MAGIS-100 Engineering Challenges

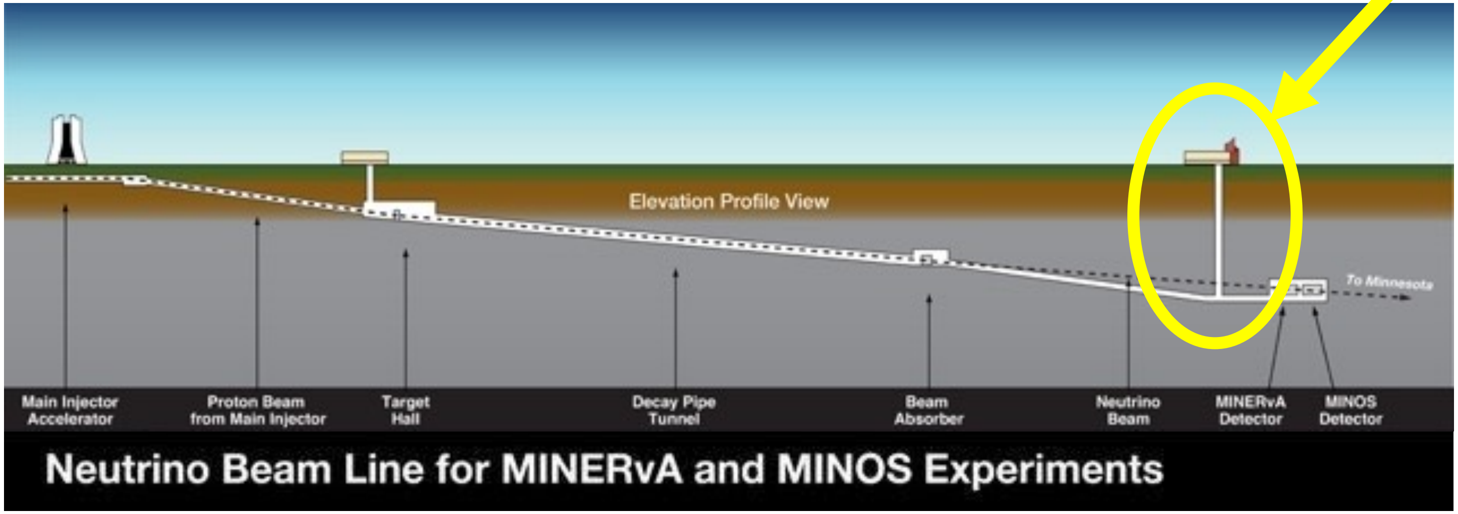
2023 All Engineers' Retreat

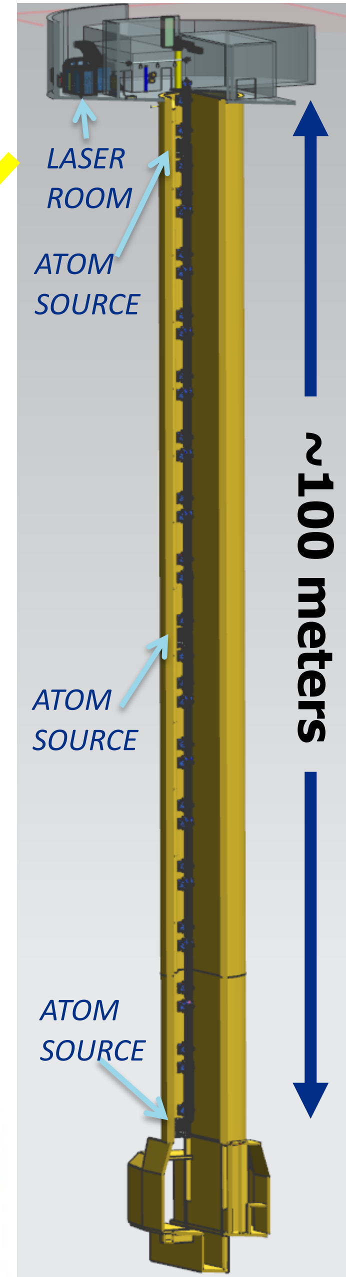
Linda Valerio, MAGIS-100 Project Engineer

24 February 2023

MAGIS-100 experiment design overview

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



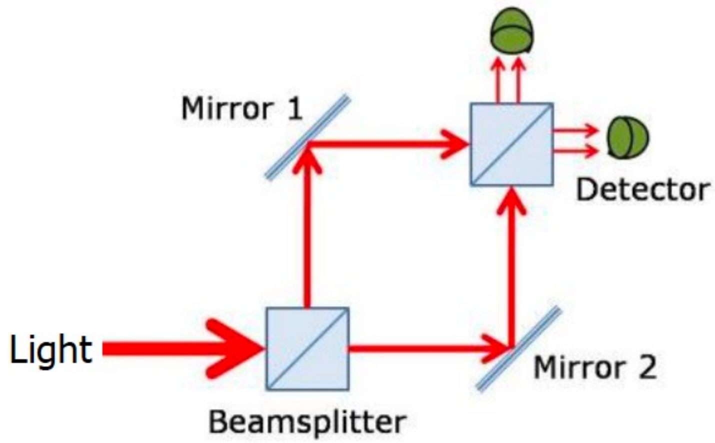


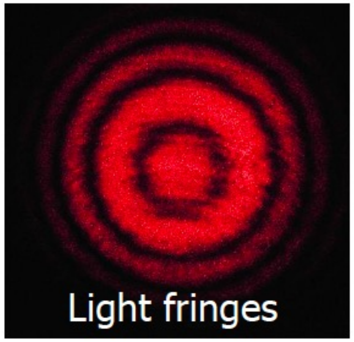
- 100-meter baseline atom interferometry in existing shaft at Fermilab
- Major sub-systems:
  - Clock atom sources (Strontium) at three positions
  - Interferometry laser system
  - 100-meter vacuum system and infrastructure

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

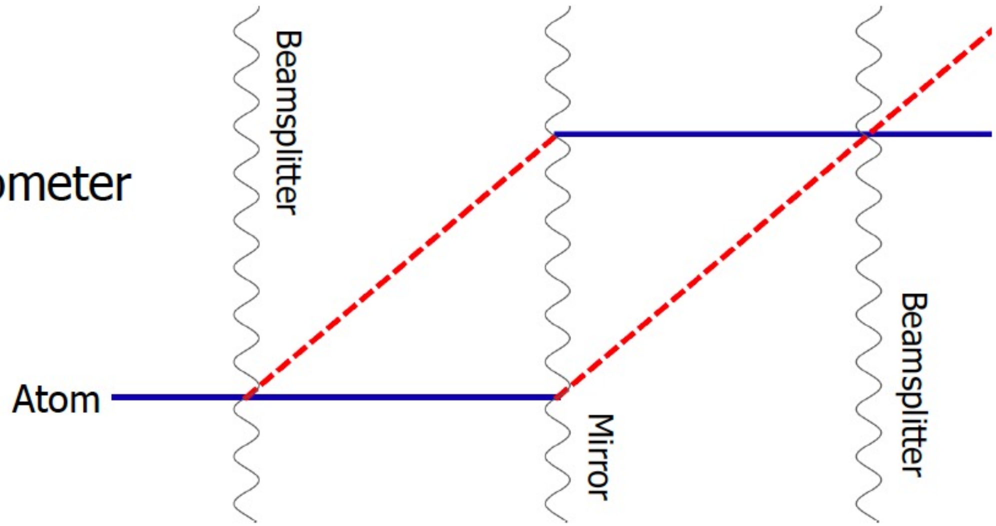
Interferometry basics

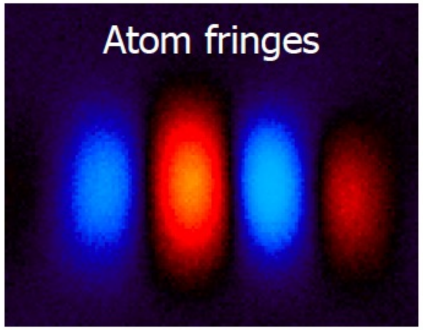
Light interferometer





Atom interferometer



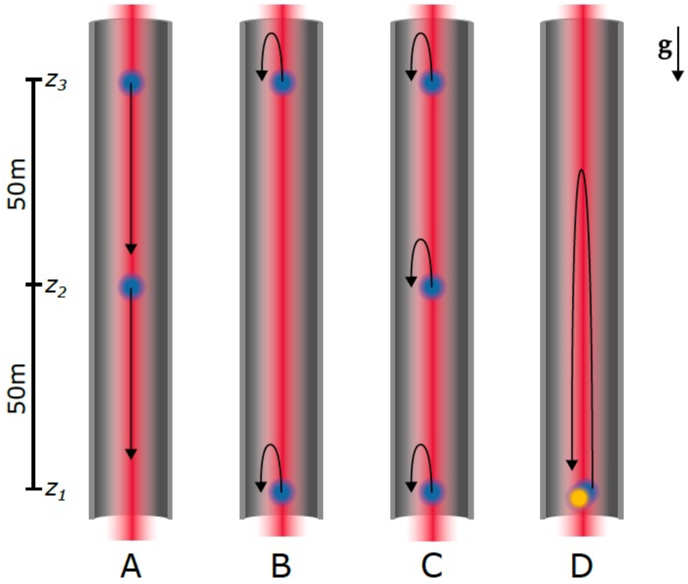


STANFORD UNIVERSITY

Slide courtesy of Jason Hogan.

http://scienceblogs.com/principles/2013/10/22/quantum-erasure/
http://www.cobolt.se/interferometry.html

MAGIS-100 operating modes (why vertical?)



Four distinct operating modes (A-D) use the three atom sources that connect to the 100 m vacuum tube at locations z1, z2 and z3.

At these locations, atom clouds can be prepared, dropped, launched, and detected. Light pulses (red beam) travel along the vacuum tube in both directions and interact with the atoms (blue clouds) while they are in free fall.

Mode A: Maximum gradiometer drop time. *Atoms are dropped from locations z3 and z2 over 50 m and are detected at locations z2 and z1, respectively.*

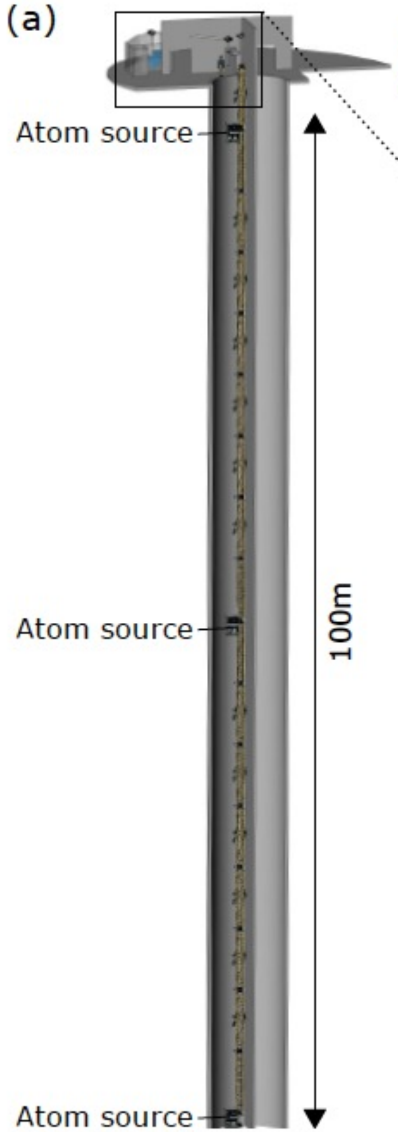
Mode B: Maximum gradiometer baseline. *Atom clouds are launched for several meters from z1 and z3 and then detected at their initial launch positions.*

