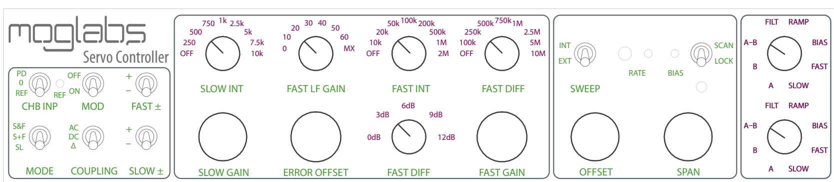
Fast servo controller



Version 0.0.3

Limitation of Liability

MOG Laboratories Pty Ltd (MOGLabs) does not assume any liability arising out of the use of the information contained within this manual. This document may contain or reference information and products protected by copyrights or patents and does not convey any license under the patent rights of MOGLabs, nor the rights of others. MOGLabs will not be liable for any defect in hardware or software or loss or inadequacy of data of any kind, or for any direct, indirect, incidental, or consequential damages in connections with or arising out of the performance or use of any of its products. The foregoing limitation of liability shall be equally applicable to any service provided by MOGLabs.

Copyright

Contact

For further information, please contact:

MOG Laboratories P/L	MOGLabs USA LLC	MOGLabs Europe
49 University St	419 14th St	Goethepark 9
Carlton VIC 3053	Huntingdon PA 16652	10627 Berlin
AUSTRALIA	USA	Germany
+61 3 9939 0677	+1 814 251 4363	+49 30 21 960 959
info@moglabs.com	info@moglabsusa.com	info@moglabs.eu
www.moglabs.com	www.moglabsusa.com	www.moglabs.eu

Preface

High-bandwidth frequency stabilisation of a tunable laser is technically challenging, with stringent demands on the frequency discriminator, laser frequency control actuators and most importantly on the feedback servo controller. High gain bandwidth, very short phase delay, low noise, and flexible control of the feedback parameters are all essential.

The MOGLabs FSC servo controller provides class-leading technical specifications, and also an accessible and intuitive user interface. All critical parameters can be easily adjusted with simple clearly labelled controls on the front panel. The important controls are not tiny inscrutable DIP switches or tiny trimpots or screwdriver-adjusted selectors, but readily accessible knobs and toggle switches. Monitored signals are easily selectable for output to a standard two-channel oscilloscope. A frequency sweep ramp is provided. Two input channels accept signals from photodetectors or other measuring devices, and low-noise DC power for the detectors is available via standard M8 connectors. Everything needed to lock your laser to a high-finesse optical cavity and achieve strong linewidth narrowing, all in one box which connects directly to AC mains power and to your laser.

We hope that you enjoy using the FSC, and please let us know if you have any suggestions for improvement in the FSC or in this document, so that we can make life in the lab better for all.

MOGLabs, Melbourne, Australia
www.moglabs.com

Safety Precautions

Safe and effective use of this product is very important. Please read the following safety information before attempting to operate. Also please note several specific and unusual cautionary notes before using the MOGLabs FSC, in addition to the safety precautions that are standard for any electronic equipment.

WARNING High voltages are exposed internally, particularly around the mains power inlet and internal power supply unit. The unit should not be operated with cover removed.

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

Contents

Preface **i**

Safety Precautions **iii**

1 Introduction **1**
1.1 Schematics 5

2 Connections and controls **11**
2.1 Front panel controls 11
2.2 Rear panel controls and connections 15
2.3 Internal DIP switches 17

3 Operation **19**
3.1 Laser and controller configuration 20
3.2 Achieving an initial lock 22
3.3 Optimisation 23

A Specifications **27**

B 115/230 V conversion **29**
B.1 Fuse 29
B.2 120/240 V conversion 29

References **34**

1. Introduction

The MOGLabs FSC provides the critical elements of a high-bandwidth low-latency servo controller, primarily intended for laser frequency stabilisation and linewidth narrowing. The FSC can also be used for amplitude control, for example to create a "noise-eater" that stabilises the optical power of a laser, but in this manual we assume the more common application of frequency stabilisation.

Feedback frequency stabilisation of lasers can be complicated. We encourage readers to review control theory textbooks [1,2] and literature on laser frequency stabilisation [3].

The concept of feedback control is shown schematically in figure 1.1. The frequency of the laser is measured with a *frequency discriminator* which generates an *error signal* that is proportional to the difference between the laser frequency and the desired or *setpoint* frequency.

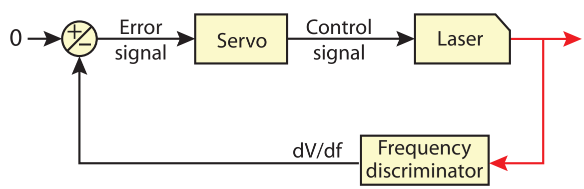


Figure 1.1: Simplified block diagram of the FSC.

Common discriminators include optical cavities and Pound-Drever-Hall (PDH) [4] or Hänsch-Couillaud [5] detection; offset locking [6]; or many variations of atomic absorption spectroscopy [7–10].

The key common feature is that the error signal should reverse sign as the laser frequency shifts above or below the setpoint, as in figure 1.2. From the error signal, a feedback servo or *compensator* generates a *control signal* for a transducer in the laser, such that the laser frequency is driven towards the desired setpoint.

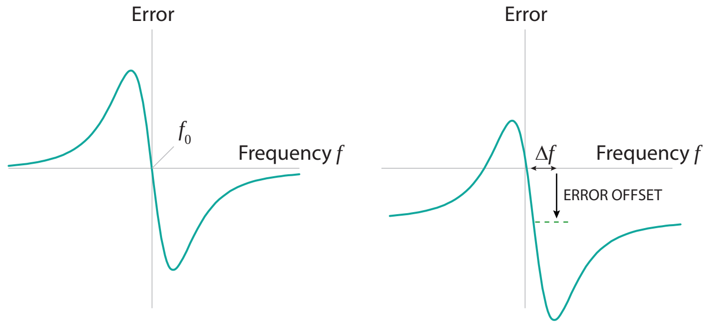


Figure 1.2: A theoretical dispersive error signal, proportional to the difference between a laser frequency and a setpoint frequency. An offset on the error signal shifts the lock point (right).

