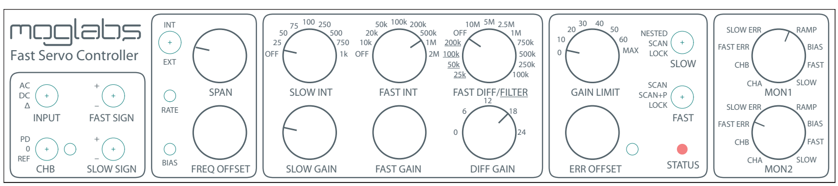
Fast servo controller

FSC100



Version 0.1.1, Rev 2 hardware

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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 instantaneous laser frequency and the desired or *setpoint* frequency. 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].

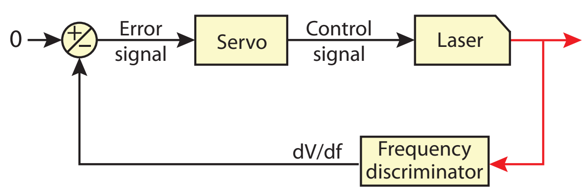


Figure 1.1: Simplified block diagram of the FSC.

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.

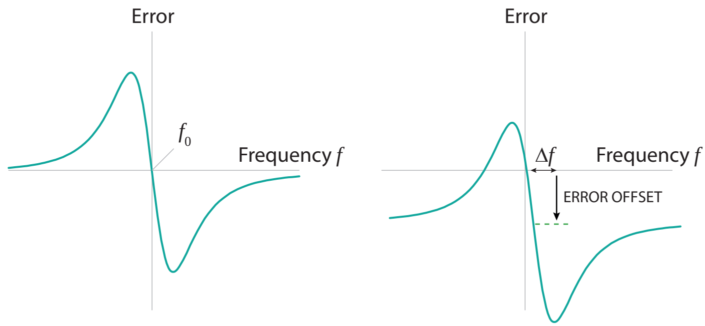


Figure 1.2: A theoretical dispersive error signal, proportional to the difference between a laser frequency and a setpoint frequency. An offset on the error signal shifts the lock point (right).

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 ($f = f_0 \pm 1\,\text{MHz}$). Regardless, the Fourier frequency of the disturbance is either 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 also 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 laser mode-hop.

The differentiator compensates for the finite response time of the system and has gain that increases at 20 dB per decade. To prevent oscillation and limit the influence of high-frequency noise, there is an adjustable gain limit that restricts the differentiator at high frequencies.

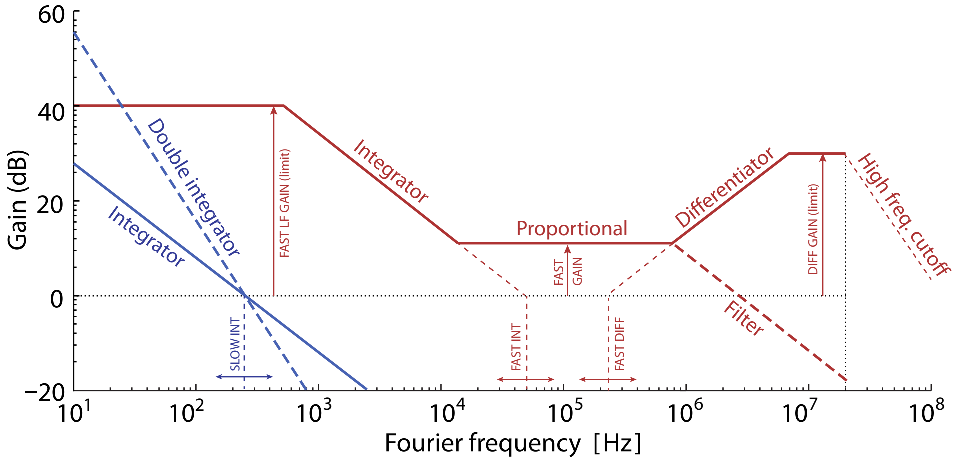


Figure 1.3: Conceptual Bode plot showing action of the fast (red) and slow (blue) controllers. The slow controller is either a single or double integrator with adjustable corner frequency. The fast controller is PID with adjustable corner frequencies and gain limits at the low and high frequencies. Optionally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

Alternatively, applications that do not require a differentiator may benefit from low-pass filtering of the fast servo response to further reduce the influence of noise. This can be achieved by switching on the “filter” mode, which causes the servo response to roll-off at the specified frequency.

