Quantum bits and RF technology

Raymond Schouten

QuTech institute, location: Delft University of Technology

QuTech is a research institute combining science and engineering founded by Delft University and TNO

Main industrial partners are:
Intel and Microsoft

Government:
Economic affairs & education

A Quantum Computing lab:

Researchers and T&M equipment

Cooling machines compressors etc.

QuTech: around 220 persons, 12 labs. Research, theory and computer architecture groups

In the lab: a measurement setup

In this setup the behaviour of single electrons is controlled and measured, enabling quantum operations

In the cooling machine: temperature stages

Typical cooling power: ~ 1 W at 4 K, but only ~ 1 mW at 20mK

RF coaxes
& d.c. lines

Attenuators
Filters

Room temperature

300 K

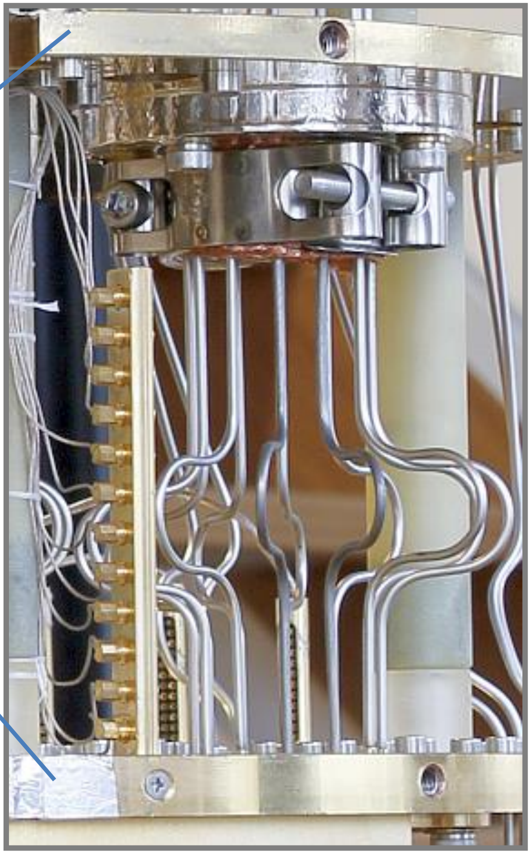
4 K

20 mK

Base temperature

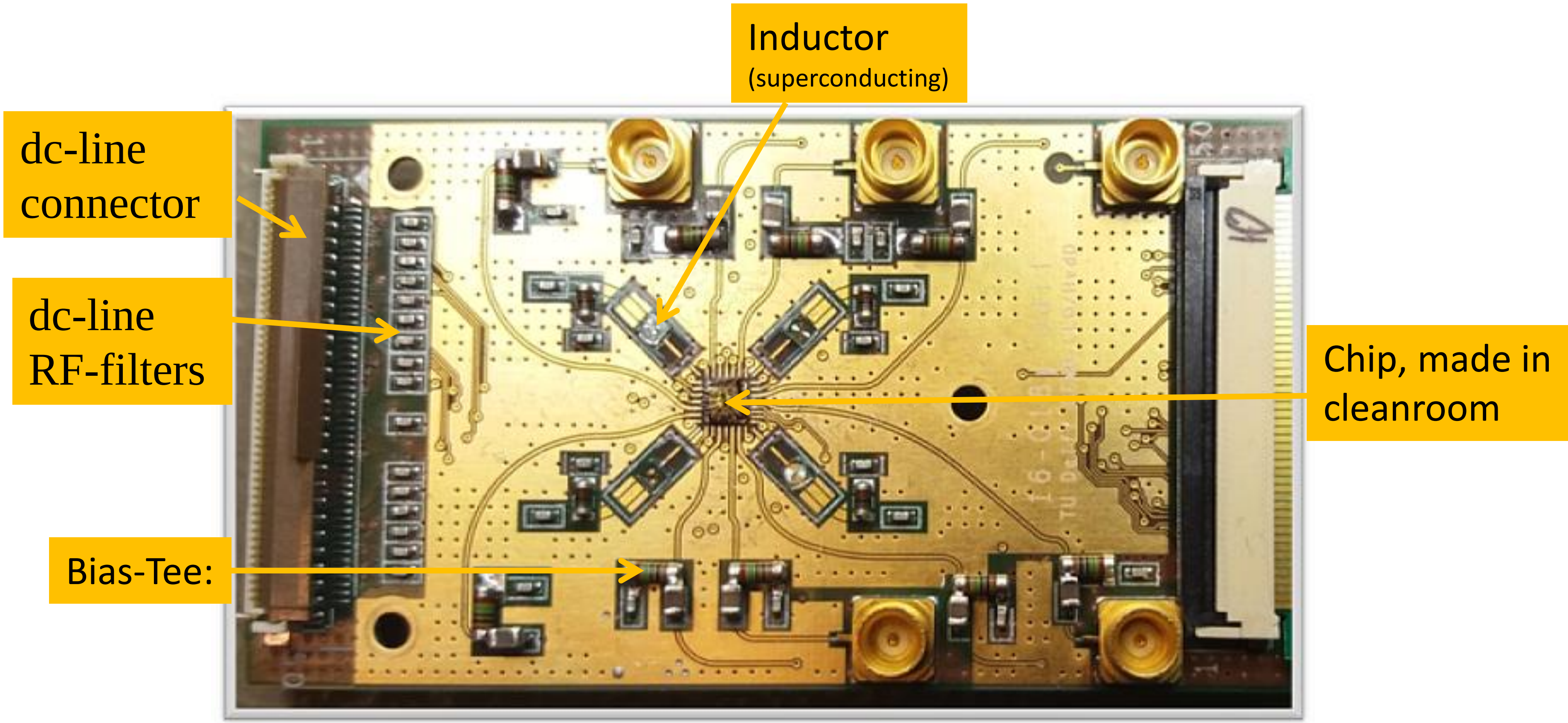
[Picture courtesy: Bluefors]

RF coaxes with thermal anchoring and thermal stress relief (bend):

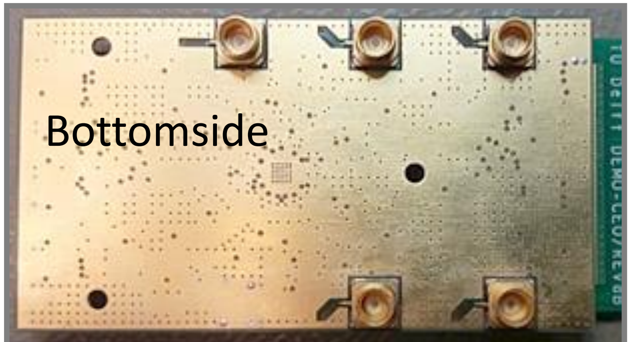


Copper coax can not be used: thermal conductivity is too high

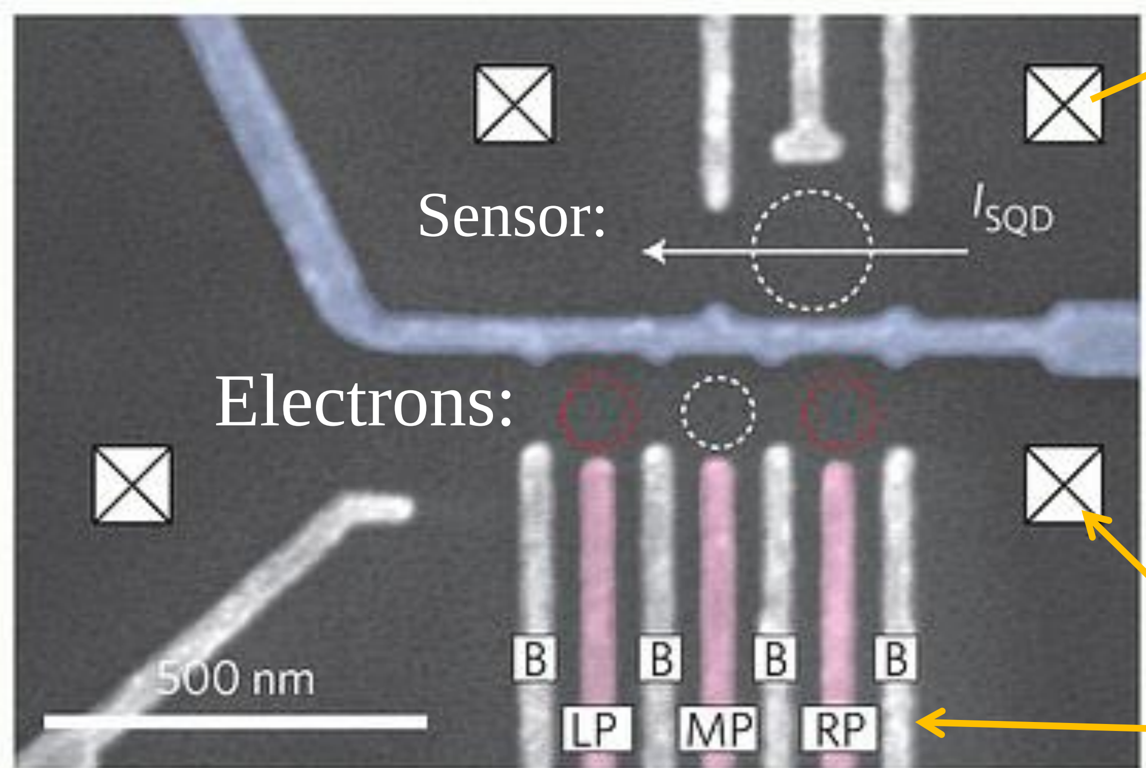
In the cooling machine, at 20mK**: a PCB** with a chip



PCB 64 x 35 mm, 8 layer FR4
10 RF lines (top & bottom)
33 d.c. lines
9 Bias Tee's
4 LC tank circuits (explained later)

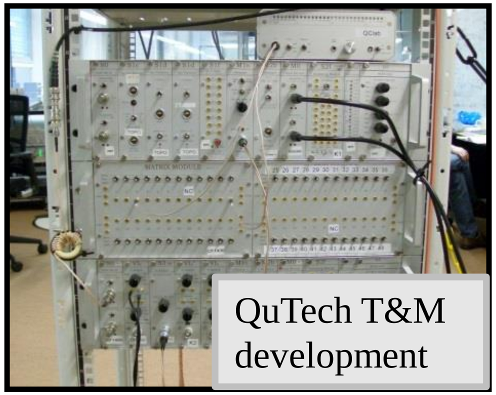


On the PCB at 20mK: **a chip** (spin qubit lab, Lieven Vandersypen)



Sensor readout

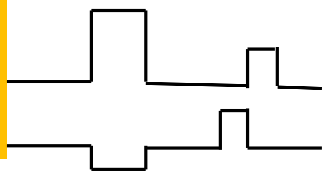
dc control &readout



d.c. bias
d.c. gates

RF bursts are used to rotate the spins of the electrons

Pulse sequences manipulate electron positions



MW vectorsources
up to 20GHz

Arbitrary Waveform Generators
(AWG) 1Gs/s

On the chip: quantum physics (if all is tuned well)

