LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

LIGO Laboratory / LIGO Scientific Collaboration

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Characterization and intensity stabilization of a high-power CO_2 laser for fiber-pulling

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Table of Contents

1 Introduction

1.1 Purpose and Scope

The IGR fibre-pulling rig is based on a Firestar 100 CO_2 laser. As of September 2006, the intensity stability of the laser left something to be desired, leading to irregular fibres. This document describes measurements that were made to characterize the laser and power meter. It also details a LabView-based control system that was added to smooth out fluctuations, and serves s an instruction manual for the laser/controller system.

1.2 Version history

10/16/06: Pre-rev-00 draft.

11/1/06: Initial release - 00

2 Equipment

The laser, the power meter and the pieces of the control system were already largely in place – they just needed to be characterized. In this section, the specifications of the various components are collected for convenience.

2.1 Laser

The laser is a firestar f100:

http://www.synrad.com/fseries/f100.htm

firestar f -series 100 Watt Specifications:

Output Power	100W
Mode Quality	TEM00, 95% Purity M^2<1.2
Ellipticity	<1.2
Rise Time	<150µsec
Beam Diameter	3.5mm
Beam Divergence (full angle)	4.0mR
Wavelength	10.2-10.7µm
Power Stability:	
cold start (guaranteed):	±10%
after 2 minutes (typical):	±6%
Polarization	Linear (Horizontal)
Cooling	Water
Heat Load (max)	2000W
Flow Rate (18-22°C)	2.0 GPM, <60PSI
Input Voltage / Current	96 VDC / 18A
Dimensions, laser head	25.1 x 6.3 x 5.6 (in) / 638 x 160 x 142 (mm)
Weight	38 lbs / 17.2 kg

The key item to note is the power stability, which is not guaranteed to be particularly good, and indeed isn't.

2.2 Power Meter

The power meter is a Gentec-EO UP19K-150W head with a TPM300 readout:

http://www.gentec-eo.com/en/up19k.html

http://www.gentec-eo.com/en/tpm300.html

UP19K-150W specifications:

Spectral Range	0.19 - 11 µm
Power Range	20 mW - 150 W
Energy Range	0.2 J - 15 J
Rise Time (nominal)a	0.6 sec
Maximum Average Power Density	36 kW/cm2
Peak Power Density, short pulse (ns)	143 MW/cm2
Maximum Energy Density (long pulse: µs-ms)	5 J/cm2
Maximum Energy Density (short pulse: ns)	1 J/cm2
Aperture	19 mm Ø

TPM 300 specifications:

Power Ranges	1 mW to 10 kW
Power Scales	12 scales: 0.03W, 0.1W, 0.3W, 1W, 3W, 10W, 30W, 100W, 300W, 1kW, 3kW, 10kW
Resolution (digital)	100 µW on the 30 mW scale
Monitor Accuracy	±0,5 %
Response Time	1 s (with UP19K series, varies with detector head)
Analog Display	91 x 40 mm analog panel meter
Digital Display	4 digit LCD readout, 46 x 19 mm
Analog Output	0 - 1 volt, full scale, ±0.6 %
Connector Ports	BNC and RS-232
Battery	5 rechargeable 1.2 V NiCad AA
Battery life	8 hours
Battery charge time	9 hours to full charge
External Power Supply	110 volt CSA/UL approved Input : 100/120 VAC, 60Hz, Output 12 VDC, 800 mA 220 volt CE/VDE/TÜV approved Input : 220/240 VAC, 50Hz, Output 12 VDC, 1A
Dimensions (with mount)	243 (W) x 100 (D) x 120 (H) mm
Dimensions (without mount)	200 (W) x 100 (D) x 93 (H) mm
Weight (with mount)	1,6 kg

The key item here is the response time of 0.6 s for the head and 1.0 s for the combination. This tends to limit the bandwidth of a controller that could be implemented using such a sensor. However to get a substantially faster response requires a photodiode, and at such a long wavelength, photodiodes are expensive and/or require LN_2 cooling.

2.3 LabView cards

The computer system used for the controller is a Windows PC running LabView.

The input is a National Instruments NI PCI-6221:

http://sine.ni.com/nips/cds/view/p/lang/en/nid/14132

The output is a National Instruments NI PCI-6723:

http://sine.ni.com/nips/cds/view/p/lang/en/nid/12551

These have ample bandwidth.

3 Characterization

3.1 Laser

3.1.1 Warm-up profiles

Previous experience with the laser suggested that the stability improved after a warm-up period, so a number of logging runs were done to investigate. Typical warm-up curves can be seen in Figure 1 and Figure 2. It is very unstable for approximately the first 10 minutes (600 s) but then improves somewhat. There is a mixture of long-term drift plus occasional more rapid changes. After about 45 minutes the glitches appear to disappear. The relative instability is slightly larger for the higher power (and the absolute instability is much greater).