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.

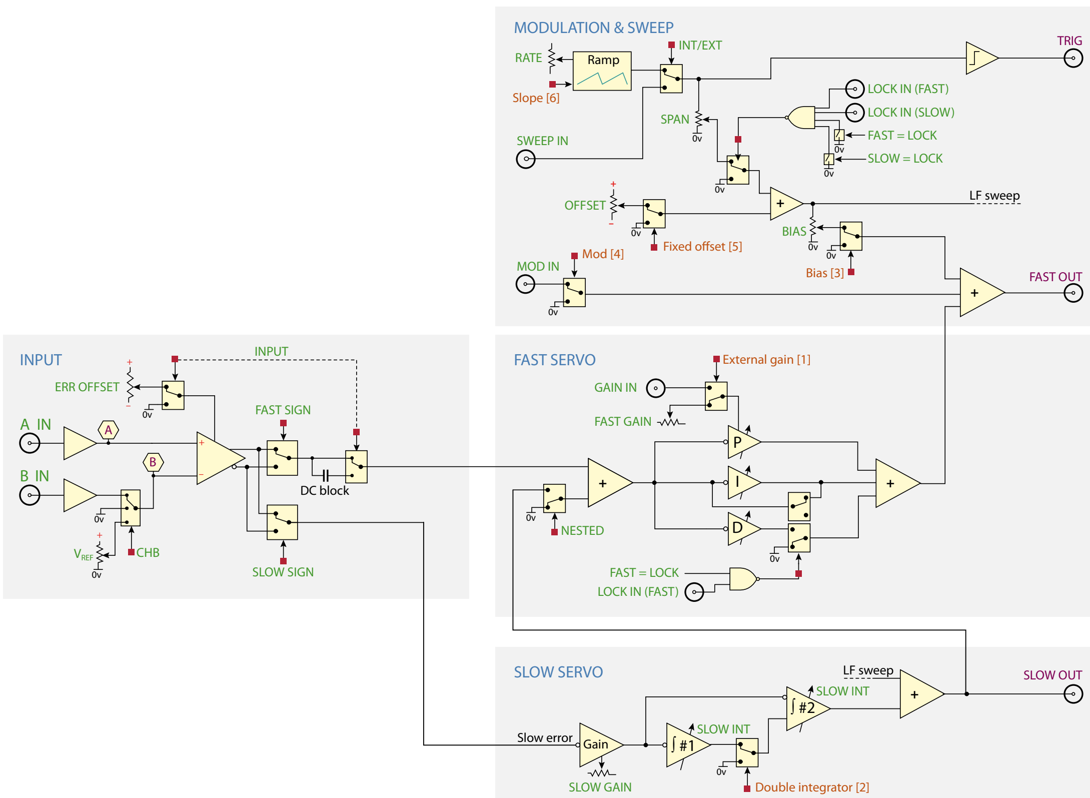


Figure 1.4: Schematic of the MOGLabs FSC. Green labels refer to controls on the front-panel and inputs on the back-panel, brown are internal DIPswitches, and purple are outputs on the back-panel.

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 selector switch, which chooses between the “B IN” SMA connector, $V_B = 0$ or $V_B = V_{\mathrm{REF}}$ as set by the adjacent trimpot.

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 ERR OFFSET for up to ±0.1 V shift, provided the INPUT selector is set to “offset” mode (Δ). Larger offsets can be achieved with the REF trimpot.

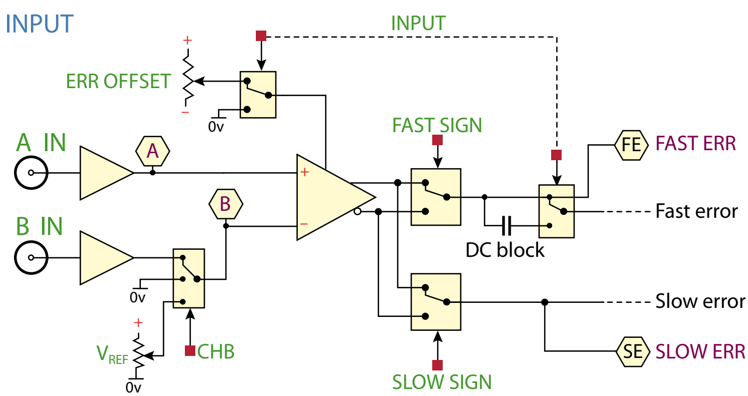


Figure 1.5: Schematic of the FSC input stage, showing coupling, offset and polarity controls. Hexagons are monitored signals available via the front-panel selector switches.