Note the distinction between an *error signal* and a *control signal*. An error signal is a measure of the difference between the actual and desired laser frequency, which in principle is instantaneous and noise-free. A control signal is generated from the error signal by a feedback servo or compensator. The control signal drives an actuator such as a piezo-electric transducer, the injection current of a laser diode, or an acousto-optic or electro-optic modulator, such that the laser frequency returns to the setpoint. Actuators have complicated response functions, with finite phase lags, frequency-dependent gain, and resonances. A compensator should optimise the control response to reduce the error to the minimum possible.

The operation of feedback servos is usually described in terms of the Fourier frequency response; that is, the gain of the feedback as a function of the frequency of a disturbance. For example, a common disturbance f_m is mains frequency, $f_m = 50\,\text{Hz}$ or $60\,\text{Hz}$. That disturbance will alter the laser frequency f by some amount, at a rate of 50 or 60 Hz. The effect of the disturbance on the laser might be small (e.g. $f = f_0 \pm 1\,\text{kHz}$ where f_0 is the undisturbed laser frequency) or large ($f = f_0 \pm 1$ MHz). The Fourier frequency of the disturbance f_m in both cases is 50 or 60 Hz.

To suppress that disturbance, a feedback servo should have high gain at 50 and 60 Hz. Gain has a low-frequency limit usually defined by the gain-bandwidth limit of the opamps used in the servo controller. The gain must alo fall below unity gain (0 dB) at higher frequencies to avoid oscillations such as the familiar high-pitched squeal of audio systems, commonly called "audio feedback", for frequencies above the reciprocal of the minimum propagation delay of the combined laser, frequency discriminator, servo and actuator system. Typically that limit is dominated by the response time of the actuator and for laser piezos that is usually of order kHz.

Figure 1.3 is a conceptual plot of gain against Fourier frequency for the FSC. To minimise the laser frequency uncertainty, the area under the gain plot should be maximised. PID (proportional integral and differential) servo controllers are a common approach, where the control signal is the sum of three components derived from the one input error signal. The proportional feedback (P) attempts to promptly compensate for disturbances, whereas integrator feedback (I) provides high gain for offsets and slow drifts, and differential feedback (D) adds extra gain for sudden changes.

When using a single integrator, the gain decreases at 20 dB per decade of Fourier frequency change, indicating a stronger response at lower frequencies. Adding a second integrator increases this to 40 dB per decade, reducing the long-term offset between actual and setpoint frequencies. Increasing the gain too far however, results in oscillation as the controller "overreacts" to changes in the error signal. For this reason it is sometimes beneficial to restrict the gain at low frequencies, such as in the fast servo loop, where a large response can cause a mode-hop.

The differentiator has increasing gain at 20 dB per decade.

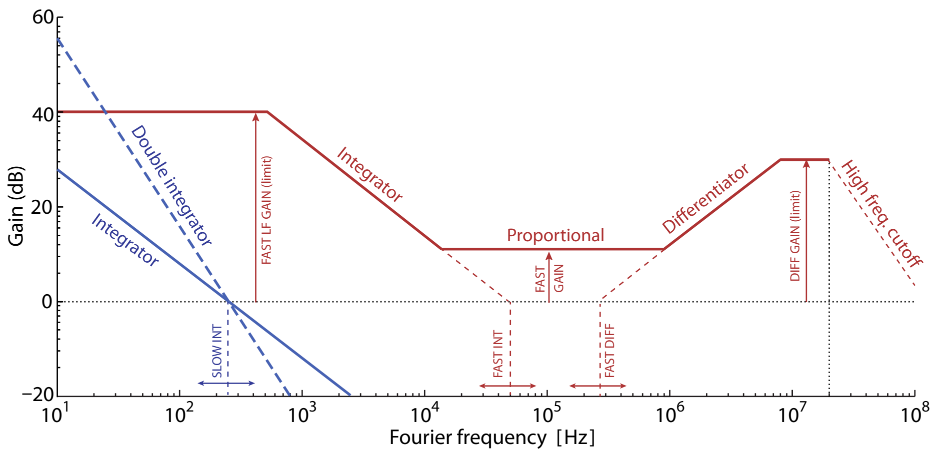


Figure 1.3: Conceptual Bode plot showing action of the fast (red) and slow (blue) controllers. The slow controller is either a single or double integrator with adjustable corner frequency. The fast controller is PID with adjustable corner frequencies and gain limits at the low and high frequency limits.

1.1 Schematics

The FSC has two parallel feedback channels that can drive two actuators simultaneously: a “slow” actuator with large range (usually a piezo-electric transducer), and a second “fast” actuator (such as the injection current of a diode laser, or an electro-optic modulator). The FSC provides precise control of each stage, a gain limit at low frequency, offsets, a sweep (ramp) generator, and convenient signal monitoring (figure 1.4).

