MicroTCA Control System for Neutral Atom Quantum Computing

9th Virtual MicroTCA Workshop for Industry and Research

Robin Coxe
2 December 2020

ATOM COMPUTING

Atom Computing, Inc.

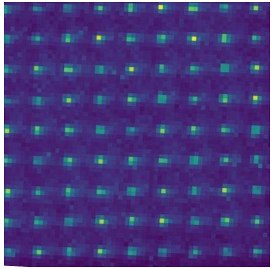
Neutral Atom Quantum Computing startup company located in Berkeley, CA USA.

Founded in 2018 by Ben Bloom and Jonathan King.

- Applying techniques from other quantum computing technologies, we are creating Noisy Intermediate Scale Quantum (NISQ) devices using arrays of neutral atoms
- Gate-based, Nearest Neighbor couplings
- Funding from venture capital, US National Science Foundation, and other sources

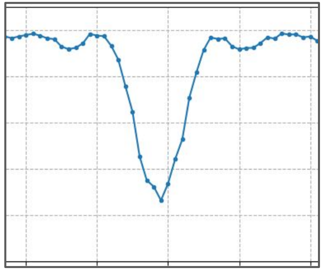
Aug 2018

Sep 2019



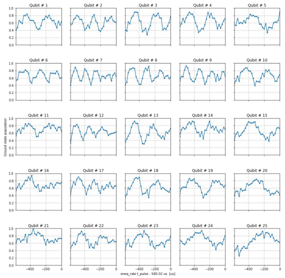
Single atoms

Jan 2020



Clock spectroscopy

July 2020



1Q Rabi flopping

Who am I?

Chief Control Systems Engineer at Atom Computing in Berkeley, CA (9/2019-Present)

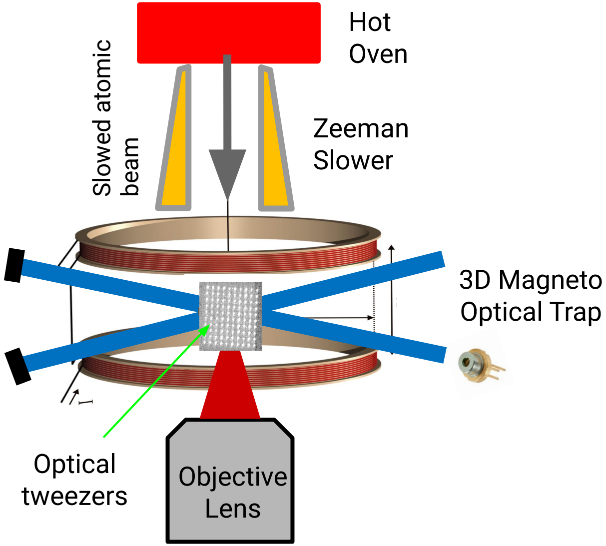
R&D Manager for Ettus Research USRP **Software Defined Radio** product line at National Instruments (2015-2019)

Lead the team that developed Digital Predistortion IP for the AD9375 RF Integrated Transceiver at **Analog Devices** targeted for 4G LTE Basestations (2011-2015)

FPGA designer and system engineer for software defined cellular basestations, point-to-point microwave modems, and satellite image processors and communication links (2000-2010).

Ph.D. in **Experimental Particle Physics** from the University of Chicago on the OPAL Experiment at CERN. Searched for a rare decay of the top quark at the CDF Experiment at Fermilab and built prototype detectors at SLAC as a Harvard undergraduate.

Neutral Atom Quantum Computing: Advantages



- Long coherence times (>10s) for qubits.
- Clean state preparation.
- High fidelity qubit gate operations actuated at a variety of timescales.
- Arrays of identical atoms. No semiconductor process variation across qubits.
- Trap and cool with lasers. Can operate at room temperature. No dilution refrigerators.
- Low-loss readout by taking images. Obviates the need for dedicated readout electronics for each qubit.
- Smaller than semiconductor qubits. Potential to fit more qubits in smaller area. Scale to 1000s of qubits with current levels of laser power.

References:
https://www.sciencemag.org/news/2018/09/arrays-atoms-emerge-dark-horse-candidate-power-quantum-computers
https://arxiv.org/abs/2011.03031

Quantum Control of Neutral Atoms

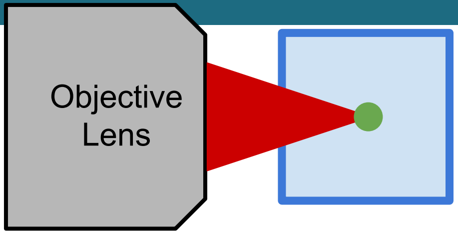
1. Make a single qubit
    - Start with a cloud of Sr87 and trap and isolate individual atoms in magneto-optical traps (MOTs)
2. Scale to many qubits
    - Make an array of traps, remove entropy
3. Perform gate operations on qubits
    - Address individual atoms
    - Construct single and two-qubit gates

