MAGIS-100 Overview

VLB Atom Interferometry Workshop

Robert Plunkett, Fermilab

13 March, 2023

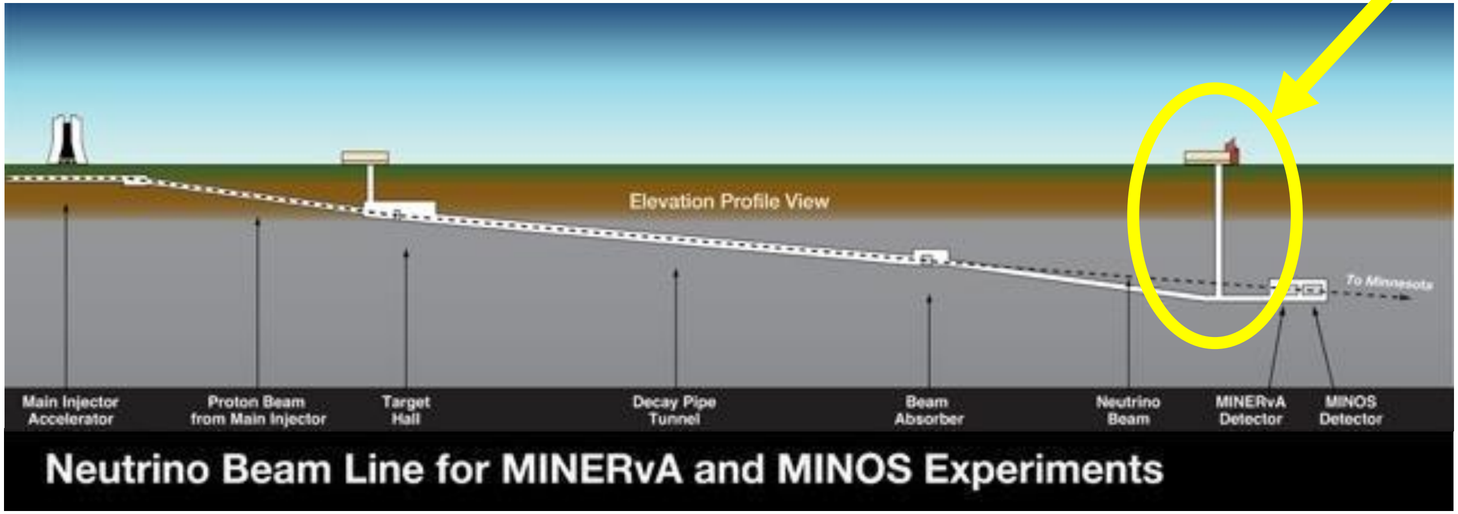
MAGIS-100 Collaboration

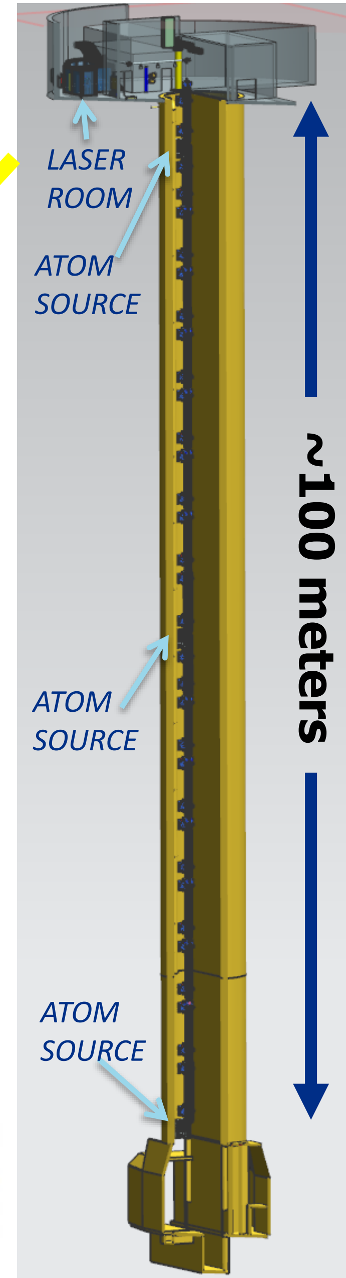
- US/UK International Collaboration to bring LB Atom Inteferometry to Fermilab.
- Collaboration initiated 2017.
- Funding Sources: Gordon and Betty Moore Foundation, US DOE, STFC/AION, Kavli Foundation. Our thanks!

Kavli Foundation

MAGIS-100 experiment design overview

Matter wave **A**tomic **G**radiometer **I**nterferometric **S**ensor





- 100-meter baseline atom interferometry in existing shaft at Fermilab
- Major sub-systems:
  - Clock atom sources (Strontium) at three positions
  - Interferometry laser system
  - 100-meter vacuum system and infrastructure

Stanford, Johns Hopkins University, Northwestern University, Fermilab, SLAC, Old Dominion University, University of Cambridge, Northern Illinois University, University of Oxford, University of Liverpool

MAGIS-100 Scientific Objectives

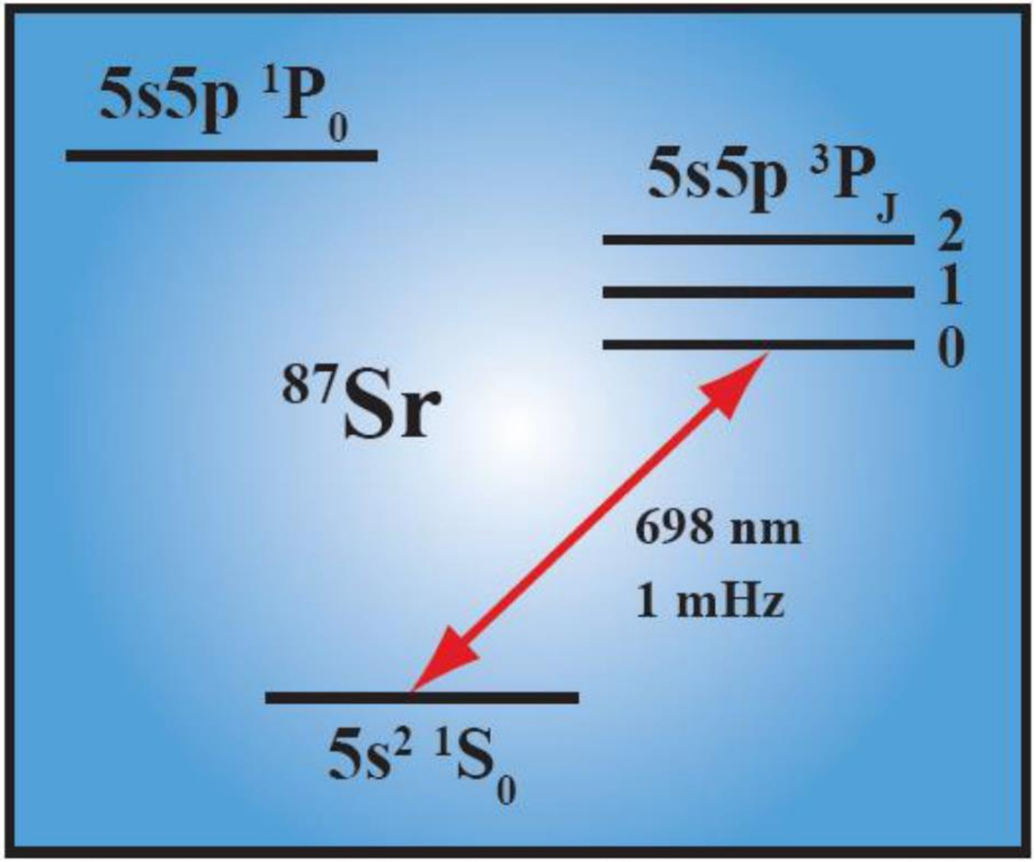
- Quantum Science: Demonstrate/test quantum superposition over distances of several meters and times of several seconds.

- Dark Matter: Search for DM in the mass range 10^{-15} eV – 10^{-14} eV, based on DM effects that result in time dependent changes to the atomic energy levels. Demonstrate/establish the sensitivity of this method.

- Dark Matter: Search for DM in the mass range 10^{-17} eV – 10^{-15} eV, for DM that causes time dependent accelerations, based on a dual Sr isotope interferometer with maximal launch height.

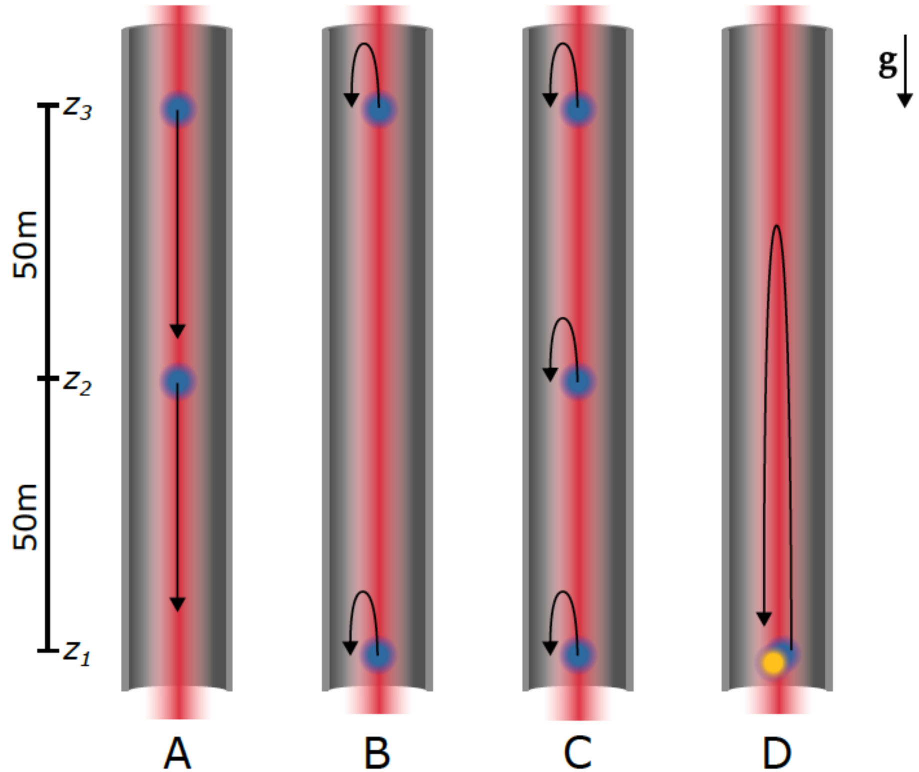
- Gravitational Waves: Within the frequency range 0.3 Hz – 3 Hz, establish a record sensitivity to gravitational waves, corresponding to a strain sensitivity of $\leq 10^{-14} / \sqrt{\text{Hz}}$.

Strontium Clock Transition



Metastable, nearly forbidden, long-lived transition

MAGIS-100 operating modes



Mode A: Maximum gradiometer drop time.

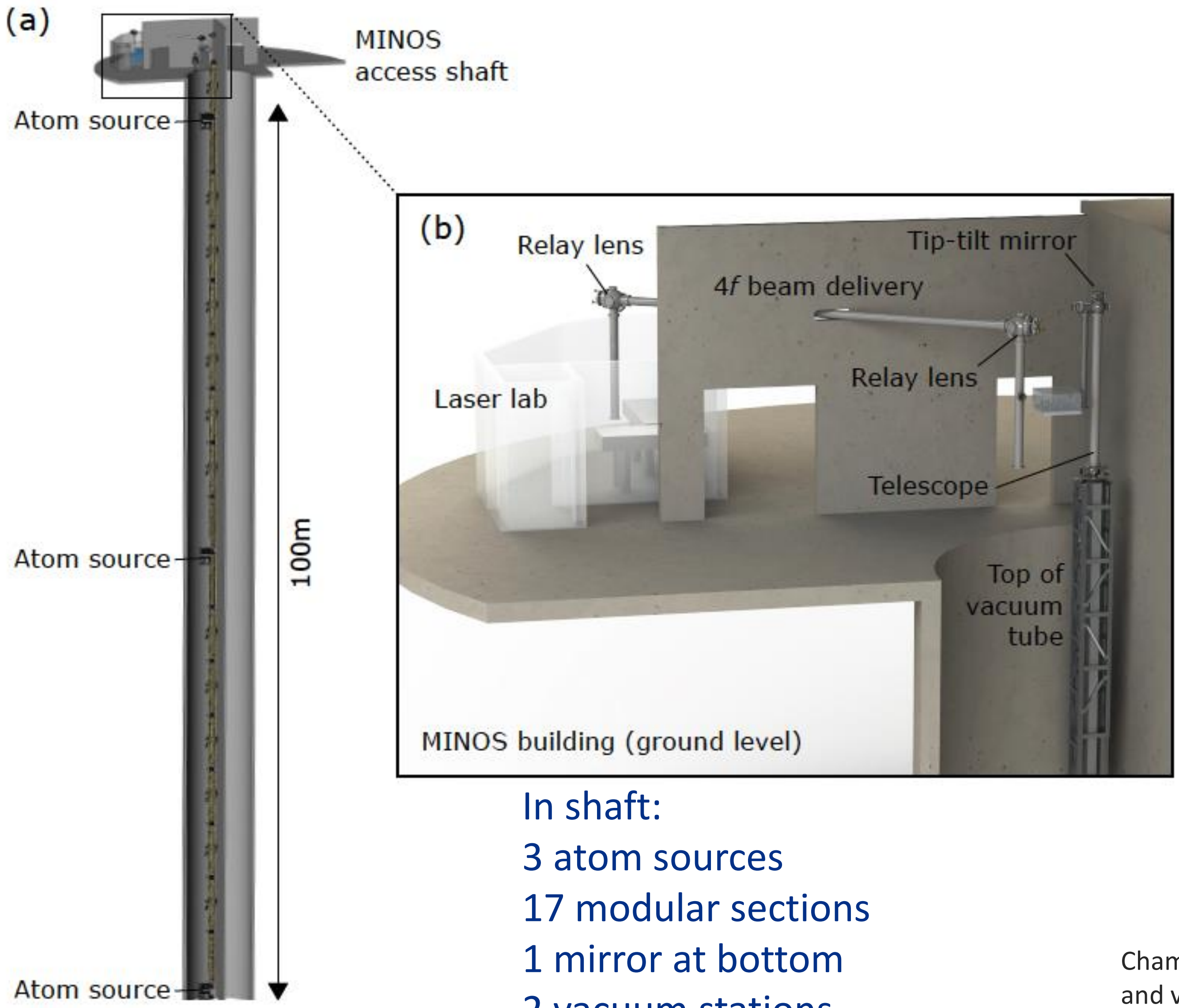
Mode B: Maximum gradiometer baseline.

