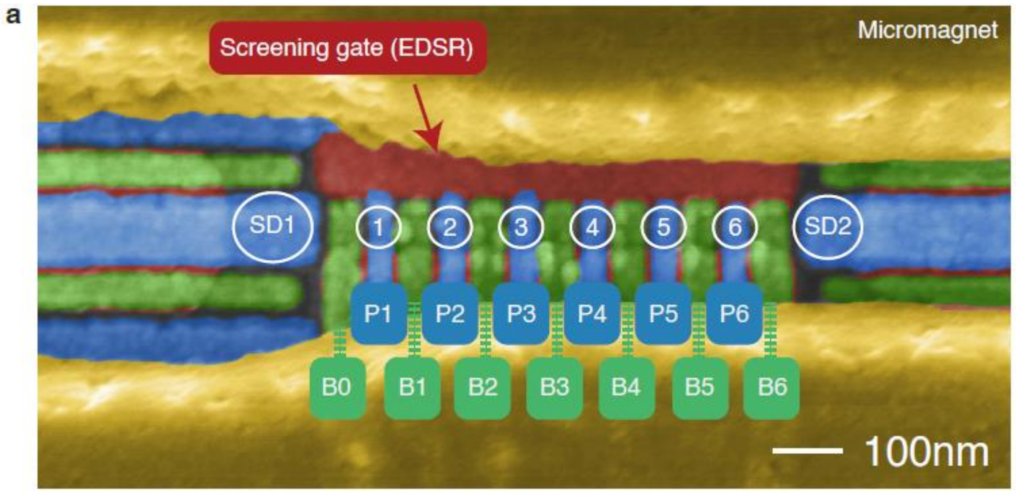
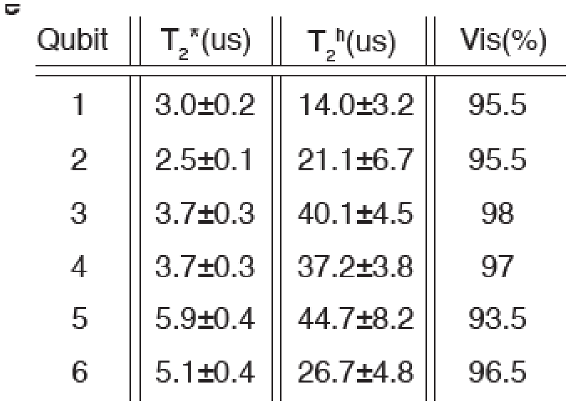
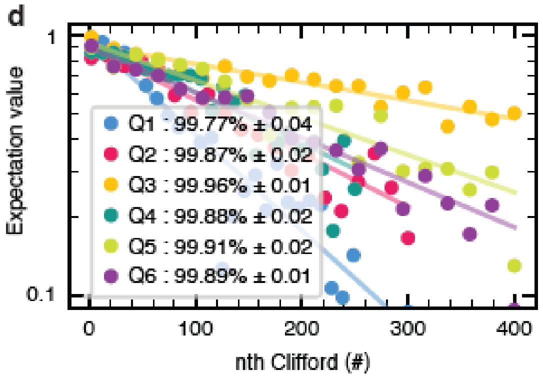
Universal control of a six-qubit quantum processor in silicon

Stephan G.J. Philips*[1], Mateusz T. Mądzik*[1], Sergey V. Amitonov[1], Sander L. de Snoo[1], Maximilian Russ[1], Nima Kalhor[1], Christian Volk[1], William I.L. Lawrie[1], Delphine Brousse[2], Larysa Tryputen[2], Brian Paquelet Wuetz[1], Amir Sammak[2], Menno Veldhorst[1], Giordano Scappucci[1], and Lieven M.K. Vandersypen† [1]





Qubit	T_2^*(us)	T_2^h(us)	Vis(%)
1	3.0±0.2	14.0±3.2	95.5
2	2.5±0.1	21.1±6.7	95.5
3	3.7±0.3	40.1±4.5	98
4	3.7±0.3	37.2±3.8	97
5	5.9±0.4	44.7±8.2	93.5
6	5.1±0.4	26.7±4.8	96.5