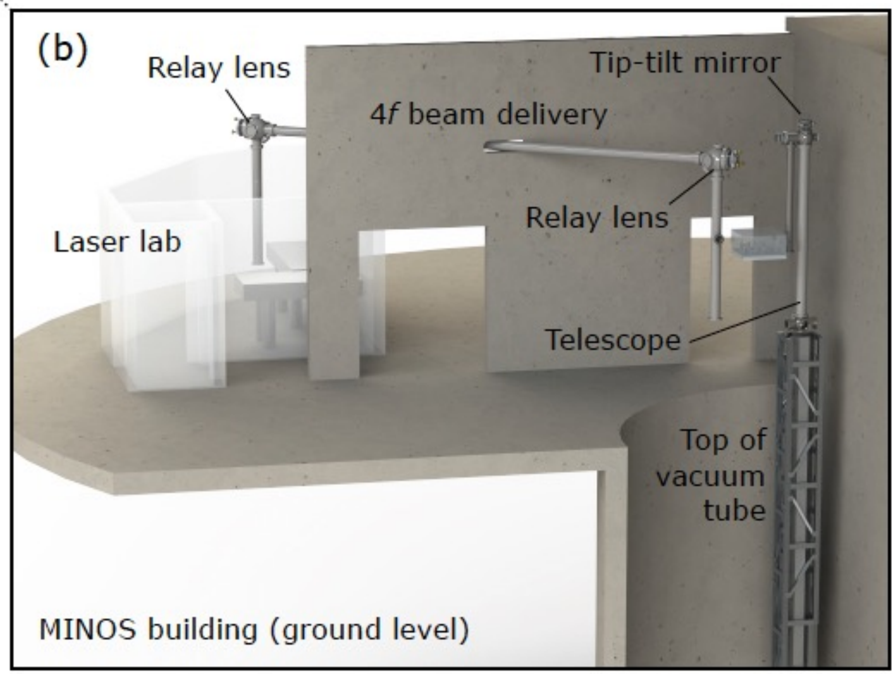
Mode C: Gravity gradient noise (GGN) characterization. *All three sources can be used with short launches in order to explore Newtonian noise variation along the baseline.*

Mode D: Dual-isotope launch. *In this alternative dark matter detection mode two Sr isotopes (blue and orange clouds) are simultaneously launched from z1.*

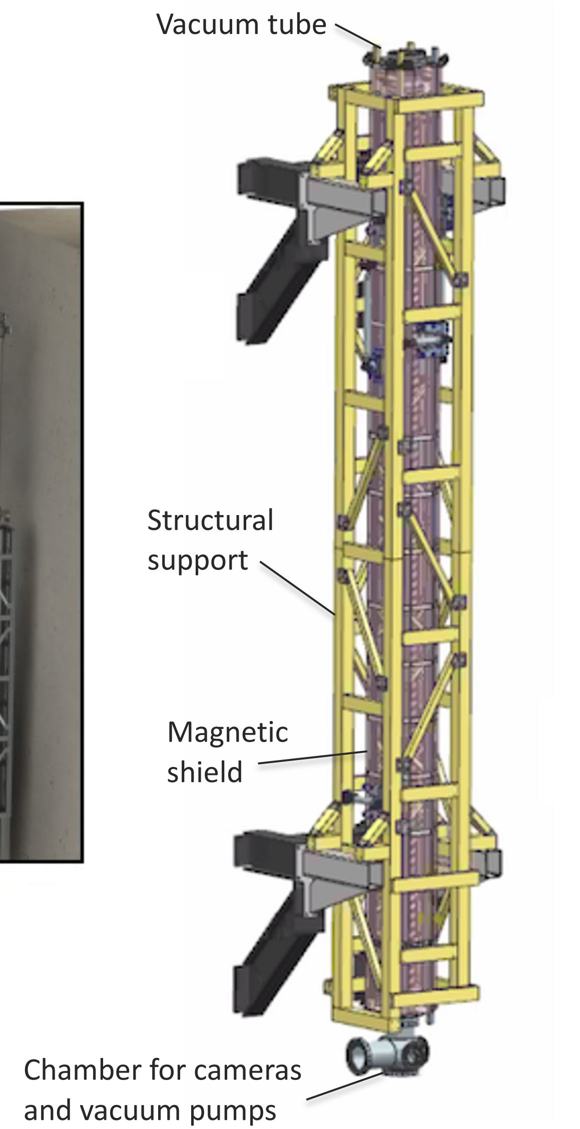
For additional information, see 2021 publication linked at magis.fnal.gov.

Systems overview

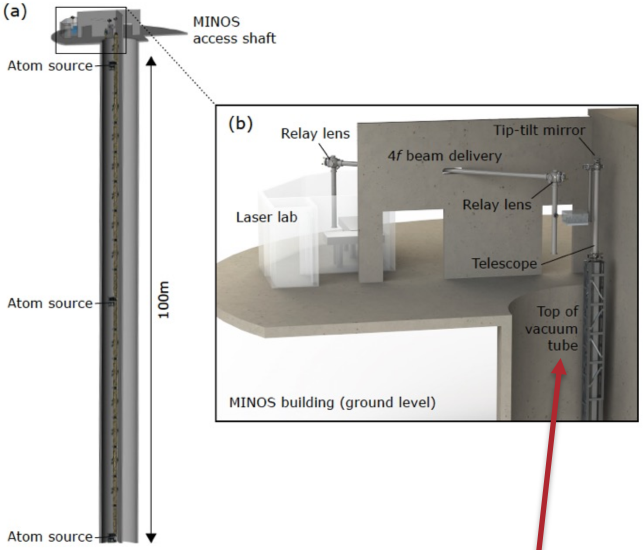




In shaft:
3 atom sources
17 modular sections
1 mirror at bottom
2 vacuum roughing stations



Location – MINOS building



Laser lab to be built behind this wall.

Ground level of MINOS building.

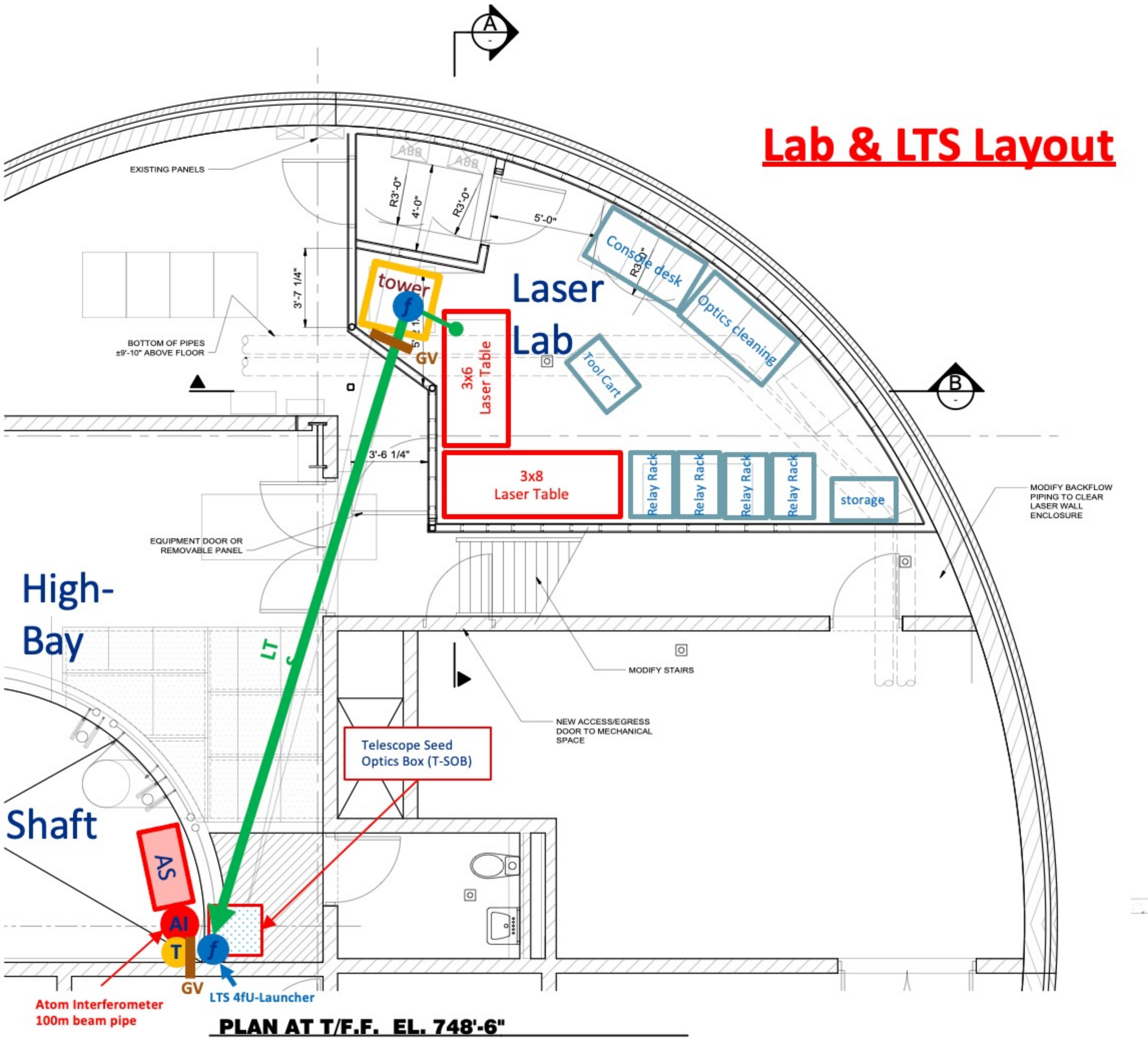
Location – shaft in MINOS building

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

Location – shaft in MINOS building

The view from the top, perspective aligned with experiment location.

Laser lab and laser transport system layout



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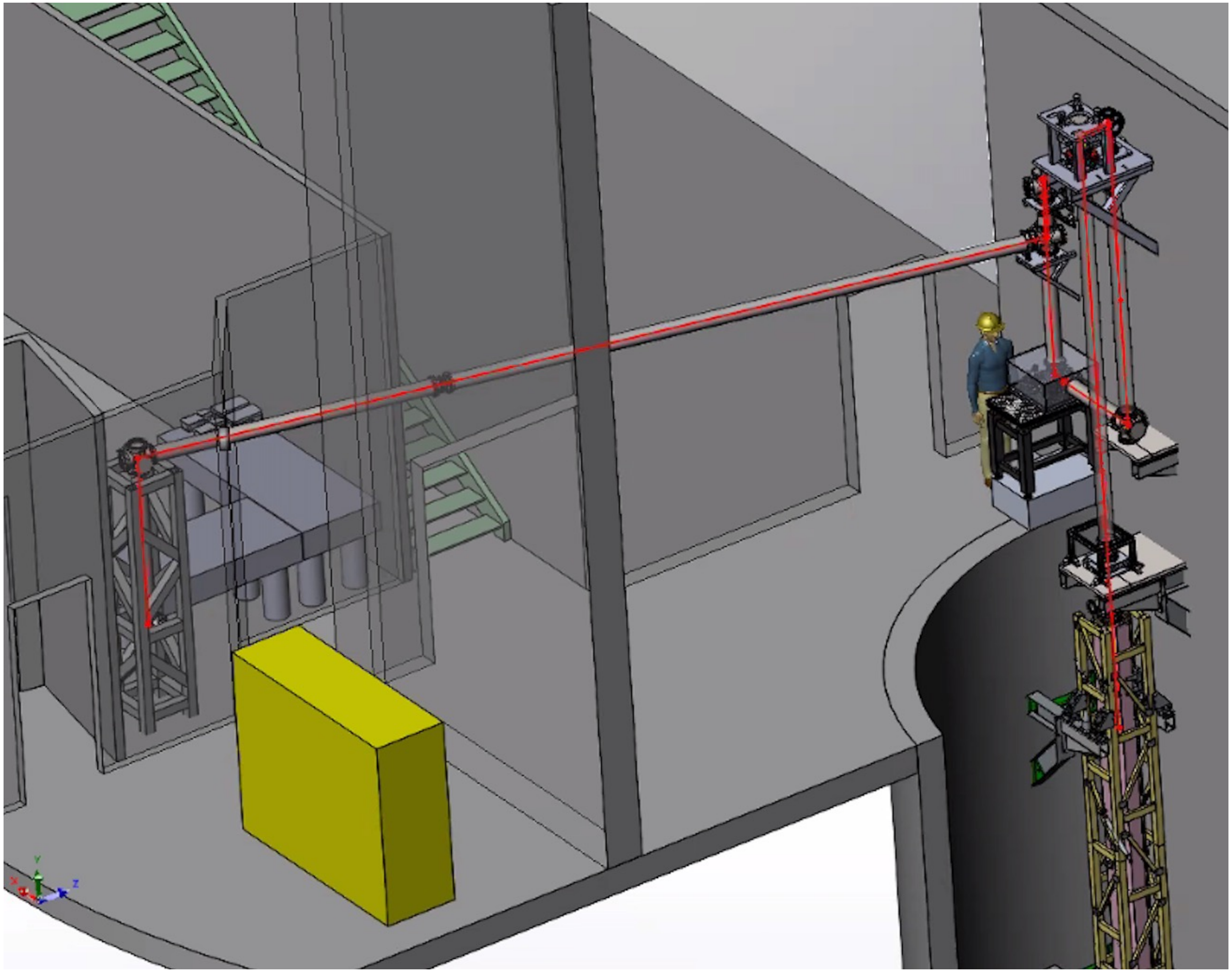
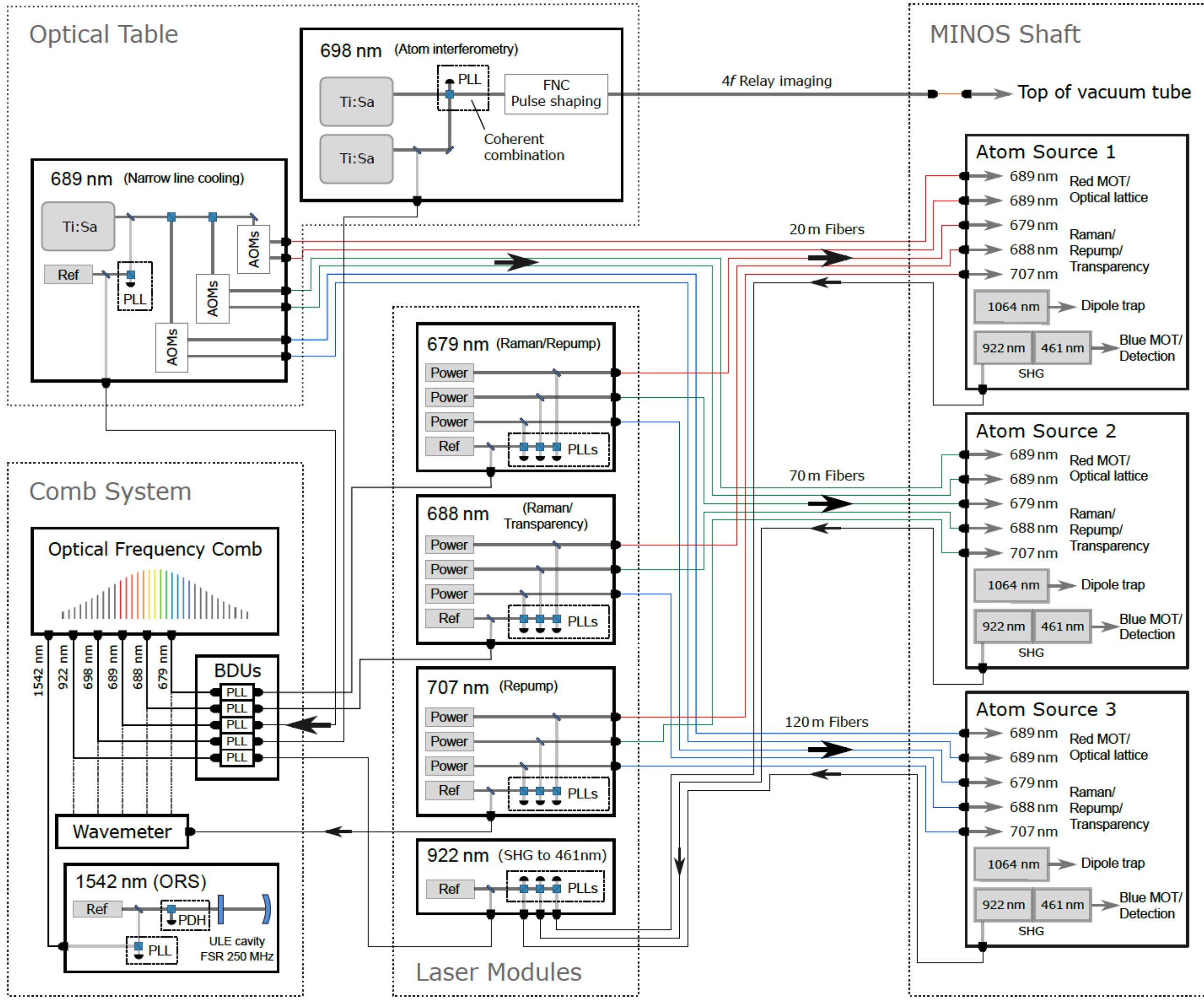
Laser lab and laser transport system layout



