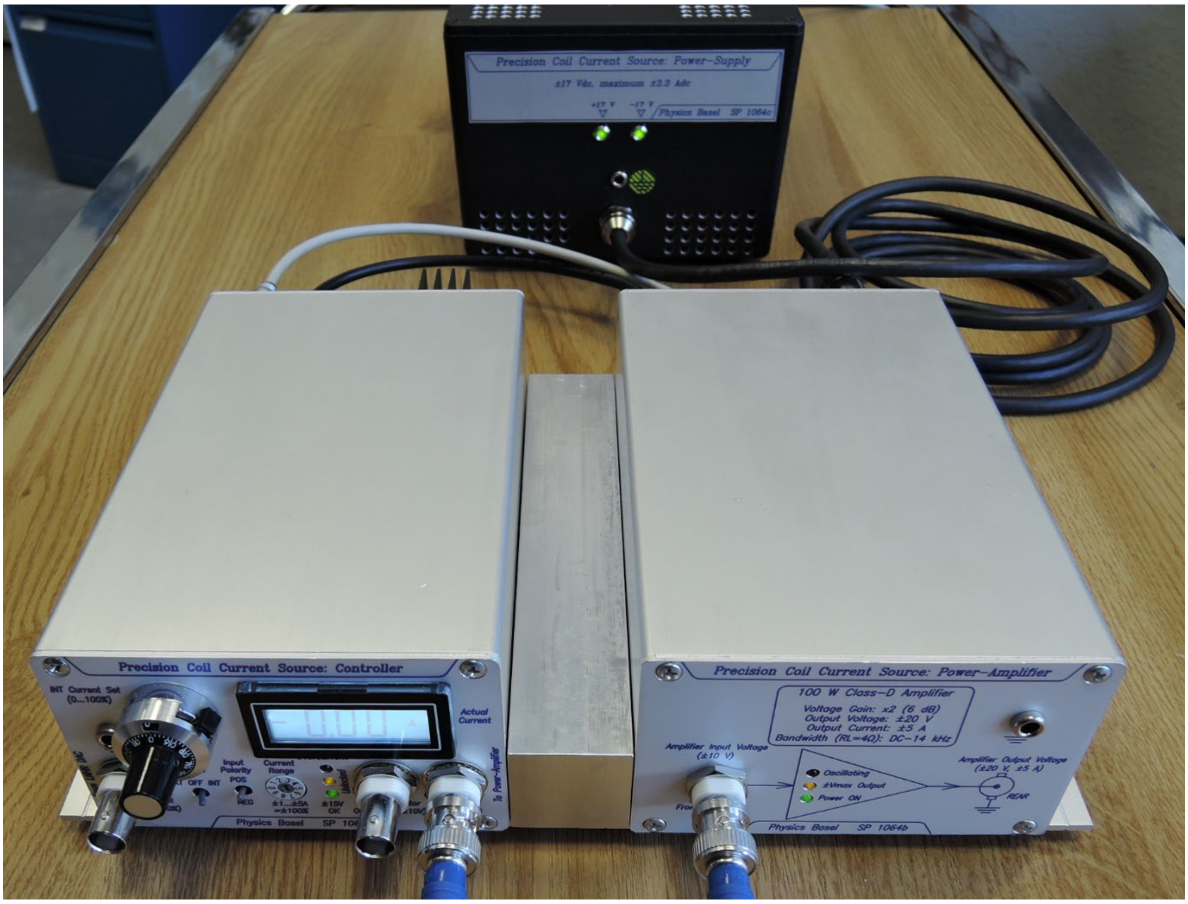
# Precision Coil Current Source

## Physics Basel SP 1064

## User's Manual | Revision 1.0

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# 1 Key Features

- Precise bipolar current source for resistive to inductive loads (coils)
- Wide range of current sources from ±100 mA to ±5 A
- Drives currents up to ±5 A at ±20 V (100 W)
- Ultra-low thermal drift (1.4 ppm/°C)
- Very stable over time (10 ppm over 12 hours)
- High current accuracy (±1.5 %)
- Easy adaptation to different loads with two plug-in components (R and C)
- Red warning LED when system is oscillating
- Five Selectable current ranges (±1 A, ±2 A, ±3 A, ±4 A, ±5 A)
- Selectable current set source (Internal or External)
- Internal current setting via stable reference and high-quality potentiometer
- External set voltage (±10 V) isolated from ground and with switchable polarity
- Low noise Class-D Power-Amplifier minimizes power dissipation
- Low self-heating
- Local display of the actual current
- Broadband Power-Amplifier with a bandwidth of 14 kHz @4 Ohm
- Power-Supply can be up to 2.5 meters away from the Controller/Amplifier module
- Wide mains voltage (100 Vac…240 Vac, 50/60 Hz)
- Quiet operation
- No mechanical vibrations since no fans are used
- Helpful status LEDs: Unlocked, Overcurrent, Oscillation, ±Vmax Output
- Robust and well shielded modular aluminum housings
- Three-axis (x, y, z) stackable and bolt-on Controller/Amplifier modules

# 2 Safety Precautions

- The Precision Coil Current Source (PCCS) is designed for indoors dry laboratory use by qualified and authorized persons only.
- Read this manual carefully before installing and use the PCCS.
- All the safety precautions marked with CAUTION must be respected.
- Do not remove any cover. Since the internal parts are precisely adjusted, do not try to adjust or modify any part of the PCCS. This does not apply to the $R_c$ and $C_c$ components on the Controller and the dither-jumpers on the Power-Amplifier.
- Make sure that the housings of the devices are always connected to protection ground/earth and use the 4 mm ground jackets on the front or rear panels to make a proper ground connection.
- This device is not approved for use on humans or animals.

# 3 Disclaimer

Physics Basel hereby disclaims all responsibility for personal injury, property damage and fine of penalty which results from misuse, not respecting the safety precautions, improper maintenance or improper application of this product.
Compliance with all applicable environment and personnel safety regulations is the sole responsibility of the user.

# 4 Used Abbreviations

The Following abbreviations are used in this manual:

| Abbreviation | Meaning |
|---|---|
| BNC | Bayonet Nut Connector |
| DAC | Digital/Analog Converter |
| DC | Direct Current |
| DVM | Digital Voltage Meter |
| EMI | Electromagnetic Interference |
| IC | Integrated Circuit |
| LED | Light Emitting Diode |
| PCB | Printed Circuit Board |
| PCCS | Precision Coil Current Source |
| PI | Proportional/Integral |
| ppm | Parts per million (1E-6) |
| PWM | Pulse Width Modulation |
| RMS | Root Mean Square (Effective Value) |
| SMD | Surface-Mounted Device |
| T | Temperature [K] |

# 5 Introduction

Many physical experiments require controllable magnetic fields generated by coils, which are often designed as air coils in a Helmholtz configuration. If the two coils carry an equal current in the SAME directions, a uniform magnetic field is generated in the center of the Helmholtz coils. In the anti-Helmholtz configuration, the two coils carry an equal current in the opposite directions, so a uniform magnetic field gradient is created in the central area of the anti-Helmholtz coils.

The magnetic field or the gradient is proportional to the current flowing through the pair of coils. For a precise and stable magnetic field, the current must be constant and low noise. Since the resistance of the coil, which is usually made out of copper, increases with temperature (copper +3'900 ppm/°C) and the coil temperature depends on the actual current flowing, current stabilization is essential to achieve stable conditions for sensitive experiments.

The Precision Coil Current Source (PCCS) is a controllable bipolar current source for such coils in sensitive applications. It can be adapted to almost any coil; also, purely resistive loads can be driven by the PCCS. The coil current can be up to ±5 A with a maximum output voltage of ±20 V; this corresponds to a DC resistance of the coil of 4 Ohm and a power dissipation in the coil of 100 W.

The current range can be set from ±1 A to ±5 A in increments of 1 A using a rotary switch on the front panel. This allows the PCCS to be flexibly adapted to different current requirements. Therefore, this same system can also be used for changing current requirements.

A DC current can be set by using the internal SET multi-turn potentiometer which is connected to a low-drift and low noise voltage reference source. For dynamic controlling the coil current an external SET voltage can be applied whose voltage of ±10 V corresponds to ±100% of the selected current range.

To maintain the excellent performance of the PCCS, this external SET voltage must also be low-drift and low-noise. The "Low Noise / High Resolution DAC II (SP 1060)" is an optimal voltage source to drive the PCCS.

## 5.1 Overview Block Diagram

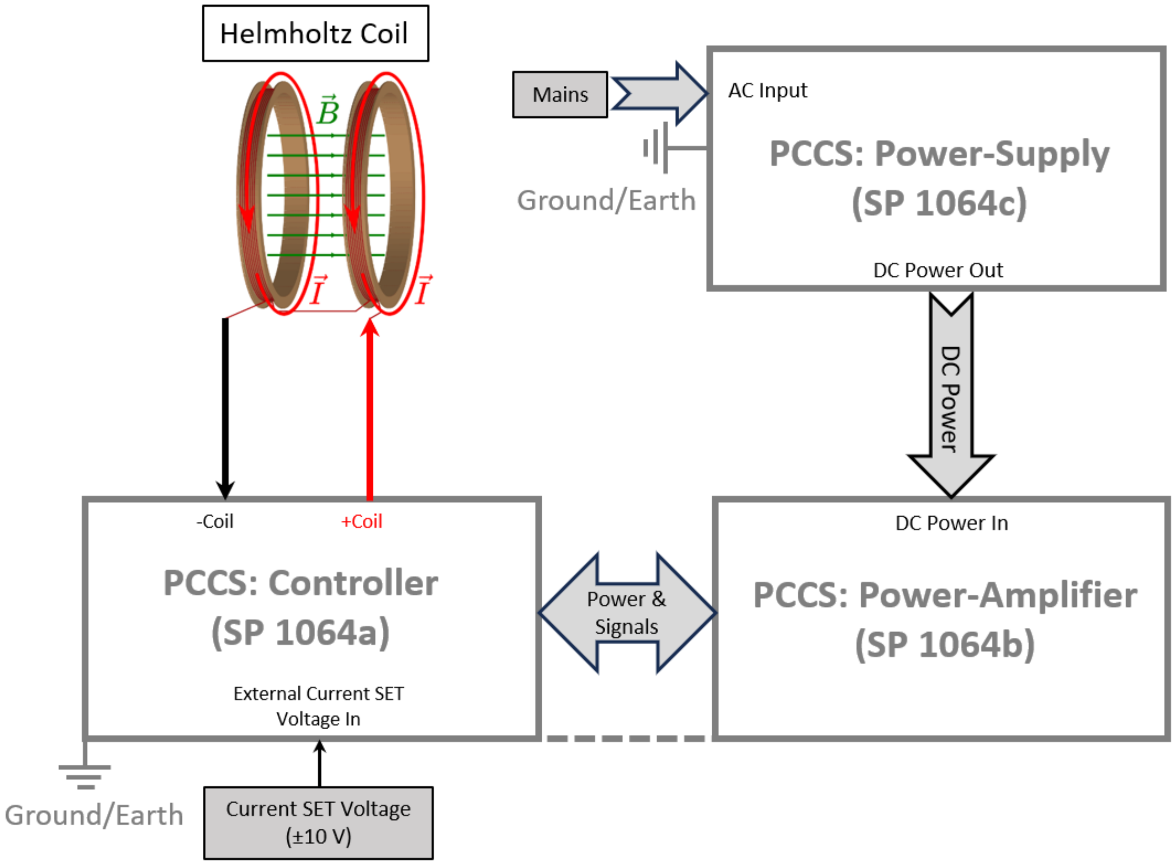
The PCCS is a modular system consisting of three devices connected by cables:

- Controller (SP 1064a)
- Power-Amplifier (SP 1064b)
- Power-Supply (SP 1064c)

On delivery, the Controller and the Power-Amplifier modules are screwed together and form a single unit. Due to the Class-D design of the Power-Amplifier (switching amplifier), its self-heating is minimal and it can therefore be mounted close to the Controller. Short cables for connection of these two modules are part of the delivery. If required, the Controller and the Power-Amplifier can also be easily separated from each other using longer cables.