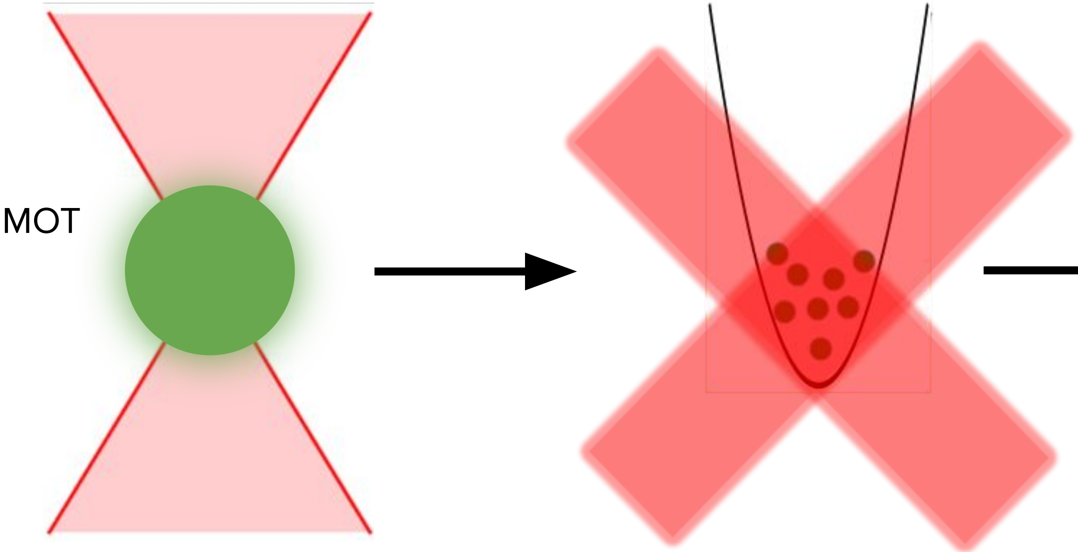
Neutral Atom Quantum Computing: Control System Requirements

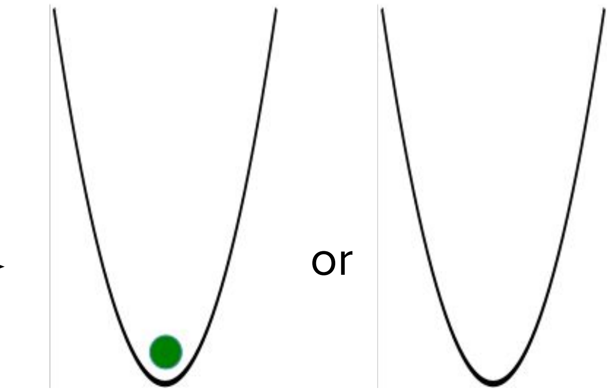
- Stabilize frequency of CW lasers and servo magnetic fields to prepare atomic states, trap, and cool qubits
- Minimize intensity fluctuations of Raman beams to maximize gate fidelity and stability of Rabi frequency and Stark shift calibrations
- Rearrange atoms/ions with chirped FM RF pulses [80-200 MHz] to fill the array of qubits
- Manipulate qubits over nanosecond timescales and maintain phase coherence between controllers
- Control & stabilize frequency combs to perform quantum gate operations [not in plans for MTCA-based control system at present]

