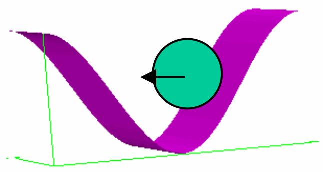
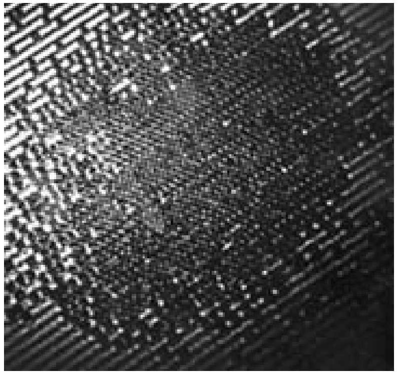
Laser-Trapped Mirrors in Space





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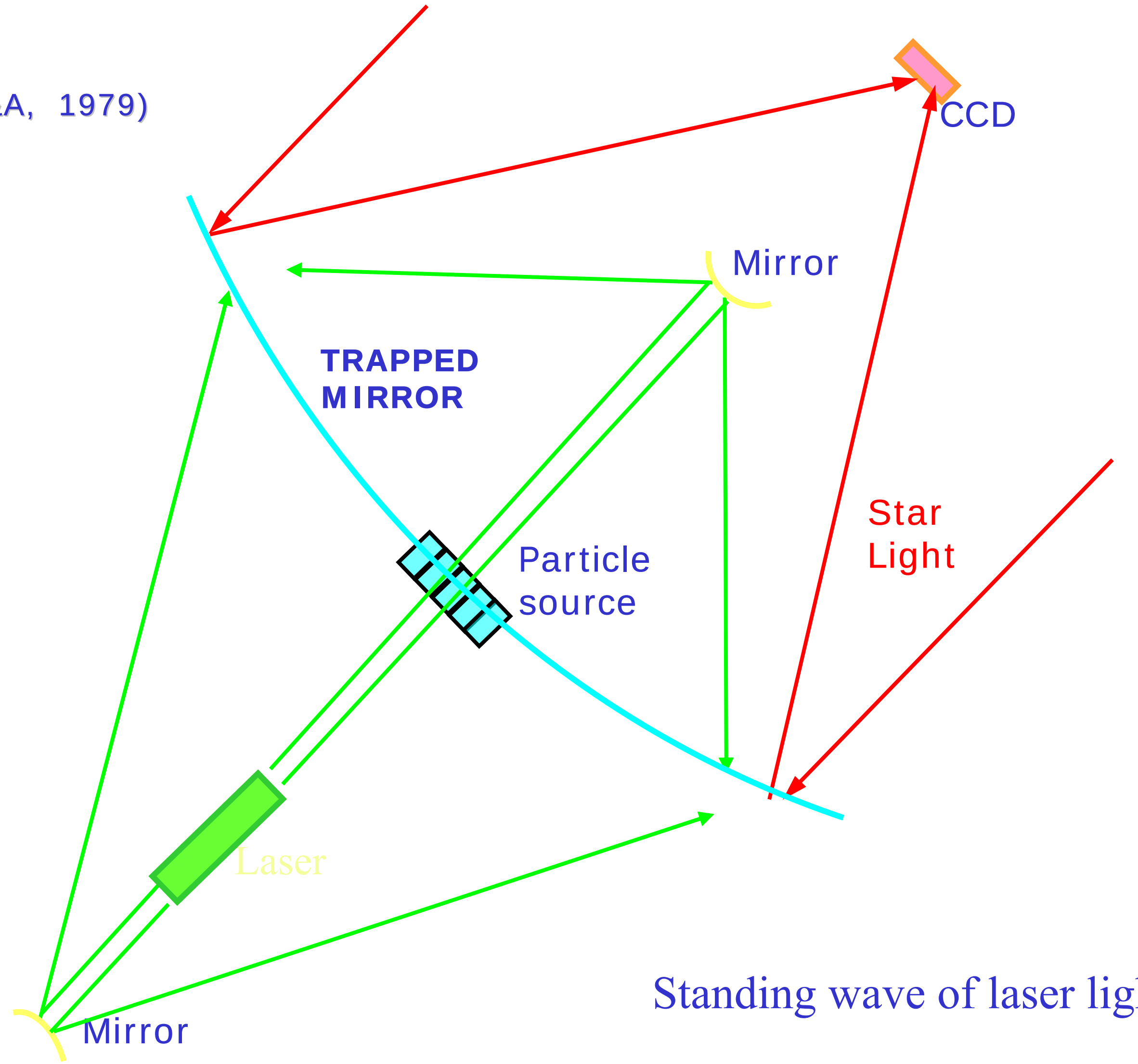
The Project

Can Laser Trapped Mirrors be a practical solution to the problem of building large, low-mass, optical systems in Space?

- The Laser-Trapped Mirror (LTM) Concept
- NASA Goals
- Light-Induced Trapping Forces
- Role of Optical Binding
- Experimental Work
- Numerical Calculations
- Project Goals

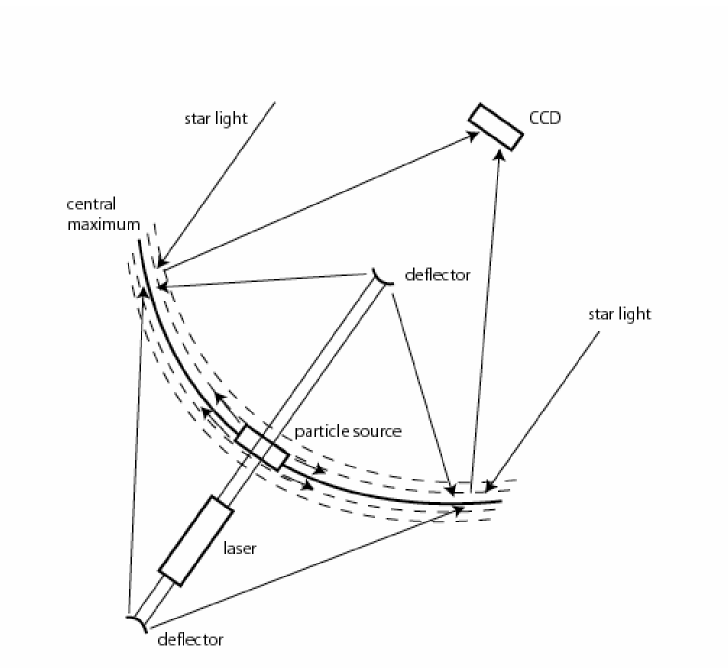
The LTM Design

(Labeyrie, A&A, 1979)



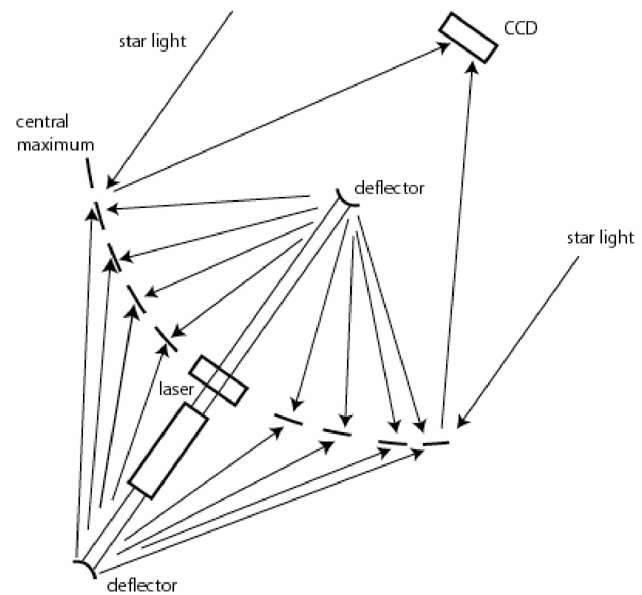
Standing wave of laser light traps particles

The LTM Concept



- Beams emitted in opposite directions by a laser strike two deflectors.
- Reflected light produces a series of parabolic fringe surfaces.
- Through diffractive and scattering forces, dielectric particles are attracted toward bright fringes, and metallic particles towards dark fringes.
- Ramping the laser wavelength permits sweeping of particles to the central fringe.
- Result is a reflective surface in the shape of a mirror of almost arbitrary size.

