Stabilising and Measuring Optically Levitated Microtargets

Tim Klee & Thomas Smith
Email: tk716@ic.ac.uk tjs17@ic.ac.uk
Supervisor: Prof. Roland Smith, Plasma Physics

1) The Field of High Intensity Laser-Matter Interactions

The irradiation of thermally isolated, micron-sized targets by high intensity laser pulses allows for the production of micro plasmas and transient non-isotropic beams of high energy ions (MeV range) [1]. These have a range of potential applications [1]:

- Diagnostic techniques of short temporal duration phenomena, such as transient electromagnetic fields.
- Hadron therapy, where tumors are irradiated by 60-250 MeV protons or carbon ions.

The Imperial Plasma Physics Group recently [2] pioneered an optical levitation system (OLS) for trapping a target by exploiting the balance between gravity and radiation pressure from a vertically propagating beam. The particle must be held to within ± 1 µm of the pulses focal spot in order to ensure a well-defined interaction. This prevents the waste of the large amounts of resources and time required for a single shot of the group's low repetition rate, very high pulse energy (≥ 1 J) laser system.

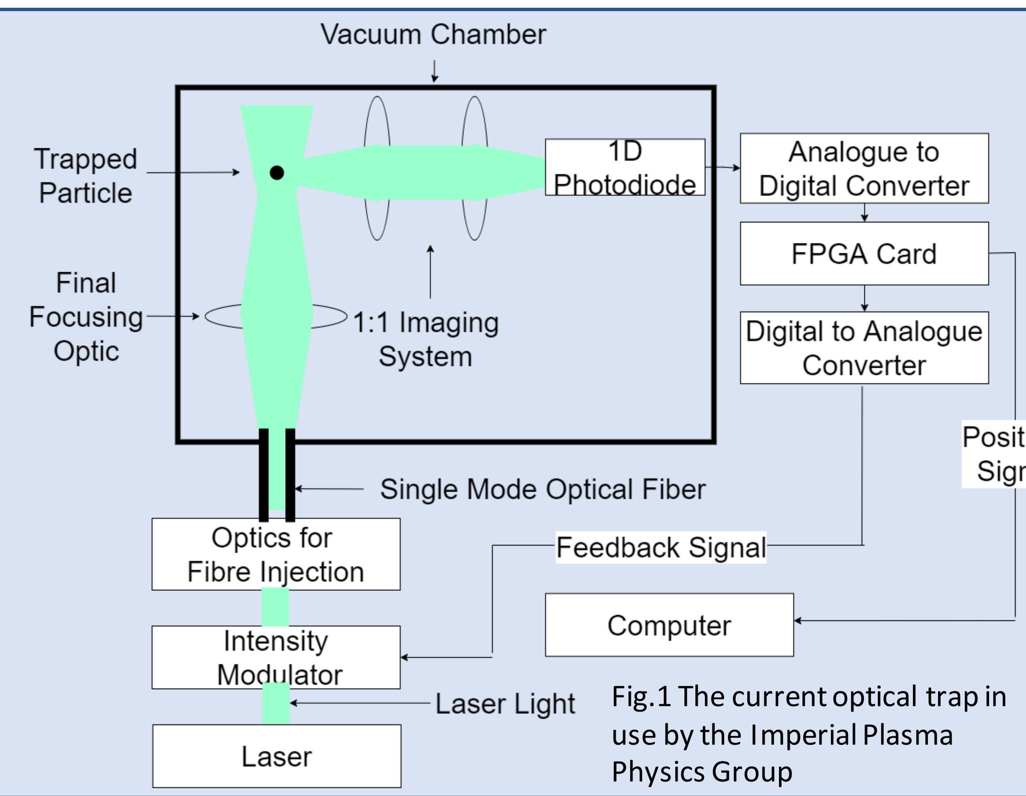

Fig.1 The current optical trap in use by the Imperial Plasma Physics Group

Current Iteration of the Particle Tracking System/Feedback System:

- Scattered trap light from the particle is imaged onto a photodiode which outputs 2 analog current signals.
- These are processed via a field programmable gate array (FPGA) card, providing the particle position in one dimension.
- The FPGA card also acts as the controller in a feedback system, which improves particle localization.
- Feedback is achieved via the FPGA card outputting an analogue voltage signal that controls the power of the trapping beam via a Pockels Cell as determined via a PID algorithm.

Research Objectives:

This project aims to improve the current OLS via:

- Replacing the FPGA card with a single board computer.
- Develop techniques for extracting the particle's mass, first using a self-developed 1D simulation of the OLS, and then via experimental data.

