

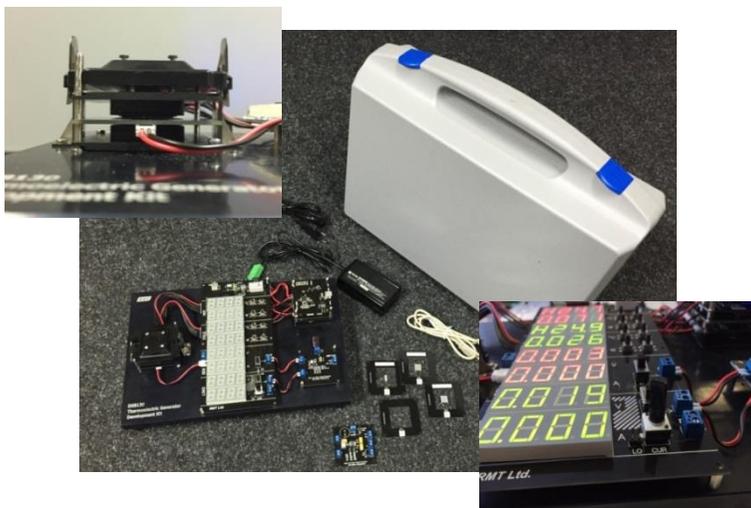


PL Engineering Ltd.

THERMOELECTRIC GENERATOR DEVELOPMENT KIT

DX8130

Manual



Moscow, 2020

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PL ENGINEERING LLC also provides a 3-month warranty for the following parts and components included in the standard delivery set of the product: the cables, program disks and documentation

If the Development Kit fails during the warranty period PL ENGINEERING will repair the Development Kit or replace it or its parts.

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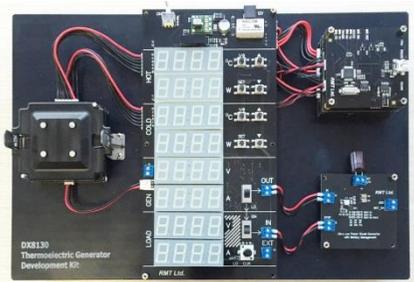
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1. INTRODUCTION



The Thermolectric Generator Development Kit DX8130 (hereinafter the Development Kit) is a tabletop laboratory for studying thermoelectric micro-generators, testing their operating parameters, optimizing the design of thermoelectric devices converting thermal energy

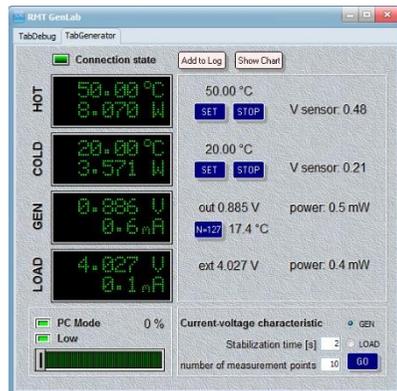
(energy harvesting), simulating their work in real conditions.

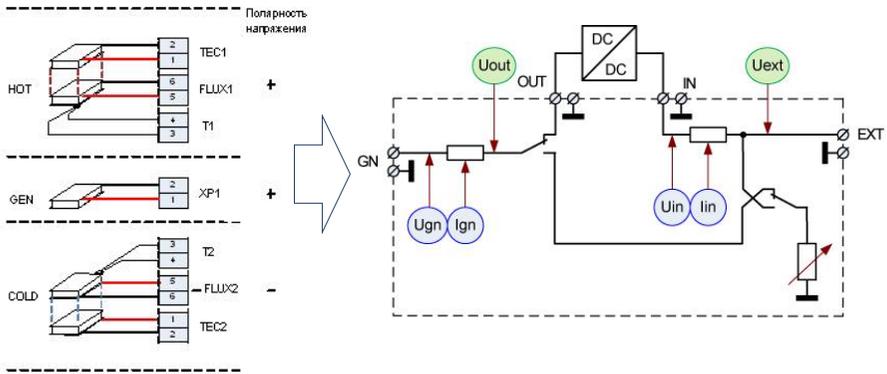
The tabletop laboratory is useful both for development of practical devices and laboratory studies.

- ✓ ***Thermolectric Generator Development Kit DX8130 is unique equipment having no analogues.***
- ✓ ***It is a powerful assistant for designers, experienced users and researchers in the field of thermoelectric energy harvesting***

The Development Kit is based on an open circuit and enables constructing "on the table" prototypes of thermoelectric energy harvesting devices with thermoelectric generators. High-performance miniature thermoelectric generators can be selected from the supplied Development Kit set. Other modules can be used too.

Simple interconnections like in electronic snap circuits allow building a thermoelectric converter circuit with DC/DC converter. Modules of modern DC/DC converters are included in the Development Kit.

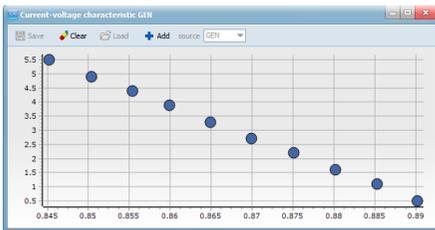




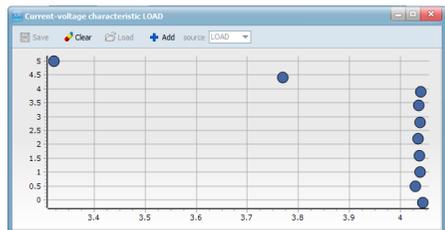
Mounting scheme of generator between thermal sources

Wiring diagram of generator

The controller modules, fine measurement electronics and precise programmable heat sources, computer remote control and data logging provide modeling of operation of assembled thermoelectric energy harvesting device prototypes in a wide range of operational conditions. The measurement electronics provides data logging of acquired test data. The software provides data processing, investigating standard performance parameters and plots, such as volt-ampere characteristics, temperature dependences of performance parameters and others.



Volt-Ampere characteristics of thermoelectric generator



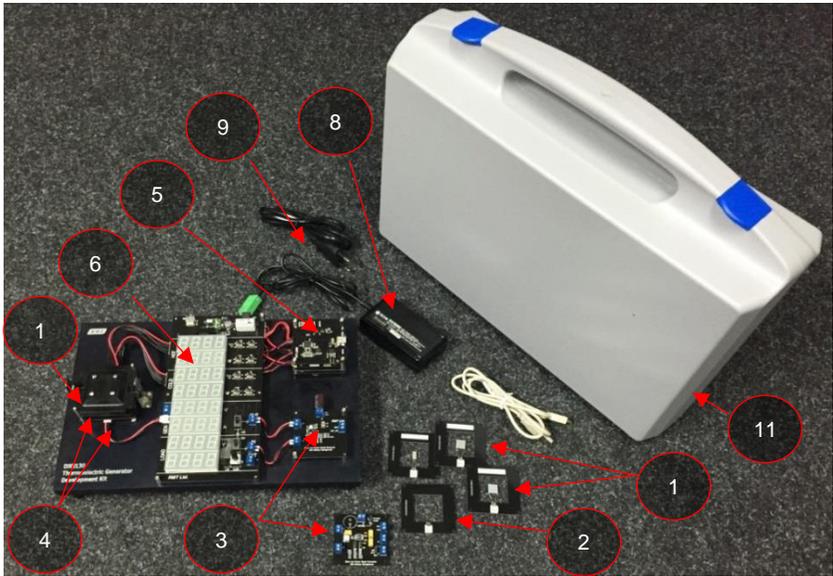
Volt-Ampere characteristics of thermoelectric generator with DC-DC converter

2. SPECIFICATIONS

#	Parameter	Units	value
1	Temperature range of stabilizing of every programmable heat loads (two units in the Kit)	°C	+10 ... +100
2	Maximal temperature difference between hot and cold sides	°C	50
3	Output voltage range of TEG	V	0 ... 9.999
4	Electric current range of the TEG	A	0 ... 1.000
5	Heat flux range	W	0 ... 9.999
6	Output voltage of DC-DC converter	V	0 ... 9.999
7	Load current		
7.1	High current mode	A	0 ... 0.100
7.2	Low current mode	mA	0 ... 5.0
8	Computer interface		USB
9	Dimensions of TEGs, min...max		
9.1	A x B	mm ²	2x2 ... 30x30
9.2	H	mm	0.5 ... 5.0
10	Power Supply of the Kit	V	110 ... 240
11	Maximal power consumption	W	60
12	Overall dimensions of Kit AxBxH, max	mm ³	200x300x80
13	Weight	Kg	3.0
14	Dimensions of main modules		
14.1	Test bench	mm ³	200x300x20
14.2	Electronic plate	mm ³	100x200x25
14.3	Controller unit	mm ³	55x55x35
14.4	Programmable heat flux unit	mm ³	55x55x8
14.5	DC/DC converter unit	mm ³	55x55x10

