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Ministero dell'Università e della Ricerca

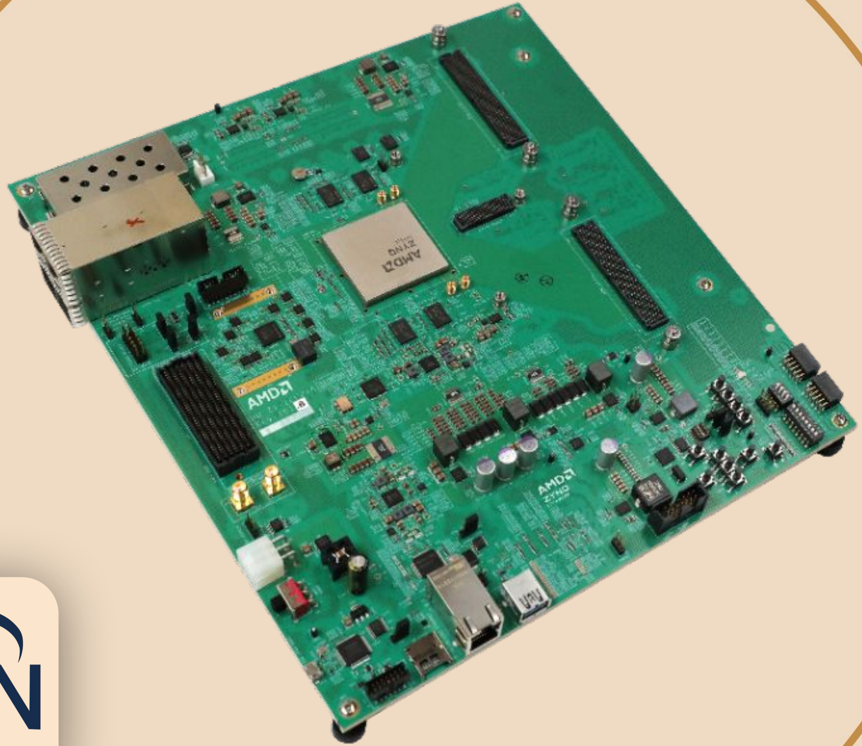
Italiadomani
PIANO NAZIONALE DI RIPRESA E RESILIENZA

NQSTI
National Quantum Science and Technology Institute

Missione 4 Istruzione e Ricerca

Superconducting qubits control using FPGAs

Rodolfo Carobene (UNIMIB)



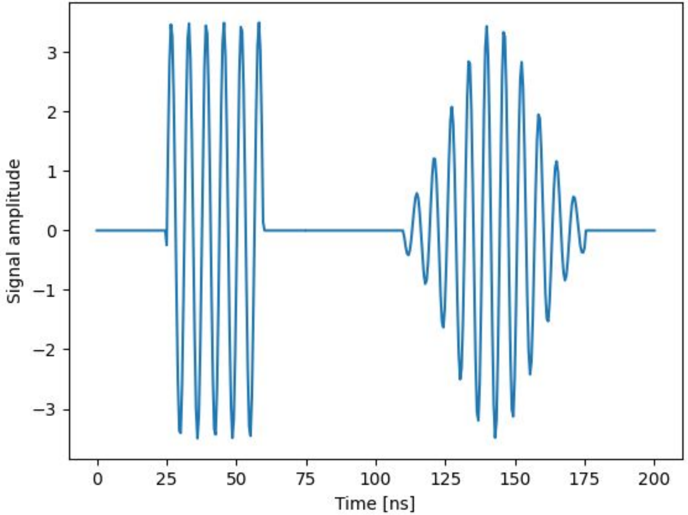
UNIVERSITA' DEGLI STUDI DI MILANO BICOCCA