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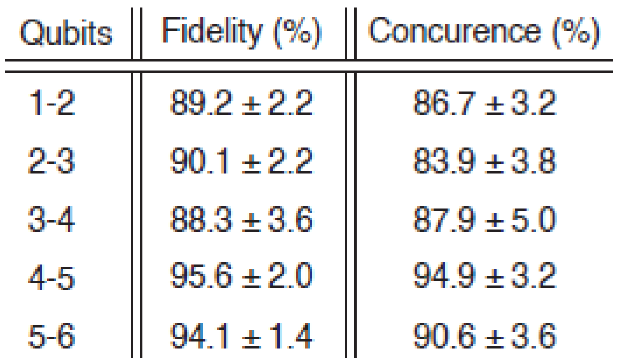
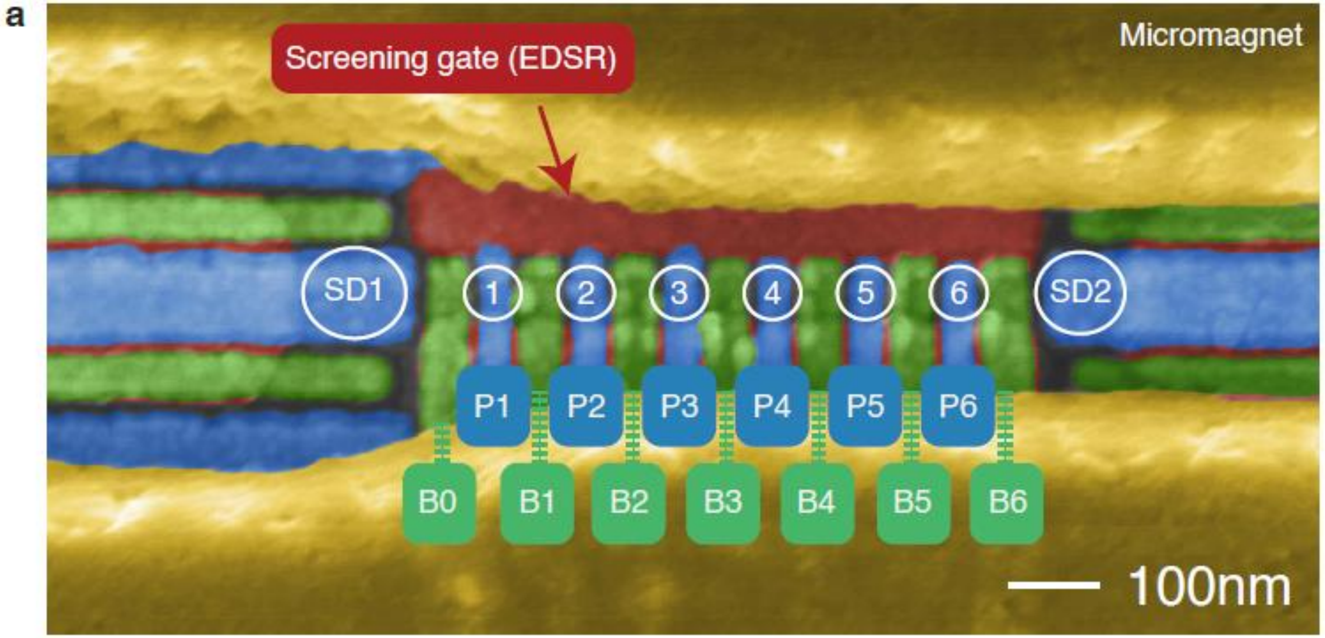


Qubits	Fidelity (%)	Concurence (%)
1-2	89.2 ± 2.2	86.7 ± 3.2
2-3	90.1 ± 2.2	83.9 ± 3.8
3-4	88.3 ± 3.6	87.9 ± 5.0
4-5	95.6 ± 2.0	94.9 ± 3.2
5-6	94.1 ± 1.4	90.6 ± 3.6

