Beam Pointing Stabilisation on the Gemini Laser System

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Introduction

Pointing changes are a common problem for many types of experiments. Whether aiming a laser beam at a target or aiming one laser beam at another, many experiments have precise alignment requirements that can be ruined by mechanical vibrations. These can manifest as random jitter affecting each laser pulse independently, or as a long-term drift that needs to be corrected periodically.

To mitigate these problems, we installed a pointing stabilisation system on the south beam of the Gemini laser system. Properly tuned, this system can prevent long-term pointing drift, as well as significantly reducing the random shot-to-shot pointing jitter.

Overall Design

It is impossible to correct for high-frequency vibrations with a low repetition rate laser. Therefore, the pointing stabilisation system uses a separate CW pilot beam that follows the path of the main beam. A co-propagating pilot beam would require a detector to be placed next to the target (in our case a gas cell), where it would get in the way and be susceptible to damage from the main beam. We therefore use a counter-propagating beam, launched from the gas cell and passing back through the main amplifier.

Before reaching the front-end, the pointing stabilisation beam is separated from the main beam and brought to a focus. The position of this focus indicates the direction of the pilot beam. Anything that changes the main beam pointing between the gas cell and the detector will be reflected in the pointing of the pilot beam; correcting the pilot beam pointing will also correct the main beam, as long as the correction is applied using a mirror common to both beams.

The pointing of the main beam is stabilised relative to the source of the pilot beam. By attaching the source directly to the gas cell, the system will not only correct for jitter in the beam pointing, but also for movement or vibrations of the gas cell.

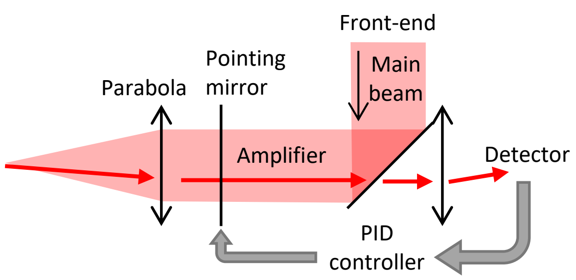

Figure 1: a schematic diagram of the whole stabilisation system

Source

The pilot beam is generated by a Thorlabs diode laser, which is coupled into a fibre. The bare end of this fibre forms the "focus" of the counter-propagating beam, which is horizontally offset from the main beam focus, but in the same plane. Since the system needs to fit around and be firmly attached to the gas cell, it needs to be carefully designed.

Since there is not room to place the fibre end adjacent to the real focus, the fibre is mounted at 90° from the main beam. A mirror is used to redirect the pilot beam, placing a virtual image of the fibre end in the correct place, as shown in Figure 2. Positioning of this mirror requires care: it must be far enough from the main beam to avoid damage and must not significantly clip the pilot beam.

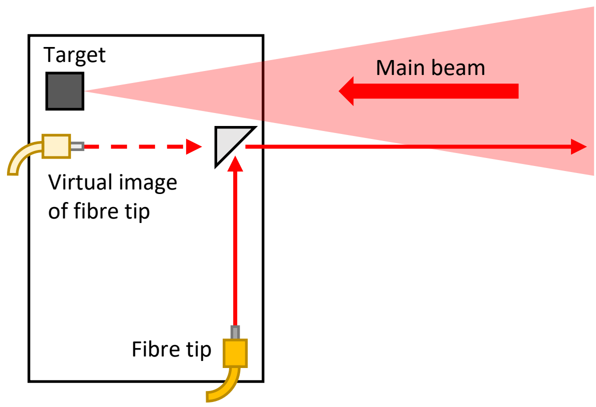

Figure 2: Schematic diagram of the assembly for mounting the fibre tip to the gas cell (or other target)

Beam path

The pilot beam, diverging as it leaves the fibre tip, follows the path of the converging main beam to the parabola. Since the longitudinal position of the fibre tip matches the real focus, the pilot beam will be collimated by the parabola. The horizontal offset means that the pointing of the pilot beam will slightly differ from the main beam. As the pilot beam continues up the beam path, this difference means that the edges of the pilot beam will be clipped by some of the optics.

