Designing the MAGIS-100 Vertical Vacuum System

OLAV-VI: 6th Workshop on the Operation of Large Vacuum Systems 2024

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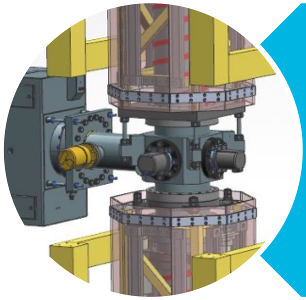
Overview

Experiment overview, layout, and site photos

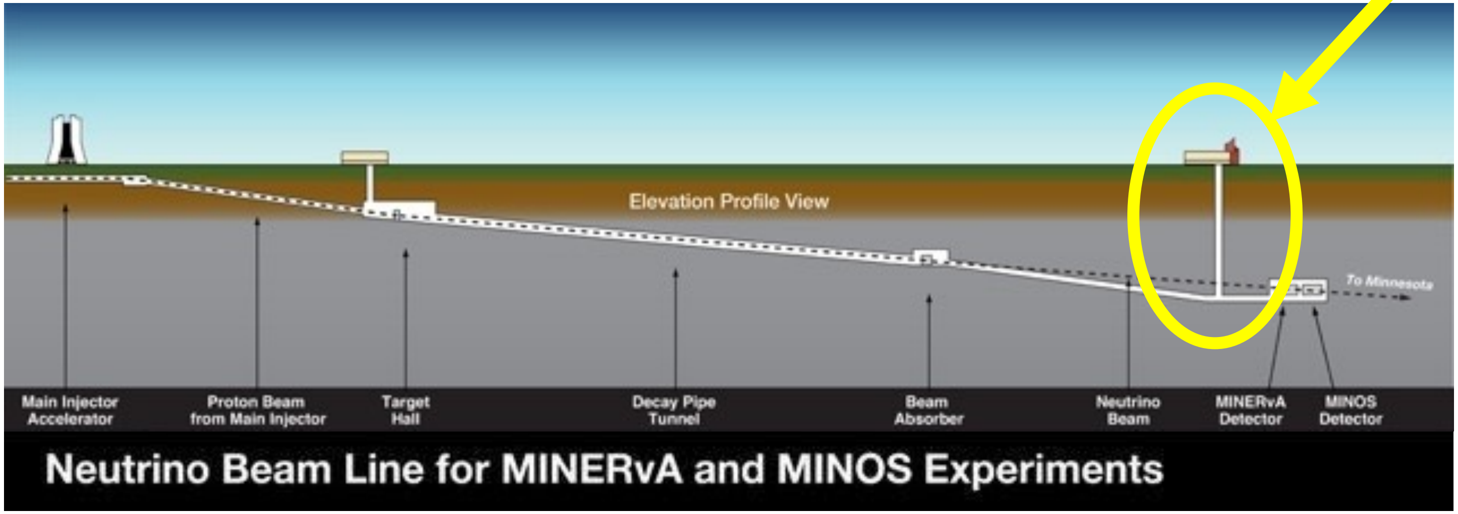


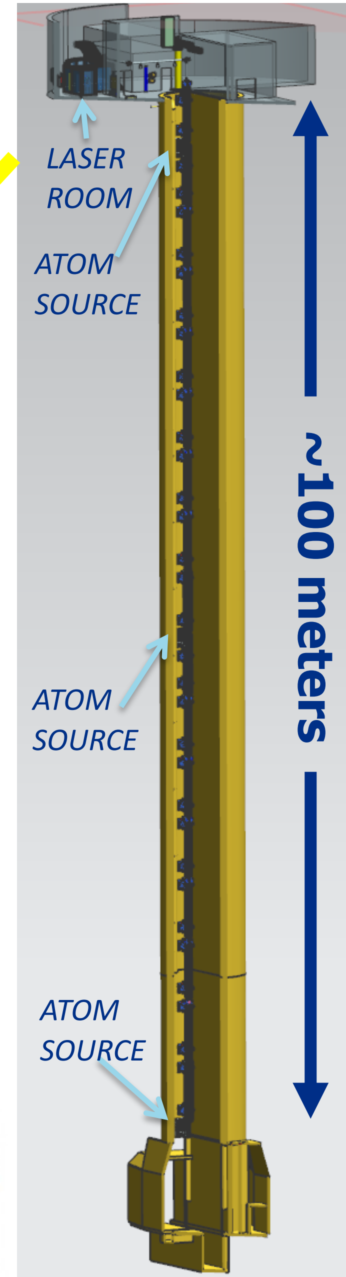
Vacuum system requirements

Challenges in vacuum system design, assembly, and installation

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

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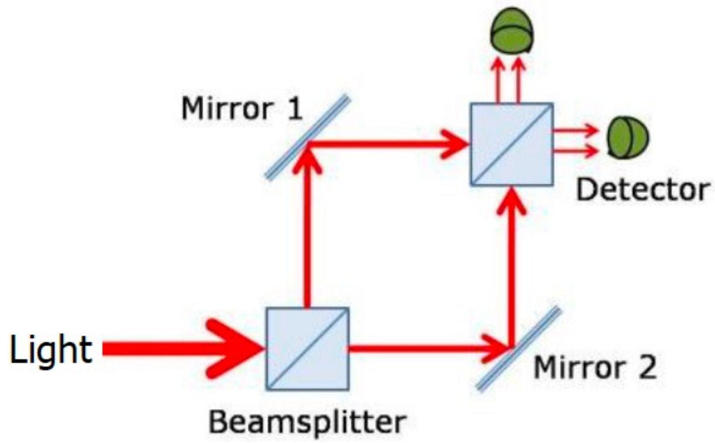
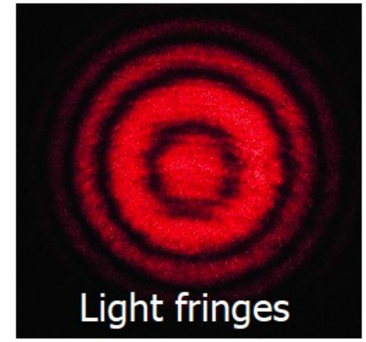
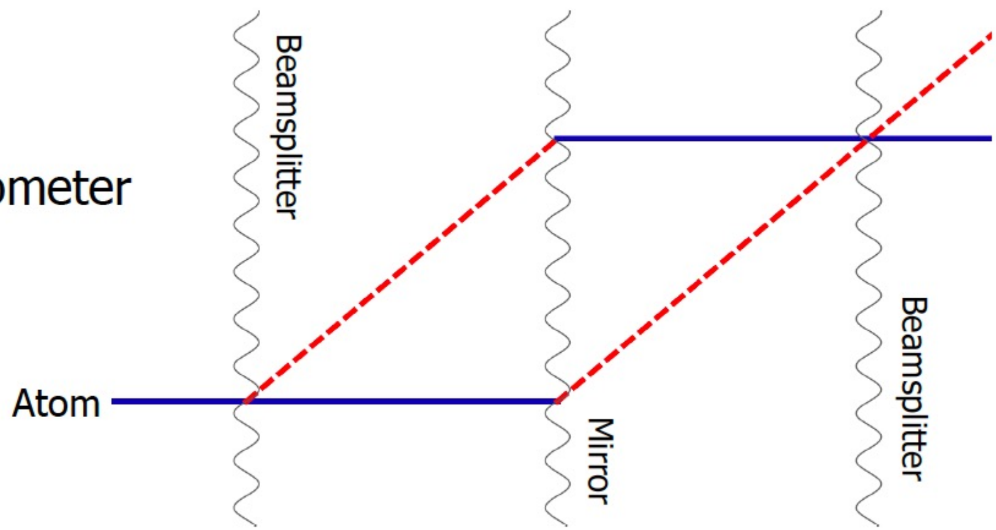
Interferometry basics

