moglabs

External Cavity Diode Laser Controller

Models DLC-202, DLC-502

Revision 3.00

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Preface

Diode lasers can be wonderful things: they are efficient, compact, low cost, high power, low noise, tunable, and cover a large range of wavelengths. They can also be obstreperous, sensitive, and temperamental, particularly external cavity diode lasers (ECDLs). The mechanics and optics needed to turn a simple $10 120 mW AlGaAs diode laser into a research-quality narrow-linewidth tunable laser are fairly straightforward [1,2], but the electronics is demanding – and, until now, not available commercially from a single supplier, let alone in a single unit.

The MOGlabs range of ECDL controllers change that. With each DLC unit, we provide everything you need to run your ECDL, and lock it to an atomic transition. In addition to current and temperature controllers, we provide piezo drivers, sweep ramp generator, modulator for AC locking, lock-in amplifier, feedback servo system, laser-head electronics protection board, even a high-speed low-noise balanced photodetector.

We would like to thank the many people that have contributed their hard work, ideas, and inspiration, especially Lincoln Turner, Karl Weber, and Jamie White, as well as those involved in previous controller designs, in particular Mirek Walkiewicz and Phillip Fox.

We hope that you enjoy using the DLC as much as we do. Please let us know if you have any suggestions for improvement in the DLC or in this document, so that we can make life in the laser lab easier for all, and check our website from time to time for updated information.

Robert Scholten and Alex Slavec
MOGlabs, Melbourne, Australia
www.moglabs.com

Safety Precautions

Please note several specific and unusual cautionary notes before using the MOGlabs DLC, in addition to the safety precautions that are standard for any electronic equipment or for laser-related instrumentation.

WARNING The rear-panel connector for the laser is similar to standard DVI (Digital Video Interface) plugs as used for consumer digital display devices. The pins on this connector can be at high potential (up to 120 V). These can be hazardous to life and should be protected by connection of the correct cable to the laser. Under no circumstances should a standard DVI device such as an LCD display be connected to this socket!

CAUTION Please ensure that the unit is configured for the correct voltage for your AC mains supply before connecting. The supply must include a good ground connection.

WARNING The internal circuit boards and many of the mounted components are at high voltage, with exposed conductors, in particular the high-voltage piezo driver circuitry. The unit should not be operated with covers removed.

WARNING If using a Zeeman coil modulator as described in appendix C, the secondary potential can easily be hundreds of volts. Please ensure that your coil and balance capacitor do not have exposed connections, and that all components have sufficient voltage rating.

NOTE The MOGlabs DLC is designed for use in scientific research laboratories. It should not be used for consumer or medical applications.

Protection Features

The MOGlabs DLC includes a number of features to protect you and your laser.

Softstart A time delay followed by linearly ramping the diode current; total of 2.5 s.

Circuit shutdown Many areas of the circuitry are powered down when not in use. The high voltage supply and piezo drivers, the diode current supplies, the coil driver, and others are without power when the unit is in standby mode, if an interlock is open, or a fault condition is detected.

Current limit Sets a maximum possible diode injection current, for all operating modes. Note that current supplied through the RF connector on the laser headboard is not limited.

Cable continuity If the laser is disconnected, the system will switch to standby and disable all laser and piezo power supplies. If the laser diode, TEC or temperature sensor fail and become open-circuit, they will be disabled accordingly.

Short circuit If the laser diode, TEC or temperature sensor fail and become short-circuit, or if the TEC polarity is reversed, they will be disabled accordingly.

Temperature If the detected temperature is below −5°C or above 35°C, the temperature controller is disabled.

Internal supplies If any of the internal DC power supplies (+5, ±10, ±12 V) is 1 V or more below its nominal value, the respective components (temperature controller, diode current supply) are disabled.

Protection relay When the power is off, or if the laser is off, the laser diode is shorted via a normally-closed solid-state relay at the laser head board.

Laser LED Bright white LED illuminates when laser is switched on.

Mains filter Protection against mains transients.

Key-operated The laser cannot be powered unless the key-operated STANDBY switch is in the RUN position, to enable protection against unauthorised or accidental use.

Interlocks Both the main unit and the laser head board have interlocks, to allow disabling of the laser via a remote switch, or a switch on the laser cover.

RoHS Certification of Conformance

MOG Laboratories Pty Ltd certifies that the MOGlabs Diode Laser Controller (Revision 3) is RoHS-5 compliant. MOG Laboratories notes, however, that the product does not fall under the scope defined in *RoHS Directive 2002/95/EC*, and is not subject to compliance, in accordance with *DIRECTIVE 2002/95/EC Out of Scope; Electronics related; Intended application is for Monitoring and Control or Medical Instrumentation*.

MOG Laboratories Pty Ltd makes no claims or inferences of the compliance status of its products if used other than for their intended purpose.

Contents

1. Introduction

The MOGlabs DLC can be used in various configurations, including simple current/temperature controller, passive frequency controller with internal or external sweep/scan, and as a complete system for active frequency stabilisation with AC, DC or external locking signal. Here is a quick outline of some modes of operation, so that you can connect and go as quickly as possible. Details are provided in chapter 3.

1.1 Simplest configuration

In the simplest application, the DLC will control the diode current and temperature. Thus the DLC must be connected to the diode, a thermoelectric Peltier cooler (TEC), and a temperature sensor.

Figure 1.1: The MOGlabs DLC is readily connected to a laser diode, temperature sensor and thermo-electric cooler via the provided laser head board.

All connections between the MOGlabs DLC and the laser head are via a single cable. An interface breakout board, located as close as possible to the laser itself, includes protection relay and passive protection filters, a laser-on indicator, and MOLEX connectors for the diode, TEC and sensor (10 k NTC thermistor, AD590, or AD592). See appendix F for details.

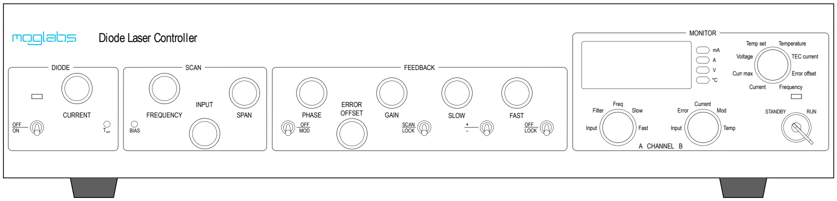


Figure 1.2: MOGlabs DLC front panel layout.

The front-panel display selector switch can be used to monitor the diode current, current limit, diode dropout voltage, temperature and temperature setpoint, and TEC current; see figure 1.2.

1.2 Passive frequency control

The MOGlabs DLC can control the laser frequency via the diode current, or with high voltage (120 V) outputs for piezo electric actuators, to control the cavity length of an ECDL. The actuators should be connected to the laser head board via the provided MOLEX connectors.

One or two piezo elements can be controlled. Typically, only a single "stack" actuator, such as the Tokin AE0203D04 (available from Thorlabs, `www.thorlabs.com`), will be required. The single stack actuator allows frequency scanning and frequency offset selection, and active slow feedback (up to $\approx$ 100 Hz). A second piezo actuator, typically a disc, can be added for faster active feedback control (see below).

In normal (SCAN) mode, a sawtooth is supplied to the stack (or diode current bias), at frequency of 3 to 8 Hz; for example as in figure 1.3. At the midpoint of the sweep, a trigger (low to high) pulse is output via the rear panel TRIG connection, for synchronising to an oscilloscope or external experiment.

Critical DLC signals can be monitored using the CHANNEL A and CHANNEL B outputs on the rear panel, synchronised to the TRIG trigger output, which should be connected to the equivalent inputs

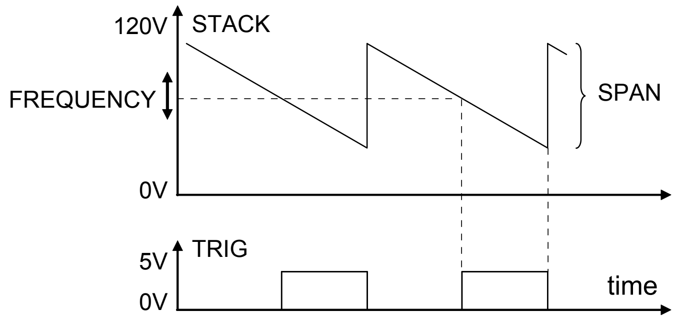


Figure 1.3: Stack (or current bias) output and trigger pulse, when scanning. Note that the ramp slope can be inverted. Details of the ramp behaviour are described in section A.2.

on a two-channel oscilloscope. The particular signals are selected from the front-panel CHAN A and CHAN B selector switches. The signals are described in detail in the following chapter.

1.3 DC locking to an atomic transition

Figure 1.4 shows one possible configuration in which a MOGlabs DLC is used to lock an ECDL to an atomic transition. Locking is to the side of an absorption peak in a vapour cell; see for example Demtröder [3] for more information on spectroscopy. The passive configuration of §1.2 is extended with the MOGlabs DLC photodetector (see appendix E), and an atomic vapour absorption cell. Alternately, a Fabry-Perot optical cavity or other reference could be used.

The schematic shows a saturated absorption spectroscopy arrangement, but often simply locking to the side of a Doppler-broadened absorption peak will be adequate. The photodetector can be used in single channel mode (default) or with balanced differential inputs, for example to subtract a Doppler background from a saturated absorption spectrum.

