# Progress on improving stability of the short picosecond pulse by fast stabilisation in Vulcan

**Contact:** `laurence.bradley@stfc.ukri.org`

**L.E. Bradley, M. Galimberti, A. Kidd, P. Oliveira,**
**A. Aiken, C. Suciu, J. Patel and I.O. Musgrave**
*Central Laser Facility*
*STFC Rutherford Appleton Laboratory*
*Harwell Campus*
*OXON. OX11 0QX*

## Abstract

Energy stability of the short picosecond CPA pulse in Vulcan can vary over time. This creates operationally dynamic conditions as the energies between shots can deviate from user requested energies. We present progress in stabilising the beams near-field while identifying future interventions to improve stability.

## 1 Introduction

Providing laser pulses which are both reliable and stable in energy is crucial for experiments in high-powered laser facilities such as Vulcan [1]. Energy and positional instability of laser beams can arise from many sources, including misalignment, thermal effects [2], air dynamics and cavity instabilities [3]. A system on the scale of Vulcan with a large of number optical tables and longer beam path lengths, understanding movement between the several optical components is essential.

The propagation of the laser beam at any position with respect to the optical system can essentially be described by the transverse shift and angular tilt of the beam. In fact, beam stabilisation may be completely characterised with these two independent quantities. Attempts have been made to characterise pointing stability using different methods which use a moment approach [4], a oblique-incidence transmittance difference technique [5] and interference methods for measuring angular tilt [6]. Stability using fast feedback control methods [7, 8] offer an attractive method to stabilise positional drifts by spatially locking both the near and far-field of the beam.

Vulcan consists of both long pulses in the few nanosecond regime to short pulses which are ∼ 1ps. Vulcan has six beamlines (main six) for the long pulse and two for the short pulse (beam 7, beam 8). The standard deviation $\sigma$ in on-shot energy in each of the Vulcan oscillators over eight experiments during July 2018–December 2019 is shown in figure 1. The shaped long pulse (SLP2) has a $\sigma$ as low as less than 5% and a maximum of 10%. Meanwhile the Insight oscillator on beams 7 and 8 fluctuates to 20% and 15% respectively. The oscillator for the petawatt beamline, the 2Hz ns OPCPA has a constant energy change overall with a 15% standard deviation.

| **Oscillator** | $\langle E \rangle$ (J) | $\sigma$ (%) | Pulse duration |
|---|---|---|---|
| SLP 2 | 207 | 6.3 | ∼ 1ns |
| Insight DS | 227 | 12.2 | ∼ 10ps |

Table 1: Disc energies measured in the laser area with energies in the 200J region. The SLP2 using beams 1-6 and the Insight using beam 8.

| **Oscillator** | $\langle E \rangle$ (J) | $\sigma$ (%) | Pulse duration |
|---|---|---|---|
| SLP | 72 | 17.1 | ∼ 200ps |
| Insight DS | 73 | 18.5 | ∼ 1ps |
| 2Hz ns OPCPA | 120 | 14.6 | ∼ 1ns |

Table 2: Disc energies measured in the laser area with energies in the 100J region. The SLP using beams 1-6, the Insight using beam 8 and the OPCPA using beam 7.

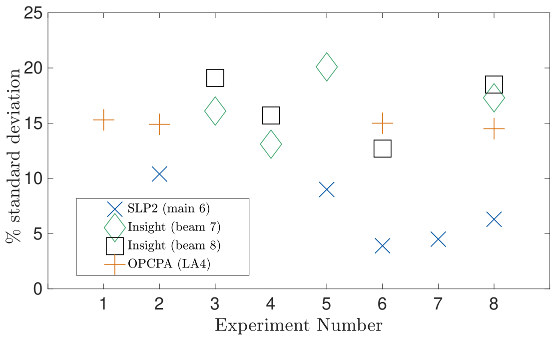

Figure 1: Standard deviation in energy for each Vulcan oscillator throughout eight experimental campaigns.