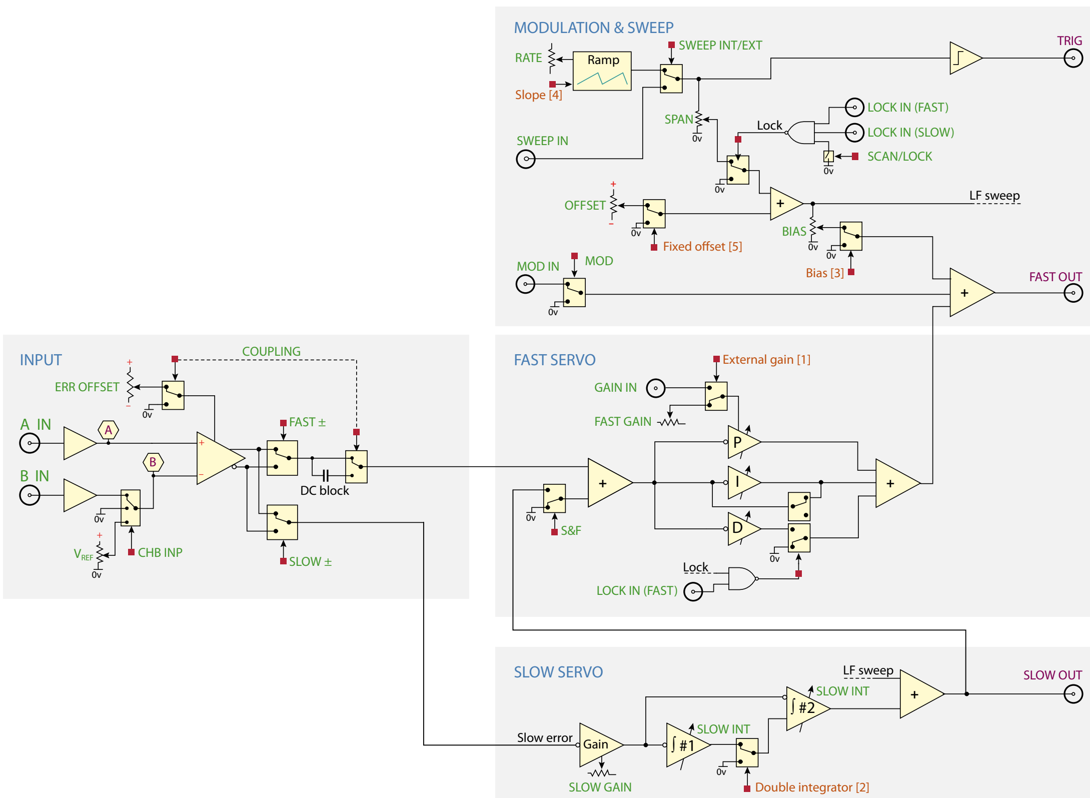


Figure 1.4: Schematic of the MOGLabs FSC. Green labels refer to controls on the front-panel and inputs on the back-panel, brown are internal DIP switches, and purple are outputs on the back-panel.

1.1.1 Input stage

The input stage of the FSC (figure 1.5) generates an *error signal* as $V_{\mathrm{ERR}} = V_A - V_B - V_{\mathrm{OFFSET}}$. V_A is taken from the "A IN" SMA connector, and V_B is set using the CHB INP selector switch, taking the input from the "B IN" SMA connector, $V_B = 0$ or $V_B = V_{\mathrm{REF}}$ as set by the trimpot marked REF.

The controller acts to servo the error signal towards zero, which defines the lock point. Some applications may benefit from small adjustments to the DC level to adjust this lock point, which can be achieved with the 10-turn knob ERROR OFFSET for up to ±0.1 V shift, provided the COUPLING selector is set to "offset" mode (Δ). Larger offsets can be achieved with the REF trimpot.

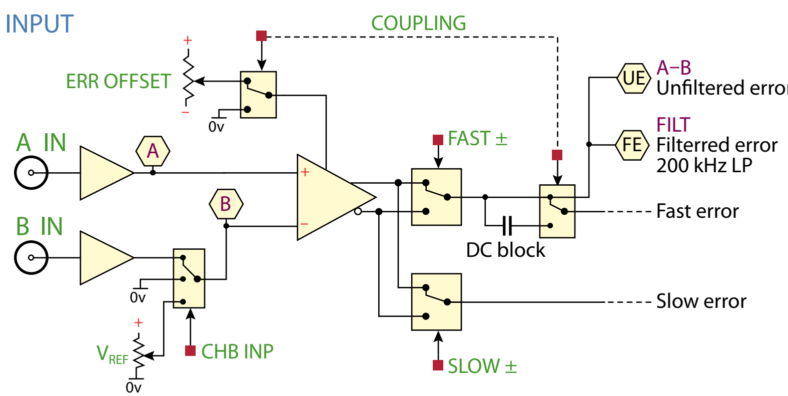


Figure 1.5: Schematic of the FSC input stage, showing coupling, offset and polarity controls. Hexagons are monitored signals available via the front-panel selector switches.

1.1.2 Slow servo

Figure 1.6 shows the slow feedback configuration of the FSC. A variable gain stage is controlled with the front-panel SLOW GAIN knob. The action of the controller is either a single- or double-integrator depending on whether DIP 2 is enabled. The slow integrator time constant is controlled from the front-panel SLOW INT knob, which is labelled in terms of the associated corner frequency.

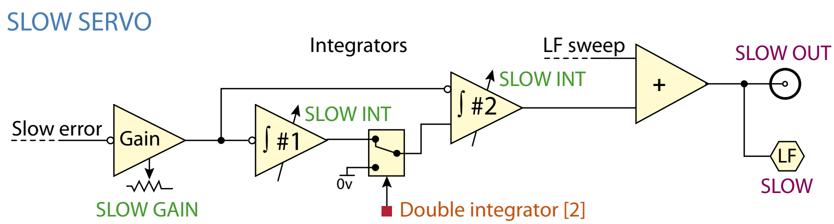


Figure 1.6: Schematic of slow feedback PI/PI^2 servo. Hexagons are monitored signals available via the front-panel selector switches.

1.1.3 Fast servo

The fast feedback servo is a PID-loop (figure 1.7) with a variable gain P-stage controlled with the front-panel FAST GAIN knob, or an external control signal through the rear-panel GAIN IN connector. The P, I and D components can be individually adjusted via front-panel selector switches, and a low-frequency gain limit is applied to prevent .

In Rev 1 devices, proportional feedback is always enabled on the fast servo. This allows determination of the fast servo sign and gain while the laser is scanning, which simplifies the locking procedure (see §3.2). Future devices will include a separate SCAN+P mode that has this behaviour.

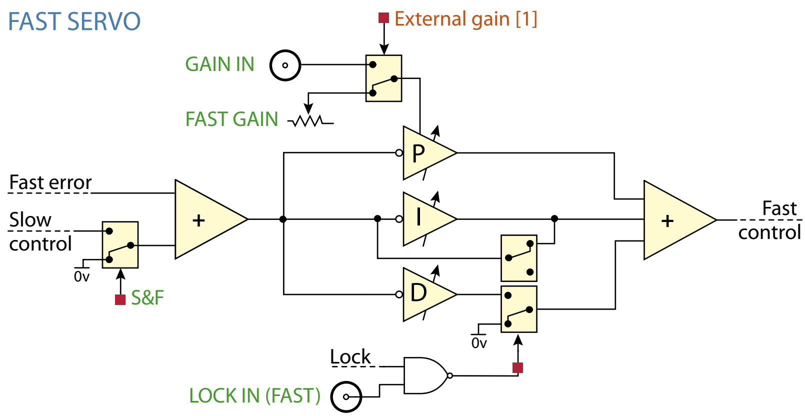


Figure 1.7: Schematic of fast feedback servo PID controller. Front panel controls for integrator and differentiator constants and limits are not shown.