The lock frequency is determined by the zero-crossing point of the

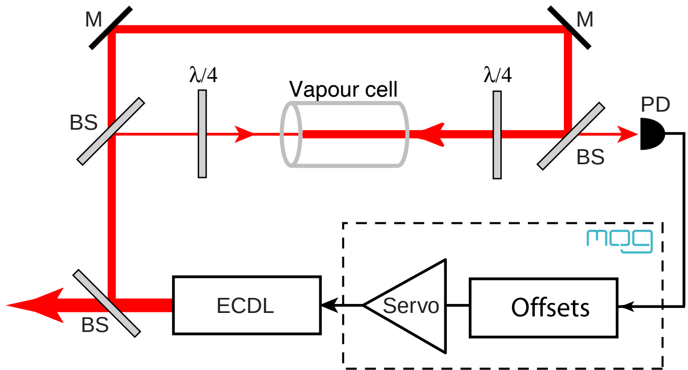


Figure 1.4: Schematic setup for DC locking to an atomic transition. PD is the DLC photodetector. BS beamsplitter, M mirror, $\lambda/4$ a quarter-wave retarder.

photosignal. The photosignal offset is adjusted via the INPUT OFFSET and LOCK OFFSET controls. Feedback can be via one or both piezo actuators, or the diode injection current, or all three.

1.4 AC locking to an atomic transition

With AC locking (FM demodulation or "lock-in amplifier" detection), the laser frequency can be locked to a peak centre. The AC approach offers the advantage of inherently lower detected noise and thus the potential for improved laser frequency stability. The setup is similar to that for DC locking, but modulation of the laser frequency, or the reference frequency, is required. The MOGlabs DLC provides an internal 250 kHz oscillator which can directly dither the diode current, or drive an external modulator. In particular, it is designed to drive a Zeeman-shift modulation coil surrounding the atomic reference vapour cell; see appendix C.

Figure 1.5 shows a simplified AC locking setup, using a coil to Zeeman-modulate the atomic reference, or an acousto-optic modulator (AOM) for modulating the frequency of the beam through the

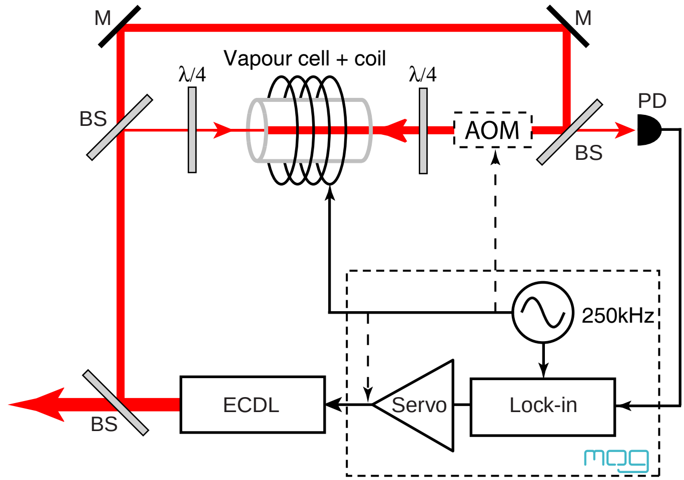
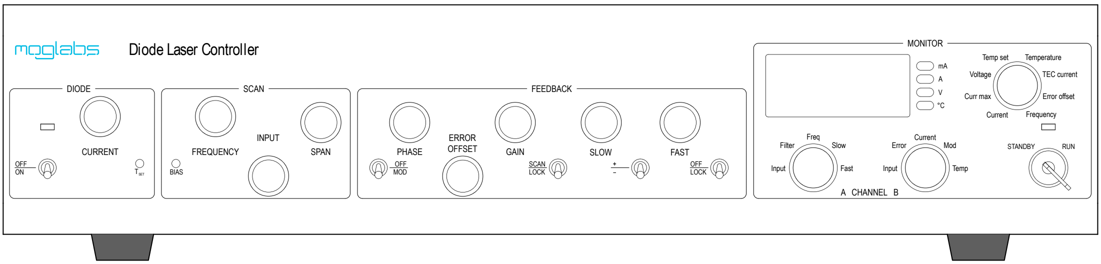


Figure 1.5: Schematic setup for AC locking to an atomic transition. PD is the DLC photodetector. BS beamsplitter, M mirror, $\lambda/4$ a quarter-wave retarder.

vapour cell. If preferred, the modulator oscillator can be set to dither the diode current (see §2.4). Feedback can again be via one or both piezo actuators, the diode current, or all three.

2. Connections and controls

2.1 Front panel controls



STANDBY/RUN In STANDBY mode, the DLC maintains the laser temperature, but powers down all other components including the high-voltage piezo power, and the main on-board low-voltage power.

In RUN mode, the DLC activates all circuits, including the laser current driver and piezo drivers. The diode current is disabled, and the STACK is on but not scanning, until the laser enable switch is ON.

On first power-up, the STANDBY indicator will be red; this is normal and indicates there has been a power failure since last switched to RUN. The unit should then be set to RUN to initiate temperature control, and back to STANDBY if further operation is not desired.

If the unit fails to switch to RUN mode (indicator does not show green), see appendix B.

OFF/ON Diode injection current enable. Also activates the STACK ramp and current bias (if DIP switch 4 in ON). The STANDBY/RUN key switch must first be on RUN and the associated indicator must be green.

If the unit fails to switch to RUN mode (indicator does not show green), see appendix B.

CURRENT	Diode injection current, 0 to 200 mA (DLC-202) or 500 mA (DLC-502). The response is not linear; that is, the change in current varies for a given rotation of the knob. The mid-range sensitivity is reduced to allow greater precision at normal operating currents.
FREQUENCY	The laser frequency will normally be controlled via a multilayer piezo-electric actuator (STACK). This knob controls the offset voltage applied to that actuator, 0 to 120 V. If BIAS is enabled (DIP switch **4**), the diode current will also be affected by the FREQUENCY setting. For DFB/DBR diodes, the lock feedback signal to the piezo actuator can instead control the diode current; see §2.4, DIP switch **16**.
SPAN	Frequency scan range, from 0 to 120 V. The span may be limited by the minimum and maximum voltage that can be applied to the actuator, 0 and 120 V; see detailed description in section A.2.
PHASE	When AC locking, the controller demodulates the error signal from the detected light intensity. PHASE adjusts the relative phase between the internal reference modulator and the detected signal, from 0 to 360°. When DC locking, the sign of the error signal can be flipped by rotating the PHASE control.
GAIN	Overall error signal gain, 0 to 40 dB.
SLOW	Gain for feedback to the slow (piezo) actuator, 0 to 40 dB.
FAST	Gain for fast feedback to the diode current, 0 to 40 dB.
T_{set}	Temperature set point, 0–30° standard; extended range optional.
BIAS	Feed-forward bias current. If DIP switch **4** is ON, changes in laser frequency, usually via the STACK actuator, will simultaneously change the current. This trimpot controls the slope dI/df of current with frequency. It can be positive or negative, with a range of ±10 mA for the full frequency span.
INPUT OFFSET	Offset of input light intensity signal, 0 to −10 V. This can be adjusted to bring the photodetector light signal close to zero on the oscilloscope, and to shift the zero frequency lockpoint for DC locking.

OFF/MOD Modulator enable, to switch on the coil driver, diode current dither, or external modulator.

LOCK OFFSET Offset of the frequency error lock signal. The DLC will lock such that the error signal plus LOCK OFFSET is zero, allowing for small adjustment of the lock frequency.

SCAN/LOCK Switch between scanning mode and lock mode. When switching from scan to lock, the controller will first reset the scanning actuator (usually STACK) to the offset voltage at the trigger point, and then lock to the nearest frequency at which the error signal is zero.

+/− Sign of fast (current) feedback. The sign of the slow feedback can be changed with the PHASE control, for both AC and DC locking.

OFF/LOCK Enable fast (current) feedback. The laser can be locked with slow (piezo) locking or fast (current) locking alone. Best performance is usually obtained with both channels of feedback; see chapter 4 for feedback optimisation.

2.2 Front panel display/monitor

Display selector

The MOGlabs DLC includes a high-precision 4.5 digit LED display with four unit annunciators and 8-channel selector switch.

Current	Actual diode current (mA)
Curr max	Current limit (mA) (−) sign indicates limit rather than actual current
Voltage	Diode voltage (V)
Temp set	Temperature set point (°C)
Temperature	Actual temperature (°C)
TEC current	Current to thermoelectric (Peltier) cooler (A)
Error offset	Error offset voltage (V)
Frequency	Frequency actuator offset, usually slow piezo (normalised to a range of ±1)

CHAN A

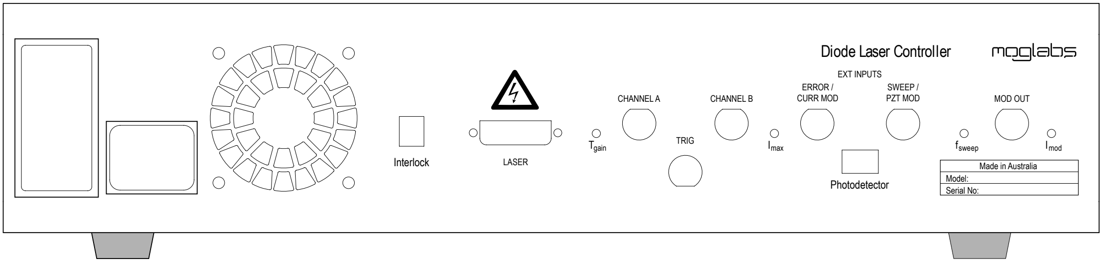
Several important signals can also be monitored externally with an oscilloscope via the rear connectors CHANNEL A, CHANNEL B and TRIG. The outputs to these can be selected with the CHAN A and CHAN B selectors.