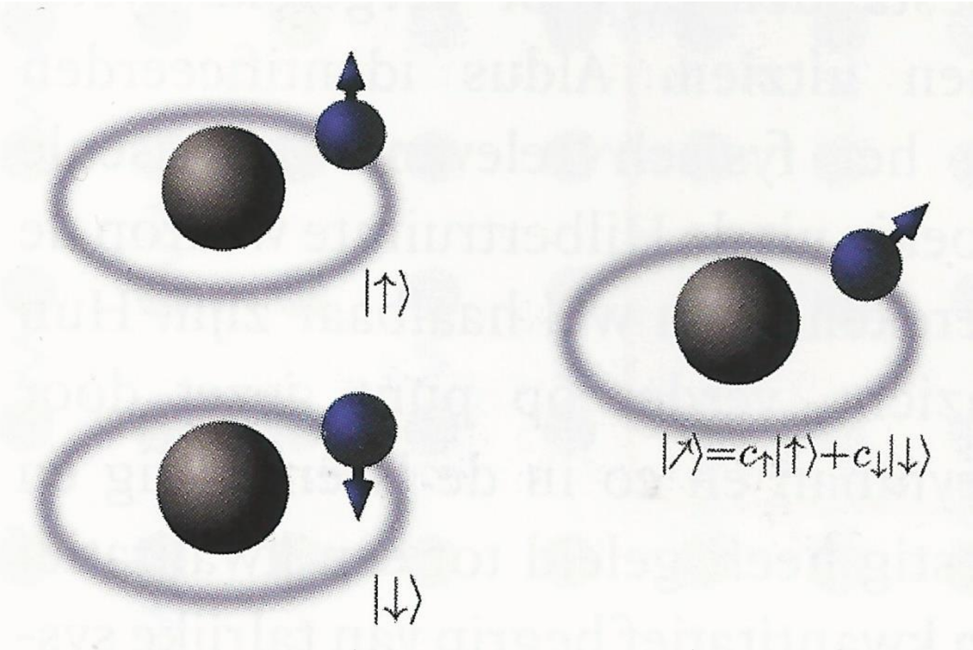
Quantum mechanics, keyword 1: **Superposition**

Superposition is a "one-particle" property.
Superposition: A particle being in all possible states **simultaneously**

Example: For the spin of an elektron this can be described as:

Spin
could be up

Spin
Could be down



picture from: Nederlands tijdschrift voor Natuurkunde

Superposition:
Spin is up and down
at the same time !!

The particle is in a superposition **until a readout is performed**

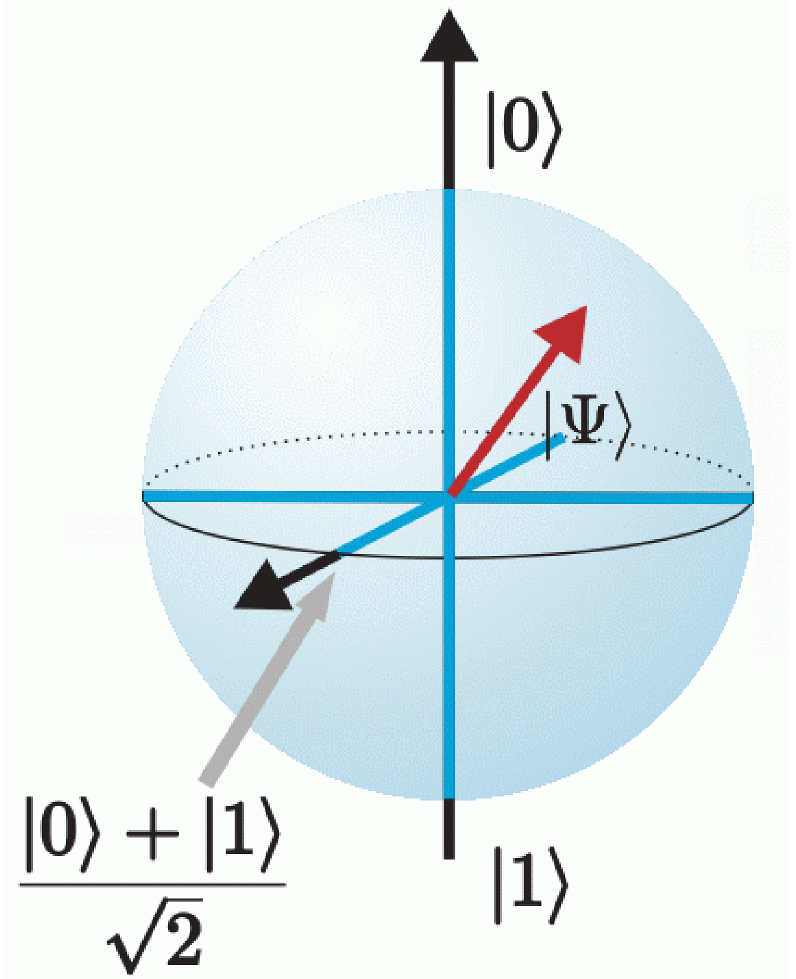
Quantum bits, superposition representation

The basic unit of a quantum computer is a quantumbit (qubit)
any state in a quantum two-level system
This can be represented by a vector.

(Classical bits can only have 0 or 1 as a state)

In practice a qubit state setting (vector position)
also changes uncontrollably in time (noise, drift)
This is called <u>decoherence</u> and limits the use.

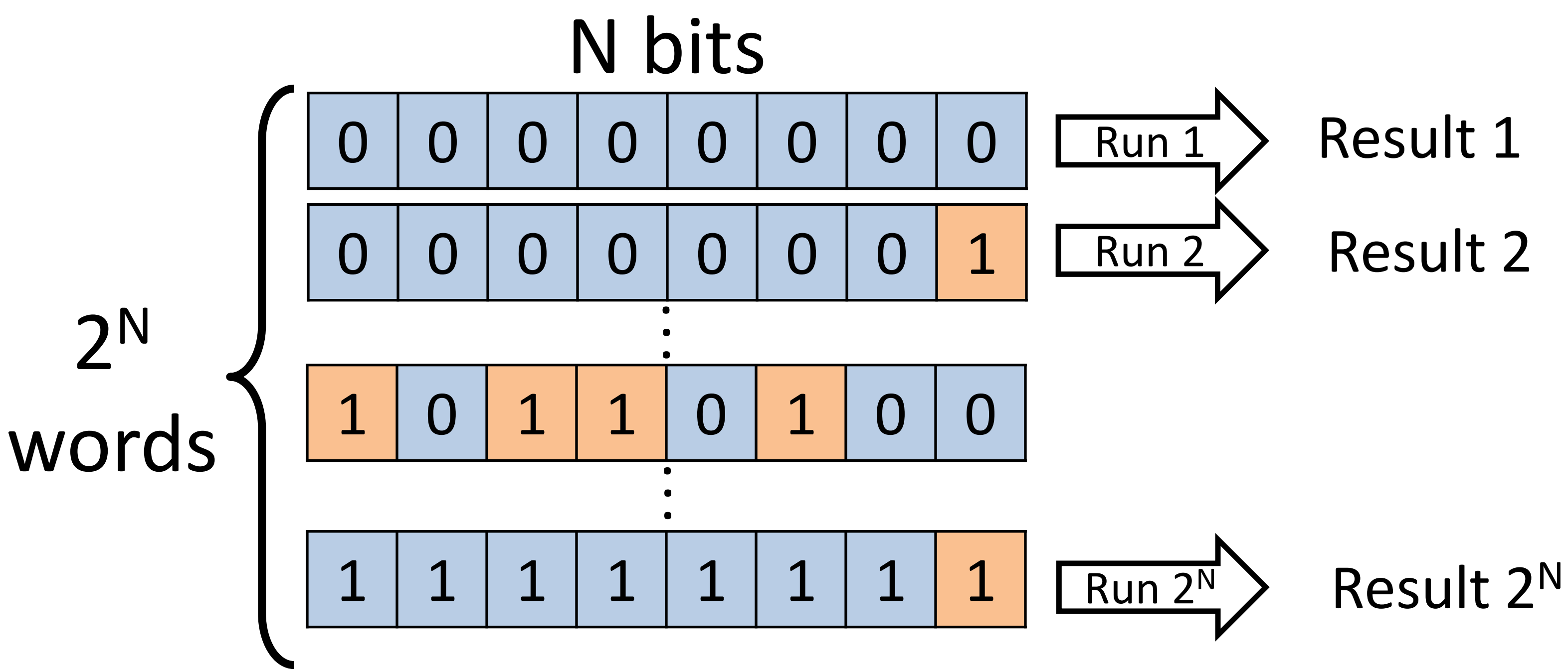
Error correction scheme's have been developped
Feasible from >99% fidelity up



Bits vs. quantum bits, advantage of superposition

Classical algorithm using bits:

(with classical bits being 1 or 0)

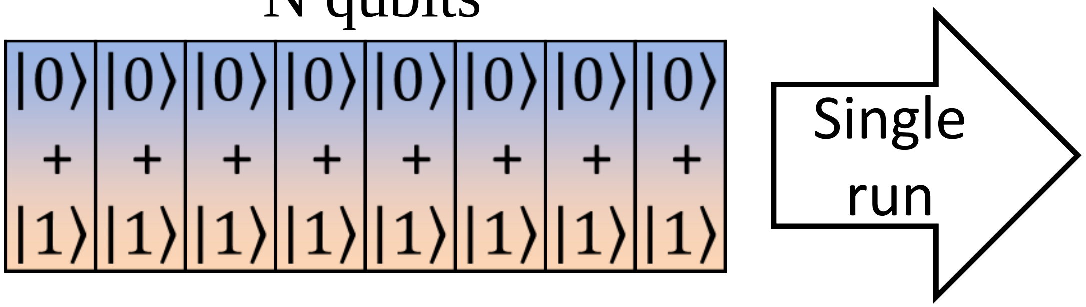


- Requires 2^N runs

Bits vs. quantum bits, advantage of superposition

Quantum algorithm using quantum bits:

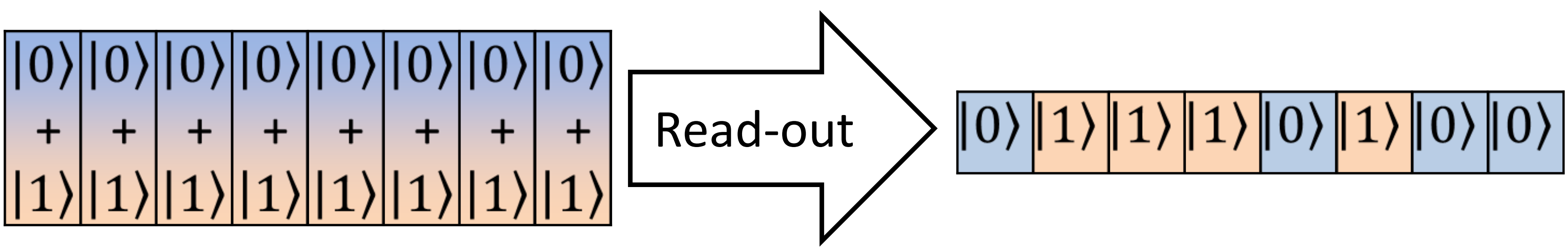
N qubits



Result
(for 2^N combination)