For applications that do not include a separate slow actuator, the slow control signal (single or double integrated error) can be added to the fast by setting the MODE switch to "S&F". The slow servo will then be locked when the fast servo is locked. Note that in this mode it is recommended that the first integrator in the slow channel be disabled with DIP 2 to prevent triple integration in the fast response.

1.1.4 Modulation and scanning

Laser scanning is controlled by either an internal sweep generator or an external sweep signal. The internal sweep is a sawtooth with variable period as set by a four-position range switch and a single-turn trimpot on the front-panel.

Changing from sweep to lock can be controlled with an external scan/lock TTL input, the front panel SCAN/LOCK switch, or with the front panel MODE switch. The SCAN/LOCK switch locks the fast servo, whereas the MODE switch controls the slow servo. The MODE switch should be set to S+F to scan the laser normally.

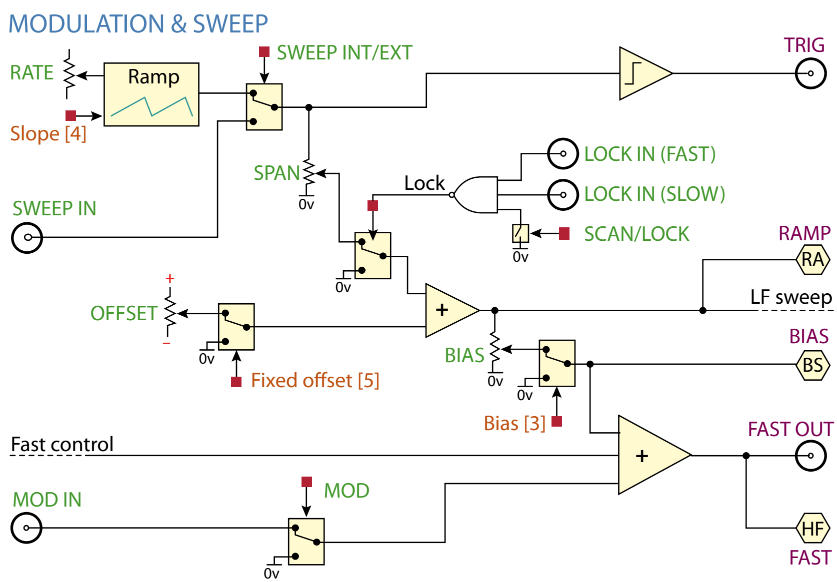
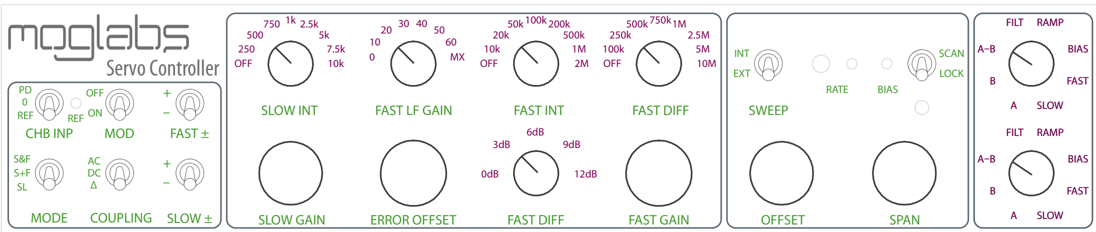


Figure 1.8: Sweep, external modulation, and feedforward current bias.

The ramp can also be added to the fast output by enabling DIP 3 and adjusting the BIAS trimpot. Note that many laser controllers (such as the MOGLabs DLC) will generate the necessary bias current using the slow servo signal and it is unnecessary to generate it within the FSC as well.

2. Connections and controls

2.1 Front panel controls



2.1.1 Configuration

CHB INP Selects input for channel B: photodetector, ground, or a variable reference adjustable with the adjacent REF trimpot.

MODE Selects the slow servo locking mode; see §1.1.2.

- **S&F** The slow control signal is nested into the fast error signal, and the SCAN/LOCK switch locks both fast and slow simultaneously. In this mode it is recommended that DIP 3 is disabled.
- **S+F** Slow unlocked: slow and fast servos are independent.
- **SL** Slow lock: scanning is disabled and the slow lock is engaged.

MOD Enables external modulation input. If ON, external modulation is added directly to the fast feedback signal; see figure 1.8.

COUPLING Selects error signal coupling mode; see figure 1.5.

- **AC** Fast error signal is AC-coupled, slow error is DC coupled.
- **DC** Both fast and slow error signals are DC-coupled.
- **Δ** Signals are DC-coupled, and the front-panel ERROR OFFSET is applied for control of the lock point.

FAST ± Sign of the fast feedback.

SLOW ± Sign of the slow feedback.

2.1.2 Loop variables

The gain of each proportional, integrator and differentiator stage can be adjusted. For integrators and differentiator stages, the gain is presented in terms of the unit gain frequency, sometimes referred to as the corner frequency.

SLOW INT Corner frequency of the slow servo integrator; can be off[1] or adjusted from 250 Hz to 10 kHz.

SLOW GAIN Additional single-turn slow servo gain; from −20 dB to +20 dB.

FAST LF GAIN Low-frequency gain limit on the fast servo, in dB. MX represents the maximum available gain.

FAST INT Corner frequency of the fast servo integrator; off or adjustable from 10 kHz to 2 MHz.

FAST GAIN Ten-turn fast servo proportional gain; from −10 dB to +50 dB.

FAST DIFF Corner frequency of the fast servo differentiator; off or adjustable from 100 kHz to 10 MHz.

FAST DIFF High-frequency gain limit on the fast servo, in dB.

2.1.3 Ramp control

The internal ramp provides a sweep function for scanning the laser frequency, normally through a piezo actuator, diode injection current, or both. It is expected that the rear-panel SLOW OUT will be connected to a piezo, and FAST OUT to the laser current control. A trigger output synchronised to the ramp is provided on the rear panel (TRIG).

[1] The slow servo integrator cannot be disabled in Rev 1 units

SWEEP Selects internal or external (via rear panel SWEEP IN) ramp.

RATE Controls the ramp time with two adjusters; the right is a single turn fine adjustment trimpot and the left is a 4-position rotary switch, which in Rev1 units corresponds to

1: 20 to 520 ms.

2: 27 to 690 ms.

3: 40 to 1040 ms.

4: 80 to 2080 ms.