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 DIP2 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.

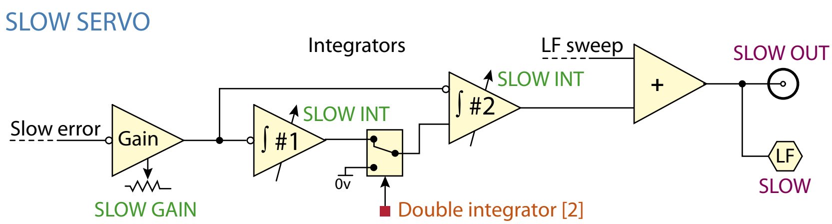


Figure 1.6: Schematic of slow feedback PI/PI^2 servo. Hexagons are monitored signals available via the front-panel selector switches.

The purpose of the slow servo is to compensate for long-term drifts and acoustic perturbations that are undesirable for the fast servo to respond to. For example, if the fast servo is modulating the laser current, then such drifts and perturbations can induce mode-hops, after which the laser cannot be brought back to the lock-point by the servo. Using a double-integrator ensures that the slow servo has the dominant response at low frequency.

1.1.3 Fast servo

The fast feedback servo (figure 1.7) is a PID-loop 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 mode-hops caused by external perturbations.

The fast servo has three modes of operation: SCAN, SCAN+P and LOCK. When set to SCAN, the feedback is disabled and only the bias is applied to the fast output (if enabled). When set to SCAN+P, the proportional feedback is applied, which allows for determination of the fast servo sign and gain while the laser frequency is still scanning, simplifying the locking and tuning procedure (see §3.2). In LOCK mode, the scan is halted and full PID-controller is engaged.

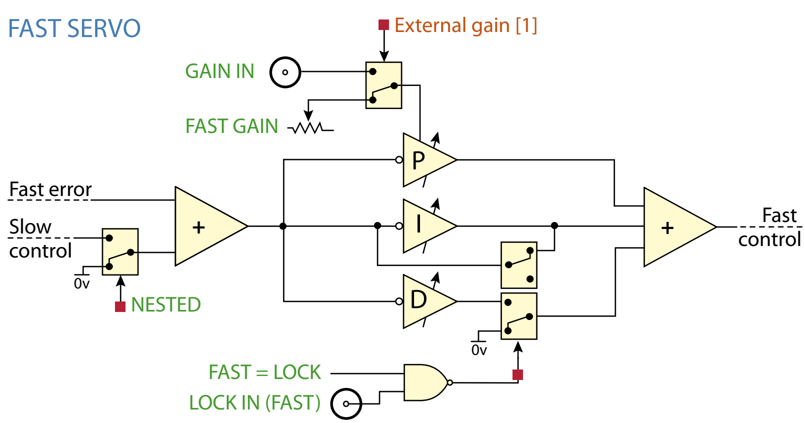


Figure 1.7: Schematic of fast feedback servo PID controller.

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 SLOW switch to “NESTED”. In this mode it is recommended that the double-integrator in the slow channel be disabled with DIP2 to prevent triple-integration.

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 an internal four-position range switch and a single-turn trimpot marked “RATE” on the front-panel.

The fast and slow servo loops can be individually engaged with either a TTL input to the rear-panel, or the associated front-panel switches. Setting either loop to LOCK stops the sweep and activates stabilisation.

