Four-Channel Coil Driver User's Manual

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1. Safety Notices

1.1 Warnings

The following warning and cautions are applicable to this device:

GROUNDING - The coil driver must be connected to AC (mains) power using a three-wire power cord with a protective ground contact. Always use a three-prong outlet that is properly grounded. Do not operate the device with any two-conductor outlet or extension cord. If using an extension cord, use a three-conductor version.

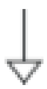
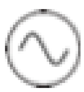
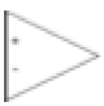
LINE FUSE - Only use line fuses with the required rated current and voltage, and the specified type (normal blow, time delay, etc.). Do not use repaired fuses or short-circuited fuse holders; to do so could cause a shock or fire hazard.

INTERNAL ADJUSTMENTS - Internal adjustments should be made only by trained service personnel. When performing internal adjustments, use adequate safety precautions to prevent the risk of electric shock. *High voltages from the AC (mains) power line will be present!*

LINE VOLTAGE SELECTION – The coil driver can operate from an AC (mains) power source with voltage between 90 and 264 VAC and a line frequency between 47 and 63 Hz. There is no line voltage selection switch - the internal power supply will automatically adjust its operation for the applied line voltage.

1.2 Symbols

The following symbols are used in this manual and/or on the coil driver:

Symbol	Description
	Caution! – Risk of electric shock
	Caution! – Risk of damage to equipment
	Earth Ground
	Reference Ground (not necessarily connected to earth ground)
	Voltage Source
	Amplifiers (op-amp, line driver, receiver, etc.)
	Resistor or General Impedance
	Capacitor
	Twisted-Pair Cable

1.3 Package Contents

Upon receiving the four-channel coil driver, inspect the packaging for damage. If the packaging shows signs of damage or excessive shock, notify the shipping company and then contact ColdQuanta. Keep packing materials, per the instructions of the shipping company.

The shipment should contain the following items:

- Four-channel coil driver
- Input cables with attached three-pin LEMO plugs, quantity = 4
- Three-prong power cord
- User's manual (this document)

If any of these items are missing, please contact ColdQuanta to obtain replacements.

2. Specifications

Parameter	Symbol	Conditions	Min	Typ	Max	Unit
Output Current[1]	I_S	$R_{Load} < 1\Omega$	-3.0		+3.0	A
Voltage Input Range Differential Common-Mode	 V_I V_{CM}		 -3 -7		 +3 +7	 V V
Input Impedance Differential Common-Mode	 Z_I Z_{CM1} , Z_{CM2}	 DC Resistance DC Resistance	 9.99	 20	 10.1	 MΩ MΩ
Accuracy Zero-Point Offset Slope		 $V_I = 0$	 -1 0.999	0.1	 1 1.001	% mA A/V
Current Monitor Slope Bandwidth[2]			 0.99	 1.00 16	 1.01	 V/A kHz
Dynamic Performance[3] Full Power Bandwidth (-3 dB) Step Response[4]		 0 – 3 A		 500 1		 Hz ms
Load Impedance for Stability DC Resistance Inductance	 R_{Load}		 2 0.5		 6 4	 Ω mH
Output Noise Integrated Broadband Peak		 10 Hz – 1 MHz 10 Hz – 10 MHz		 200 10	 720 20	 μA_{RMS} μA_{RMS}
Common Mode Rejection Ratio (CMRR) f = 100 Hz f = 1 kHz f = 10 kHz f = 100 kHz		$Z_0 = 100\ \Omega$		 96 95 82 60		dB
AC Power Requirements Voltage Frequency			 90 47		 264 63	 VAC Hz
Physical Dimensions Weight		h x w x d		 5.22 x 8.37 x 16 13.3 x 21.3 x 40.6 10 4.54		 inches cm lbs kg

[1] Output currents only specified for load resistances R_{LOAD} less than 1 Ω.

[2] Each current monitor output consists of a series 100 Ω resistor and 0.1 μF capacitor to the ground terminal. The bandwidth is only specified when connected to a high-impedance load, such as an oscilloscope input.

[3] Dynamic performance, including bandwidth and step response, depends on the inductance of the load.

[4] Values from 10% to 90% of the pulse height.

3. Description

3.1 Overview

ColdQuanta's four-channel coil driver consists of four bidirectional voltage-controlled current sources that are designed to drive inductive loads. The output currents are directly proportional to the input voltage, i.e. an input voltage of +1.0 V will set the output current to +1.0 A. Each channel is independently capable of driving up to ±3 A. Each channel has its own set of controls, indicators, input, and output. Balanced, differential inputs isolate the coil driver from control electronics.

Figures 1 and 2 show the layouts of the front and rear panels, respectively. Descriptions of the switches, jacks, and indicators appear throughout this section.

3.2 Power Requirements

The coil driver is powered with a standard three-prong power cord that inserts into the AC Power Module on the rear panel (see Figure 2). The unit can operate from a 90 to 264 VAC and a line frequency between 47 and 63 Hz. The AC power module contains the line fuse, which is a medium-blow type rated at 1 A / 250 V and measuring 5 × 20 mm.

HIGH VOLTAGE WARNING!

The coil driver must be connected to AC (mains) power using a three-wire power cord with a protective ground contact. Always use a three-prong outlet that is properly grounded. Do not operate the device with any two-conductor outlet or extension cord. If using an extension cord, use a three-conductor version.

HIGH VOLTAGE WARNING!

Only use line fuses with the required rated current and voltage, and the specified type (normal blow, time delay, etc.). Do not use repaired fuses or short-circuited fuse holders; to do so could cause a shock or fire hazard.