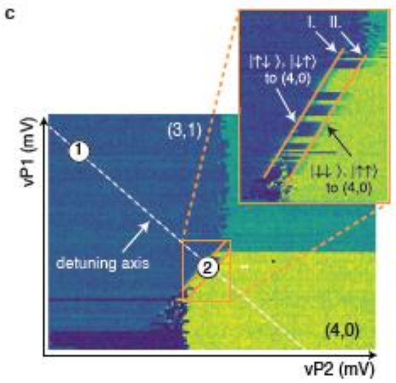
Felix J. Schupp 28/02/2022

Device

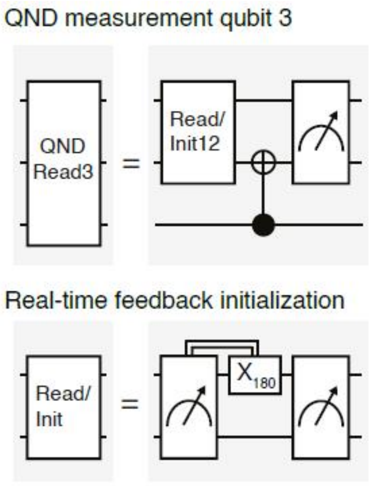


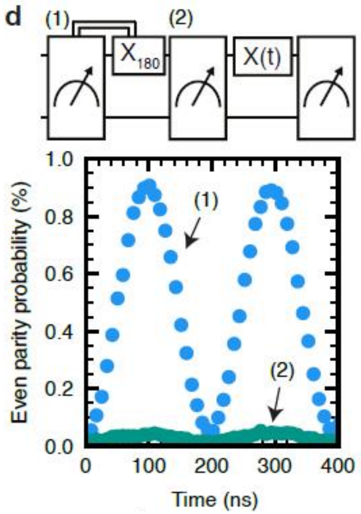
- 6 dots – can accumulate with 1e$^-$, but choose to accumulate outer dots (1,6) with 3 electrons
- 2 sensor dots on end of array
- Approach:
  screening (“slit”) gate to avoid accumulation everywhere under gates on top
  Then make 2 layers of plunger/barrier
- Isolating dielectric: AlO from ALD, gates made from Ti/Pd, SiGe/Si/SiGe heterostructure for 2DEG
- Read-out with charge sensors+tank circuit

Initialization/Measurements:



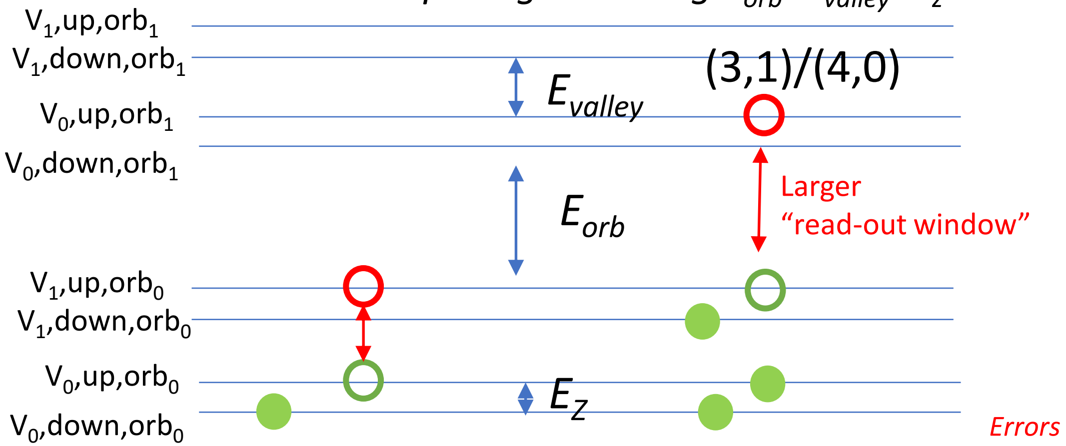
Spin-blockade read-out
-> get parity between outer two dots (1,2 or 5,6)