Progress in stabilising the ps short pulse in Vulcan is presented. A method that locks the near-field using fast stabilisation [9] is described. This method makes use of a PID (proportional-integral-differential) control loop, whereby producing a feedback between a fast piezo mirror and a positioning sensitive device (PSD). New diagnostics have been introduced to support this work with future improvements to stability considered. The aim of this work is twofold, firstly to enhance the user experience of Vulcan by improving the short pulse energy stability, secondly to improve operational efficiency in future experimental campaigns.

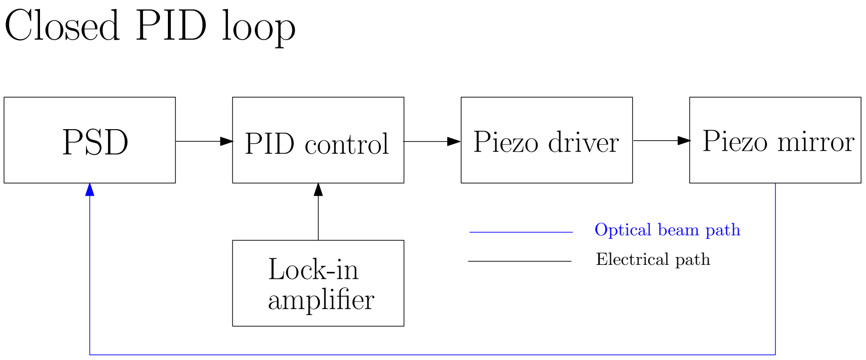

Figure 2: Diagram showing the electrical and optical connections between the positional sensitive device (PSD) and the fast Piezo mirror to create the closed feedback loop.

## 2 Stabilising the short pulse

Vulcan front-end consists of the Insight DS which is a short femtosecond commercial laser by Spectra Physics. This laser was introduced in 2016 to replace an existing SAM oscillator. The short pulse uses chirped-pulse amplification (CPA) [10] to temporally stretch the pulse to the nanosecond regime before being injected and amplified into neodymium phosphate glass gain medium in Vulcan [11].

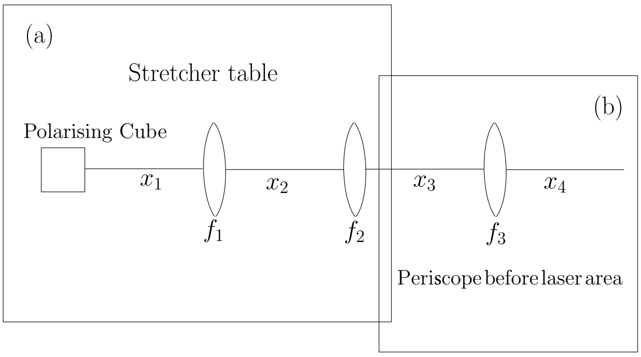

Figure 3: Lens arrangement for relay imaging of the Insight beam in the front-end, where $f_1 = 400$mm, $f_2 = 350$mm and $f_3 = 3000$mm.

### 2.1 Relay imaging

Vulcan has various relay imaging telescopes in both the front-end and around the amplification chain. The ray matrices equations have been solved to determine the positions of three lens within a constrained distance in the front-end shown in figure 3. Specifically, one lens with focal length $f_1 = 400$ mm and a second with $f_2 = 350$ mm are placed on the output of the stretcher from a polarising cube (a) of figure 3. A third lens is placed prior to entering the laser area with focal length $f_3 = 3000$ mm in (b). The final lens is important as the beam propagates the furthers distance between the front-end and laser area. Using a wave sensor, the size of the beam is measured to understand if it is well collimated and the angular beam divergence is minimised. The total beam path length is 905cm determined from the polarising cube on the stretcher output to the laser area input. Once the beam passes through the Martines stretcher, the output beam is relay imaged onto a $\phi$ =1” mirror attached to a piezo mount which is held perpendicular to a 15kg metal base. The base has Sorbothane rubber feet to ensure that frequencies from external sources are sufficiently damped.