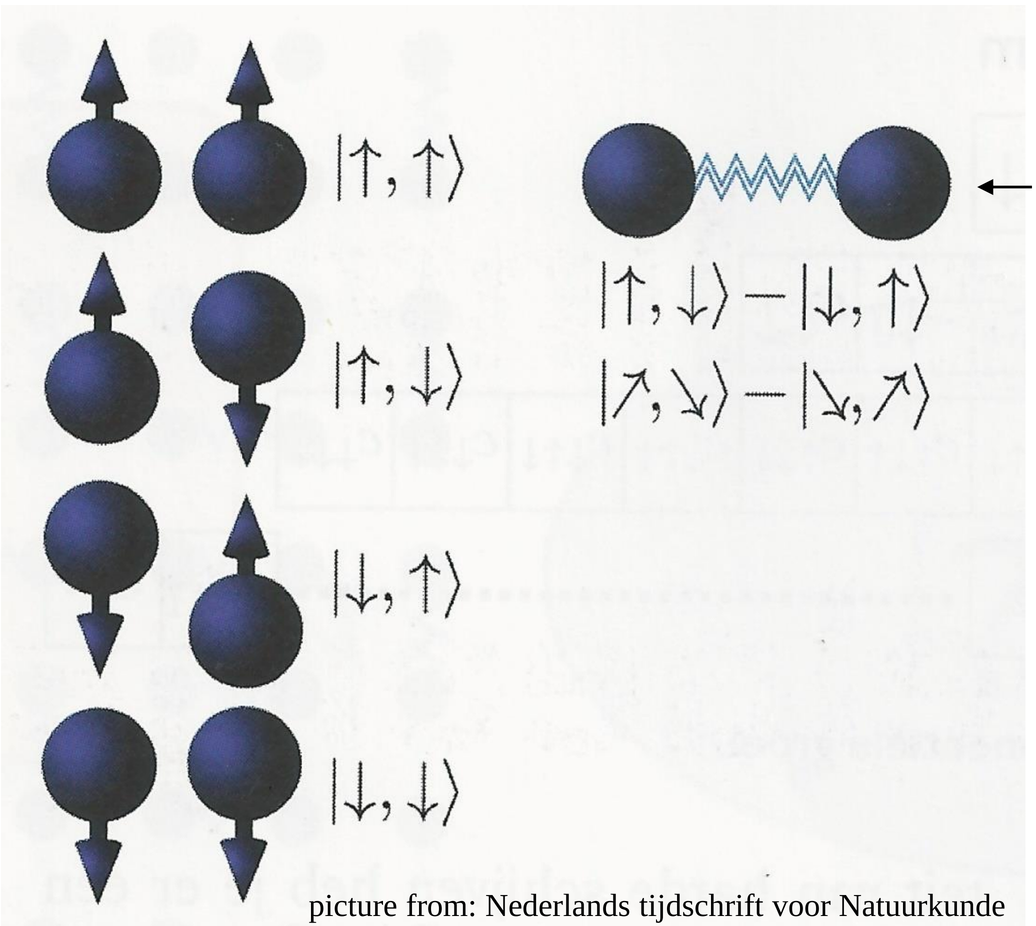
1 word *but*
encodes 2^N combinations

- Requires only a single run ⇒ exponential speed-up
- But how to read-out a superposition ? clever theorists found some ways



Quantum mechanics, keyword 2: **Entanglement**

Entanglement is a characteristic of two or more particles.
Particles can be brought in a interaction that couples their states



picture from: Nederlands tijdschrift voor Natuurkunde

← For this entangled pair:
We do not know the state of each particle but we do know they are opposite

Measuring one, immediately changes the state of the other !

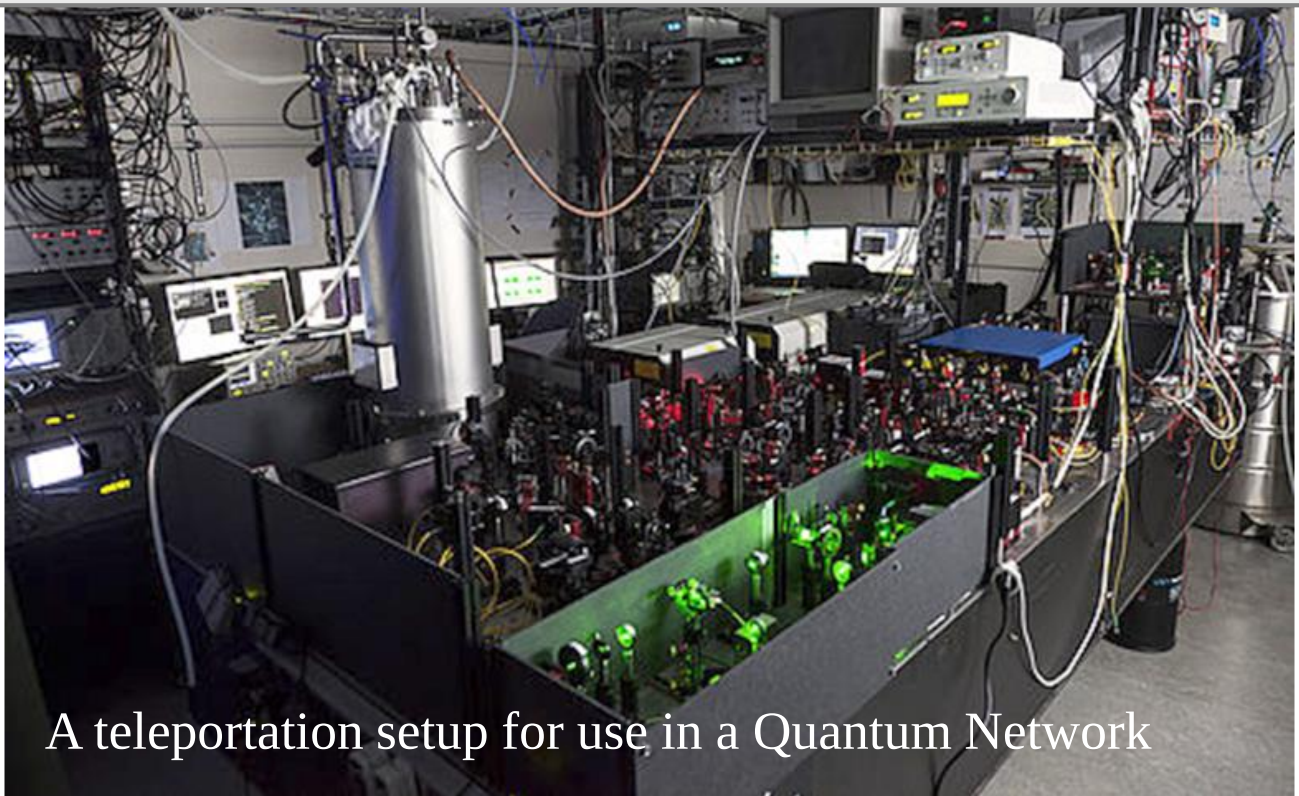
This is still possible when the particles are separated on opposite sides of the universe
(Without environmental interaction)

QuTech, optics lab Quantum communication (Ronald Hanson)

1.3 km distance entanglement demonstrated by this team.

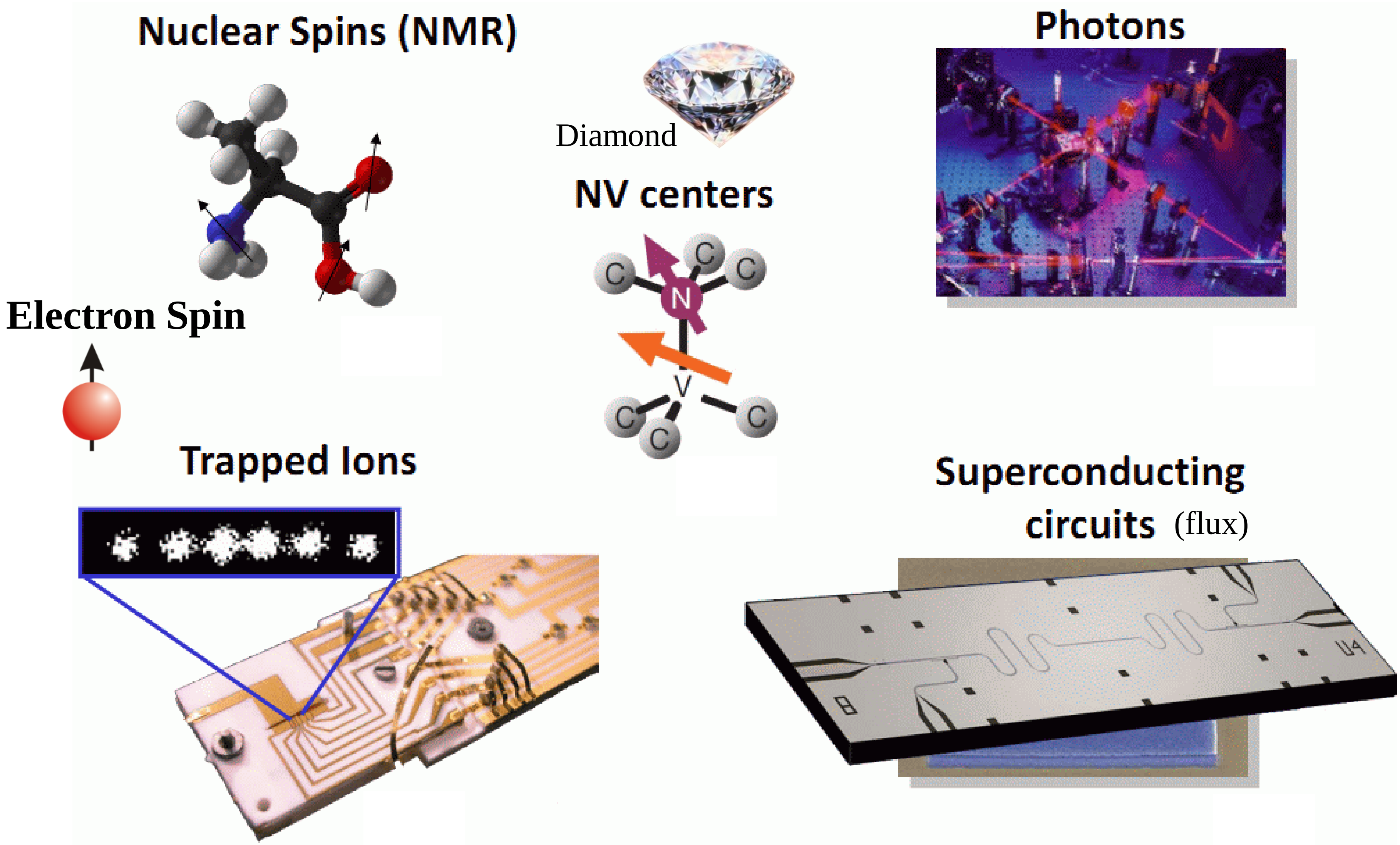
Possibilities for safe key distribution using photons send over fibers.
The key cannot be intercepted as this removes the entanglement.

Paper: Experimental loophole-free violation of a Bell inequality using entangled electron spins separated by 1.3 km. (B.Hensen et al.)



