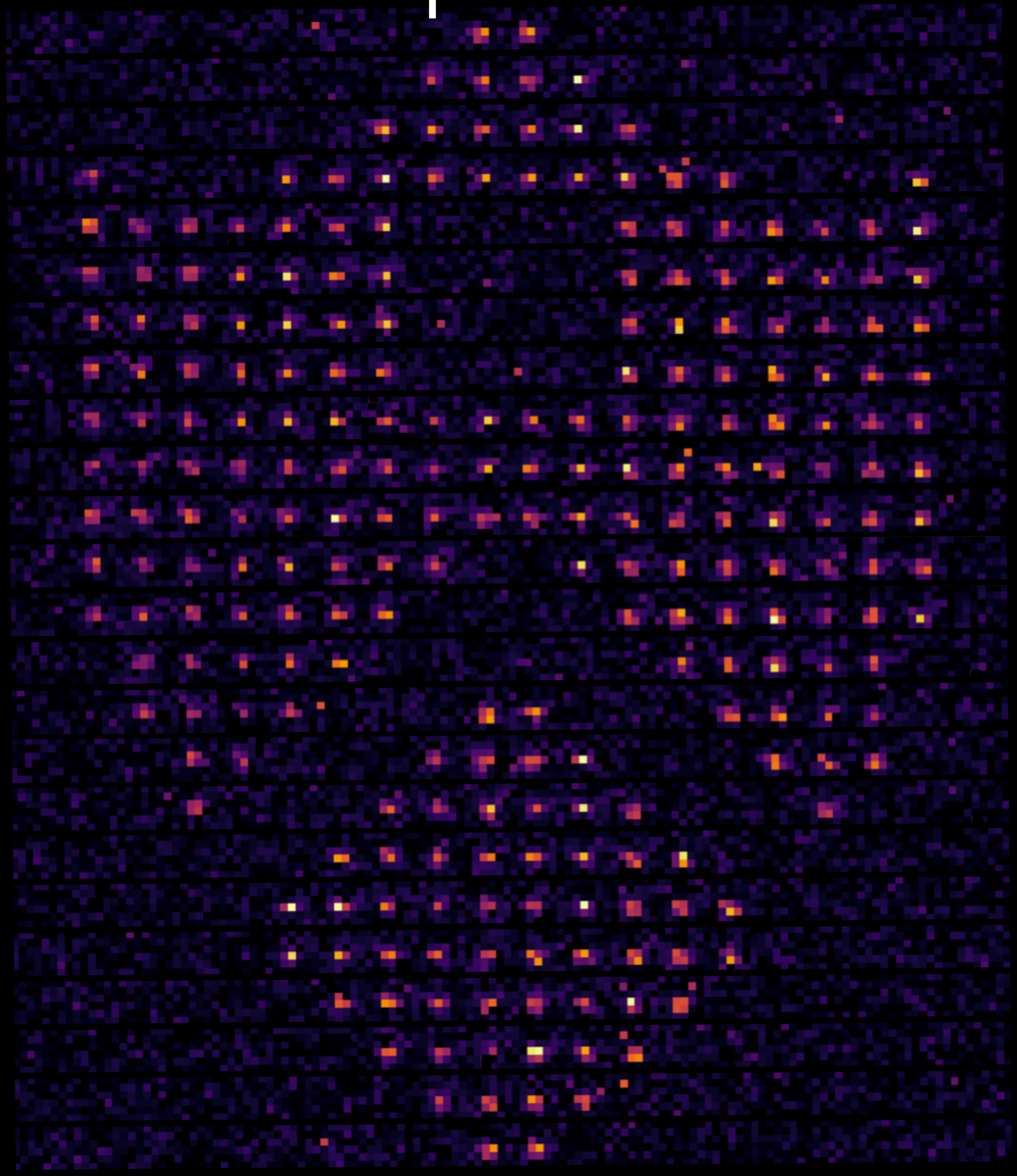
Control systems for atomic quantum computers

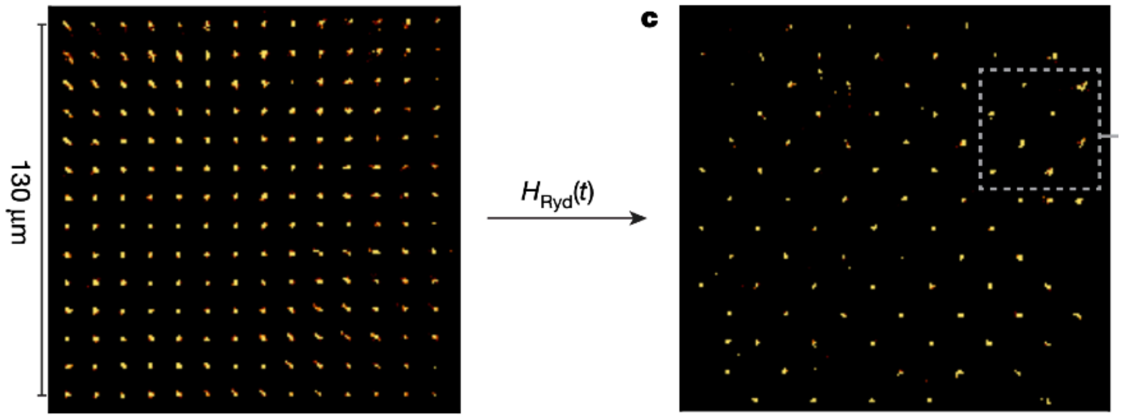


Jeff Thompson, Princeton University

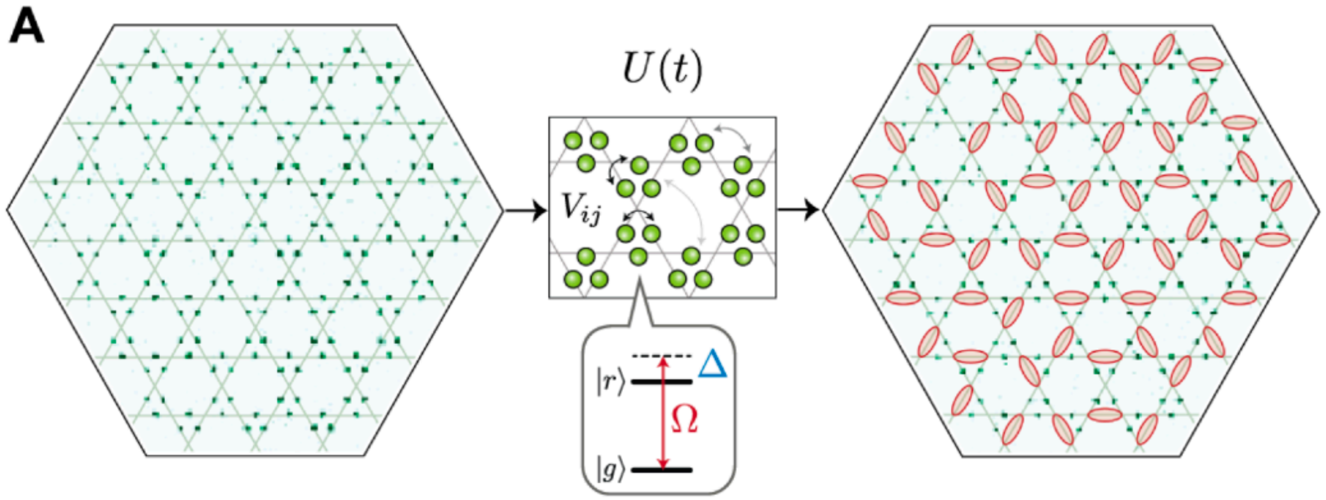
QICK Workshop, 1/12/23

Neutral atoms growing rapidly!

Large scale for quantum simulation: hundreds of atoms!