Advantages of the LTM



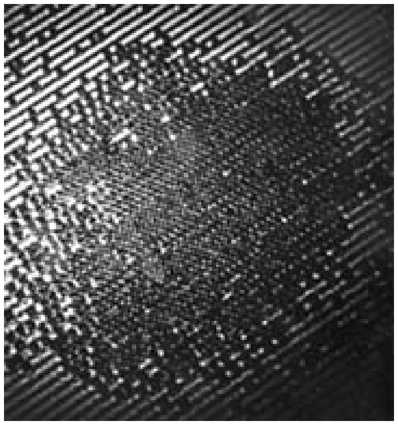
- Potential for very large aperture mirrors with very low mass (35 m--> 100g !!) and extremely high packing efficiency (35m--> 5 cm cube).
- Deployment without large moving parts, potential to actively alter the mirror's shape, and flexibility to change mirror "coatings" in orbit.
- Potential for fabricating "naturally" co-phased arrays of arbitrary shape as shown at left.
- Resilience against meteoroid damage (self-healing).
- The LTM should be diffraction limited at long wavelengths. For a trapping wavelength in the visible, e.g. 0.5 μm, and operation at 20 μm, the "flatness" of the mirror will be better than λ/80.

NASA Goals

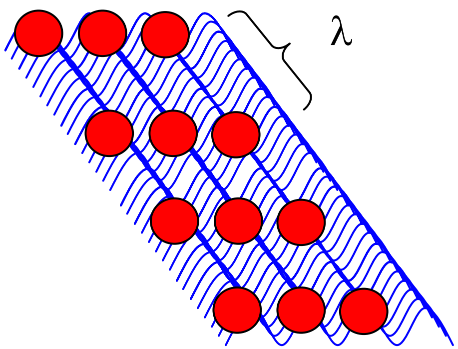
Future NASA Optical Systems Goals and their relation to the LTM

	Visible	Far IR to sub mm	Proposed work	Additional comments
Wavelength / Energy Range	400 -700 nm	20 – 800 μm	Demonstration of a mirror at >500 nm and in the near IR	LTM can also be use as a diffractive structure and can work at different wavelengths in different view directions simultaneously
Size	6-10+ m	10-25 m	1 cm	Structures of about 80 microns radius have been made in water. We will extend this work to understand the trapping of much larger numbers of particles where binding forces dominate.
Areal Density	<5 kg/m^2	< 5 kg/m^2	< 10^{-6} kg/m^2 for the mirror alone and < 0.1 kg/m^2 for the system	
Surface Figure	λ /150 at λ =500 nm	λ /14 at λ =20 μm	λ / 2 confinement at λ =500 nm (or better, if binding helps to reduce thermal agitation) and imaging at λ =20 μm gives"flatness" λ /80	In the first order, the surface figure of an LTM is independent of the size of the particles used, however, particle size will be an important factor for determining surface quality through reflectivity and scattering cross-sections.

Previous Work



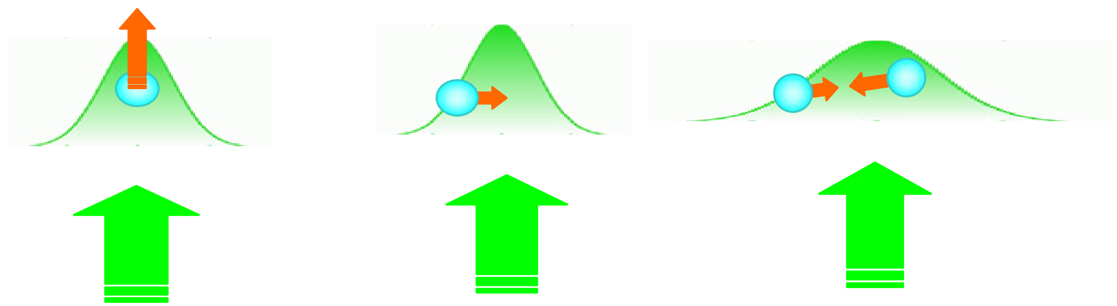
- Experiments by Fournier et al. in the early 1990’s demonstrated laser trapping of arrays of macroscopic particles along interference fringes: M. Burns, J. Fournier, and J. A. Golovchenko, Science 249, 749 (1990).



- Fournier et al. also observed that laser trapped particles can self-organize along a fringe due to photon re-scattering among the trapped particles resulting in "optical matter" (analogous to regular matter, which is self-organized by electronic interactions): M. Burns, J. Fournier, and J. A. Golovchenko, Phys. Rev. Lett. 63, 1233 (1989).

The Forces of Light

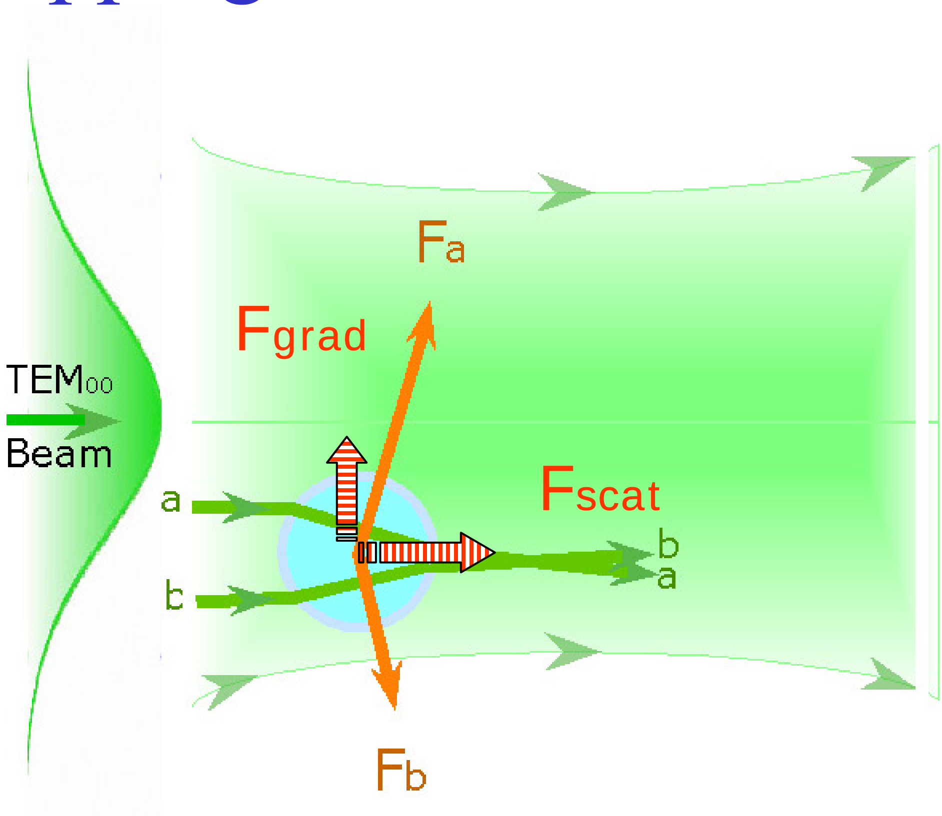
- Light fields of varying intensity can be used to trap particles.



scattering force   gradient force   binding force

- Light reflection results in repulsion (scattering force).
  Light refraction results in attraction (induced dipole and field gradient forces).
  Strongly wavelength-dependent processes.

