Electronic Loads

Installation & Operation Manual

EL300

EL1000

06/2021

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CAUTION

Prevent the input panel of the device from electrostatic discharge! This may damage the device.

Do not connect active objects such as batteries or fuel cells to the power outputs of the device when the device is off!
This may damage the device.

Unpacking

Zahner products are carefully produced, calibrated and tested to achieve a high-quality standard. Also the assembling of the accessories and packing is done with great care. Please check the shipment directly after receipt to ensure that the device and all accessories are undamaged.

The shipment must contain the following parts:

EL1000

- EL1000
- cable for connection of the EPC42 (D-Sub9 - Lemosa)
- twisted sense cable (Lemosa plug, blue & green cables)
- power cord
- this manual

EL300

- EL300 with installed control cable for connection of the EPC42 (Lemosa plug)
- 2 thick cables (blue and red) with high current banana plugs (∅ 12mm)
- twisted sense cable (Lemosa plug, blue & black cables)
- power cord
- this manual

Basics

Today, dynamic measurements on electrochemical objects are of great interest. Modern instruments for impedance measurements, cyclic voltammograms and pulse response experiments provide a broad frequency range from µHz to MHz. At the same time, they provide a huge impedance range from µΩ to GΩ. However, for most instruments there is one restriction left, they have a limited current range of few Amperes. In the field of electrochemical power generation, for example, this is only sufficient for “small” systems.

The electrochemical workstations of the Zennium family provide a current range of ±4 A (*Zennium X*) and ±3 A (Zennium Pro) and measure impedances down to µΩ. Therefore, we provide external devices (*EL, PP-Series and XPOT*) that can extend the application field of the *Zennium* systems.

The electronic loads *EL300* and *EL1000* are designed as additional potentiostats to allow dynamic investigations on technical systems up to 100 A (*EL300*) and 200 A (*EL1000*). Their main applications are discharging tests on (rechargeable) batteries and fuel cells.

The electronic loads are easily integrated into the *Zennium* system using *EPC42* controller cards. All functions are controlled directly from the Thales software. Up to 16 electronic loads may be controlled by one *Zennium* system using up to 4 *EPC42* cards.

EPC42

The *EPC42* can control up to 4 external devices like the *EL300/EL1000*, the *XPOT,* and the *PP201/211/241*. Up to four *EPC42* cards can be used for installing a total of 16 external devices in a *Zennium* system.

Each port provides analog and digital interfaces for the communication of the external devices with the *Zennium* system. The analog part of the port feeds the device with the DC potential at a resolution of 16 bit and the AC amplitude. Measured current and potential are sent from the external device to the *Zennium* to be treated there in the same way as signals from the internal *Zennium* cards. The *EPC42* has a bandwidth of 250 kHz.

A bi-directional serial communication line allows to digitally control the functions and measuring ranges of external devices.

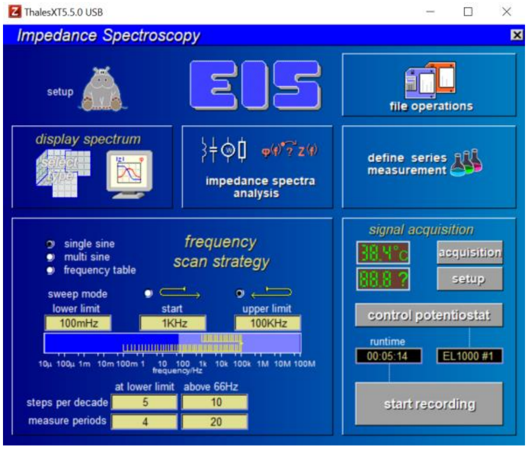
!	**Plug or unplug external devices only when both, Zennium AND the external devices, are switched off. Otherwise the devices may get damaged.**

Selecting an external device

All external *Zennium* devices are directly controlled by the Thales software. Each device has a unique device number which is identical to the *EPC42* port number. So, if a device is connected to *EPC* port 3, you address it with the device number 3. Device number “0” is reserved for the internal potentiostats of the *Zennium* system.

If an *RMUX* (relay multiplexer) card is installed, the device numbers of the external devices (ELs/PPs/XPOTs) start with 17, not with 1, because then the device numbers 1 to 16 are reserved for the 16 *RMUX* channels.

To select a device, call the *Test Sampling* page by clicking on the "**control potentiostat**" option.



Click on "**Device**" on the left side of Hippo. This will open an input box. Insert the EPC port number in which the external device is connected. Here EL1000 is connected with port 1 of EPC42.

In addition, the external device can be calibrated by clicking on the "**calibration?**" icon

If no device has been connected to the addressed *EPC42* port, an error message is displayed and the software automatically selects the internal potentiostat.

If the selected device is present but has not been activated then the software starts to calibrate it automatically.

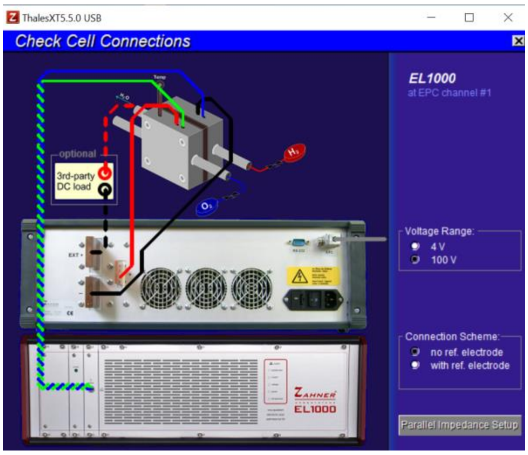
If an external device is changed then the new device has to be calibrated before use. The calibration is carried out only for the selected device. All other calibration data remains unchanged.

If a device number other than 0 is selected, the parameters of the *Test Sampling* page now are valid for the designated device.

The following methods are available for external devices:

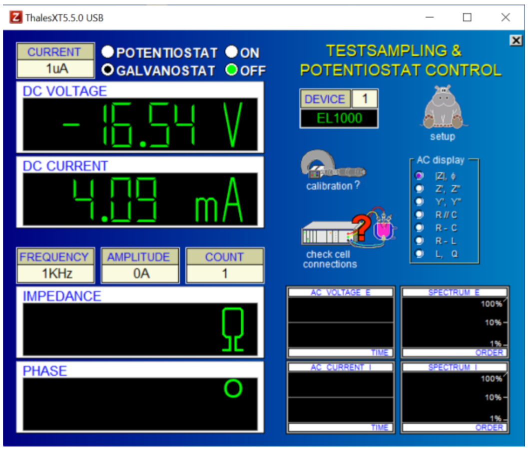
EIS	impedance measurement
C/E	Parameter based impedance measurement
I/E	current potential curve recording
MIE	Multiple parallel current potential curve recording
AS	series measurements

To change the potential range of the electronic load (here EL1000), click on the "**check cell connections**" icon.



In **check cell connections**, you can set the desired potential range and choose a reference electrode. Here for convenience, the EL1000 connection scheme with the 3rd party DC load is also shown.

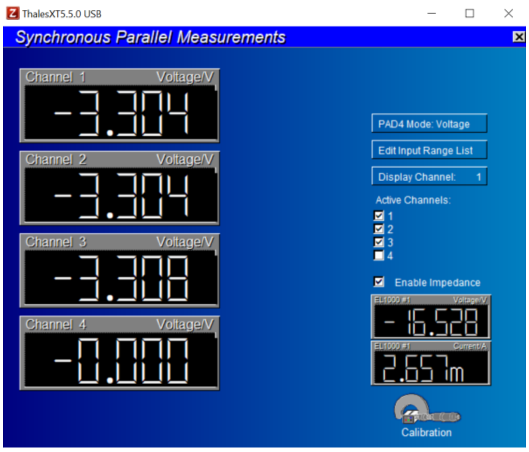
At the bottom of the page "**Parallel Impedance Setup**" is provided to setup the PAD4 connections. Once all the desired settings are complete then click "**Esc**" or click on ☒ to go back to the last window.



Now connect the sense cables from EL1000 to the device under test (DUT). Here a battery is used as a DUT.

Connect blue sense cable to the **– terminal** and green sense cable to the **+ terminal** of the DUT. This will show the correct polarity and a negative potential will be shown in the **DC VOLTAGE** window.

Now connect the power cables for the desired EL1000 arrangement. Please note that with the connection of the power cables the potential should not change considerably (connect power cables as shown for your preferred arrangement in the manual below).



If parallel impedance spectra are to be measured then click on the "**Parallel Impedance Setup**" in "**Check Cell Connections**". This will open a new window where different channels from the PAD4 cards can be chosen. Here first 3 channels are selected which are analyzing the individual cell of the DUT (battery).

