Update on a MicroTCA-based control system for quantum computers

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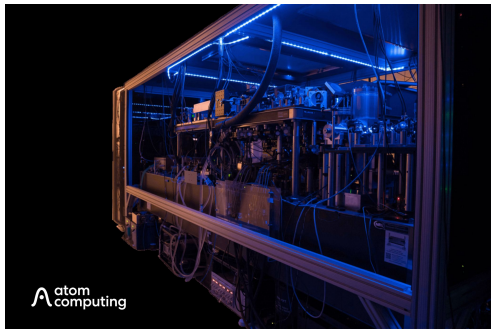
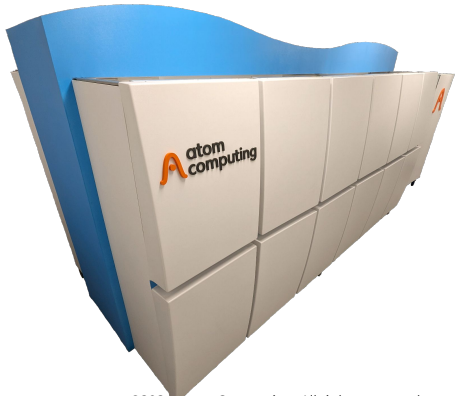
Introduction

Atom Computing

Neutral atom quantum computing startup

- Founded in 2018
- Offices in Berkeley, California and Boulder, Colorado and a satellite office in Austin, Texas
- Two generations of quantum computers:
  - 100-qubit prototype (using ^{87}Sr)
  - 1000-qubit production machine (using ^{171}Yb)





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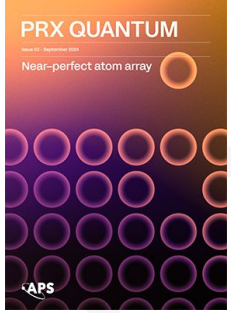
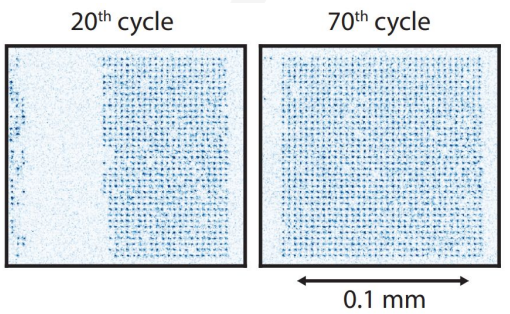
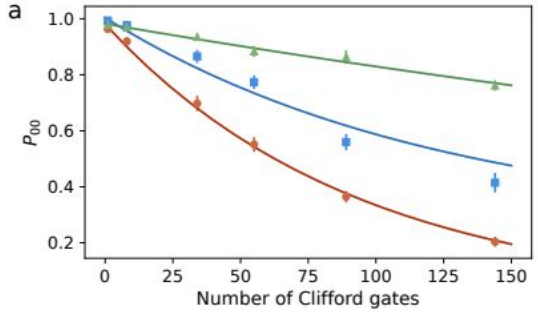
Recent results

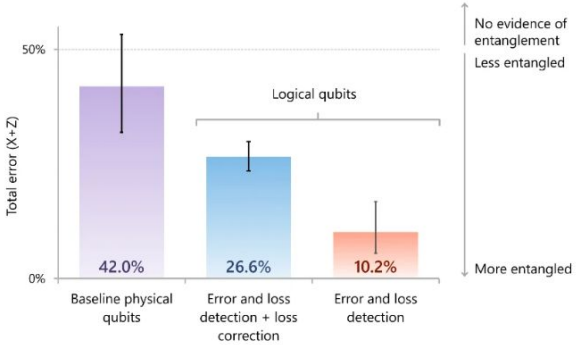
Published papers

- Iterative assembly of ^{171}Yb atom arrays with cavity-enhanced optical lattices - Jan 2024
  - https://arxiv.org/abs/2401.16177
- High-fidelity universal gates in the ^{171}Yb ground state nuclear spin qubit - Nov 2024
  - https://arxiv.org/abs/2411.11708
- Logical computation demonstrated with a neutral atom quantum processor - Nov 2024
  - Together with Microsoft Azure Quantum
  - https://arxiv.org/abs/2411.11822