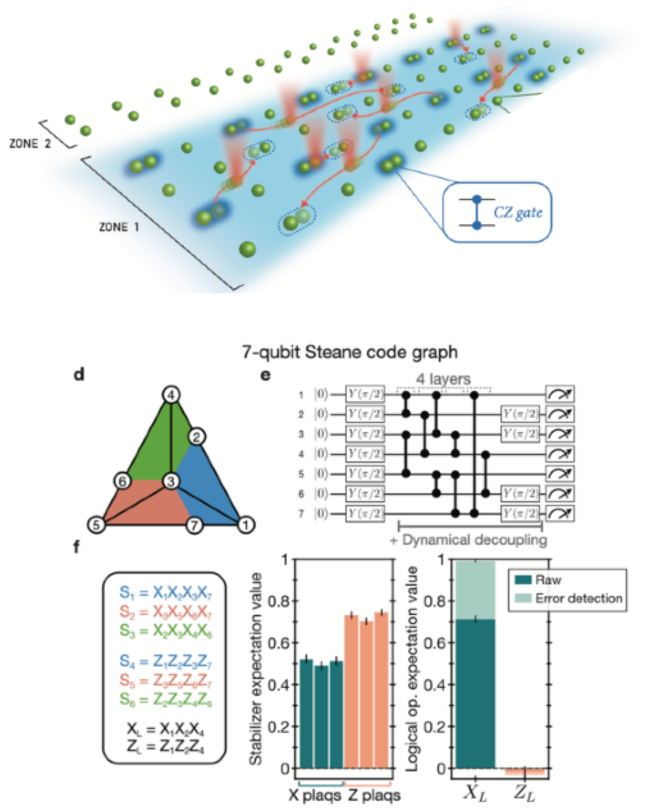


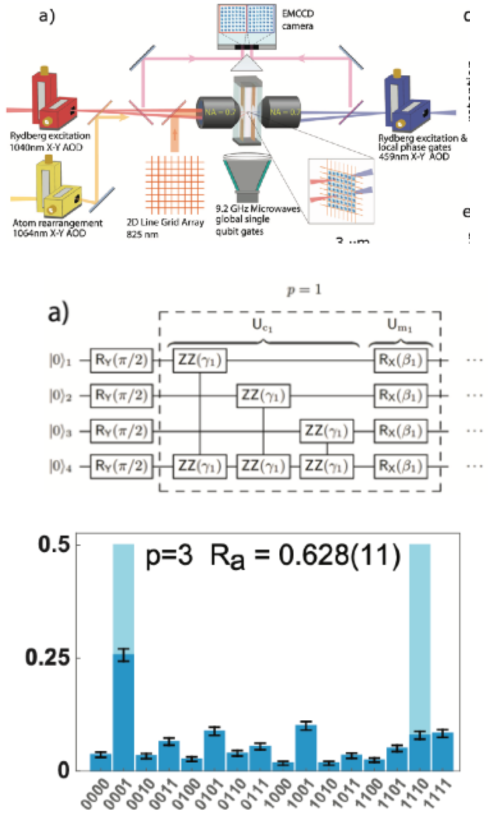
Scholl et al, Nature **595** 223 (2021), Ebadi et al, ibid.



Semeghini et al, Science 374 1242 (2022)

Beginning to implement circuits, error correction





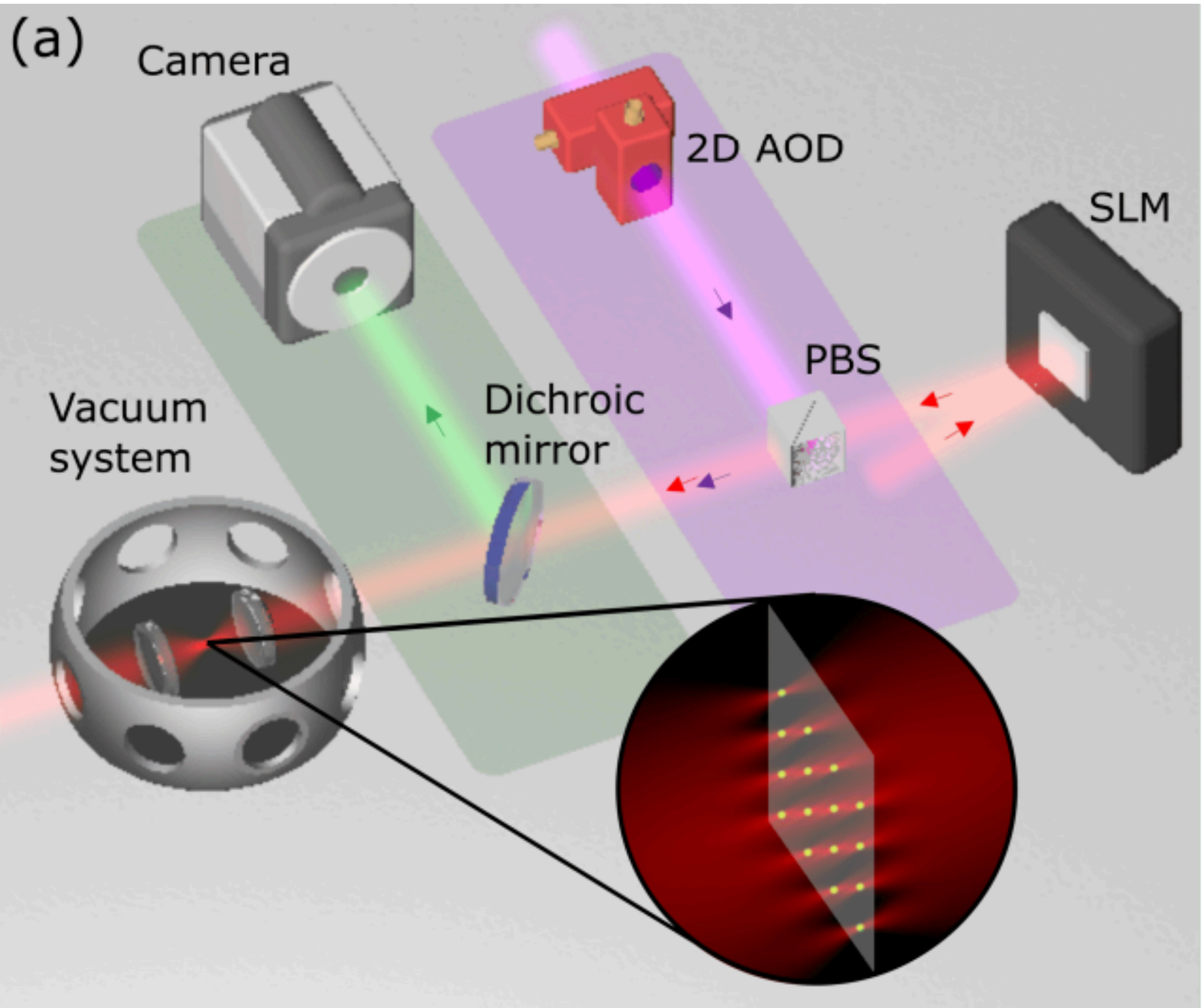
Rapidly growing field: 40+ tweezer arrays started in last 2 years around the world.

Startups: ColdQuanta, Atom Computing, Quera, Pasqal, Planqc, …

Key scaling challenge: Efficient controls

Bluvstein et al Nature 604, 451 (2022) Graham et al Nature 604, 457 (2022)

