Simulation & Analysis Workshop 2024

Summary and Review

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On behalf of the MAGIS-100 OCG

6 November 2024

2024 Simulations & Analysis Workshop

Held at FNAL + Cambridge, Sep 30 -- Oct 2

Future home of MAGIS!

>20 Participants

- ~10 in person @ FNAL
- ~3 in person @ Cambridge
- ~7 remote connection

6 Institutions represented

5 Software demos

- [FNAL] Python DM sim/ana tools
- [SLAC] GradOptics
- [Cambridge] Analytic WF calculator
- [NU] Multi-loop + stray path calculator
- [NU] Analytic phase shift calculator

Workshop Materials

Workshop drive: https://drive.google.com/drive/folders/1vQRZSBKuXS8tbfAcHNDJDVHSCYgMvNkc?usp=drive_link

Workshop index: https://docs.google.com/document/d/1IlLJwkKU8IRw-TJJMFHc3SVTwHX-u-fY7_75WdfJ-wY/edit?usp=drive_link

Presentation materials: https://drive.google.com/drive/folders/1OS0mlP3c20k-WKCRSsm39m-Y9pAlslZ8?usp=drive_link

Challenge questions & development tasks:
https://docs.google.com/document/d/1plSlPIlRdMmN2qP34Ag_82zULLwiSzPbpmiXCFlF74A/edit?usp=drive_link

Workshop report (in progress): docdb link (to be added)

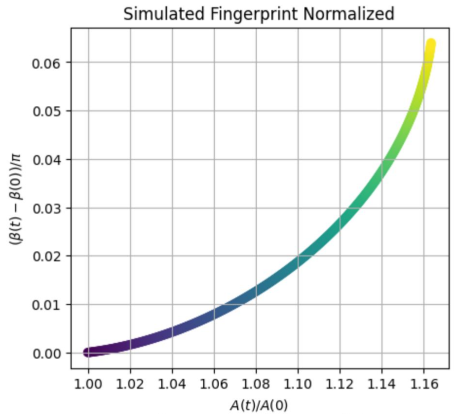
Workshop Goals

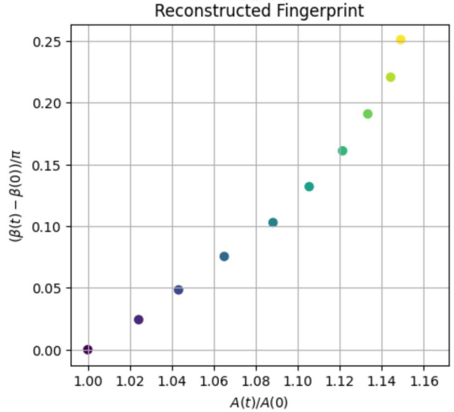
1. **Take stock of existing software tools**, which affords the collaboration opportunities to
   - identify areas of overlap and missing links to reduce duplicated effort, and
   - prepare for real data! (See LIGO talks: https://indico.fnal.gov/event/60343/)
2. **Develop hands-on expertise** in tools that have already been developed within the collaboration, and distribute that expertise across institutions.
3. **Increase usage of MAGIS GitLab space**: both users and hosted code, to centralize MAGIS-software in a common location.
4. **Set up FNAL computing accounts & site access** for collaborators, which will be needed during commissioning of the detector (at the latest).

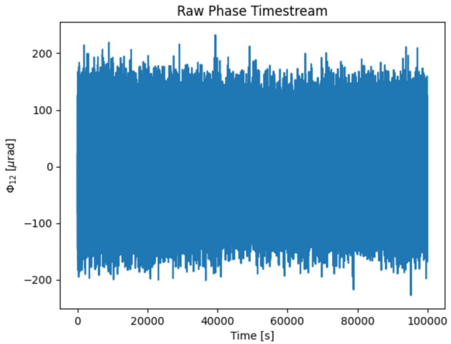
Python DM Tools

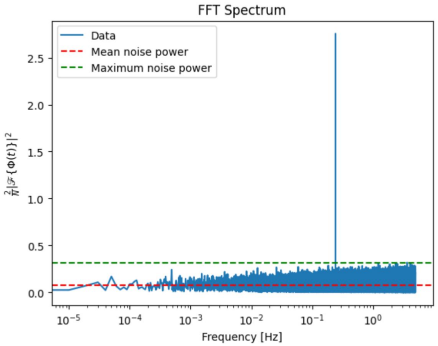
Dylan Temples, Fermilab

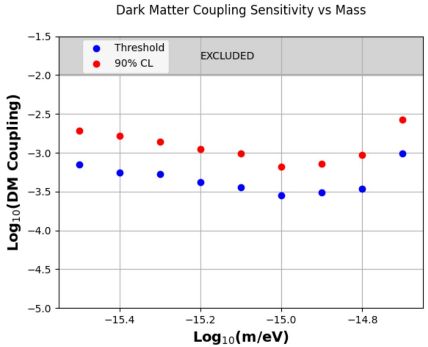
- Generate a sequence of DM-induced gradiometer phases
  - Includes decoherence of DM wave (phase/amplitude slip)
  - Parameterized instrument response
- Extract central DM frequency using Fourier analysis
  - Generate sensitivity plots (coupling vs DM mass)
- Reconstruction of DM “fingerprint”