The Power-Supply module is based on ultra-low noise switching power supplies from the company Daitron. However, it has a noticeable self-heating and also some electromagnetic emissions. With its 2.5-meter-long output cable it can be easily separated from the sensitive Controller module.

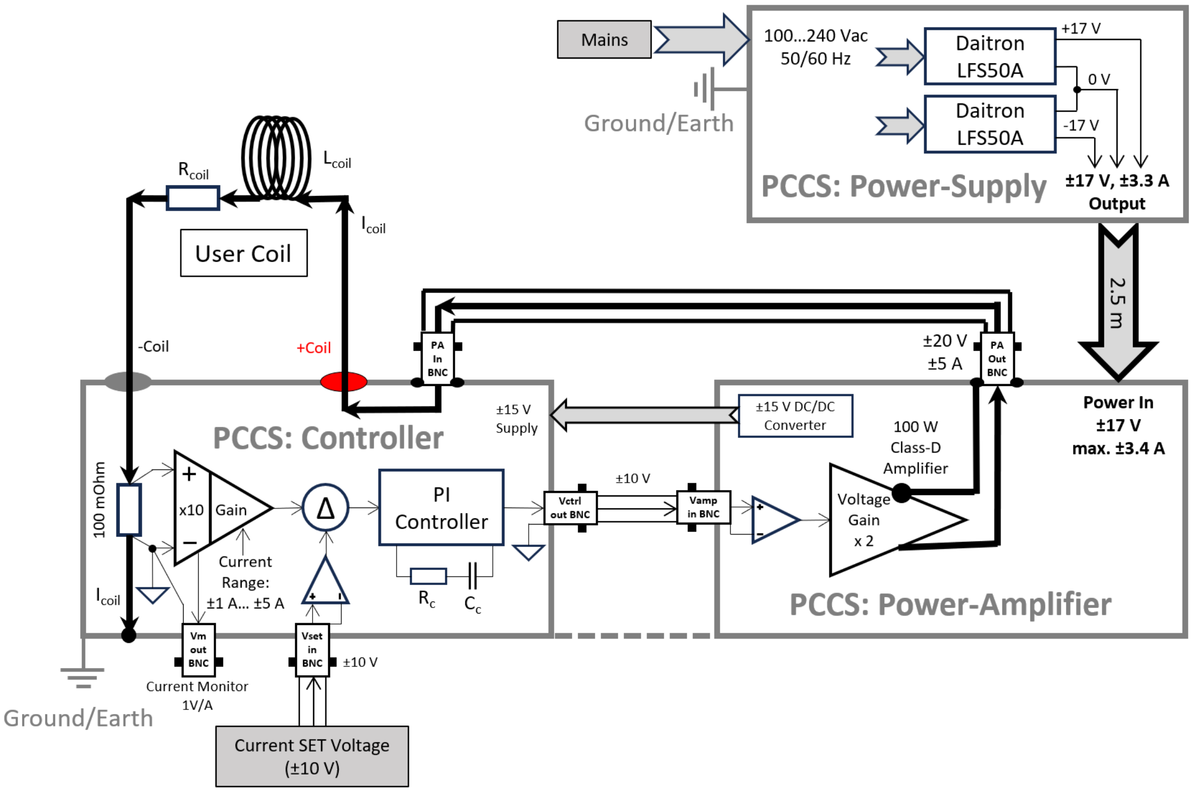
The overview block diagram of the PCCS with an attached Helmholtz Coil is given below:




Please note, that the quality (high stability and low noise) of the Current SET Voltage (±10 V) is very important.

## 5.2 Detailed Block Diagram

The detailed block diagram of the PCCS is given below:



The User Coil has to be connected to the back of the Controller via two banana jacks (4 mm). To minimize electromagnetic interference (EMI), it is strongly recommended to use a twisted and shielded cable between the Controller and the User Coil. The shield of the cable can be connected to the housing (ground/earth) of the Controller via the metal banana jack (4 mm) on the back-panel.

CAUTION: Make sure the Controller and the Power-Amplifier enclosures are always connected to the protective earth/ground.

The User Coil is shown with its two most important parameters: Its pure inductance ($L_{coil}$) and its DC resistance ($R_{coil}$). These two parameters must be known from the connected User Coil in order to determine the settings of the PI Controller later.

The current through the coil ($I_{coil}$) is driven by the Power-Amplifier, whose output is connected to the back of the Controller by a BNC cable. Inside the Controller, the coil current flows over an ultra-stable 100 mOhm current sense resistor to housing and thus to the outer-shield of the BNC connector and then back to the Power-Amplifier. Since the housing of the Controller and the Power-Amplifier must be connected to ground/earth, the User Coil has to be floating from ground/earth.

The voltage across the ultra-stable 100 mOhm current sense resistor is first amplified by a fixed gain of ten, which results in the 1 V/A Current Monitor Output voltage. This voltage is also displayed on the front-panel LCD indicated as Actual Current. The Gain of the next amplifier stage is set according to the selected Current Range, which can be set from ±1 A to ±5 A in 1 A steps.

CAUTION: Do not switch the Current Range while a coil current is flowing; switch when the current is zero or better when the system is turned off.

The ACTUAL voltage is subtracted from the Current SET voltage (±10 V) which can come from an internal or external source; the source is selected by a toggle switch. If the internal source is selected, the Current SET voltage is derived from a precision multi-turn potentiometer which is supplied by a low-drift and low noise voltage reference. The potentiometer has a mechanical locking mechanism, that prevents the value from changing due to vibrations.
If the external source is selected, the Current SET voltage must be supplied from an external device (e.g. LNHR DAC II). The external voltage is received via a differential amplifier which breaks potential ground-loops.

The error signal (ACTUAL minus SET voltage) drives the input of the PI Controller. It has two components to set the proportional (P) part through $R_c$ and the integral (I) part through $C_c$. These two components are pluggable inside the controller box and depend on the User Coil connected and the Current Range selected. To determine these components, see chapter "Estimation of the PI Controller Components".

The Controller Output (±10 V) is hooked up to the Power-Amplifier Input Voltage (±10 V) via a BNC cable. The voltage gain of the Class-D Amplifier is a factor of two; the ±10 V input voltage results in a ±20 V output voltage with a very small source resistance of around 65 mOhm.

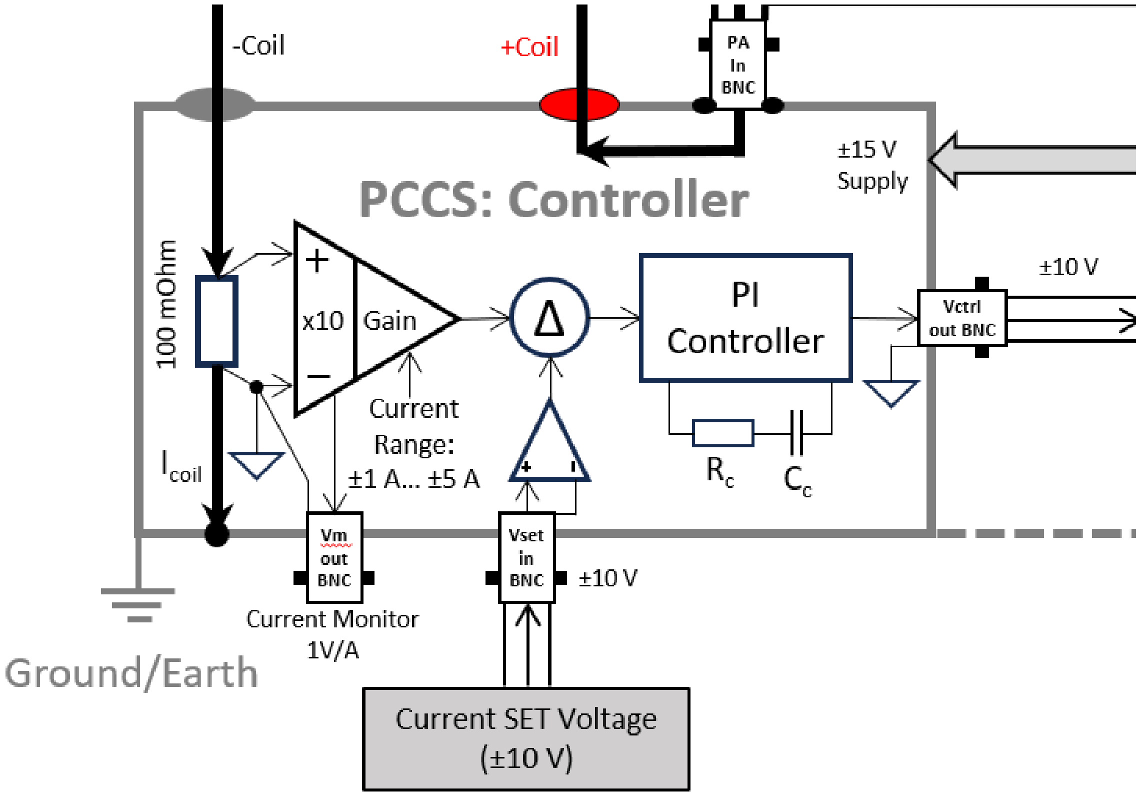
Inside the Power-Amplifier the ±15 V Power Supply voltage for the Controller is generated by a DC/DC converter; its maximum output current is ±200 mA. Via a 4 pin

LEMO cable, the Power Supply Input on the Controller is connected to the ±15 V Output Voltage on the Power-Amplifier.

The Power-Amplifier is supplied by the Power-Supply with a bipolar ±17 V DC-voltage with a maximum continuous current of ±3.3 A. This supply voltage is delivered via a 2.5-meter cable and enables the power supply unit to be spatially separated from the rest of the system. The Power-Supply accepts mains-voltages in a range from 100 Vac up to 240 Vac at a frequency between 50 Hz and 60 Hz.