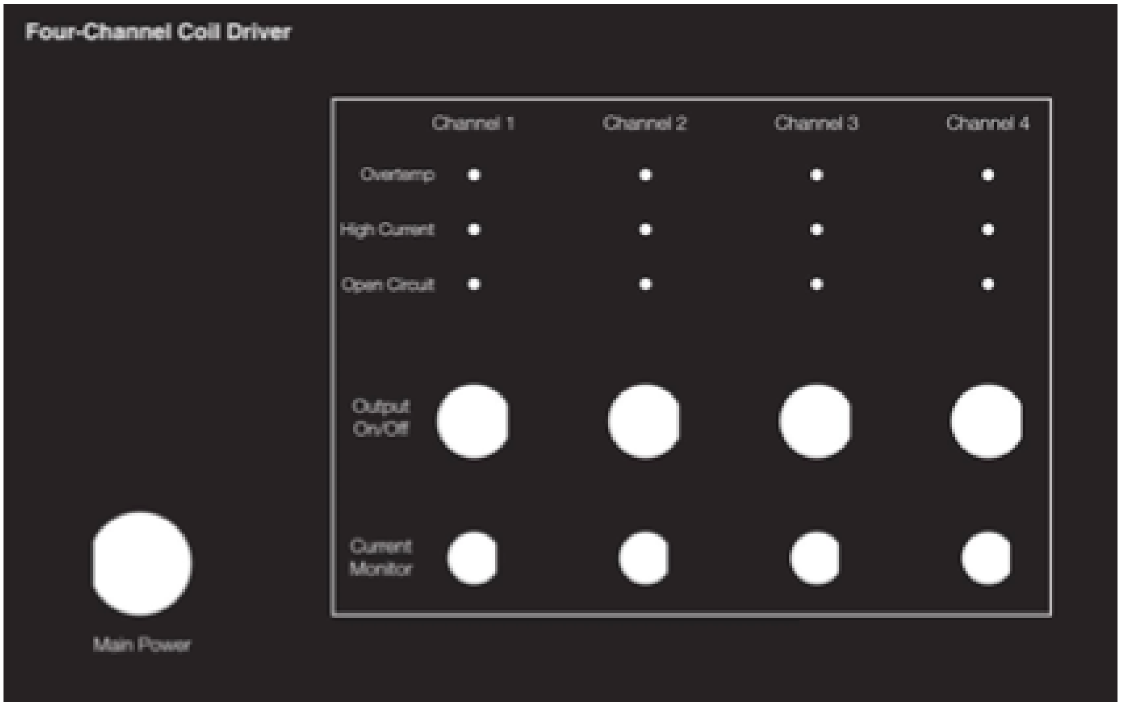


Figure 1: Front panel layout of the four-channel coil driver.

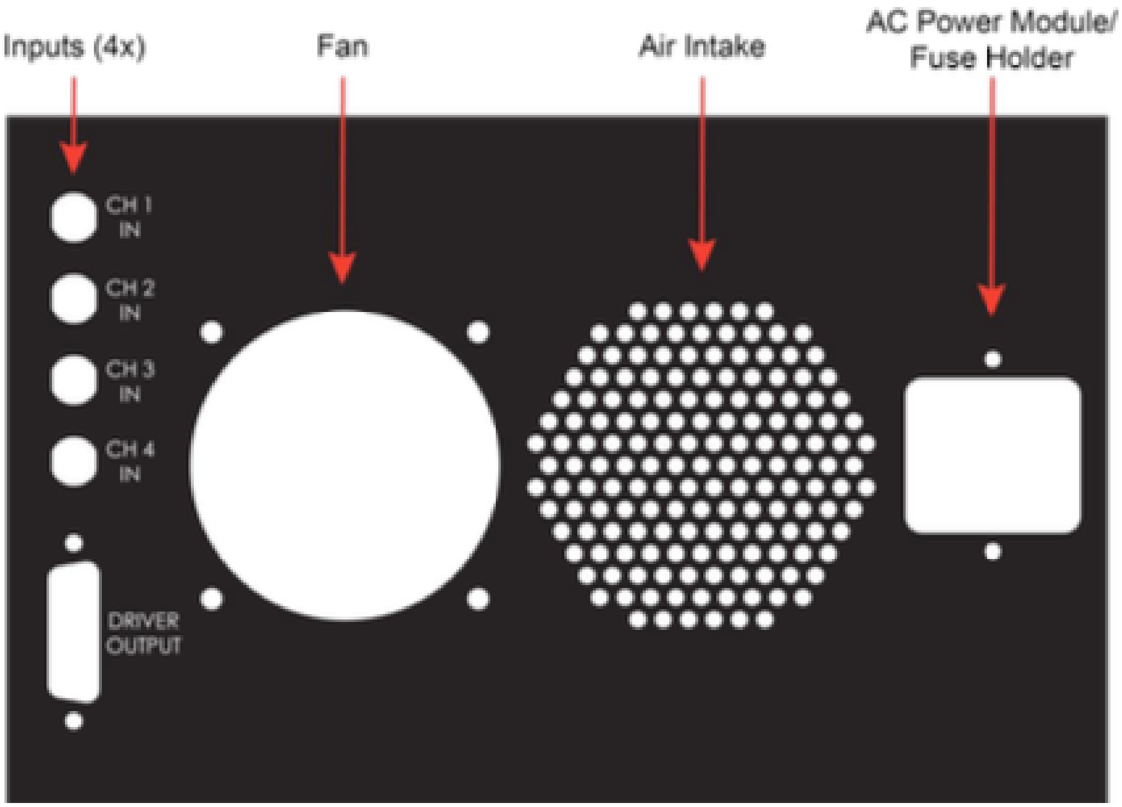


Figure 2: Rear panel layout of the four-channel coil driver.