Also click on "**Enable Impedance**" to allow the impedance measurement from the PAD4 channels. At the bottom right, the voltage and current from the sense cables of EL1000 can also be seen.

Changing devices

When changing the device number, the now inactive device will hold its DC conditions such as DC potential and on/off status as long as it is selected anew or the system is shut off. On the other hand only the selected device is internally connected to the FRA. Therefore only this device can output an AC signal superimposed to the DC potential.

Potential in electronic loads (EL)

Chemical reactions in the batteries and fuel cells provide us with energy. In the field of electrochemistry such reactions are shown on a negative potential (energy) scale. However potentials in the field of electronics and electrical engineering are shown with a positive sign. Hence to facilitate the chemists in comparing the reactions and carrying out different experiments, the potential's reading in electronic loads (EL) is reversed. e.g., if one measure a potential of a battery by a voltmeter and it reads +2 V then the EL300/EL1000 will read it as -2 V.

Safe operation conditions (SOC)

- Pay attention to the wire connections and strictly follow the guidelines of this manual. A reverse polarity may damage your device (especially EL300).
- During operation, the potential on + terminal of EL1000 should be at least 1 V higher than the – terminal of EL1000.
- Always turn **ON** the electronic load (EL300/EL1000) after turning on the external load or external power supply.
- Immediately after turning on the electronic load, no current should flow through the electronic load before the electronic load finishes the startup calibration.
- Always turn **OFF** the electronic load (EL) before turning off the external load or external power supply.
- Properly connect (with screws) the EPC42 cable with the electronic load. An accidental unplugging of the EPC42 cable during operation may damage your device.
- Remove all metallic jewelry/watches when working with high currents.
- Don’t touch the electrical connections during the operation.
- Never apply potential higher than the 12 V for EL300 and 100 V for EL1000.
- The maximum current through the + terminal of EL1000 must never exceed 200 A.
- The maximum current through the shunt resistance of EL1000 must never exceed 680 A.

EL300

The *EL300* external electronic load is a *One-Quadrant-Potentiostat*. This means that EL300 is only able to sink current but cannot source current. Typical applications are discharging experiments at (rechargeable) batteries and fuel cells. The *EL*-series potentiostats can be operated in both potentiostatic and galvanostatic modes, controlled by the Thales software. For low ohmic objects, galvanostatic mode is recommended. The output panel as well as the input panel are electrically isolated from the ground.

The *EL300* is air-cooled for operation till 25 A and needs water cooling when loaded with more than 25 A. For water cooling you find an inlet and an outlet at the backside of the *EL300*.

!	**The *EL300* may get damaged if more than 25 A are applied without water cooling!!!**

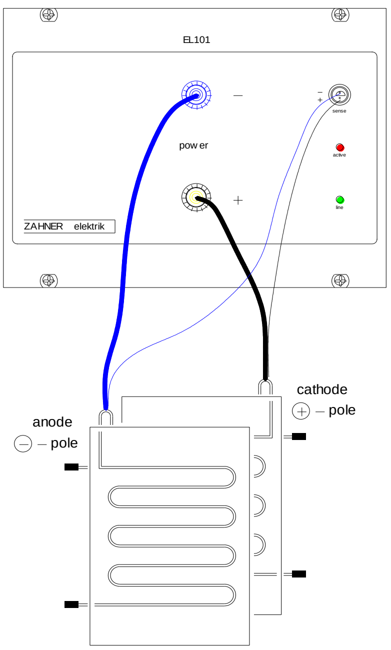
Cell Connections

It is important to know that *EL* potentiostats SINK current from the device under test (DUT) and therefore the cell connections must be as **short** and as **thick** as possible. Otherwise the measurements may be faulty and it may even seem that the *EL* is defective. For this reason, the standard cable set shipped with the *EL*s should be shortened as much as possible.

It is also important to connect the DUT with the correct polarity to the *EL* potentiostat. Whereas typical one-cell-voltages of 0.8 V or 1.2 V do not damage an *EL* when being connected with the wrong polarity, cell stacks can do very well. Therefore, we recommend connecting the sense inputs as described in section. 1 (Full Cell Configuration). Call the *Test Sampling* page of the Thales software and check for the potential polarity by connecting sense cables. It must be **negative**. Now connect the power cables according to section. 1 with the potentiostatic/galvanostatic mode switched **OFF**. The displayed potential must not change significantly when connecting the power cables.

With the correct polarity the DUT may be connected to the *EL* potentiostat in one of the following ways:

1. Full cell configuration (Standard Kelvin Scheme)



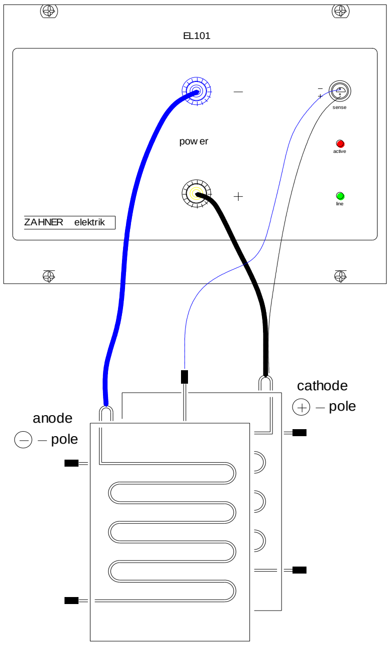
This configuration is used with DUT like (rechargeable) batteries and fuel cells if a complete cell is to be investigated.

!	**Potential ≤ 4 V / 12 V** **The potential will be indicated as negative in EL.** **The measured current must be positive I ≥ 0**

Always ensure the correct polarity by connecting the sense cables. Afterward properly connect the power cables.

The potential will be shown as **negative** in the Thales software.

2.a. Half-cell configuration – Cathode

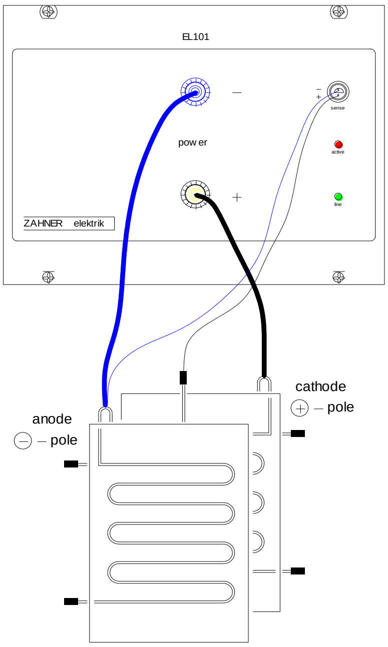


This configuration is used with DUTs like (rechargeable) batteries and fuel cells if only the cathodic part of the cell has to be investigated.

!	**Potential ≤ 4 V / 12 V** **The potential will be indicated as negative in EL.** **The measured current must be positive I ≥ 0**

Depending on the type of reference electrode the measured potential may be different from the real potential at the reference electrode site. The real potential can be calculated from the measured potential by subtracting the potential of the reference electrode.

2.b. Half-cell configuration - Anode

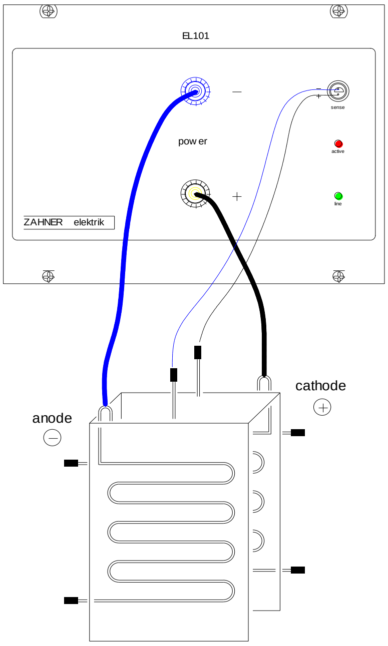


This configuration is used with DUTs like (rechargeable) batteries and fuel cells if only the anodic part of the cell has to be investigated.

!	**Potential ≤ 4 V / 12 V** **The potential will be indicated as negative in EL.** **The measured current must be positive I ≥ 0**

Depending on the type of reference electrode the measured potential may be different from the real potential at the reference electrode site. The real potential can be calculated from the measured potential by subtracting the potential of the reference electrode.

3. Partial cell configuration



This configuration may be used, if a certain part of a battery or fuel cell stack has to be investigated.

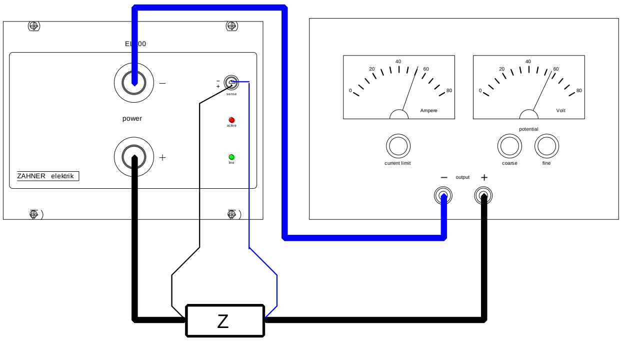
! **Potential ≤ 4 V / 12 V**

The potential will be indicated as negative in EL.