# 6 Controller (SP 1064a)

The Controller is the heart of the system, as its precision and stability determine the overall performance of PCCS. Therefore, the critical components inside the Controller are precision, high-quality and have a very low thermal drift. The circuit diagram principle of the Controller is given below:

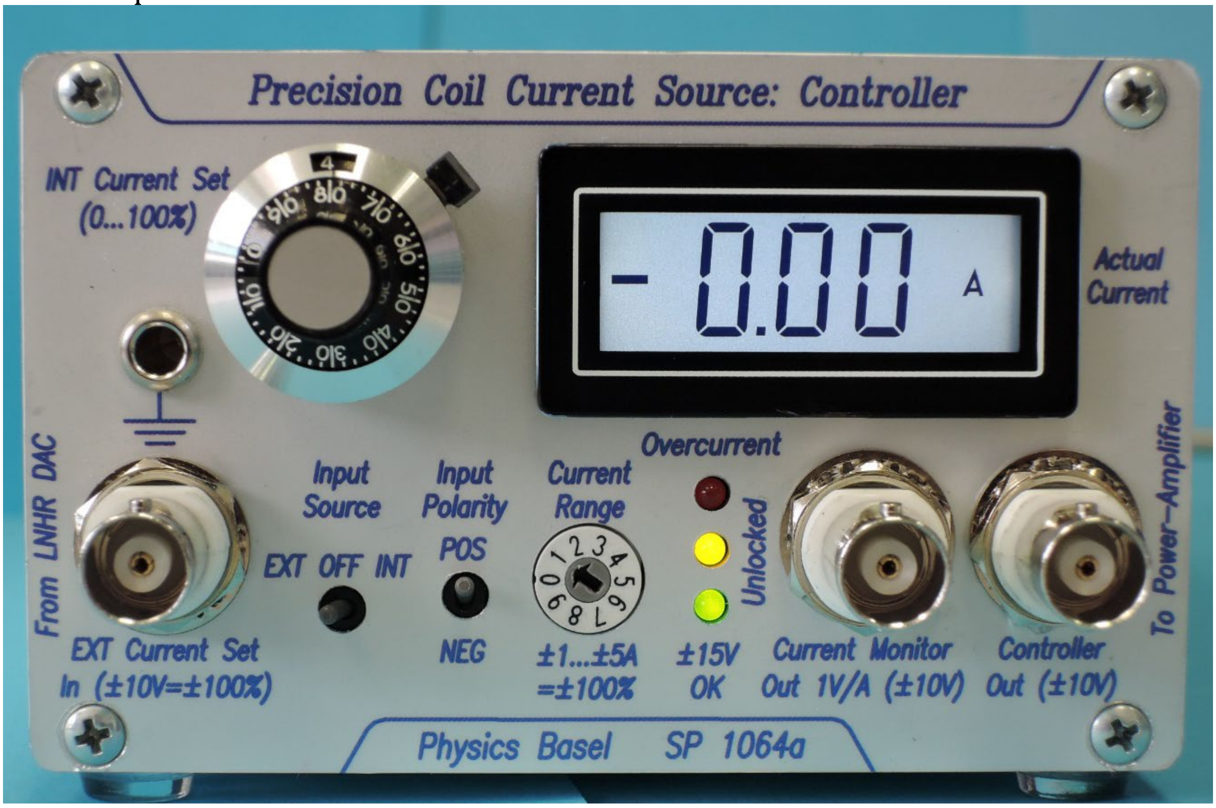



The size of the Controller is (Width x Height x Depth): 130 mm x 72 mm x 214 mm
The weight of the Controller is: 0.9 kg

When the current is set by an external SET Voltage (±10 V), this voltage must also be of high quality (low noise and low drift) in order to achieve the best performance. The "Low Noise / High Resolution DAC II (SP 1060)" is an optimal voltage source to set the current. Information about this device is available here:
https://physik.unibas.ch/en/department/technical-services/electronics-lab/

## 6.1 Front-Panel

Most connections and settings are made on the front-panel of the Controller. A photo of the front-panel with no cables connected is shown below:




The lower section on the front-panel has the following parts elements left to right:

- *EXT Current Set In (±10 V = ±100%)*
  Via this BNC connector the external set voltage in a range of ±10 V can be applied if the *Input Source* is switched to *EXT*. Depending on the selected *Input Polarity* a positive set voltage results in a positive output current (*POS*) or vice versa (*NEG*). The 10 V corresponds to 100% current of the selected *Current Range*. The voltage is received via a differential input which has a maximum common mode voltage of ±10 V. The differential input resistance is around 50 kOhm and the outer shield of the BNC connector has a resistance of around 25 kOhm to the housing/earth. The differential receiver eliminates potential ground loops.

- *Input Source EXT/OFF/INT*
  With this toggle switch the source for the set voltage can be selected. In the position *EXT* the external voltage on the BNC is selected as set-point input. In the position *OFF* the BNC input is disconnected from the circuit and the set current drops to zero (0 A). In the position *INT* the set voltage is derived from the multi-turn potentiometer called *INT Current Set (0…100%).* The polarity of the current can be selected by using the *Input Polarity POS/NEG* switch.

- *Input Polarity POS/NEG*
  With this toggle switch the polarity of the internal and external set voltage can be changed. <u>Note</u>: If the switch is operated while an output current is flowing, the polarity is immediately reversed.

- *Current Range ±1…±5A = ±100%*
  With this rotary switch the full-scale (100 %) current range can be selected from ±1 A to ±5 A with a step size of 1 A.

Note: Do not select a position outside the specified range from 1 to 5. Position 6 corresponds to a current range of ±6 A and may work under certain conditions, but nothing is guaranteed.

CAUTION: Do not turn this rotary switch while a coil current is flowing. Make the selection when the current is zero or better when the PCCS is turned off.

- *LEDs: Overcurrent (red) / Unlocked (yellow) / ±15V OK (green)*
  These three status LEDs shows the condition of the system. Normally only the green LED (*±15V OK*) is turned ON. If this LED is OFF, the ±15 V supply voltage of the Controller has failed. Verify that the 4-pin LEMO cable on the back of the Controller (*Power Supply Input*) is connected to the Power-Amplifier (*±15 V Output Voltage*). Make sure that the Power-Supply (SP 1064c) is switched on.

  The yellow LED (*Unlocked*) is turned ON if the Controller cannot get the difference between the set- and the actual current to zero. If this LED lights up continuously, the control loop is interrupted somewhere; check all connections and ensure that the coil is properly attached on the back-side of the Controller (*Coil Current Output*). This LED may light up for a short period of time while the coil current is changing from one value to the other.

  The red LED (*Overcurrent*) indicates that the coil current reaches or exceeds the set *Current Range*. In this case, make sure that the voltage at the input (*EXT Current Set In*) is within the maximum range of ±10 V and the control loop is correctly connected.

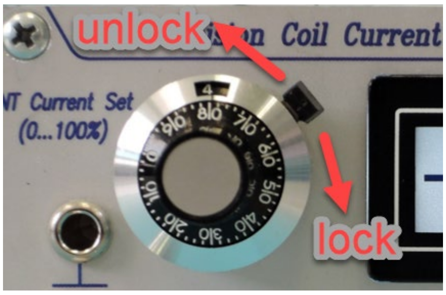
- *Current Monitor Out 1 V/A (±10 V)*
  This BNC connector allows the actual current through the coil to be monitored with an absolute accuracy of ±1.5%. The output resistance is 5 kOhm and is therefore short-circuit proof; the load error can be neglected if the load resistance is equal or greater than 10 MegOhm. An external DVM or DAQ device can be connected to this output. The scaling of the signal is fixed at 1 V/A and is normally within ±5 V since a maximum coil current of ±5 A can be controlled. However, the output voltage can be up to ±10 V, corresponding to a coil current range of ±10 A. The outer shield of the BNC is wired to an internal ground reference point that is also connected to housing/earth.

- *Controller Out (±10 V)*
  The output voltage of the PI controller is available on this BNC connector. It has an output impedance of 50 Ohm, but is only capable of driving high impedance loads greater than 1 kOhm with an amplitude of maximum ±10 V. The outer shield of the BNC is wired to an internal ground reference point that is also connected to housing/earth. The controller output voltage is normally connected to the input voltage of the Power-Amplifier. The input resistance of the *Amplifier Input Voltage (±10 V)* is 50 kOhm because it has a differential receiver.

The upper area on the front contains the following elements from left to right:

- A 4 mm metal banana socket allows the housing of the Controller to be earthed/grounded. Note: It is strongly recommended that this socket is connected to your system earth/ground.

- *INT Current Set (0...100%)*
  This multi-turn potentiometer can be used to adjust the set current from 0 to 100 % of the selected *Current Range*. To do this, the *Input Source* switch must be in the *INT* position. The potentiometer has ten turns connected to a mechanical counter that displays from 0 to 9. A set value can be blocked with the black lever; this ensures that the set-point will not change due to vibration.

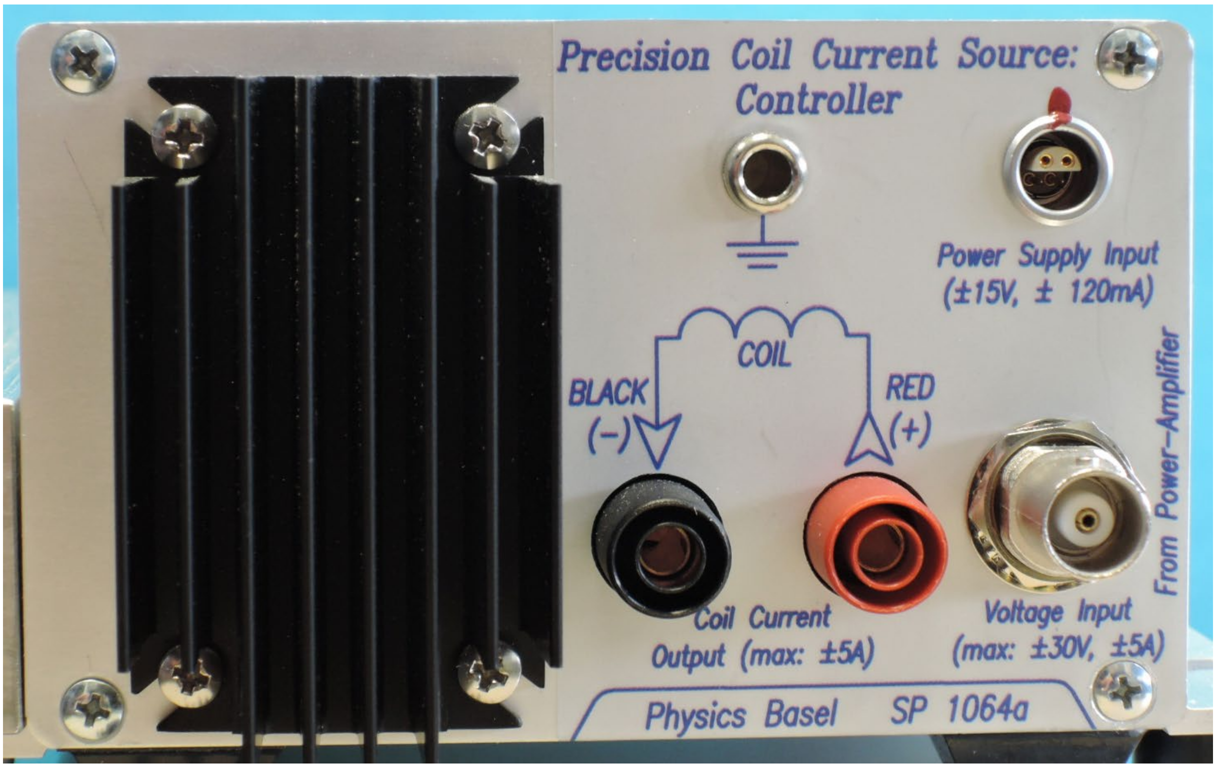



  A 10 V precision voltage reference with a maximum thermal drift of 2.5 ppm/°C is used to supply the potentiometer.

- *Actual Current Display*
  The actual DC current is displayed on the 3.5-digit LCD voltmeter with an accuracy of ±2% of the reading plus ±10 mA. The module's backlight turns on when the ±15V supply voltage is applied.

## 6.2 Back-Panel

The coil is connected to the back-panel of the Controller. A photo of the back-panel with no cables connected is shown below:




To minimize the self-heating of the 100 mOhm current sense resistor (which is a metal-foil resistor with a maximum thermal drift of 3 ppm/°C) it is mounted directly on the housing and has attached a black heatsink. At the maximum current of 5 A, the power dissipation in this resistor reaches 2.5 W and its core temperature rises by around 23°C at a constant ambient temperature.

The following three connections are located on the back-panel of the Controller:

- *COIL / Coil Current Output (max: ±5 A)*
  The floating User Coil is connected to these insulated 4 mm banana jacks: RED (+) and BLACK (-). The BLACK (-) banana jack is connected to the housing/ground via

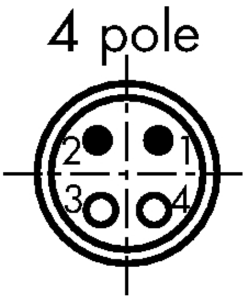
the 100 mOhm current sense resistor. A twisted and shielded cable is strongly recommended for the connection between the Controller and the User Coil. The shield of the cable must be connected to the grounded/earthed housing via the 4 mm metal banana jack located above the two insulated banana jacks. This setup minimizes the EMI.