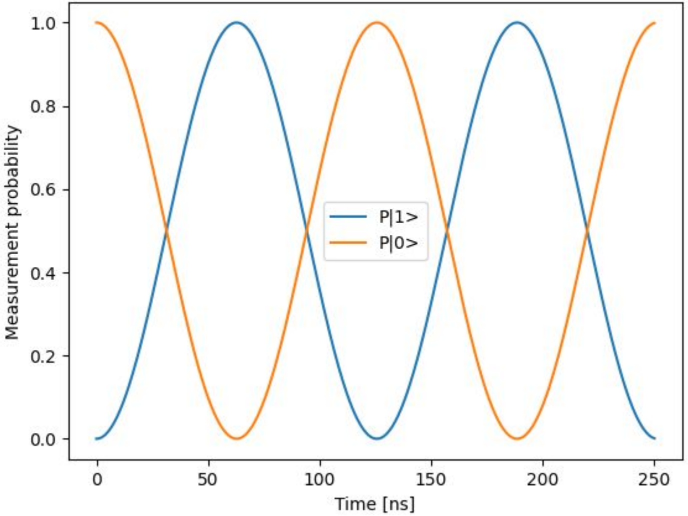
TII Technology Innovation Institute

INFN

Control of superconducting qubits

$$\vec{E} = \vec{E}_0 \cos(\omega_d t + \phi_0)$$

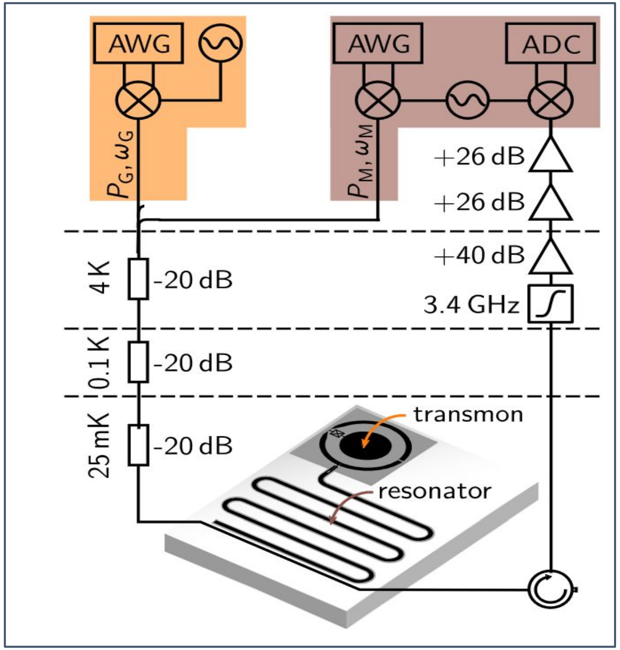




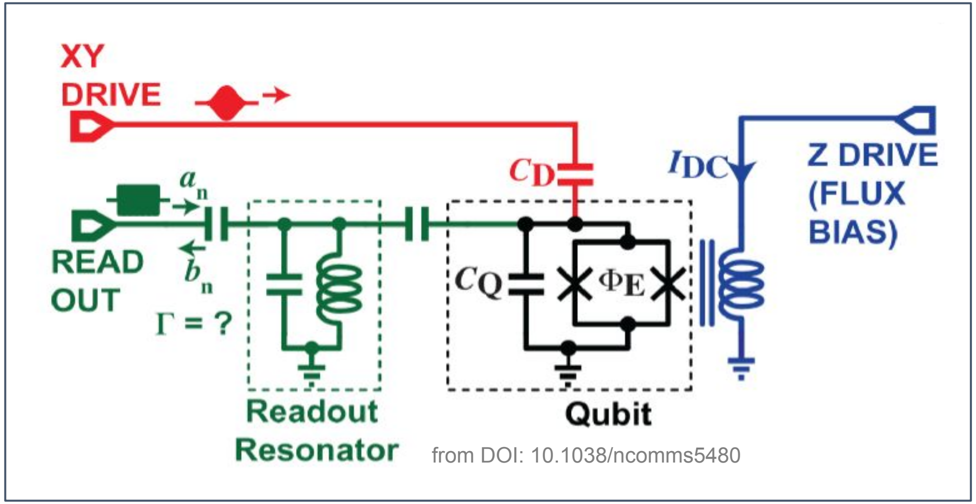
$$P(t)_1 = \frac{A^2}{\Omega^2} \sin^2\left(\frac{\Omega}{2} t\right)$$

