Controlling microwave superconducting elements for quantum computing and cosmology.

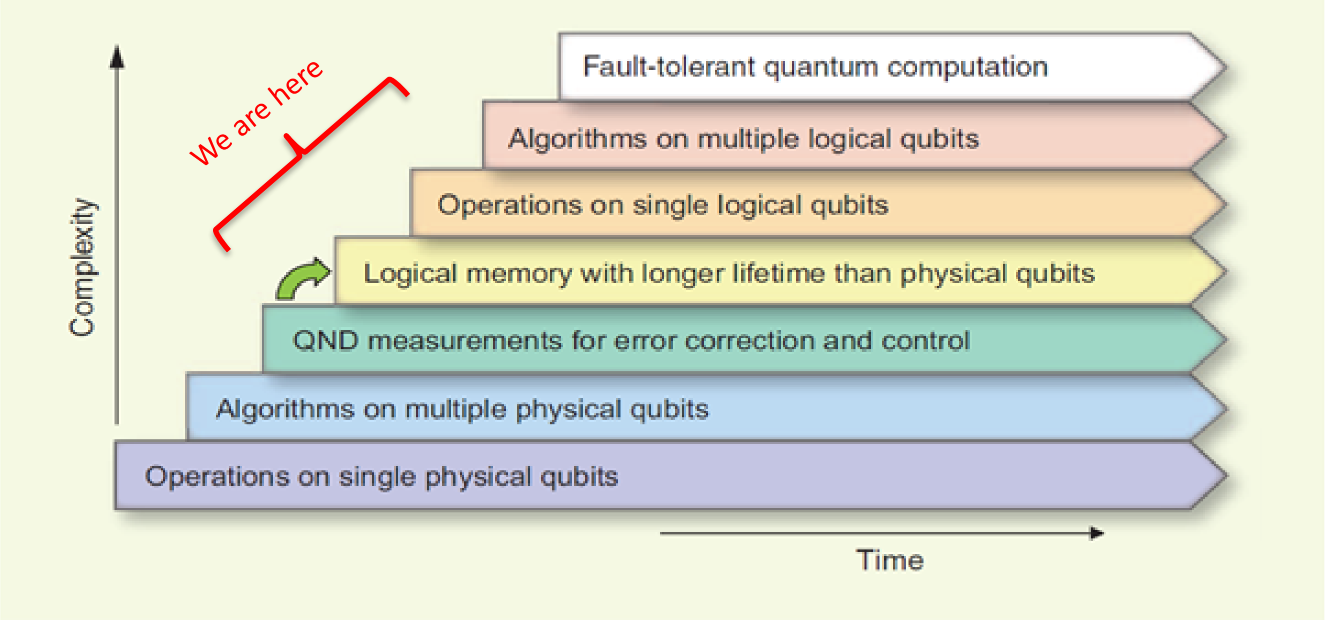
Gustavo Cancelo
Fermilab

Qubits are a concept ruled by quantum mechanic laws of physics

- It is thought that quantum bits or elements can created computers able to solve problems beyond what classical computers can solve.
- Can simulate quantum problems accurately.
- Can constitute cryptographically safe networks using entanglement and teleportation.
- Can improve sensors in search of fundamental problems of physics and cosmology.

- Qubits can be architecturally and technologically diverse (too many to enumerate):
- Architectural models: 2 level qubits, multi level qubits (qudit), quantum memories, etc.
- Technological materials: optical, superconducting, cryogenic, room temperature, silicon, etc.
- Macroscopic (micron or mm size) systems can behave as a single atom or particle.
- R&D in QIS is pushing in all those aspects: better qubits, better models, better materials.

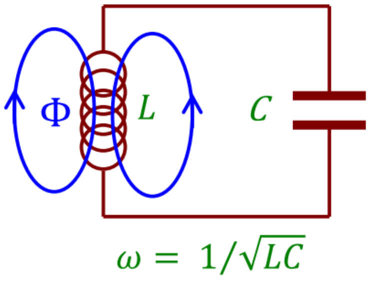
Quantum Computing

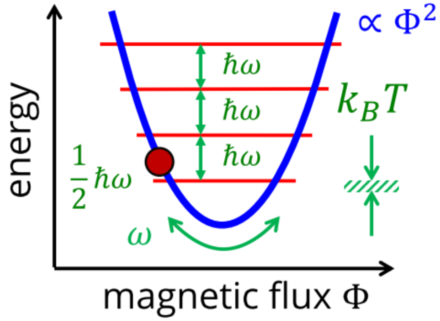


Quantum Controls is critically important:

- **Is the interface between the quantum and classical worlds.**
- **Controls and readout belong to classical physics**
  - **Control pulses prepare the state of a qubit and**
  - **Readout pulses measure the binary state of the qubit because the wavefunction collapses.**

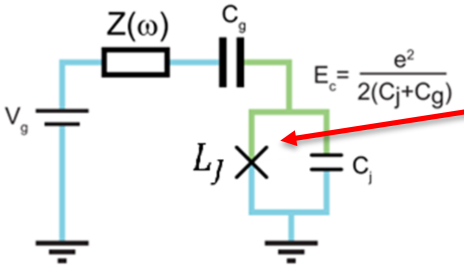
The difference between a qubit and the quantum harmonic oscillator



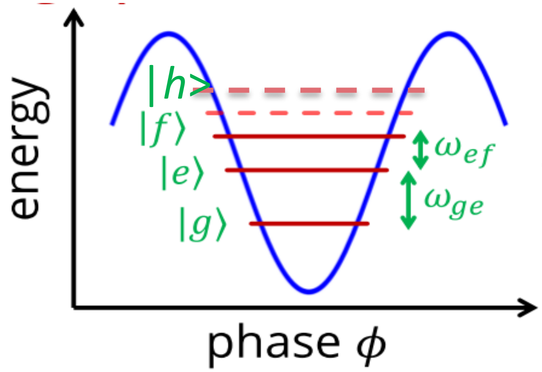


- In the harmonic oscillator the energy levels are equally spaced
- A Qubit needs anharmonicity to be controllable.

The Cooper pair box (the simplest SC-Qubit model)



The oscillator’s inductance has been replaced by a nonlinear inductance, a Josephson junction.



Now the energy levels are not equally spaced
We can control that device using different RF frequencies.
$h\omega_{ge}$ will take it from the ground to the excited state

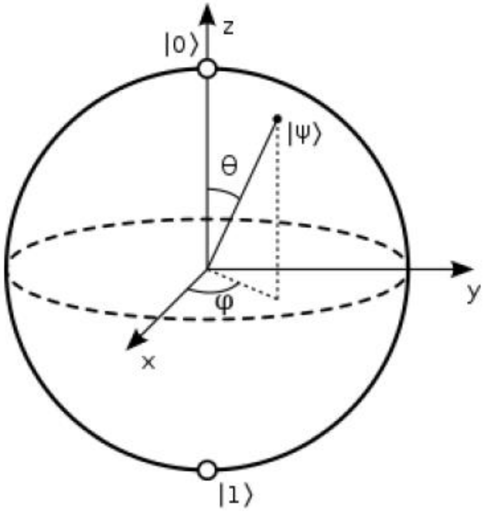
Qubit dynamics: qubit in isolation or “undressed”

- It follows the Schrodinger equation.
- $i\hbar \frac{\partial|\varphi>}{\partial t} = H|\varphi >$ H is the Hamiltonian, φ is the wavefunction and ħ is the Plank constant.

In polar coordinates:

$$\varphi(x,t) = \cos\left(\frac{\theta}{2}\right)\varphi_0(x) + \sin\left(\frac{\theta}{2}\right)\varphi_1(x)e^{i\emptyset}$$

The Block sphere



A general wave function state |φ> is in a superposition of the base states and collapses to |0> or |1> when measured.
The famous Schrodinger's cat paradox!

We can obtain information of the wave function by calculating probabilities

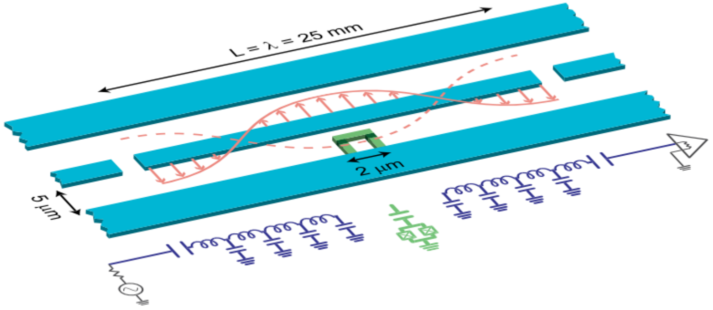
$$P(x,t) = |\varphi(x,t)|^2$$

Experiments are repeated >10K times

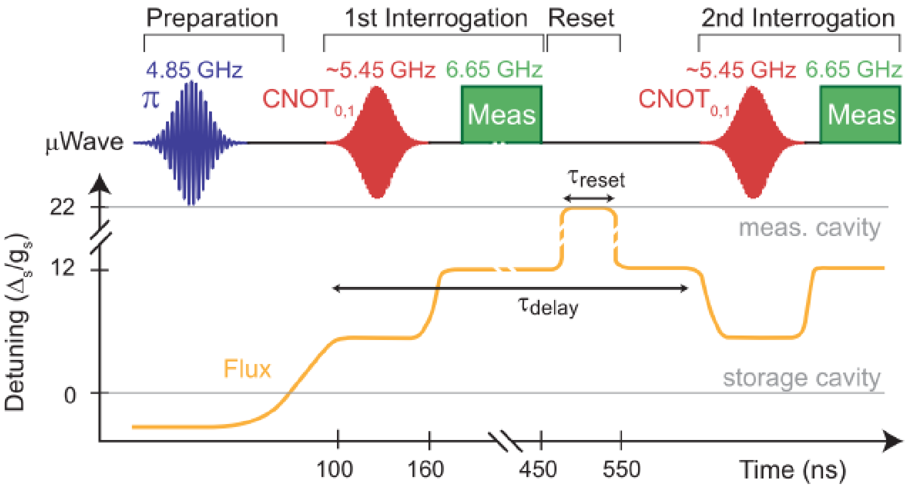
The qubit is placed inside a resonant cavity (“dressed”)

- The Jaynes-Cummings Hamiltonian governs the cavity-qubit dynamics

$$H_{\mathrm{JC}} = \underbrace{\hbar\omega_{\mathrm{r}}(a^{\dagger}a + 1/2)}_{\text{cavity}} + \underbrace{\hbar\frac{\omega_{\mathrm{a}}}{2}\sigma_{\mathrm{z}}}_{\text{qubit}} + \underbrace{\hbar g(a^{\dagger}\sigma^{-} + a\sigma^{+})}_{\text{Cavity-qubit coupling}}$$



The matrix is infinite dimensional, but using the anharmonicity, we can create a system that only allows jumps between 2 states. (or more if we want!)

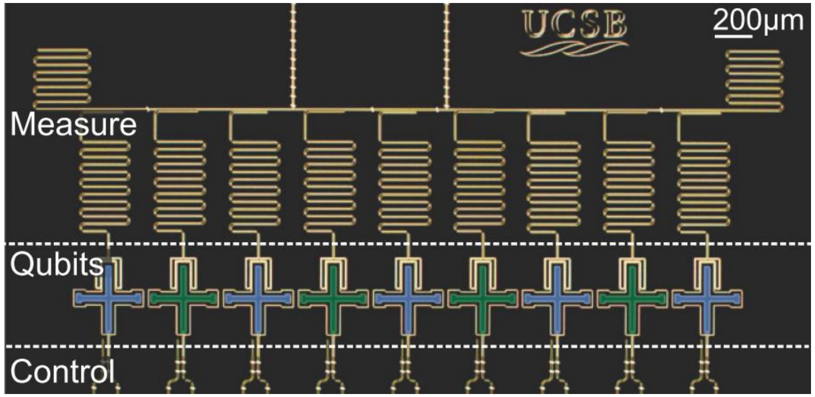


Example: Single transmon or fluxonium with fast flux control

RF control and readout channel

Fast flux control channel

Qubit state readout: Example: a 9 qubit transmon from UCSB



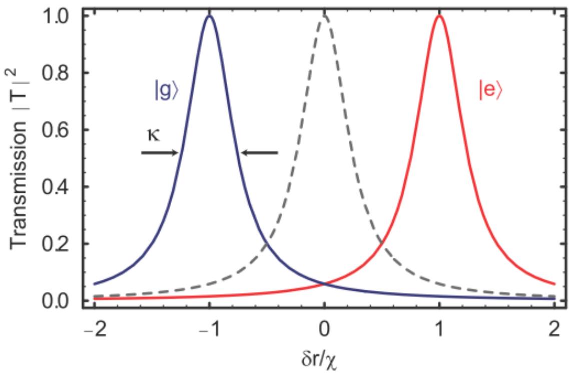
Individual qubit controls

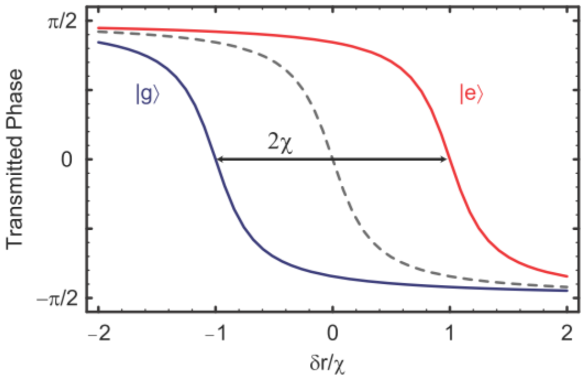
Single readout. Qubits are frequency multiplexed to an RF line.