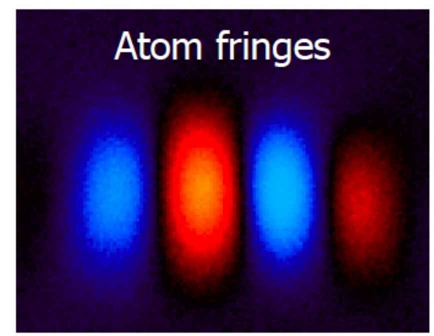
Light interferometer





Atom interferometer





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

STANFORD UNIVERSITY

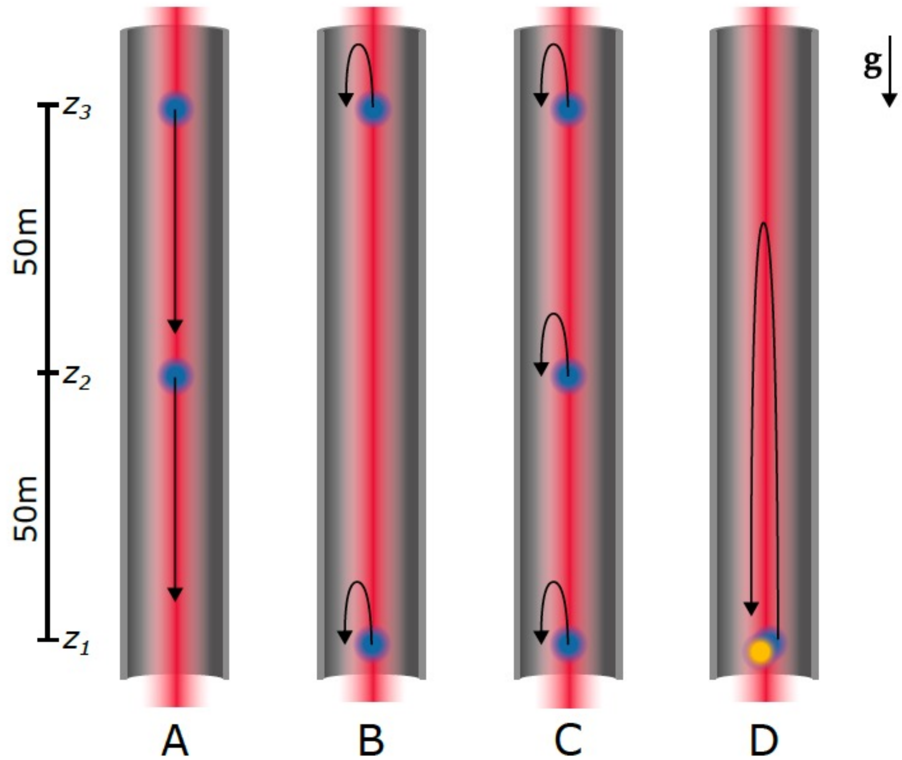
Slide courtesy of Jason Hogan.

Fermilab

MAGIS-100

MAGIS-100 operating modes (why vertical?)

Atoms are traveling with the known acceleration of gravity.
Other variables are adjusted to conduct variations of the experiment.

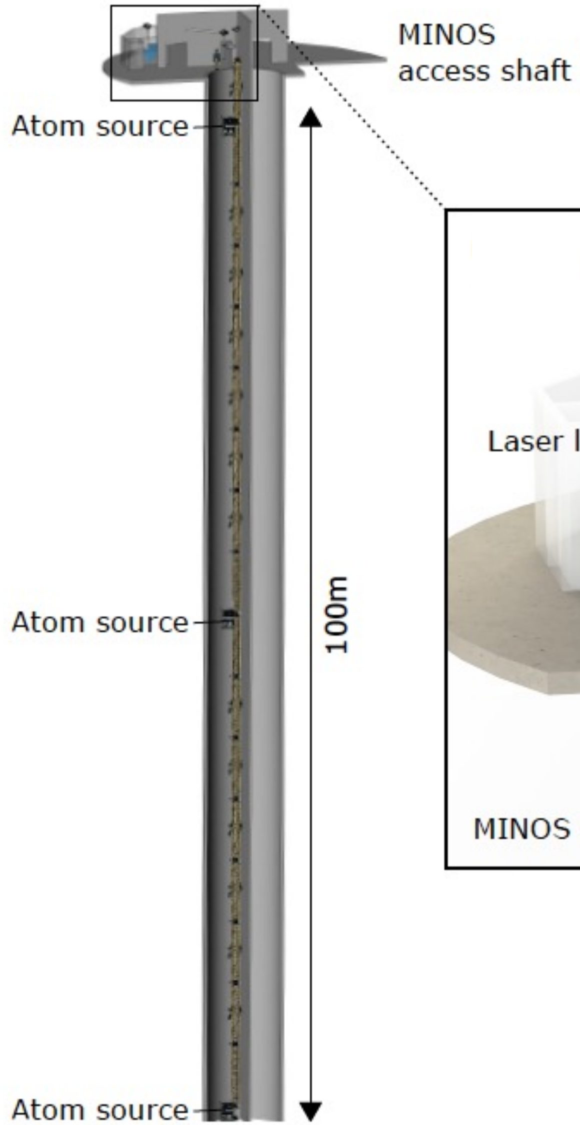


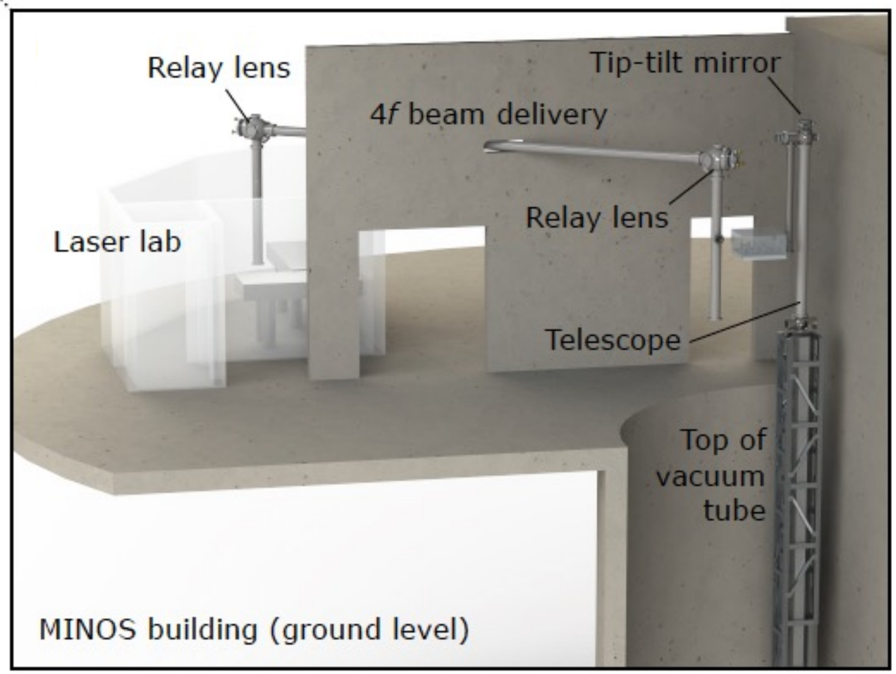
Four distinct operating modes (A-D) use the three atom sources that connect to the 100 m vacuum tube at locations z1, z2 and z3.

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.

