Development of Graphical User Interfaces for Control of Experimental Hardware and Instruments in the Context of Optically Trapped Ultra-Cold Potassium Atoms

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PROJECT IMPETUS

Existing rapid-timing instrument-tation control hardware systems lack **Graphical User** (-friendly) **Interfaces** (*GUI*).

- This hinders researchers' ability to efficiently interact with the apparatus and analyze acquired data. This limitation restricts the scope of experiments and impedes progress.
  - Formerly, user interaction with M-Lab's **Artiq** hardware, i.e. **TTL**, **DAC**, **DDS**, was through Command Line Interface (CLI).

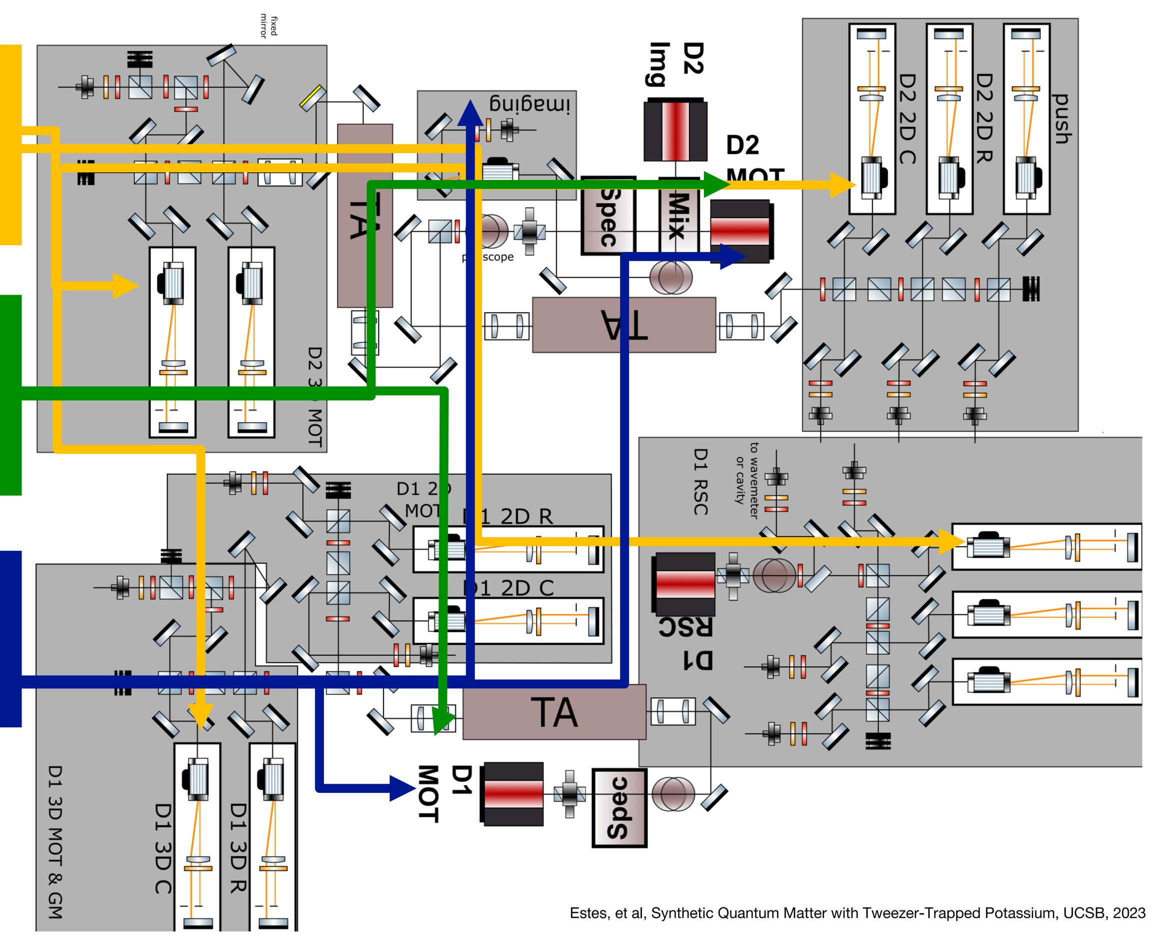
OPTICAL INSTRUMENT LAYOUT

DIRECT DIGITAL SYNTHESIZER (DDS)

