

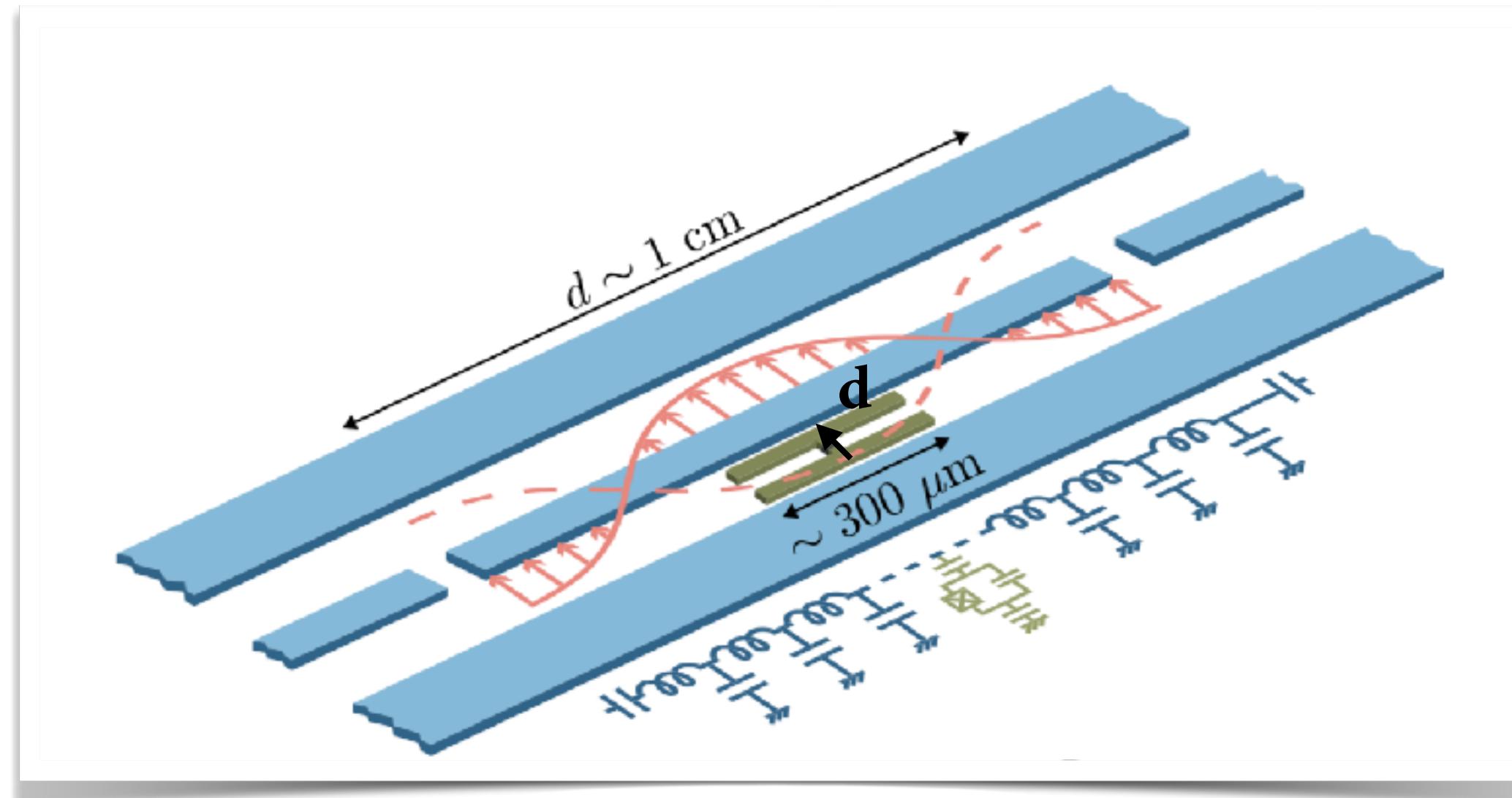
The QICK (Quantum Instrumentation Control Kit): Readout and control for qubits and detectors

L. Stefanazzi et al., arXiv:2110.00557v1 (2021)

Niyaz Beysengulov

Qubit measurements in circuit QED

Transmon qubit coupled to a 1D transmission-line resonator



$$\hat{H}_{\text{int}} = \mathbf{d} \cdot \mathbf{E}_{\text{cav}}$$

dipole moment of the transmon

resonator's zero-point electric field

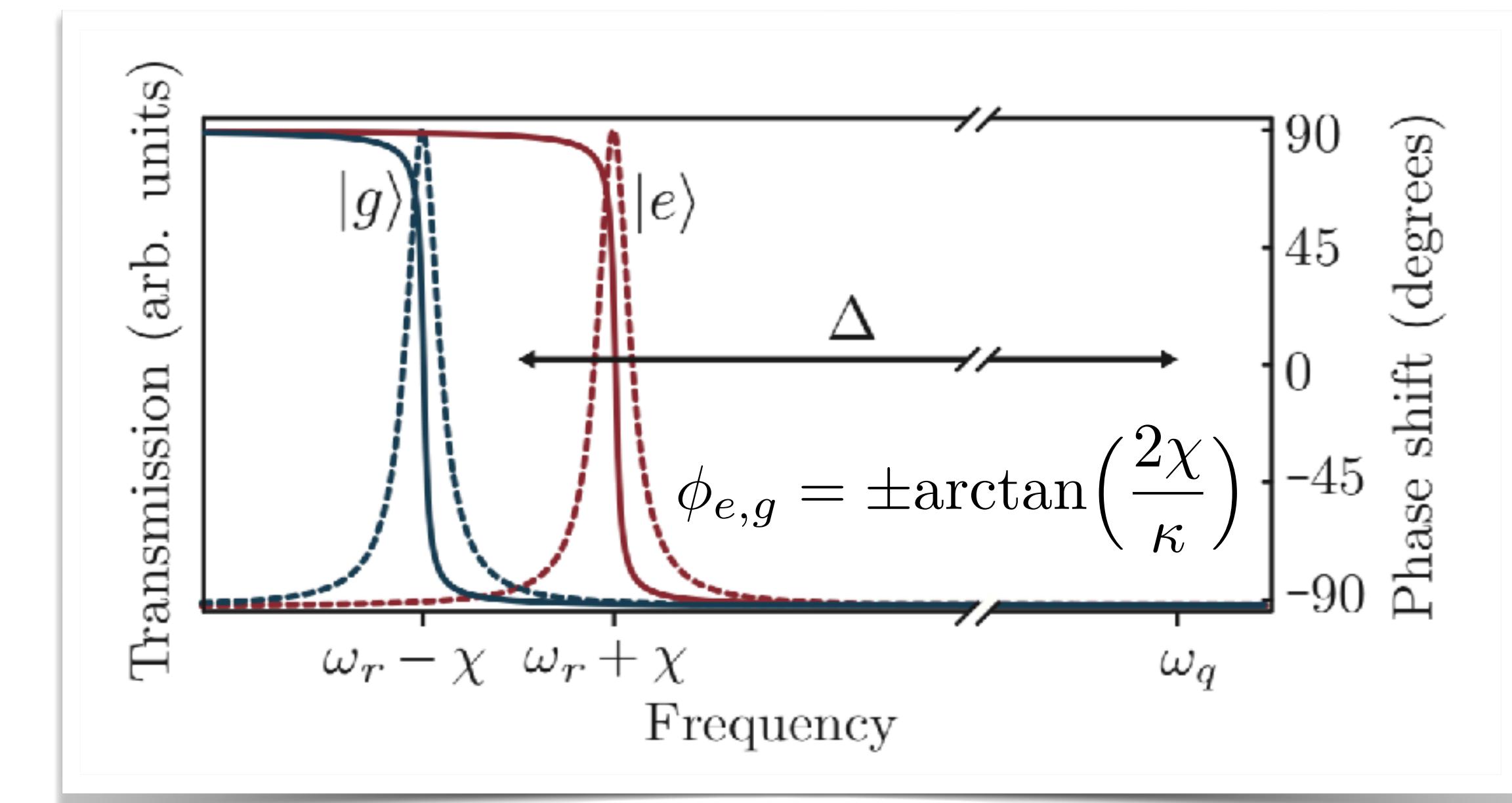
Jaynes-Cummings Hamiltonian:

$$\hat{H}_{\text{JC}} = \hbar\omega_r \hat{a}^\dagger \hat{a} + \frac{\hbar\omega_q}{2} \hat{\sigma}_z + \hbar g (\hat{a}^\dagger \hat{\sigma}_- + \hat{a} \hat{\sigma}_+),$$

dispersive regime:

$$|\lambda| = |g/\Delta| \ll 1.$$

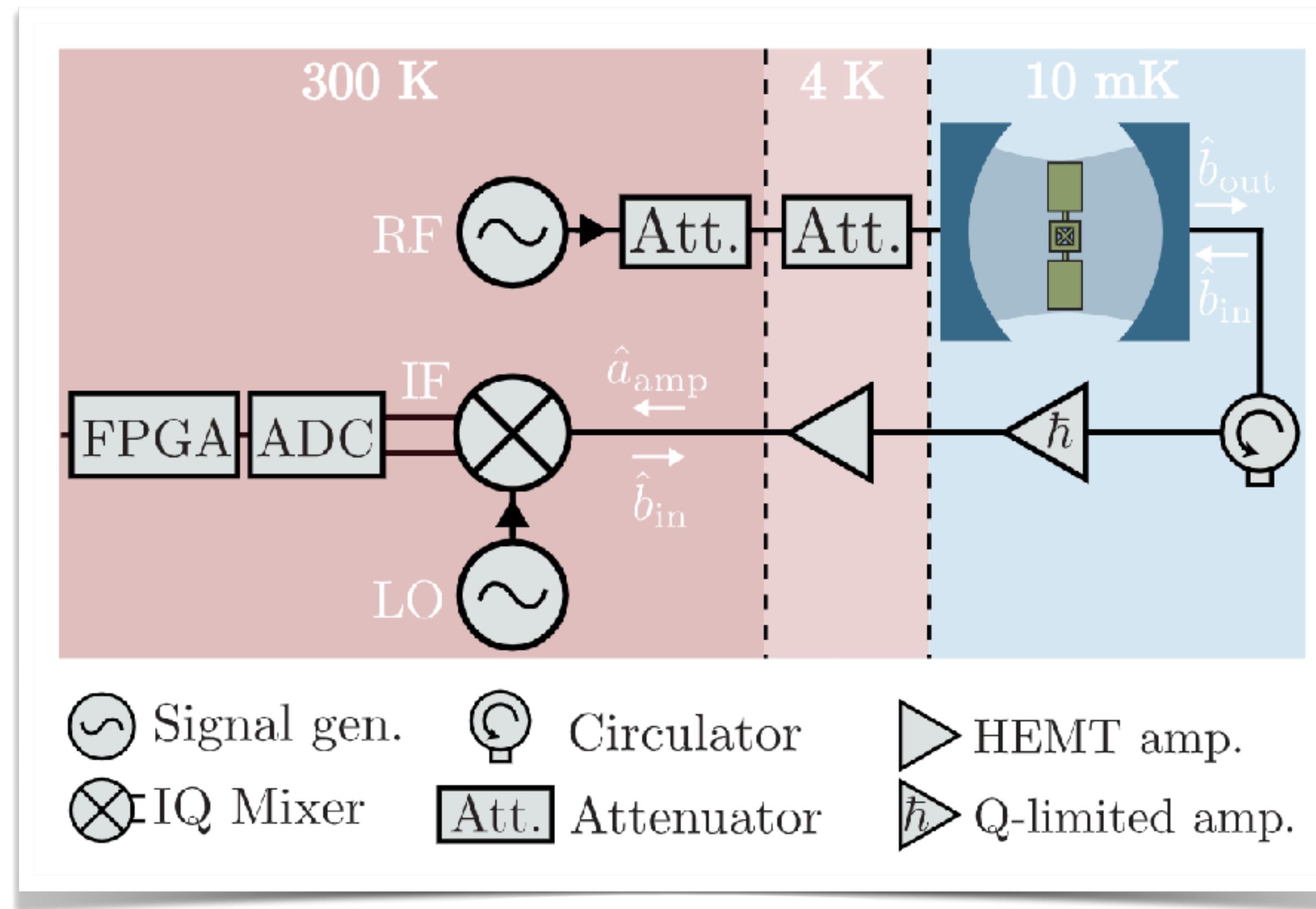
$$\hat{H}_{\text{disp}} \approx \hbar(\omega_r + \chi \hat{\sigma}_z) \hat{a}^\dagger \hat{a} + \frac{\hbar\omega_q}{2} \hat{\sigma}_z. \quad \chi = -\frac{g^2 E_C / \hbar}{\Delta(\Delta - E_C / \hbar)}.$$



QND measurement

Qubit measurements in circuit QED

The microwave measurement chain



Signal at the output of cavity (including all amplifier chain):

$$V_{\text{out}}(t) = A_{\text{out}}(t) \cos(\omega_r t + \phi_{e,g}(t))$$

$$\phi_{e,g} = \pm \arctan\left(\frac{2\chi}{\kappa}\right)$$

Local Oscillator:

$$V_{\text{LO}}(t) = A_{\text{LO}} \cos(\omega_{\text{LO}} t + \phi_0)$$

IQ mixer output:

$$I \propto \sin((\omega_r - \omega_{\text{LO}})t + \phi_{e,g}(t))$$

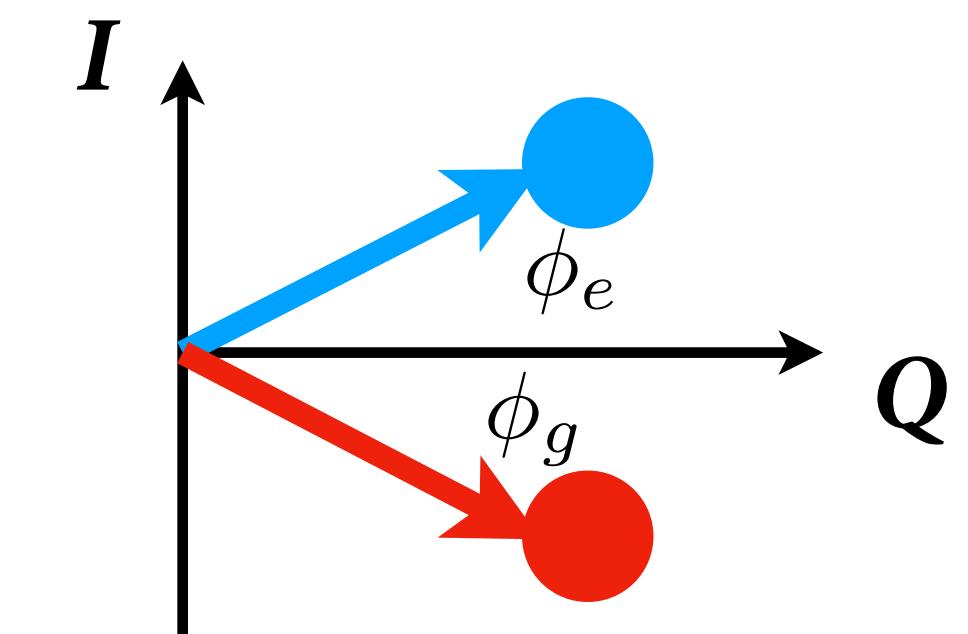
$$Q \propto \cos((\omega_r - \omega_{\text{LO}})t + \phi_{e,g}(t))$$

$$\omega_r - \omega_{\text{LO}} = 0$$

homodyne detection

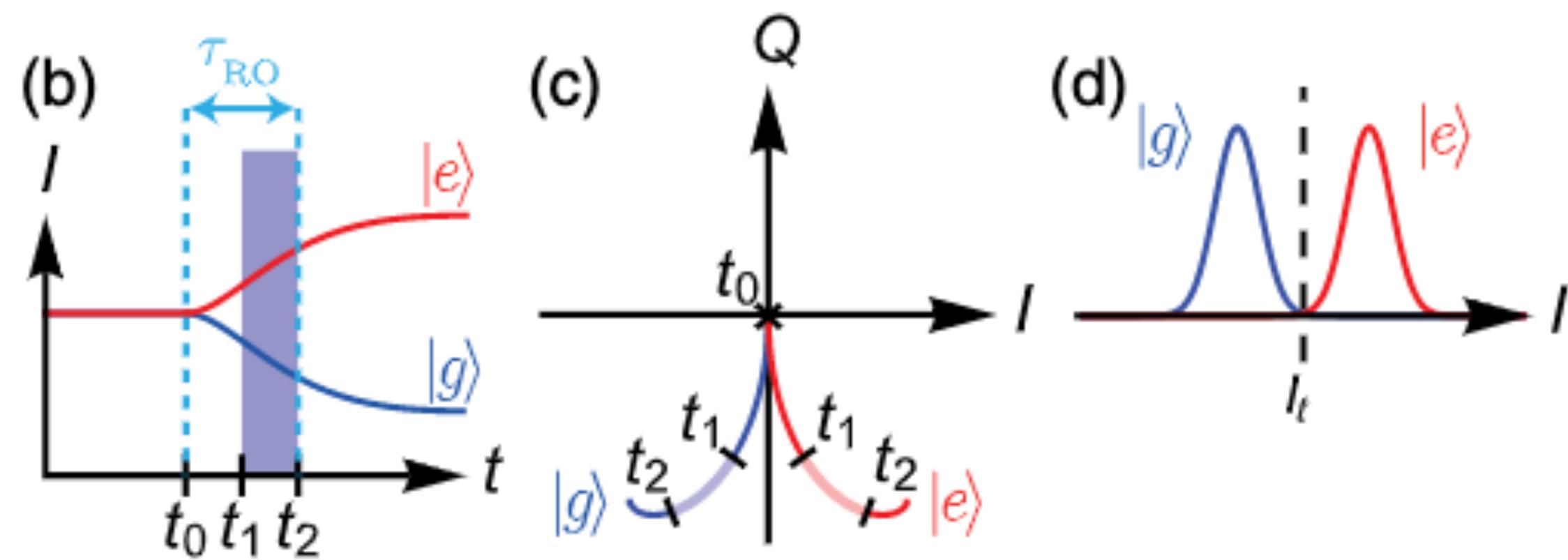
$$\omega_r - \omega_{\text{LO}} \neq 0$$

heterodyne detection



Digital demodulation and filtering

Heterodyne detection scheme (using FPGA)