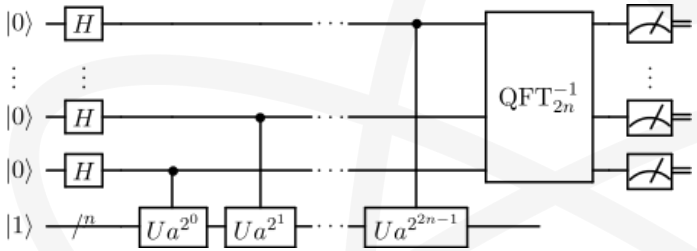


MicroTCA

Technology Stack

From high-level quantum languages to hardware

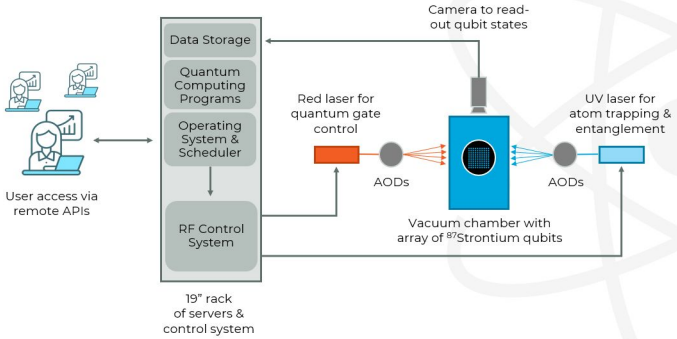
Quantum programs (circuits) are translated from a high-level quantum language to individual instructions for the control system



Quantum subroutine for order finding in Shor's algorithm, Bender2k14, CC BY-SA 4.0„ via Wikimedia Commons

Requirements for the control system:

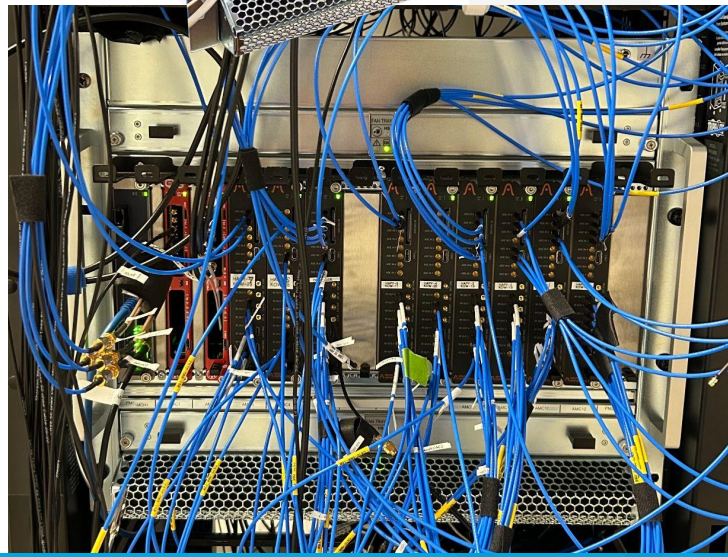
- Generate RF signals
  - Frequencies in the MHz to GHz range
- Control adaptive optics, mirrors (piezos)
- Camera capture & atom detection
- Control power supplies to generate magnetic fields
- …



Control System

Our approach

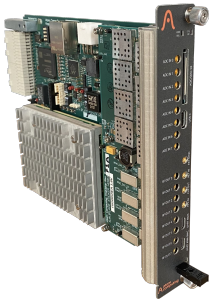
- MicroTCA platform
- Custom nVent Schroff 9U chassis
  - Double full-size slots
- NAT MCH and power supplies
- A mix of in-house developed board and COTS boards (next slide)
- IPMI for (remote) operation
- Communication interfaces
  - Gigabit Ethernet
  - PCI Express (planned),
  - point to point links (planned)
  - MLVDS
  - clock distribution