3.3 Operation

To turn on to the coil driver, use the "Main Power" switch on the far left side of the front panel. Applying power to the coil driver does *NOT* enable the outputs.

The four black buttons on the front panel marked "Output On/Off" are used to enable and disable the each channel's output. By pressing this button, an internal relay electrically connects that channel's output to the load; pressing this button again unlatches the relay, breaking the electrical connection to the load. When a channel is enabled, the blue LED on the "Output On/Off" button will be illuminated.

When a channel's output is enabled, a fault condition will automatically disable that output. The output can be re-enabled by pressing the "Output On/Off" button again. Pressing this button resets all faults conditions; however, if the fault condition still exists, the output will be immediately disabled.

3.4 Monitors

Each channel has a Current Monitor BNC jack whose output, in volts, is equal to the output current, in amperes. This monitor output is referenced to earth ground.

3.5 Faults

Several protection features have been incorporated into the coil driver to protect both the load and the driver. Fault conditions are indicated with the LEDs on the front panel. These faults are:

Overtemp – The coil driver is designed to operate continuously with all channels simultaneously outputting currents up to ±3 A. However, blocking the air intake and fan on the rear panel (see Figure 2) may cause the internal temperature to exceed the high temperature limit. If this happens, the "Overtemp" LED will illuminate and the output will be disabled.

High Current – This LED indicates one of several internal circuit faults, including permanent damage to the output-stage power transistor. If the output is connected to earth ground, a high current fault will occur. This indicator does not reflect any kind of current limiting.

Open Circuit – If no load is connected to the output, the "Open Circuit" LED will illuminate when the user tries to enable the output. If this happens, check the output cable connecting the driver to the load for bad connections.

4. Connecting the Inputs

The current outputs of the coil driver are controlled with input voltages applied to the LEMO jacks at the left side of the rear panel (see Figure 2). The output current, in amperes, is equal to the differential input voltage, in volts. Input protection prevents either of the input voltages from exceeding ±10 V (with respect to the driver's ground).

To reject ground noise and electromagnetic interference the inputs are configured as balanced receivers with very high common-mode input impedances. This architecture is particularly useful for rejecting pick-up at 50/60 Hz and its harmonics.

The subject of balanced circuitry and common-mode rejection is too extensive to be thoroughly reviewed here. For readers who want to learn more about this topic, several references are provided [1-5]. In particular, this subject arises extensively in high-end and professional audio, and many useful discussions can be found within this community.

4.1 Pin Connections

Figure 3 shows the pin diagram for the input connectors. The coil driver will output a positive current when the voltage applied to the + terminal (pin 2) is larger than the voltage applied to the – terminal (pin 3). Pin 1, which is closest to the red notch, is unconnected inside of the coil driver.

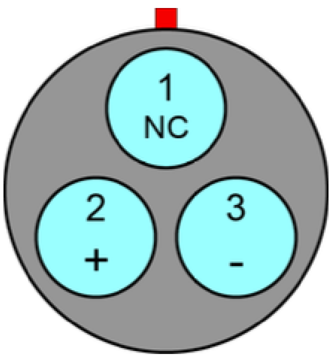


Figure 3: Pin diagram for the input connectors. Pin 1 is closet to the red notch.

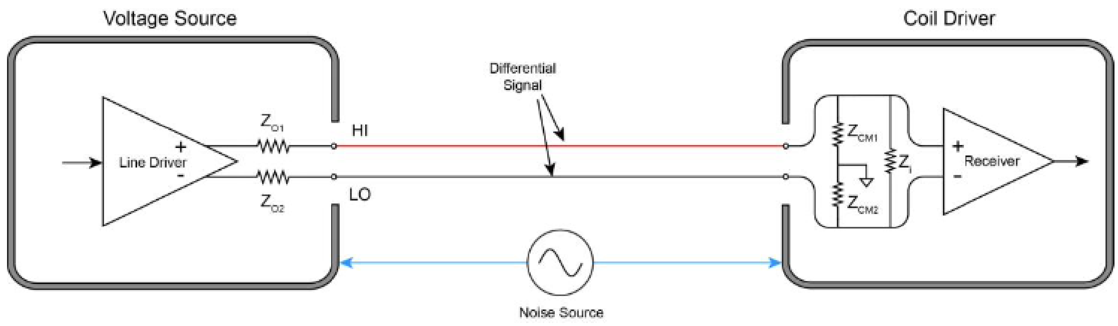


Figure 4: The four-channel coil driver uses balanced receivers to reject ground noise and provide immunity to electromagnetic interference.

4.2 THE BALANCED INTERFACE

The + and – inputs together form a balanced receiver. Here, the coil driver's output, in amperes, is equal to the voltage difference, in volts, applied across the two inputs. The DC resistance from each of these inputs to the internal ground is 10 MΩ.

Balanced inputs provide excellent common-mode rejection, helping to keep the inputs less susceptible to electromagnetic interference and ground noise. To better understand how balanced circuitry provides common-mode rejection, Figure 4 shows a schematic of a voltage source connected to one of the coil driver's inputs. Here, a line driver outputs a differential signal onto two lines labeled HI and LO. These lines have (common-mode) source impedances Z_{01} and Z_{02}, and a differential source impedance of $Z_{01} + Z_{02}$. At the coil driver, the (common-mode) load impedances to the coil driver's ground are Z_{CM1} and Z_{CM2}, and the differential load impedance is Z_I.