INPUT	Photodetector [30 mV/μW]
FILTER	Filtered photodetector, 40 kHz low pass
FREQ	Frequency-scanning actuator (STACK) [1 V/48 V]
SLOW	Slow feedback (DISC) [1 V/1.92 V]
FAST	Current feedback [1 V/100 μA]

CHAN B

INPUT	Photodetector [30 mV/μW]
ERROR	Feedback error
CURRENT	Diode current (to monitor bias) [10 V/A]
MOD	Modulator output current [1 V/A]
TEMP	Temperature [10 mV/°C]

2.3 Rear panel controls and connections



IEC power in/out The unit should be preset for the appropriate voltage for your country. Please contact MOGlabs for instructions if you need to change the power supply voltage.

The output IEC connector is a direct connection to the input power, after the input mains filter. This outlet should be used only to power a monitoring oscilloscope. It is provided to minimise ground-loop noise problems.

Fan The fan speed is temperature-controlled.

Interlock The DLC will not power on the laser unless the pins on this connector are shorted. A standard 2.1 mm DC plug is provided.

LASER Connection to laser head. This connector provides diode current, two piezo drives, temperature sense, and TEC current. A DVI-D Dual cable is provided.

WARNING: The piezo drive signals can be lethal. The high-voltage outputs, diode current and TEC current will be disabled if the cable is disconnected, or if the main or head interlocks are open-circuit, but these protection features should not be assumed.

T_{gain} Temperature control feedback gain. Increase this if the response time is too great or if the temperature error is large. Reduce this if the temperature oscillates.

CHANNEL A, B Monitor outputs; connect to oscilloscope, channels 1 and 2.

TRIG Oscilloscope trigger, TTL-level. Connect to external trigger input on oscilloscope. Set oscilloscope triggering for external, rising edge.

I_{max} Diode current limit. The current limit can be set approximately with the display selector set to ***Curr max***. For more precise adjustment, the laser current should be set above the desired maximum (using a dummy load, e.g. ordinary diode) and then the current limit can be adjusted while reading the actual current.

ERROR/CURR MOD Input for externally derived feedback error signal (DIP switch **5**) or for current modulation (DIP switch **6**). Applies in lock mode.

Signal normally $< \pm 1$ V; max ± 8 V. Impedance 5 kΩ. Gain for error modulation: 1 V per volt; for diode current: 100 μA per volt. Polarity change via PHASE adjust.

SWEEP/PZT MOD Input for externally generated frequency control (STACK, DIP switch **13**) or for piezo DISC modulation (DIP switch **14**).

Signal normally $< \pm 1$ V; max ± 2.5 V. Impedance 5 kΩ. Gain 48 V per volt (120 V max).

Photodetector Connection to photodetector unit. A standard 6-pin FireWire (IEEE-1394) cable is provided.

f_{sweep} Scan rate, 3 – 8 Hz.

MOD OUT Connection to external modulator, output is 0 to ± 500 mA, ± 8 V. Current sensing; that is, if a voltage is required, connect across an external resistor. See appendices C, D.

I_{mod} Modulation depth.

2.4 Internal switches and adjustments

See appendix H for the location of relevant internal components.

DIP switches

	OFF	ON
1	See below	
2	See below	
3	Current dither OFF	Current dither ON
4	Current bias OFF	Current bias ON
5	Internal error	External error
6	External current mod OFF	External current mod ON
7	AC lock	DC lock
8	Single photodiode	Dual photodiode
9	Internal sweep	External sweep
10	STACK feedback +	STACK feedback –
11	STACK sweep +	STACK sweep –
12	AC current feedback	DC current feedback
13	STACK internal	STACK external
14	DISC internal	DISC external
15	Factory test only	
16	Current mod by SLOW control signal (for DBR/DFB)	

Switches **1**, **2** can be set for several different configurations of feedback to two different piezo actuators. It is assumed that STACK is a wide-range but slow device, such as an NEC-Tokin AE0203D04 stack, while DISC is faster but with smaller range, such as a piezo disc [1,2].

Switch 1	Switch 2	Operation
OFF	OFF	STACK fast, DISC fixed
OFF	ON	No feedback; both STACK, DISC are fixed
ON	OFF	STACK fixed, DISC fast
ON	ON	STACK slow, DISC fast (preferred)

Feedback to the slow actuator STACK can be very slow, to compensate for slow temperature-related drifts, with fast primary feedback to a faster piezo disc (1, 2 = ON, ON). Alternately, feedback to STACK can be fast, to provide primary locking feedback (1, 2 = OFF, OFF). Usually the latter is adequate, and feedback to a second fast piezo is not required.

The sign of the response of the two piezo actuators can be reversed with switches **10, 11**. For example, increasing the potential on STACK may increase or decrease the cavity length, while DISC may act in the same or the opposite sense. It is important for locking that both operate in the same sense. Also, it may be useful to reverse the scan for some applications. To achieve the same effect as changing the sign of DISC, the sign of the error signal should be reversed, and the STACK and current feedback also reversed.

Switches **13, 14** allow measurement of the actuator response functions. With the appropriate switch ON, the EXT SWEEP piezo signal is added to the internally generated STACK and/or DISC signals. To measure an actuator response, connect an external variable-frequency oscillator to the EXT SWEEP input, and sweep through the frequency range of interest. Measure the laser frequency modulation amplitude, preferably with a lockin amplifier. The frequency modulation amplitude can be measured by passing the laser beam through a Fabry-Perot adjusted such that the laser is on the side of a fringe, or on the side of a saturated absorption transmission peak in a vapour cell (e.g. fig. 1.4).

Switch **15** is used internally by MOGlabs for trimming the modulator (dither) frequency to match the internal notch filters. It should not be necessary to make such adjustments outside the factory.

Switches **12, 16** allow operation of DFB/DBR lasers without external cavity feedback and thus with only current as an actuator. Scanning and locking can be achieved by modulating the current with what is normally the scanning piezo drive signal. Both **16** and **4** can be active simultaneously. Switch **12** allows DC coupling of the current feedback, rather than the default AC coupling, to allow current-only feedback locking.

Interlock Link LK1 (rear right of main board) can be shorted internally to avoid the requirement for an external interlock, if permitted by local safety regulations.

Internal trimpots

RT6	Current dither amplitude
RT12	Phase lead
RT13	Ambient temp for active sensors (AD590, AD592)
RT15	TEC current limit

RT6 For AC locking, either the laser frequency or the external reference must be modulated at the DLC dither frequency, 250 kHz. An external modulator (see appendix D) is normally used, but instead the laser injection current can be modulated directly. The modulation depth is then controlled by **RT6**.

RT12 A phase-lead circuit is included on the current feedback channel, to boost the output at higher frequencies (tens of kHz). **RT12** controls the phase lead and can be adjusted for different diodes; see appendix 4.

RT13 Offset adjustment for active temperature sensors (AD590, AD592), so that temperature reads in °C.

RT15 Current limit for TEC output. To set, change the set temperature suddenly, and adjust **RT15** while reading the TEC current.

3. Operation

3.1 Simplest configuration

In the simplest application, the MOGlabs DLC will be used to control the diode injection current, and temperature. Thus the DLC must be connected to the diode, a thermoelectric Peltier cooler (TEC), and a temperature sensor (fig. 1.1).

All connections are via a single cable. A laser head interface board includes protection relay and passive protection filters, a laser-on LED indicator, and MOLEX connectors for the diode, TEC and sensor (either 10 kΩ thermistor, AD590 or AD592). The laser head board can be fitted to the supplied laser head panel. See appendix F for further information.

To operate in passive configuration:

1. Connect the diode, TEC and sensor to the laser head board (fig. 1.1) using the provided MOLEX 2- and 3-pin connectors. Please note the polarities.
2. Adjust the temperature setpoint: first select **Temp set** on the display selector, then adjust T_{set} via the front-panel trimpot.
3. Ensure the power is on, and the STANDBY/RUN switch is on STANDBY. In this mode, most circuits will be switched off, including much of the main internal board, low and high voltage DC supplies, photodetector, piezo and diode outputs. On first power-up, the STANDBY indicator will be red; this is normal. The switch should be set to RUN to initiate temperature control.
4. Switch from STANDBY to RUN. The indicator should change from red (if just powered up), or orange, to green. If the indicator is not green, the TEC or sensor is not correctly wired. In RUN mode, all electronics will be powered up, except for the

diode injection current supply and piezo drivers.

5. If the controller is switched back to STANDBY, all electronics will be powered down, *except for the temperature controller*, which will continue to operate normally.
6. It may be helpful to adjust the temperature controller response time; that is, the integrator gain, via the rear-panel trimpot labelled T_{gain}, while monitoring the temperature error via CHANNEL A output and the front panel CHAN A selector switch set to **Temp**.
7. Adjust the current control knob to minimum (fully anti-clockwise).
8. Set the diode maximum current: select **Curr max** on the display selector, then adjust the maximum allowed diode injection current via the rear panel I_{gain} trimpot. Note that with the display set to **Curr max**, a negative sign (−) provides a visual reminder that the limit is being displayed rather than the actual current.
9. Switch the laser on. The indicator on the laser head board should illuminate, and the front-panel indicator above the switch should turn green.

Note that the SCAN/LOCK and fast-channel OFF/LOCK switches must be set to SCAN and OFF respectively. Other protection features will prevent current to the diode, including main cable disconnect, and open circuit on the rear-panel or laser head interlocks.

3.2 Laser frequency control

High voltage (120 V) outputs are provided for piezoelectric actuators to control the frequency of an ECDL. These should be connected to the laser head board via the provided MOLEX connectors.

One or two piezo elements can be controlled. Typically, only a single "stack" actuator, such as the Tokin AE0203D04 (available from Thorlabs, www.thorlabs.com), will be required. The single stack actuator allows frequency scanning and frequency offset selection, and active slow (up to $\approx$ 100 Hz) feedback. A second actuator, typically a disc, can be added for faster active feedback control.