Digital demodulation and filtering

Heterodyne detection scheme (using FPGA)

1. Digitisation

Voltage signal at the ADC input:

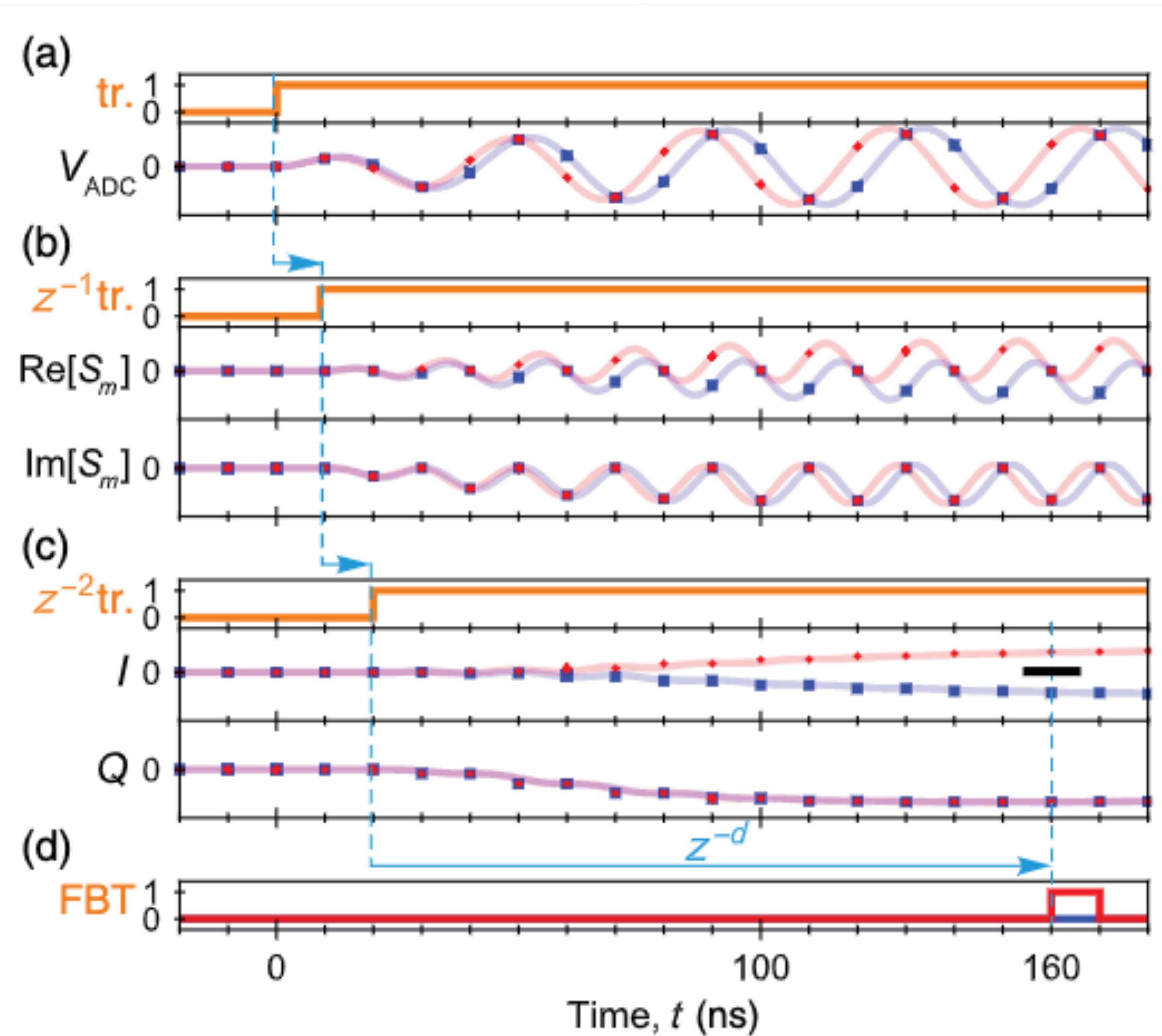
$$\begin{aligned} V_{\text{ADC}}(t) &= \tilde{A}(t) \cos[\omega_{\text{IF}}t + \phi(t)] \\ &= \frac{\tilde{A}(t)}{2} (e^{i[\omega_{\text{IF}}t + \phi(t)]} + e^{-i[\omega_{\text{IF}}t + \phi(t)]}). \end{aligned}$$

ADC sample rate: $f_s = 100 \times 10^6$ samples/s.

IF frequency: $\omega_{\text{IF}}/(2\pi) = f_s/4 = 25$ MHz

ADC resolution:

± 1 V range and 14 bit: discretisation step $2^{-13} \text{ V} \approx 0.12 \text{ mV}$



Digital demodulation and filtering

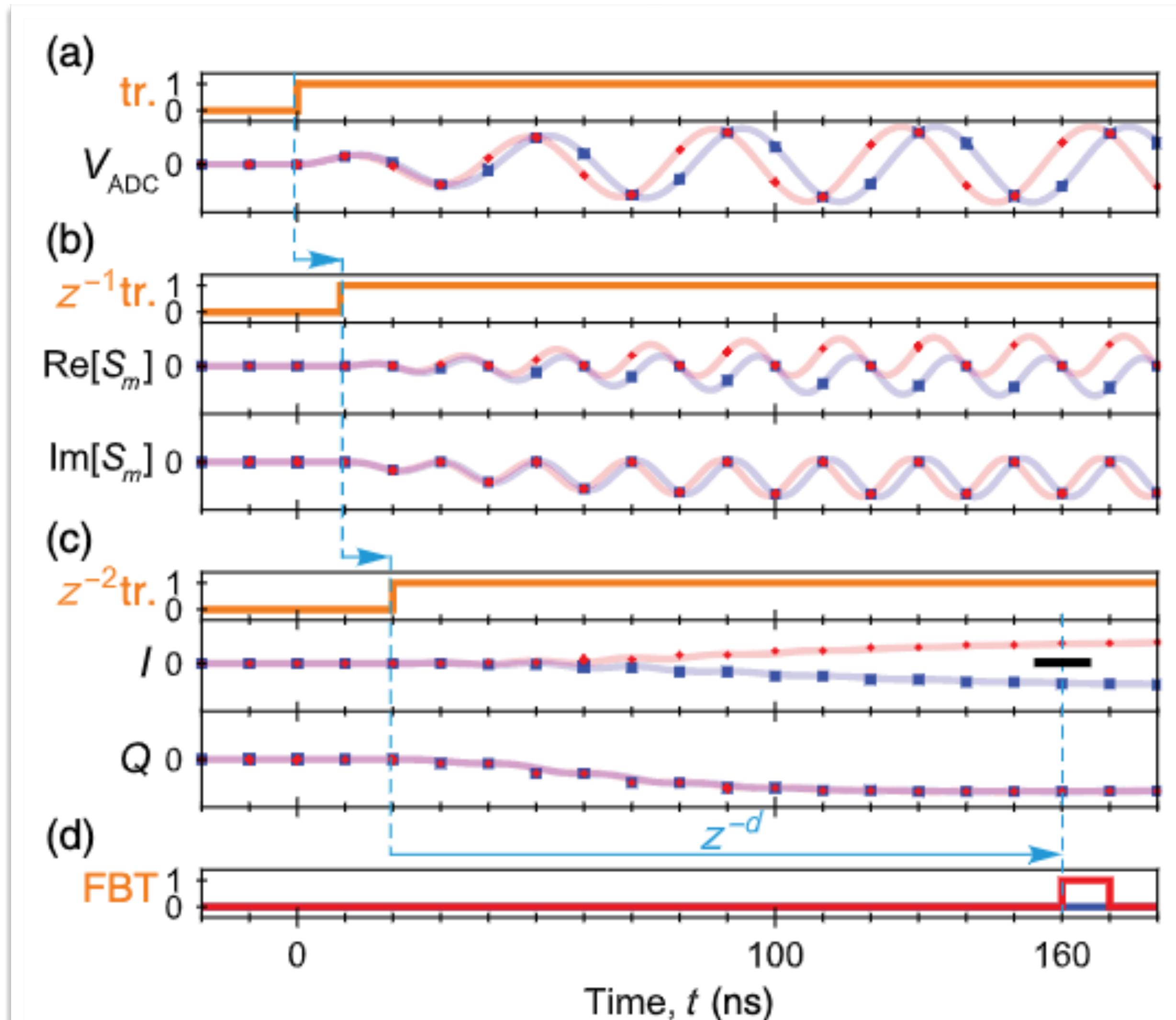
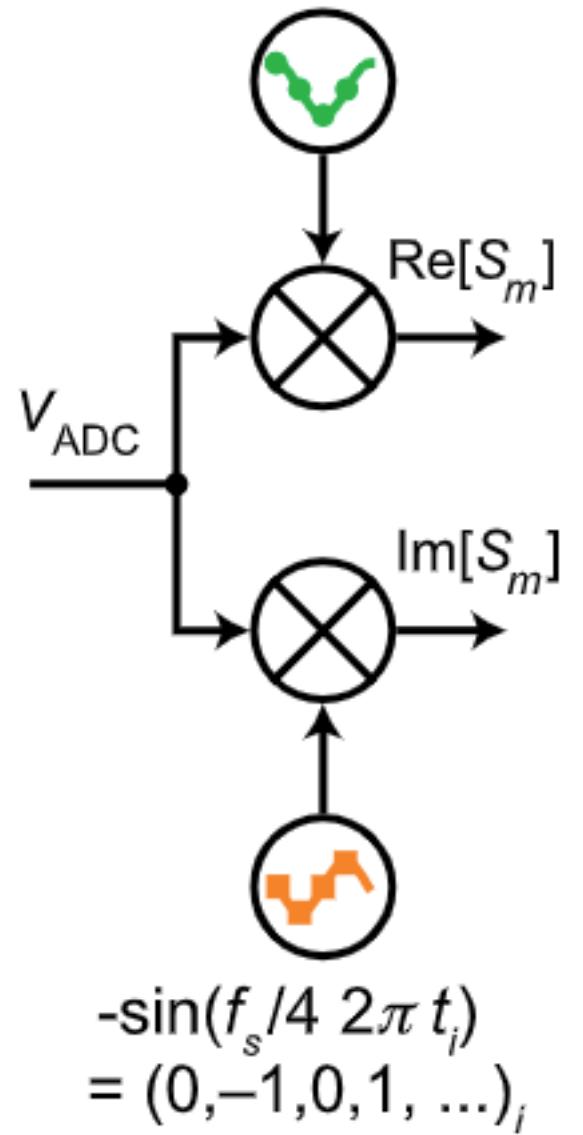
Heterodyne detection scheme (using FPGA)

