Coriolis Force Compensation for Long Baseline Atom Interferometry

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Terrestrial Very-Long-Baseline Atom Interferometry Workshop

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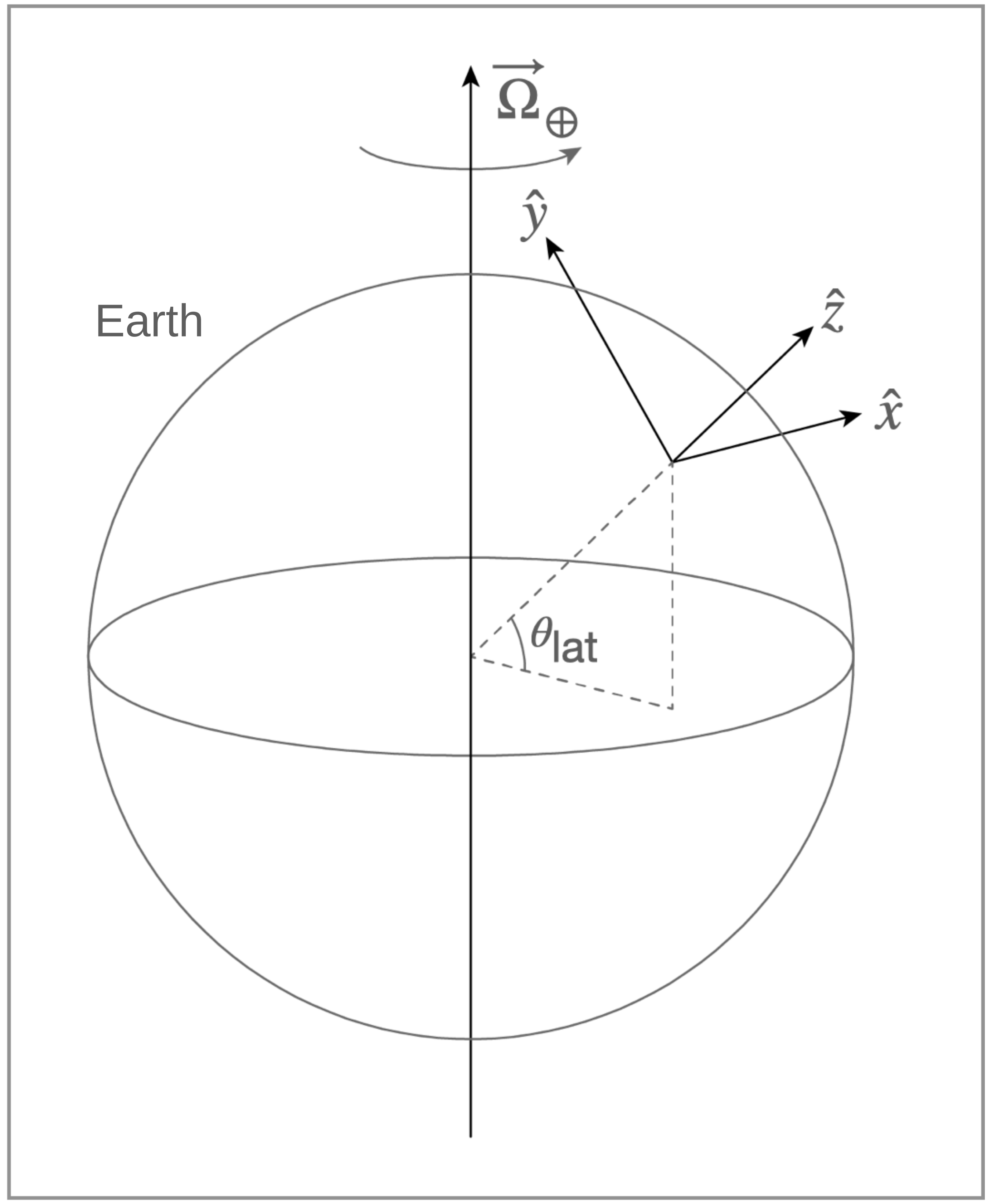
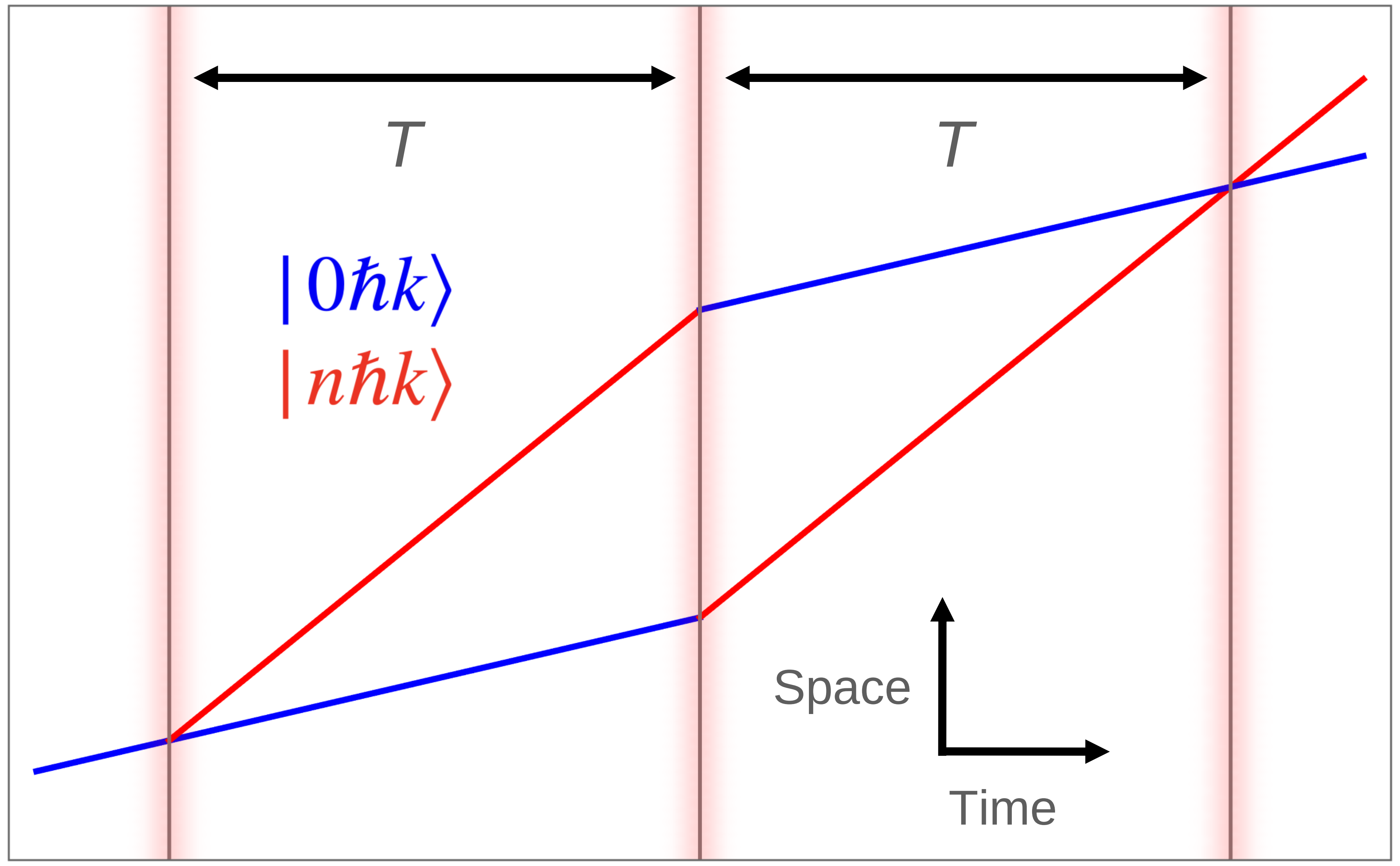
Atom Interferometry — The Coriolis Force

- Coriolis forces caused by the rotation of the Earth induce velocity dependent phase shifts in an atom interferometer, which increase with increasing *T and n*
- Traditional compensation schemes can break down for longer baseline interferometers
- A new scheme can achieve suppression of Coriolis induced phase shifts for long baseline interferometers (see Glick et al., AVS Quantum Sci. 6, 014402 (2023) for more details)

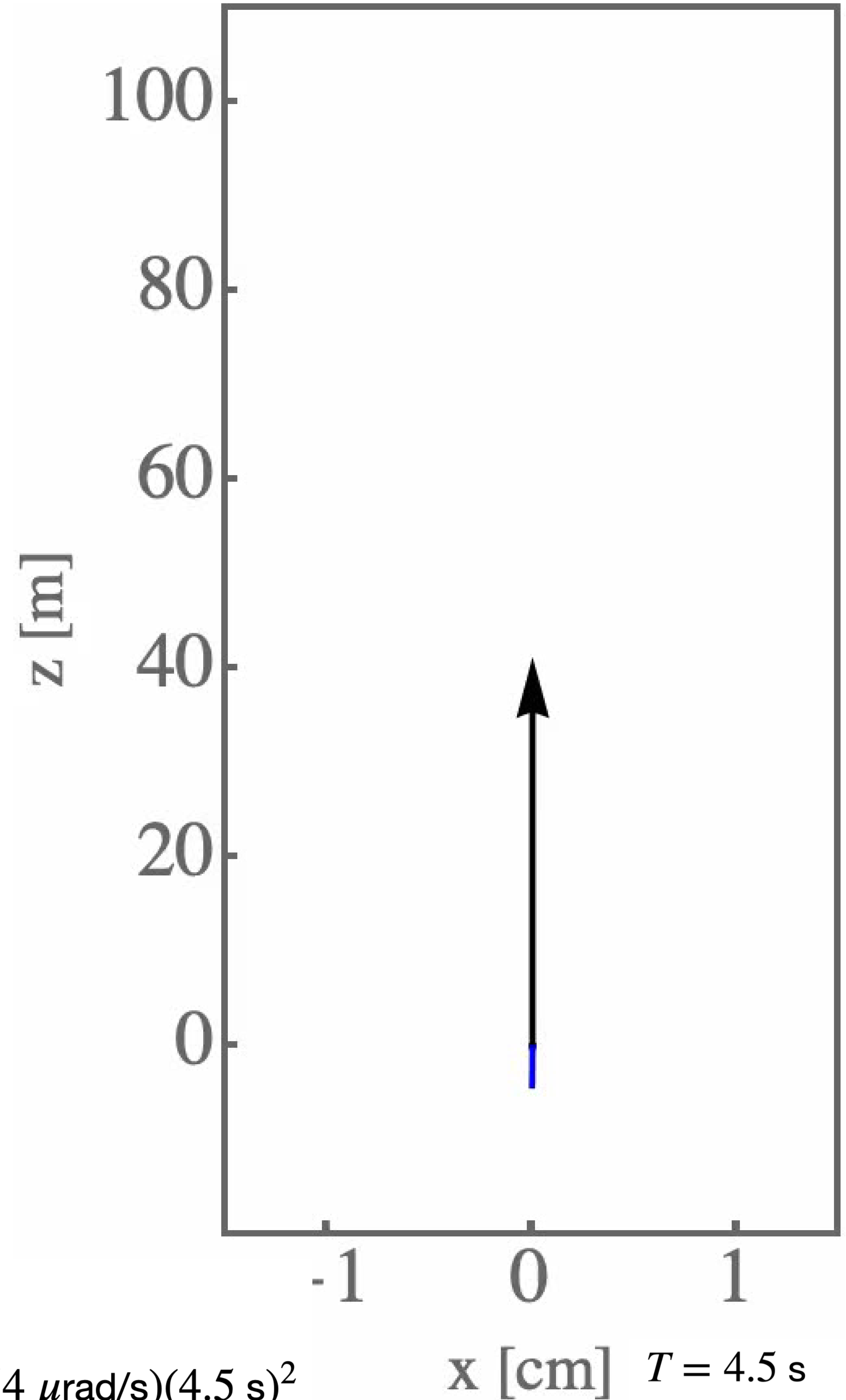


If the interferometer axis is along the *z*-axis, the dominant contribution comes in through the *y*-component of the earth's rotation axis in lab frame coordinates

Consider a Mach-Zehnder atom interferometer where atom-optics pulses are performed by two photon transitions



$$\begin{aligned}\Delta\phi_{\text{Coriolis}} &\approx 2nkv_x\Omega_y T^2\\ &\approx 2(100)(2\pi/679\text{ nm})(10\ \mu\text{m/s})(54\ \mu\text{rad/s})(4.5\text{ s})^2\\ &\approx 20\text{ rad}\end{aligned}$$



$T = 4.5$ s
$n = 100$
$v_z \approx 41.2$ m/s

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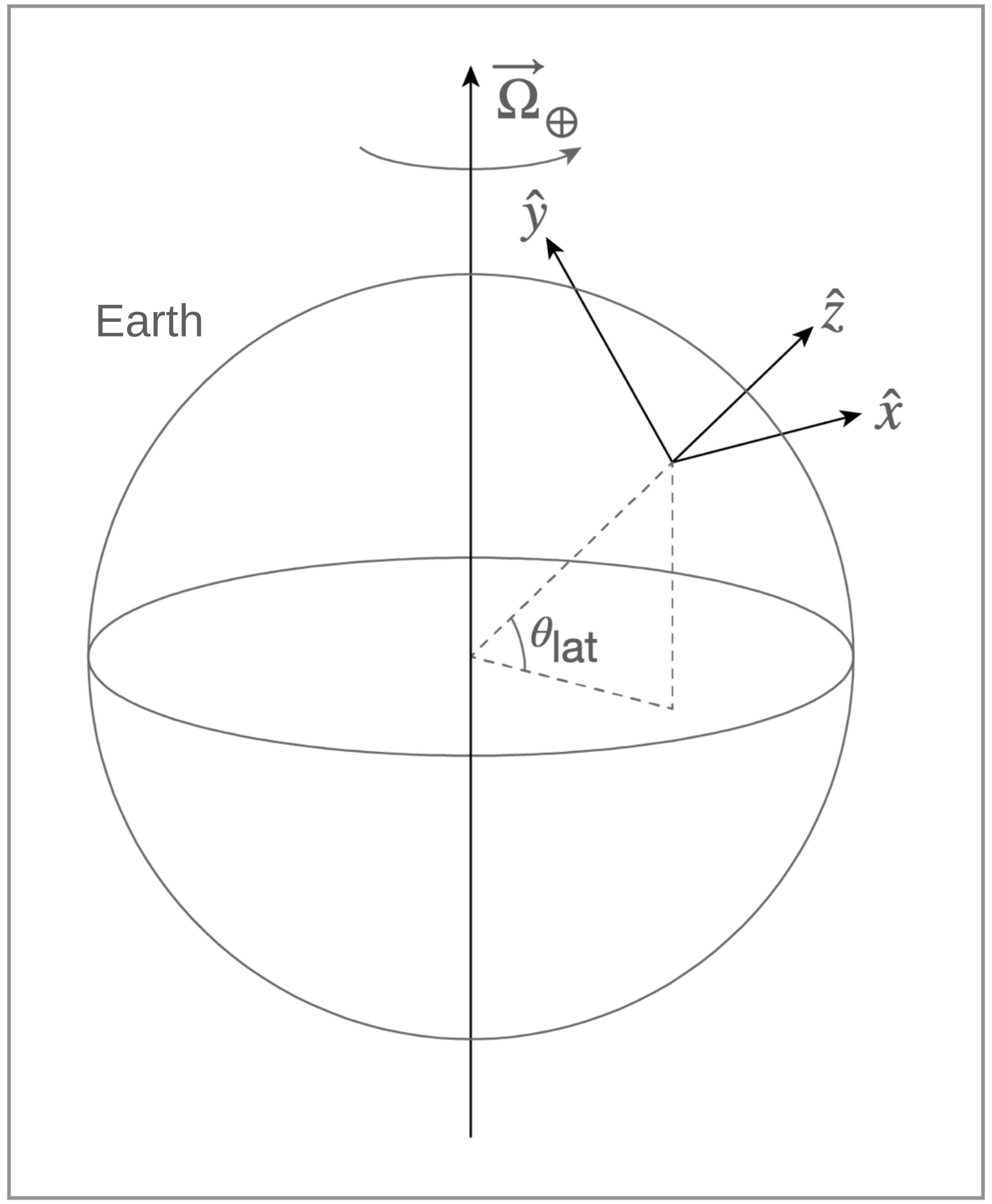