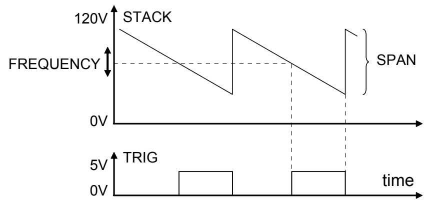


Figure 3.1: Stack output voltage and trigger signal, when scanning.

In normal (SCAN) mode, a sawtooth ramp is supplied to the the stack, at frequency of 3 to 8 Hz; see fig. 3.1. At the nominal midpoint of the sweep, a trigger (low to high) signal is output via the rear panel TRIG connection, for synchronising to an oscilloscope or external experiment. The trigger is not precisely at the midpoint of the apparent frequency sweep, because the piezo stack has limited range and thus the sweep can saturate (see section A.2 for details). Several adjustments of the frequency sweep are possible:

SCAN/LOCK	The SCAN/LOCK switch should be on SCAN.
FREQUENCY	Sets the mid-point voltage of the ramp.
SPAN	Sets the height of the ramp (limited at 0 and 120 V); see fig. 3.1.
BIAS	The BIAS front-panel trimpot controls a feed-forward bias injection current which follows the ramp, to enable wider mode-hop-free scans. The bias can be adjusted in a trial-and-error manner to achieve the widest possible scans. BIAS is disabled unless internal DIP switch **4** is ON.
f_{sweep}	The rear-panel f_{sweep} trimpot adjusts the ramp rate from 3 to 8 Hz.

Critical signals can be monitored using the CHANNEL A, B outputs on the rear panel, synchronised to the TRIG trigger output. These signals should be connected to the equivalent inputs on a two-channel oscilloscope. The particular signals are selected from the front-panel CHAN A and CHAN B selector switches.

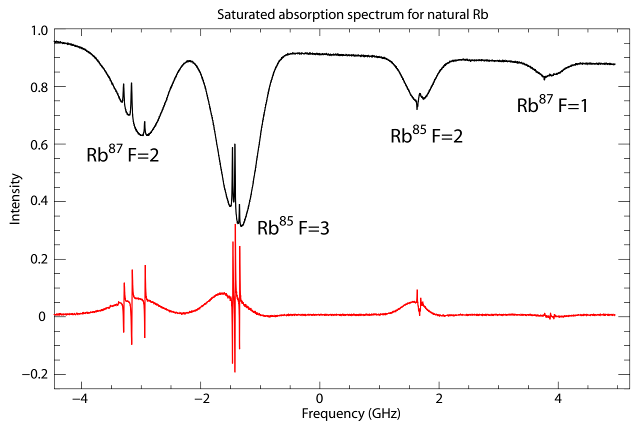


Figure 3.2: A saturated absorption spectrum of rubidium using a standard uncoated laser diode and low diffraction efficiency grating in Littrow configuration (upper trace). The entire 780 nm rubidium hyperfine structure can be scanned, for both naturally occurring isotopes (nearly 10 GHz), by ramping both the external cavity length and simultaneously the injection current, with appropriate adjustment of the feed-forward BIAS. The figure also shows (lower trace) the AC-modulation error signal (see §3.5).

3.3 External scan control

An external source can be used to control the laser frequency while in SCAN mode.

1. Connect the external frequency control (ramp, or DC) signal to the rear-panel SWEEP external input.
2. Select external signal by setting DIP switch **9** to ON.
3. Set SCAN/LOCK to SCAN. The FREQUENCY and SCAN knobs will be inactive.

3.4 Locking to an atomic transition: DC

Figure 3.3 shows how an ECDL can be locked to an atomic transition as determined from absorption in a vapour cell. The basic configuration described in §3.2 is extended with the DLC photodetector, and an atomic vapour absorption cell. A Fabry-Perot optical cavity or other frequency reference could also be used.

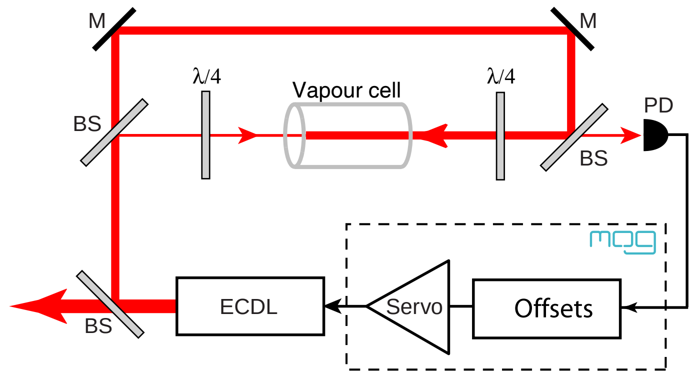


Figure 3.3: Schematic setup for DC locking to an atomic transition. PD is the DLC photodetector. BS beamsplitter, M mirror, $\lambda/4$ retarder.

The photodetector can be used in single channel mode (default) or with balanced differential inputs, for example to subtract a Doppler background from a saturated absorption spectrum.

Sample oscilloscope traces obtained in DC locking (“side of fringe”) mode are shown below, for wide and narrow spans. These traces were obtained with an 8 cm long Rb vapour cell at room temperature.

To operate in DC locking configuration:

1. Select DC locking by setting internal DIP switch **7** to ON.
2. If using differential inputs, set internal DIP switch **8** to ON.
3. Connect the diode, TEC and temperature sensor as above. Also connect a two-channel oscilloscope to the CHANNEL A, B and TRIG outputs.

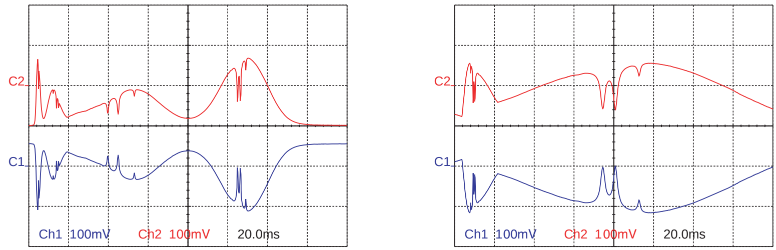


Figure 3.4: Examples of spectra for DC locking, for wide and narrow spans (lower traces) and error signals (upper traces).

4. Connect the DLC photodetector module.
5. Using an optical beamsplitter, a stray reflection, or by other means, deflect a fraction of the laser output through the vapour cell. The MOGlabs DLC is designed to operate best with about 250 μW incident on each of the Si-PIN photodiodes. Lensed and filtered photodiodes are standard, to minimise the influence of background light, but best results will be obtained if light from incandescent or fluorescent lamps is eliminated.
6. If using balanced inputs, the second light beam should illuminate the second photodiode.
7. Find an appropriate spectral feature.
8. Adjust front-panel INPUT OFFSET and LOCK OFFSET to obtain a zero-crossing ERROR signal at the desired frequency. The slope should normally be positive (depending on DIP switches **10, 11**); it can be inverted by coarsely adjusting the PHASE control.
9. Set SLOW and FAST gains to minimum (fully anti-clockwise).
10. Switch SCAN/LOCK to LOCK.
11. Switch OFF/LOCK to LOCK.
12. Increase SLOW and FAST gains to minimise the error signal, ideally using an external audio spectrum analyser. The gains should be increased until the onset of oscillation, and then

reduced. See chapter 4 for additional discussion of feedback optimisation.

Note that it is not necessary to "zoom in" on the desired lock point. The controller will automatically lock to the zero-crossing closest to the trigger point, i.e. to the centre of the oscilloscope trace.

When the laser is locked (step 10 above), the photodetector (INPUT) signal should be fixed at the value corresponding to the lock frequency – in this case zero since for DC locking, the controller locks to the zero-crossing.

3.5 Locking to an atomic transition: AC

Figure 3.5 shows a typical setup for AC ("top of fringe") locking. The laser frequency can be directly modulated via the diode current (see §2.4, DIP switch **3**), or using an external modulator. The controller includes a modulator driver with sufficient power to drive a coil directly for Zeeman modulation, or an external modulator such as an acousto-optic modulator can be used; see appendix C.

Sample oscilloscope traces obtained in AC locking mode are shown below, for wide and narrow spans. These traces were obtained with an 8 cm long Rb vapour cell at room temperature, using a Zeeman modulation coil as described in appendix C.

To operate in AC locking configuration:

1. Select AC locking by setting internal DIP switch **7** to OFF.
2. Connect the diode, TEC and temperature sensor as above. Also connect a two-channel oscilloscope to the CHANNEL A, B and TRIG outputs.
3. Connect the photodetector module and optimise the photosignal on CHANNEL A. The MOGlabs DLC is designed to operate best with about 250 μW incident on the Si-PIN photodiode. Lensed and filtered photodiodes are standard, to remove most background light, and when AC locking at 250 kHz modula-

tion frequency, any remaining photocurrent from background lighting should not be a problem.

4. Adjust the INPUT OFFSET such that saturated absorption trace is near zero.
5. Switch the modulation on with OFF/MOD.
6. Find an appropriate spectral peak and observe the dispersive error signal with CHAN B set to ERROR.
7. Optimise the error signal (usually for maximum slope) by adjusting the front panel PHASE. The error signal slope should normally be positive (depending on DIP switches **10, 11**) at the desired frequency.
8. Adjust the GAIN such that the error peaks are roughly 250 mV peak-to-peak.
9. Adjust front-panel LOCK OFFSET such that the error signal is crossing zero at the desired frequency.
10. Set SLOW and FAST gains to minimum (fully anti-clockwise).

