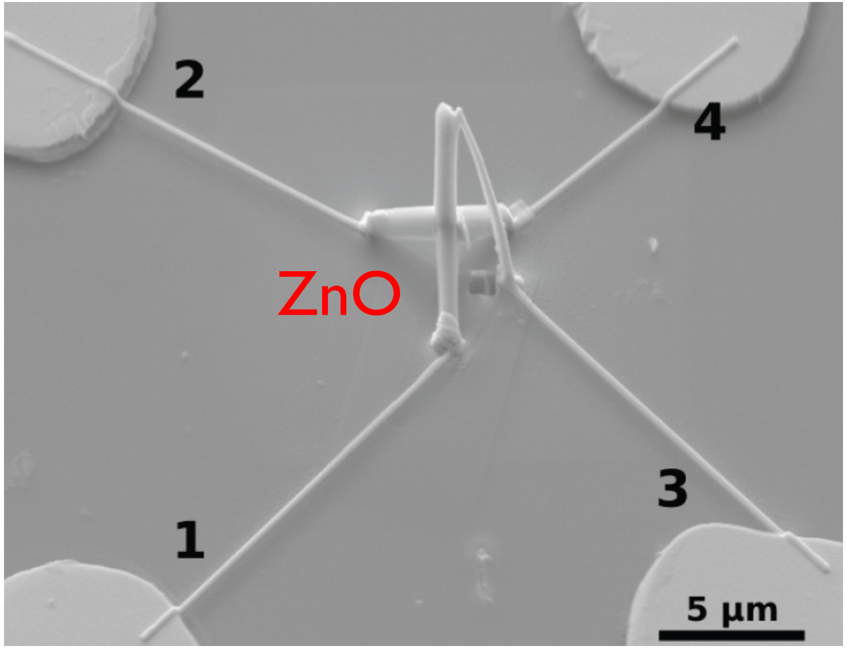
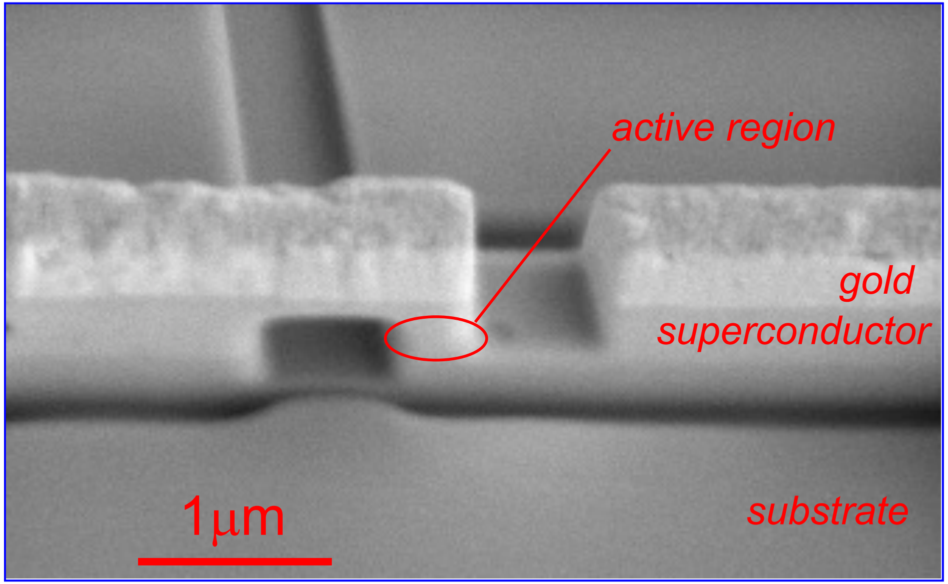
3-D Ga-FIB Nanofabrication



ZnO tetrapod: four-terminal superconducting contacts by Ga-FIB deposition



$Tl_2Ba_2CaCu_2O_8$ intrinsic junction stack by lateral Ga-FIB milling

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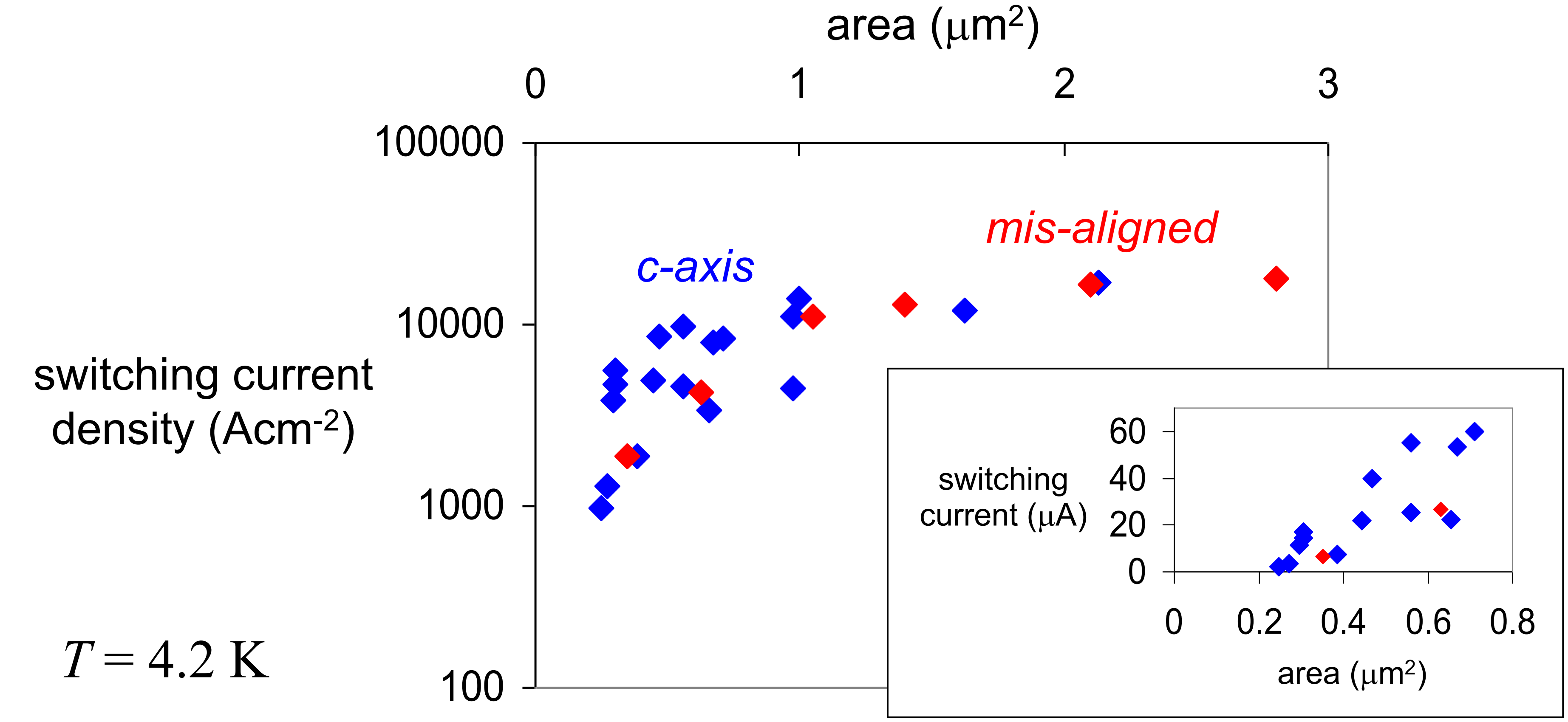
Ga Implantation in $Tl_2Ba_2CaCu_2O_8$