3. DELIVERY KIT

#	Item	Q-ty
1	Set of standard thermoelectric microgenerators of PL Engineering (one unit each)*: <ul style="list-style-type: none"> - 1MD06-127-08TEG (13x13x1.9 mm - 5.9 Ohm – 50 mV/K) - 1MD04-127-08TEG (9.8x9.8x1.9 mm – 16.3 Ohm – 50 mV/K) - 1MD06-071-05TEG (9.8x9.8x1.9 mm - 2.1 Ohm – 28 mV/K) - 1MD03-060-05TEG (4.0x7.5x1.1 mm - 6.8 Ohm – 24 mV/K) 	1 set
2	Standard mounting frame (for mounting of optional TEG)	1 pc
3	Set of DC-DC converter boards with standard DC-DC circuits (one unit each): <ul style="list-style-type: none"> - BQ25504RGT (Texas Instruments) - LTC3108EGN (Linear Technology) 	1 set
4	Programmable precise heat flux unit	2 pc
5	OEM controller DX5100 to manage by heat flux units	1 set
6	Control electronic and indication board	1 pc
7	Software TEGLab (flesh disk)	1 set
8	Power supply	1 pc
9	Set of cables	1 set
10	User Guide (flesh disk)	1 pc
11	Plastic safety bag	1 pc



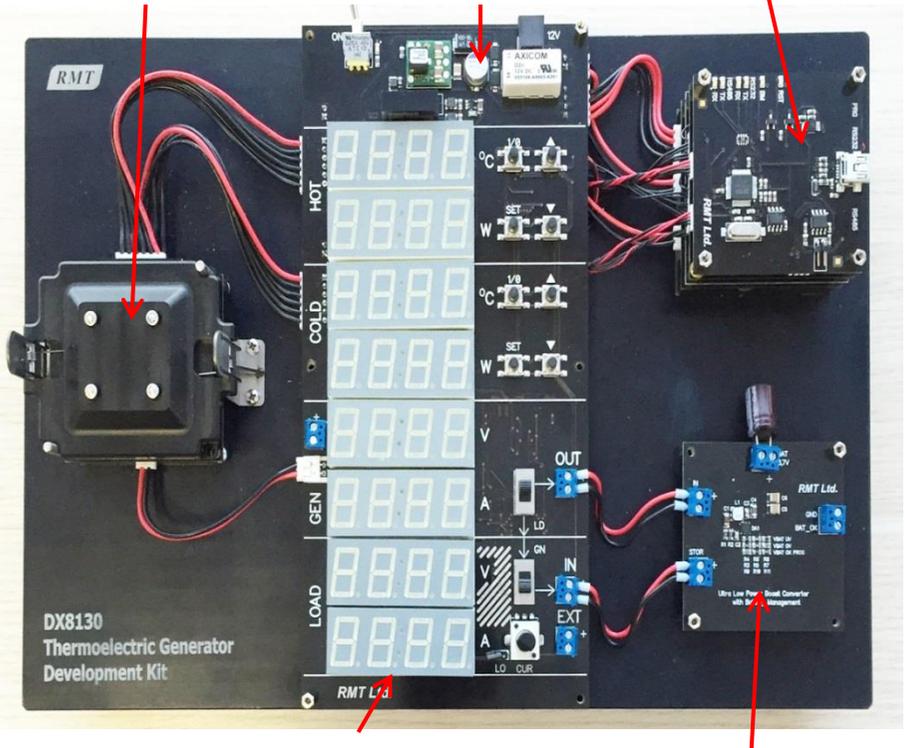
Delivery kit

4. DESCRIPTION OF THE DEVELOPMENT KIT

Thermoelectric generator unit

Control and Indication board

Controller of heat sources



Test bench

Board of DC/DC converter

Thermoelectric Generator Development Kit with preset components assembled

The thermoelectric generator development kit consists of the following.

- Set of standard thermoelectric micro-generators of PL Engineering. The set may be extended at the request of additional types of micro-generators produced by PL

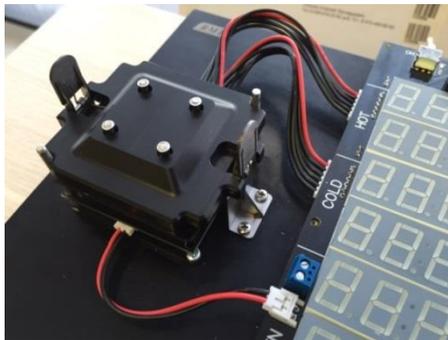
Engineering, or a User can apply another generator, of other manufacturers.

- Fully functional boards with DC/DC converters to obtain voltage needed from the standard generator. The kit consists of two boards with modern DC/DC converters from the companies Linear Technology and Texas Instrument. Electronic circuits of DC/DC converters of other types can be supplemented to the Development Kit on request.
- Controlled precision heat sources. Two identical modules that stabilize the top temperature (hot side) and bottom temperature (cold side) of a thermoelectric generator tested. They include temperature and heat flux sensors.
- Controller of heat sources. The controller is based on the range of commercially available controllers DX5100 of PL Engineering.
- Control and indication board. The Development Kit provides a convenient way to connect all the elements are included, a detailed indication of the operating parameters of the experiment, connection to an external computer. The Development Kit is controlled either by the control elements on the board or by the software TEGLab on an external computer.
- Software TEGLab to be installed on an external computer. It provides the control of the Development Kit: setting of all operating parameters, work indication, recording current-voltage characteristic of a generator and selected DC/DC converter, data logging.
- Elements of the laboratory Development Kit are located on the test bench - a small aluminum plate carrier. All the elements are accessible, can be easily installed and can be removed by a User depending on experiments.

The Development Kit is supplied assembled and packed in the plastic case.

The Development Kit with pre-assembled components is ready to use.

1.1 Thermoelectric Generator Unit

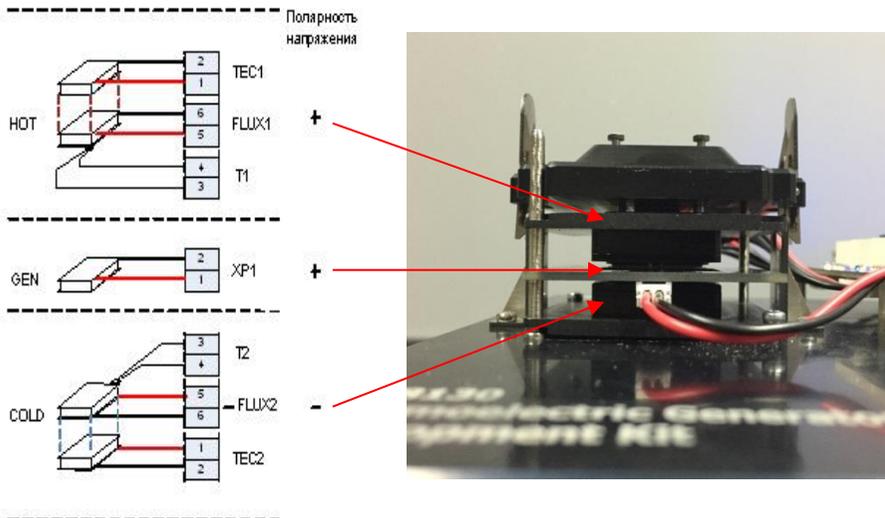


The thermoelectric generator is placed between two heat precision sources controlled.

In the Development Kit it is taken for the rule that the upper heat source works as a heater (HOT), the bottom one works as a cooler (COLD).

Each of the heat sources contains a built-in thermoelectric module as a heat source, a thermoelectric heat flux sensor and the platinum thermistor Pt1000.

The heat flux sensor of the top (HOT) heat source controls the heat generated. The lower heat flux sensor (COLD) measures the amount of heat that passed through the tested thermoelectric module.



Layout of the generator GEN between the heat sources (HOT and COLD)



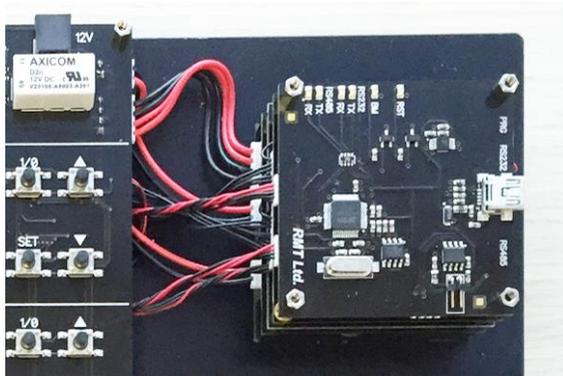
Attention! *The generator orientation should comply with the drawing.*

The temperature sensors measure the given and maintained temperature and allow obtaining the overall temperature difference between the heat sources. The overall temperature difference includes that of the thermoelectric generator tested (operating temperature difference) and of contact layers (losses).

To ensure a good thermal contact and to reduce losses on top, this sandwich (thermoelectric generator-heat source) is pressed by a spring clamp.

1.2 Controller of Heat Sources

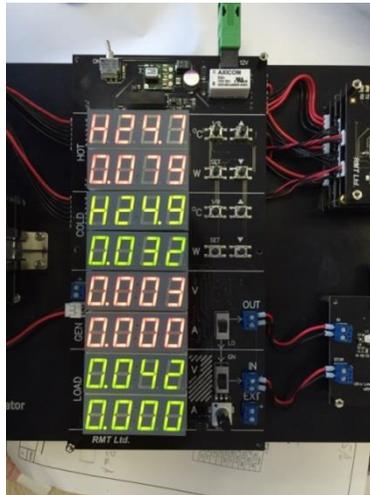
The precision heat sources are controlled by the two-channel controller created on the basis of the controllers' family DX5100 OEM (<http://promin.ru/products/dx51xx/dx5100oem/>).