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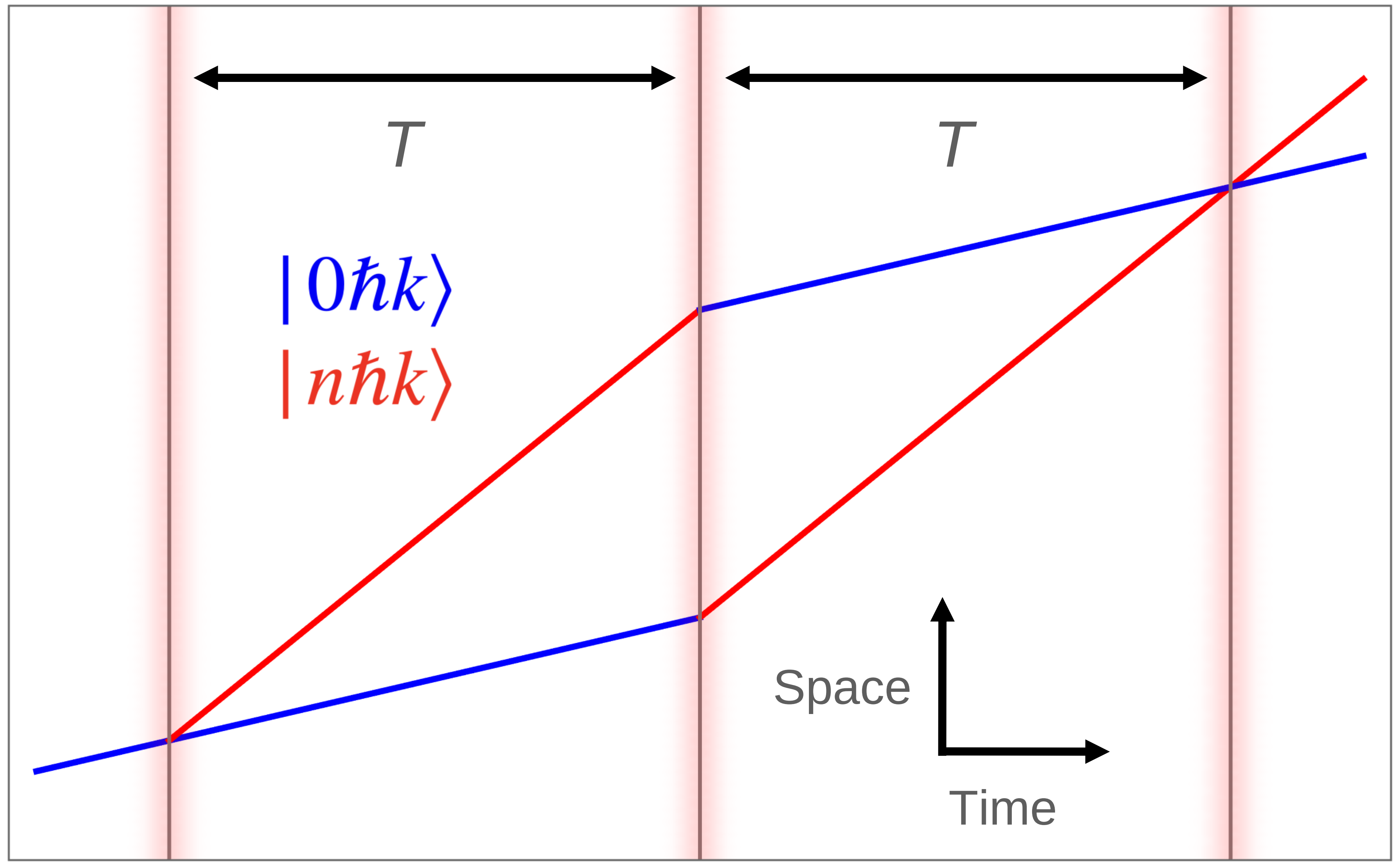

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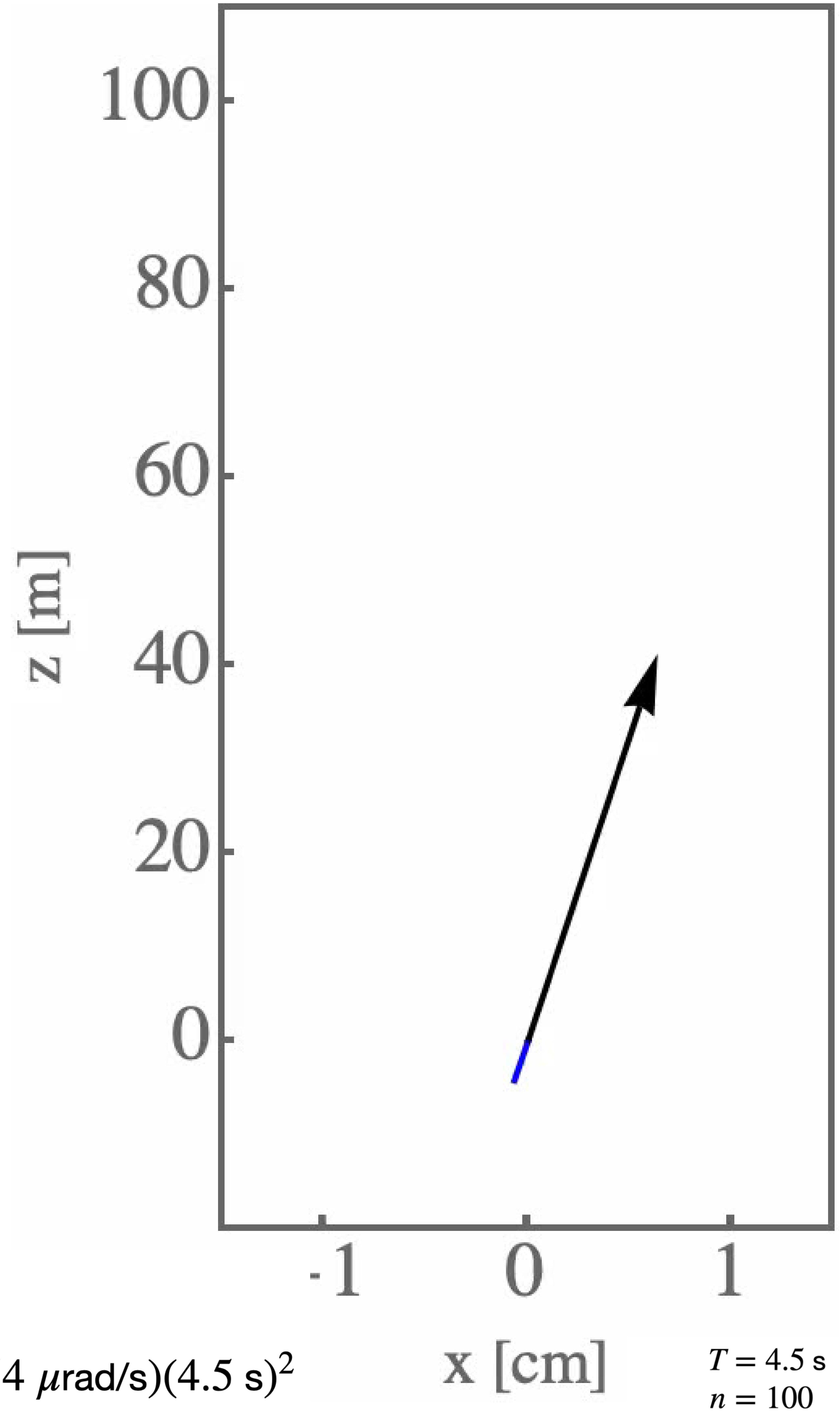
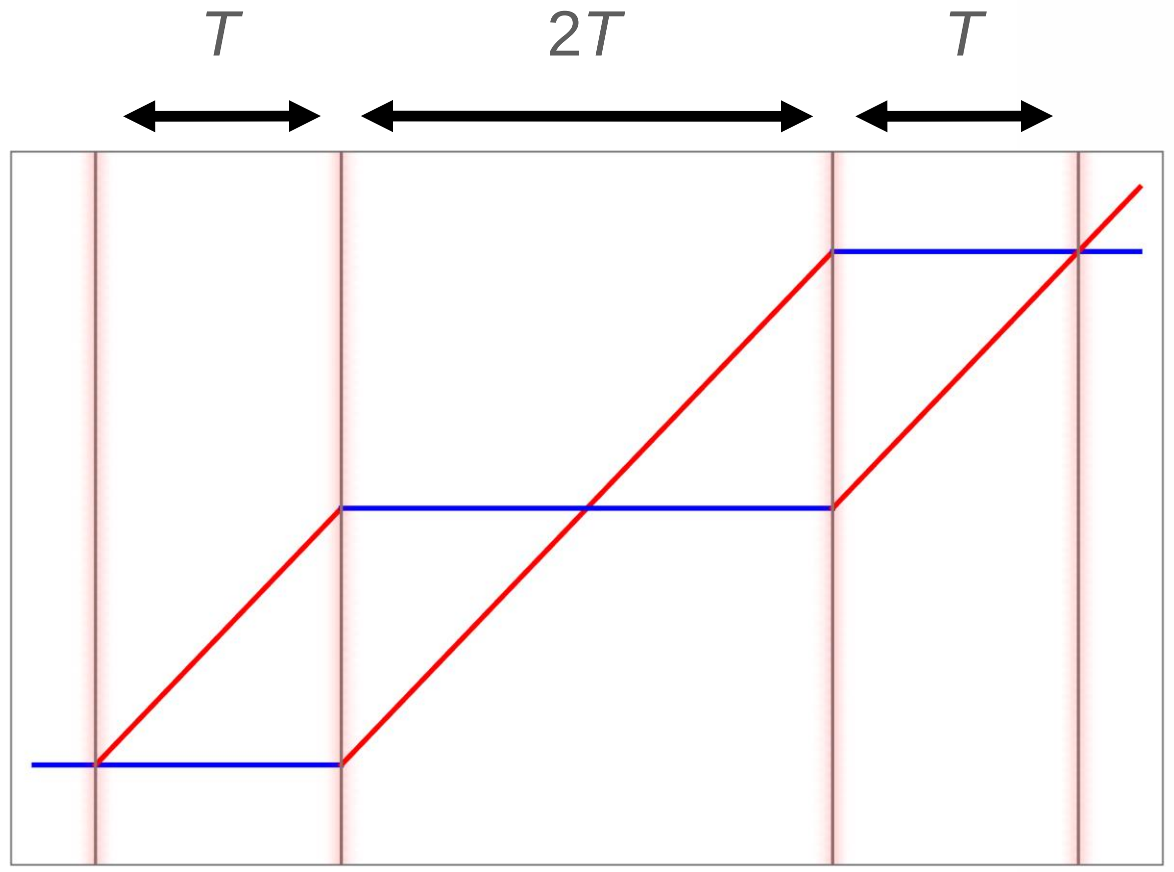


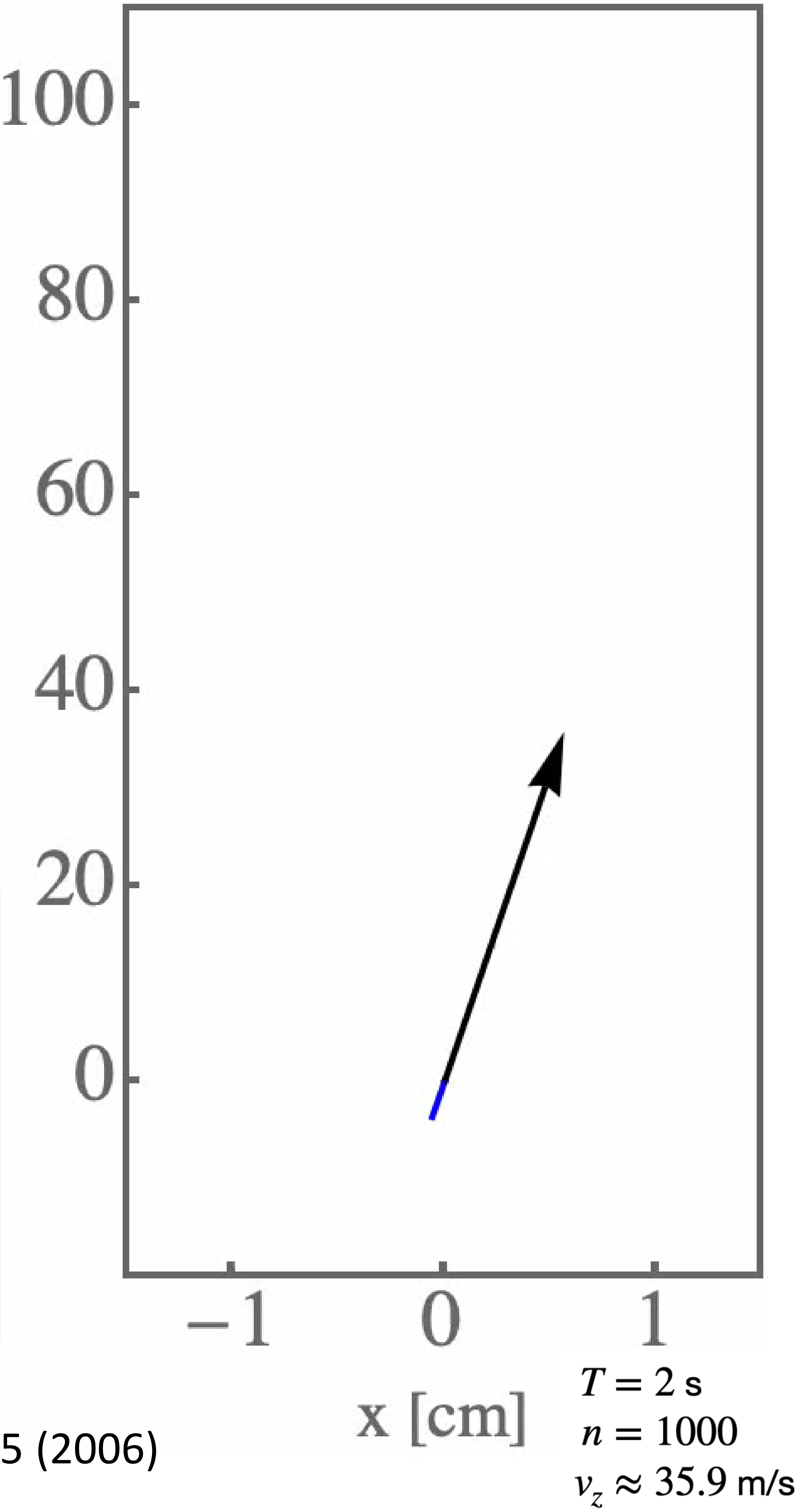
$T = 4.5$ s
$n = 100$
$v_z \approx 41.2$ m/s
$\theta_{\text{launch}} \approx 0.16$ mrad

