Status of MAGIS-100

R. Plunkett, Project Manager

Fermilab Physics Advisory Committee meeting

9 December 2020

MAGIS-100 Collaboration

STANFORD

Fermilab

Northwestern University

UNIVERSITY OF LIVERPOOL

Northern Illinois University

JOHNS HOPKINS UNIVERSITY

SLAC

UNIVERSITY OF OXFORD

UNIVERSITY OF CAMBRIDGE

GORDON AND BETTY MOORE FOUNDATION

GBMF7945

QuantiSED 2019

UKRI Science and Technology Facilities Council

UK STFC

Kavli Foundation

The Big Picture

- MAGIS-100 is E-1101, approved by Fermilab Director with advice from PAC.
- Nominally 5 year duration, 3 years construction, commissioning and early science. Out years for datataking and key science results.
- Public and private funding.
  - GBMF grant began 1/1/2019
  - QuantISED funds available 10/1/2019

MAGIS-100 Timeline

January 2019 – Funding from GBMF (Gordon and Betty Moore Foundation) begins.

February 2019 – Fermilab Director grants Stage 1 Approval.

August 2019 – Fermilab Director's Review.

September 2019 – Fermilab Director grants Stage 2 Approval.

October 2019 – Funding from DOE QuantiSED program begins.

September 2020 – Director's Cost and Schedule Review.

October 2020 – Begin SLAC LDRD (Schwarzman).

October 2020 – Begin Cambridge Kavli Fellow.

Early 2021 – Anticipated Start of STFC funding (UK).

Project Objectives

1a) Technical: Demonstrate operation of a quantum sensor network with 2 nodes, each node consisting of an atom interferometer with the atom sources each producing $\geq 10^6$ useful atoms/sec, 100 $\hbar k$ atom optics, a launch height of O(10m), and a phase noise $\leq 10^{-3}$ rad/$\sqrt{\text{Hz}}$.

1b) Technical: Demonstrate operation of a quantum sensor network with 3 nodes, each node consisting of an atom interferometer with the atom sources each producing $\geq 10^6$ useful atoms/sec.

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

3) 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.

4) 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 isotope interferometer with a launch height of O(10 m), 100 $\hbar k$ atom optics, and a phase noise $\leq 10^{-3}$ rad/$\sqrt{\text{Hz}}$.

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

Atom Interferometry

- Laser pulses act as beam splitters and mirrors for atomic wavefunction
- Highly sensitive to accelerations (or to time-variations of atomic energy levels)

$$|\text{atom}\rangle = |p\rangle$$

π/2 pulse "beamsplitter"

$$\frac{1}{\sqrt{2}}(|p\rangle + e^{i\Delta\phi}|p + \hbar k\rangle)$$

π pulse "mirror"

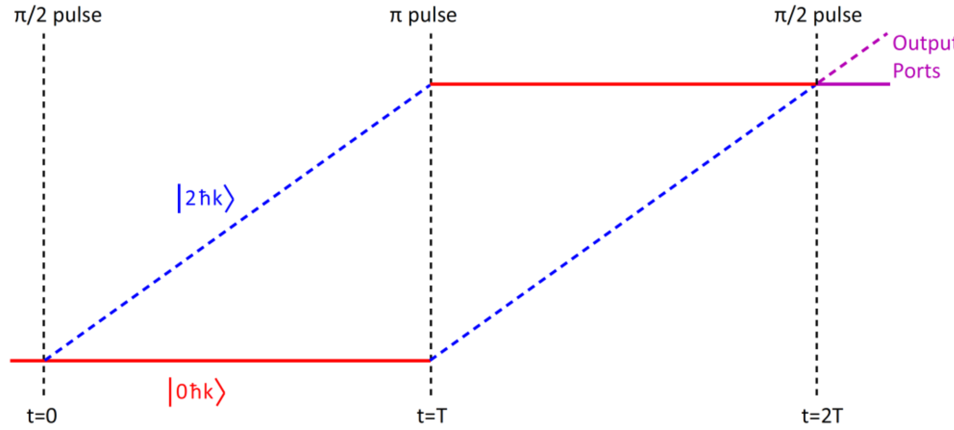
$$\frac{1}{\sqrt{2}}(|p + \hbar k\rangle + e^{i\Delta\phi}|p\rangle)$$

π/2 pulse "beamsplitter"

$$\frac{1}{2}((1 + e^{i\Delta\phi})|p\rangle + ((1 - e^{i\Delta\phi}))|p + \hbar k\rangle)$$

$$\text{Probability in State } |p\rangle = \cos^2\left(\frac{\Delta\phi}{2}\right)$$

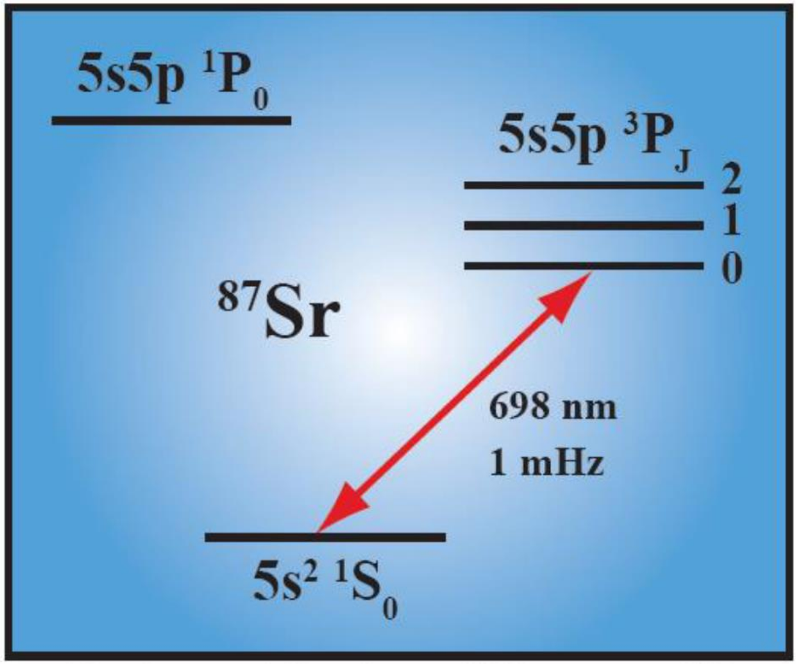
$$\text{Probability in State } |p + \hbar k\rangle = \sin^2\left(\frac{\Delta\phi}{2}\right)$$

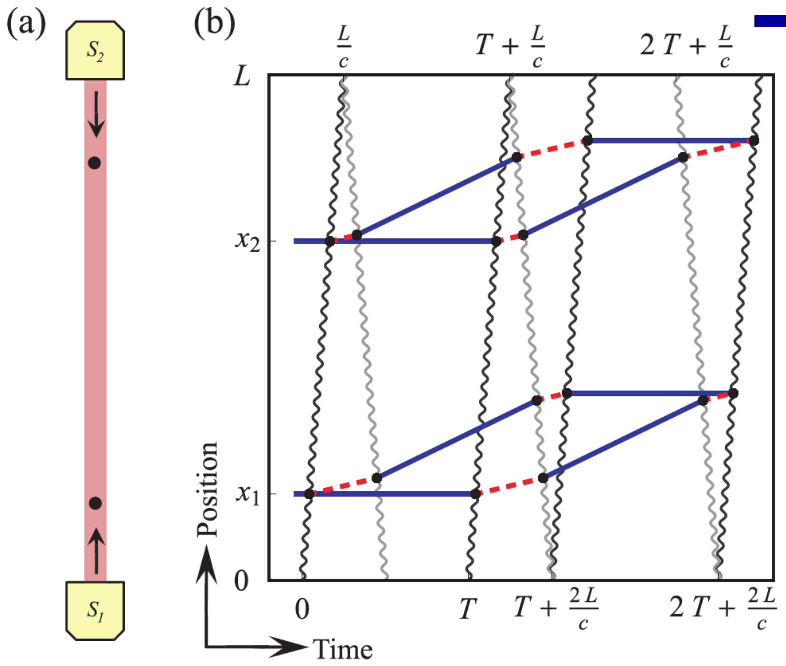


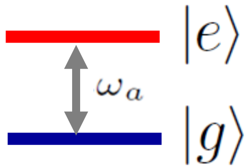
Effects scale like AREA, so

Long T good
High Momentum Good

Hybrid Clock/Accelerometer







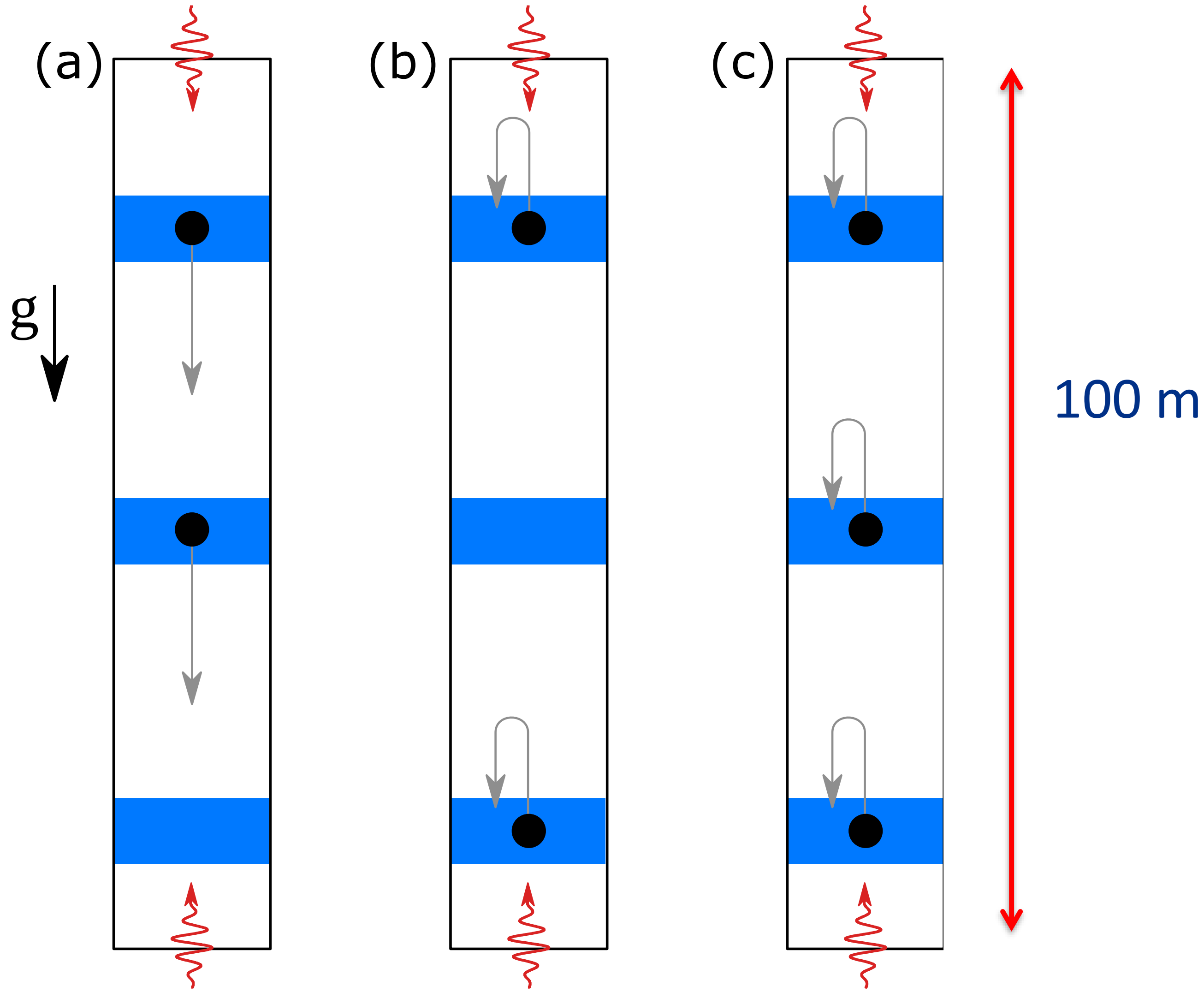
Sr has a narrow optical clock transition with a long-lived excited state that atoms can populate for >100 s without decaying.

Graham et al., PRL 110, 171102 (2013)

- Beamsplitter—Mirror—Beamsplitter sequence makes interferometer insensitive to initial atom position and velocity

- Only sensitive to relative *acceleration* of baseline between two clocks/interferometers

MAGIS-100 Modes



DM Landscape

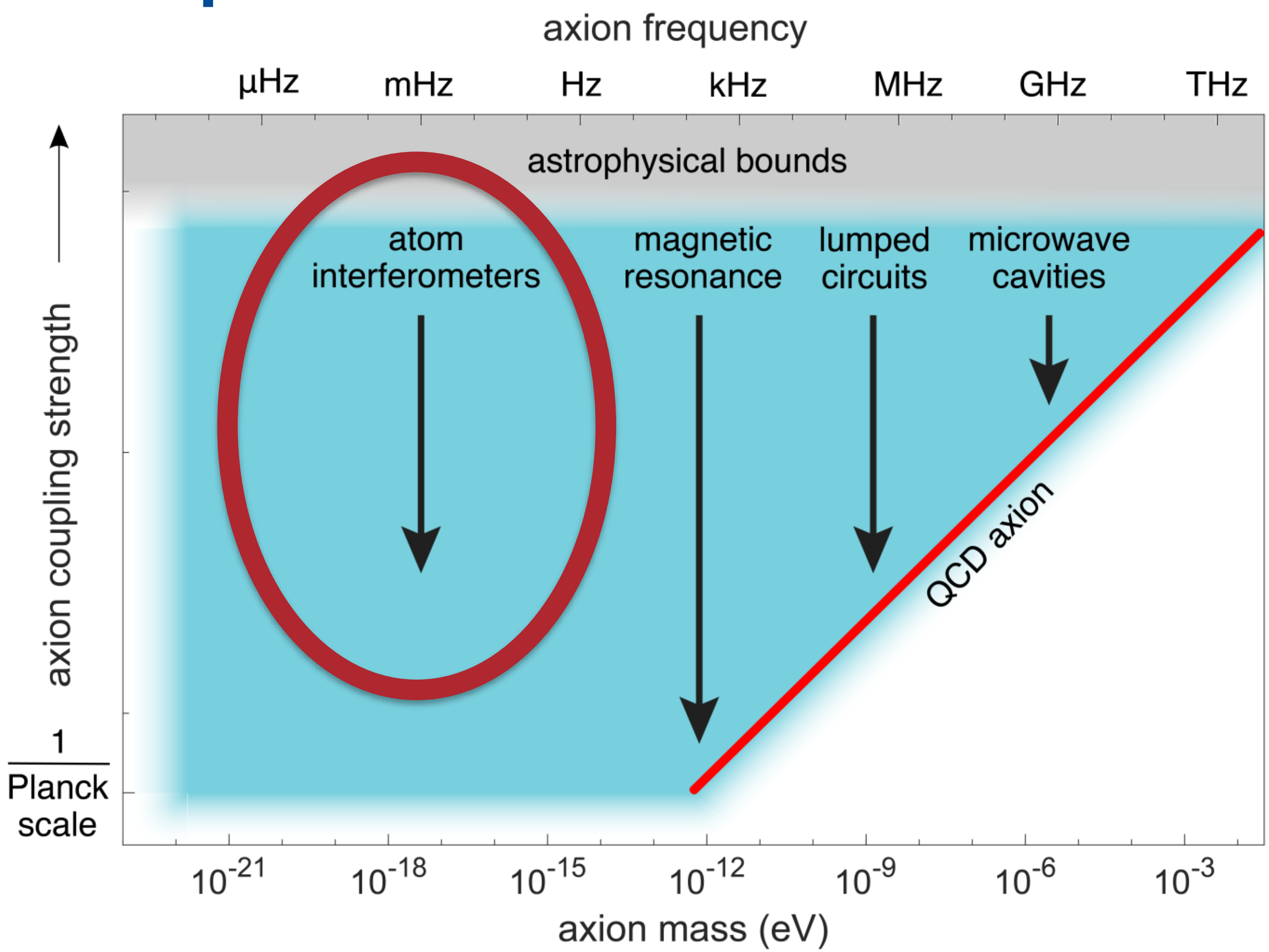
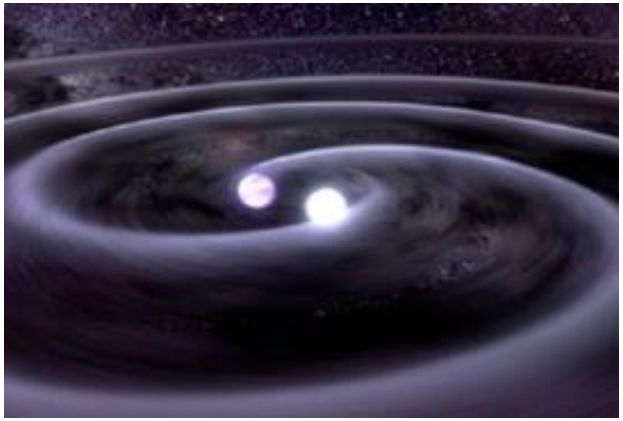
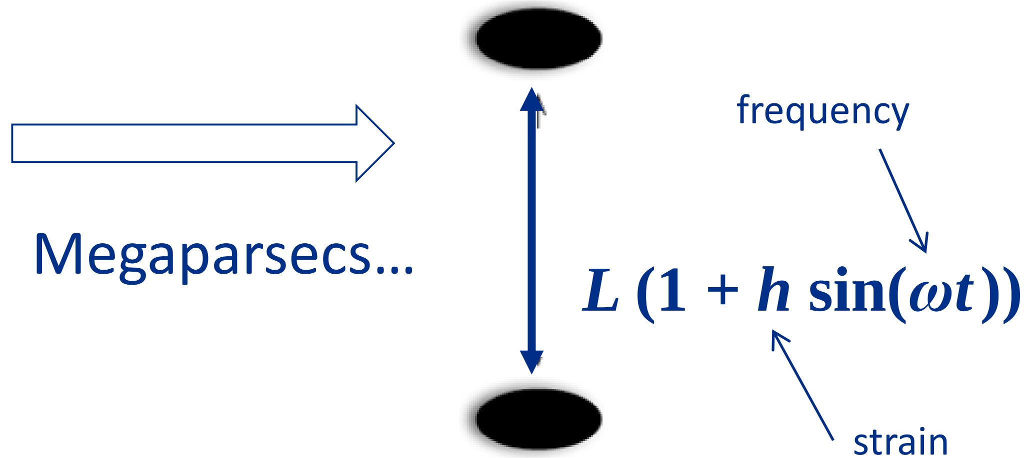