Controller of heat sources (HOT and COLD)

1.3 Control and Indication Board

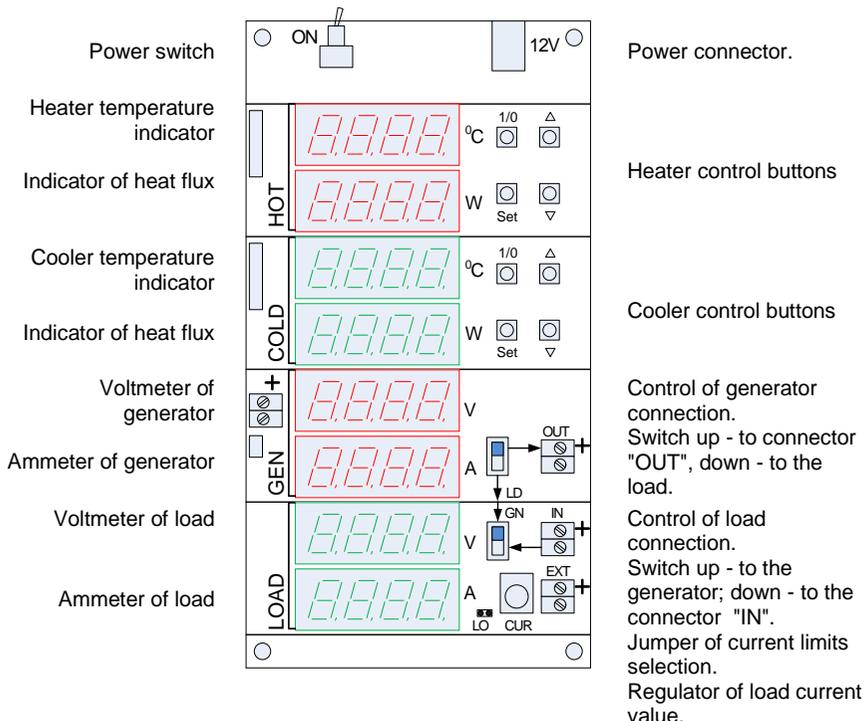
All the measurements and indication control is performed by this board.



Control and indication board

The control and display board is in the center of the test bench and includes several indicators, commutation elements (terminals and switching connectors) and control elements (buttons, switches).

1.1.1 Control and Indication Elements



Elements of control and indication on the control board.

1.1.2 Buttons

Button of start and stop temperature control



Button to increase the setpoint temperature

! The cooler temperature setpoint cannot be above that of the heater.

Button to go to the setpoint correction mode.

Exit from the mode setpoint correction if the button is pushed, or after a time delay if no button is pushed.



Button to decrease the setpoint temperature

! The heater temperature setpoint cannot be below that of the heater.

1.1.3 Temperature Indication



control

*The current temperature is displayed.
Temperature regulation is on.*

Idle
(hold)

*The current temperature is displayed
with the index "H" (Hold).
Temperature regulation is off.*



setting

*The temperature indication is flashing
in the setpoint correction mode.*

1.1.4 Current Indication and Selection of Current Limit



*The current unit is 1 A (the jumper of
current limits selection LO is not
connected). The value of the load
current is up to 500 mA. The
minimum load resistance is 1 Ohm.*



*The current unit is 1mA (the jumper
of current limits selection LO is
connected). The value of the load
current is up to 5 mA. The minimum
load resistance is 100 Ohm.*

The current value is regulated by the variable resistor (by a local control) or from the program (by a computer). When operating by the computer the jumper of current limit selection should not be connected.

1.4 Boards of DC/DC Converters

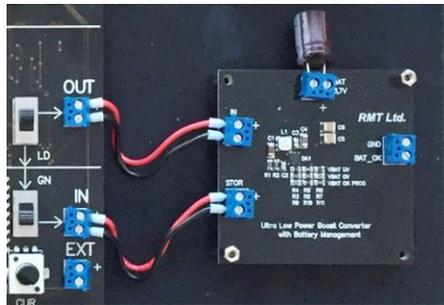
There are two variants of boards with DC/DC converters in the Thermoelectric Generator Development Kit DX8130.

Generally a DC/DC converter is necessary for converting the thermoelectric generator output voltage changing with temperature difference to the standard value of the supply voltage of electronic devices.

Most modern microcircuits of DC/DC converters provide the majority of known standard voltages (3.3, 4, 5 V, etc.) by an output switching of the circuit.

The important properties of using DC/DC converters with thermoelectric generator are:

- Minimal input signal of starting the converter work;
- Converter efficiency.



The minimum input signal providing the DC/DC converter startup and work is important as thermoelectric microgenerators in energy harvesting applications operate by very low heat fluxes and with small temperature differences. Therefore, the thermoelectric generator produces almost zero thermoelectric power.

The efficiency of the DC/DC converter circuit is important in any case. In the case of a thermoelectric generator, this value is even more critical as the efficiency of the thermoelectric generator itself is very low - 0 ... 4-5% depending on the source of heat (difference of temperatures). Therefore, the most effective subsequent energy conversion is crucial.

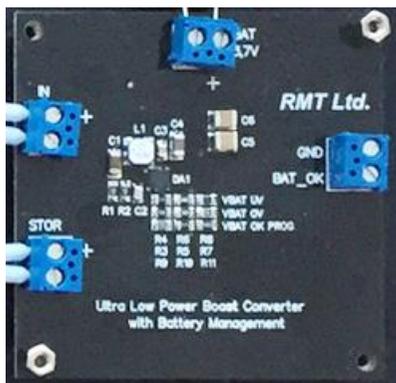
There are two boards with modern DC/DC converters optimized for use with a thermoelectric generator in energy harvesting applications in this delivery kit:

- BQ25504RGT (Texas Instruments)- Ultra Low-Power Boost Converter With Battery Management for Energy Harvester Applications
- LTC3108EGN (Linear Technology) - Ultralow Voltage Step-Up Converter and Power Manager

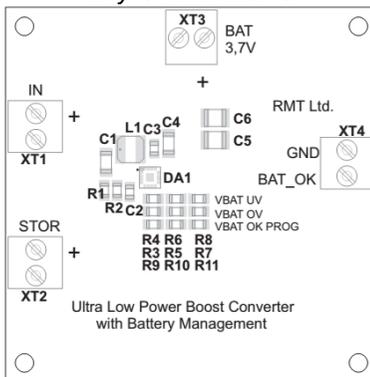
If necessary, a User can connect another board with a different DC/DC converter to the circuit of the test bench. Replacement procedure is described in this manual.

1.1.5 Board with DC/DC Converter BQ25504RGT

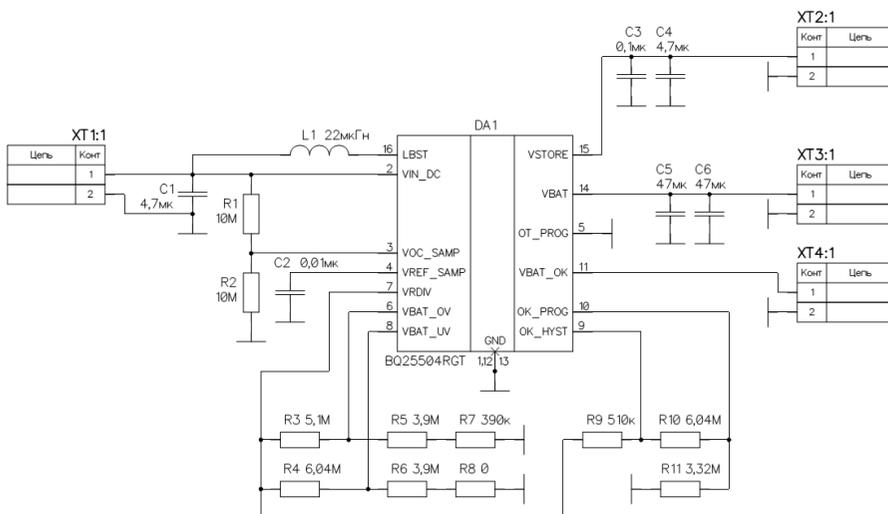
Appearance



Layout of elements



Circuitry

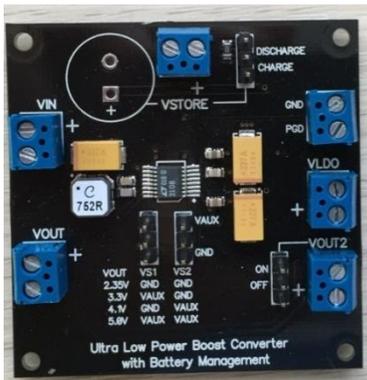


Detailed technical documentation on the DC/DC converter BQ25504RGT (and related links)

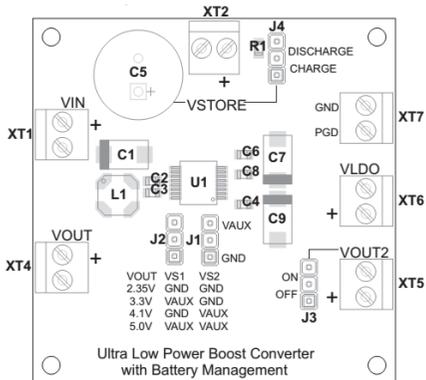
<http://www.ti.com/product/BQ25504/description>.