In the coil driver, the receiver is a differential amplifier that produces an output only in response to a potential *difference* across its inputs. As a result, common-mode signals (i.e. signals that appear identically on both of the inputs) are suppressed via subtraction. Assume that the driver is referenced to a ground that has superimposed on it a noise voltage, as measured with respect to the receiver's ground. The voltage at each of the receiver's inputs, again measured with respect to the receiver's ground, is the sum of the desired transmitted signal and the unwanted ground noise voltage. The ground noise will appear identically on both of the inputs, and therefore will be removed by the receiver upon subtraction.

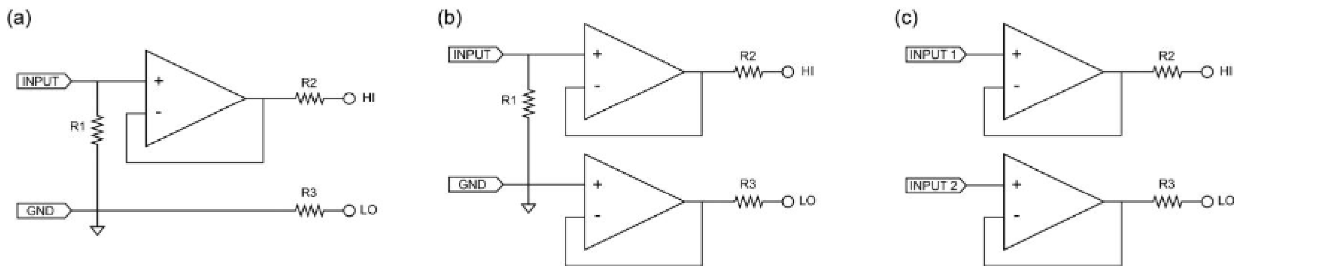


Figure 5: Balanced drivers: (a) In the single op-amp circuit, setting R2 = R3 approximately matches the source impedances for the HI and LO lines. (b) To account for the rise in op-amp output impedance as a function of frequency, the ground reference can also be buffered with an op-amp. (c) Two DAC channels can also be used.

4.3 Balanced Line Drivers

The coil driver's inputs must be properly driven to maximize common-mode rejection. To see this, note that the voltage on the HI line will be slightly reduced due to the voltage divider formed by Z_{01} and Z_{CM1}. Similarly, the voltage on the LO line will also be reduced, this time by the voltage divider formed by Z_{02} and Z_{CM2}. For perfect subtraction of common-mode signals, the voltage dividers should be matched as well as possible. Given the limitations imposed by the 1% tolerance of typical resistors, the mismatch between the two voltage dividers can be minimized by reducing the source impedances and increasing the load impedances, i.e. $Z_0 \ll Z_{CM}$. To meet this condition for Z_{CM} = 10 MΩ, the driver should have a low output impedance. For example, with Z_0 = 100 Ω the voltage on each line will be reduced by a factor of 10 MΩ / (100 Ω + 10 MΩ) ≈ 0.99999. Assuming that the source impedances are set with resistors with a tolerance of 1%, the voltage dividers on the HI and LO lines will be matched to 1 part in 10^{-7}, corresponding to a common-mode rejection ratio (CMRR) of 20 log 10^{-7} = -140 dB. The actual CMRR that can be attained will be limited by the performance of the receiver's subtraction circuit. Actual CMRR values typically exceed 90 dB for frequencies up to 1 kHz.

Figure 5 shows three op-amp circuits recommended as balanced line drivers. Figure 5a shows the simplest line driver: a single op-amp buffer. Here, the source impedances for the HI and LO lines are set by R2 and R3, respectively. The line impedances are balanced when R2 = R3.

The circuit in Figure 5a assumes a perfect op-amp, i.e. one with zero output impedance. While this is a good assumption at low frequencies, real-world op-amps have output impedances that increase with frequency (usually a result of stray inductance in the op-amp leads). Due to this frequency-dependence, the source impedances of the two lines can become unbalanced at higher frequencies. The circuit in Figure 5b is a solution: buffer the driver GND with the same op-amp used to buffer the INPUT signal. For convenience, the two buffers can be part of a dual op-amp packaged in a single chip. Now, the frequency dependence of the two source impedances will be matched, helping to prevent degradation of CMRR at higher frequencies.

Figure 5c shows a circuit that may offer additional noise rejection when used with certain digital-to-analog converters (DACs). Here, both the + and – inputs of the coil driver are driven with voltages produced by independent DACs.

Another common architecture for balanced drivers is the active floating source. This circuit is available in a single-chip, including Analog Devices' SSM2142 and Texas Instruments' DRV134/135. Unlike the circuits in Figure 5, the active floating source has very high common-mode output impedances that make the circuit's stability strongly dependent on cable capacitance and inductance. For this reason, the active floating source is not recommended.

SUMMARY

Do's

- Use a balanced line driver to provide good common-mode rejection.
- Use dual op-amps to keep source impedances matched with frequency.
- Minimize output impedance to reduce the dependency of CMRR on impedance mismatches.

Don'ts

- Use an active floating source.

4.4 Shielding and Grounding the Input Cables

This section shows how to connect the coil driver's inputs to four types of voltage sources:

(1) an earth-grounded balanced line driver

(2) a floating balanced line driver

(3) an earth-grounded single-ended line driver

(4) a floating single-ended line driver

These wiring configurations are shown schematically in Figure 6. Earth-grounded balanced line drivers are preferred since they are less likely to generate common-mode voltages large enough to exceed the input range of the receiver. However, floating line drivers may also be used. In addition, single-ended (i.e. unbalanced) line drivers may be used, although there will be no rejection of common-mode noise and pick-up.

All of the coil driver's internal circuitry is referenced to AC earth ground. Improperly referenced and/or grounded voltage sources can generate common-mode voltages on the input lines that can exceed the input range of the coil driver's balanced receivers. Under these conditions, the coil driver will not operate.