Traditional Coriolis Force Compensation Schemes

Multiloop interferometry

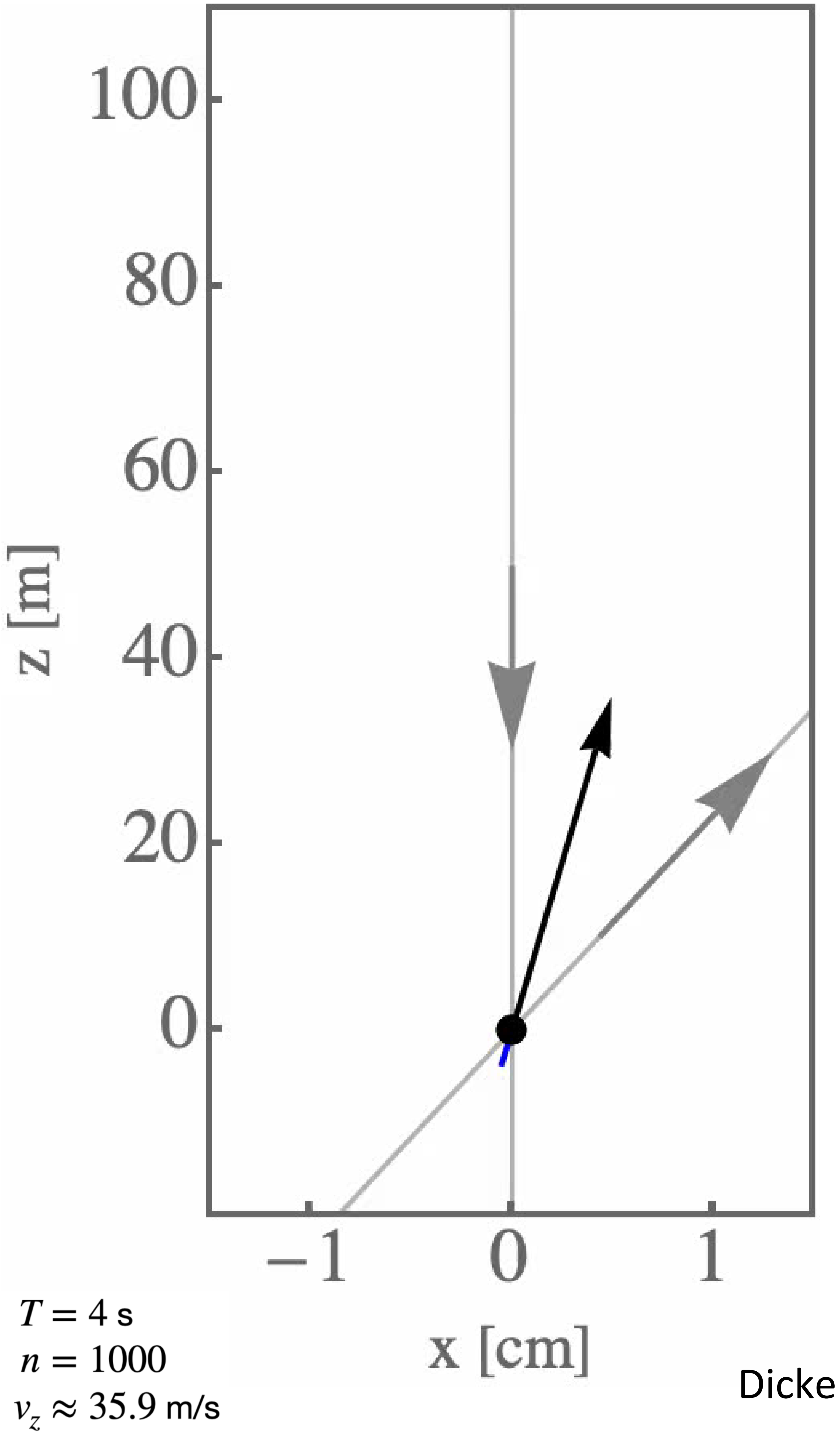
- Performing atom optics pulses in such a way that the two arms of the interferometer cross and form two loops surpasses Coriolis force induced phase shifts, in addition to gravity gradients
- This sequence also suppresses the response of the interferometer to low frequency signals
- The atoms sample weaker regions of the interferometer beam during the mirror pulses



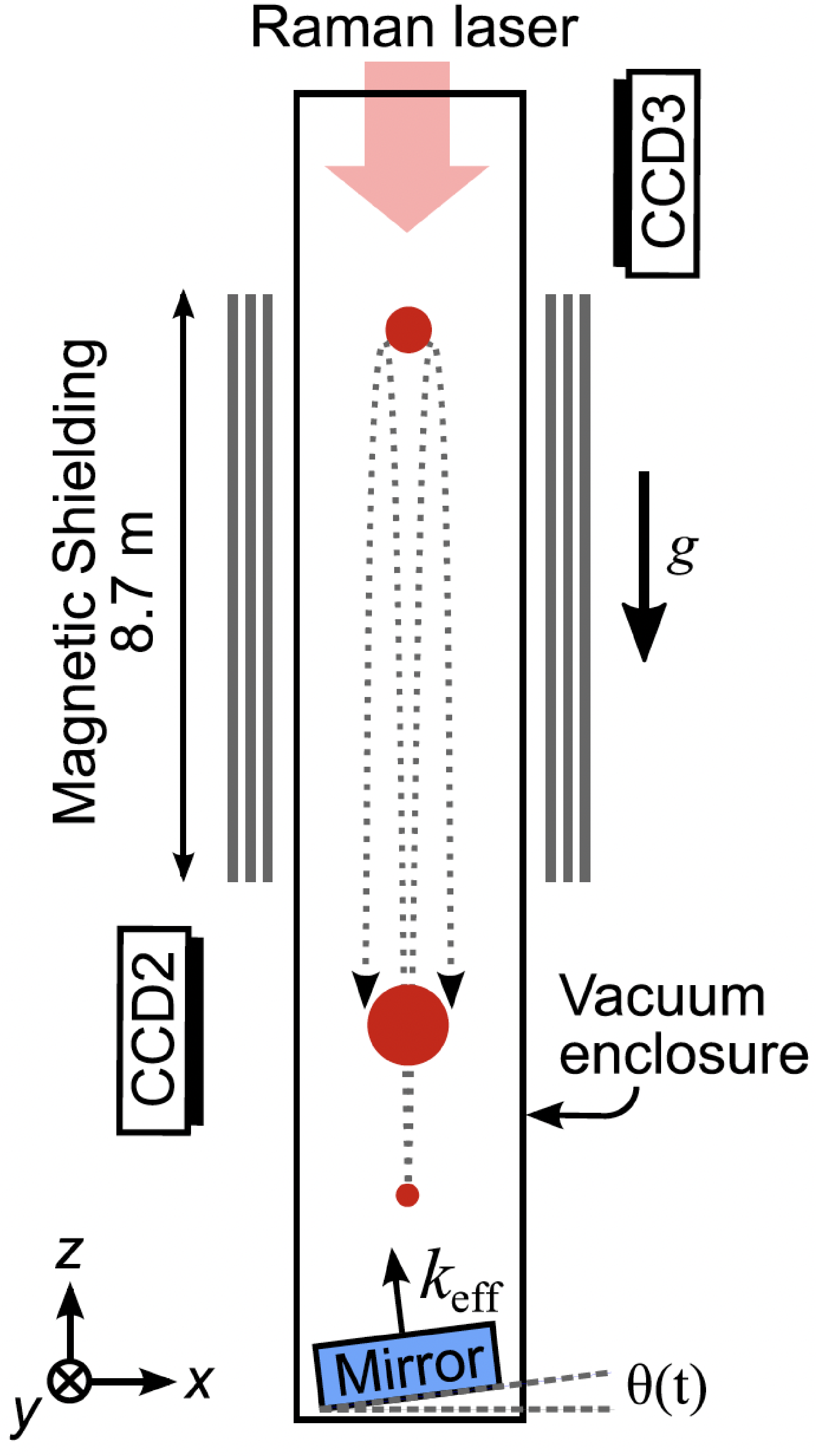


Dubetsky et al., Phys. Rev. A 74, 023615 (2006)

Counter-Rotation of Interferometer Beam



- Rotating the interferometer beam against the rotation of the earth suppresses Coriolis induced phase shifts

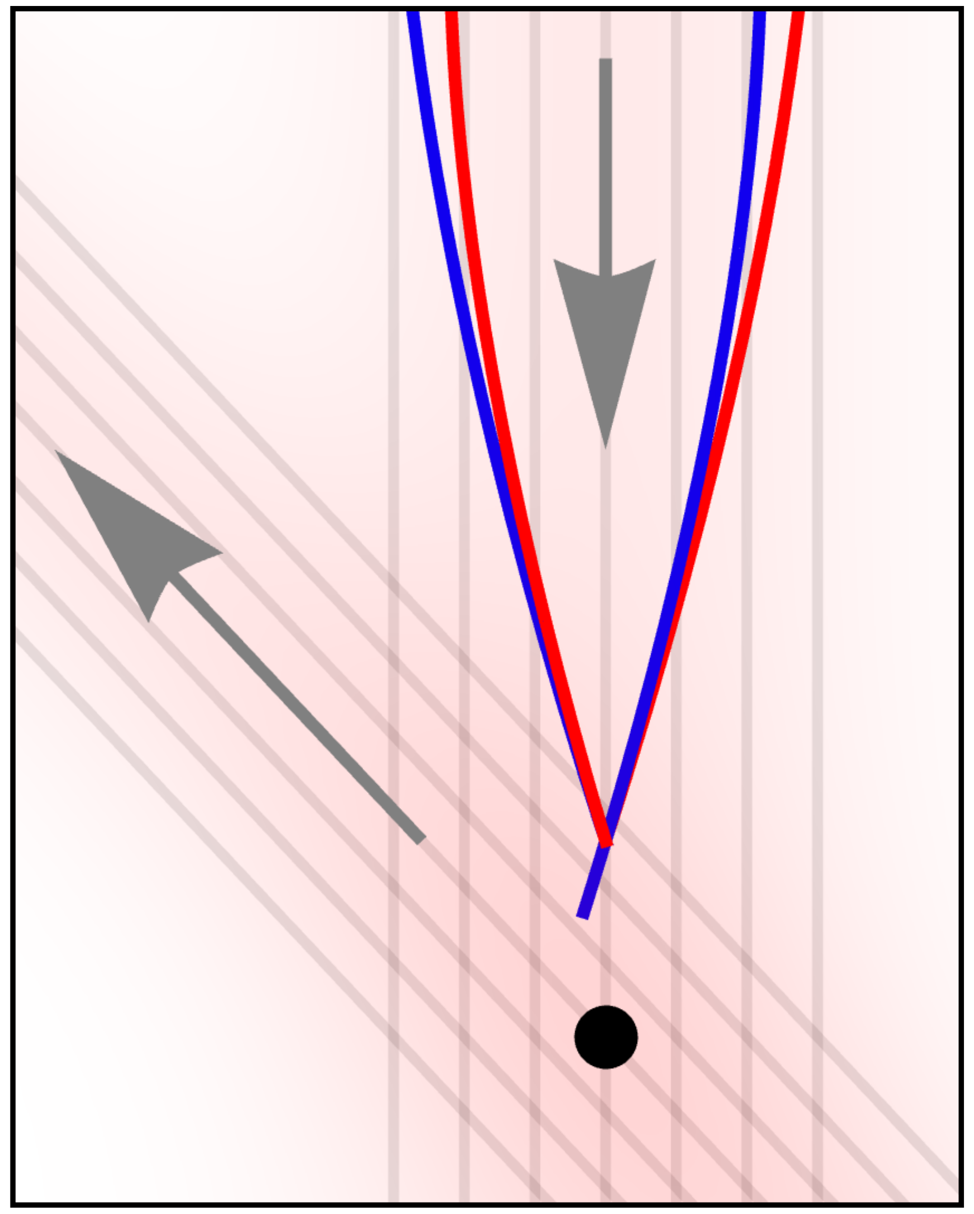


Dickerson et al., PRL 111, 083001 (2013)

Challenges of Scaling Traditional Scheme to Longer Baselines

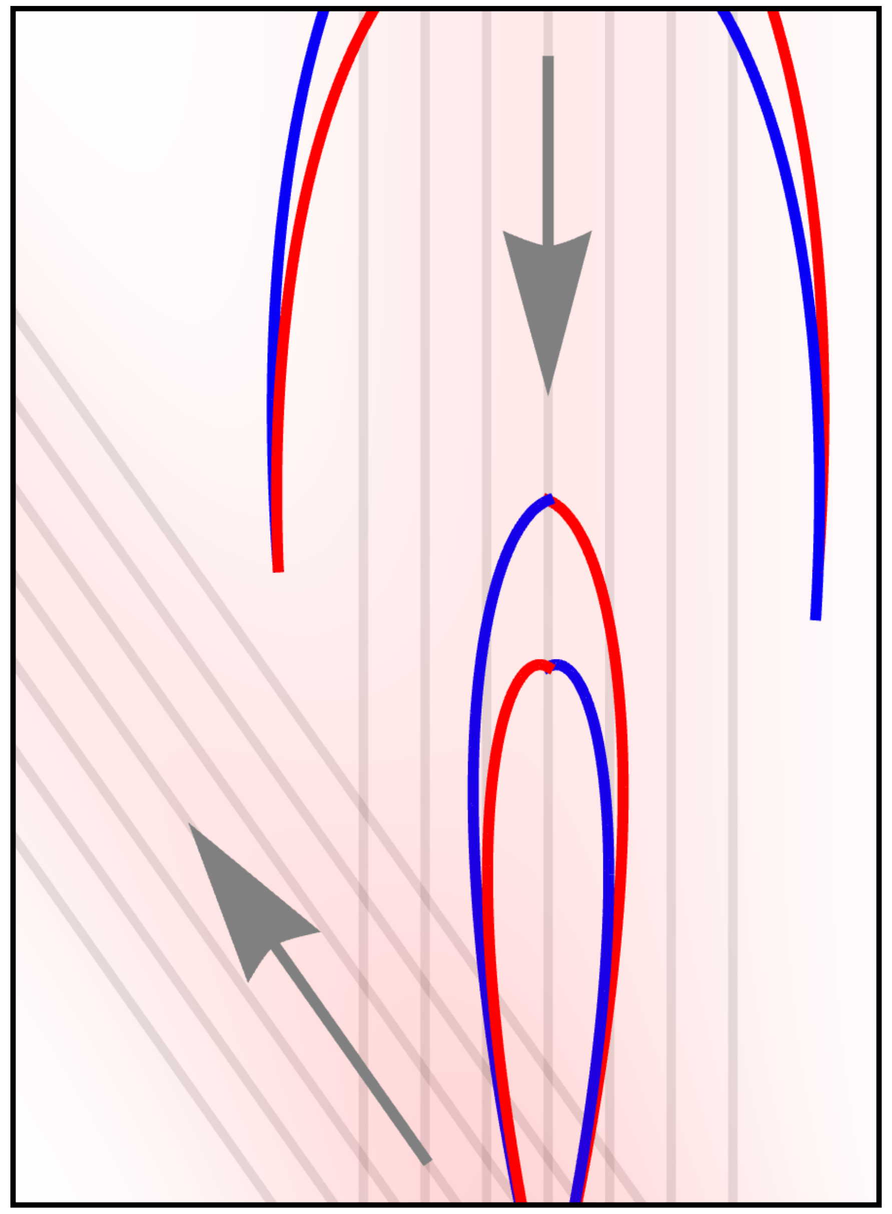
- In the traditional approach, the pivot point of the interferometer beam is set by the location of the retro mirror at the bottom of the interferometer
- Engineering constraints in long baseline interferometers can cause the position at which the atoms are launched to be far from the retro-reflecting mirror
- The longer lever arm between pivot point of the interferometer beam and the atoms can cause the center of the interferometer beam to transversely shift away from the atom cloud as the beam is rotated

Atoms not centered on the reflected interferometer beams experience a weaker effective Rabi frequency



Lateral offset : 4.3 mm

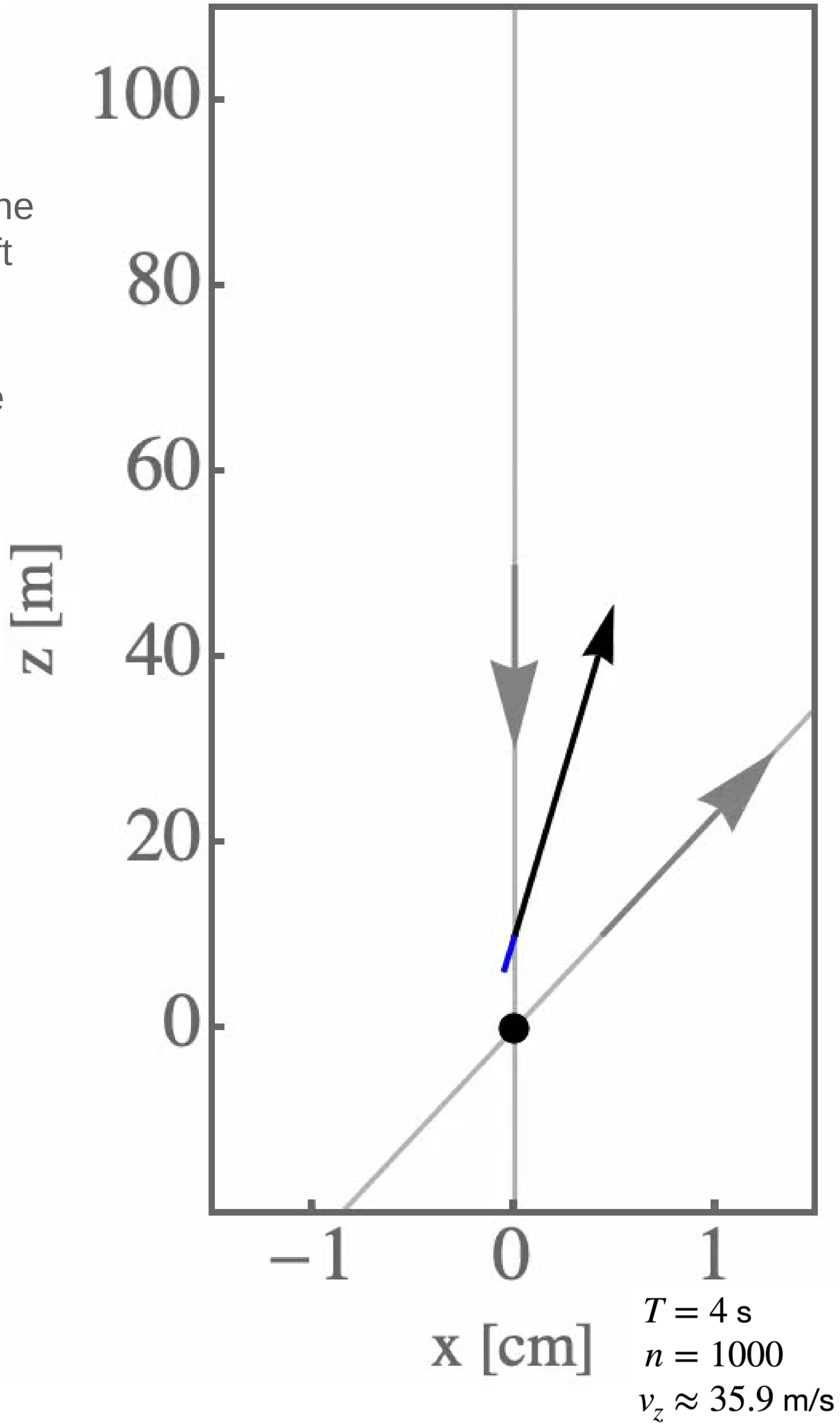
In a gradiometer configuration, the reflected interferometer beam can miss the atoms more dramatically