Neutral atom quantum computing



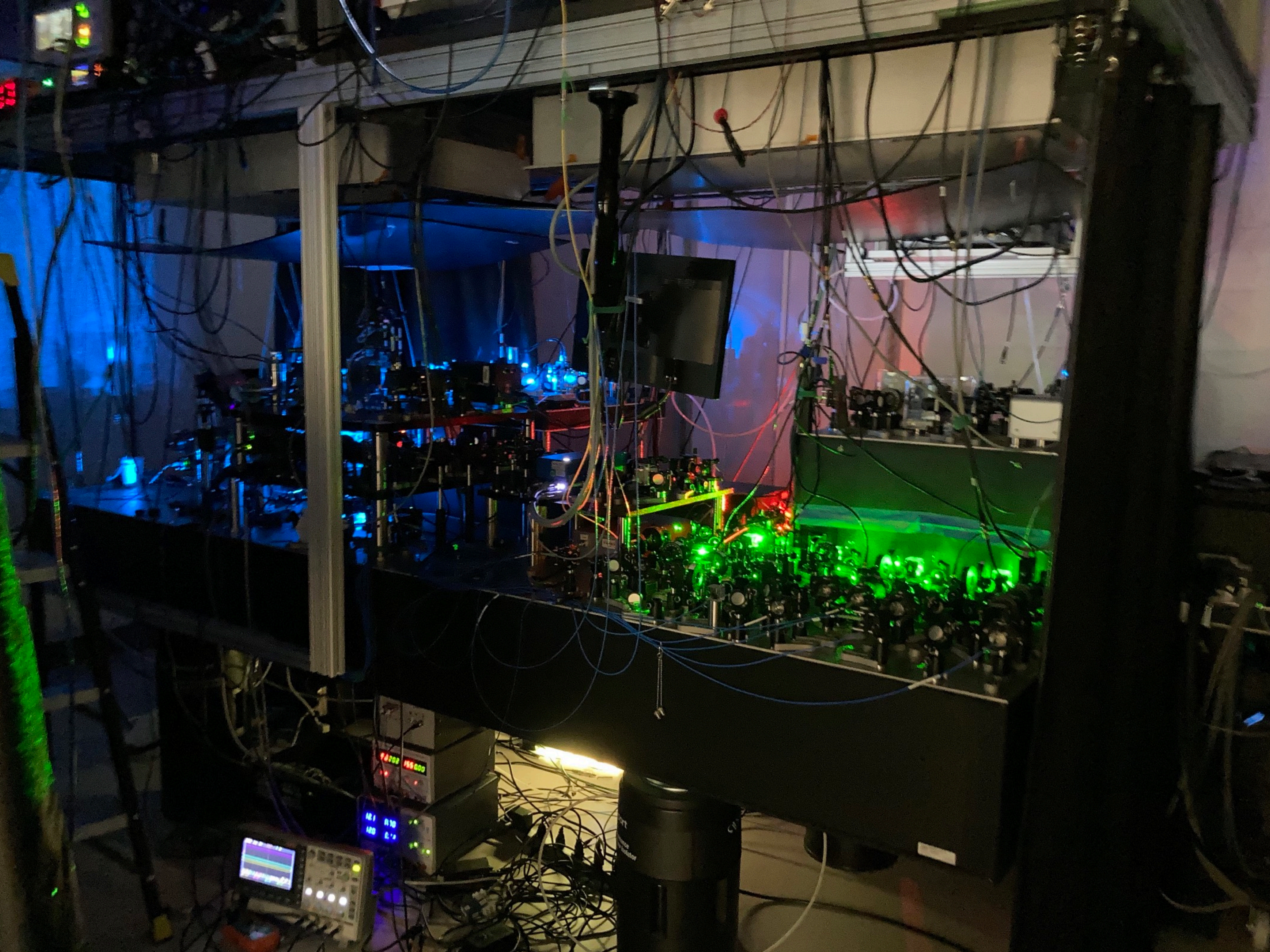
Henriet et al, Quantum 4, 327 (2020)