The measured current must be positive I ≥ 0

Depending on the type of reference electrode the measured potential may be different from the real potential at the reference electrode site. The real potential can be calculated from the measured potential by subtracting the potential of the reference electrode.

4. Applications with an additional power supply



This configuration may be used if the voltage drop on the power lines is too high to reach the high-current test conditions. In addition it allows experiments on passive objects and batteries under charging conditions and electrolysis cell

! **Potential ≤ 4 V / 12 V**

The potential will be indicated as negative in EL.

The measured current must be positive I ≥ 0

Built-in buffer amplifier

The built-in buffer amplifier may be used to increase the potential range of the *EL* up to +/-12 V. To select the buffer amplifier, select the corresponding voltage range (±4V / ±12V) at the check cell connection page.

EL1000

The *EL1000* external electronic load is a *One-Quadrant-Potentiostat*. This means that it can sink current (but cannot source current) in a given polarity. Hence when EL1000 is connected with a battery then it can only discharge the battery and charging is not possible without a 3rd party source. Typical applications of EL1000 are discharging experiments at (rechargeable) batteries and fuel cells. The *EL*-series potentiostats can be operated in both potentiostatic and galvanostatic modes, controlled by the Thales software. For low ohmic objects like batteries and fuel cells the galvanostatic mode is strongly recommended.

Measuring floating objects

On the rear of the *EL1000* you will find two connectors with a jumper.
Silver banana jack (earth ground) ⇔ black banana jack (system ground)

If the device under test (DUT) is floating (no metallic or electrolytic contact to ground) it is necessary to set the jumper. Then the EL1000 signal ground (- Terminal of EL1000) is connected to earth ground via a 100 Ω protective resistor.
If any part of the cell is grounded, the jumper must be removed. Then the EL1000 power stage is only AC coupled to earth ground.

!	**When investigating floating objects the jumper must be set and vice versa.**

EL1000 connection

EL1000 must only be connected or disconnected to the Zennium system if both, the *Zennium* and the *EL1000* are switched off.

If you want to use the *EL1000* as a stand-alone device, unselect it in the *Test Sampling* page of the *Thales* software (you may e.g. change the device number to the main potentiostat). The inactive device will hold its DC conditions such as DC potential and on/off status as long as it is selected anew or the system is shut off. Now you may unplug the *EL1000* at the *EPC42* connector. For regaining access to the *EL1000*, connect it to the *EPC42* and select it in the *Test Sampling* page of the *Thales* software.

Note: AC potential is modulated by the FRA in the Zennium device; hence a stand-alone EL1000 can only provide the DC potential (without internal connection to FRA). For AC signaling, the EL1000 must be in contact with the Zennium device.

Cell connections

It is important to know that *EL* potentiostats SINK current from the DUT and therefore the cell connections must be as **short and** as **thick** as possible. Otherwise the measurements may be faulty and it may even seem that the *EL* is defective.

It is also important to connect the DUT to the *EL* potentiostat with the correct polarity. When being connected with the wrong polarity, the EL1000 has a protection circuit and will indicate polarity error. Therefore, we recommend connecting the sense cables as described in EL1000 operation steps. Call the *Test Sampling* page of the Thales software and check for the potential polarity. It must be **negative**. Now connect the power cables according to the scheme provided below with the potentiostatic/galvanostatic mode switched **OFF**. The displayed potential must not change significantly when connecting the power lines.

EL1000 operation steps

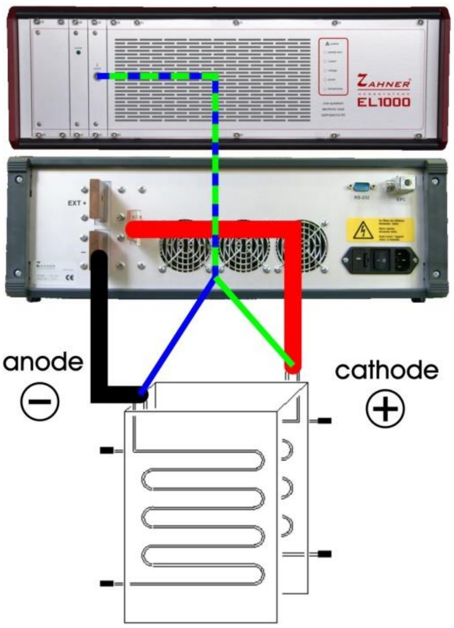
- Check if the device under test (DUT) is grounded or not. Then adjust the grounding of EL1000 accordingly.
- Turn **ON** external power supply/load (if any is required)
- Turn **ON** Zennium device and EL1000 (allow for 15 minutes warm-up time)
- Start Thales software
- Select the EL1000 device in the **Test Sampling Window**. This will start a calibration of EL1000
- Select desired potential range and reference electrode
- Connect the sense cables to the DUT with correct polarity -connect blue sense cable at negative terminal and green sense cable at the positive terminal of the DUT -
- Potentials in test sampling window must be **negative**
- The potential difference between the positive and negative terminal of EL1000 must not exceed 100 V (in any input voltage range: 4V/100V)
- Connect power cables to DUT (to an external power supply or load/sink) -according to the preferred configuration-
- Connect PAD4 cables (if required) and choose the PAD4 option from the Thales software.
- Choose potentiostat/galvanostat mode and turn **ON** (for low ohmic DUT, galvanostatic mode is recommended)
- Perform the desired experiment
- Turn **OFF** the potentiostat/galvanostat mode
- Shut down the Thales software
- Turn **OFF** the EL1000 and Zennium
- Turn **OFF** the external power supply/load
- Remove all the cables (sense and power cables).

NOTE: If the external power supply is required to power the DUT then skip the last two steps (section 6).

With the correct polarity, the DUT may be connected to the *EL1000* potentiostat in one of the different ways described in the rest of this manual.

1. Full cell configuration (Standard Kelvin Scheme)

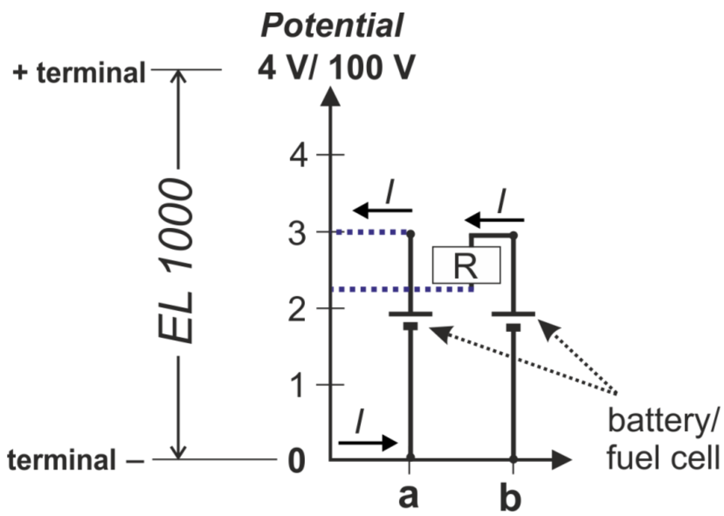
This configuration is used with DUTs like (rechargeable) batteries and fuel cells if a complete cell has to be investigated. Here, first the sense cables are attached to the DUT with the correct polarity and then power cables are connected. Since EL1000 is a one quadrant potentiostat so it cannot act as a source but only work as load. Hence it is recommended to use as short and as thick as possible cables to minimize the resistive losses during operation.



Potential ≤ 4 V / 100 V

! **The potential will be indicated as negative in EL**

The measured current must be positive I ≥ 0



Graph 1: One-Quadrant representation showing battery or fuel cell connection with the EL1000

Graph 1 shows the one quadrant representation of the EL1000 connection with the DUT (3 V battery or fuel cell). In this graph the X-axis represents the **– terminal** of EL1000 and the Y-axis represents the **+ terminal** (with the maximum potential limit of 100 V). In part ***a***, the anode (negative electrode) of the DUT is connected with the **– terminal** of EL1000 and is at **system ground**. While the cathode (positive electrode) is connected to the **+ terminal** of EL1000 (connected to the Y-axis via blue line). Here the potential is positive but it will be indicated as negative in Thales software. In this representation the current flow is counterclockwise (**current > 0**). EL1000 will read the potential with sense cables (around DUT – battery) and will always read -3 V. However between the **+** and **– terminals** of the EL1000, the output potential will be less than 3 V. This decrease (see Graph **1*b***) is due to the voltage drop **(*V* = *I***R*)** within the system. This voltage drop depends on the current flowing through the system. Hence if the current is high then the voltage drop will also be high. When sinking high currents from low cell potentials (like big single fuel cells) the input potential (at EL1000 + terminal) can become less than 1 V. In such conditions, the EL1000 will not work properly. Hence when controlling current, keep in mind that high currents will increase the voltage drop and pay attention to the input potential.