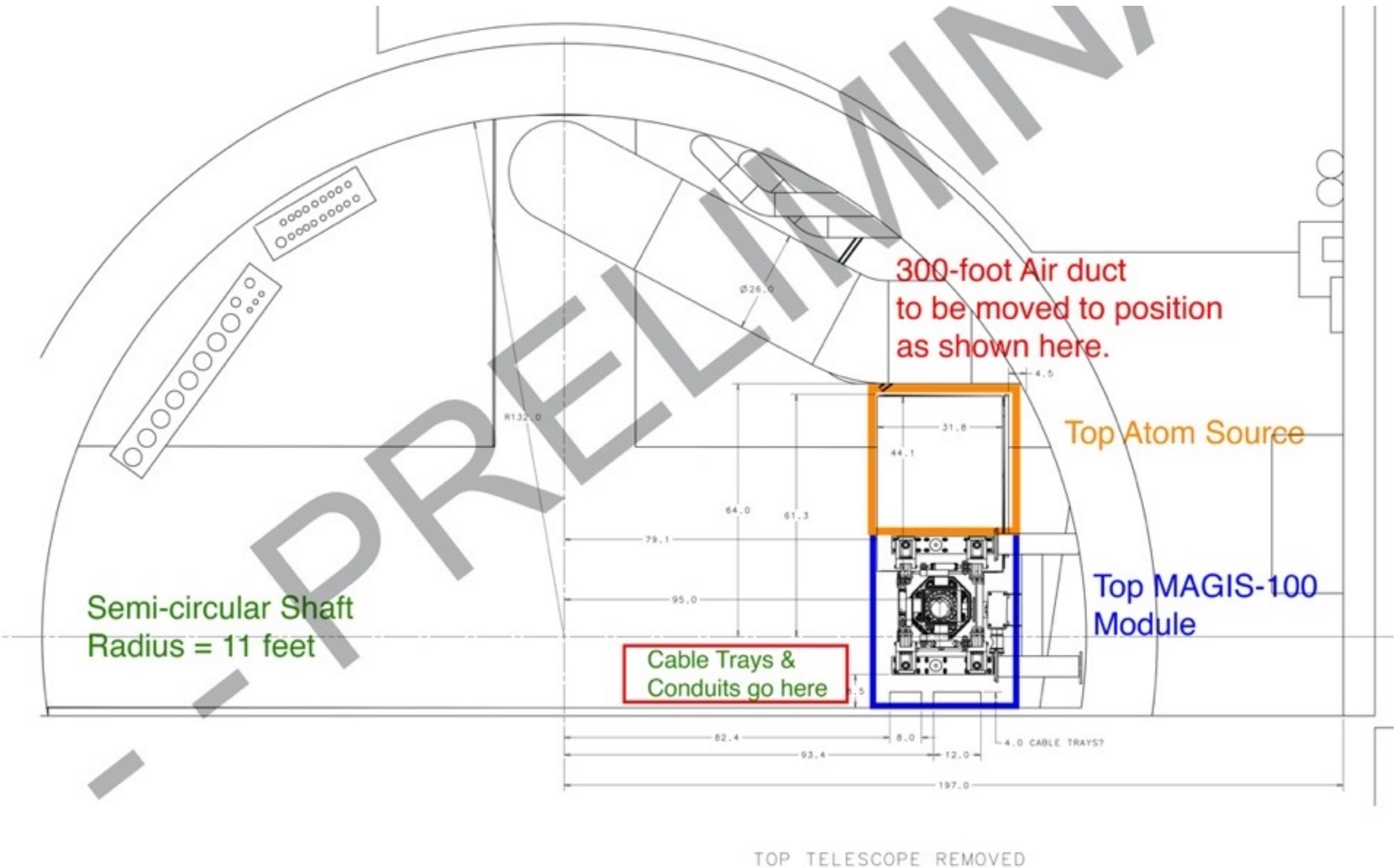
Laser system schematic

Complex laser system contains:

- 5 laser-controlled areas (LCA's)
- 22 lasers
- 8 wavelengths



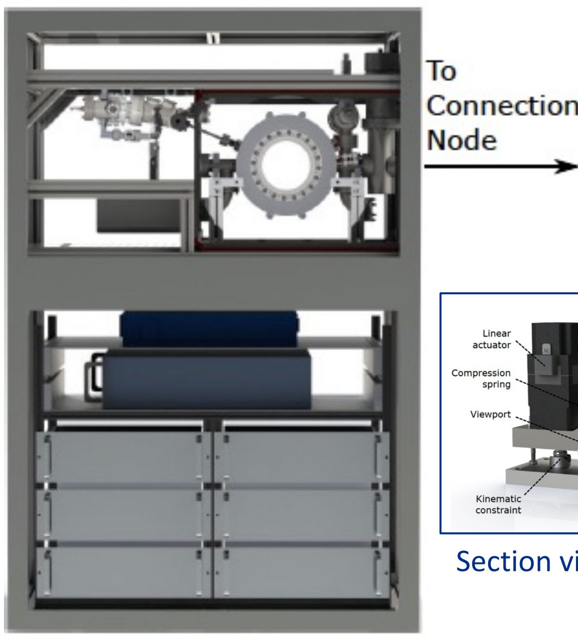
Component layout in the shaft



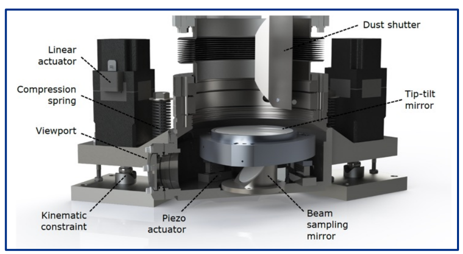
Plan view of the experiment in the shaft.

Atom sources

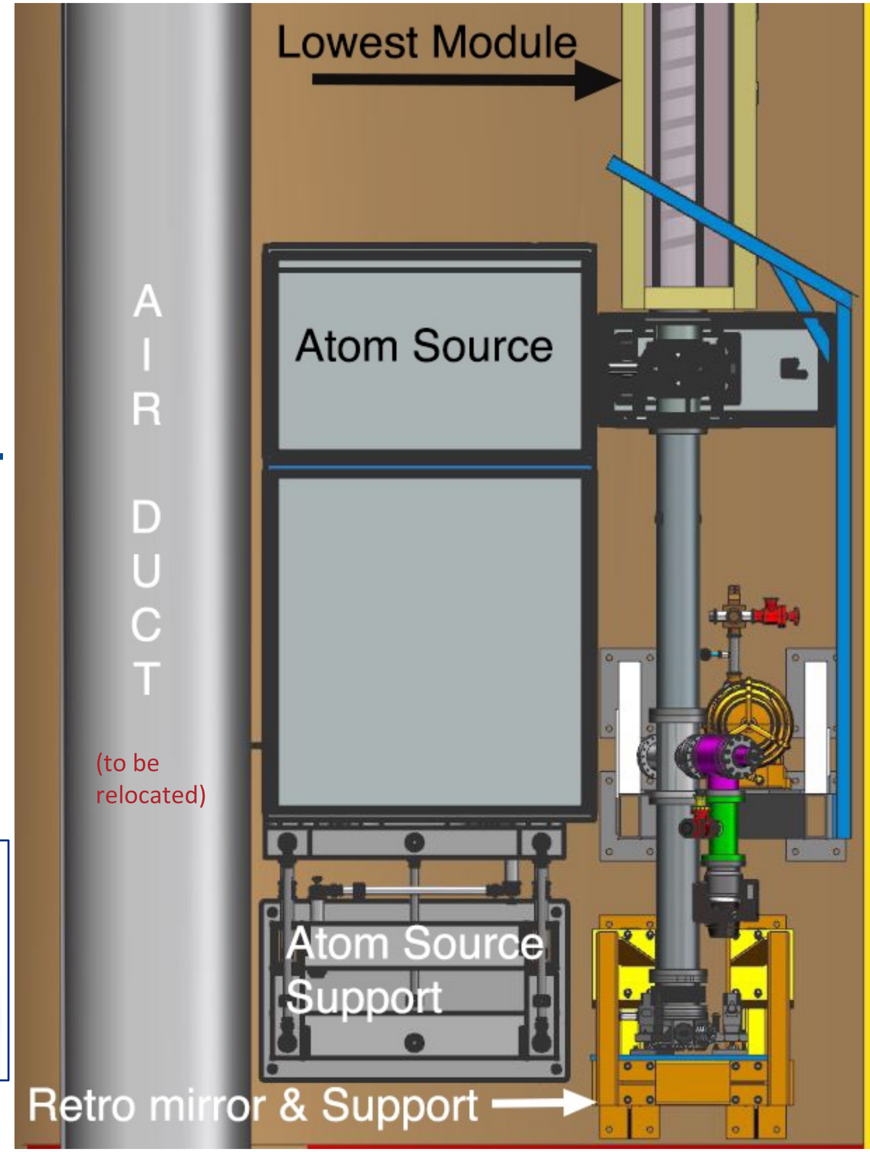
- Up to 1,000lb weight.
- Top, middle, and bottom of shaft.
- Last components installed.
- Approximate cost $1M each.
- Designed and built at Stanford University.
- Transportation will be planned and tested.