1.1.6 Board with DC/DC Converter LTC3108EGN

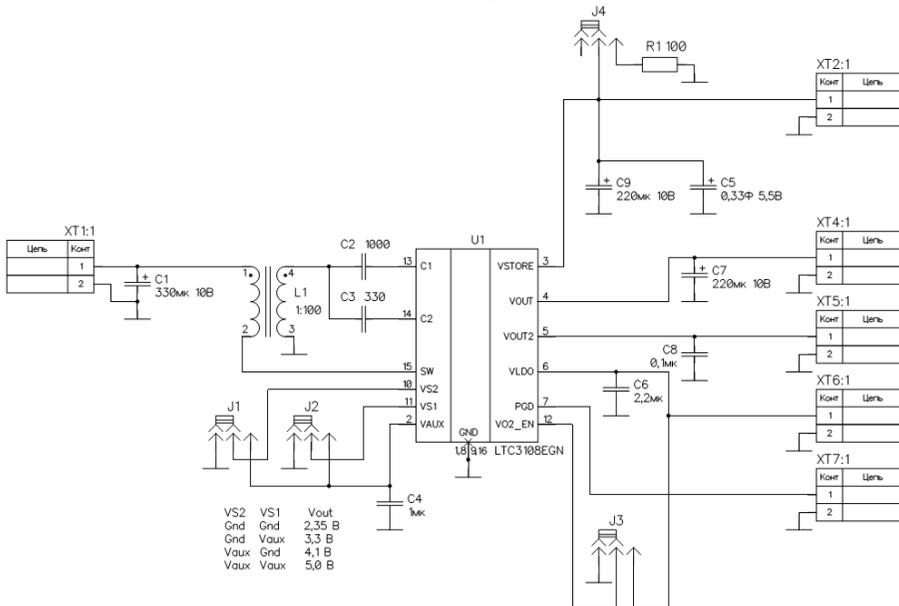
Appearance



Layout of elements

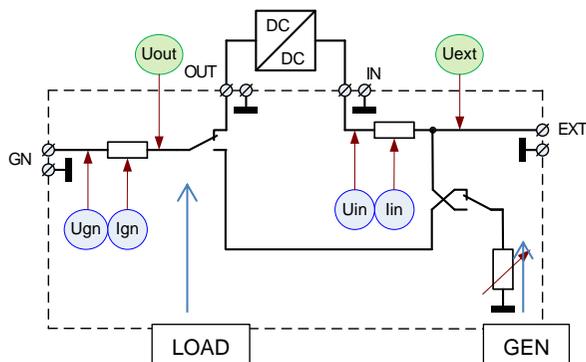


Circuitry



Detailed technical documentation on the DC/DC converter LTC3108 (and related links) - <http://www.linear.com/product/LTC3108>.

1.5 Wiring Diagram



General wiring diagram

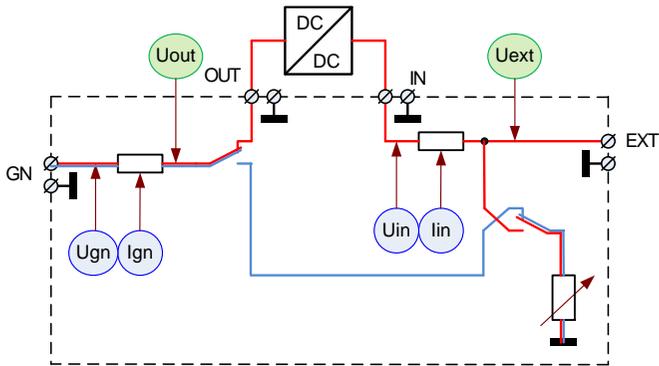
A thermoelectric generator is connected to the terminal block GN, the board of DC/DC converter is connected between the terminal blocks OUT and IN. To terminal block EXT can be connected to the external load. The wiring provides four ways of switching the thermoelectric generator shown in Table 1.

Table 1. Connection options of thermoelectric generator

#	Option connection	Position of switches
1	Generator circuit is open 1)	Switch GEN is down Switch LOAD is down
2	Generator to internal load1)2)	Switch GEN is down Switch LOAD is up
3	Generator to DC/DC converter and internal load	Switch GEN is up Switch LOAD is down
4	Generator to DC/DC converter and external load EXT	Switch GEN is up Switch LOAD is up

- 1) The voltmeter of the group LOAD (U_{in}) may show incorrect values, as it is not connected.

- 2) Internal load is controlled both by the board, and by a computer.



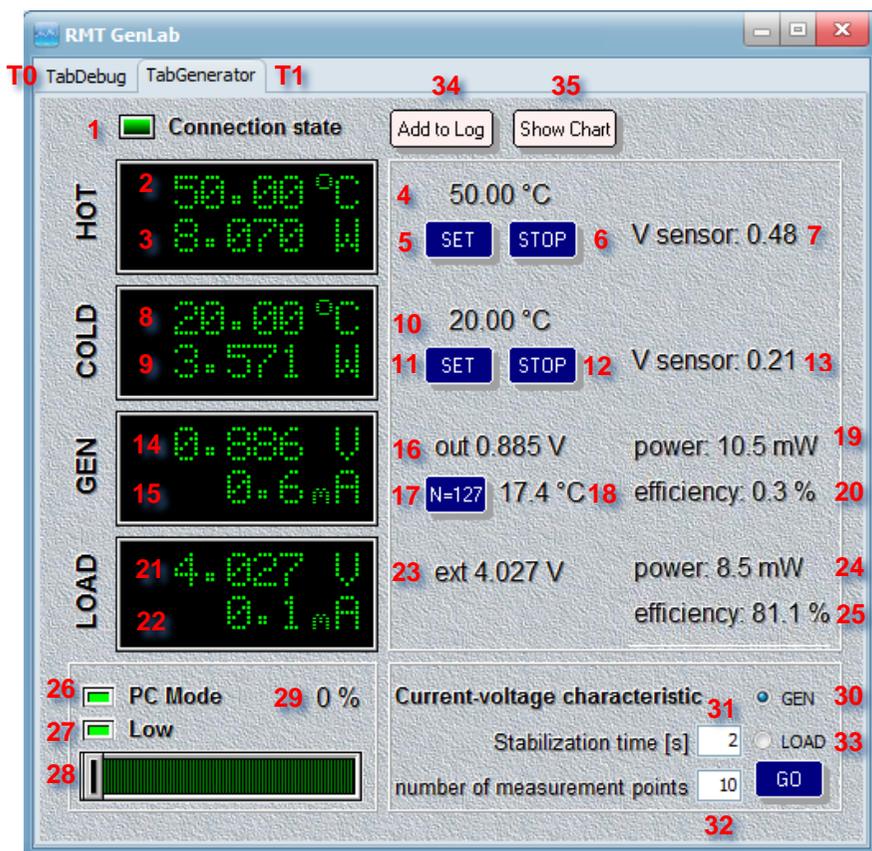
Switching circuitry of the thermoelectric generator (red - to the board of the DC/DC converter; blue - directly to the internal load)

5. SOFTWARE TEGLAB

There is control software TEGLab in the delivery kit.

To work with the program, simply copy its folder (a flash drive as part of delivery) to the control computer.

1.6 Program Window. Main Tab



The main window of the software TEGLab

1.1.7 Elements of main window

#	Description	Conditions of indication
1	Indicator of commutation of the program and test bench	
Heater (HOT)		
2	Current temperature	
3	Heat flux from heater (Qhot)	
4	Current setpoint of temperature	
5	Entering the setpoint temperature	
6	Status indicator and start/stop of control (temperature maintenance)	
7	Voltage of heat flux sensor	1
Cooler (COLD)		
8	Current temperature	
9	Heat flux to cooler (Qcold) through the generator	
10	Current setpoint of temperature	
11	Entering the setpoint temperature	
12	Status indicator and start/stop of control (temperature maintenance)	
13	Voltage of heat flux sensor	1
Generator		
14	Thermoelectric generator voltage (Ugn)	
15	Generator current (Ign)	
16	Voltage at the terminals OUT ($U_{out}=U_{gn}-I_{gn}*R_{shunt}$)	
17	Field to enter the number of generator pairs of elements	
18	Generator temperature difference estimated	2
19	Generator power ($P_{gen}=U_{gn}*I_{gn}$)	
20	Generator efficiency ($eff=P_{gn}/Q_{cold}$)	3
Load		
21	Voltage at the terminals IN (Uin)	