To maximize common-mode rejection of ground noise and electromagnetic interference, the use of shielded, twisted-pair cables is *strongly* recommended. This section shows where to connect cable shields so that ground loops and shield current induced noise (SCIN) are avoided. In addition, several improper connections involve the cable shields are described.

4.4.1 Proper Wiring of the Control Inputs

The coil driver is shipped with four input control cables. On one end of each cable, the two signal wires have been soldered to a LEMO plug that mates with the control inputs on the rear panel of the coil driver. The cable drain wires have not been soldered to pin 1 of their respective LEMO plugs. In addition, the cable shield has *not* been connected to the metal housing of the LEMO plug, as described in Section 4.4.2.3.

The other ends of the control cables have not been connectorized. The user should carefully review the following scenarios to determine the proper way to connect the cables' shields and signal wires to voltage sources.

4.4.1.1 Earth-Grounded Balanced Line Drivers (Preferred)

The preferred wiring configuration to the coil driver's inputs is shown in Figure 6a. Here, a voltage source and balanced line driver that are referenced to earth ground drives a shielded, twisted-pair cable. The cable shield should be directly connected to earth ground *only* at the voltage source. At the receiver (i.e. the coil driver's input), the cable shield should *not* be connected to earth ground or the coil driver's chassis.

To obtain the best shielding and common-mode rejection, the electrical connection from the cable shield to earth ground should be made with a wire soldered directly to the internal ground of the voltage source. Do not rely on the electrical connection to earth ground through a metal enclosure! A soldered wire provides a lower impedance path to earth ground.

4.4.1.2 Floating Balanced Line Drivers

The voltage source may be floating in some situations, such as when the circuit is powered by batteries or transformer-isolated from the AC power line (see Figure 6b). In this case, the voltage of the floating reference ground, as measured with respect to the receiver's ground, will be a common-mode signal that is rejected by the receiver. Ensure that the outputs of the floating source have not drifted out of the receiver's common-mode input range.

For a floating voltage source, the cable shield should be connected *only* to the reference ground of the voltage source. At the receiver (i.e. the coil driver's input), the cable shield should *not* be connected to earth ground or the coil driver's chassis.

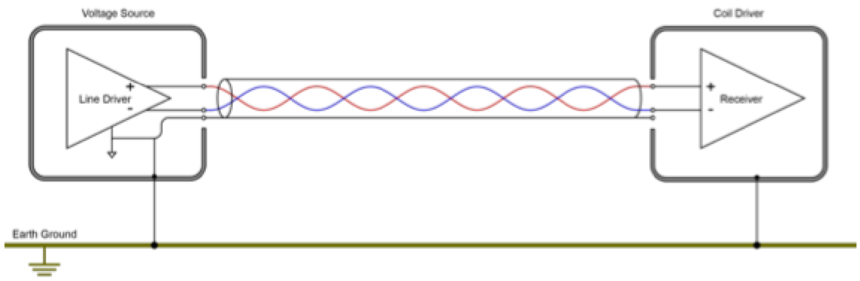
4.4.1.3 Earth-Grounded Single-Ended Line Drivers

The coil driver can be controlled with single-ended voltage sources. However, there will be no rejection of common-mode noise and pickup. To use an earth-grounded single-ended voltage source with the supplied input cable, the LO signal line and cable shield should be tied to earth ground at the voltage source (see Figure 6c). At the receiver (i.e. the coil driver's input), the shield should *not* be connected to earth ground or the coil driver's chassis.

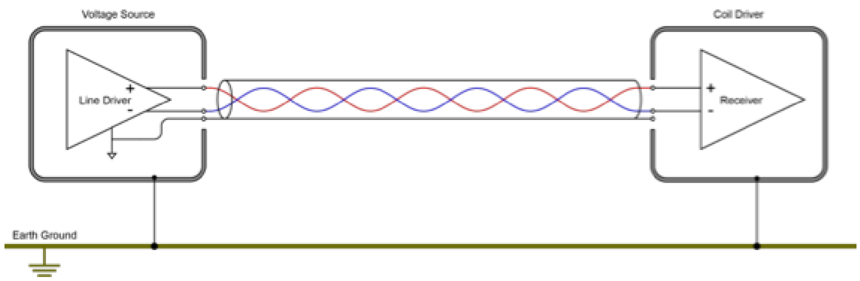
4.4.1.4 Floating Single-Ended Line Drivers

Similar to balanced line drivers, the coil driver may be controlled with a single-ended voltage source that is floating. Again, care must be taken to ensure that the control voltages, as measured with respect to the coil driver's ground, do not drift out of the coil driver's common-mode input range. The cable shield should be connected *only* to the reference ground of the voltage source (see Figure 6d). At the receiver (i.e. the coil driver's input), the shield should *not* be connected to earth ground or the coil driver's chassis.