Mode C: Gravity gradient noise (GGN) characterization.

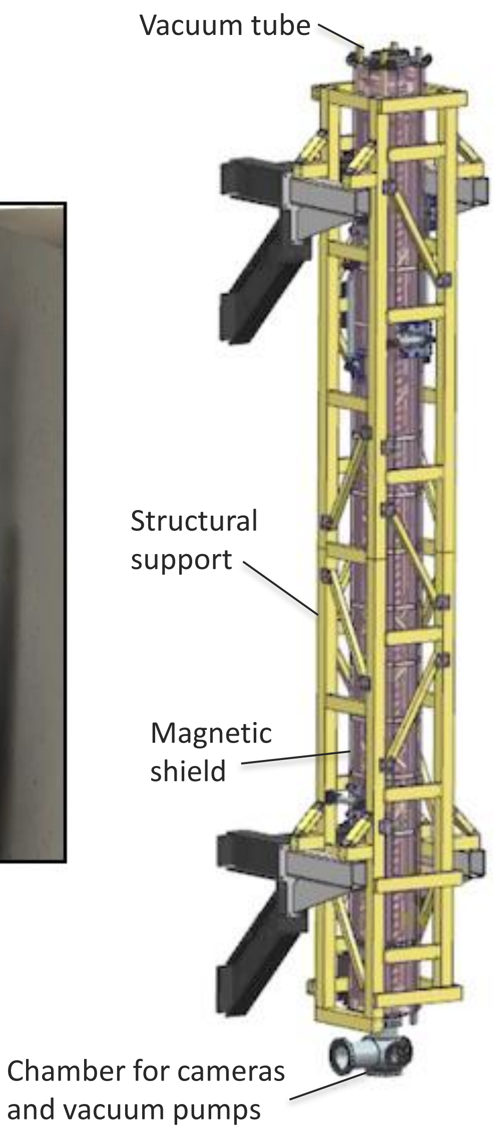
Mode D: Dual-isotope launch for alternative dark matter searches.

For additional information, see 2021 publication linked at magis.fnal.gov.

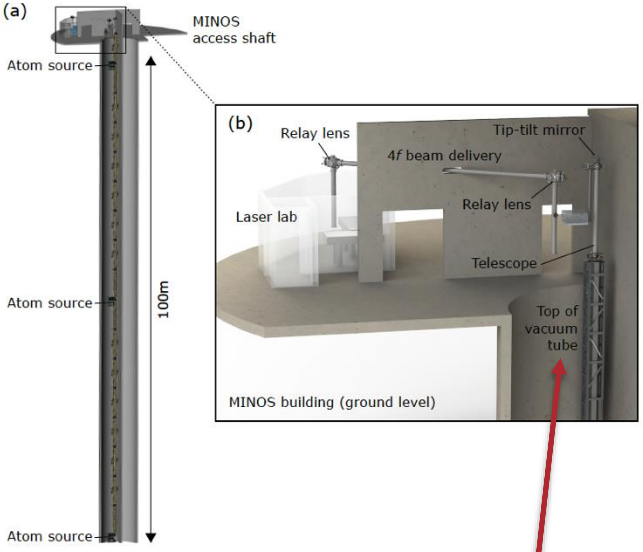
Systems overview

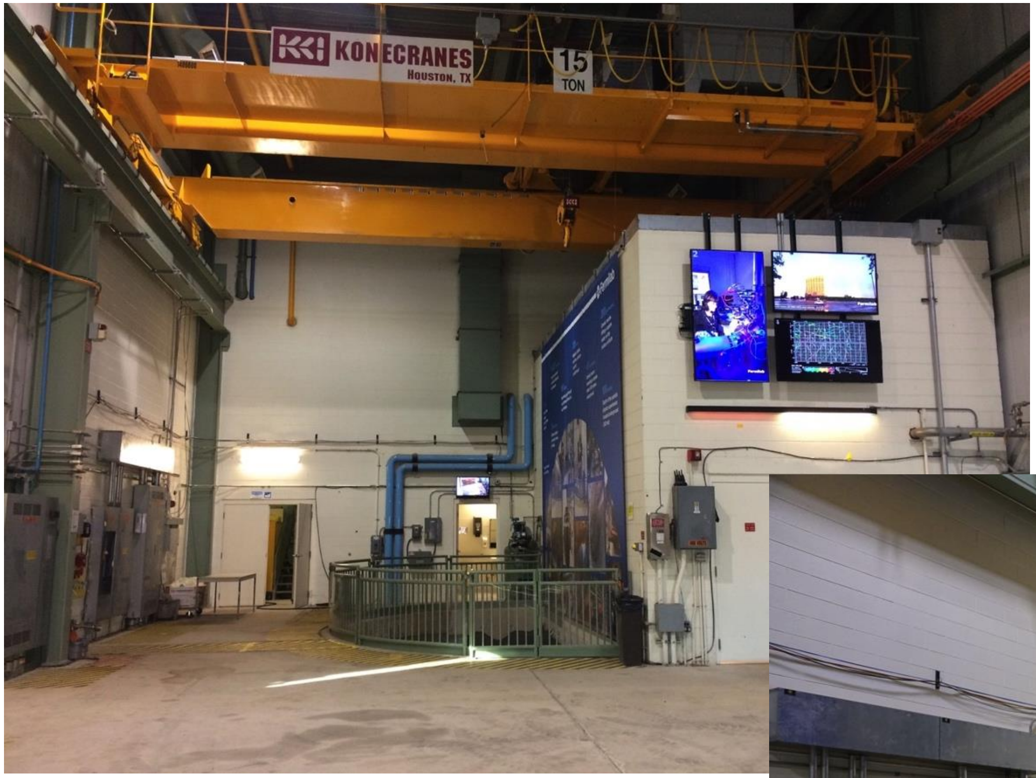


In shaft:
3 atom sources
17 modular sections
1 mirror at bottom
2 vacuum stations



Location – MINOS building

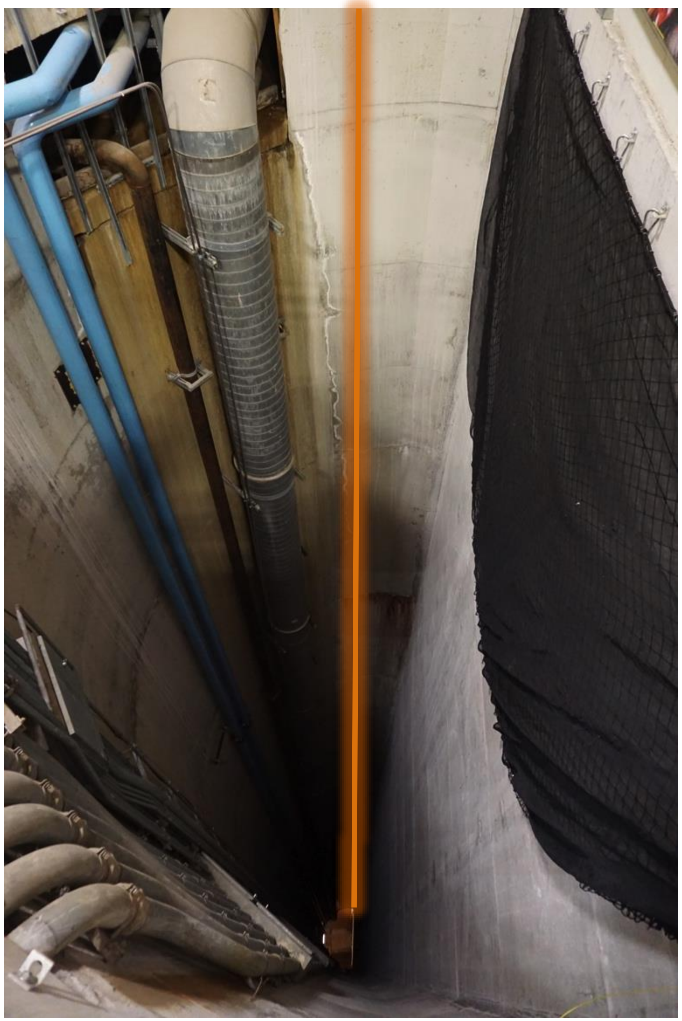




Laser lab to be built behind this wall.

Ground level of MINOS building.

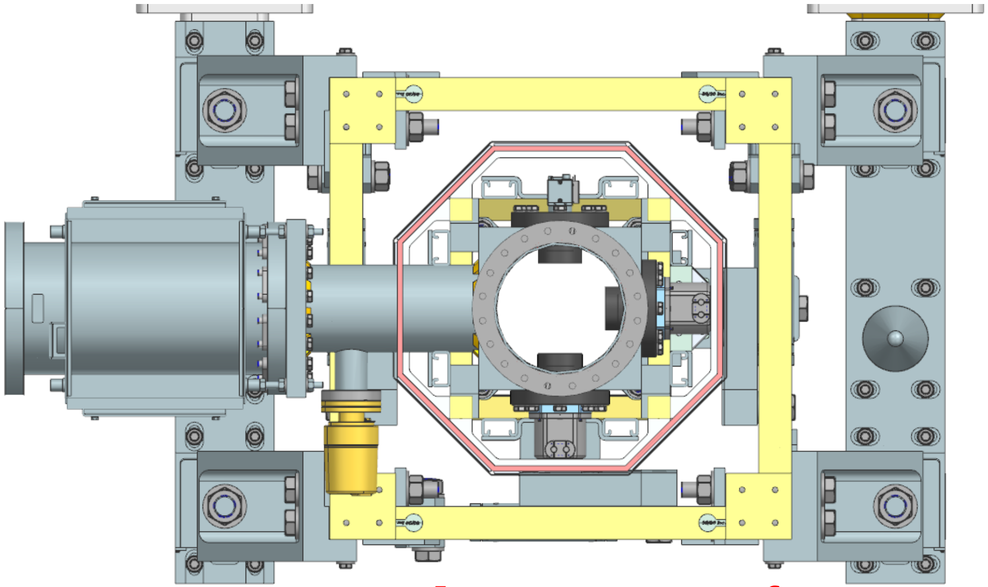
Location – shaft in MINOS building



Top and bottom of ~100m shaft. Proposed experiment location follows orange line.

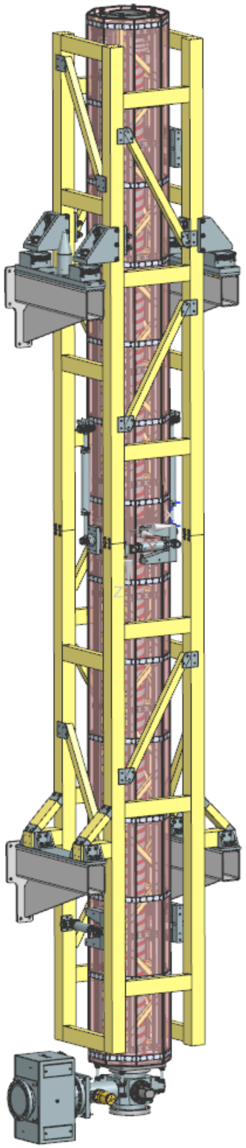
Modular sections

- Modular assembly concept uses 17 sections, each ~5.2m (17') long and ~2,000 lb. weight.
- Eight sections between each atom source and one section above the top atom source.
- Each section has a support frame containing a 6" diameter vacuum tube, heating/insulation system with controls and temperature sensors, bias field coils, octagonal mu metal shield with support frame, and magnetometer.
- Vacuum pumps and viewports with cameras will be placed between tube sections.



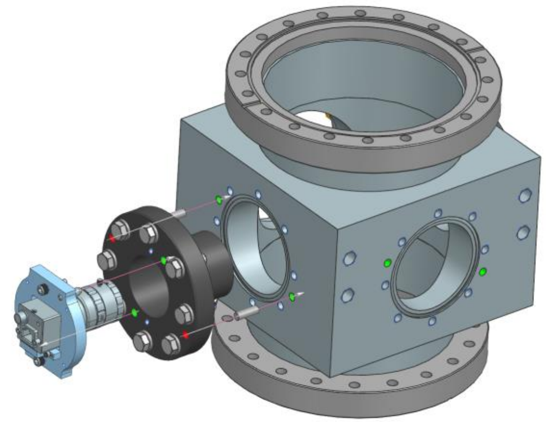
Cross section view.