BIAS When DIP 3 is enabled, the slow output is added to the fast output as scaled by this trimpot. This bias feed-forward is typically required when adjusting the piezo actuator of an ECDL to prevent mode-hopping. However, this functionality is already provided by some laser controllers (such as the MOGLabs DLC) and should only be used when not provided elsewhere.

SCAN/LOCK Engages the fast servo. When switching from scan to lock, the sweep controller drives the slow and fast outputs to the midpoint of the ramp, and activates the locking feedback.

Status LED Multi-colour indicator displaying status of the lock.

Green Power on, lock disabled.

Orange Lock engaged but error signal goes out of range, indicating the lock has failed.

Blue Lock engaged and error signal is within limits.

OFFSET Adjusts the DC offset on the slow output, effectively providing a static shift of the laser frequency.

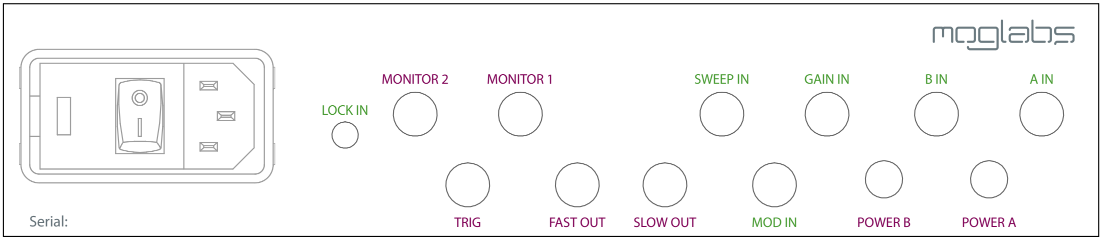
SPAN Adjusts the ramp height, and thus the extent of the frequency sweep.

2.1.4 Signal monitoring

Two rotary encoders select which of the specified signals is routed through to the rear-panel Monitor 1 and Monitor 2 outputs. The TRIG output is a TTL compatible output that switches from low to high at the centre of the sweep. The table below defines the signals.

A	Channel A input (−1 ... +1 V)
B	Channel B input (−1 ... +1 V)
A – B	Error signal (including offset if relevant)
FILT	Filtered error signal (200 kHz low-passed)
RAMP	Ramp as applied to SLOW OUT
BIAS	Ramp as applied to FAST OUT
FAST	FAST OUT control signal
SLOW	SLOW OUT control signal

2.2 Rear panel controls and connections

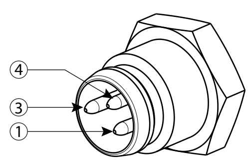


All connectors are SMA, except as noted. All inputs are over-voltage protected to ±15 V. All outputs have valid operating range of ±2.5 V, with maximum ±5 V.

IEC power in The unit should be preset to the appropriate voltage for your country. Please see appendix B for instructions on changing the power supply voltage if needed.

A IN, B IN Inputs for *A*, *B*, typically photodetectors. High impedance, ±2.5 V.

POWER A, B Low-noise DC power for photodetectors; ±12 V, 125 mA. M8 connector, TE Connectivity part number 2-2172067-2, Digikey A121939-ND, 3-way male. To be used with standard M8 cables, for example Digikey 277-4264-ND.



1	+12 V
3	−12 V
4	0 V

Figure 2.1: M8 connector pinout for POWER A, B. Rev1 units have female connectors; later units have male connectors as shown.

GAIN IN Voltage-controlled proportional gain of fast servo, $\pm 1\ V$, corresponding to the full-range of the front-panel knob. Replaces front-panel FAST GAIN control when DIP 1 is enabled.

SWEEP IN External ramp input allows for arbitrary frequency scanning, 0 to 2.5 V. Signal must cross 1.25 V, which defines the centre of the sweep and the approximate lock point.

MOD IN Modulation input, added directly to fast control output, $\pm 1\ V$.

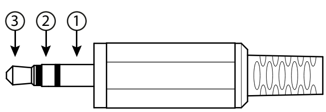
SLOW OUT Slow control signal output, normally connected to a piezo driver or other slow actuator.

FAST OUT Fast control signal output, normally connected to diode injection current, acousto- or electro-optic modulator, or other fast actuator.

MONITOR 1, 2 Selected signal output for monitoring.

TRIG Low to high TTL output at sweep centre.

LOCK IN TTL scan/lock control; 3.5 mm stereo connector, left/right (pins 2, 3) for slow/fast lock; low (ground) is active (enable lock). Front-panel scan/lock switch must be on SCAN for LOCK IN to have effect. Digikey cable CP-2207-ND provides a 3.5 mm plug with wire ends; red for slow lock, thin black for fast lock, and thick black for ground.



1	Ground
2	Fast lock
3	Slow lock

Figure 2.2: 3.5 mm stereo connector pinout for TTL scan/lock control.

2.3 Internal DIP switches

There are five internal DIP switches that provide additional options, all set to OFF by default.

WARNING There is potential for exposure to high voltages inside the FSC. Take care around the power supply and ensure that objects, particularly electrically conducting objects, do not enter the unit.

CAUTION The cover should be left on to ensure proper airflow and cooling.

		OFF	ON
1	Fast gain	Front-panel knob	External signal
2	Slow feedback	Single integrator	Double integrator
3	Bias	Ramp to slow only	Ramp to fast and slow
4	Sweep	Positive	Negative
5	Offset	Normal	Fixed at midpoint

DIP 1 Fast servo gain determined by the potential applied to the rear-panel GAIN IN connector instead of the front-panel FAST GAIN knob.

DIP 2 Slow servo is a single (OFF) or double (ON) integrator. Should be disabled if using “nested” slow and fast servo operation (S&F mode).

DIP 3 Generate a bias current in proportion to the slow servo output to prevent mode-hops. Only needs to be enabled if not already provided by the laser controller (unnecessary when used in combination with MOGLabs DLC).

DIP 4 Reverses the direction of the sweep.

DIP 5 Disables the front-panel offset knob and fixes the offset to the midpoint. Useful in external sweep mode, to avoid accidentally changing the laser frequency by bumping the offset knob.

3. Operation

A typical application of the FSC is to frequency-lock a laser to an optical cavity using the PDH technique, as shown in figure 3.1. The cavity acts as a frequency discriminator, and the FSC keeps the laser on resonance with the cavity by controlling the laser piezo and current through its SLOW and FAST outputs, reducing the laser linewidth. A separate application note is available that provides practical advice on implementing a PDH apparatus.