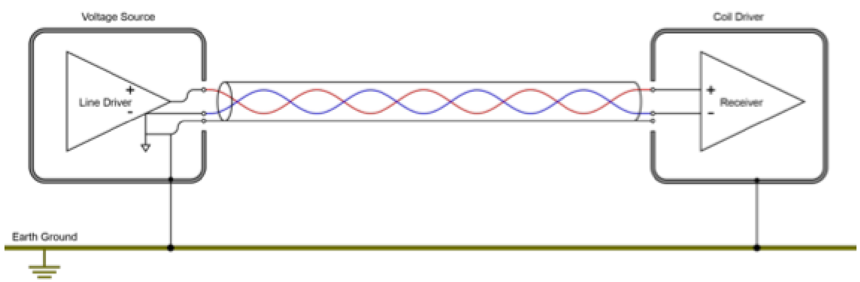
(a) Earth-Grounded Balanced Driver (Preferred)



(b) Floating Balanced Driver



(c) Earth-Grounded Single-Ended Driver



(d) Floating Single-Ended Driver

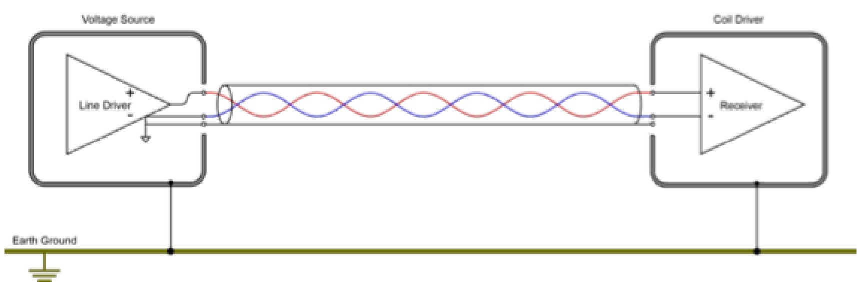


Figure 6: Connecting the coil driver to voltage sources. (a) The preferred setup uses an earth-grounded balanced line driver and shielded twisted-pair cable to achieve high rejection of common-noise noise and pick-up. (b) If the voltage source is floating, the cable shield should be connected to the floating ground of the line driver. (c) Single-ended voltage sources can be used with the coil driver, although there will be no rejection of common-mode signals. (d) For a floating single-ended voltage source, the cable shield and negative signal line should both be connected to the floating ground of the voltage source.

4.4.2 Improper Wiring of the Control Inputs

Figure 7 shows three improper techniques for wiring the coil driver's inputs: a cable shield grounded at both ends, a cable shield connected only at the receiver, and a cable shield connected to the metal housing of the coil driver's input plug. The problems that arise from these connections are described below.

4.4.2.1 Shield Earth-Grounded at Two Points

As indicated by the purple line in Figure 7a, a cable shield grounded at both of its ends creates a ground loop. Due to this loop, voltage noise on the earth ground will drive a noise current through the cable shield. Imperfections in cable manufacturing give rise to imbalances in magnetic and capacitive couplings between the cable's shield and two signal lines. As a result, currents flowing along the shield will couple differentially into the signal lines. The coupled noise will appear as normal-mode to the receiver, and will therefore not be rejected. This effect is known as *shield current induced noise*, or SCIN.

4.4.2.2 Cable Shield Connected only at Receiver

As mentioned in the previous section, imperfections in cable manufacturing give rise to an imbalance in capacitive coupling between the cable's shield and each of two signal lines. These cable capacitances interact with the line driver's common-mode output impedances to form low-pass filters. If the shield is connected only at the coil driver input, as shown in Figure 7b, then voltage noise on the earth ground will be filtered differently on each of the two signal lines. The result is a significant degradation of common-mode rejection of this ground noise. The problem can be mitigated by *always* tying the cable shield to the reference voltage of the line driver.

4.4.2.3 Cable Shield Connected to Housing of Input Jack

The LEMO plug that connects to the coil driver's control input has a metal housing that can be internally tied to the cable shield. When this connection is made, the cable shield is directly tied to earth ground through the coil driver's metal enclosure. This creates the same ground loop shown in Figure 7a. To prevent this ground loop from forming, the cable shield should *never* be tied to the metal housing of the input plug.