As the pilot beam propagates through the main amplifier, it needs to pass through the vacuum spatial filters (VSFs). Each is a pin-hole in a focal plane, designed to cut out high spatial frequencies in the amplified beam. As each of these planes is an image of the real focus in the target area, the pilot beam misses the pinhole. To allow the pilot beam to pass, the single pinholes were replaced with custom-made plates with two pinholes: one for the main beam and one for the pilot beam. These are installed in rotation mounts so that the pilot beam pinhole can be moved around the main beam pinhole, but the distance between the two is fixed. This fixes the horizontal offset of the pilot beam in the target area for a given f-number of parabola.

After passing through the main amplifier, the pilot beam reaches the beamsplitter that divides the forward-going main beam into north and south beams. Some part (approximately half) of the pilot beam is reflected into the beam path to the front-end (where it will be blocked by a VSF), but the transmitted part goes into the CW injection line (see Figure 3). The lens of the CW expander telescope brings the pilot beam to a focus next to the CW focus, and here it is separated from the injected CW beam by a small mirror and sent to the detector.

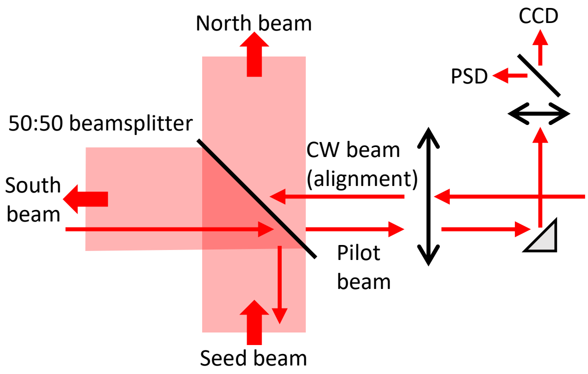

Figure 3: The counter-propagating pilot beam is separated from the main beam (thick arrows) at the 50/50 beamsplitter, and from the CW alignment beam with a mirror.

Detector

The pilot beam is focused through a beamsplitter onto two detectors. A CCD (Allied Vision Manta G-033B) allows the focal spot shape and position to be viewed, which aids in aligning the system. A position-sensitive detector produces three voltage outputs, corresponding to the total power in the pilot beam focus and its position in the x and y directions. The position signals are also proportional to the sum, so the system gain depends on the power reaching the detector.

Feedback system

The position signals are fed into two independent control loops, each consisting of a low-pass filter followed by a PID controller. A lock-in amplifier can feed an AC signal into the PID controller's set-point and measure its effect on e.g. the controller error.

Stabilisation mirror

The output from the PID controllers is sent to piezoelectric actuators attached to a mirror near the amplifier output. This mirror is designed to be as light-weight as possible, to maximise its resonant frequency, which acts as a high-frequency cut-off for the feedback system. Unfortunately, the thin substrate is also not very rigid, and the requirement to glue it onto its support means that it is not completely flat. The mirror inevitably introduces aberrations into the main beam wavefront, which have to be corrected with a deformable mirror, positioned immediately before the stabilisation mirror. The wavefront sensor controlling the AO is part of the beam diagnostic suite which samples the beam just before it enters the compressor.

Loop tuning

Tuning a PID loop is often quite difficult, but it can be performed offline if the open-loop response of the system is known. This was measured for each axis with the help of the lock-in amplifier. The output of the lock-in amplifier is fed to the piezo mirror, replacing the output of the PID loop. The lock-in amplifier then measures the detector signal (the PID input) as a function of frequency. The result is the complex open-loop gain of the system as a function of frequency; that is, the gain of the control loop excluding the PID controller.