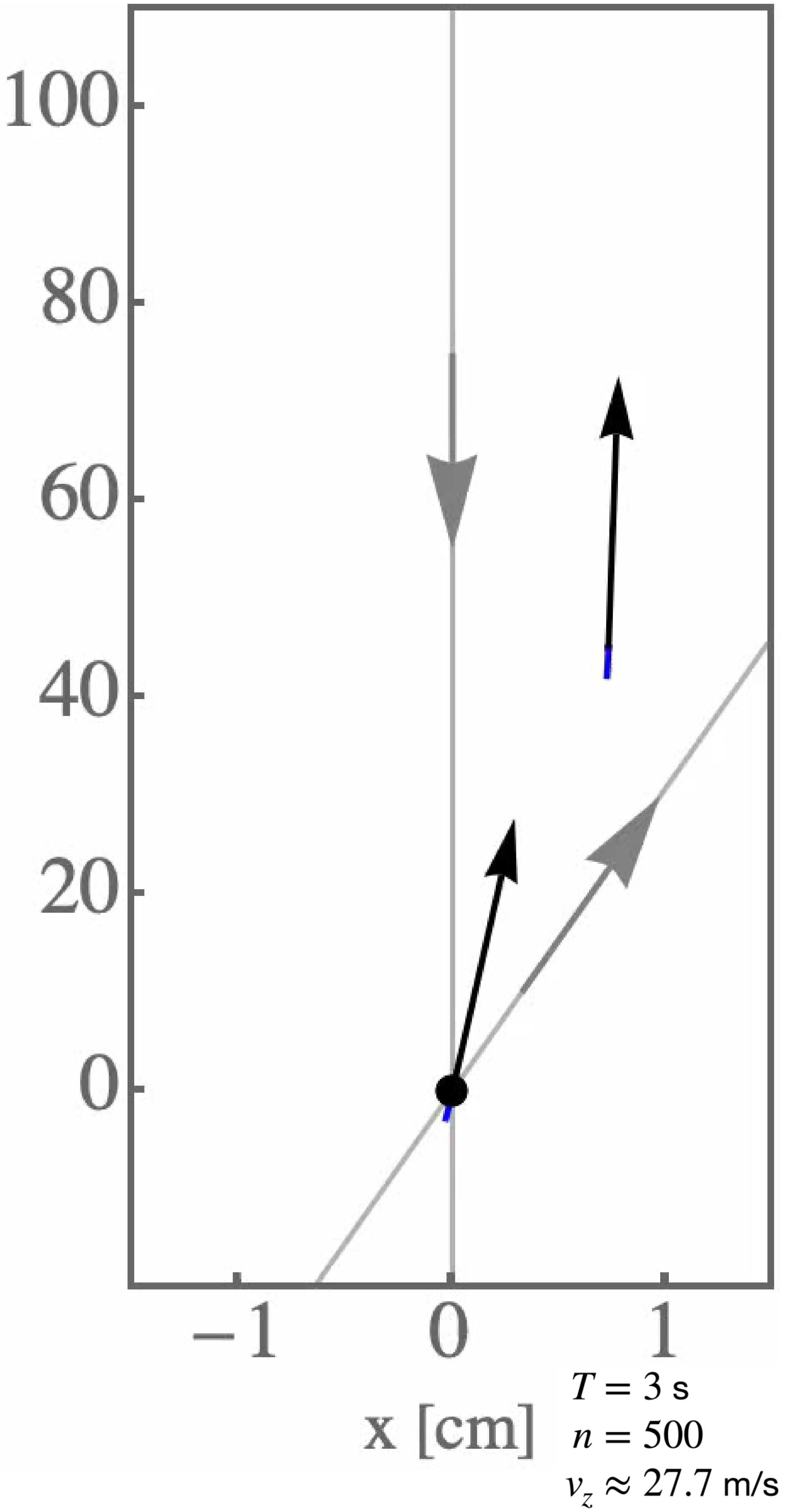
Lateral offset : 1.5 cm

A radial beam waist of 1 cm is envisioned from MAGIS

Dual-isotope Differential Accelerometer Configuration



Gradiometer Configuration

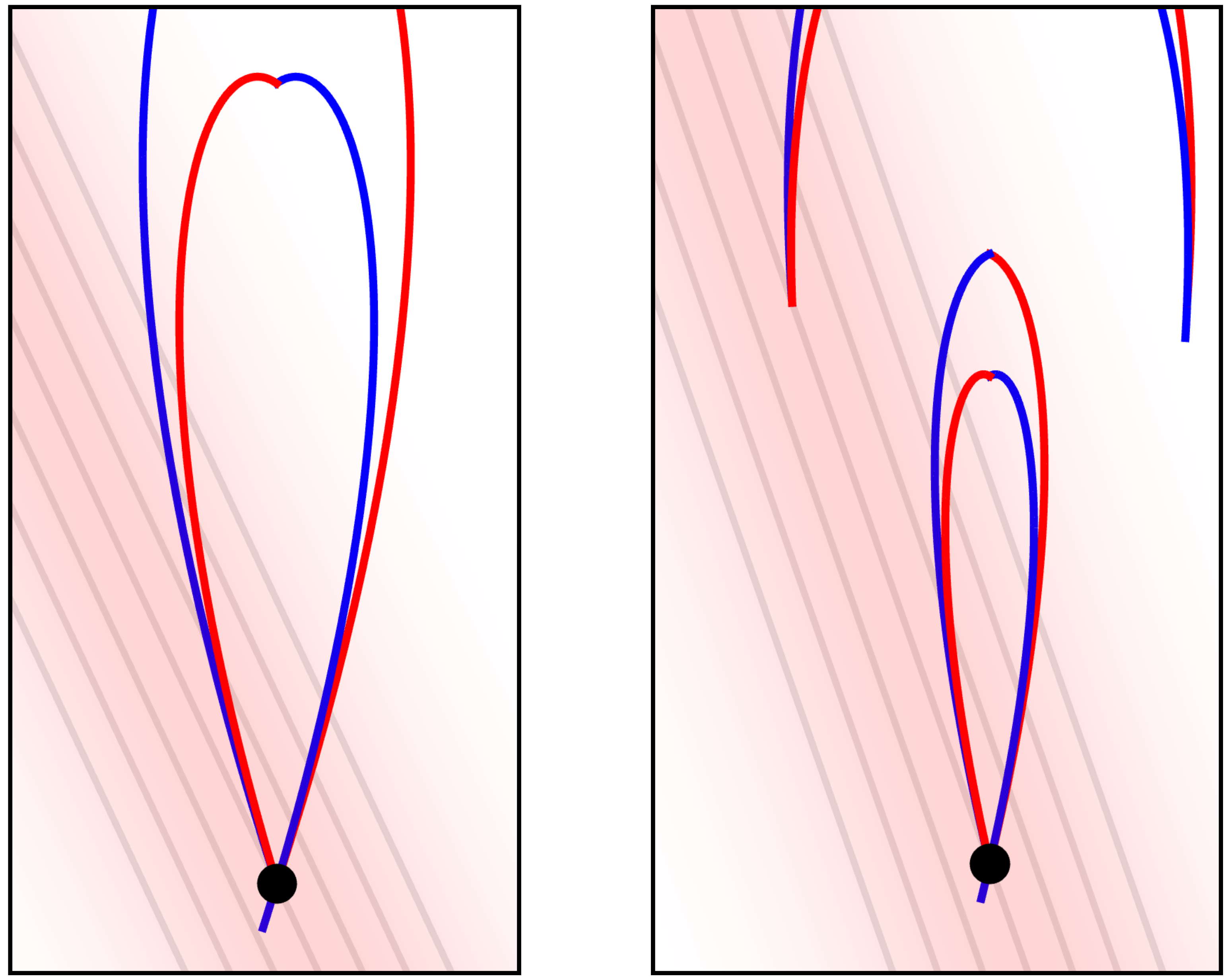


New Scheme for Scaling Coriolis Force Compensation Scheme to Longer Baselines

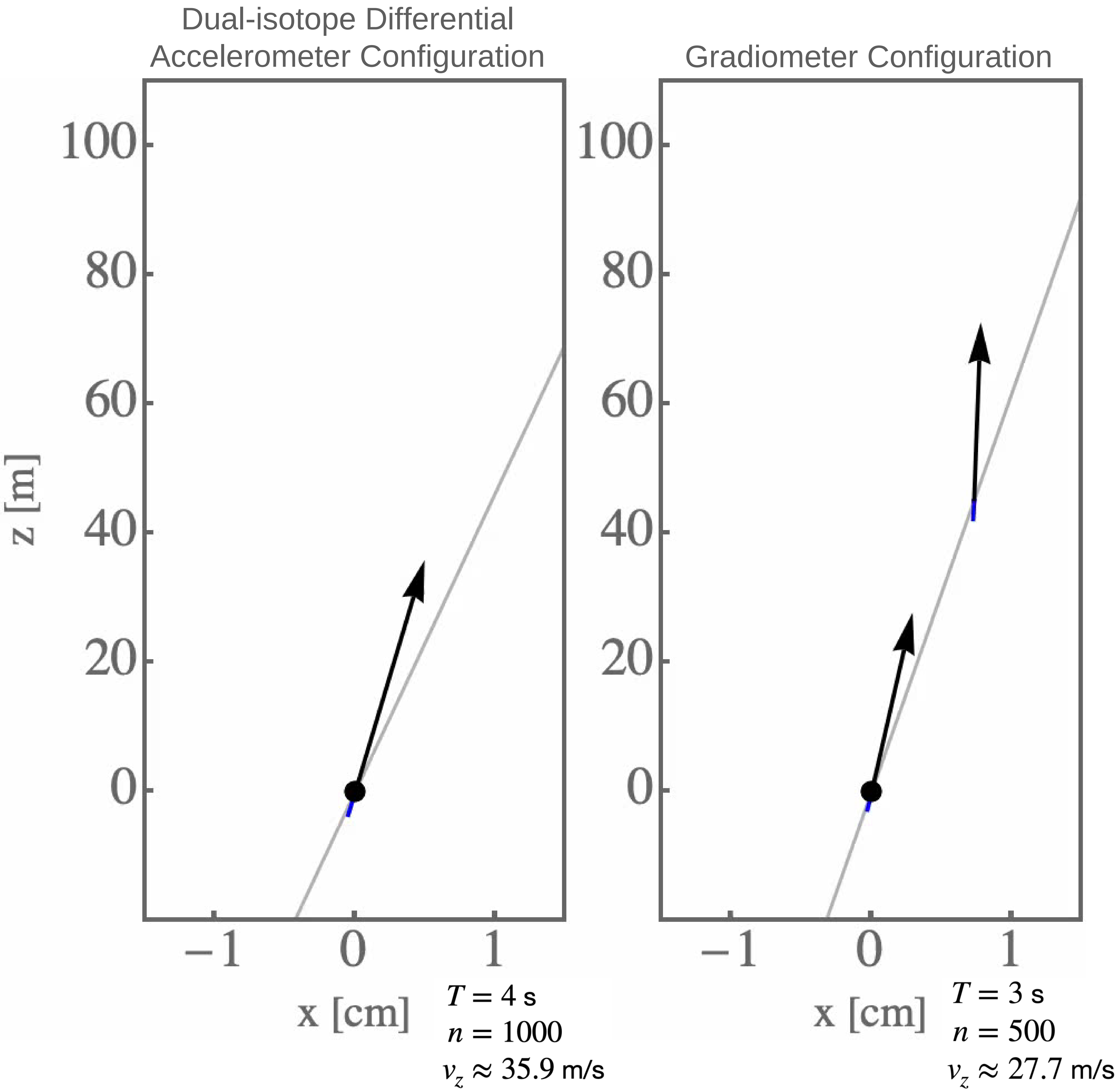
- If the beam delivery system could
  - Keep the ‘downward’ and ‘upward’ propagating beams collinear
  - Adjust the point along the baseline that the interferometer beam pivots

  then rotation compensation can be achieved in such a way that the atoms stay centered with the center of the interferometer beam during the atom-optics pulses

- This approach also requires the ability to adjust the initial kinematics of the of the different atom clouds individually



The atoms stay aligned with the interferometer beam during the key atom optics operations



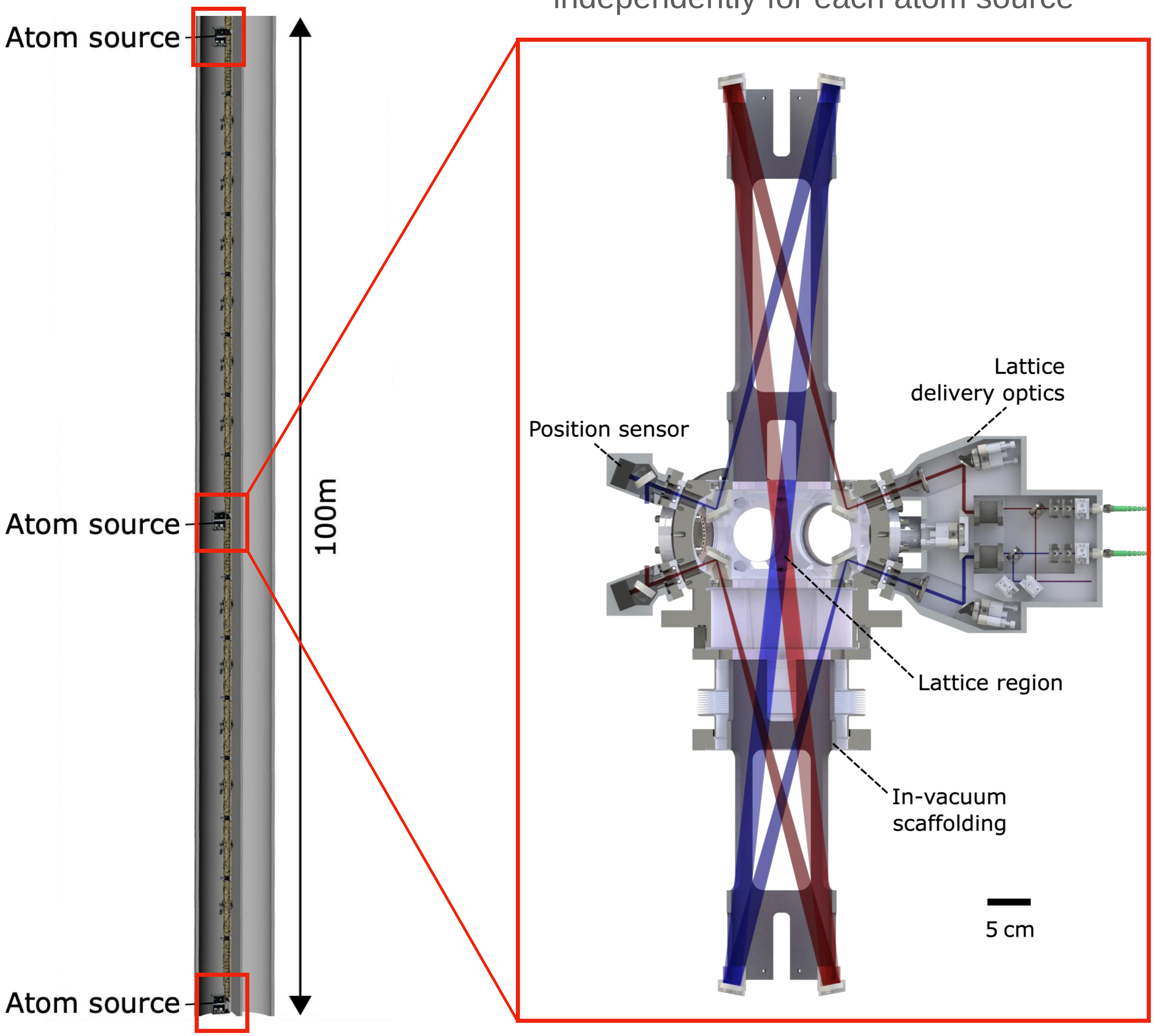
Dual-isotope Differential Accelerometer Configuration