2) Replacing the FPGA Card with a Raspberry Pi

A Raspberry Pi (RP) (fig. 2) would yield several improvements:

- An intuitive Linux based OS with integrated GUI.
- C/Python based control over 40 GPIO pins for interactions with peripheral devices.
- If destroyed by an EMP, the RP can be cheaply and quickly replaced.

Experimental Investigation into Effective Sample Rate of ADC:

- The analogue signal generated by the photodiode is converted to a digital signal and sent to the RP via an analogue-to-digital converter (ADC).
- To ensure the short time scale motion of the particle [2] is captured, an effective sample rate (ESR) in excess of 100Hz.
- Fig. 3 shows how programming the RP in C, rather than Python, reduces the time between data transactions, therefore improving the ESR.
- The bit depth (a measure of the resolution of the ADC) of a least 10 bits is required to ensure the feedback system can localize the particle to the required ± 1 µm.
- Fig. 4 summarizes the ESR of the various ADC investigated and the important parameters.
- The ADC DAC Pi Zero (fig. 2) is the most likely candidate due to its sufficient bit depth and high ESR for both Python and C (44/110 kHz respectively).

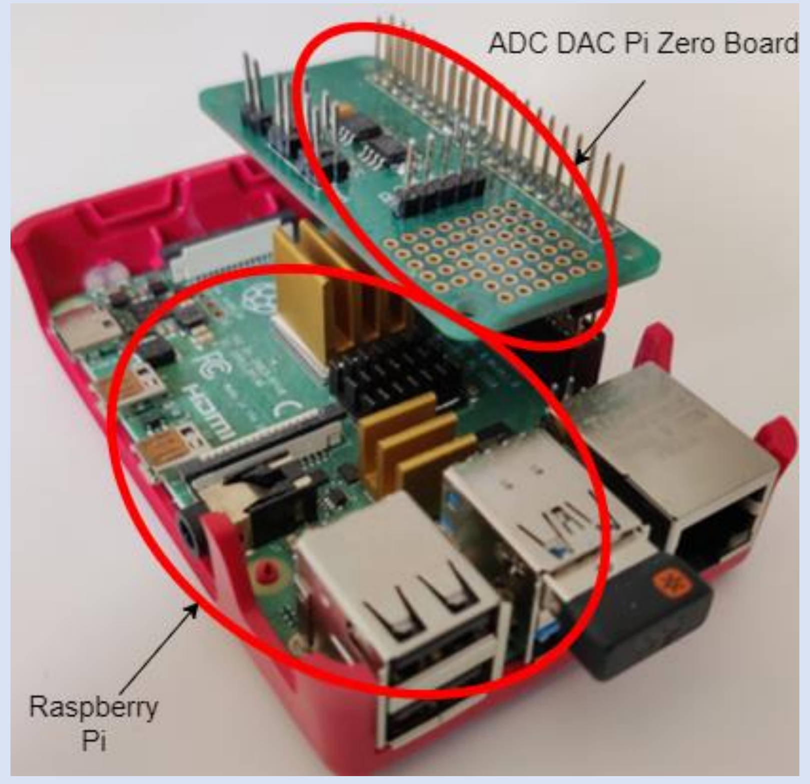

Fig. 2. One of the Raspberry Pi 4s used to test ADC and DAC performance (including ADC DAC Pi Zero expansion board).