The measurement process was slightly modified to ensure the beam did not wander off the detector during the approximately 40 minutes required for the measurement. The PID controller was switched on, but the low-pass filter was set to a few Hz cut-off, so it was effectively disabled at the frequencies of interest. The lock-in amplifier's output was then connected to the PID controller's set-point input. The PID controller amplifies this signal (so the gain must be known) and sends it on to the piezo mirror, while also applying whatever low-frequency signal is needed to keep the pointing stable.

The measured open loop gain can be combined with PID and filter settings to predict how the control loop will behave. This allows those settings to be optimised offline. They are then applied to the real PID controller when the system is tested.

Results

To measure the effect of this stabilisation system on the main beam pointing in the target area, we used a camera to measure the beam pointing during 200 full power laser shots, half with the stabilisation switched on. This is not a perfect way of measuring the system performance, because the beam is locked to the gas cell but the camera might move relative to the cell. Nevertheless, the results (see figure 4) show a significant reduction in beam jitter.

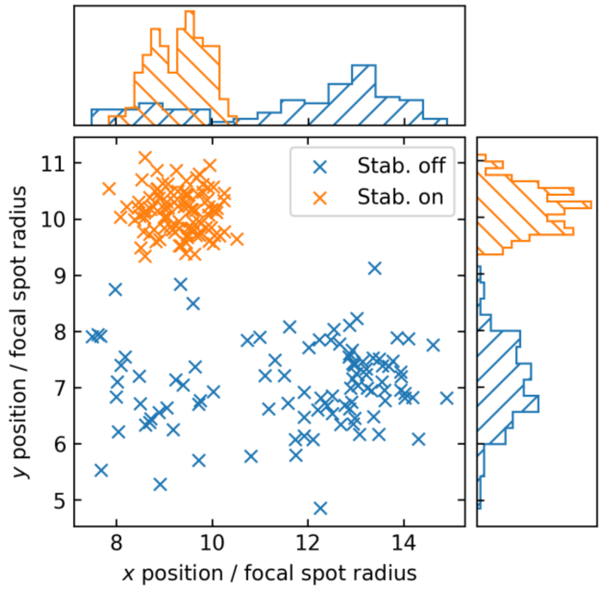

Figure 4: The beam pointing with stabilisation switched on and off, measured in multiples of the focal spot radius

Part of the spread can be attributed to a long-term drift in the beam pointing. By subtracting a centred rolling average over 20 points (called the drift), we can isolate the jitter. The standard deviations of the different components of the pointing (total, drift, jitter) are shown in Table 1, with stabilisation off and on.

Standard deviation (focal spot radii)		x	y
Stabilisation off	Drift	1.73	0.11
	Jitter	0.68	0.73
	Total	2.05	0.75
Stabilisation on	Drift	0.39	0.11
	Jitter	0.38	0.36
	Total	0.56	0.39

Table 1: Standard deviations of beam pointing measurements

The jitter is reduced by about 50%, and the drift in the x axis is significantly reduced.

This system was later used during an electron acceleration experiment. Using the stabilisation system reduced the pointing variation by a factor of 3 in the x direction and 1.8 in the y direction. Although this had no significant effect on the electron beam pointing, the stabilisation against long-term drift was still useful.

Conclusions

The pointing stabilisation system is available for use on the Gemini south beam now, although planning is needed to ensure that the proposed experiment is compatible with it, and to be certain the pilot beam input mirror can be installed next to the target. We also plan to install a similar system on the north beam, eventually allowing the two beams to be stabilised relative to each other.

The fact that stabilising the beam pointing had no effect on electron beam pointing is disappointing, but suggests that the jitter in electron beam pointing is caused by other factors. The system should still have significant benefits for a colliding beam experiment, since the effect of laser beam pointing is multiplied by the (large) focal length, while the effect of the electron beam pointing is multiplied only by the (hopefully small) distance between the source and the collision point.

Acknowledgements

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