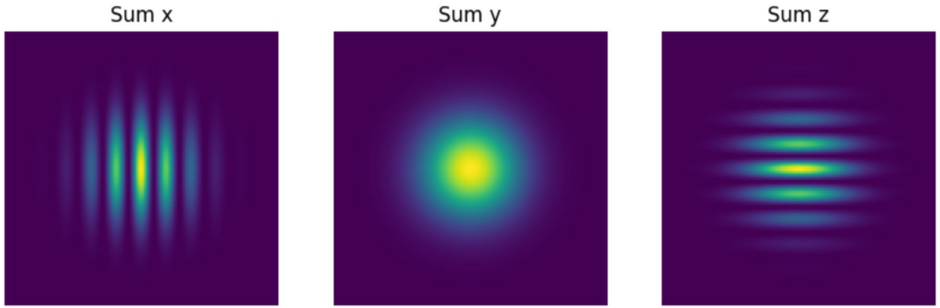


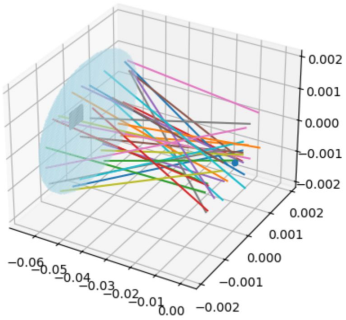
Demo materials: https://gitlab.developers.cam.ac.uk/phy/magis-100/user-projects/dtemples/pydmtools-demo-workshop-2024

GradOptics

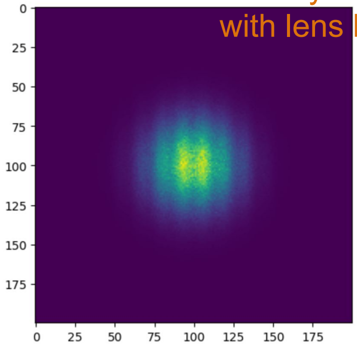
Sean Gasiorowski, SLAC

- Creating a scene: atom cloud (light source) and lens+sensor (camera)
- Rendering an image
  - Forward ray tracing
  - Backward ray tracing
- Utilizing differentiability to understand how images depend on input





BW ray tracing with lens blur

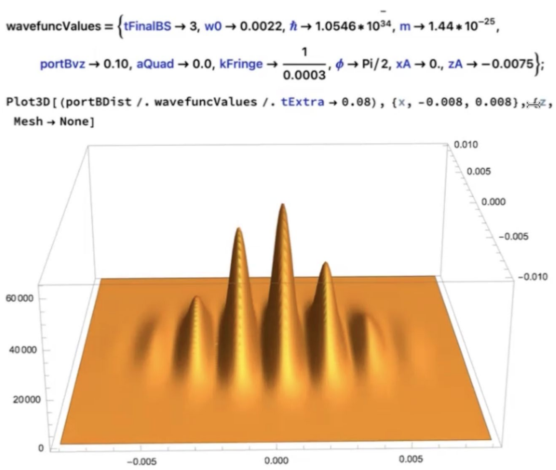


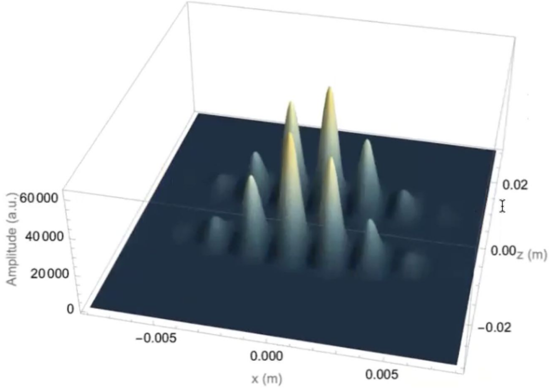
Demo recording: https://drive.google.com/drive/folders/1Uuu2UrOEI3wAhz0wsXomTUB8AetcWLfy?usp=drive_link

Analytic Wavefunction Calculator

Jeremiah Mitchell, Cambridge

- One entry in a suite of bespoke analytic tools
- Starts from free-particle solution to S.E.
- From initial WF, determine final WF after absorbing some # of photon momentum
  - Accounts for expansion and time dependence of WF between pulses
  - Does not simulate a 3-pulse interferometry sequence
  - Applies linear & quadratic phase shear readout and relative positioning between clouds and cameras
- Output: spatial distribution of atoms at output ports from which to sample