Qubits encoded in atoms in *optical tweezers*

Dynamically reconfigurable geometry

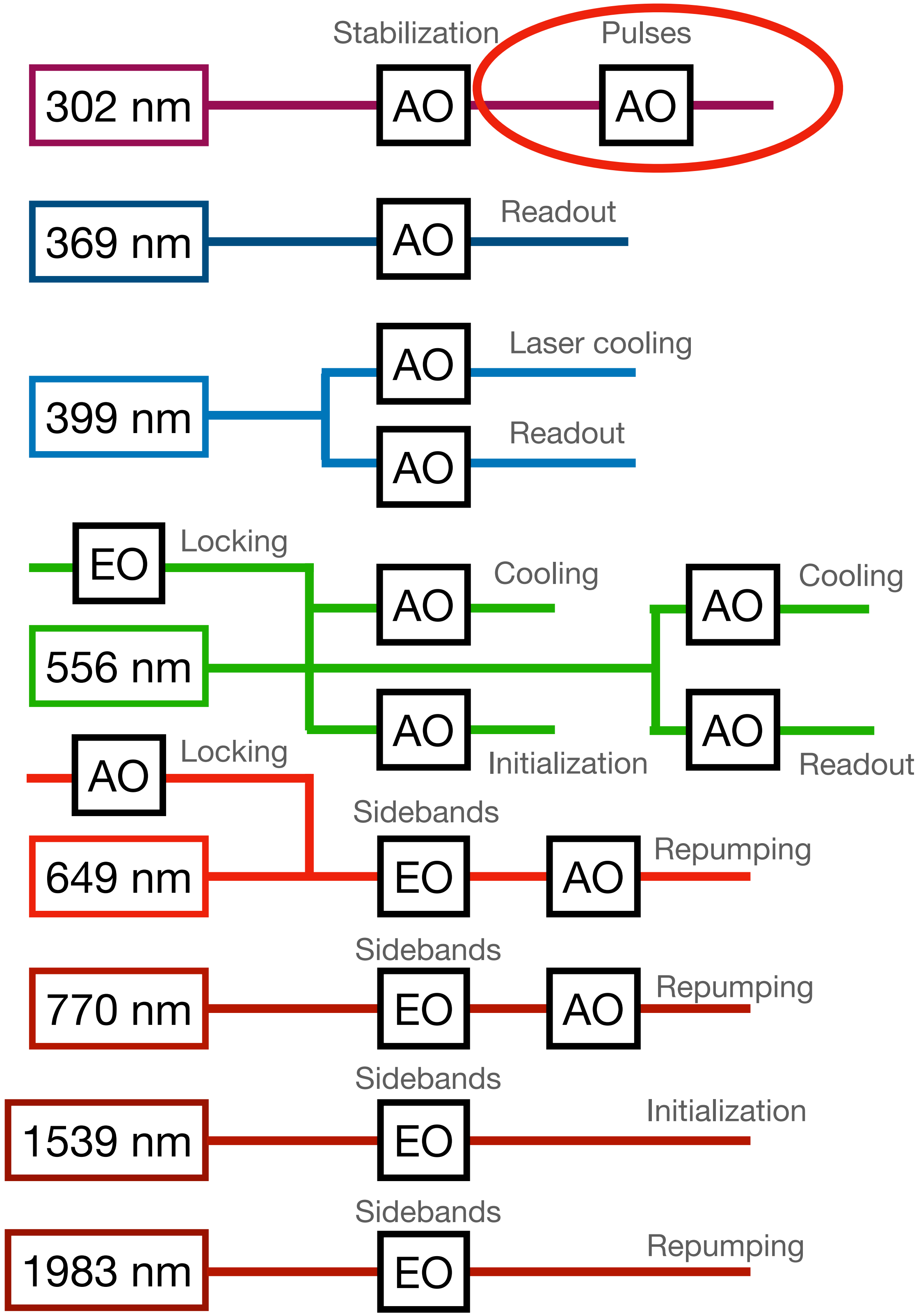
Gates controlled by *light*

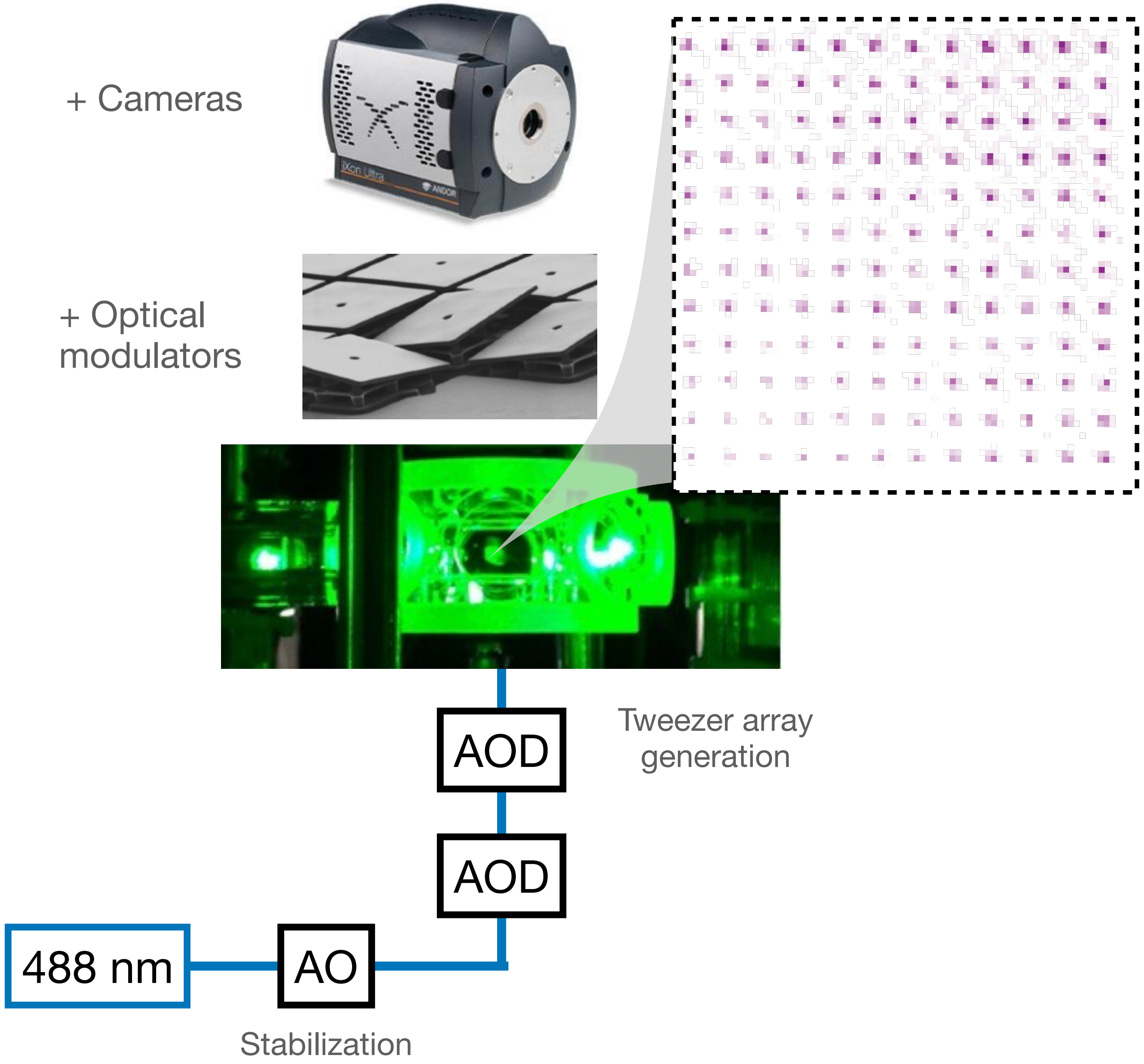
Interactions using *Rydberg states*



Atomic QC = RF-controlled lasers

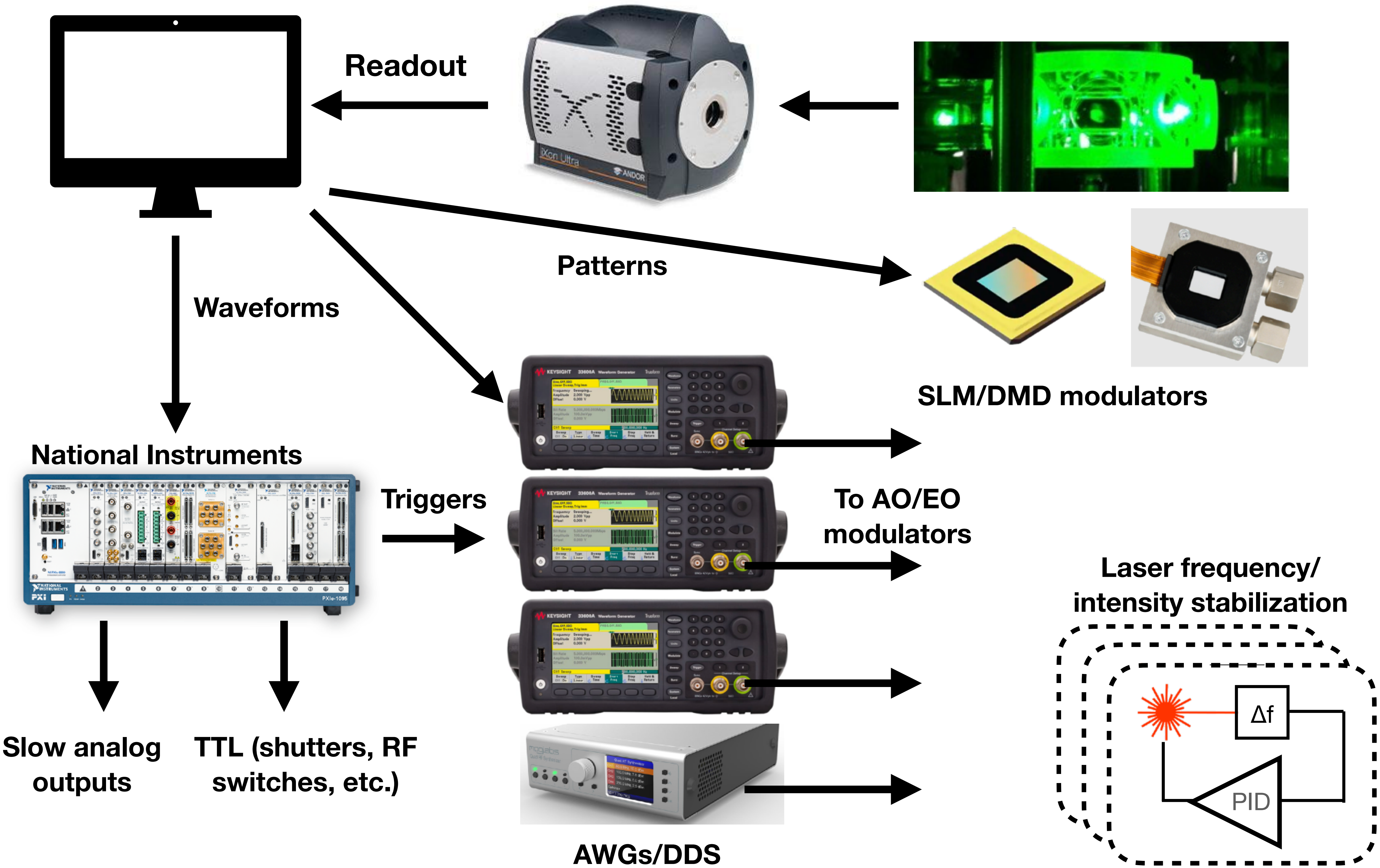
- 16 Acousto-Optic modulators (50-350 MHz)
  - 1/4 VCOs, 1/4 AWGs, 1/2 DDS
- 5 Electro-optic modulators (0.1-5 GHz)
- 4 intensity feedback loops
- 8 frequency feedback loops





Typical current architecture

- NI timing core + AWGs, DDSs, cameras,



Readout

Patterns

Waveforms

SLM/DMD modulators

National Instruments

Triggers

To AO/EO modulators

Laser frequency/ intensity stabilization

Slow analog outputs

TTL (shutters, RF switches, etc.)