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

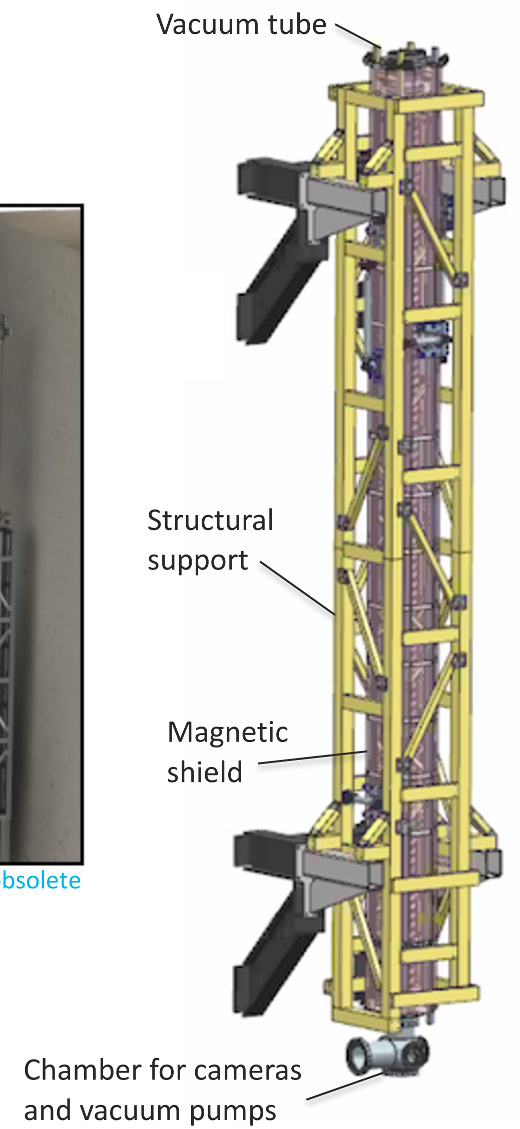
Systems overview



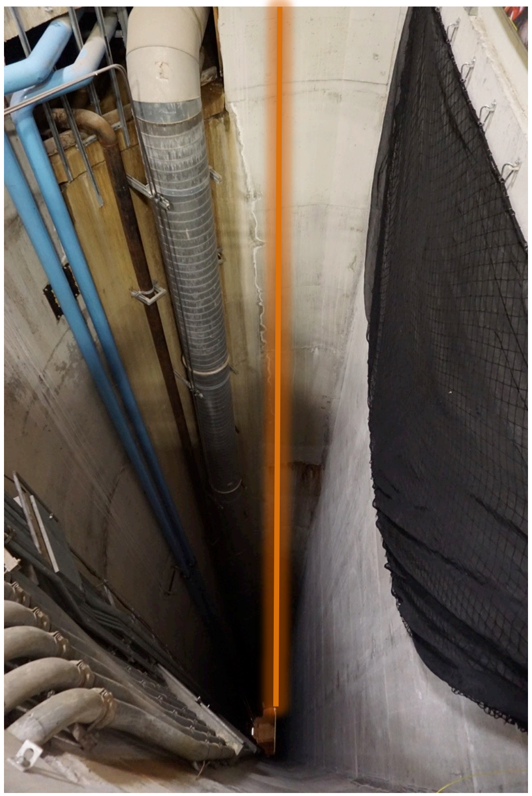


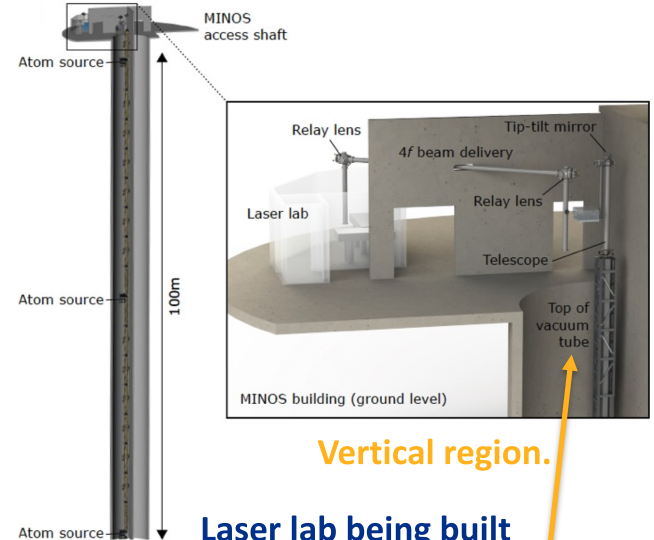
Some geometric details above are obsolete

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



Site – MINOS building





Vertical region.

Laser lab being built behind this wall.

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

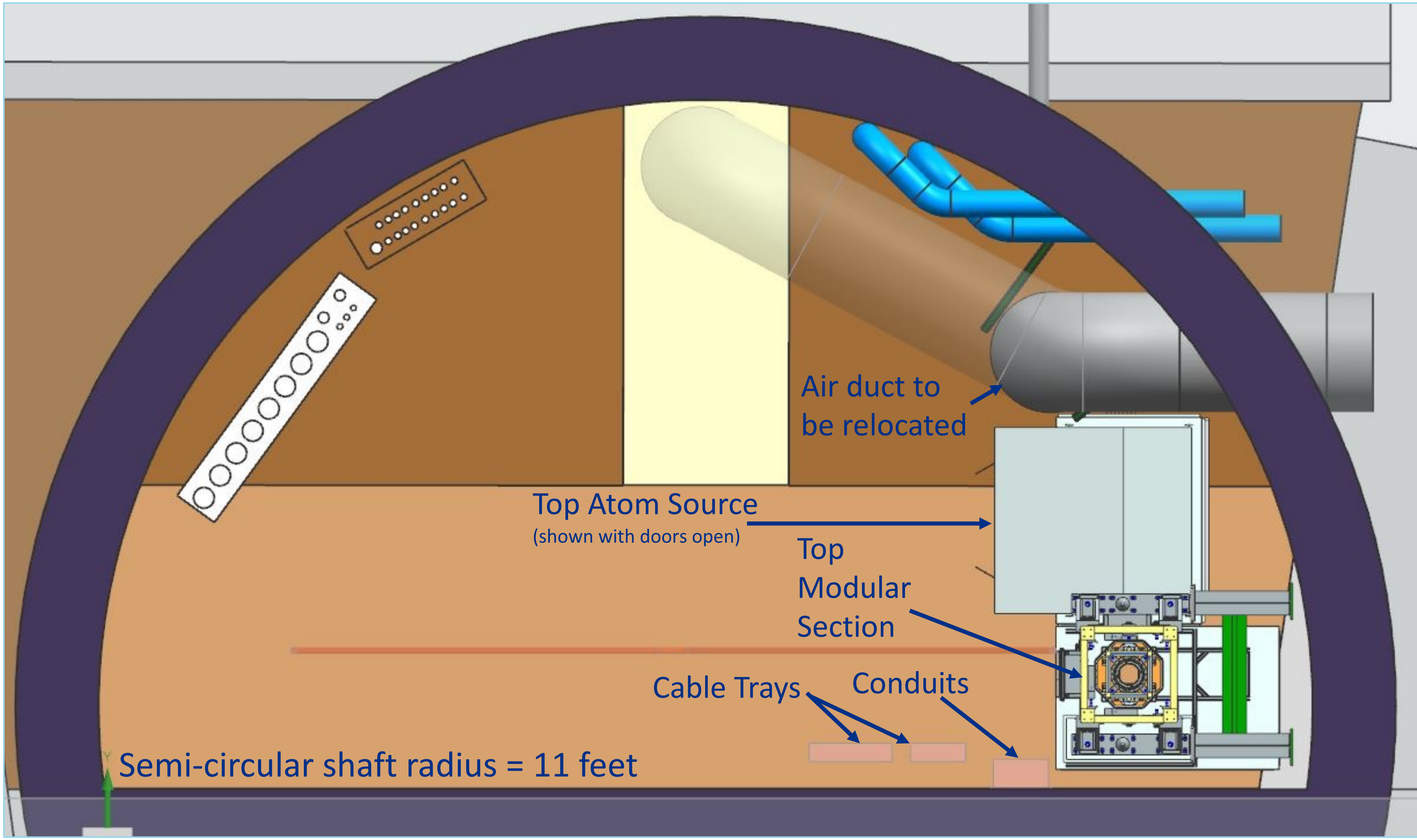
Site – shaft in MINOS building

View from the top, perspective aligned with experiment location.

View looking up from inside shaft.

Site challenges include:
- Small space
- Must accommodate other uses of shaft
- Curved wall for load bearing
- Environmental (water, thermal gradients)
- Installation and access (more on this later)