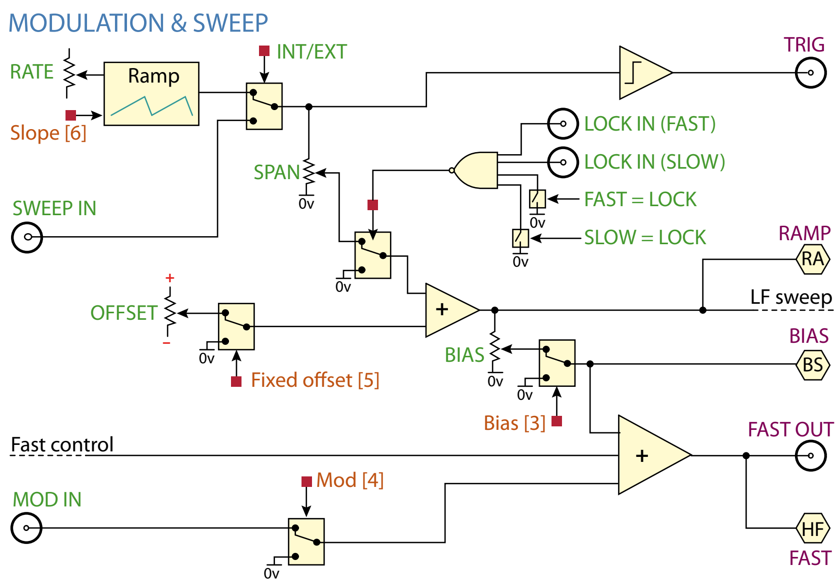


Figure 1.8: Sweep, external modulation, and feedforward current bias.

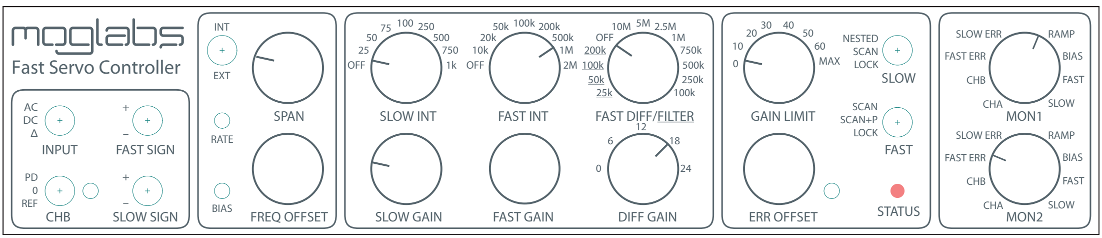
The ramp can also be added to the fast output by enabling DIP3 and adjusting the BIAS trimpot, which may be useful for direct current modulation of the laser. Note that many laser controllers (such as the MOGLabs DLC) will generate the necessary bias current using the slow servo signal and it is unnecessary to also generate it within the FSC.

2. Connections and controls

2.1 Front panel controls

The front panel of the FSC has a large number of configuration options that allow the servo behaviour to be tuned and optimised.

Please note that switches and options may vary between hardware revisions, please consult the manual for your specific device as indicated by the serial number.



2.1.1 Configuration

INPUT 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.

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

FAST SIGN Sign of the fast feedback.

SLOW SIGN Sign of the slow feedback.

2.1.2 Ramp control

The internal ramp generator provides a sweep function for scanning the laser frequency through a piezo actuator, diode injection current, or both. A trigger output synchronised to the ramp is provided on the rear panel (TRIG).

INT/EXT Internal or external sweep mode.

RATE Trimpot to adjust internal sweep rate.

BIAS When DIP3 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.

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

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

2.1.3 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 disabled or adjusted from 25 Hz to 1 kHz.

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

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/FILTER Controls the high-frequency servo response. When set to "OFF", the servo response remains proportional. When turned clockwise, the differentiator is enabled with the associated corner frequency. Note that decreasing the corner frequency increases the action of the differentiator. When set to an underlined value, the differentiator is disabled and instead a low-pass filter is applied to the servo output. This causes the response to roll-off above the specified frequency.

DIFF GAIN High-frequency gain limit on the fast servo; each increment changes the maximum gain by 6 dB. Has no effect unless the differentiator is enabled.

2.1.4 Lock controls

GAIN LIMIT Low-frequency gain limit on the fast servo, in dB. MAX represents the maximum available gain.

ERROR OFFSET DC offset applied to the error signals when INPUT mode is set to Δ. Useful for precise tuning of the locking point or compensating for drift in the error signal. The adjacent trimpot is for adjusting the error offset of the slow servo relative to the fast servo, and may be adjusted to ensure the fast and slow servos drive towards the same exact frequency.

SLOW Engages the slow servo by changing SCAN to LOCK. When set to NESTED, the slow control voltage is fed into the fast error signal for very high gain at low frequencies in the absence of an actuator connected to the slow output.

FAST Controls the fast servo. When set to SCAN+P, the proportional feedback is fed into the fast output while the laser is scanning, allowing the feedback to be calibrated. Changing to LOCK engages the full PID control action.