Trapping in a Gaussian Beam



$$\langle \vec{F}_{grad} \rangle = \alpha \,.\, \vec{\nabla} \langle E^2 \rangle \qquad \langle \vec{F}_{scat} \rangle = 1/3\ \alpha^2\ \vec{k}^4\ \langle E^2 \rangle$$

Trap Strength

- Dipole interaction traps dielectric particles in regions of high field intensity.

$$U = P \cdot E \cong \frac{1}{2}\alpha E \cdot E$$

$$\alpha = \frac{n^2 - 1}{n^2 + 1} a^3$$

- For two counter-propagating plane waves, the trap strength is:

$$U_{trap} = \frac{2\pi\alpha}{c} I$$

- For 1 micron-sized particles with a reasonable index of refraction, n=1.6 and I expressed in Watts/m^2:

$$U_{trap} = 6 \times 10^{-20} I \quad \square\square\ \square\square$$

This is the challenge;
this number is very small.

- Equivalent to a temperature of milliKelvins
and an escape velocity of 10^{-4} cm/s.
Compare to infrared background at T ~ 30K

Estimate of Evaporation Time

- At 30 K, background photons: $n_\gamma \sim 10^6$ cm^{-3}, $\lambda = 10^{-2}$ cm.

$$\Delta E = \frac{p_\gamma^2}{2m} = \frac{(h/\lambda)^2}{2m}$$

$\Delta E \sim 10^{-34}$ ergs/collision

- Given a cross-section, $\sigma = 10^{-2}$ σ□□□□□□□□□, for the interaction of silica with these photons, the rate of increase of the kinetic energy of a trapped particle is:

$$\frac{dE}{dt} = \Delta E n_\gamma \sigma c$$

dE/dt ~ 10^{-26} ergs/sec

- Integrating and evaluating for a 1 micron-sized particle, we get:

$$\tau_{evap} = \frac{4\pi\alpha m\lambda^2}{h^2 n_\gamma \sigma c^2} I$$

$$\tau_{evap} \approx 1.5 \times 10^8 I \sec$$

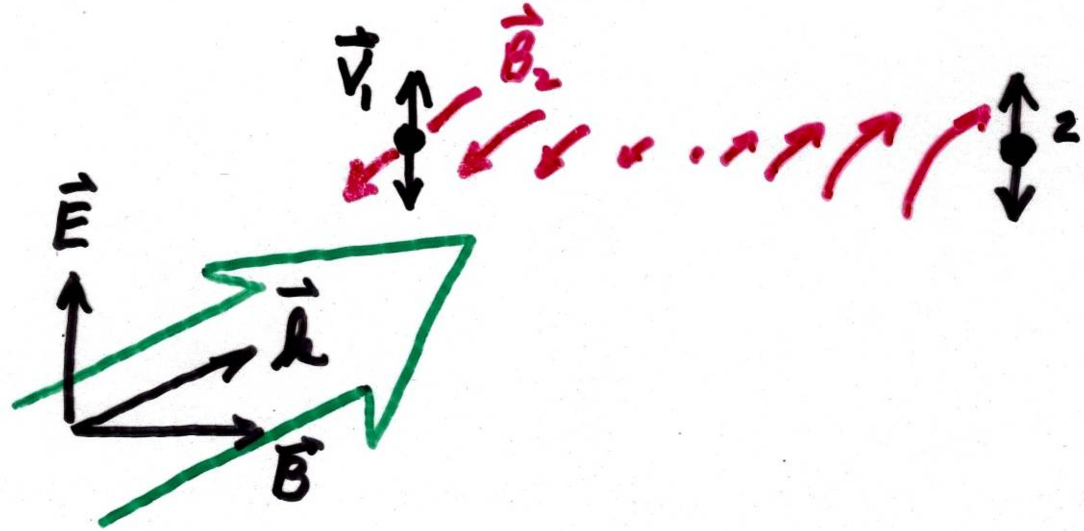
□□□□□□with radius ~*a*□:
Particle size is critical.

where *I* is expressed in Watts/m^2.

- A respectable number: about 5 years for $I = 1$ Watt/m^2 and ~ months for currently available laser intensities.

100 nm-sized particles --τ_{evap} ~ hours, will need damping.

Optical Binding Force



Consider all fields:
Incident and scattered,
Near and far

$$\vec{F}_p = \vec{\nabla}(\vec{p}\cdot\vec{E}) + \frac{\dot{\vec{p}}}{c} \times \vec{B}$$

Pair of oscillators:
Driven by fields and
radiating like dipoles

Find time average:

Solve for self-consistency

$$\langle F_\perp \rangle = \alpha^2 k^3 \langle E^2 \rangle \frac{\sin k r}{r}$$

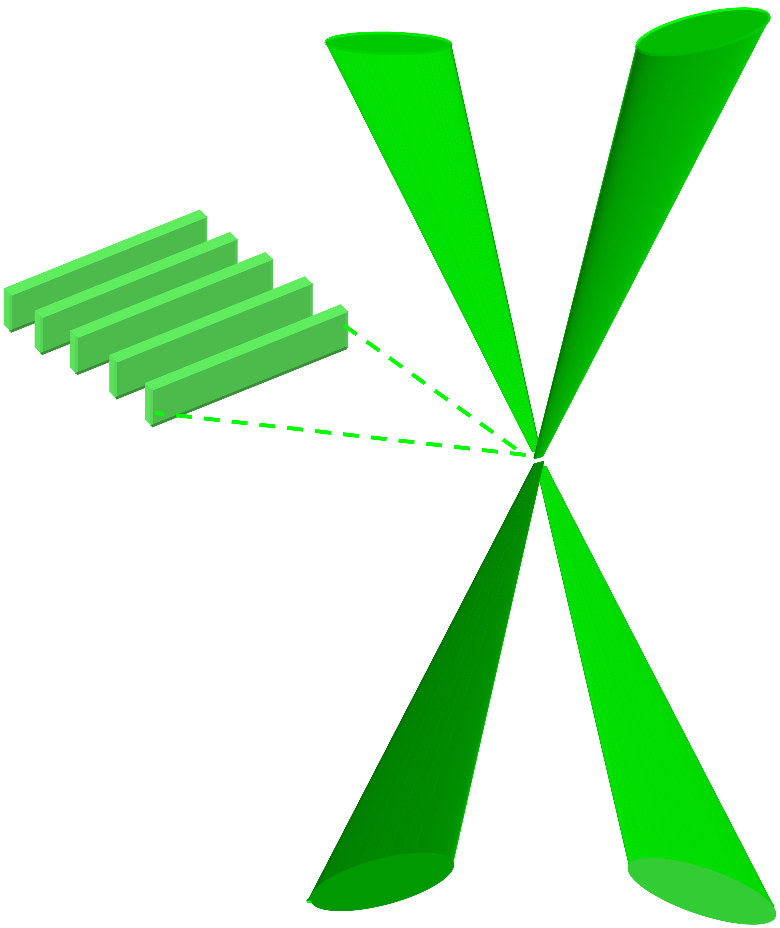
$$\boxed{W_\perp = -\frac{\alpha^2 k^2}{r}\langle E^2\rangle \cos k r \sin^2\theta} + O\left(\frac{1}{r^2}\right)$$