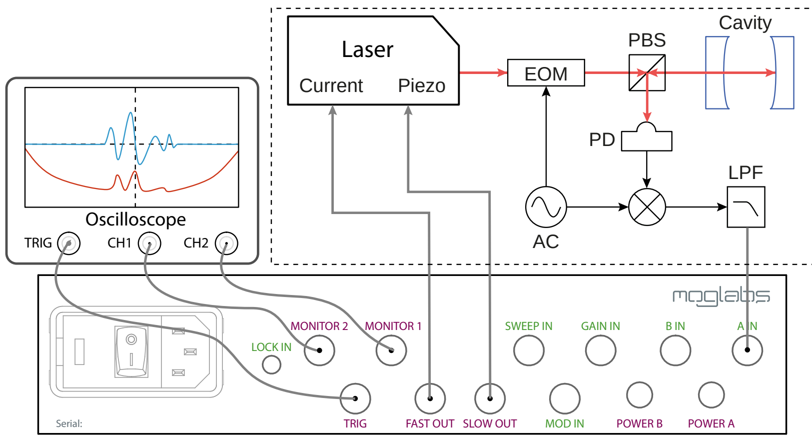


Figure 3.1: Simplified schematic for PDH-cavity locking using the FSC. An electro-optic modulator (EOM) generates sidebands, which interact with the cavity, generating reflections that are measured on the photodetector (PD). Demodulating the photodetector signal produces a PDH error signal.

A variety of other methods can be used to generate error signals, which will not be discussed here. The rest of this chapter describes how to achieve a lock once an error signal has been generated.

3.1 Laser and controller configuration

The FSC is compatible with a variety of lasers and controllers, provided they are correctly configured for the desired mode of operation. When driving an ECDL (such as the MOGLabs CEL or LDL lasers), the requirements for the laser and controller are as follows:

- High-bandwidth modulation directly into the laser headboard.
- High-voltage piezo control from an external control signal.
- Feed-forward ("bias current") generation for lasers that require a bias of $\gtrsim 1$ mA across their scan range[1].

MOGLabs laser controllers and headboards can be easily configured to achieve the required behaviour, as explained below.

3.1.1 Headboard configuration

MOGLabs lasers include an internal headboard that interfaces the components with the controller. A headboard that includes an SMA connector is required for operation with the FSC, which should be connected directly to the "FAST OUT" from the FSC.

The B1240 headboard is strongly recommended for maximum modulation bandwidth, although the B1040 is an acceptable substitute for lasers that are incompatible with the B1240. The headboard has a number of jumper switches which much be configured for **DC coupled** and **buffered** ("BUF") input, where applicable.

[1] The FSC is capable of generating a bias current internally but the range is limited by the headboard, and it may be necessary to use bias provided by the laser controller.

3.1.2 DLC configuration

Although the FSC can be configured for either internal or external sweep, it is significantly simpler to use the internal sweep mode and set the DLC as a slave device as follows:

- Connect the "SLOW OUT" of the FSC to the "SWEEP / PZT MOD" input of the DLC.
- Set DIP9 ("external sweep") of the DLC to enabled.
- Set DIP3 ("bias generation") of the FSC to disabled[2].
- Set FREQUENCY to zero and SPAN to full on the DLC.
- Ensure that SWEEP on the FSC is "INT".
- Set OFFSET to mid-range and SPAN to full on the FSC and observe the laser scan.
- If the scan is in the wrong direction, invert DIP4 of the FSC.

It is important that the FREQUENCY and SPAN knobs of the DLC are not adjusted once set as above, as they will impact the feedback loop and may prevent the FSC from locking. Only the FSC controls should be used to adjust the sweep.

[2]The DLC automatically generates the current feed-forward ("bias") from the sweep input, so it is not necessary to generate a bias within the FSC.

3.2 Achieving an initial lock

The SPAN and OFFSET controls of the FSC can be used to tune the laser to sweep across the desired lock point (e.g. cavity resonance) and narrow down on it. The following steps are illustrative of the process required to achieve a stable lock. Values listed are indicative, and will need to be adjusted for specific applications. Further advice on optimising the lock is provided in §3.3.

- Connect the error signal to the "A IN" input on the back-panel.
- Ensure that the error signal is of order $10 - 100$ mVpp.
- Set COUPLING to "Δ" (offset mode) and CHB INP to "0".
- Set MONITOR 1 to "A-B" and observe on an oscilloscope. Adjust the ERROR OFFSET knob until the DC level shown is zero[3].
- Reduce the FAST GAIN to zero.
- Set SCAN/LOCK to "SCAN" and MODE to "S+F", and scan across the resonance.
- Increase FAST GAIN until the error signal is seen to "stretch out" as shown in figure 3.2. If this is not observed, invert the FAST ± switch and try again.
- Set FAST DIFF to "OFF" and FAST LF GAIN to 30. Reduce FAST INT to ~150 kHz.
- Set SCAN/LOCK mode to "LOCK" and the controller will lock to the zero-crossing of the error signal. It may be necessary to make small adjustments to OFFSET and ERROR OFFSET.
- Optimise the lock by adjusting the FAST GAIN and FAST INT while observing the error signal.

[3] If there is no need to adjust the DC level, the COUPLING can be set to DC and the ERROR OFFSET knob will have no effect, preventing accidental adjustment.

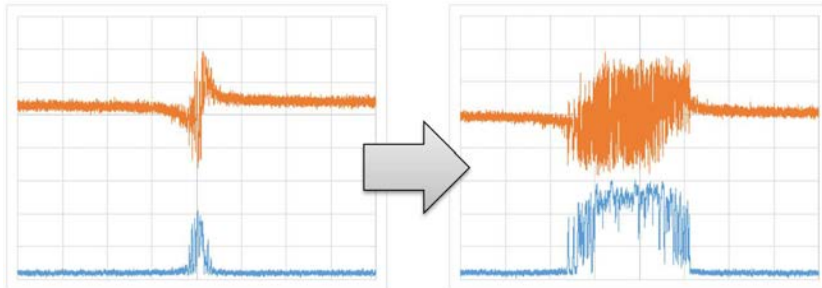


Figure 3.2: Scanning the laser with P-only feedback on the fast output while scanning the slow output causes the error signal (orange) to become extended when the sign and gain are correct (right). In a PDH application, the cavity transmission (blue) will also become extended.