Atom source detail.

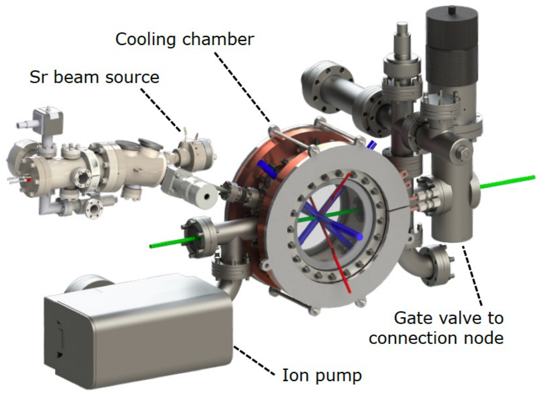


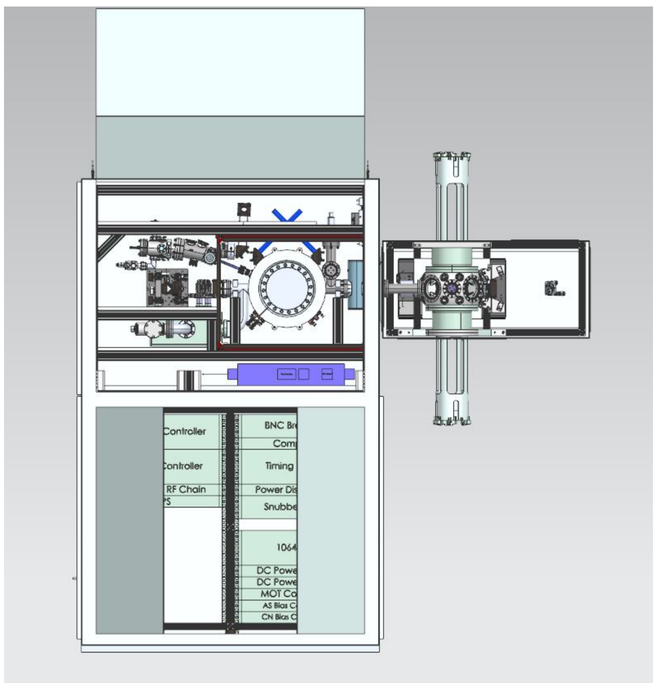
Section view of retro mirror.

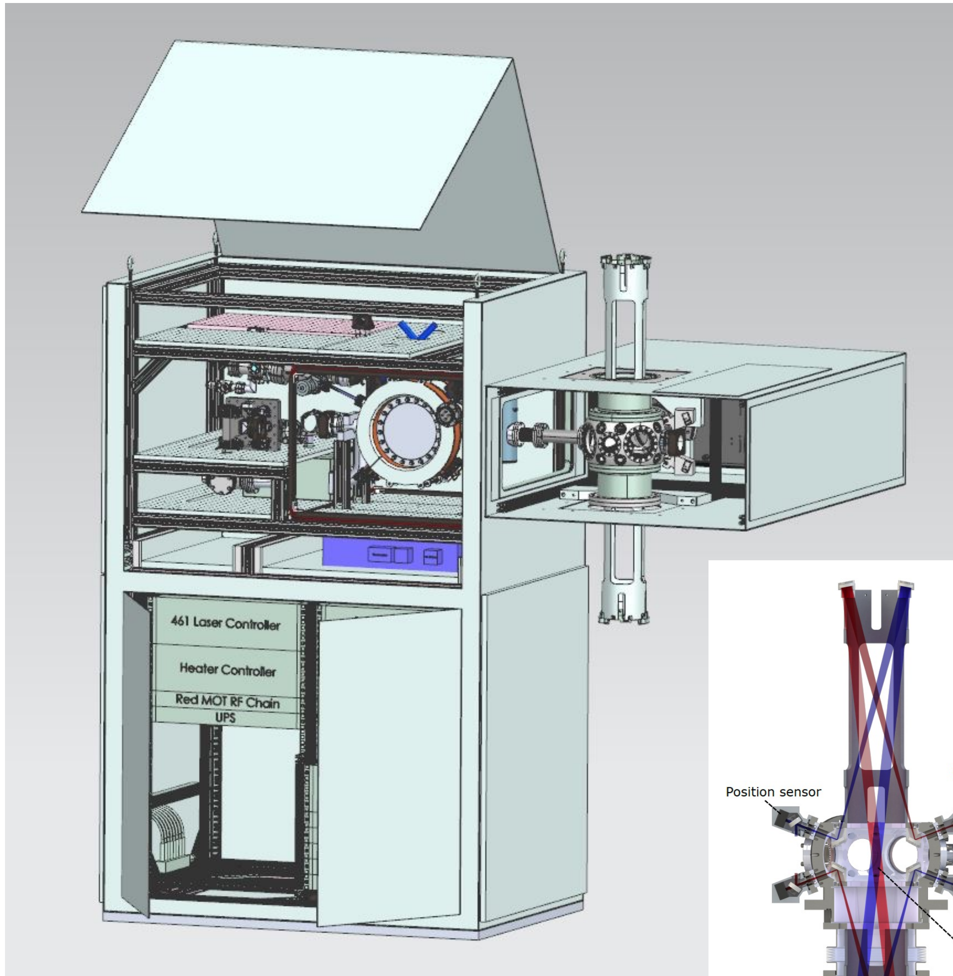


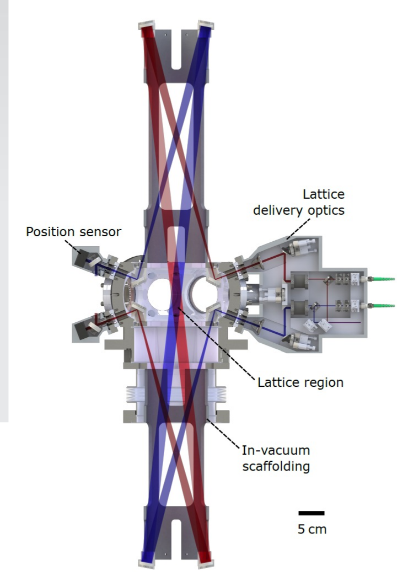
Bottom atom source, atom source connection node, vacuum rough pumping station, and retroreflective mirror shown.

Atom source details





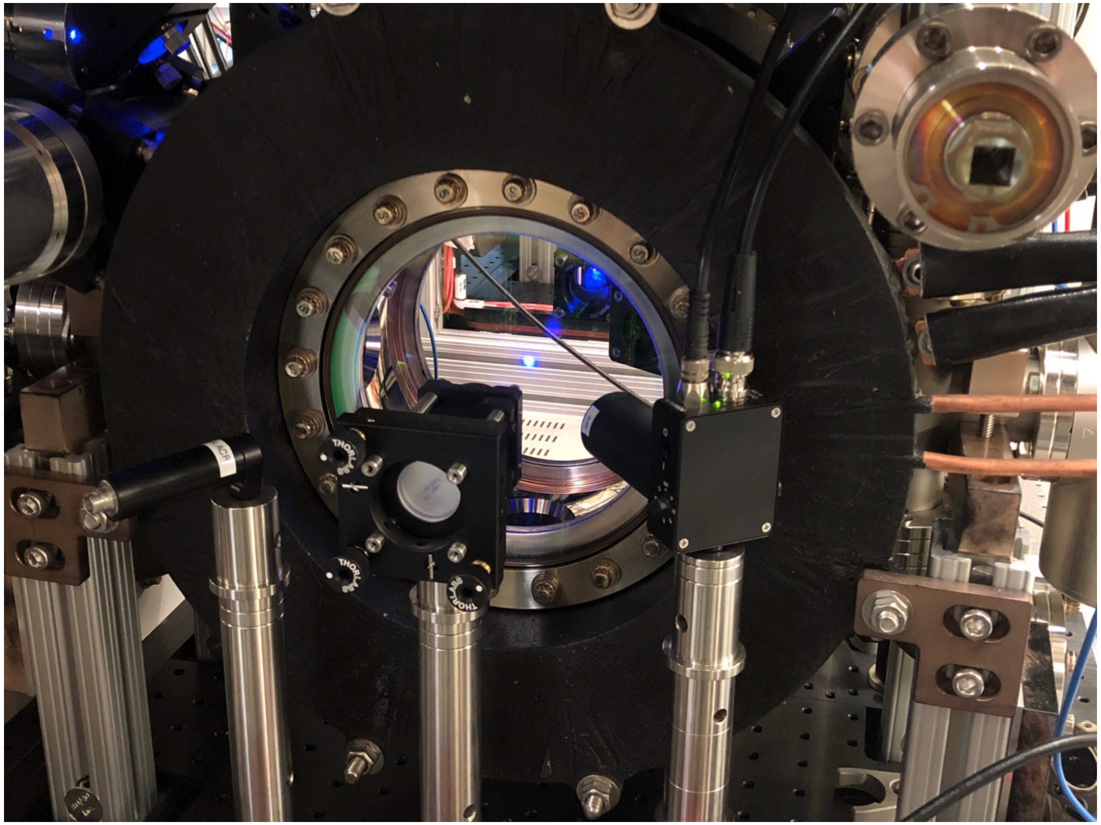




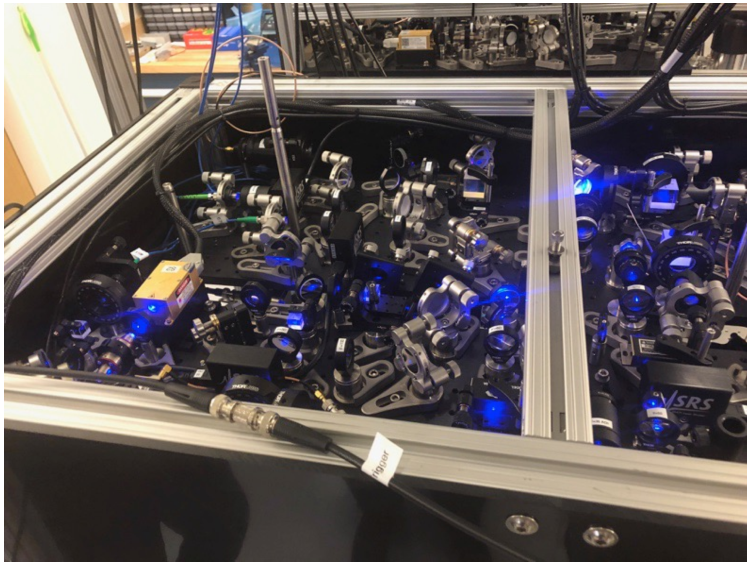
Views inside the atom source enclosure and adjacent atom source connection node.

In-vacuum scaffolding extends into modular section vacuum tubes.

Prototype atom source at Stanford University



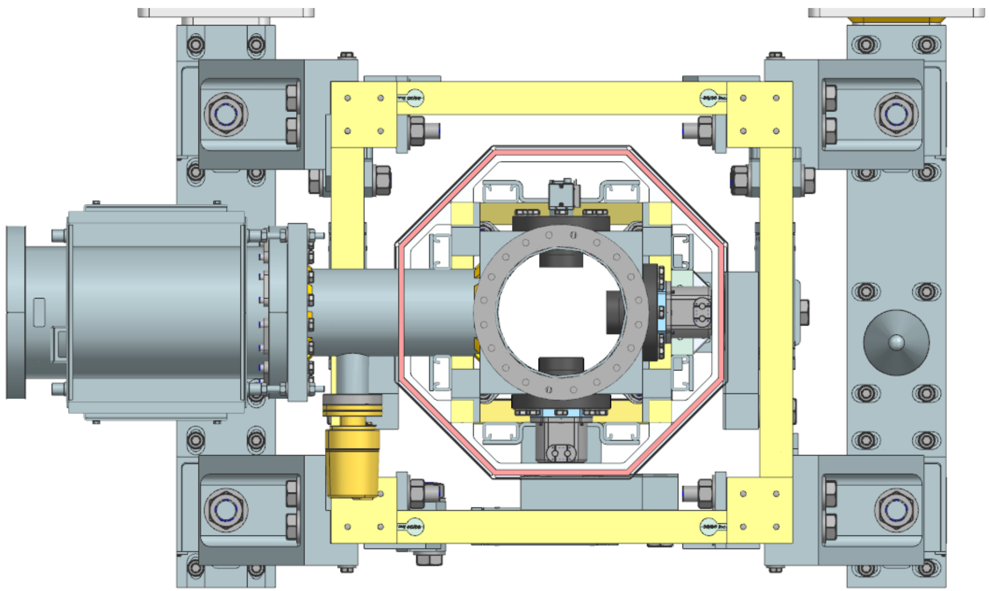
One billion strontium (Sr) atoms are captured in the blue dot in the magneto-optical trap (MOT).