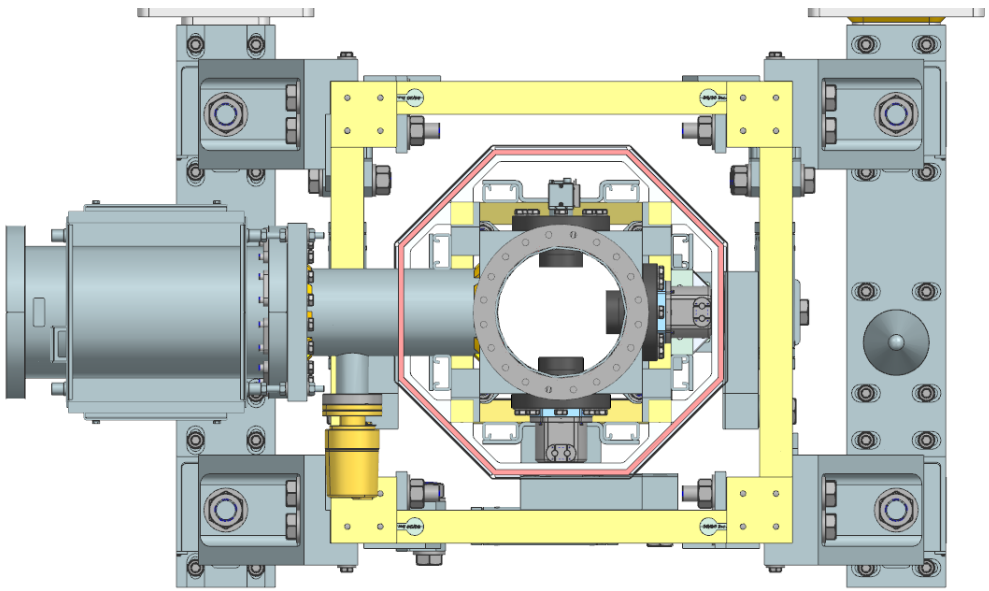
Component layout in the shaft



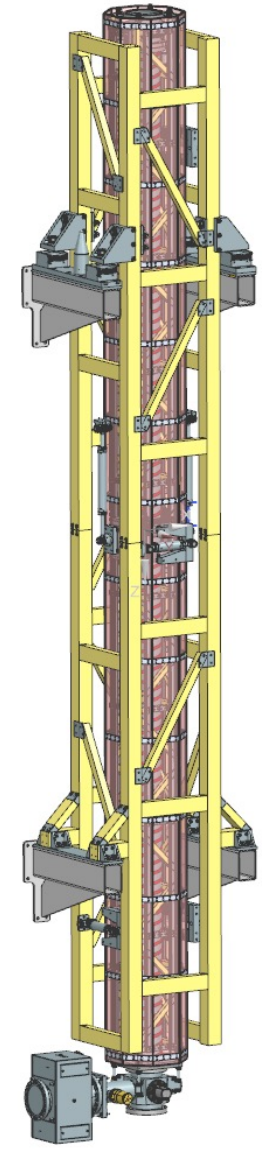
Plan view of the experiment in the shaft, without telescope shown.

Modular section design

- **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.

Vacuum system requirements & specifications

REQUIREMENTS

All Sections
6” OD tube
Straightness 0.045”/3ft
Minimize dust (not particle free)

Laser Transport (rough vacuum)
<1^{e-2} torr
Nonreflective tube ID

Telescope Region (UHV)
<1^{e-8} torr
Nonreflective tube ID

Modular Sections (UHV)
<1^{e-10} torr
Tube magnetic permeability μ ≤ 1.02
Nonreflective tube requirement pending
Additional magnetic requirements pending

Gate Valves

- As required for machine protection, laser safety, isolating high maintenance items
- Challenges: space available, dust creation


6” OD vacuum tubes purchased

SPECIFICATIONS

All Sections

- 6” OD tube, 0.083” wall thickness, 316L SS, laser welded
- 316L silver-plated hardware
- Minimize dust (not particle free)
- UHV clean

Laser Transport (rough vacuum)

- Mill finish tube

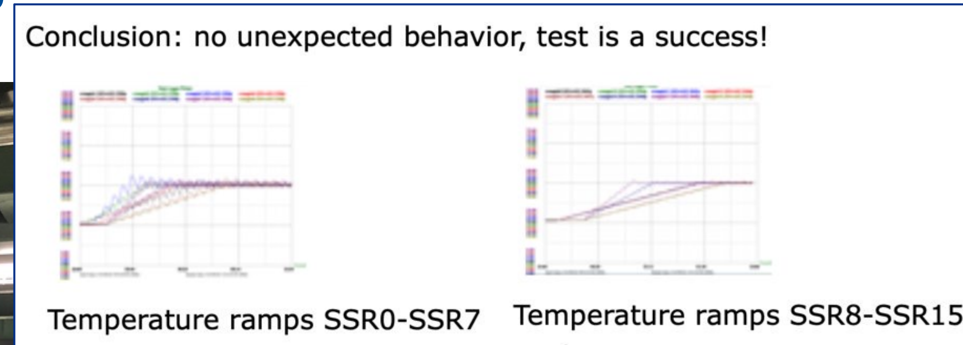
Telescope Region (UHV)

- Mill finish, hydrogen degassed tube
- Metal seals only

Modular Sections (UHV)

- Electropolished and hydrogen degassed tube
- Beamline flanges Conflat® type, 316LN SS
- Metal seals only
- IP/TSP or IP/NEG, no line of sight to beamline
- *In situ* bakeout

UHV bakeout challenges



Excerpt from bake test e-log.

16-channel bake test setup.

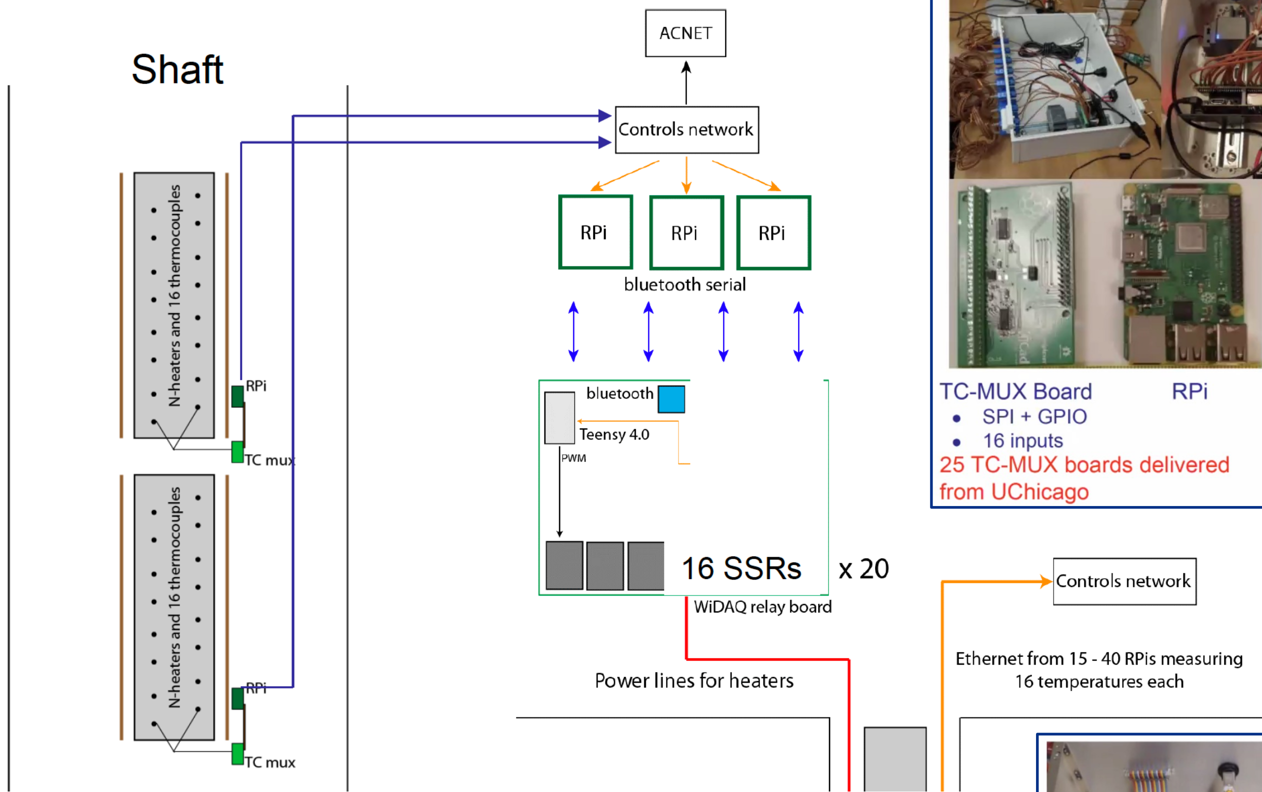
Bakeout System Components

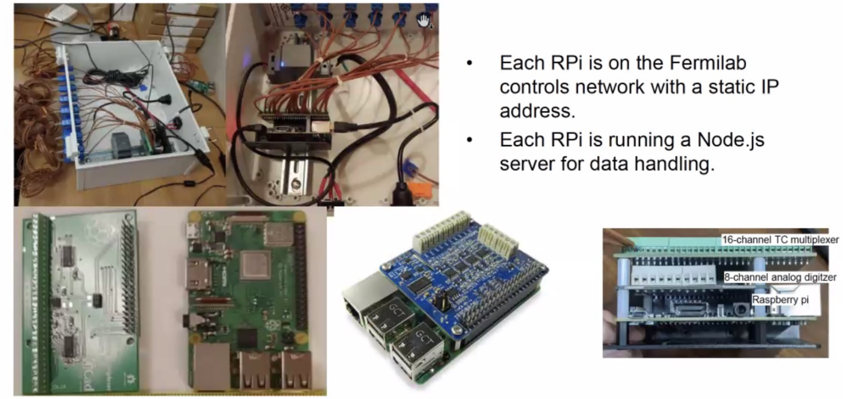
- **Flexible silicone heaters for tube**
- **Jackets for bellows, valves, etc.**
- **Oven or jacket for connection nodes**