#	Description	Conditions of indication	
22	Current of the terminals IN (lin)		
23	Voltage at the terminals EXT ($U_{ext}=U_{in}-I_{in}*R_{shunt}$)		
24	Power at the terminals IN ($P_{in}=U_{in}*I_{in}$) $P_{in}=P_{load}$		
25	Efficiency of DC/DC converter $eff= P_{load} / P_{gn}$	4	
Load current			
26	Indicator / Switch of load current control locally/by computer		
27	Indicator / Switch of load current control LO / HIGHT	5	
28	Load current controller	5	
29	Indication of load current - % of the maximal value	5	
Current-voltage characteristic (CVC)			
30	Place of load connection	5	
	Switch of group GEN (top)	Switch of group LOAD (bottom)	
	GEN down	up	Generator CVC
	LOAD up	down	DC/DC converter CVC
31	Delay before measurement after setting the current	5	
32	Number of measurement points (number of intervals of current change)	5	
33	Button of starting CVC.	5	
34	Button of recording current measurements in the logging file.		
35	Display of the logging file saved		
T0	Terminal tab	1	
T1	Main tab	1	

1.1.8 Indication Conditions

1. Displayed if the expert mode is enabled.



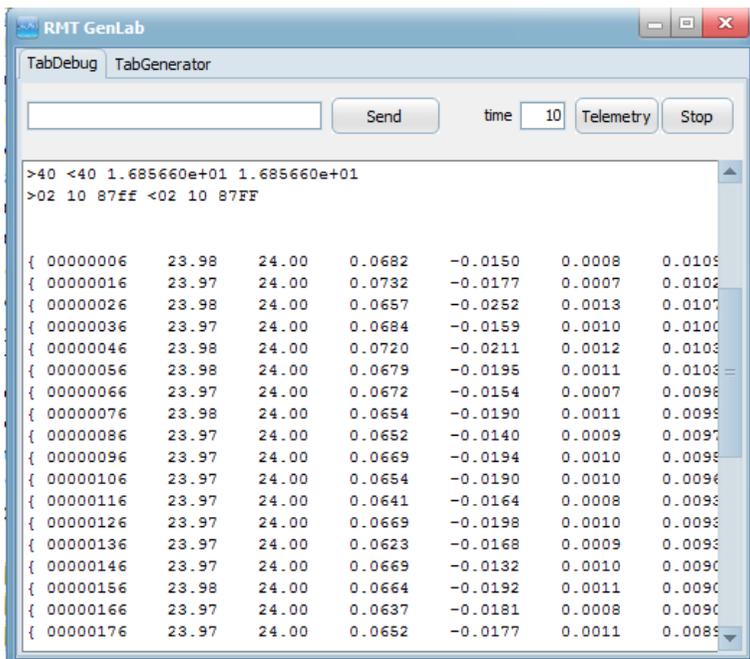
Attention! Expert mode is on/off with the key combination **CNTRL+DEL**.

2. Displayed at the generator current less than 3mA.
3. Displayed if Pgn >10 mW.
4. Displayed if Pload >0.5 mW.
5. Control of load current from the computer

1.7 Program Window. Terminal Tab

By the keys CNTRL+DEL the Expert mode is enabled - tab TabDebug and debug window.

The debug window shows the current telemetry of the device.



Additional window of the program TEGLab. It is only enabled in the expert mode by the keys CNTRL+DEL.

6. WORK WITH DEVELOPMENT KIT

1.8 Getting Ready

- Remove the test bench of Thermoelectric Generator Development Kit DX8130 from the plastic case.
- Place the test bench on a flat surface of the table.



Attention! Make sure that the toggle switch on the control circuit board is in the "off" position (1).

- Connect the power supply to the control board (2).
- Connect the power supply to an AC outlet.

In this case, the blue LED on the control board near the toggle switch lights steadily (3).

- Connect the USB cable to the controller (4) that controls the heat sources and to a computer with pre-installed program TEGLab running.

On top of the controller board the blue LED RST will light up, which indicates connection to the computer (5).

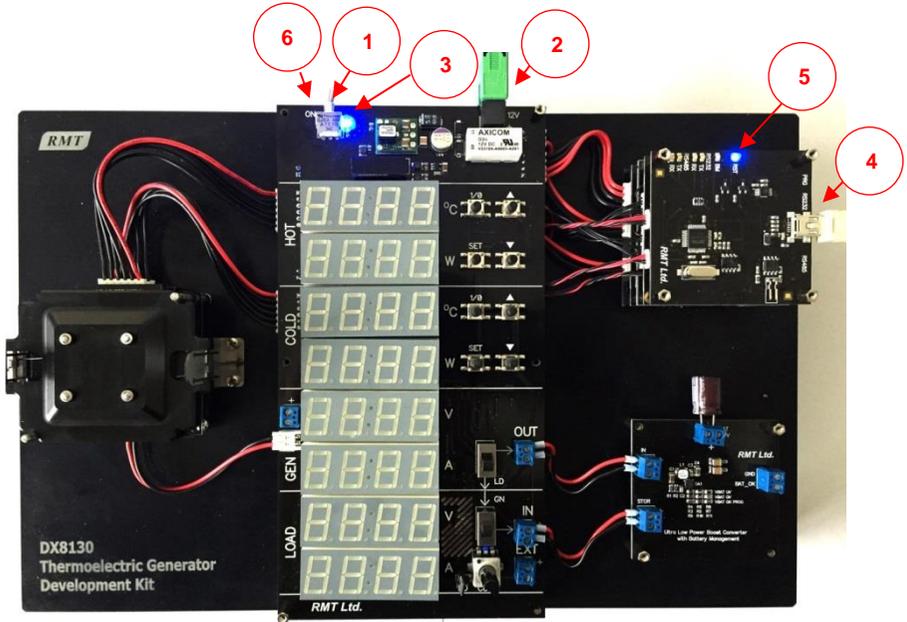
- Turn on the power switch of the control board (6).

The indicators on the control board turn ON. Similar indicators of the control program are beginning to give out similar information.

The fan of the heat sink turns on (a poor sound) on the test bench.

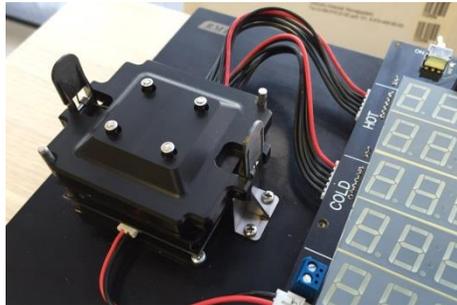
- The test bench and all its components are ready for operation.

Indicators of heat sources on the hot and cold sides indicate the status **Hold**.

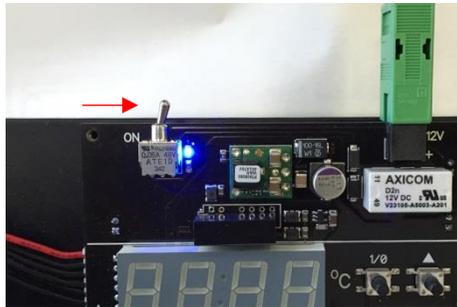


1.9 How to Mount/Replace Thermoelectric Generator

In the Thermoelectric Generator Development Kit assembled, the unit of thermoelectric generator is located in the left half of the test bench. It is assembled using one of the standard thermoelectric micro-generators of the supplied kit (see the Section "**Delivery Kit**").



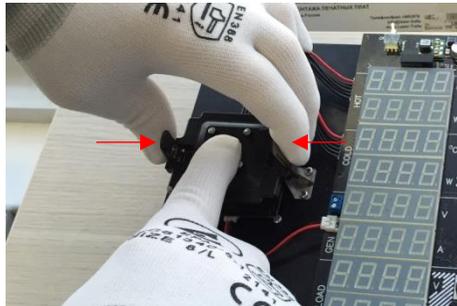
! Before mounting /replacing, make sure that the control board is switched off. The toggle switch is in the "OFF" position.



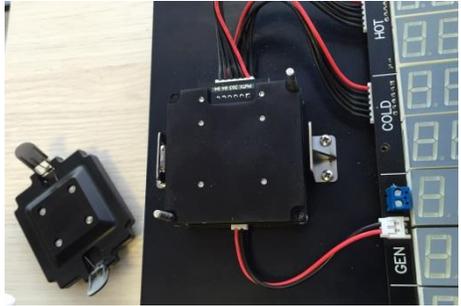
The microgenerator is replaced in the following sequence.

Hold the upper spring-loaded clamp and, press lightly on top.

Keep a little closer the locks of the spring-loaded clamp (indicated by arrows).

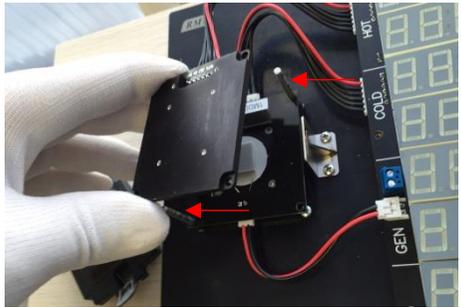


Remove the spring-loaded cover.