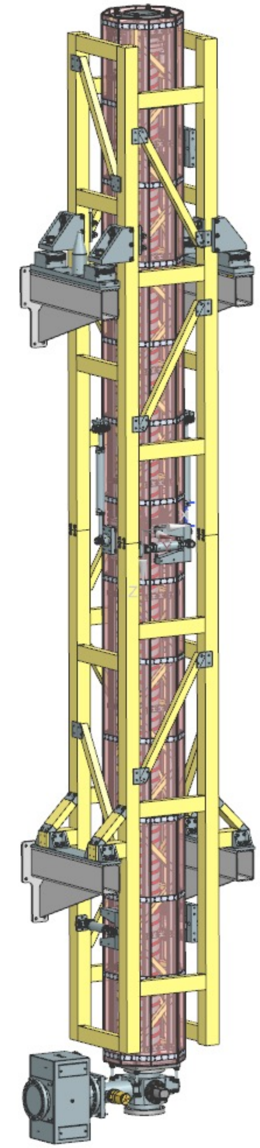
Optics in the top layer of the atom source.

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.

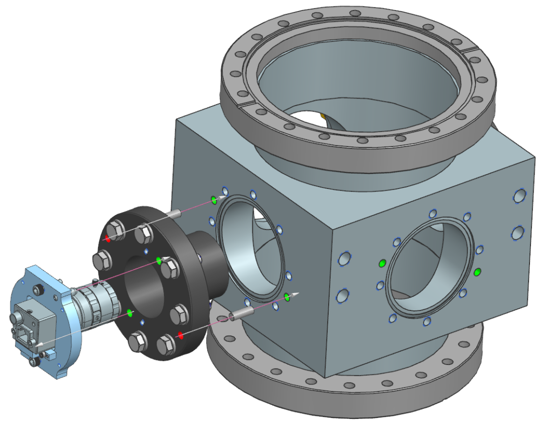


Cross section view.

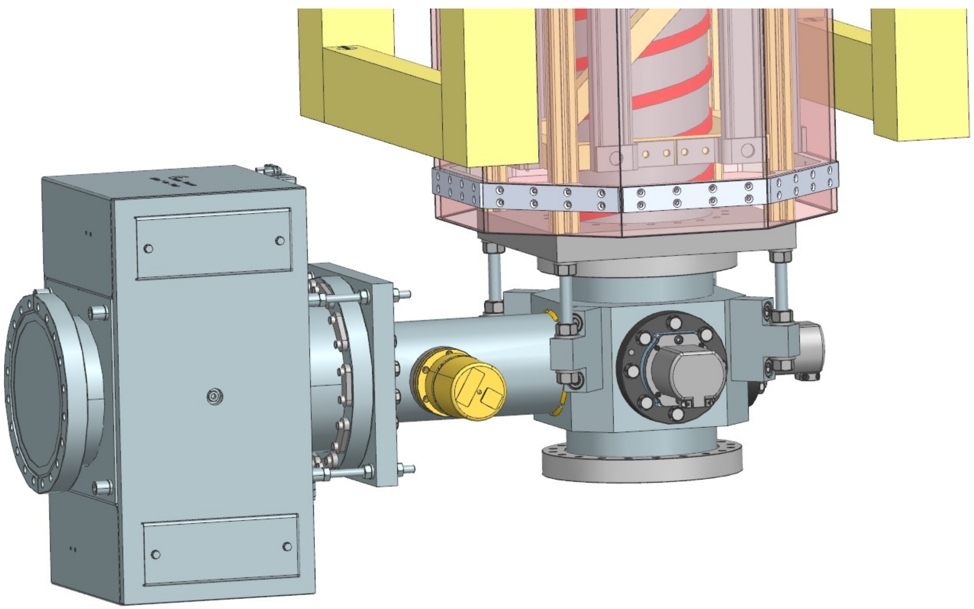


Single module with adjustable supports.

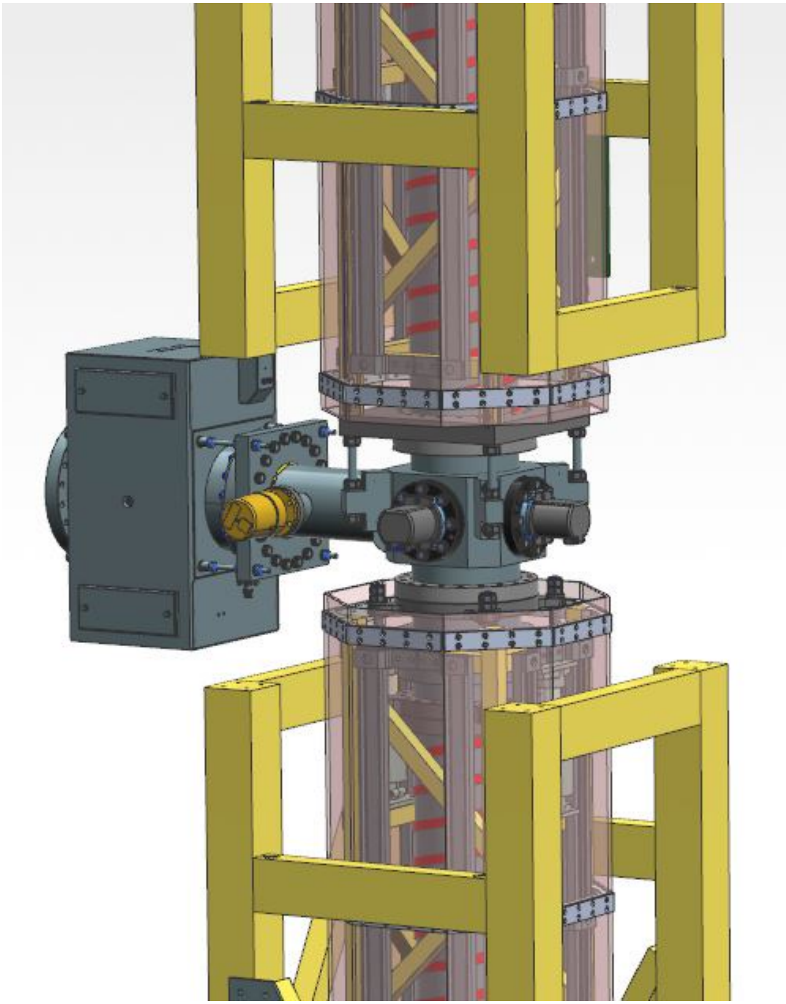
Modular connection nodes



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



Detail of modular connection node.



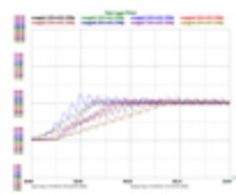
Two modules connected.

Ultra high vacuum (UHV)

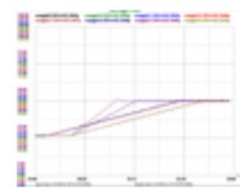
- Required pressure e-11 Torr or better for interferometry region.
- Dual pumps (ion pump + titanium sublimation pump OR non-evaporable getter pump + small ion pump) will be on each modular section.
- Vacuum bake required to reach this pressure.
- Minimally magnetic 316L stainless steel tubes and non-magnetic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

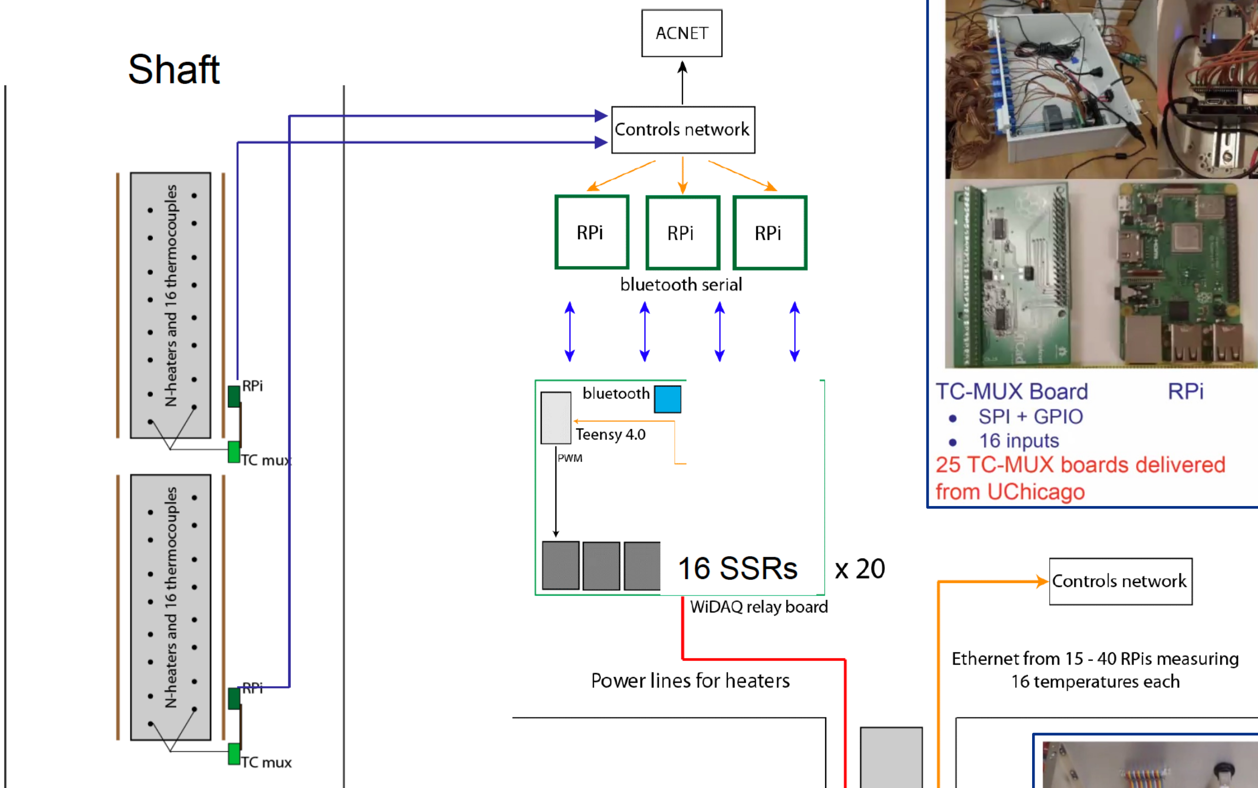


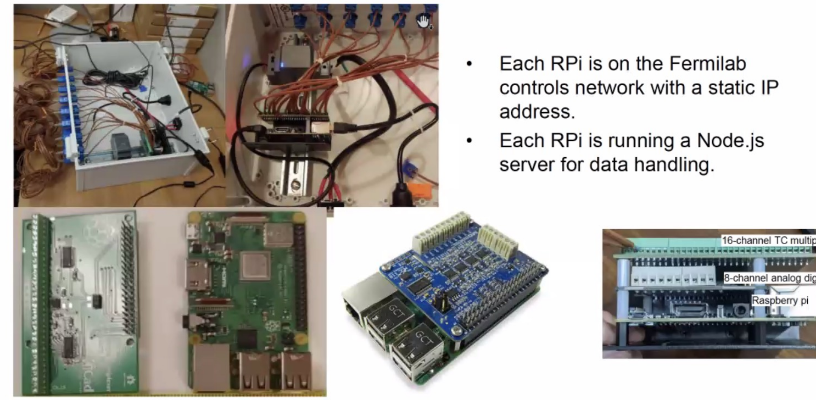
Temperature ramps SSR8-SSR15

Excerpt from bake test e-log.

6” OD vacuum tubes.

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

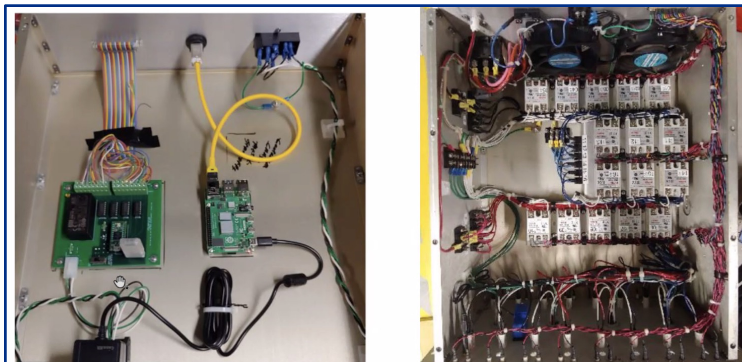
25 TC-MUX boards delivered from UChicago

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.