Figure from DOE Dark Matter Research Needs Report, 2018

Gravitational Wave Detection



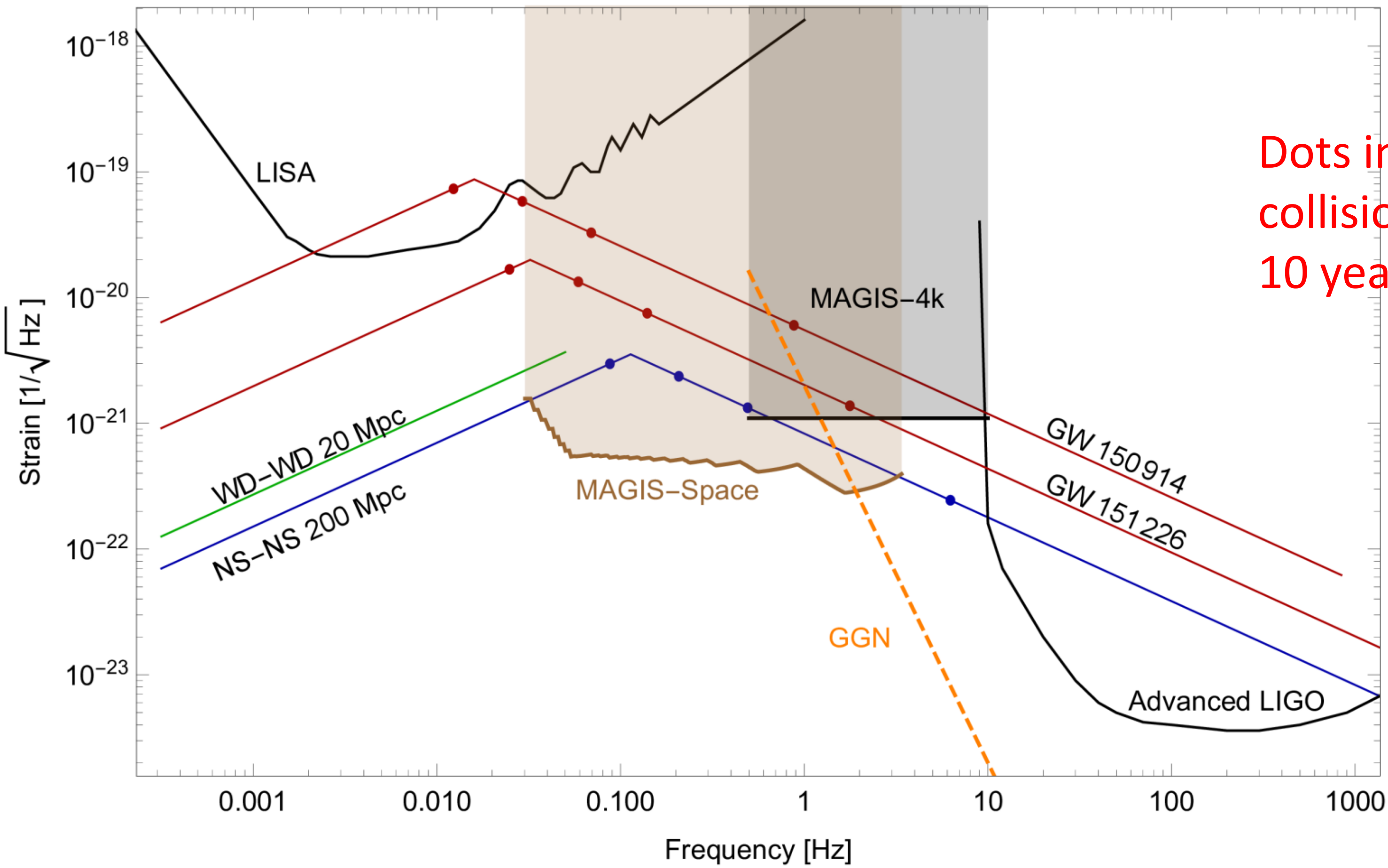


New carrier for astronomy: Generated by moving mass instead of electric charge

Tests of gravity: Extreme systems (e.g., black hole binaries) test general relativity

Cosmology: Can see to the earliest times in the universe

Long Range Program Sensitivity



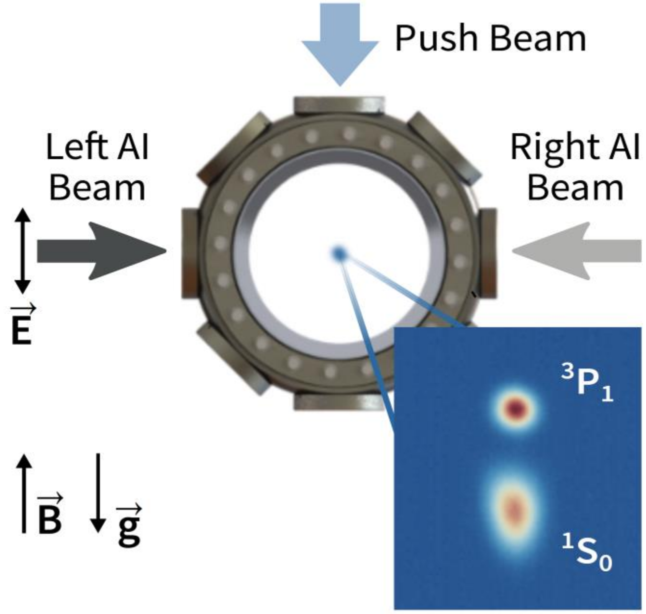
Dots indicate time-to-collision ranging from 10 years to 0.01 year.

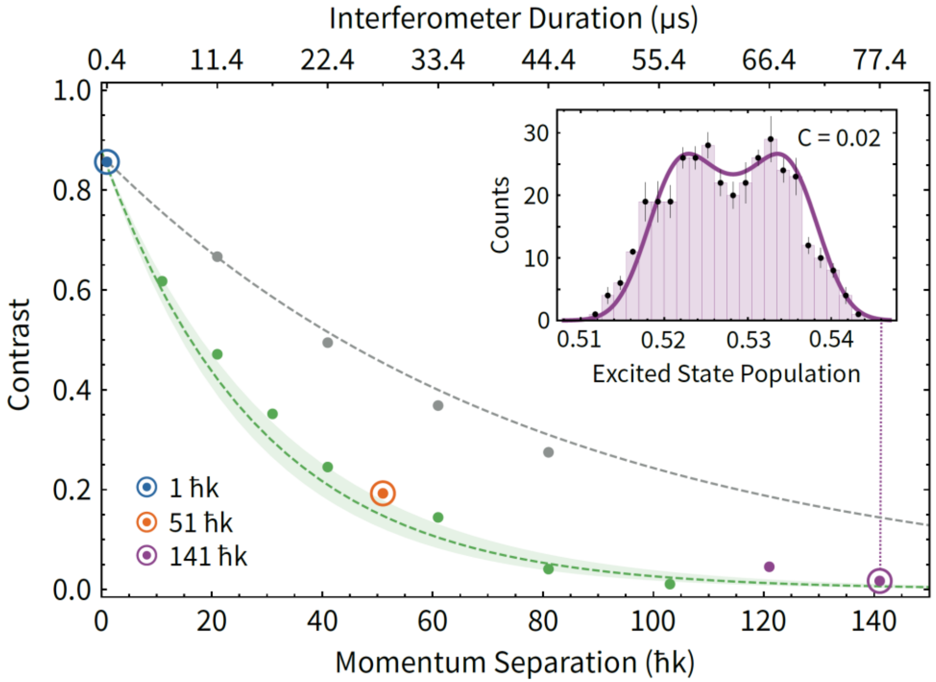
Full Scale future MAGIS detector fills frequency sensitivity gap in ~1 Hz range. MAGIS-100 will give limits in this range several orders of magnitude beyond existing (but no known sources of such strength.)

Important Advances and Decisions

- Science
- Infrastructure
- Technology
- Organization

Clock Atom Interferometry Demonstration (Stanford)





First LMT clock interferometers using sequential single-photon transitions

Record LMT interferometer (141 ħk)

Demonstrated 81 ħk gradiometer (power limited)

Demonstrated T > 1 ms (>> lifetime)

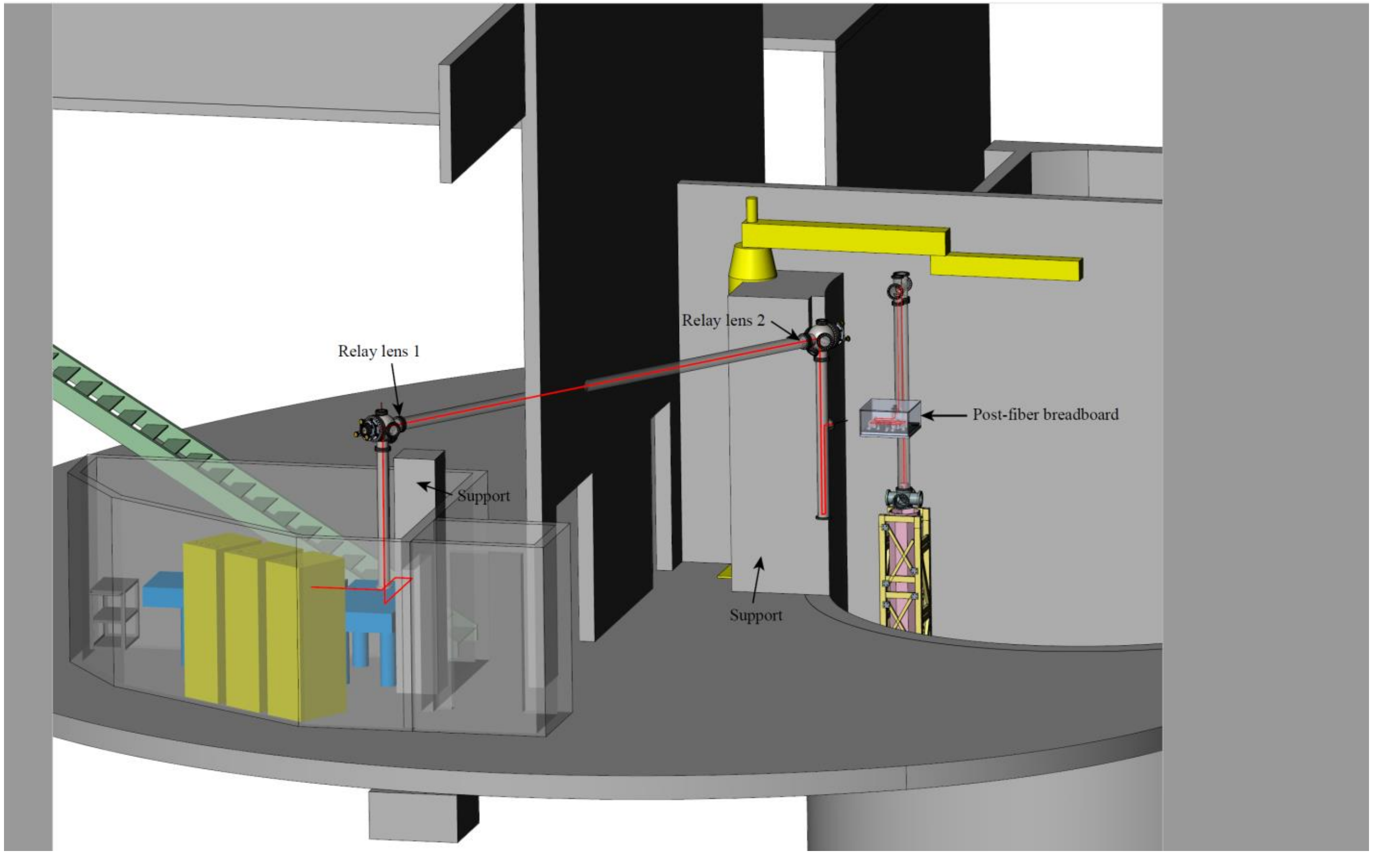
Current work: upgrade to 1000 ħk

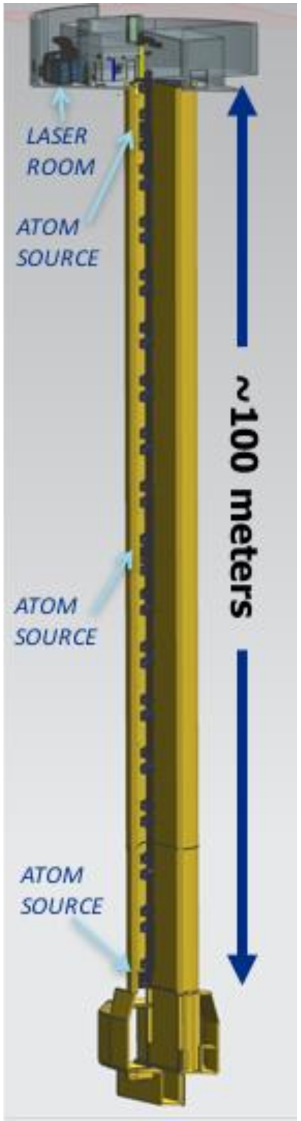
J. Rudolph, PRL **124**, 083604 (2020)