- Set SLOW GAIN to mid-range and SLOW INT to ∼1 kHz.
- Set MODE mode to "SL". If the servo unlocks immediately, try inverting the SLOW ±. It may also be necessary to make small adjustments to the ERROR OFFSET.
- Adjust SLOW GAIN and SLOW INT for improved lock stability.
- Some applications may benefit by increasing FAST DIFF to improve loop response.

3.3 Optimisation

The purpose of the servo is to lock the laser to the zero-crossing of the error signal, which ideally would be identically zero when locked. Noise in the error signal is therefore a measure of lock quality. Spectrum analysis of the error signal is therefore a powerful tool for understanding and optimising the feedback. RF spectrum analysers can be used but are comparatively expensive and have limited dynamic range. A good sound card (24-bit 192 kHz, e.g. Lynx L22) provides noise analysis up to a Fourier frequency of 96 kHz with 140 dB dynamic range.

Ideally the spectrum analyser would be used with an independent frequency discriminator that is insensitive to laser power fluctuations [11]. Decent results can be achieved by monitoring the in-loop error signal but an out-of-loop measurement is preferable, such as measuring the cavity transmission in a PDH application. To analyse the error signal, connect the spectrum analyser to one of the MONITOR outputs set to “A-B”.

High-bandwidth locking typically involves first achieving a stable lock using only the fast servo, and then using the slow servo to improve the lock stability. The slow servo is required to compensate for thermal drift and acoustic perturbations, which would result in a mode-hop if compensated with current alone. In contrast, simple locking techniques such as saturated-absorption spectroscopy are typically achieved using the slow servo, with the fast servo compensating higher-frequency fluctuations only. It may be beneficial to consult the Bode plot (figure 3.3) when interpreting the error signal spectrum.

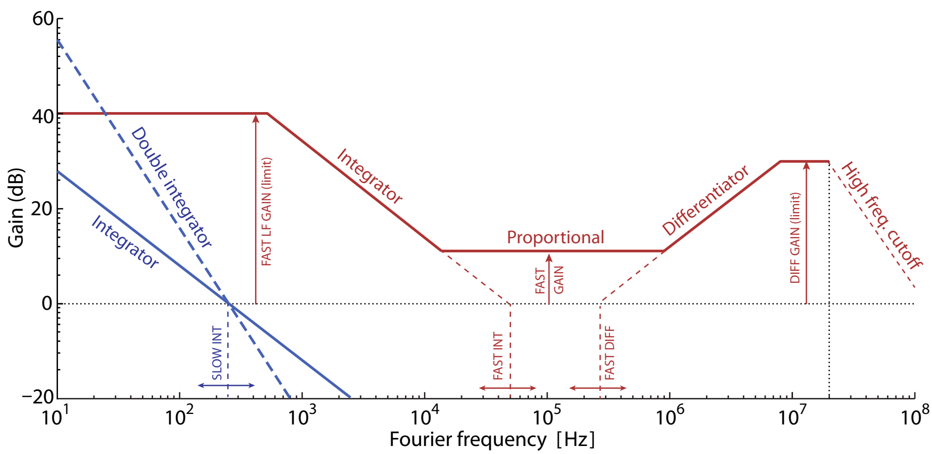


Figure 3.3: Conceptual Bode plot showing action of the fast (red) and slow (blue) controllers. The corner frequencies and gain limits are adjusted with the front-panel knobs as labelled.

When optimising the FSC, it is recommended to first optimise the fast servo through analysis of the error signal, and then the slow servo to reduce sensitivity to external perturbations. In particular, scanning with P-only feedback on the fast servo provides a convenient way to get the feedback sign and gain approximately correct.

Note that achieving the most stable frequency lock requires careful optimisation of many aspects of the apparatus, not just the parameters of the FSC. For example, residual amplitude modulation in a PDH apparatus results in drift in the error signal, which the servo is unable to compensate for. Similarly, poor signal-to-noise ratio (SNR) will feed noise directly into the laser.

One procedure for optimising the fast servo is to set FAST DIFF to "OFF" and adjust FAST GAIN, FAST INT and FAST LF GAIN to reduce the noise level as far as possible. Then optimise the FAST DIFF to reduce high-frequency noise components.

The slow servo can then be optimised to minimise the over-reaction to external perturbations. The high gain on the fast servo means that external perturbations can induce mode-hops in the laser mode. It is therefore preferable that these (low-frequency) fluctuations are compensated in the piezo instead. Adjusting the SLOW GAIN and SLOW INT will therefore not necessarily produce an improvement in the error signal spectrum, but when optimised will reduce the sensitivity to acoustic perturbations and prolong the lifetime of the lock.

A. Specifications

Parameter	Specification
Timing	
Gain bandwidth (-3 dB)	> 35 MHz
Propagation delay	< 28 ns
External modulation bandwidth (-3 dB)	> 35 MHz
Input	
A IN, B IN	SMA, 1 MΩ, ± 2.5 V
SWEEP IN	SMA, 1 MΩ, 0 to $+2.5$ V
GAIN IN	SMA, 1 MΩ, ± 2.5 V
MOD IN	SMA, 1 MΩ, ± 2.5 V
LOCK IN	3.5 mm female audio connector, TTL

Analogue inputs are over-voltage protected up to ± 10 V.
TTL inputs take < 1.0 V as low, > 2.0 V as high.
LOCK IN inputs are -0.5 V to 7 V, active low, drawing $\pm 1\ \mu$A.

Parameter	Specification
Output	
SLOW OUT	SMA, 50 Ω, BW 20 kHz
FAST OUT	SMA, 50 Ω, BW $>$ 20 MHz
MONITOR 1, 2	SMA, 50 Ω, BW $>$ 20 MHz
TRIG	SMA, 0 to +5 V
POWER A, B	M8 female connector, ±12 V, 125 mA

All outputs are limited to ±5 V.
50 Ω outputs 20 mA max (20 mW, +13 dBm).

Parameter	Specification
Mechanical & power	
IEC input	110 to 130V at 60Hz or 220 to 260V at 50Hz
Fuse	5x20mm anti-surge ceramic 250 V/2.5 A
Dimensions	W×H×D = 250 × 79 × 292 mm
Weight	2 kg
Power usage	$<$ 10 W

B. 115/230 V conversion

B.1 Fuse

The fuse is a ceramic antisurge, 2.5A, 5x20mm, for example Littlefuse 021502.5MXP. The fuse holder is a red cartridge just above the IEC power inlet and main switch on the rear of the unit (Fig. B.1).