DIGITAL-ANALOG CONVERTER (DAC)

TRANSISTOR-TRANSISTOR LOGIC (TTL)

- M-Lab's **Artiq** hardware, i.e. **TTL**, **DAC**, **DDS**, controls **optical, magneto-optical** and **imaging instruments,** through voltage inputs, and frequency-specified waveforms



Estes, et al, Synthetic Quantum Matter with Tweezer-Trapped Potassium, UCSB, 2023

M-LABS HARDWARE 'SINARA' for 'ARTIQ' SOFTWARE

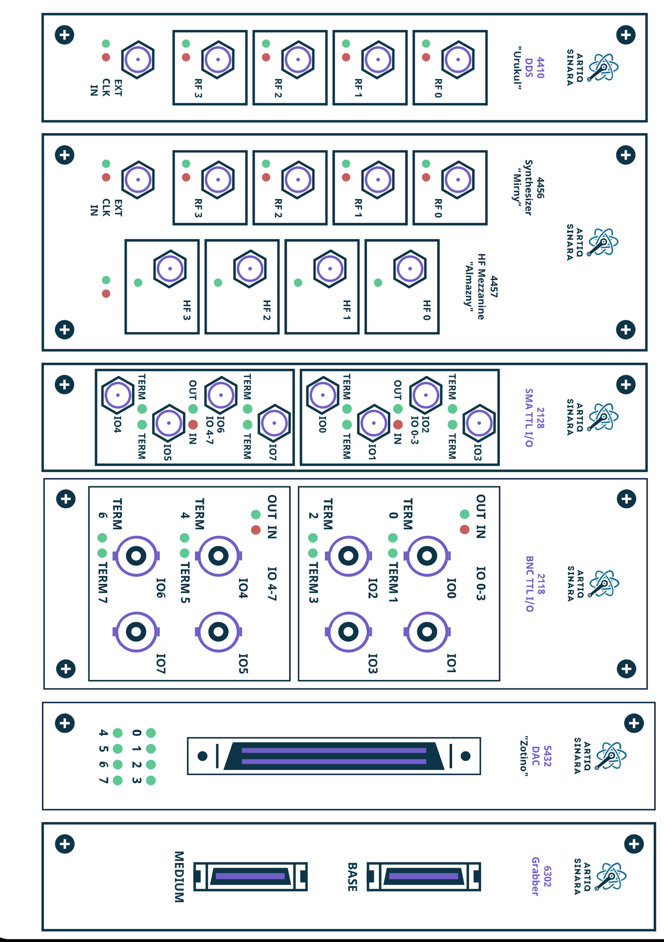
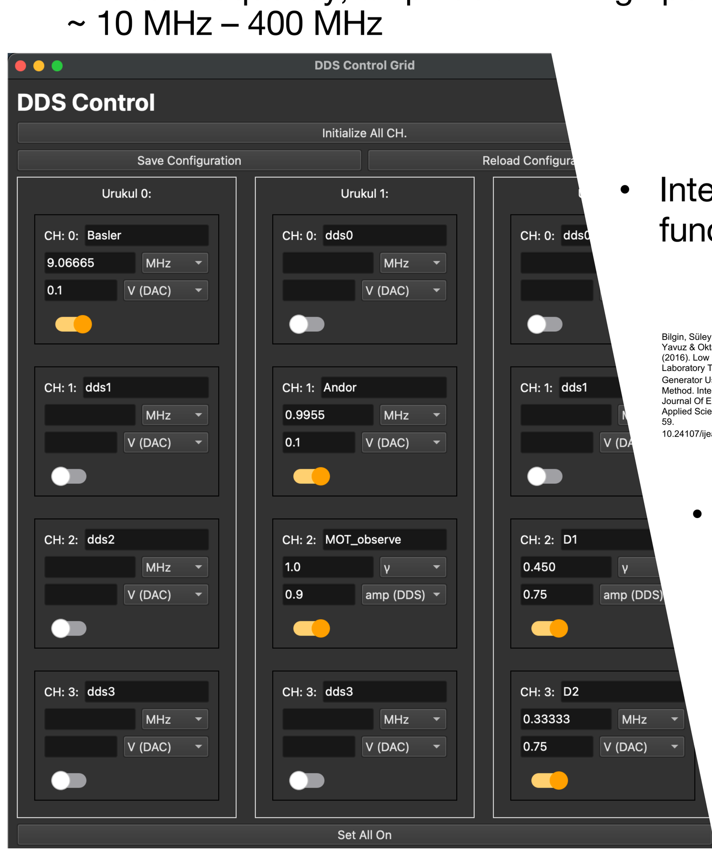