Some Technical Highlights

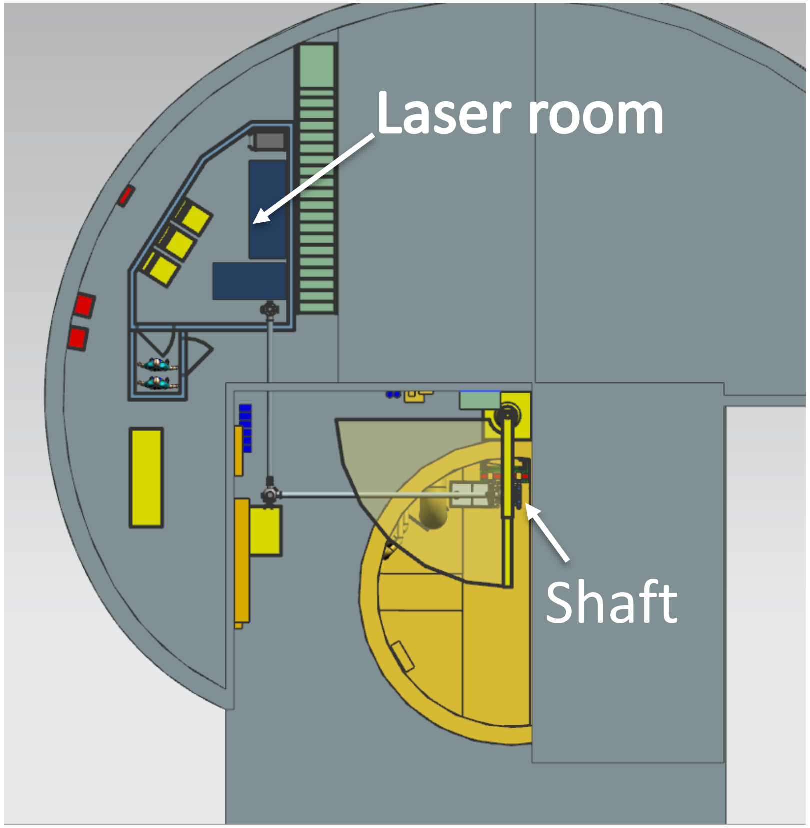
- Physical layout
- Support Structure and Magnetic Shield
- Installation
- Laser Beam Delivery
- Frequency Comb
- Launch lattice
- Simulation

Experiment Layout: Surface and Shaft

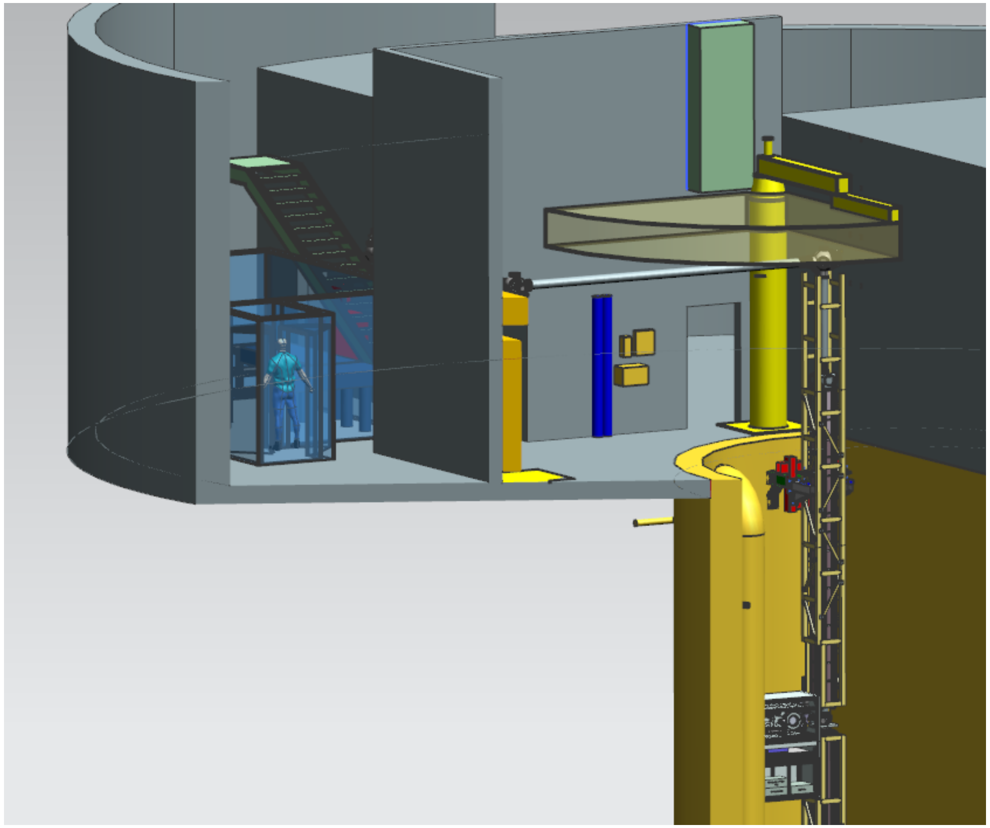




Civil Construction – Laser Room



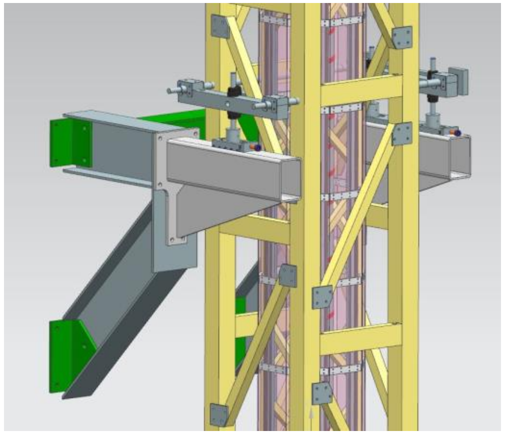
Plan view of shaft and laser room location.



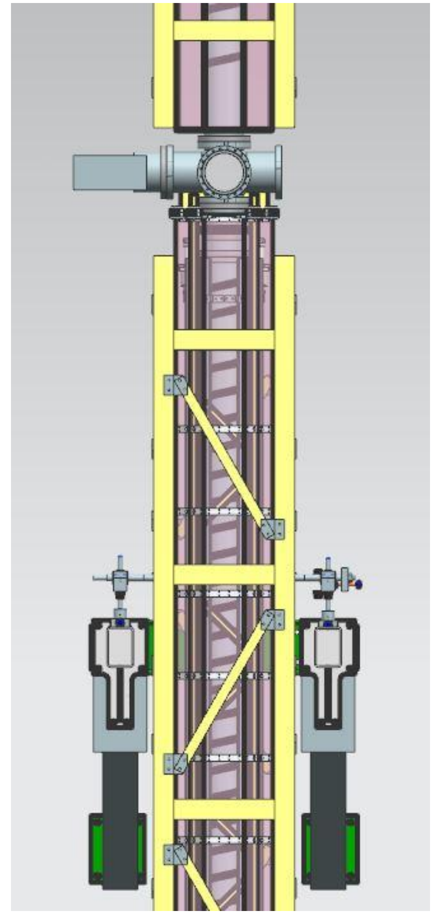
Cutaway view of shaft and laser room location.

A laser room will be constructed in a vacant room close to the shaft, providing a controlled space for the interferometry laser system.

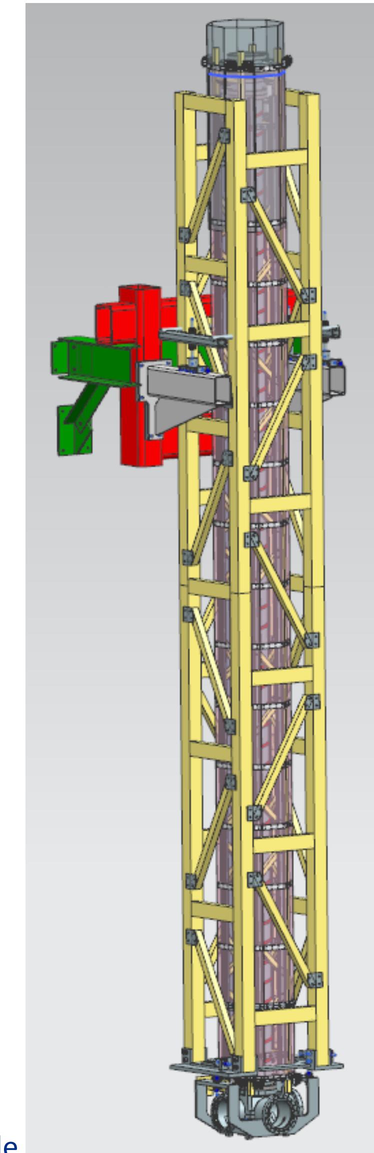
Modular Sections – Preliminary Design



- Modular assembly concept uses 17 sections, each ~5.3m long and ~2,000 lb weight.
- Stainless Steel vacuum tube, Al frames.
- 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 wires, octagonal mu metal shield with skeleton, and magnetometer.
- Vacuum pumps and viewports with cameras will be placed between tube sections.

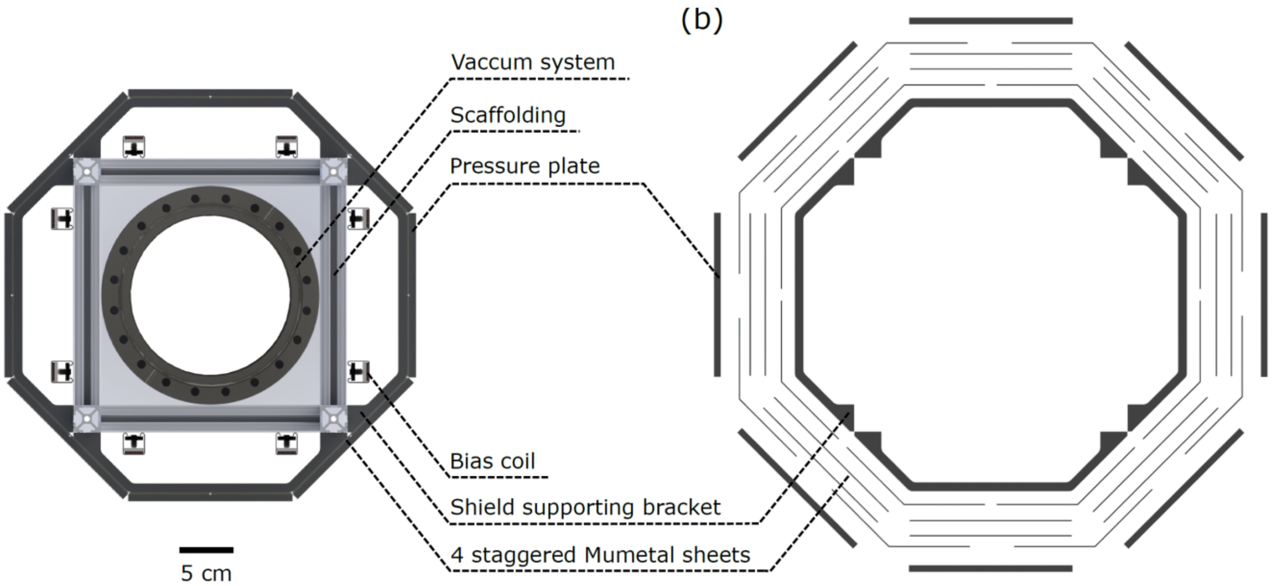


Two modules connected.



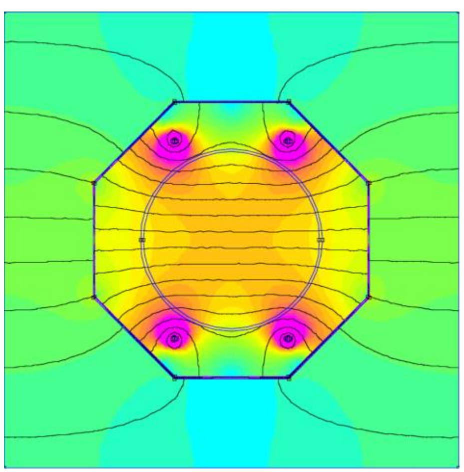
Single module.

Magnetic Shield

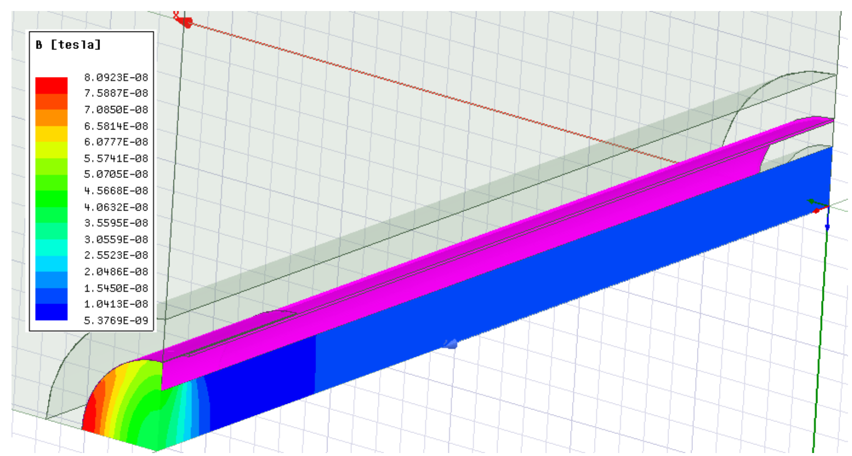


New shield design and simulation work

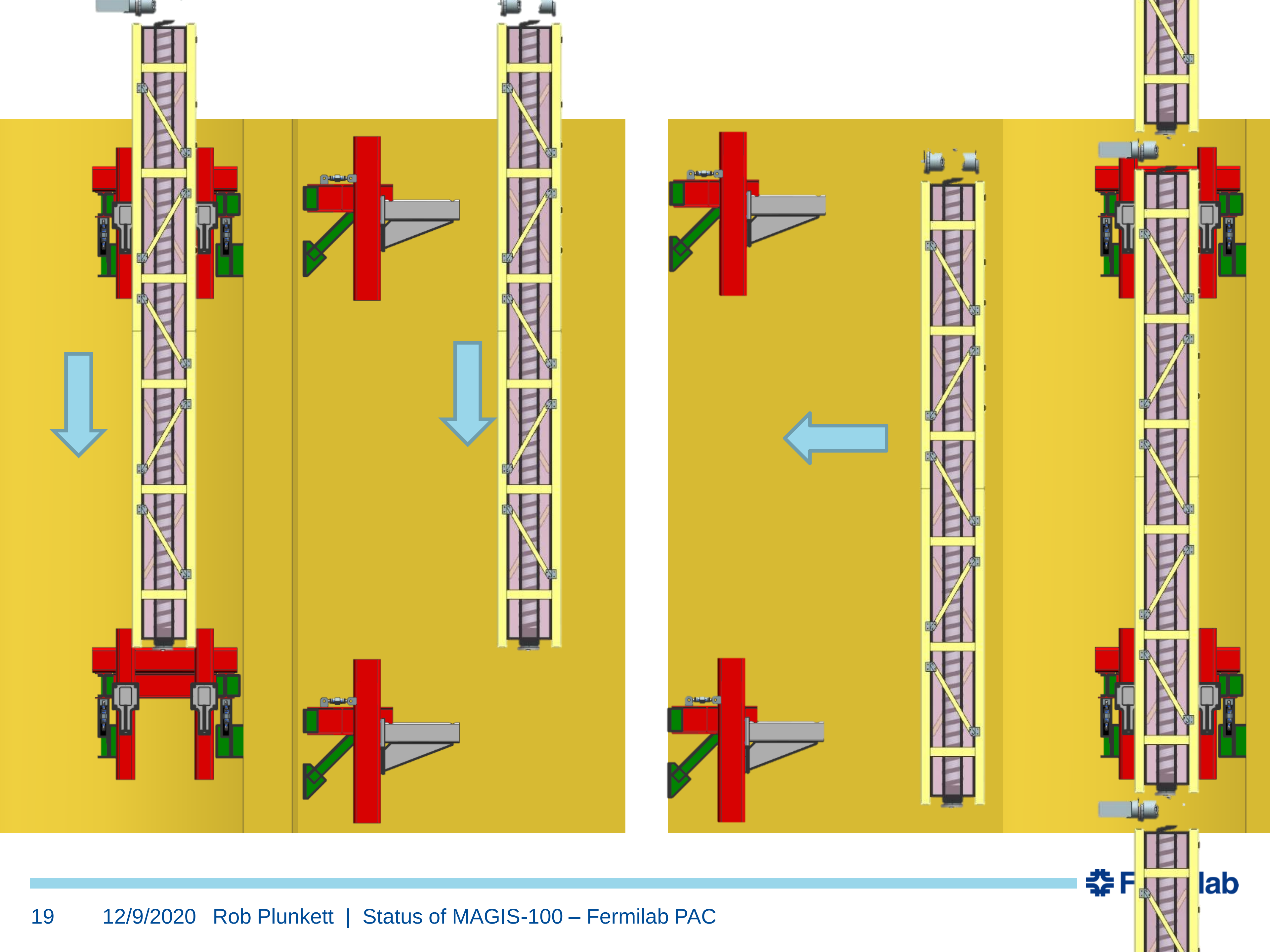
Octagon shield
4 sheet, overlapping design
Internal bias coils