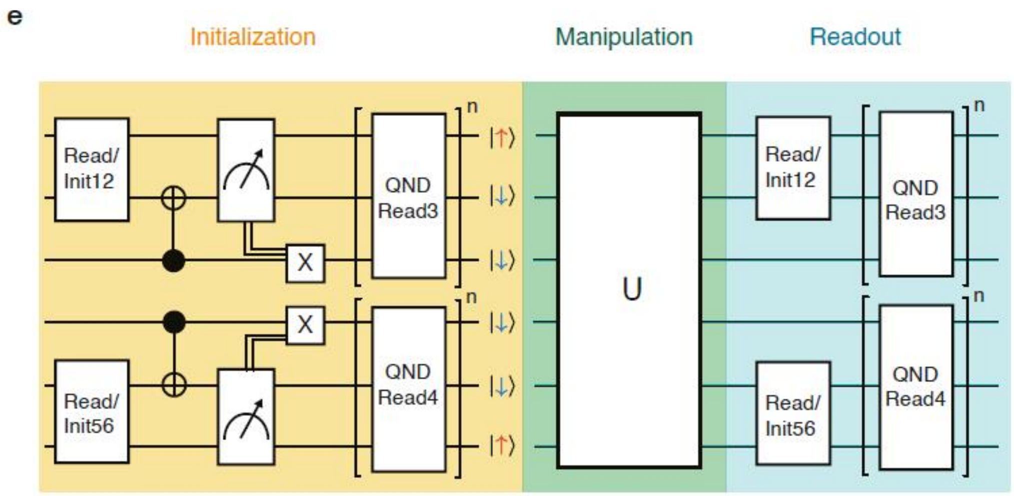


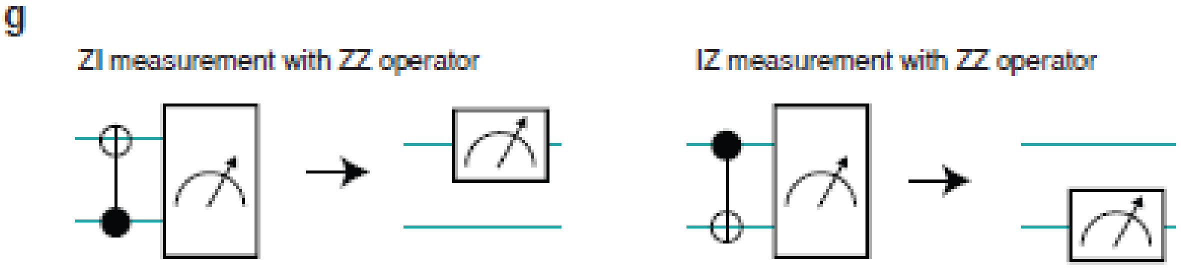


Why 3,1 -> 4,0:

Consider level spacing assuming $E_{orb}>E_{valley}>E_z$



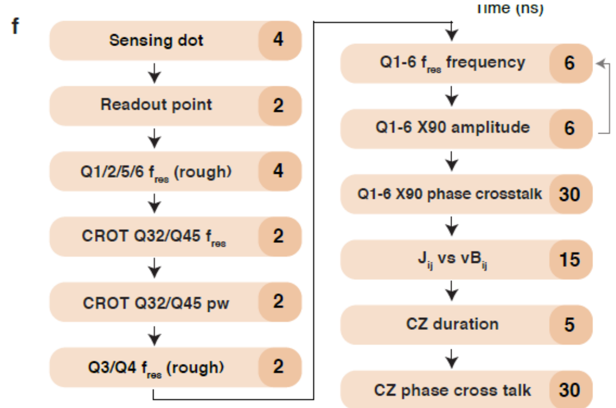




00	00	even	Left was 0
01	11	even	Left was 0
10	10	odd	Left was 1
11	01	odd	Left was 1