Requirements & Challenges

- **Maintain 100º-150ºC**
- **Nonmagnetic heaters (those that remain in place), μ<1.010**
- **120V, <9A each**
- **Self-regulating or other overtemp protection**
- **NRTL certified**
- **Custom controls system for ~200 channels**

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

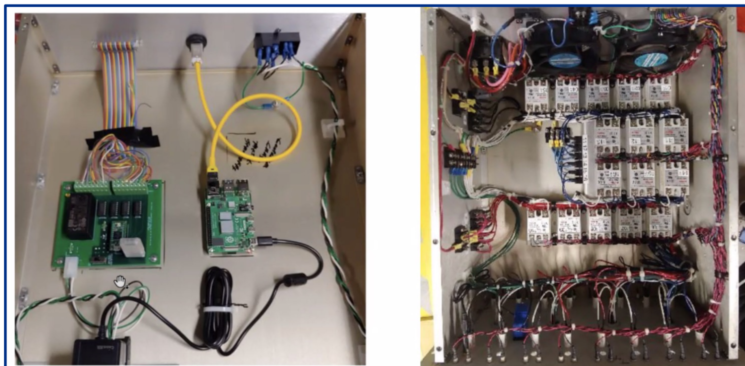
25 TC-MUX boards delivered from UChicago

RPi

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

In shaft

Top of shaft



16-channel PWM*

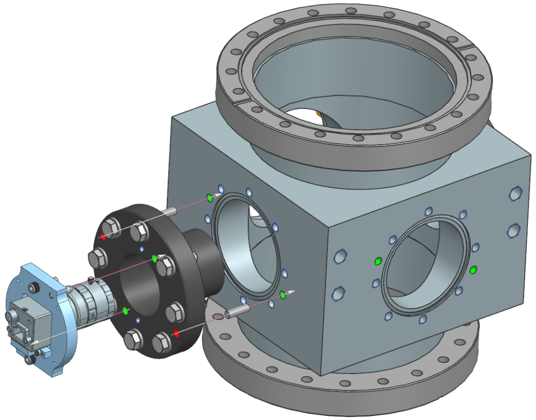
16-channel SSR *

*Pulse Width Modulation, Solid State Relay

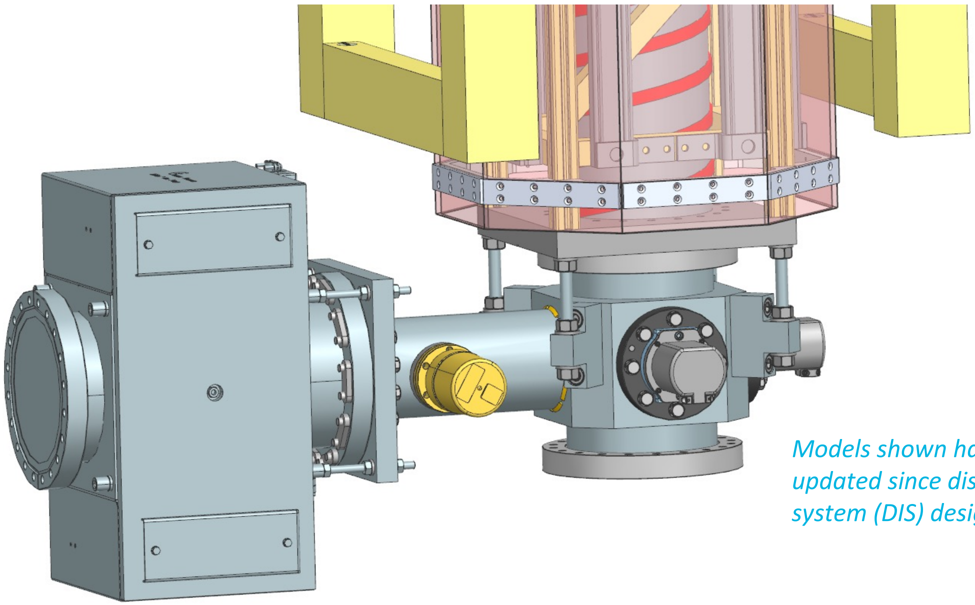
Bake controls system uses Raspberry Pis and thermocouples with a temperature module box on each section in the shaft and power control modules at the top of the shaft.

All images from Sergei Nagaitsev.

Modular connection node design

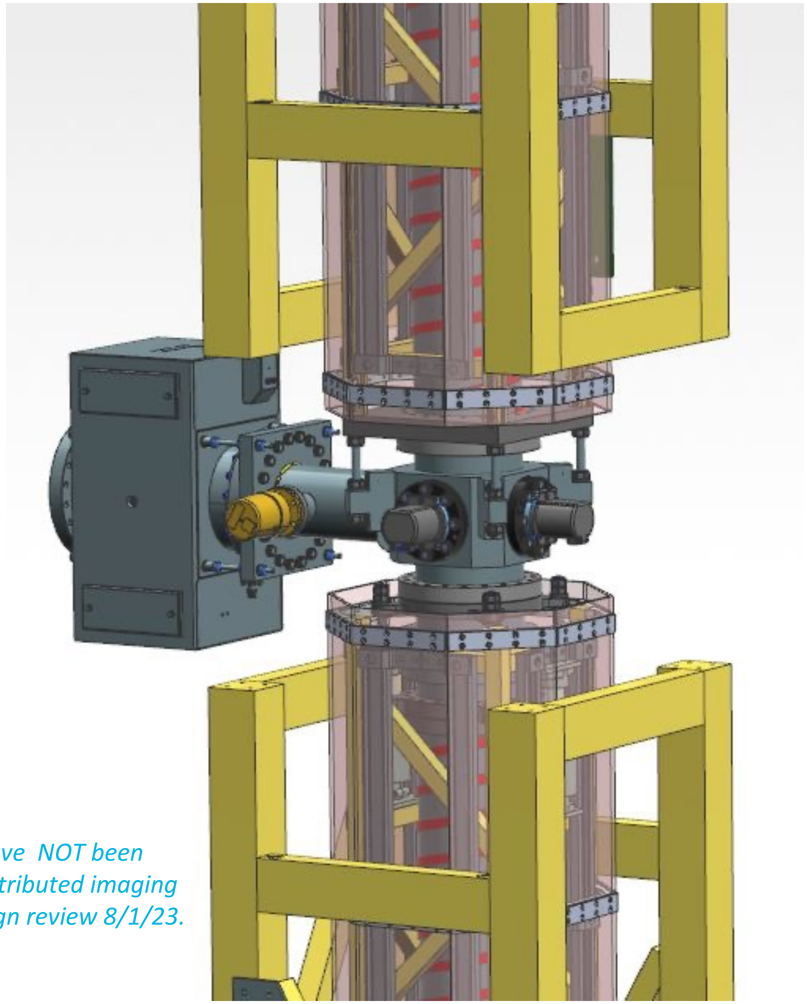


Cameras mount inside re-entrant viewports with light tight covers.



Models shown have NOT been updated since distributed imaging system (DIS) design review 8/1/23.

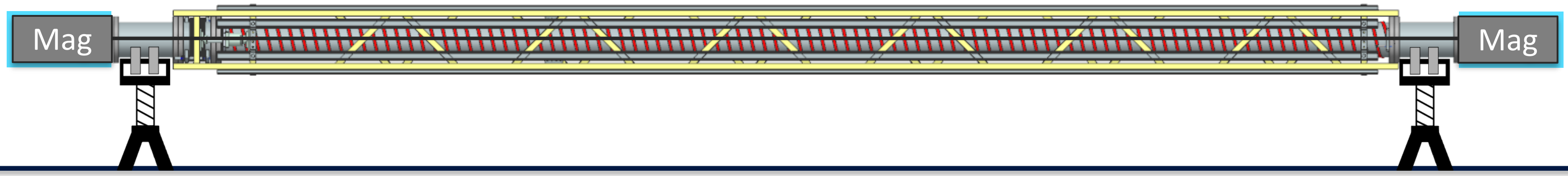
Detail of modular connection node shown with large pump (placeholder).