Hardware components

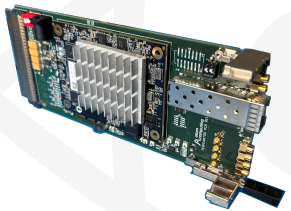
A mix of COTS and in-house developments

Kowalski
RFSoC, 8 DAC and 8 ADC channels



DAMC-FMC2ZUP (COTS)
Zynq UltraScale+ MPSoC

The Terminator
Kintex UltraScale



Skipper
Trigger/SFP RTM

Opus DAC
6 channel DAC

Opus ADC
6 channel ADC

+ COTS boards for
CoaXPress and SFPs

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MMC Stamp

Implementation of the MMC on the boards

- All our boards use DESY MMC Stamp to implement the MMC
  - We have licensed the SDK to customize it for our boards
- Robust and reliable implementation
- Easily customizable
- A lot of nice-to-have features
  - UART over IPMI (`mmcterm`)
    - We contributed a small ease-of-use patch `mmcterm <HOST>` **`AMC<slot number>`**
  - JTAG switching
  - I2C mailbox (partially our contribution)
  - FRU records for custom modules
  - FRU generator (`frugy`)

```
KOWALSKI AMC@0x76 MMC>fru
FRU #0:                                          AMC
Product info: ATOM COMPUTING KOWALSKI AMC
              S/N 0000 P/N 0000
              Version revC
  Board info: ATOM COMPUTING KOWALSKI AMC
              S/N 26 P/N 0000
              Mfg.Date 2023-02-10 19:42:00
Module current requirements: 6.5A
Zone3 interface compat: Class D1.1

FRU #1:                                          RTM
Product info: ATOM COMPUTING SKIPPER RTM
              S/N 0000 P/N 0000
              Version revB
  Board info: ATOM COMPUTING SKIPPER RTM
              S/N 1234 P/N 0000
              Mfg.Date 2023-03-29 22:10:00
Module current requirements: 2.5A
Zone3 interface compat: Class D1.1

FRU #2:                                  custom AFE board
Product info: Atom Computing Frobisher variantA
              S/N 9999 P/N 0000
              Version revD
  Board info: Atom Computing Frobisher variantA
              S/N 9999 P/N 0000
              Mfg.Date 2024-06-14 15:40:00
```

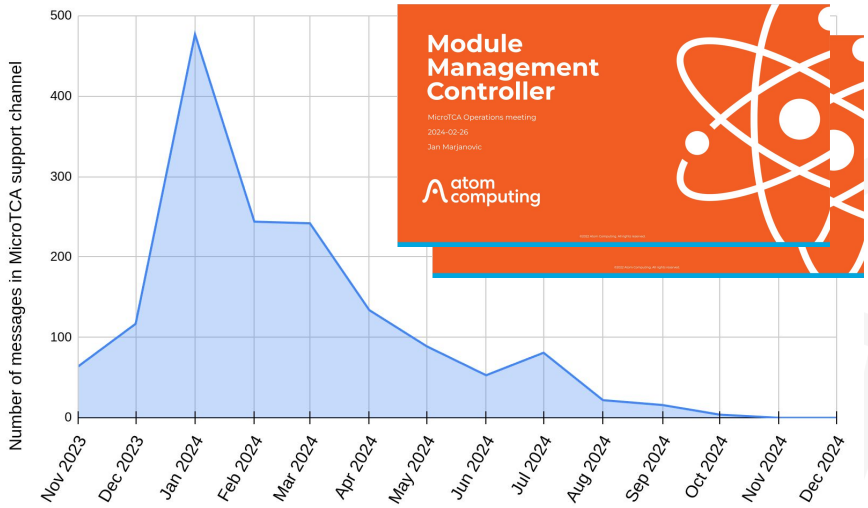
Operational experience

Reliability and user experience

Leveraging the advantages of MicroTCA

- Reliability
  - The control system is operating very reliably
  - Excellent uptime
  - Linux on ARM + package manager + versioning = easy upgrades
- User Experience
  - Dedicated Slack support channel
  - Series of lectures, focused on day-to-day work
  - Number of messages in a MicroTCA support Slack channel reduced dramatically

```
ZUP #1       :  up  80 days,  1:59
ZUP #2       :  up 238 days,  4:16
Hapyxelor #1:  up 238 days,  4:11
Hapyxelor #2:  up  56 days,  5:12
Hapyxelor #3:  up 237 days, 12:39
Hapyxelor #4:  up 238 days,  4:11
Hapyxelor #5:  up 238 days,  4:11
Hapyxelor #6:  up 238 days,  4:11
Hapyxelor #7:  up 202 days,  4:44
```