Shield + bias field simulation (Stanford)



3D horizontal field simulation (Fermilab)

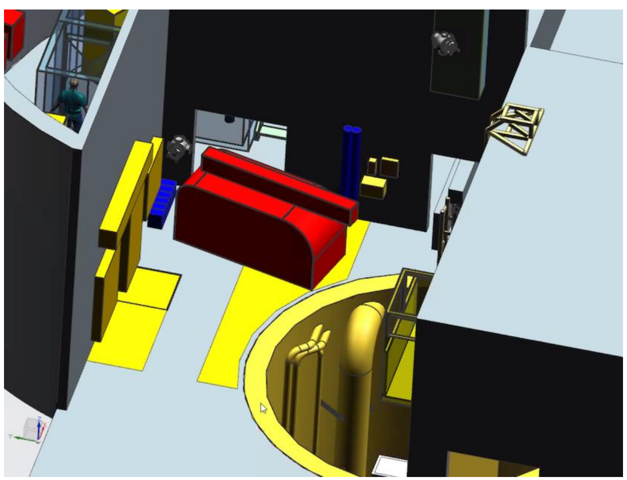


Additional Installation Progress at Fermilab

- Developed first draft of installation procedure, starting with staged, assembled modular strongback sections through the process of installation; focused on required fixtures, coordination of two cranes and personnel basket, and connecting to wall supports.

- Discussions with FESS and ES&H - presented updated project schedule and identified information that will be needed to proceed with civil contract for shaft.

- Investigated alternative auxiliary crane options, including mobile crane or second trolley on main bridge crane. Further investigation of mobile crane in progress with plan to bring crane to Fermilab for a maneuverability test.



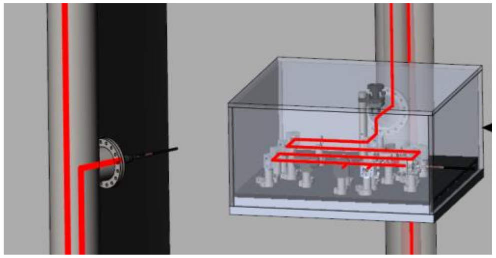
Laser Beam Delivery

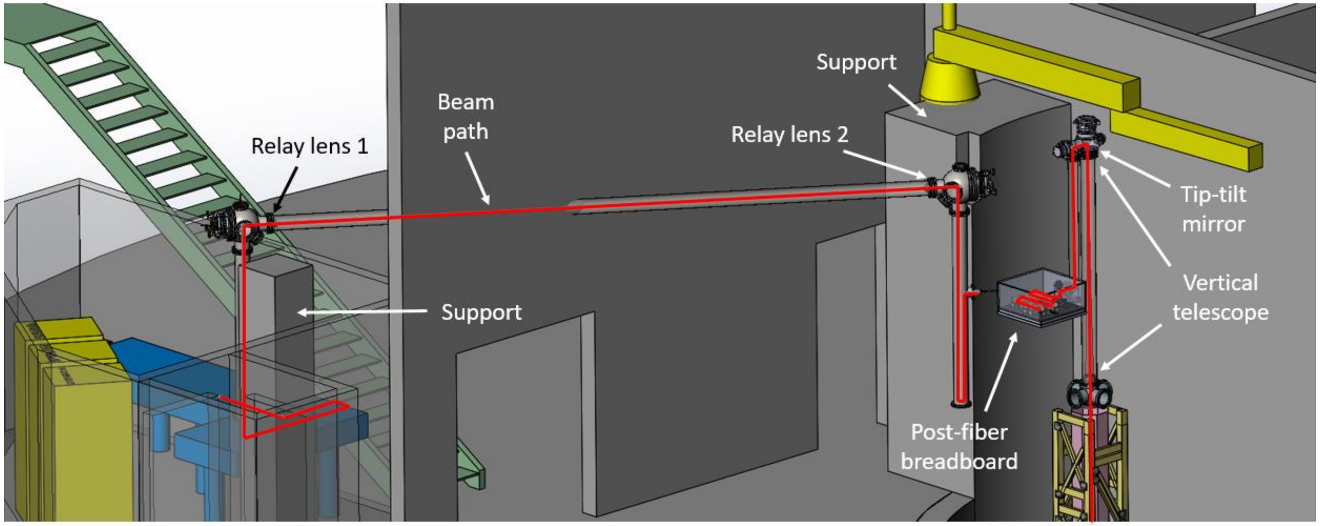
Carried out detailed analysis of options for beam delivery, balancing pointing stability, cost, and space constraints.

Optimal choice determined to be laser room away from shaft, **optical fiber after in-vacuum propagation to shaft to eliminate pointing jitter from delivery path** (relay image beam to fiber to maintain stable fiber couple, laser power servo after fiber).

Anchor final delivery optics near shaft to stable supports, possibly including high ceiling to right of shaft (support design currently in progress, informed by ongoing vibration measurements).

Fiber output pointing independent of input pointing.





Design review: ND-DOC-1069-v1

Optical Frequency Comb

Frequency comb

MenloSystems

Reviewed: 3/2019
Purchased: 9/2019

Ti:Sa integration and locking complete.

Diode laser integration next step (lasers shipped).

Delivery Dec. 2020

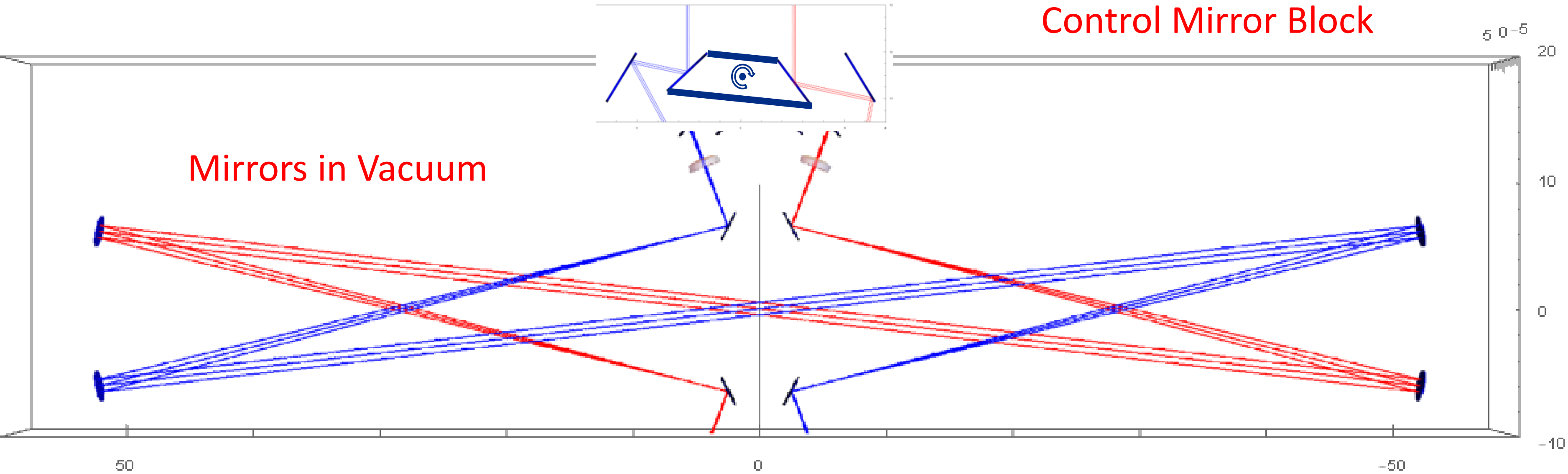
Wavelengths
1542 nm (cavity)
698 nm (atom optics)
689 nm (Red MOT)
707 nm (Repump)
679 nm (Repump/Raman)
688 nm (Raman/transparency)
922 nm (SHG Blue MOT)

Optical reference cavity

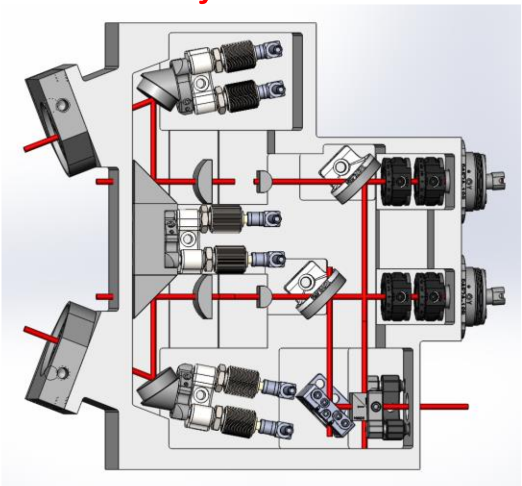
KEY SPECIFICATIONS

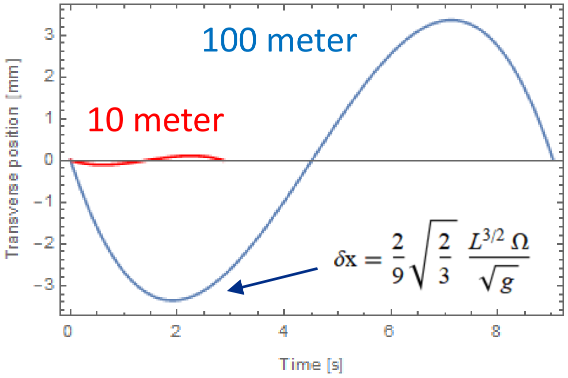
- Linewidth <1 Hz
- Allan Deviation <0.7-2 x 10^{-15}
- Wavelength range: 500 - 1600 nm
- Finesse ≈ 250 000
- 12 cm cylindrical ULE spacer

Optical Lattice Launching



Optics Controls outside for adjustment





Coriolis Compensated Launch for 3 pulse sequence

Experimental Simulation – getting ready for Science

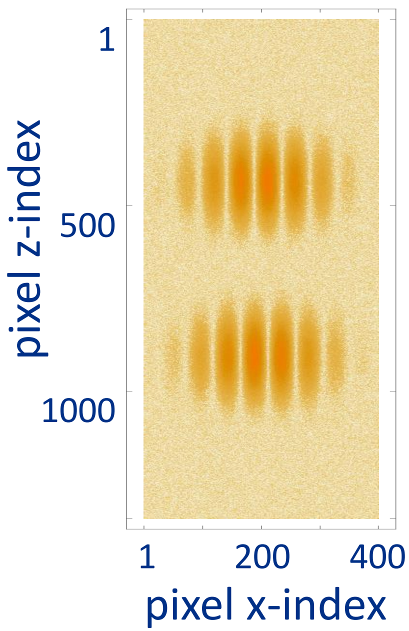
Start with

- analytically derived wavefunction → atom population at end of interferometer sequence, in imaging region

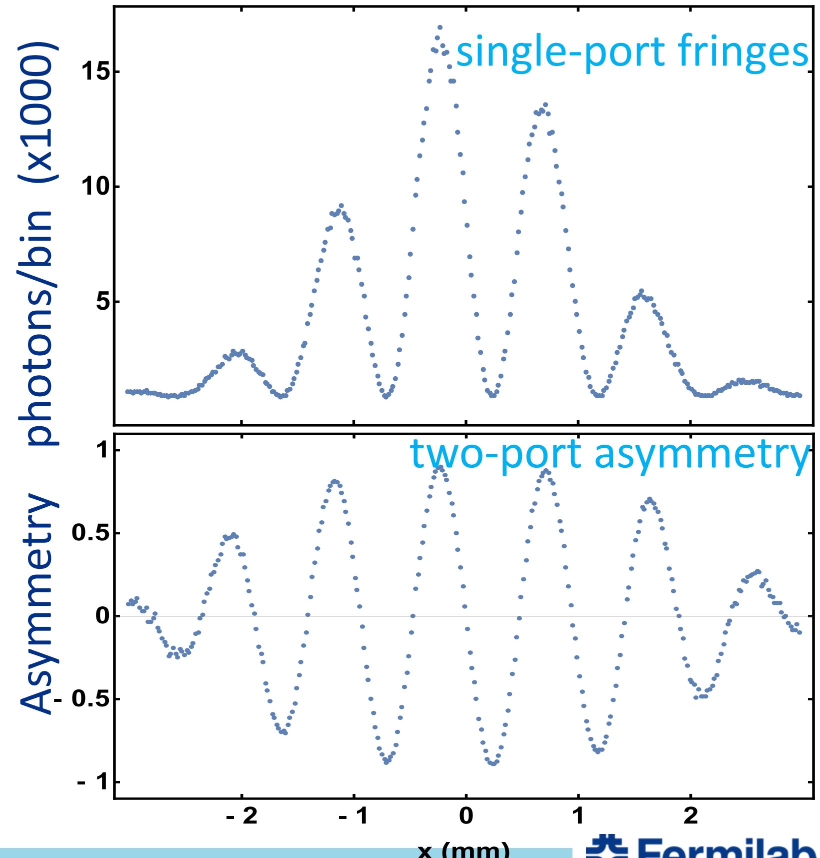
Simulation ingredients

- photon emission rate & imaging time
- optics: geom. acceptance & magnification
- CCD pixel geometry & quantum efficiency
- pixel readout noise + Gaussian fluctuations
- Atom statistics + Poisson fluctuations
- Photon emission statistics + Poisson fluctuations

Simulated Data



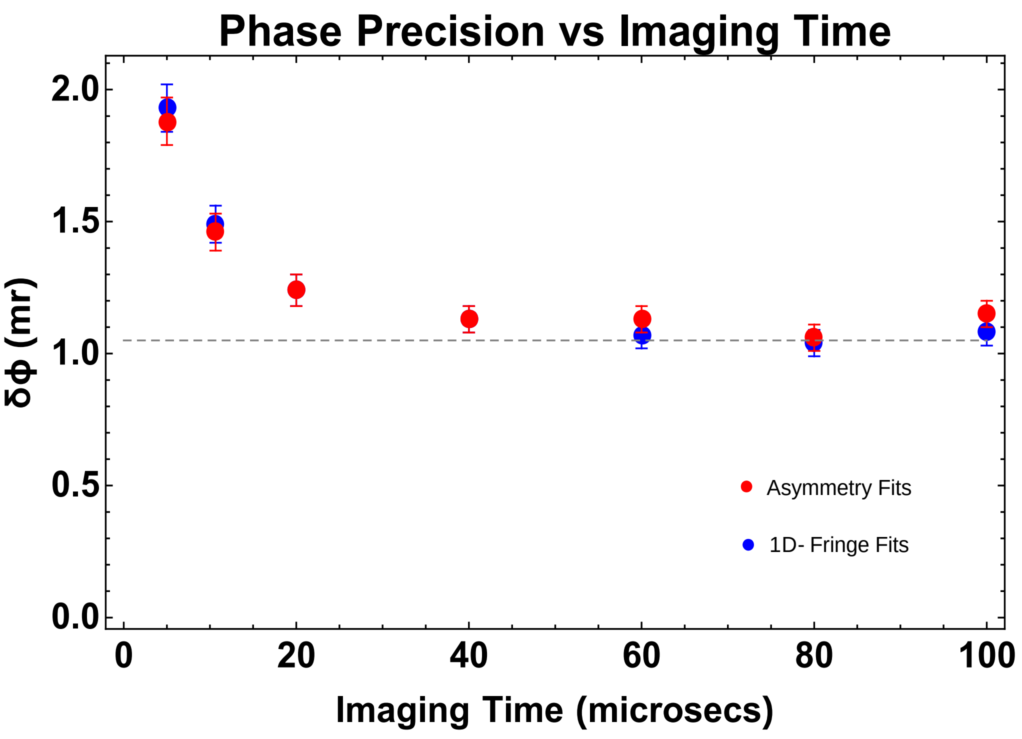
Simulated Data



Questions being addressed by Simulation

- What is the optimum imaging time –> impact of diffusion?
- How are various camera options likely to perform (noise, resolution, …)?
- What optical resolution (depth of field) is needed?
- What are the optimum operating parameters for the various science measurements?
- ….