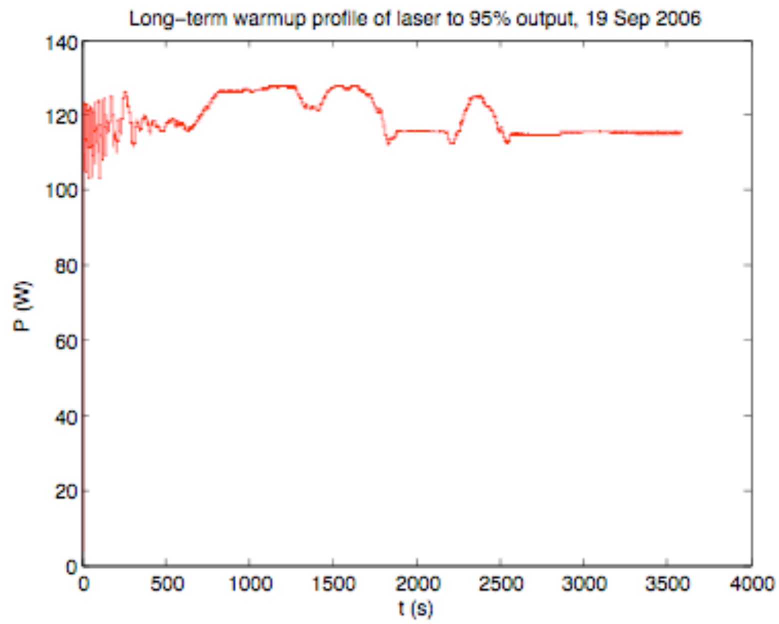

Figure 1: Warm-up profile of laser – 95% power

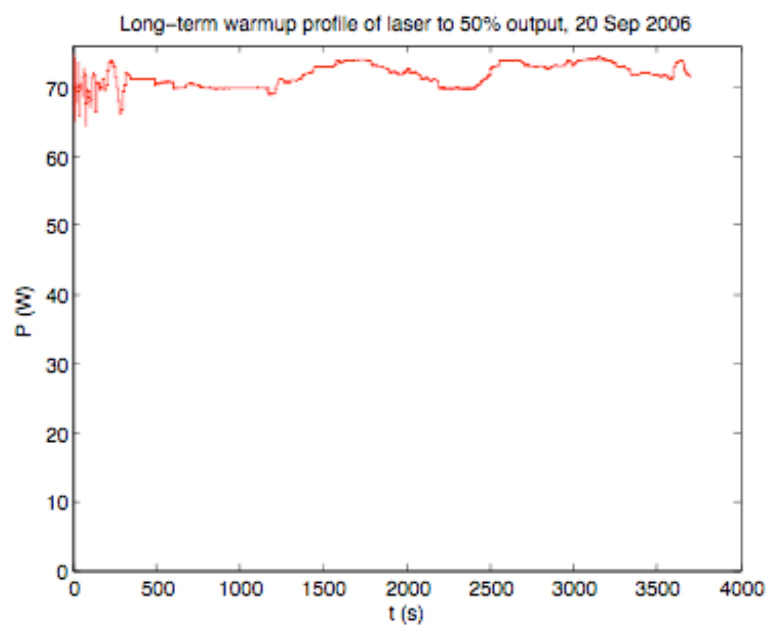

Figure 2: Warm-up profile – 50% power

3.1.2 Effect of cooling water flow

The initial warm-up runs were taken with the cooling water tap on by several turns, to a point where flow noise had stopped diminishing, but possibly not to the absolute maximum. To check whether this was important, profiles were taken with three different flow rates, calibrated by timing the output flow into a bucket. (Check: is cooling for power meter in series or parallel with laser??? If parallel, then laser share of quoted values is less than 1.0 by some fraction.)

The results are dramatic: for the tap fully open (13.3 l/min) the instability largely vanishes after 10 minutes, for moderate flow (5.6 l/min) there are occasional glitches for the whole hour of logging, and for restricted flow (2.0 l/min) there was severe instability for 20 minutes followed by a shutdown caused by the thermal protection circuit. By comparison, the minimum flow rate specified in the manual is 7.8 l/min. Clearly it is important to meet or slightly exceed the spec.