Current setting in EL1000

EL1000 has 3 terminals at the backside of the device labeled as positive (**+**), negative (**-**) and external positive (**EXT +**) terminals. EL1000 is a one quadrant potentiostat and can only work as a load. So it allows current (*I*) flow only in one direction (clockwise inside EL1000) between its **+** and **–** terminals (see Fig. 01). This means that a DUT (e.g., battery) can only be connected with EL1000 in one polarity. If that DUT is connected with EL1000 in the wrong polarity, the polarity error LED will indicate this. However, when EL1000 is used with an external power supply via **Ext +** terminal (see chapter 6) then the current (***i***) can flow in both directions between the **EXT +** and **–** terminals.

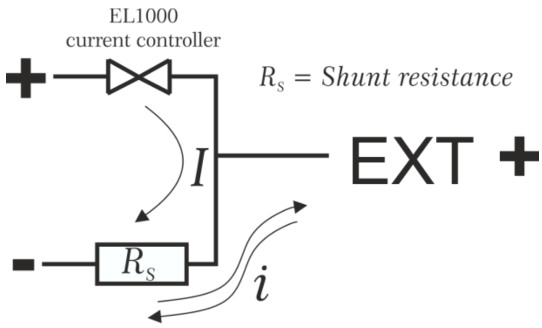
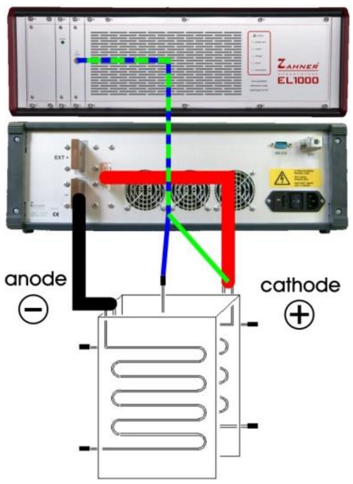


Fig 01: Current flow direction between **+** and **–** terminals and **–** and **EXT +** terminals of EL1000

For ease, we will distinguish the current between the **+** and **–** terminals of EL1000 with ***I*** and current between EXT **+** and **–** terminals of EL1000 with ***i***.

In EL1000, the **+** terminal is thinner as compared to **–** and **EXT +** terminals because the maximum allowed current which can flow from **+** terminal is 200 A whereas between **–** and **EXT +** terminals, a maximum current of 680 A can flow.

2.a. Half-cell configuration – Cathode

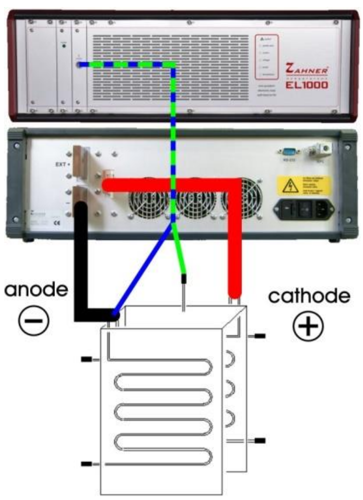


This configuration is used with DUTs like (rechargeable) batteries and fuel cells if only the cathodic part of the cell has to be investigated.

!	**Potential ≤ 4 V / 100 V** **The potential will be indicated as negative in EL** **The measured current must be positive I ≥ 0**

Depending on the type of the reference electrode, the measured potential may be different from the real potential at the reference electrode site. The real potential can be calculated from the measured potential by subtracting the potential of the reference electrode.

2.b. Half-cell configuration - Anode

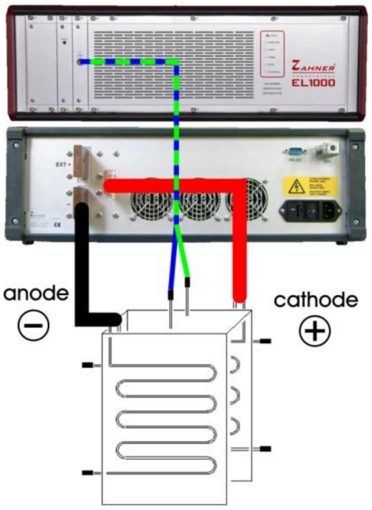


This configuration is used with DUTs like (rechargeable) batteries and fuel cells if only the anodic part of the cell is to be investigated.

!	**Potential ≤ 4 V / 100 V** **The potential will be indicated as negative in EL** **The measured current must be positive I ≥ 0**

Depending on the type of the reference electrode, the measured potential may be different from the real potential at the reference electrode site. The real potential can be calculated from the measured potential by subtracting the potential of the reference electrode.

3. Partial cell configuration



This configuration may be used, if a certain part of a battery or fuel cell stack has to be investigated.

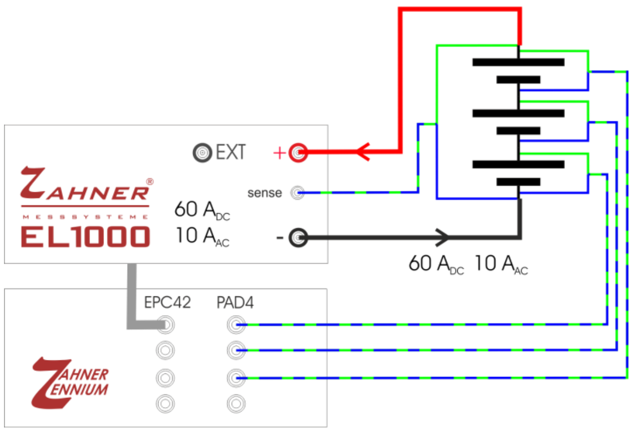
> **!**
> **Potential $\leq$ 4 V / 100 V**
>
> **The potential will be indicated as negative in EL**
>
> **The measured current must be positive I $\geq$ 0**

Depending on the type of the reference electrode, the measured potential may be different from the real potential at the reference electrode site. The real potential can be calculated from the measured potential by subtracting the potential of the reference electrode.

PAD4 connection

A PAD4 card provides 4 additional channels for impedance measurements. These channels allow for a simultaneous investigation of different parts of the DUT. With Zennium X, up to 4 PAD4 cards can be installed and 17 parallel impedance measurements can be carried out. An application of such a setup is a simultaneous investigation of 17 cells in a battery. A schematic of such a system with 3 PAD4 channels is shown.

NOTE: The **+**, **-** and **EXT +** terminals are provided at the back of EL1000 whereas the sense cable connection is at the front of EL1000.

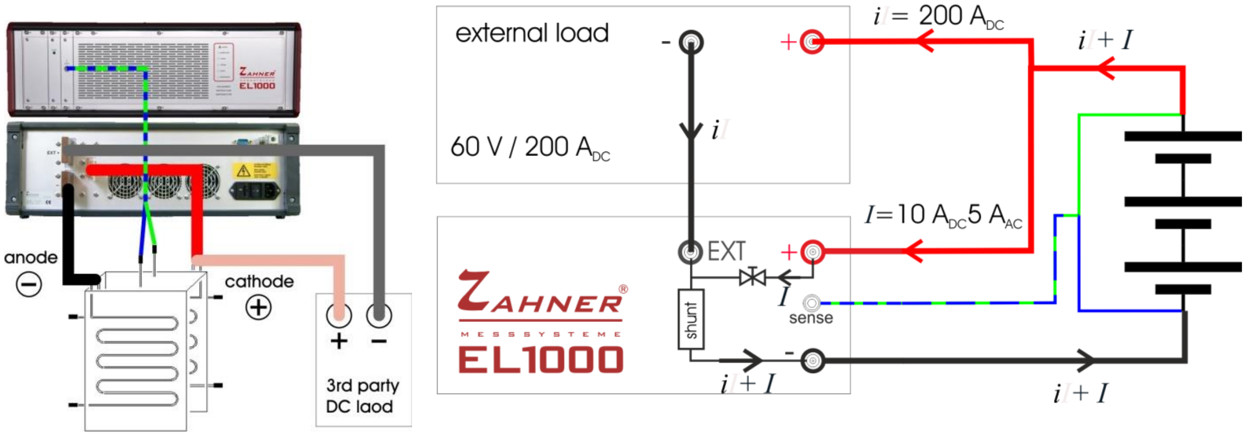


> The current carrying cables (black and red) must be twisted together to minimize the inductance.
>
> The sense cables (green and blue) must be twisted together to minimize the artefacts.