$T = 4.2$ K

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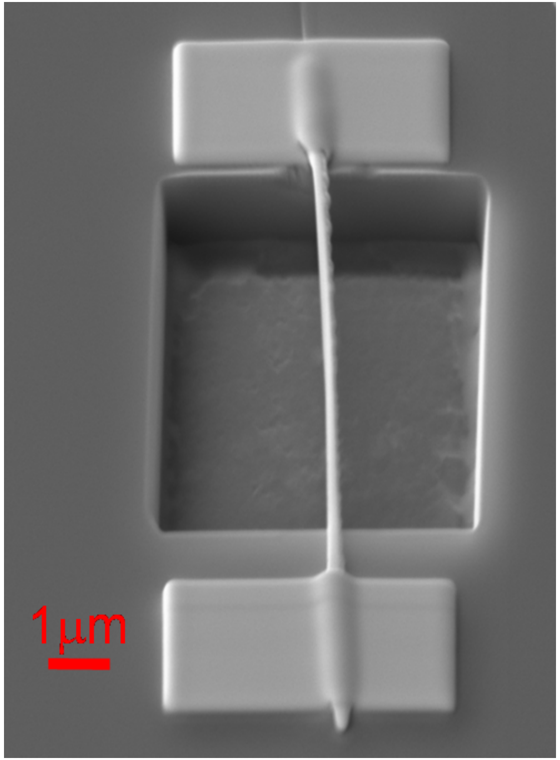
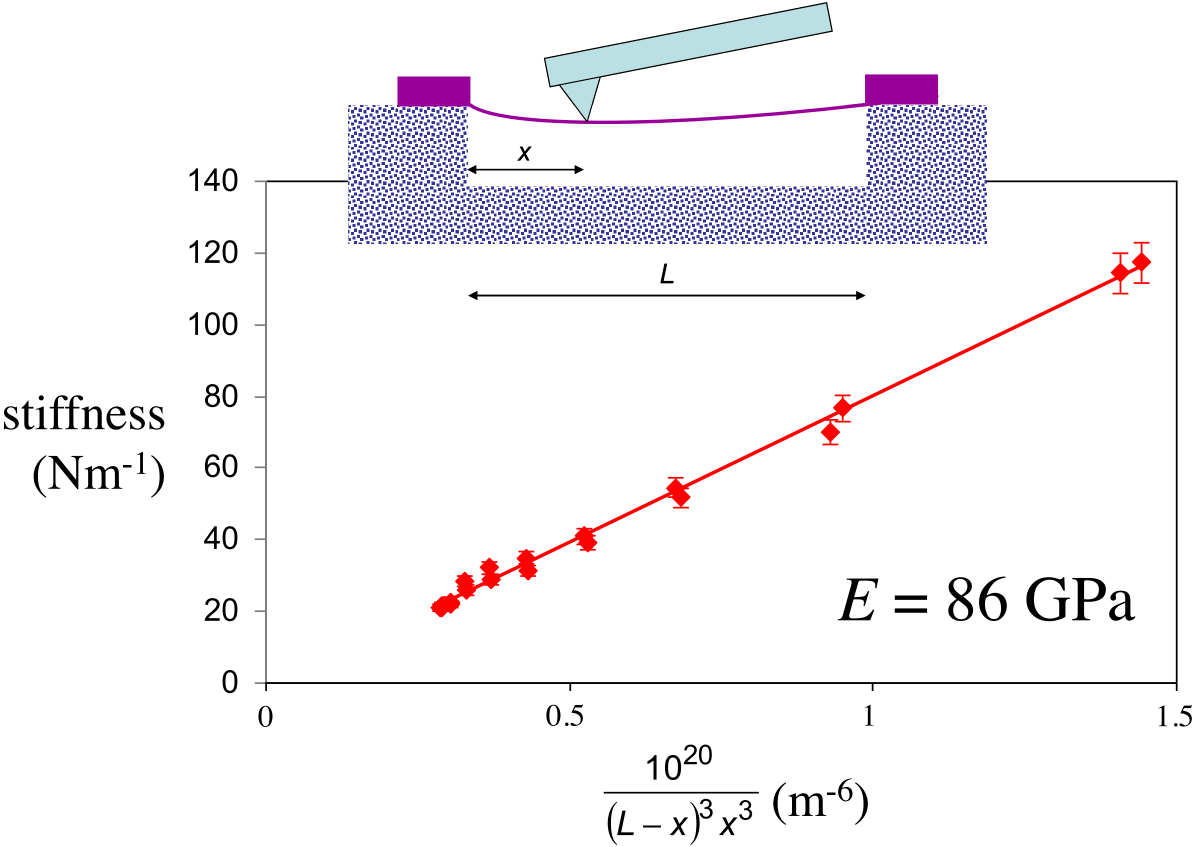
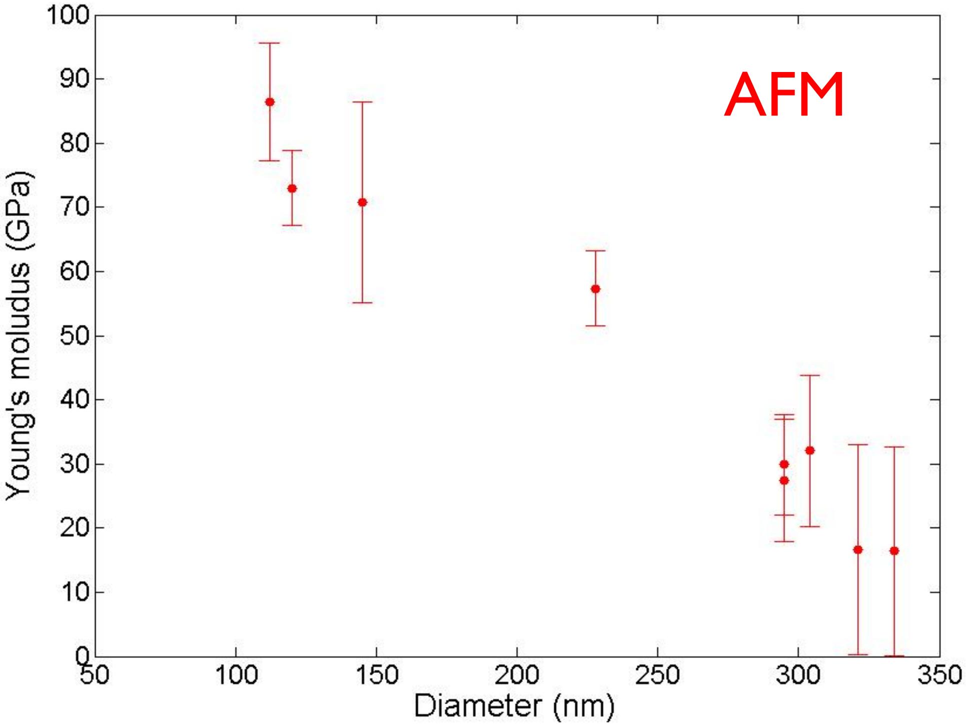
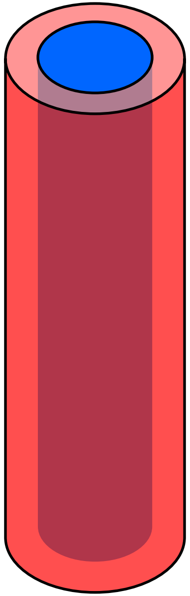
Ga-FIB-Deposited Nanomechanics