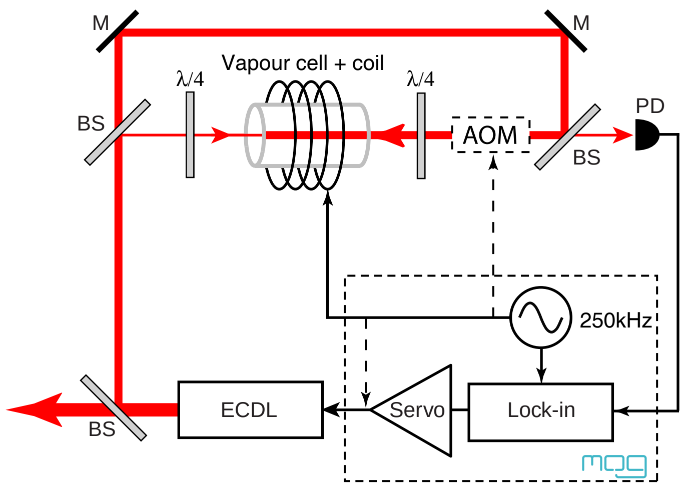


Figure 3.5: Schematic setup for AC locking to an atomic transition. PD is the DLC photodetector. BS beamsplitter, M mirror, $\lambda/4$ retarder.

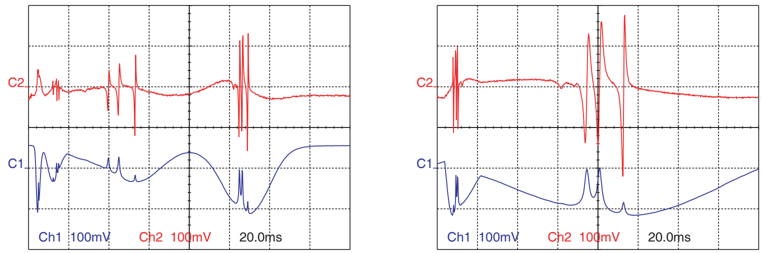


Figure 3.6: Examples of spectra for AC locking, for wide and narrow spans (lower traces), with error signals (upper traces).

11. Switch SCAN/LOCK to LOCK.
12. Switch OFF/LOCK to LOCK.
13. Increase SLOW and FAST gains to minimise the error signal, ideally using an external audio spectrum analyser (see chapter 4). The gains should be increased until the onset of oscillation, and then reduced. See chapter 4 for additional discussion of optimisation.

Note again that it is not necessary to "zoom in" on the desired lock point. The controller will automatically lock to the zero-crossing of the error signal (in this case the peak of a spectral feature) closest to the trigger point, at the centre of the oscilloscope trace.

When the laser is locked (step 11 above), the photodetector (INPUT) signal should be fixed at the value corresponding to the lock frequency. In contrast to the DC locking case, this should be the INPUT signal at the peak of the spectral feature, *not* zero.

3.6 Locking using an external signal

The MOGlabs DLC can be used for Pound-Drever-Hall [5] or offset locking [6,7], or indeed using a wide variety of externally generated dispersive signals. See appendix D for examples.

To operate with externally generated locking signal:

1. Connect the external error signal to the rear-panel ERROR external input.
2. Select the external locking signal by setting internal DIP switch **5** to ON.
3. Follow the procedure above for DC locking.

Note that actually the external error signal is *added* to the internal error signal, so it may be advisable to switch off the internal modulator.

3.7 External control of lock frequency setpoint

It is often useful to have external control of the lock frequency setpoint, for example to suddenly change the detuning of a laser.

The rear-panel ERROR external input is *added* to the internally generated error signal. Thus the controller can be used to lock a laser, even with external error enabled via setting DIP switch **5** to ON.

4. Optimisation

Laser frequency stabilisation is a complex and ongoing research topic. A thorough treatment would require extensive discussion of control theory, actuator response, mechanical design, laser-atom interactions and electronics. Here we consider the problem from a pragmatic perspective.

The laser is assumed to be moderately stable, operating close to the desired frequency, with a linewidth of a few MHz averaged over a typical measurement time of about one second. The very short-term linewidth is determined by the Schawlow-Townes (S-T) limit, which is typically about 500 kHz. The MOGlabs DLC will stabilise the laser frequency to an external reference, usually an atomic absorption feature, and reduce the effective linewidth as close as possible to the S-T limit.

Achieving the best frequency locking stability requires careful optimisation of the signal-to-noise ratio (SNR) of the frequency discrimination signal obtained from the saturated absorption or other reference. Then the phase and gain settings must be optimised, preferably by measuring the feedback error signal spectrum.

4.1 Frequency reference

The frequency reference is critical to the MOGlabs DLC performance: the controller cannot reduce the laser frequency noise without an appropriate frequency-dependent reference signal.

The DLC has been designed to work with a saturated absorption reference, as shown in figures 3.5 and 3.6. Users should familiarise themselves with saturated absorption spectroscopy, for example as described in Demtröder [3].

The frequency discriminator ("ERROR") SNR should be optimised to produce large, clear (low-noise) dispersive error signals as shown in the upper trace of fig. 3.6. Factors to consider include:

Probe power The probe power should be about 250 μW. Higher power will increase the photosignal, but the detector saturates at about 500 μW.

Probe intensity The probe intensity should be low to reduce power-broadening. Thus, the probe beam should be expanded to 5 or 10 mm diameter, to allow high power and low intensity.

Polarisation The frequency discriminator (ERROR) signal is sensitive to the pump and probe polarisations. Good polarisers and careful alignment can be very helpful.

Coil design See appendix C.

Shielding The Zeeman coil produces substantial magnetic fields, oscillating at 250 kHz. These fields can readily induce problematic potentials and currents in the laser head and/or main circuit board. In particular, it is quite possible to produce a larger frequency modulation from induced currents in the laser diode than from the Zeeman modulation of the reference. It is vital that the coil be located far from the main unit and from the laser, or that it be shielded. A layer of high-permeability material (soft iron or mu-metal) is probably adequate. To test this, simply reverse the polarity of the coil connection. If the error signal is also reversed, but otherwise similar, then the shielding is probably adequate.

4.2 Noise spectra

The master, slow and fast gains can be set as described in chapter 3, increasing them until the onset of oscillation, and then reducing slightly. If possible, an audio frequency spectrum analyser can be used to provide better guidance. A generic computer sound card with spectrum analysis software gives reasonable results up to 20 kHz. A

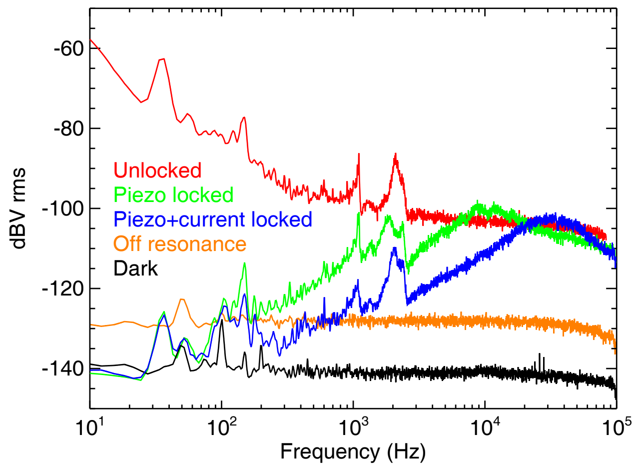


Figure 4.1: Error signal spectra, with laser unlocked, locked with SLOW (piezo) feedback only, and with SLOW and FAST (piezo+current) feedback. The off-resonance and dark noise spectra provide information on the effective noise floor.

good sound card (24-bit 200 kHz, e.g. Lynx L22 or E-Mu 1212m) provides noise analysis up to 100 kHz with 140 dB dynamic range, surpassing most standalone audio spectrum analysers, at very low cost. Connect the spectrum analyser to the CHANNEL B output, and set the CHAN B selector to ERROR.

You should see curves similar to those shown in fig. 4.1. The noise spectrum with laser unlocked was obtained in scan mode, but with zero span, and the frequency carefully set to an atomic resonance (the highest saturated absorption dip in fig. 3.6). Similarly for the *Off resonance* curve, but with the laser tuned far away from all resonances, outside a Doppler absorption peak. The *Off resonance* spectrum gives the frequency discriminator noise floor: it is meaningless to try to reduce the laser frequency noise below this level.

With SLOW feedback enabled, the noise for low Fourier frequencies is drastically reduced. A double-integrator is used for slow feedback, such that the suppression is 40 dB/decade. The SLOW gain adjusts the 0 dB gain point; in the figure, this reaches approximately 5 kHz. Higher gains result in oscillation at a frequency corresponding to a pole in the piezo actuator response (i.e. a mechanical resonance).

If configured to work with the stack actuator only (see §2.4), then the SLOW feedback will suppress noise only to a few tens of Hz.

FAST feedback adds an additional 20 dB/decade suppression, with 0 dB gain beyond 20 kHz, even as high as 40 kHz, depending on the diode, optical feedback, the frequency discriminator noise floor and other details. Typically we find that the laser diode itself has a 90° phase lag at 15 to 100 kHz. Some compensation for that phase lag is provided by a phase lead compensator (see RT12, page 16).

Ideally, the SLOW and FAST gains should be adjusted to minimise the integrated noise (the area under the error spectrum). The data in fig. 4.1 show a small “Bode bump” at around 30 kHz, indicating excessive current gain, leaving the laser marginally stable. For lower FAST gain, the Bode bump will be reduced, at the expense of reduced suppression of the mechanical resonance noise peaks around 2 kHz.

The frequency discriminator SNR – that is, the difference between the *Unlocked* and the *Off resonance* spectra (in the data shown above, about 20 dB for high frequencies) – is critical. Improvements to the reference, for example using a Fabry-Perot etalon rather than saturated absorption spectroscopy, can provide much greater SNR and correspondingly greater laser frequency noise suppression. See §D.2, page 46, for one approach.