L. Valerio, N. Curfman, Fermilab

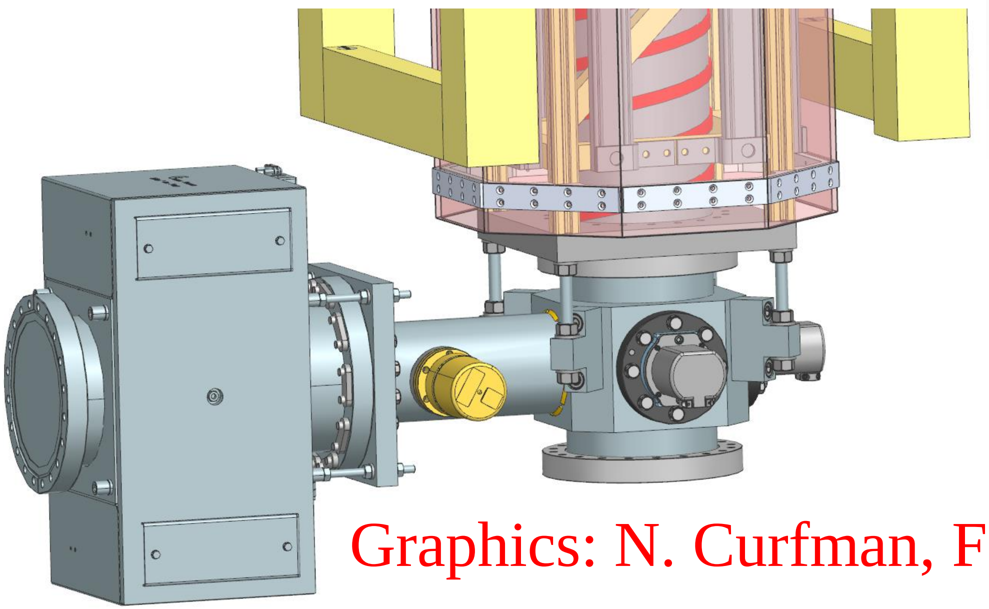


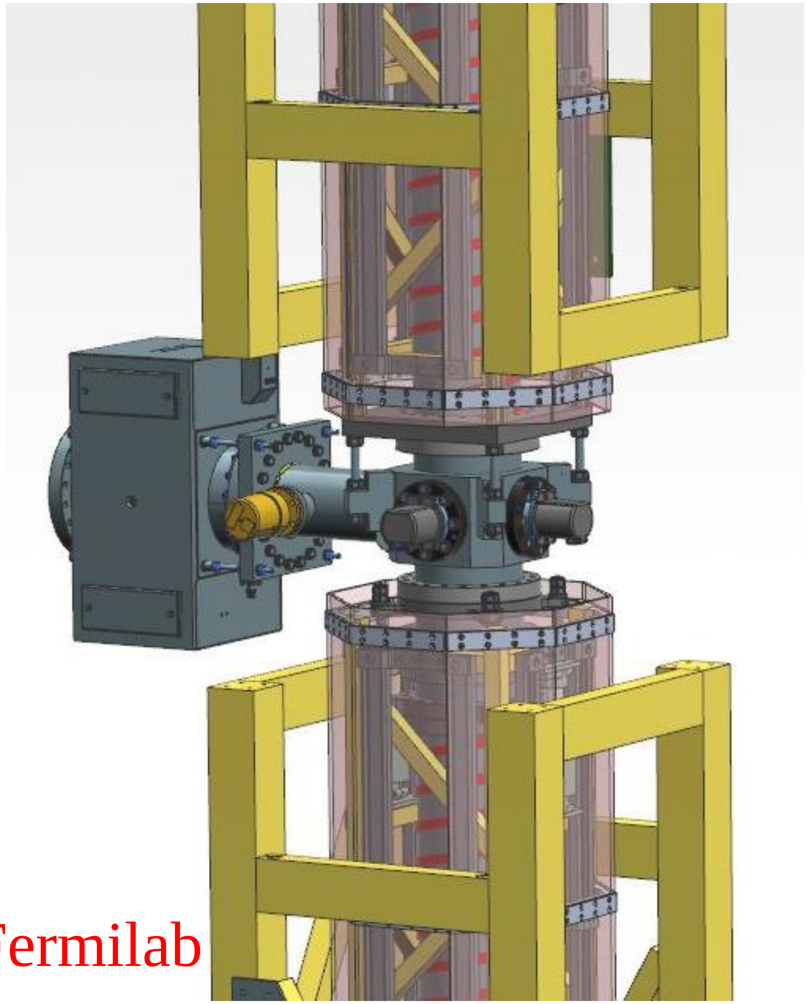
Single module with adjustable supports.

Modular connection nodes



Cameras mount inside re-entrant viewports with light tight covers.





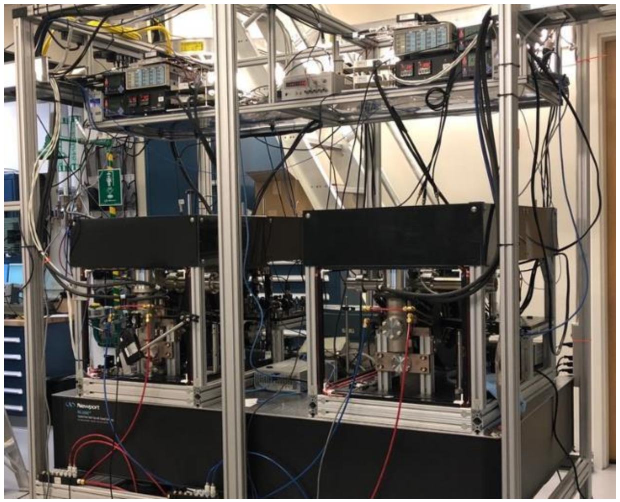
Graphics: N. Curfman, Fermilab

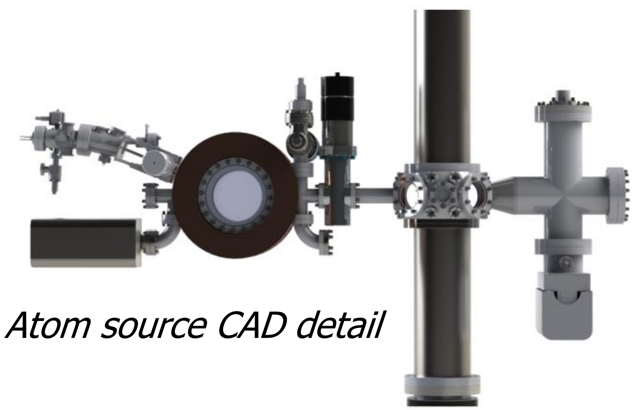
Detail of modular connection node.

Two modules connected.

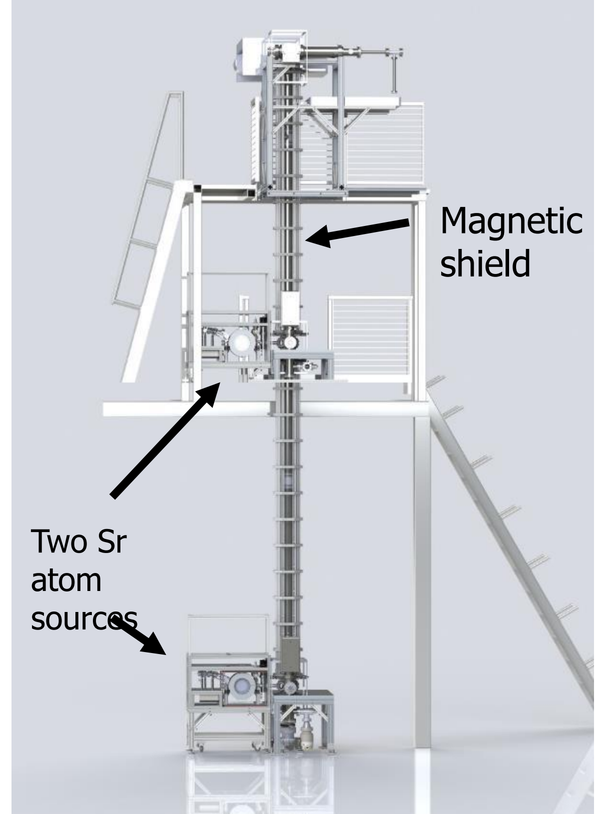
Stanford 10-meter Sr prototype

Two assembled Sr atom sources



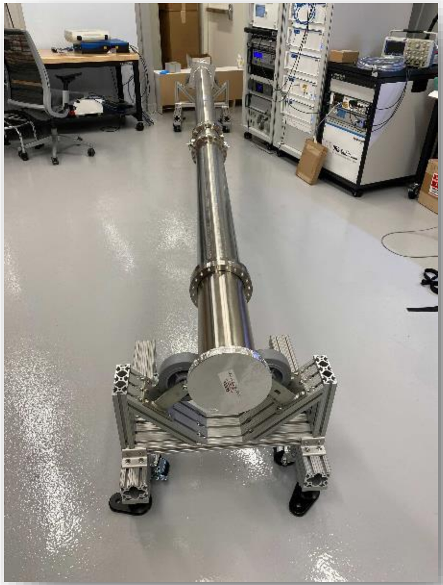


Atom source CAD detail

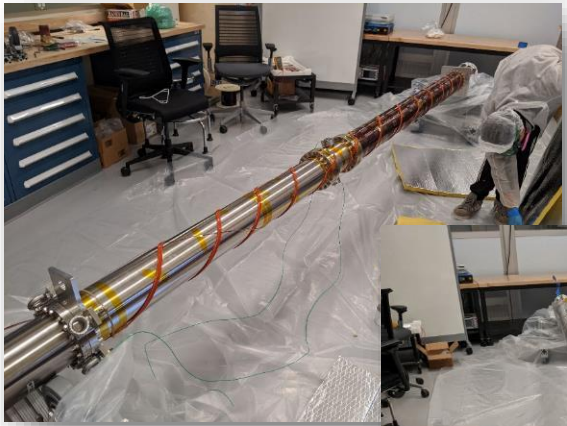


10-m tower CAD model

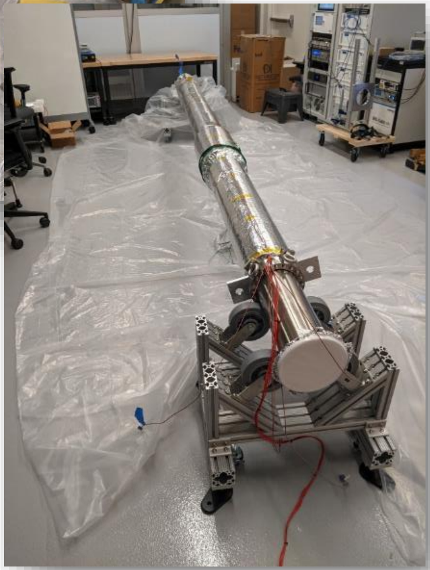
Prototype tower section assembly



Vacuum tube



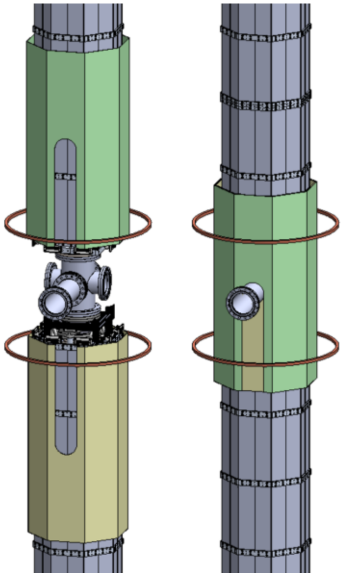
Heat tape

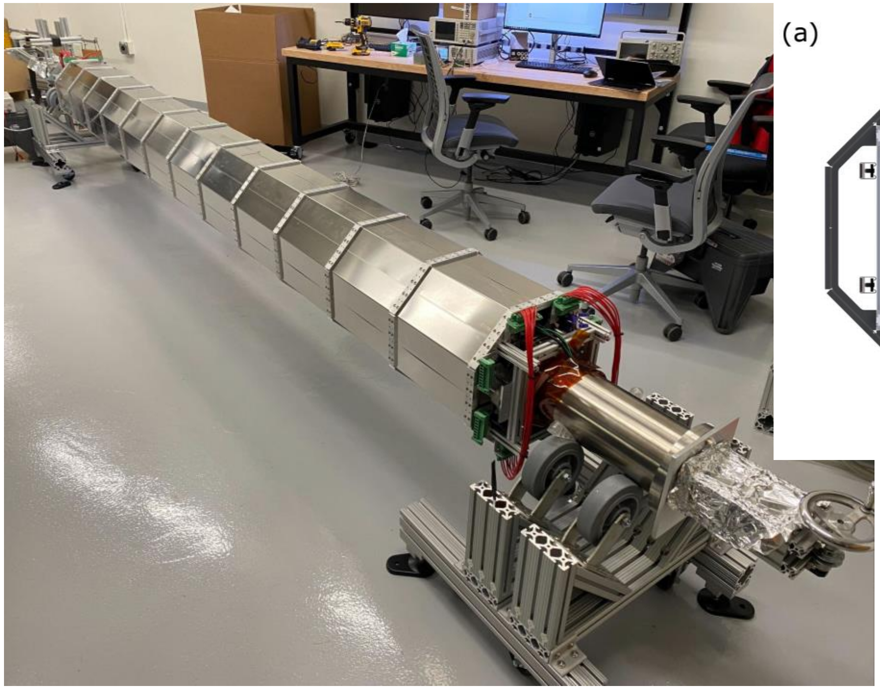


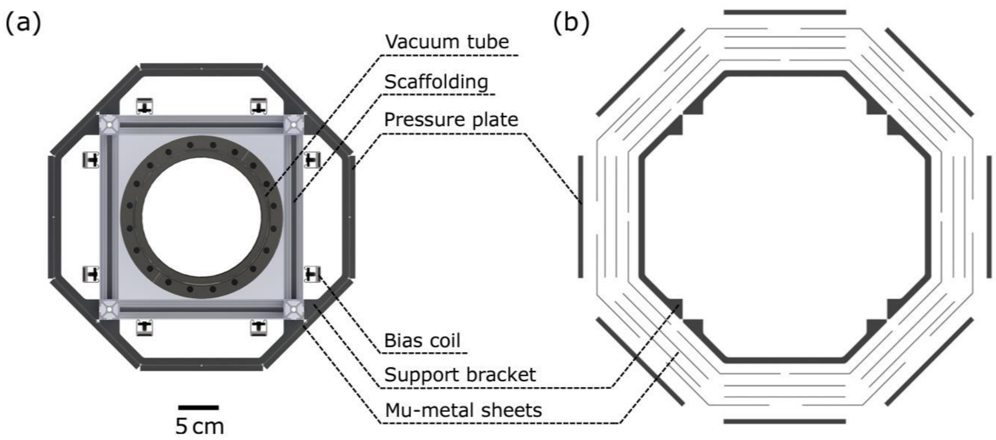
Insulation

Magnetic field

- Magnetic field is controlled with mu metal shielding and optimally placed magnet coils.
- Mu metal cannot have mechanical stresses – creates magnetic “holes” in shield.
- Sections are longer than typical mu metal annealing furnaces.
- Adapted from an existing design, octagonal shield chosen with four layers of staggered seams using flat and angled pieces.
- Fixtures required for successful tight-fitting assembly.