Radially-Varying Young's Modulus





Core:
large E/ρ

Outer layer:
small E/ρ

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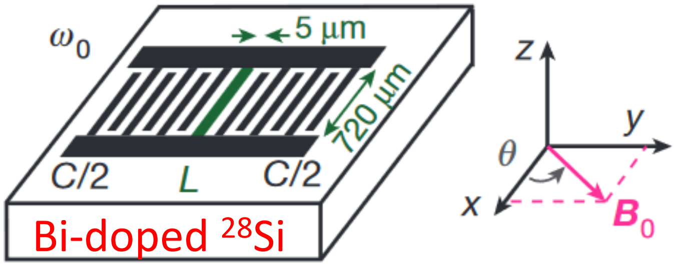
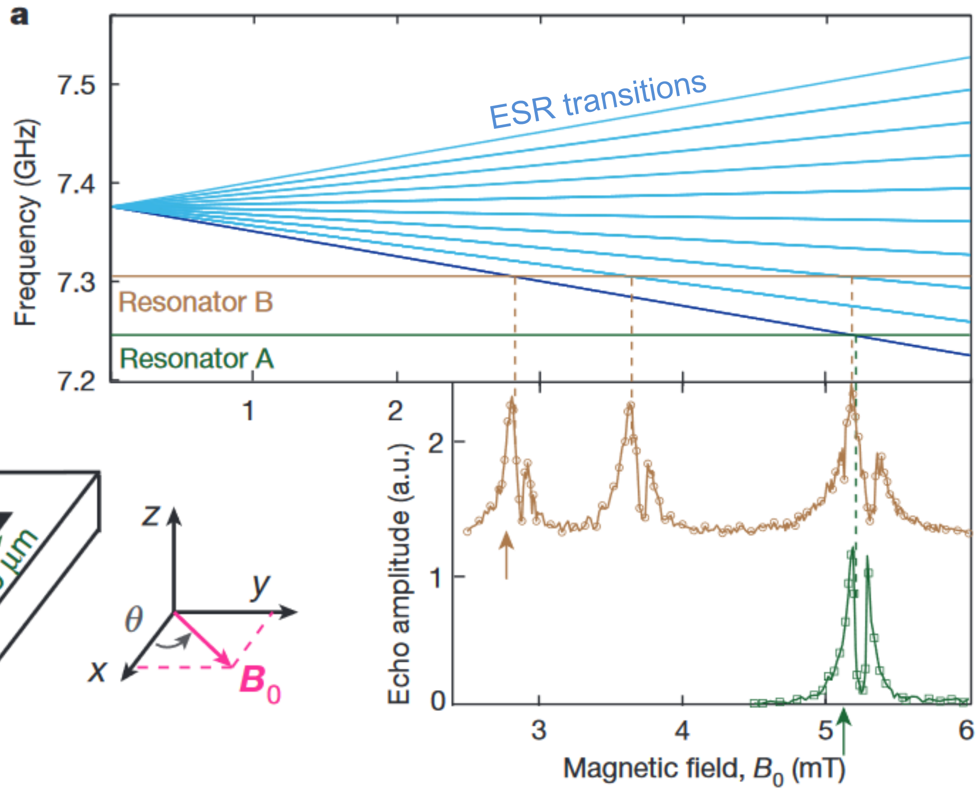
Readout of Spin Qubits

Bienfait *et al.*
Nature **531** 74
(2016)





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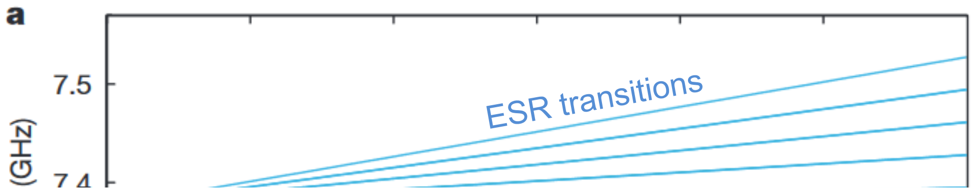
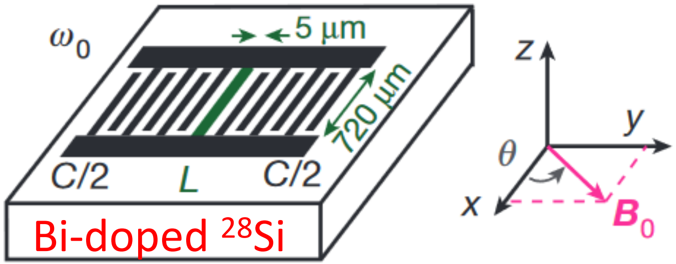
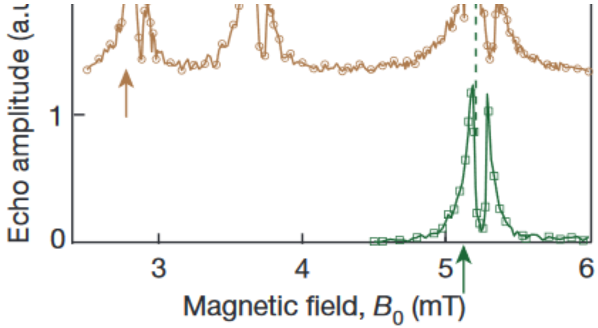


Can we make the superconducting resonator *tuneable*?