A teleportation setup for use in a Quantum Network

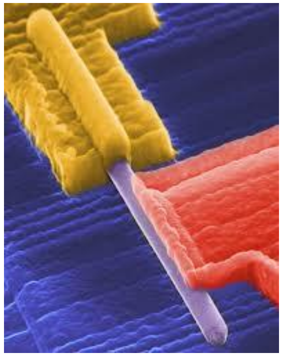
Quantum bits can be created in physical structures like:



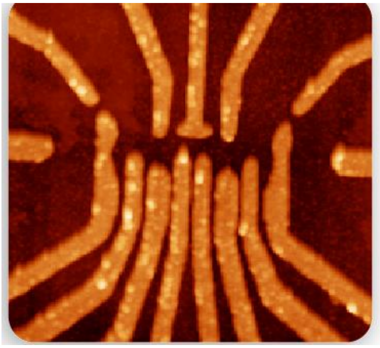
(Just like classic bits are created in transistor circuits)

QuTech research groups cover four fields of interest

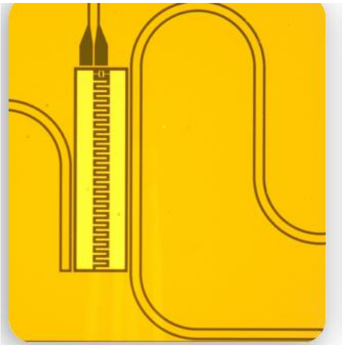
Manipulating single electrons *Manipulating flux* *Optics (photons)*



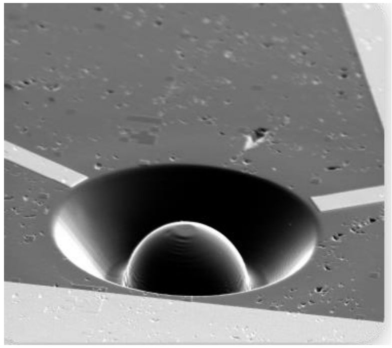
One-dimensional nanostructures



Electronic spins In nanostructures



Superconducting circuits



NV centers In diamond

Relating to the following applications:

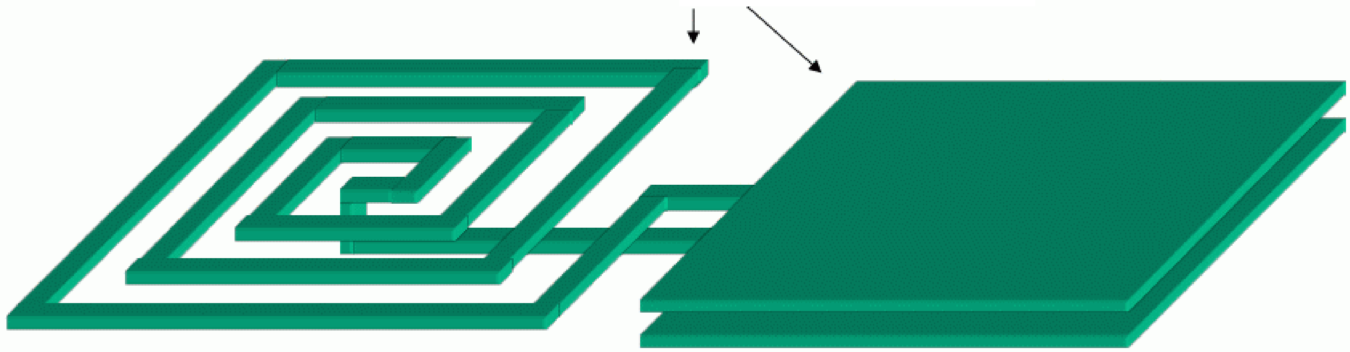
Storage	Computing	Communication
Topological Quantum computing	Fault-Tolerant Quantum Computing	Quantum Internet

Building a Quantum Computer, a 2 qubit example

(superconducting circuits lab, Leo Di Carlo)

We first need a system that “holds” our qubit

Simplest example: the LC resonator circuit



$$\omega_r = \frac{1}{\sqrt{LC}}$$

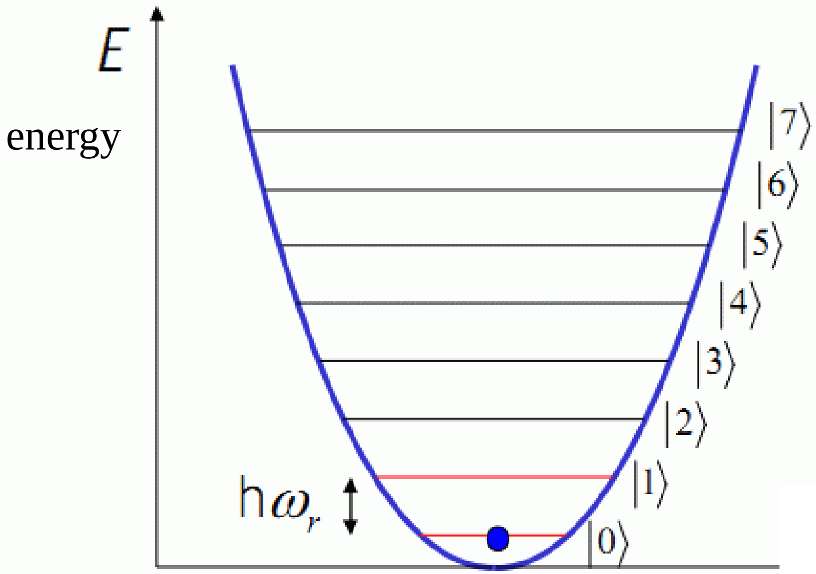
Microfabrication → L ~ 10 nH, C ~ 100 fF, ω_r /2p ~ 5 GHz

Now make the energy levels *low enough* to see **quantised** energy steps

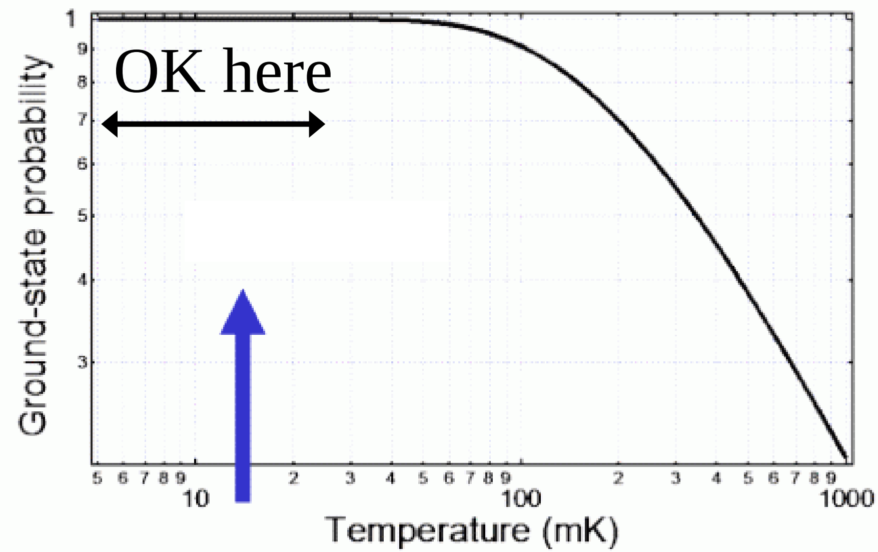
Building a Quantum Computer, a 2 qubit example

Why microwave frequencies + cryogenic temp?

CAN PLACE CIRCUIT IN ITS QUANTUM GROUND STATE = lowest-energy state



Low temperature needs are:



Energy packet: $\hbar\omega_r \leftrightarrows k_B T$

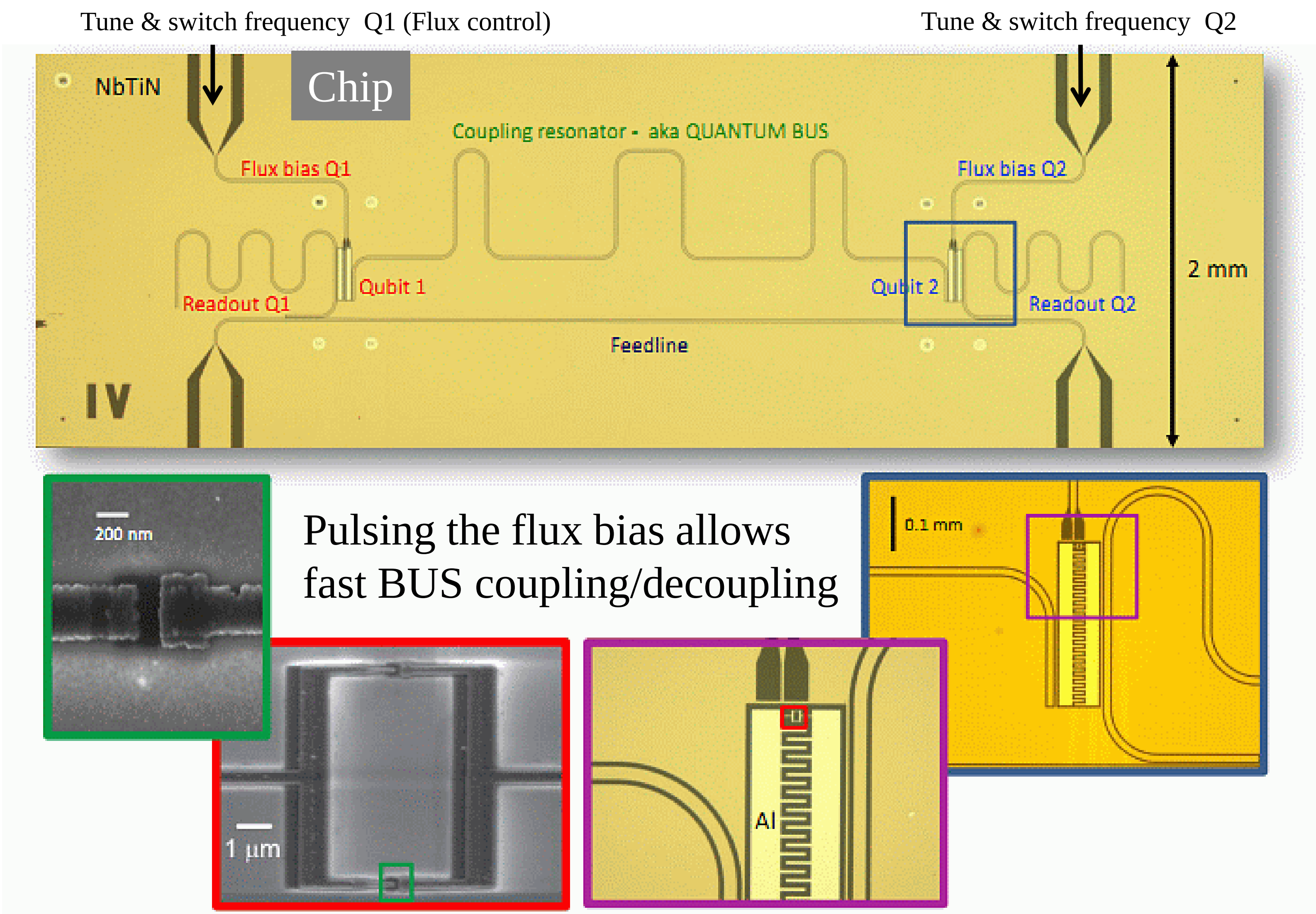
5 GHz

(Thermal energy)

$$P(n=0) = 1 - e^{-\hbar\omega_r / k_B T}$$

Note: We add a **non-linear** inductive element (named SQUID) to be able to make the separation of the states **unequal** and to tune the resonator (using <u>flux bias</u>)