A. Specifications

Parameter	Specification
Current regulator	
Output current	0 to 200 mA (DLC-202) or 500 mA (DLC-502)
Max diode voltage	5 V
Display resolution	±0.01 mA
Noise	< 10 nA rms (10 Hz – 1 MHz)
Stability	Warmup time: 15 minutes
External modulation	SMA 50 Ω, 16 MHz – 2.5 GHz See spectrum below
BIAS	±10 mA over full sweep
Temperature controller	
TEC current max	±2 A
TEC voltage max	±6 V
TEC power max	12 W
Stability	±5 mK/°C
Sensor	NTC 10 kΩ, AD590, AD592; autodetected
Range	0–30° standard; extended range optional
Display resolution	±0.01°

Parameter	Specification
Piezos	
STACK	0 to 120 V for FREQUENCY
DISC	100 ± 16.4 V feedback
Scan rate	3 to 8 Hz
Photodetector	
Photodiodes	Si-PIN, IR filtered 740 nm – 1100 nm, 1×1 mm^2 sensor, ±10° field of view Options: unfiltered 400 nm – 1100 nm, ±20°, ±70° See appendix E for spectral response.
Coupling	AC and DC, single or differential
Diode separation	10 mm
Bandwidth	720 kHz
Dimensions	25 × 25 × 60 mm
Feedback system	
MOD OUT	250 kHz, ±8 V, ±500 mA Current output (1 Ω sense) Control via I_{set} rear-panel trimpot
PHASE	0 to 360° (min)
INPUT OFFSET	0 to −10 V
LOCK OFFSET	±0.5 V
GAIN	MASTER ±20 dB SLOW MASTER ±20 dB FAST MASTER ±20 dB
Bandwidth (gains at midpoint)	SLOW 0 dB at 700 Hz FAST 0 dB at 80 kHz

Parameter	Specification
Protection and status	
External interlock	2.1 mm DC power plug (provided)
Laser head enclosure interlock	2-pin MOLEX connector (provided)
Key switch interlock	STANDBY/RUN
Delayed soft-start	1 s delay + 1.5 s ramp
Open circuit detect	Laser cable, TEC, temperature sensor
Diode current limit	Rear panel trimpot I_{max}
STANDBY/RUN LED	DARK: AC mains off, or fault condition detected (TEC failure, polarity reversed, open-circuit, cable unplugged, missing sensor, temperature out of range) RED: AC mains power on ORANGE: Standby (temperature controller on) GREEN: Fully operational (piezo, current, ramp)
STATUS LED	RED: Start sequence error or fault (Either LOCK switch ON, interlock open, head cable disconnected, temperature controller fault detected) ORANGE: Ready GREEN: Diode running

Parameter	Specification
Mechanical & power	
Display	4.5 digit LED; standard colour red
Fan	12 V DC ball-bearing Temperature controlled
IEC input	110 to 130 V 60Hz or 220 to 260 V 50Hz
IEC output	Common ground with power input Intended for oscilloscope; 1 A max
Dimensions	Standard 2U 19", WxHxD = 422 × 84 × 200 mm
Weight	4.3 kg (excluding cables, laser head board, photodetector). 8 kg shipping

A.1 RF response

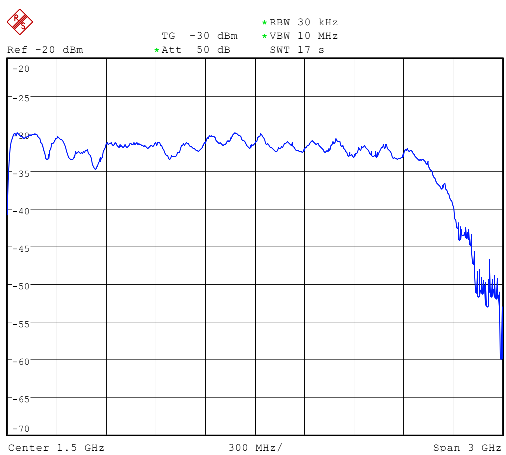


Figure A.1: RF response, SMA input on laser headboard to diode SMA output.

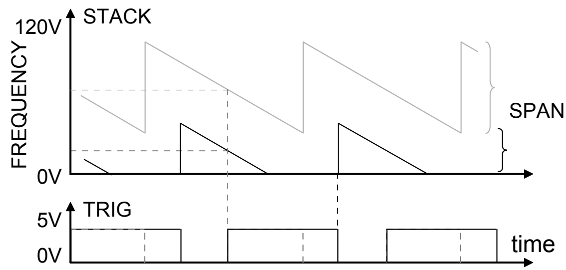


Figure A.2: STACK output voltage and trigger pulse, when FREQUENCY is set close to 0 V and the output voltage exceeds the maximum range.

A.2 Sweep saturation and trigger

In normal scanning mode, a sawtooth is supplied to the stack piezo (or other laser frequency actuator), at a frequency of 3 to 8 Hz; see fig. A.2. At the nominal midpoint of the sweep, a trigger (low to high) signal is output via the rear panel TRIG connection, for synchronising to an oscilloscope or external experiment.

The span may be limited by the minimum and maximum voltage that can be applied to the actuator, 0 and 120 V. That is, the ramp may "saturate", as shown in fig. A.2. The period remains fixed, but the trigger is not precisely at the midpoint of the apparent frequency sweep, because of the saturation.

The exact relationship is complicated. Let f be the voltage representing the internal sweep oscillator (0 to +2.5 V); f_0 the offset determined by the front-panel FREQUENCY knob (−1 to +1 V); and Δf the width of the sweep, set by the front-panel SPAN knob (0 to 1 V). The stack voltage is then

$$V_{\text{stack}} = 48\left[(V_0 - f)\Delta f + V_0\right] \quad \text{where} \quad V_0 = 1.25 - 0.9 f_0$$

and the trigger output is low when $(V_0 - f) < 0$, high otherwise.

B. Troubleshooting

The MOGlabs DLC detects a wide range of fault conditions and deactivates related circuitry accordingly. The front-panel LEDs provide indication of the state of these functions.

B.1 STANDBY/RUN indicator

Colour	Status
DARK	Temperature controller off. Reset via keyswitch, RUN → STANDBY → RUN Possible faults: • AC mains off • TEC open or short-circuit • TEC polarity reversed • Cable disconnected • Temperature sensor disconnected • Temperature out of range ($< -5°C$ or $> 35°C$)
RED	AC mains power failure (temperature controller off)
ORANGE	Standby (temperature controller on)
GREEN	Fully operational (piezo, current, ramp)

B.2 Diode OFF/ON indicator

Colour	Status
RED	Fault Reset via OFF/ON switch ON → OFF → ON Possible faults: • SCAN/LOCK switch not up (SCAN) • OFF/LOCK switch not up (OFF) • Rear interlock disconnected • Laser head interlock disconnected • Laser head cable disconnected • TEC disabled (temperature out of range) • Any one of $+5, \pm 10, \pm 12$ V internal supplies below nominal by more than 1 V
ORANGE	Standby: above conditions satisfied, diode ready to start
GREEN	Diode fully operational, piezos active

C. Modulation coils

The MOGlabs DLC is designed to lock to an atomic transition, particularly using AC locking. The frequency of the laser light can be modulated (e.g. using internal current modulation or an external modulator), or the reference can be modulated. In the latter case, an atomic reference can be modulated at low cost using a solenoid coil wrapped around an atomic vapour cell, as shown below.

Figure C.1: Vapour cell, Zeeman coil, and primary excitation coil.

C.1 Field requirements

Ideally the Zeeman dither coil should produce a frequency shift of about half the peak width, typically a few MHz. Atomic "stretched" state transitions will be Zeeman shifted by

$$\mu_B = \frac{e\hbar}{2m_e} = 1.4\,\text{MHz/Gauss} \tag{C.1.1}$$

so we need fields of around one Gauss (10^{-4} Tesla). The magnetic field inside a long solenoid is

$$B = \mu_0 n i \tag{C.1.2}$$

where n is the number of turns per unit length and i the current. For wire diameter 0.4 mm, $n = 2500\,\mathrm{m}^{-1}$, and the current requirement is only 22 mA/MHz.

C.2 Coil impedance

However, driving an oscillating current through a coil is problematic because the impedance grows with the frequency. The impedance is given by $X_L = \omega L$ where ω is the radial frequency and L the inductance. The inductance for a long solenoid is

$$L = \mu_0 n^2 A l \tag{C.2.1}$$

where A is the cross-section area of the coil (πr^2 for a circular cross-section) and l is the coil length. In practice, the inductance will be less (e.g. see Wheeler [8]):

$$L_{\mathrm{Wheeler}} = \frac{N^2 r^2}{228r + 254l} \qquad \text{(mH)} \tag{C.2.2}$$

where N is the total number of turns, r is the coil radius in metres, and l is the length in metres ($l > 0.8r$). We have found that for dimensions typical of coils wound around vapour cells, these two formulae agree within a factor of two.

Note that the inductance increases with n^2 whereas the magnetic field and hence modulation depth grows with n; thus for our purposes, we generally prefer small n and large currents. On the other hand, the driving voltage requirement (the “back emf”) is given by

$$\epsilon = -L\frac{di}{dt} \qquad \epsilon_{\mathrm{max}} = L i_0 \omega \tag{C.2.3}$$

for a sinusoidal current of amplitude i_0. The required output slew rate is

$$dV/dt = -L\frac{d^2 i}{dt^2} \qquad \mathrm{Max} \equiv L i_0 \omega^2. \tag{C.2.4}$$

The MOGlabs DLC operates at $\omega = 250\,\mathrm{kHz}$. For a cell of length 8 cm, 0.4 mm wire, and 20 mA, we find $L_{\mathrm{Wheeler}} \approx 650\,\mu\mathrm{H}$, and $\epsilon_{\mathrm{m}ax} = 20\,\mathrm{V}$, and the maximum slew rate is $32\,\mathrm{V}/\mu\mathrm{s}$.