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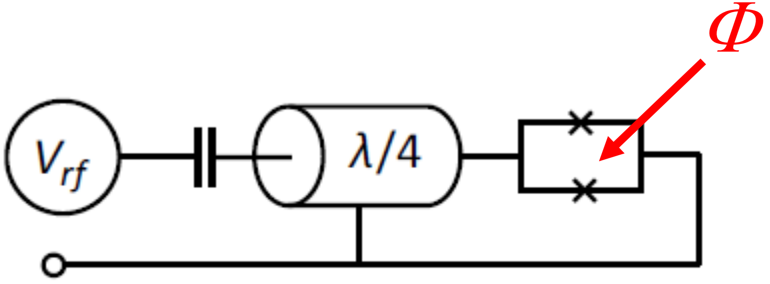
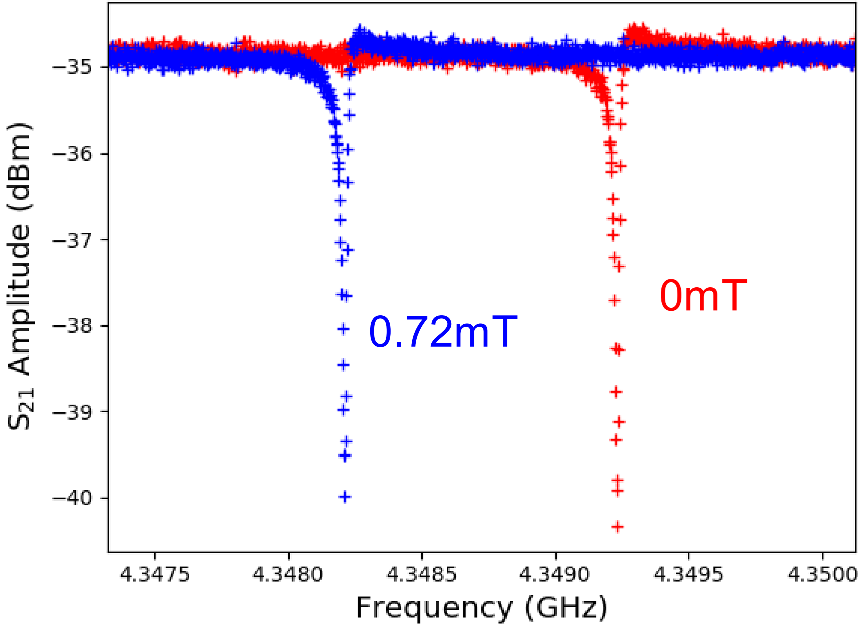
Tuneable Readout of Spin Qubits



$$L_k = \frac{\Phi_0}{4\pi I_c \left|\cos\left(\frac{\pi\Phi}{\Phi_0}\right)\right|}$$



Challenge: High *Q* in field up to ~ 100 mT

e.g. clock transitions in Bi-doped Si – Wolfowicz *et al. Nature Nanotech.* **8** 561 (2013)

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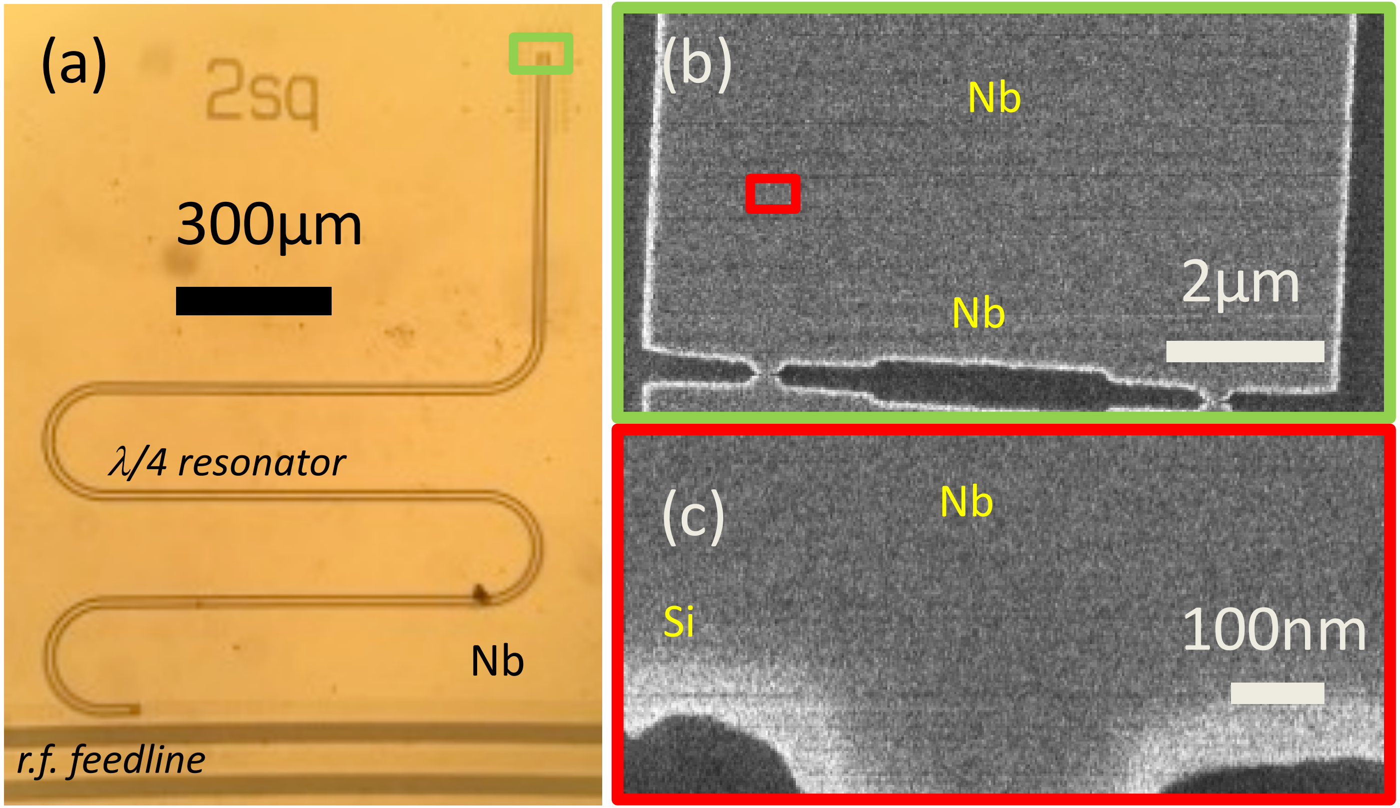
Milling with Neon

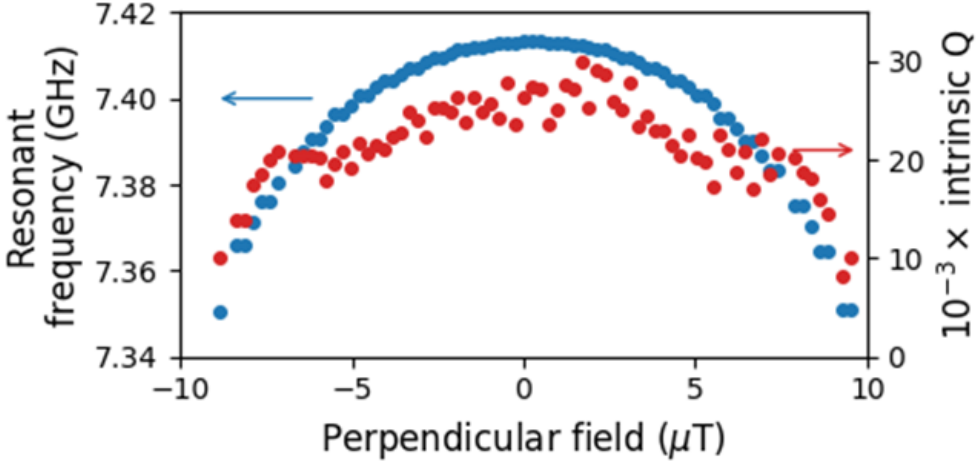
	helium	neon	gallium
Au Sputter yield (30 kV)	0.153	1.78	3.9
Al Sputter yield (30 kV)	0.06	4.39	17.4
Current	0.1 - 2 pA	0.2 - 5 pA	1 pA - 100 nA
Minimum beam diameter	0.5 nm	2 nm	5 nm
Sample damage	Amorphisation	Amorphisation	Amorphisation and **poisoning**
Min Feature size	<10nm?	<20nm	20-40nm