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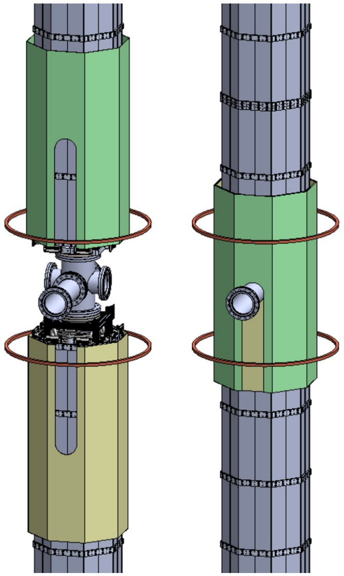
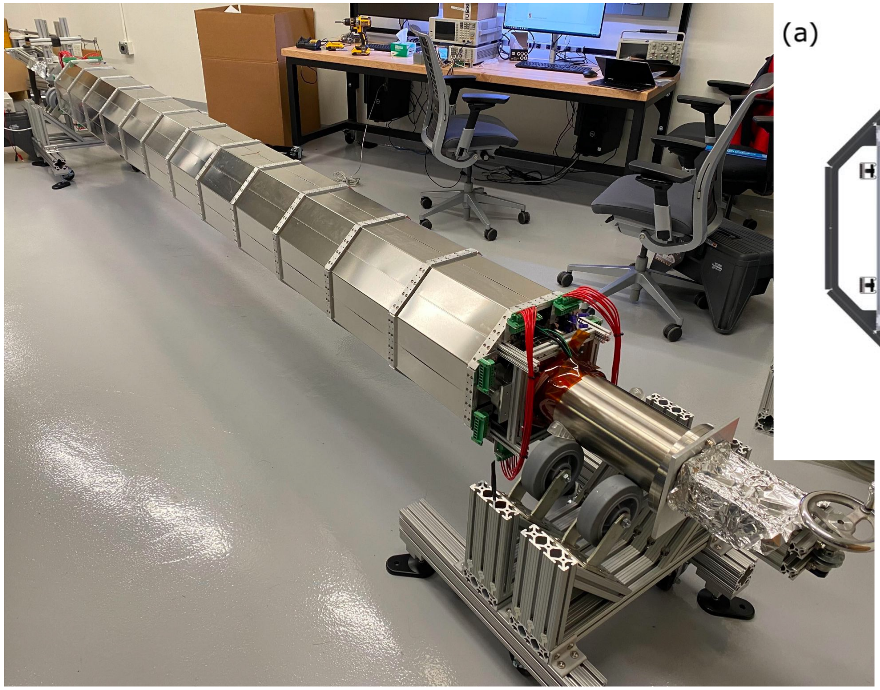
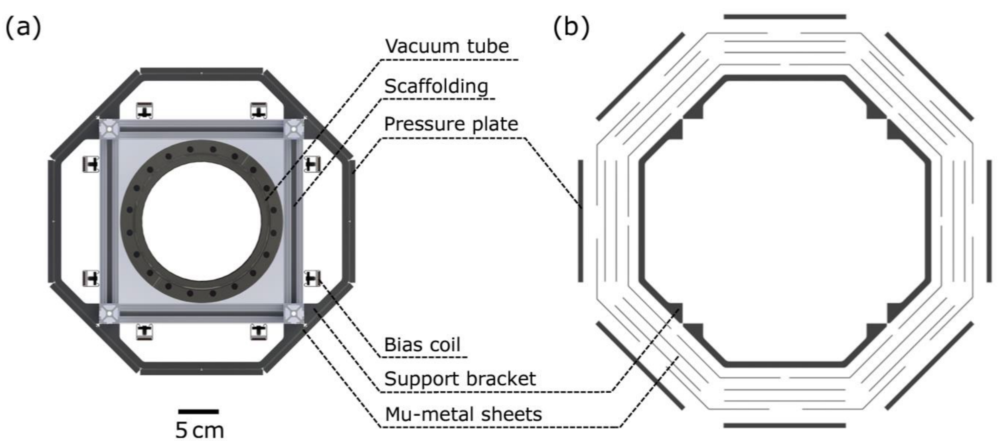
MAGIS-100

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.



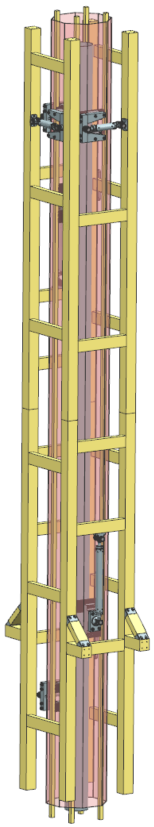


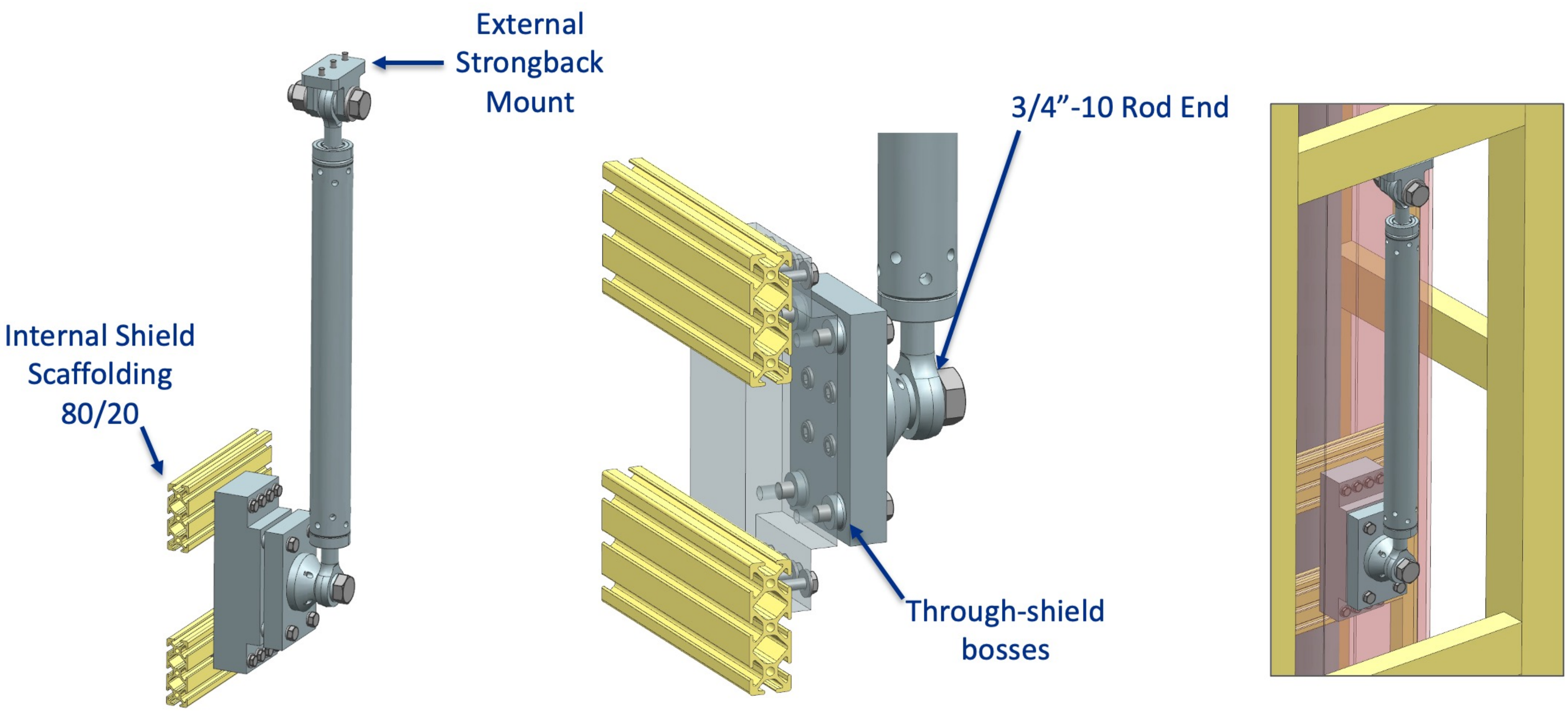


Left: Prototype section assembly at Stanford University 2022.
Above: Cross-section view of magnetic shield and bias coils.
Above right: Magnetic coupler and additional coils will be placed around modular connection nodes.

Structural challenges

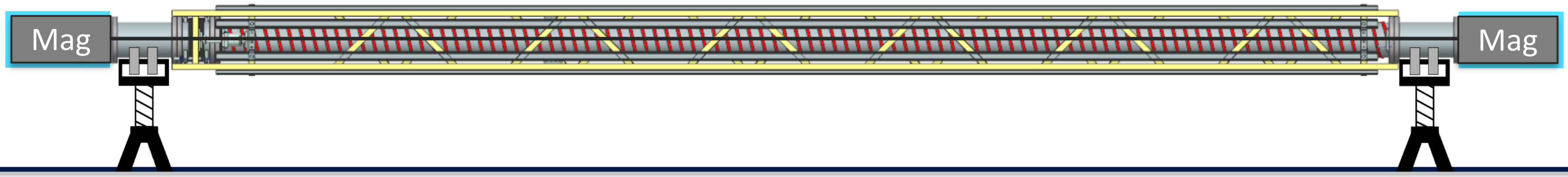
- **Adjustable supports required for alignment.**
- **Must minimize penetrations in magnetic shield.**
- **Six-strut system will be used for positioning modular sections inside frames.**