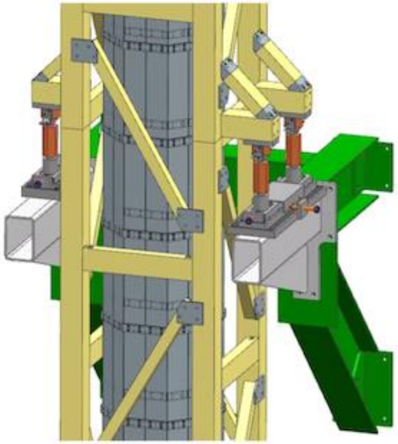
Simulation Result



Additional Recent Engineering Progress at Fermilab

- Working on integration at connection nodes. Added SLAC collaborators to weekly engineering meeting to ensure integration of camera systems.
- Alignment specification document was created and discussed with the collaboration; revisited alignment process with a meeting that included metrology experts from both Fermilab and SLAC to discuss both optical and wire alignment methods.
- Adjustor/support design for strongbacks for improved alignment tolerance and accessibility.

Details of Adjustment Fixtures



- Developed magnetic shield coupler details – studied magnetic effects and orientation, mechanical design, and impacts to other systems.
- Started small, focused weekly design meetings with Stanford to address details including supporting beam tubes within strongbacks, connection node design, vertical bias coils, assembly process for modular sections, and adjustor and strongback support design.

Partners and Task Division

- Atom Sources and Laser Systems are being built at universities using GBMF funds.
  - Major partners Stanford, Northwestern, Liverpool, Cambridge, NIU, SLAC.
- Conventional Construction handled by Fermilab.
- Some hardware purchased by universities, integrated and qualified at FNAL.
  - Example UHV pipe sections
- Funding Sources reflected in WBS

UK Contributions to MAGIS-100

- Funding comes as part of the BID to build AION
  - AION companion proposal in the UK
  - MAGIS-style detector, goal to provide verification of potential signals identified by MAGIS-100 using coincident detection
- Aim is to provide a detection sub-system for MAGIS-100
  - A similar system will be provided for AION
- Detection subsystem consists of:
  - Cameras + associated cooling and camera housing mechanics
  - DAQ, Timing, Network, control electronics,
  - Tip tilt stages for phase shear. Optics for lattice launch, in vacuum optics mechanical components
- Associated post-doc and engineering effort have been applied for
  - deliver the detection system
  - participate in data-analysis and preparation

UNIVERSITY OF CAMBRIDGE

UNIVERSITY OF LIVERPOOL

UNIVERSITY OF OXFORD

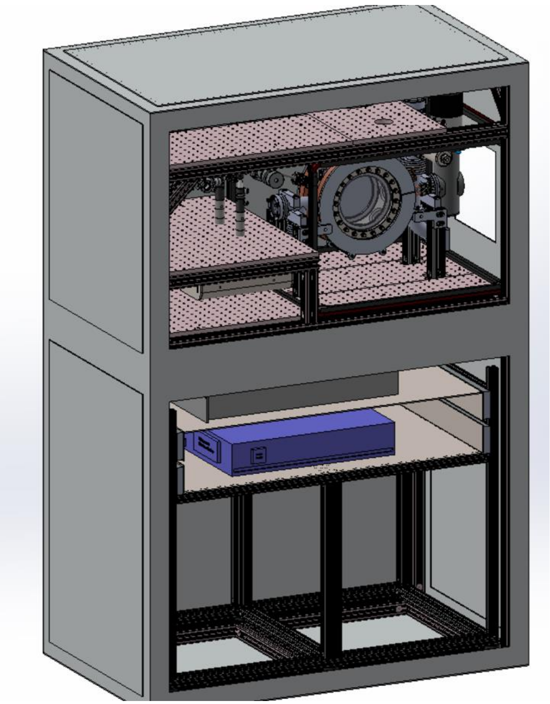
Present UK status

- Proposal has been successful.
- Currently finalising budget.
  - Hopeful to start in Feb 2021
- All involved UK Universities are now members of the collaboration.
- Cambridge post-doc has started with a Kavli grant.
- Looking forward to participating with a substantial contribution.

DOE Scope

- Provision of Site and Infrastructure
- Supports along Shaft Wall
- Installation System
- Mobile Work Platform
- Vacuum System Assembly
- Modular Section Strongback and Adjustable Supports
- Laser room
- Interlock Systems
- Controls and Networking
- Project management, Integration and Installation
- Commissioning and Data Collection
- Science Exploitation

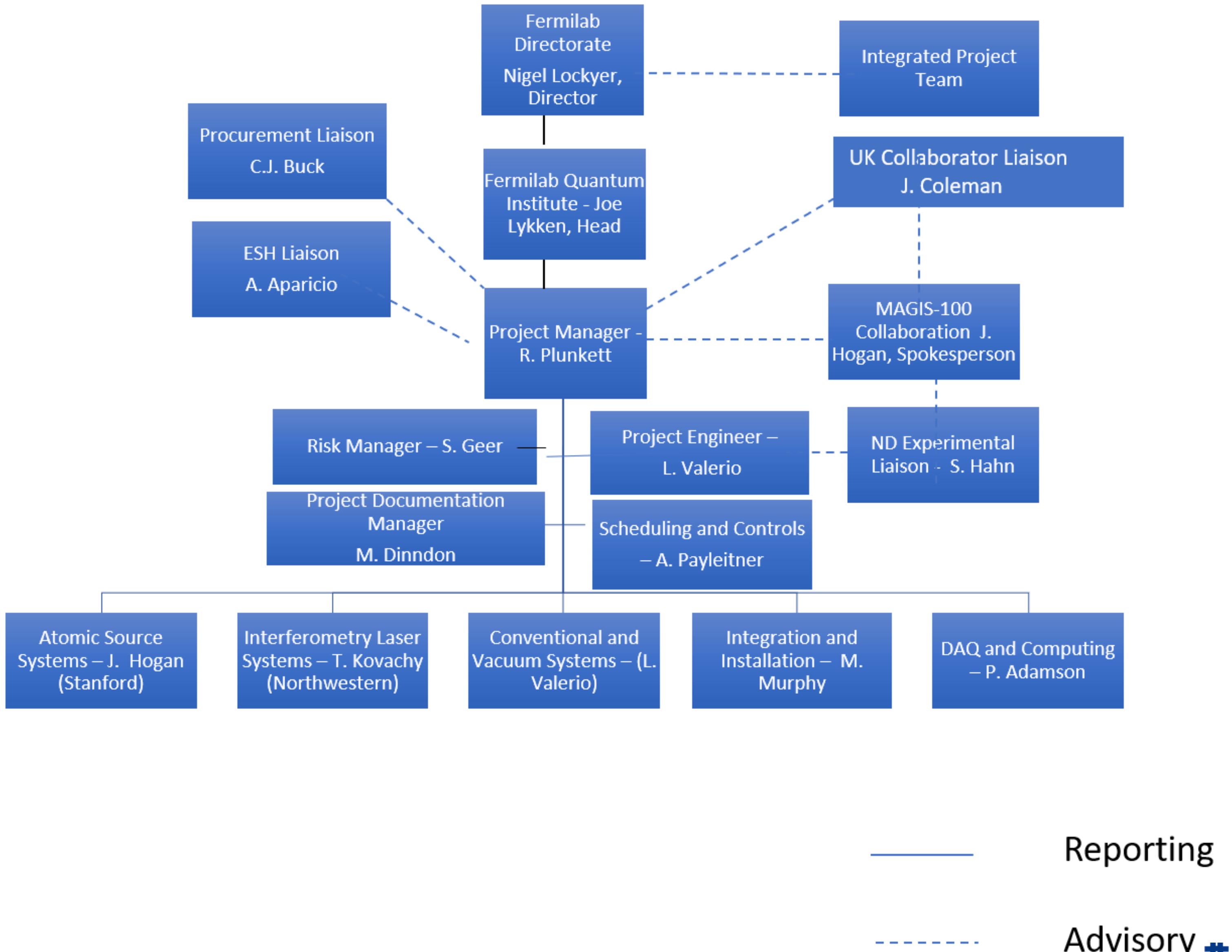
In-Kind Scope



- Strontium Atom Sources
- Vacuum System
- Connection Nodes
- Interferometry Laser System
- Magnetics control
- Environmental isolation and monitoring
- Cameras and detection systems
- Front-end DAQ
- Science Exploitation

- *Note that Procurement, ESH, Quality, Project Office Oversight, Building Management are In-Kind from Fermilab.*

Current Organizational Chart



Our Reviews

- E-1101 went through usual Fermilab PAC process for approval including presentations at 2 full PAC meetings
- GBMF proposal approved fall 2018
- Fermilab Director’s Review held August of 2019
- Followed by approval of QuantiSED proposal for $2.5 M
- Fermilab Director’s Cost and Schedule Review held September of 2020 (very thorough)

Financial Resources

- In-kind Scope from GMBF ~ $ 6 M
- Current QuantiSED budget $2.5 M in FY20-21.
  - Maximum possible award in funding round.
- Anticipate significant contribution from UK.
  - Reduces risk for in-kind contributions.
- Resource Loaded Schedule gives us DOE cost estimate.
- As presented in 2020 Review base cost is $ 5.7 M dollars for DOE scope.
- Standard project contingency rules (half from our risk register) work out to approx. additional $ 2.9 M.
  - Note this is for entire project, not just DOE scope.

Cost and Profiles

- Funding gap was expected.
  - Clearly pointed out in 2019 review – funding then was partially targeted at development of better estimate.
- Working with lab and DOE to increase funding.★
- Evaluating of additional funding profiles and interaction with schedule.
- Beginning discussion with FY21 at suggestion of DOE.
- Will look at FY22 and 22-23 for final funding.

People Resources

- Growing collaboration
  - Recent additions of Oxford, Cambridge, SLAC.
  - First Ph.D. awarded to NIU student!
- Recently added vacuum engineer, additional project management assistance, laser coordinator, installation coordinator.
  - Evaluating adding more engineering resources.
- Using other lab engineering resources (PPD, FESS) as available and needed. ★

- University collaborator headcount: 15 faculty/staff, 6 postdocs, 12 students.
- Labs headcount (Fermilab + SLAC): 9 staff, 1 student.

Fermilab Collaboration

- Senior Scientists
  - Rob Plunkett, Project Manager
  - Steve Geer, Risk Manager, Computing and Simulation
  - Phil Adamson, Controls and Monitoring
- Other Scientific Staff
  - Jamie Santucci, Lasers
  - Marty Murphy, Installation and Integration (new)
  - Steve Hahn (Experimental Liaison, Neutrino Division)
  - Mandy Kiburg (requested)
- Engineering and Technical
  - Linda Valerio, Project Engineer
  - Lucy Nobrega, Vacuum Engineer (new)
  - Noah Curfman, Mechanical Engineer (new)
  - Arv Vasyonis, FESS Civil
  - Marcel Borcean, FESS Cranes
  - Ron Kellett, Vacuum
  - Dirk Hurd, Design
  - Electrical engineering and technician support will be needed at times. (requested)
- Project Management
  - Alyssa Payleitner – Project Controls
  - Mike Dinnon – Project Documentation (new)
- Plus occasional matrixed help from PPD.

Most Staff part-time.

Preliminary Timeline

RLS is technically driven calendar.
Currently working on resource leveling.
Agreement on longer term budget profile can cause impacts.

- Civil construction to be started late 2021.
  Procurement time consuming.
- Modular assembly to start mid 2021 (if technicians available).
- Experiment installed by June 2022 (Infrastructure) – Nov 2022 (Atom Sources).
- Commissioning early 2023.

Schedule with shaft construction prioritized and resource leveling in progress (Nov 2020):

					Accelerator Shutdown (technicians scarce)				Accelerator Shutdown (technicians scarce)	
	FY20	FY21				FY22				FY23
	July-Sept 20	Oct-Dec 20	Jan-March 21	April-June 21	July-Sept 21	Oct-Dec 21	Jan-March 22	April-June 22	July-Sept 22	Oct-Dec 22
Phase	*Design*	*Design/Procure*			*Civil Construction contracts prepared*	*Civil Construction - Shaft and Laser Room*	*Prepare for Installations*	*Laser Installation*	*Awaiting In-kind contributions*	*Final Shaft Installation*
					Modular Assembly			*Shaft Installation*		

Fermilab

Critical Path

Using P6 Scheduling Tool to define a realistic critical path. ★

Part of resource leveling ongoing exercise.

Items expected to be on or near the resulting critical path include:

- Procurement and execution of shaft renovation contract
- Design and delivery of vacuum system
- Design and delivery of magnetic shield and bias coils
- Design and delivery of 3 special connection nodes
- Assembly of 17 modular sections
- Qualification and installation of atom sources, comb, and DAQ

Important Milestones from Project Plan ★

Milestone	Definition	Baseline Date
Start Project	Funding available	10/1/19
Construction		
Civil Design	Shaft support design complete	7/1/21
Vacuum system	Complete installation of vacuum pipe in shaft	10/1/22
Atom Sources	Two atom sources installed at FNAL	4/1/23
First beam	Turn on of laser; interaction with atoms from a source	7/1/23
Commissioning	Atom interferometry with multiple atom sources; preliminary quantum science results	10/1/23
Science Exploitation		
Data taking and Analysis	Preliminary physics search results	8/1/25

COVID-19 Impacts and Schedule

- Comprehensive statusing assessed in mid-August.
- Impacts up to present:
  - Closure followed by restrictions of university lab facilities.
  - Reduced efficiency of design phase at Fermilab.
  - Reduced speed of on-site planning work.
  - Reduced efficiency of personnel matrixed to other COVID-19 related responsibilities.
- These delays were covered by the base schedule.
- Additionally, COVID-19 inefficiencies were applied to each task in P6 to create COVID-19 “medium” and “high” scenarios for planning purposes.