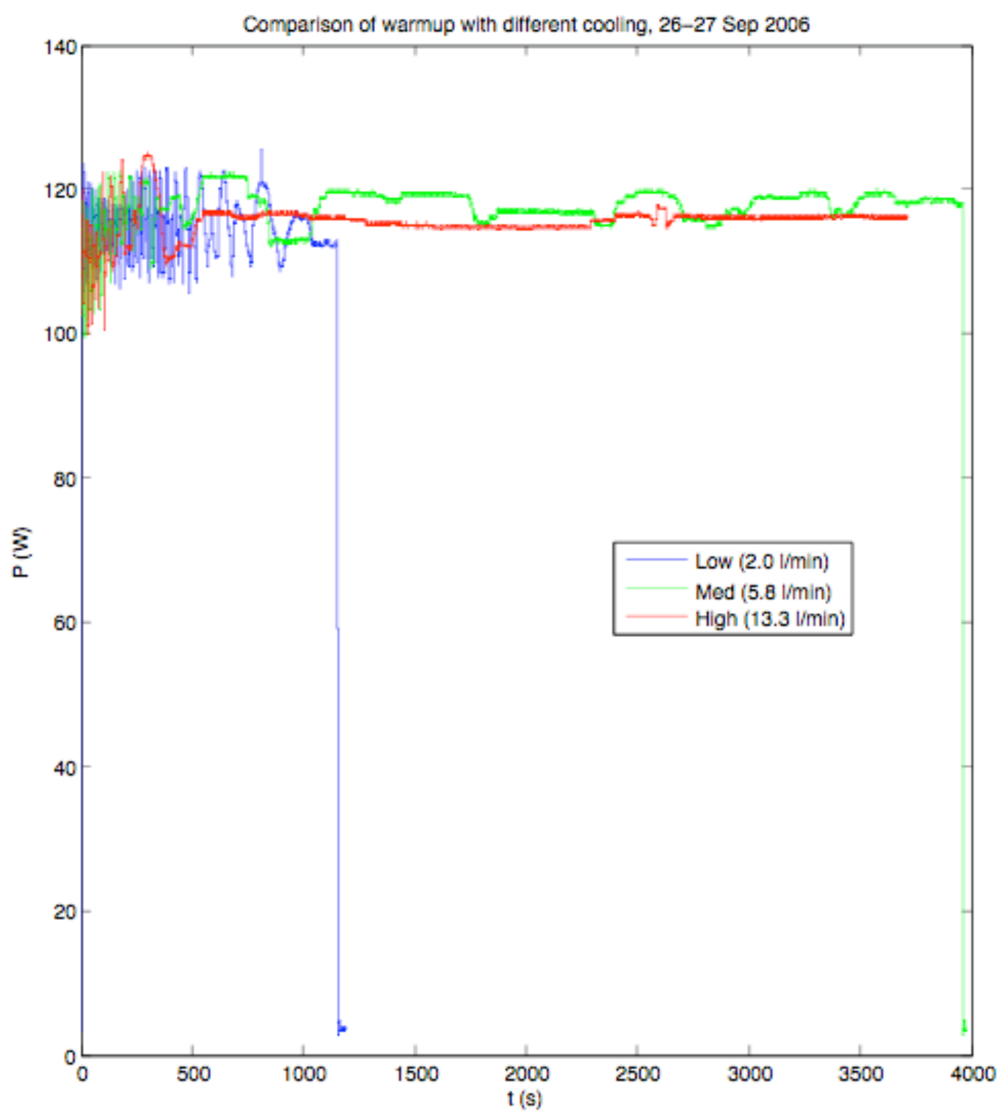

Figure 3: Warm-up profiles - 95% power; 2.0, 5.6 and 13.3 l/min water flow

3.1.3 Effect of occluding the beam

The faster glitches suggest that there may be some mode-hopping. To test this, a warmup profile was taken with the beam 50% occluded by a vertical edge. If there is beam-jitter associated with the mode-hopping, one would expect the relative instability to increase. Indeed, this is what was observed. This doesn't suggest any easy fixes, but to the extent possible optics should be designed to tolerate some jitter.

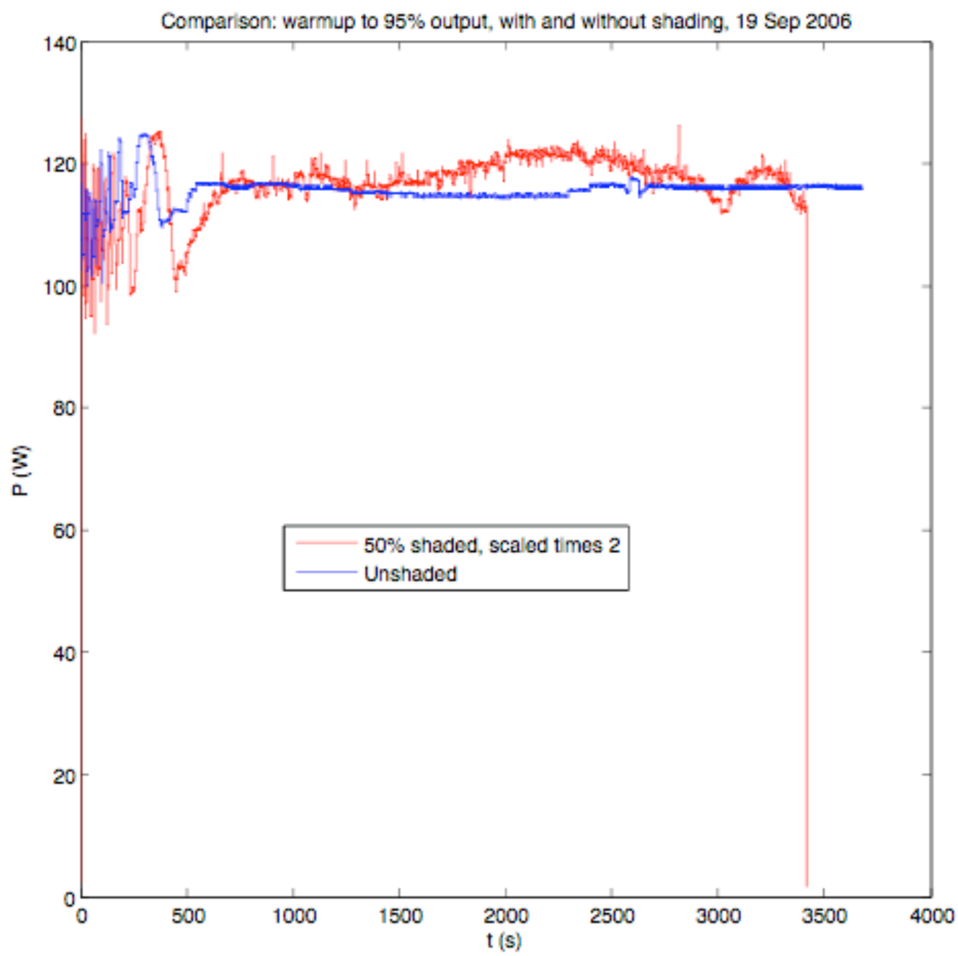

Figure 4: Warm-up profile – 95% power, with and without 50% beam shading. The 50% curve has been multiplied by 2 to allow easy comparison of relative stability.