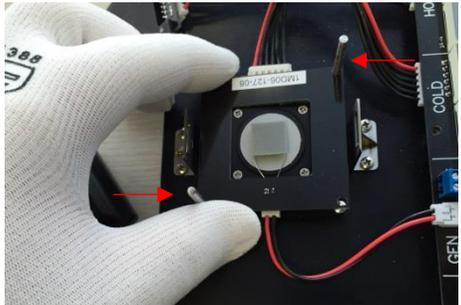


Carefully remove the upper controlled heat source along the guides (arrow) upwards.

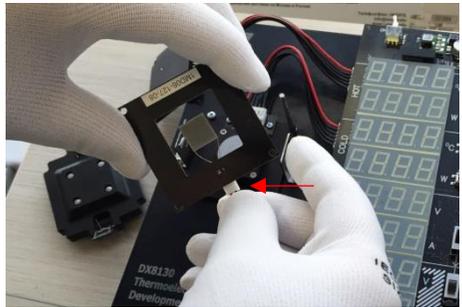
It is not necessary to disconnect the heat source from the connector.



Carefully by the guides (see the arrows) remove the frame with the soldered thermoelectric generator upwards.

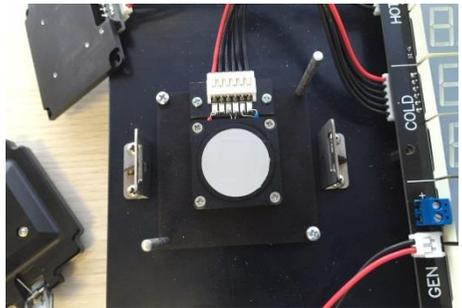


Disconnect the cable from the connector on the frame (see the arrow).



After removing the frame with the generator there is only a bottom heat source left in the generator unit.

It is not necessary to dismount it.



Select another thermoelectric generator from the kit (there are four thermoelectric micro-generators produced by PL Engineering).



If you want to apply another thermoelectric generator, use the free frame supplied.



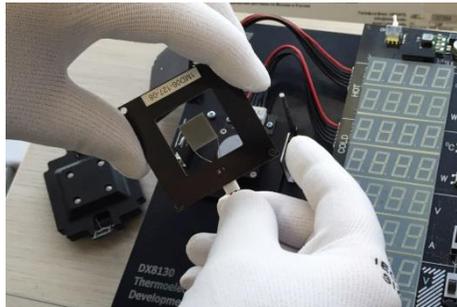
Solder the terminals of the generator to the contacts on the frame as done for the samples available.



! Polarity should be observed in accordance with the Figure.

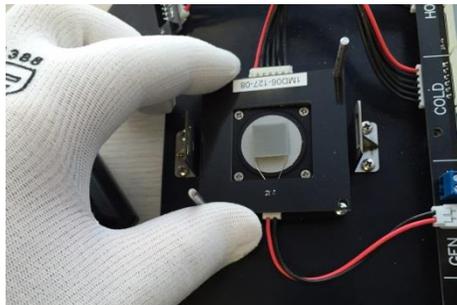
The generator unit is assembled in the reverse order.

Connect the generator cable back to the connector on the frame.

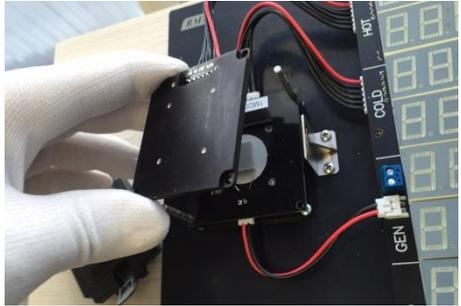


Carefully lower the frame by the guides to the bottom controllable heat source.

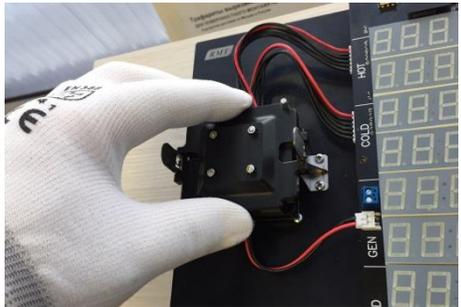
! The connector on the generator frame should be turned down.



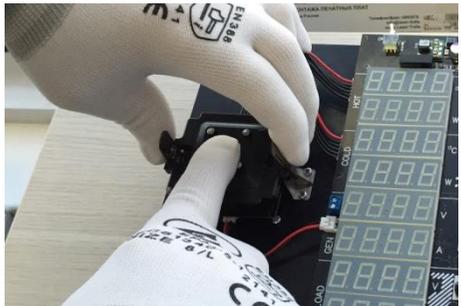
L. Lower the upper heat source by the guides on the frame with the generator.



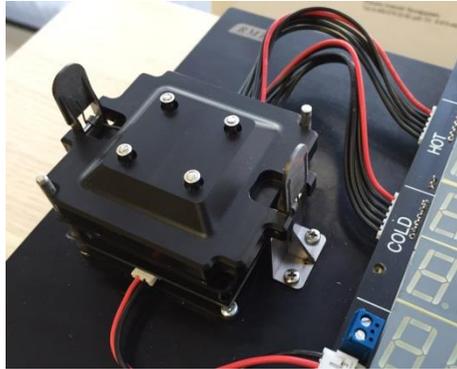
From above put on the spring-loaded clamp.



Keep slightly closer the side locks and push the top of the spring-loaded clamp. Release the side locks.



The unit is assembled.



1.10 Serviceability of Thermolectric Generator

Prepare the test bench of Thermolectric Generator Development Kit DX8130 for work in accordance with the instructions "Getting Ready".

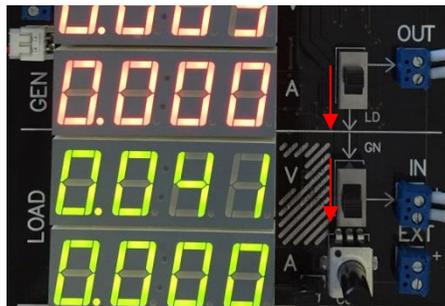
As an example, a thermolectric generator from the delivery kit is installed in the thermolectric generator unit.

For example, the module 1MD06-127-08.

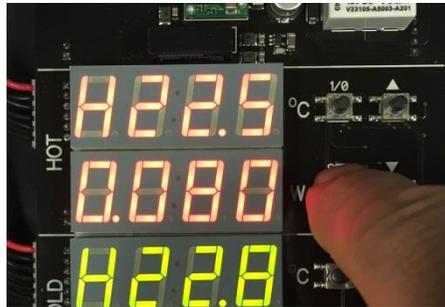
The specification for this type is available from PL Engineering's site - <http://promln.ru/products/te-generators/hdtegs/>

Turn the switch of the group GEN to the position down, and the switch of the group LOAD to the position down.

So, this is the case "Generator is open" (Section "Wiring Diagram", Table 1)



Press the button "Set" of the group "HOT".

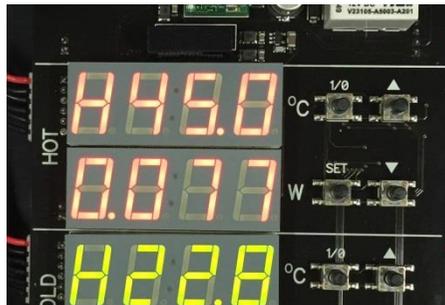


The temperature indicator in the flashing mode will start showing the preset temperature of the upper heat source.



The settings can be changed using the arrow buttons "up" and "down".

After setting the desired temperature, press "Set".



The temperature indicator shows the current temperature.

The index "H" (Hold) before the temperature readings indicates that the heat source is turned off, not active.



Press the power button on the heat source "1/0".

The symbol "H" disappears. The temperature indicator shows the actual temperature reaching the set point.

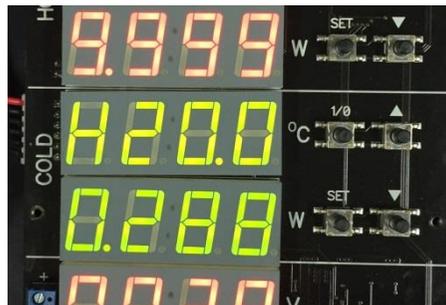
This process takes time - a few minutes.



Repeat the same temperature setting of the bottom heat source by the group "COLD".

Take steps as in items B-F, but for the bottom heat source "COLD".

Press the button "Set" of the group "COLD".



The temperature indicator in the flashing mode will start showing the preset temperature of the bottom heat source.

The settings can be changed using the arrow buttons "up" and "down".

After setting the desired temperature, press "Set".



The temperature indicator shows the current temperature.

The index "H" (Hold) before the temperature readings indicates that the heat source is turned off, not active.



Press the power button on the heat source "1/0".

The symbol "H" disappears. The temperature indicator shows the actual temperature reaching the set point.

This process takes time - a few minutes.



Wait for the temperature values of both heat sources achieving the steady state.

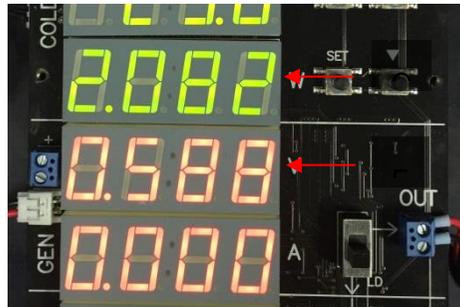
The overall temperature difference is the difference of the top and bottom steady-state temperatures.