Status of COVID Analysis in RLS

A1207030	Final Alignment of Experiment Milestone		08-Nov-2022
A1207060	Milestone - construction complete		10-Nov-2022
A1503340	Milestone - commisioning complete		30-Jun-2023

Laboratory Proposed COVID Impact Calendars

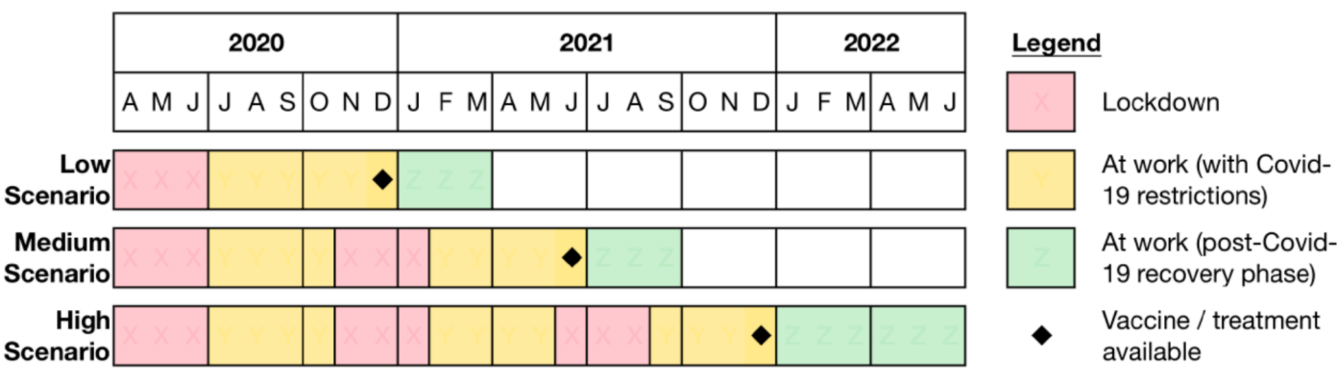
Proposed MEDIUM Scenario

14-Feb-2023
16-Feb-2023
14-Aug-2023

Individual task efficiencies set by project

Proposed HIGH Scenario

28-Jun-2023
30-Jun-2023
03-Jan-2024



Expect additional cost of $50K - $250K depending on scenario.

Conclusions

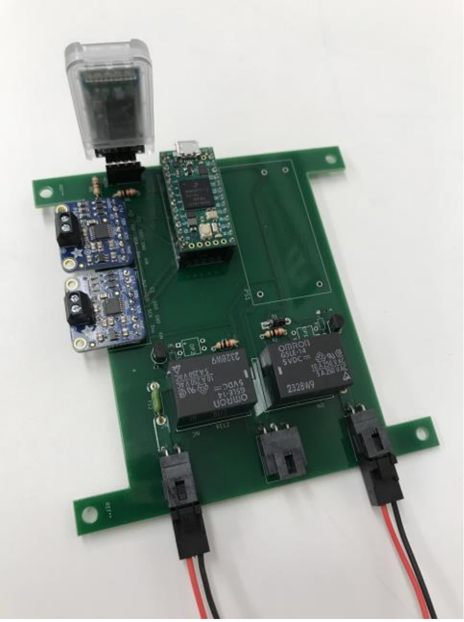
- MAGIS-100 has made significant technical and management progress and key design decisions.
- Continuing to strengthen project team and collaboration.
- Moving forward with Simulation and Computing
  - Vital emphasis for early science results!
- Integrating use of RLS throughout project.
  - Vital for continued development of cost profiles.
- Need to augment current QuantiSED funding.
- COVID remains a challenge for all schedules.
- Encouragement by Fermilab PAC has been vital at every step.
- We request your continued support as we press forward with design, construction, commissioning, and science.

Backup

Additional Recent Technical Progress at Fermilab

- Continued to work toward characterizing vibrations in the MINOS building; fabricated wall bracket, scanned elevator wall, and developed plan to mount new accelerometer strategically on that wall.
- Planned epoxy vacuum outgassing tests and purchased materials to test proposed materials for piezo actuators.
- Conducted successful “proof-of-concept” vacuum heat system test with proposed heat tapes and controllers.

Heat tape wrapped around 6” OD tube in the Fermilab Village.



Prototype control system for the heat tape used for a vacuum bake.

Significant Accomplishments

- Collaboration reviewed and procured major in-kind items:
  - Optical comb,
  - Most lasers,
  - Optical table (first phase),
  - Magnetic shield for 10 m prototype at Stanford.
- Stanford accomplished record momentum transfer to Sr atoms.
- Location and preliminary design of laser room.
- Laser scheme for interface with comb.
- Down-selected laser transport system.
- Advanced strongback design.
- Advanced design of 10 m prototype at Stanford.
- Advanced modeling and design of magnetic shield.
- Identified installation crane candidates.
- Identified installation system candidates.
- Preliminary installation scheme.
- Design of advanced in-vacuum optics for launch lattice and beam reflections.
- Modular design of atom source enclosure and support electronics.
- Experimental simulation written.
- Established detailed WBS, BOE's and Resource Loaded Schedule.
- Expanded Risk Register with contingency analysis.
- Liaison with Equipment Transportation Oversight Committee.

★ Review Recommendation

Additional Recent Progress by Collaborators (1) - Stanford and others

- Optical lattice shuttle design completed, including delivery optics, ray tracing, and lattice loss simulations. The next step will be to construct a test prototype.
- 100 meter horizontal magnetic bias field simulation created. The simulation addresses field anomalies due to gaps between modules, and quantifies the advantages of a segmented design with individually tuned currents compared to a constant current approach.
- Atom source laser local oscillator system assembled and shipped to optical comb vendor for locking and integration. This assembly consists of rack-mounted diode lasers for each wavelength needed for laser cooling.
- Designed a magnetometer shuttle system for measuring the magnetic field profile inside the magnetic shield during module assembly and testing.
- Validated laser beat note detection circuit with phase locked loop test and laser lock. This circuit will be used to lock all the atom source lasers to the comb-stabilized lasers with individually tunable offsets.
- Camera design and alignment concepts by SLAC and UK.

Additional Recent Progress by Collaborators (2)

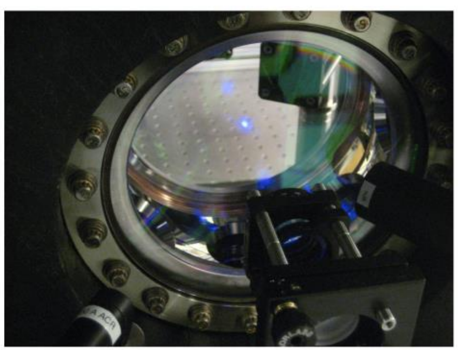
Northwestern and others

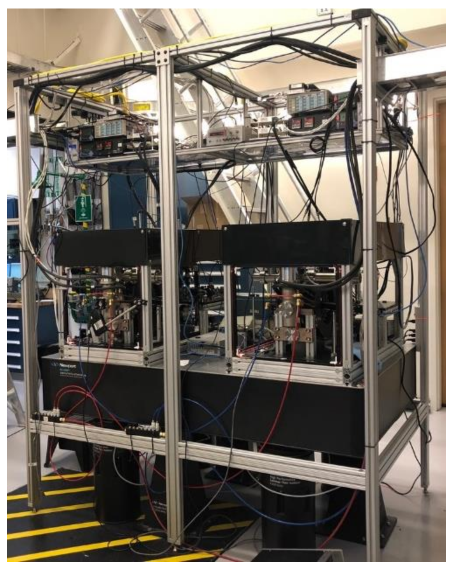
- Detailed schematics of optical components on laser table developed and reviewed, and most components already ordered.
- Have taken delivery of loaner Ti:Sa lasers from and many associated optical elements, allowed testing to begin at Northwestern
- Designed and reviewed laser table layout, laser table recently delivered.
- Coordinating with vendor on some aspects of testing (including coherent combination of two Ti:Sa lasers, fast/broad frequency tunability, and stabilization to frequency comb)
  - Serves to mitigate risk; vendor doing this work at no additional cost
  - Testing now completed
- Numerical and analytical calculations to analyze spatial filtering of the laser beam's wavefront/intensity profile via free space propagation before telescope
  - Informed design of in-vacuum beam delivery path
- Design and sourcing of ultra-high quality in-vacuum mirrors and lenses for telescope and tip-tilt mirrors
- Design and sourcing of upper tip-tilt mirror systems
- Vibration and seismometry measurements by NIU.

Stanford 10-meter MAGIS prototype

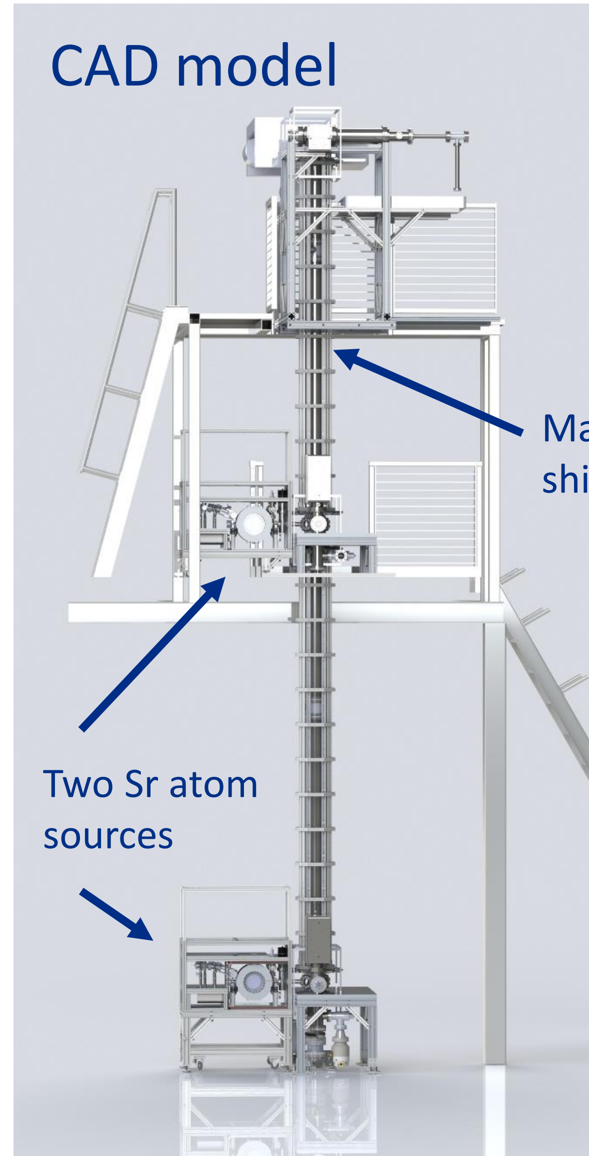
- ✓ Design, procurement complete
- ✓ All major components **received**
- ✓ Optical lattice launch setup test alignment
- ✓ Both atom sources operating
- ✓ **Next:** Magnetic shield assembly & test

Sr MOT





Two Sr atom sources



Possible Mobile Crane

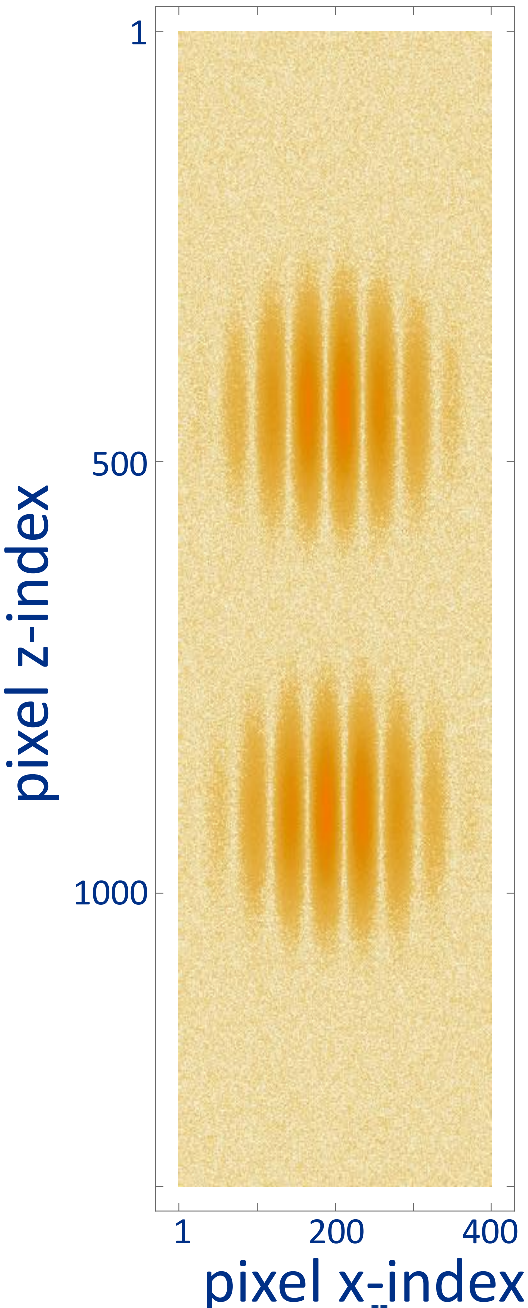
Simulation - details

Start with

- analytically derived wavefunction → atom population at end of interferometer sequence, in imaging region
- Phase shear technique

Simulation ingredients

- photon emission rate & imaging time
- Atom diffusion during imaging
- optics: geom. acceptance & magnification & resolution
- CCD pixel geometry & quantum efficiency
- pixel readout noise + Gaussian fluctuations
- Atom statistics + Poisson fluctuations
- Photon emission statistics + Poisson fluctuations



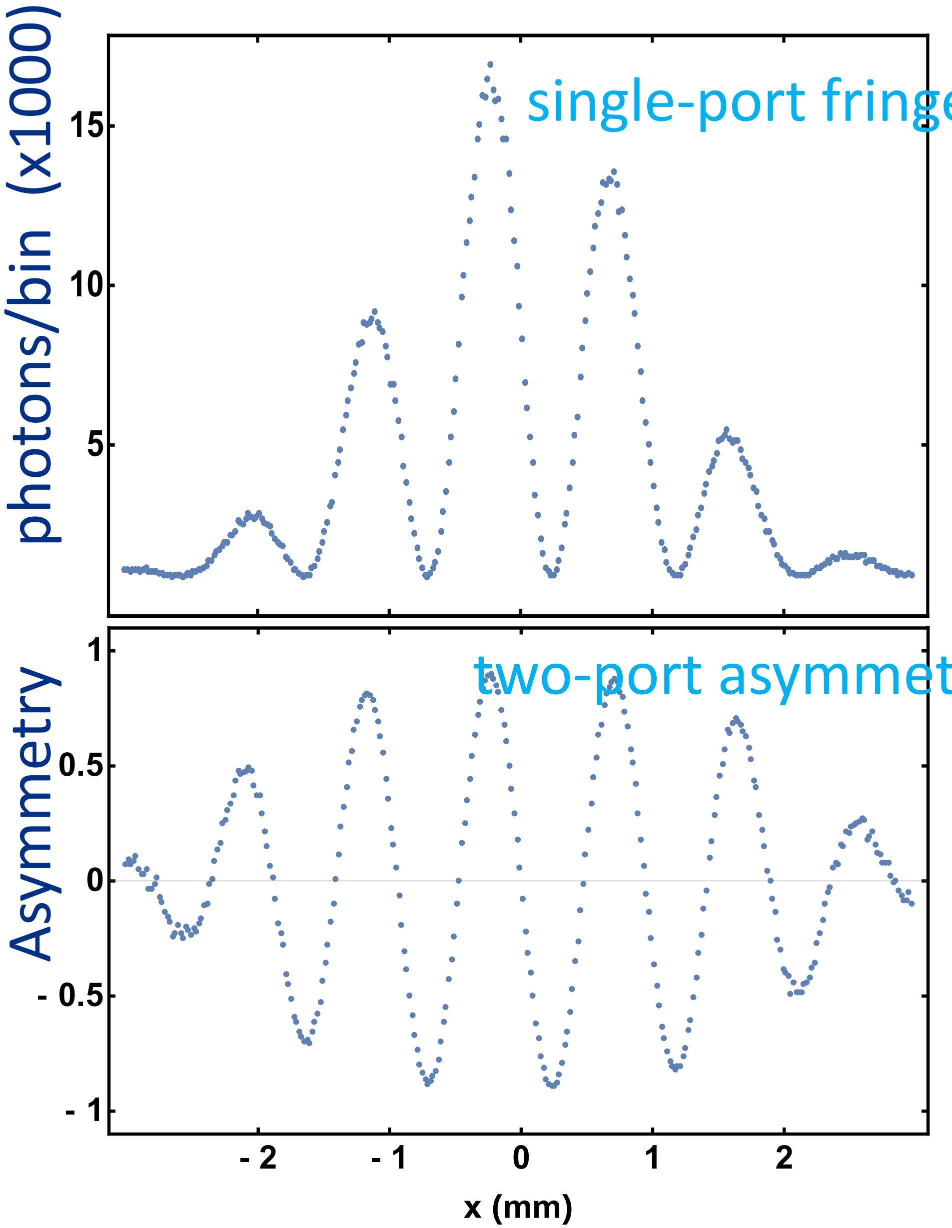
Simulation Results

Phase Extraction

- Various analysis techniques being explored to fit for the interference pattern for the phase.