STATUS 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.

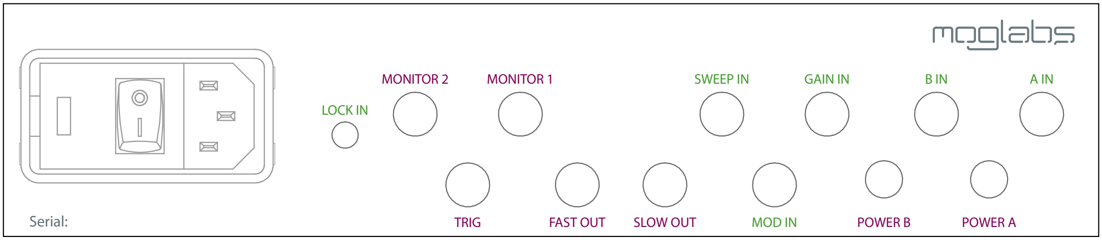
Blue Lock engaged and error signal is within limits.

2.1.5 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.

CHA	Channel A input (−1 ... +1 V)
CHB	Channel B input (−1 ... +1 V)
FAST ERR	Error signal of the fast servo
SLOW ERR	Error signal of the slow servo
RAMP	Ramp as applied to SLOW OUT
BIAS	Ramp as applied to FAST OUT when DIP3 enabled
FAST	FAST OUT control signal
SLOW	SLOW OUT control signal

2.2 Rear panel controls and connections

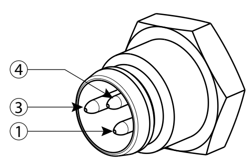


All connectors are SMA, except as noted. All inputs are over-voltage protected to ±15 V. All outputs have valid operating range of ±2.5 V, with maximum ±5 V.

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 channels *A* and *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. Ensure that photodetectors are switched off when being connected to the power supplies to prevent their outputs railing.



1	+12 V
3	−12 V
4	0 V

Figure 2.1: M8 connector pinout for POWER A, B.

GAIN IN Voltage-controlled proportional gain of fast servo, ±1 V, corresponding to the full-range of the front-panel knob. Replaces front-panel FAST GAIN control when DIP1 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 High-bandwidth modulation input, added directly to fast output, ±1 V. Requires DIP4 to be enabled.

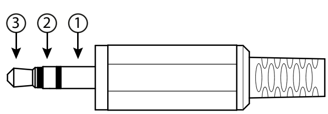
SLOW OUT Slow control signal output, normally connected to a piezo driver or other slow actuator.

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 several 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	External MOD	Disabled	Enabled
5	Offset	Normal	Fixed at midpoint
6	Sweep	Positive	Negative

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 OFF if using “nested” slow and fast servo operation mode.

DIP 3 Generate a bias current in proportion to the slow servo output to prevent mode-hops. Only enable if not already provided by the laser controller. Should be OFF when the FSC is used in combination with a MOGLabs DLC.

DIP 4 Enables external modulation through the MOD IN connector on the back-panel, which is added directly to FAST OUT.

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

DIP 6 Reverses the direction of the sweep.

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 (AN002) is available that provides practical advice on implementing a PDH apparatus.

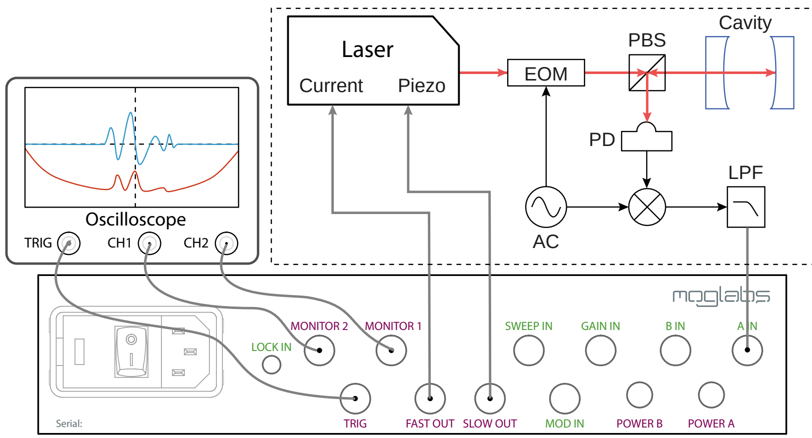


Figure 3.1: Simplified schematic for PDH-cavity locking using the FSC. An electro-optic modulator (EOM) generates sidebands, which interact with the cavity, generating reflections that are measured on the photodetector (PD). Demodulating the photodetector signal produces a PDH error signal.