Figure B.1: Fuse catridge, showing fuse placement for operation at 230 Vac.

B.2 120/240 V conversion

The controller can be powered from AC 50 to 60 Hz, 110 to 120 V (100 V in Japan), or 220 to 240 V. To convert between 115 V and 230 V, the fuse cartridge should be removed, and re-inserted such that the correct voltage shows through the cover window.

Figure B.2: To change fuse or voltage, open the fuse cartridge cover with a screwdriver inserted into a small slot at the left edge of the cover, just to the left of the red voltage indicator.

When removing the fuse catridge, insert a screwdriver into the recess at the *left* of the cartridge; do not try to extract using a screwdriver at the sides of the fuseholder (see figures).

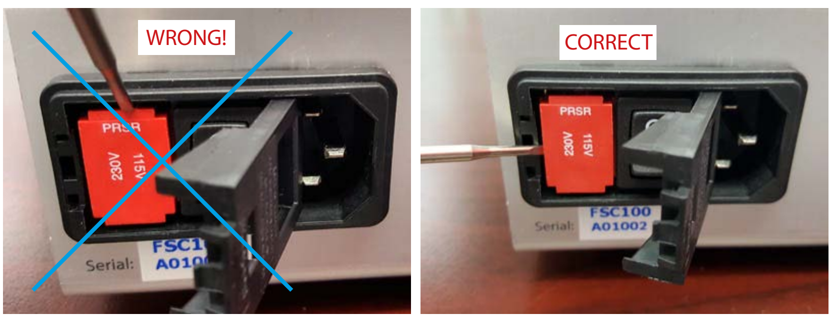


Figure B.3: To extract the fuse cartridge, insert a screwdriver into a recess at the *left* of the cartridge.

When changing the voltage, the fuse and a bridging clip must be swapped from one side to the other, so that the bridging clip is always on the bottom and the fuse always on the top; see figures below.

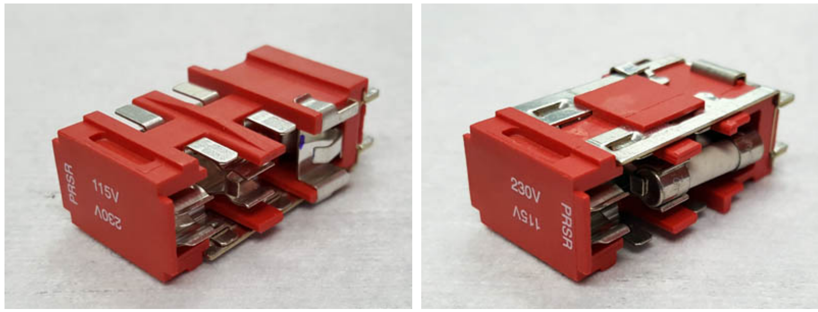


Figure B.4: 230 V bridge (left) and fuse (right). Swap the bridge and fuse when changing voltage, so that the fuse remains uppermost when inserted.

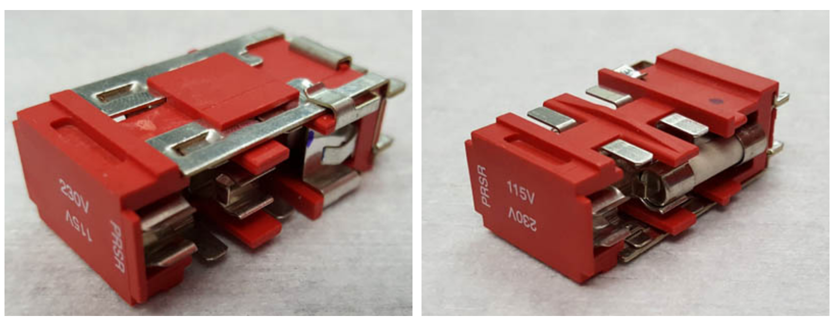


Figure B.5: 115 V bridge (left) and fuse (right).

Bibliography

[1] Alex Abramovici and Jake Chapsky. *Feedback Control Systems: A Fast-Track Guide for Scientists and Engineers*. Springer Science & Business Media, 2012. 1

[2] Boris Lurie and Paul Enright. *Classical Feedback Control: With MATLAB® and Simulink®*. CRC Press, 2011. 1

[3] Richard W. Fox, Chris W. Oates, and Leo W. Hollberg. Stabilizing diode lasers to high-finesse cavities. *Experimental methods in the physical sciences*, 40:1–46, 2003. 1

[4] R. W. P. Drever, J. L. Hall, F. V. Kowalski, J. Hough, G. M. Ford, A. J. Munley, and H. Ward. Laser phase and frequency stabilization using an optical resonator. *Appl. Phys. B*, 31:97–105, 1983. 1

[5] T. W. Hänsch and B. Couillaud. Laser frequency stabilization by polarization spectroscopy of a reflecting reference cavity. *Optics communications*, 35(3):441–444, 1980. 1

[6] M. Zhu and J. L. Hall. Stabilization of optical phase/frequency of a laser system: application to a commercial dye laser with an external stabilizer. *J. Opt. Soc. Am. B*, 10:802, 1993. 1

[7] G. C. Bjorklund. Frequency-modulation spectroscopy: a new method for measuring weak absorptions and dispersions. *Opt. Lett.*, 5:15, 1980. 1

[8] Joshua S Torrance, Ben M Sparkes, Lincoln D Turner, and Robert E Scholten. Sub-kilohertz laser linewidth narrowing using polarization spectroscopy. *Optics express*, 24(11):11396–11406, 2016. 1

[9] S. C. Bell, D. M. Heywood, J. D. White, and R. E. Scholten. Laser frequency offset locking using electromagnetically induced transparency. *Appl. Phys. Lett.*, 90:171120, 2007. 1

[10] W. Demtröder. *Laser Spectroscopy, Basic Concepts and Instrumentation*. Springer, Berlin, 2e edition, 1996. 1

[11] L. D. Turner, K. P. Weber, C. J. Hawthorn, and R. E. Scholten. Frequency noise characterization of narrow linewith diode lasers. *Opt. Communic.*, 201:391, 2002. 24

MOG Laboratories Pty Ltd
49 University St, Carlton VIC 3053, Australia
info@moglabs.com Tel: +61 3 9939 0677