Optical Binding Potential

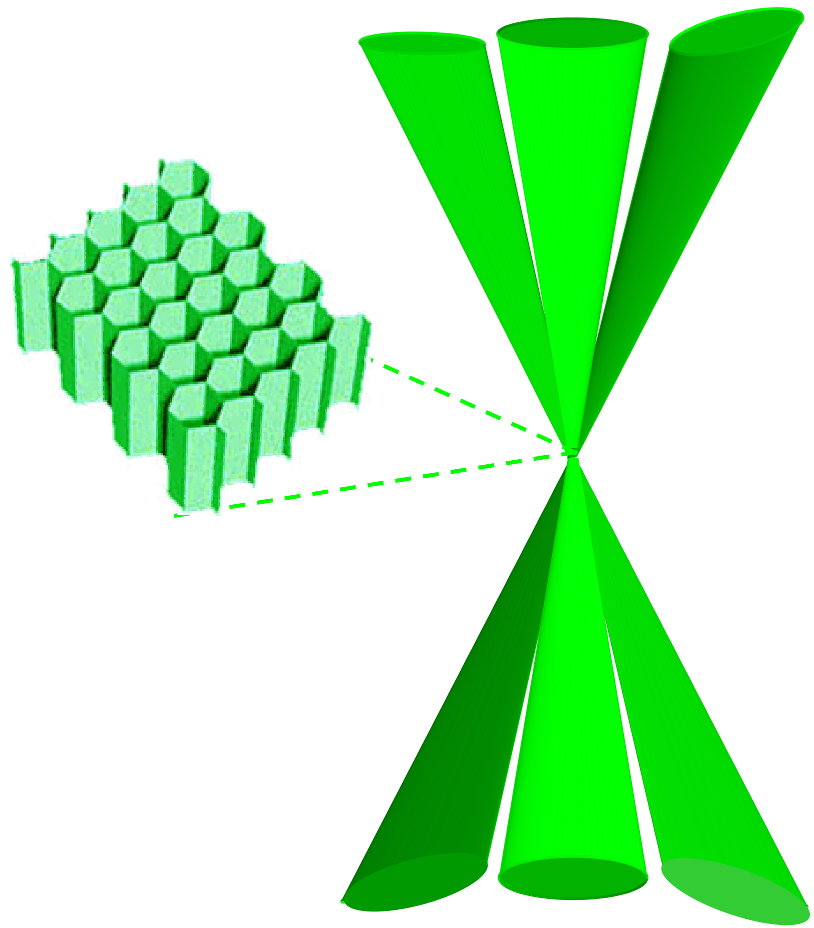
- Induced dipole moments in adjacent spheres will give rise to electromagnetic forces between the spheres.
- Burns, et al. give an approximation for this interaction energy: long-range interaction which oscillates in sign at λ and falls off as $1/r$.
- Calculations of this two-particle binding potential look encouraging. However, results are based on approximations not necessarily valid in the regime where particle radius $\sim \lambda$.
- Need to explore this effect with no approximations, i.e., in the Mie scattering regime.