CAUTION: Never unplug a coil while it is energized! High voltage will be generated and may destroy the electronics.

If the Power-Amplifier (SP 1064b) is used, the open-loop output resistance of this *Coil Current Output* is around 165 mOhm. This consists of the 100 mOhm from the current sense resistor plus the 65 mOhm output resistor of the Power-Amplifier (SP 1064b).
Note: The virtual closed-loop output resistance (ΔU/ΔI) of the current source is very high, since the current is almost independent (ΔI=0) form the load resistance.

- *Voltage Input (max: ±30 V, ±5 A)*
  This BNC is connected to the *Coil Current Output* and it is wired with a short BNC cable to the output voltage of the Power Amplifier, which is up to ±20 V at a current of up to ±5 A.

- *Power Supply Input (±15 V, ±120 mA)*
  This is the supply voltage for the Controller; the nominal voltage is ±15 V and the typical quiescent current is +45 mA and -15 mA. The maximum current that can be drawn by the Controller is ±120 mA. The connector that fits in this socket is a 4-pin LEMO Series 0S with the following part number: FFA.0S.304.(CLAC44)




On the left is a view to the LEMO socket mounted on the Controller. The pin assignment is shown below:

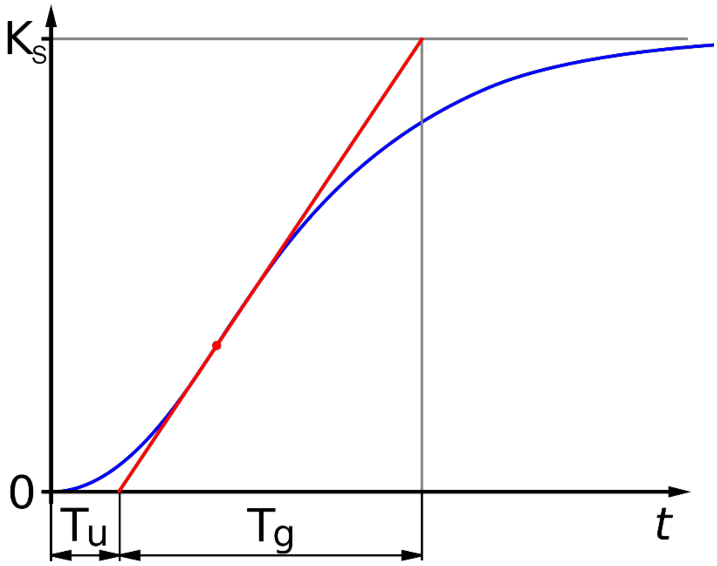
PIN 1: +15 V Input/ +120 mA max
PIN 2: -15 V Input / -120 mA max
PIN 3: not connected
PIN 4: 0 V Input / Ground
(Shield is connected to housing and 0 V)

CAUTION: Turn off the Power-Supply before connecting or disconnecting this connector.

## 6.3 Estimation of the PI Controller Components

Depending on the connected User Coil and the selected Current Range, the PI controller components must be adapted, otherwise, the closed-loop system may have large overshoots or start to oscillate.

Based on the rule of thumb of "Chien et al.", the parameters of the PI controller can be estimated from the step response of the controlled system in open loop configuration:




The following three values of the step response of the controlled system must be known:

$K_s$: Amplification of the control path (for time = ∞)

$T_u$: Delay time [sec] (derived from the turning tangent)

$T_g$: Compensation time [sec] (derived from the turning tangent)

From these tree values ($K_s$, $T_u$ and $T_g$), the parameters of the PI controller ($K_p$ and $T_n$) can be calculated for an <u>aperiodic set-point response with no overshoot</u>:

PI controller proportion gain: $K_p = 0.35 \cdot \frac{T_g}{T_u \cdot K_s}$

PI controller reset time [sec]: $T_n = 1.2 \cdot Tg$

These two PI controller parameters ($K_p$ and $T_n$) are needed to determine the two components $R_c$ and $C_c$ that can be plugged into the Controller:

Proportional (P) part Resistor [Ohm]: $R_c = K_p \cdot 5\ kOhm$

Integral (I) part Capacitor [F]: $C_c = \frac{T_n}{R_c}$

To save the user the trouble of measuring the controlled system with the step response, the components ($R_c$ and $C_c$) can also be estimated from the coil parameters ($L_{coil}$ and $R_{coil}$) and the selected Current Range ($CR$):

$L_{coil}$: Inductance [H] of the coil, measured at a low frequency (e.g. 100 Hz).
$R_{coil}$: DC-Resistance [Ohm] of the coil, including lead resistance.
$CR$: Selected Current Range on the Controller (e.g. 5 A: CR =5)

$$R_c = 8.75 \cdot CR \cdot (1.65 + 10 \cdot R_{coil}) \cdot \left( \frac{L_{coil}}{18 \cdot 10^{-6} \cdot (R_{coil} + 0.165)} + 1 \right)$$

$$C_c = 1.2 \cdot \frac{\left( \frac{L_{coil}}{R_{coil} + 0.165} + 18 \cdot 10^{-6} \right)}{R_c}$$

The previous estimation of the components is derived from the PCCS system parameters. They result in an aperiodic set-point response with no overshoot. These values are normally a good starting point and result in a relatively slow set-point response.
Further tuning may be required for faster response. To speed up the response, increase the proportional (P) resistor ($R_c$) or decrease the integral (I) part capacitor ($C_c$).

Example:
$L_{coil}$ = 290 µH
$R_{coil}$ = 2.35 Ohm
*Current Range* = 4 A-> CR = 4

$$\boldsymbol{R_c} = 8.75 \cdot 4 \cdot (1.65 + 10 \cdot 2.35) \cdot \left( \frac{290 \cdot 10^{-6}}{18 \cdot 10^{-6} \cdot (2.35 + 0.165)} + 1 \right) = \boldsymbol{6.52\ kOhm}$$

$$\boldsymbol{C_c} = 1.2 \cdot \frac{\left( \frac{290 \cdot 10^{-6}}{2.35 + 0.165} + 18 \cdot 10^{-6} \right)}{6.52 \cdot 10^{3}} = \boldsymbol{24.54\ nF}$$

There is also a small Excel spreadsheet called “Estimation_PI-Controller_Components_Rc_Cc_Rev_1.xlsx” where you can enter the Coil Inductance [H] and the Coil DC-Resistance [Ohm] and it will calculate the Estimated PI-Controller Components ($R_c$ and $C_c$) for all Current Ranges [1…5 A] according to the formulas given above.
The values of the example coil ($L_{coil}$ = 290 µH, $R_{coil}$ = 2.35 Ohm) are entered in the cells marked in blue, and the component values ($R_c$ and $C_c$) for the 4 A Current Range are calculated in the row marked in green:

**Precision Coil Current Source (SP 1064)**
Estimation of the PI-Controller Components (Rc and Cc)
with a Aperiodic Damping (no overshoot)
Physics Basel, M. Steinacher, May 2024, Revison 1.0

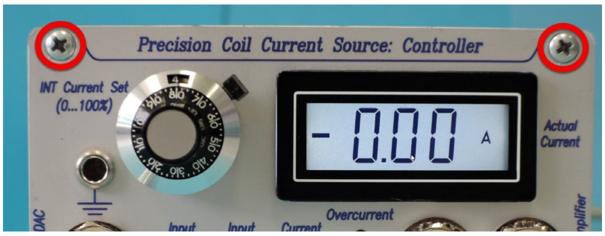
Coil Name: 290 µH and 2.35 Ohm

| User Input (edit only first row) | | | Estimated PI-Controller Components | |
|---|---|---|---|---|
| Current Range [A] | Coil Inductance [H] | Coil DC-Resistance [Ohm] | Rc [Ohm] | Cc [F] |
| 5 | 290.0E-6 | 2.35 | 8.15E+3 | 19.63E-9 |
| 4 | 290.0E-6 | 2.35 | 6.52E+3 | 24.54E-9 |
| 3 | 290.0E-6 | 2.35 | 4.89E+3 | 32.72E-9 |
| 2 | 290.0E-6 | 2.35 | 3.26E+3 | 49.08E-9 |
| 1 | 290.0E-6 | 2.35 | 1.63E+3 | 98.15E-9 |

The nearest standard values for the resistor (E24 series) and the capacitors (E6 series) are the following:

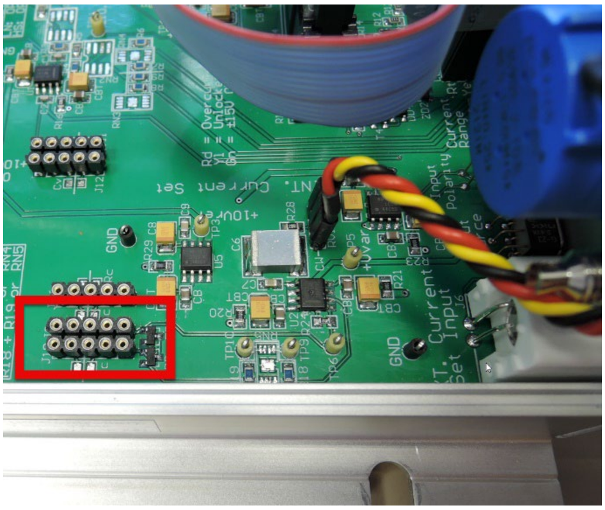
$R_c$ = 6.8 kOhm
$C_c$ = 22 nF

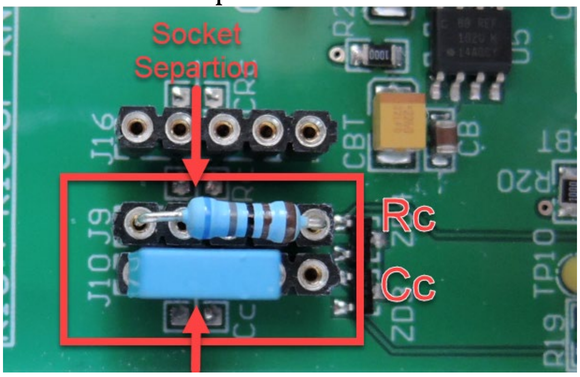
Note: First disconnect the power supply input cable. To open the top housing cover of the Controller, first remove the following four top cross-head screws:





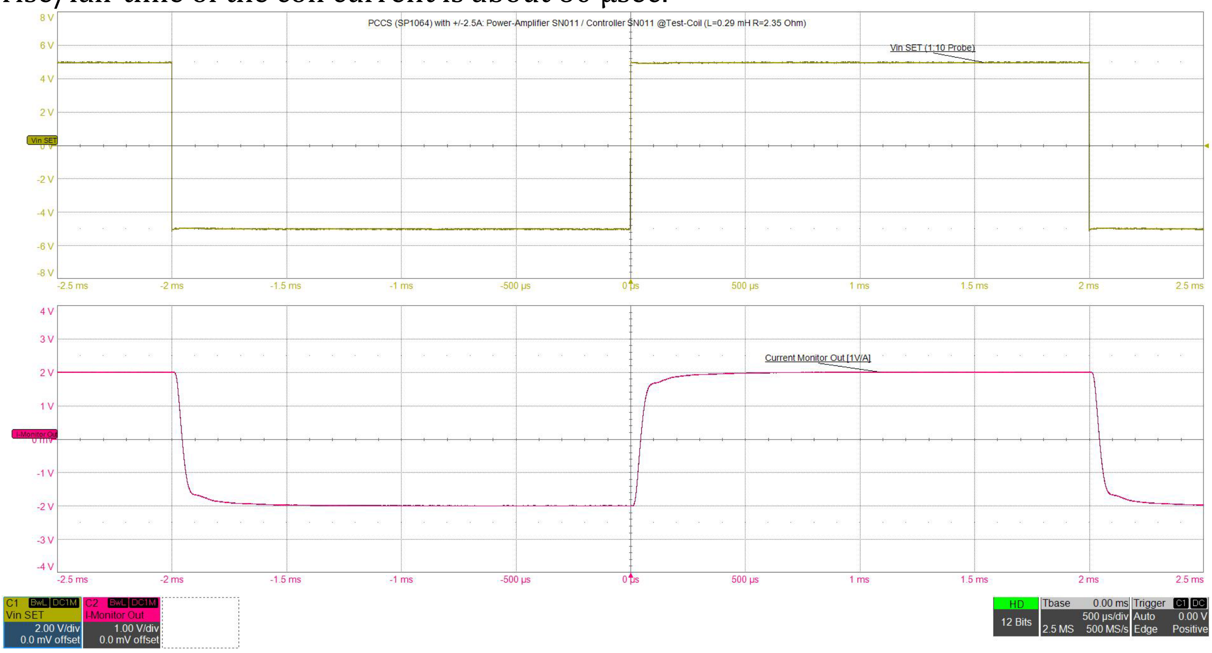
You can now pull the top of the Controller upwards to access the printed circuit board (PCB). In the front left part, you will find the two sockets to install the two components ($R_c$ and $C_c$) that set the PI parameters. Socket J9 is for the resistor $R_c$ and socket J10 is for the capacitor $C_c$, but they are equivalent and can also be used in reverse. Different sizes of components can be installed on these two sockets; SMD (0805) components can also be soldered in. The line on the silk-layer indicates the separation of the socket:






After installing the two components $R_c$ = 6.8 kOhm and $C_c$ = 22 nF from the previous example, the step response of the closed control loop can be measured with an oscilloscope and with such a test coil ($L_{coil}$ = 290 µH, $R_{coil}$ = 2.35 Ohm). This test coil is connected to the output of the Controller.

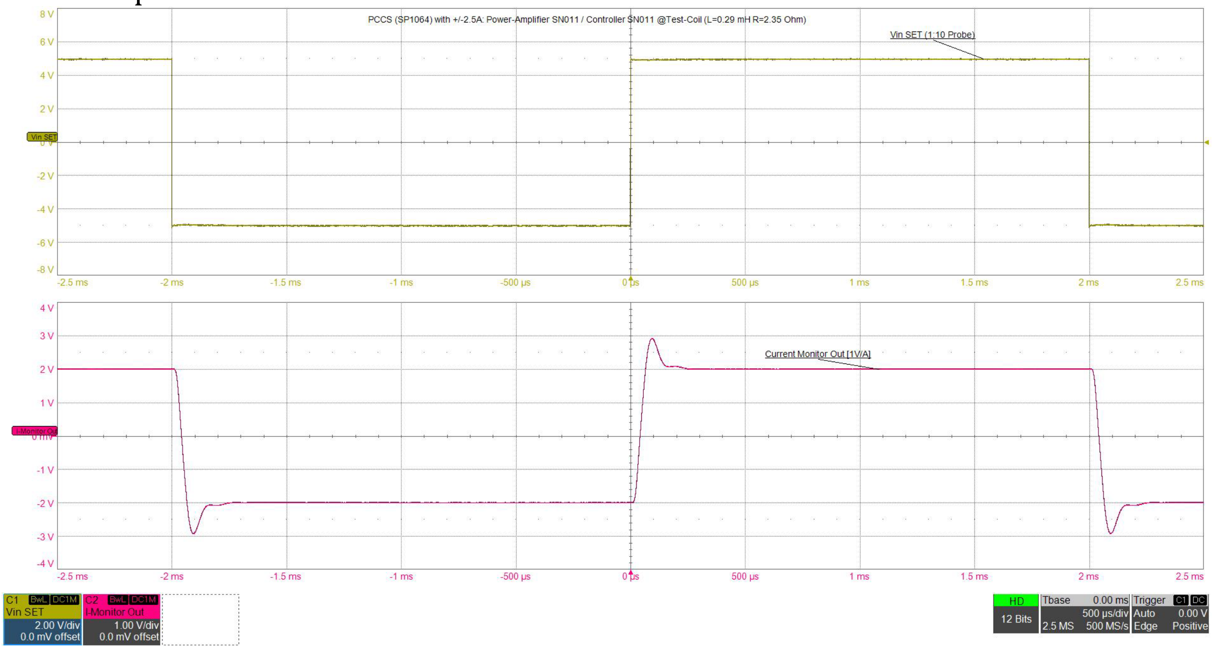
The upper trace (yellow) shows the set input voltage (*EXT Current Set In*) which is a square-wave with an amplitude of ±5 V and a frequency of 250 Hz. With the selected *Current Range* of *±4A*, the current changes between -2 A to +2 A. The lower trace (red) shows the voltage on the *Current Monitor Out*, which has a scaling of 1 V per 1 A. The rise/fall-time of the coil current is about 60 µsec:



Since the PI controller parameters were estimated for an aperiodic set-point response with no overshoot, the coil current transition is smooth and relatively slow, with no overshoot. It takes about 0.7 msec for the coil current to reach the set value.

## 6.4 Tuning Process

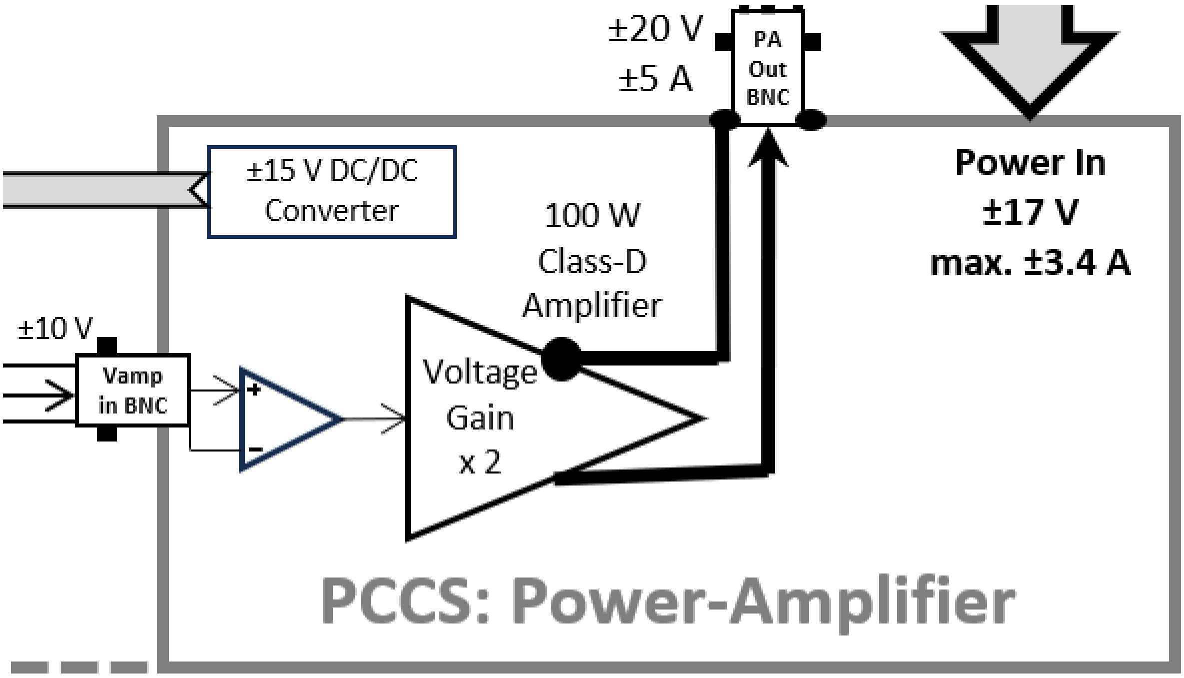
If a faster step response is required, increase the proportional (P) part by using a larger resistor ($R_C$) and/or decrease the integral (I) part by installing a smaller capacitor ($C_C$). For this tuning process, it may be helpful to use a trim potentiometer at the position of the resistor ($R_C$). Once the optimum values have been determined, it is advisable to install fixed component values.




If an overshoot of about 23% is acceptable, a rise time of 36 µsec can be achieved by using the components $R_C$ = 10 kOhm and $C_C$ = 6 nF (nominal value 6.8 nF). With these components, it takes only about 0.35 msec for the coil current to reach the set-point, which is twice as fast as using the first estimated components for an aperiodic response.

# 7 Power-Amplifier (SP 1064b)

This Power-Amplifier has a fixed voltage gain of two: The ±10 V input voltage results in an output voltage of ±20 V. This large voltage swing is achieved by using a floating balanced amplifier technique with the inverting output connected to housing/ground. This principle allows the output voltage swing of ±20 V to be greater than the supply voltage of ±17 V. Unlike audio amplifiers, this Power-Amplifier is fully DC coupled and can output DC voltages/currents. The circuit diagram principle of the Power-Amplifier is given below:




The size of the Power-Amplifier is (Width x Height x Depth): 130 mm x 72 mm x 201 mm
The weight of the Power-Amplifier is: 0.96 kg

The output resistance of the Power-Amplifier is very low (about 65 mOhm) and it can drive an output current of up to ±5 A. Under certain conditions, it may be possible to drive up to ±6 A, but nothing is guaranteed. At its maximum output voltage and maximum output current, it delivers 100 Watt to a 4 Ohm load.

CAUTION: Make sure your coil does not overheat and is always properly cooled.

Note: Copper has a coefficient of thermal expansion of 17 ppm/°C. As the temperature increases, the diameter of the copper Helmholtz coils increases while their separation remains constant. This results in a slightly different magnetic field or gradient. To avoid this thermal expansion drift, the coils must be maintained at a constant temperature; water cooling the coils is an effective method.

Due to its Class-D design (switching amplifier), this Power-Amplifier has a very high efficiency (91.5% at 100 W output) and therefore low self-heating. That's why it can be mounted close to the Controller without the drawback of extensive heating and additional thermal drift. In addition, for coils with a relatively low DC-resistance, the Class-D design has the following advantage: The ±20 V output voltage makes the current transition in the coil very fast, while the steady-state voltage across the coil is only a few volts; even at such low output voltages, its internal power dissipation is minimal. This is in contrast to a linear Class-AB power amplifier.