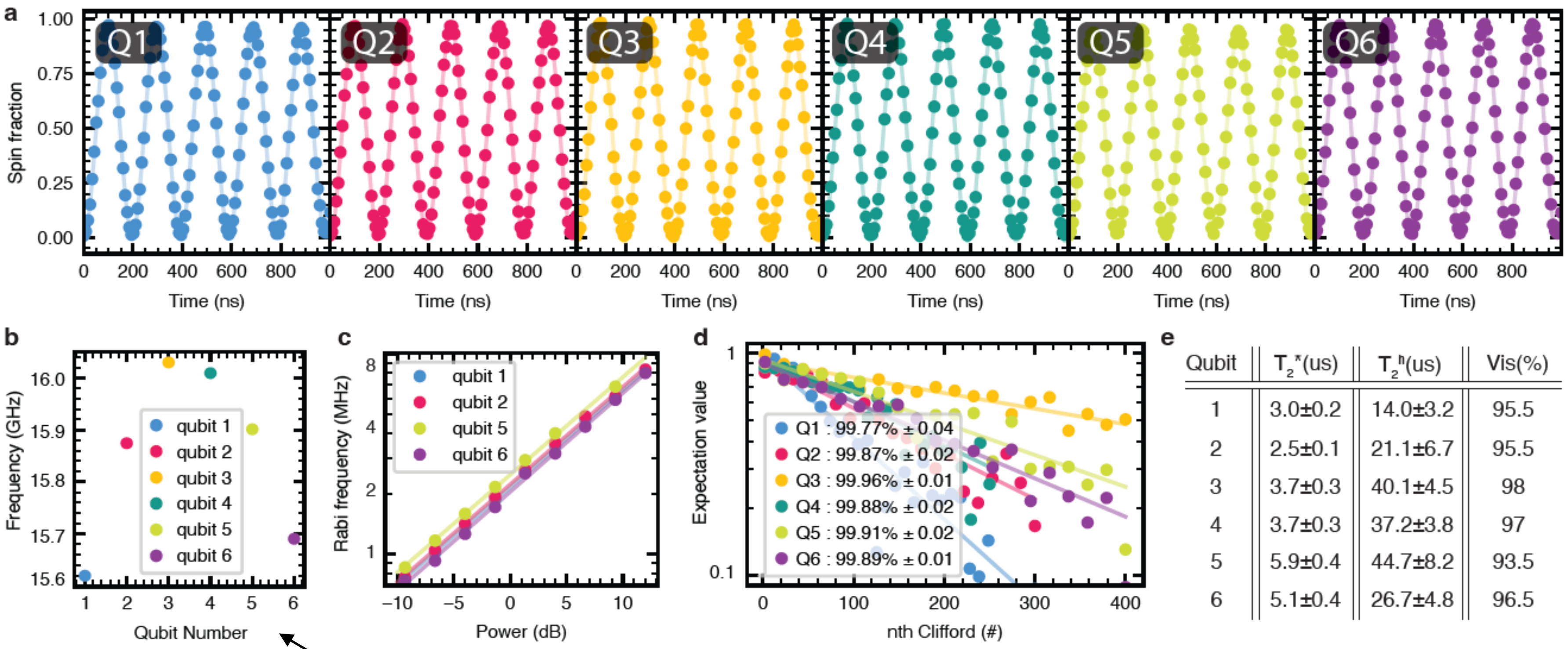
…analogous

Calibration routines and single qubit benchmarking



…details well documented in SI

They calibrate every day everything but crosstalk
They do full calibration 2xweek
And specific calibrations when needed



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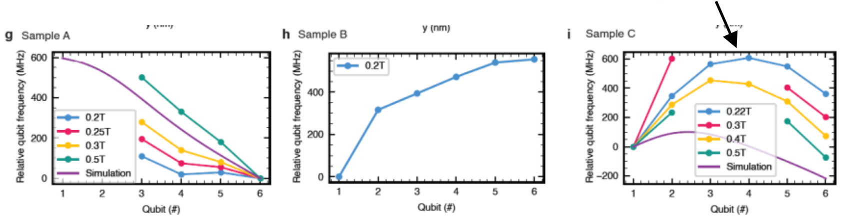
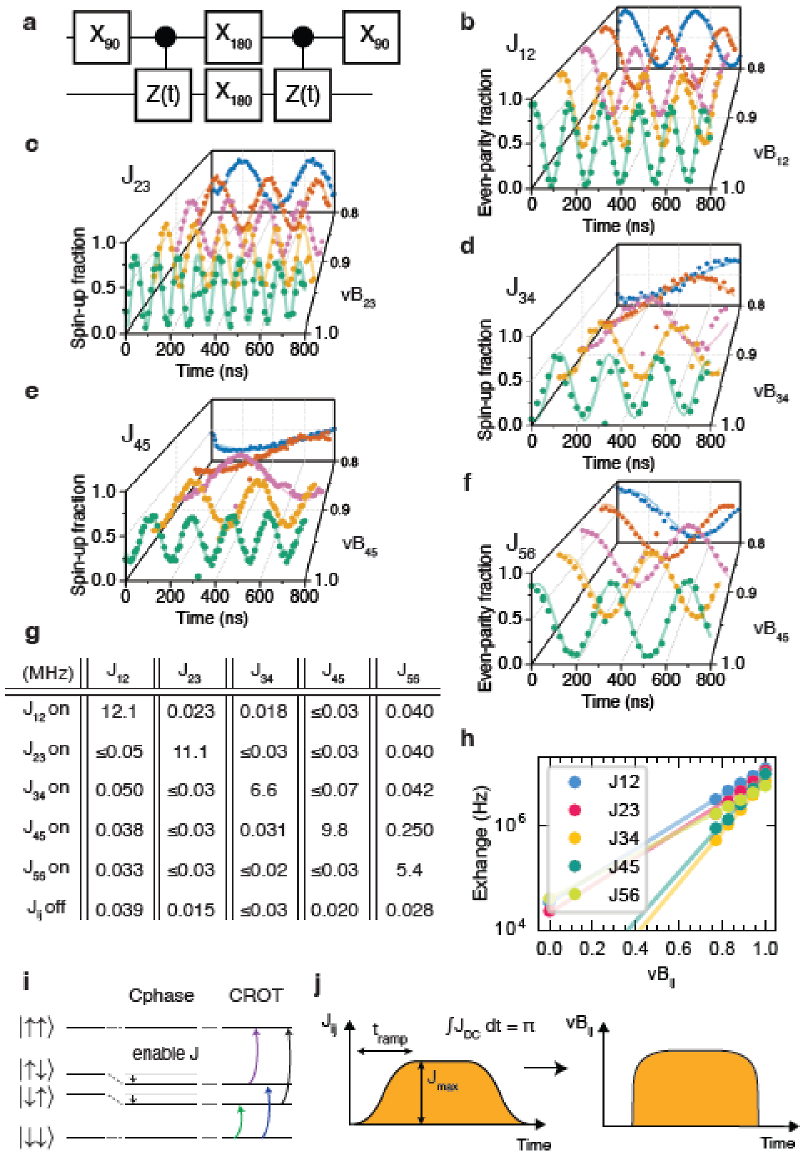
Note that qubit frequencies are monotonically increasing…
The magnet design is discussed in the SI
(including simulations etc), but this looks a bit random…
Have we spotted a weakness in the shiny armour of the Vandersypen group?