Interferometric Templates

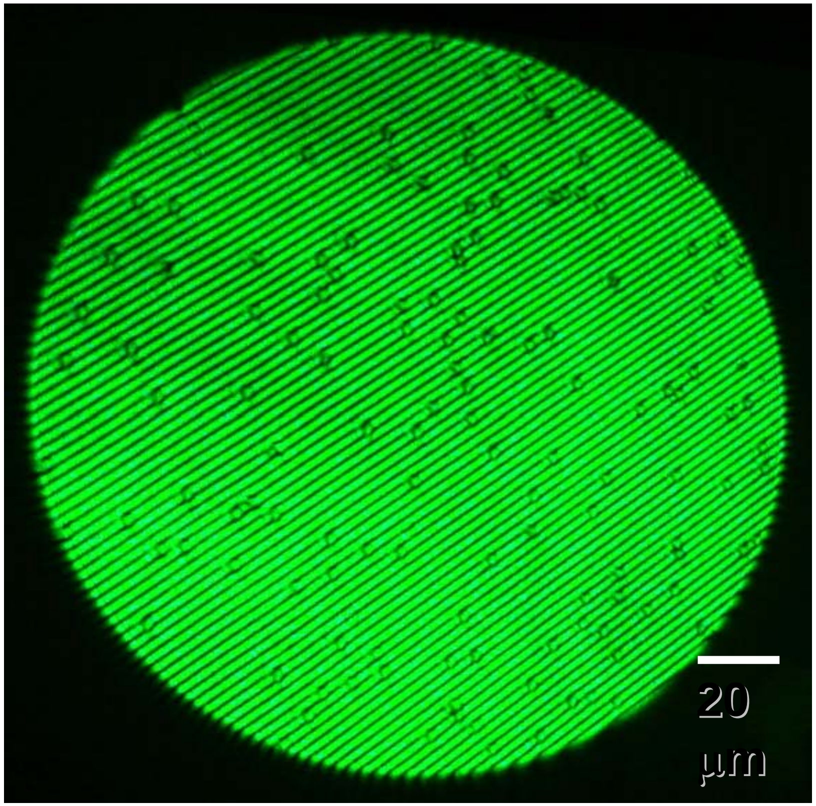
2 Beams

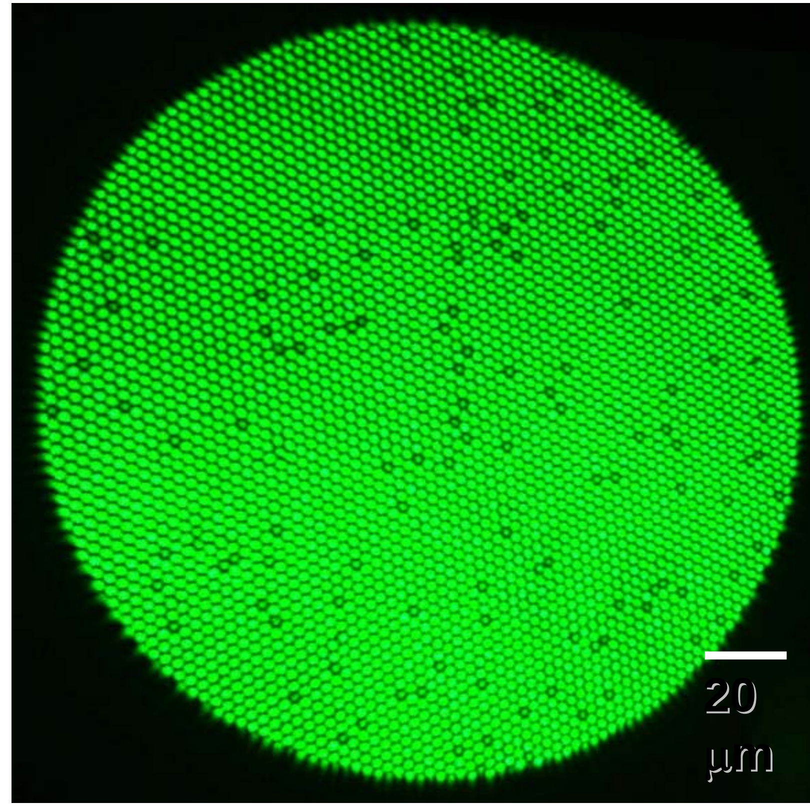


3 Beams

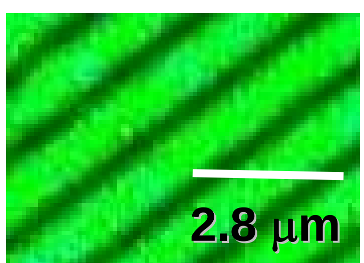


One- and Two-Dimensional Traps



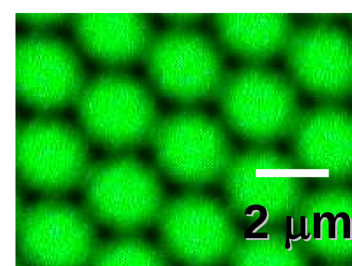


2 Beams



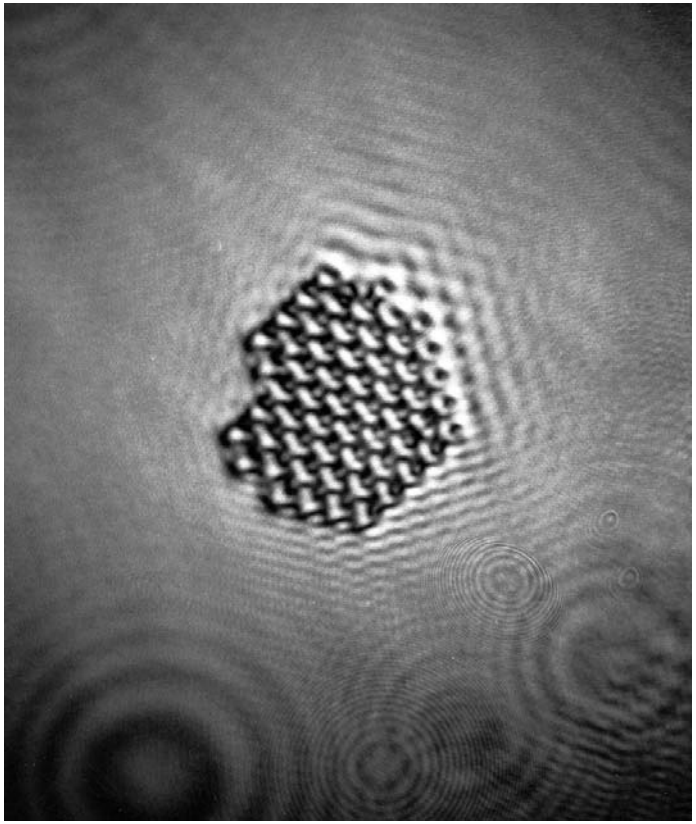
1500 traps

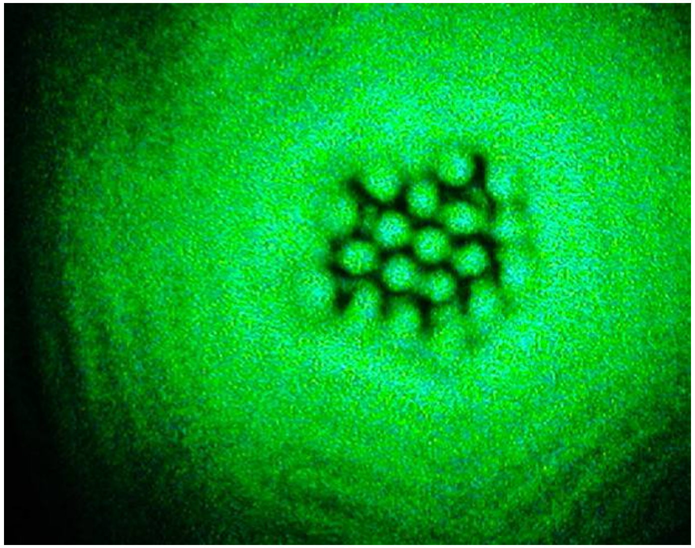
3 Beams



Observation of optical binding and trapping in a Gaussian beam

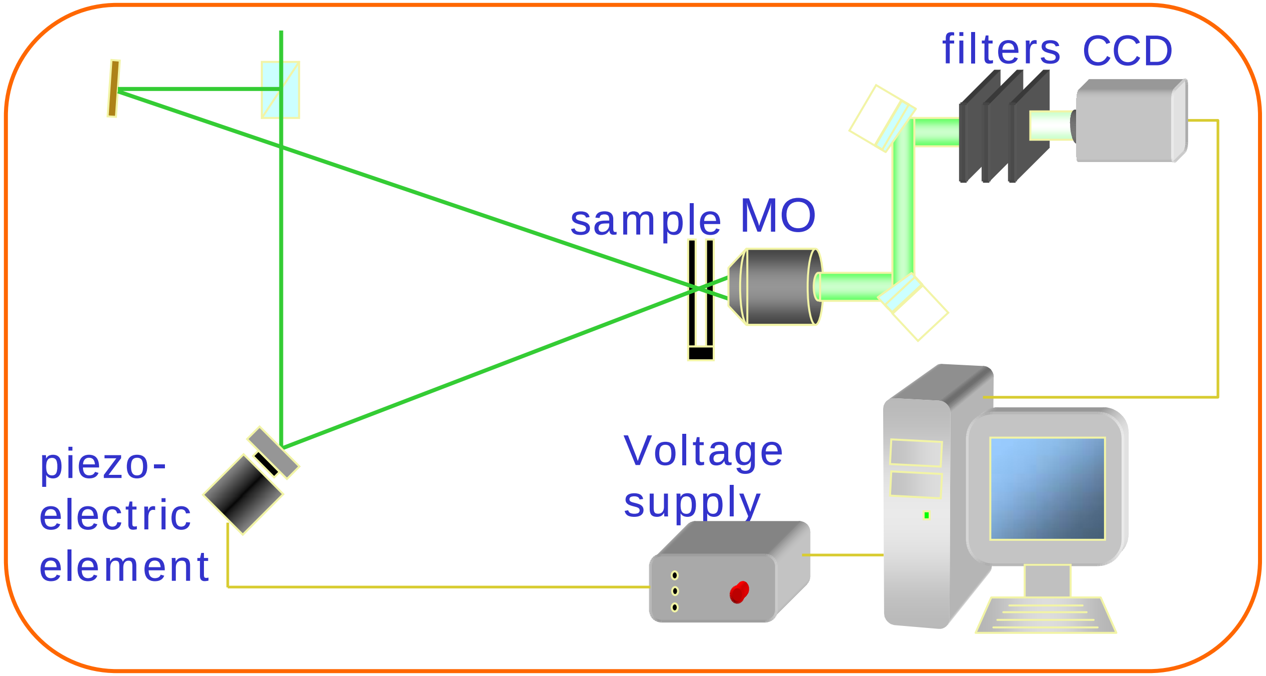
1 beam

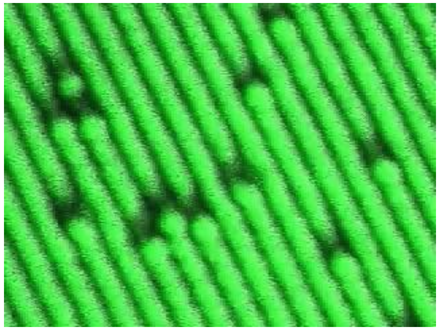




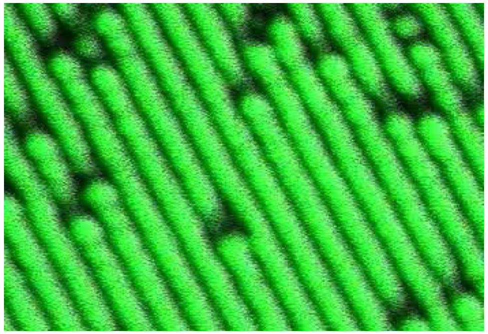
Auto-arrangement of 3 μm polystyrene beads at the waist of a Gaussian beam