4. Applications with an additional DC load

4.a. DUT connected with DC sink and EL1000

This configuration may be used to sink more current through the DUT than 200A. The total amount of current from the EL1000 and the additional electronic load must not exceed 680A!



Potential ≤ 4 V / 100 V

The potential will be indicated as negative in EL

There are two current loops and both currents flow through the EL1000 shunt
1) **From EL1000 to DUT**
2) **EL1000 Ext + to 3rd party load to DUT**

The measured current (total of both current) must be positive I ≥ 0

! **The total current must NOT EXCEED 680 A (max. 200 A from EL1000)**

Ensure to switch ON the external load before switching ON EL1000

Ensure to switch OFF EL1000 before switching OFF the external load

During EL1000 startup and calibration do not sink external DC current

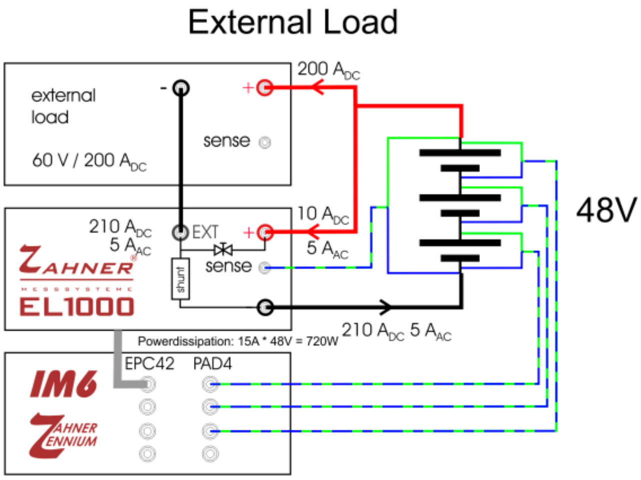
EL1000 DC current has to be defined as the sum of both currents -> The EL1000 controls the current through the DUT

The maximum power dissipation in EL1000 should not increase the EL1000's limit of 1000 W.

Example:
DUT: Battery of 48 V potential at 210 A_{DC} and measure EIS with 5 A amplitude:
EL1000 part of the DC current: 10 A
EL1000 AC amplitude: 5 A
EL1000 power dissipation: 48 V * 15 A = 720 W (<1000 W)
External load DC current: 210 A - 10 A = 200 A
EIS settings in the control potentiostat menu: Galvanostatic, DC current 210A, Amplitude 5A

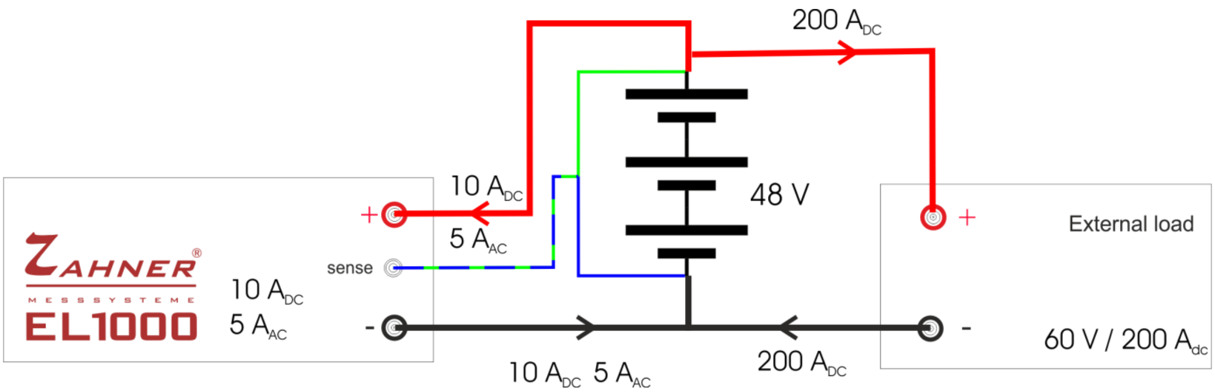
Note:– Maximum allowed current through EL1000 in above example = 1000 W / 48 V = 20.8 A

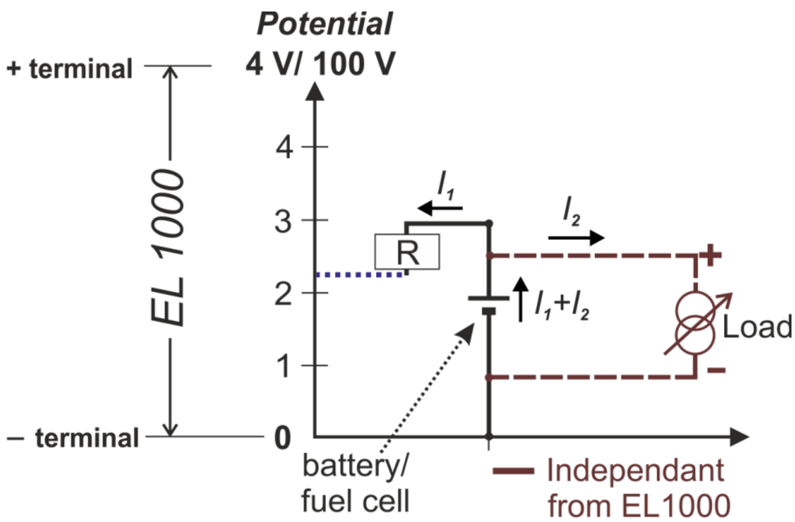
Here PAD4 cards can also be used to investigate the individual cells of a battery or fuel cell. The potential range of PAD4 cards is fixed at **±4 V** with the compliance voltage of **±100 V**. Higher input voltage ranges can be achieved by special sense cables (**±5 V**, **±10 V**, **±12 V**, **±20 V**, **±24 V**). However with increasing potential range, the resolution of the impedance spectra measured by PAD4 will decrease.



4.b. DUT connected with DC load and EL1000 (in parallel)

To sink more current from DUT than allowed by an EL1000, an external load can also be connected in parallel to the DUT and EL1000 as shown below. This allows for an independent control of EL1000 and external load on DUT





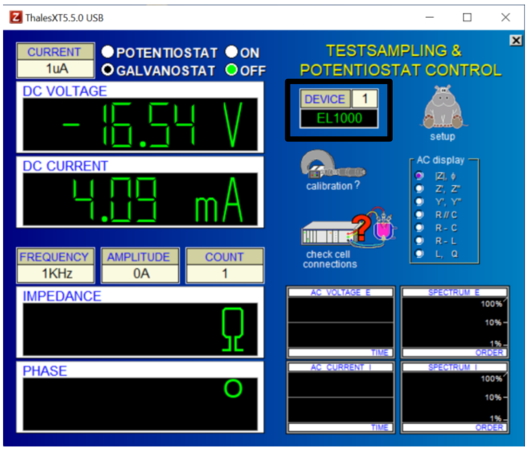
Graph 2: EL1000 and an external load in parallel connection with a DUT (battery/fuel cell)

In Graph 2, the X-axis represents the **– terminal** of EL1000 and the Y-axis represents the **+ terminal** of EL1000. Graph 2 illustrates the two independent current loops for the parallel connection of the

EL1000 and an external load with the DUT. Here the current flowing through the external load (I_2) does not flow through EL1000 and can be independently controlled by the external sink and limitations from EL1000 do not apply to I_2. Since the current flowing through the external load is not flowing through the **EXT +** terminal of EL1000 hence it is not labeled with i but I_2.

Resistance box **(R)** in Graph 2 represents the voltage drop in the EL1000 current loop during operation.

Upon selecting the EL1000 in the test sampling window (here DEVICE=1), EL1000 carries out a DC offset calibration. Therefore, it is essential that no current flows through the EL1000 during the calibration.