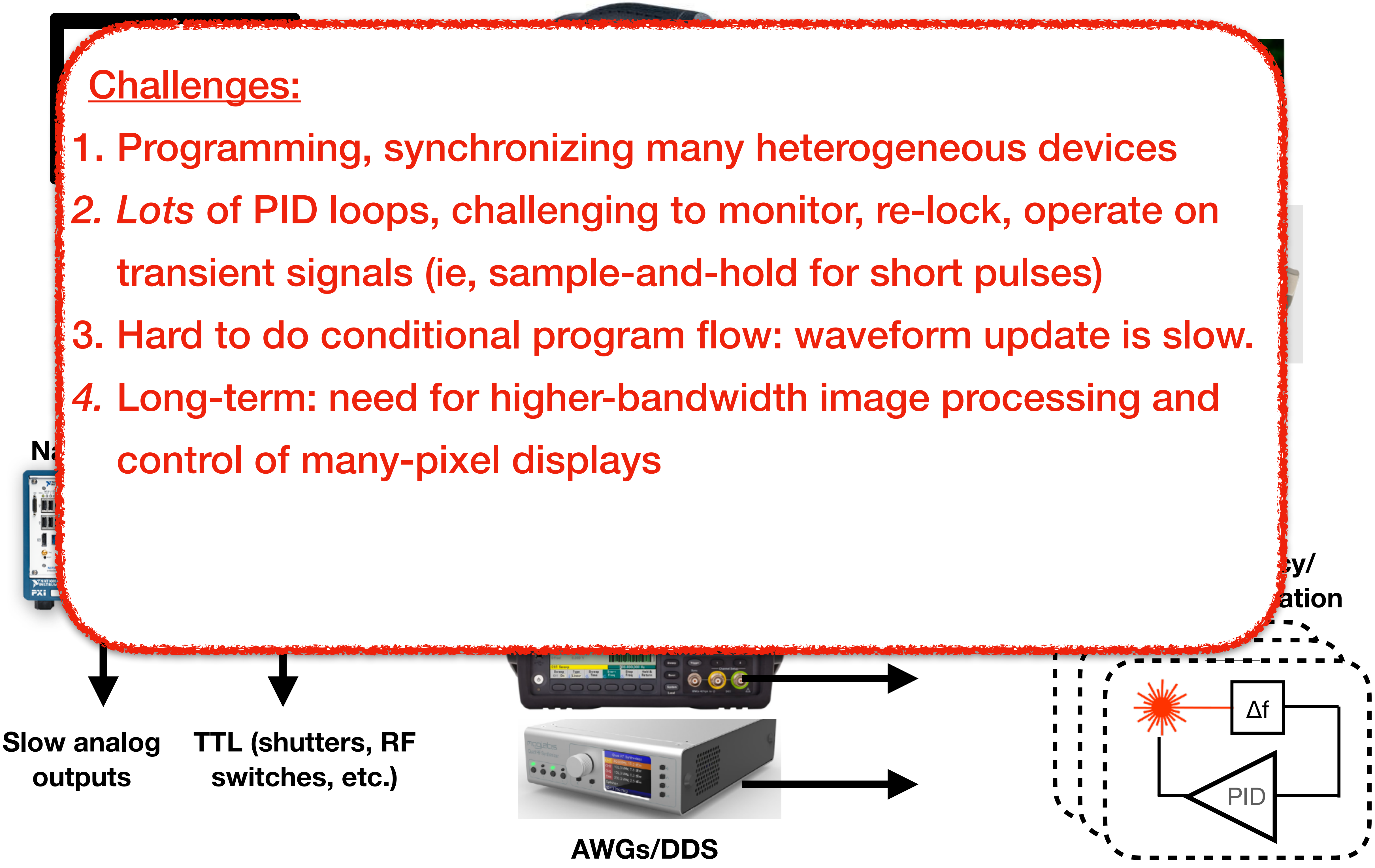
AWGs/DDS

Typical current architecture

- NI timing core + AWGs, DDSs, cameras,

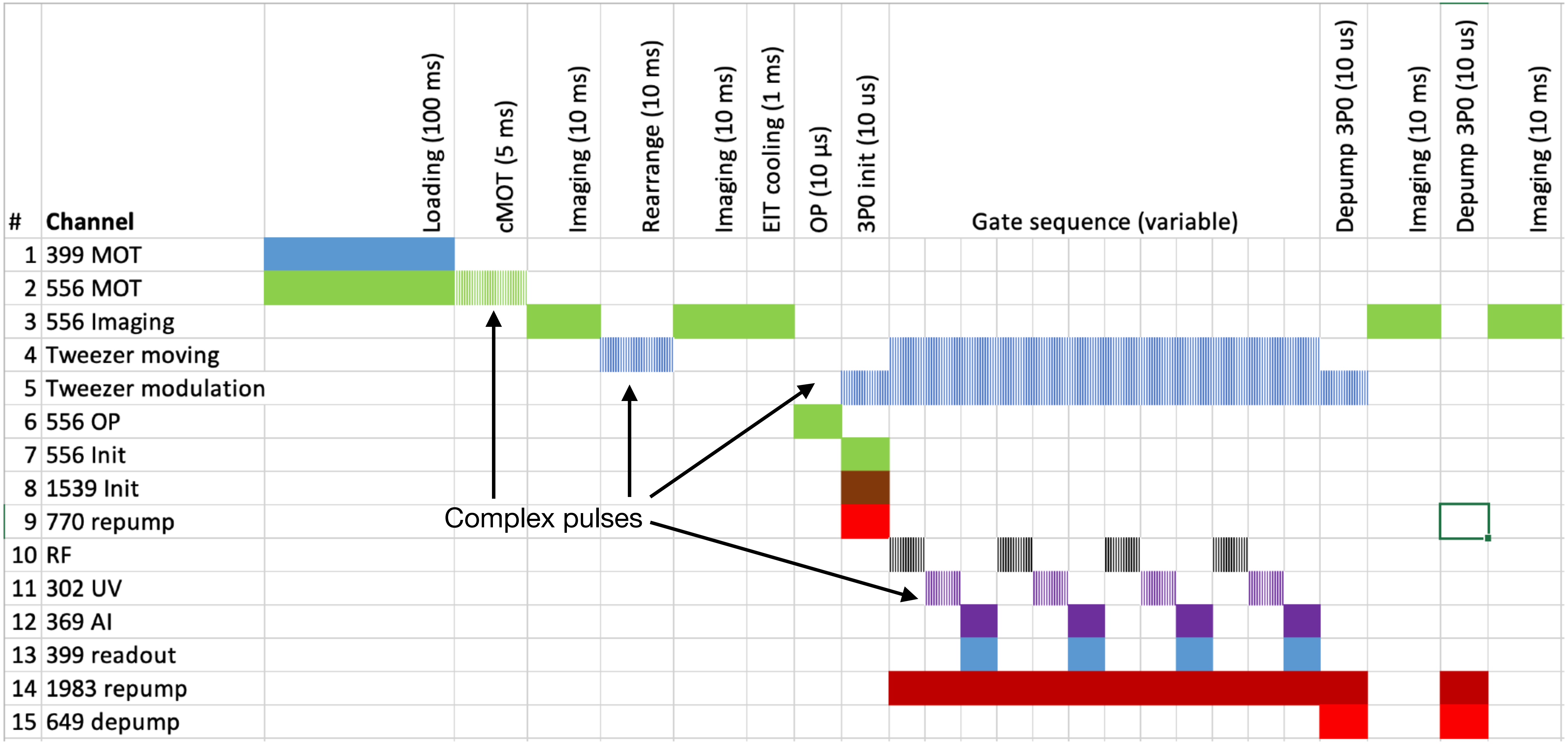
Challenges:

1. Programming, synchronizing many heterogeneous devices
2. *Lots* of PID loops, challenging to monitor, re-lock, operate on transient signals (ie, sample-and-hold for short pulses)
3. Hard to do conditional program flow: waveform update is slow.
4. Long-term: need for higher-bandwidth image processing and control of many-pixel displays



Example sequence

From Thompson lab Yb array ~Jan 2023



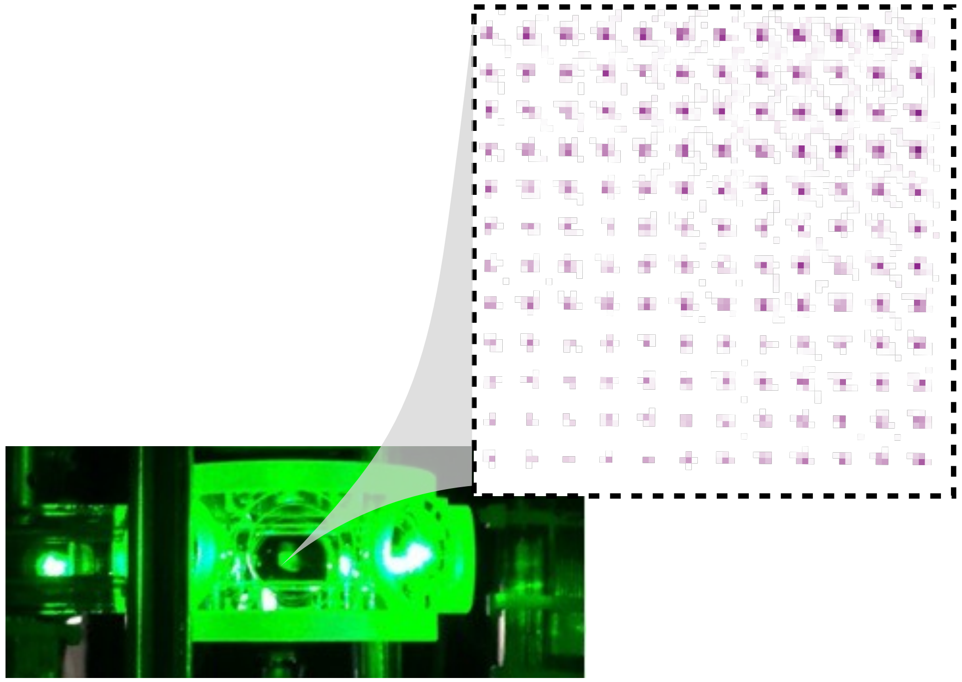
#	Channel	Loading (100 ms)	cMOT (5 ms)	Imaging (10 ms)	Rearrange (10 ms)	Imaging (10 ms)	EIT cooling (1 ms)	OP (10 µs)	3P0 init (10 us)	Gate sequence (variable)	Depump 3P0 (10 us)	Imaging (10 ms)	Depump 3P0 (10 us)	Imaging (10 ms)
1	399 MOT	🟦												
2	556 MOT	🟩	▥											
3	556 Imaging			🟩		🟩	🟩					🟩		🟩
4	Tweezer moving				▥					▥				
5	Tweezer modulation								▥	▥	▥			
6	556 OP							🟩						
7	556 Init								🟩					
8	1539 Init								🟫					
9	770 repump								🟥					
10	RF									▥ ▥ ▥ ▥				
11	302 UV									▥ ▥ ▥ ▥				
12	369 AI									🟪 🟪 🟪 🟪				
13	399 readout									🟦 🟦 🟦 🟦				
14	1983 repump									🟥	🟥		🟥	
15	649 depump										🟥		🟥	