Paper device



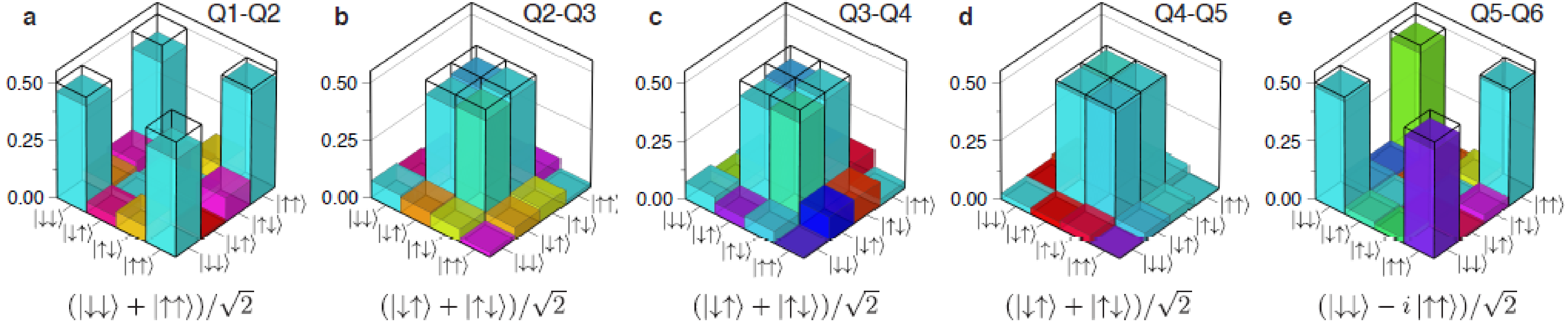
Two qubit gates



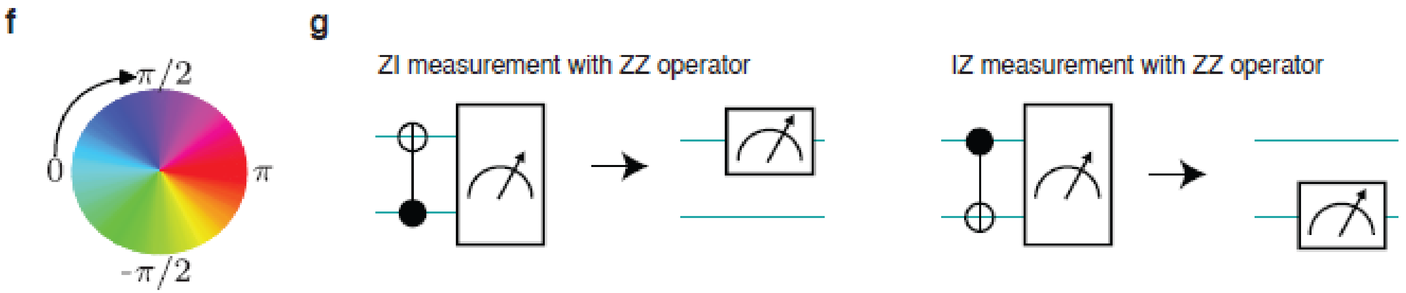
(MHz)	J_{12}	J_{23}	J_{34}	J_{45}	J_{56}
J_{12} on	12.1	0.023	0.018	≤0.03	0.040
J_{23} on	≤0.05	11.1	≤0.03	≤0.03	0.040
J_{34} on	0.050	≤0.03	6.6	≤0.07	0.042
J_{45} on	0.038	≤0.03	0.031	9.8	0.250
J_{56} on	0.033	≤0.03	≤0.02	≤0.03	5.4
J_{ij} off	0.039	0.015	≤0.03	0.020	0.028