The MOGlabs DLC does not have that direct output capability. Reducing n helps: inductance, and thus ϵ and dV/dt fall with n^2 while the frequency modulation depth falls with n. Thus a coil of about 40 turns ($500\,\mathrm{m}^{-1}$) and current amplitude of 150 mA should result in a modulation depth of 1.3 MHz. However, we prefer to use a two-coil impedance matching arrangement to increase the modulation depth at smaller currents.

C.3 Impedance matching

The DLC can drive up to $\pm 0.5\,\mathrm{A}$ and $\pm 8\,\mathrm{V}$, with a slew rate of $6\,\mathrm{V}/\mu\mathrm{s}$. This can be impedance-matched to a high current coil using a transformer, or quite effectively by directly winding a primary on the main Zeeman coil, as shown in the photo above.

For the main Zeeman coil, 0.4 mm or 0.6 mm diameter wire wound around the vapour cell, about 120 to 200 turns, works well. The coil is "balanced" for the standard modulation frequency of $\omega = 250\,\mathrm{kHz}$ using a capacitor. The coil is excited inductively by a primary, about five to ten turns, connected directly to the DLC modulator output (see figure).

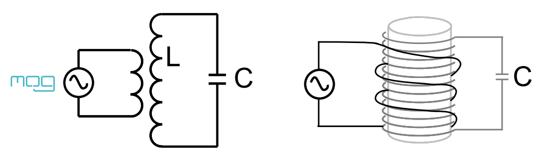


Figure C.2: Circuit diagram for Zeeman coil and excitation coil. Typically the primary is 5 to 10 turns, and the secondary 120 to 200 turns.

The capacitor should be chosen such that the capacitive impedance equals the inductive impedance. That is,

$$\omega L = \frac{1}{\omega C} \qquad\qquad C = \frac{1}{\omega^2 L}. \tag{C.3.1}$$

Using the long-solenoid equation for inductance,

$$C = \frac{1}{\omega^2 \mu_0 n^2 A l} \tag{C.3.2}$$

although in practice we find that the inductance is about half the long-solenoid prediction and hence the capacitance should be doubled, typically about 1 to 2 nF. With this arrangement, energy is stored in the inductor-capacitor "tank", and the DLC need only drive a small current (e.g. 50 mA peak-to-peak) to compensate for losses.

WARNING! The potential across the secondary Zeeman coil can easily be hundreds of volts! Please ensure that your coil and capacitor do not have exposed connections! Also be sure to use capacitors with adequate voltage rating.

C.4 Tuning

To maximise the current in the secondary, the capacitor should be chosen to tune the circuit to the DLC modulation frequency. Drive the coil with a function generator and measure the magnetic field with another independent coil (e.g. 20 turns of fine wire on a 1 cm diameter former) connected to an oscilloscope. Adjust the capacitor by adding or removing small capacitors in parallel, until the detected field is maximum at 250 kHz. Again, be sure to use capacitors with sufficient voltage rating.

In some cases the Q of the circuit may be *too* high, such that a series resistor of about 0.5 ohm (as in photo C.1) can result in increased current at 250 kHz, and reduced sensitivity to frequency drifts.

C.5 Shielding

Large magnetic fields oscillating at 250 kHz can readily cause problematic electromagnetic interference (EMI). Induction in the laser head or the cable to the laser head can easily produce substantial diode current modulation. The coil (and vapour cell) should be located far from the laser and from the controller, or shielded with soft iron or a high permeability alloy such as mu-metal or Conetic. We find that a tube made from thin (0.25 mm) sheet mu-metal, about 50% longer than the cell and coil, is adequate.

D. External modulators and injection current modulation

The MOGlabs DLC is designed for AC locking a laser to an external reference such as an atomic resonance or an optical cavity. In many cases it is convenient to use the internal modulator driver, and Zeeman modulation of an atomic transition, as described in appendix C. Zeeman modulation is not always possible (e.g. if the reference is an optical cavity), or desirable (e.g. due to magnetic interference). The MOGlabs DLC can dither the laser diode injection current (DIP switch 3), or drive an external modulator, such as an electro-optic modulator (EOM) or acousto-optic modulator (AOM).

D.1 Coupling circuit

The DLC provides a current-controlled modulation output. Normally some impedance-matching will be needed to drive an external modulator, and typically a DC level shift. The circuit below provides these functions, specifically for RF amplifiers used for AOMs such as the D323B from ISOMET.

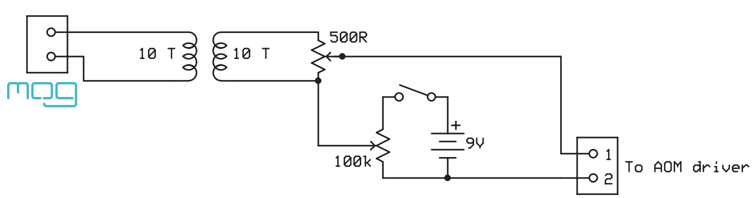


Figure D.1: Coupling from MOD OUT to an external modulator.

The ISOMET D323B RF driver has a frequency control input with 4 to 17 V range. We AC couple using a simple 10T:10T ferrite bead transformer. Primary and secondary were wound with 10 turns of PVCinsulated hookup wire around a ferrite bead approximately 15 mm diameter. A 500 Ω potentiometer allows control of the modulation amplitude, and a 9 V battery and 100 kΩ potentiometer provide a DC shift to set the centre modulator frequency. The latter allows frequency offset control of the modulated light beam.

D.2 Injection current modulation

The MOGlabs DLC can dither the laser diode injection current (set by DIP switch **3**), at the standard 250 kHz, or with high frequency modulation (e.g. 10 MHz) via the SMA RF input on the laser headboard. Very narrow linewidths can be achieved with suitably high bandwidth frequency discrimination, for example by phase locking two lasers. The diagram below shows an arrangement to lock two lasers to an EIT (electromagnetically induced transparency) resonance, which obtained a beatnote linewidth below 1 kHz [9].

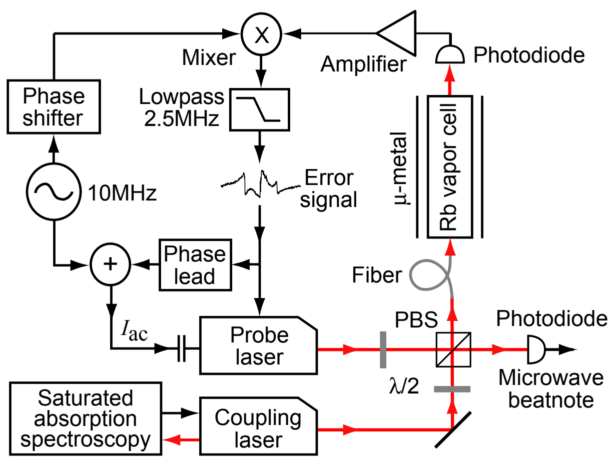


Figure D.2: High bandwidth locking based on FM sideband demodulation [4,5]. The probe laser is locked with high bandwidth, relative to the coupling laser, using electromagnetically induced transparency as a dispersive reference.

The coupling laser was locked to the $5^2S_{1/2}F = 2 \rightarrow 5^2P_{3/2}F = 2$ transition of ^{87}Rb using the Zeeman modulation technique, as in section 3.5. The probe laser was tuned to the $F = 1 \rightarrow F = 2$ transition and modulated at 10 MHz. The two lasers copropagated through a Rb vapour cell and onto a photodiode. An electromagnetically induced transparency provided a dispersive reference. A frequency error signal was obtained by FM demodulation [4,5]. The error signal is returned to the external error input on the probe laser MOGlabs DLC, which locked the laser with bandwidth up to about 40 kHz. The error signal was also coupled through a single stage passive phase-lead (high-pass) filter, and then combined with the 10 MHz modulation using a passive bias tee, and injected into the SMA modulation input, to provide feedback bandwidth of about 600 kHz.

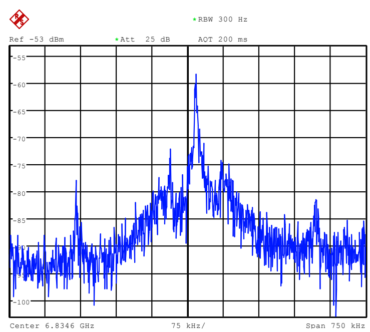


Figure D.3: RF beatnote from two MOGlabs DLC-locked lasers. The −3 dB peak width was 750 Hz with a spectrum analyser RBW setting of 300 Hz. For a 20 s average, the width was about 4 kHz.

E. Photodetector

The MOGlabs photodetector, shown below, can be used as a single detector (left photodiode, seen from front), or as a differential pair, via internal DIP switch **8**. The photodetector is connected via the rear socket and cable provided. A number of M4 and 8-32 threaded holes allow mounting in different configurations to minimise the footprint on an optical bench (see figure E.2).

Figure E.1: MOGlabs DLC balanced differential photodetector.

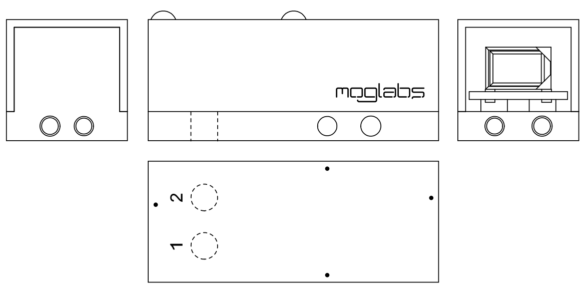


Figure E.2: M4 mounting holes are marked with a dot; others are 8-32. Single channel photodiode 1, differential signal $1 - 2$.