Trapping a Single Atoms in an Optical Tweezer

- Tightly-focused laser beam forms a dipole trap

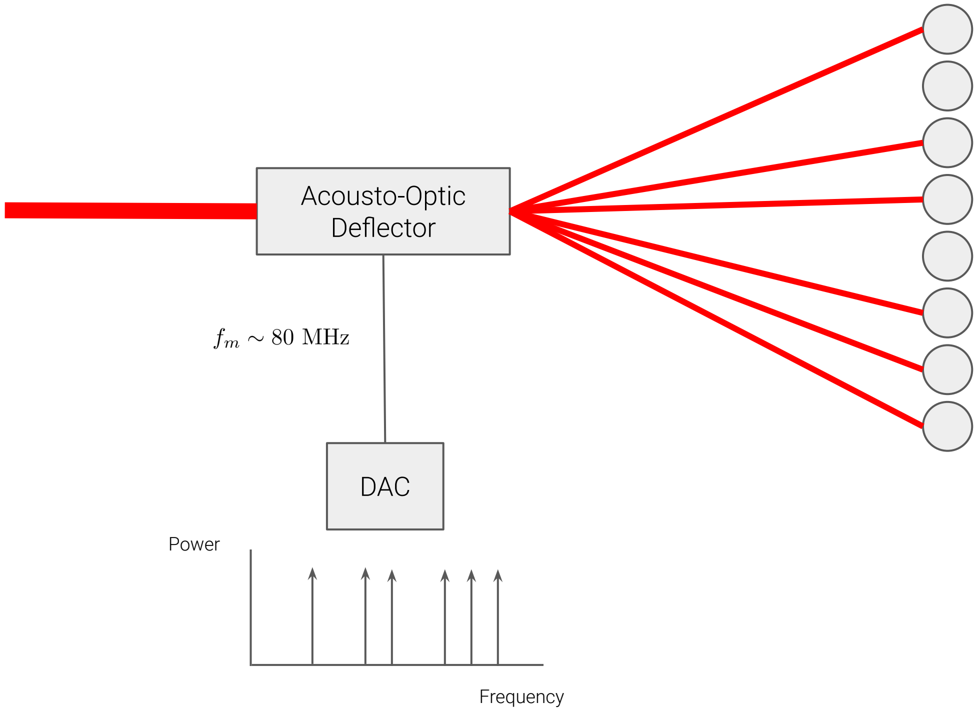


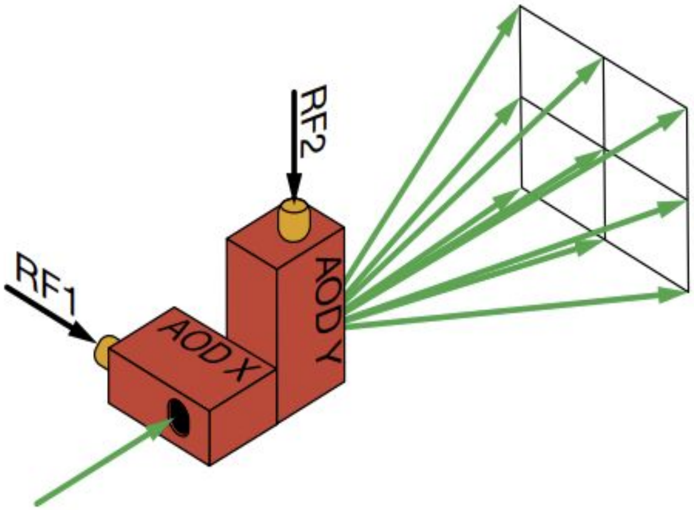




Collisional blockade: Schlosser, et. al, PRL (2002).

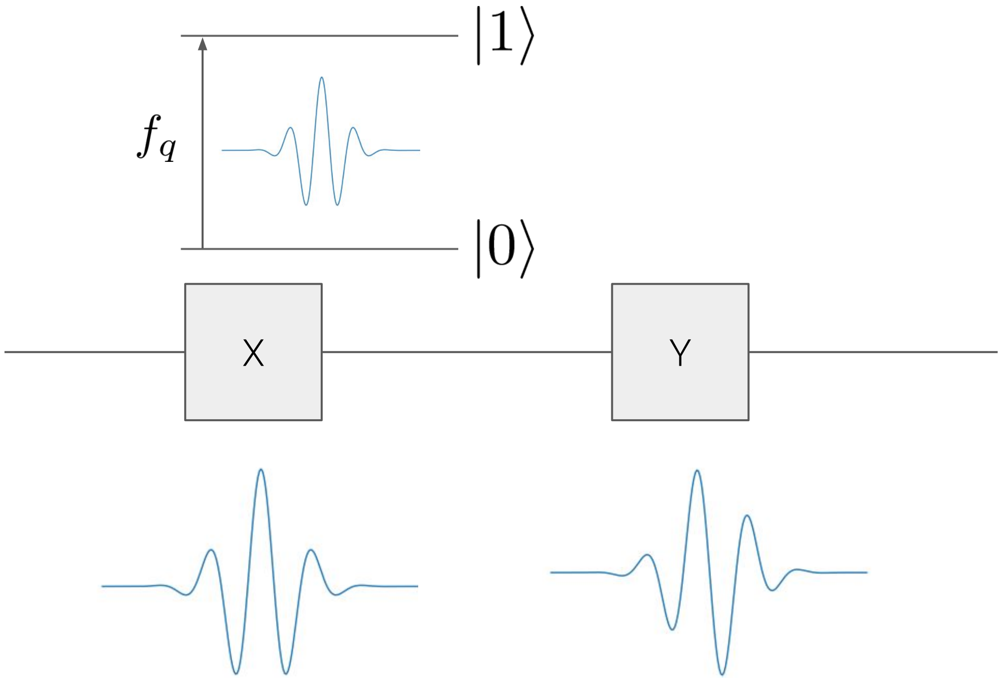
Address multiple atoms selectively with AODs





Phys. Rev. X 8, 041055 (2018)