2-Beam Interference



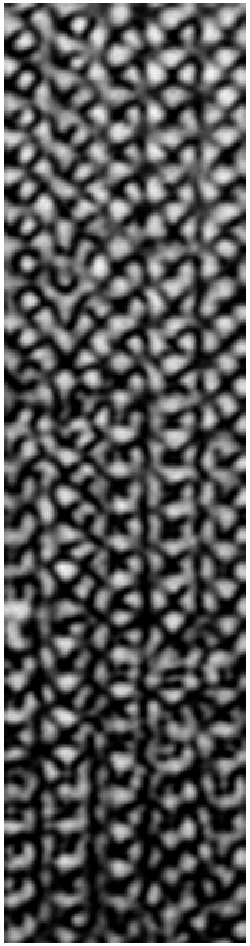


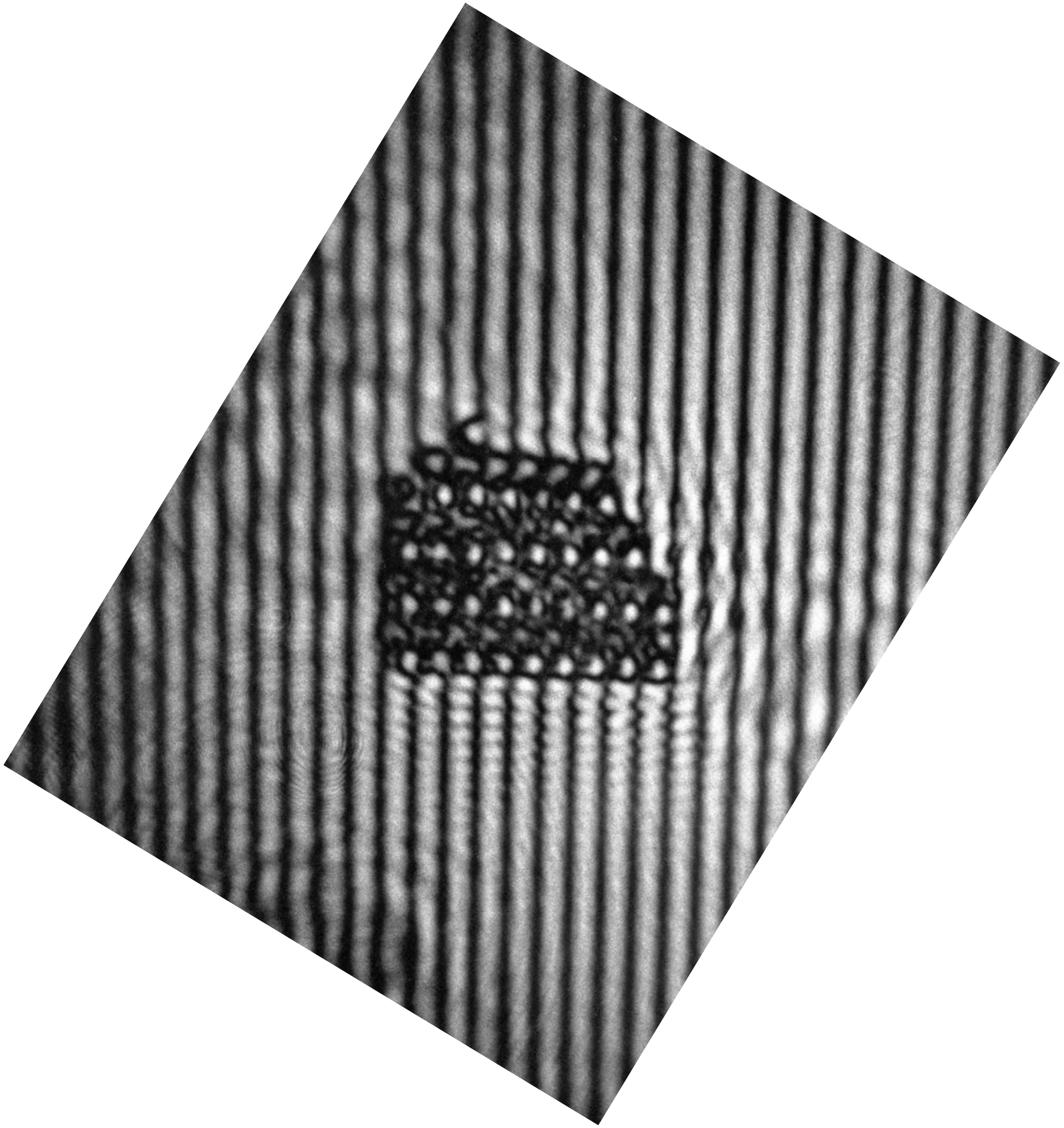
Fringes translation with piezo-electric element



