Novel active near-field and far-field fast beam stabilisation of a picosecond short pulse

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Abstract

We describe the use of an active fast beam stabilisation to achieve spatial locking of the beam in the near-field and far-field references. The beam has been stabilised comprising a PID feedback loop between two position sensitive detectors (PSD) and two fast piezo mirrors, improving on previous work that locked one reference. Our stabilisation scheme is operational in user experiments demonstrating that this proof of concept may be extended to other beamlines within the Central Laser Facility and other high-power laser facilities.

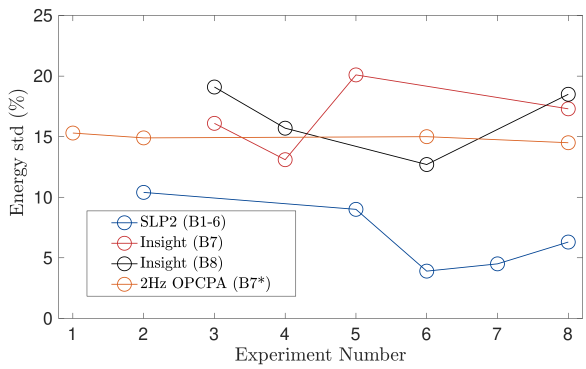

Figure 1: Shot Statistics from eight experiments showing the percentage standard deviation in energy stability. The short pulse Insight oscillator has an energy std of between 10-20%.

1 Introduction

High-power laser facilities require stable laser pulses to generate high quality beams in high-intensity laser-plasma experiments. Beam stability and control of laser properties can play a significant role in the outcome of gas jet experiments, in regard to optimising the pointing of laser wakefield generated electron beams [1–3]. Active stabilisation of a laser beam in the near-field and far-field would maintain the pointing stability during short-to-shot operation. Spatially locking the beam in both references is desirable to overcome pointing drift and unpredictable energy variations over the experiments duration. Facilities use automatic alignment via picomotors which actively moves a mirror such that the beam is set to a desired referenced location in the near-field. However, using this method alone is slow for the drift of the beam and works passively between shots at a few Hz. The solution to this is a much faster active method requiring a fast piezo mirror to stabilise on the order of kHz.

The exact cause for unstable pointing of the beam during shot-to-shot operation can be difficult to measure. It may be due to imperfect alignment, thermal instability from cooling amplifiers and air dynamics which can all contribute to an unstable laser beam. Firstly to define the near-field and far-field of a beam. For a near Gaussian beam, the near-field can be thought of as how the beam appears at the beam waist w_0 and the far-field is a picture of the beam as it divergences far from w_0.

Our work is based around developments in the HAPPIE Lab project for coherent beam recombination [4, 5] and stability using fast piezo mirrors [6]. Far-field beam stability has been achieved on the Gemini laser system [7] but two references have yet to be spatially locked.

In this report, we describe the operation of an active fast beam stabilisation scheme to spatially lock the beam in two references; the near-field and far-field. A description of the PID feedback loop is given and the operational considerations are discussed in using our scheme in a rapid shot mode.

2 PID background theory

Our stabilisation scheme uses proportional-derivative-integral (PID) theory and is a *three term* controller [8]. In our case, the three terms minimise the positional error between a chosen setpoint and a measurement of the laser beams position. The output voltage is calculated by

$$v(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{de(t)}{dt} + \text{Offset} \quad (1)$$