Quantum Circuits Represented as EM Pulses



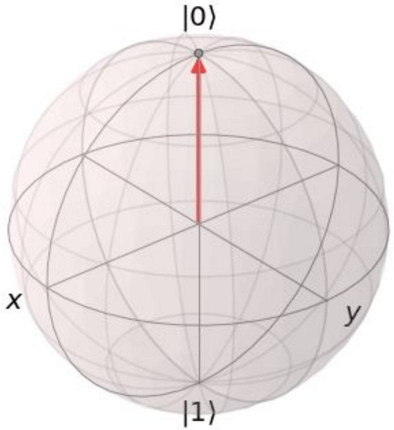
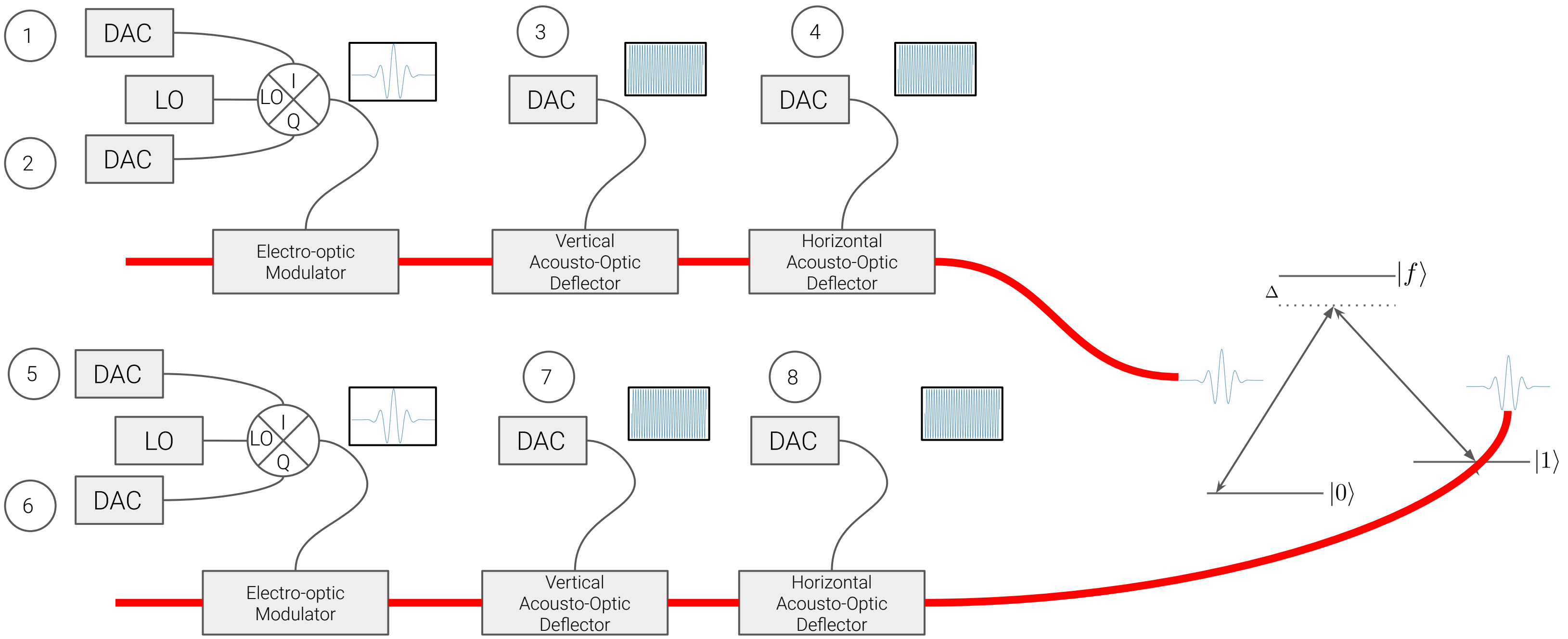
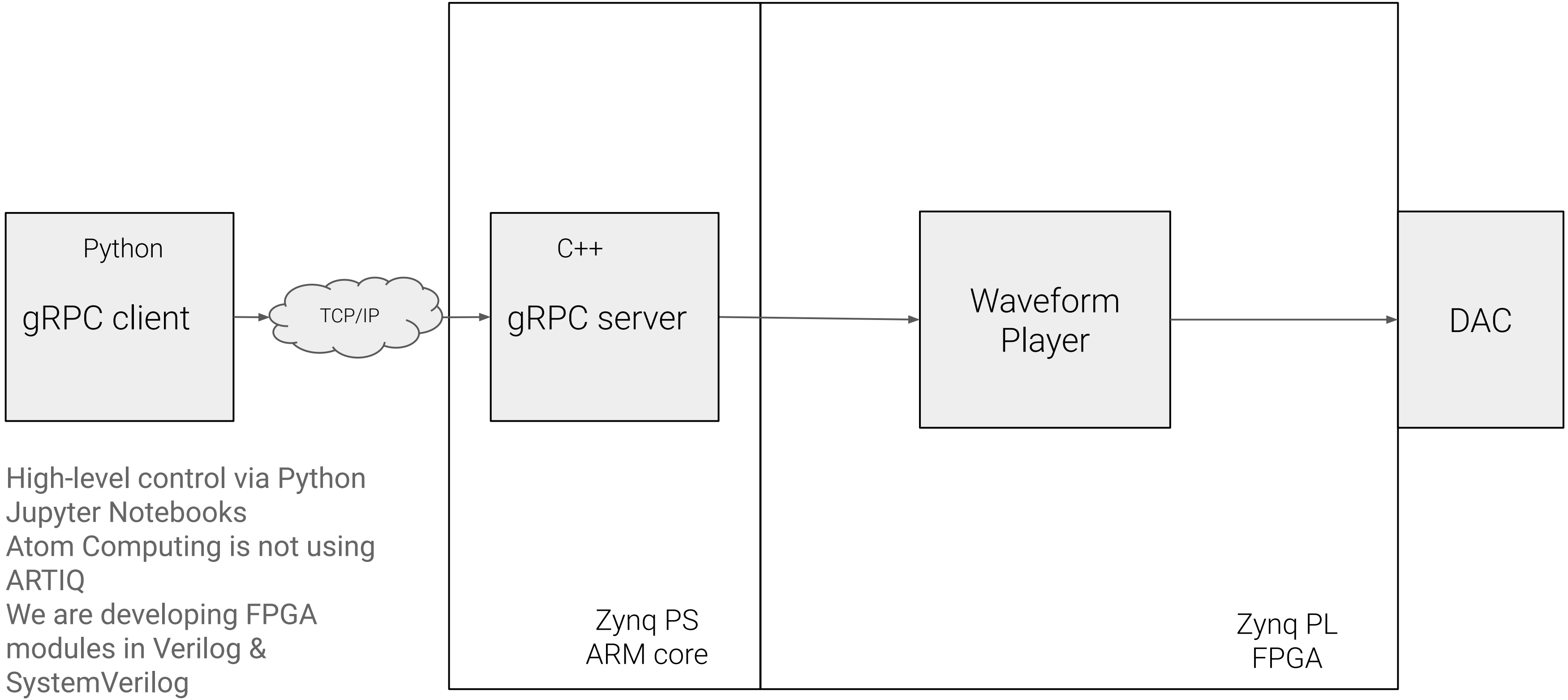


Image Credits: Prasahnt Sivarajah

8 DAC channels required to drive single qubit gates



RF Pulser Firmware & Software Architecture

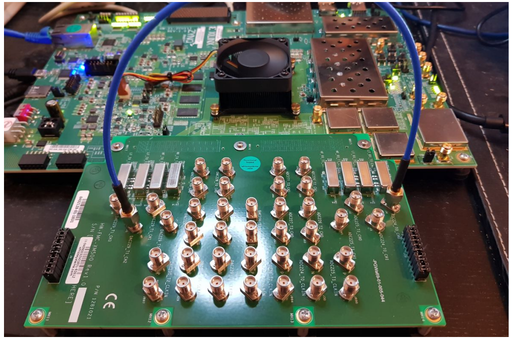


- High-level control via Python Jupyter Notebooks
- Atom Computing is not using ARTIQ
- We are developing FPGA modules in Verilog & SystemVerilog

Control System HW Development Approach

Unified Control System Hardware Architecture (replace hodgepodge of boxes!)