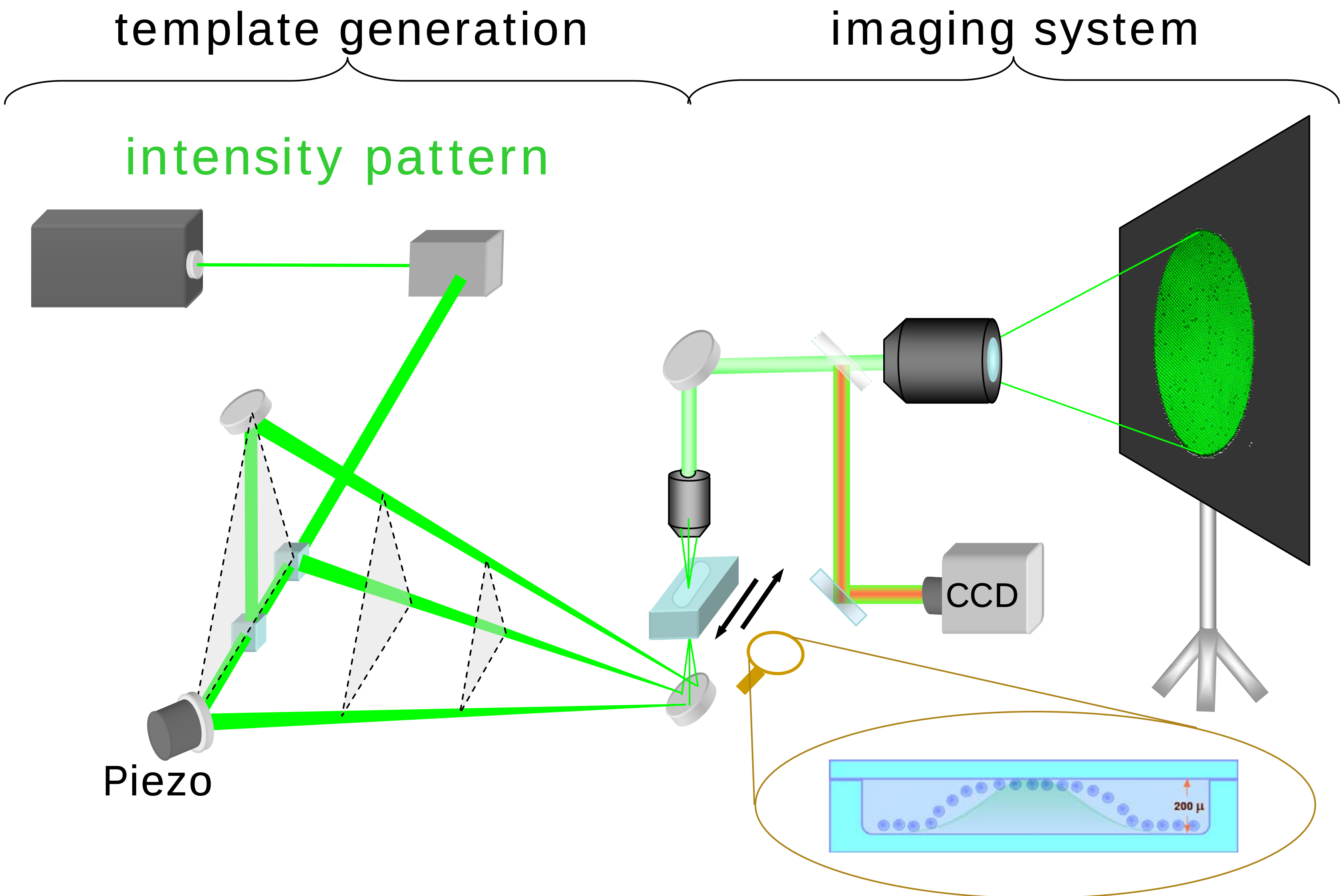
2 μm beads in motorized dragged cell

Optical Binding in 2-Beam Trap

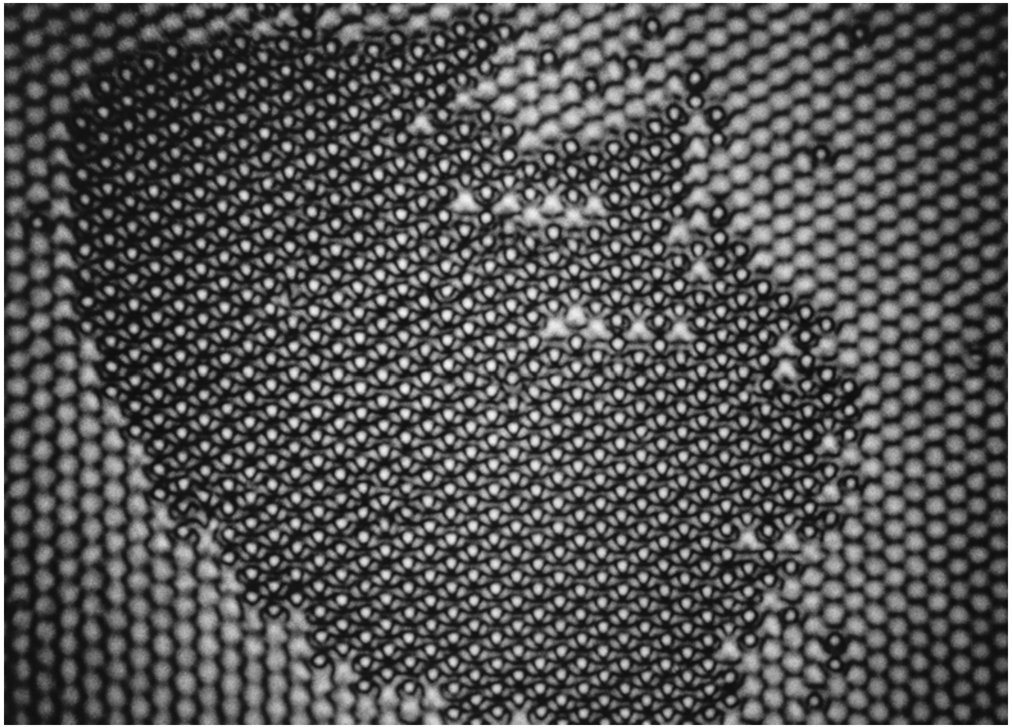




3-Beam Interference



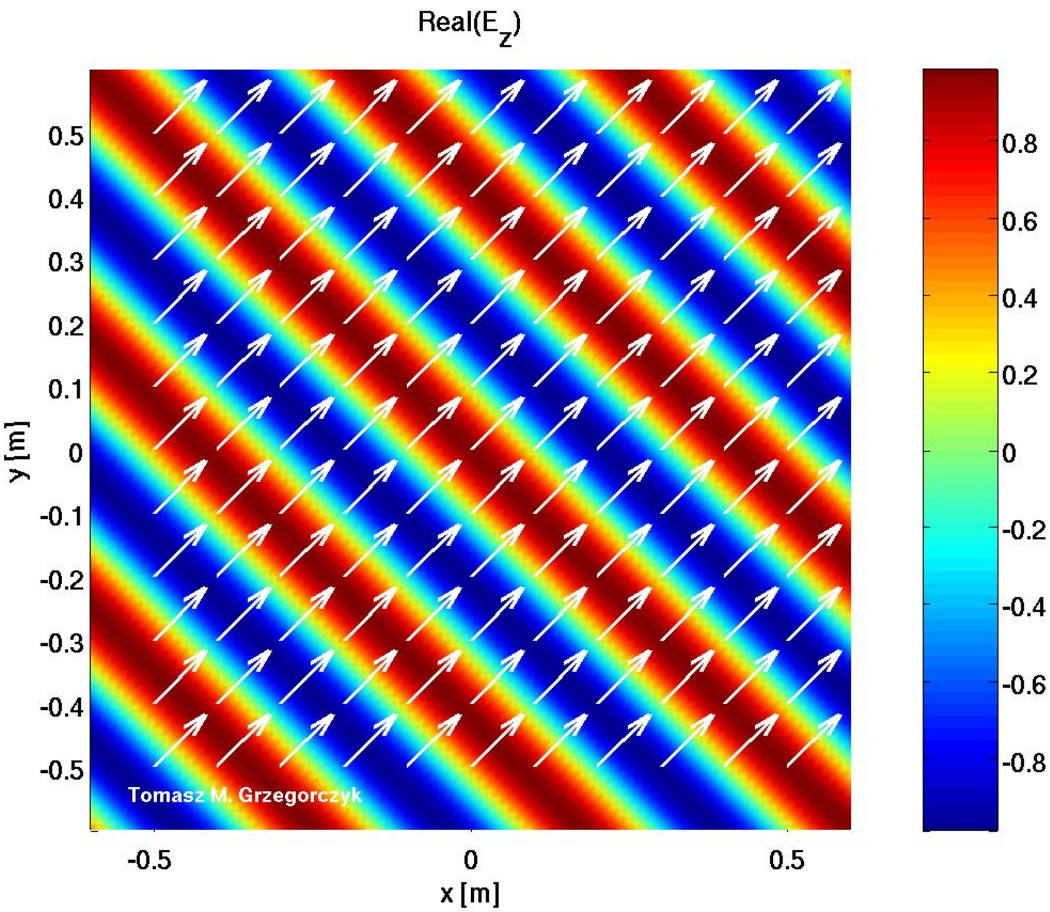
Optical Binding in 3-Beam Trap



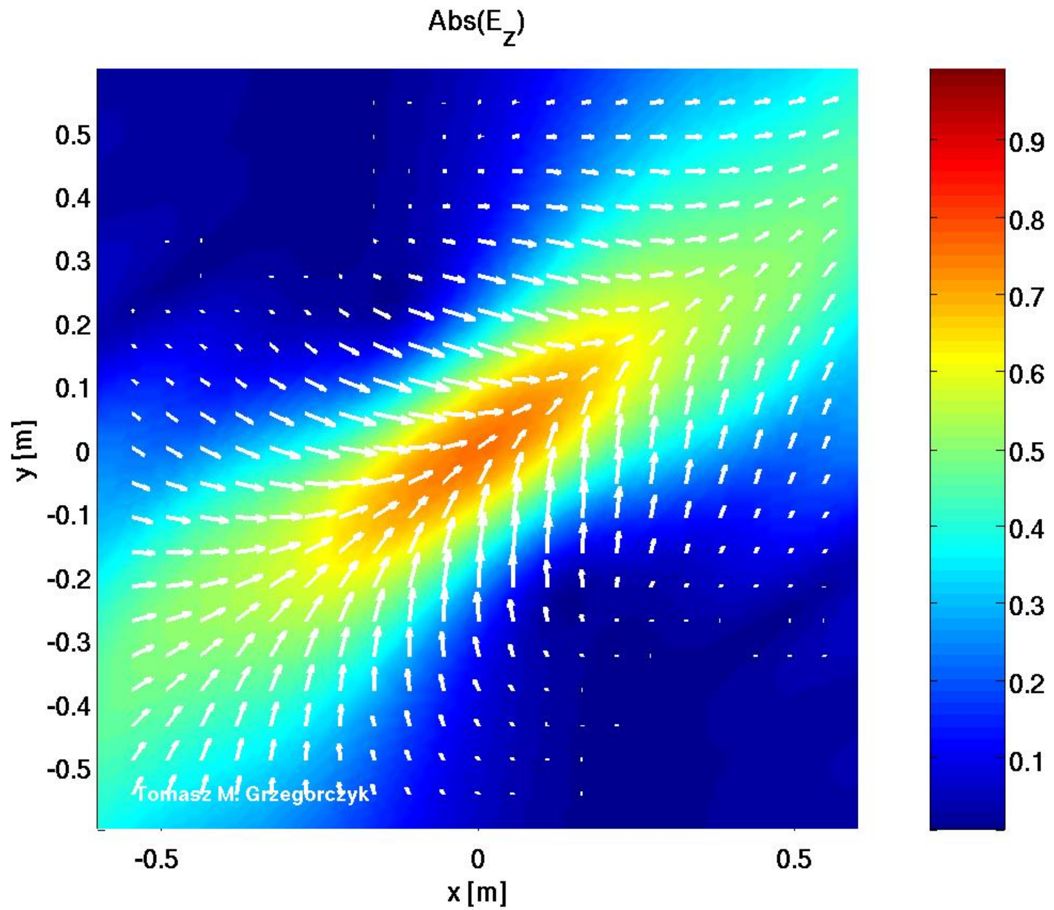
J.-M. Fournier, M.M. Burns, and J.A. Golovchenko, *“Writing Diffractive Structures by Optical Trapping”*, Proc. SPIE **2406** “Practical holography**”,** pp. 101-111, 1995.

