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SRF LEVITATION AND TRAPPING OF NANOPARTICLES

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Abstract

A proposal has been conceived to levitate and trap mesoscopic particles using radio frequency (RF) fields in a superconducting RF (SRF) cavity. Exploiting the intrinsic characteristics of an SRF cavity, this proposal aims at overcoming a major limit faced by state-of-the-art laser trapping techniques. The goal of the proposal is to establish a foundation to enable the observation of quantum phenomena of an isolated mechanical oscillator interacting with microwave fields. An experiment supported by LDRD funding at JLab has started to address R&D issues relevant to these new research directions using existing SRF facilities at JLab. A patent application has been submitted.

Introduction

Quantum properties occur when a macroscopic matter particle, being trapped in an optical field and behaving like a mechanical oscillator, is further cooled, either by the same trapping optical field or by an external laser, to its fundamental quantum ground state.

Coherent control of a macroscopic quantum system has potentially game-changing implications for fundamental physics as well as technology.

Mechanical oscillators have recently shown their potential to serve as quantum memories for microwave signals and to allow information retrieval from the memory on demand.

Levitated nanoparticles, by virtue of being highly decoupled from the environment, allows mechanical oscillators with extremely high quality factors (theoretically expected up to 10^{12}).

Challenges

Four current challenges are identified for nanoparticle trapping and cooling with light fields in an optical cavity:

- Stable trapping at high vacuum.
- Minimizing the mechanical occupation.
- Minimizing the photon shot noise.
- Maximizing the optomechanical coupling.

Our Solution

We proposed an experiment on levitation and trapping mesoscopic particles by RF fields in an SRF cavity, SRF levitation and trapping of nanoparticles, aimed at enabling the ultimate observation of quantum phenomena in the context of quantum science and technology. Our approach is expected to bring a new tool that is unfamiliar to the field of optomechanics. Most critically, by virtue of much longer wavelength (factor of 10^5), ultra-high vacuum (down to 10^{-10} - 10^{-11} mbar), and cryogenic temperatures (1-4 K), it addresses three of the four currently identified challenges faced by optomechanical nanoparticle levitation, therefore promises to advance nanoparticle levitation well beyond the state of the art demonstrated by optical cavities. Expected gains in other metrics:

- Photon scattering, $P_{scat} = |\alpha|^2 k_L^4 I_{opt}/6\pi\varepsilon_0^2$, reduced by 10^{20}.
- Mechanical phonon occupation, $n_m = k_B T_{env}/\hbar\omega_q$, reduced by 10^2.
- Cavity internal loss k_{cav} reduced by a factor of 10^4.

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Theory

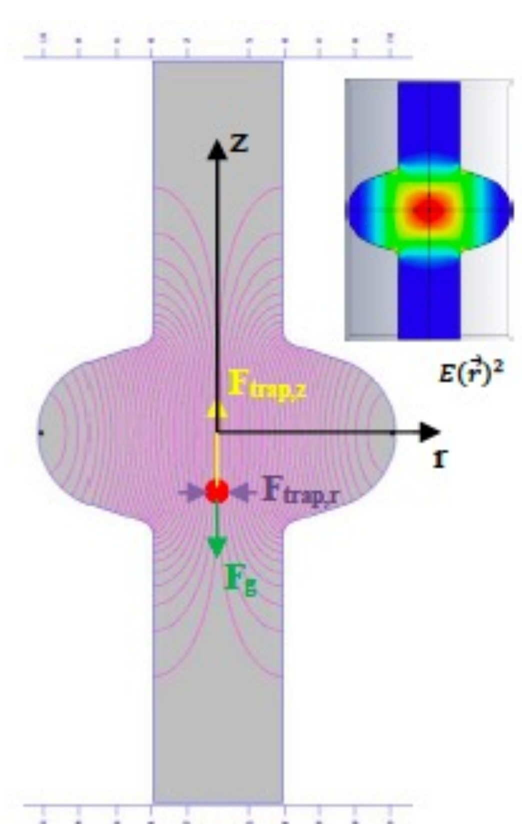
The gradient force is the major driving force behind the SRF levitation and trapping. Such a force arises in an EM field where a spatial variation in the field amplitude, electric or magnetic, exists. For a dielectric particle in air or vacuum, in the Rayleigh regime with the particle radi-us, r, being sufficiently smaller than the wavelength of the electromagnetic field λ, r < λ/20, the time-averaged gradient force arises from spatial variation of the electric field amplitude,

$F_{grad,e} = \frac{1}{4}\alpha\nabla E_{(\vec{r})}{}^2$,

where α is the polarizability of the particle,

$\alpha = 4\pi r^3\varepsilon_0\frac{\varepsilon_{r-1}}{\varepsilon_r+2}$.