1. Pick a form factor. [We chose MTCA.]
2. Survey commercially available & open source reference designs.
3. Create an overarching system architecture.
4. Buy all available HW elements that meet requirements.



The PCB needed for my application doesn't exist. What now?

1. Proof of concept with vendor evaluation boards.
2. Build quick-turn prototype PCBs to validate custom interfaces.
3. Verify functionality in The Quantum Computer.
4. Integrate existing designs with custom elements targeted to MTCA form factor.
5. Use standard interfaces as much as possible.
6. Open source, license, or "productize" if it makes business sense.

Enabling Technologies

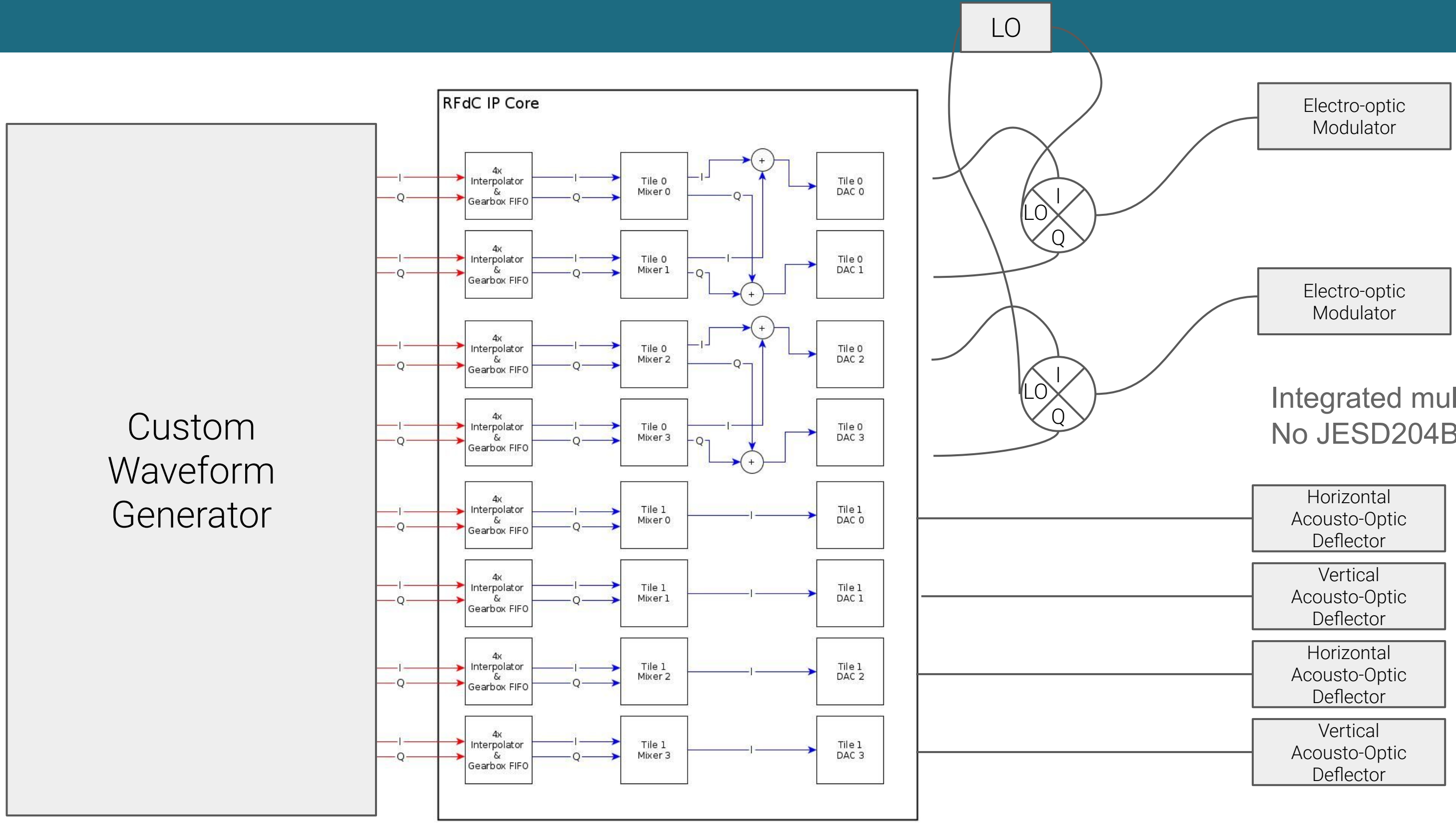
Ettus Research USRP N310
(10 MHz-6 GHz)

- **Software Defined Radio**:
  - Programmable RF Pulser is essentially a wired SDR
  - COTS SDRs can be used for monitoring laser frequency locks and controlling AODs
  - RF DACs/ADCs, RF integrated transceivers and components, and FPGA IP
  - But no cost-effective commercially available SDRs can transmit >6 GHz
- **Particle and AMO Physics**:
  - Open source electronics developed for particle accelerator control
  - Sinara/ARTIQ: MicroTCA AMC/RTM + EEM modules, Migen Python-based middleware to develop FPGA designs [Not using EEM, Migen, Artiq software infrastructure]
  - Instrumentation developed by academic/national labs: e.g., NIST analog and digital servos
  - Evaluated White Rabbit, but 10 MHz and 1 PPS GPS references should be sufficient for timing & synchronization.