3.1.4 Effect of step function control change

To see whether the laser responded predictably to control inputs when suitably warmed up, the input was stepped down from 95% to 4.5% in steps of about 4.5% at 20 minute intervals. (The laser cut out entirely for 4.5% duty cycle input – the last input that produced non-zero output in this test was 8.5%.) Below about 80 W, the output looks tolerably like a staircase. Above 80 W, each input step set off another round of glitches of size somewhat more than the step, so that the linear trend was still apparent but the staircase pattern was largely obscured.

The conclusion is that even with plenty of warm-up, the uncontrolled laser is not usable above 80 W if there is going to be any need to adjust the laser power through the course of a run.

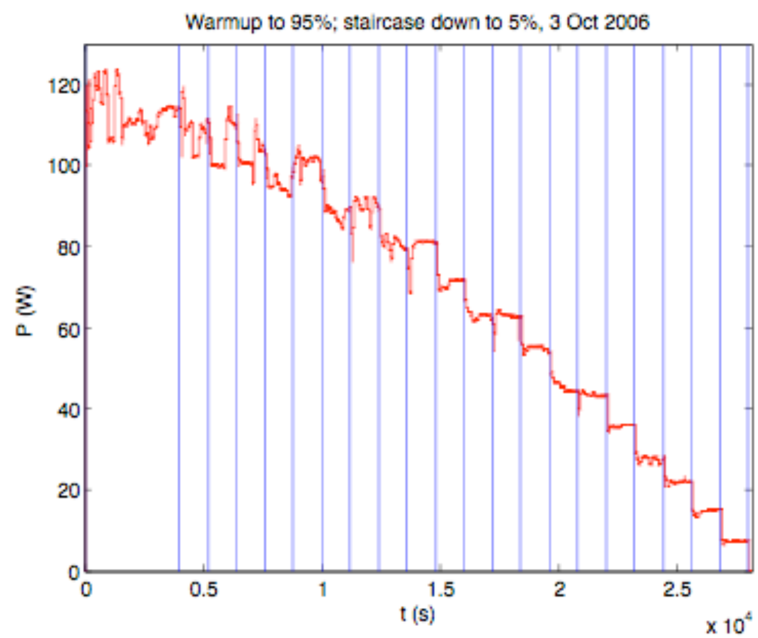

Figure 5: Effect of repeated negative step functions (nominally 5 W each, or approx 4.5% duty cycle)

3.2 Power Meter

To confirm the response of the power meter, the laser was allowed to warm-up at 50% power, the secondary shutter in front of the built-in shutter was closed for approximately 1 minute to allow the power meter to come to thermal equilibirum and then the shutter was reopened. The resulting transient did have a rise time of around 0.6 s and was well-fitted by eye to the following Laplace transform (see Figure 6):