The output voltage of the Class-D amplifier is very well filtered, so that the broadband (5 Hz…1 MHz) noise voltage at a resistive load of 4 Ohm is only about 4 $mV_{RMS}$. This value is reached over the entire output voltage range of ±20 V. The attached user coil forms a low-pass filter which efficiently suppresses most of the residual high-frequency noise generated by the Class-D amplifier. The cut-off frequency $fc_{coil}$ (-3 dB) of the user coil can be determined by the following equation:

$$fc_{coil} = \frac{1}{2\pi\left(\frac{L_{coil}}{R_{coil} + 0.165}\right)}$$

<u>Example</u>:
$L_{coil}$ = 290 µH
$R_{coil}$ = 2.35 Ohm

$$\boldsymbol{fc_{coil}} = \frac{1}{2 \cdot 3.1416\left(\frac{290 \cdot 10^{-6}}{2.35 + 0.165}\right)} = \mathbf{1.38\ kHz}$$

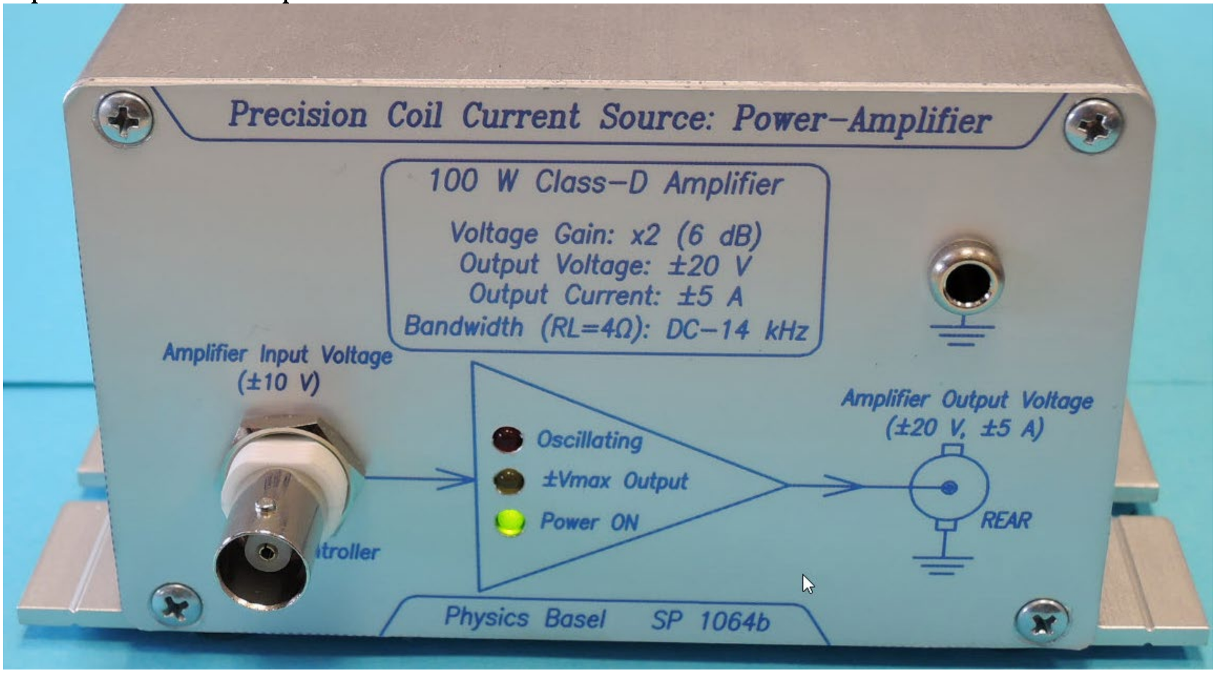
This first-order low-pass filter with a cut-off frequency of 1.38 kHz effectively suppresses high-frequency noise. At 14 kHz, it achieves a factor of 10 (20 dB) noise voltage rejection.

The Power-Amplifier is capable of driving a wide range of load impedances without oscillation problems. This feature is very important because the PCCS can drive almost any user coil. Since the bandwidth of the Power-Amplifier depends on the load resistance, the optimum range of the coil's DC-resistance is between 2 and 10 Ohm. However, coil resistances down to 0.3 Ohm and up to 100 Ohm can still be used. The table below shows the typical bandwidth (-3 dB) of the Power-Amplifier at various load impedances:

| **Load Impedance (RL)** | **Bandwidth (-3 dB)** |
|---|---|
| 100 Ohm | DC…20 kHz |
| 8 Ohm | DC…16.8 kHz |
| 6 Ohm | DC…15.5 kHz |
| 4 Ohm | DC…13.5 kHz |
| 2 Ohm | DC…9.5 kHz |

## 7.1 Front-Panel

A photo of the front-panel with no cables connected is shown below:




The front-panel has the following elements from left to right:

- *Amplifier Input Voltage (±10 V)*
  This BNC connector is the input voltage of the Power-Amplifier which can be maximum ±10 V maximum. The voltage is received via a differential input which has a maximum common mode voltage of ±10 V. The differential input resistance is around 50 kOhm and the outer shield of the BNC connector has a resistance of around 25 kOhm to the housing/earth. The differential receiver eliminates potential ground loops.

- *LEDs: Oscillating (red) / ±Vmax Output (yellow) / Power ON (green)*
  These three status LEDs shows the condition of Power-Amplifier. Normally only the green LED (*Power ON*) is turned ON. If this LED is OFF, the ±17 V supply voltage from the Power-Supply has failed. Verify that the 6-pin DIN device plug on the back of the Power-Amplifier (*Power Input, ±17 V, ±3.3A*) is connected to the Power-Supply (*±17 V Output Voltage*). Make sure that the Power-Supply (SP 1064c) is switched on.

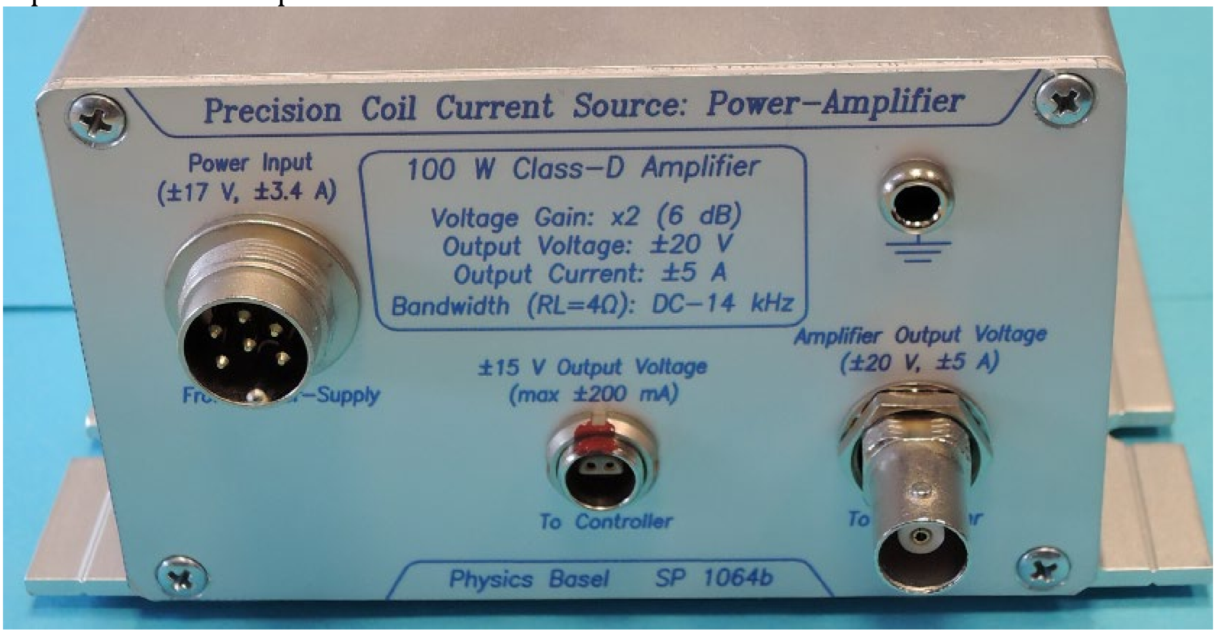
  The yellow LED (*±Vmax Output*) is turned ON if the maximum output voltage of ±20 V is reached. In closed-loop mode, this indicates that the desired coil current cannot be achieved. If this LED lights up continuously, the control loop is interrupted somewhere; check all connections and ensure that the coil is properly attached on the back-side of the Controller (*Coil Current Output*). This LED may light up for a short period of time while the coil current is changing from one value to the other: In this case, the output voltage of the Power-Amplifier may briefly reach the maximum output voltage of ±20 V.

  The red LED (*Oscillating*) indicates that the output voltage of the Power-Amplifiers is oscillating at a frequency greater than a few kHz. If this happens while the PCCS is required to drive a DC current, it indicates that the control loop is unstable and has gone into self-oscillation. In this case, turn off the Power-Amplifier immediately to prevent from overheating. Double check, that the PI controller components ($R_c$ and $C_c$) inside the Controller are correct for the coil connected and the Current Range selected. See the chapter “Estimation of the PI Controller Components”.

- A 4 mm metal banana socket allows the housing of the Power-Amplifier to be earthed/grounded. Note: It is strongly recommended that this socket is connected to your system earth/ground.

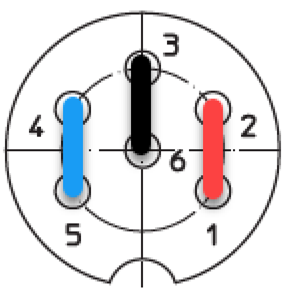
## 7.2 Back-Panel

A photo of the back-panel with no cables connected is shown below:




The back-panel has the following elements from left to right:

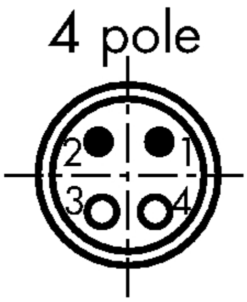
- *Power Input (±17 V, ±3.4 A)*
  This is the supply voltage of the Power-Amplifier coming from the Power-Supply (SP 1064c).




On the left is the view to the Lumberg 6-pin socket (SFV 60) mounted on the Power-Amplifier. The pin assignment
is as follows:
PIN 1 + 2: +17 V Input/ +3.4 A max
PIN 4 + 5: -17 V Input / -3.4 A max
PIN 3 + 6: 0 V Input
(Shield/Thread is connected to housing and 0 V)

CAUTION: Turn off the Power-Supply before connecting or disconnecting this connector.

- *±15 V Output Voltage (max. ±200 mA)*
  This is a ±15 V output voltage with maximum output current of ±200 mA. It can be used to supply the Controller (SP 1064a). The connector that fits into this socket is a 4-pin LEMO Series 0S with the following part number: FFA.0S.304.(CLAC44)
  Use a 1:1 LEMO cable to supply the Controller (SP 1064a).




On the left is a view to the LEMO socket mounted on the Controller. The pin assignment is shown below:

PIN 1: +15 V Output/ +200 mA max
PIN 2: -15 V Output / -200 mA max
PIN 3: not connected
PIN 4: 0 V Output / Ground
(Shield is connected to housing and 0 V)

CAUTION: Turn off the Power-Supply before connecting or disconnecting this connector.