Results

- Fits give good descriptions of simulated images
- Fits yield shot-noise limited phase precision when operation parameters optimized
- Dependence of precision on statistics and readout noise is well understood.



High Level WBS and Responsibilities

WBS	Name	Type
1.00	Project Management, Safety, and Quality	DOE
2.00	Strontium Atom Sources	In-kind
3.00	Interferometry Laser Systems	In-kind
4.00	Frequency Comb	In-kind
5.00	Connection Nodes	In-kind
6.00	Interferometer Support Systems	In-kind
7.00	Vacuum System Components	In-kind
8.00	Structural Systems	DOE
9.00	Site Facility Systems	DOE
10.00	DAQ Computing and Front End	In-kind
11.00	Controls and Networking	DOE
12.00	Design and Integration Effort	DOE
13.00	Calculations and Analysis	DOE and collaboration
14.00	Experimental Commissioning	DOE and collaboration
15.00	Camera System	In-kind
16.00	Equipment Qualification and Assembly	DOE
17.00	Integration and Installation	DOE

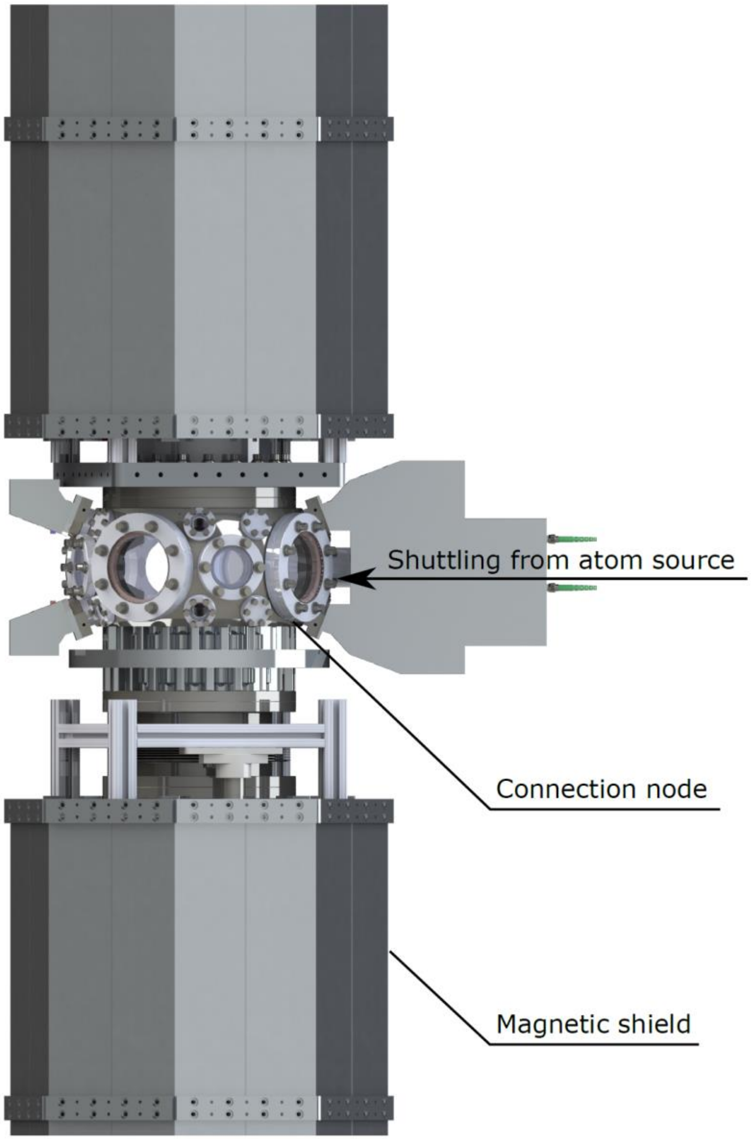
Milestones for Management

- RLS contains 99 milestones, with appropriate logical connections to tasks.
- Have avoided “hanging” milestones with no task connections.
- Milestones for both Fermilab and In-kind WBS elements.

Sample Milestones

MAGIS100 - WS	MAGIS 100 - Milestone List	Standard Schedule		Medium Scenario v2		High Scenario v2	
Activity ID	**Activity Name**	**Start**	**Finish**	**Start**	**Finish**	**Start**	**Finish**
A1203050	Receive frequency comb		16-Sep-22		16-Sep-22		16-Sep-22
A1203010	Receive first atom source		26-Sep-22		28-Dec-22		15-May-23
A1203020	Receive second atom source		26-Sep-22		28-Dec-22		15-May-23
A1203030	Receive third atom source		26-Sep-22		28-Dec-22		15-May-23
A1203410	Receive DAQ for atom sources		26-Sep-22		16-Nov-22		23-Mar-23
A1203420	Receive DAQ for laser system		26-Sep-22		16-Nov-22		23-Mar-23
A1203430	Receive central computer		26-Sep-22		16-Nov-22		23-Mar-23
MAGIS100-WS.16.02 Assembly							
A1503290	Assembly of modular sections 30% complete - milestone		28-Sep-21		4-Apr-22		17-Aug-22
A1503300	Assembly of modular sections 60% complete - milestone		21-Dec-21		24-Jun-22		8-Nov-22
A1503310	Assembly of modular sections 100% complete - milestone		21-Mar-22		19-Sep-22		8-Feb-23
MAGIS100-WS.17 Installation & Integration							
MAGIS100-WS.17.01 Installation							
A1206100	Milestone - Phase 1 shaft installation complete		10-Jun-22		12-Dec-22		1-May-23
A1503220	Installation of Laser Transport System Complete- Milestone		6-Jul-22		5-Oct-22		9-Feb-23
A1206110	Milestone - Phase 2 shaft installation complete		10-Nov-22		16-Feb-23		30-Jun-23
MAGIS100-WS.17.02 Qualification and operational integration							
A1207030	Final Alignment of Experiment Milestone		8-Nov-22		14-Feb-23		28-Jun-23
A1207060	Milestone - construction complete		10-Nov-22		16-Feb-23		30-Jun-23
A1503340	Milestone - commisioning complete		30-Jun-23		14-Aug-23		3-Jan-24

Optical lattice launch



689 nm lattice for vertical atom launching before interferometry

Lattice optics design

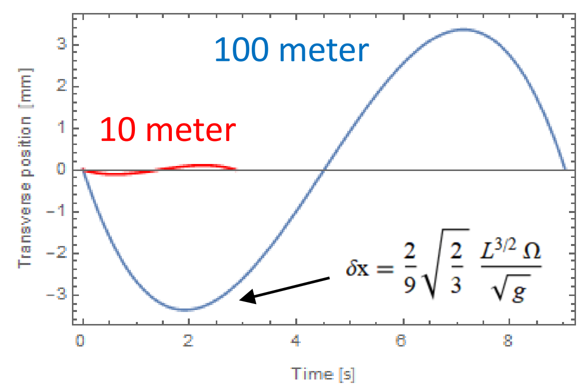
In-vacuum optics minimize shield gap

X beam path design supports independent launches for each source

Dynamic launch angle fine tuning with PZT mirror for Coriolis pre-compensation

Beam position sensing photodiodes

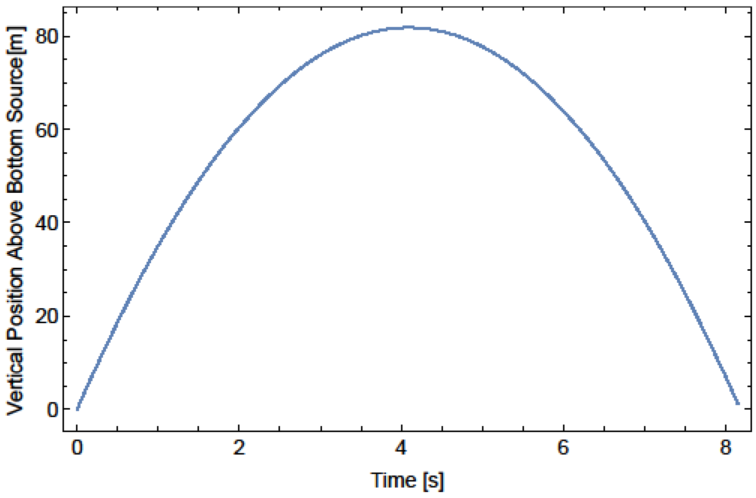
Monolithic beam delivery module



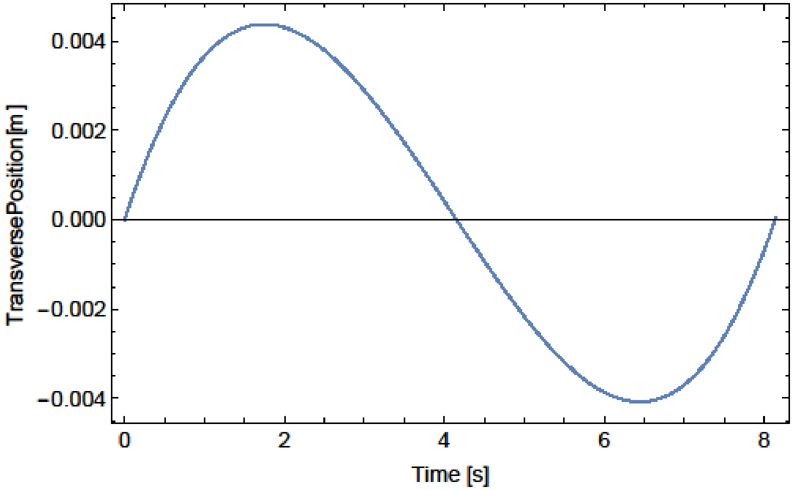
Minimum Coriolis displacement launch

Coriolis Trajectories

Trajectory for a launch from the bottom



For the correct launch angle, the transverse displacement of the atom cloud is zero at the first beam splitter pulse sequence, the mirror pulse sequence, and the final beam splitter pulse sequence



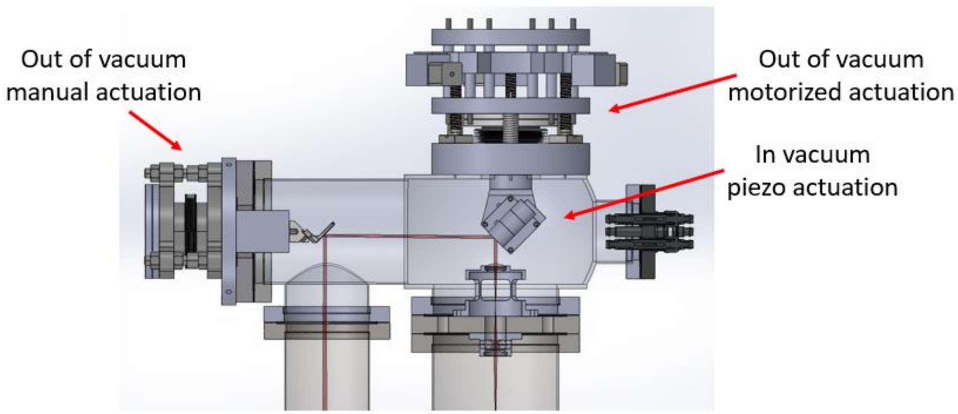
Laser Beam Delivery

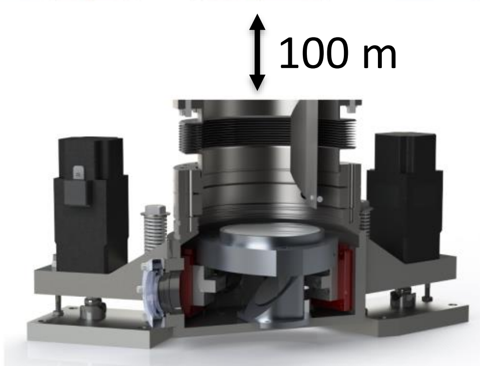
Upper tip-tilt mirror before 30x magnification telescope (telescope de-magnifies beam pointing fluctuations from any earlier optics by a factor of 30)

Free space propagation before telescope cleans beam's spatial mode

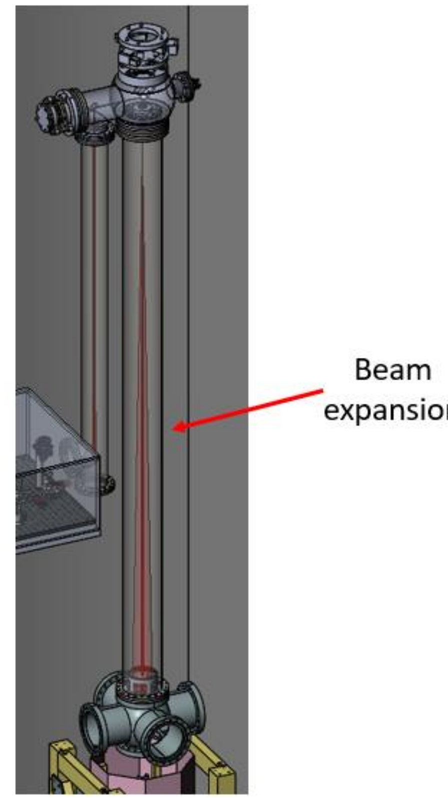
Second tip-tilt mirror at bottom of shaft, back reflects beam

Upper tip-tilt mirror





Lower tip-tilt mirror

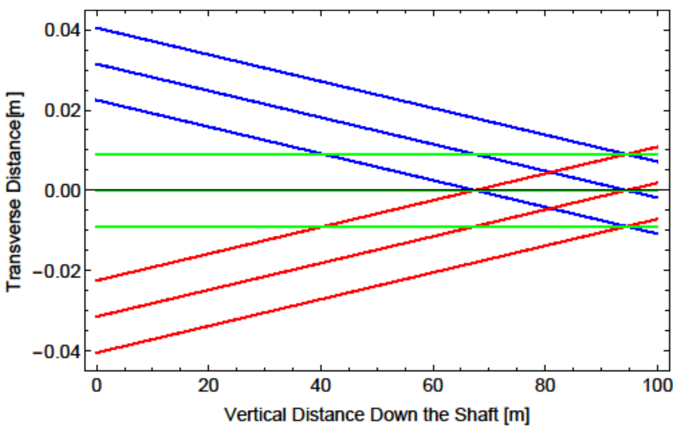


Pivot Point Considerations

For tip-tilt mirror ~5 cm in front of first telescope lens, can place pivot point of rotation near bottom atom source

Bottom tip-tilt mirror back reflects beam

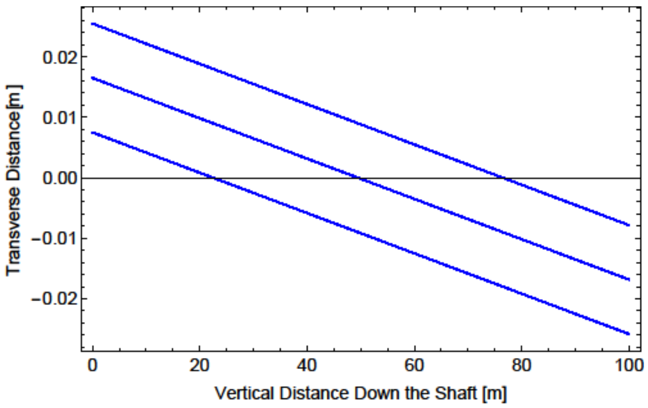
For launch from the bottom, beam centered on atoms at all 3 pulse zones



Can also translate the beam by adjusting the beam to be transversely off center from the telescope, transverse displacement magnified by telescope magnification (in this example, there is a 500 micron displacement)

Translation performed by out-of-vacuum translation stages

Allows beam to be centered on atoms for all pulses if we launch or drop from a different atom source



Strategy of Project Management

- Hybrid Project
  - Very significant in-kind contributions
- Focus on Requirements flowing down from Science Goals.
  - Docdb 366
- Manage project to minimize identified Risks
  - Docdb 372 and 1078
  - Risk Manager reports directly to PM
- Reporting for In-kind focuses on statusing
  - Separate funding with its own demands.
- Project home Division now Fermilab Quantum Institute
  - Resources will come from wherever most available.
- DOE scope follows laboratory management recommendations
- ESHQ on site follows Fermilab procedures, off site consults with university safety colleagues.