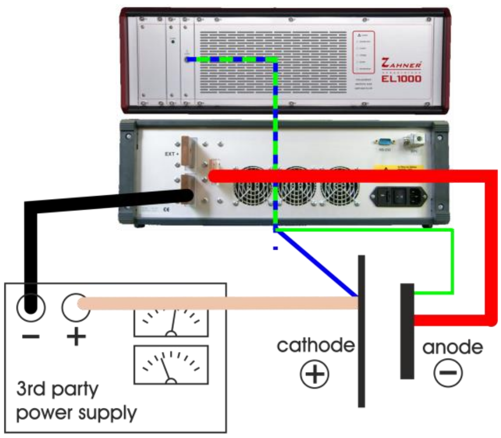
5. Applications with an additional power supply (serial)

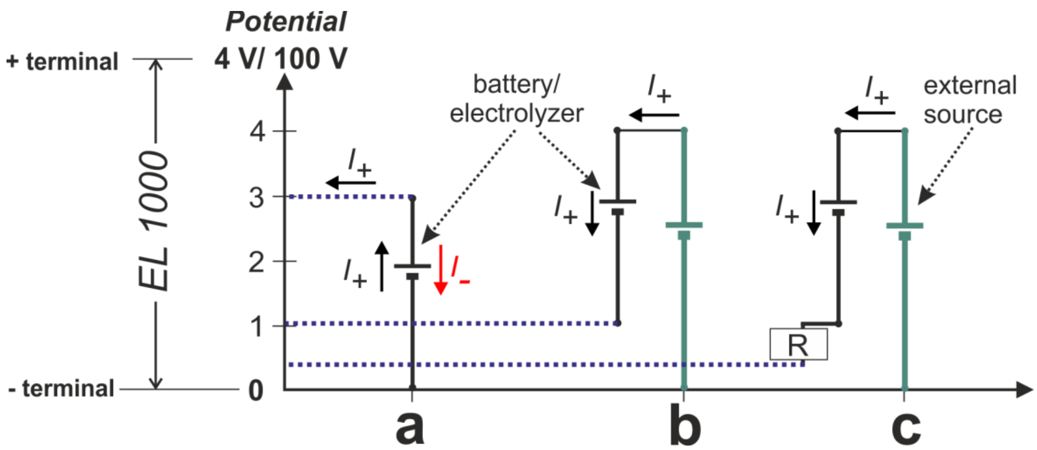
This configuration may be used if the voltage drop on the power lines is too high to reach the high-current test conditions. In addition it allows experiments on passive objects and batteries under charging conditions and electrolysis cell. Here EL1000 is connected in series with DUT (inversed battery) and the external power supply.

5.a. Charging batteries

This configuration is used for experiments on batteries under charging conditions and electrolysis cells.

> **!**
>
> **The DC potential applied must not exceed Umax = 100 V.**
>
> **Potential ≤ 4 V / 100 V**
>
> **The potential will be indicated as positive in EL (because the battery connection is reversed with sense cables)**
>
> **The measured current must be positive I ≥ 0**





Graph 3: EL1000 in series connection with a battery and an external source (power supply).

Graph 3 follows the same scheme as described previously in this manual. The X-axis represents the **– terminal** of EL1000 and the Y-axis represents the **+ terminal** of EL1000. Graph 3 (Part **a**) is the same as shown in Graph 1(**a**). As explained in previous graphs that the EL1000 allows current flow in one direction (counter-clockwise) and here this current flow is represented as I_+. When EL1000 as a load is connected with a battery then it discharges the battery. For charging the battery, a reverse current (I_-) should flow through the battery which is not possible with EL1000. Hence to charge a battery during the experiment with EL1000, an external source is required as shown in Graph 3(**b**). This external source applies a potential against the battery and changes the current direction in the battery, charging it. It should be noted down here that the potential of the external source should be higher than the battery's potential. Graph 3(**c**) indicates the same situation as described in Graph 3(**b**), however here voltage drop in the system is also taken into account. The blue line at the y-intercept shows the potential output between the **+** and **– terminals** of EL1000. A simple schematic is Graph 3(**c**) is also shown below to clearly indicate the connections of battery (reversed) with EL1000 and external source.

Note: Normally a cathode (positive terminal) of battery is connected with the **+ terminal** of EL1000 (Graph 4**a**) however during charging (Graph 3**b**,**c**) the anode (negative terminal) of the battery is

connected with the **+ terminal** of EL1000. Hence it is also described as the reverse connection of battery with EL1000.
Fig. 02 shows the same connection as shown in Graph 3(**c**). Here, EL1000 will read a potential of less than 1 V between its **+** and **– terminals**. Here the potential applied by the external power source should be increased up to an extent that the total potential becomes positive after compensating for the opposing battery potential and the voltage drop (R).

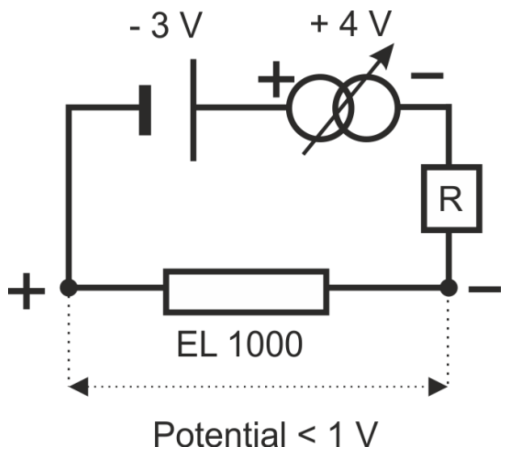
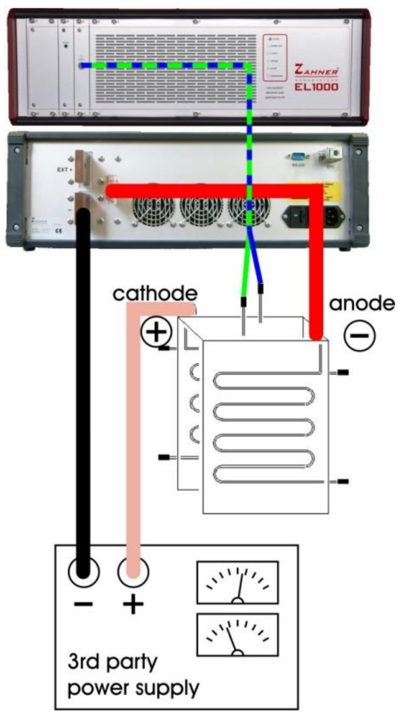


Fig. 02: EL1000 in series connection with a battery (reversed connections) and an external power source.

5.b. Electrolysis of fuel cells

This configuration is used to allow experiments during the electrolysis of fuel cells. Electrolysis of the fuel cell has the same cell connection as for the section of **5.a. Charging batteries**.



!

Potential ≤ 4 V / 100 V

The potential will be indicated as positive in EL.

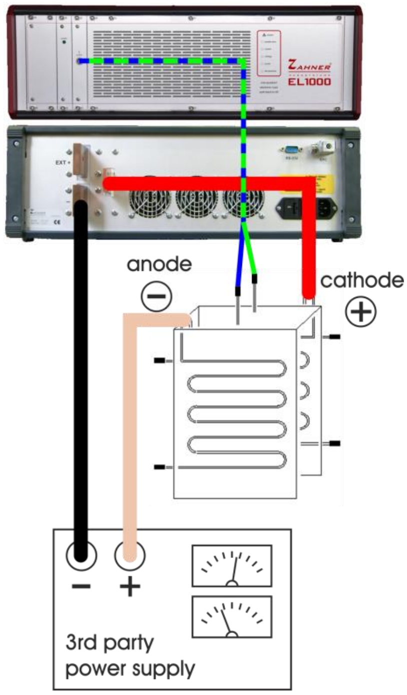
The measured current must be positive I ≥ 0

The graphical representation for fuel cell will also look similar as the Graph 4 for batteries. However since the individual fuel cell has a potential of nearly 1.1 V so an external power supply with less potential is normally used.

In section 5.a and 5.b, the currents can be disrupted directly from EL1000. Since the external power supply is in series with EL1000 so by stopping the current in EL1000, the current flow by the external power supply will also seize.

5.c. Compensation for voltage drop (Zero Volt Option)

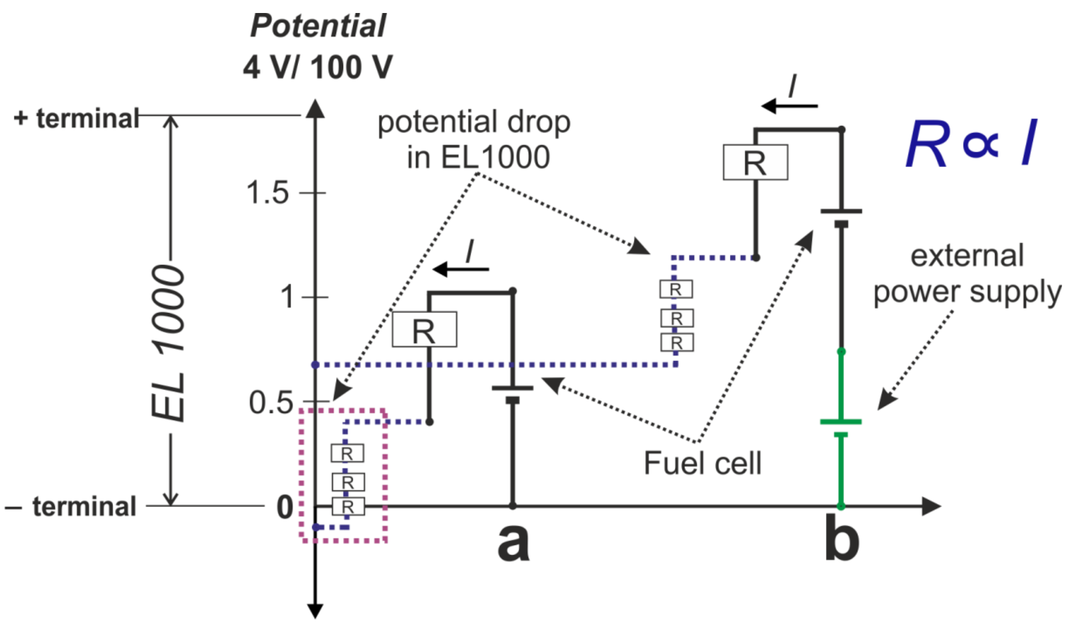
In contrast to the last two series arrangements, the DUT is not reversed in the zero volt option.