Gradiometer Configuration

New Scheme for Scaling Coriolis Force Compensation Scheme to Longer Baselines

Adjusting Initial Cloud Kinematics

- Stanford team building lattice launching system to tune initial kinematics independently for each atom source

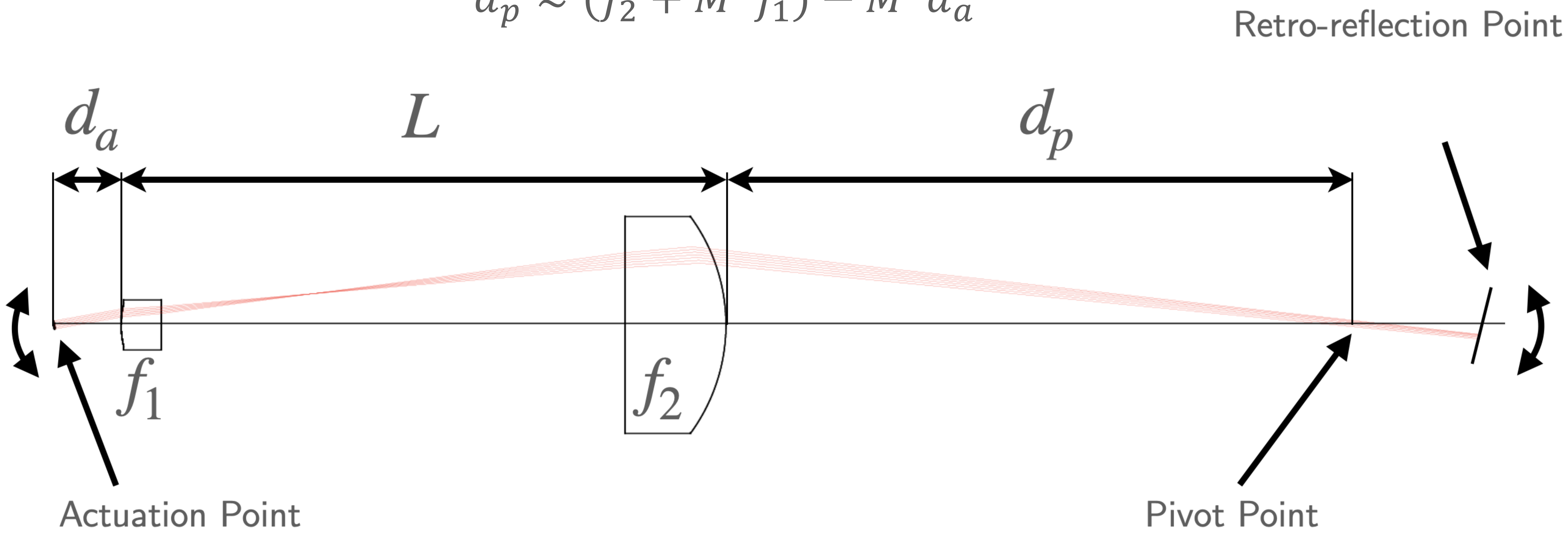


Abe et al., Quantum Sci. Tech. 6, 044003 (2021)

Leverage Beam Expansion Telescope to set pivot point and keep up and downstream beams Collinear

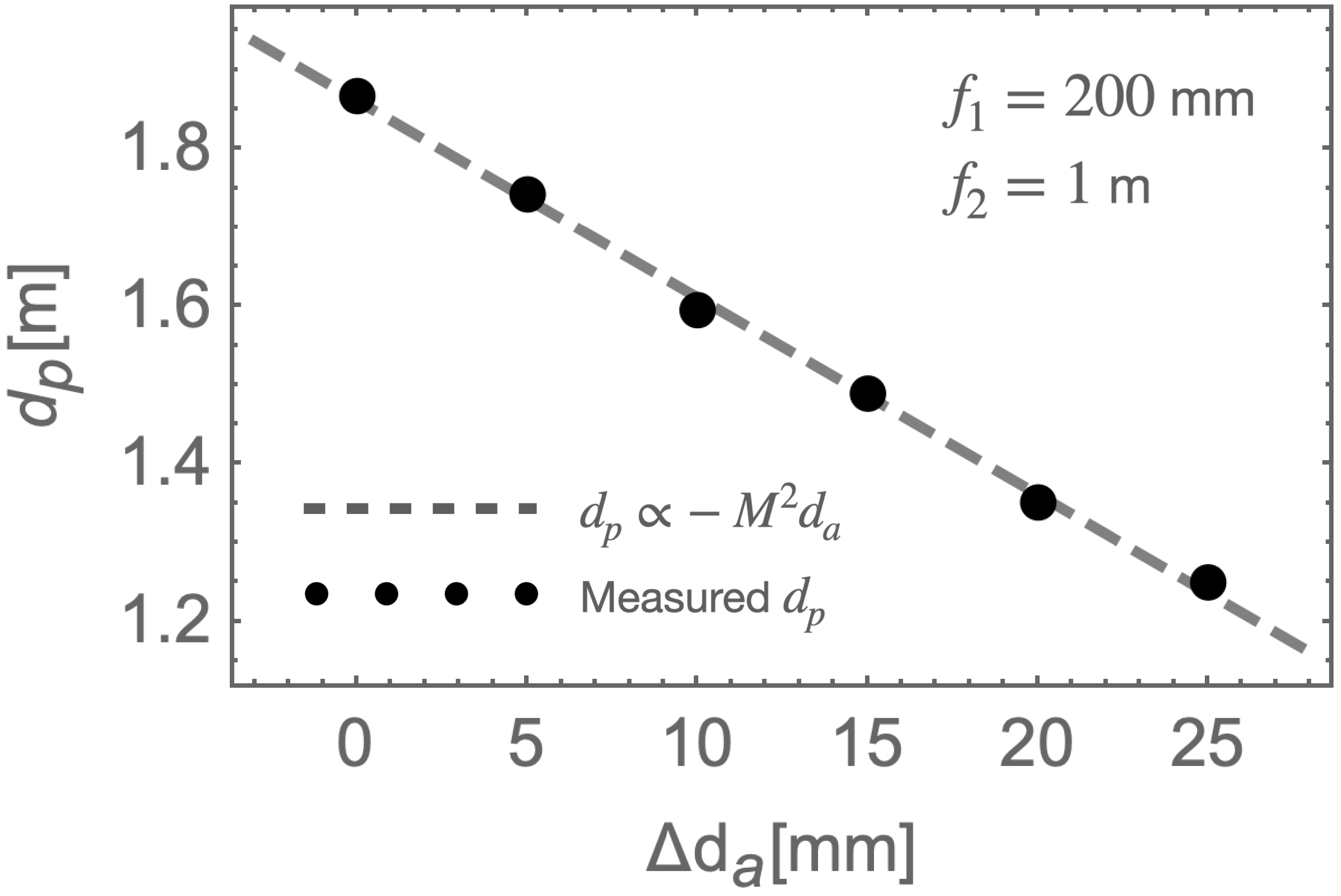
- The optical configuration associated with the pivot point scheme consists of having piezo-actuated mirrors on each end of the baseline
- The scheme leverages the telescope used to expand the interferometer beam to a cm-scale waist
- The point along the baseline that the interferometer beam pivots can be tuned by adjusting d_a

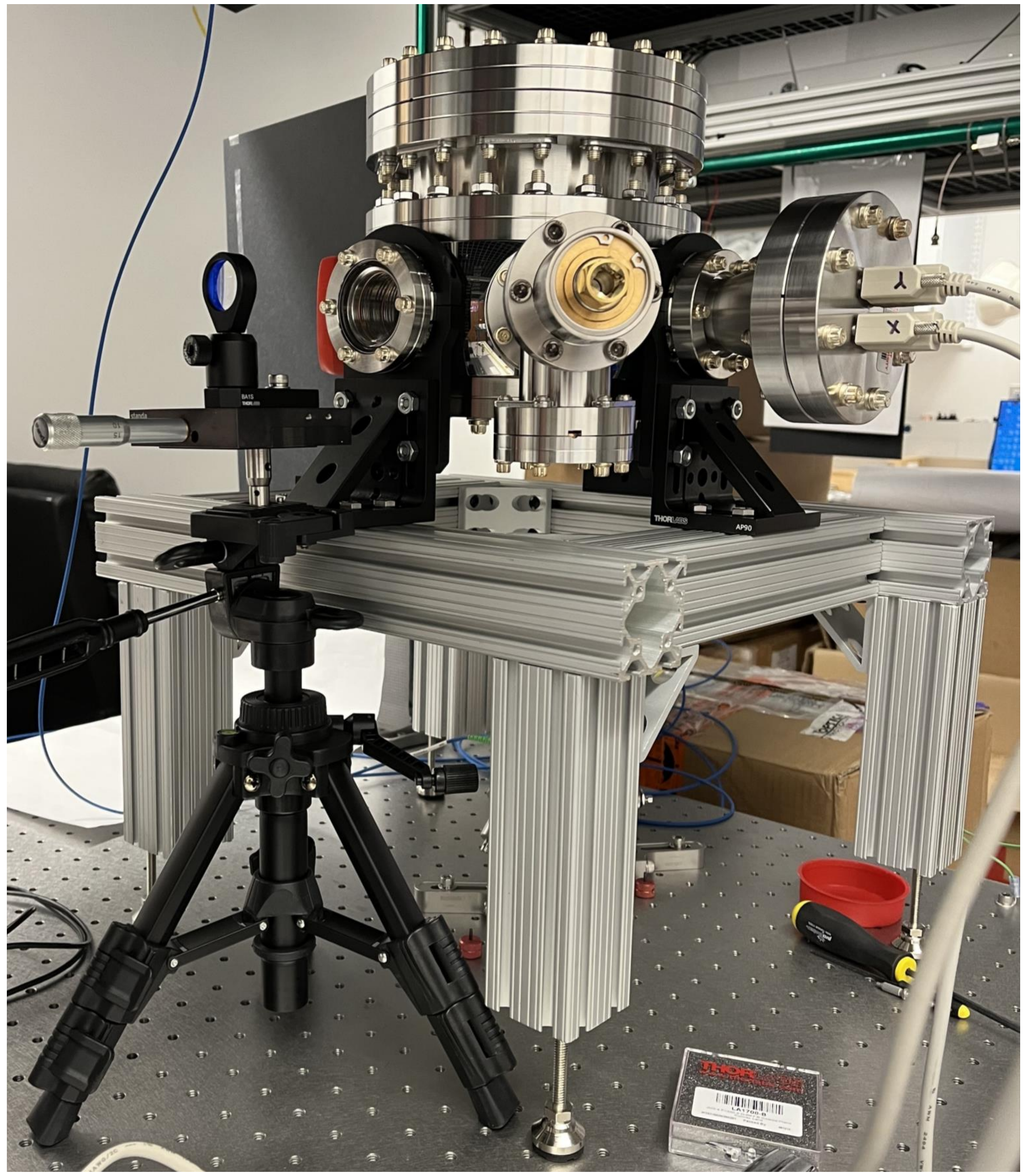
$$d_p \approx (f_2 + M^2 f_1) - M^2 d_a$$