2. Digital mixing

$$\begin{aligned} S_m(t_n) &\equiv V_{\text{ADC}}(t_n)e^{-i\omega_{\text{IF}}t_n} \\ &= \frac{\tilde{A}(t_n)}{2} (e^{i\phi(t_n)} + e^{-i[2\omega_{\text{IF}}t_n + \phi(t_n)]}). \end{aligned}$$

sideband at zero frequency $I + iQ \equiv \tilde{A}(t)e^{i\phi(t)}/2$

$$\begin{aligned} \cos(f_s/4 2\pi t_i) \\ = (1, 0, -1, 0, \dots)_i \end{aligned}$$



Digital demodulation and filtering

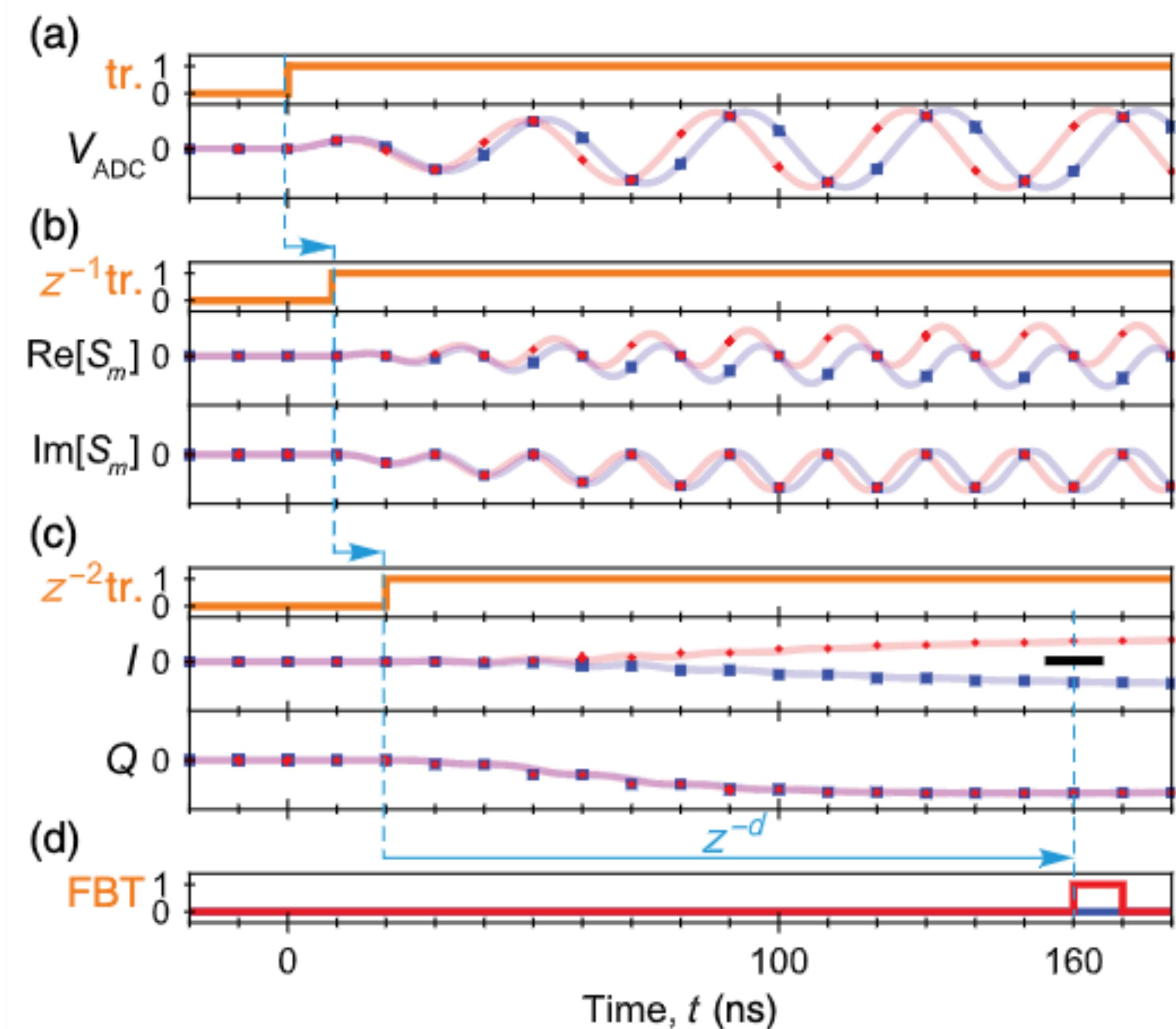
Heterodyne detection scheme (using FPGA)