M.M. Burns, J.-M. Fournier, and J.A. Golovchenko, *"Optical Matter"*,
US Patent # 5,245,466, 1993

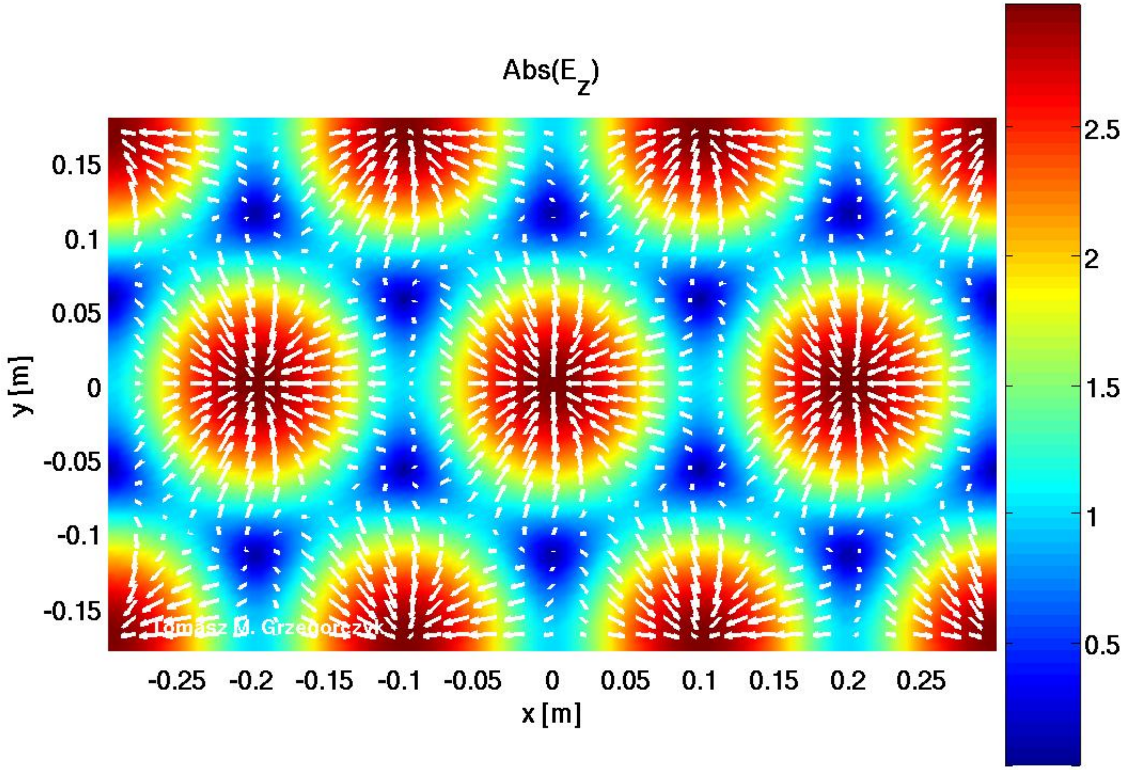
Force Calculation: Single Plane Wave



Force Calculation: Gaussian Beam



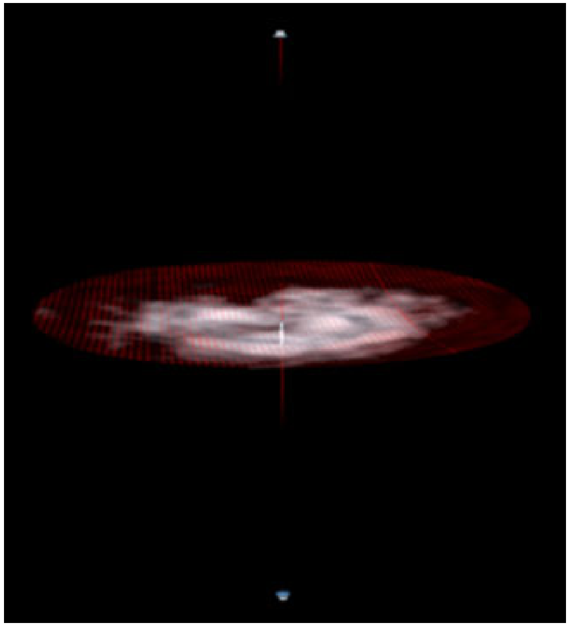
Force Calculation: Three Intersecting Plane Waves

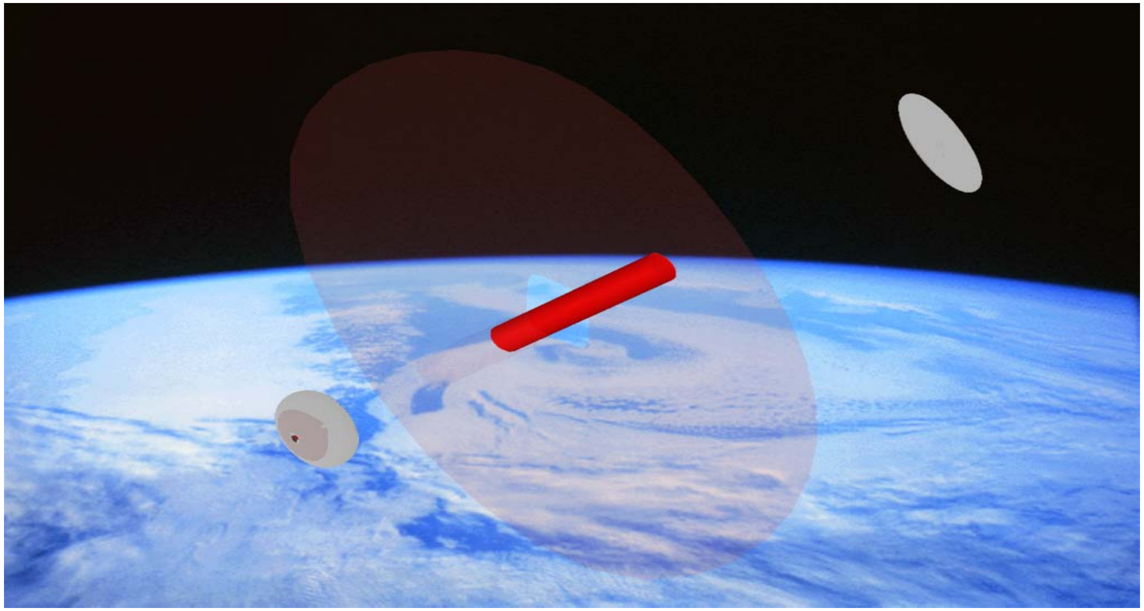


Project Goals

- Demonstrate and characterize a small, floating LTM in water.
- Develop and use computational algorithms to model an LTM which include all optical forces including optical binding effects.
- Combine lab measurements with particle design and the computational models to obtain estimates for the mirror stability and quality, and for the laser power requirements in a vacuum environment.

Laser Trapped Mirrors in Space





Artist's view of Laser Trapped Mirror
(NASA study by Boeing- SVS)