In the case shown $\Delta T = 45^{\circ}\text{C} - 25^{\circ}\text{C} = 20^{\circ}\text{C}$.



In the steady state the heat flux indicator of the group "COLD" displays the heat flux through the sample thermoelectric generator.

The voltage indicator of the group "GEN" shows the thermal e.m.f. of tested the thermoelectric generator under these conditions (at a steady-state temperature difference).



More information on the system operation is displayed in the main window of the running software TEGLab.

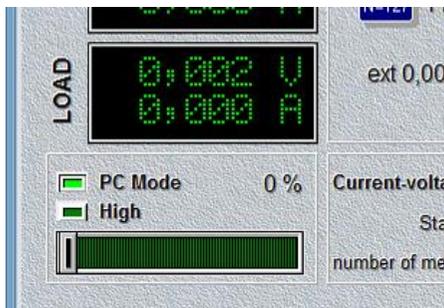
To control the Development Kit by your computer, click on the button "Local".



The additional control elements are open.

The button switches to the status "PC Mode" meaning control of the advanced settings from the computer (see below).

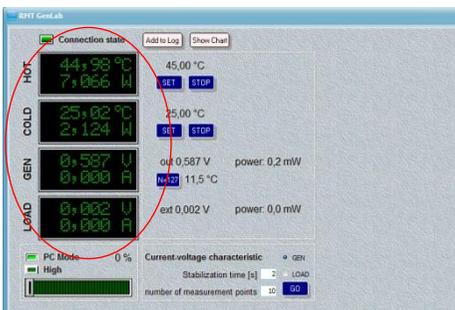
To be able to control the load current as fully as possible, the jumper "LO" should be removed from the board.



The indications of the indicators in the program repeat those of the indicators on the control board.

However, there are some differences.

The values of the heat flux indicators on the board are limited to one digit of integer. Therefore, the maximum displayed value is 9.999. The corresponding indicator in the program TEGLab is free of this drawback and shows the true value even if it exceeds 9.999. The program also indicates a sign (direction) of the hat flux.



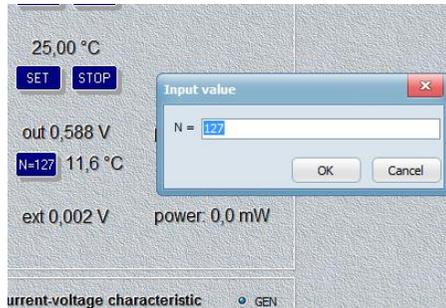
The software also enables calculating operating temperature difference on the sides of the generator ΔT_w .

For that, it is necessary:

Press the button "N="

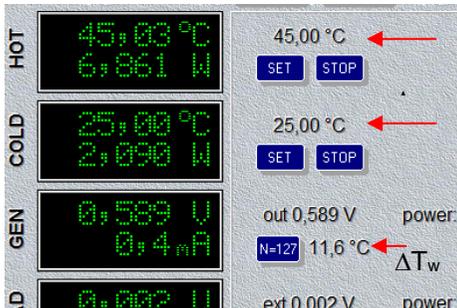
Specify the number of pairs of elements of the generator tested.

"OK"



By the approximate value of thermal e.m.f. per elements pair, the program calculates and displays the value of the working temperature difference ΔT_w on the generator. This value is always less than the total temperature difference ΔT .

The difference ($\Delta T - \Delta T_w$) is thermal loss on the interfaces – contacts of the heat sources with the tested generator.



In the example above (A-Q) the thermoelectric generator operation is checked at given top and bottom temperatures.

The generator at a given temperature difference produces thermal e.m.f., displayed on the indicators of the control board (L) and of the program TEGLab (O).

To test the thermoelectric generator at different temperatures, it is necessary to repeat items A-Q for other temperature conditions.

1.11 Thermal Resistance of Contact Layers

One of the challenges of effective use of a thermoelectric generator is taking into account thermal losses in a particular design.

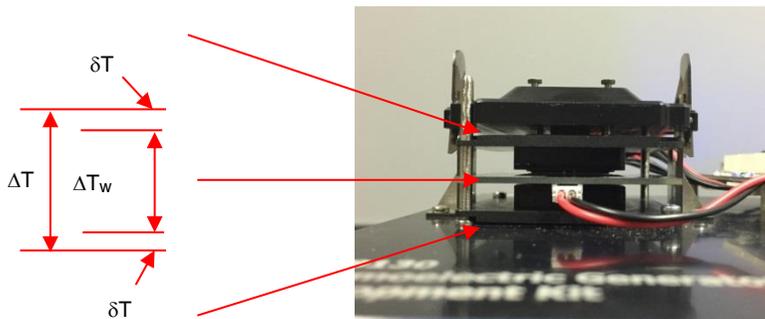
A thermoelectric generator efficiency (E) directly depends on the operating temperature difference on its sides (ΔT_w).

$$E = \alpha \times \Delta T_w$$

Here α is the Seebeck coefficient per pair of elements (in average about $400 \mu\text{V}/^\circ\text{C}$); N is a number of pairs of elements in the generator.

However, when the heat flux passing through the assembly with a thermoelectric generator, there are several contact areas where the useful temperature drop is lost due to the heat resistance of contact layers and materials.

In the **Thermoelectric Generator Development Kit DX8130** a tested thermoelectric generator is located between two controlled heat sources. Thus, there are two contact areas (top and bottom) that have thermal resistance.



$$\Delta T = \delta T + \Delta T_w + \delta T$$

To decrease the temperature losses (δT) special conductive layers are applied (3M™ Thermally Conductive Silicone Interface Pads 5519 0.5mm).

Nevertheless, the loss of temperature difference should be taken into

account.

- A. Repeat the actions of the items A-Q of the Section "Checking Thermoelectric Generator Operation".

The exemplary temperature values set on the temperature indicators of the hot and cold sides are 25 and 45°C, respectively.



- B. For the tested thermoelectric generator with the number of pairs of elements 127, the estimated value of the operating temperature difference providing generation of working thermal e.m.f. is 11.6 °C.

Therefore:

$$\Delta T = 20 \text{ }^{\circ}\text{C} (=45-25^{\circ}\text{C})$$

$$\Delta T_W = 11.6 \text{ }^{\circ}\text{C}$$

$$2 \times \delta T = 8.4 \text{ }^{\circ}\text{C} (20-11.6^{\circ}\text{C})$$

$$\delta T = 4.2 \text{ }^{\circ}\text{C}.$$

The heat flux that passed through the generator and measured by the bottom heat source sensor is $Q=2.09 \text{ W}$.

The thermal resistance of the contact layer is:

$$R_t = \frac{\delta T}{Q} = \frac{4.2}{2.09} \approx 2 \text{ K/W}$$

The thermal resistance of the thermoelectric generator is:

$$R_{TEG} = \frac{\Delta T_W}{Q} = \frac{11.6}{2.09} \approx 5.6 \text{ K/W}$$

C. Generally the thermal resistance has temperature dependence.

Check the thermal resistance in other temperature conditions, as described below.

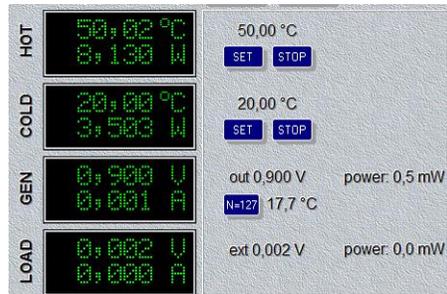
D. Repeat actions of items A-Q of the Section "**Checking Thermoelectric Generator Operation**" but with other temperatures of the top and bottom heat sources. For example:

$$T_{\text{hot}}=50^{\circ}\text{C}$$

$$T_{\text{cold}}=20^{\circ}\text{C}$$

$$\Delta T=30^{\circ}\text{C}$$

E. After temperature stabilizing, the generator thermal e.m.f. power reaches a stationary value.



F. Repeat the calculations of the item B.

$$\Delta T = 30^{\circ}\text{C} (=50-20^{\circ}\text{C})$$

$$\Delta T_w = 17.7^{\circ}\text{C}$$

$$2 \times \delta T = 12.3^{\circ}\text{C} (=30-17.7^{\circ}\text{C})$$

$$\delta T = 6.15^{\circ}\text{C}$$

The heat flux that passed through the generator and measured by the bottom heat source sensor is $Q = 3.503 \text{ W}$.