3. Digital low-pass filter

moving average

$$I(t_n) + iQ(t_n) \equiv \frac{1}{l} \sum_{k=n-l+1}^n S_m(t_k),$$

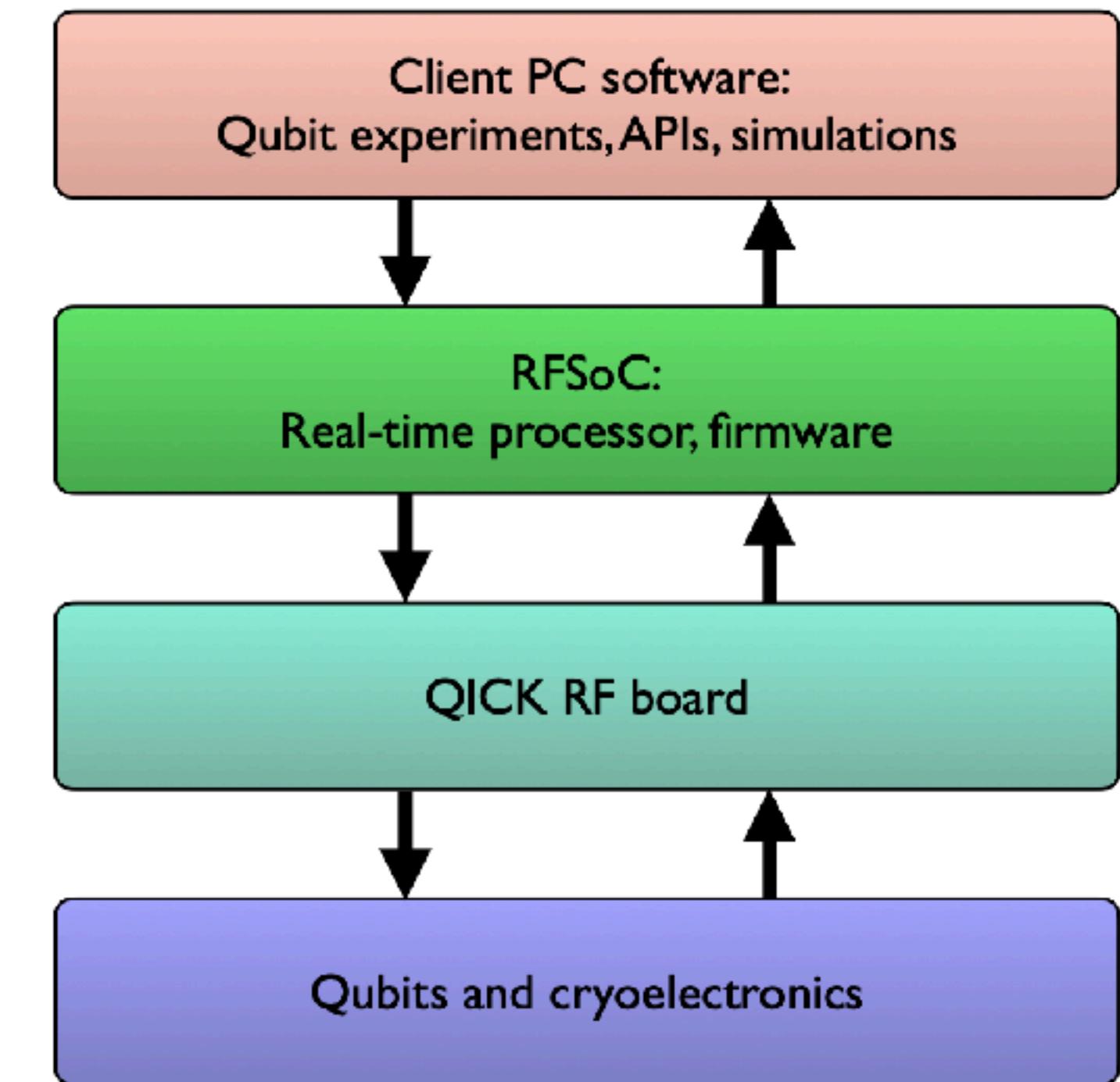
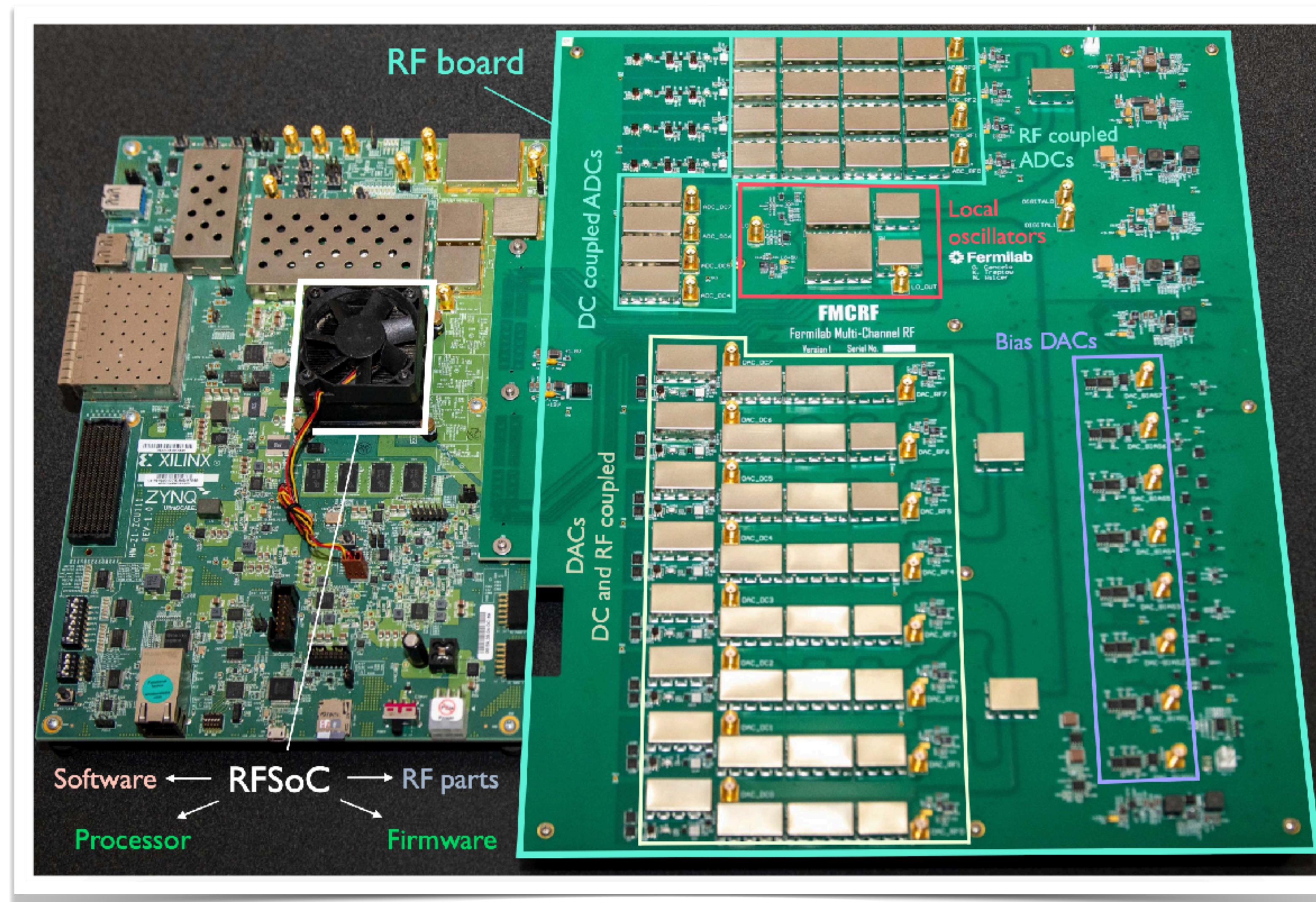
4. State discrimination



Quantum Instrumentation Control Kit

New *FPGA* platform

L Stefanazzi et al., arXiv:2110.00557v1 (2021)



- high speed DAC
- high speed ADC
- programmable FPGA logic
- conventional microprocessor