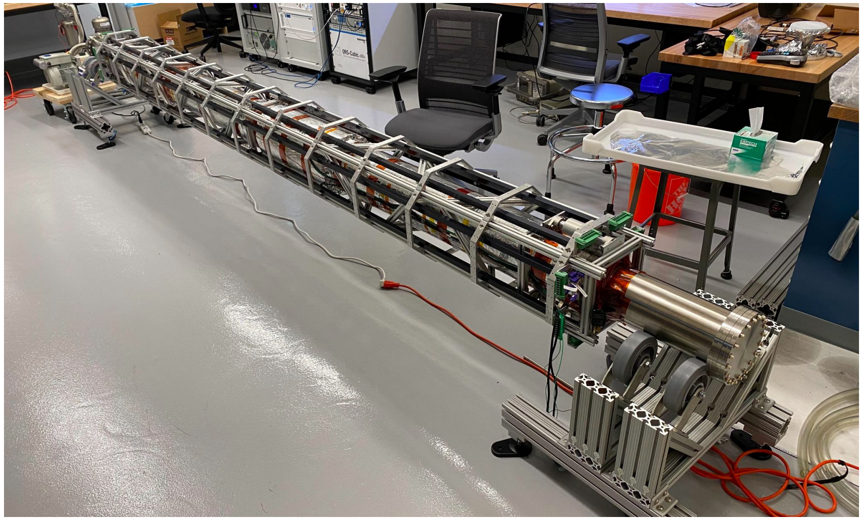


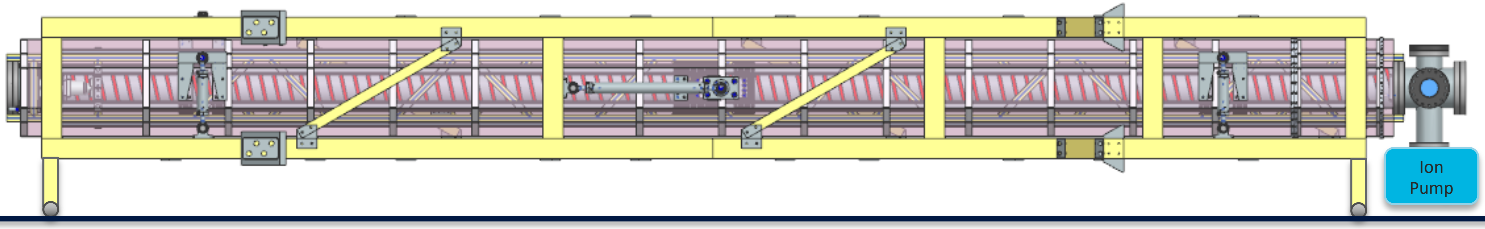
Modular section assembly

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



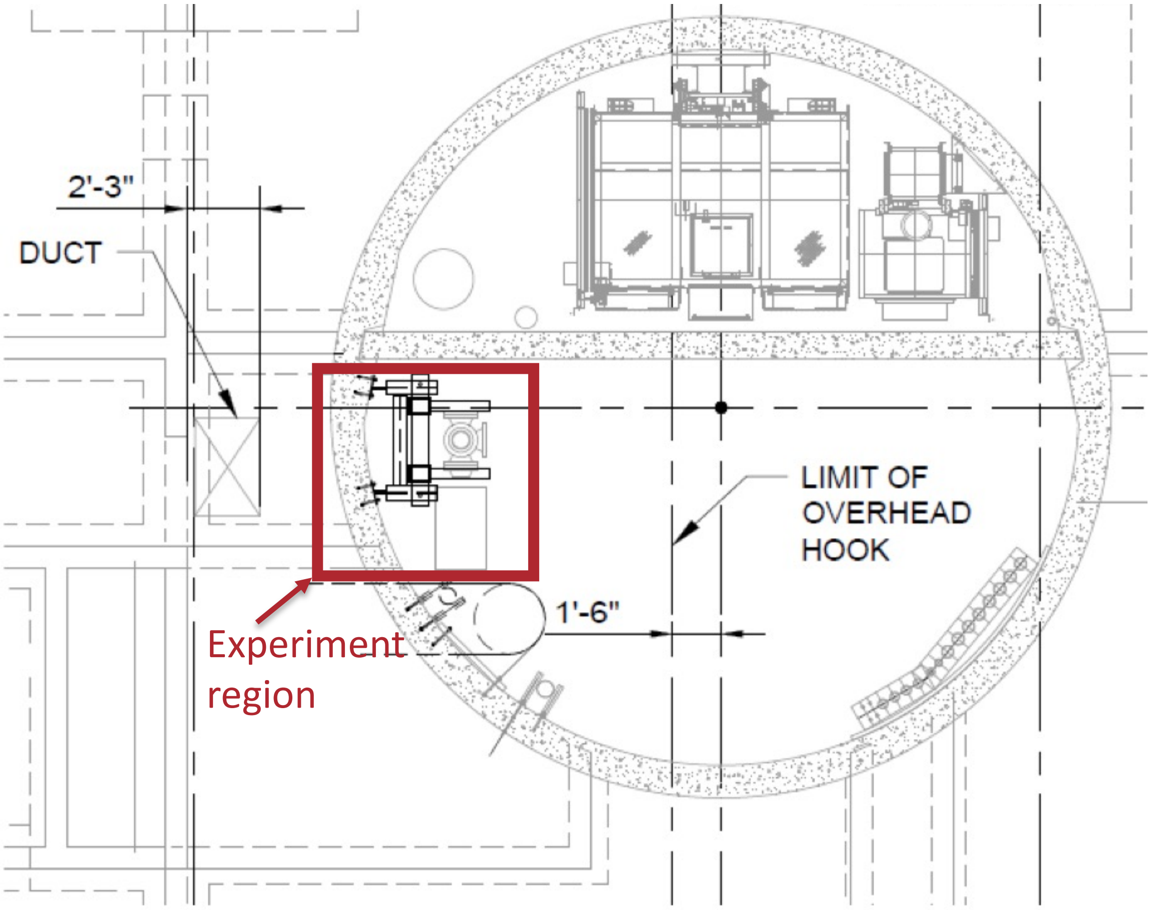
Above: Schematic of assembly on rotisserie fixture.
Right: Prototype assembly at Stanford University.
Below: Schematic of complete assembly.





Installation challenges

- **Vertical installation – the most obvious challenge.**
- **Added complexity – overhead crane does not reach experiment region.**
- **Must do infrastructure work prior to experiment installation.**
  - Electrical
  - Water
  - Air



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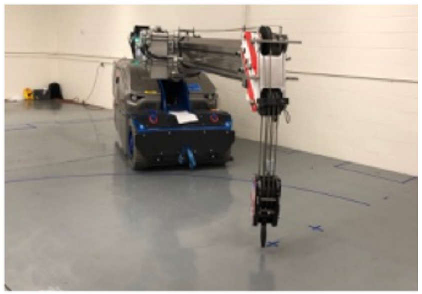
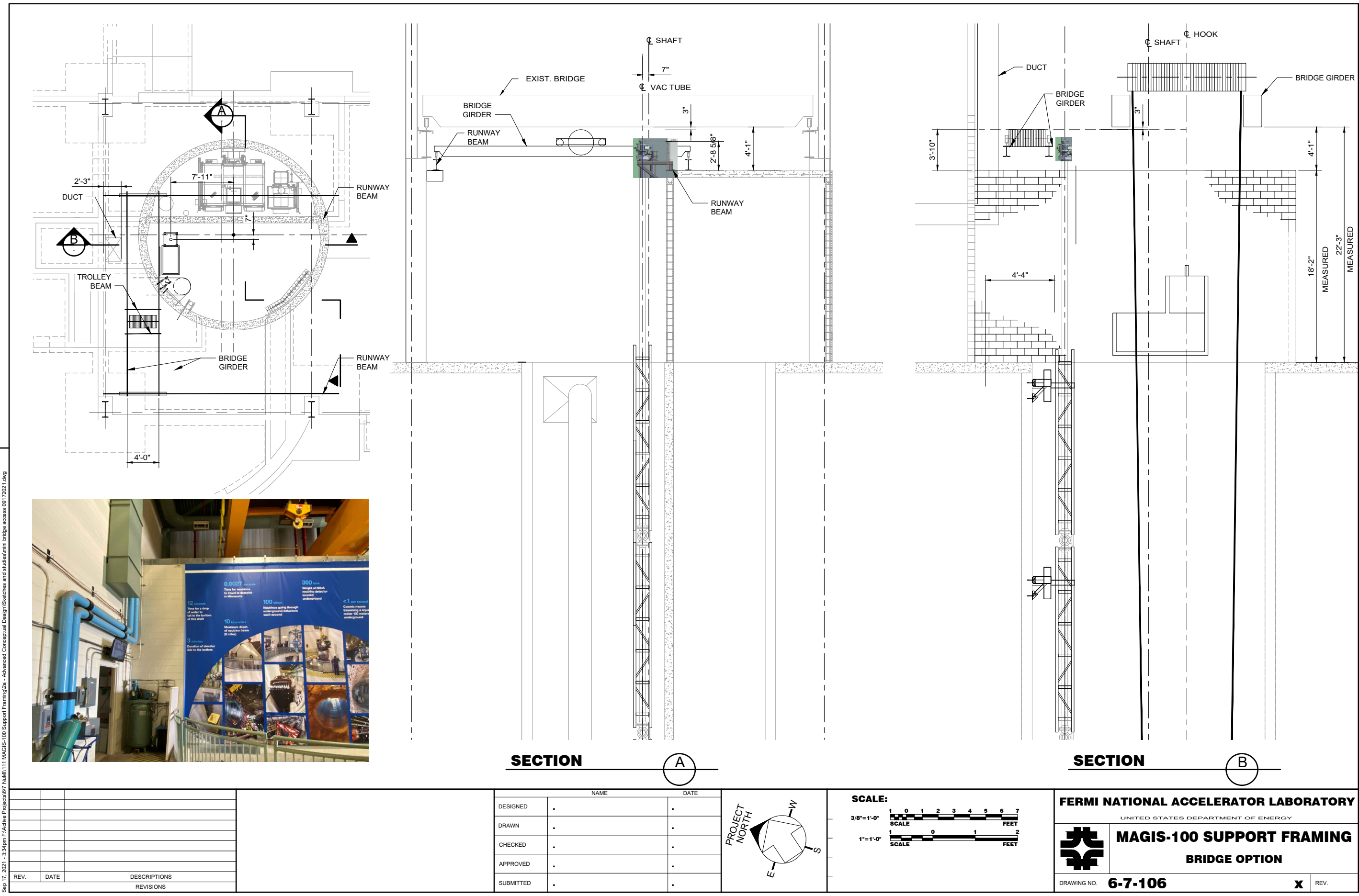
Crane challenges

- Mobile crane would be tight fit and requires floor modifications.
- Plan to build secondary bridge crane under the existing crane.



Mobile crane test.

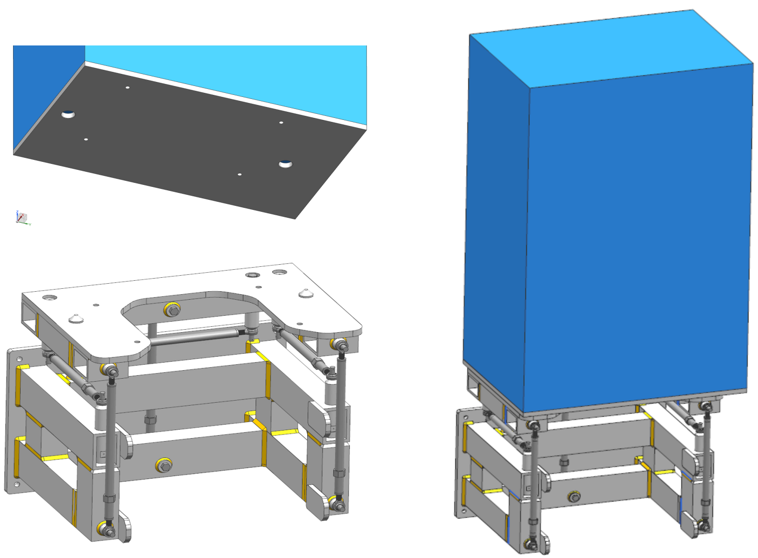
Crane unspooling into shaft.



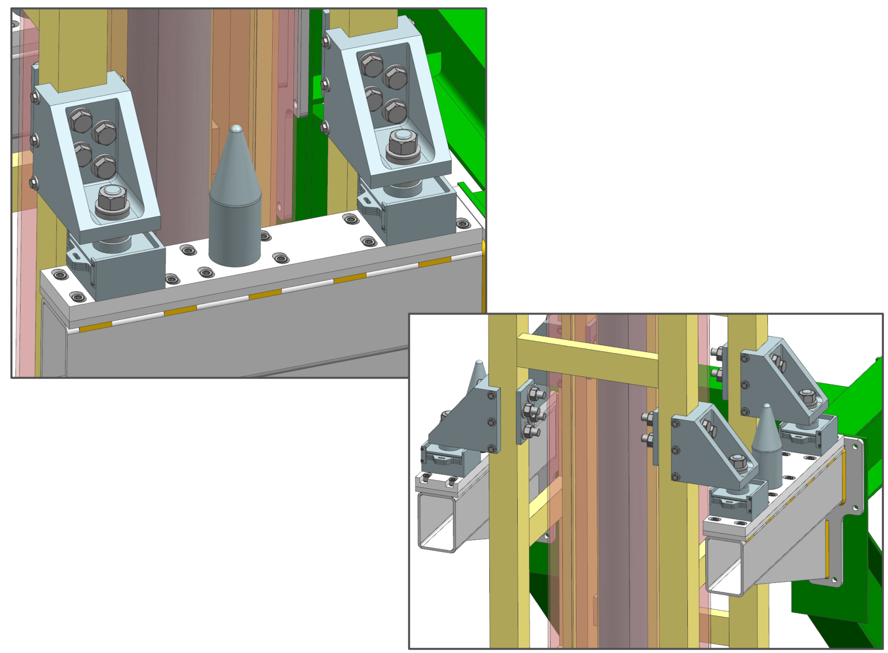
Secondary bridge crane proposal.

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.



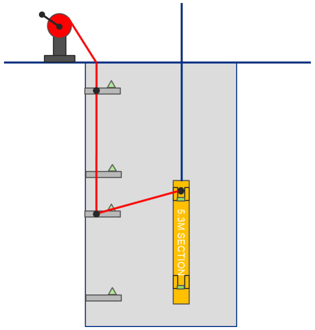
Atom source and adjustable wall support.

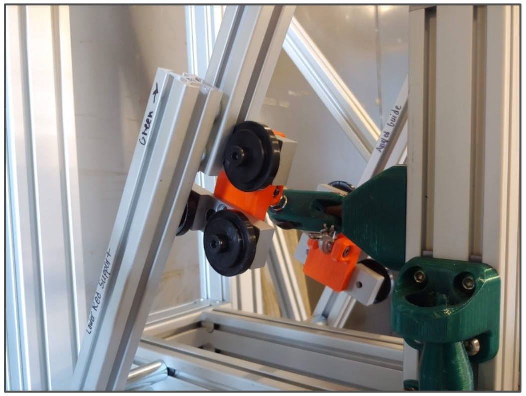


Modular section adjustable wall support.