Regular Project Meetings

- Local engineering meeting weekly (Mon)
- Project office bi-weekly (Mon)
- Collaboration engineering meeting weekly (Tues)
- Laser meeting bi-weekly (Wed)
- Simulation Case study meeting bi-weekly (Wed)
- General Collaboration meeting bi-weekly (Thur)
- Project management team bi-weekly (Thur)
- DOE phone call monthly
- Numerous (8) meetings with FESS on Civil Construction issues.
- Local and collaboration meetings for special topics as needed
- Institutional Board meetings as needed

- *With the exception of the PO, DOE, and local eng meetings, all other meetings are widely attended by the collaboration.*
- *MAGIS-100 Meeting Calendar on Outlook.*

Representative BOE

MAGIS-100 Basis of Estimate (BOE) File

NOTE: Grayed cells are filled in automatically from the Labor and M&S Sheet data. Fill in light blue cells.

SUMMARY

WBS:	16.00
WBS Name:	Equipment Qualification & Assembly
BOE File ID:	16.02
BOE File ID Title:	Assembly
BOE File ID Description:	Preparation of work space, assembly fixtures, and vacuum equipment. Assembly of 17 modular sections. Assembly of Laser Transport System tubes, optics, and supports.
Estimator:	Linda Valerio
Contributors:	
Date:	9/2/2020 Estimate date
Organization:	Fermilab

Base Labor (hours):	4,487
Labor Estimate Type:	Preliminary
Base M&S ($):	$0
M&S Estimate Type:	Preliminary
Most Likey Duration (Working Days):	See labor tab for task breakdown and durations.
Optimistic Duration Working Days):	
Pessimistic Duratiion (Working Days):	

Labor Summary By Resource Type (hours):

Year 1 is the year when the task starts. The duration of most tasks is less than 2 months (exceptions are planning packages and LOE tasks)

Resource Role	Total	Year 1	Year 2	Year 3	Year 4	Year 5
Mechanical Engineer	424	424	0	0	0	0
Mechanical Engineer Sr	20	20	0	0	0	0
Mechanical Technician	2,518	2,518	0	0	0	0
Mechanical Technician Sr	1,389	1,389	0	0	0	0
Electrical Technician Sr	136	136	0	0	0	0
0		0	0	0	0	0
		0	0	0	0	0
		0	0	0	0	0
		0	0	0	0	0
		0	0	0	0	0
		0	0	0	0	0
		0	0	0	0	0
		0	0	0	0	0
		0	0	0	0	0
		0	0	0	0	0
		0	0	0	0	0
		0	0	0	0	0
		0	0	0	0	0
TOTAL	4,487	**4,487**	**0**	**0**	**0**	**0**

BOE ASSUMPTIONS

Common Assumptions — **These assumptions are common to all BOEs**

Estimates are for MAGIS-100 project activities only
M&S Costs are in 2020 dollars and do not include indirects and escalation
Duration estimates are in calendar days
Labor estimates are in working hours
1 FTE = 1768 hours for an average year

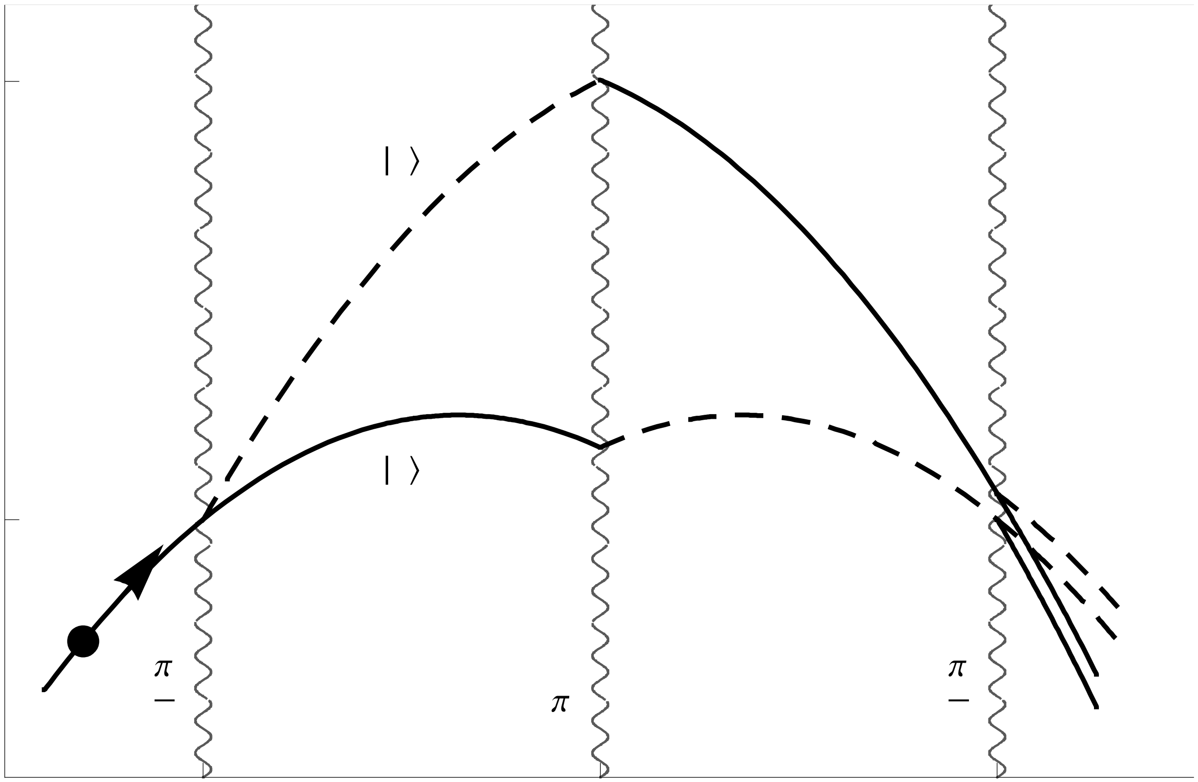
BOE File ID Assumptions — **These assumptions are specific to this BOE**

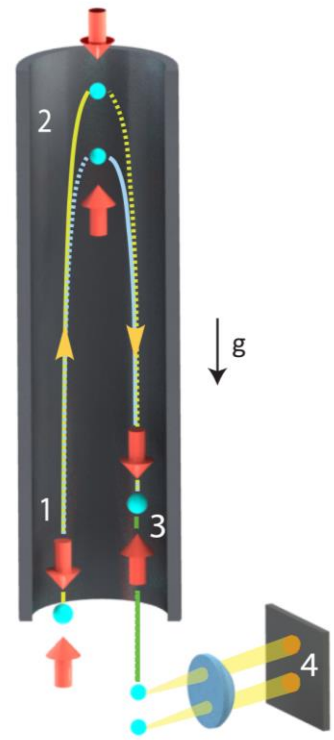
Did NOT use multi-year features of BOE form.
Assume Project Engineer, Installation Coordinator, and Laser Engineering Physicist will provide LOE oversight not explicitly counted here (counted in WBS 1.01).

RLS Budget Table

		FY20	FY21	FY22	FY23	FY24	Total
Labor							
	FTE	2.42	5.62	5.42	1.97		15.43
	SWF direct+indirect + escalation	752,545	1,469,111	1,331,169	484,536		4,037,361
	SWF Estimate Uncertainty Contingency	225,763	415,257	349,417	108,160		1,098,597
	Total	978,308	1,884,369	1,680,587	592,696		5,135,959
NonLabor							
	FTE	0.07	0.04				0.11
	SWF direct+indirect + escalation	26,094	14,352				40,446
	SWF Estimate Uncertainty Contingency	7,828	4,306				12,134
	Total	33,922	18,658				52,580
M&S							
	M&S direct+indirect + escalation		1,624,371				1,624,371
	M&S Estimate Uncertainty Contingency		487,311				487,311
	Total		2,111,682				2,111,682
Total							
	Direct+indirect + escalation	778,639	3,107,835	1,331,169	484,536		**5,702,179**
	Estimate Uncertainty Contingency	233,592	906,874	349,417	108,160		**1,598,043**
	Total	1,012,230	4,014,709	1,680,587	592,696		**7,300,222**

Fountain Interferometer





EVMS Plan

- Due to limited project complexity, propose a modest level of EVMS.
- Monthly statusing of WBS activities.
- Monthly simple EV using P6.
- In most cases, earned value to be taken as % of completion.

ESHQ Documentation

- Safety planning will be performed in accordance with FNAL procedures.
- Assembly procedures will be documented in the Docdb.
- Principle special concerns are work at heights and laser safety.
- ESH roles and liaisons documented in the PMP
- Installation Coordinator has been identified
  - Also Documentation Controller
  - Will work to record more safety procedures

Statusing (from L. Valerio)

Sample monthly status sheet

- Project team chose to use tasks for tracking collaborator accomplishments. Tasks are more helpful than milestones – anticipate delays before they are past and allows application of COVID inefficiencies.
- Team will complete first monthly update after the review by following this procedure :
  - Check "planned" start and finish dates (columns E and H) from P6 schedule.
  - If update needed, enter into column F or G and column I or J. (Anticipated is best guess, actual is fact.) No answer = no change.
  - Answer K with best estimate.

MAGIS-100

Activity ID	Activity Name	Activity Type	Planned Start	Actual Start	Anticipated Start	Planned Finish	Actual Finish	Anticipated Finish	Planned Duration	Activity % Complete	UPDATED Activity % Complete
MAGIS100-WS.02 Strontium Atom Sources											
MAGIS100-WS.02.01 Atom source assembly											
A0201000	Atom Source Assembly Start Milestone	Start Milestone	02-Feb-21						0d	0%	
A0201010	Atom source 1 (monthly report as % complete)	Task Dependent	02-Feb-21			04-Jan-22			232d	0%	
A0201020	Atom source 2 (monthly report as % complete)	Task Dependent	02-Feb-21			04-Jan-22			232d	0%	
A0201030	Atom source 3 (monthly report as % complete)	Task Dependent	02-Feb-21			04-Jan-22			232d	0%	
A0201040	Atom source 1 030% complete - milestone	Finish Milestone				03-May-21			0d	0%	
A0201050	Atom source 1 060% complete - milestone	Finish Milestone				02-Aug-21			0d	0%	
A0201060	Atom source 1 100% complete - milestone	Finish Milestone				04-Jan-22			0d	0%	
A0201070	Atom source 2 030% complete - milestone	Finish Milestone				03-May-21			0d	0%	
A0201080	Atom source 2 060% complete - milestone	Finish Milestone				02-Aug-21			0d	0%	
A0201090	Atom source 2 100% complete - milestone	Finish Milestone				04-Jan-22			0d	0%	
A0201100	Atom source 3 030% complete - milestone	Finish Milestone				03-May-21			0d	0%	
A0201110	Atom source 3 060% complete - milestone	Finish Milestone				02-Aug-21			0d	0%	
A0201120	Atom source 3 100% complete - milestone	Finish Milestone				04-Jan-22			0d	0%	
MAGIS100-WS.02.02 Vacuum system											
A0202010	Vacuum System Design	Task Dependent	01-Oct-19			01-Oct-20			253d	0%	
A0202020	Vacuum System Procurement	Task Dependent	02-Nov-20			04-Jan-21			40d	0%	
MAGIS100-WS.02.03 AOSense Sr beam sources											
A0203010	AO Sense Sr Beam Sources Design	Task Dependent	01-Oct-19			01-Apr-20			125d	0%	
A0203020	AO Sense Sr Beam Sources Procurement	Task Dependent	10-Feb-20			15-Dec-20			217d	0%	
MAGIS100-WS.02.04 Magnetic coils (quadrupole and bias)											
A0204010	Magnet Coils Design	Task Dependent	01-Oct-19			01-Oct-20			253d	0%	
A0204020	Magnet Coils Procurement	Task Dependent	02-Nov-20			01-Feb-21			59d	0%	
MAGIS100-WS.02.05 Toptica blue lasers											
A0205010	Toptica Blue Lasers Design	Task Dependent	01-May-19			01-Oct-19			107d	0%	
A0205020	Toptica Blue Lasers Procurement	Task Dependent	28-Oct-19			01-Oct-20			234d	0%	
MAGIS100-WS.02.06 MOT laser system											
A0206010	MOT Laser System Design	Task Dependent	01-Oct-20			01-Dec-20			42d	0%	
A0206020	MOT Laser System Procurement	Task Dependent	02-Dec-20			15-Jan-21			29d	0%	
MAGIS100-WS.02.07 Electronics											
A0207010	Electronics Design	Task Dependent	01-Oct-19			01-Feb-21			333d	0%	
A0207020	Electronics Procurement	Task Dependent	02-Dec-19			01-Apr-20			83d	0%	
MAGIS100-WS.02.08 Dipole trap laser system											
A0208010	Dipole Trap Laser System Design	Task Dependent	01-Oct-19			01-Feb-21			333d	0%	
A0208020	Dipole Trap Laser System Procurement	Task Dependent	02-Feb-21			03-May-21			65d	0%	
MAGIS100-WS.02.09 Shuttle lattice											
A0209010	Shuttle Lattice Design	Task Dependent	01-Oct-19			30-Dec-20			313d	0%	
A0209020	Shuttle Lattice Procurement	Task Dependent	04-Jan-21			01-Mar-21			40d	0%	
MAGIS100-WS.02.10 Imaging											
A0210010	Imaging Design	Task Dependent	01-Oct-19			01-Feb-21			333d	0%	
A0210020	Imaging Procurement	Task Dependent	02-Feb-21			03-May-21			65d	0%	
MAGIS100-WS.02.11 Remote diagnostics and controls											
A0211010	Remote Diagnostics and Controls Design	Task Dependent	01-Oct-19			01-Oct-20			253d	0%	
A0211020	Remote Diagnostics and Controls Procurement	Task Dependent	02-Oct-20			04-Jan-21			61d	0%	
MAGIS100-WS.02.12 Enclosure											
A0212010	Enclosure Design	Task Dependent	01-Oct-19			15-Oct-20			263d	0%	
A0212020	Enclosure Procurement	Task Dependent	16-Oct-20			30-Dec-20			50d	0%	
MAGIS100-WS.02.13 Qualification											
A0213010	Atom Source 1 qualification	Task Dependent	05-Jan-22			12-Sep-22			175d	0%	
A0213020	Atom Source 2 qualification	Task Dependent	05-Jan-22			12-Sep-22			175d	0%	
A0213030	Atom Source 3 qualification	Task Dependent	05-Jan-22			12-Sep-22			175d	0%	
MAGIS100-WS.02.14 Equipment transport											
A0214010	Atom Source 1 shipped – milestone	Finish Milestone				12-Sep-22			0d	0%	
A0214020	Atom Source 2 shipped – milestone	Finish Milestone				12-Sep-22			0d	0%	
A0214030	Atom Source 3 shipped – milestone	Finish Milestone				12-Sep-22			0d	0%	