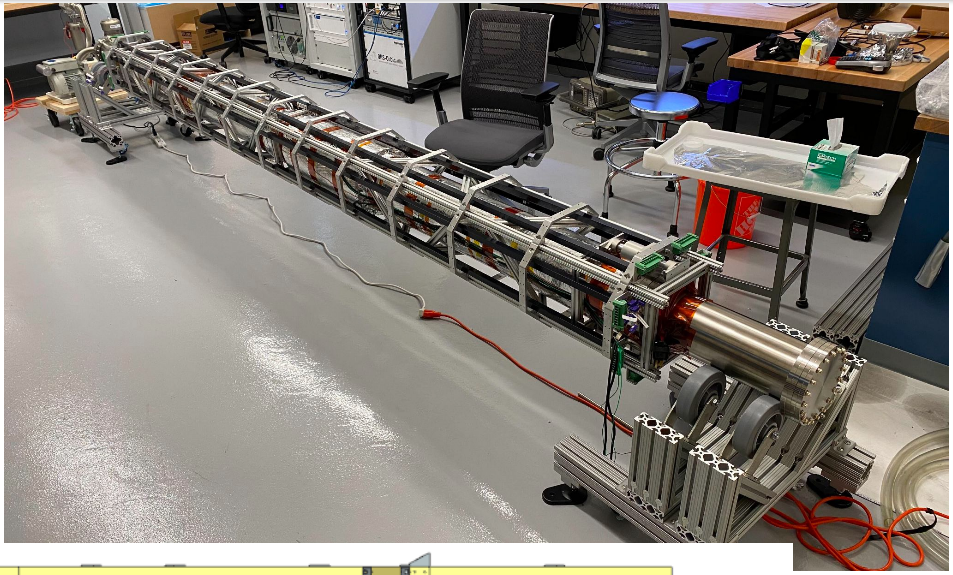
Two modules connected.

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.

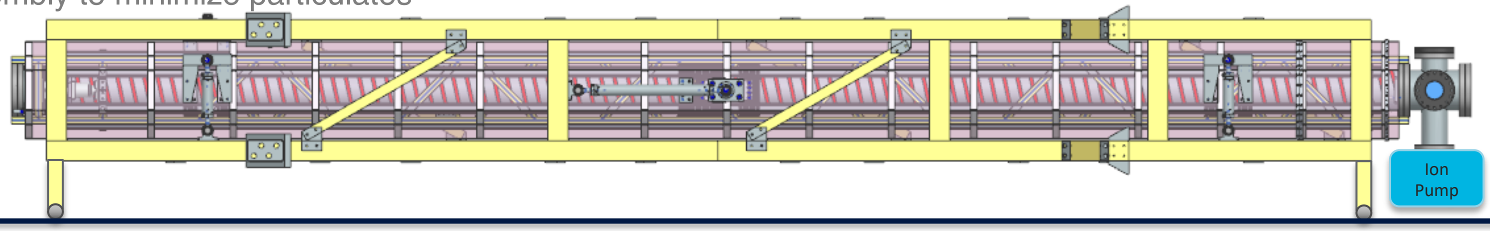


Bake and certification

- Water bake
- RGA scan
- Ultimate pressure verification

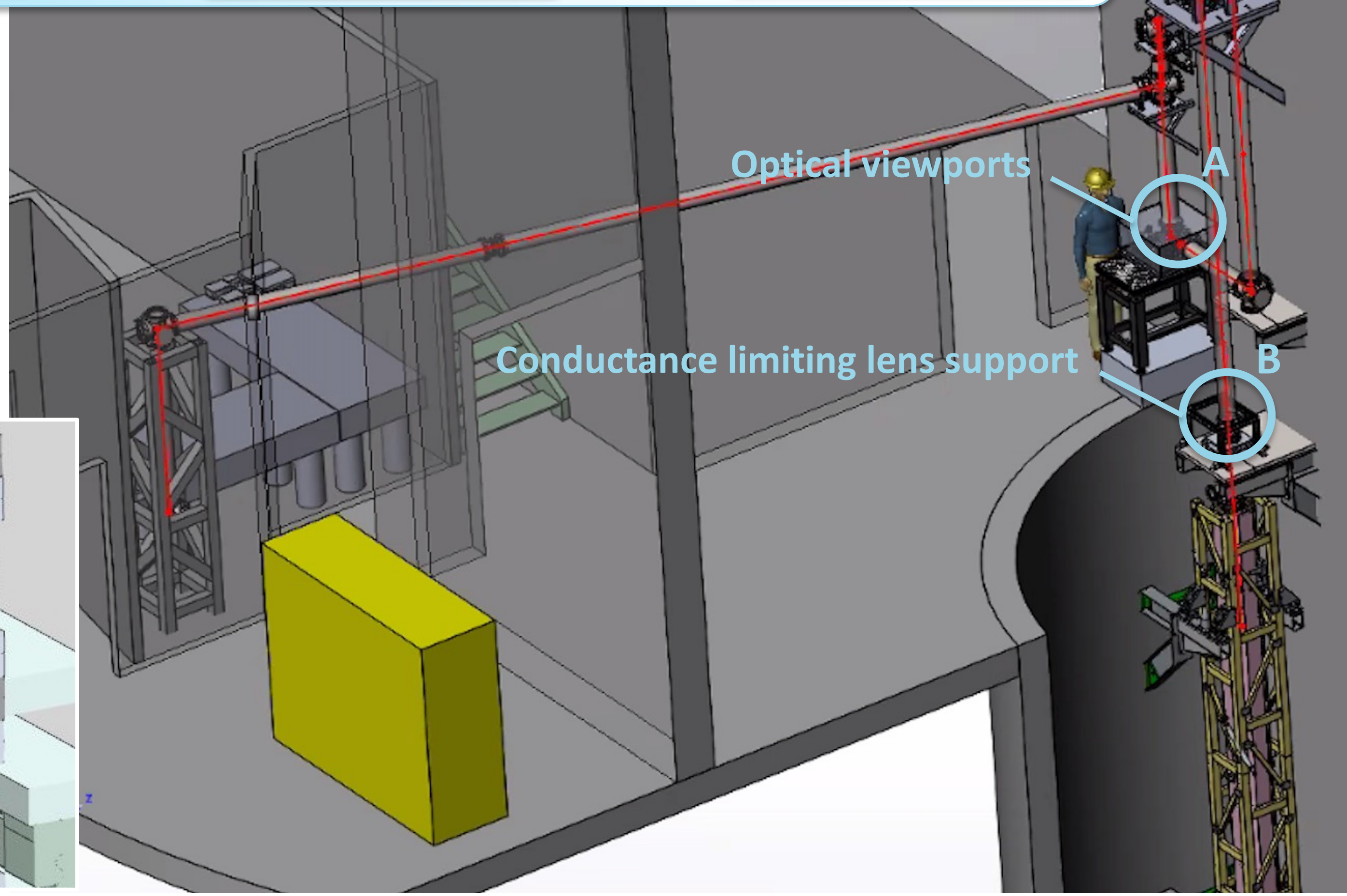
Focus on cleanliness

- Only clean wires/components inserted into vacuum space
- Portable cleanrooms enclose each open end of assembly to minimize particulates



Laser lab and laser transport system (LTS) layout

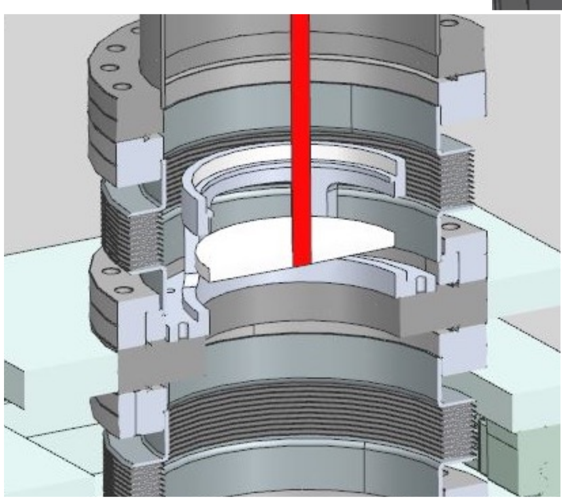
Laser Transport Rough vacuum → A → **Telescope Region** <1e^{-8} torr → B → **Modular Sections** <1e^{-10} torr



LTS optical route from Northwestern University team

Gate valve locations

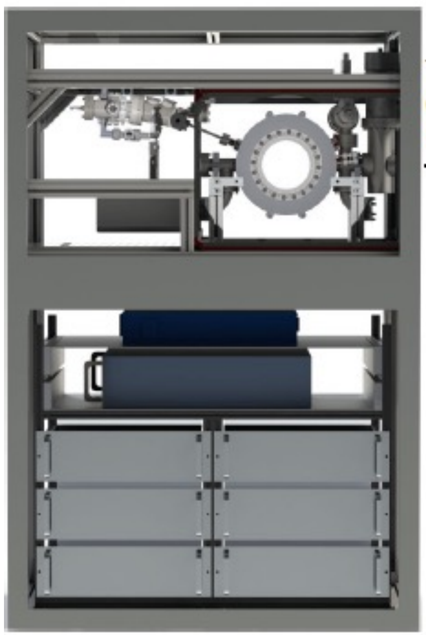
- Telescope/Modular Sections interface
- Atom sources
- Laser Transport (laser safety)
- Above Retroreflective Mirror