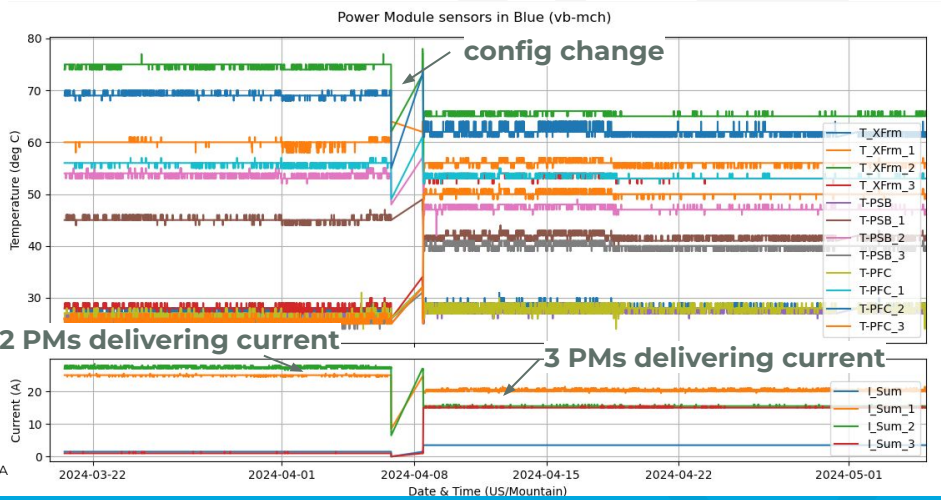


Example: temperature

Power Module redundancy configuration

- An incident earlier this year
  - HVAC went down
  - one of the Power Modules tripped from over-temperature
  - the system went into a strange state
  - power cycle was required to restore
- Deployed a tool to monitor the status
- Initially operated the crate in 2+2 PM redundancy configuration, some of temp sensors close to critical
- Used `frugy` to change the PM assignment configuration
- With 3+1 PM redundancy configuration the temperatures are lower

Power Modules in a custom 9U crate

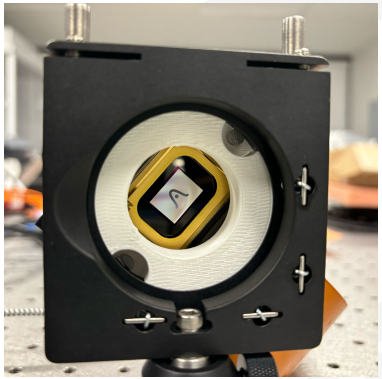


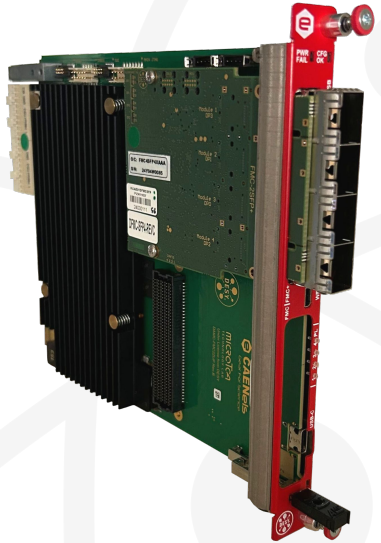
Hardware development

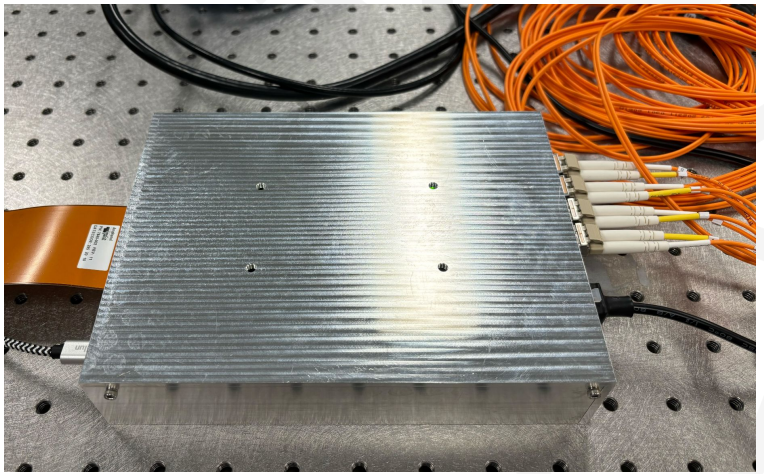
DMD controller

Interface to a Digital Micromirror Device

- A new requirement for the system:
  control a Digital Micromirror Device as a part of the sequence
- Interface part:
  custom board with Kintex UltraScale+
  - Interfaces with the DMD with parallel LVDS interface (ribbon cable)
- MicroTCA part:
  DAMC-FMC2ZUP with FMC-4SFP+
- Link between boards:
  Aurora 64b/66b at 4x10 Gbps