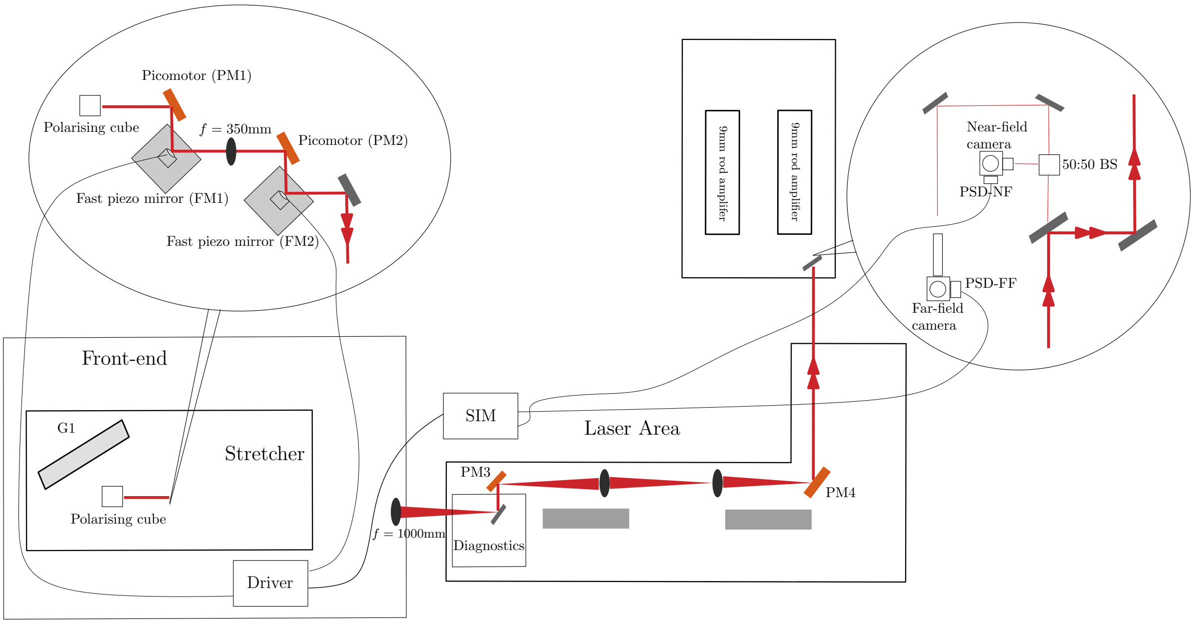

Figure 2: Operational set up showing the optical beam path. The beam propagates from the front-end stretcher with two output fast mirrors (FM1 and FM2) to the two position sensitive detectors (PSD) in the Vulcan laser area before amplification.

where,

$$\begin{aligned} e(t) &= \text{the error at instantaneous time} t \\ v(t) &= \text{the output voltage} \\ K_p &= \text{the proportional gain} \\ K_i &= \text{the integral gain} \\ K_d &= \text{the derivative gain} \end{aligned}$$

The steps involved in the operation of the stable loop is shown in figure 3. The constant parameters K_p, K_i and K_d define the stable open feedback loop between the PSDs and PID controller. The error $e(t)$ is simply the difference between the setpoint and measured beam position. The gain K_p term is the current error value and has the largest effect on the stable loop, K_i is the integrated error so considers the long term drift over time of $e(t)$ and K_d is the derivative term that finds the instantaneous rate of change of $e(t)$.

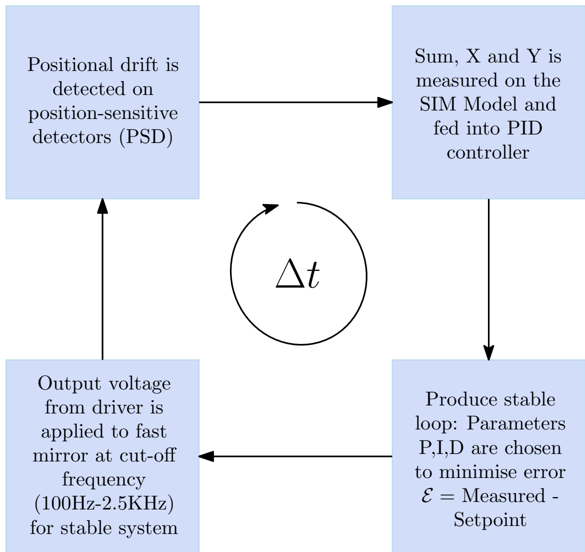

Figure 3: The steps and operation of a stable open loop system.

3 Characterisation of system & results

The experimental set up is shown in figure 2 and is described as follows. Two 15kg metal mounts with a 1" silver mirror attached to a piezoelectric (by Physik Instrumente) controlled mirror have been placed on the output of the stretcher. Sorbothane rubber feet support the base underneath to sufficiently damp higher frequencies from the mirror onto the optics on the stretcher optical table. There is imaging of both mirrors onto the diagnostic cameras. The two mirrors are in Fourier planes of one another in order to reduce the coupling effect between them such that they function independently. Therefore, a change in the first mirror changes the beam position but not the pointing in the far-field. A voltage is applied to the piezo motor by a driver, where the voltage is controlled by one of two SIM900 (Stanford Research Systems) which contains the Analog PID Controller and analog filter. The Setpoint range is selected to ±5V for each NF-X,NF-Y and FF-X,FF-Y. A second-order *Butterworth filter* [9] is applied in a low pass mode to significantly minimise high-frequency noise. The role