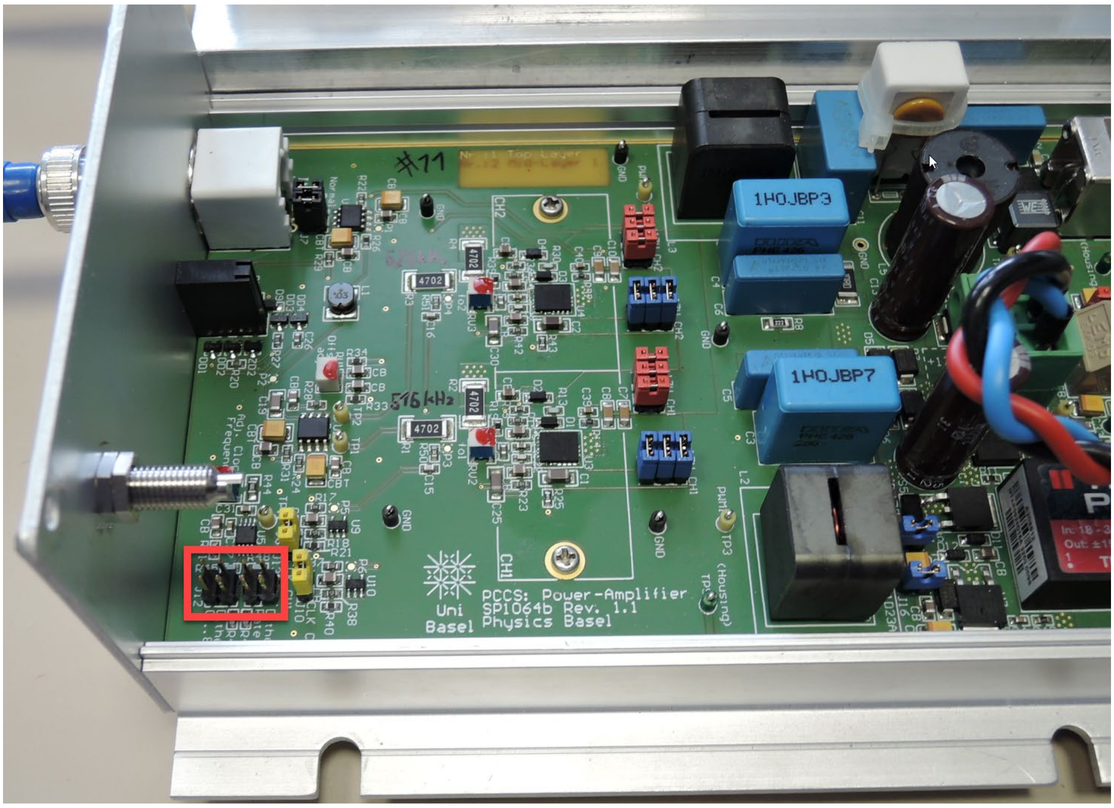
- *Amplifier Output Voltage (±20 V, ±5 A)*
  This BNC connector provides the output voltage of the Power-Amplifier which is up to ±20 V at a current of up to ±5 A. It is connected to the Controller with a short BNC cable. The outer shield of the BNC is connected to housing/ground.

- A 4 mm metal banana socket allows the housing of the Power-Amplifier to be earthed/grounded. Note: It is strongly recommended that this socket is connected to your system earth/ground.

## 7.3 Background

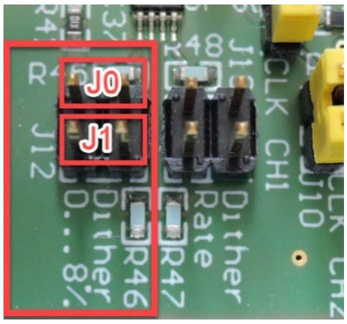
This Power-Amplifier is a Class-D amplifier based on high-frequency pulse-width modulation (PWM). The main advantage of this design is its high efficiency, which results in low power dissipation and therefore low self-heating.
It is based on the integrated analog input Class-D audio amplifier chip IR4321 from the company Infineon. The nominal switching frequency of the PWM is at 380 kHz (±1 kHz).

If necessary, the switching frequency can be dithered to reduce the peak emission radiation of the Power-Amplifier. Dithering is disabled by default, but can be enabled by placing jumpers on the Power-Amplifier's circuit board. To access to the PCB, open the top cover of the Power-Amplifier. Note: Disconnect the power supply before removing the four top cross-head screws as described in the Controller section. The dither-jumpers are located in the front right part of the PCB:



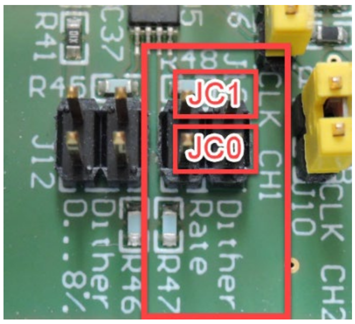

The peak-to-peak PWM-frequency dither can be selected between these values: 0% (fix 380 kHz, default), 2% (376.2…383.8 kHz), 4% (372.4… 387.6 kHz) and 8% (364.8…395.2 kHz). This dither percentage is set by the two jumpers J0 and J1 on J12:

| J1 | J0 | Dither (f Range) |
|---|---|---|
| open | open | 0% (fix 380 kHz, default) |
| open | CLOSED | 2% (376.3…383.8 kHz) |
| CLOSED | open | 4% (372.4…387.6 kHz) |
| CLOSED | CLOSED | 8% (364.8…395.2 kHz) |



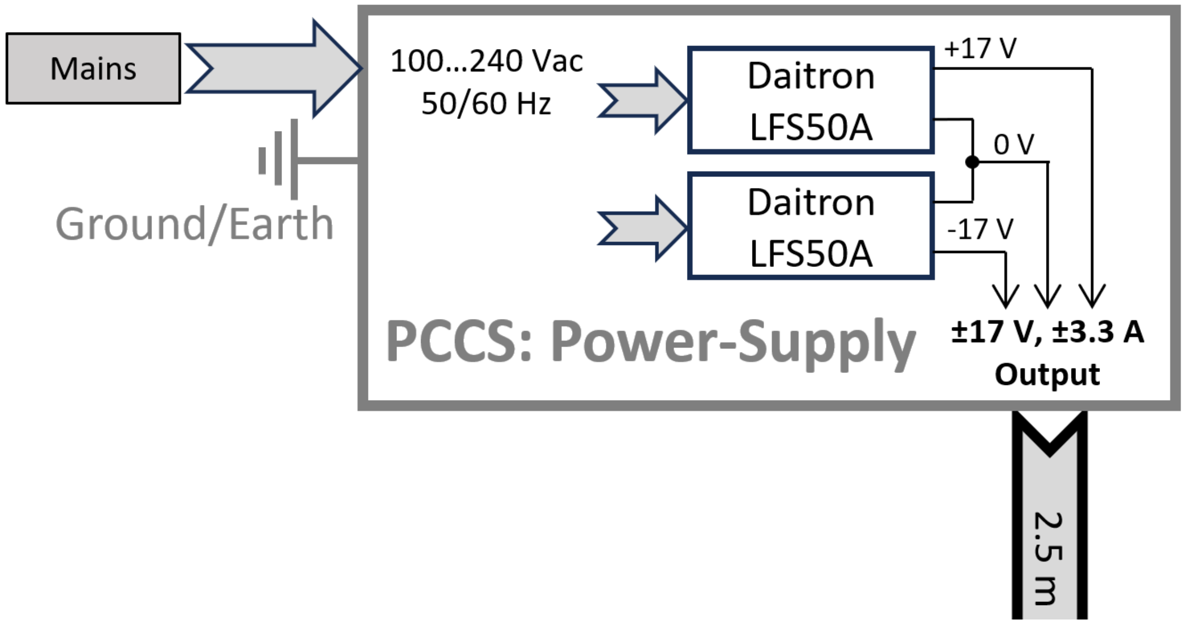

The PWM frequency is swept in a triangular shape; the frequency of this triangular modulation is also selectable: 12kHz (default), 6 kHz, 3 kHz and 1.5 kHz. This dither modulation frequency is selected by the two jumpers JC0 and JC1 on J13:

| JC1 | JC0 | Triangle Modulation f |
|---|---|---|
| open | open | 12 kHz (default) |
| open | CLOSED | 6 kHz |
| CLOSED | open | 3 kHz |
| CLOSED | CLOSED | 1.5 kHz |



# 8 Power-Supply (SP 1064c)

From the mains voltage the Power-Supply generates the ±17 V supply voltage for the PCCS. The circuit diagram principle of the Power-Supply is given below:




The size of the Power-Supply is (Width x Height x Depth): 147 mm x 114 mm x 250 mm
The weight of the Power-Supply is: 1.86 kg

It is based on two 50 W ultra-low noise AC/DC switching power supplies from the company Daitron of Japan. One unit generates the +17 V and the other generates the -17 V DC supply voltage. The power supplies are capable of delivering 3.3. A continuously and 3.4 A for a short time. They are therefore suitable for supplying the PCCS, which requires ±17 V at a maximum current of ±3.4 A. The ±17 V DC power supply is provided by a shielded cable of 2.5 meters in length. This allows the Power-Supply to be physically separated from the Controller/Amplifier.

Note: The shield of the 2.5 meter cable is connected only to housing/earth of the Power-Supply; the housing is connected to the protective earth/ground via the power cord. The metal housing of the ±17 V cable connector is not connected to the shield. Therefore, the Power-Amplifier/Controller unit is floating and its case must be connected to the experiment ground/earth.

The mains input voltage range of 100 Vac to 240 Vac at 50/60 Hz makes this Power-Supply suitable for worldwide use. The mains voltage is connected by a three-pole IEC device plug.

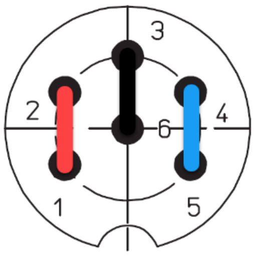
CAUTION: Do not cover the Power-Supply. Doing so may cause it to overheat due to blocked convection.

## 8.1 Front-Panel

Below is a photo of the front-panel with 2.5m cable outlet:


The front-panel has the following elements from bottom to top:

- *Power Output Cable (±17 Vdc, ±3.3 Adc)*
  This is the ±17 V DC supply voltage for the PCCS. It must be attached to the back-panel of the Power-Amplifier (SP 1064b).




On the left is the front view to the Lumberg 6-pin connector (KV 60) mounted on the 2.5 meter cable. The pin assignment is as follows:
PIN 1 + 2: +17 V Output/ +3.3 A (+3.4 A max)
PIN 4 + 5: -17 V Output / -3.3 A (-3.4 A max)
PIN 3 + 6: 0 V Output
(Shield/Thread is floating)

CAUTION: Turn off the Power-Supply before connecting or disconnecting this connector.

- A 4 mm metal banana socket enabled connection to the housing, which is connected to the protective earth/ground via the power cord.

- Two green LEDs indicate when the +17V and -17V voltages are present. Check the fusey on the back-panel if they do not light when the power is turned on.

## 8.2 Back-Panel

Below is a photo of the back-panel with a gray power cord connected:


The back-panel has the following elements:

- *Power Entry Module*
  The power cord plugs into the Power Entry Module, which includes a line filter, fuse drawer and a power ON/OFF switch. The input voltage range is 100 to 240 Vac at 50 or 60 Hz. The maximum power consumption is 150 W.

- *Power ON/OFF Switch*
  When the toggle switch is in the up position, the Power-Supply is on and the two green LEDs (+17V and -17V) on the front-panel should light up.

- *Fuses*
  There are two fuses installed in the Power Entry Module. The line neutral and line phase are separately fused; both fuses must be good. The fuses are 3.15 A slow blow with a size of 5 x 20 mm. The power cord must be disconnected before the fuse drawer can be opened by pressing the tabs at the top and bottom.

# 9 Closed Loop Current Noise

The total current noise through the user coil is strongly dependent on its cut-off frequency $fc_{coil}$ (-3 dB), which can be determined by the following equation:

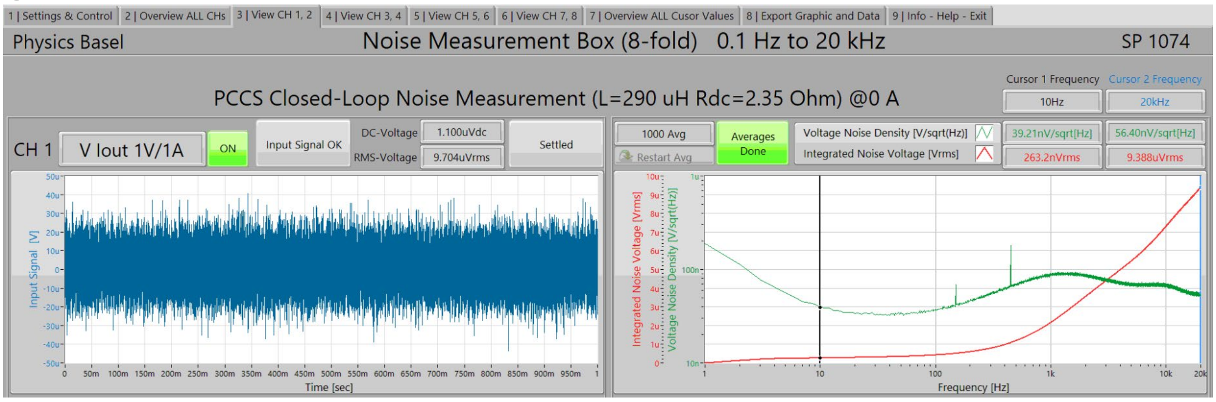
$$fc_{coil} = \frac{1}{2\pi\left(\frac{L_{coil}}{R_{coil} + 0.165}\right)}$$

The lower the cut-off frequency the lower the total current noise because this first-order low-pass filter effectively suppresses high-frequency noise.