$$\frac{1}{1+0.81s+0.25s^2}$$

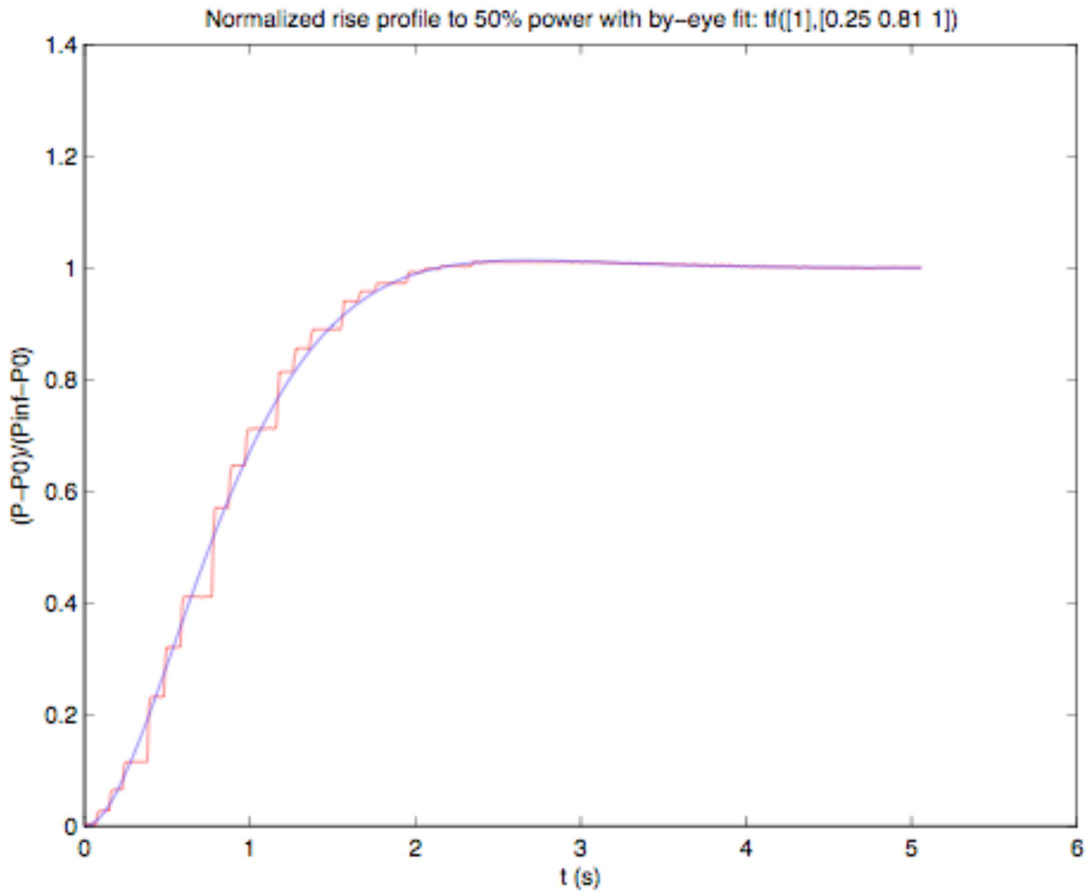

Figure 6: Transient response of power meter to step power input.

4 Controller

4.1 Design and Implementation

The controller was implemented in LabView. The PID controller VI ("virtual instrument") was written by Graham Gibson and adapted for the laser by Iain Martin with guidance from Jim Hough. It was then debugged and refined by the primary author (Mark Barton).

The sub-VI for reading the power meter (Figure 7) was improved with a second range calibration input and an offset. The input labeled "Range (W/V)" should be set to match the RANGE knob setting on the TPM-300. The "Calibration" input should be set to the reciprocal of the reflectivity of any pickoff mirror used. The "Zero" input should be set to the VI output with Range=Calibration=1 and Zero=0. If Voltage is the TPM-300 output, the VI output is

Range*Calibration*(Voltage-Zero)

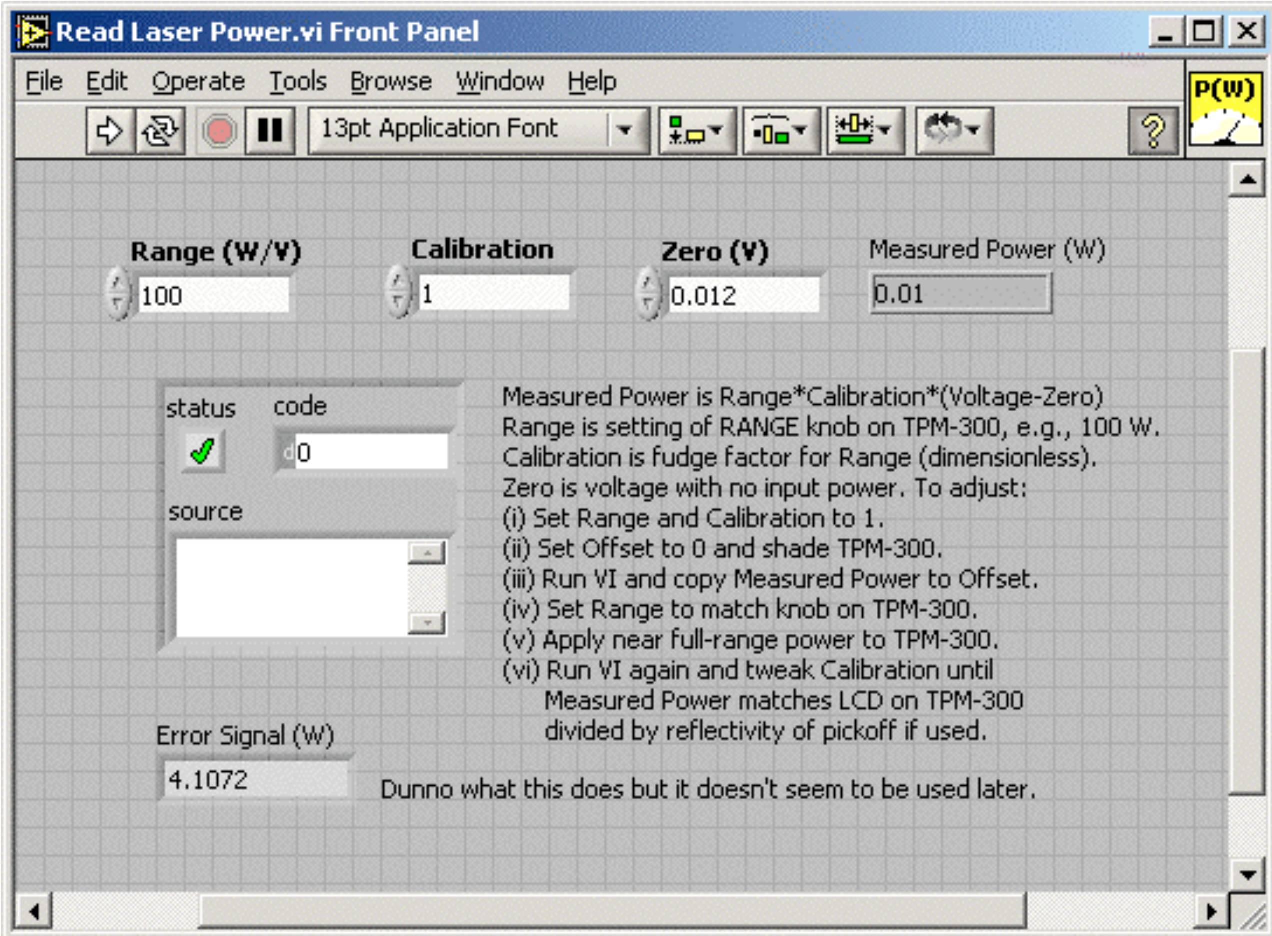

Figure 7: VI for reading laser power

The VI for setting the laser power was improved with a new default calibration of 14.4 V/W. (This value is not particularly critical but getting a good approximation reduces the correction the controller has to make.)