Why MicroTCA 4?

- A random collection of box instruments is not scaleable.
- Active hardware ecosystem (much of it open source) driven by accelerator control for high energy physics at CERN, DESY, SLAC, and sinara-hw (ARTIQ).
- Many COTS FPGA Mezzanine Cards (FMCs): CoaXPress imager interface, Digital Trigger Distribution
- (European) Commercial Vendors: NAT Europe, Schroff, Creotech, Caen Els, Struck, IOxOS, etc.
- Custom Development (we'd buy it now if we could, but…): RFSoC AMC, RF/Microwave FMCs/RTMs.
- Also considered VPX, but not widely used in physics and mil/aero environmental specs are overkill.

Xilinx RFSoC provides 8 DAC channels



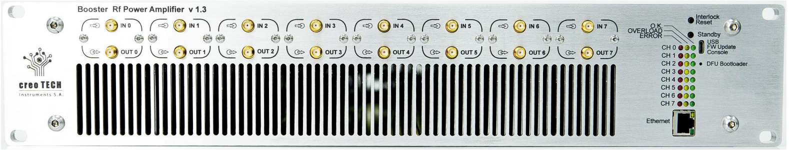
Integrated multi-GSPS RF DACs/ADC.
No JESD204B links to FPGA fabric!

Atom Computing MTCA Control System

- NAT Europe Native-R9 MTCA 4 Chassis
  - NAT-LLRF-backplane installed, but we probably will not use it
  - White Rabbit option, but 10 MHz GPS option + 1 PPS should be sufficient to meet timing and synchronization requirements
- NAT-MCH-PHYS80 MTCA Carrier Hub: gigE interfaces to AMCs with option to migrate to PCIe
- NAT-PM-AC600D Power Module
- Functional Modules (AMC + RTM + FMC) Under Development:
  - **Digital Trigger Distribution (installed)**
  - **Precision Digital Servo (B-field prototype installation coming soon, RTM HW design in progress)**
  - **RF Pulse Generator (prototype installed, AMC HW design in progress)**
  - **Image Capture and Atom Identification (FPGA development in progress, no custom HW)**
- Prototype all elements of MTCA Control System in current apparatus, refine PCB designs, and replicate for future neutral atom quantum computers

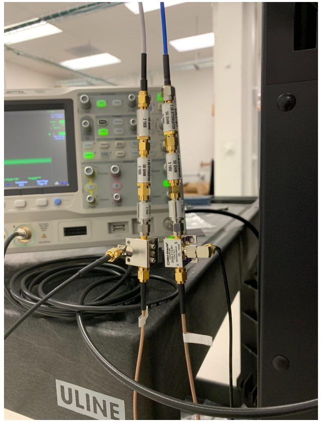
RF Pulse Generator

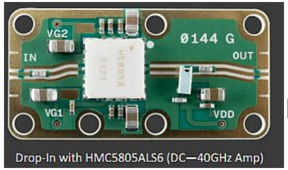
- Prototype System: ZCU111 + Custom RF Interface PCB + standalone SMA RF components from Mini-Circuits & Marki Microwave
- If the RFSOC-AMC were available today, we would buy it, but it is not, so Plan B:
  - Knowledge Resources RFSoC SOM (KRM-4ZU27DR/KRM-4ZU47DR)
  - Custom AMC Carrier Card with clock, AMC backplane & RTM interfaces, and RF converter interface connector
- Custom RF Interface PCB
  - ZCU111-style Samtec LPAM/LPAF connectors
  - 8x AC-coupled RF DAC interfaces: Can use direct conversion TX for AODs
  - 8x DC-coupled RF ADC interfaces: servo laser intensities with feedback from TIA photodiode outputs
- EOM RF Chains: Rack-mounted Integrated Microwave Assembly with Power Amplifiers
- AOD Power Amplifiers: Creotech Booster



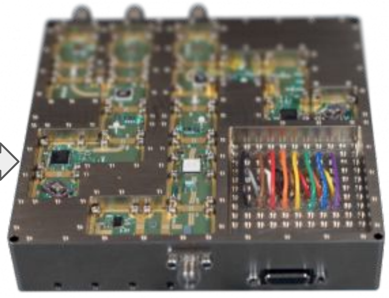
RF/Microwave Modules

- RF and Microwave design is highly specialized and not easy! Board-level design and packaging are particular pain points.
- Simulation software such as ADS or AWR is prohibitively expensive.
- Connectorized modules are great for prototyping but will always be $$$ and can turn into a Frankensteinian mess quite quickly.
- X-Microwave: “Lego Blocks” of TI, ADI, Marki etc. components with power modules underneath the plate. Prototype platforms→ Integrated Microwave Assembly with minimal NRE.