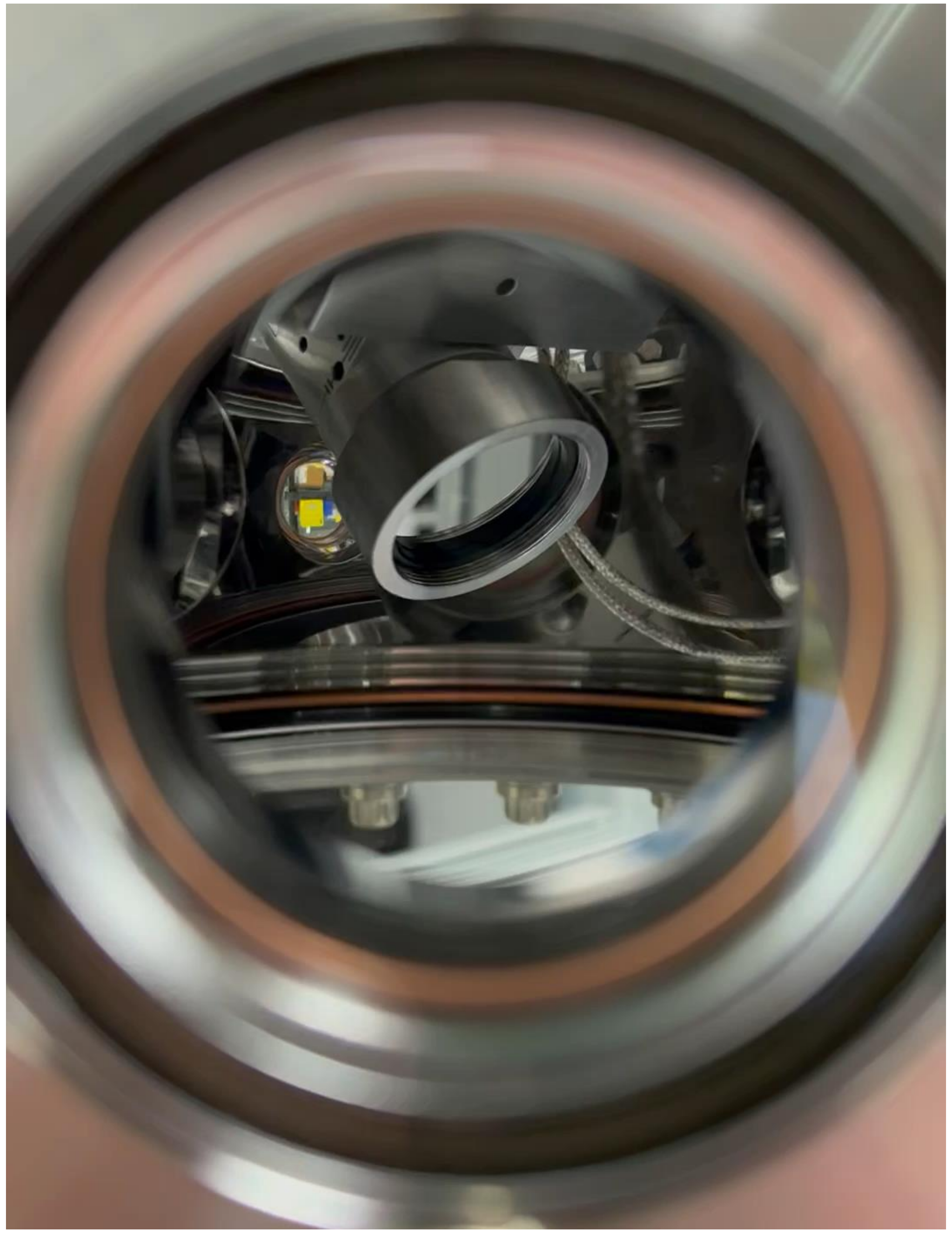


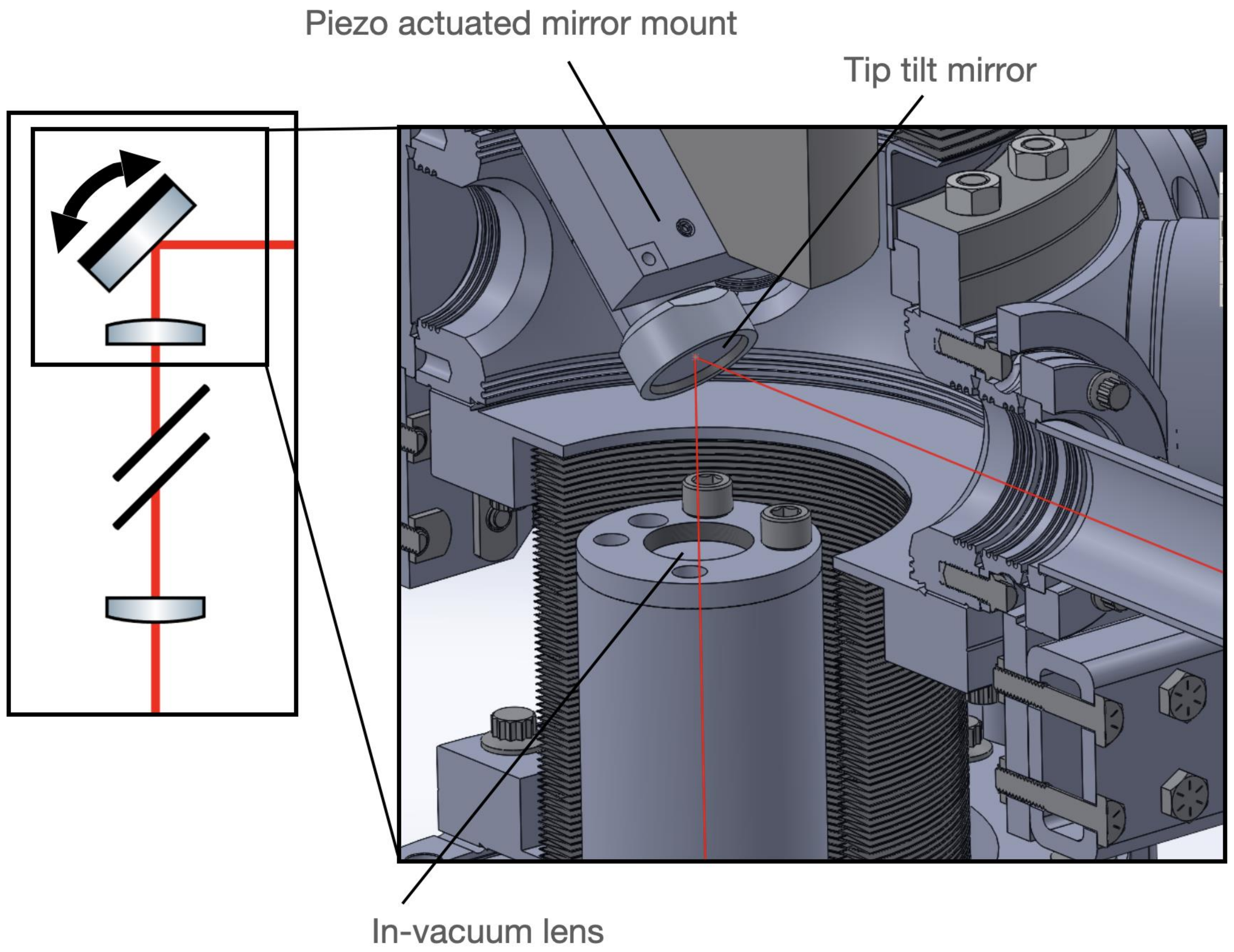
Pivot Point Method — Tip Tilt System

- The Interferometer beam will reflect off a piezo actuated mirror just before the first telescope lens
- 10 mrad total angular range — 20 nrad resolution
- A prototype of the tip tilt system has been assembled and optical tests are ongoing









Residual Phase Shifts from Rotation Rate Errors

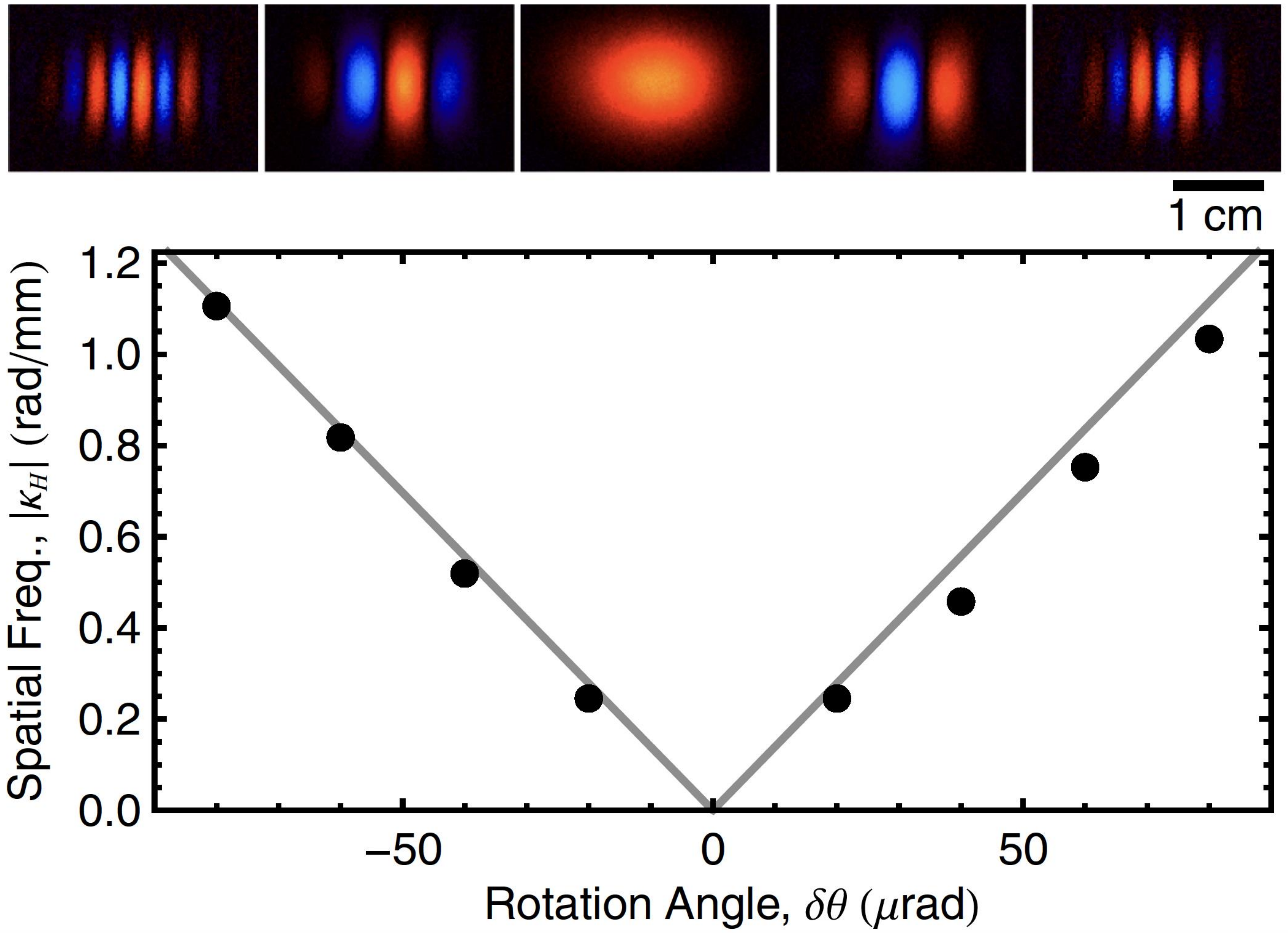
- Errors in the rotation rate manifest as Coriolis phase shifts which scale with the error in the rotation rate of the beam, rather than with the rotation rate of the earth

- In a dual isotope operating mode:

$$\begin{aligned}\Delta\phi_{\text{Coriolis}} &\approx 2nkv_x\delta\Omega_B T^2 \\ &\approx (2)(100)(2\pi/679\text{ nm})(10\ \mu\text{m/s})(10\text{ nrad/s})(2\text{ s})^2 \\ &\approx 0.7\text{ mrad}\end{aligned}$$

which is below the QPN limit for 10^6 atoms

- To reach smaller Coriolis-induced phase noise, point source interferometry (PSI) and phase shear readout could provide additional mitigation
  - Position-velocity correlations allow for rotation errors to be inferred directly through spatial imaging of atom cloud
  - Rotation compensation is essential when reading out the phase with PSI because otherwise interference fringes could be too high a spatial frequency to resolve in imaging



Sugarbaker et al., PRL 111, 113002 (2013)

Residual Phase Shifts from Rotation Rate Errors

- In a gradiometer configuration, the requirements for rotation rate error suppression are relaxed by a cancelation that occurs between the differential Coriolis phase shift and the differential centrifugal shift.
- Considering the differential phase between the top and bottom interferometers:

$$\Delta\phi_{\text{Coriolis}} \approx 2nk\Delta v_x(\delta\Omega_B)T^2 \approx -145 \text{ mrad}$$

$$\Delta\phi_{\text{centrifugal}} \approx nk\Delta z_0(2\delta\Omega_B\Omega_y)T^2 \approx 145 \text{ mrad}$$

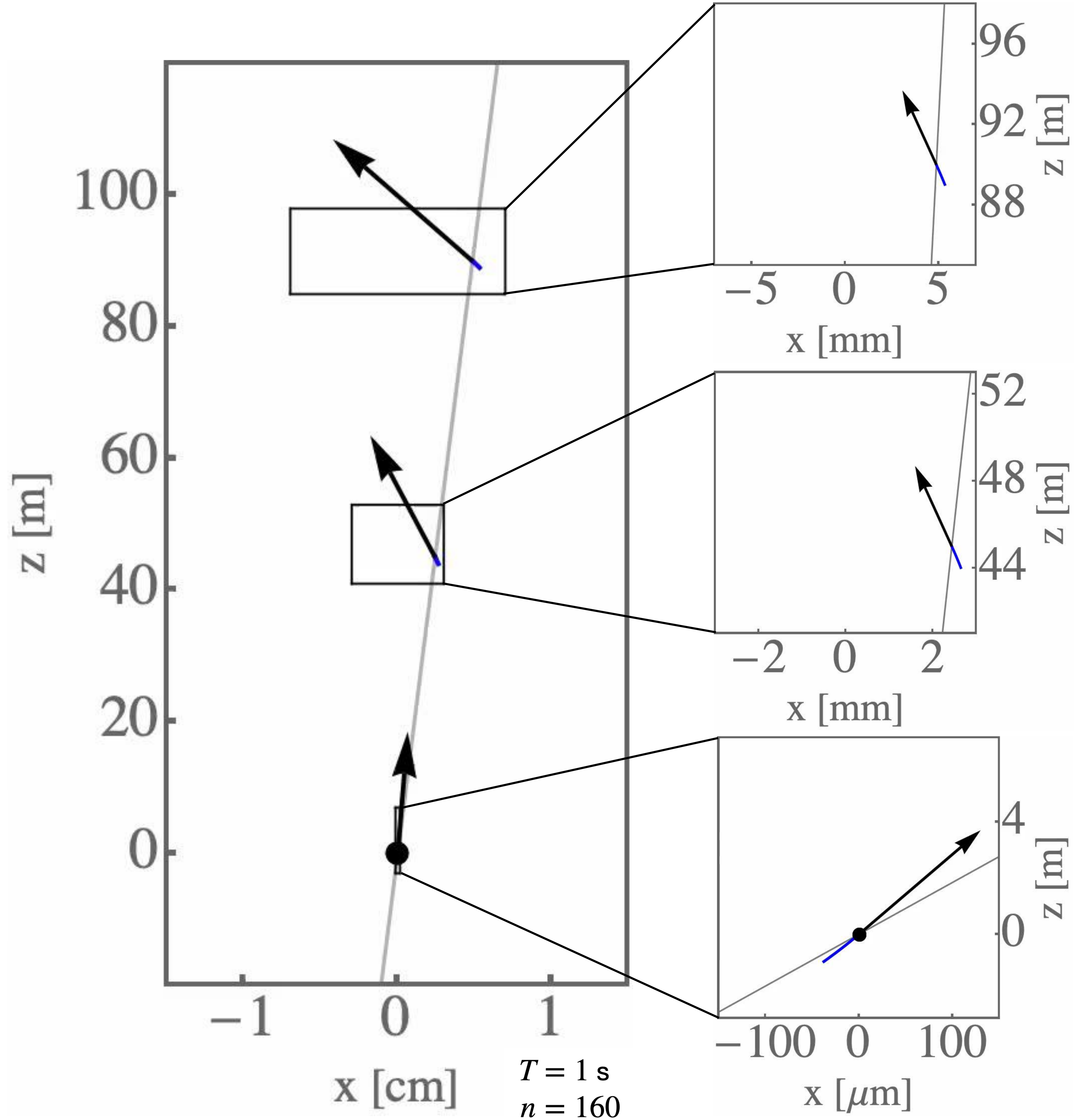
Taking $\Delta v_x = -\Omega_y \Delta z_0$ causes a cancellation between these two terms

- Leading order phase shifts are expected to come from shot to shot fluctuations in the transverse velocity and contributes below the QPN limit

$\delta\Omega_B$: error in rotation rate of interferometer beam

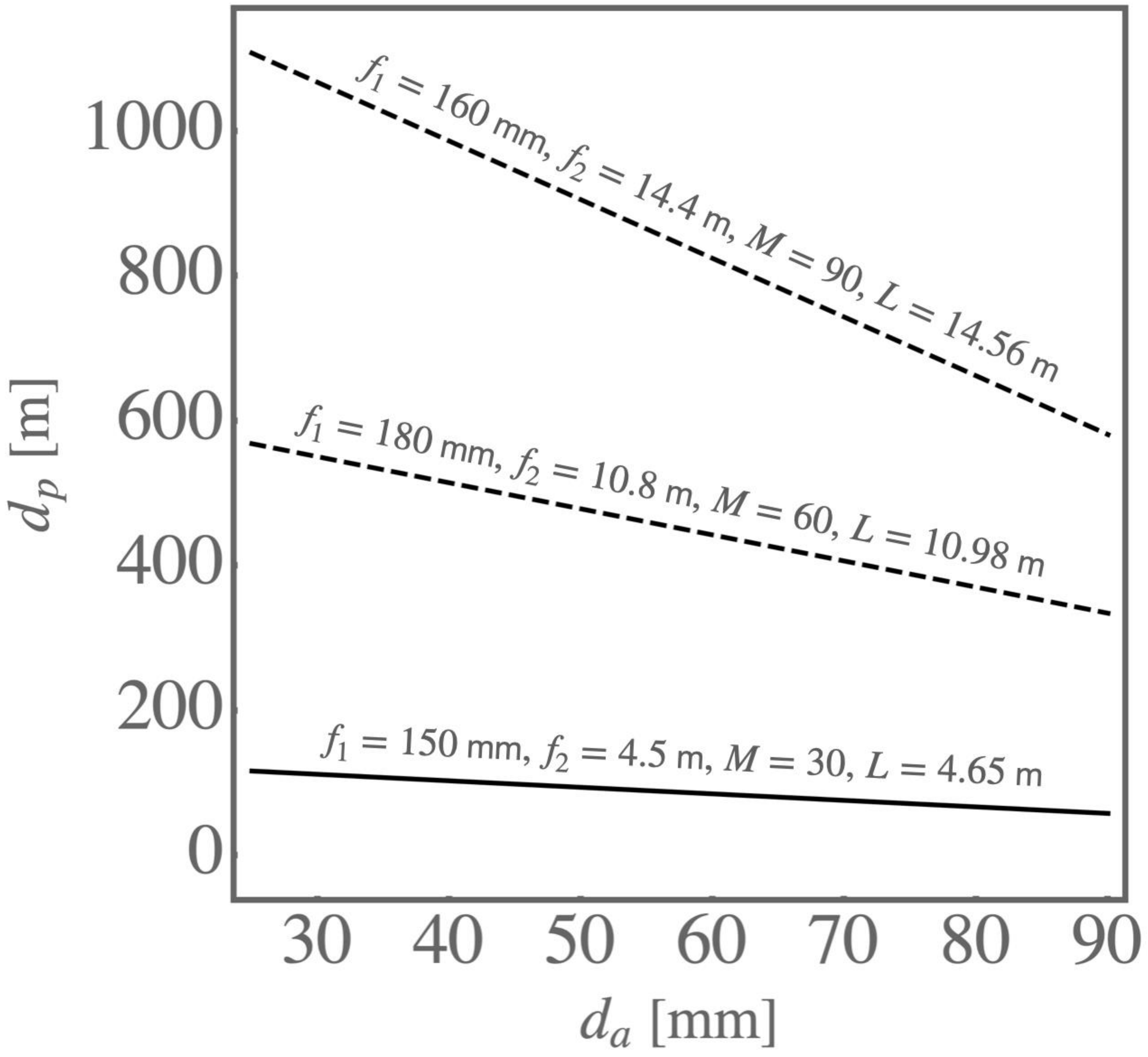
Δv_x: difference in initial transverse velocities between two interferometers