E.1 Photodiodes

The standard photodetector uses Si-PIN photodiodes encapsulated in a coloured plastic which transmits in the near-infrared and blocks most room light. The diodes include a lens to reduce the acceptance angle to ±10°. Unfiltered diodes, and wider acceptance angles, are also available.

Photodiode Specifications		
Parameter	Standard	Options
Spectral range(10% of max)	750 – 1100 nm	400 – 1100 nm
Peak sensitivity	900 nm	850 nm
Half angle	±10°	±20° ; ±75°
Sensitive area	$1 \times 1\,\text{mm}^2$	
Max incident power	500 μW	
Apparent sensitivity (CHAN A)	30 mV/μW	

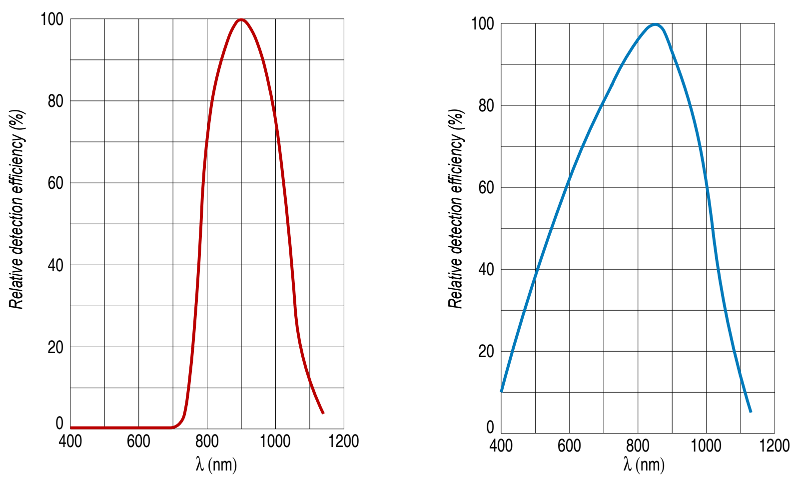


Figure E.3: Photodiode spectral response, standard filtered and unfiltered.

F. Laser head board

The laser head interface board (see below) provides convenient connection breakout to the laser diode, TEC, sensor, piezo actuators, and laser head interlock. It also includes a solid-state protection relay and passive protection filters, a laser-on LED indicator, and an SMA connection for direct diode current modulation.

MOLEX connectors are supplied for the diode (3-pin), TEC and sensor (either 10 kΩ thermistor, AD590 or AD592), interlock, and piezo actuators (2-pin). The laser head board can be mounted to the supplied laser head panel. For high bandwidth RF modulation (see below), the diode should be connected to the SMA connector rather than the MOLEX. Another very small circuit board, to connect directly to the diode, is also available from MOGlabs, with SMA and MOLEX connectors. The MOGlabs DLC does not provide a mechanism for optical power control or measurement for diodes with an internal photodiode.

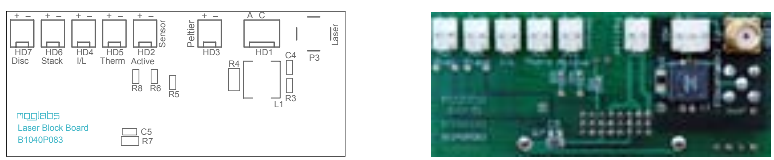


Figure F.1: MOGlabs DLC laser head board showing headers for connection of laser diode, piezo actuators, temperature sensor, TEC and head enclosure interlock.

RF coupling

The SMA connector on the laser head board allows high-frequency current modulation. The RF input is AC coupled, with low- and high-frequency limits of about 16 MHz and 2.5 GHz (see fig. A.1). Capacitor C4, normally 100 pF, can be changed to adjust the low-frequency cutoff (e.g. 10 nF for 160 kHz). For higher bandwidths, use an external bias-tee such as the Mini-Circuits ZFBT-4R2GW-FT between the head board and the diode.

The input sensitivity depends on the diode impedance, typically about 50 Ω. Thus a 0 dBm signal correponds to about 0.2 V and a current of around 4 mA at the diode. That is, the current sensitivity is approximately 20 mA/V.

WARNING: The RF input is a direct connection to the laser diode. Excessive power can destroy the diode. It is separated from the head board relay by an inductor, and thus the relay does *not* provide protection from high frequency signals.

G. Connector pinouts

G.1 Photodetector

The photodetector is connected via standard 6-pin IEEE-1394 (FireWire) connectors.

Pin	Signal
1	Gnd
2	Differential
3	Signal −
4	Signal +
5	+12 V
6	−12 V

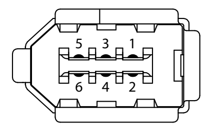


Figure G.1: PHOTODETECTOR connector on rear panel. Differential output is enabled if pin 2 is TTL high (+5 V).

G.2 Laser

WARNING: The LASER connector on the rear panel is a standard DVI-D Dual socket as used for consumer digital display devices. It should only be connected to the corresponding MOGlabs laser head board. It supplies the high-voltage signals to drive the laser piezo-electric actuators. In principle, the piezo drivers will be disabled if the cable is disconnected, but nevertheless considerable care should be taken to ensure that non-MOGlabs devices are not connected via this connector.

The MOGlabs cable can be replaced with a standard digital DVI-D Dual cable. There is a bewildering assortment of apparently similar cables available; only high quality dual-link digital DVI-D cables should be used.

Pin	Signal	Pin	Signal	Pin	Signal
1	TEC –	9	DIODE –	17	DISC +
2	TEC +	10	DIODE +	18	DISC –
3	Shield	11	Shield	19	Shield
4	TEC –	12	DIODE –	20	STACK +
5	TEC +	13	DIODE +	21	STACK –
6	AD590/592 –	14	Relay GND	22	
7	AD590/592 +	15	Relay +5V	23	NTC –
8		16	Interlock +5V	24	NTC +

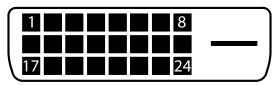


Figure G.2: LASER connector on rear panel.

G.3 Interlock

The rear-panel interlock socket is a standard 2.1 mm cylindrical DC power jack. The outer conductor is supplied with 5 V via a 5 k resistor. The inner pin is connected to ground via a 10 k resistor. The laser should be enabled by shorting the two contacts.

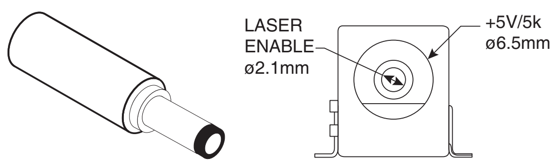
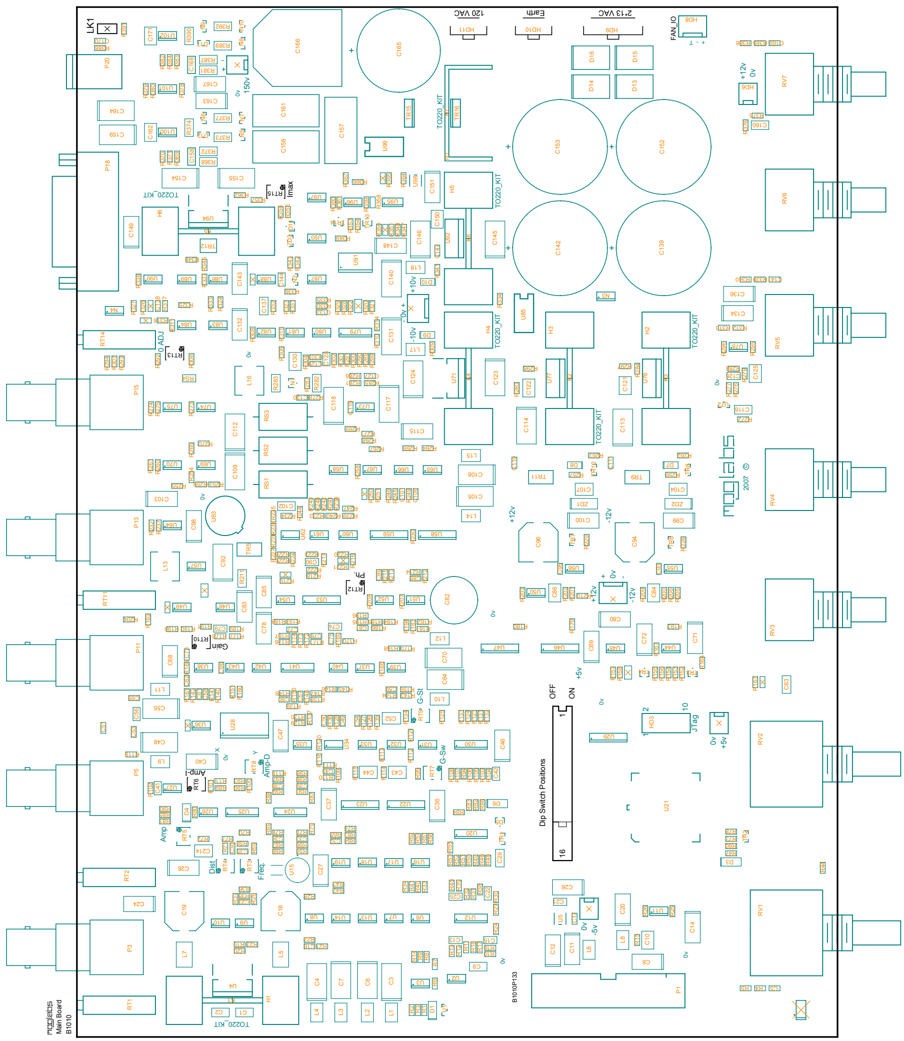


Figure G.3: INTERLOCK connector on rear panel.

H. PCB layout



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