### 2.2 Fast beam stabilisation

Fast stabilisation has previously been adopted to spatially and temporally lock coherent beams [12, 13]. It has also been implemented on the Gemini laser system [14] at the Central Laser Facility (CLF). The beam is stabilised with a PID (proportional-integral-differential) control loop. The output is given by

$$\text{Output} = P\left(\mathcal{E} + I\int \mathcal{E}dt + D\frac{d\mathcal{E}}{dt}\right) + \text{Offset}$$

where, $\mathcal{E}$ = Setpoint - Measure is the error. Essentially, the three parameters describe the way in which the system minimises the error $\mathcal{E}$. The proportional parameter $P$ minimises the current error, the difference in the measured beam position to the set point. The integral term gives a corrective factor which integrates $\mathcal{E}$ with time. The derivative term $D$ takes the current value of $\mathcal{E}$ to predict future values of $\mathcal{E}$ adjusting the output as required. A position sensitive device (PSD) is used to measure positional drift of the beam which is set up further in the system. A visual representation of this closed feedback loop is shown in figure 2. This method has been implemented in the Vulcan front-end with the PSD in the Vulcan laser area. The feedback loop has been tested to lock the near-field.

A lock-in amplifier has been used to create a successful closed loop. The lock-in amplifer interfaces between the PID control and the piezo driver in figure 2. A frequency range of a few hundred Hz was chosen, the attenuation in both X and Y of the piezo mirror is shown in figure 4. Approximately 20 shots were taken with the fast stabilisation turned on. It was found that the pointing moved vertically on-shot. While it was speculated that Vulcan amplifier flash lamp light was causing the PSD to move the fast mirror, this was not conclusive and efforts were made to conceal scattered light from the PSD.

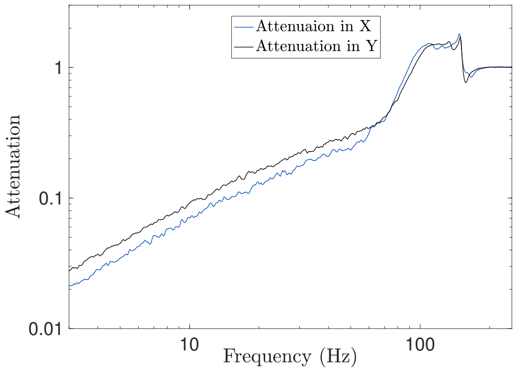

Figure 4: Log-log plot showing the closed loop attenuation as a function of frequency for the lock-in amplifier.

### 2.3 *Changes to the Petawatt beamline*

The Vulcan Petawatt beamline uses the technique of optical parametric chirped pulse amplification (OPCPA) [15]. A Ti:sapphire seed and a ns OPCPA pump operating at 2Hz repetition rate is the seed for the petawatt beamline [16]. The mirrors from the front-end into the laser area have been replaced in order to deploy a 'green' pilot beam. These have been replaced with ten new hybrid silver coated mirrors which are highly reflective at wavelengths 1053nm and 527nm. The reflectivity as a function of wavelengths is plotted in figure 5.

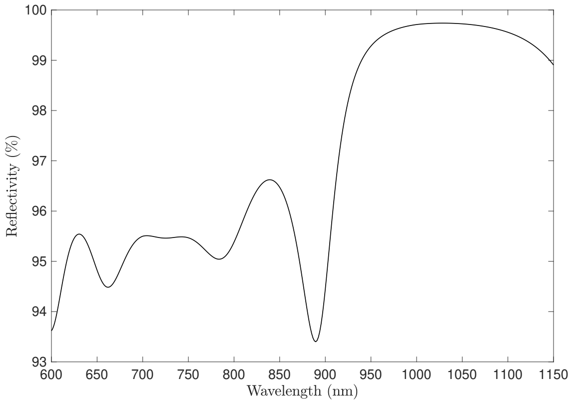

Figure 5: Percentage reflectivity for a given wavelength in hybrid mirrors.