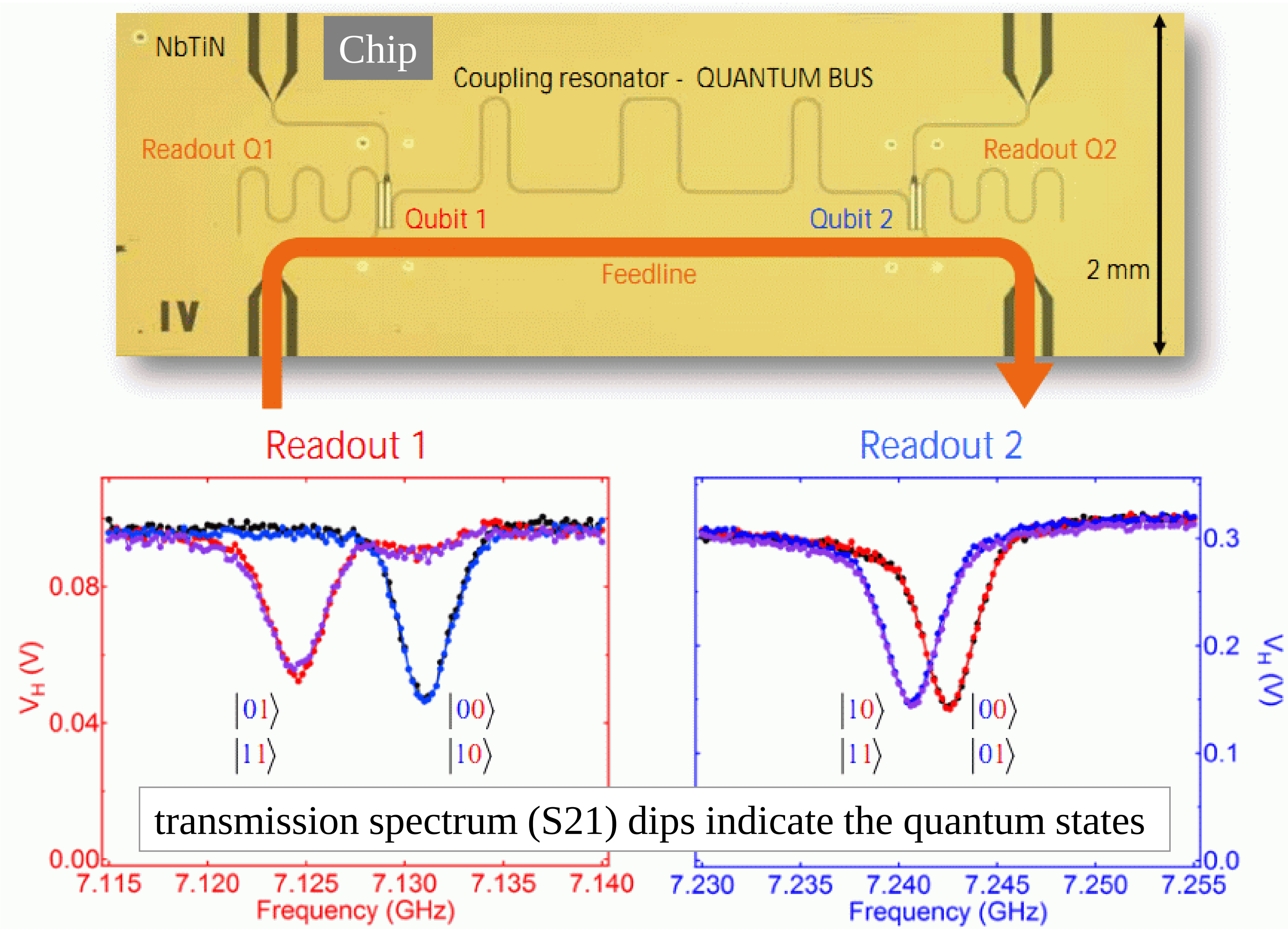
Building a Quantum Computer, a 2 qubit example



Pulsing the flux bias allows fast BUS coupling/decoupling

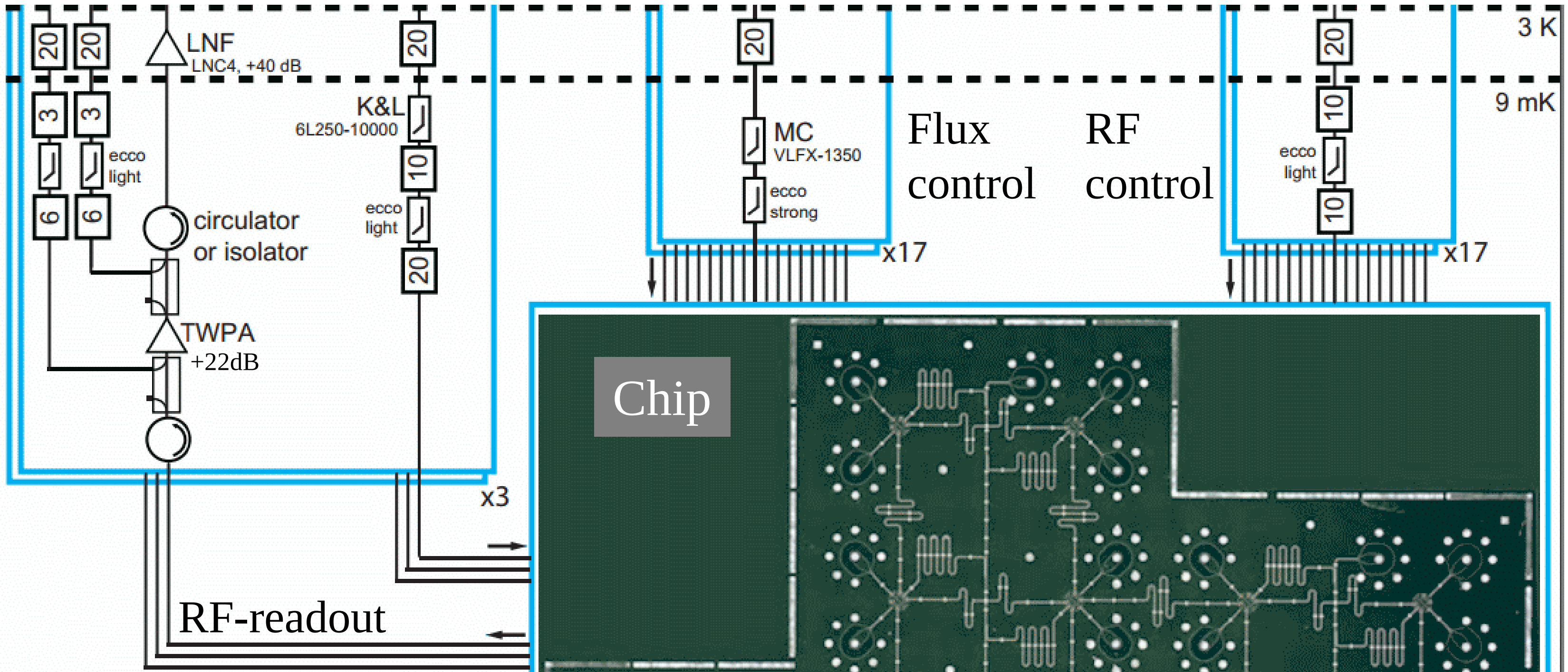
Figure 5.3: **Microscope image of the device.** Bottom two ports are used to measure transmission of the feedline. Each transmon qubit is coupled to an individual resonator for readout and a quantum bus to couple the qubits (blue inset). The qubits consists of two aluminum islands and are tuned by changing the flux in the SQUID loop (red inset).

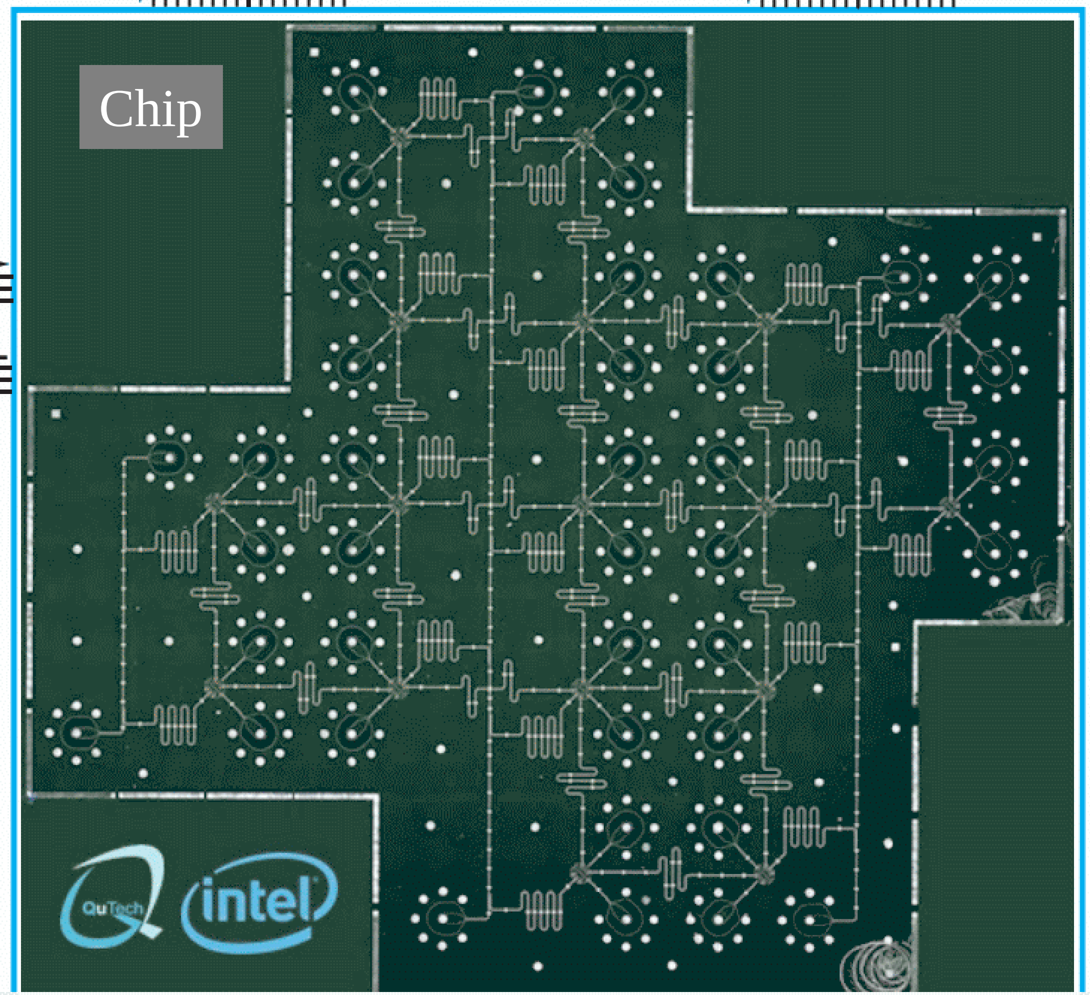
Building a Quantum Computer, a 2 qubit example