What do we measure?

How do we know the state of the qubit?

We measure amplitude and/or phase of the transmitted power over the RF readout line: S21



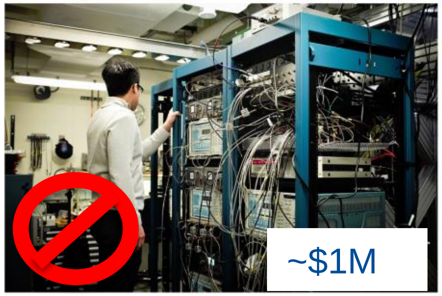


Quantum non demolition: The qubit projects its state on the cavity.
Single shot measurements are difficult due to S/N ratio. Many measurements to average noise.

Fermilab control and readout replaces expensive commercial equipment and messy cabling and discrete RF components.

Currently at IBM and most QIS big labs

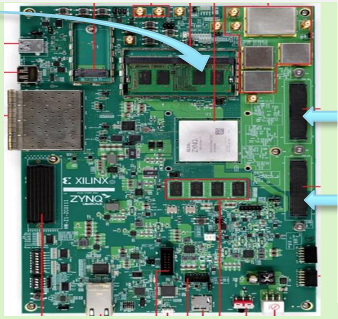
Quantum Experience.



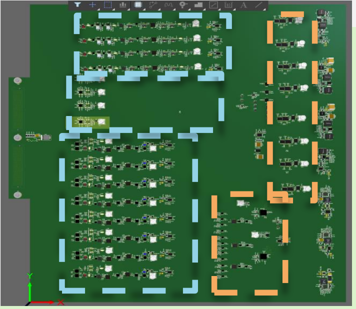
No Missed Connections
Jerry M. Chow, PhD, manager of theory of quantum computing and information at IBM Research, inspects the cables connecting a vast array of microwave equipment powering quantum computing processors in the lab.

Gen3 (RFSoC) : FNAL Readout and Control: Up to ~80 qubits/module (if FMUXed) >1000 qubits/system

FPGA+ADC+DAC+memory+interfaces

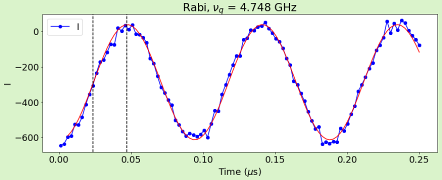


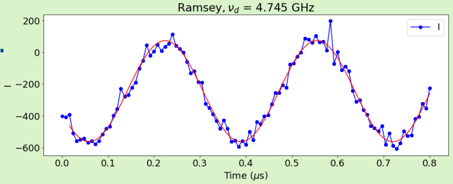
RF inputs, outputs, LO, fast flux control, high precision bias



FNAL Gen3 electronics stakeholders:

- U. Chicago: Davis Schuster lab.
- U Princeton: Andrew Hock lab.
- Fermilab: SQMS (A. Grassellino)
- Fermilab: QSC Thrust 3 (A. Chou)
- UCSB: Ben Mazin Lab.
- U. Perdue: Alex Ruichao Ma.
- IIT-FNAL: Rakshya Khatiwada.
- Fermilab CMB MKIDs (B. Benson).
- Fermilab DM MKIDs: Noah Kurimsky.
- Fermilab DE MKIDs: Juan Estrada.

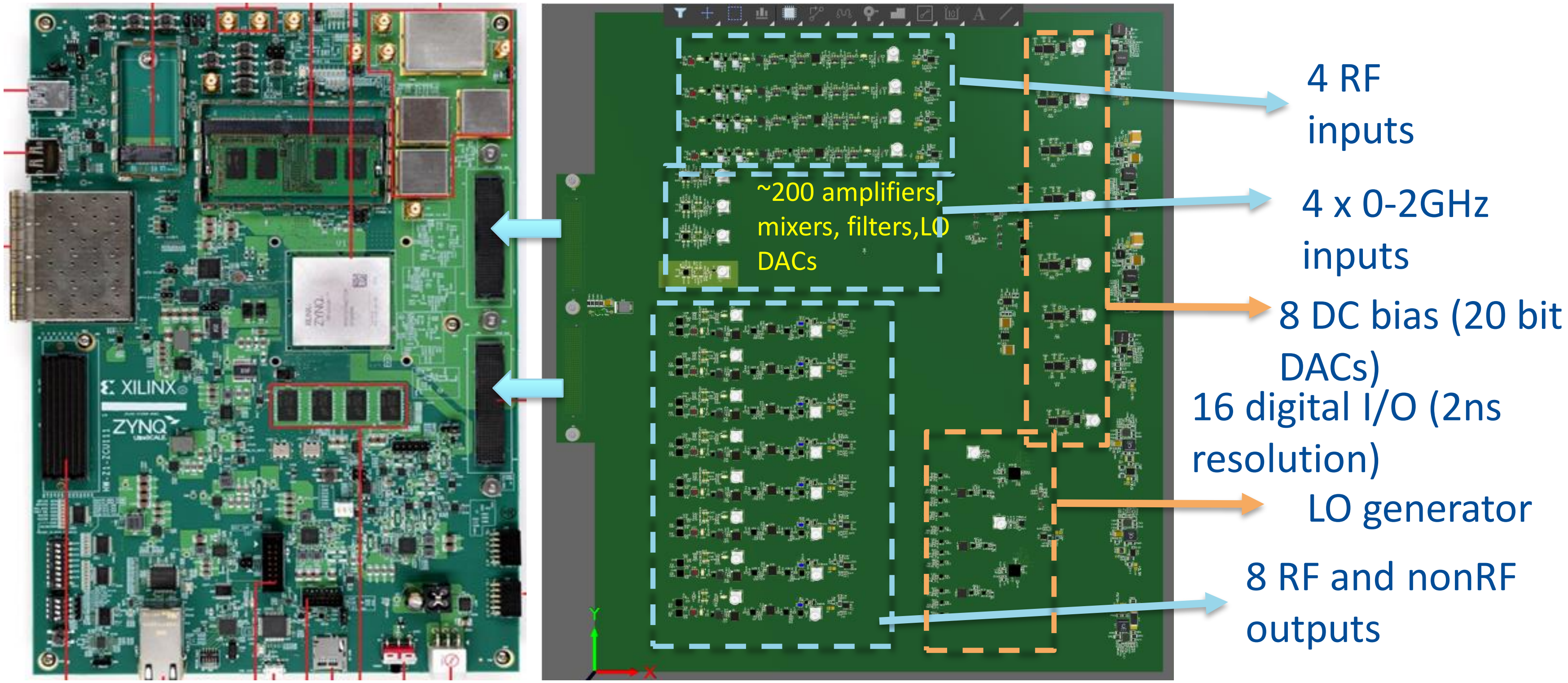




Qubit measurements at U. Chicago.
D. Schuster lab

FNAL Readout and Control electronics

The RF board is in fabrication, to arrive at FNAL on April 15th.



4 RF inputs

4 x 0-2GHz inputs

8 DC bias (20 bit DACs)

16 digital I/O (2ns resolution)

LO generator

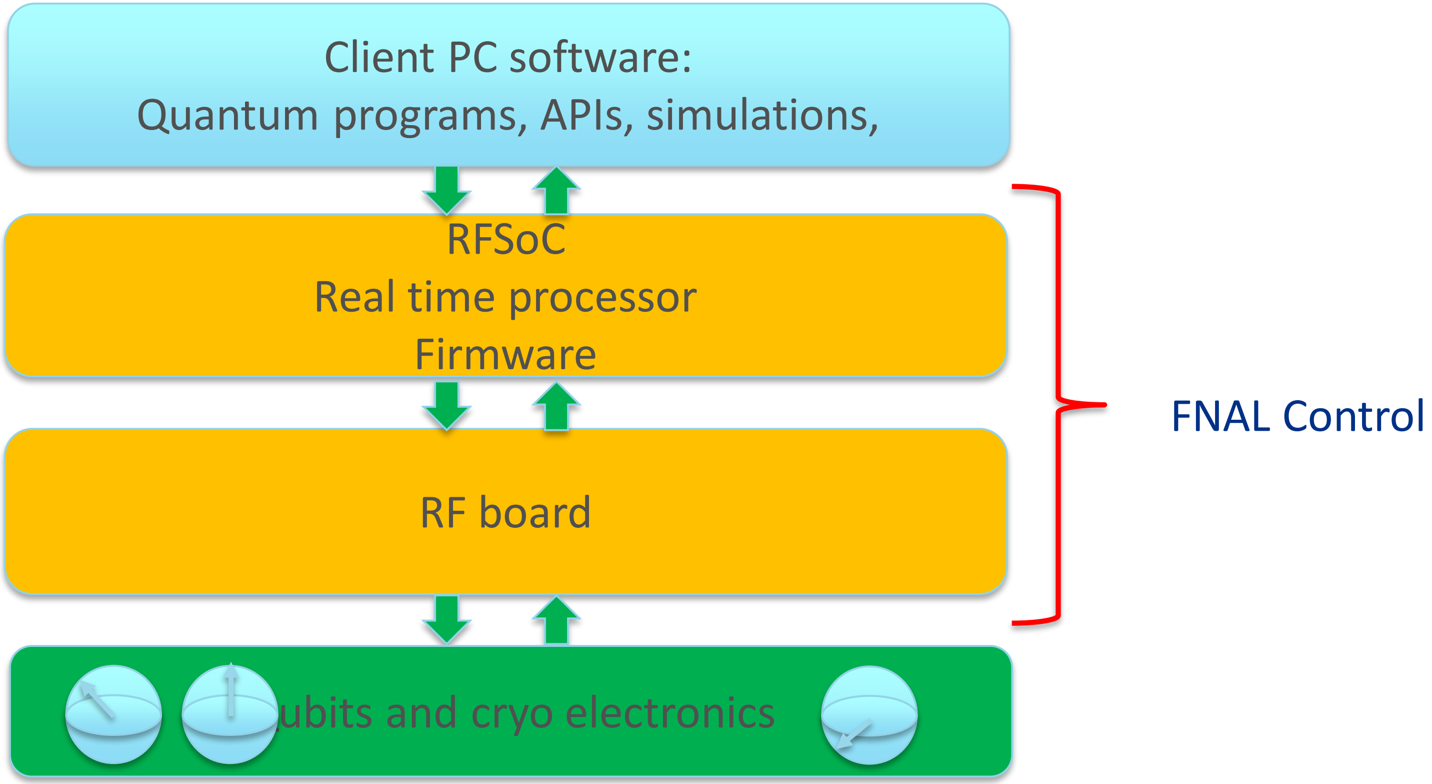
8 RF and nonRF outputs

FPGA+ADC+DAC+memory +interfaces

RF inputs, outputs, LO, fast flux control, high precision bias,

More than 200 amplifiers, mixers, filters, LO generators, etc.