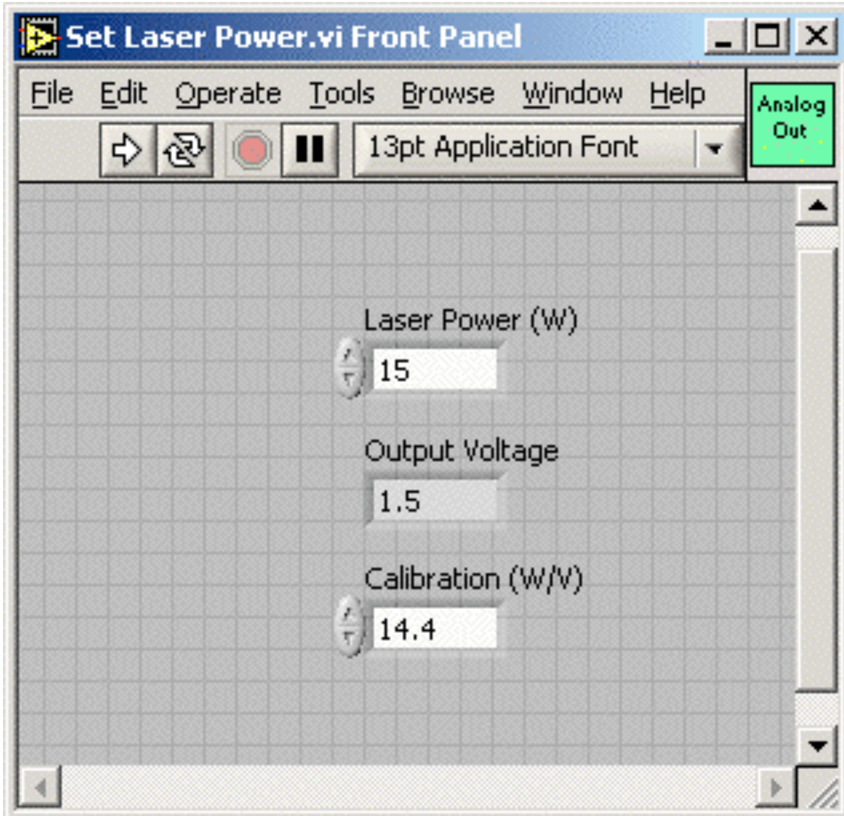

Figure 8: VI for setting laser power

The main controller VI (Figure 9) was improved in a few minor ways:

- A new global gain parameter G multiplying all the others was added to allow more flexibility in applying different tuning recipes. The net control signal is

$$G\left(P\left(L-L_0\right)+D\dot{L}\tau_d+\int\frac{I}{\tau_i}\left(L-L_0\right)dt\right)$$

where L is the laser power, L_0 is the setpoint, P, I and D are the usual PID gains, and τ_d and τ_i are characteristic time constants.

- The point of applying the integral gain was moved to before the integrator

$$\frac{I}{\tau_i}\int\left(L-L_0\right)dt\rightarrow\int\frac{I}{\tau_i}\left(L-L_0\right)dt$$

so that changing the gain doesn't produce a step function perturbation if the accumulated value of the integral is non-zero.

- Constraints were placed on some of the input fields to minimize the chance of unstable behaviour.
- The front panel was tidied up and commented.