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 fast current modulation via an SMA connector is required for operation with the FSC. The headboard should be connected directly to the FSC "FAST OUT".

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 DIP13 ("STACK external") of the DLC to enabled.
- Set DIP3 ("bias generation") of the FSC to disabled[2].
- Set FREQUENCY and SPAN to zero on the DLC.
- Ensure that SWEEP on the FSC is "INT".
- Set FREQ 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 zoom in 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 mVpp.
- Set INPUT to "Δ" (offset mode) and CHB to "0".
- Set MONITOR 1 to "FAST ERR" and observe on an oscilloscope. Adjust the ERR OFFSET knob until the DC level shown is zero[3].
- Reduce the FAST GAIN to zero.
- Set both FAST and SLOW to "SCAN", and locate the resonance using the sweep controls.
- 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 SIGN switch and try again.
- Set FAST DIFF to "OFF" and GAIN LIMIT to 30. Reduce FAST INT to $\sim$100 kHz.
- Set FAST 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 FREQ OFFSET and ERR OFFSET.
- Optimise the lock by adjusting the FAST GAIN and FAST INT while observing the error signal. It may be necessary to relock the servo after adjusting the integrator.

[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.

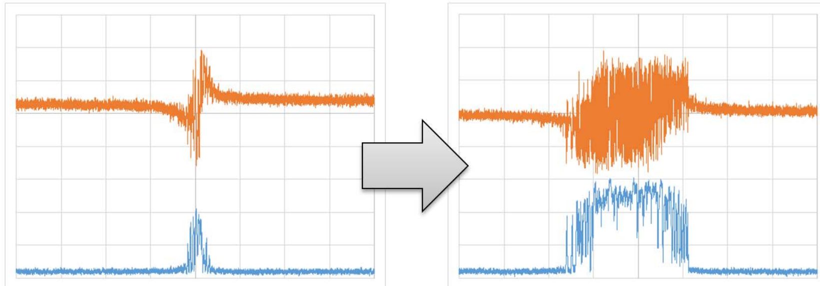


Figure 3.2: Scanning the laser with P-only feedback on the fast output while scanning the slow output causes the error signal (orange) to become extended when the sign and gain are correct (right). In a PDH application, the cavity transmission (blue) will also become extended.

- Set SLOW GAIN to mid-range and SLOW INT to ~100 Hz.
- Set SLOW mode to "LOCK". If the servo unlocks immediately, try inverting the SLOW SIGN. It may also be necessary to make small adjustments to the ERR OFFSET and associated trimpot.
- 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 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]. Good 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 "FAST ERR".

High-bandwidth locking typically involves first achieving a stable lock using only the fast servo, and then using the slow servo to improve the long-term 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.

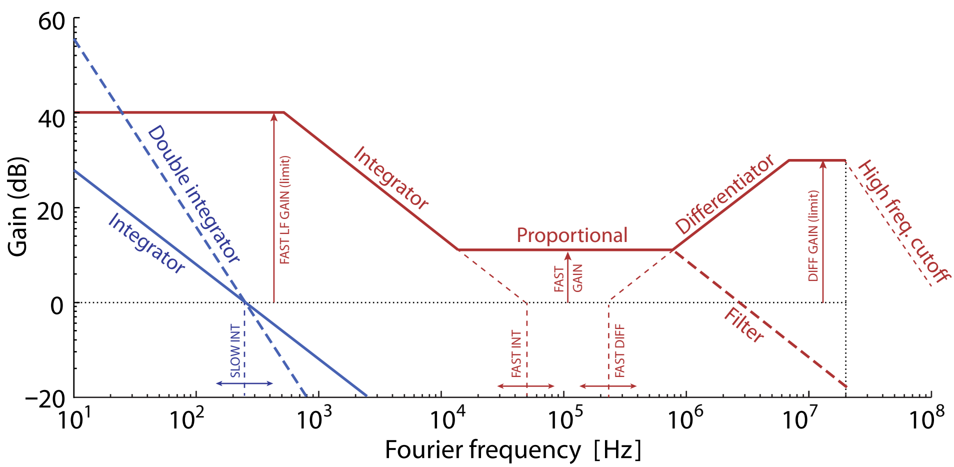


Figure 3.3: Conceptual Bode plot showing action of the fast (red) and slow (blue) controllers. The corner frequencies and gain limits are adjusted with the front-panel knobs as labelled.