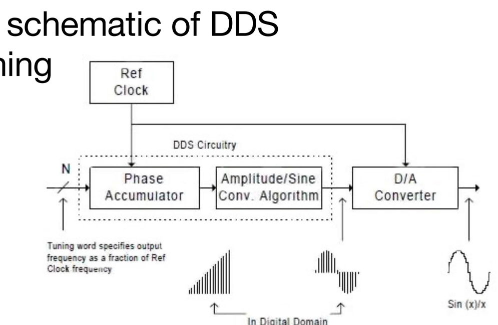
Figure Courtesy of M-Labs

DIRECT DIGITAL SYNTHESIZER (DDS)

- (12) 3 Cards (0-2), 4 Channels per Card (0-3) Makes sine waves in radio frequency (RF) -> choose frequency, amplitude with high power ~ 10 MHz – 400 MHz
  - Make RF to be amplified and to drive acousto-optical modulators (AOMs)
  - Generate any other sine waves needed.

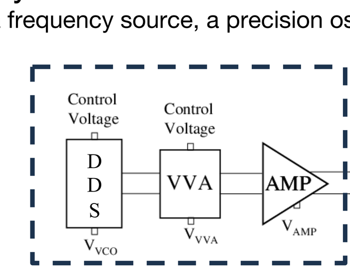


- Internal schematic of DDS functioning



Bilgin, Süleyman & User, Yavuz & Oktay, Mustafa. (2016). Low Cost Laboratory Type Signal Generator Using DDS Method. International Journal Of Engineering & Applied Sciences. 8. 59-59. 10.24107/ijeas.281464.

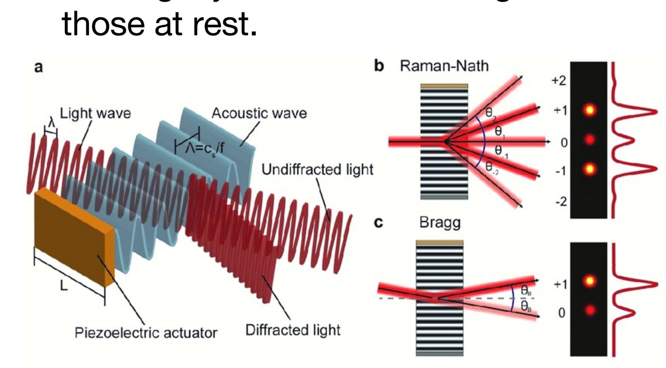
- DDS layout
  DDS is a frequency source, a precision oscillator



Mccarron, Daniel. (2023). A Guide to Acousto-Optic Modulators.