$$\vec{v} = \frac{1}{\Omega}(A\cos\phi, -A\sin\phi, \Delta)$$

Control of superconducting qubits

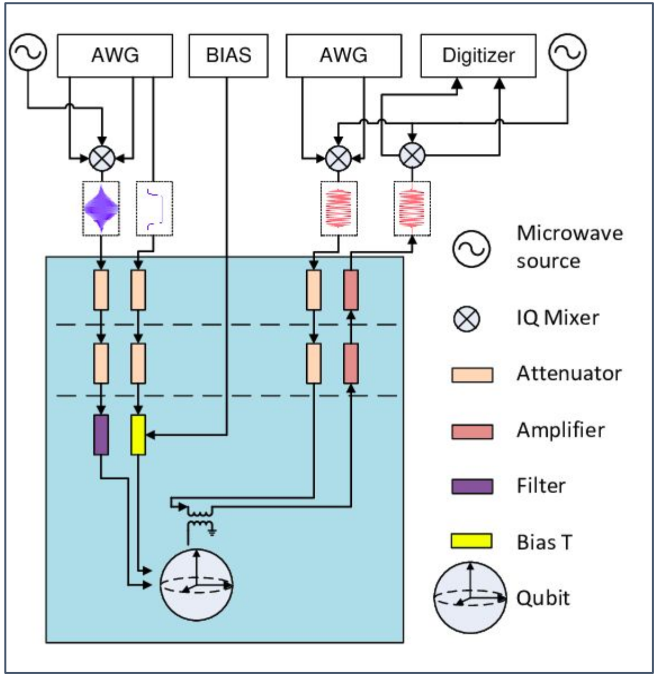


from DOI: 10.1038/s41534-020-00287-w



from DOI: 10.1038/ncomms5480

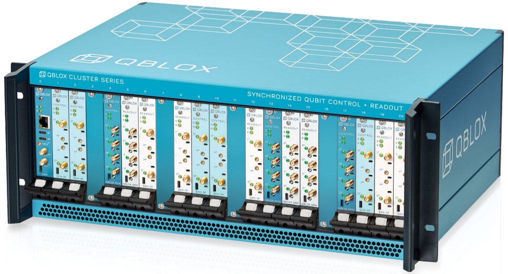
Typical setup with standard multi-purpose instruments



- Qubit control pulses
  - AWG (2 channels)
  - Local Oscillator
  - IQ mixer
- Qubit bias
  - Voltage source
- Readout
  - AWG (2 channels)
  - Local Oscillator
  - 2 IQ mixer
  - ADC (2 channels)
- Trigger AWG for timing

Quantum-specific hardware

- Much simpler setups
  (although usually still require up/down conversion)
- Higher cost
- Limited control
- Limited bandwidth
- Require constant support for software and hardware



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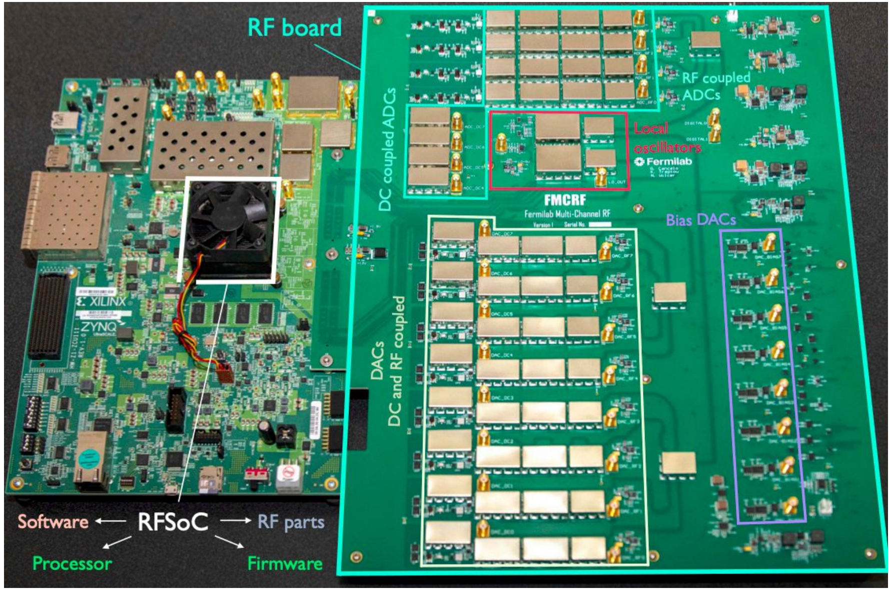
Radio Frequency System on Chip (RFSoC)

- Board with CPU - FPGA - RF DACs and ADCs
- High bandwidth (6 GHz, 10 GHz)
- Lower cost per qubit
- Different boards are available
  ZCU216 enables for control of 7 flux-tunable qubits
- FPGA firmware is configurable