Lower lens and support

Atom sources

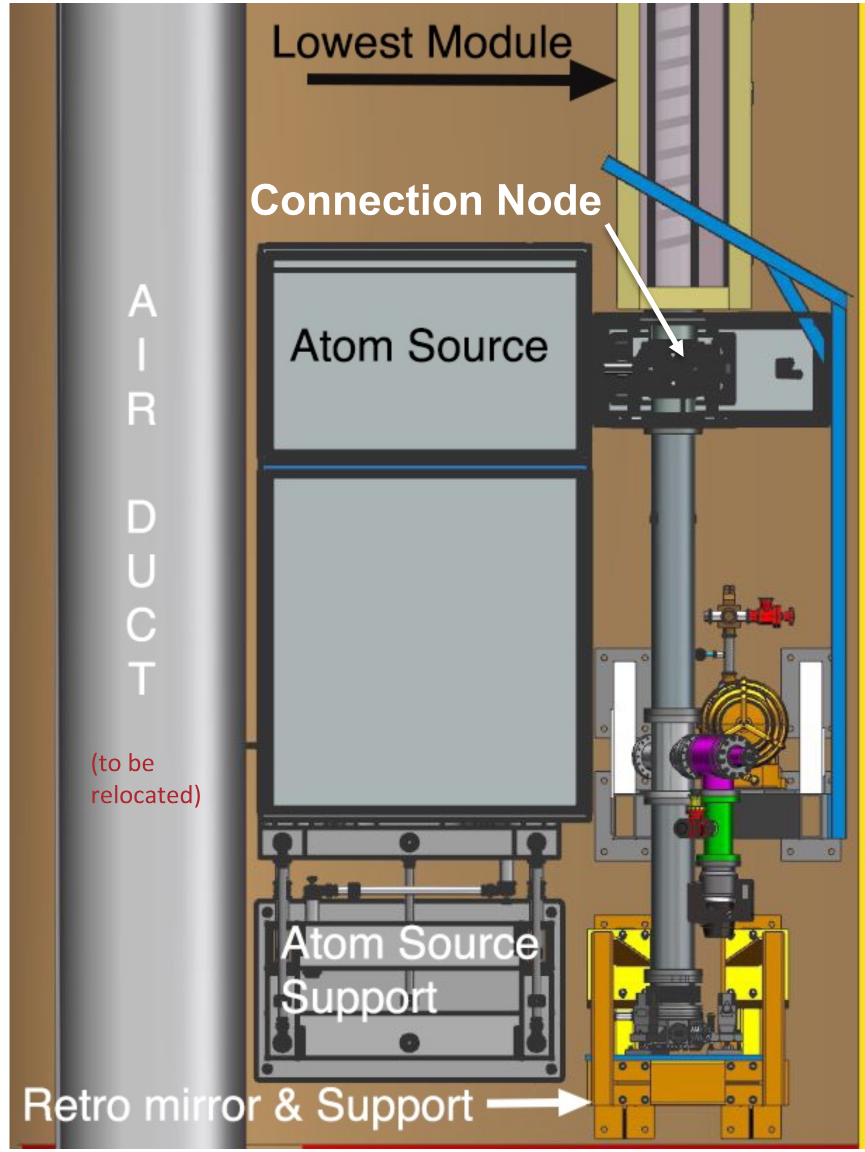
- Top, middle, and bottom of shaft.
- Up to 1,000lb weight.
- Last components installed.
- Approximate cost $1M each.
- Designed and built at Stanford University with access challenges considered.
- Transportation will be planned and tested.



Atom source detail.

Vacuum details

- Atom source (AS) arrive prebaked and under vacuum (IP/TSP)
- Interface pressure 3e-11 torr
- Connection node pumps sized for AS & optical components

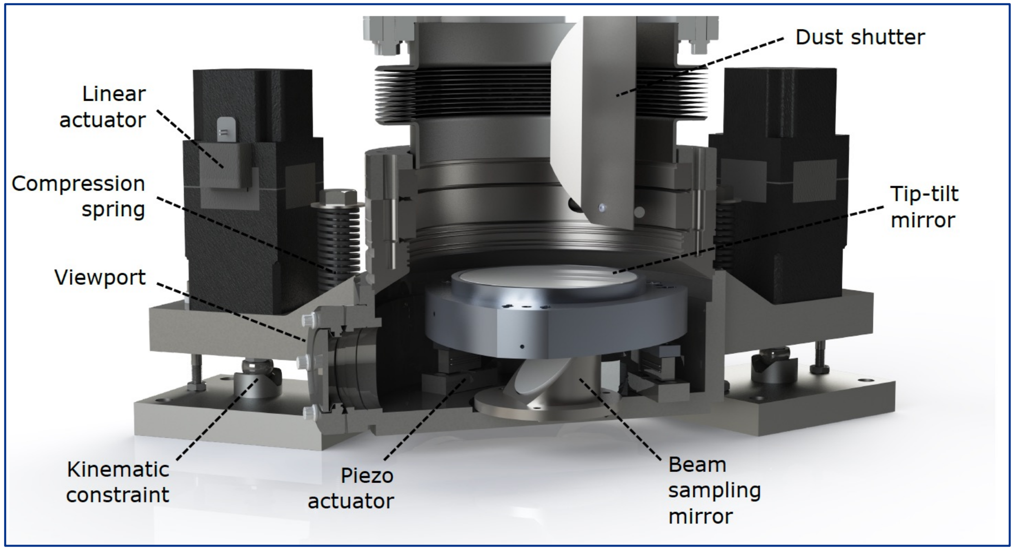


Bottom atom source, atom source connection node, vacuum rough pumping station, and retroreflective mirror shown.

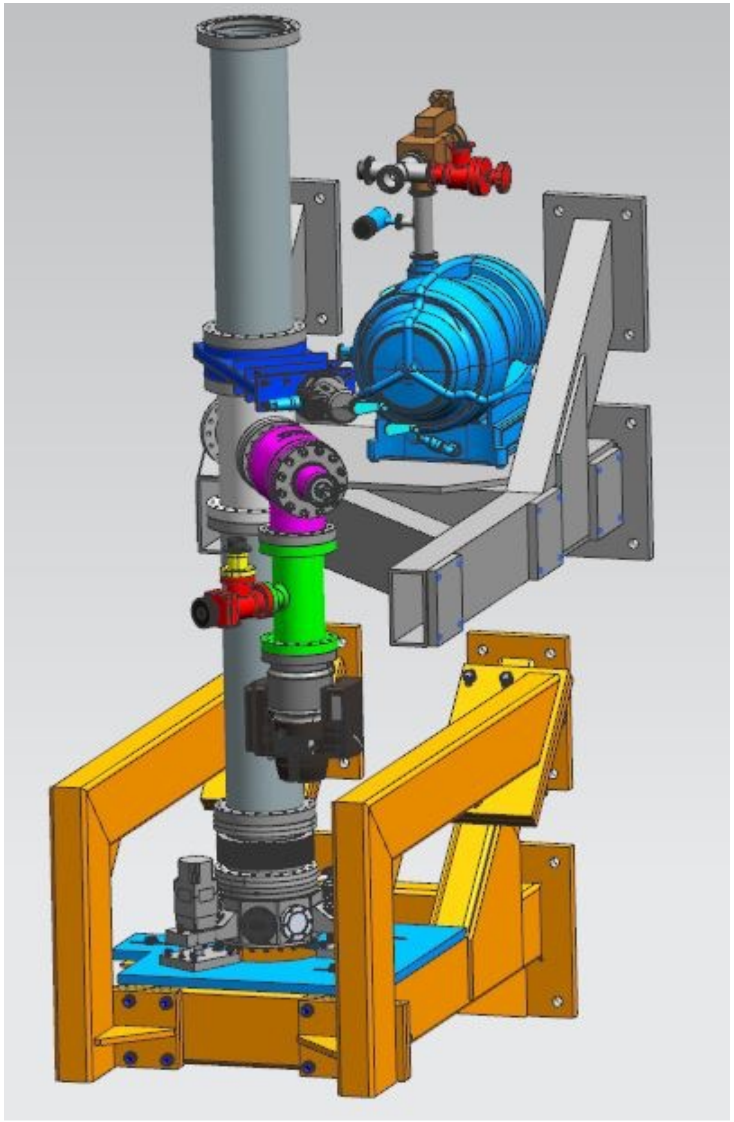
Retroreflective Mirror

Challenges

- Gas load e-7 torr*L/s
- Breaking vacuum for maintenance (gate valve isolates section)
- Outgassing tests and RGA scans used to choose and validate
  - piezo actuators (epoxy, solder, wiring, etc.)
  - coated mirrors