EBL / Neon-FIB Mix-and-Match



O.W. Kennedy, PAW *et al.* *Phys. Rev. App.* **11**, 014006 (2019)

Nb Tuneable Resonator



T = 300 mK
$\Delta f_0/f_0$ = 0.81% in 10 μT
Q = 25,000
Flux focussing factor: 124
β_L>3.4

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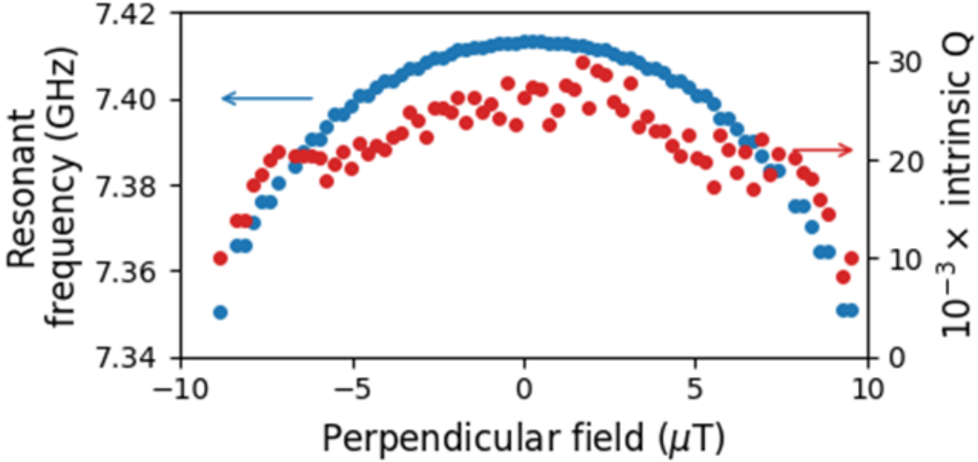

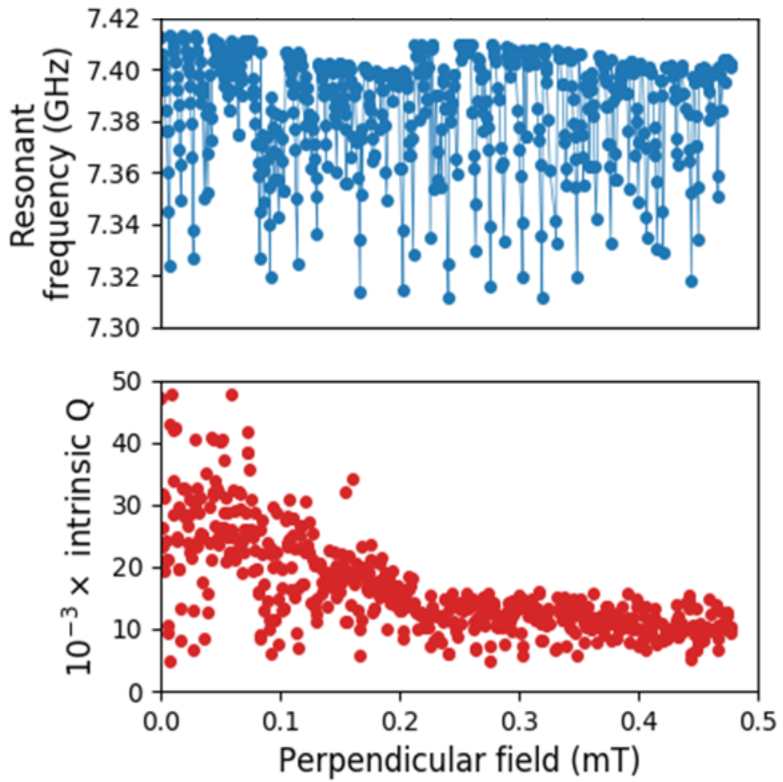

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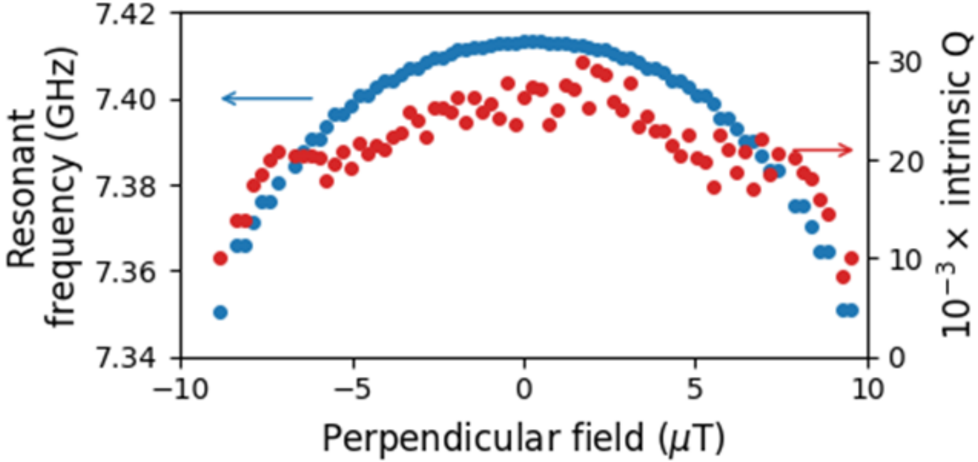