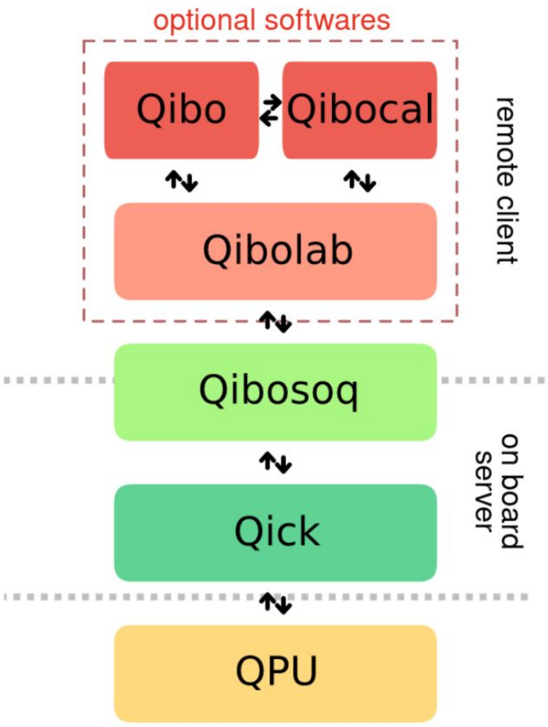
RFSoC firmware: the QICK project

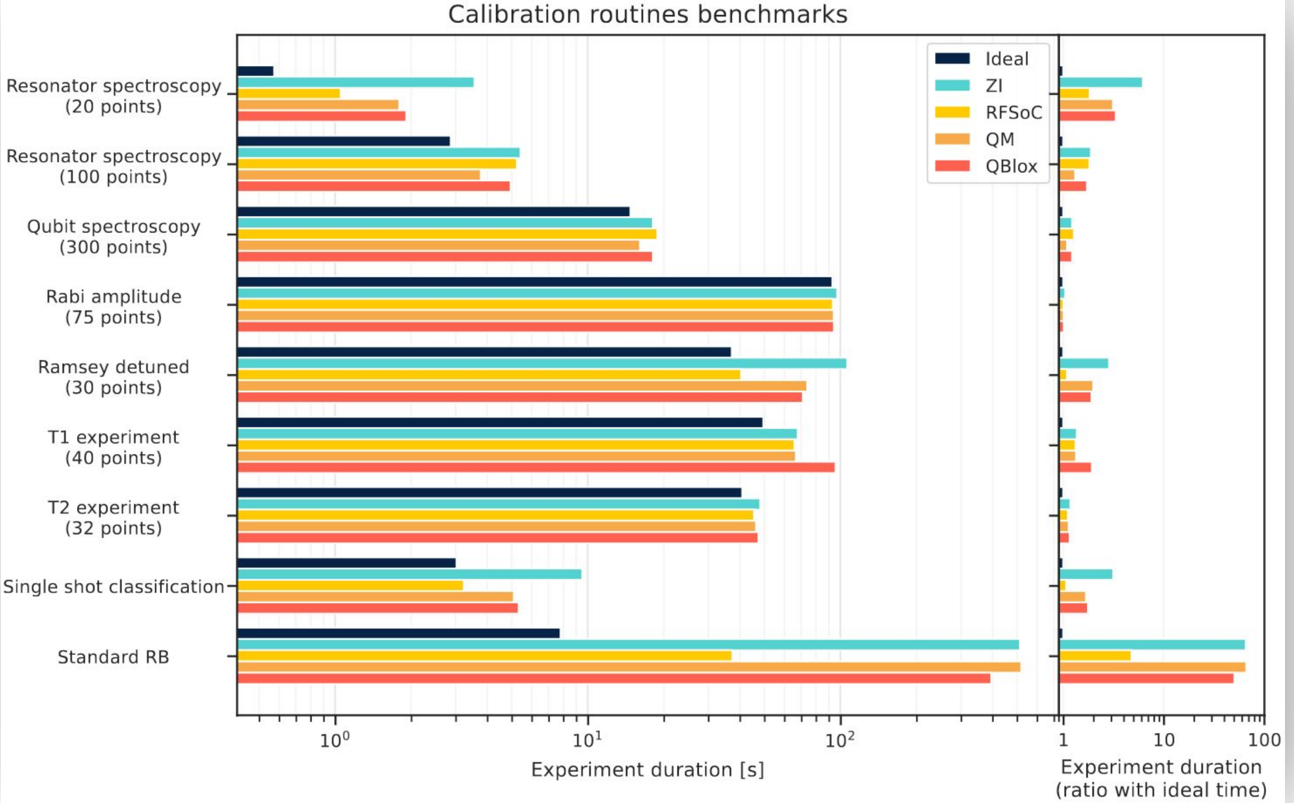
- Presented in 2021
  The QICK (Quantum Instrumentation Control Kit): Readout and control for qubits and detectors (**arXiv:2110.00557**)
- Basic software with PYNQ
- Open-source firmwares
  Flux-tunable qubits and multiplexed readout supported.
- Xilinx (AMD) boards supported