Drop-In with HMC5805ALS6 (DC—40GHz Amp)



Neutral Atom Control Systems: Rearrangement

- Rearranging atoms to fill holes in array with chirped FM RF pulses.
  - Use dynamic motion of an optical tweezer

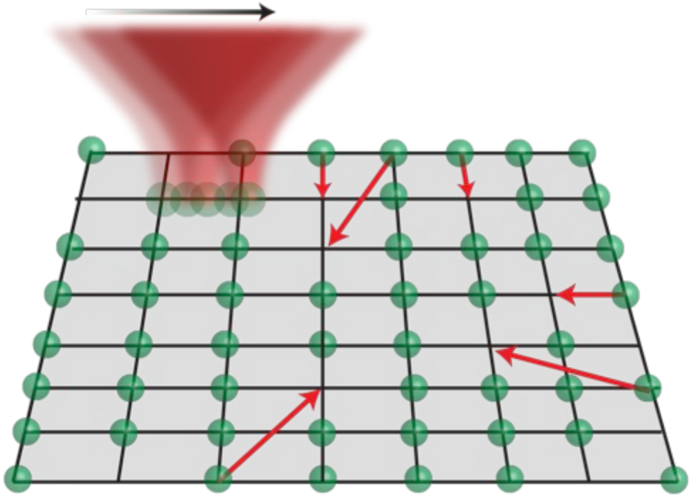
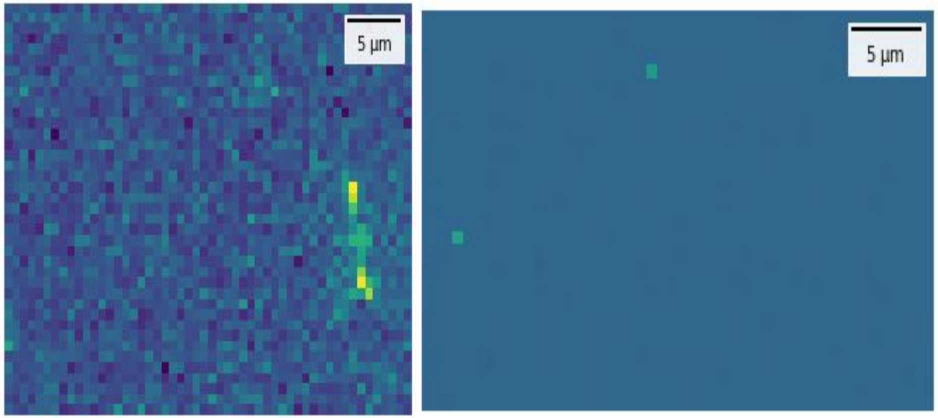
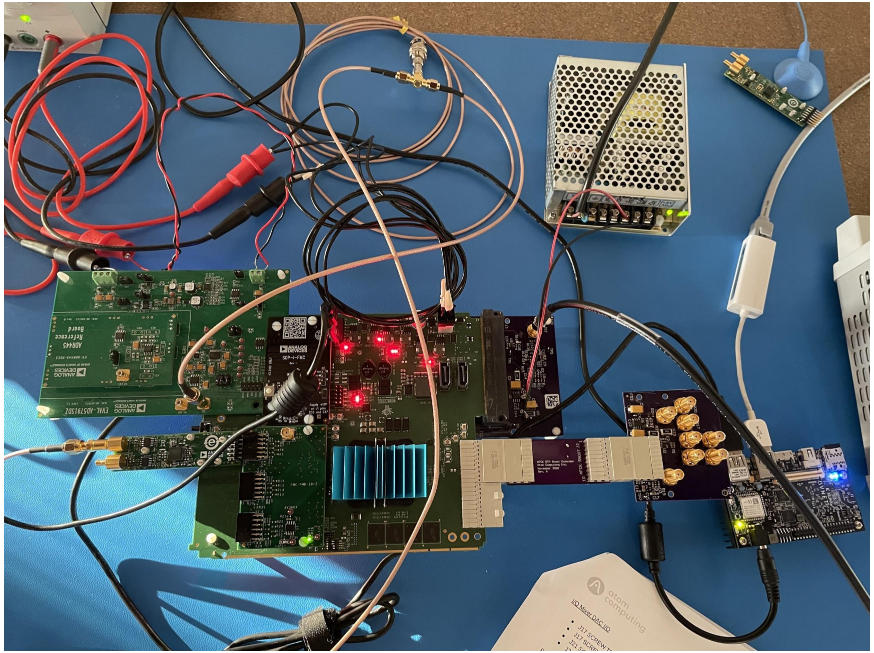


Image Credit: Regal Lab (JILA)



B-Field Servo Prototype:
Creotech AFCK AMC Carrier Card + + Avnet Ultra96 v2
+ADAQ4003 ADC/AD5791 DAC FMC Evaluation Boards



Development Plans:

- Replace AFCK + Ultra96v2 (running the GRPC server) with AFCZ or Caen Els DAMC-FMC2ZUP but very long lead times :(
- Analog Front End: Custom RTM with 4xADAQ4003 ADC and 4xAD5791 DAC
- Digital PID implemented as FIR or IIR filter in FPGA
- FMC for Digital IO: Sundance DSP GPIO68-SE Digital triggers for laser shutters, imager, and magnetic field controls