Complex pulses

+ 10-12 PID loops running continuously in parallel

In near future, mid-circuit measurement and continuous array reloading will need conditional execution and branching

Comparison to superconducting qubit control



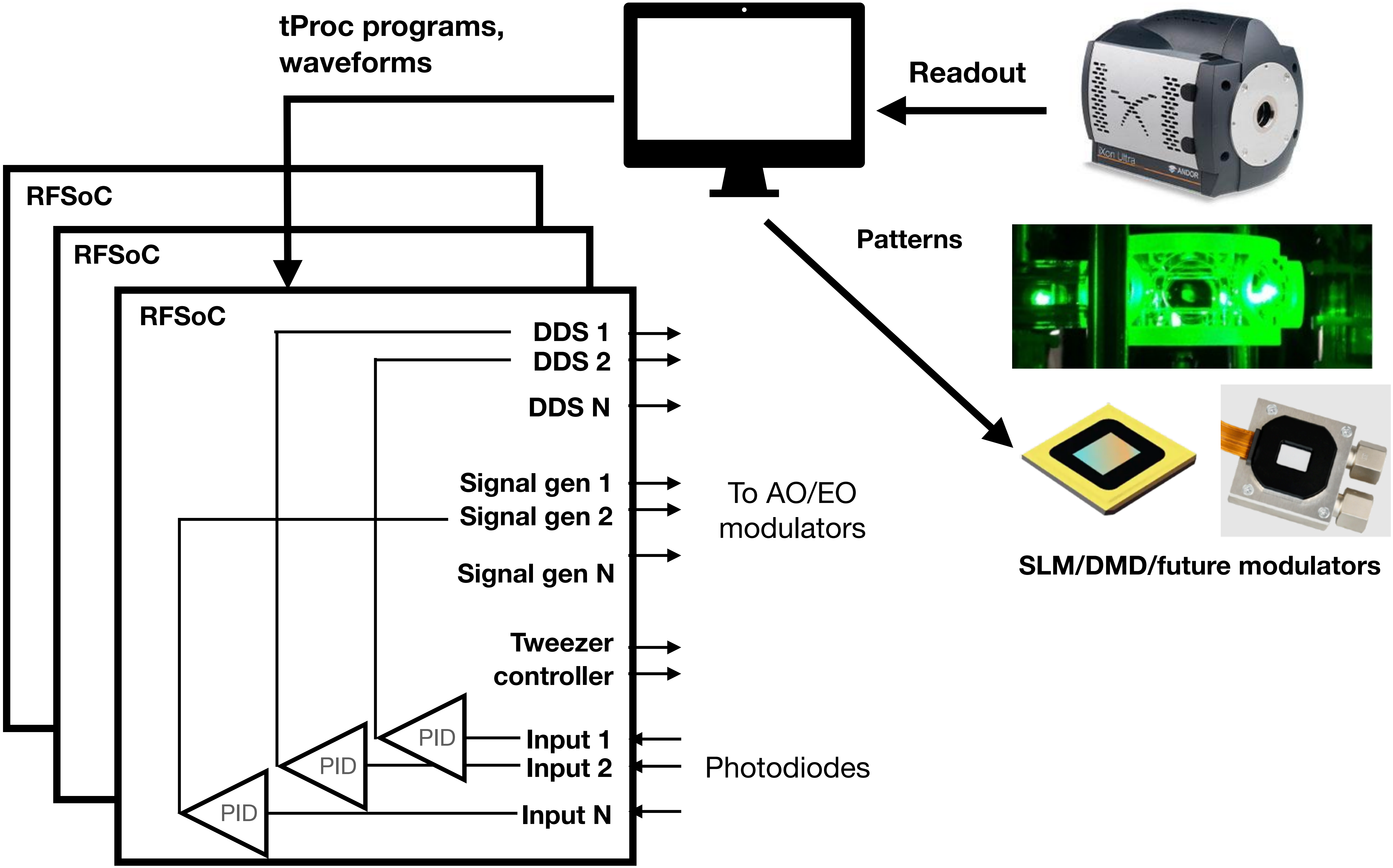
Similarities

- Mostly RF/MW control
- Need for complex pulses, tight multi-channel synchronization

Differences

- Channel count ~independent of # qubits (high starting cost, good scaling)
- Lasers are noisy oscillators -> PID on everything!
- Need some I/O with other devices: cameras, SLM/DMD, etc.
- QEC latency ~ms instead of ~μs