Control software, firmware and hardware



Client PC software:
Quantum programs, APIs, simulations,

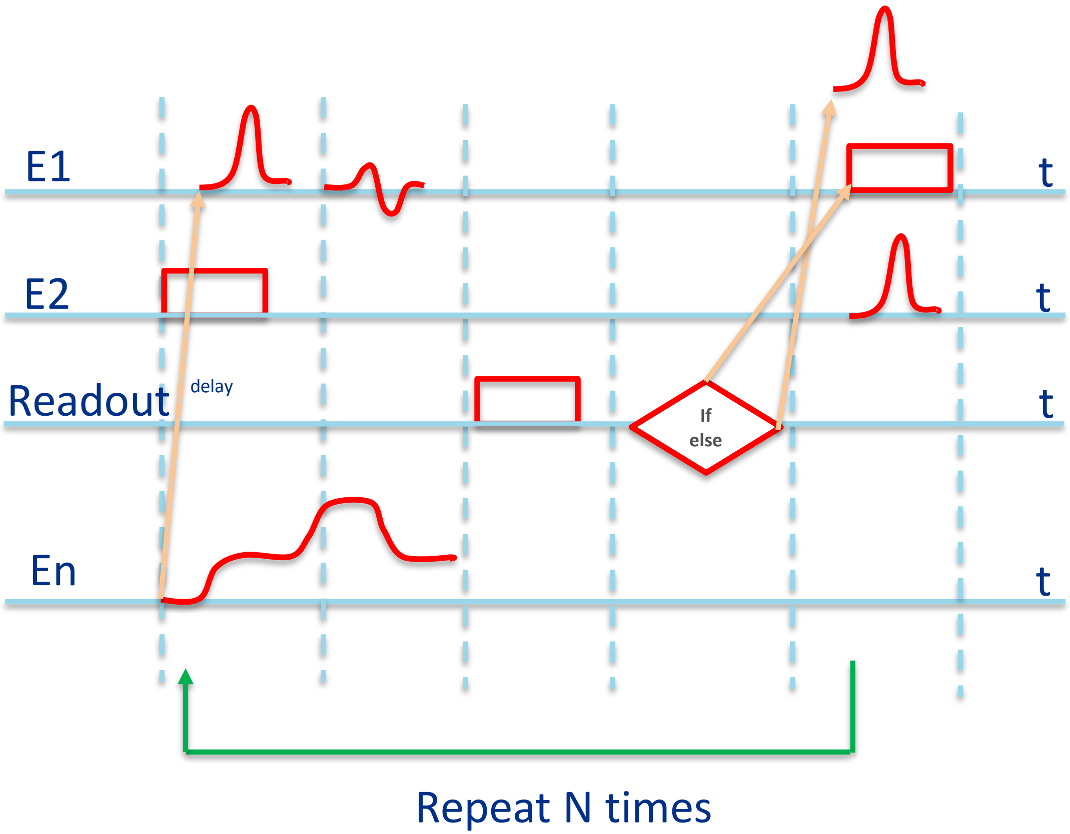
RFSoC
Real time processor
Firmware

RF board

ubits and cryo electronics

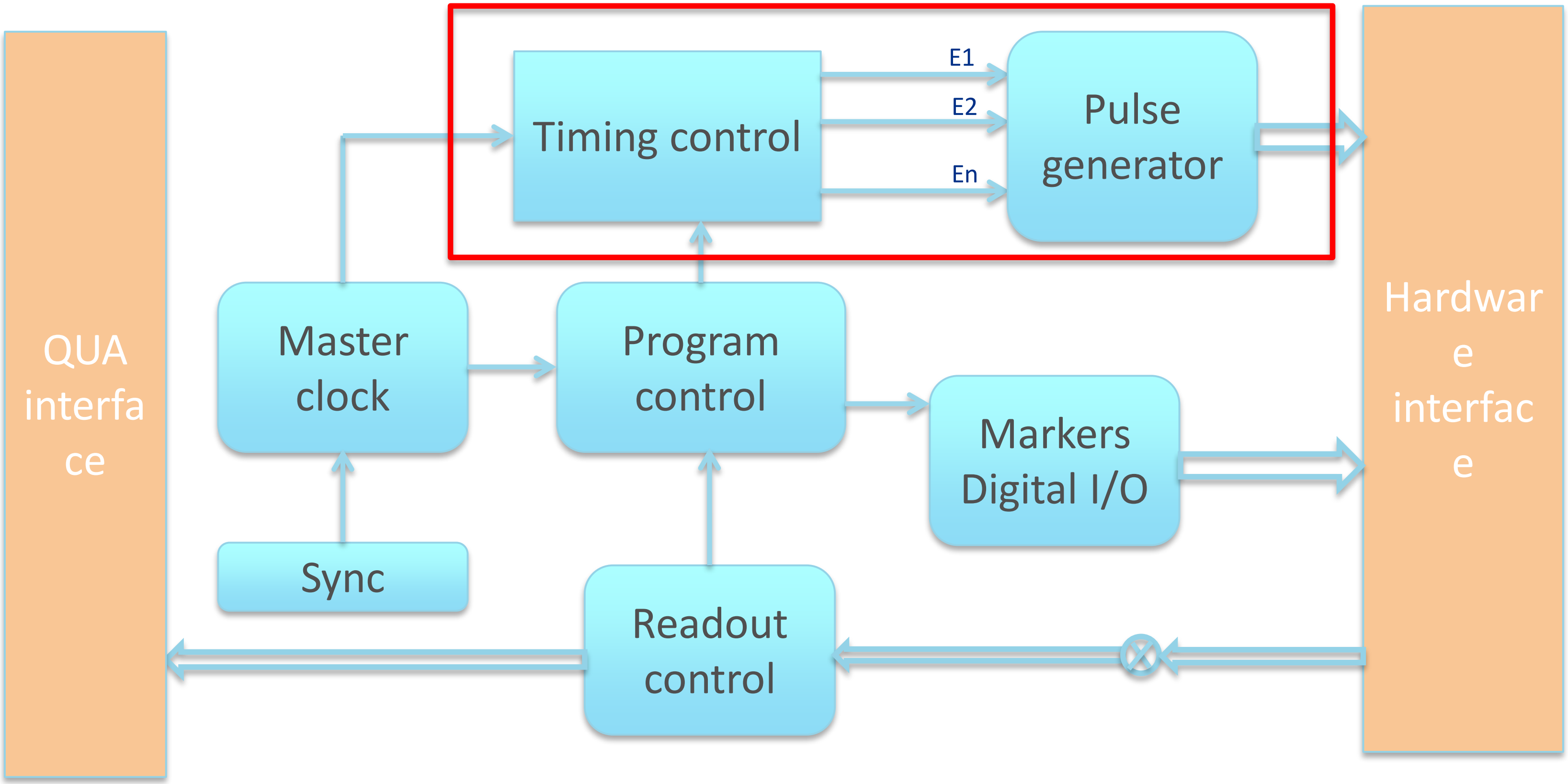
FNAL Control

Parallel computing

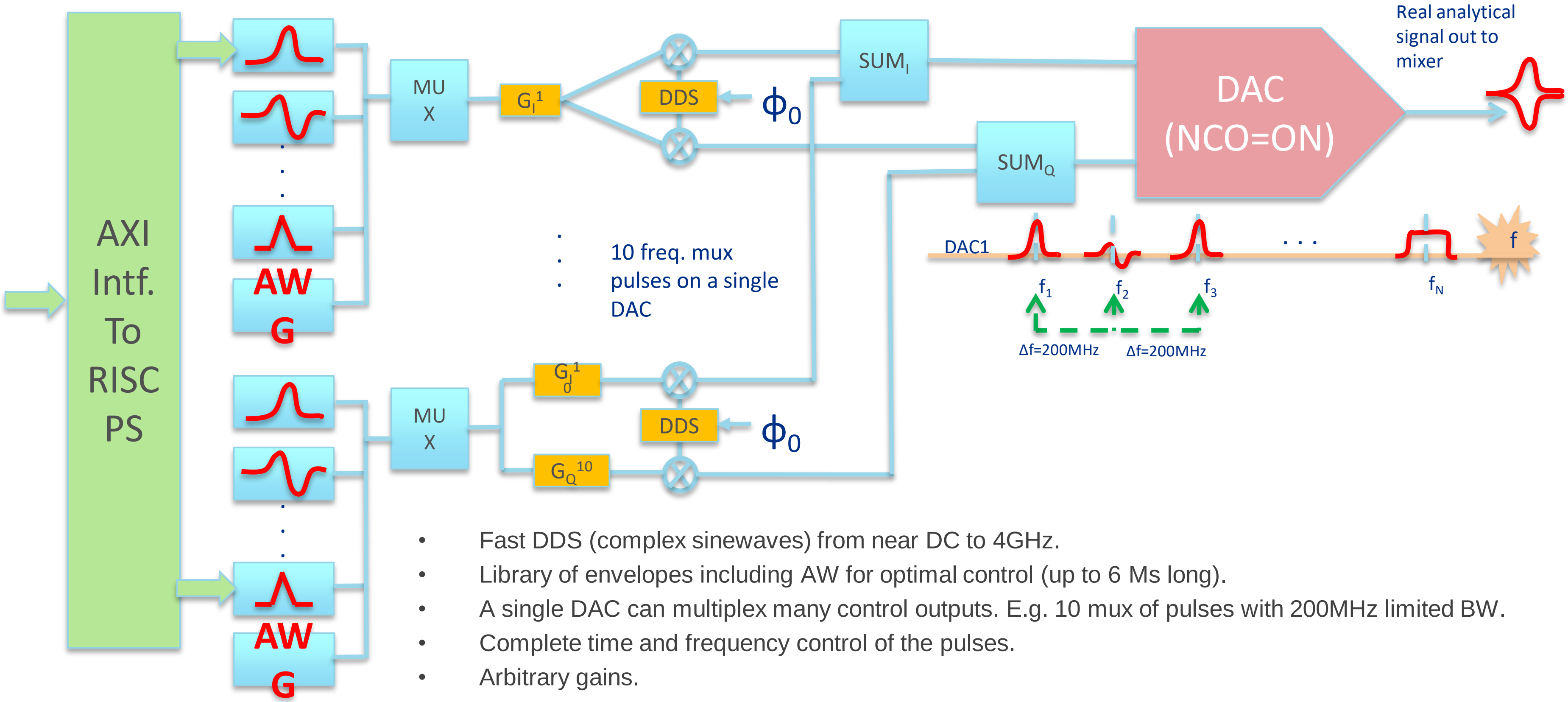


- Things may happen to all elements at once, things may happen at times defined by an offset.
- Allow for conditional programming.
- Allow for deterministic and conditional loops.
- Allow for pulse parameters such as:
  - Amplitude, phase, delay, time duration.

Multiple qubit programming model, multiple elements.

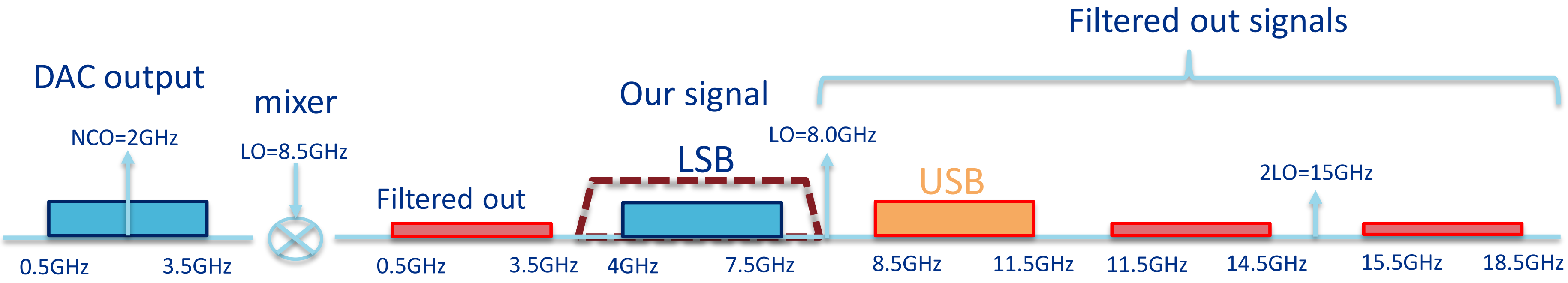


Pulse generator (one DAC shown) for outputs



- Fast DDS (complex sinewaves) from near DC to 4GHz.
- Library of envelopes including AW for optimal control (up to 6 Ms long).
- A single DAC can multiplex many control outputs. E.g. 10 mux of pulses with 200MHz limited BW.
- Complete time and frequency control of the pulses.
- Arbitrary gains.
- Initialized by software, dynamically run at firmware speed.
- Low latency, allows error correction algorithms.