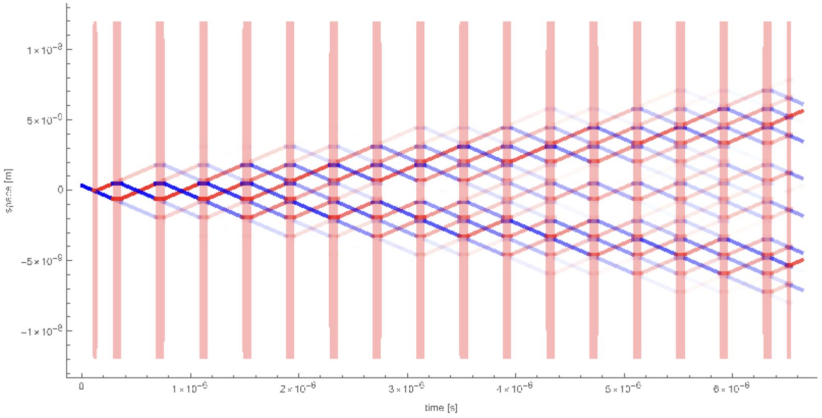


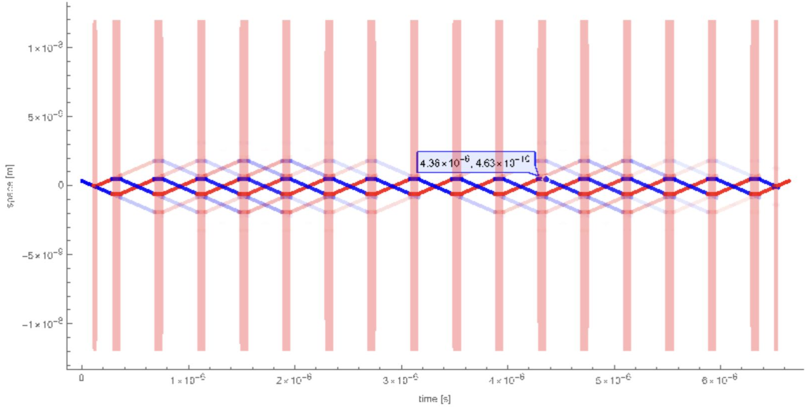
Demo recording: https://drive.google.com/drive/folders/1U8MkqQ_KtT_I_uihW7_0q75Tusmc5oZB?usp=drive_link

Multi-Loop & Stray Path Calculator

Jonah Glick, Northwestern

- Resonant, multi-loop interferometry sequences with non-ideal pulses
- Apply phase modulation to each pulse → enhance contrast
- Calculating and visualizing all atom paths due to pulse inefficiencies
  - See: https://arxiv.org/abs/2407.11246





Demo recording: https://drive.google.com/drive/folders/1VXJH-qaYJMn42i-O7VKC9Z4nki3jrq8T?usp=drive_link

Analytic Phase Shift Calculator

Tim Kovachy, Northwestern

- Determine analytic expressions for terms contributing to AI phase shift
- Starts from Lagrangian -- can add in as many effects as you want
  - Example: constant gravity
- Walks through methodology of calculating the phase shift terms up to a specified order in T
- Can be expanded to reproduce the table in Jason's lecture notes: https://arxiv.org/abs/0806.3261

```
total phase shift

ϕTot = (ϕLaser + ϕProp + ϕSep // Simplify // Normal) /. ϵ → 1 // Expand
-g k n T^2

ϕTotSeries = Series[ϕTot, {T, 0, 2}] // ExpandAll // Normal // Expand
-g k n T^2

numbers = {k → (2 * π)/(780. * 10^-9), n → 2, g → 9.8, T → 1}
{k → 8.05537×10^6, n → 2, g → 9.8, T → 1}

ϕTotSeries /. numbers
-3.09455×10^8
```

Demo recording: https://drive.google.com/drive/folders/1U8MkqQ_KtT_I_uihW7_0q75Tusmc5oZB?usp=drive_link

Other Talks and Sessions

Collaborative software development practices

- GitLab space overview and workflow
- How to write readable and maintainable code
- Python package development guidelines

Simulations & analysis “roll call”

- Identify all in-development or soon-to-be started software tools
- Identify a point person and institution for each

Working sessions

- Hands on time with software tools to solve “challenge problems”
- Discussions on restructuring code / implementing new functionality (e.g. differentiability)
- Discussion on the components of a first demonstration of an “end-to-end” simulation pipeline

Progress Toward Initial Goals

1. The simulations & analysis call sheet has been updated with the current point of contact and status of the software tools under development at each institution.
2. **5 software tools were demonstrated** with 10–20 collaboration members in attendance. All participants were able to follow along, or identified reasons they could not, which were subsequently fixed.
3. **13 new users** were added to MAGIS GitLab space. 10 new users created personal project space on GitLab.
4. **4 collaborators** received Fermilab computing accounts & site access.