Quantum Instrumentation Control Kit

Motherboard

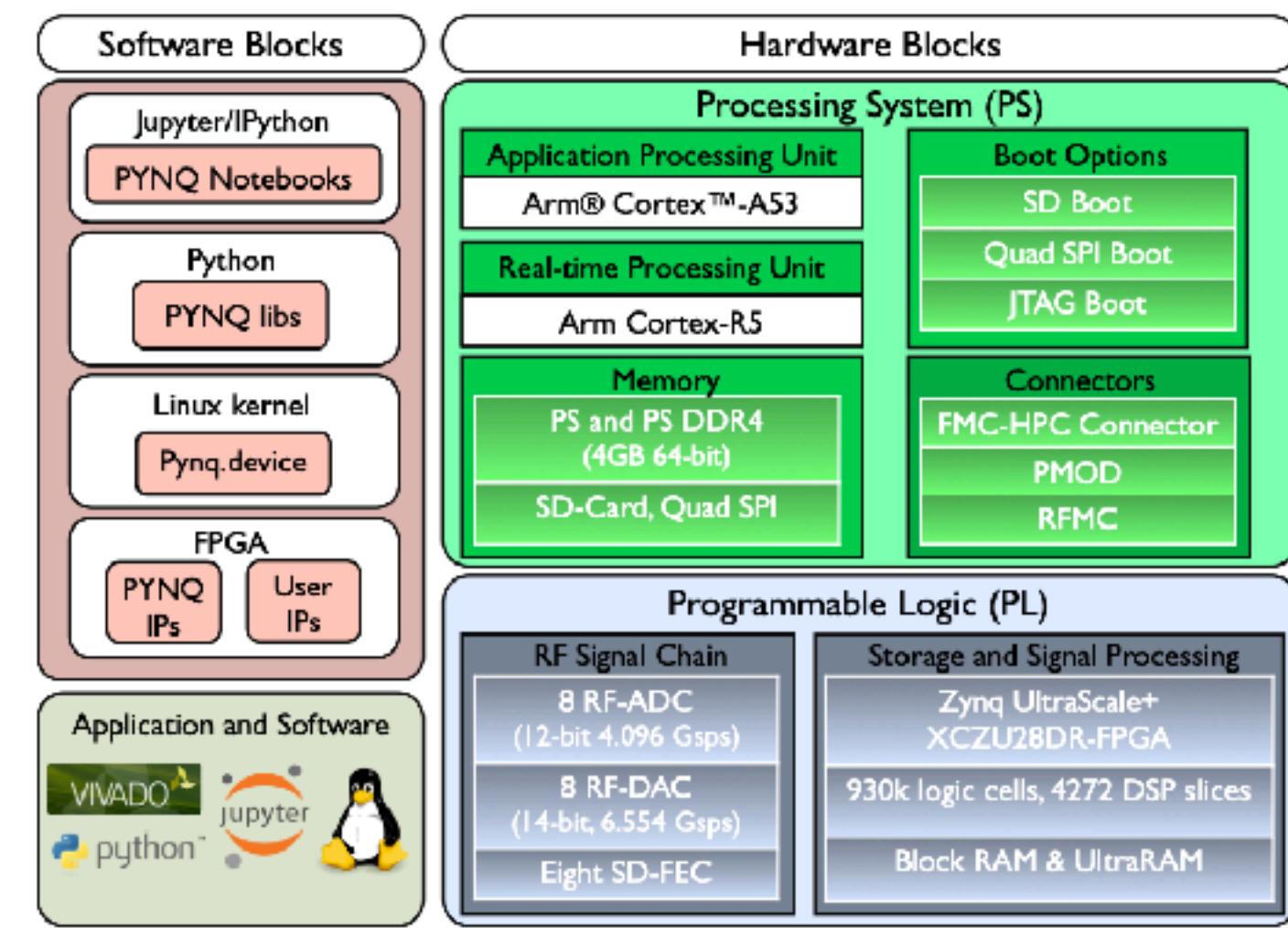
Xilinx ZCU111 RFSoC evaluation board

XCZU28DR RFSoC chip

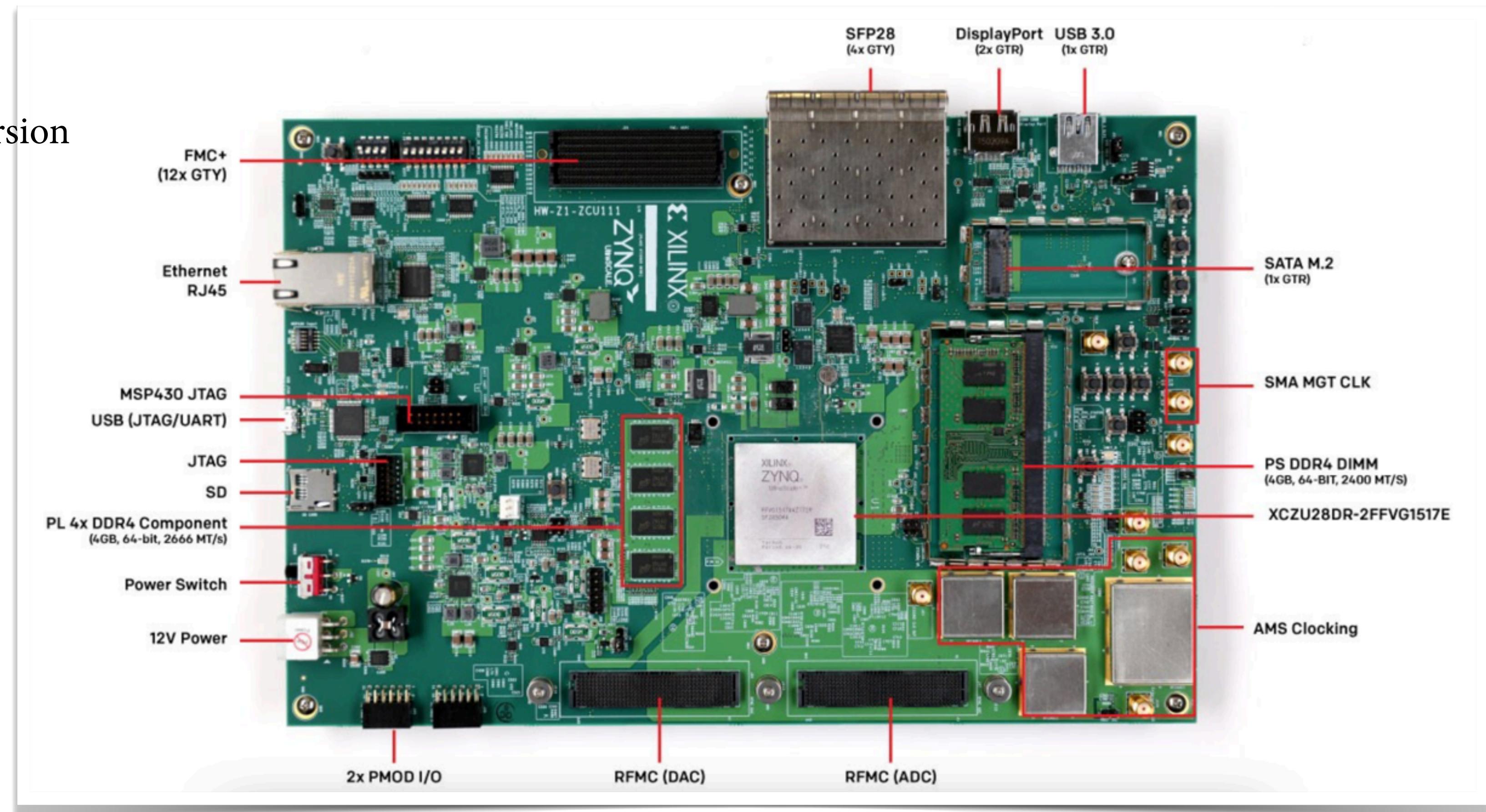
- eight 6.5 Gs/s DACs
- eight 4 GS/s ADCs

Includes:

- configurable IQ digital up/down conversion
- integrated num.controlled oscillator
- gain matrix
- digital filters



direct synthesize carrier frequencies up to 3 GHz in first Nyquist zone
and up to 6 GHZ in the second Nyquist zone mode



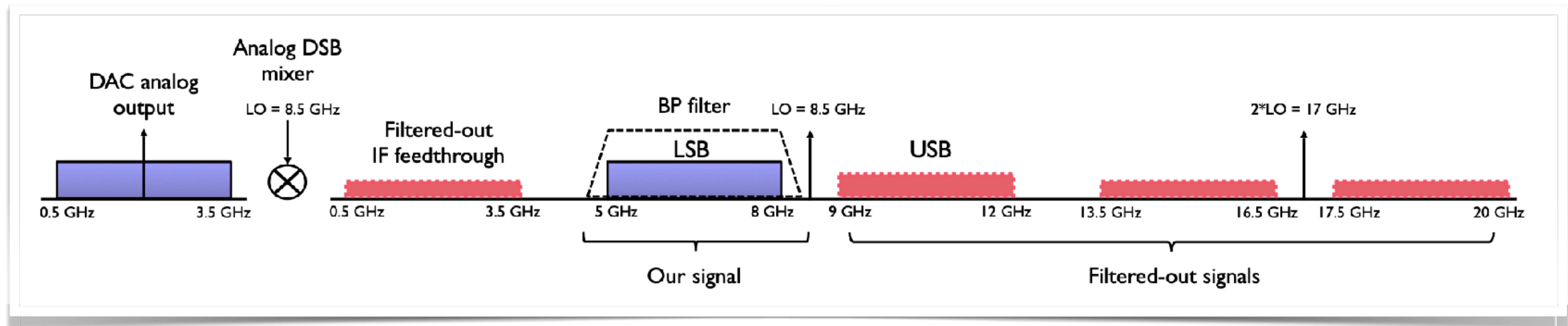
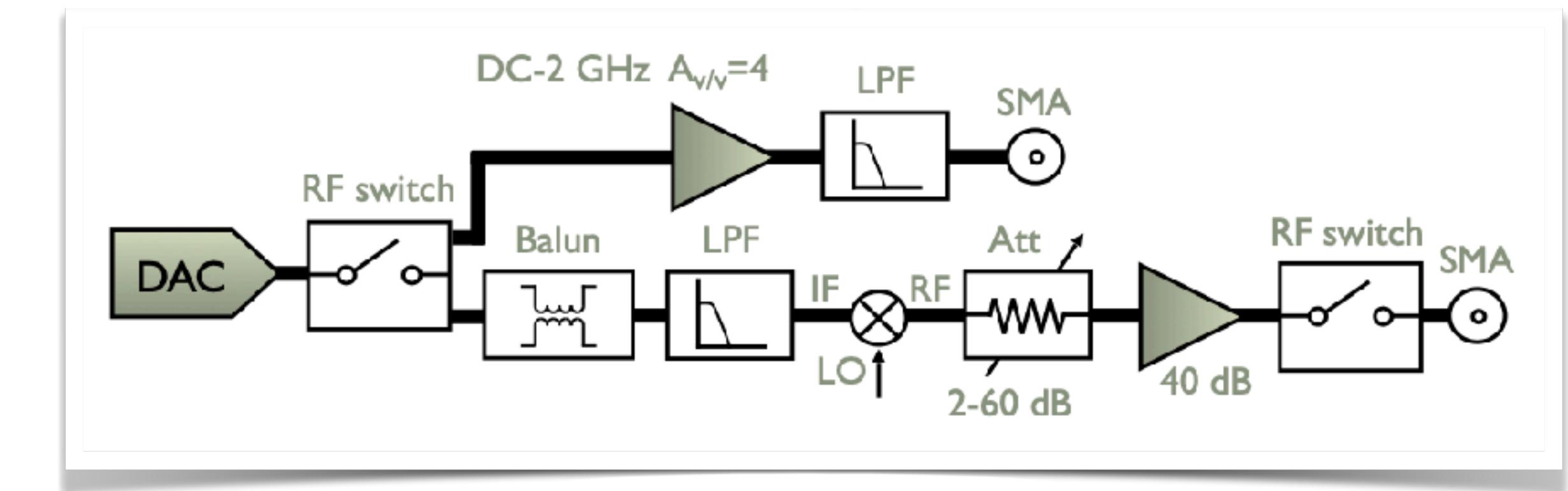
Quantum Instrumentation Control Kit