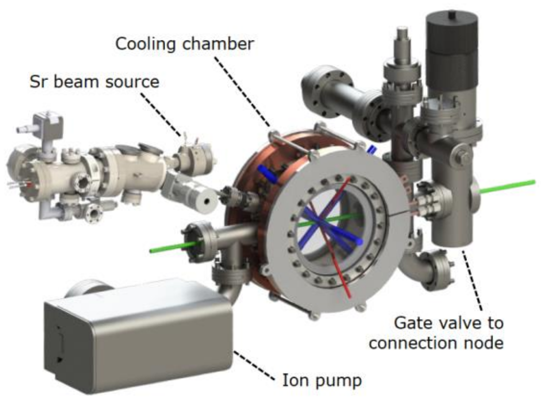


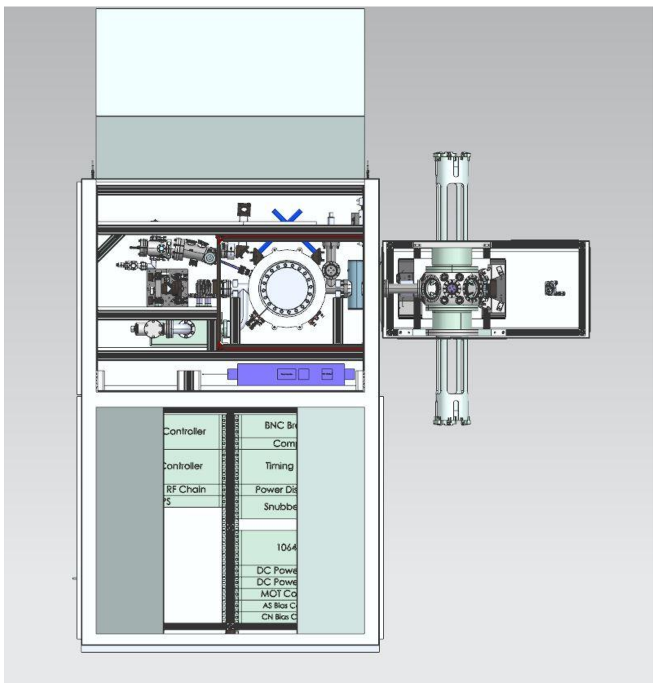


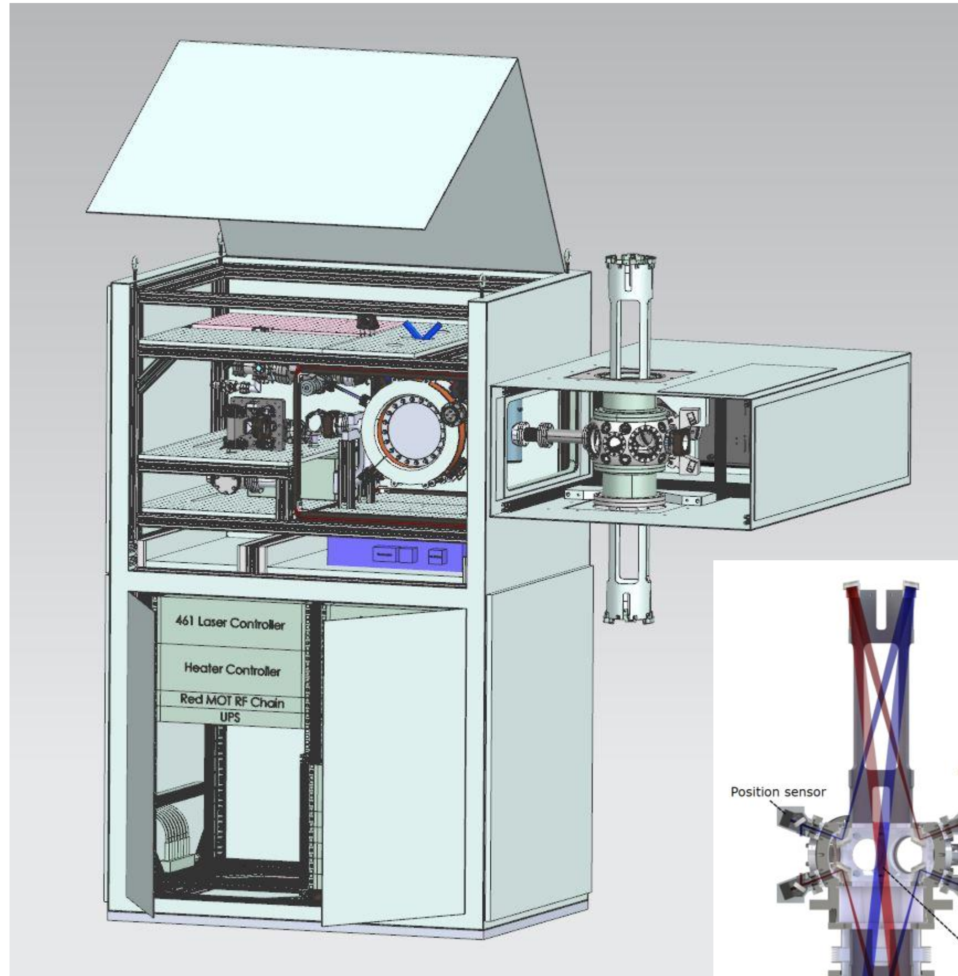


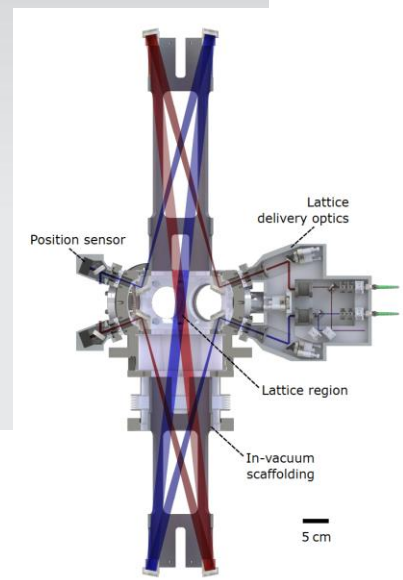
Left: Prototype section assembly at Stanford University 2022.
Above: Cross-section view of magnetic shield and bias coils.
Above right: Magnetic coupler and additional coils will be placed around modular connection nodes.

Atom source details









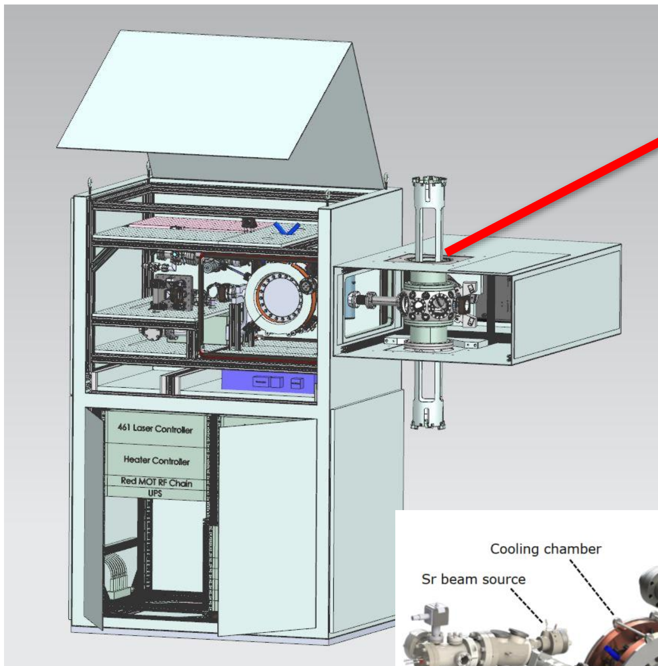
Views inside the atom source enclosure and adjacent atom source connection node.

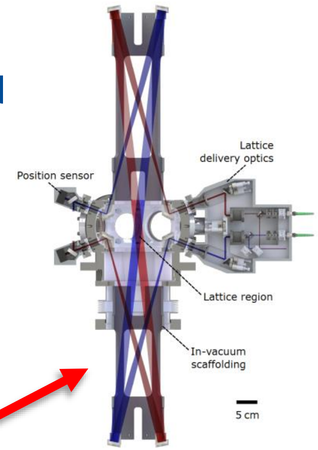
In-vacuum scaffolding extends into modular section vacuum tubes.

Atom sources

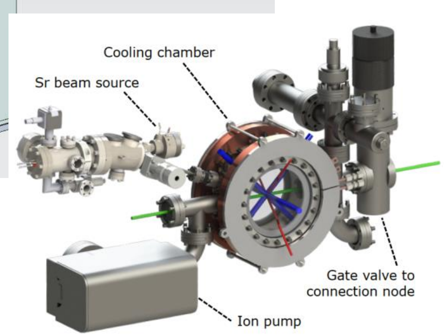
- **Top, middle, and bottom of shaft**
- **Last components installed.**

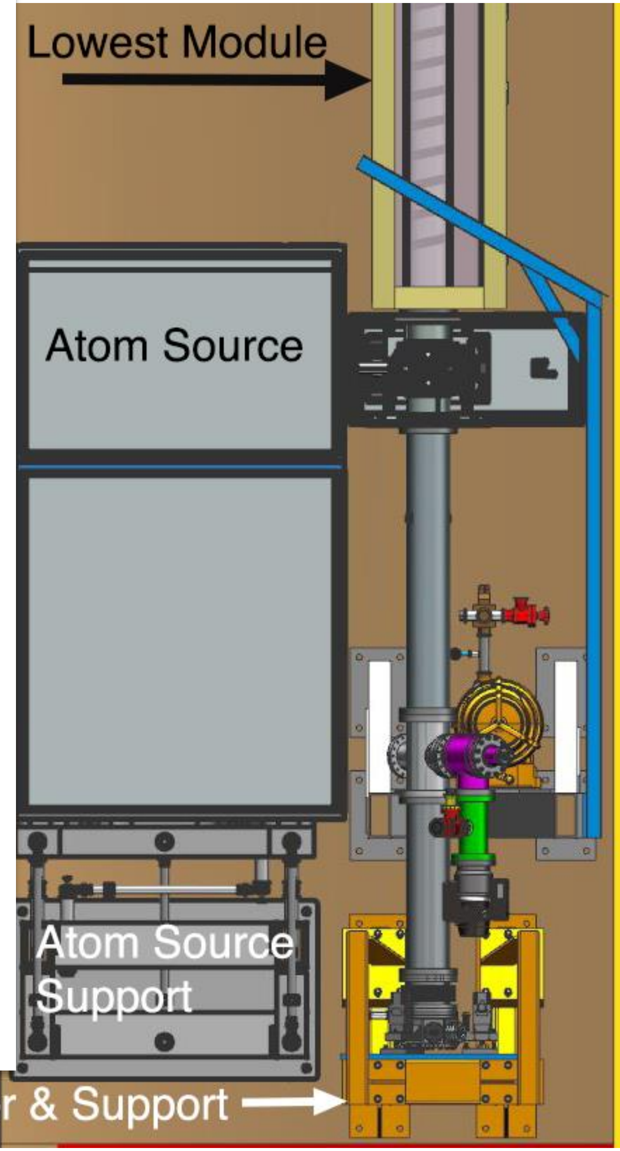
- **Designed and built at Stanford**





Launch Lattice



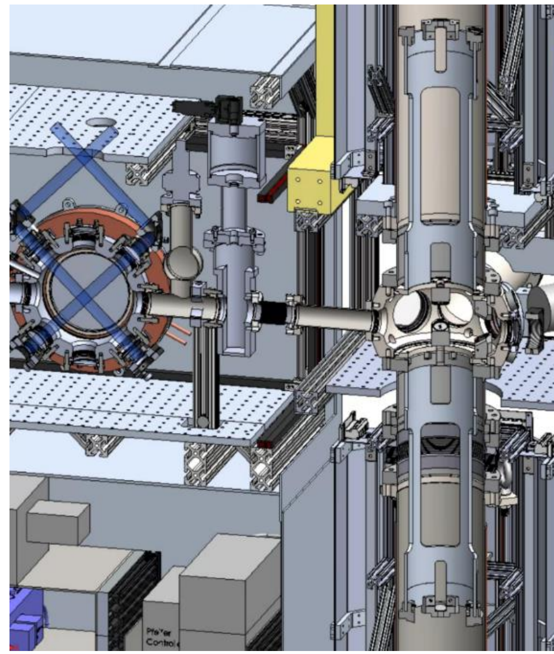


Connection node – Stanford

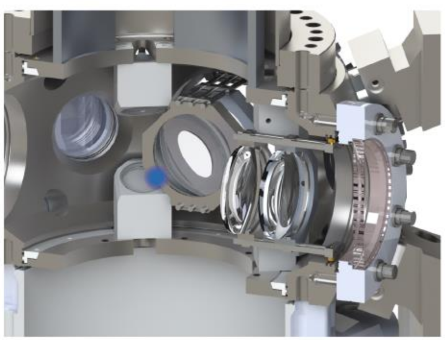
Three special "connection nodes" are at the interface between each atom source and the 100 meter interferometer region.

Functions:

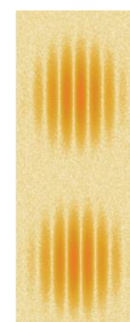
- Horizontal atom shuttle
- Optical lattice atom launch
- State prep
- Atom detection and imaging
- Vacuum pumping
- 100m module connection
- Thermal expansion joint (bellows)