Workshop Output

- All but one of the software demos were recorded and made available to the collaboration at large. These will continue to provide an entry point for new collaboration members to get started in simulations and analysis.
  - Current collaboration members that were unable to attend the workshop have already begun using them to familiarize themselves with existing software tools.
  - Future workshops featuring demos of different (or improved) software tools will continue to add to the library of demos.
- A software collaboration effort to leverage Sean's expertise (SLAC) in differentiable simulation development for implementing differentiability in Jonah's multi-path calculator (Northwestern) has begun.
- Identified simulation components for a simplified end-to-end simulator

Demonstration of Simulation Pipeline: Alignment

(1) Simulation of loading the MOT.

a. Atom boil off into collimator, potentially including partitioning of states of atoms.
b. 2D MOT cooling
c. Longitudinal cooling
d. 3D MOT holds onto the atoms for further cooling (watch atoms as they load into the trap)
    i. Concern: What are the online handles to monitor this preparation step? Do we have cameras? Are we monitoring the lasers? Is it easy to remotely recover the system?
e. Further cooling steps

Proposed Tool(s): AtomECS (TBD if state partitioning is included in AtomECS), with Mathematica notebooks serving as additional analytic inputs

Demonstration of Simulation Pipeline: Alignment

(2) Shuttle lattice simulator for transporting the atoms from the MOT to the interferometry region.

a. (?) using the semi-classical approximation. Caveat: shuttle may induce heating.
b. (?) What is MAGIS doing for shuttle?
c. (?) What processes need to be simulated for this step?

Proposed Tool(s): Yijun may have been working on a simulation of this.

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(3) The matter-wave lensing sequence, which constitutes the final cooling step.

Proposed Tool(s): A numerical implementation of Tim's Mathematica notebook.

Demonstration of Simulation Pipeline: Alignment

(4) Optical lattice launch or drop.

a. Simulation of the initial wavefunction, which is the initial step for simulation of a single experiment/shot.
b. (?) Are there any heating effects from launch?

Proposed Tool(s): A numerical implementation of Tim's Mathematica notebook.

Demonstration of Simulation Pipeline: Alignment

(5) Simulation of the interferometry sequence including atoms, lasers, and their interaction for any of the different operation modes

Not simulated in first demonstration!

a. Optimal quantum control & pulse sequences
b. Wavefunction evolution
c. Semi-classical stray paths
d. Signal simulators: Dark Matter and Gravitational Waves affect phase accumulated during interferometer sequence
e. Environmental noise sources: GGN, electro/magnetic fields, moving masses, Coriolis/Centrifugal forces, Blackbody radiation. Discarded atom noise (atoms falling from upper AI being imaged at the lower atom source interferes with “true” cloud).
f. Laser noise sources: wavefront aberrations, pointing stability & jitter
g. Final atom cloud densities in each port, in each interferometer. Atoms continue to fall, time evolve (cloud diffuses, fringe contrast is lost)

Proposed Tool(s): NU+SLAC Julia code, python DM tools, and more . . .

Demonstration of Simulation Pipeline: Alignment

(6) Atom fluorescence and imaging process

a. Fluorescence process (laser component)
b. Geometric & wave optics. **Proposed Tool(s):** GradOptics
c. Sensor response. **Proposed Tool(s):** Pyxel + Oxford tools

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(7) Simulation output: One image for each camera for each shot simulated, which can be passed to the analysis tools.

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(8) Reloading for next launch

Demonstration of Simulation Pipeline: Alignment

For each step of the pipeline, we need to

- Identify an appropriate set of tools
  - Get them on GitLab
- Determine the necessary inputs and standardized output
- Validate the output against data
- Identify a point person

Next Steps & Recommendations

Action items.

1. Write a "quick start" guide for new collaborators, host it on the internal MAGIS website (https://magis-internal.fnal.gov/)
2. Take stock of existing tools used by other collaborations that we can leverage (e.g., sky localization for GW and vector DM).
3. Address the questions in the simulation pipeline flow.

Recommendations.

1. Host a monthly simulations check-in meetings with (at least) one representative from each institution.
2. Convene an in-person collaboration meeting within the next 6 months.
3. Convene a follow-up workshop in one year, with an emphasis for in-person participation.

Thanks! Questions? Comments?

Sean + Jonah → simulator into PyTorch, Jonah has been playing around for optimization, using SLAC cluster