transmission spectrum (S21) dips indicate the quantum states

Building a Quantum Computer, 17 qubit, low temperature part



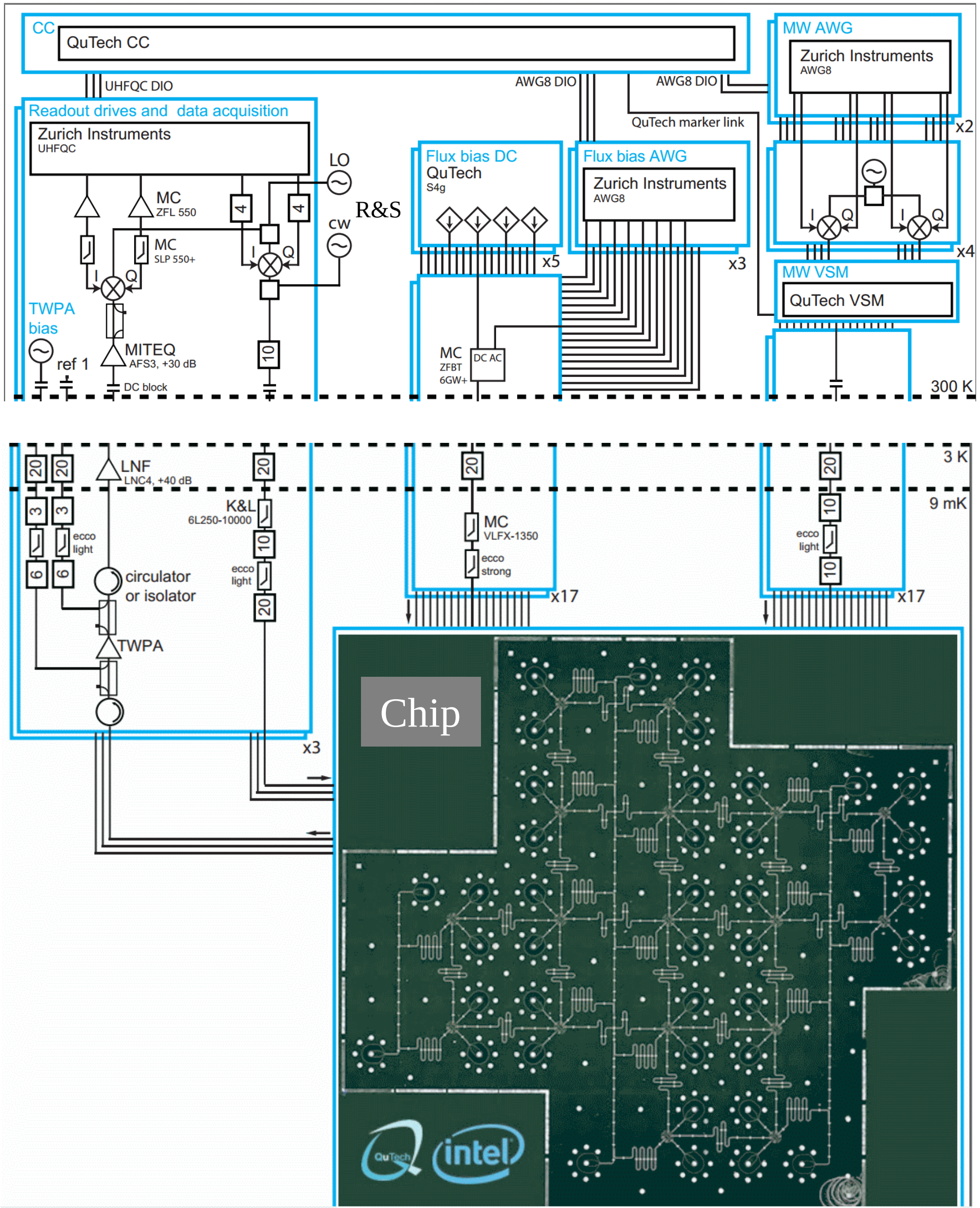


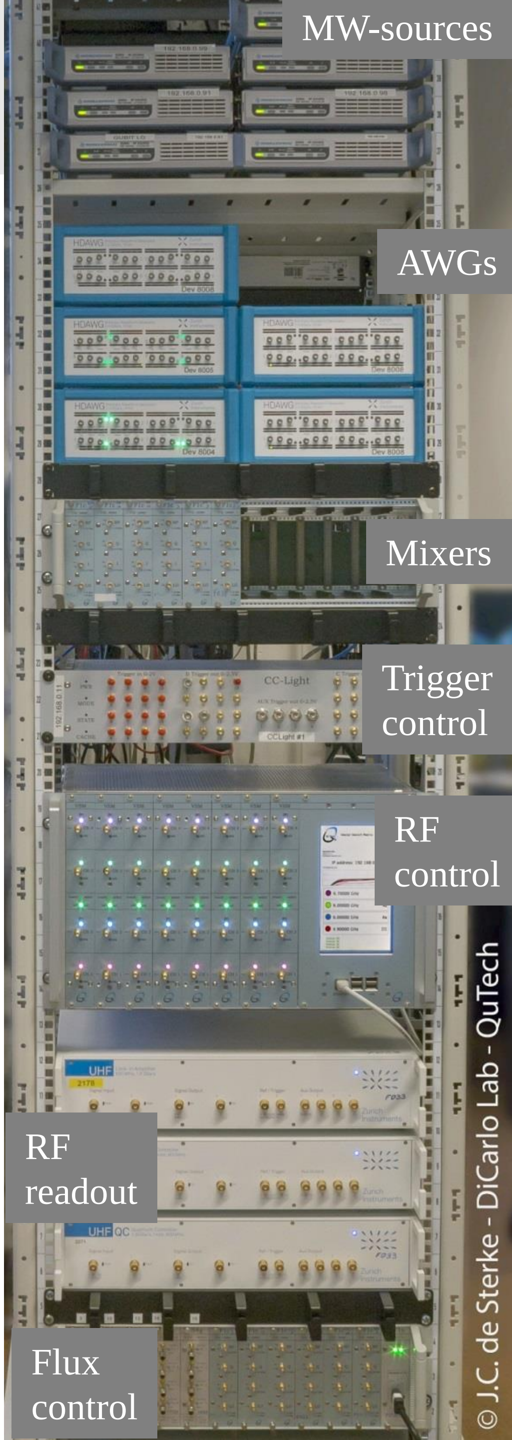
Using Traveling Wave
Parametric Amplifiers (TWPA)
extremely low noise:
Noise figure < 0.01dB

TWPA followed by 0.05dB NF
Post amplifiers (LNF)

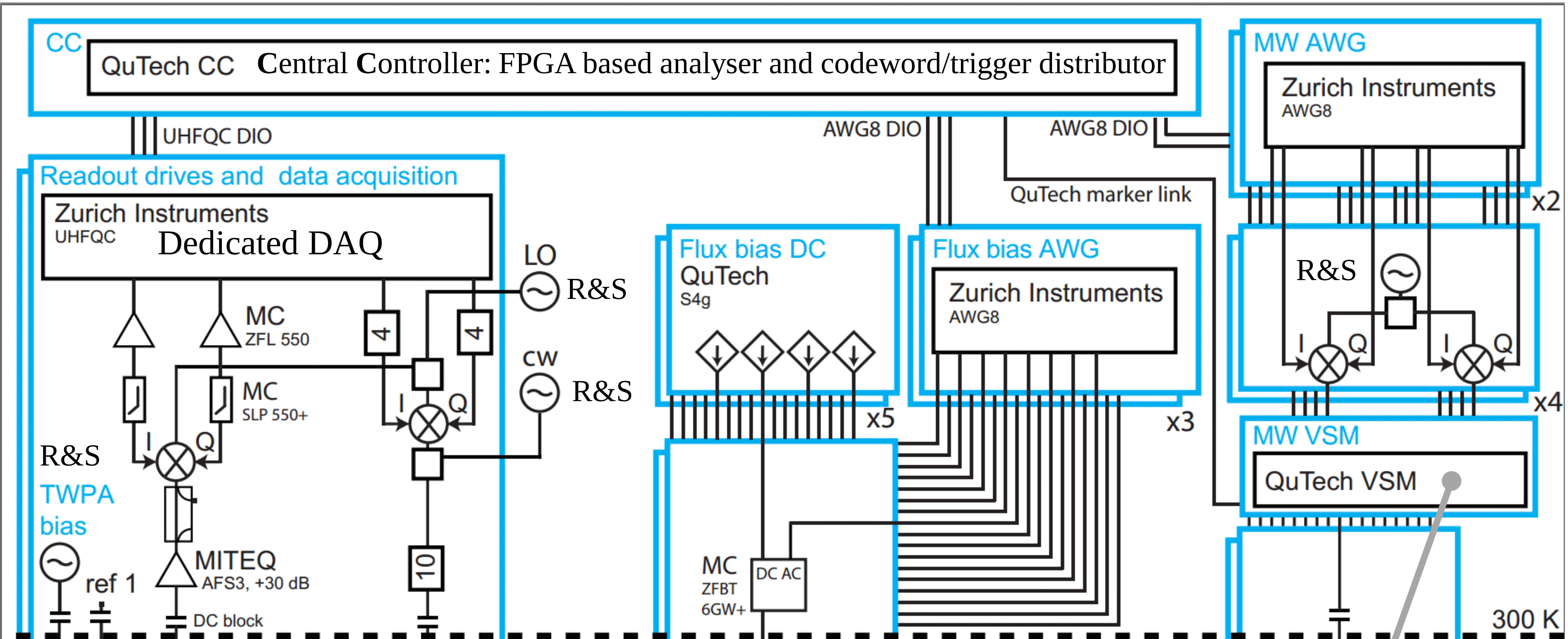
Building a Quantum Computer,

Test&Measurement needs for 17 qubit, superconducting circuits lab





Building a Quantum Computer, T&M (room temperature) needs for 17 qubit



QuTech T&M development:

Vector **S**witch **M**atrix:
Enables real-time switching between individual IQ parameters for each qubit

Microwave Vector Switch Matrix for superconducting qubit control

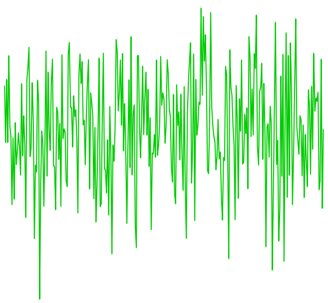
Duije Deurloo, TNO 14h00-14h25

QuTech T&M development

Low latency AWG in a feedback control loop

(application: error correction)

Measurement
(RF-readout)