- Use Crot gate:
  -> pulse target on equator
  -> Switch exchange on via barrier gate for time T
- Important: T and J need to be chosen such that the phase accumulated on target is pi if control was up
  Only then we call this Crot
- Pulse target back (should be 180 degrees rotated if control was up)
- Trick 1: Here they also use the barriers on the sides of the pair to push the wavefunctions closer together and increase J
- Trick 2: Use a smooth pulse on barrier (not rectangular pulse) to ensure adiabatic operation

Characterize two qubit: Bell-state tomography



$(|\downarrow\downarrow\rangle + |\uparrow\uparrow\rangle)/\sqrt{2}$ $(|\downarrow\uparrow\rangle + |\uparrow\downarrow\rangle)/\sqrt{2}$ $(|\downarrow\uparrow\rangle + |\uparrow\downarrow\rangle)/\sqrt{2}$ $(|\downarrow\uparrow\rangle + |\uparrow\downarrow\rangle)/\sqrt{2}$ $(|\downarrow\downarrow\rangle - i\,|\uparrow\uparrow\rangle)/\sqrt{2}$



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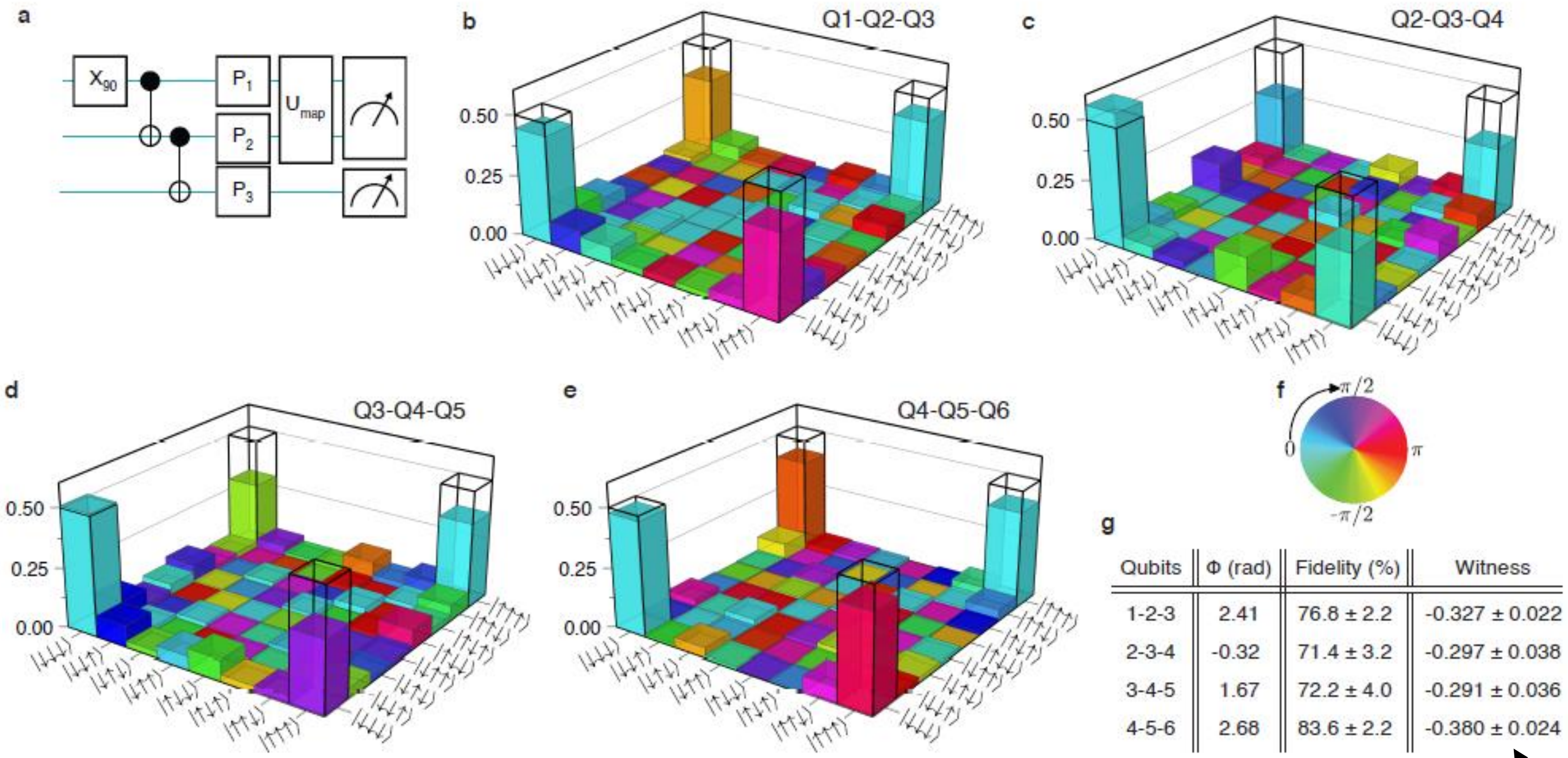
= measure for entanglement!