Δz_0: difference in initial altitudes between two interferometers

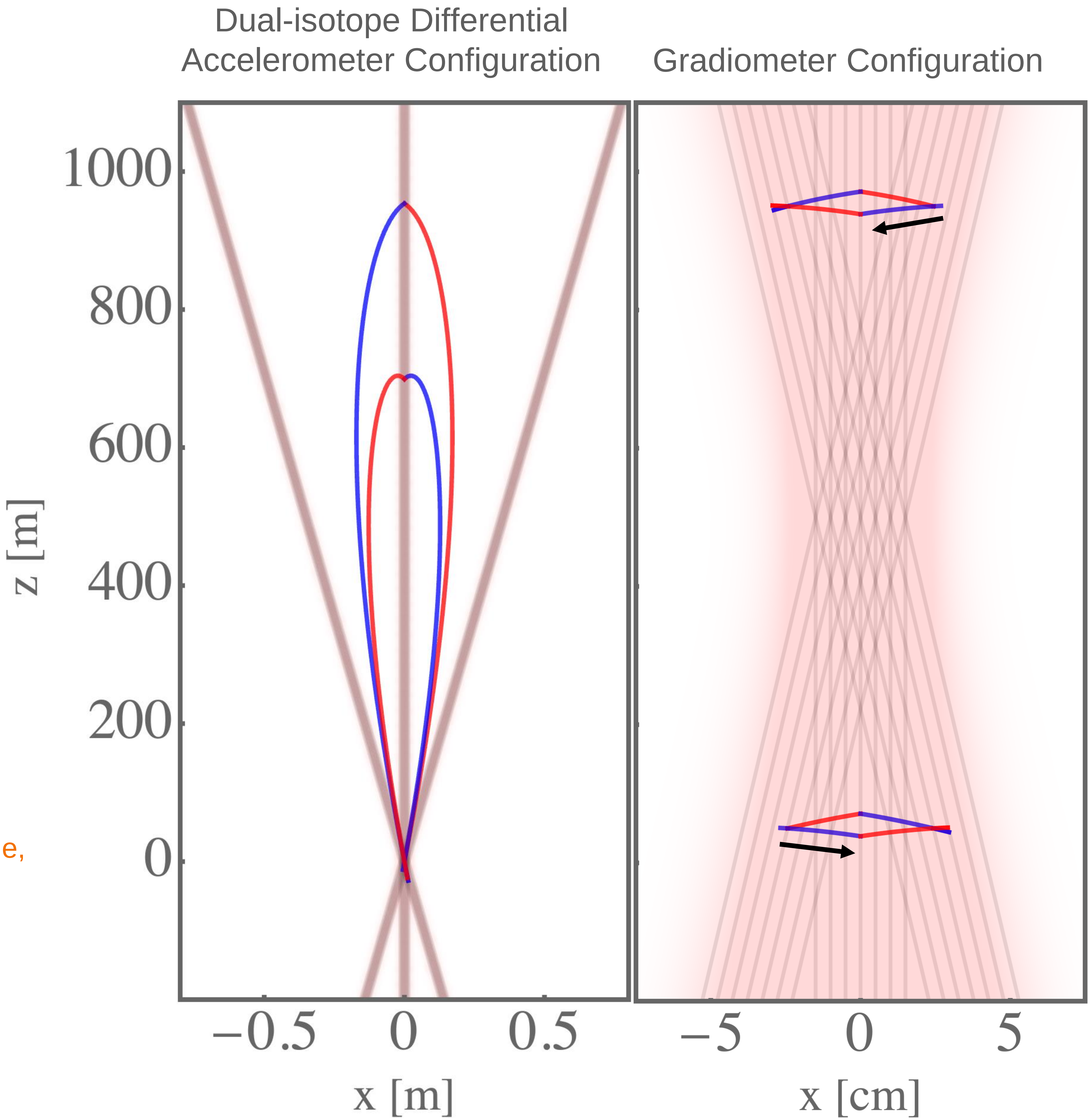


Challenge of Scaling to km Baselines

- Larger diameter vacuum tubes and optics required
  - In a dual-isotope configuration, where the atom trajectories span the full length of the baseline, the deflection of the interferometer beam is large — meter-scale diameters on optical components and vacuum tubes are required
  - In a gradiometer configuration, the deflection of the beam is smaller (owing to the smaller *T*) and requirements for the gradiometer configuration are more relaxed



Is it realistic to extend this method to a longer baseline, or would is an alternate approach be required?



$T = 13$ s
$n = 3000$
$v_z \approx 117.4$ m/s

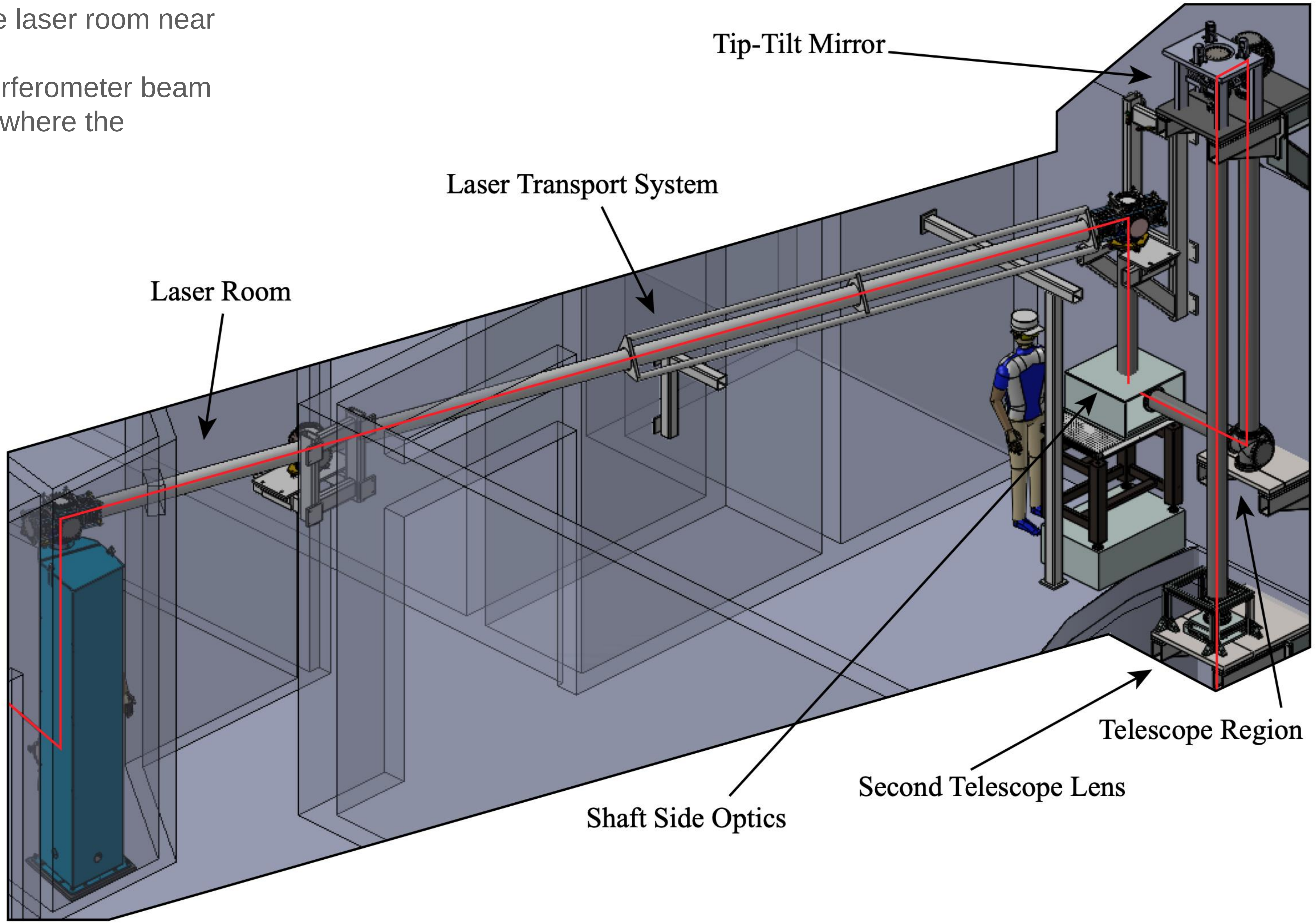
$T = 1$ s
$n = 3000$

Thank you!

Laser Transport / Backup

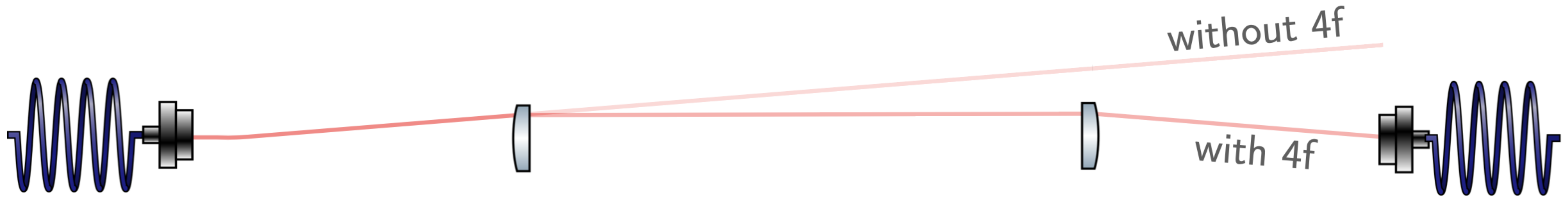
Beam Delivery System — Mechanical Design

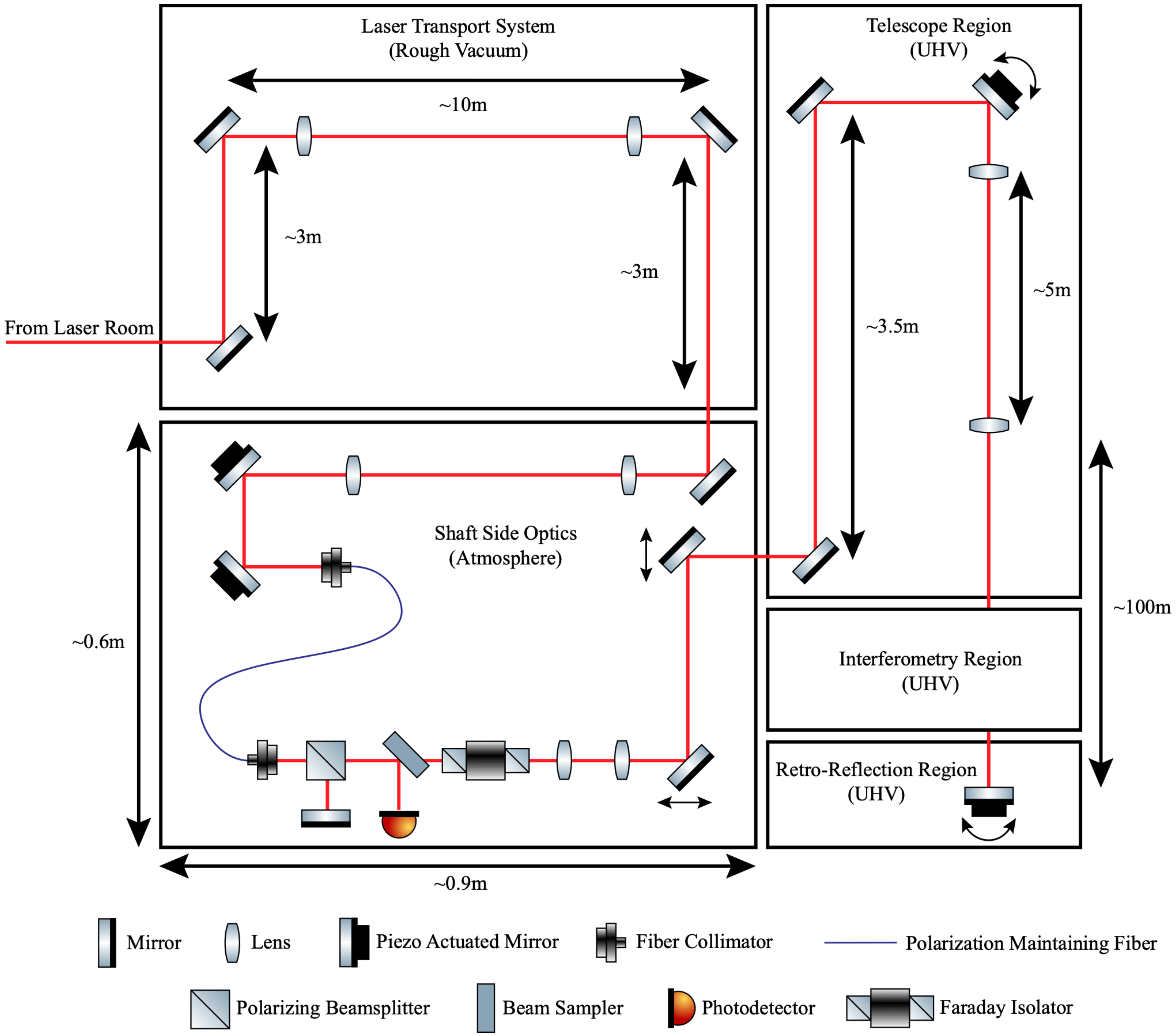
- Having a dedicated laser room allows for temperature control and laser safety
- In facilities that can accommodate long baseline interferometers, but which are not purpose built for them, it can be difficult to position the laser room near the main experiment
- The laser transport system for MAGIS-100 transports the interferometer beam from where it is generated in the laser room over to the shaft where the interferometry is being done



Beam Delivery System — Mechanical Design

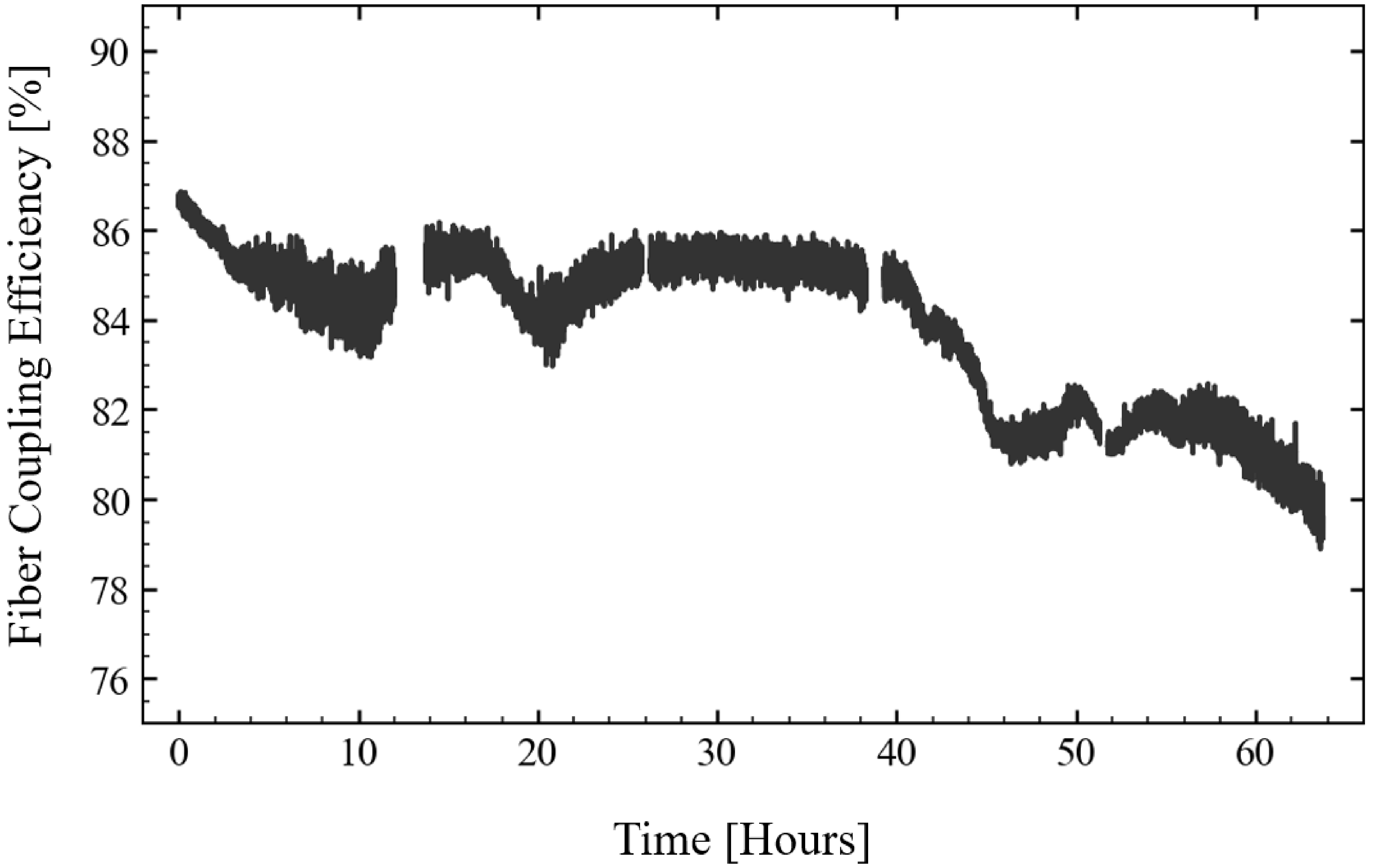
- A key advantage of fiber-based transport is that the position and pointing of the post-transport beam are determined solely by the fiber, which can be anchored to a structurally stable floor, but beam power loss from stimulated Brillouin scattering discourages fiber-based transport
- Free-space beam delivery is more susceptible to alignment drifts, especially with a relatively long $10m$ lever arm
- The beam devilry system for MAGIS-100 uses a combination of stable mechanical mounts, a relay-imaging system, and a short fiber to provide both passive pointing stability and a stable multi-Watt interferometer beam power.