E.G. USED FOR AOM (Acousto-optical modulators)

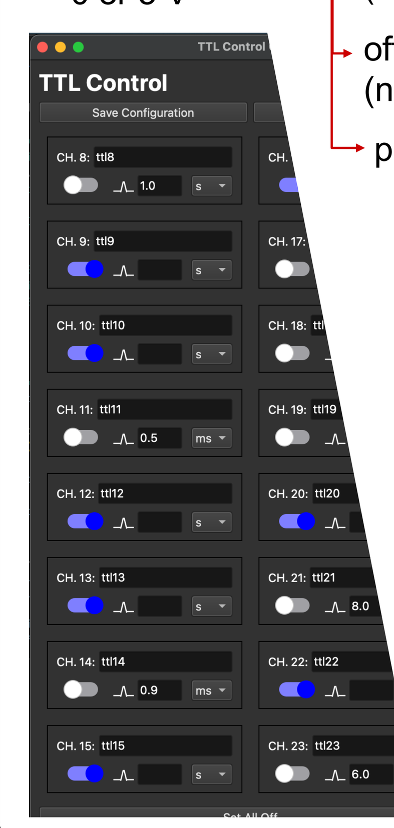
- One of the important features of our atoms is the specificity of the laser transitions.
  - One must use lasers whose wavelengths are very well controlled to match the energy level differences between the atomic states. These energies and wavelengths are so specific that the Doppler effect is important -- atoms that are moving see slightly different wavelengths than those at rest.



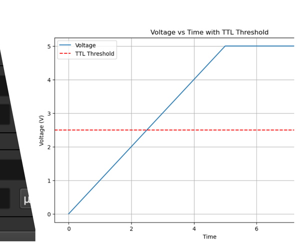
Duocastella, Martí & Surdo, Salvatore & Zunino, Alessandro & Diaspro, Alberto & Saggau, Peter. (2020). Acousto-optic systems for advanced microscopy. Journal of Physics: Photonics. 3. 012004. 10.1088/2515-7647/abc23c.

TRANSISTOR-TRANSISTOR LOGIC (TTL)

- (16) Numbered 8 - 23
  0 or 5 V
  - on(): TTL goes high (no timeline advance)
  - off(): TTL goes low (no timeline advance)
  - pulse(t): on() delay(t) off()

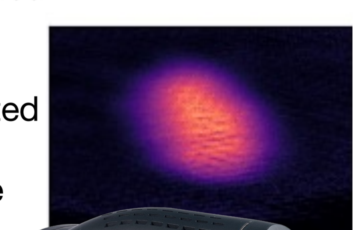


- Switches (MOSFETs, transistors)
- Camera trigger > takes picture on TTL rising edge



E.G. USED FOR EMCCD (Electron-multiplying charge-coupled detector) CAMERA

CCDs are silicon imaging devices that convert photons into electrical signals via pixels. The pixels shift charge along the sensor to be amplified and digitized.



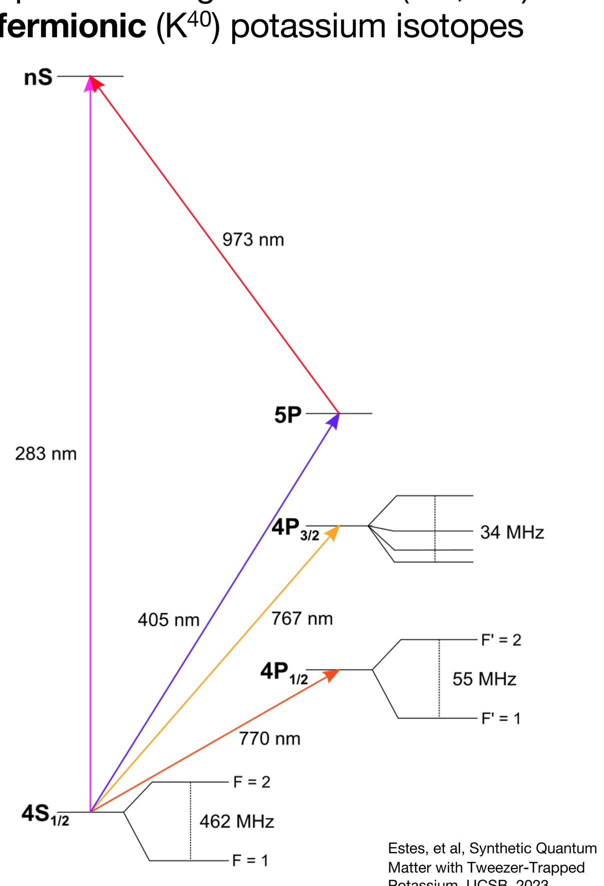
Photons are collected and converted to electrons which are shifted along the pixel array.