Analog front-end

QICK RF board

More than 200 components: amplifiers, mixers, filters, local oscillator generators, switches, drivers

Eight RF or DC coupled outputs



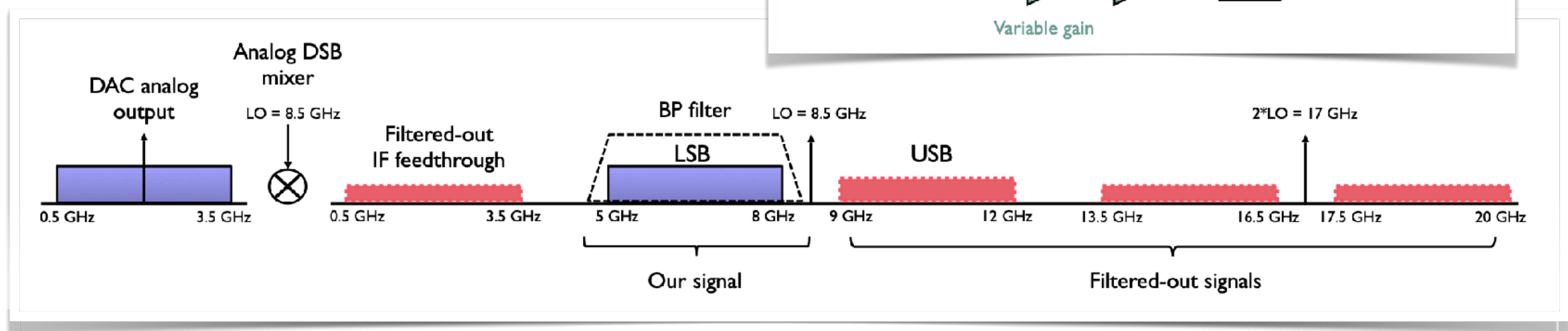
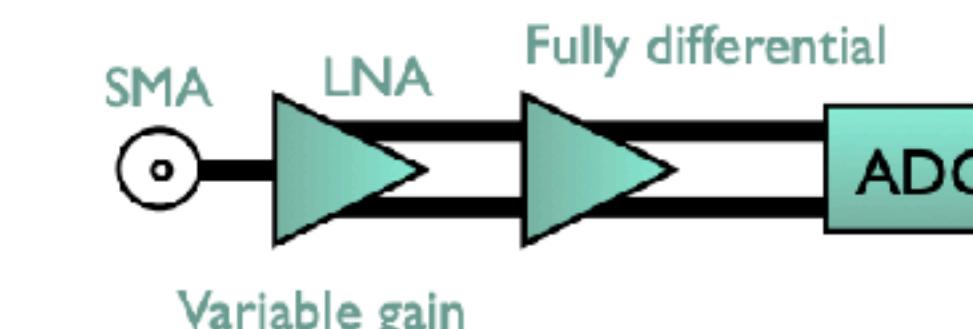
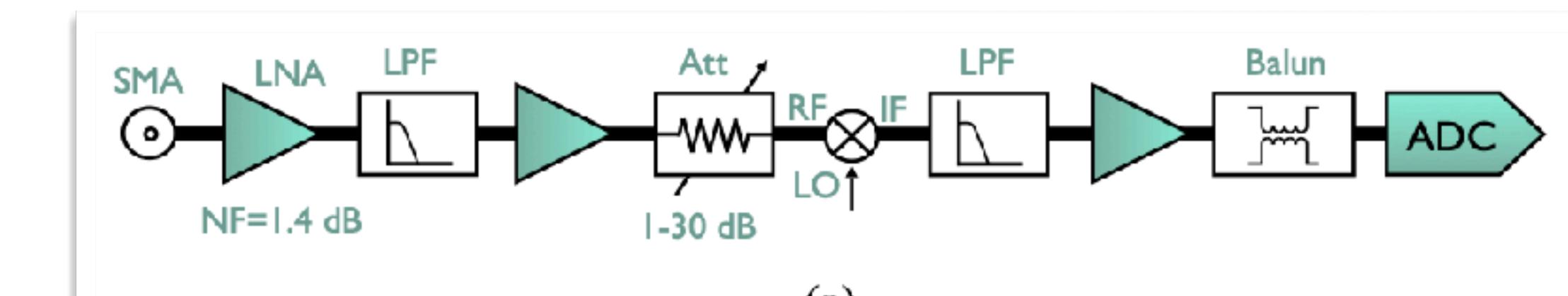
Quantum Instrumentation Control Kit

Analog front-end

QICK RF board

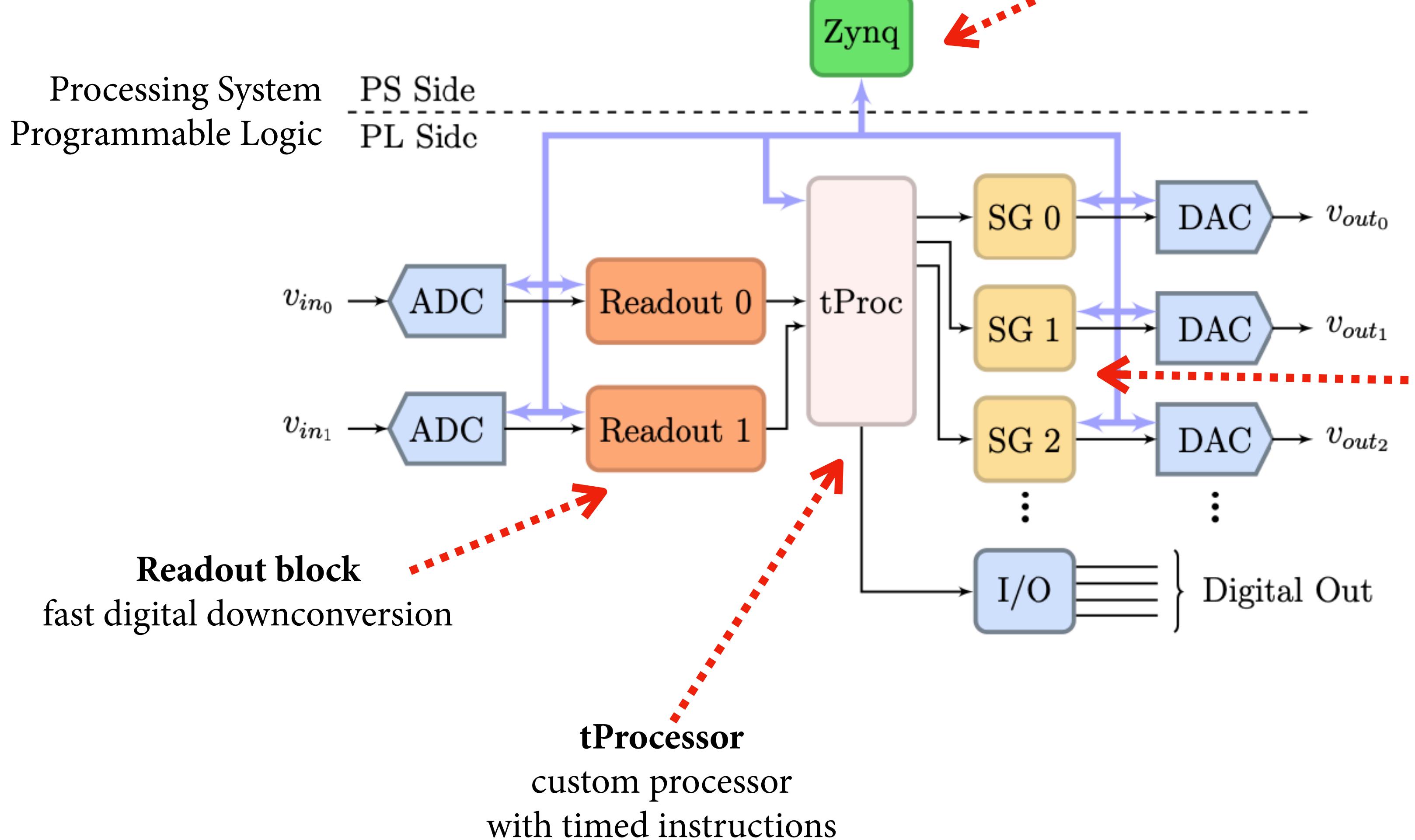
More than 200 components: amplifiers, mixers, filters, local oscillator generators, switches, drivers