> **Set potential ≤ 4 V / 100 V**
>
> **!** **The potential will be indicated as negative in EL.**
>
> **The measured current must be positive I ≥ 0**

During normal operation of fuel cells the current flowing through the cell is usually very high (a few hundred amperes). At such high currents, the potential drop (*ΔV* = *I*R*) is also very high. Fuel cells normally have a potential of around 1 V and one has to keep in mind to apply the currents with which the voltage drop in the system is less than the potential of the fuel cells. If in EL1000, a current value is set (galvanostatic mode) for which the voltage drop will exceed the fuel cell potential then the EL1000 will not reach the set current value.

Graph 4 shows the voltage drop through the resistance (R) of the system. Additionally, in EL1000, there are some additional resistances (e.g. shunt resistances and so on) which lead to further voltage drop. Graph 4(**a**) shows this two-steps voltage drop for very high currents. Since the voltage drop here is higher than the potential of the fuel cell hence the set current (in EL1000) is not achievable. Therefore to compensate for the voltage drop, a small additional potential of usually 1 V is provided by the external power supply to the fuel cell to compensate for the high voltage drop at high current applications (Graph 4**b**). This keeps the output potential between the **+** and **– terminals** of EL1000 positive, and enables the high current experiments with EL1000.



Graph 4: Compensation of voltage drop in a system with an external power supply at high current applications

6. Applications with an additional power supply (external input)

This configuration allows experiments under the following conditions:

- Charging batteries
- State of charge (SoC)
- Discharging batteries
- Fuel cell and electrolysis cell operation

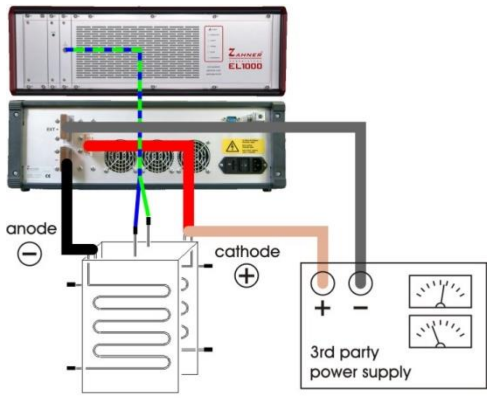
!

The external power supply operates as a Galvanostat

EL1000 setting DC current:

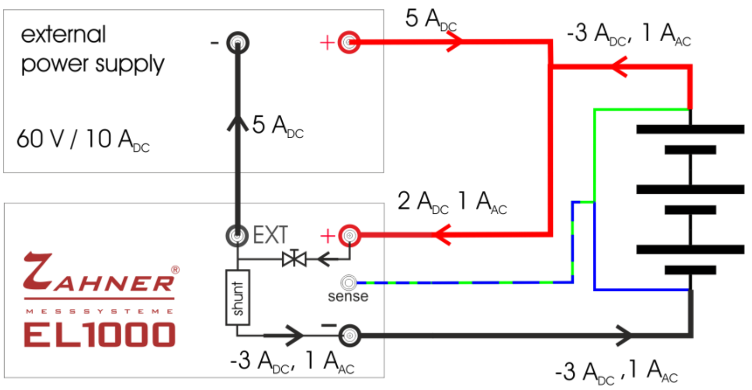
Charging: current through DUT is NEGATIVE
SOC: current through DUT is ZERO
Discharging: current through DUT is POSITIVE

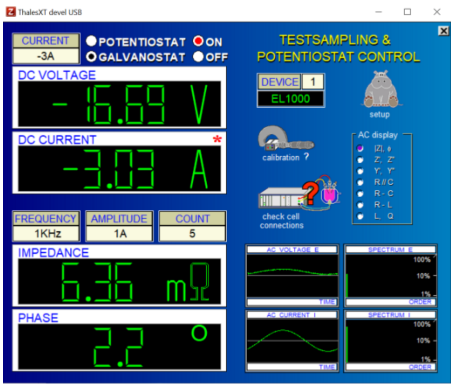
During EL1000 startup and calibration, do not sink or source external DC current.



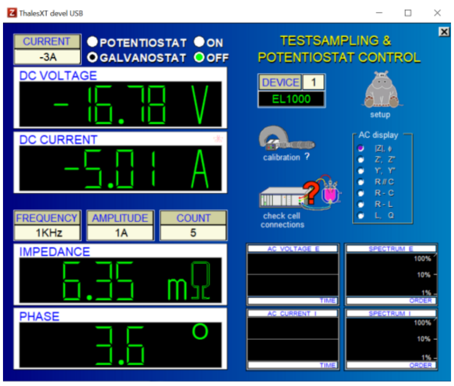
Charging:

The schematic diagram shows the current scheme during the charging of the DUT (battery) with electrical connections among EL1000, external power supply and DUT. Here, a charging current of 3 A_{DC} is flowing through the battery. –3 A_{DC} indicates that the current direction is reversed than illustrated (current flowing in the battery). The additional current (2 A_{DC}) provided by the power supply flow towards the **+** terminal of EL1000 and from there to **EXT +** terminal of EL1000, eventually back to the power supply. The AC current is in the reverse direction than the charging current. As between the **+** and **– terminals** of EL1000 the current flow is allowed in only one direction.





The current provided by the external power supply is set by the power supply and the current flowing through the DUT is adjusted in the Thales window. Here, a charging current of 3 A (a negative sign of current: because the current is flowing in the battery) and an amplitude of 1 A_{AC} are provided as an input in the Thales window. The DC current flowing to the **+** terminal of EL1000 should be higher than the EIS amplitude as the EL1000 only allows current in one direction. If the DC current is less than the EIS amplitude then a complete sine excitation from EL1000 is not possible. In the above-provided scheme, EL1000 is connected in parallel with the external power supply and when EL1000 (galvanostat in Thales window) is turned off then all the current provided by the external power supply flow through the DUT, charging the DUT. This way, one does not have to remove all the electrical connections and remove EL1000 from the setup. Just turning the EL1000 off is sufficient. Fig on right shows that the complete charging current of 5 A provided by the external power supply is flowing through the battery when the galvanostat (EL1000) is turned off.

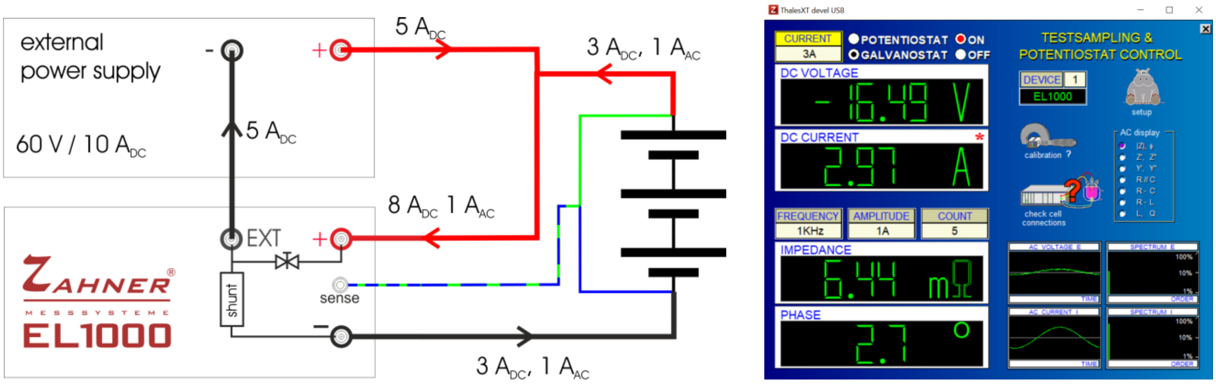


The DC current flowing to the **+** terminal of EL1000 should be higher than the EIS amplitude (A_{AC}), as EL1000 only allow current in one direction. If the DC current is less than the EIS amplitude then a complete sine excitation from EL1000 is not possible.