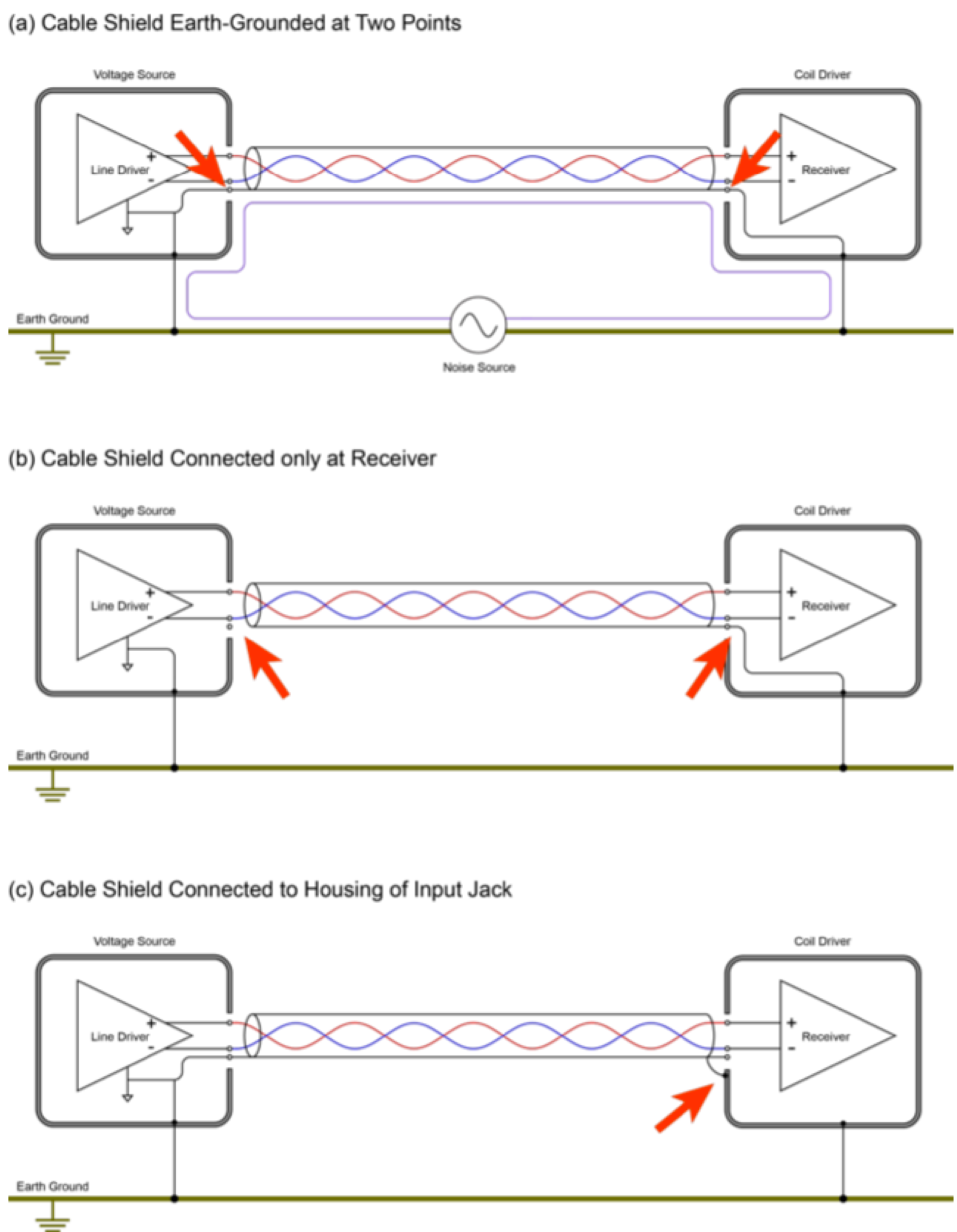


Figure 7: Improper wiring of the coil driver's control inputs.

SUMMARY

Do's

- Use shielded twisted-pair cables for the inputs.
- *Always* connect the cable shield directly to reference ground at the signal source. Leave the shield unconnected at the coil driver's inputs.
- Make connections to earth ground with a star-grounding technique, i.e. solder a wire directly to the earth ground tab on the AC input power module.

Don'ts

- Connect the cable shield *only* at the coil drivers' inputs.
- Ground the cable shield at both the voltage source and coil driver.
- Connect the cable shield to the metal housing of the input jack.
- Rely on electrical connections to earth ground through a metal enclosure. Instead, use a wire soldered directly to the earth ground tab on the AC input power module.

5. Connecting the Outputs

The coil driver's outputs can be connected to the load using a standard DB15 cable. Coil assemblies purchased from ColdQuanta are shipped with a cable that directly connects to the connector on the coil driver's rear panel.

CAUTION!

NEVER connect the output to AC ground, earth ground, or the coil driver enclosure (which is tied to earth ground). Doing this will cause a High Current fault.

5.1 Pin Connections

Figure 8 shows the pin diagram for the output 15-pin D-sub connector. The black text indicates pin numbers according to the standard convention for D-sub connectors. The four channel outputs are indicated by yellow text. Currents flow in the direction of the red arrows, i.e. from the top row of pins (#1 to 8) to the bottom row of pins (#9 to 15).

When ColdQuanta's coil assembly is connected to the DA-15 connector in Figure 8 using the cable supplied with the assembly, the four coil driver channels will be configured to produce bias and quadrupole fields along the x direction, and only bias fields along the y and z directions. In this scenario, the Y coils are connected in series by tying pins 4 and 11 to each other inside of the cable housing. Similarly, the Z coils are connected in series by tying pins 6 and 13 together. The table below summarizes the connections:

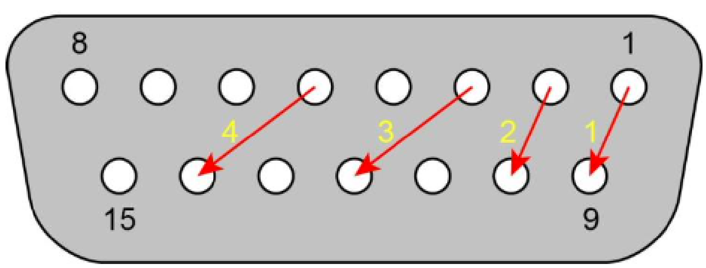


Figure 8: Pin diagram for the DA-15 output connectors. Currents flow in the direction of the red arrows, with channel numbers indicated in yellow. Currents flow out of the top row of pins (#1 to 8) and return to the bottom row of pins (#9 to 15).

Coil Driver Channel #	D-sub Pin #	Coil Name	Field Direction	Field Type	Value
1	1 → 9	X1	Front ($\hat{x}$)	Quadrupole or Bias	15.1 G/(cm·A) or +22.6 G/A $\hat{x}$
2	2 → 10	X2	Rear ($\hat{x}$)		
3	3 → 12	Y1 + Y2	Left + Right ($\hat{y}$)	Bias	+22.6 G/A $\hat{y}$
4	5 → 14	Z1 + Z2	Top + Bottom ($\hat{z}$)	Bias	+15.6 G/A $\hat{z}$

5.2 Output Cable Types

Unshielded twisted-pair cables are recommended for the coil driver's outputs. The twisted-pair geometry minimizes coupling of external magnetic fields onto the cables by reducing the area of the magnetic "receiver" formed by the cables, load, and coil driver [2]. Furthermore, since the currents flowing on the two lines are equal and opposite in direction, twisted-pair cables produce a net magnetic field that is zero when averaged over the distance of one twist. Minimizing the magnetic fields generated by the chip currents reduces coupling to other electronics and cables.

The coil driver is *NOT* designed to operate with shielded output cables. The use of a shielded output cable can couple noise onto the outputs.

SUMMARY

Do's

- Use a twisted-pair output cable.