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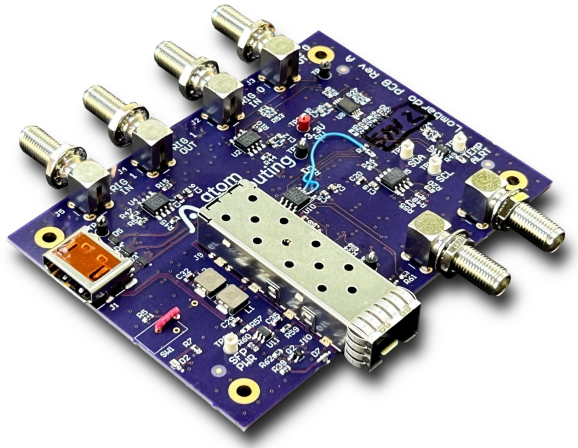
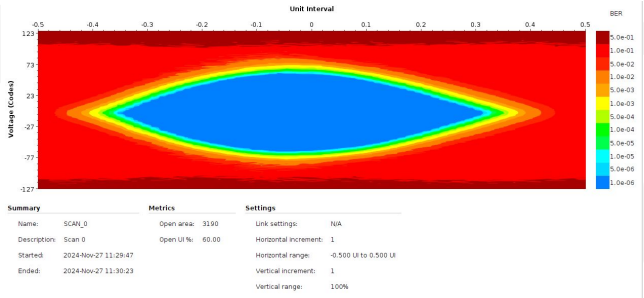
Lombardo

Trigger/SFP extender board for DAMC-FMC2ZUP

- DAMC-FMC2ZUP has a MicroHDMI connector on the front panel for extra triggers, clocks and a transceiver link
- Our requirement:
  - Trigger boards in 1U chassis (LVTTL or White Rabbit)
  - (optional) 10 Gbps Ethernet uplink
- We developed a board called Lombardo
  - Connect to DAMC-FMC2ZUP with MicroHDMI to HDMI cable
  - CC-BY-SA-4.0 license
  - https://github.com/atom-computing/lombardo-extender-board



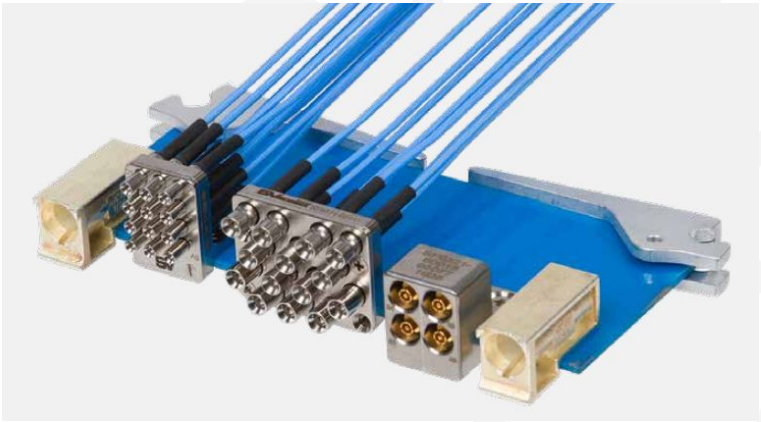


Plans for the future

Plans for the future

Scaling the control system for larger computers

- Multi-chassis synchronization
  - Currently one large chassis (MLVDS triggers on the backplane) + smaller 1U chassis (front panel trigger)
  - Evaluate White Rabbit
- RF analog front end on an RTM
  - Limited space on the front, cabling
  - (maybe) a new Zone 3 class
    - 8 DACs and 8 ADCs (RF freq)
    - VITA 67 inspired
- A new board will likely be based on Versal AI RF



Source: Amphenol SV Microwave

Summary

Summary

Our experience with MicroTCA

- The control system worked flawlessly and enabled us to achieve excellent results
- Modularity, scalability, remote management, … are hugely beneficial for QC
- Developed new hardware
  - DMD controller and trigger extender board for DAMC-FMC2ZUP
- Thinking about the next generation control system

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Thank you!

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