The following measurements were made with the example coil ($L_{coil}$ = 290 µH, $R_{coil}$ = 2.35 Ohm), which has a cut-off frequency of about 1.4 kHz. The PI controller contains the components for an aperiodic set-point response ($R_C$ = 6.8 kOhm and $C_C$ = 22 nF). A current range of 4 A is used and the actual current is set internally by the multi-turn potentiometer.

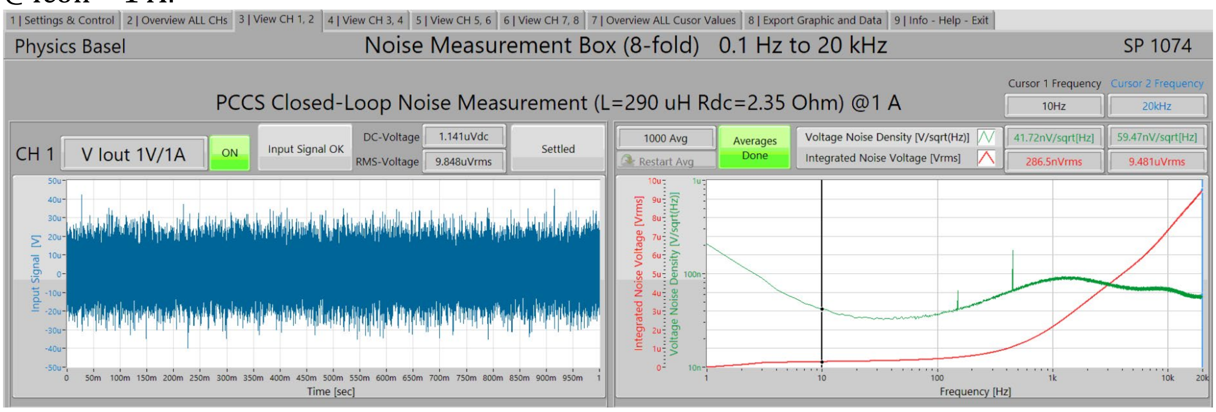
The current noise is measured at the *Current Monitor Out 1V/A* using the "Noise Measurement Box (SP 1074)". Information about this device is available here:
https://physik.unibas.ch/en/department/technical-services/electronics-lab/
Since the scaling on the current monitor output is 1 V per 1 A, the measured noise voltages correspond 1:1 to the noise current. Noise measurements were taken from 1 Hz to 20 kHz and from 0 A up to 4 A in 1 A increments. 1000 noise spectra have been averaged and the two cursors are set to 10 Hz and 20 kHz. The left graph shows the time signal and the right graph shows the noise spectral density (green) and the integrated noise (red):

@ Icoil = 0 A:



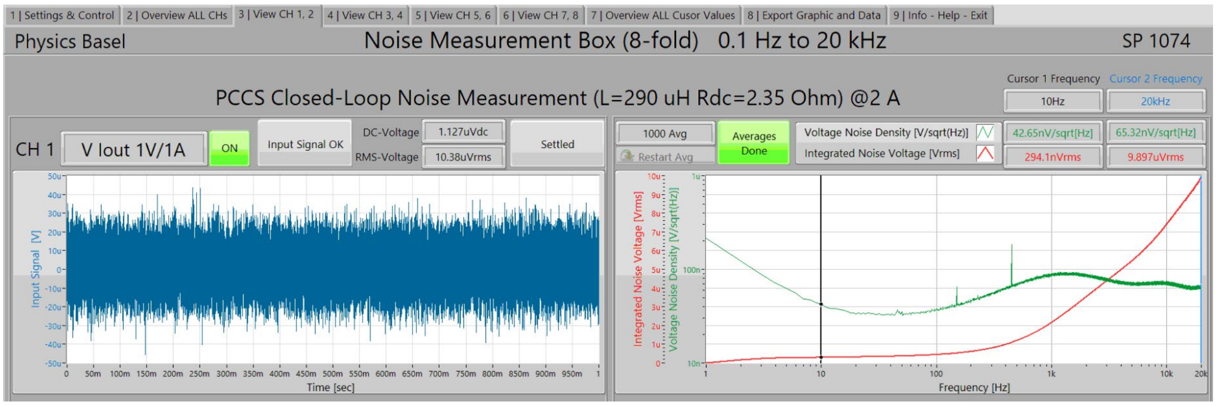

Total current noise (1 Hz to 20 kHz) = 9.388 µArms

@Icoil = 1 A:



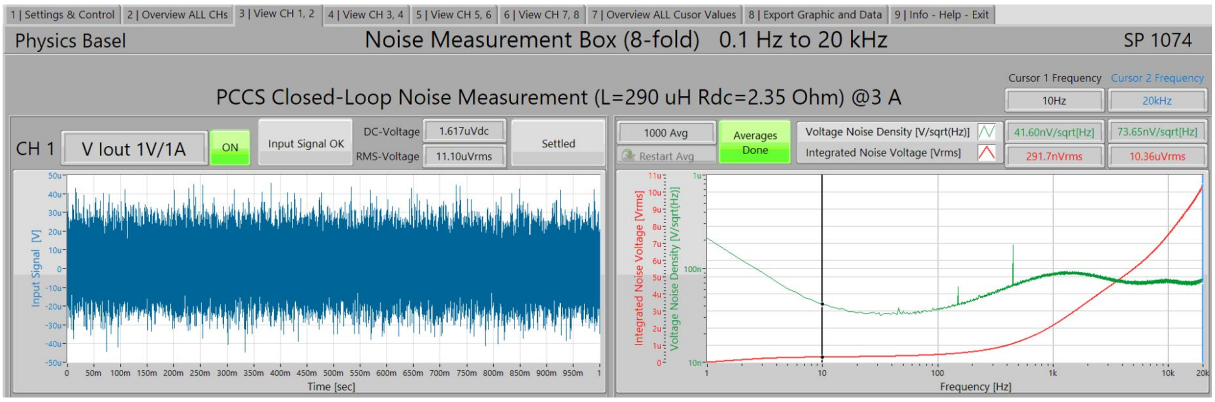

Total current noise (1 Hz to 20 kHz) = 9.481 µArms

@Icoil = 2 A:



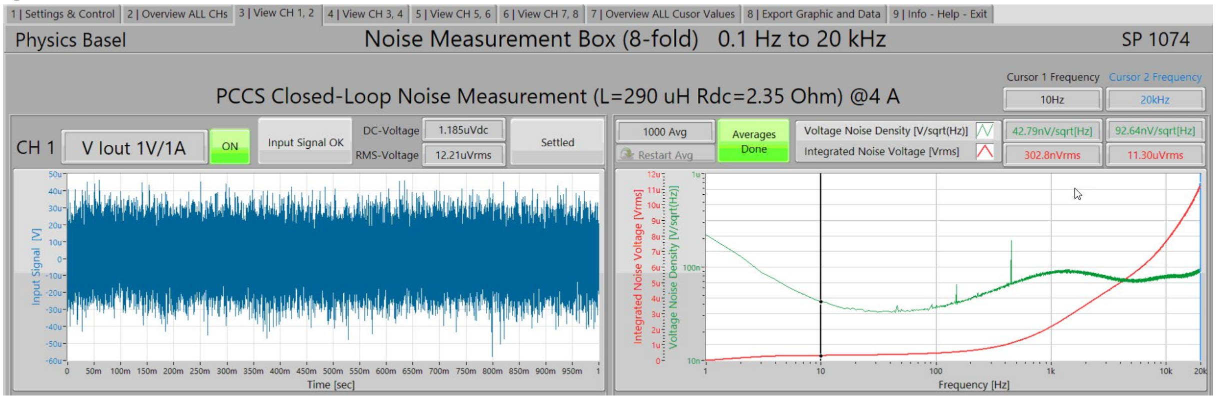

Total current noise (1 Hz to 20 kHz) = 9.897 µArms

@Icoil = 3 A:



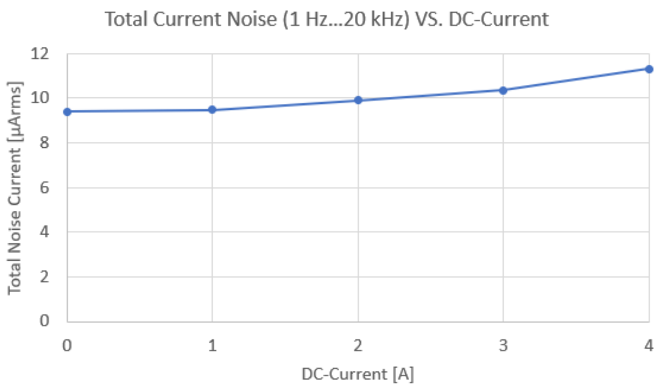

Total current noise (1 Hz to 20 kHz) = 10.36 µArms

@Icoil = 4 A:




Total current noise (1 Hz to 20 kHz) = 11.30 µArms

As these figures show, the total current noise is only slightly dependent on the set DC-current:




At 4 A DC, the total current noise of 11.3 µArms is equivalent to an RMS noise of 2.83 ppm.

# 10 Three-Axis System

In many physics' experiments, it is often necessary to control the magnetic field in all three spatial axes. The three PCCS can be stacked to form a single block of Controllers/Power-Amplifiers for the X, Y and Z axes:


The three Power-Supplies can be easily separated from the Controllers/Amplifiers and; these are preferably arranged horizontally to allow cooling by air circulation:


This results in a stable and clear three-axis coil current control system.

# 11 Specifications (Typical @Temperature 25°C, 2 h Warm-up)

- Coil DC resistance range: 2 Ohm (minimum 0.3 Ohm) to 100 Ohm
- Coil inductance range: 0 to 2 H
- Maximum coil current: ±5 A (±6 A possible, but not guaranteed)
- Maximum coil voltage: ±20 V
- Maximum output power: 100 W
- Absolut current accuracy @external control: ±1.5 %
- Displayed (LCD) current accuracy: ±2 %
- Long-term drift @constant temperature: 10 ppm over 12 hours
- Current Noise (1 Hz…20 kHz) @4 A (L=290 µH, R=2.35 Ohm): 11.3 µArms
- Temperature drift:
  External set: 1.4 ppm/°C
  Internal set: 2.7 ppm/°C
- Class-D Power-Amplifier PWM switching frequency: 380 kHz (±1 kHz)
- Mains voltage: 100 Vac…240 Vac, 50/60 Hz
- Maximum mains power consumption: 150 W
- Total weight (including cables and mechanics): 4.4 kg
- Warm-up time: 2 hours

# 12 Operation Conditions

- Environment: Indoors dry laboratories only
- Ambient Temperature: Between 10°C (50°F) and 40°C (104°F)
- Altitude: Up to 5'000 m (16'400 ft)
- Relative humidity: Maximum 90% for temperatures up to 31°C (88°F), decreases linearly to 50% at 40°C (104°F)
- Pollution: Degree 1 (no pollution or only dry and non-conductive pollution)