Don'ts

- *Never* connect any of the outputs to earth ground.
- Use shielded output cables.

6. Troubleshooting

Description	Solution
"Main Power" indicator does not illuminate when button is depressed.	The unit is not receiving power from the input AC (mains) line: • Check that the power cord is properly inserted into a three-prong protective-grounded power output. • Check that the power cord is properly plugged into the input power module on the back of the coil driver. • Check that the correct fuse has been inserted into the fuse holder on the back of the coil driver. If the fuse is blown, replace with a fuse of the same current rating, voltage rating, and type (i.e. slo-blo, fast blo, etc.).
"Output On/Off" indicator does not illuminate when button is depressed.	• Check that the unit is properly powered from the AC (mains) line. • If the unit is properly powered from the AC (mains) line, a fault condition may be immediately causing the unit to disable its output. Check to see if one of the fault LED indicators on the front panel is illuminated. If so, refer to the description below associated with that fault.
No current is outputted when the "Output On/Off" indicator is illuminated.	• Check that the input control line is properly connected to both the voltage source and the appropriate input jack on the rear panel.
Output current does not reach the maximum specification of ±3 A.	• Check that the load resistance R_{LOAD} is less than 1 Ω. • If 0.5 Ω < R_{LOAD} < 1 Ω, the maximum output current specification is ±3 A. • When the coil driver is driven with floating voltage sources, the reference ground may have exceeded the common-mode input voltage range of the coil driver. Switch to earth-grounding of the voltage sources.
"Overtemp" LED indicator is illuminated.	• The internal circuitry of the coil driver is too hot. Wait several minutes for the circuits to cool down. If this problem occurs repeatedly, move the unit to an area where there is better air flow.
"High Current" LED indicator is illuminated.	• Check that the output is not connected to earth ground. • Check that outputs from different channels are not connected to each other. • If the unit cannot be brought out of this fault condition, please contact ColdQuanta.
"Open Circuit" LED indicator is illuminated.	• The coil driver does not see a load. Check that the output cable is properly connected. • If the output is properly connected, check that the total load resistance R_{LOAD} is less than 1 Ω.

7. References

[1] B. Whitlock, "Design of High-Performance Balanced Audio Interfaces," downloaded from http://sound.westhost.com/, September 12, 2013.

[2] A. Rich, "Shielding and Guarding, How to Exclude Interference-Type Noise, What to Do and Why to Do It—A Rational Approach," Analog Dialogue, issue 17-1, Analog Devices, Norwood, Massachusetts, 1983.

[3] R. Morrison, *Grounding and Shielding: Circuits and Interference*, 5th Ed., John Wiley & Sons, Hoboken, New Jersey, 2007.

[4] B. Whitlock, "Balanced Lines in Audio Systems: Fact, Fiction, and Transformers," J. Audio Eng. Soc., vol. 43, no. 6, pp. 454-464, 1995.

[5] J. Brown and B. Whitlock, "Common-Mode to Differential-Mode Conversion in Shielded Twisted-Pair Cables (Shield-Current-Induced Noise)," Audio Engineering Society 114th Convention, Amsterdam, The Netherlands, 2003.

8. Limited Warranty

1. Definitions

a) "Delivery" means standard ColdQuanta shipping to and arrival at the receiving area at the "Ship To" address specified in Customer's Order.
b) "Exhibits" means attachments that describe or otherwise apply to the sale of Products.
c) "Products" means hardware, documentation, accessories, supplies, parts and upgrades that are determined by ColdQuanta to be available from ColdQuanta upon receipt of Customer's Order. "Custom Products" means Products modified, designed or manufactured to meet Customer requirements.
d) "Specifications" means specific technical information about ColdQuanta Products that has been delivered by ColdQuanta to the Customer with Customer's Order.
e) "Support" means hardware maintenance and repair; training; and other standard support services provided by ColdQuanta. "Custom Support" means any agreed nonstandard support, including consulting and custom project services.

2. Limited Warranty

a) ColdQuanta warrants ColdQuanta hardware Products against defects in materials and workmanship for a period of one year from the delivery date.
b) ColdQuanta does not warrant that the operation of Products will be uninterrupted or error free.
c) If ColdQuanta receives notice of defects, ColdQuanta will, at its option, repair or replace the affected Products. If ColdQuanta is unable, within a reasonable time, to repair, replace or correct a defect or non-conformance in a Product to a condition as warranted, Customer will be entitled to a prorated refund of the purchase price upon prompt return of the Product to ColdQuanta. Such refunded amount will be prorated based on a four-year straight line depreciation schedule. Customer will pay expenses for return of such Products to ColdQuanta. ColdQuanta will pay expenses for shipment of repaired or replacement Products.
d) ColdQuanta warrants that ColdQuanta Support will be provided in a professional and workmanlike manner. Some newly manufactured ColdQuanta Products may contain and ColdQuanta Support may use remanufactured parts that are equivalent to new in performance.
e) The above warranties do not apply to defects resulting from:
   (i) improper or inadequate maintenance by Customer;
   (ii) customer or third party supplies;
   (iii) unauthorized modification;
   (iv) improper use or operation outside of the Specifications for the Product;
   (v) abuse, negligence, accident, loss or damage in transit;
   (vi) improper site preparation; or
   (vii) unauthorized maintenance or repair.

f) THE ABOVE WARRANTIES ARE EXCLUSIVE AND NO OTHER WARRANTY, WHETHER WRITTEN OR ORAL, IS EXPRESSED OR IMPLIED. TO THE EXTENT PERMITTED BY LAW, COLDQUANTA SPECIFICALLY DISCLAIMS THE IMPLIED WARRANTIES OF MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE, TITLE, AND NONINFRINGEMENT.