Eight RF or DC (1.5 GHz bandwidth) coupled inputs



System architecture and functionality

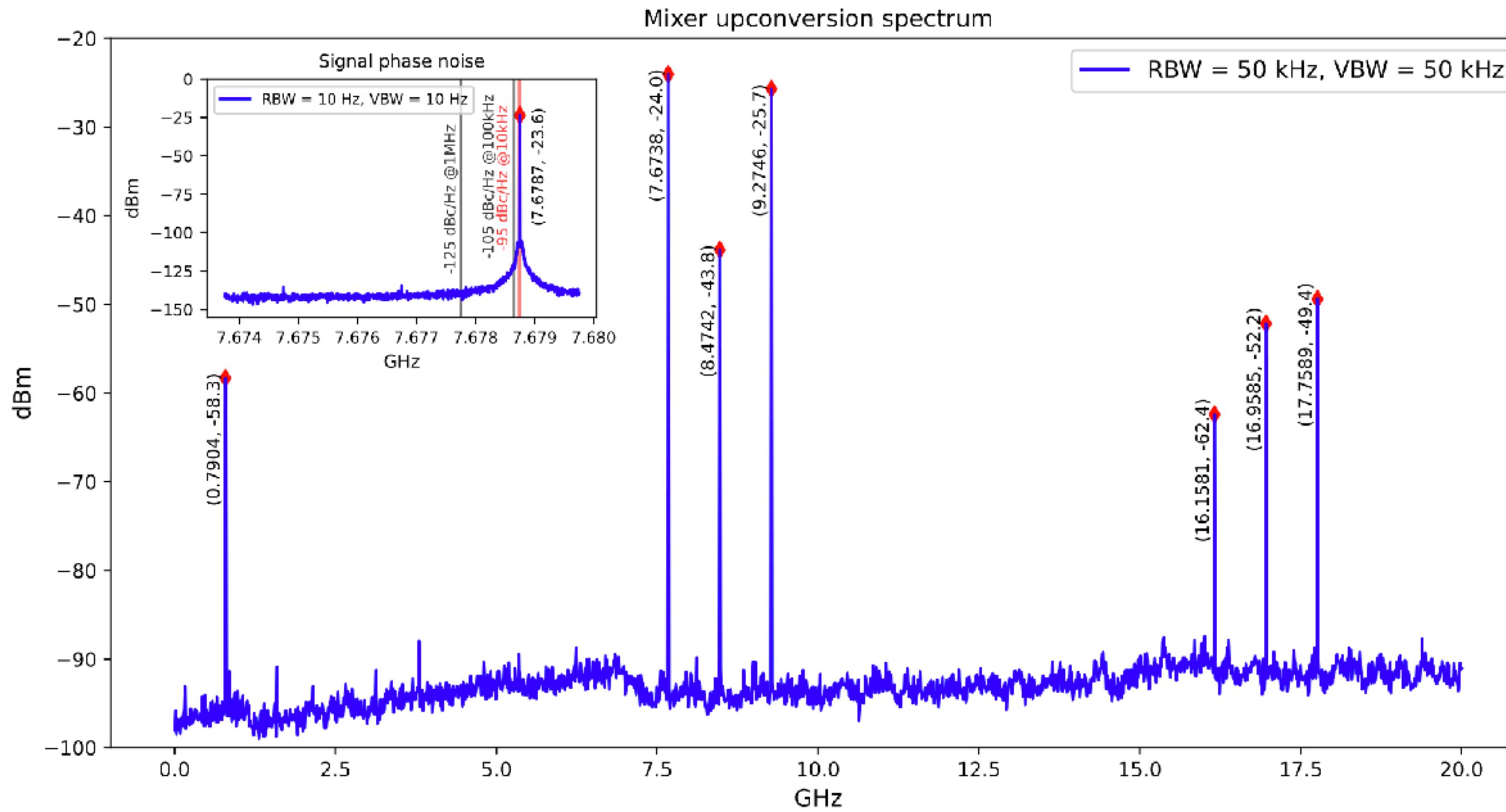
QICK firmware block diagram



Signal generators
pulses with complex envelopes
which modulates a high-speed carrier

QICK RF board Performance

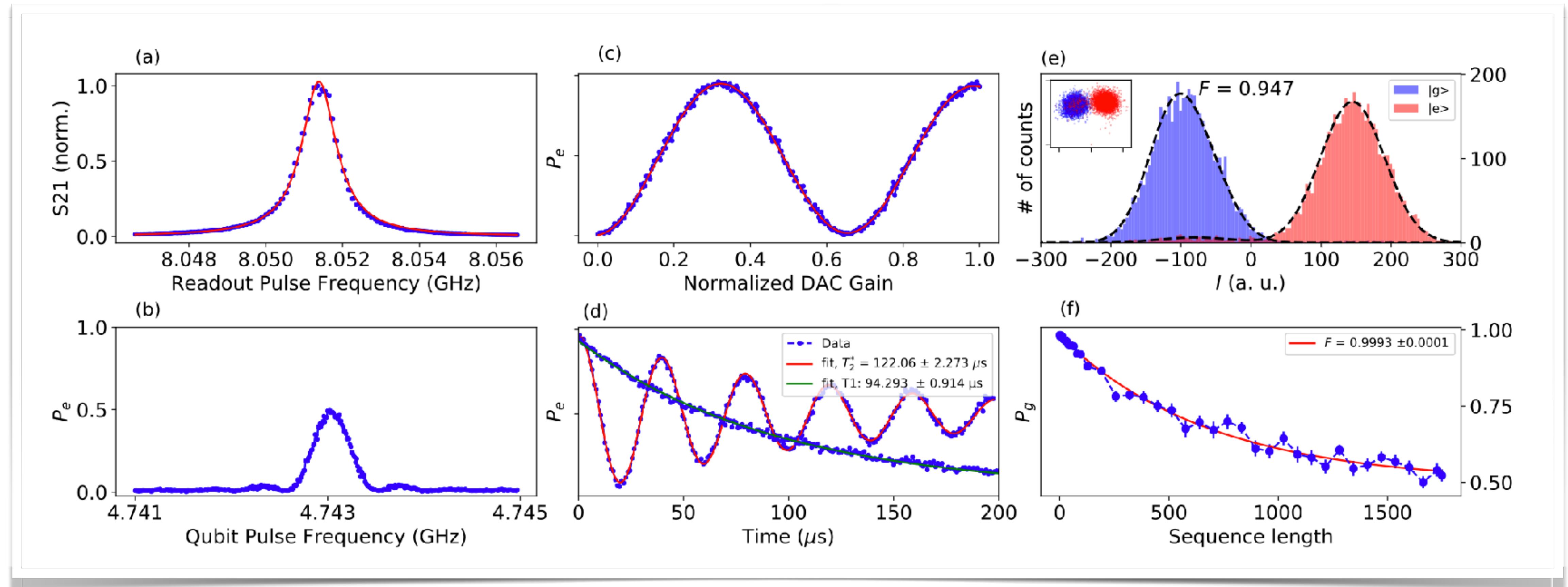
Spectrum of mixer upconversion



Latencies

Sampling freq. (MHz)	Functions	Clocks	Latency
ADC:4096 DAC:6144	ADC and DAC with all digital features bypassed	46	90 ns
ADC:4096 DAC:6144	ADC and DAC with NCO enabled	58	113 ns
ADC:4096 DAC:6144	ADC and DAC, NCO enabled, and interpolation/decimation enabled	60	117 ns
ADC:4096 DAC:6144	Conditional evaluation and address jump	16	42 ns
ADC:4096 DAC:6144	Next pulse latency if address jump=TRUE	20	52 ns

Characterization of a transmon qubit



<https://github.com/openquantumhardware/qick>