Performance



Filtered out signals

DAC output

mixer

Our signal

NCO=2GHz

LO=8.5GHz

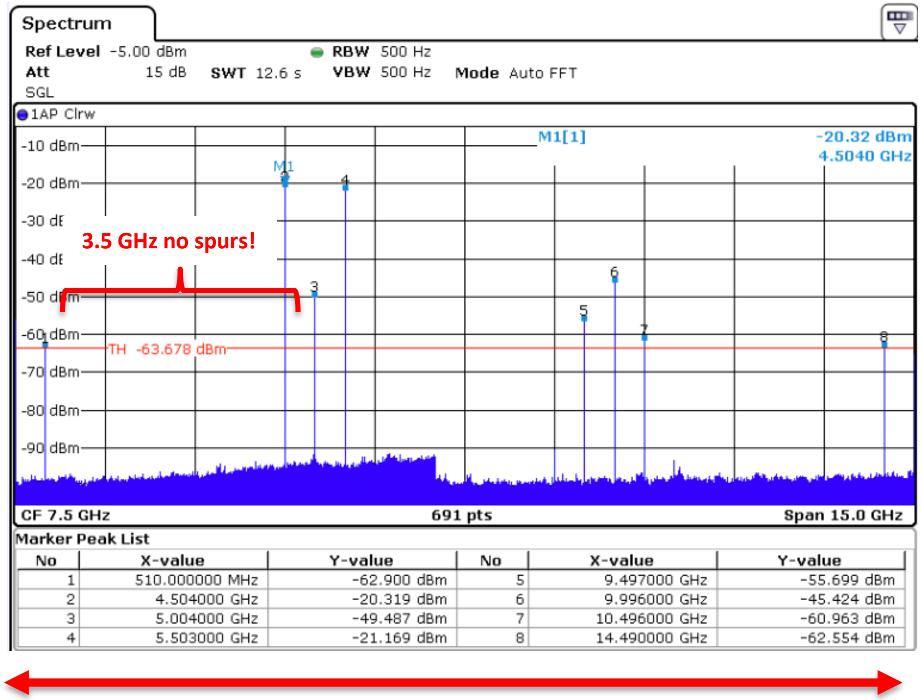
LSB

LO=8.0GHz

USB

2LO=15GHz

Filtered out



Spectrum

Ref Level -5.00 dBm RBW 500 Hz

Att 15 dB SWT 12.6 s VBW 500 Hz Mode Auto FFT

SGL

1AP Clrw

M1[1] -20.32 dBm 4.5040 GHz

TH -63.678 dBm

CF 7.5 GHz 691 pts Span 15.0 GHz

3.5 GHz no spurs!

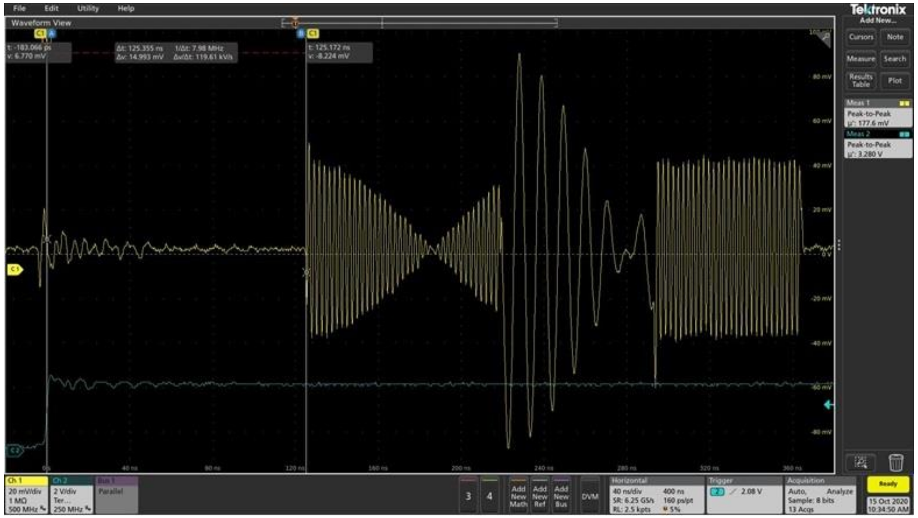
Marker Peak List

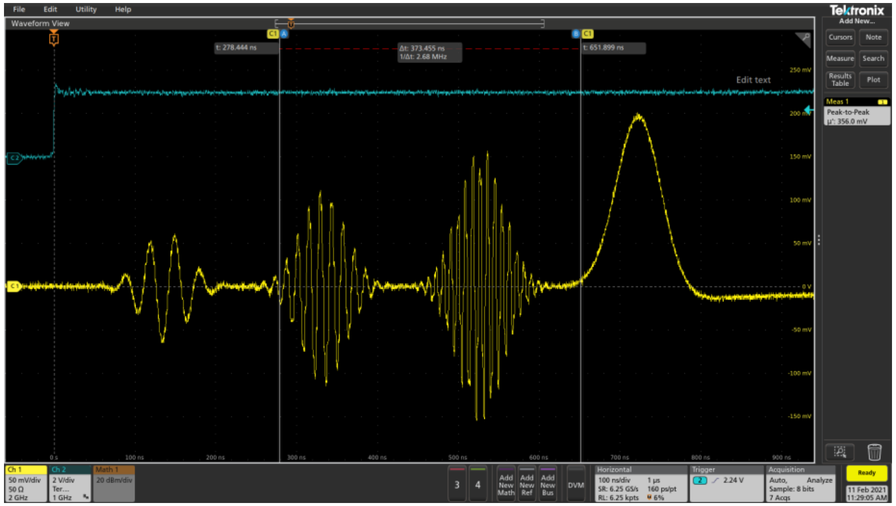
No	X-value	Y-value	No	X-value	Y-value
1	510.000000 MHz	-62.900 dBm	5	9.497000 GHz	-55.699 dBm
2	4.504000 GHz	-20.319 dBm	6	9.996000 GHz	-45.424 dBm
3	5.004000 GHz	-49.487 dBm	7	10.496000 GHz	-60.963 dBm
4	5.503000 GHz	-21.169 dBm	8	14.490000 GHz	-62.554 dBm

15 GHz span

Due to fast digital DDS and DSB mixer, there are no spurs in the operational spectrum 4-8 GHz. No spurious signals exciting qubit modes by mistake.

All control signals are synchronized to the qubit reference frame

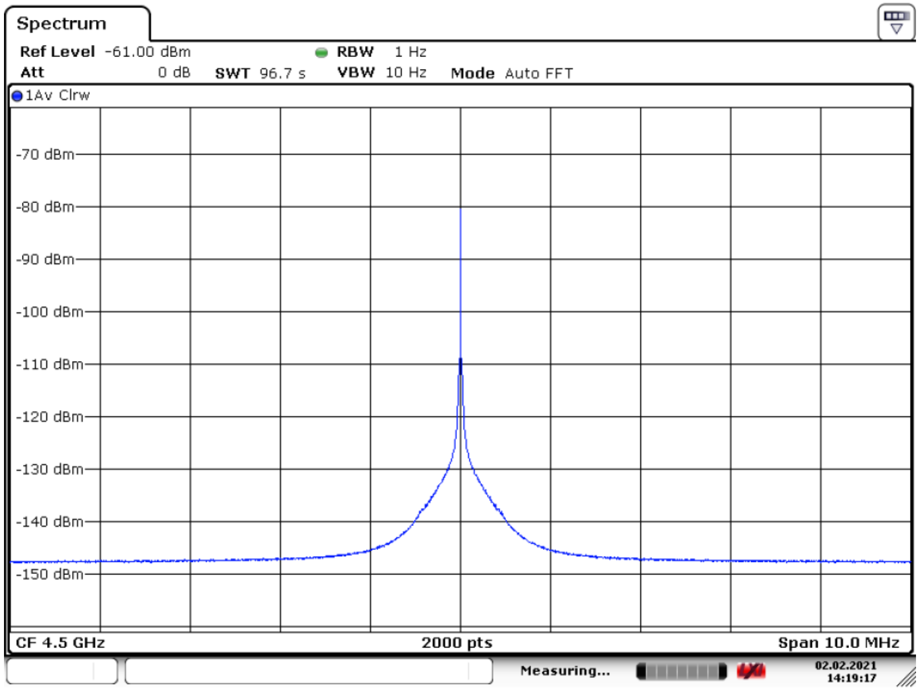




Several sine waves at different Freq. synced to phi=0 at t=0

Gaussian pulses modulating a fast DDS IF

Close in noise and stability



Spectrum

Ref Level -61.00 dBm
Att 0 dB **SWT** 96.7 s **RBW** 1 Hz **VBW** 10 Hz **Mode** Auto FFT

● 1Av Clrw

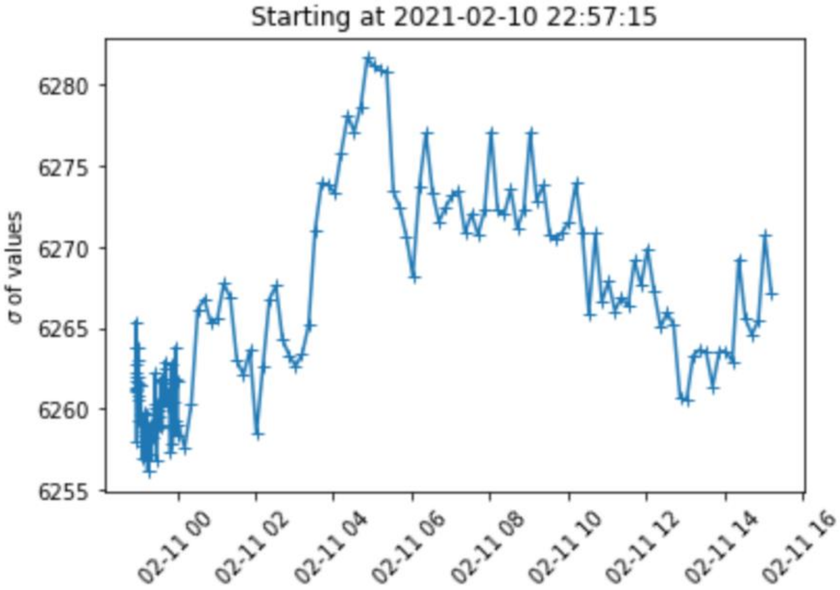
CF 4.5 GHz 2000 pts **Span** 10.0 MHz

Measuring...

02.02.2021 14:19:17

Date: 2.FEB.2021 14:19:17

Phase noise -145dBc/Hz at 1MHz

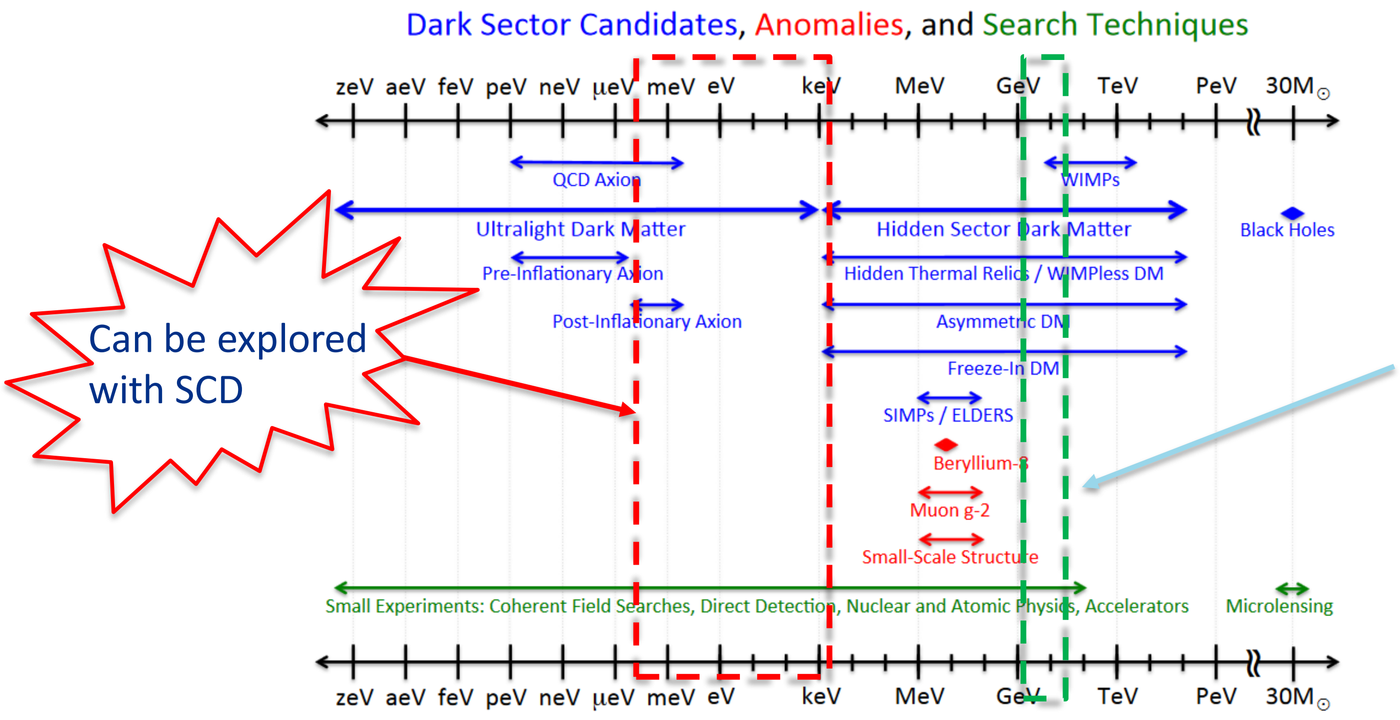


Tone drift over 16 hours: ~7e-4

- a

Superconducting detector/element map

- Light Dark Matter: searching for low energy WIMPs and Axions.

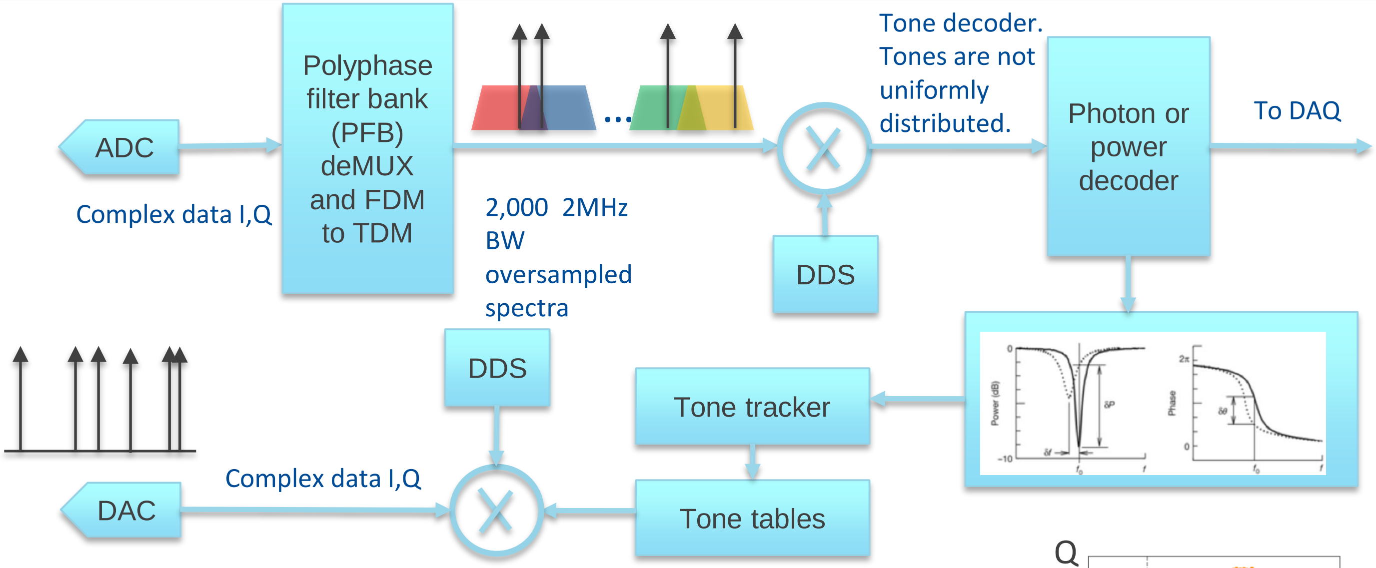


Can be explored with SCD

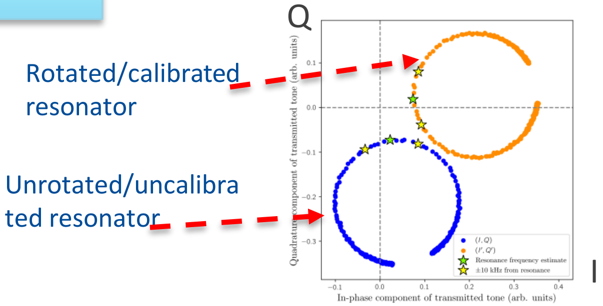
Large mass detectors (e.g. the liquid xenon LZ) are close explore down to 10^{-48}.
Solar Neutrino floor?