Section view



In-vacuum detection optics

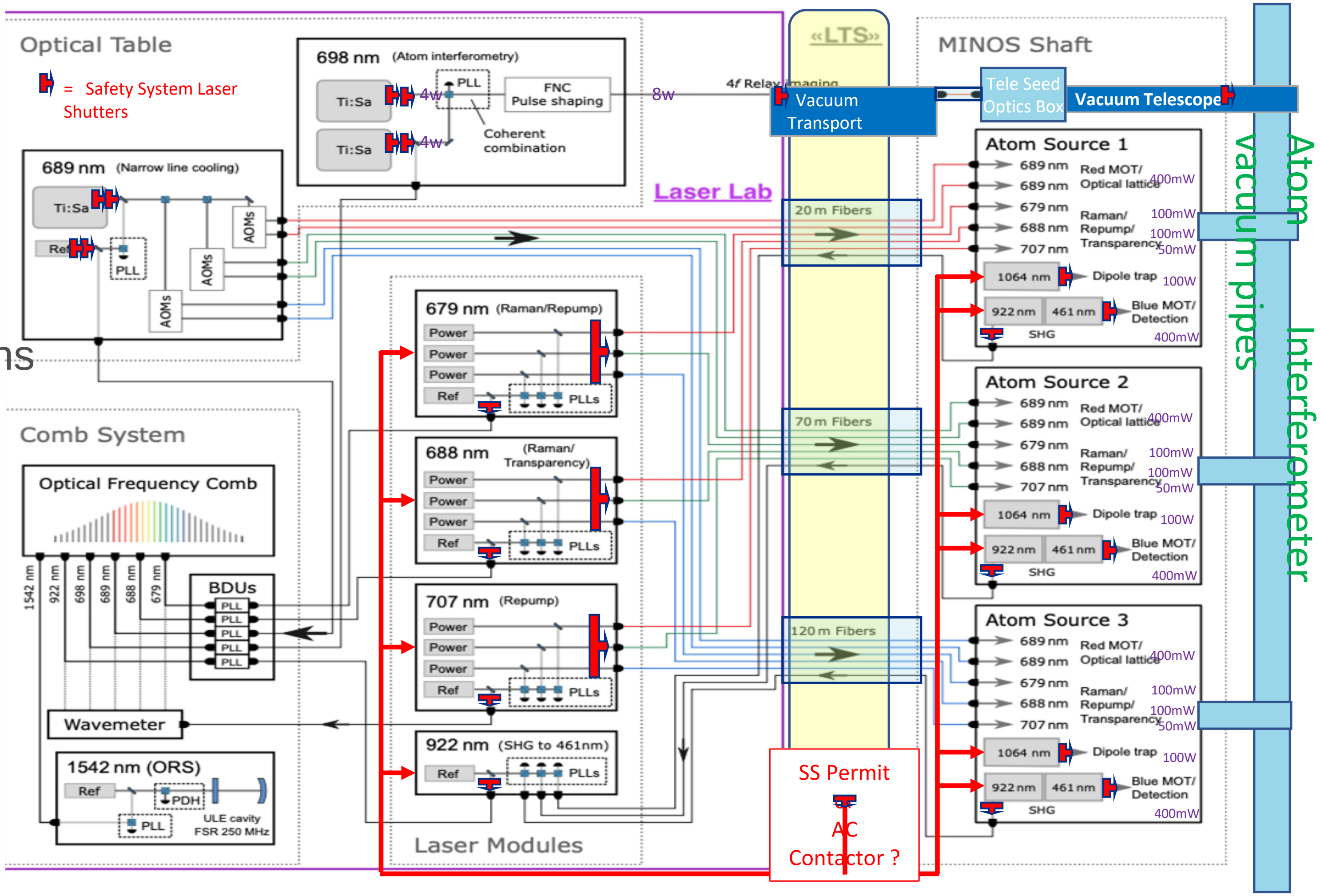


Simulated image of atom interference pattern

MAGIS-100

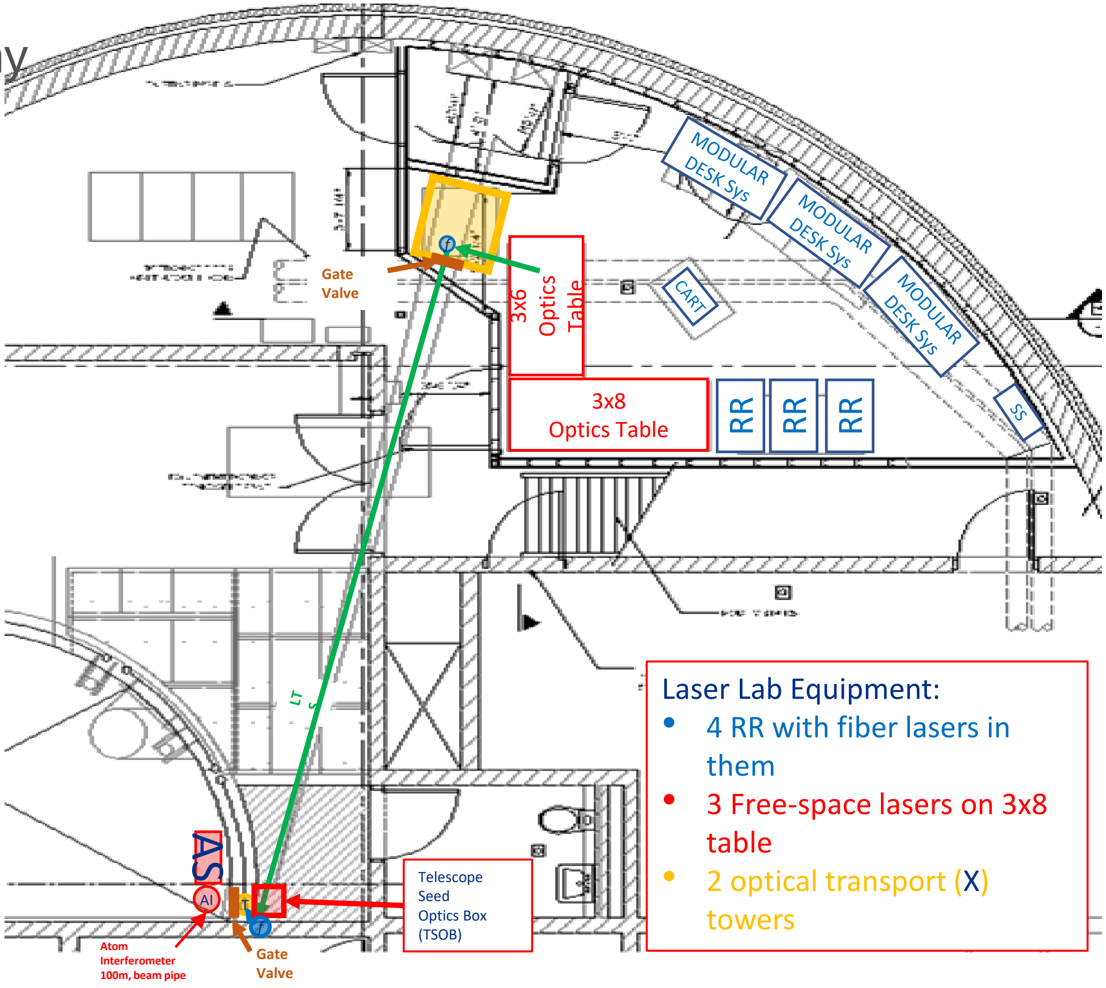
Laser System

- Laser System Schematic
  - 22 lasers
  - 8 wavelengths
- On surface and in shaft
- Integrated via optical comb

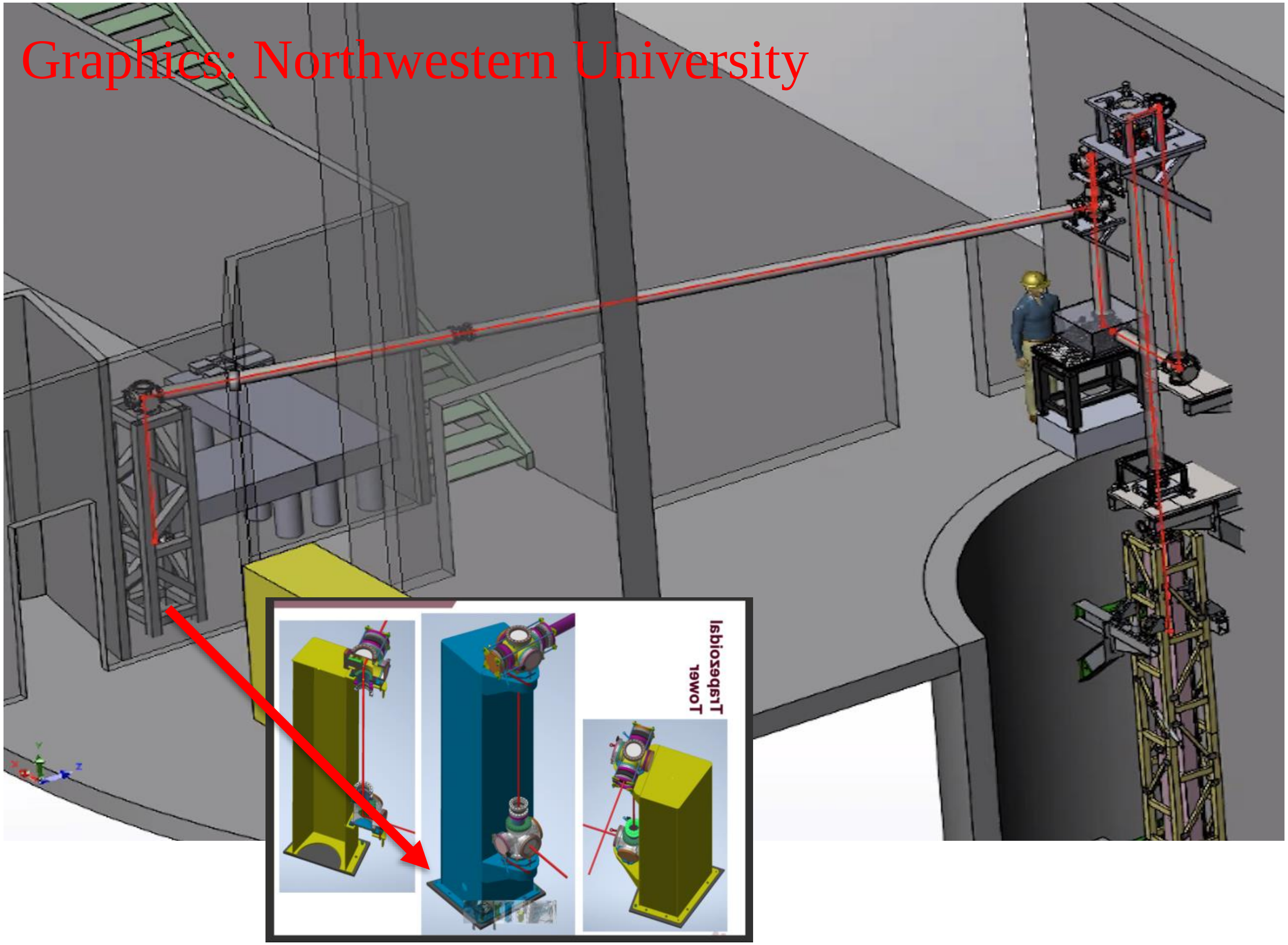


Laser Laboratory

- Holds Interferometry Lasers, many others.
- Houses Optical Comb
- Support system for transport system.
- Safety Interlocks.
- Utilities on second level
- Finalizing contract. Expect construction in summer.



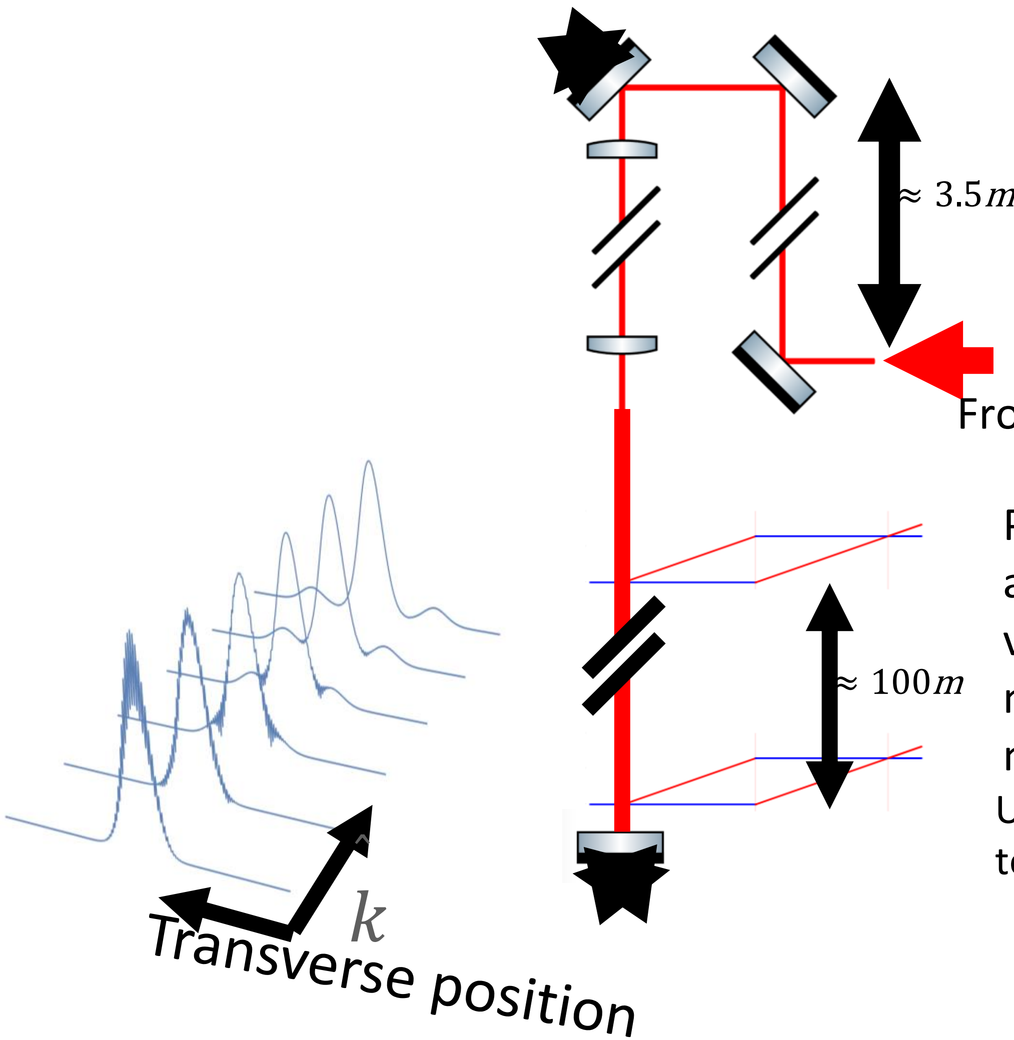
Laser transport system layout

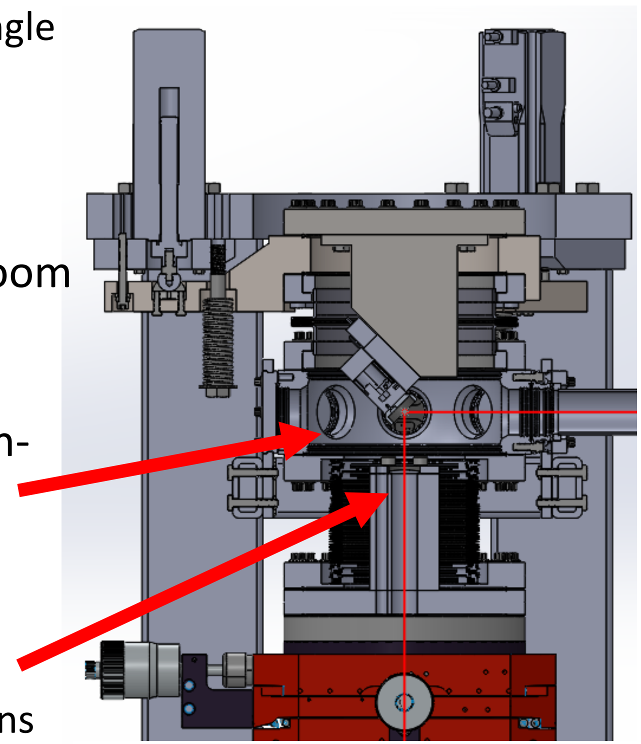


ANL Engineering

Laser Transport Details - Top

- Piezo controlled tip-tilt mirrors at the top and bottom of the shaft provide dynamic laser pointing control for Coriolis force compensation
- 5m vertical telescope both expands the beam and demagnifies the beam angle