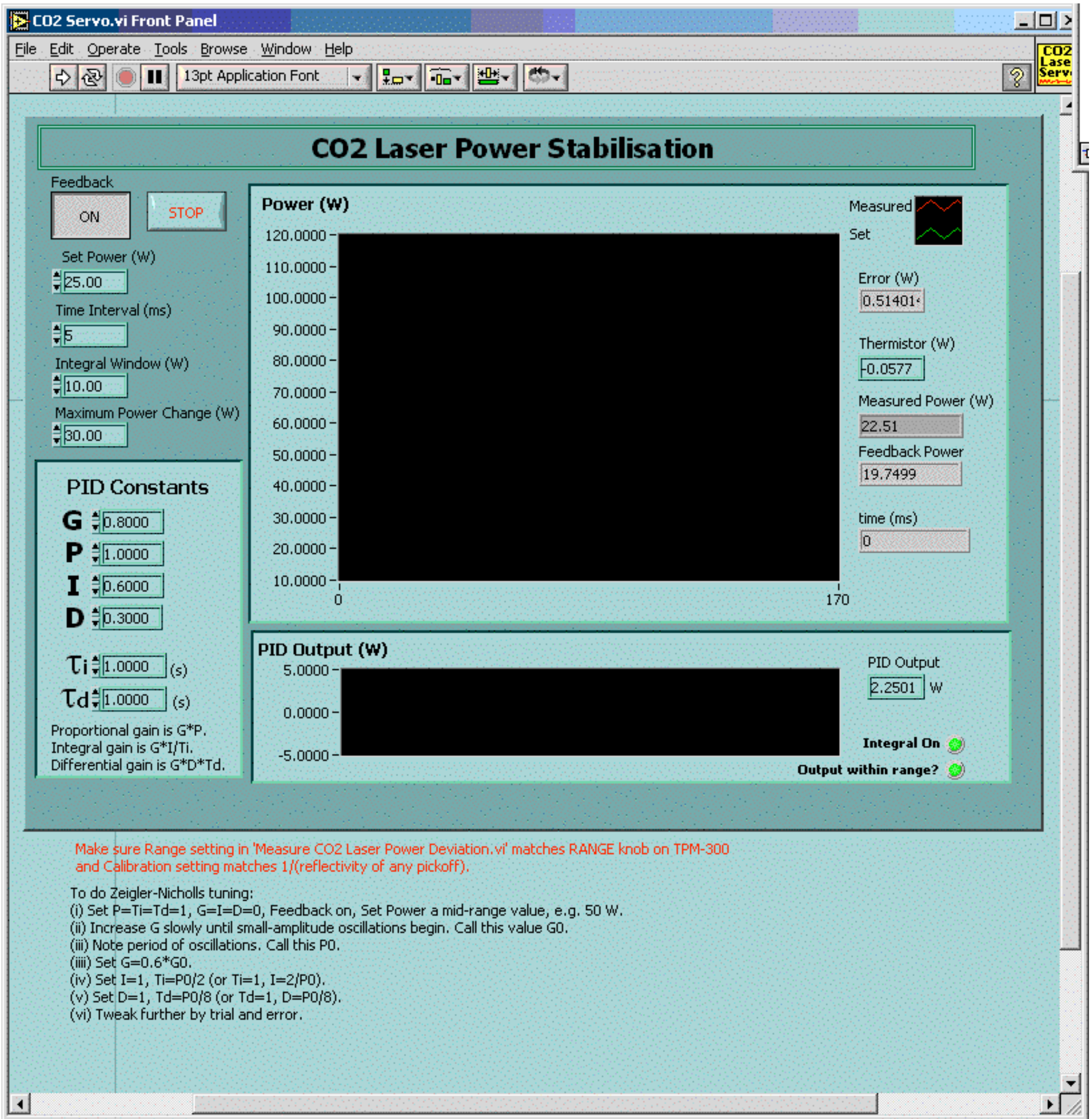

Figure 9: Controller VI main screen

4.2 Tuning

The Zeigler-Nichols tuning procedure was implemented according to the recipe at

http://en.wikipedia.org/wiki/PID_controller

which gave G=0.8, P=1.0, I=0.6 and D=0.3.

4.3 Performance

A staircase test similar to that in Figure 5 was performed with the controller on. The laser was initially cold. Some observations:

- The performance was generally much better than without the controller. With one or two exceptions, the controller was able to bring the power output precisely to the setpoint value within a few seconds of a change and there was negligible slow drift thereafter. Thus the overall staircase profile was clearly visible. See Figure 10.
- The controller struggled for about the first 6 minutes, presumably due to the extreme glitchiness of the unwarmed-up laser.
- The controller was only moderately effective against glitches. It couldn't react quickly enough to suppress them completely, but it did restore the output to the setpoint within a few seconds, thereby reducing a step function disturbance to a pulse. See Figure 12.
- At a few setpoint values, especially 90W, the controller was apparently unstable. It is not clear whether this is a true instability or whether the laser is just particularly glitchy at these power levels. See Figure 13. Comparing the two periods with a setpoint of 60 W gives hope that if there is initial glitchiness it can sometimes be cured by changing the setpoint away and then back again.