EMCCDs also collect photons as electrons, but multiply the electrons with an additional gain register before reading out, enabling detection of much weaker signals.

Figure Courtesy of Oxford Instruments, Weld Group

K^{39} STRUCTURE

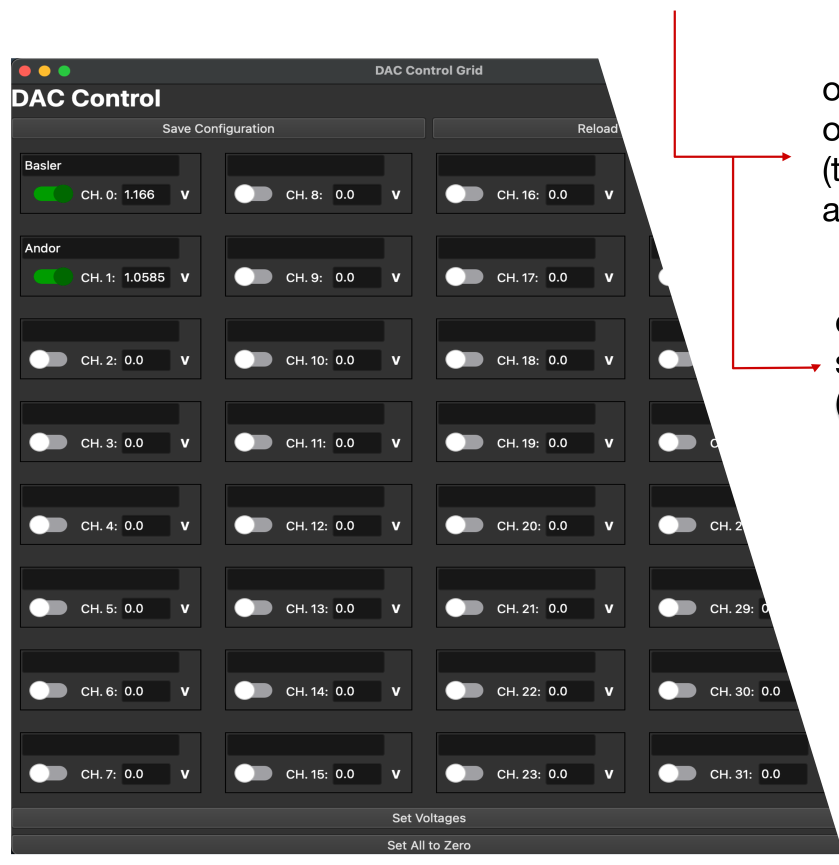
- Detuning frequency manipulation for optical cooling of **bosonic** (K^{39}, K^{41}) **and fermionic** (K^{40}) potassium isotopes



Estes, et al, Synthetic Quantum Matter with Tweezer-Trapped Potassium, UCSB, 2023

DIGITAL-ANALOG CONVERTER (DAC)

- (32) Numbered 0 - 31
  [-10 V, 10 V]
  - Current supply analog control
    An electrically controlled knob (slow timing ~ 10 ms)



on(): DAC outputs (time line advances)

off(): DAC shuts down (no timeline advance)

- M-Labs' Field Programmable Array (FPGA) receives compliable code to run an experiment, schedules it with 'first in first out' (FIFO) protocol