Herein ε_0 is the permittivity of vacuum, and ε_r is the relative permittivity of the particle.



Analytical Model

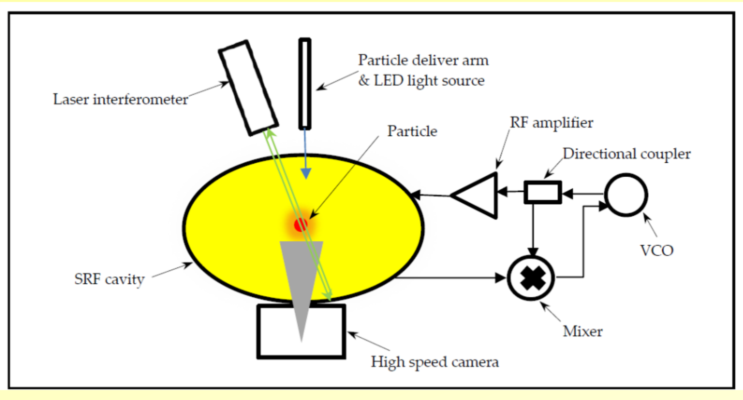
Figure on the left illustrates a single-cell 1.3 GHz TESLA shape cavity with a dielectric particle levitated and trapped in the electric field of the TM_{010} mode.

The trapping force is directed toward the center of the cavity where $E(\vec{r})^2$ has a local maximum. The gravity force F_g is balanced by the axial trapping force $F_{trap,z}$, together with radial trapping force $F_{trap,\,r}$.

In using a fused silica sphere (relative permittivity $\varepsilon_r = 2.2$; particle mass density $\rho = 2650\ kg/m^3$) we demonstrate levitation is achievable with modest cavity RF fields corresponding to an accelerating field, E_{acc}, of 13 MV/m in the TM_{010} mode. This is a field level easily attainable in today's SRF niobium cavities.

Experimental Consideration

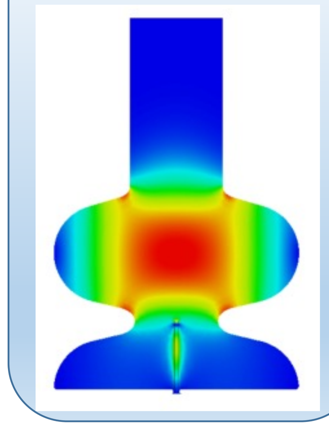
Figure on the right illustrates a sketch of the experimental elements, including an SRF cavity driven by a phase-locking circuit, a particle delivery device that also serves as a light source for particle illumination, a high-speed camera. A laser interferometer may be added for quantitatively assessing the particle oscillation amplitude.



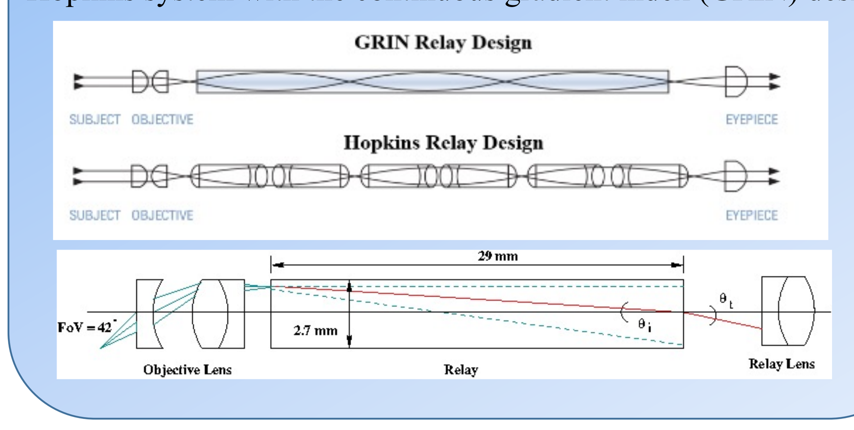
Status of Experiment

Host cavity identified

Particle launcher by tube concept determined



Schematic of endoscopic relay section, comparing discrete-element Hopkins system with the continuous gradient index (GRIN) design.



Conclusion

In conclusion, a proposal has been conceived to levitate and trap mesoscopic particles using RF fields in an SRF cavity, aimed at establishing a foundation to enable observation of quantum phenomena of an isolated mechanical oscillator interacting with microwave fields. An experiment supported by LDRD funding at JLab has started to address R&D issues relevant to these new research directions using existing SRF facilities at JLab. This experiment, if successful, will establish a platform enabling exploration of an electromechanical system consisting of a trapped macroscopic mechanical oscillator and a superconducting RF resonator, aimed at ultimately generating entanglement between the motion of a trapped particle mechanical oscillator and a propagating microwave field.

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