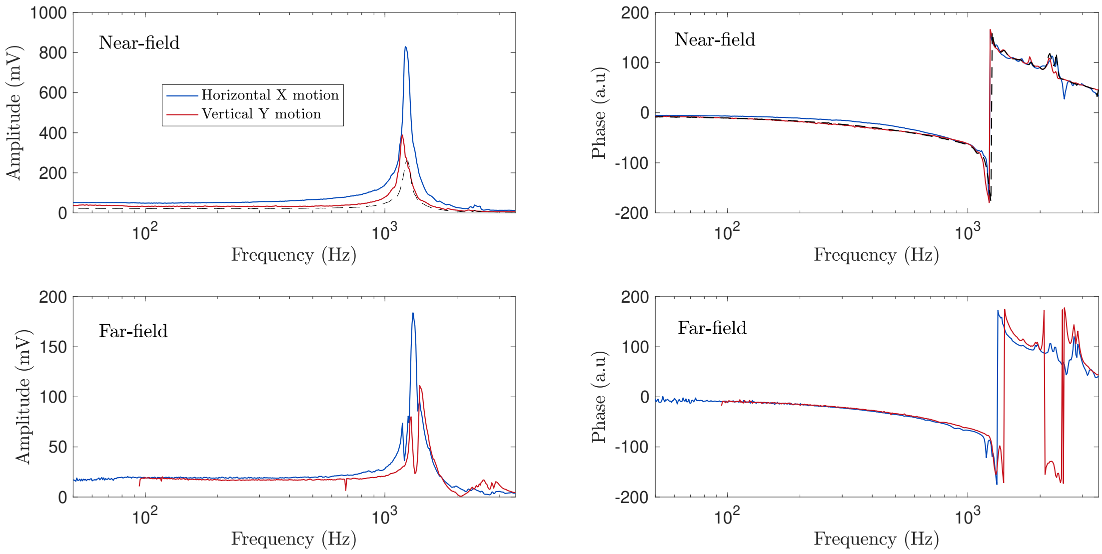

Figure 4: Stability characterisation: performing the frequency sweep between 30Hz to 4.0kHz with the near-field and far-field piezo mirrors. Black line shows the sweep after sufficient damping to the horizontal motion in the near-field.

of the filter is to remove noise outside of a given frequency range to maintain a step function. The output of the PID controller is connected to the PSD and monitors the sum, X and Y as the beam pointing changes.

As it is important to ensure the beam is sufficiency collimated for both near-field and far-field references to be used in our optical set up. Three lens were placed between the fast mirrors and the input of the laser area to ensure a well collimated beam. The focal lengths of the lens are $f_1 = 400$mm, $f_2 = 350$mm and $f_3 = 3000$mm.

3.1 Open loop frequency scan

The open loop frequency scan is achieved with the use of the lockin amplifier (figure 6). The frequency range is performed from 30Hz to 4.0kHz with the cut off frequency set to $F_c = 5$Hz, the gain parameter $K_p = 1$ and $K_i = 10$. A sweep though the low to high frequencies are plotted showing the sharp resonance curves that exist in our experimental set up. Figure 4 shows that these occur around the 1-2kHz regime. Previous efforts have dampened these peaks with appropriate taping attached to the side of the piezo motor mount.

We obtain the values for the open loop found in the two tables below by running a Monte Carlo sampling code. This code works by calculating the Fourier transform of equation 1

$$\mathcal{F}\left[v(t)\right] = v(\omega) = K_p e(\omega)(1 - iK_i\omega^{-1} + K_d i\omega)$$

where the angular frequency is $\omega = 2\pi f$, sampling many terms of K_p, K_i, K_d to converge on the most stable loop.

Axis	X	Y
K_p	0.6	1.2
K_i [Hz]	3400	2900
K_d [s]	6.5×10^{-5}	5.6×10^{-5}
F_c [Hz]	578	566
Filter [order]	2nd	2nd

Table 1: Stable parameters used to spatially lock the near-field without any damping.