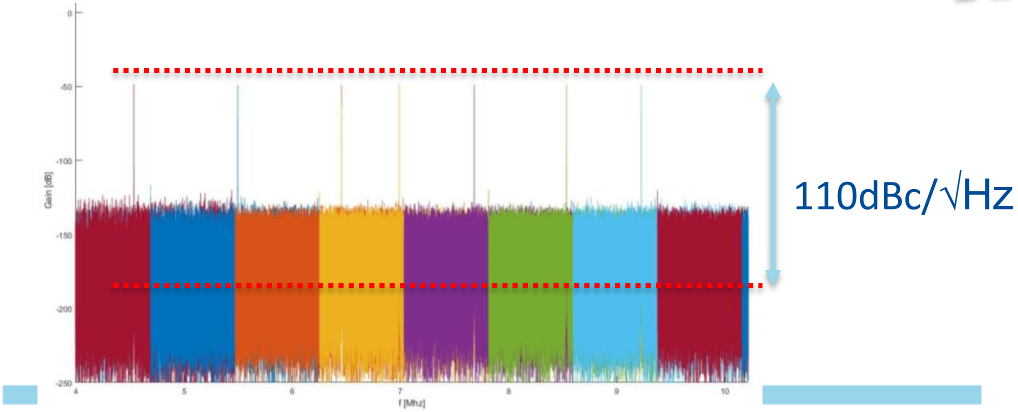
- Superconducting elements in 2D or 3D can also be used in:
  - Dark energy: CMB and Low-resolution spectroscopy of billions of galaxies.
  - Quantum computing.

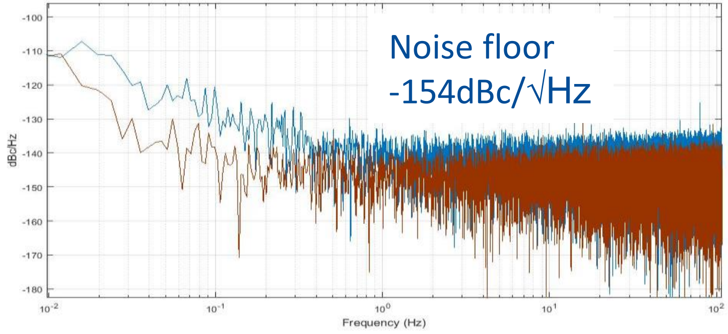
Firmware and software (RF part not shown)



- Software must find resonant frequencies, calibrate powers, rotate I, Q loops, calculate resonator parameters, program Tone tables or DDS.
- Take data and make images.







Team: Fermilab, ANL, U. Chicago, Instituto Balseiro (Argentina)

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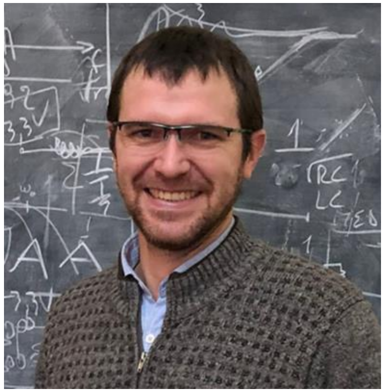


Sara Sussman (U. Princeton)

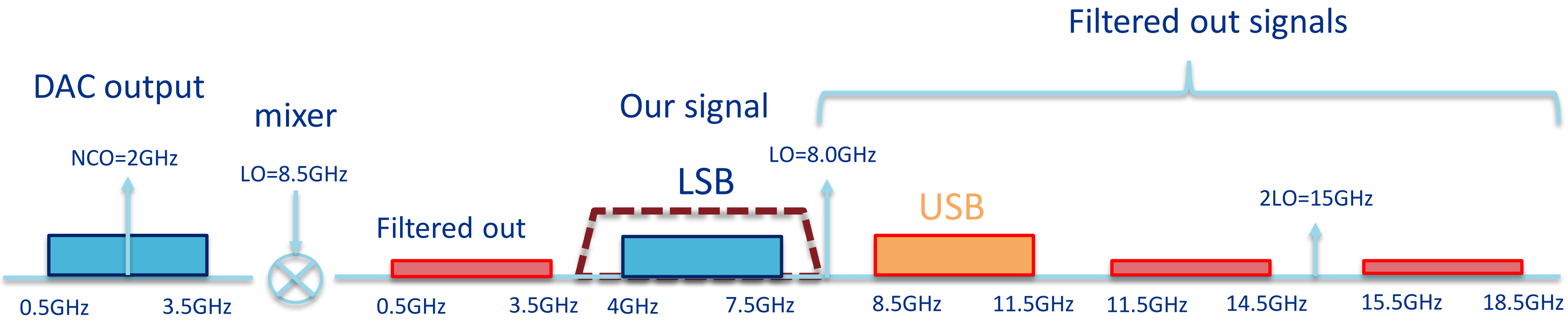
Chris Stoughton (FNAL)

David Schuster (U.Chicago)

Gustavo Cancelo(FNAL)

Thank you

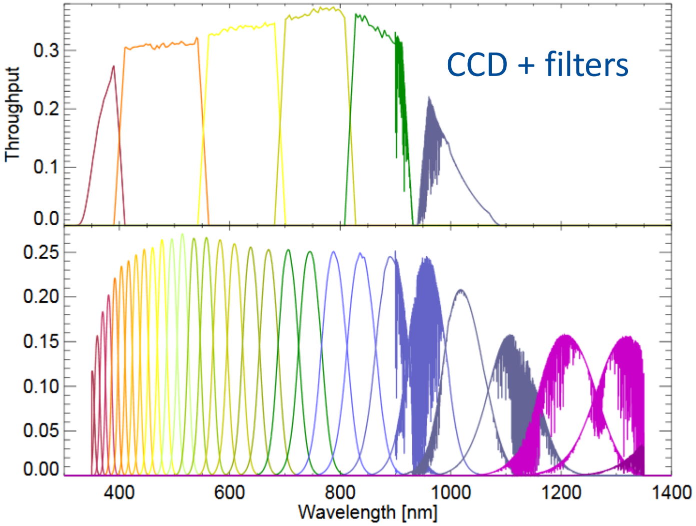
Bandpass filter to clean up the spectrum

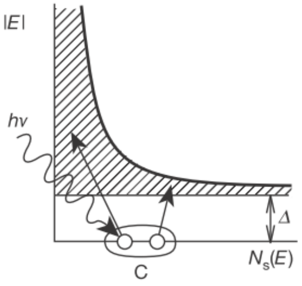


- Readout (Firmware)
- Functions that are already implemented:
  - Averaging scope: an experiment is run N times, every time generates M samples, the saved result is the N-average of M-long vector.
  - Qubit state: the readout generates a single complex value which describes the state of a qubit (or several values for more than one qubit). N readouts generate N different values.
  - The qubit state can be used for fast feedback and error correction.

Advantages of superconducting elements

- SC elements are operated at 30-100mK << $T_{critical}$ and << than the T of a 5-100 GHz photon used in sensors or qubits.
  - At $T_{operation}$ << $T_{critical}$ superconducting materials have very stable parameters.
- In a sensor a single photon (from the CMB or optical spectrum) generates thousands of quasiparticles that can be measured.
  - Enough quasiparticles to measure single photon wavelength with resolution of R~100 in the optical/near IR





Bandgaps of ~10meV
1,000+ quasiparticles allow low resolution spectroscopy without external filters.

MKID: Microwave Kinetic Inductance Detector

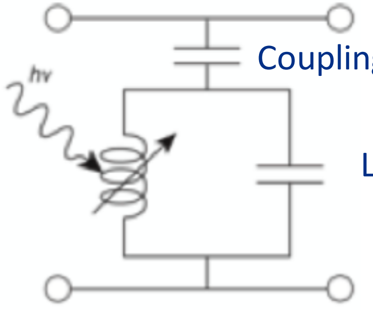
Each pixel is a low-resolution spectrometer in real time ~1us.

Similar detectors are used to measure power (CMB) or phonons (CDMS)

One example of a superconducting detector the Microwave Kinetic Inductance Detector (MKID)

One pixel

A microwave or optical photon deposits energy on the inductor breaking Cooper pairs into electrons

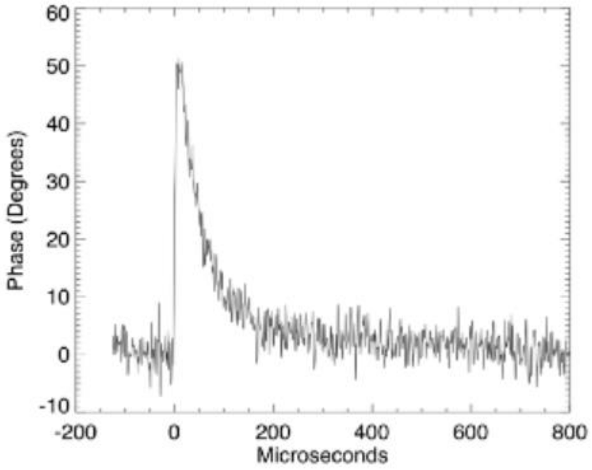


RF transmission line

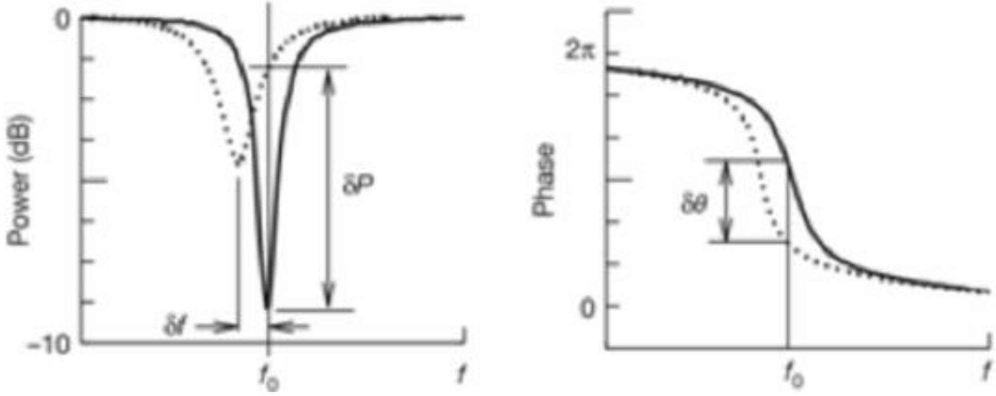
Coupling capacitor

LC resonator

Phase jump and recovery
The electrons go back to Cooper pairs in 100 usec time.