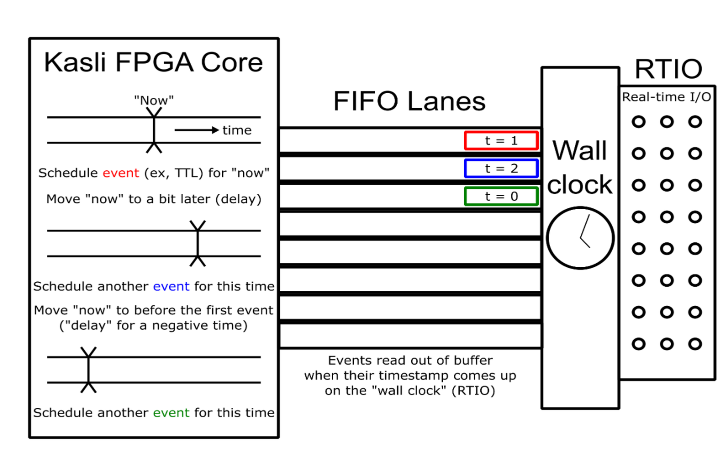
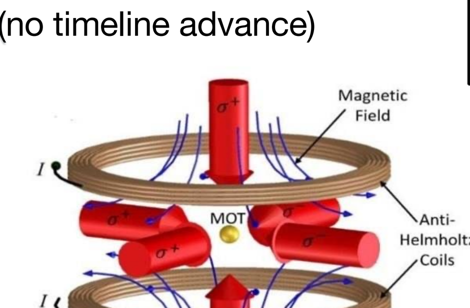


Figure Courtesty of Jared Pagett



- Control voltage,
  i.e. current, value of magnets:
  e.g. Anti-Helmholtz coils

Travagnin, Martino. (2021). Cold atom interferometry sensors: physics and technologies A scientific background for EU policymaking. 10.2760/315209.

E.G. USED FOR MOT (Magneto-Optical Trap)

A MOT traps and cools atoms using the interaction of a weak magnetic field and red-detuned laser beams. As atoms move away from the field's center, the Zeeman shift brings them into resonance, causing scattering that pushes them back. This scattering also slows the atoms by momentum transfer during repeated absorption and emission. Thus, a MOT can trap and cool fast-moving atoms down to slower speeds.

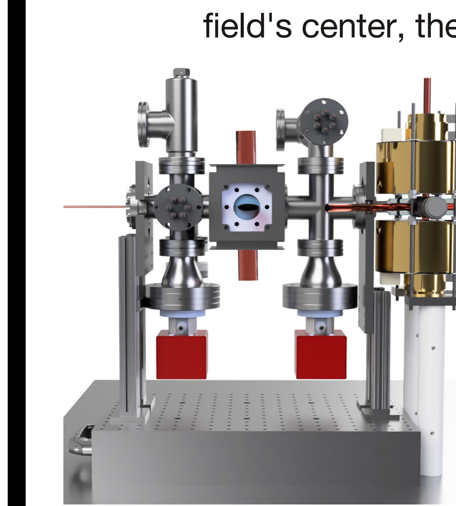


Figure Courtesy of Weld Group

DOPPLER COOLING

- This method involves light with frequency tuned **slightly below** an electronic transition in an atom.
- Because the light is detunded to the "red" (i.e. at lower frequency) of the transition, the atoms will **absorb more photons** if they move **towards** the light source, due to **the Doppler effect.**