Why not rdm benchmarking? -> Possible but costly…

Characterize three qubit: GHZ states



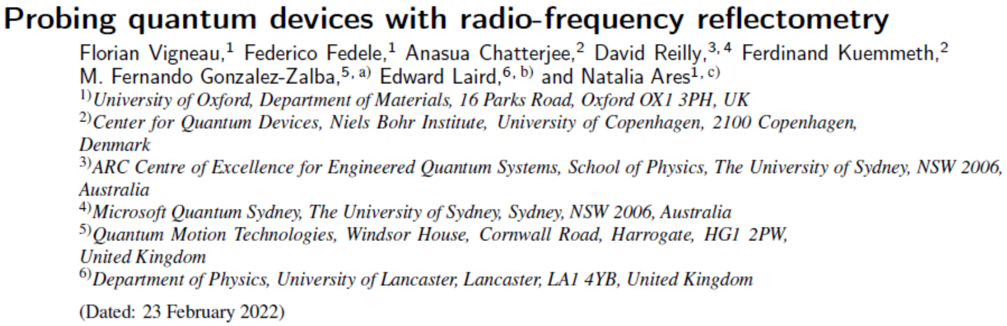
Qubits	Φ (rad)	Fidelity (%)	Witness
1-2-3	2.41	76.8 ± 2.2	-0.327 ± 0.022
2-3-4	-0.32	71.4 ± 3.2	-0.297 ± 0.038
3-4-5	1.67	72.2 ± 4.0	-0.291 ± 0.036
4-5-6	2.68	83.6 ± 2.2	-0.380 ± 0.024

$$|\psi_{\mathrm{GHZ}}\rangle = (|000\rangle + e^{i\phi}\,|111\rangle)\sqrt{2},$$

= measure for entanglement!

Final comments:

- Probably the most advanced experiment in spin-qubits
- They mention issues with parallelization of gates/initialization (here they do everything consecutively, e.g. 1,2,3 and 4,5,6 initialization)
- They suspect there is an issue with heating… they see that in charge sensor and in the qubit performance
- I think they cannot control their magnets very well
- Valleys also seem to be an issue – especially when scaling up… bonus point for holes I would say!
- I encourage every new student to really try and understand the concepts here – it has almost everything you need and it is well documented in the SI/extended data
  On that note, also check out this great review from last week on reflectometry (almost textbook level detailed explanation):



Probing quantum devices with radio-frequency reflectometry

Florian Vigneau,[1] Federico Fedele,[1] Anasua Chatterjee,[2] David Reilly,[3,4] Ferdinand Kuemmeth,[2]
M. Fernando Gonzalez-Zalba,[5, a)] Edward Laird,[6, b)] and Natalia Ares[1, c)]
1) University of Oxford, Department of Materials, 16 Parks Road, Oxford OX1 3PH, UK
2) Center for Quantum Devices, Niels Bohr Institute, University of Copenhagen, 2100 Copenhagen, Denmark
3) ARC Centre of Excellence for Engineered Quantum Systems, School of Physics, The University of Sydney, NSW 2006, Australia
4) Microsoft Quantum Sydney, The University of Sydney, Sydney, NSW 2006, Australia
5) Quantum Motion Technologies, Windsor House, Cornwall Road, Harrogate, HG1 2PW, United Kingdom
6) Department of Physics, University of Lancaster, Lancaster, LA1 4YB, United Kingdom

(Dated: 23 February 2022)