Axis	X	Y
K_p	1.8	3.3
K_i [Hz]	410	18000
K_d [s]	1.00×10^{-4}	1.50×10^{-4}
F_c [Hz]	694	2960
Filter [order]	2nd	2nd

Table 2: Stable parameters used to spatially lock the far-field without any damping.

4 Operational considerations

Our scheme has been developed on the Chirped Pulse Amplification [10] (CPA) beamline of Vulcan laser [11] to stabilise the short picosecond oscillator for beam 7 and 8 to target area west (TAW). A detailed review of the diagnostics in Vulcan has previously been reported [12]. Here we have added a new set of diagnostics, a near-field and far-field camera and a second diagnostic set to capture the beam after the two double pass amplification stages, figure 2. Figure 5 compares the beam with the PID loop on and with it off during shot oper-

Axis	X	Y
K_p	1.3	0.81
K_i [Hz]	4300	3700
K_d [s]	5.6×10^{-5}	5.0×10^{-5}
F_c [Hz]	723	629
Filter [order]	2nd	2nd

Table 3: Stable parameters used to spatially lock the near-field with damping.

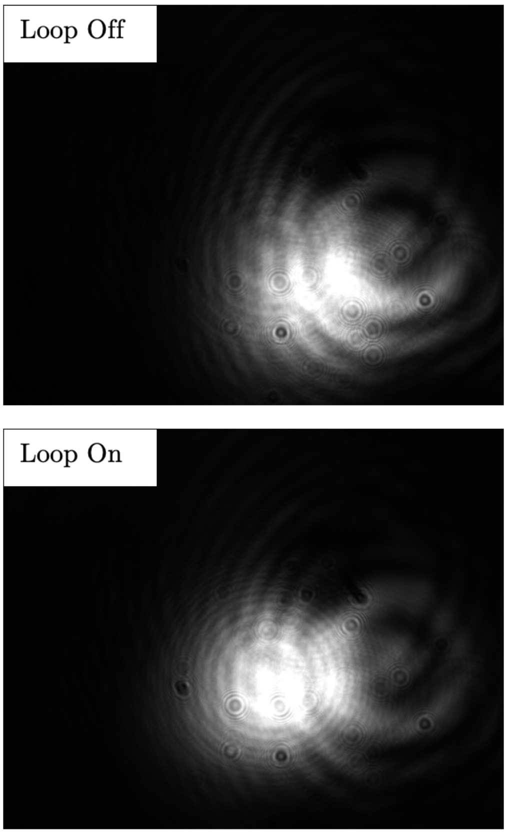

Figure 5: On-shot comparison of the beam spatial profile with the open stable feedback loop on and off in both NF and FF.

ation, where the beam is at the millijoule level and ∼ns duration before amplification.

The primary concern in our stability scheme is sufficiently isolating amplifier flash lamp light from the two position sensitive detectors. This effect has been mitigated by adding black glass to the cameras. Our tests also involved checking the output voltage on shot to determine whether the amplifiers cause the beam to deviate from the Setpoint in either the horizontal or vertical.

We also report on finding little differences between shot pointing stability with lower few joule energy shots and hundreds of joules from amplifying the pulse in full disc shots. At the point in which the beam is amplifying through the discs, gain narrowing means pointing stability becomes less important and temporal saturation effects ensue changing the spatial coupling with less control over the pulse.

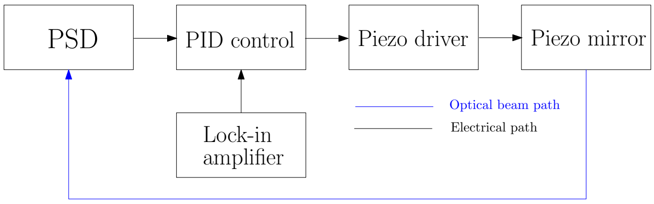

Figure 6: Schematic of the PID closed loop giving the electrical (black) and optical (blue) connections.

5 Conclusion

In conclusion, this report has described the operation of an active fast beam stabilisation to stabilise two references; the beams near-field and far-field. Our stability scheme has been realised by measuring the beam on two position sensitive detectors and controlling the beam with two fast piezo mirrors in a PID loop.

Our results demonstrate that locking both references sufficiently ensures that the beam remains stable during shot-to-shot operation and has been made into a permanent system.

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