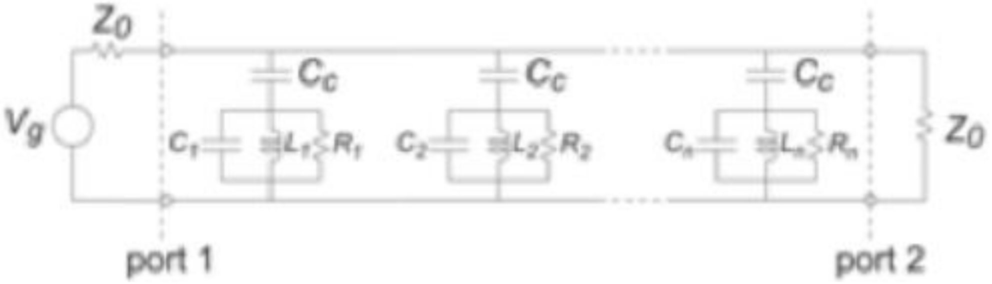


Resonator Q~30,000

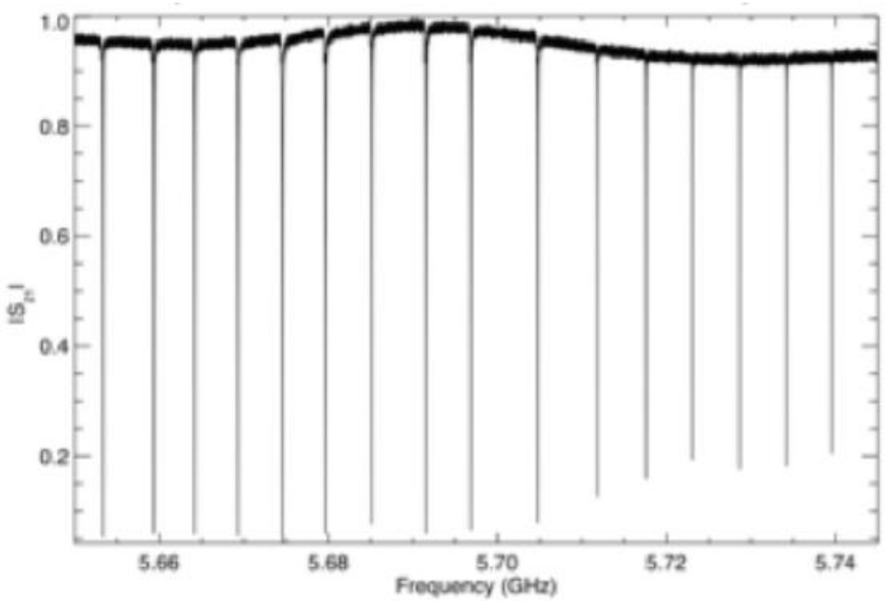


- The superconducting part of the inductance is the kinetic inductance and used for detection. The capacitors are used for frequency multiplexing and coupling.
- Typical bandwidth ~ 250KHz.

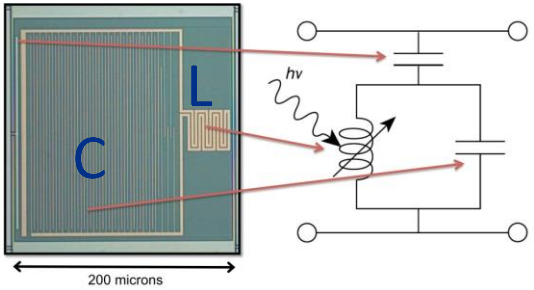
MKIDs can be frequency multiplexed



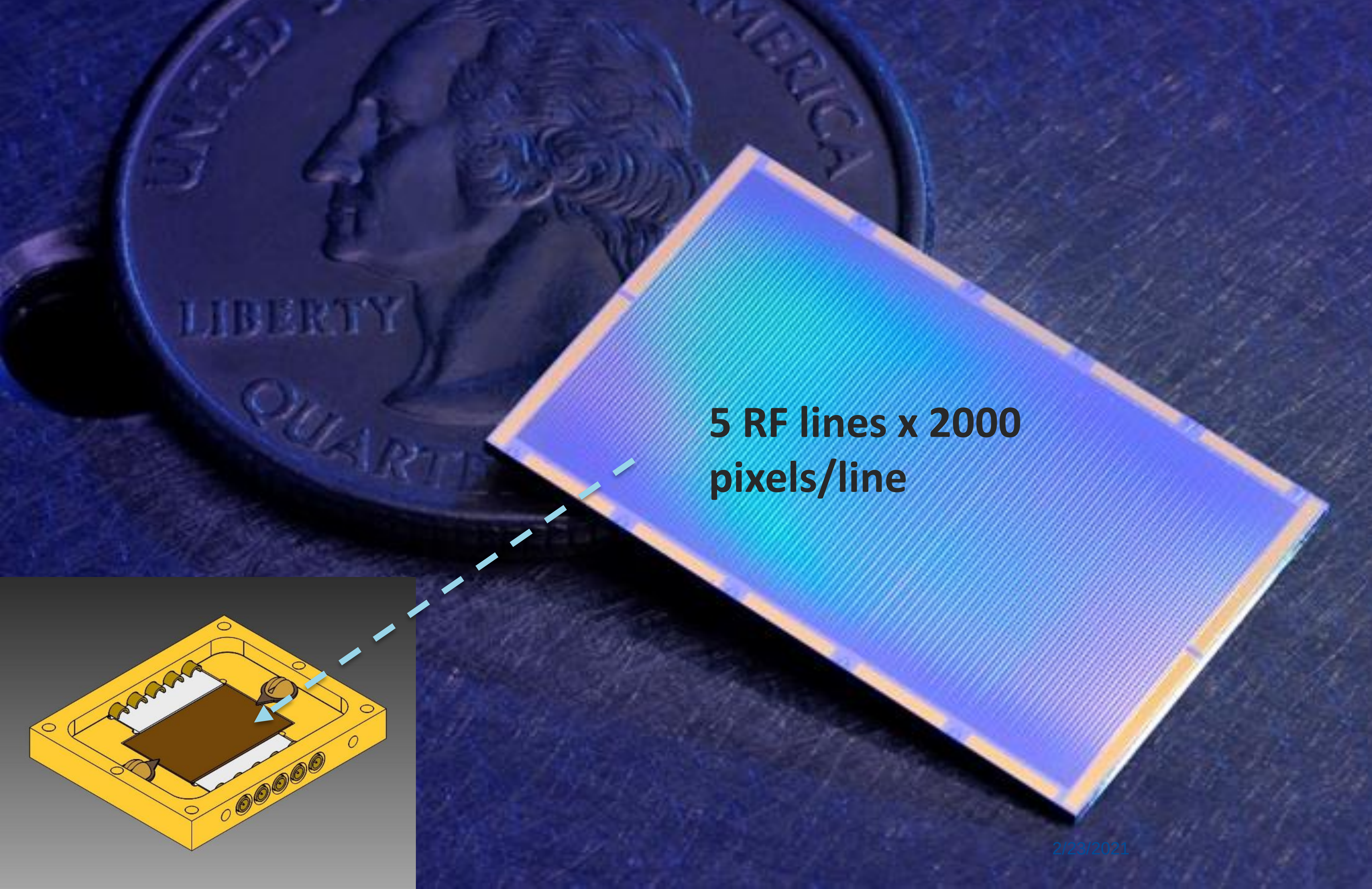
- A typical detector may have 2K MKIDs separated by 2MHz on a single RF line.



A frequency scan made by a VNA instrument of the S21 amplitude (zoomed at 16 resonators centered at ~5.7GHz)

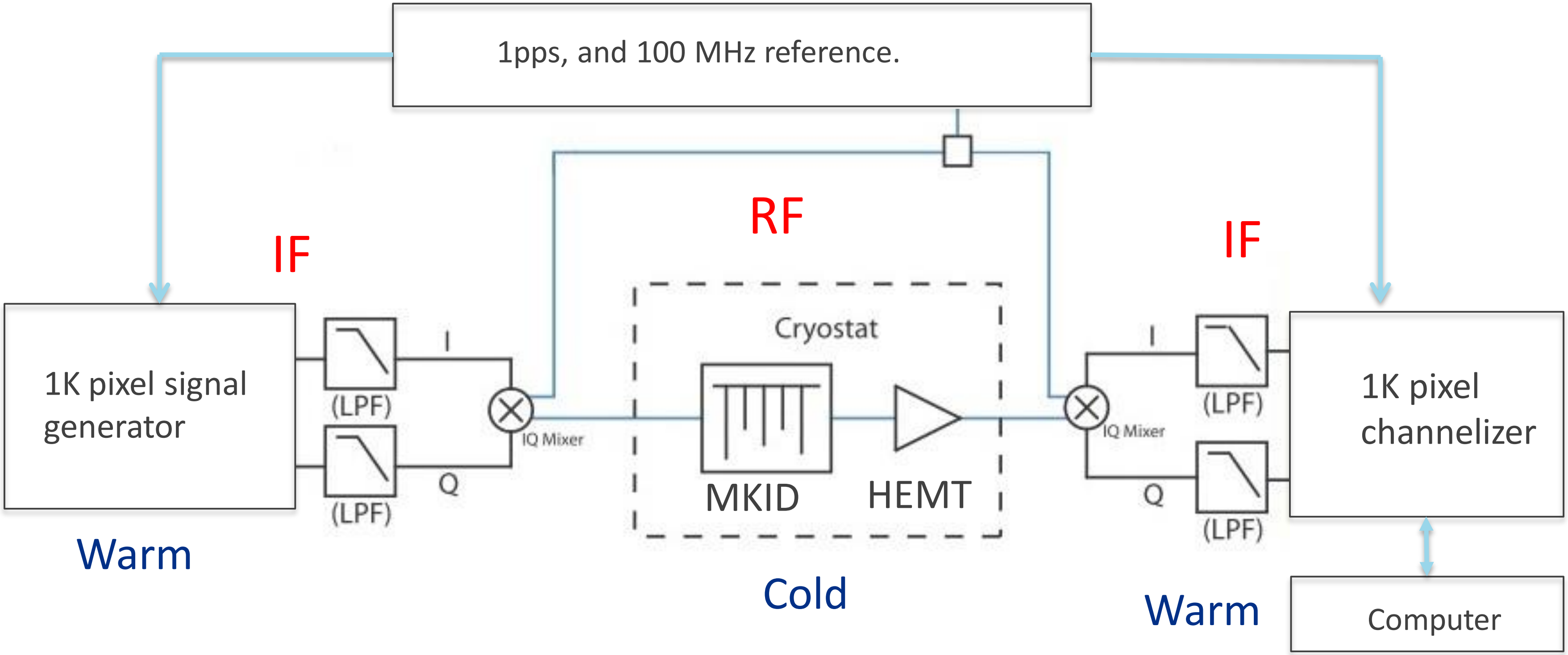


A 10 K pixel MKID designed by UCSB (B. Mazin)



5 RF lines x 2000 pixels/line

Fermilab readout and control system: fMESSI (2016)



Instrument developed for DARKNESS

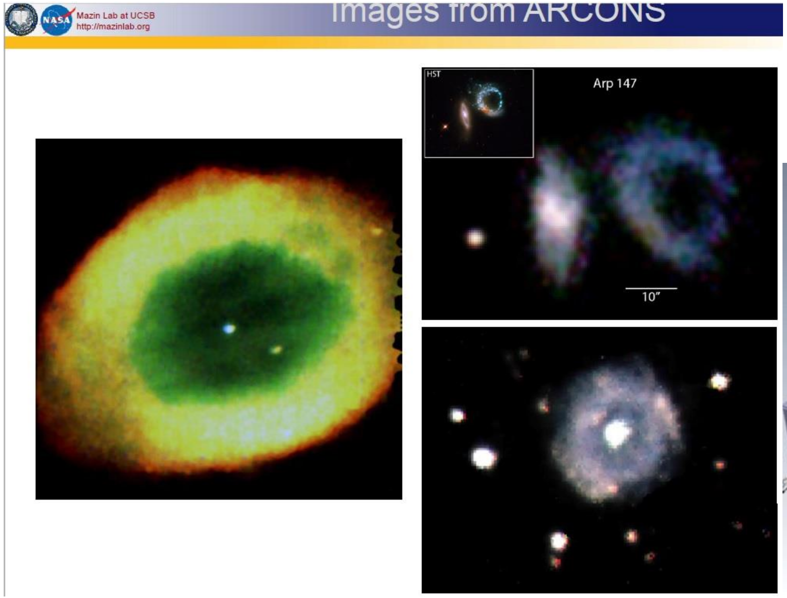
Mazin Lab at UCSB
http://mazinlab.org

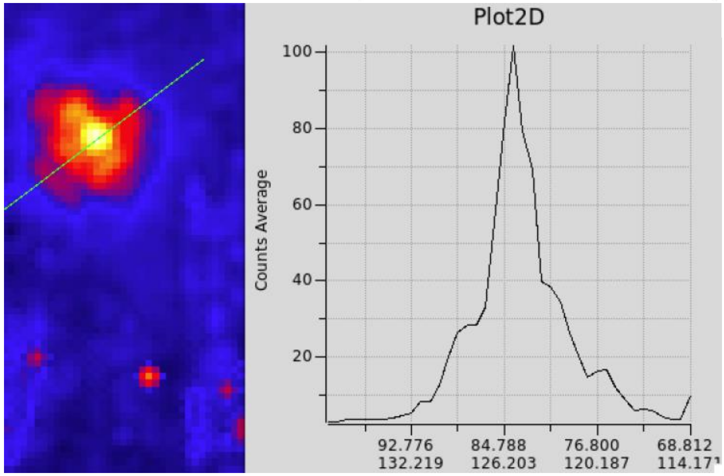
On-sky, July 23 2016

-

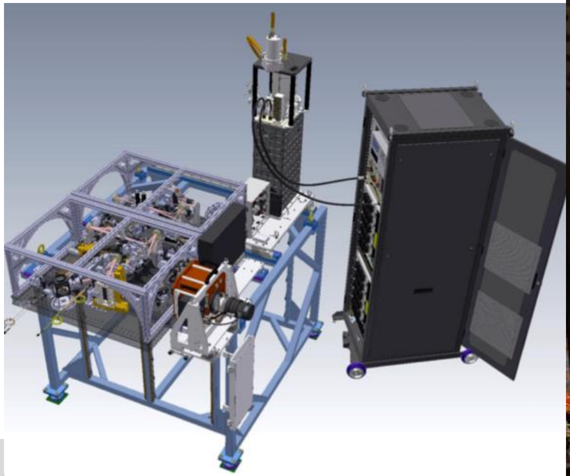
FMESSI (Frequency Multiplexed Electronics for Superconducting Sensor Instrumentation)