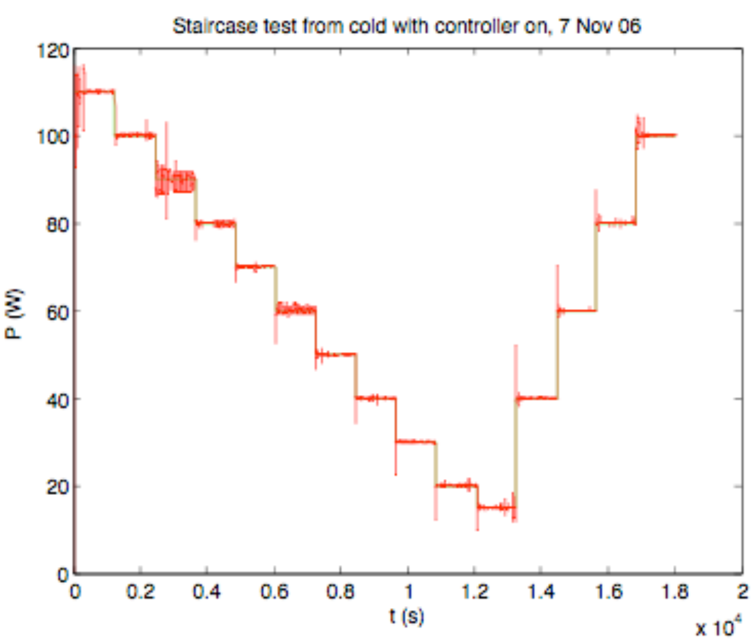

Figure 10: Staircase test with controller on

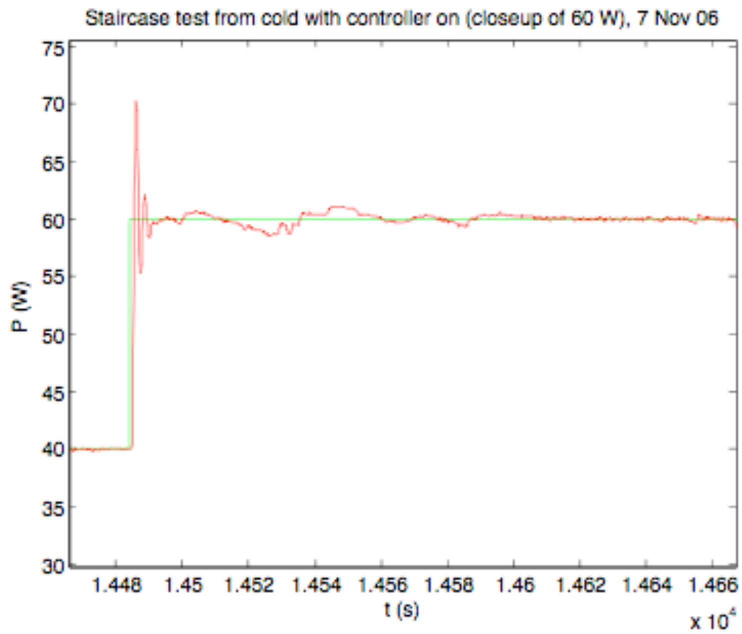

Figure 11: Closeup of transient between 40 W and 60 W

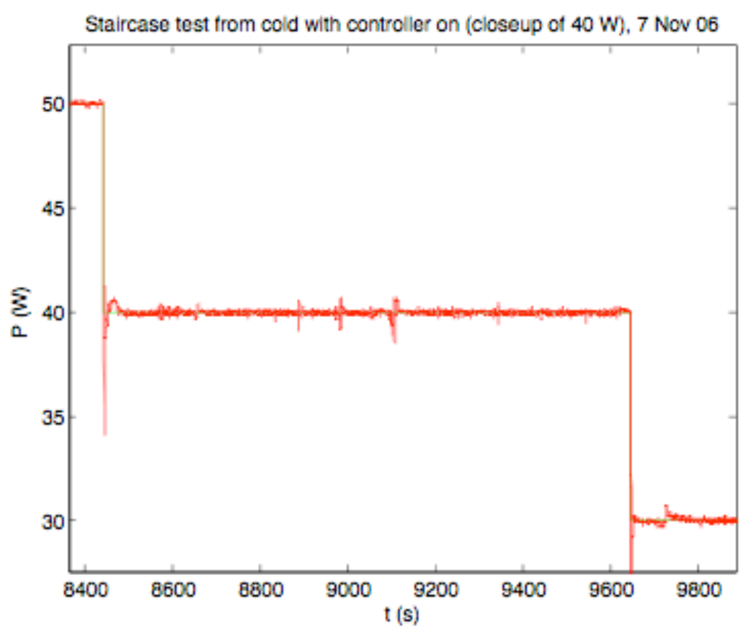

Figure 12: Closeup of 40 W setpoint tracking

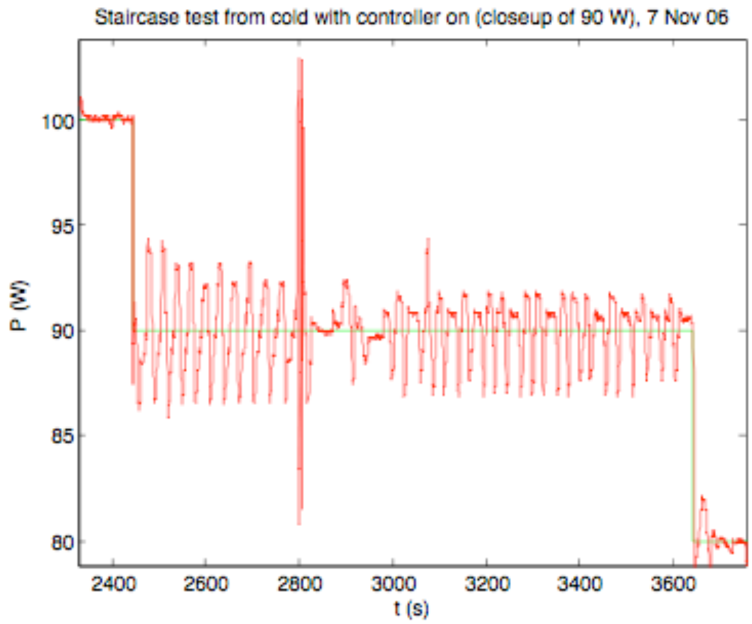

Figure 13: Closeup of apparent instability at 90 W setpoint

5 Conclusions

- The controller improves the overall performance considerably.
- There should be no problem with obtaining a power level reproducible from run to run.
- There is still a potential problem with incompletely suppressed glitches producing point defects in fibres. Experience with pulling actual fibres will be required to know whether the current performance is acceptable.
- If better suppression is found to be required, it can probably be achieved by replacing the power meter with a sensor with faster response, probably as a mercury-cadmium-telluride photodetector.