QICK-AMO Architecture Vision



tProc programs, waveforms

Readout

Patterns

RFSoC

RFSoC

RFSoC

DDS 1
DDS 2
DDS N

Signal gen 1
Signal gen 2
Signal gen N

Tweezer controller

PID
PID
PID

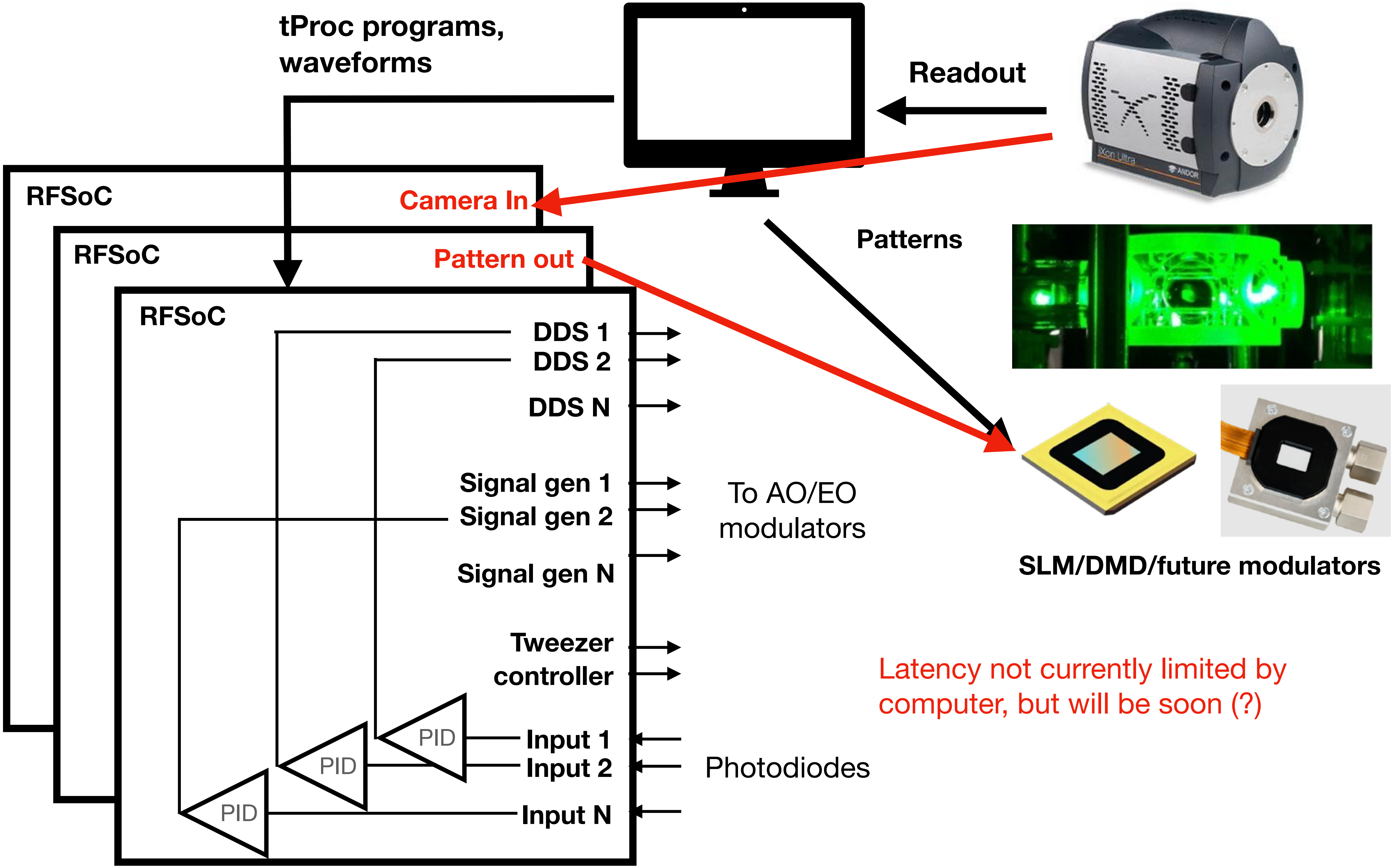
Input 1
Input 2
Input N

To AO/EO modulators

Photodiodes

SLM/DMD/future modulators

QICK-AMO Architecture Vision



tProc programs, waveforms

Readout

RFSoC

Camera In

RFSoC

Pattern out

RFSoC

DDS 1

DDS 2

DDS N

Signal gen 1

Signal gen 2

Signal gen N

Tweezer controller

PID

PID

PID

Input 1

Input 2

Input N

Patterns

To AO/EO modulators

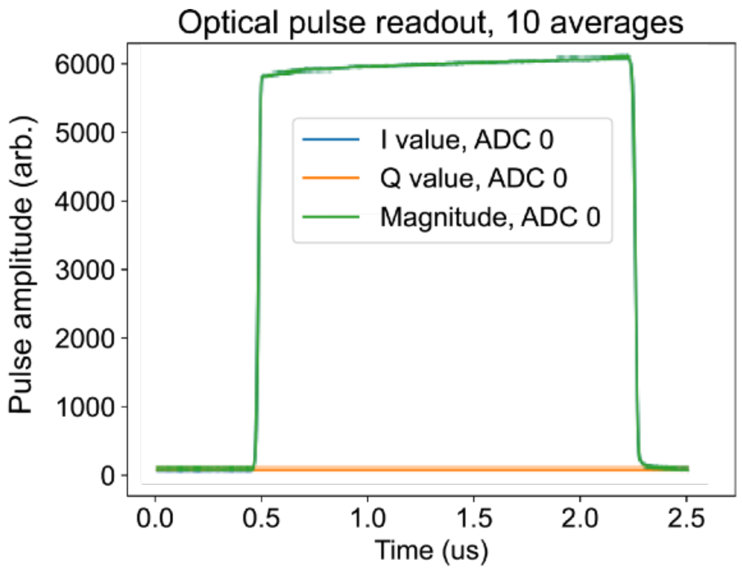
SLM/DMD/future modulators

Photodiodes

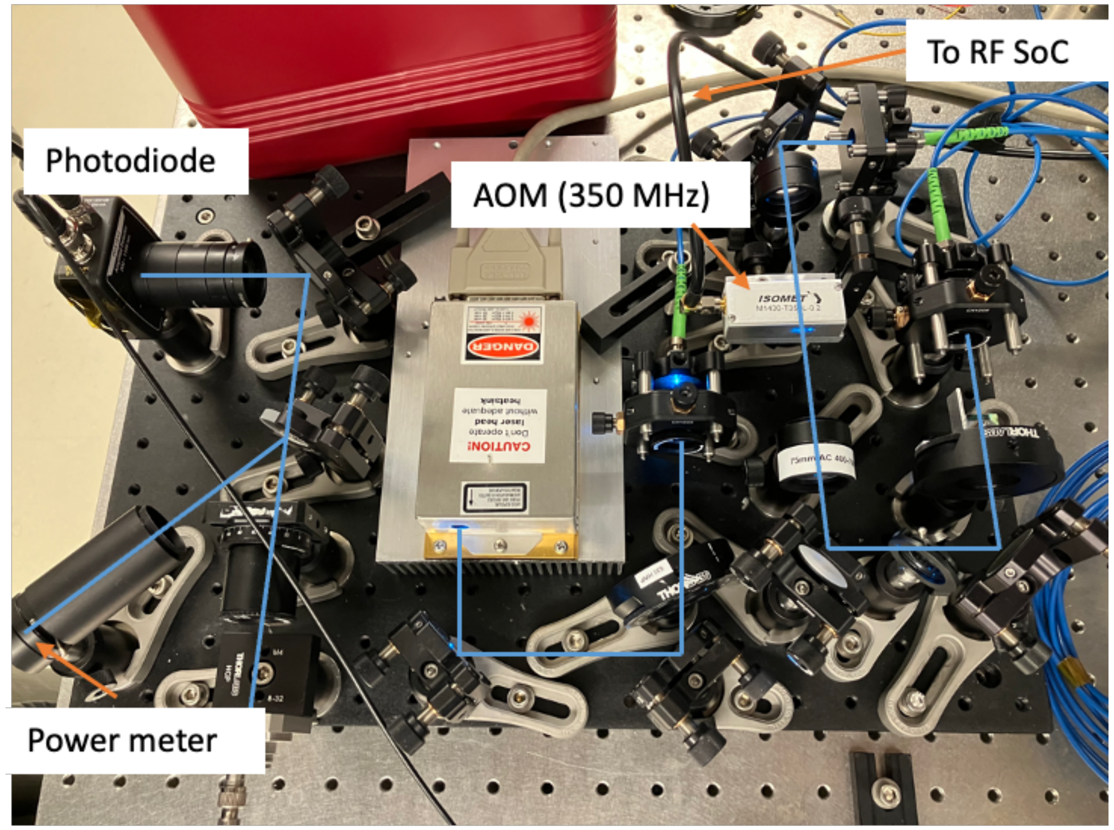
Latency not currently limited by computer, but will be soon (?)

Laser pulse stabilization with QICK

- Generate 350 MHz RF pulse with complex waveform -> AOM
- Use photodiode to capture pulse envelope, read with ADC to integrate pulse area
- Stabilize consecutive pulses to a target amplitude


Optical pulse readout, 10 averages

Optical layout



RF SoC (ZCU216)

Slide: Sebastian Horvath
Thanks to Sara Sussman + QICK team for support!