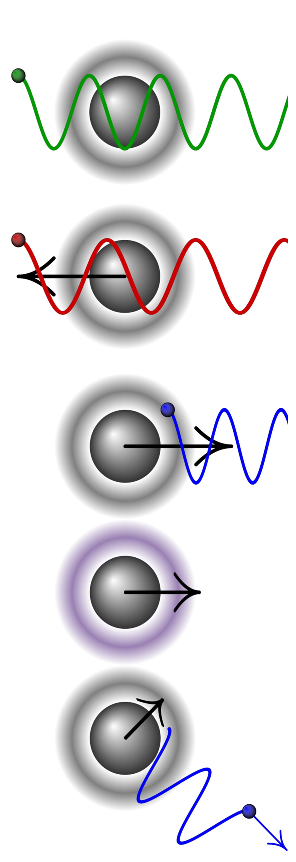
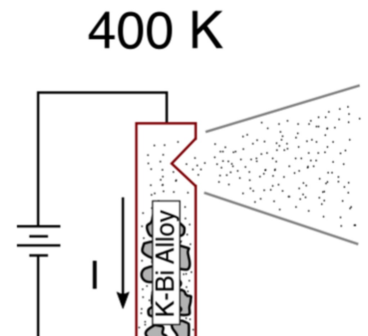


Figure Courtesy of Cmglee, Wikipedia 2013

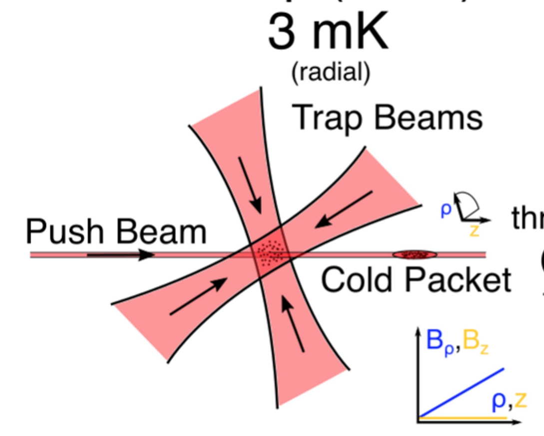
DIFFUSION – COOLING – TRAPPING – BEC - IMAGING

Atomic Potassium Dispensers
400 K



Resistive heating of dispenser creates hot atomic K flux

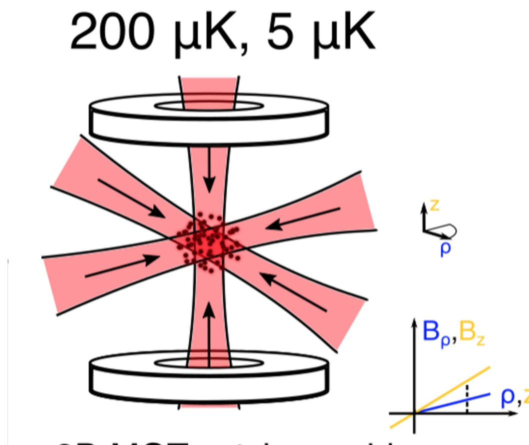
2D Magneto-Optical Trap (MOT)
3 mK
(radial)



Atoms travel through small tube (maintains Δp) to science cell

2D MOT traps atoms in transverse directions to form cold atomic beam

3D MOT, Gray Molasses
200 μK, 5 μK



3D MOT catches cold atomic beam, cools + traps in 3D, GM cools further

Adjust trap strength to switch between single atoms or Bose-Einstein Condensates

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CURRENT & FUTURE WORK

- Current progress: **sub-Doppler cooled atoms**
- Developing **tweezer load procedure**
- First target: measure the **magic wavelength** of the D1 transition in 39K
- Designing and building **tweezer optics, experimental control system architecture,** and **Rydberg excitation schema**

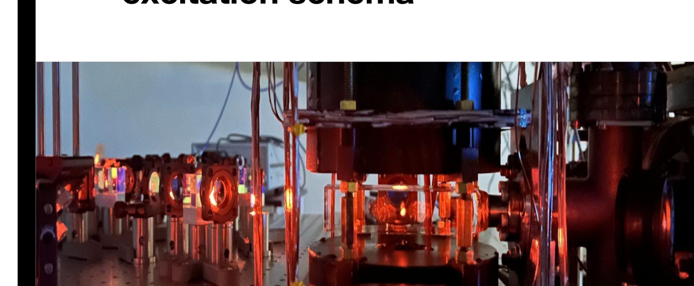

Image Courtesy of Madeleine Jun Leibovitz