Section view of retro mirror

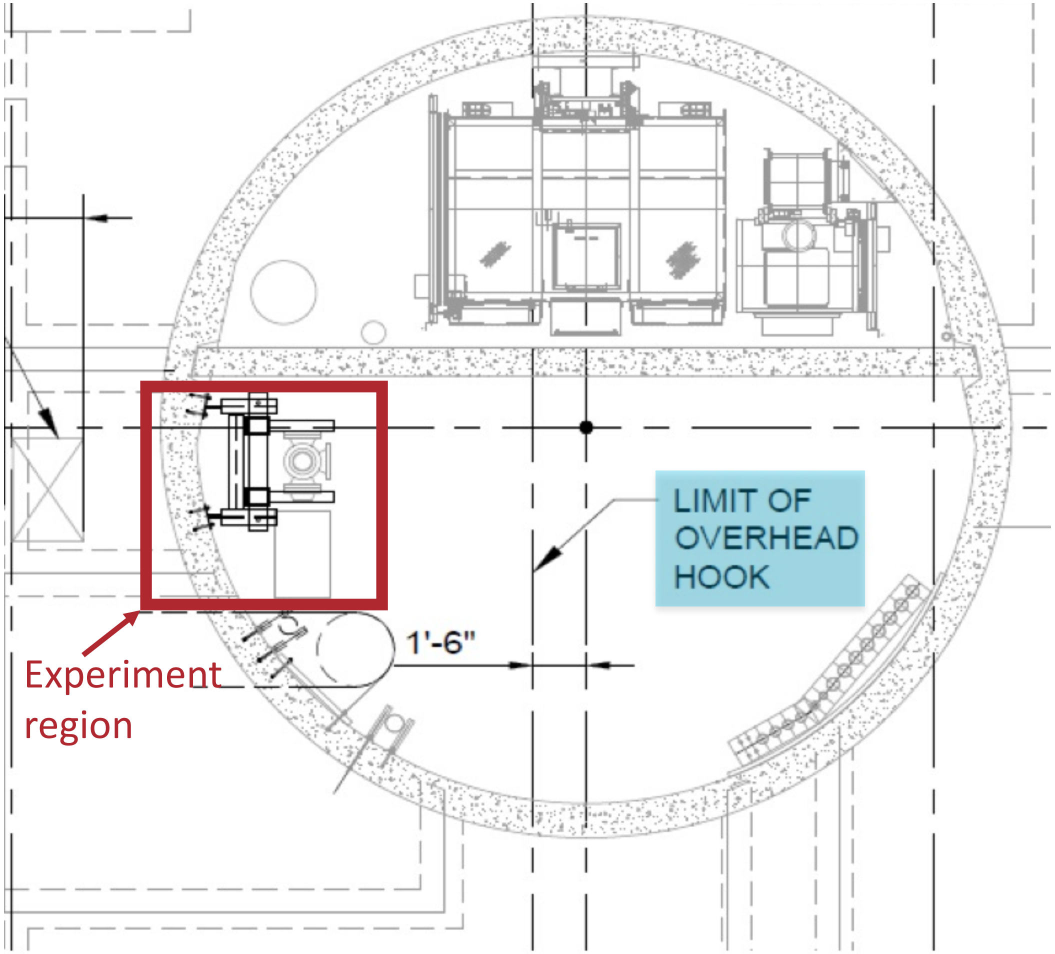


Vacuum rough pumping station and retroreflective mirror

Installation challenges

- **Vertical installation – the most obvious challenge.**
- **Added complexity – overhead crane does not reach experiment region. Need an engineered system.**

Crane unspooling into shaft.



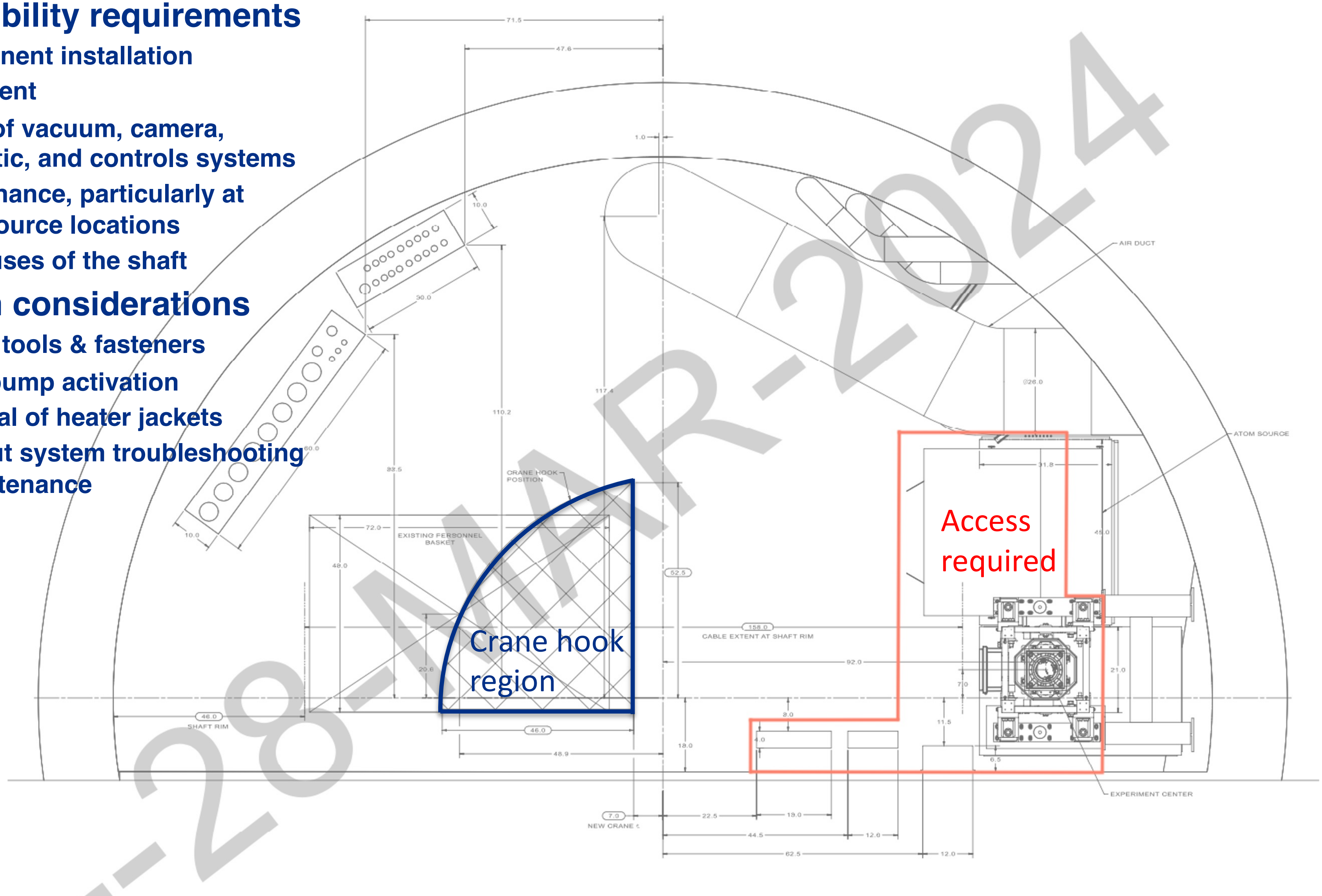
Personnel access challenges

Accessibility requirements

- Component installation
- Alignment
- Setup of vacuum, camera, magnetic, and controls systems
- Maintenance, particularly at atom source locations
- Other uses of the shaft

Vacuum considerations

- Falling tools & fasteners
- Local pump activation
- Removal of heater jackets
- Bakeout system troubleshooting & maintenance



Closing thoughts

The MAGIS-100 collaboration is building a long baseline atom interferometer at Fermilab to be commissioned in 2027.

Much of the experiment is currently in the design and prototype phase.

Typical challenges for developing a UHV system are paired with unique science and site requirements.

For additional information, visit magis.fnal.gov.