Stabilization Routine

- Discrete time PID in tProc assembly

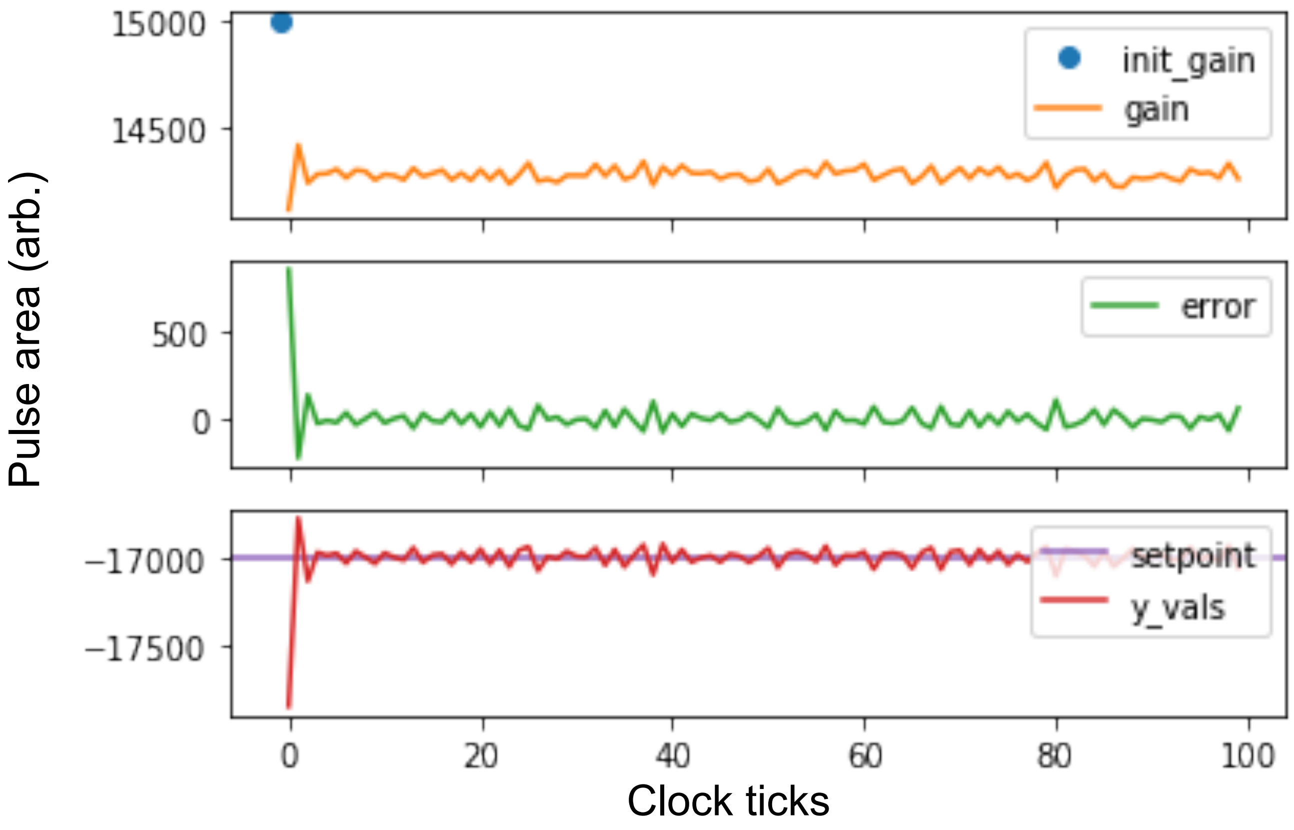
```
LOOP_I: regwi 0, $31, 17;                       //out = 0b0000000000010001
        seti 7, 0, $31, 150;                    //ch =0 out = $31 @t = 0
        seti 7, 0, $0, 160;                     //ch =0 out = 0 @t = 0
        regwi 0, $27, 0;                        //t = 0
        set 0, 0, $22, $24, $26, $0, $0, $27;   //ch = 0, pulse @t = $27
        waiti 0, 541;
        synci 17991;
        mathi 0, $3, $2 + 0;
        mathi 0, $2, $1 + 0;
        read 0, 0, lower $6;                    //read in phase ADC component
        read 0, 0, upper $7;
        math 0, $1, $4 - $6;
        memw 0, $6, $16;
        mathi 0, $5, $1 * -1070;                //proportional
        mathi 0, $11, $2 * 90;                  //integral
        mathi 0, $12, $3 * -20;                 //derivative
        math 0, $5, $5 + $11;
        math 0, $5, $5 + $12;
        bitwi 0, $10, $10 << 10;                //scale by bitshifting
        math 0, $10, $10 + $5;                  //compute next DAC value
        bitwi 0, $10, $10 >> 10;
        condj 0, $10, >, $9, @MINJMP;
        regwi 0, $10, 0;
MINJMP: condj 0, $10, <, $8, @MAXJMP;           //write to gain register
        regwi 0, $10, 30000;
MAXJMP: bitwi 0, $24, $10 << 16;
        memw 0, $10, $17;
        synci 35000;
        mathi 0, $17, $17 - 1;
        loopnz 0, $16, @LOOP_I;
```

Slide: Sebastian Horvath

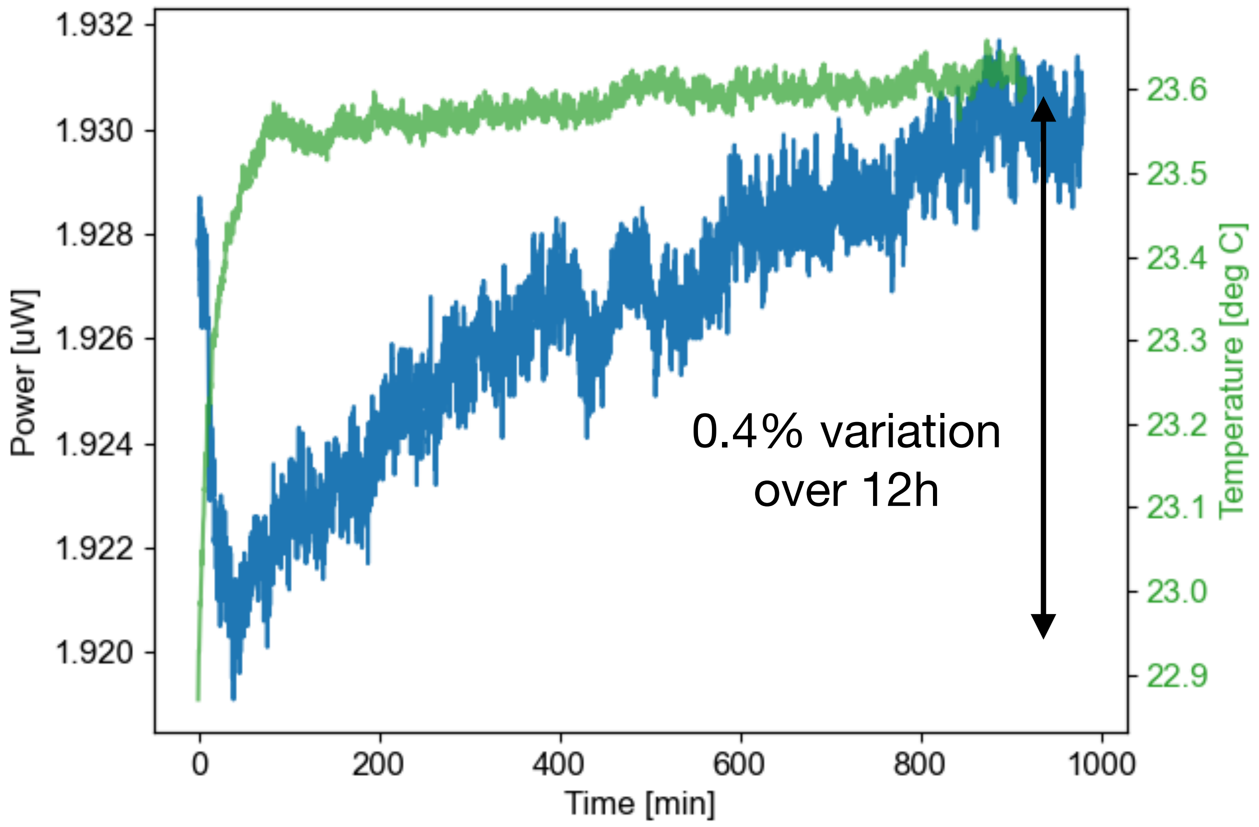
Thanks to Sara Sussman + QICK team for support!

Stabilization Performance

- Rapidly converges to target pulse amplitude
- Negligible noise/drift from RFSoC
- Long-term stability limited by optical components used to pick off reference beam for stabilization!



Initializing stabilization



Power meter readout while stabilizing

0.4% variation over 12h

Slide: Sebastian Horvath

Thanks to Sara Sussman + QICK team for support!

Our experience with QICK

- Off-the-shelf hardware easy to set up
- Example notebook w/simple superconducting circuit runs easily
- Performance as expected
- Getting “under the hood” to take full advantage is less easy:
    - tProc documentation is very good
    - Software stack between tProc and Jupyter somewhat opaque
- Relatively bug free, but would benefit from more users trying to test it in different ways

QICK in the ecosystem

ARTIQ	QICK	Quantum Machines
Open-source hardware	Off-the-shelf hardware	Closed hardware
Open-source software	Open-source software	Closed software

Acknowledgements

- Thompson lab QICKer: Sebastian Horvath
- Houck lab, esp. Sara Sussman, for support and encouragement
- QICK team for new module development and discussions