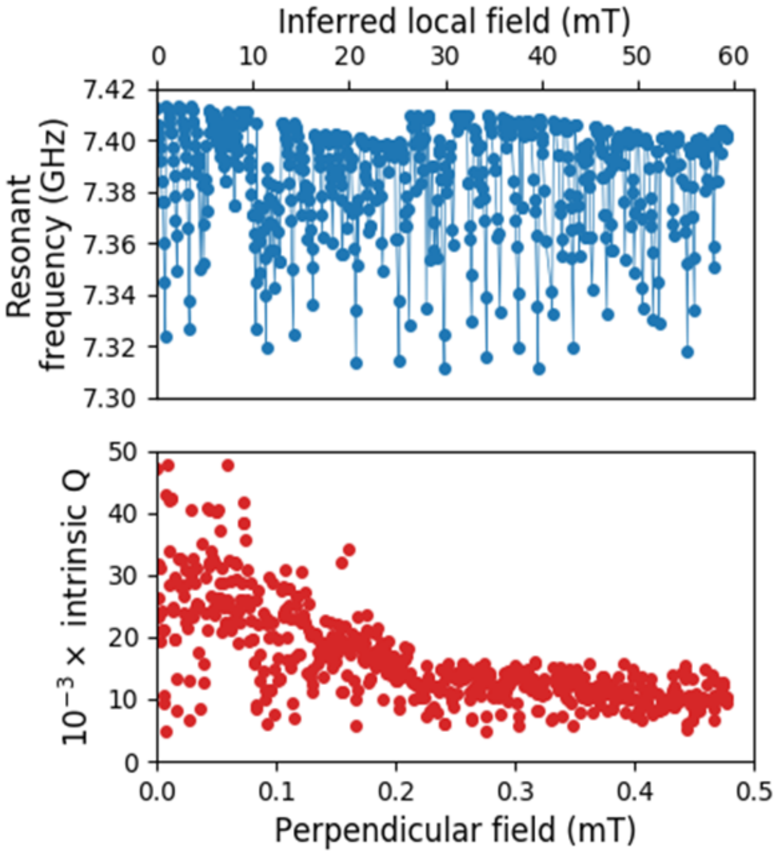

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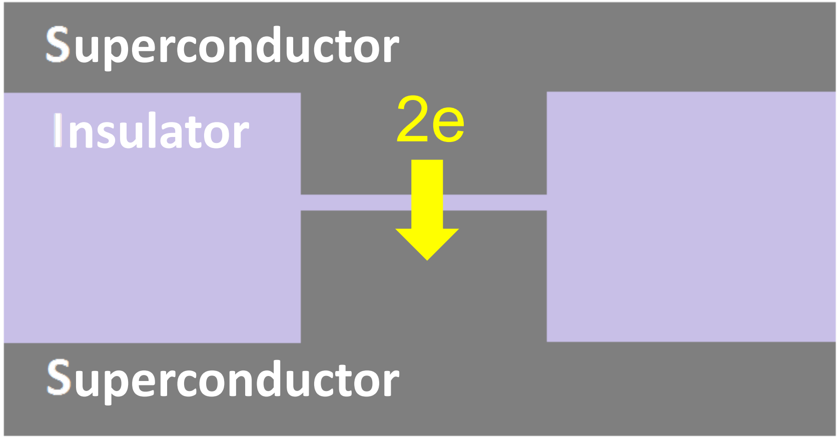
Coherent Quantum Phase-Slip

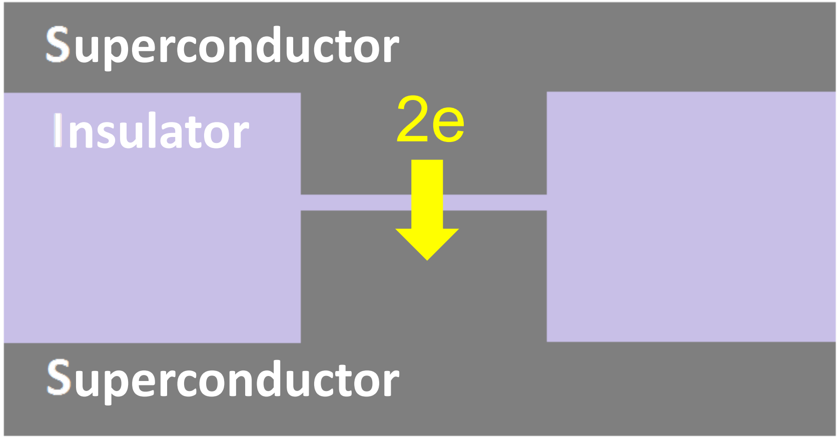
Josephson Junction



Coherent tunnelling of electric charge through the insulating barrier

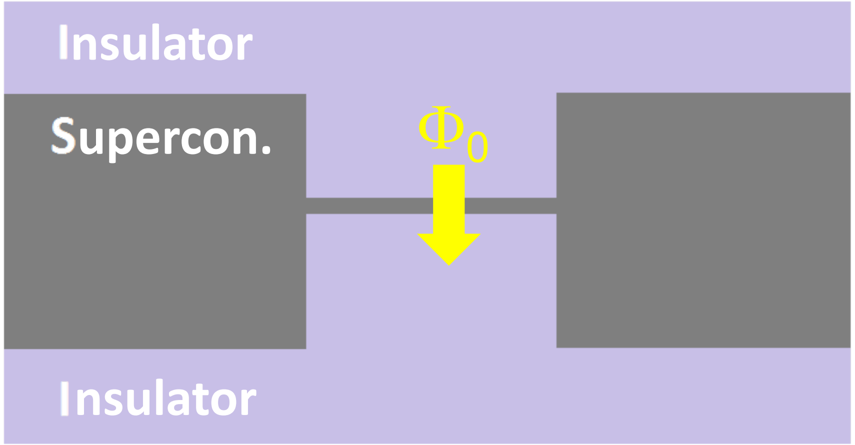
Coherent Quantum Phase-Slip

Josephson Junction



Coherent tunnelling of electric charge through the insulating barrier

Quantum Phase-Slip Nanowire



Coherent tunnelling of *magnetic flux* through the *superconducting* barrier

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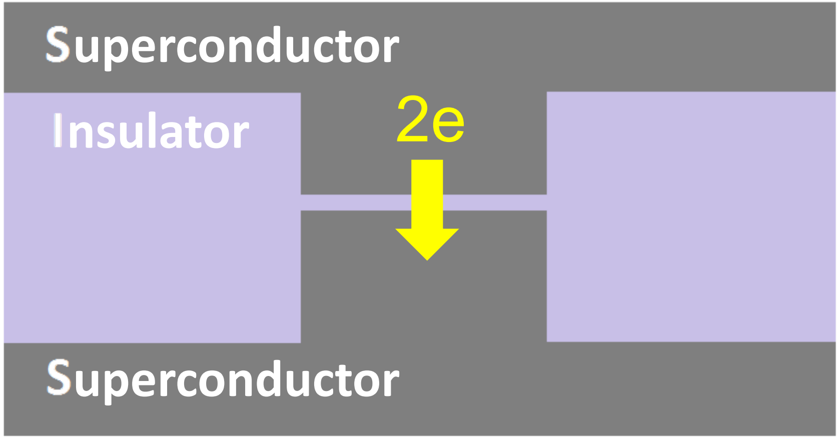

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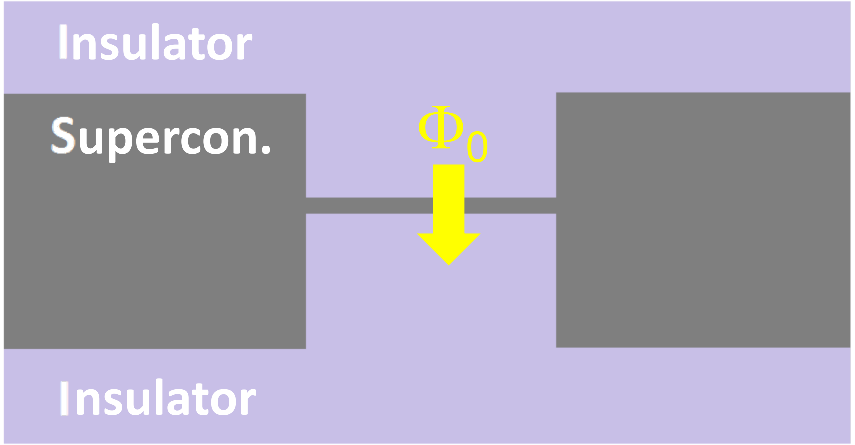