Component installation concepts

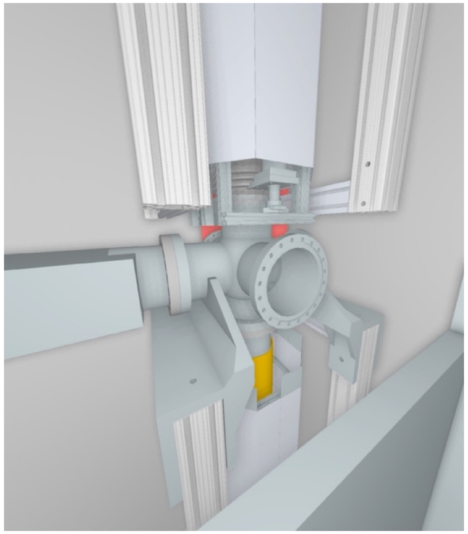
- **Guiding Sections into place from the personnel basket**
  - 5.2m sections supported from secondary crane
  - Individuals in basket guide sections
- **Use of a cantilever lifting fixture on the main crane**
  - No secondary crane
  - Load must be unhooked remotely
  - Basket not in shaft during section positioning
- **Cable-guide system**
  - 5.2m sections supported from secondary crane
  - Basket not in shaft during section positioning
- **Quad-rail trolley system**
  - 5.2m sections supported from secondary crane
  - Basket not in shaft during section positioning
- **Tilting ramp system**
  - 5.2m sections supported from secondary crane
  - Basket not in shaft during section positioning





Personnel access system

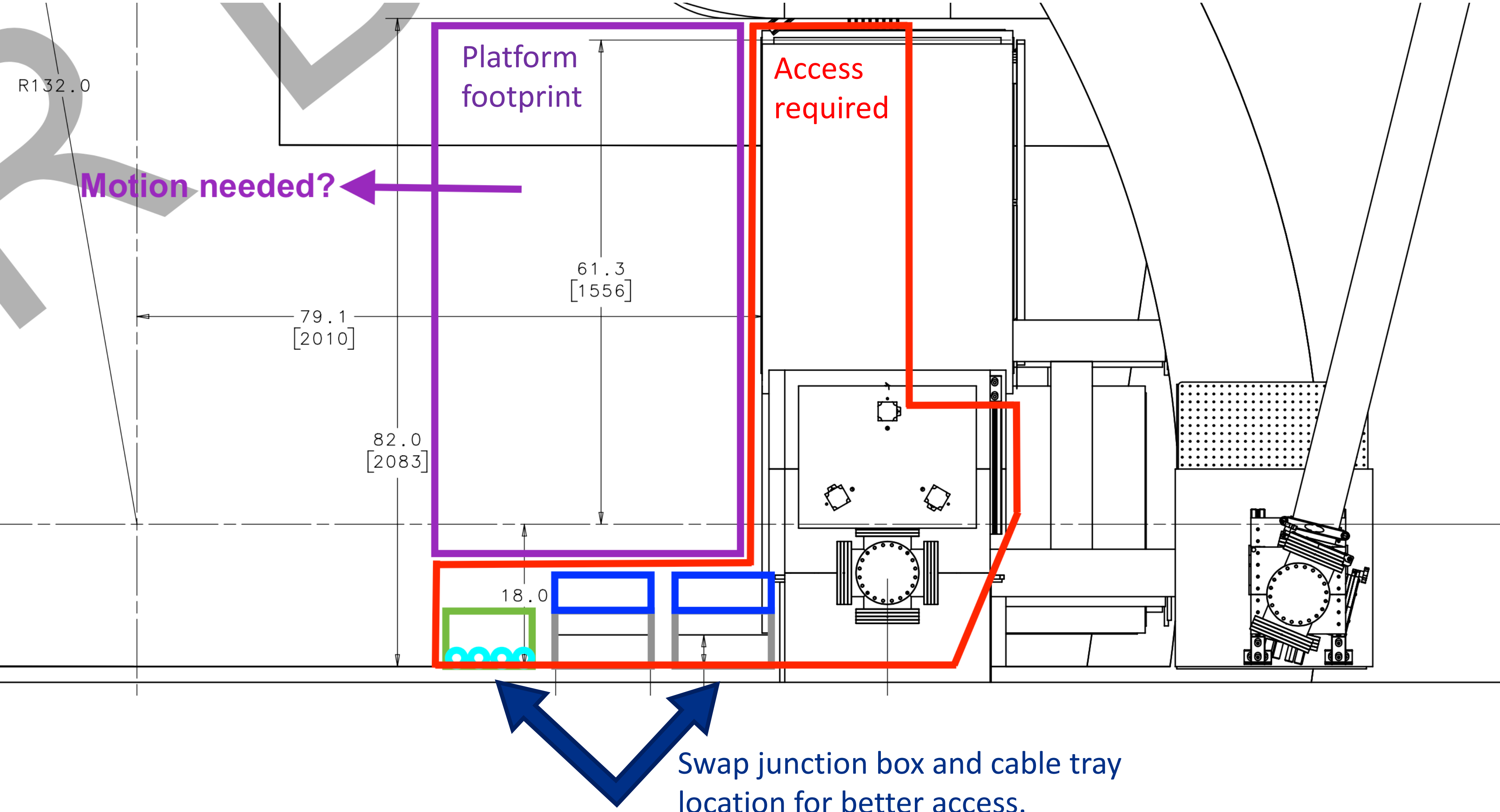
- Accessibility required from personnel basket or platform for installation, alignment, vacuum connections, pump down, bake, maintenance.
- Custom new cantilever or oversized basket required for proper placement along experiment if using crane.
- Independent scaffolding systems being investigated.
- Must position and stabilize basket while allowing emergency crane operation (method in development).
- Virtual Reality (VR) model can confirm if components are able to be reached from basket or if special tooling must be designed.


VR model image.


Existing personnel basket in use.


View from camera on top of personnel basket.

Personnel access challenges

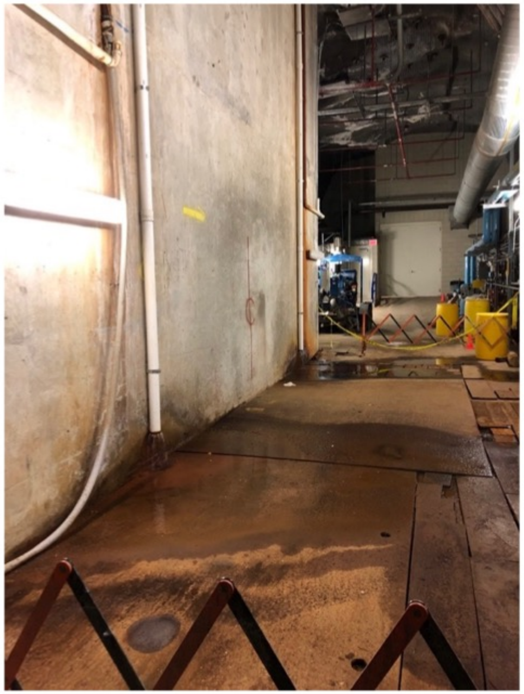


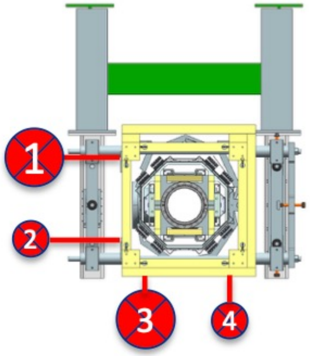
Alignment conceptual plan

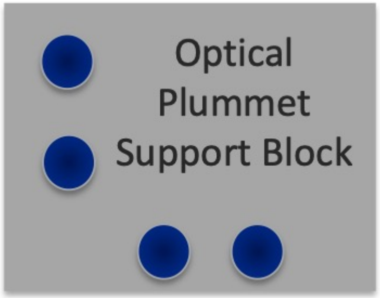
Optical plummets will be mounted at the bottom of the shaft to achieve required alignment.

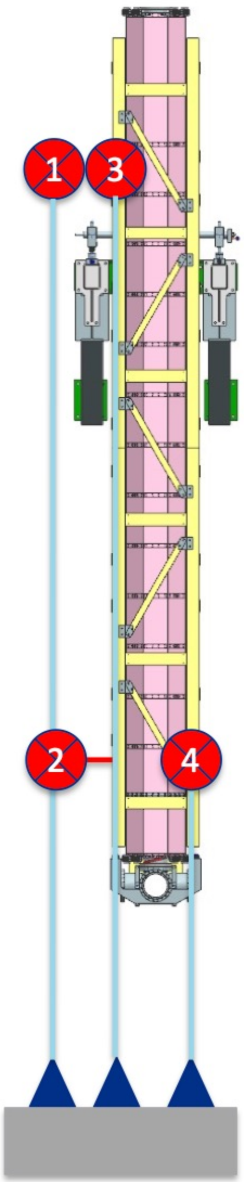
- **Mounting base must be sturdy.**
- **Bottom of shaft has metal plates which will flex and is also a "stay clear" zone. Original plan was to use concrete block.**
- **Consider if mounting base to elevator wall would work better.**

Details still developing.









Fermilab MAGIS-100 Collaborators

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Questions?

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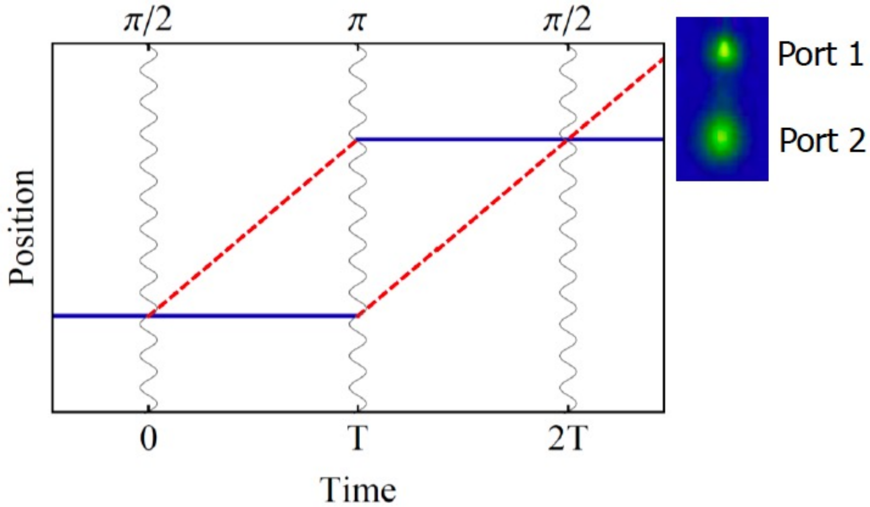
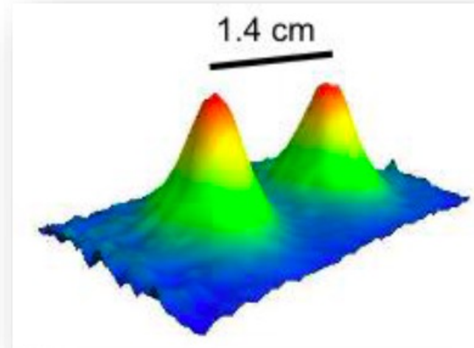
Atomic interference at long interrogation time



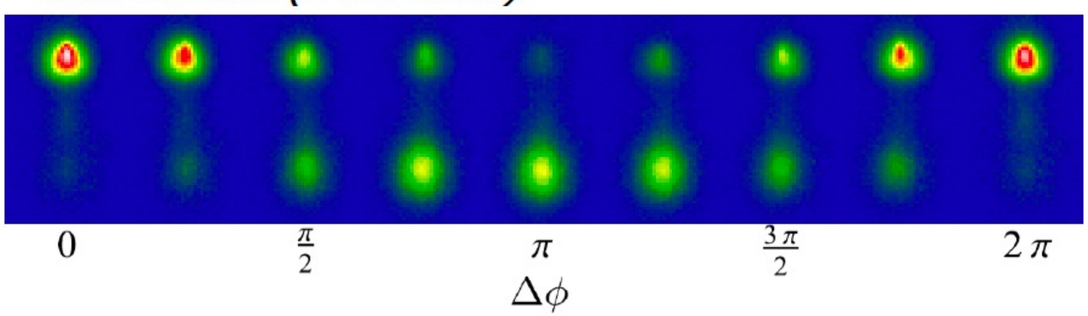
2T = 2.3 seconds

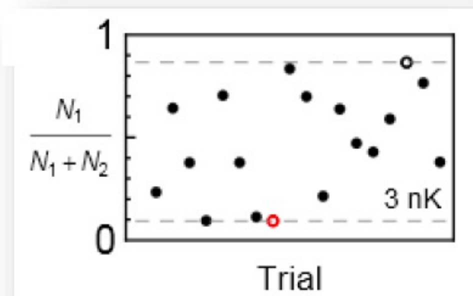
1.4 cm wavepacket separation



Wavepacket separation at apex (this data 50 nK)

Interference (3 nK cloud)





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Slide courtesy of Jason Hogan

Dickerson, et al., PRL **111**, 083001 (2013).

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