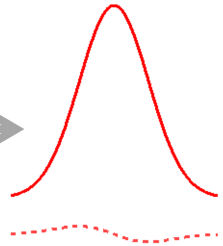


Analysis and decision

Waveform
Select and
trigger

Selected feedback signals

I quadrature



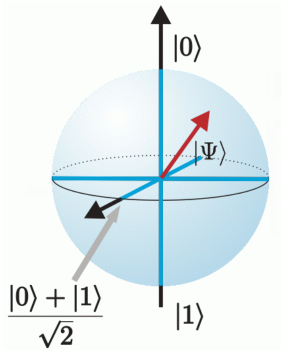
Q quadrature

CC light
(QuTech)

ADC>FPGA>control

QWG (QuTech)
6x 4chan 1 Gs/s AWG

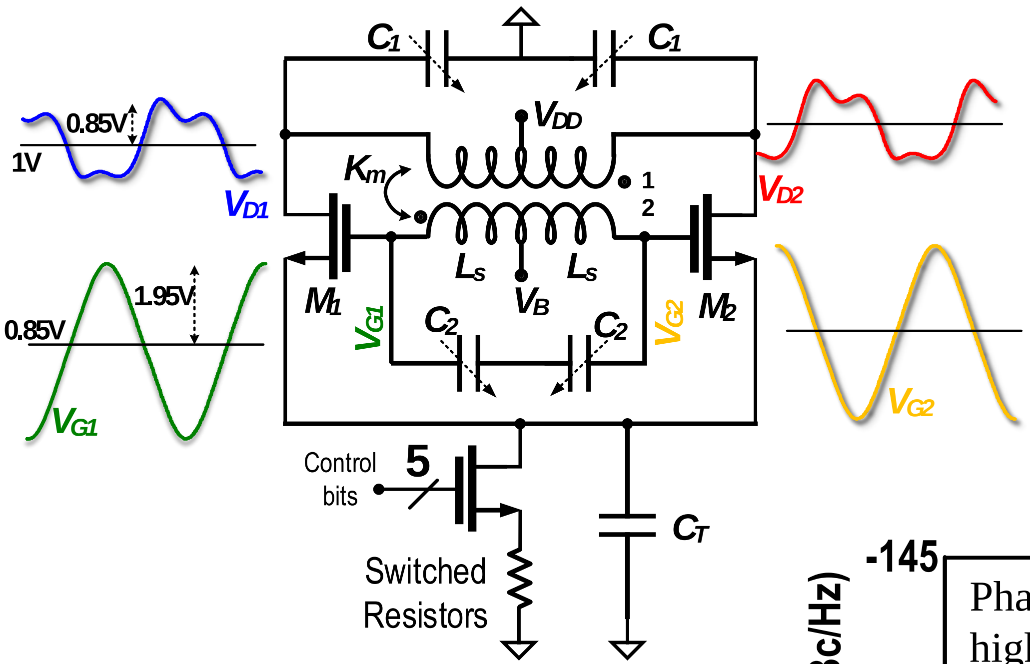
Most commercial AWGs
Have > 500ns latency



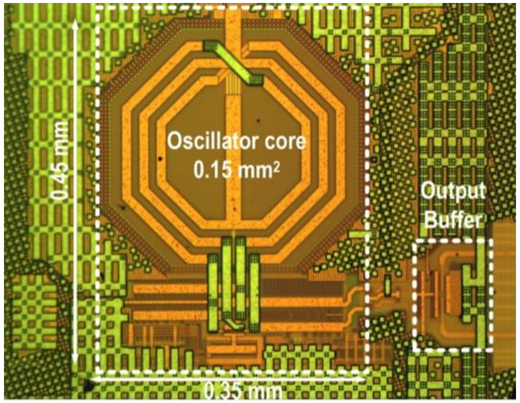
300 ns typ. **110 ns typ.** **80 ns typ.** **30 ns typ.**

Cryo-CMOS, 6GHz tunable LC Oscillator

Delft, electrical engineering dept. (Masoud Babaie, Fabio Sebastiano)



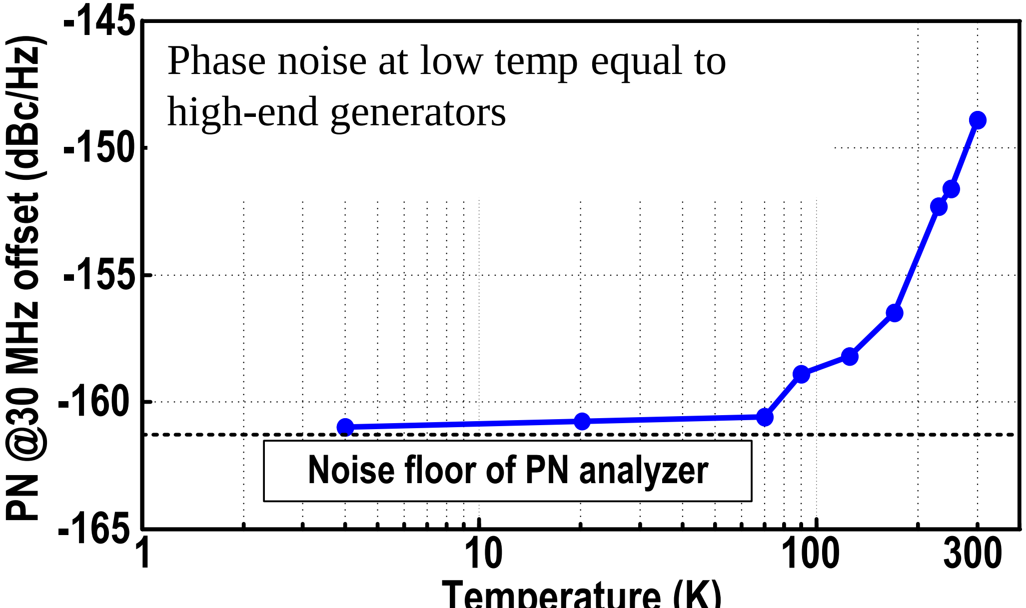
Oscillator chip: 40-nm CMOS



Tuning range: 5.7 - 7.2 GHz

Supply: 1V, 20mA

Measured phase noise:



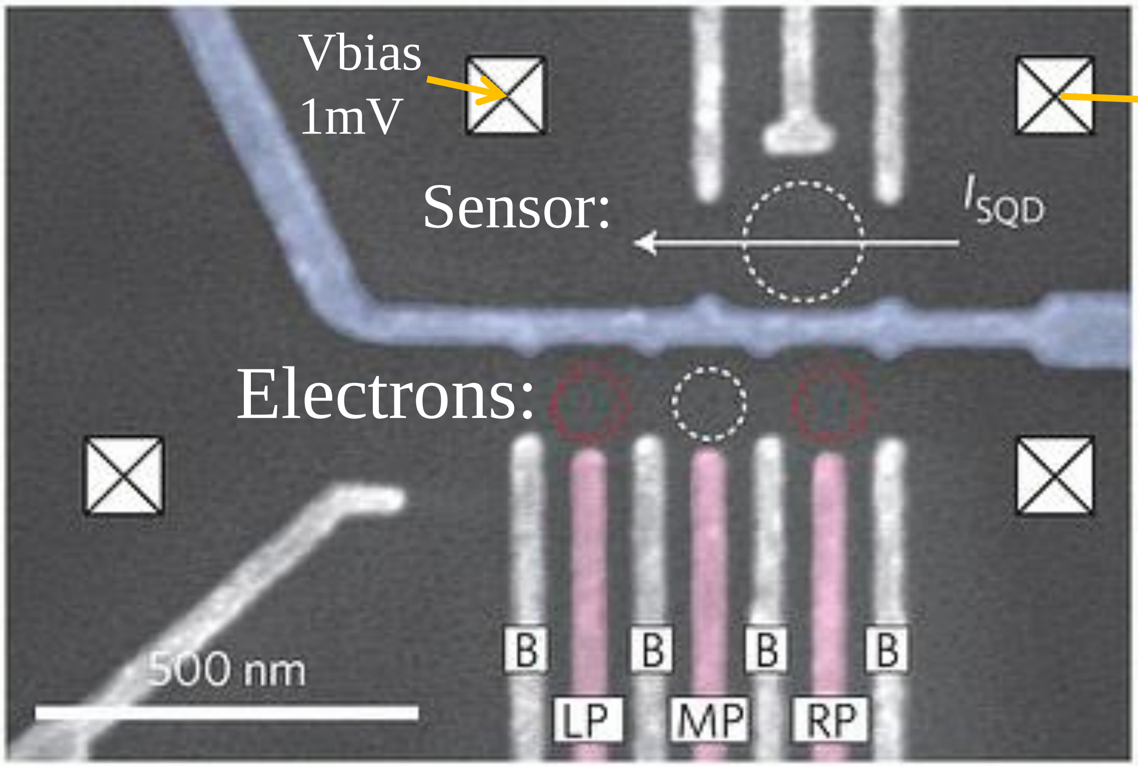
A Cryo-CMOS LNA has also been developed

[ISSCC 2017, JSSC 2017]

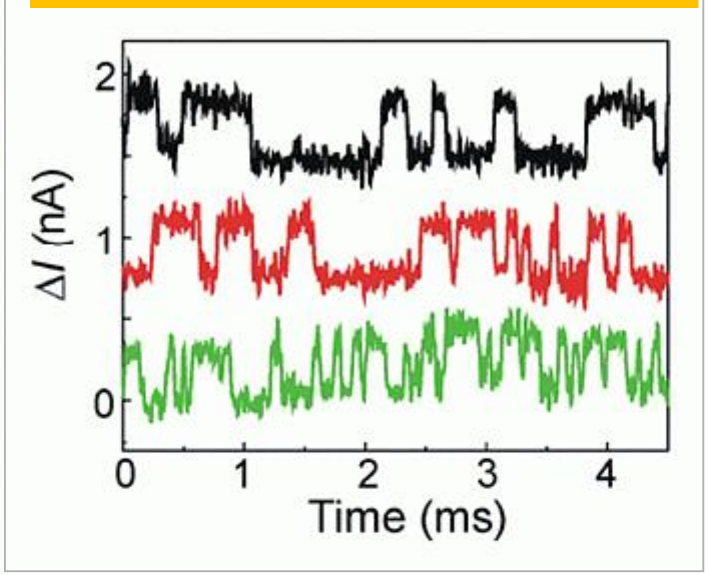
RF measurement technique example: Reflectometry

The chip from our introduction (at 20mKelvin) :

One electron passing by results in 1% change in our sensor resistance



Resistive (25kΩ) sensor readout
Sensor current traces show
Individual electrons passing :

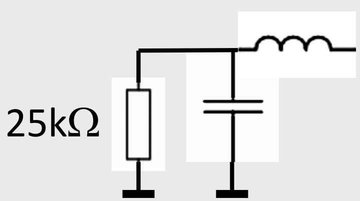


Problem: we want to detect the steps at a higher rate (ideally up to 10MHz).
However, roomtemperature based readout from this 25kΩ sensor (1mV max bias) via 3 meter wire and filters (capacitance) is technically limited to approx. 100kHz.