Coherent tunnelling of *magnetic flux* through the *superconducting* barrier

.... Requires highly disordered superconductor

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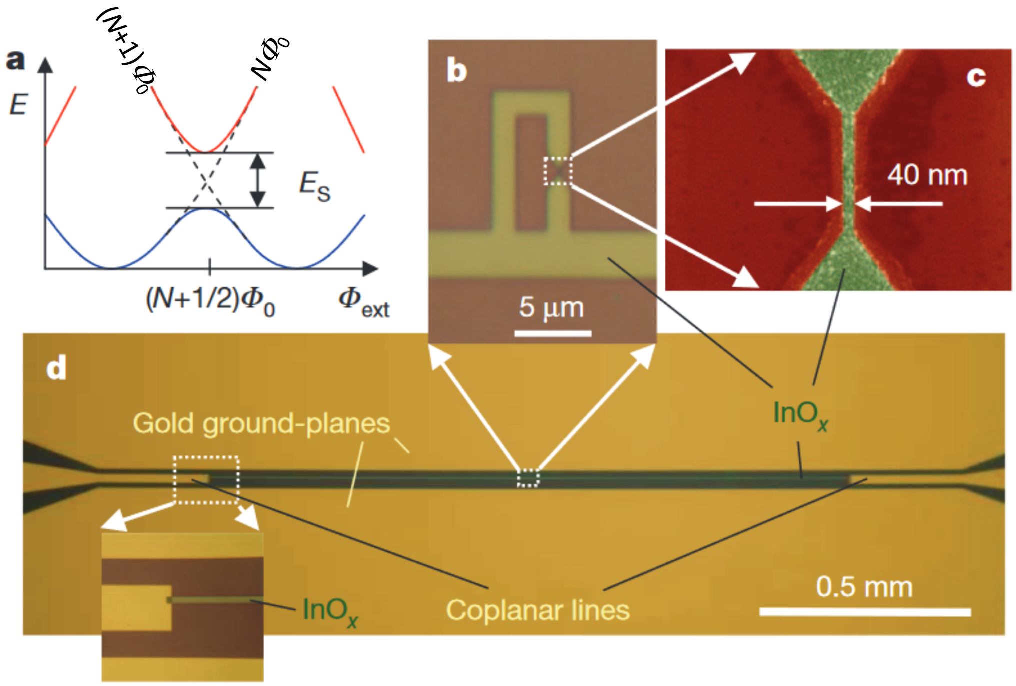
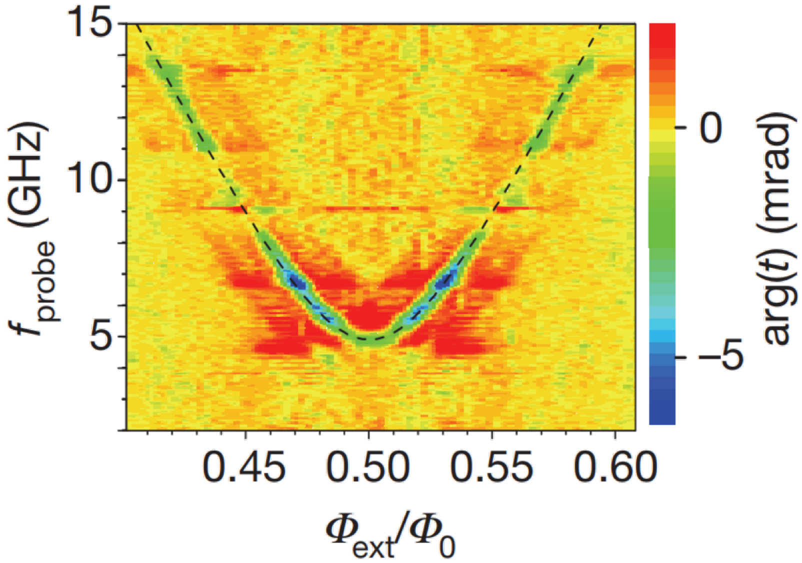
Coherent Quantum Phase-Slip

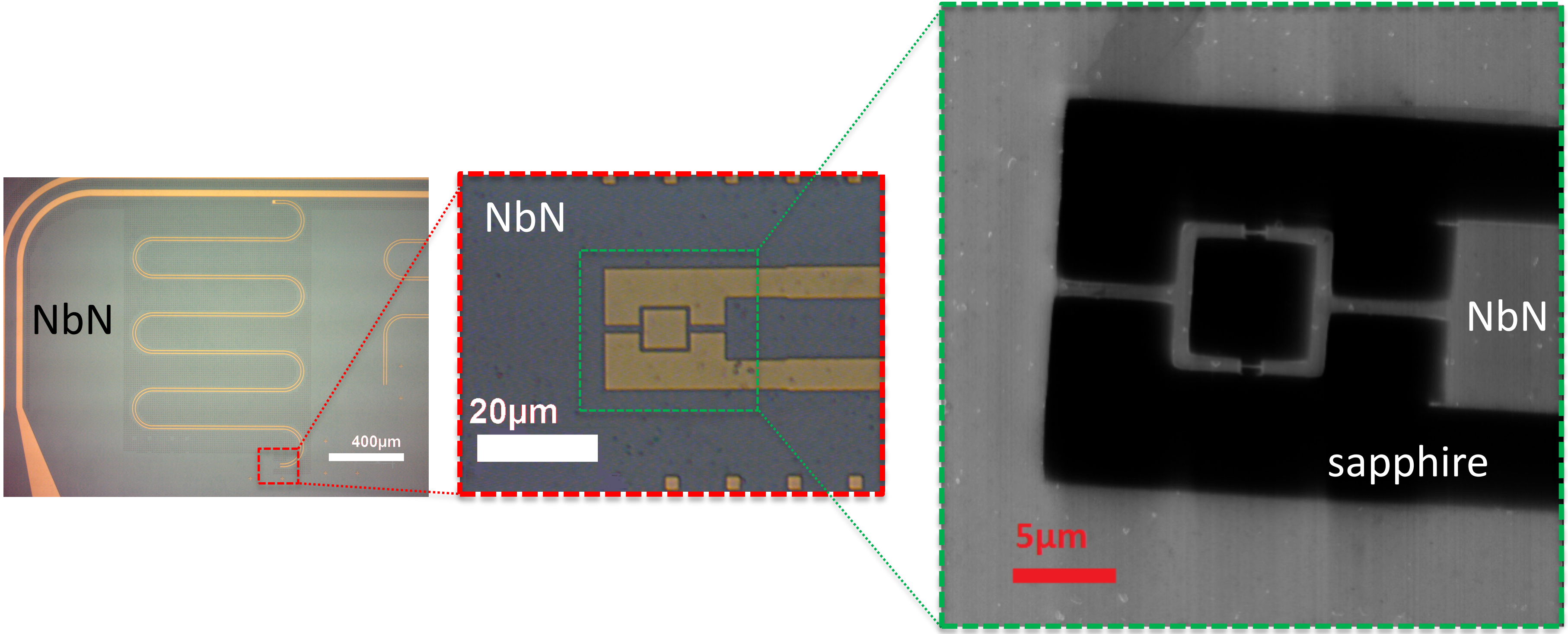


Astafiev *et al.* Nature **484**, 355 (2012)