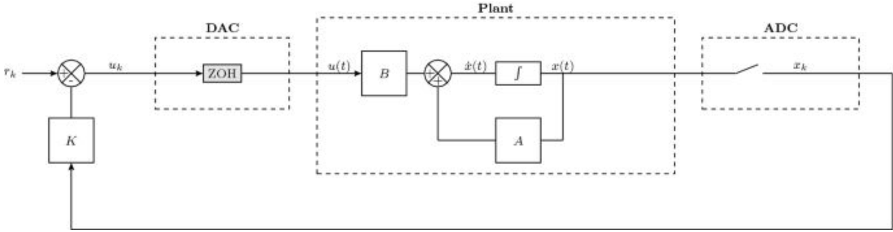
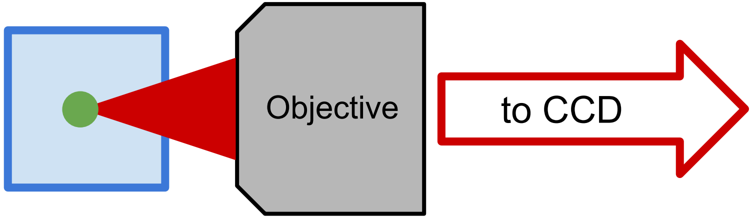
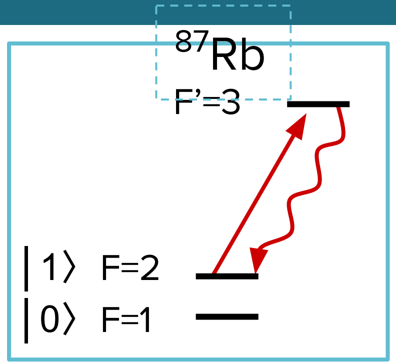
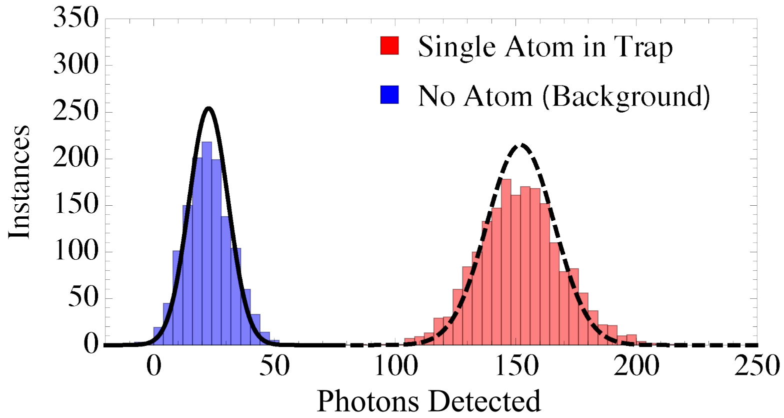


Image Single Atoms

- Excite the atom with resonant light
- Measure photons from spontaneous emission with CCD imager

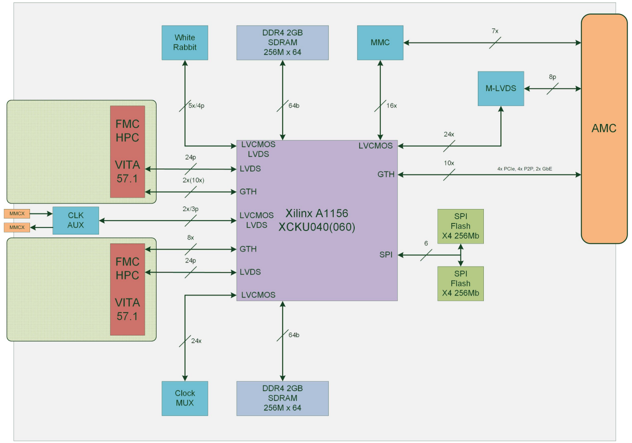






Plot from: Lester, et al., Phys. Rev. A (2014).

Image Processing: Struck SIS8160 AMC Kintex Ultrascale AMC + Easii IC CoaXPress FMC



- Framegrabber + Real-time Image Processor: Is there an atom in Trap X or not?
- Option to bypass DSP to store raw images in backend database
- FMC: CoaXpress imager interface
- Cannot use AFCK because the DDR3 clocking architecture isn’t compatible with our application.
- Not MTCA 4-compliant: No RTM connector, but not needed for this application.

Atom Computing Status: December 2020

We have a reliable qubit-array platform:

- 10x10 array with 40-50% loading fraction.
- Reproducible day-to-day and can be operated fully remotely.

We can address individual atoms:

- Single-site addressability and programmable control of optimal parameters per qubit.
- Deployed RF/MW SDR technology (AWGs, direct digital synthesis) with acousto- and electro-optics.
- Automated rearrangement of atoms (NEW!)

We have a gate scheme:

- Recently observed 1Q Rabi and Rabi oscillations. Gates coming soon!
- 2Q gates under development.

In 2021, we will have a unified MTCA Control System!

- RF Pulse Generator with analog and digital channel managers
- Digital servos for B-field and laser power stabilization
- Framegrabber and image processor to for qubit readout

Atom Computing, Inc.

Dr. Benjamin Bloom, CEO & Co-Founder
Dr. Jonathan King, Lead Scientist & Co-Founder
Dr. Peter Battaglino, Software Engineer
Dr. Kayleigh Cassella, Quantum Engineer
Dr. Robin Coxe, Chief Control Systems Engineer
Dr. Nicole Crisosto, Quantum Engineer
Ms. Oriana Havlicek-Allen, Office Manager
Dr. Stanimir Kondov, Senior Scientist
Dr. Krish Kotru, Senior Scientist
Dr. Brian Lester, Senior Quantum Engineer
Mr. Joseph Lauigan, FPGA Engineer
Dr. Michael McDonald, Quantum Engineer
Dr. Sandeep Narayanaswami, Software Engineer
Dr. Remy Notermans, Quantum Engineer
Dr. Lucas Peng, Quantum Engineer
Dr. Albert Ryou, Quantum Engineer
Mr. Emme Yarwood, Principal FPGA Engineer

We are hiring Hardware, Software, and Firmware Engineers.