Such a parallel connection scheme among EL1000, external power supply and the DUT can be used for **charging batteries or for electrolysis** when the EL1000 is not being used for measurement. In this way, one doesn't have to remove the EL1000 setup after measurement.

Discharging:

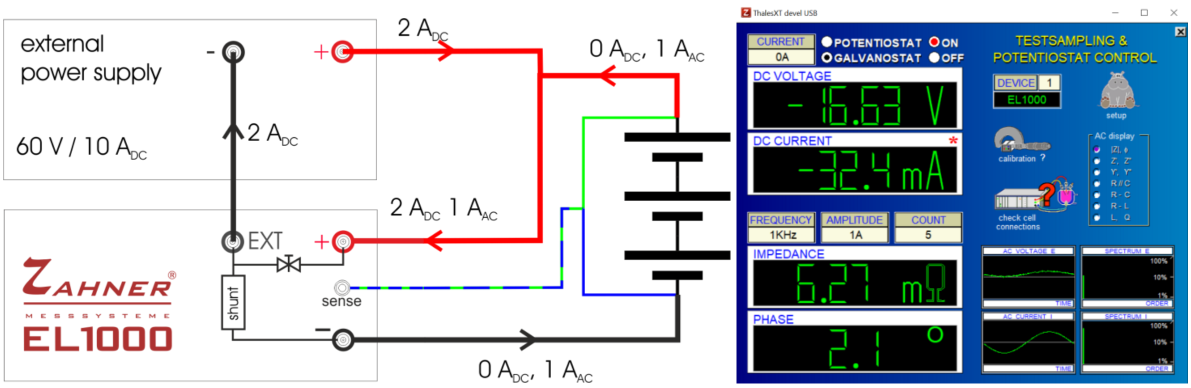
The schematic diagram shows the current scheme during the discharging of a DUT (battery) with electrical connections among external power supply, EL1000 and the DUT. Here in the Thales window, the current is assigned a positive value (a discharging current of 3 A_{DC}). The schematic diagram shows that the 5 A_{DC} from the external power supply and the 3 A_{DC} from the battery flow towards the **+** terminal of EL1000. Here discharging current and the AC current flow in the same direction contrary to the current flow in charging scheme.



Here if the EL1000 is turned off then the power supply will start charging the DUT with a charging current of 5 A.

State of charge (SoC)

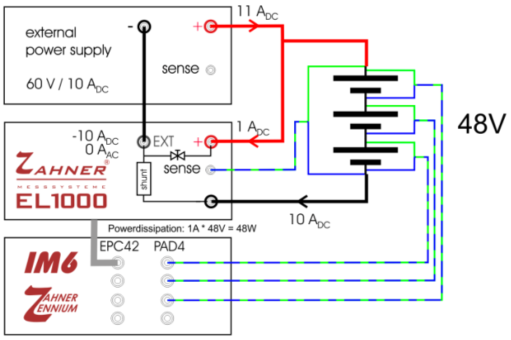
The schematic diagram illustrates the current scheme during the state of charge (SoC) measurement of a DUT (battery) with electrical connections among external power supply, EL1000 and the DUT. In SoC, the DC current through the DUT is zero. This zero current is given as an input in the Thales window. Here, the current provided by the external power supply completely flow through **+** terminal of EL1000 and used as the buffer current for the EIS excitation. DC current provided by the external power supply should be higher (preferably 1 A higher) than the AC amplitude used for EIS excitation.



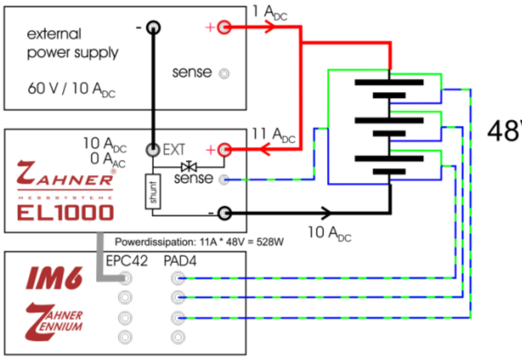
Here if the EL1000 is turned off then the power supply will start charging the DUT with a charging current of 2 A_{DC}.

PAD4 can also be used to analyze the individual part of the DUT. Schematics shown below illustrate the connection schemes with PAD4 for charging, discharging and SOC scenarios.

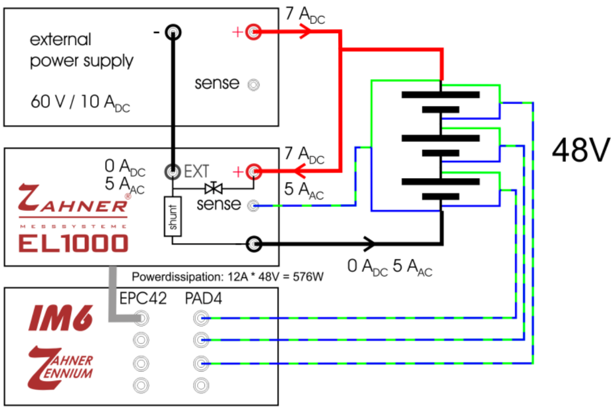
Charging



Discharging



SOC Impedance



Built-in buffer amplifier

The built-in buffer amplifier may be used to increase the potential range of the *EL* up to +/-100 V. Select the potential range at the cell connection scheme page. The corresponding gain factor will be set automatically. The *EL1000* will control -4 V...+4 V and -100 V...+100 V.

!	**Never plug or unplug an *EL1000* at the D-Sub9 connector at the backside of the device with the *Zennium* switched on. This may damage the system. It is recommended to fix the D-Sub9 connector with the screws to prevent accidental unplugging.**

If the *EL1000* is unplugged while being selected in the *Test Sampling* page of the *Thales* software, it will shut off the current. This is a precaution to prevent undefined situations.

The *EL1000* needs a warm-up time of about 15 minutes after power on. A calibration procedure is initiated automatically with the first access by the *Zennium* system. If you access an *EL1000* during the warm-up time, please do a forced calibration (*EIS* menu -> *Calibrate*) after about 15 minutes.

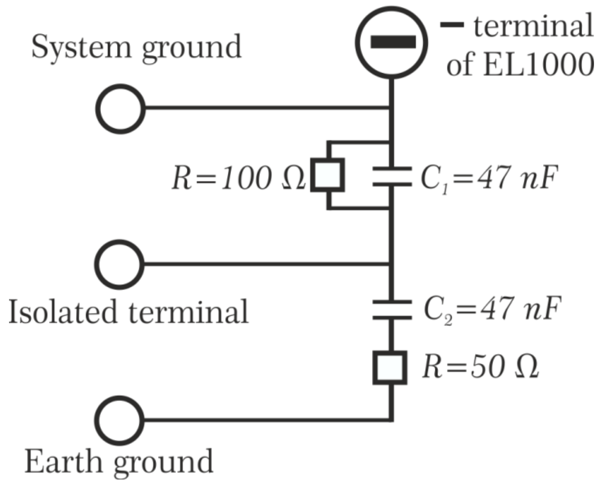
As the *EL1000* is optimized for high current (some 100 mA to 200 A) an erroneous current display of some mA is acceptable.

The current carrying cables (black and red) must be twisted together to minimize the inductance.

The sense cables (green and blue) must be twisted together to minimize the artefacts.

Grounding circuit

The electrical circuit shown below illustrates the grounding setting of the EL1000. The **– terminal** of EL1000 is at system ground. And the isolated terminal of EL1000 is connected to the **– terminal** of EL1000 (system ground) with a 100 Ω resistance. Capacitor (C_1) is used to protect the system from spiked AC signals. For grounding, the isolated terminal is short-circuited with the earth ground via a bridge. In grounding state the – terminal of EL1000 is connected with the grounding via a 100 Ω resistance. When the bridge is removed then the EL1000 is at floating condition (at system ground).



Specifications

	EL300	EL1000
Operating modes	pot/gal	pot/gal
Potential range	±4V / ±12V	±4V / ±100V
Pot. accuracy	±0.25% / ±2mV	0.1% / ±5mV
Current range	0A … 100A	0A … 200A 0A … 650A (ext)
Current accuracy	0.25% / ±3mA	0.25% / ±20mA <20A 0.25% / ±200mA <650A
Power dissipation	100W @ T_a 300W water-cooled	1000W @ T_a
Frequency range	10µHz - 3kHz @100A 10µHz - 10kHz @25A	10µHz - 10kHz @200A 10µHz - 100kHz @50A
Impedance range	1µΩ - 1kΩ*	1µΩ - 1kΩ*
Amb. temperature	0°C … 25°C	0°C … 25°C
System requirements	Zennium system + EPC42	Zennium system + EPC42

*Impedances below 1mΩ must be measured galvanostatically.