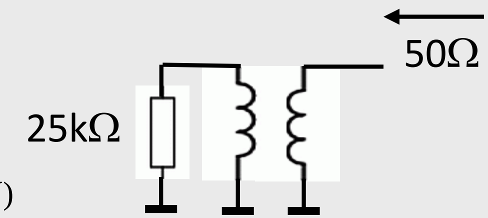
RF measurement technique example: Reflectometry

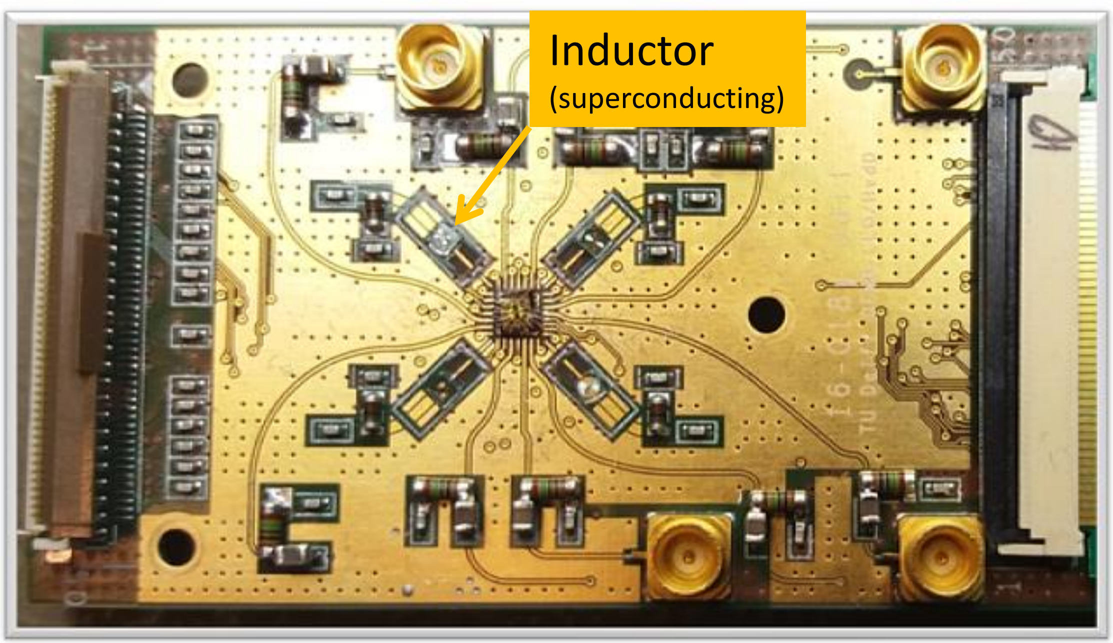
Approach:

We make the sensor resistance and the stray capacitance of the bonding pad part of an LC resonator by adding a lumped element inductor. Within the resonance bandwidth this results in an impedance transformer that we design for getting 50Ω

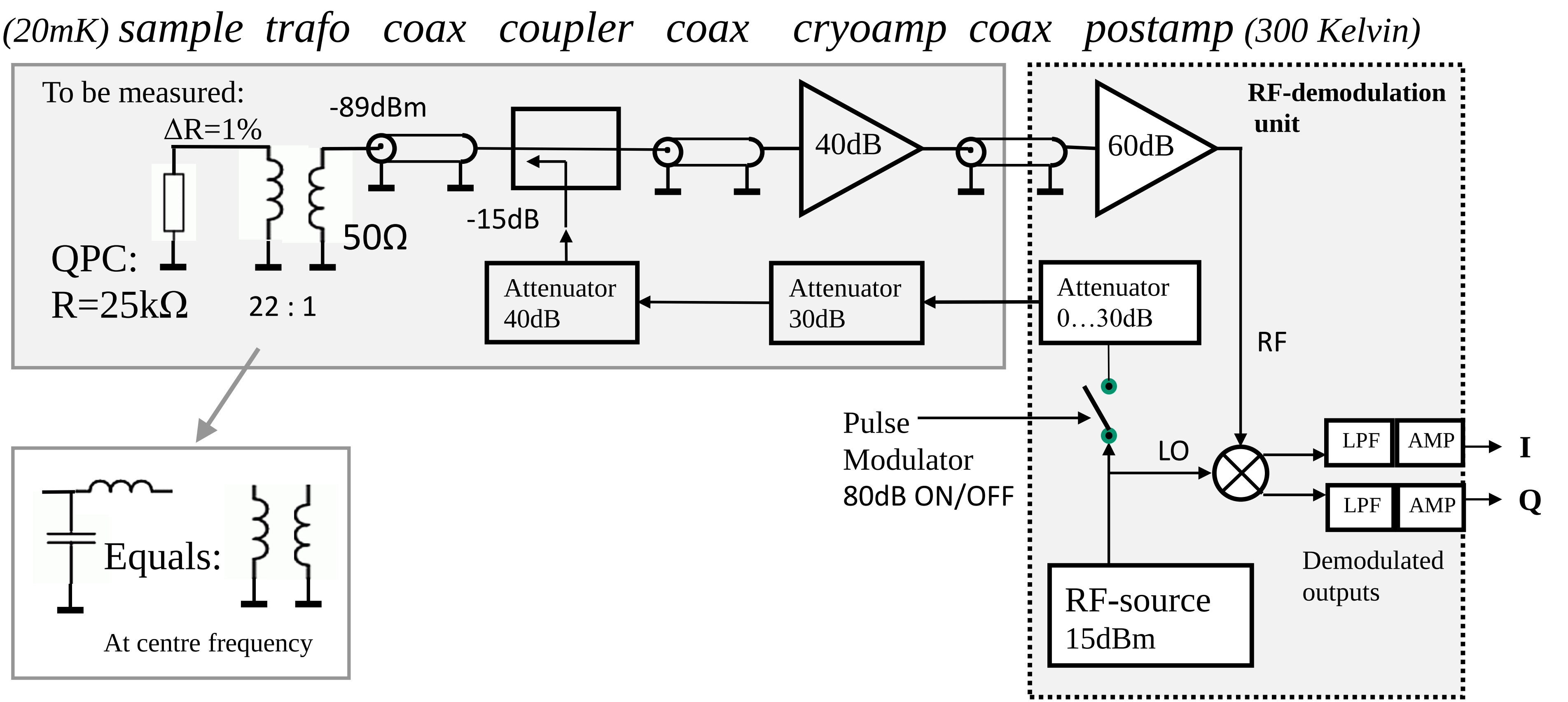


Equals:
At resonance
(centre frequency)





RF measurement technique example: Reflectometry



Signal levels:

-89dBm is send to the sample
= 1.2 pW
= 8 uVrms in 50 Ω
= 180 uVrms in 25 kΩ

Assume 1% change to be measured
= 12 fW
= 80 nVrms in 50 Ω
= 1800 nVrms in 25 kΩ

RF-reflectometry example , signal to noise ratio

Assume 1% change to be measured
Signal power P= 12 fW

System noise temperature Ts=9 K
(we use a cryoamp with input noise 4K)

S/N (power) ratio = P / kTsB

k= Boltzmann constant
B=bandwidth

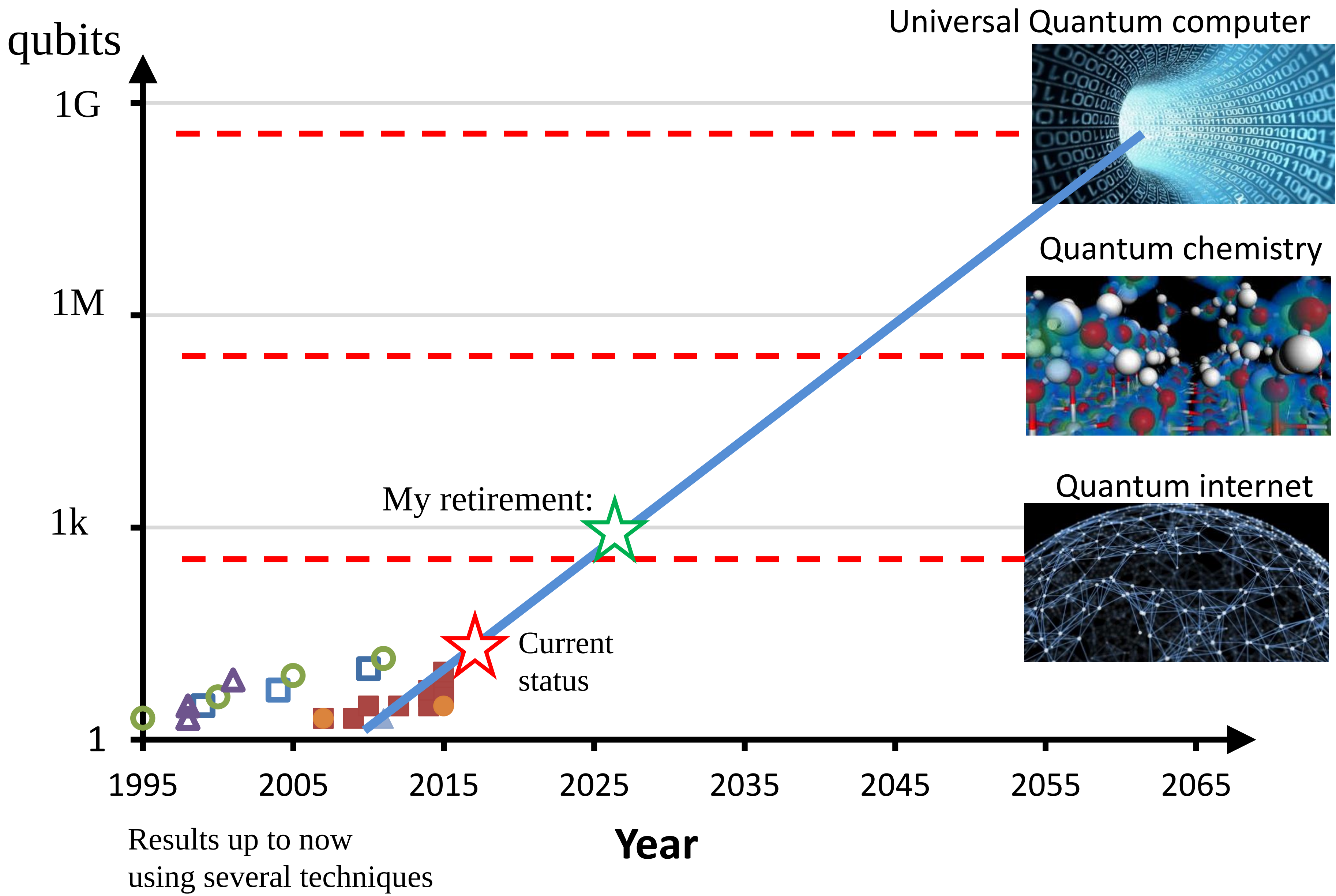
For a 10MHz bandwidth: S/N = 9:1 (power ratio)

Reflectometry readout implementation example: (40MHz-1.5GHz)

QuTech T&M development

Roundup, are we done yet ?

(What growth is expected and what is needed for applications)



Summary

- Quantum Mechanics offers weird but useful tools: *superposition* and *entanglement*
- Quantum Computing offers *unique speed-up* possibilities for certain computational areas.
- Quantum Networks offer the possibility for a *perfectly safe communication* channel

- High-end T&M equipment is used extensively in Quantum research
- World-wide interest in Quantum Computing gives a boost to research
- Expected upscaling of quantum circuits asks for dedicated scalable T&M

End of presentation