## 3 Laser camera diagnostics

Vulcan has various near-field (NF) and far-field (FF) diagnostic cameras throughout the amplification chain [17]. New diagnostics have been added which include a NF and FF on the input to the 9mm amplifiers and another NF and FF after the pulse has made a double-pass through the two amplifiers. These diagnostics have been added at these positions to facilitate operational alignment and to determine if the beam drops over the distance from entering the laser area to the first two double-pass amplification stages. The two positions are shown in figure 6. A wavefront sensor device was also used to determine the collimation of the beam and understand if the beam was the correct size for the small aperture Pockels cell just after the first set of diagnostic cameras.

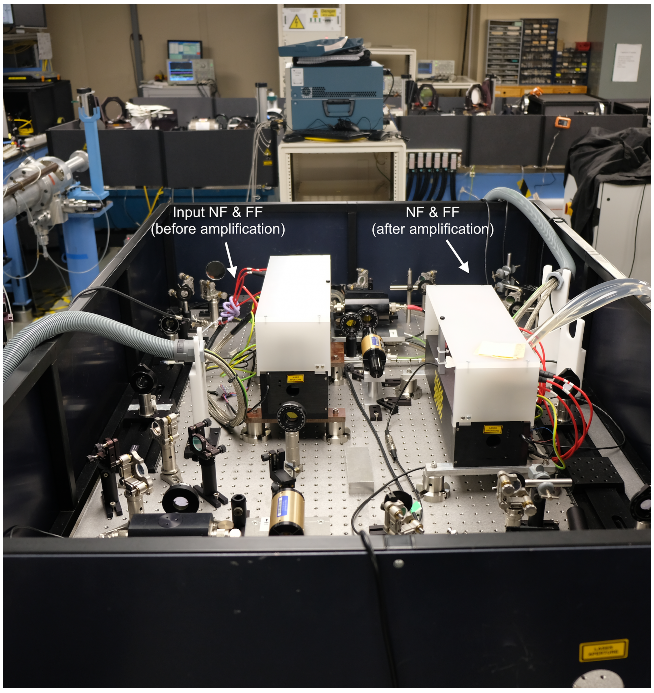

Figure 6: Near-field and far-field diagnostics installed before and after the short pulse is amplified through the two double pass 9mm amplifiers.

## 4 Future stability work

Future work on the 2Hz ns OPCPA beamline will involve adding a pilot beam to propagate through the Vulcan chain from the front-end to the 6mm aperture. Vulcan has spatial filtering through the system which is described as the 6mm aperture. The aim of this exercise is to spatially overlap the two beams and identify any changes needed to the beam path.

Although the near-field has been locked using the closed PID loop, it has been identified that a second fast mirror is needed to lock the far-field of the beam. Solely locking the beam near-field has yet to conclusively demonstrate energy stability has been improved. Future work will therefore involve the addition of a second fast piezo mirror placed before the stretcher and the first fast piezo mirror.

## 5 Conclusion

Energy statistics from recent experimental campaigns indicate that the short ps pulse in Vulcan has an energy variation of 20%. Recent progress has been made to improve stability of the short pulse by using fast beam stabilisation in Vulcan. It has been identified that locking only the beam near-field has not conclusively solved energy stability and therefore future interventions have been considered.

## References

[1] C. Hernandez-Gomez, P. Brummitt, D. Canny, and others., "Vulcan petawatt-operation and development," *Journal de Physique IV (Proceedings)*, vol. 133, 06 2006.

[2] W. A. Clarkson, "Thermal effects and their mitigation in end-pumped solid-state lasers," *Journal of Physics D: Applied Physics*, vol. 34, pp. 2381–2395, aug 2001.

[3] A. E. Siegman and S. W. Townsend, "Output beam propagation and beam quality from a multimode stable-cavity laser," *IEEE Journal of Quantum Electronics*, vol. 29, no. 4, pp. 1212–1217, 1993.