DARKNESS at Palomar





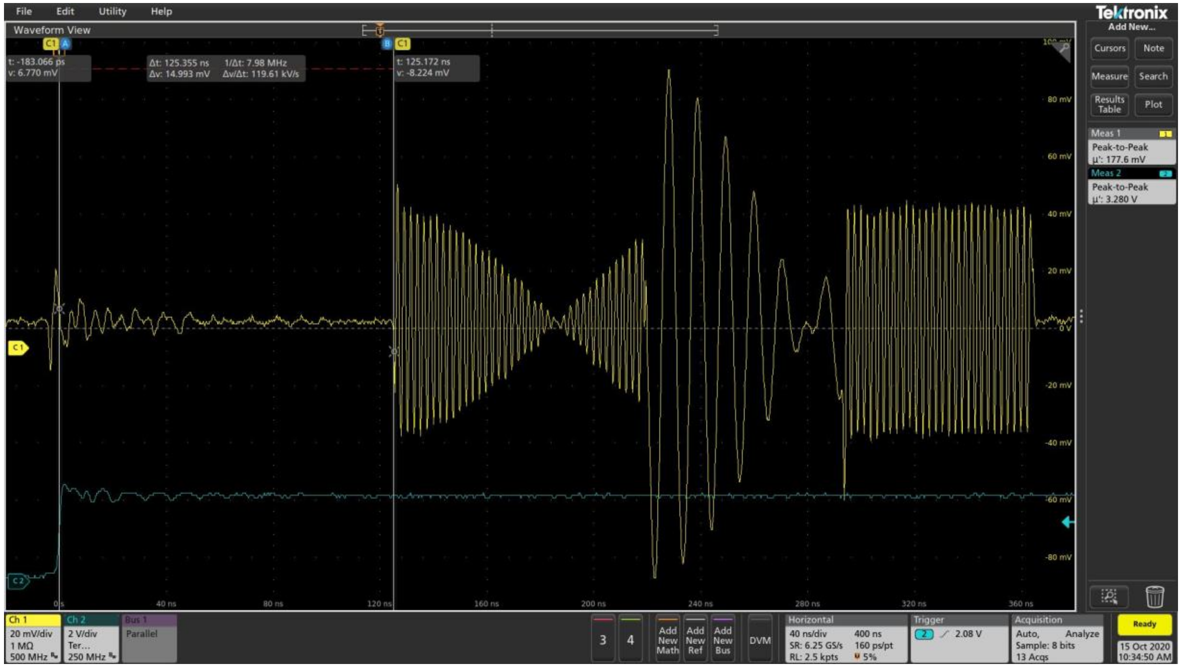
- DARKNESS: 10,000 pixel instrument
- 2 observation runs at Palomar
- MEC: 20,000 operating at the Subaru telescope in Mauna Kea since 2018.



https://web.physics.ucsb.edu/~bmazin/projects/mec.html

Phase synchronization in the qubit rotating frame

- Even when you hop frequencies you always need to be synced up to a master phase in the qubit rotating frame.



t: -183.066 ps
v: 6.770 mV

Δt: 125.355 ns 1/Δt: 7.98 MHz
Δv: 14.993 mV Δv/Δt: 119.61 kV/s

t: 125.172 ns
v: -8.224 mV

Meas 1
Peak-to-Peak
µ': 177.6 mV

Meas 2
Peak-to-Peak
µ': 3.280 V

Ch 1
20 mV/div
1 MΩ
500 MHz

Ch 2
2 V/div
Ter...
250 MHz

Bus 1
Parallel

Horizontal
40 ns/div 400 ns
SR: 6.25 GS/s 160 ps/pt
RL: 2.5 kpts 5%

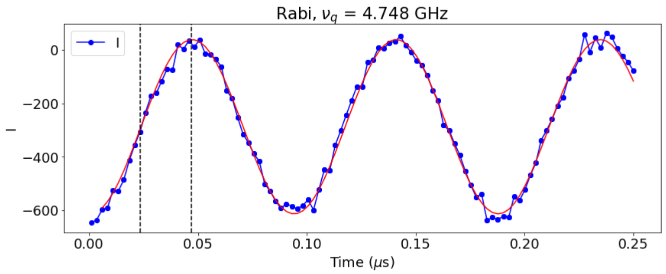
Trigger
2 2.08 V

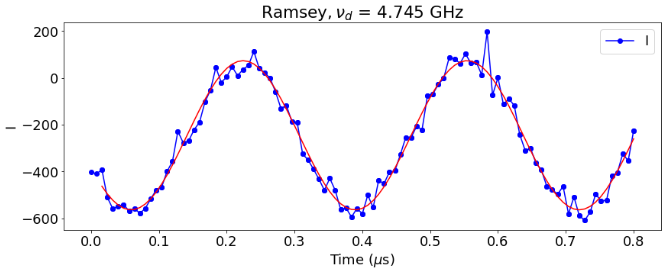
Acquisition
Auto, Analyze
Sample: 8 bits
13 Acqs

15 Oct 2020
10:34:50 AM

The plot shows how we can create arbitrary intervals of modulated signals with arbitrary gain. The phase is always synchronized to the master clock phase.

Early measurements with qubits at U. Chicago: David Schuster’s lab Feb 2020





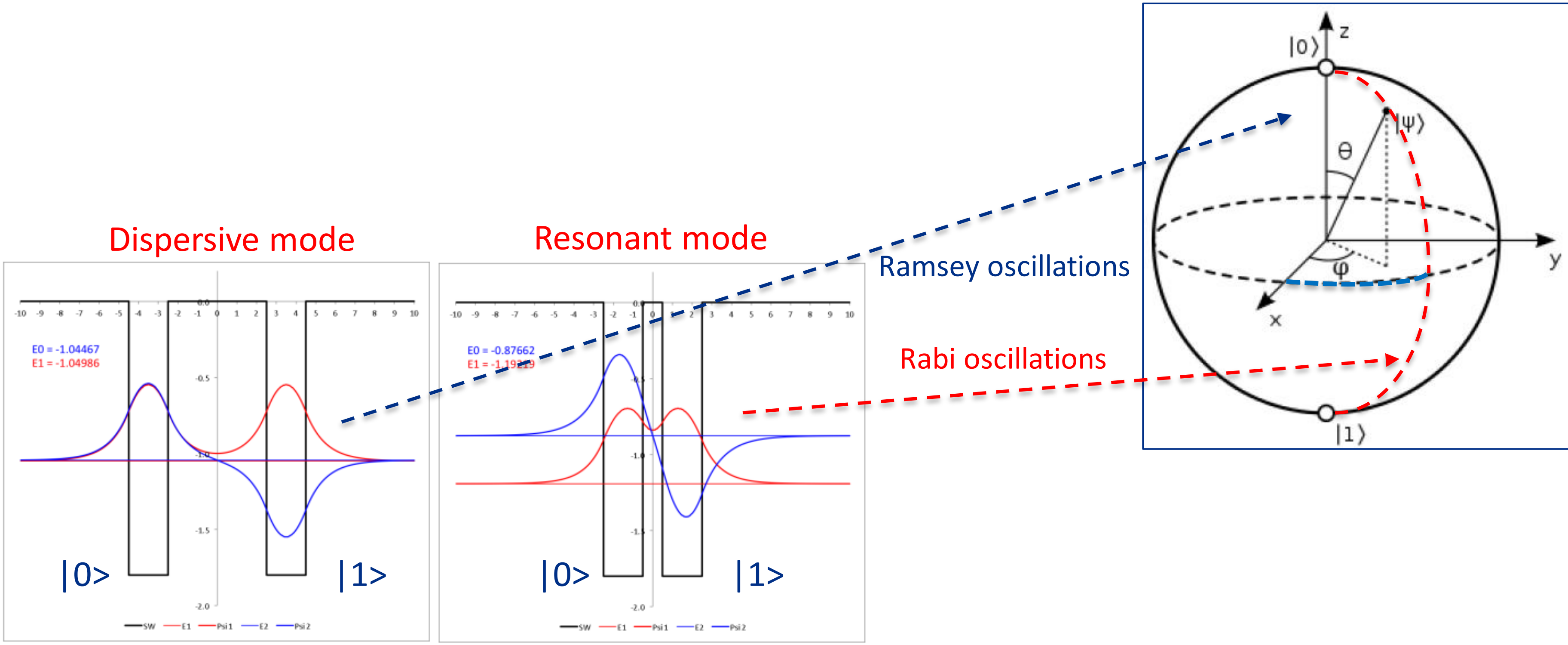
- One day test before lab closed due to Covid.
- Now with limited lab access time has to be distributed over many student projects that are late.
- We have not pushed to make new measurements because we are still building the system.
- We will measure again in few weeks when few blocks of the firmware and software come together.
- Active qubit reset will make measurements a lot faster at the lab
- Most exciting measurements will come when the RF board is working.

Summary

- Many fundamental questions of particle and quantum physics can be answered, at least in part, by experimental cosmology.
- Superconducting technology is taking a substantial portion of current and future detectors for cosmology.
- Superconducting detectors can also be used as macroscopic quantum devices.
- Major challenges for engineers!
  - Warm and cold electronics, RF, firmware and hardware development, signal processing, noise, ASIC design, and more.
- Fermilab is open to new collaborations!

Two level quantum system

Here the two square wells represent the qubit states |0> and |1>
If the wells are far away from each or at different potential the keeps its location and energy state. If the wells are closer the red wavefunction is shared and the state will jump.



Dispersive mode

Resonant mode

|0> |1>

|0> |1>

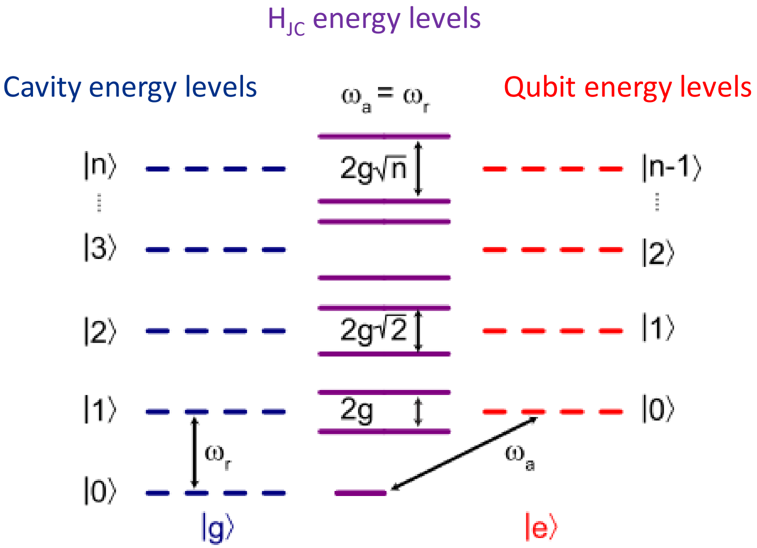
Ramsey oscillations

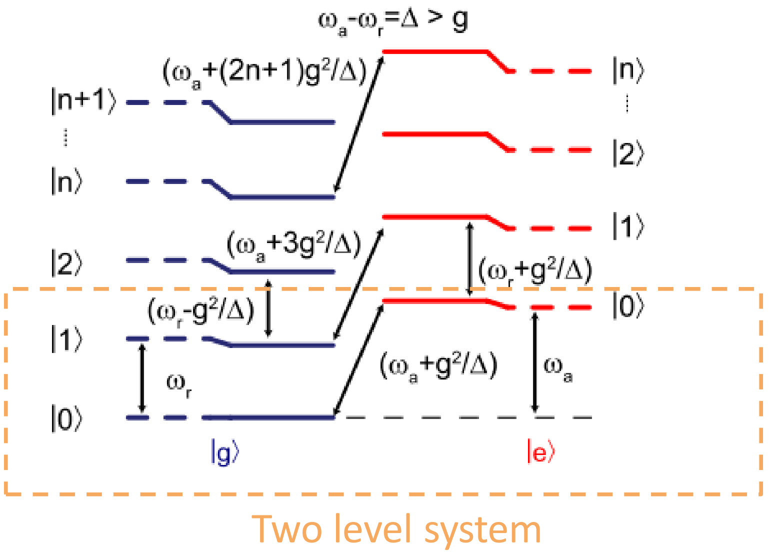
Rabi oscillations

Cooper pair box energy levels (solution to H_{JC})

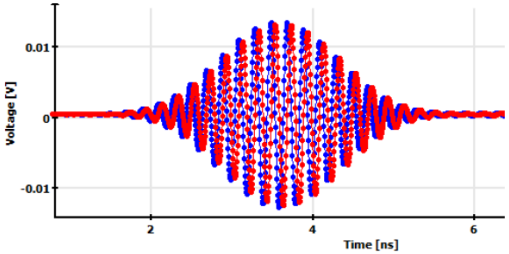
Resonant mode: the qubit is strongly coupled to the cavity. Cooper pairs jump back and forth.

Dispersive regime: qubit detuned from cavity, very low probability of jumping.