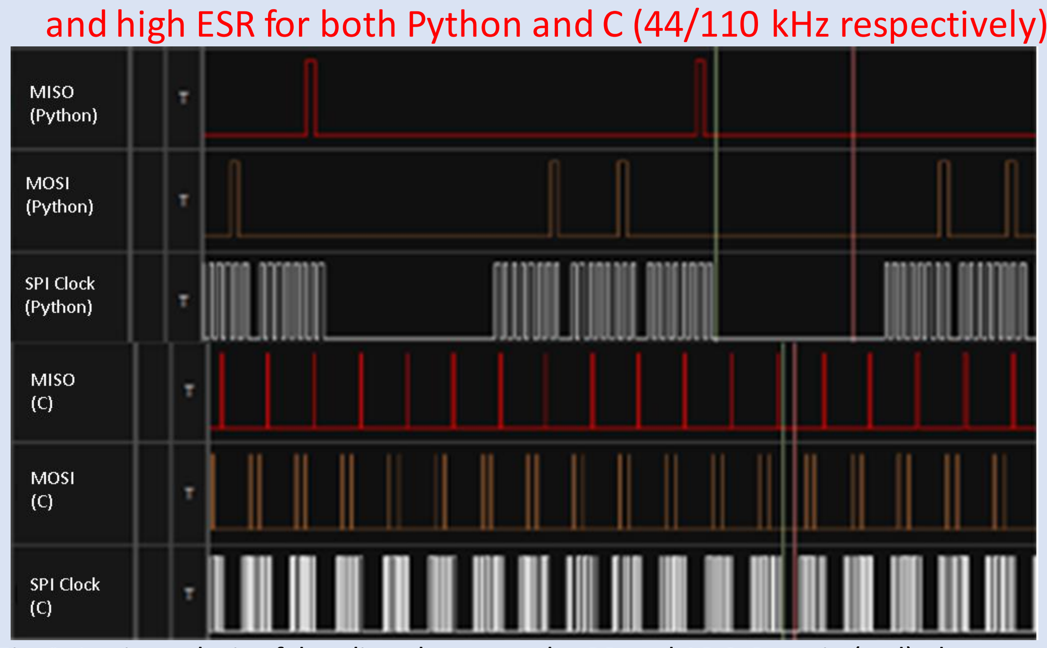

Fig. 3. Logic analysis of data lines between the RP and ADC. Data-in (red), data-out (brown), and clock (white) are shown, for a Python (above) and C (below) based code.

Model and CIF used	Bit depth	Code Type	ESR (Hz)
ADC Pi Zero (ADC): SPI	18	Python-Commercial	4
MCP3008: SPI	10	Python-Commercial Python-Self developed	12'000 23'000
ADC DAC Pi Zero (ADC):SPI	12	Python-Commercial Python-Self developed C-Self developed	20'000 44'000 110'000
STM34F030: I2C	12	Python-Commercial	5200

Fig.4 The dependence of ESR of the ADC's investigated on bit depth, code type and communication interface (CIF) used.

3) Development of numerical model

Motivation:

- Build up an intuition of how trapped particles behave.
- Measure how particle motion changes with respect to size.
- Test and benchmark parameters for control system.
- Test whether certain particles are trappable.

Simplifications:

- Model the particle as a partially reflective mirror, rather than calculating refraction of all possible incident rays. This avoids having to perform numerical integration within the solver for the equation of motion.
- Particle motion is only calculated in the axial direction.

Forces modelled:

- Radiation pressure
- Gravity
- Drag – Using a corrected form of Stokes Law [3].
- Brownian motion – Using Einstein's theory of Brownian motion [4].
- Photophoretic force – Using Rohatschek's model [5].

Choice of Numerical Solver:

The equation of motion is solved using the Runge-Kutta 45 method for three reasons:

1. Stability and accuracy
2. Speed – Does not perform an unnecessarily large number of steps.
3. Ability to cope with random effects such as Brownian motion and laser noise.

Key Outcomes

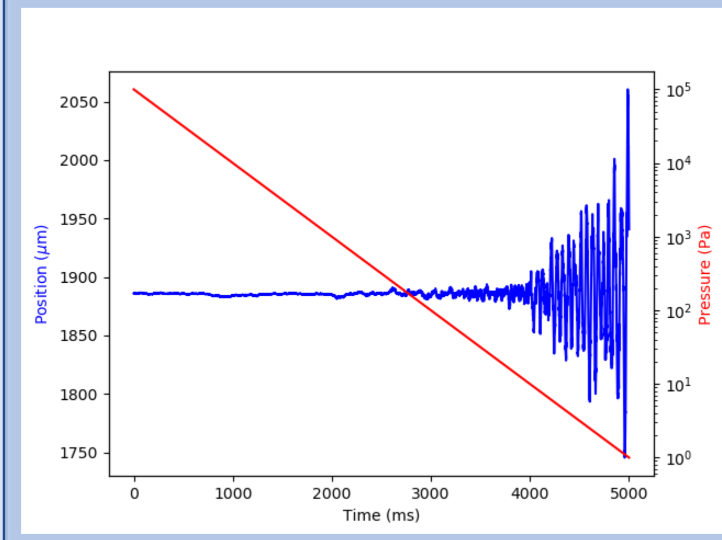

Fig. 5. Particle position relative to laser beam focus as pressure is lowered.

- Figs. 5-7 show simulated motion of trapped silicon oil droplets.
- Fig. 5 demonstrates the need for a control system, as particle motion greatly increases at low pressures due to Brownian motion and lack of drag.
- Laser interaction experiments are performed at <1Pa so stability is crucial in this regime.