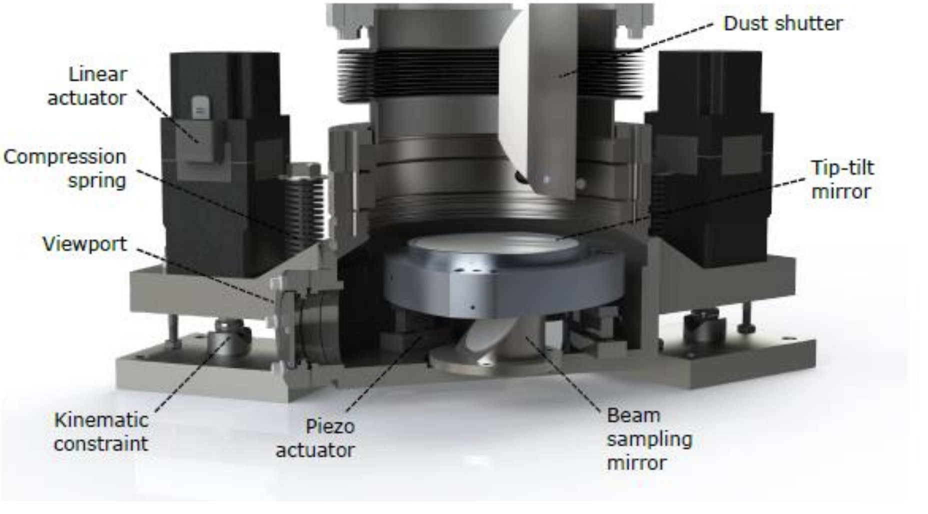




Mahiro Abe *et al* 2021 *Quantum Sci. Technol.* **6** 044003 2

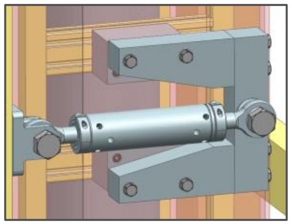
Retro-reflection Phase-shear Platform

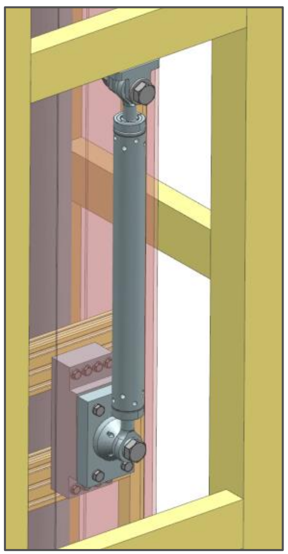
- UHV chamber housing retro-reflection mirror
- Mirror needs precise control for
  - Interferometry beam monitoring and alignment
  - Coriolis corrections
  - Phase-shear imaging
- Designed together with Stanford

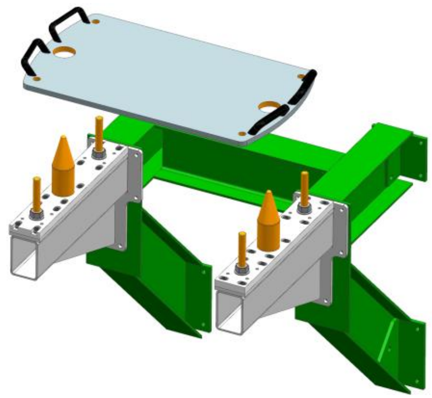


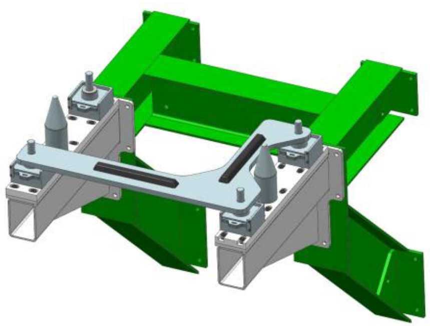
Gedminas Elertas
G.Elertas@liverpool.ac.uk - 13/03/2023

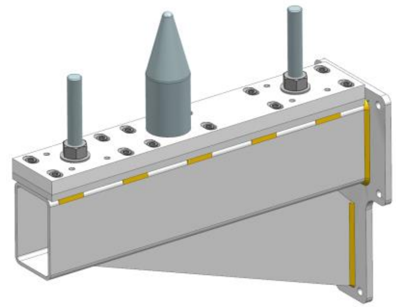
Strongbacks and Support Hardware

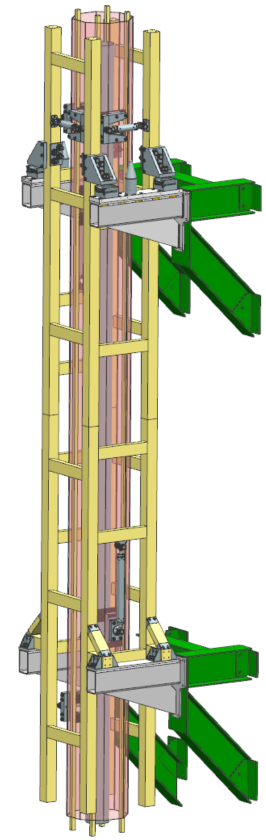




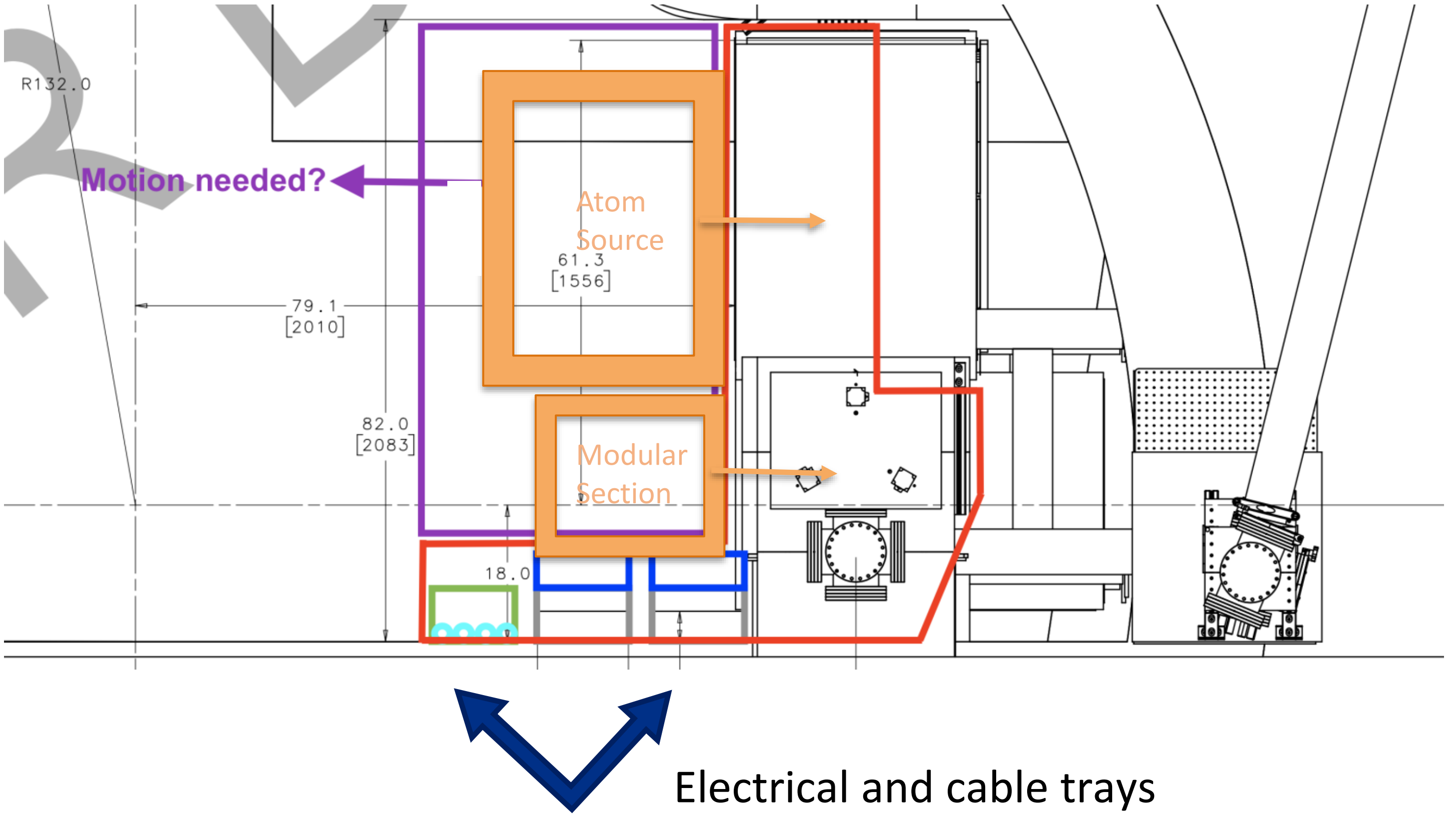








Top View of Shaft, Showing Installation Concepts

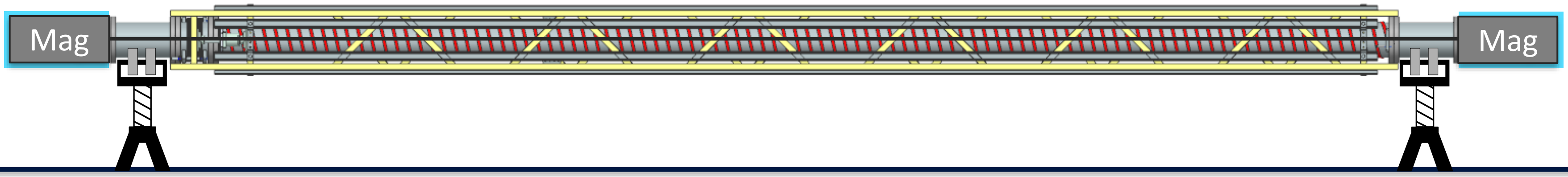


L. Valerio, Fermilab

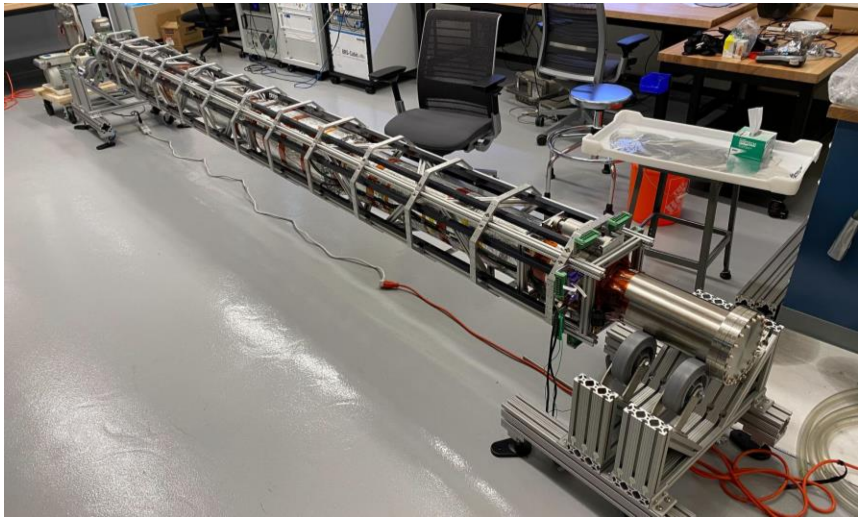
MAGIS-100

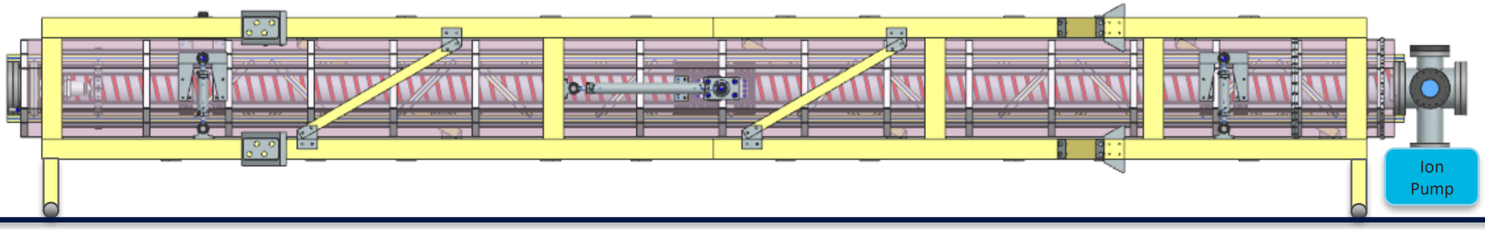
Modular section assembly

- Assembly will be done at Fermilab.
- Rotisserie fixture and magnetometer shuttle already tested at Stanford.



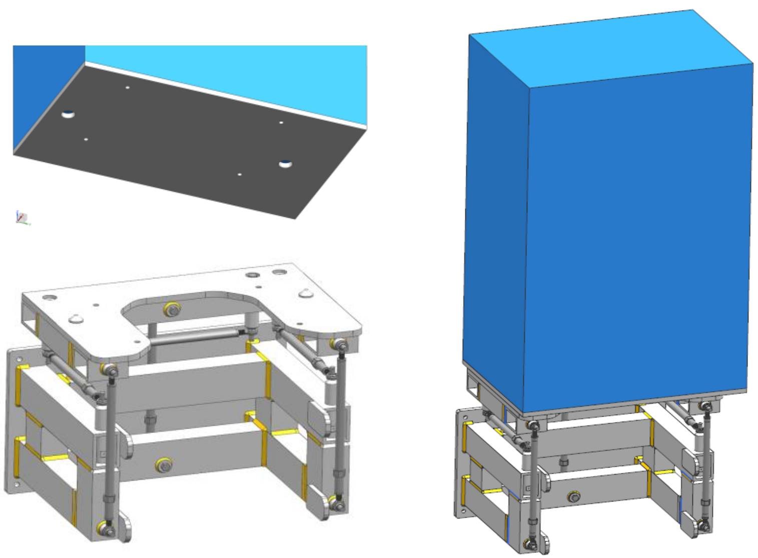
Above: Schematic of assembly on rotisserie fixture.
Right: Prototype assembly at Stanford University.
Below: Schematic of complete assembly.