Q < 40

Embedding Nanowires in Resonators

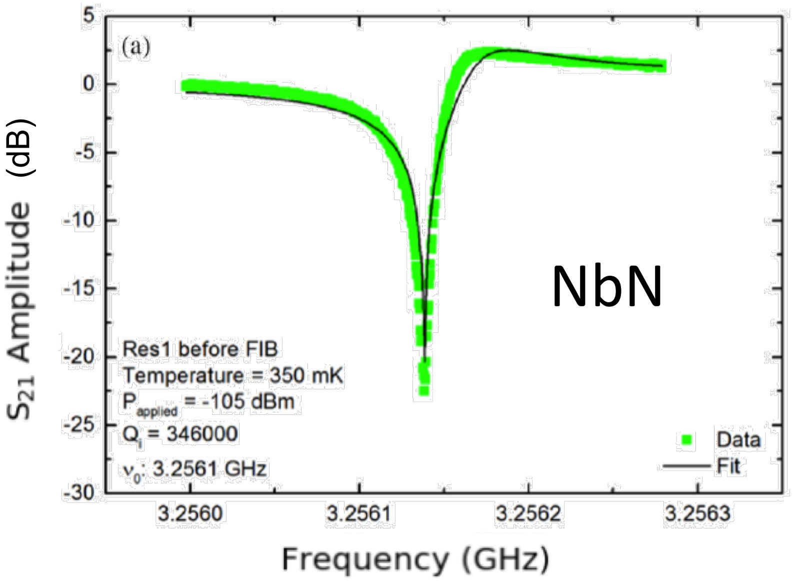


Nanowire Width = 100 nm

J. Burnett, PAW *et al. Phys. Rev. App.* **8**, 014039 (2017)

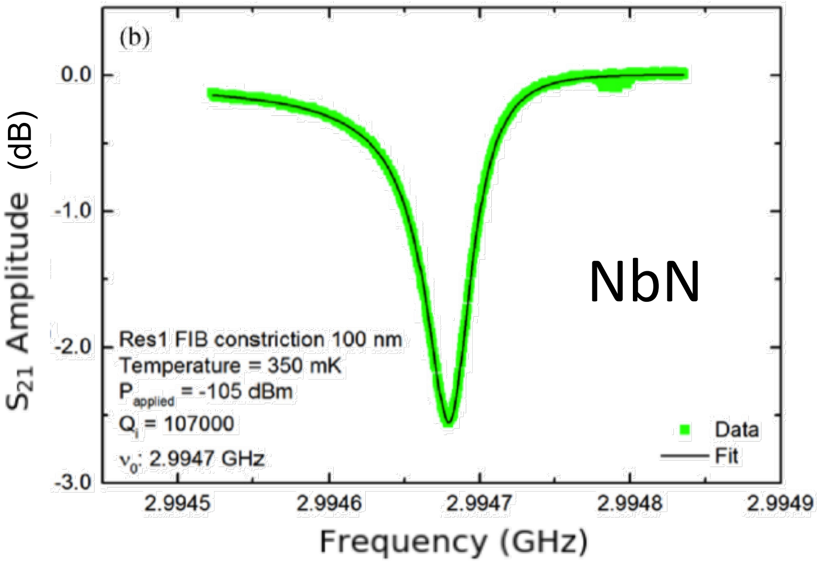
Before Neon-FIB

Intrinsic Q = 346,000



After Neon-FIB

Intrinsic Q = 107,000



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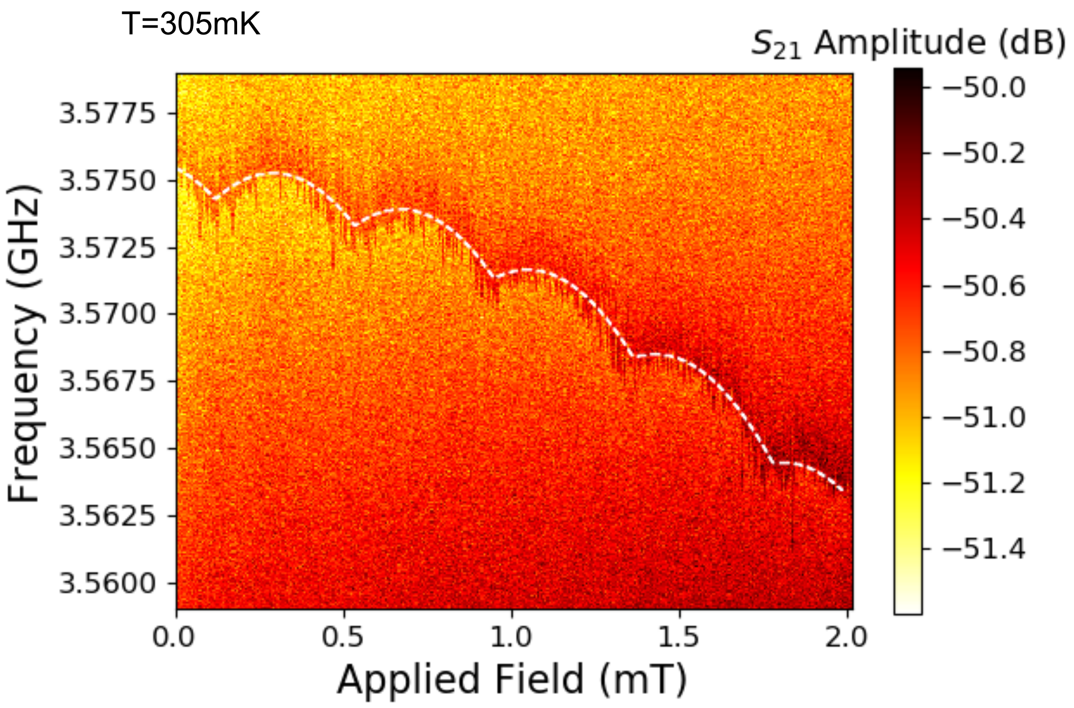
Nanowire Width = 35 nm

Evidence of incoherent quantum phase slips



Q ≈ 1000

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Conclusions

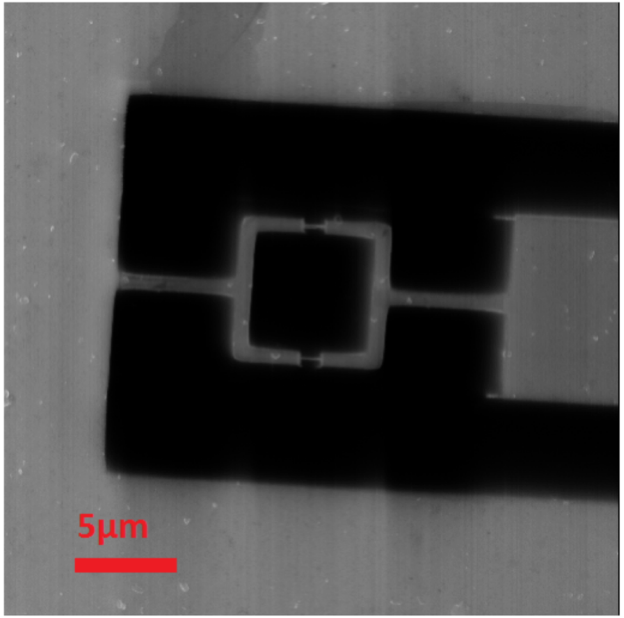
- Neon-FIB milling for Nb Dayem bridges

  Resonator $Q > 10{,}000$ for fields up to 60 mT

- Neon-FIB milling for NbN nanowires

  Resonator $Q \sim 1{,}000$

  Smaller dimensions and lower T needed for CQPS



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Acknowledgements

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