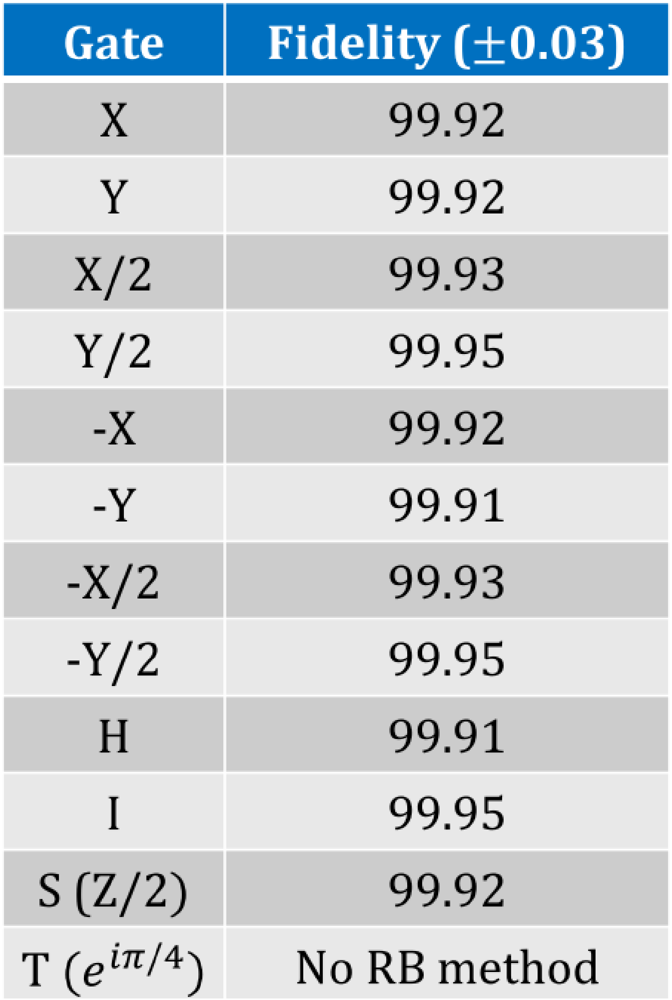


ω_a, g, Δ are tunable control parameters of H_{JC} which have a correspondence in the Cooper pair box parameters E_C, E_J, N_g.



E.g. of a control pulse: RF pulse with a certain envelope and freq.

Qubit logic operations



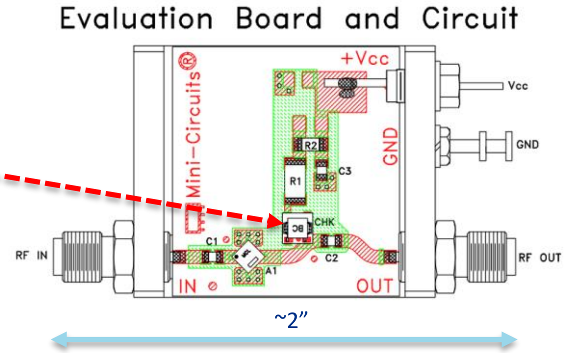
Gate	Fidelity (±0.03)
X	99.92
Y	99.92
X/2	99.93
Y/2	99.95
-X	99.92
-Y	99.91
-X/2	99.93
-Y/2	99.95
H	99.91
I	99.95
S (Z/2)	99.92
T ($e^{i\pi/4}$)	No RB method

- Perform rotations in the Block sphere with more than 99% fidelity (not enough for QC).
- Multi qubit logic operations CNOT (2 qubits)
- Toffoli gate (3 qubits)
- H: Hadamard (1 qubit)
- Phase shift $R_Z(\Phi)$ (1 qubit)
- Why nobody has achieved a fault tolerant QC yet?
  - Fidelities need to be 99.999999… (17 nines)

Cost and size of RF electronics

Typical amplifier

0.12x0.12x0.045”



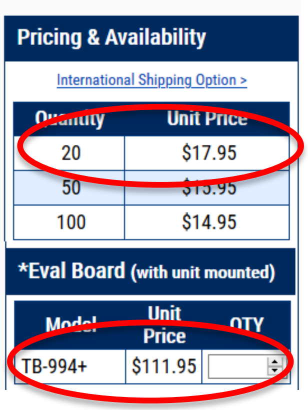
Pricing & Availability

International Shipping Option >

Quantity	Unit Price
20	$1.35
50	$1.35

*Eval Board (with unit mounted)

Model	Unit Price	QTY
TB-413-39+	$111.95	
2000	$1.25	



Pricing & Availability

International Shipping Option >

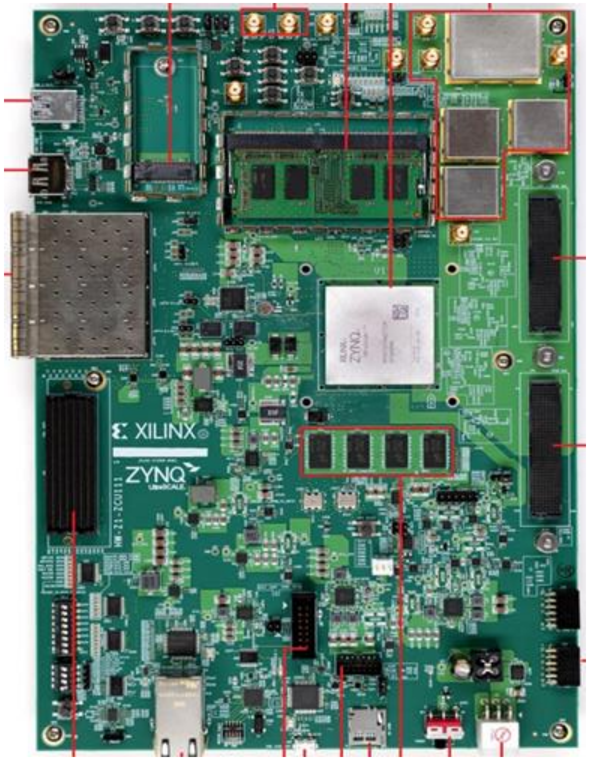
Quantity	Unit Price
20	$17.95
50	$15.95
100	$14.95

*Eval Board (with unit mounted)

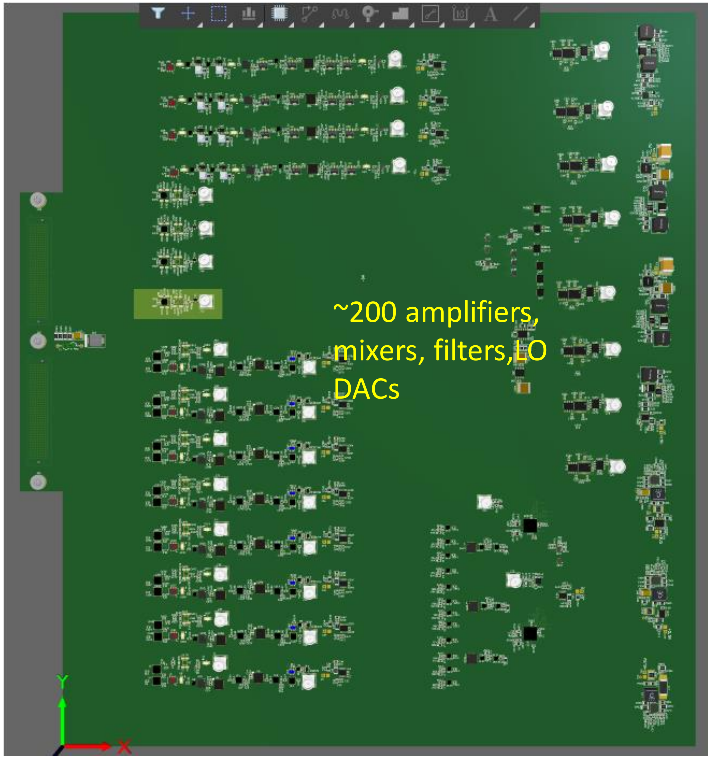
Model	Unit Price	QTY
TB-994+	$111.95	

- By designing and integrating all the needed RF (warm) components we achieve factor of 10 to 20 reduction in area, plus we do not need hundreds of costly and messy cables.
- The cost of connectorized amplifiers (sold as evaluation boards) cost x10 and x100 times more.
- FNAL RF board has 200 active components (amplifiers), mixers and filters.
- When you design entire RF amplifier chain you can control impedances and S-parameters much better. You can simulate the entire chain.

FNAL Readout and Control electronics



FPGA+ADC+DAC+memory +interfaces



RF inputs, outputs, LO, fast flux control, high precision bias,

The RF board is in layout stage.

Available in Jan 2021.

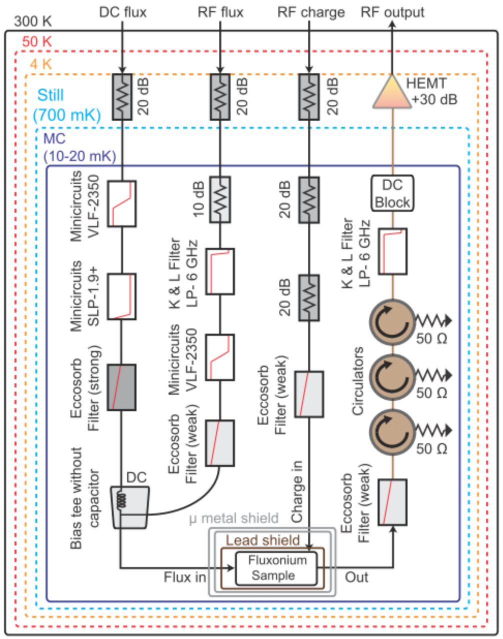
All features have been designed specifically for QIS in terms of power, BW, etc.

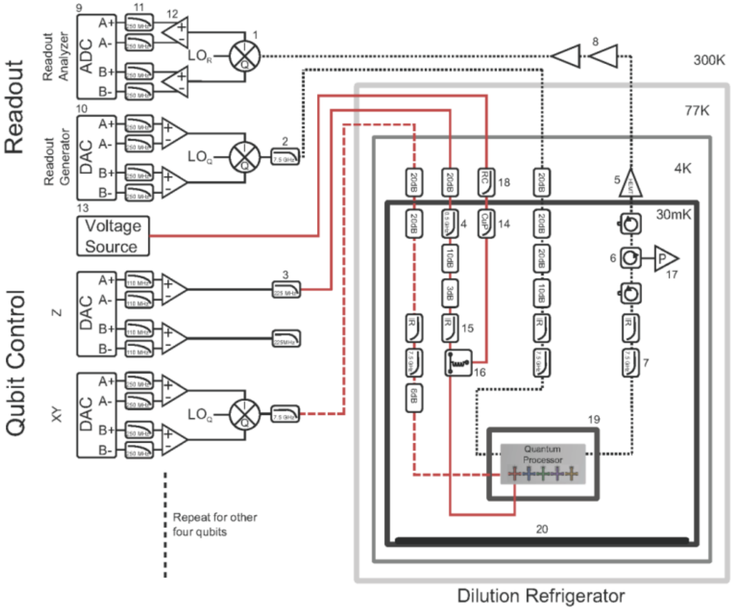
A large system with 20 or more of these boards is easy to do.

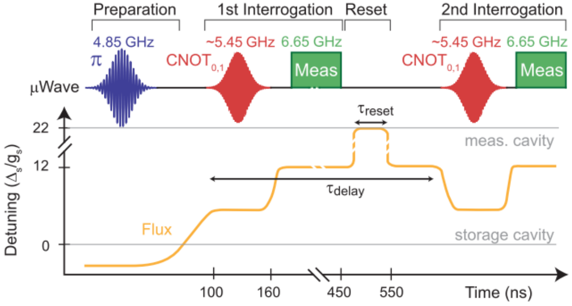
Each board could control 50 to 100 qubits if we do some multiplexing.

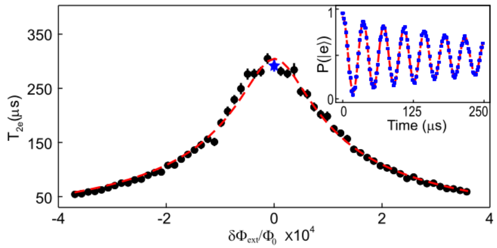
Transmon, fluxonium, and more

RF pulses at several frequencies modulated by envelopes (Gaussian, AW, triangular, etc.)
Fast flux control with no modulation.









T1 and T2 critically depend on the Flux bias

Going deeper into the FNAL RF and Control

- 8x DAC outputs (6.5 Gs/s) can be used in RF mode (4-8GHz) or DC mode (0-2GHz).
  - The RF outputs are used for XY control: AM modulated by pulse envelopes, 70ps resolution, up to 60us length.
  - Power control of over 60dB and maximum power of 10dBm.
  - Spur free over 3GHz of bandwidth.
  - Carrier frequency hoping takes 1 sample (70ps).
- 8x 20bit high resolution DACs for flux biasing.
  - Very low 1/f noise with knee at 10Hz.
- 4 RF ADCs for qubit/cavity readout
  - 80dB of gain, few dB of flatness over 4-8GHz.
  - 60dB selectable dynamic range.
- 4 non RF ADCs 2 GHz BW for scope or spectrum analysis.
- 16 digital I/Os for triggering and synchronizing to external instruments.