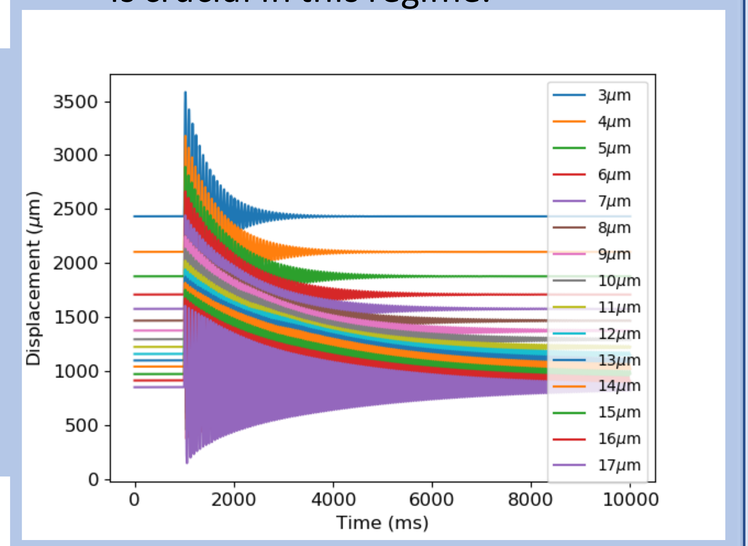

Fig. 6. Droplet positions with respect to laser focus with a 10ms spike in laser power after 1000ms.

- Fig. 6 shows the motion of droplets after being perturbed by a spike in laser power.
- The size of a droplet can be estimated based on both its decay time, and frequency of oscillation.

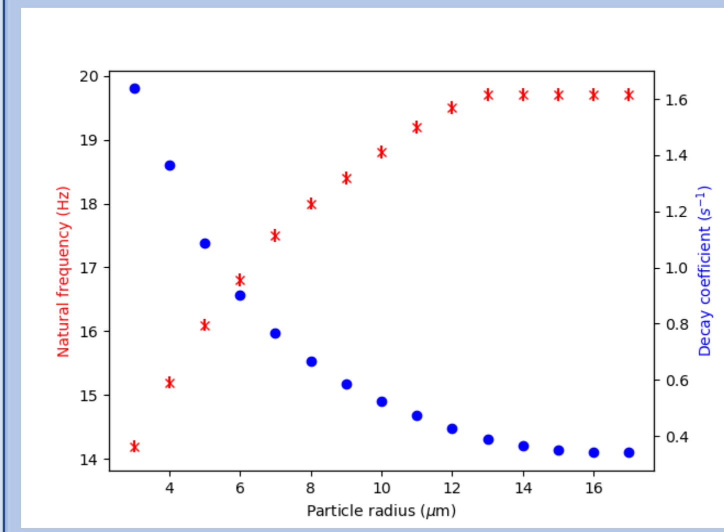

Fig. 7. Frequency of oscillation and decay coefficient for each particle in fig. 6.

- Fig. 7 summarises how these quantities vary with particle radius.
- Droplets of lower radii are most distinguishable. Methods like this could provide an alternative to optical techniques for measuring particles, which are inaccurate for small radii.

4) Conclusion

Demonstrating the feasibility of a single board computer for optical levitation traps

- Sampling rates of 44kHz can be achieved via the ADC DAC Pi Zero. This is more than enough to accurately track and control particle motion.
- The RP can be controlled via Python/C allowing simple implementation of control algorithms and position data processing.
- RP are expendable due to their low cost and simplicity in terms of preparing them for use in the OLS.

Developing a simplified high-speed numerical model for simulating motion of trapped particles

- We can use this to investigate methods of extracting particle parameters based on their motion. This could lead to new methods for measuring particle size. This information could be useful when selecting targets for laser interaction experiments.
- Based on its size and material, we can determine whether a particle can be trapped and how easy it will be to stabilise.
- Our simulations show that trapped particles oscillate at around 10-20Hz, therefore a control system sampling at over 10'000Hz should be sufficient to capture and control not just fundamental oscillations, but higher frequency components as well.

Overall, our work will contribute towards improving the stability of optical traps and choices of targets. This will improve the success rate of laser interaction experiments, potentially leading to more reliable sources of highly collimated energetic proton beams.

Next Steps

Near Term:

- Implement a PID control algorithm in the numerical model to investigate optimal parameters/tuning methods.
- Investigate sources of non-linearities in the position detection system so that they can be accounted for by the control system.
- Use a Raspberry Pi to sample in-trap particle position data at atmospheric pressure.
- Test simple techniques for extracting parameters of real trapped particles from their motion at atmospheric pressure.

Long Term:

- Use the RP-based control system to stabilise particles down to vacuum conditions.
- Investigate methods for extracting particle parameters based on the Fourier transform of the particle motion in vacuo [6].
- Try using or adapting the control system to stabilise microshells.

References
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