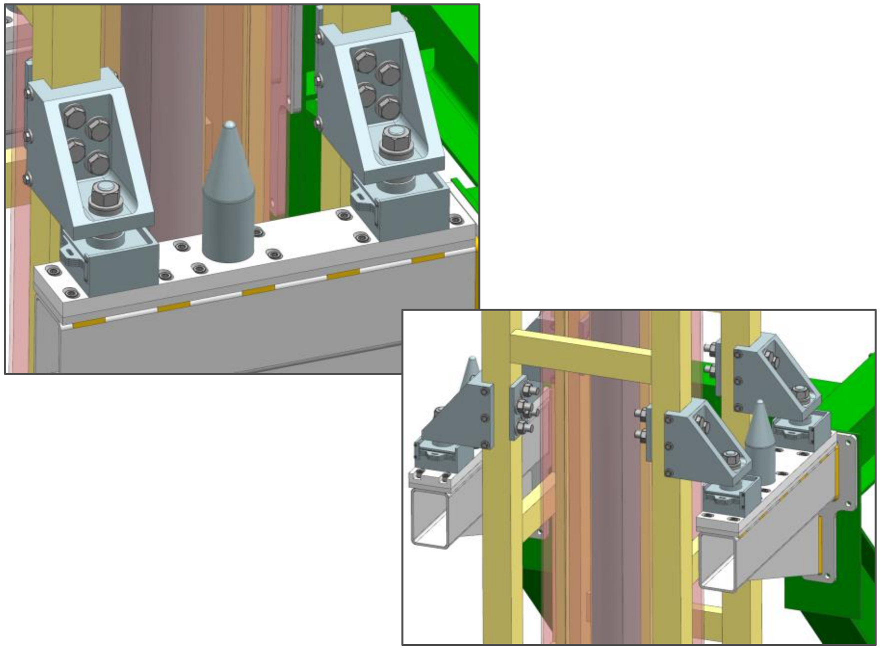


Component installation plan

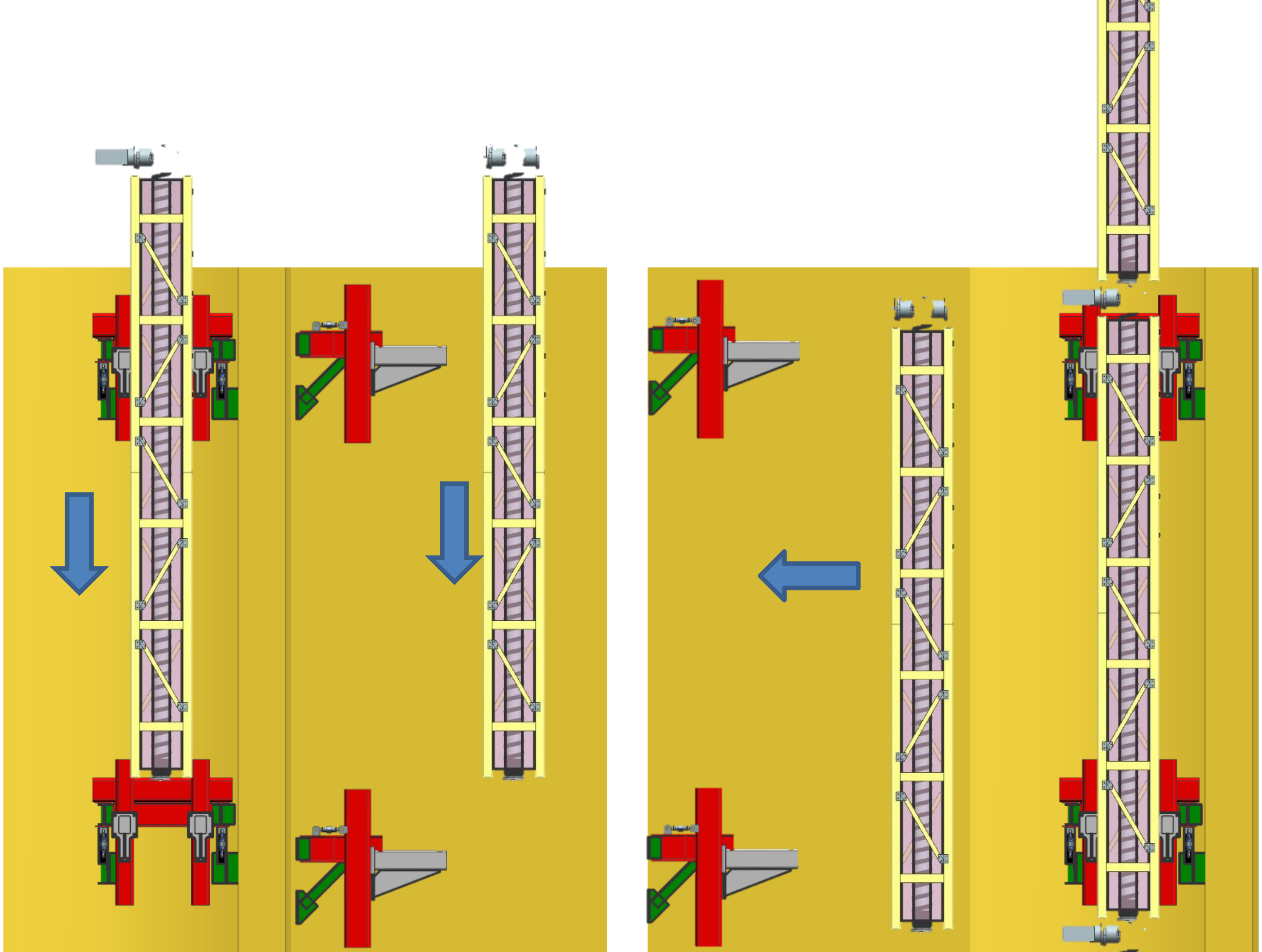
- Wall supports will be installed through a civil construction contract.
- Plan to land components on wall supports with dagger system.
- Use cameras (with lights) for crane operator feedback instead of people in basket above load.
- Then people descend in basket to firmly connect components to supports and disconnect auxiliary crane hook and cameras.
- Concern about two cranes entangling is minimized with this approach.
- Work ongoing to stabilize crane loads.
- Mock-up will be tested.



Atom source and adjustable wall support.



Modular section adjustable wall support.



Installation Sequence - Conceptual

Status and Conclusions

- Many components are in hand, others are in either advanced design or prototyping state.
- Collaboration close-knit and participation outstanding.
- Laser lab construction will occur soon.
- Installation remains challenging but progress is occurring.
- The future of MAGIS-100 is bright!

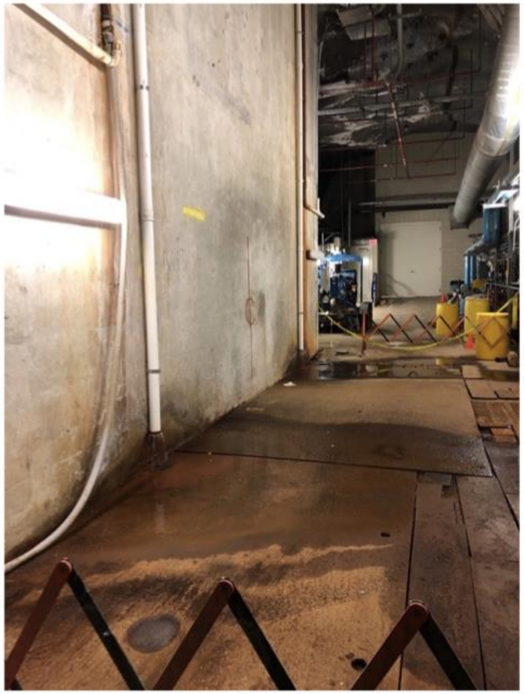
Backup

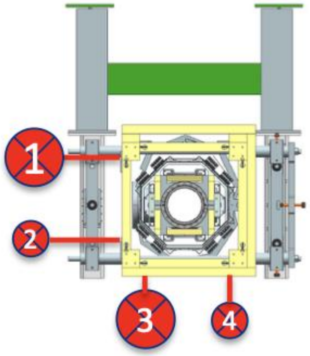
Alignment conceptual plan

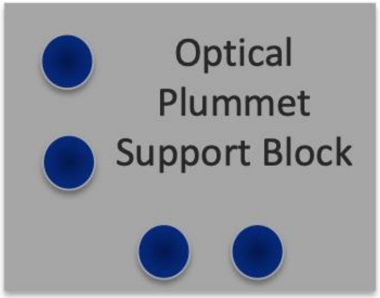
Optical plummets will be mounted at the bottom of the shaft to achieve required alignment.

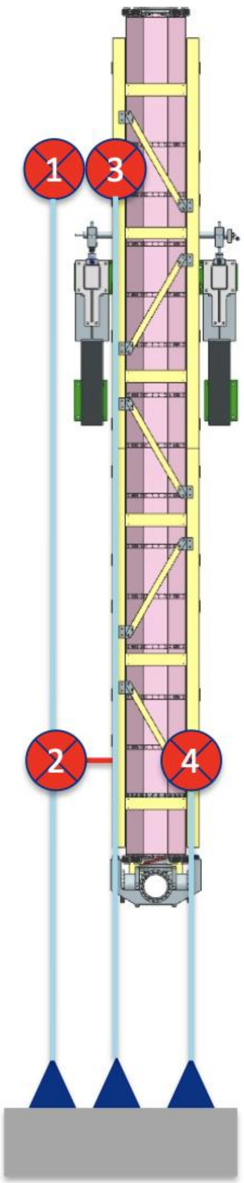
- **Mounting base must be sturdy.**
- **Bottom of shaft has metal plates which will flex and is also a "stay clear" zone. Original plan was to use concrete block.**
- **Consider if mounting base to elevator wall would work better.**

Details still developing.

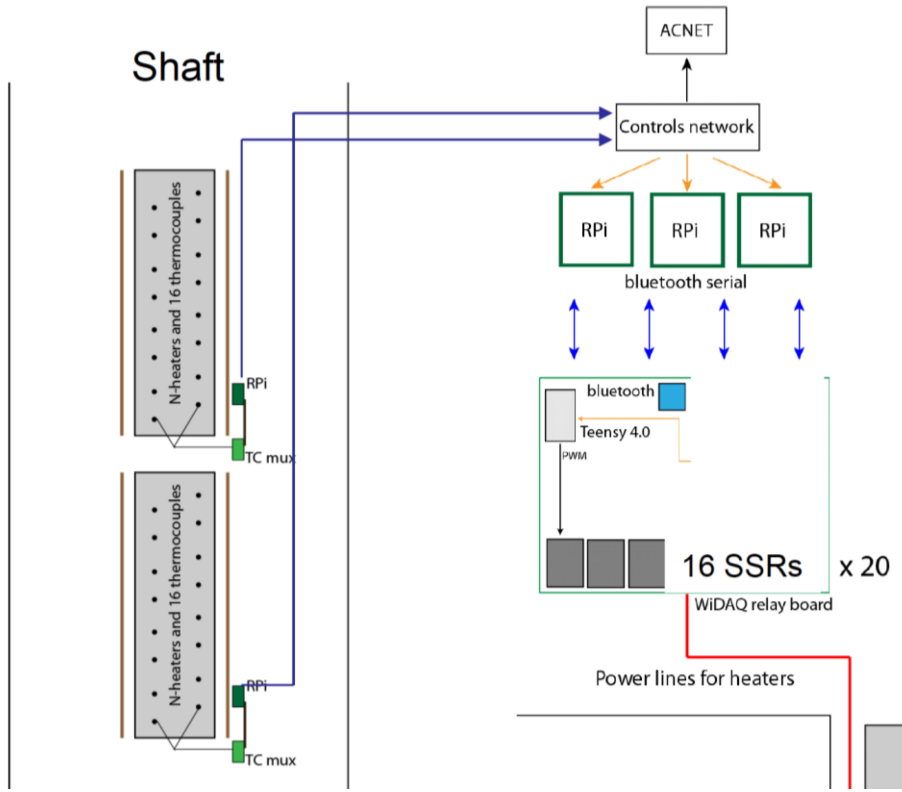


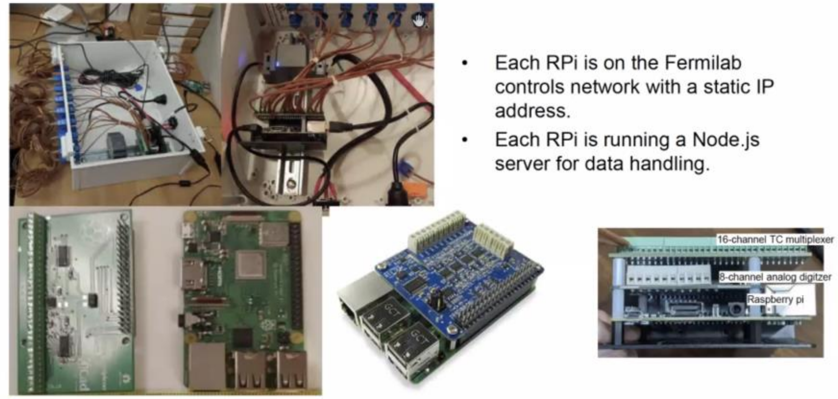






Bake out controls system





- Each RPi is on the Fermilab controls network with a static IP address.
- Each RPi is running a Node.js server for data handling.

TC-MUX Board
- SPI + GPIO
- 16 inputs

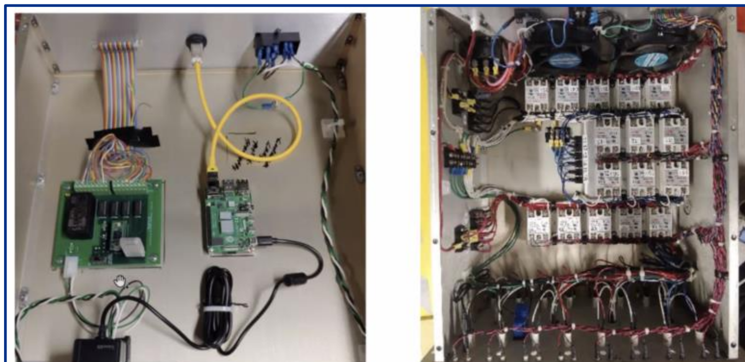
25 TC-MUX boards delivered from UChicago

RPi

MCC-118 ADC
- 8 analog inputs
- Stackable: expand to 64 channels

In shaft

Top of shaft



16-channel PWM

16-channel SSR

Bake controls system uses Raspberry Pis and thermocouples with a temperature module box on each section in the shaft and power control modules at the top of the shaft.

All images from Sergei Nagaitsev.