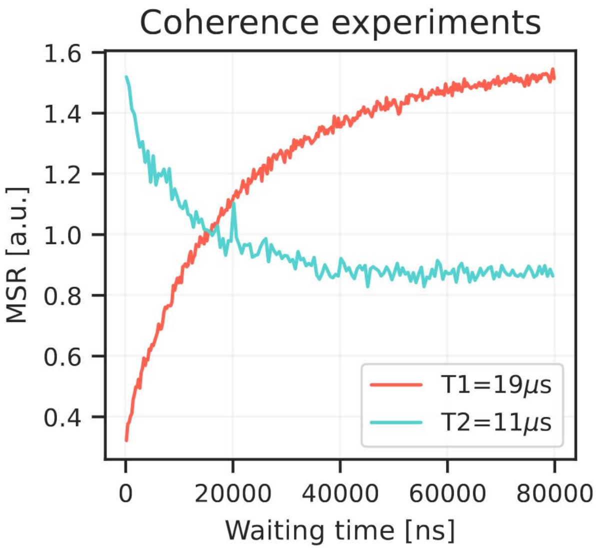
Control software: Qibosoq

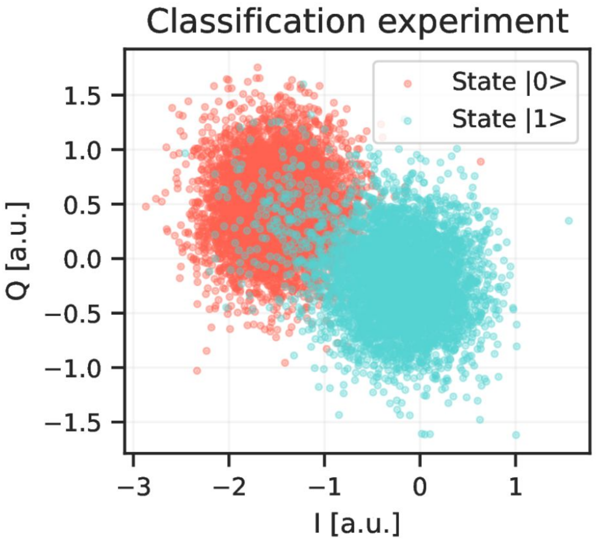
- Presented on arxiv
  Qibosoq: an open-source framework for quantum circuit RFSoC programming (**arXiv:2310.05851**)
- Enables to control QICK remotely with simpler coding syntax
- Integrates QICK in the Qibo framework
  Qibolab allows control for complete experimental setups (multiple instruments); Qibocal allows for semi-automated calibration; Qibo for gate-based application deployment
- Tested on all the QICK RFSoC boards
  Tested with a maximum of 3 flux-tunable qubits controlled at the same time.

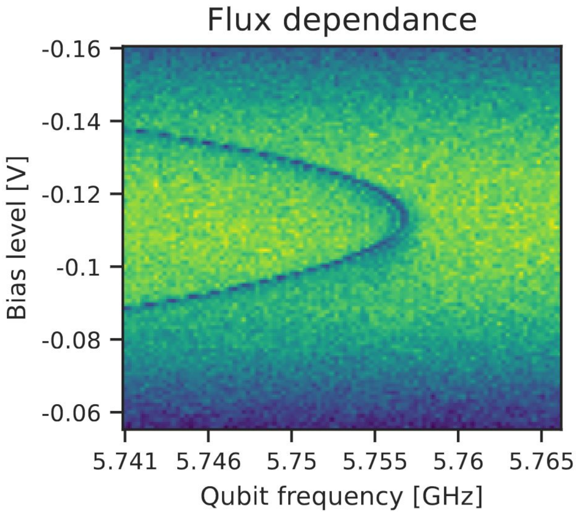



Calibration routines benchmarks
Resonator spectroscopy (20 points)
Resonator spectroscopy (100 points)
Qubit spectroscopy (300 points)
Rabi amplitude (75 points)
Ramsey detuned (30 points)
T1 experiment (40 points)
T2 experiment (32 points)
Single shot classification
Standard RB
Ideal
ZI
RFSoC
QM
QBlox
10^0
10^1
10^2
Experiment duration [s]
1
10
100
Experiment duration (ratio with ideal time)