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, SCAN+P mode 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 (RAM) 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.

In particular, the high gain of the integrators means that the lock can be sensitive to ground loops in the signal-processing chain, and care should be taken to eliminate or mitigate these. The earth of the FSC should be as close as possible to both the laser controller and any electronics involved in generating the error signal.

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

In some applications, the error signal is bandwidth-limited and only contains uncorrelated noise at high frequencies. In such scenarios it is desirable to limit the action of the servo to prevent coupling this noise back into the control signal. A "filter" option is therefore provided to cause the fast servo response to roll-off at a specific frequency. This option is mutually-exclusive to the differentiator, and should be tried if enabling the differentiator is seen to increase the measured noise.

The slow servo can then be optimised to minimise the over-reaction to external perturbations. The high gain integrators 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 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. Similarly, activating the double-integrator (DIP2) may improve stability by ensuring that the overall gain of the slow servo system is higher than the fast servo at these lower frequencies.

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).

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 V.

B.2 120/240 V conversion

The controller can be powered from AC at 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).

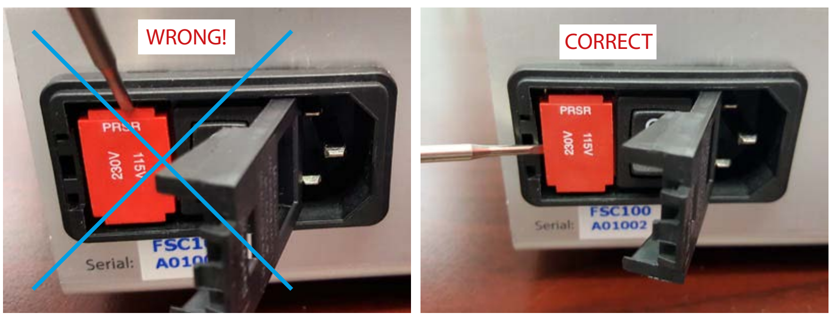


Figure B.3: To extract the fuse cartridge, insert a screwdriver into a recess at the *left* of the cartridge.

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.

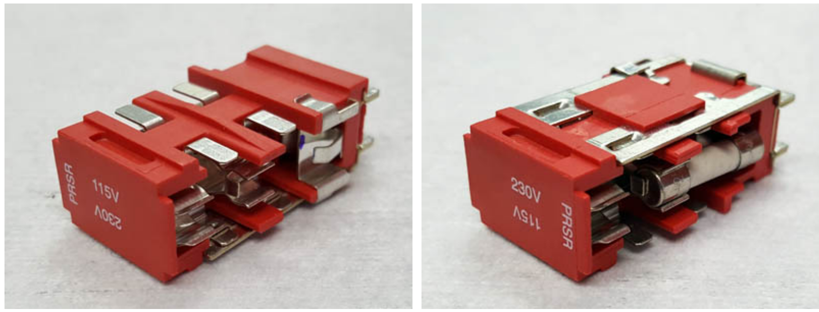


Figure B.4: 230 V bridge (left) and fuse (right). Swap the bridge and fuse when changing voltage, so that the fuse remains uppermost when inserted.

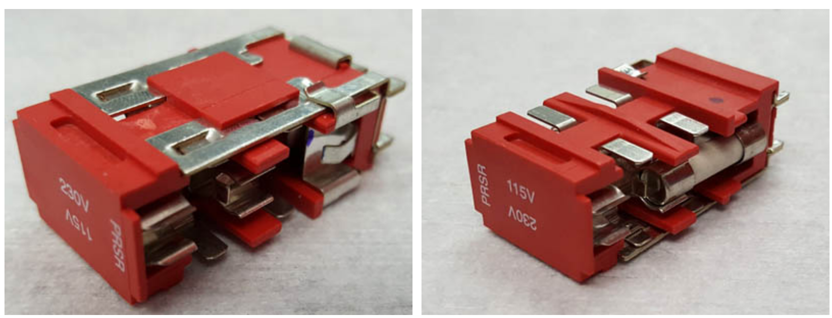


Figure B.5: 115 V bridge (left) and fuse (right).

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