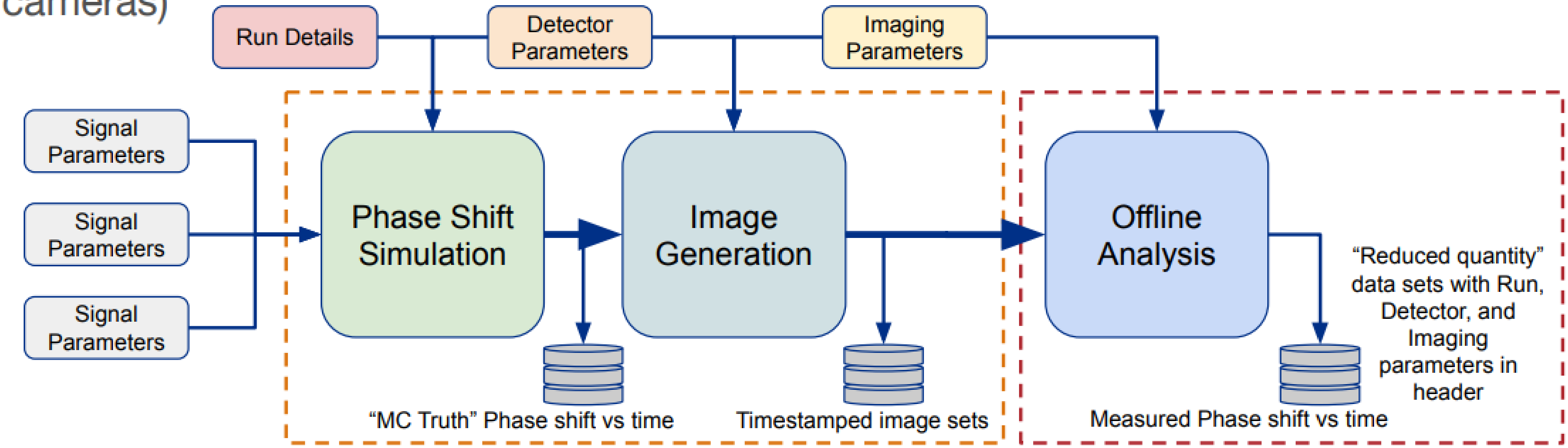
Computing activities

- Move away from the crunchy hardware details to software and resources.
- Participation and organization of software workshop.
- Simulation activities
- Organizational
  - Biweekly meeting forum (Geer).
  - Proposal for collaboration software organization.
- Much of this familiar to many here, who are very active.

MAGIS-100

Production Simulations and Analysis

Production simulation: pick some set of signals with chosen parameters, simulate the phase shift, detector effects, up to creating images (in same format as real cameras)



Production analysis: starting from the images, fit the patterns and extract a phase shift. Should be able to run on both simulation and real data with minor user input. These algorithms used in both Online and Offline processing

Fermilab

MAGIS-100

Dark Matter Simulation Results – Docdb 1290

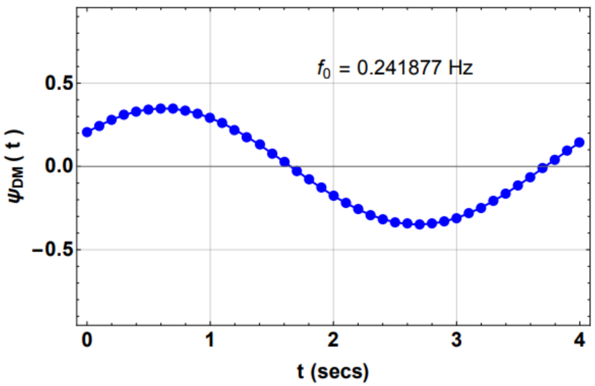


Figure 3: First cycle of a simulated DM background wave produced from an incoherent sum over 1000 indiv sinusoidal waves with the frequency distribution shown in Fig. 2. The individual points are spaced with the anticipated cadence of the MAGIS-100 interferometer measurements. The curve shows the expected sinusoida variation.

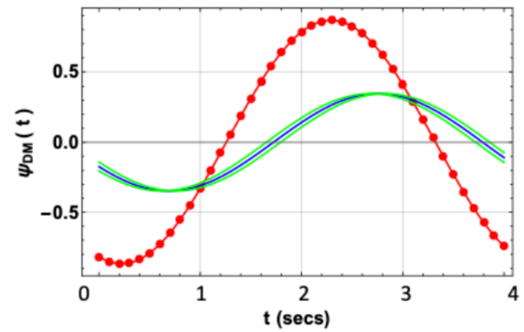
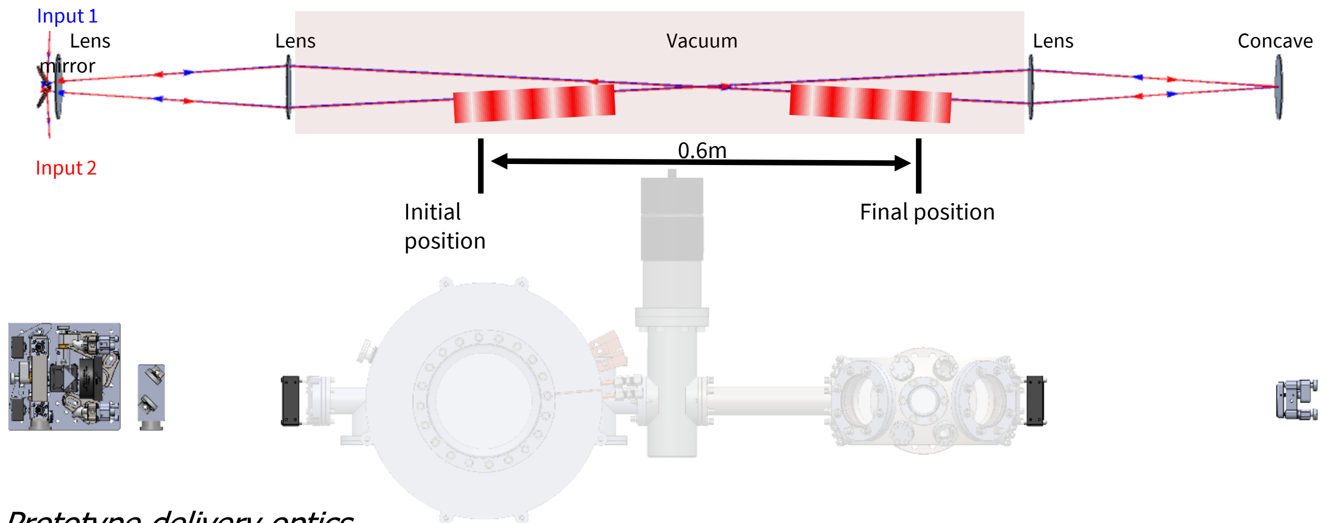


Figure 4: Comparison of two cycles of a simulated DM background wave for a DM particle with $m_0 = 10^{-15}$ eV. The cycles are separated by a time interval of 10^7 secs which $\approx \tau_{coh}$. The red points are the late cycle, and the blue curve shows a fit to the early cycle (shown in Fig. 3) projected forward in time. The green curves indicate the uncertainty on the projection. Note that both the amplitude and phase of the wave have evolved.

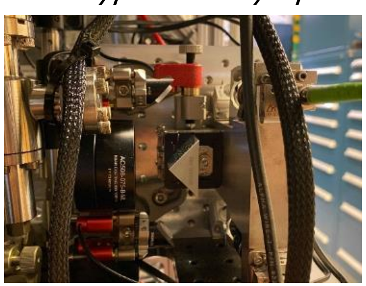
MAGIS-100

Horizontal shuttle optical lattice - Stanford

- Long shuttle distance (0.6m)
- Use two tilted lattices to null vertical acceleration



Prototype delivery optics



- Overlapping paths maximizes acceleration distance
- Nearly independent control over lattice angle/position
- Delivery optics on custom stainless steel breadboard
- Picomotors for remote control of all required DC
- Next step: demonstration with atoms

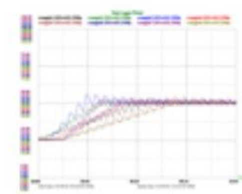
MAGIS-100

Ultra high vacuum (UHV)

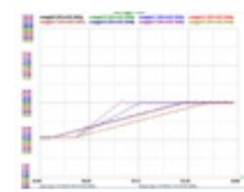
- **Required pressure e-11 Torr or better for interferometry region.**
- **Dual pumps (ion pump + titanium sublimation pump OR non-evaporable getter pump + small ion pump) will be on each modular section.**
- **Vacuum bake required to reach this pressure.**
- **Minimally magnetic 316L stainless steel tubes and non-magnetic heaters required.**
- **Tubes have been electropolished and will be hydrogen degassed.**

16-channel bake test setup.

Conclusion: no unexpected behavior, test is a success!



Temperature ramps SSR0-SSR7



Temperature ramps SSR8-SSR15

Excerpt from bake test e-log.

6” OD vacuum tubes.

Progress on bakeout system (Fermilab, Chicago)

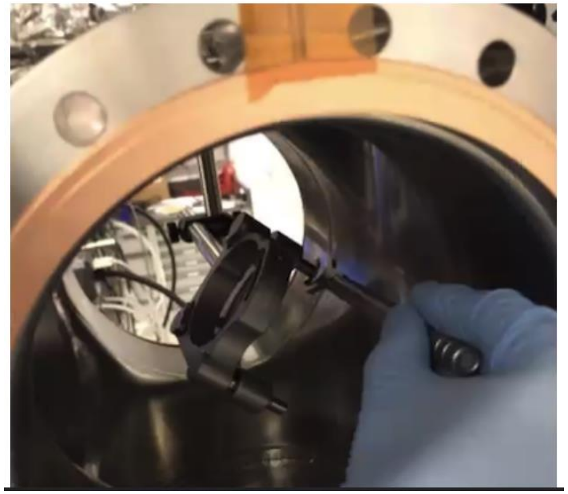
Setting up for test at CMTF facility.

17 boxes needed. Big job!

16 channel SCR controller box

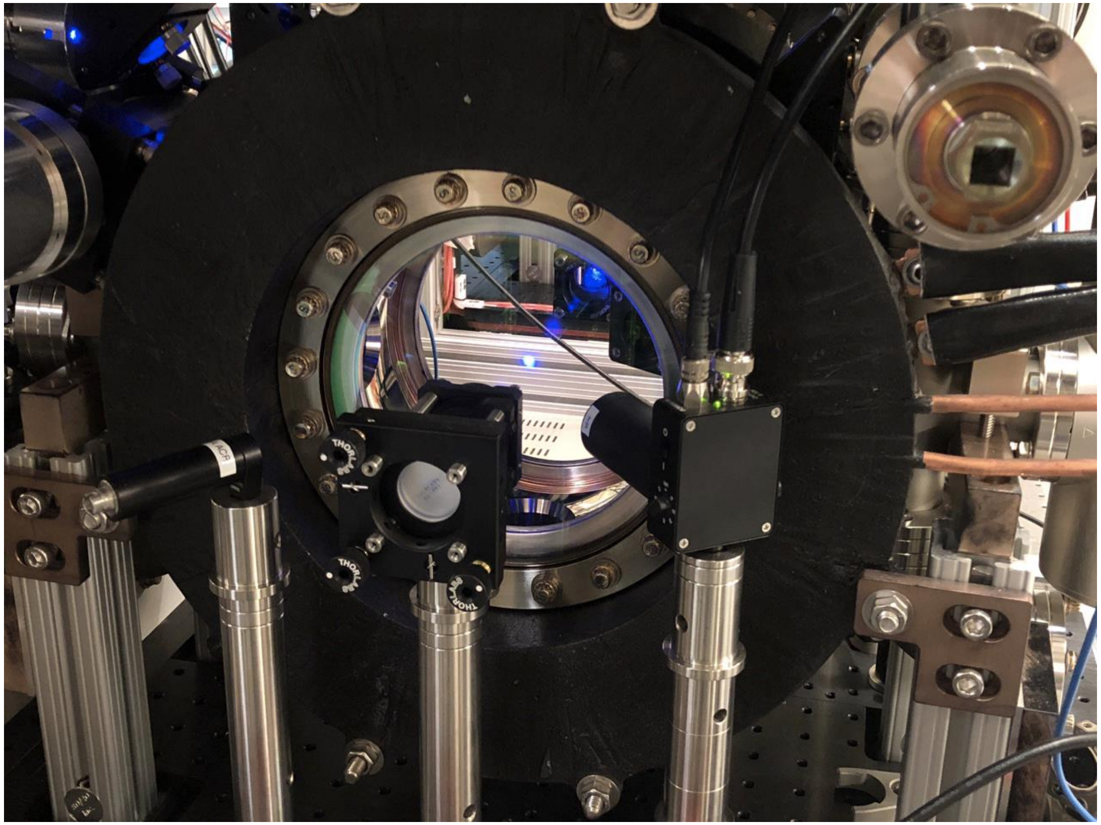
MAGIS-100

Large amount of vacuum testing.
Example: Control Box and Optics Mounts

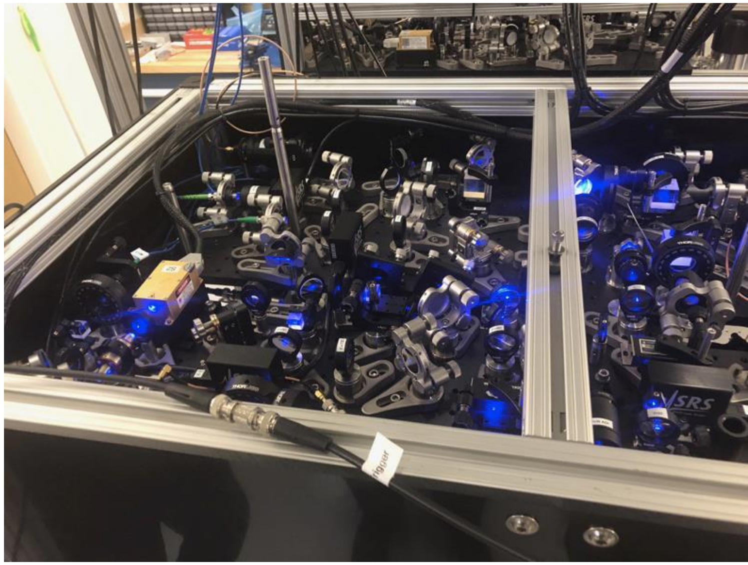


Achieved required pressure with optics
coatings after some work.

Prototype atom source at Stanford University



One billion strontium (Sr) atoms are captured in the blue dot in the magneto-optical trap (MOT).



Optics in the top layer of the atom source.