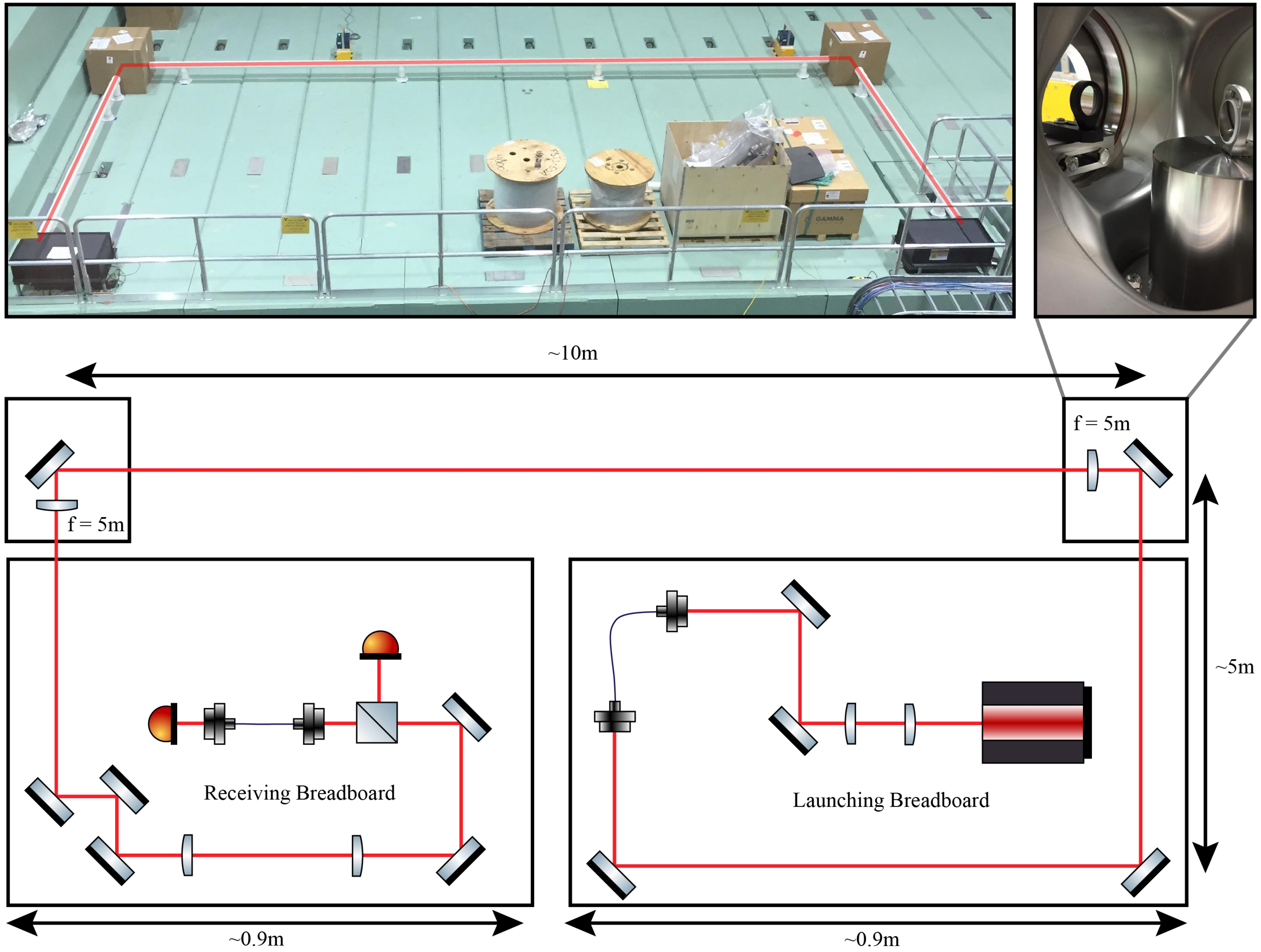




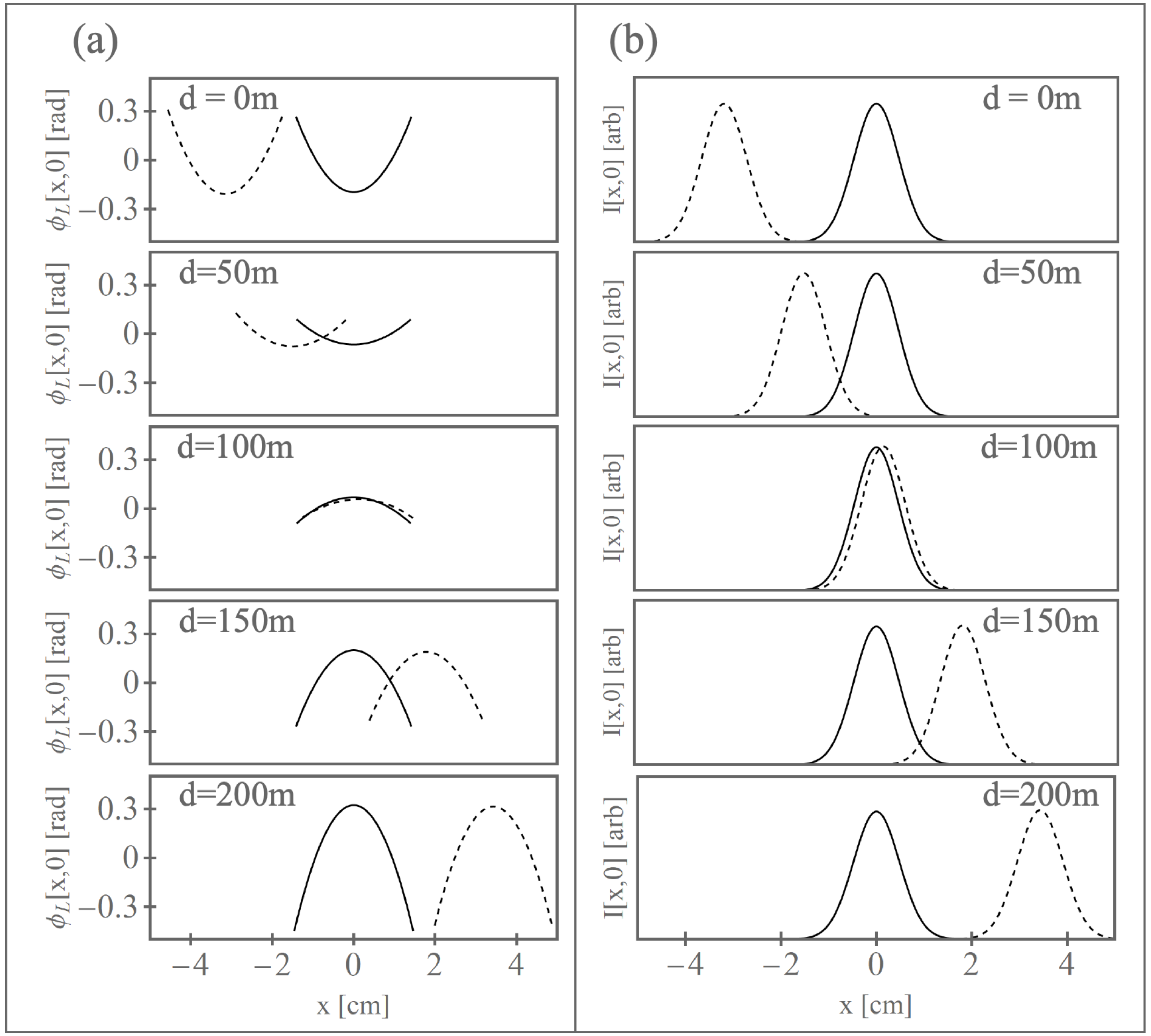
Beam Delivery System — Prototype Test

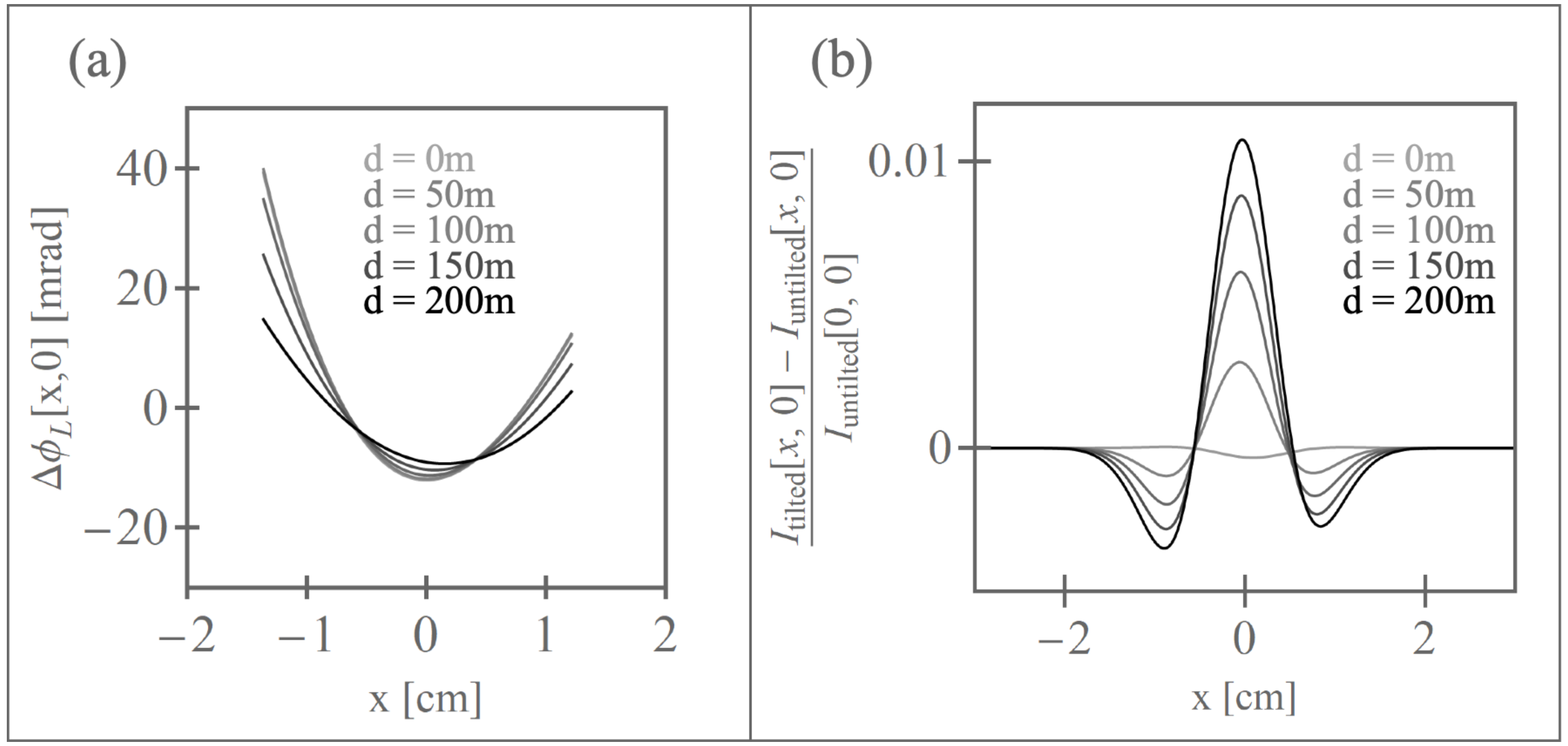
- We constructed a prototype of the laser transport system to demonstrate the feasibility of coupling the interferometer beam into a short fiber following $\approx 20m$ of free propagation and to monitor the passive stability of the fiber coupling efficiency
- We achieve a $> 80\%$ fiber coupling efficiency over $40hrs$

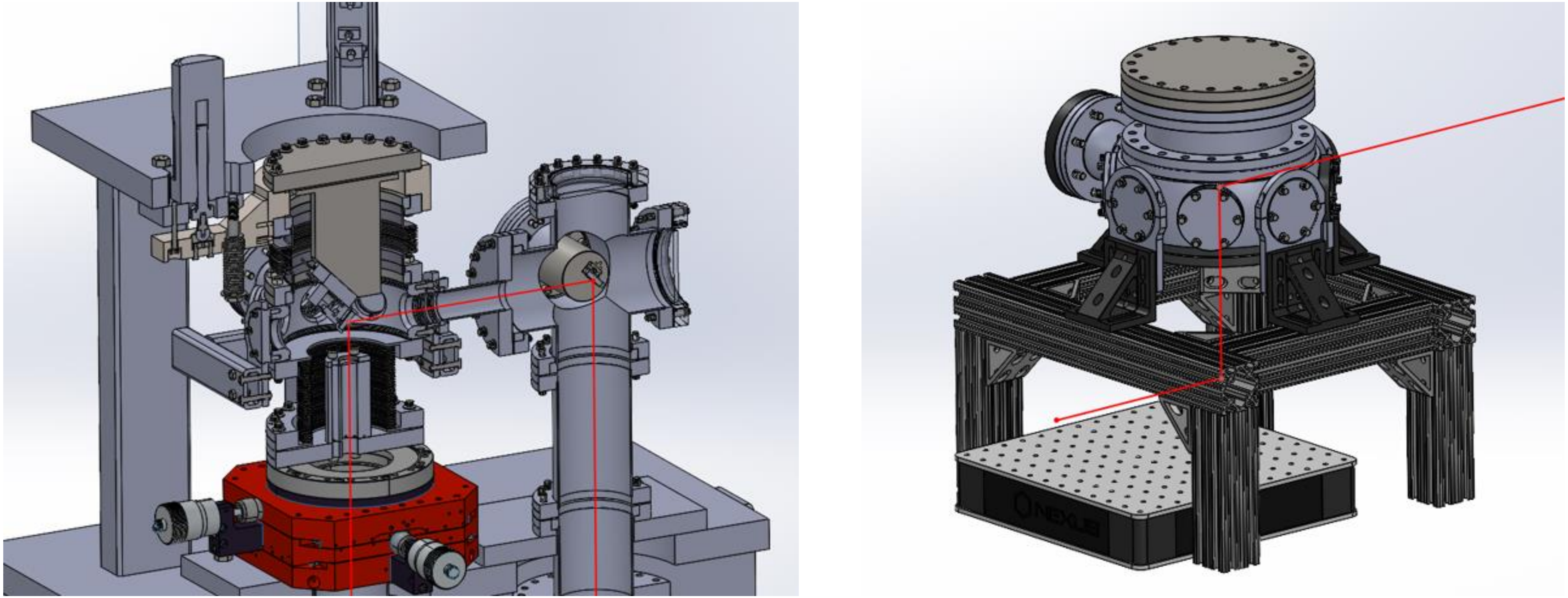




Effect of Spherical Lens Aberrations from Telescope Lenses






NEXUS