Calibration experiments using a RFSoC board







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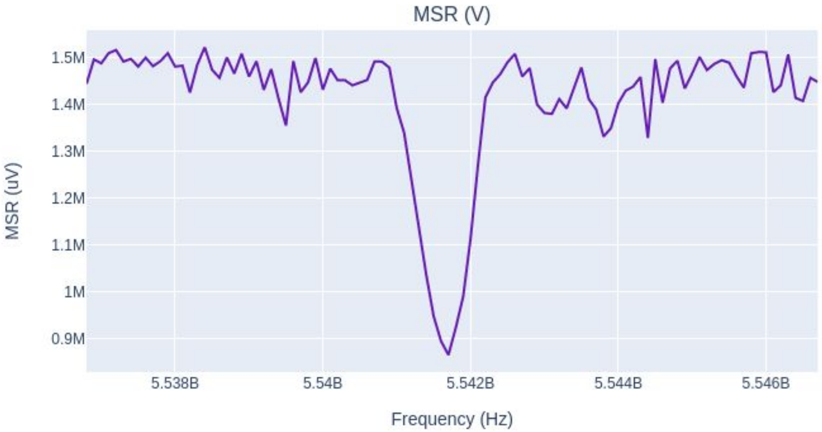
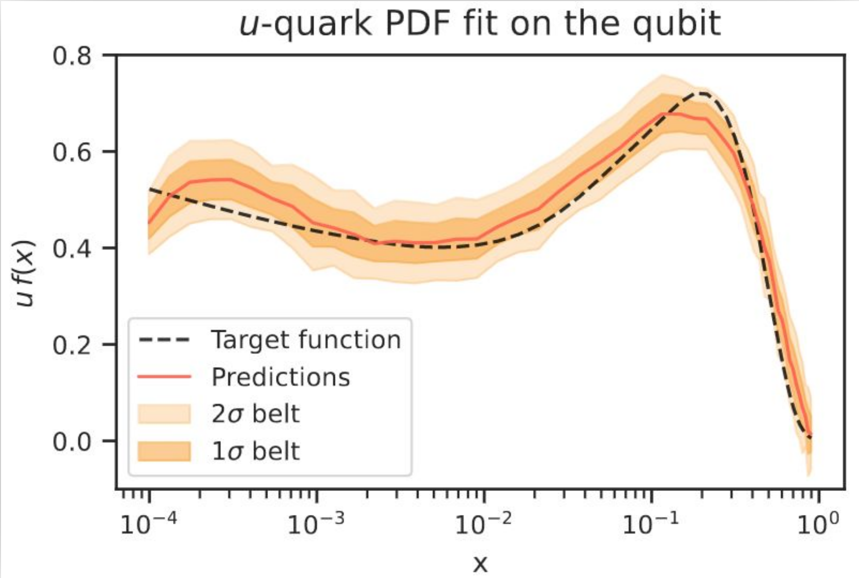
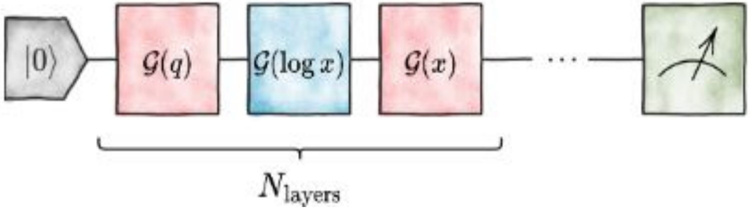
Definition of new experiments




```python
from qibolab import Platform
from qibolab.pulses import *

platform = Platform("zcu111")

ps = PulseSequence()
drive_q0 = platform.create_RX_pulse(
    duration=2000,
    amplitude=0.01)
read_q0 = platform.create_MZ_pulse(
    start=2000)
ps.add(drive_q0)
ps.add(read_q0)

sweeper = Sweeper(
    Parameter.frequency,
    range(5e9, 6e9, 1e6),
    [drive_q0])

res = platform.sweep(ps, sweeper,
    nshots=1024)
msr_values = res.magnitude
```

Gate-level control using a RFSoC board





Multi-variable integration with a variational quantum circuit

(arXiv:2308.05657)

Conclusions and next steps

- RFSoC4x2, ZCU111, ZCU216 fully compatible and tested
- Single qubits fully controlled

- Extend support for other RFSoC boards: ZCU208, HiTech Global
- Reach firmware-modification capabilities (in QICK)
- Design custom boards and control RFSoC through PCI