[4] M. Morin, P. Bernard, and P. Galarneau, "Moment definition of the pointing stability of a laser beam," *Opt. Lett.*, vol. 19, pp. 1379–1381, Sep 1994.

[5] J. Gray, P. Thomas, and X. D. Zhu, "Laser pointing stability measured by an oblique-incidence optical transmittance difference technique," *Review of Scientific Instruments*, vol. 72, no. 9, pp. 3714–3717, 2001.

[6] M. Dobosz and O. Iwasinska-Kowalska, "Interference method for ultra-precision measurement and compensation of laser beam angular deflection," *Appl. Opt.*, vol. 53, pp. 111–122, Jan 2014.

[7] W. Zhao, J. Tan, L. Qiu, L. Zou, J. Cui, and Z. Shi, "Enhancing laser beam directional stability by single-mode optical fiber and feedback control of drifts," *Review of Scientific Instruments*, vol. 76, no. 3, p. 036101, 2005.

[8] G. Genoud, F. Wojda, M. Burza, A. Persson, and C.-G. Wahlström, "Active control of the pointing of a multi-terawatt laser," *Review of Scientific Instruments*, vol. 82, no. 3, p. 033102, 2011.

[9] D. Shepherd, B. Parry, and M. Galimberti, "Fast beam stabilisation of a large diameter CW laser in its far field using 3 inch piezo mounted mirrors," *STFC Annual Report*, 2017.

[10] D. Strickland and G. Mourou, "Compression of amplified chirped optical pulses," *Optics Communications*, vol. 56, no. 3, pp. 219 – 221, 1985.

[11] C. Danson, L. Barzanti, Z. Chang, A. Damerell, C. Edwards, S. Hancock, M. Hutchinson, M. Key, S. Luan, R. Mahadeo, I. Mercer, P. Norreys, D. Pepler, D. Rodkiss, I. Ross, M. Smith, R. Smith, P. Taday, W. Toner, K. Wigmore, T. Winstone, R. Wyatt, and F. Zhou, "High contrast multi-terawatt pulse generation using chirped pulse amplification on the vulcan laser facility," *Optics Communications*, vol. 103, no. 5, pp. 392 – 397, 1993.

[12] A. Rogers, I. Musgrave, C. Hernandez-Gomez, B. Parry, M. Galimberti, and P. J. Phillips, "Experimental setup of the vulcan happie laboratory 2 for spatially and temporally coherent multibeam recombination," *CLF Annual Report*, 2013-2014.

[13] P. J. Phillips, C. Hernandez-Gomez, and J. Collier, "Experimental setup in the vulcan happie laboratory for multi-beam combination to achieve diffraction limit pulses," *CLF Annual Report*, 2009-2010.

[14] C. J. Hooker, S. Blake, O. Chekhlov, R. J. Clarke, J. L. Collier, E. J. Divall, K. Ertel, P. S. Foster, S. J. Hawkes, P. Holligan, B. Landowski, W. J. Lester, D. Neely, B. Parry, R. Pattathil, M. Streeter, and B. E. Wyborn, "Commissioning the astra gemini petawatt ti:sapphire laser system," *Conference on Lasers and Electro-Optics/Quantum Electronics and Laser Science Conference and Photonic Applications Systems Technologies*, p. JThB2, 2008.

[15] I. Ross, P. Matousek, M. Towrie, A. Langley, and J. Collier, "The prospects for ultrashort pulse duration and ultrahigh intensity using optical parametric chirped pulse amplifiers," *Optics Communications*, vol. 144, no. 125, 1997.

[16] B. Parry, P. Oliveira, A. Boyle, W. Shaikh, and I. Musgrave, "A new ns opcpa front end for vulcan petawatt," *CLF Annual Report*, 2013.

[17] I. Musgrave, M. Galimberti, A. Boyle, C. Hernandez-Gomez, A. Kidd, B. Parry, D. Pepler, T. Winstone, and J. Collier, "Review of laser diagnostics at the vulcan laser facility," *High Power Laser Science and Engineering*, vol. 3, p. e26, 2015.