The thermal resistance of one contact layer is

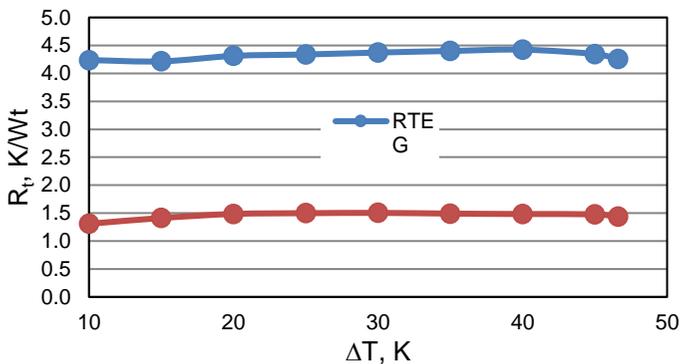
$$R_t = \frac{\delta T}{Q} = \frac{6.15}{3.503} \approx 1,76 \text{ K/W}$$

The thermal resistance of the thermoelectric generator is:

$$R_{TEG} = \frac{\Delta T_W}{Q} = \frac{17.7}{3.503} \approx 5.05 \text{ K/W}$$

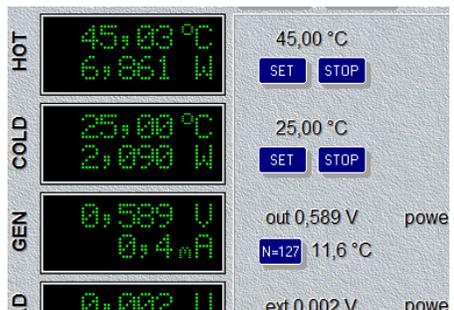
- G. By measuring the thermal resistance under various temperatures, we can plot the thermal resistance dependence on the temperature difference.

The figure shows an example measured for one of the microgenerators from the supplied kit (1MD06-127-08TEG).



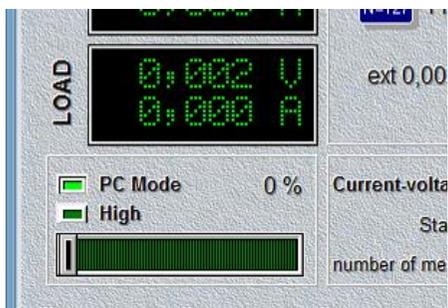
1.12 Current-Voltage Characteristics

- A. Repeat the actions of the items A-Q of the Section "Checking Thermoelectric Generator Operation".



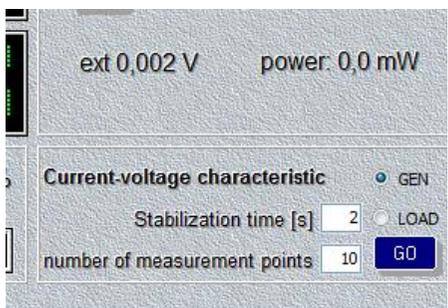
B. Set the range of workloads by the button Low/High.

- In the case "High" the load will be set in the range of current – 0...100 mA
- In the case "Low" the load will be set in the range of current – 0...5 mA.



C. Set the following parameters of the Current-Voltage Characteristic (CVC):

- value of stabilization time before the measurement,
- number of points on the current-voltage characteristic

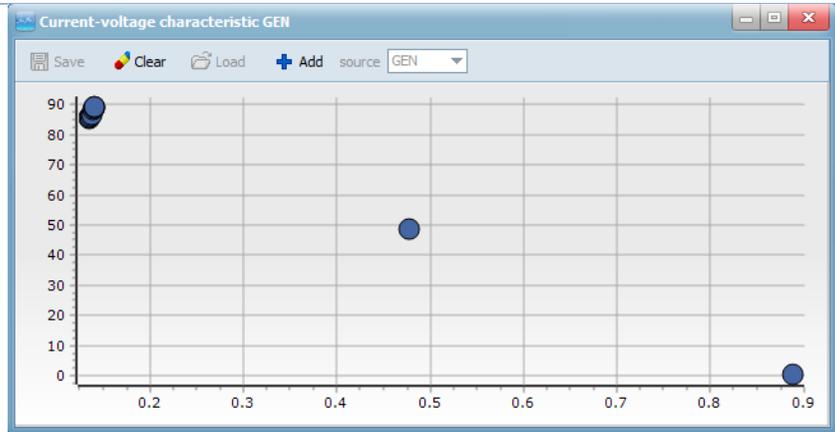


Or use the software defaults (2 seconds and 10 points).

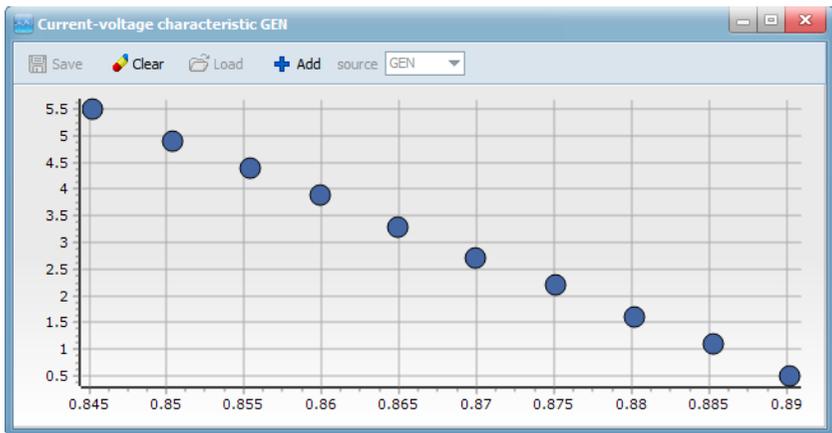


Attention! The switch "GEN-LOAD" must be in the position "GEN"- measuring current-voltage characteristic of the generator. Choose the connection of the load to the generator by the switches on the board: the top switch - down; the bottom switch - up.

Press the button "GO". The current-voltage characteristic window will appear and the real-time CVC will start plotting: on the X axis - the generator voltage, on the Y axis – the load current.



Example of Current-Voltage Characteristic (CVC) at high current



Example of CVC at small loads

1.13 Thermoelectric Generator with DC/DC Converter

Prepare the Thermoelectric Generator Development Kit DX8130 to work in accordance with the instructions "Getting Ready".

As an example, a thermoelectric generator module is installed from the supplied kit - 1MD06-127-08.

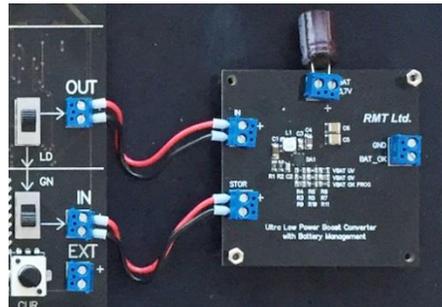
The specification for this type is available on PL Engineering's site - <http://promln.ru/products/te-generators/hdtegs/>.

- A. The board of the DC/DC converter BQ25504RGT (Texas Instruments) is mounted and connected on the test bench.

Schemes of the boards with converters are given in the Section "**Boards of DC/DC Converters**".

In the delivery kit there is also a board with the converter LTC3108EGN (Linear Technology).

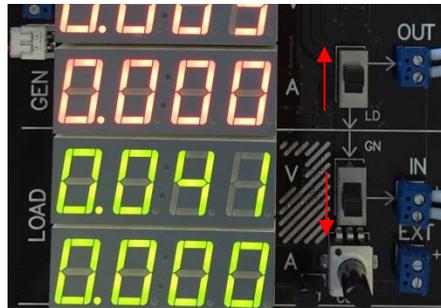
If it is necessary to replace the converter, use the instructions in Section "**Connection/replacement of DC/DC converter board**".



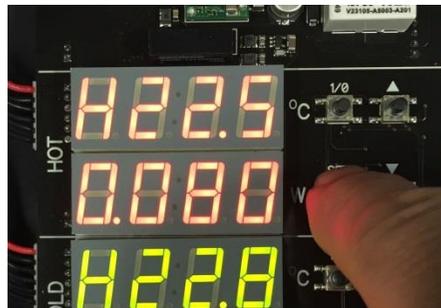
- B. Turn the switch of the group GEN in the "up" position.

Turn the switch of the group LOAD in the "down" position.

- C. Thus, the connection "Generator to DC/DC converter and internal load" is done (Table 1).



- D. Press the button "Set" of the group "HOT".

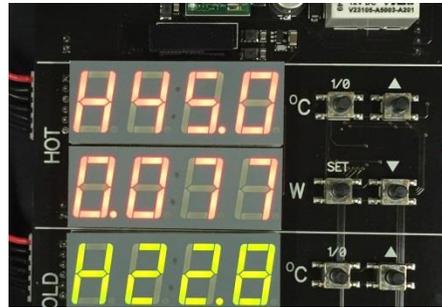


- E. The temperature indicator flashing will start showing the preset temperature of the top heat source.



- F. The setting can be changed by the arrows up/down.

After setting the desired temperature, press "Set".



- G. The temperature indicator shows the current temperature.

The index "H" (Hold) before temperature readings indicates that the heat source is turned off.



- H. Switch on the heat source "1/0".

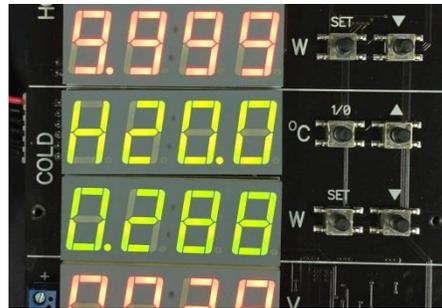
The index "H" disappears. The temperature indicator shows the actual temperature reaching the desired value.

Temperature steadying takes time - a few minutes.



- I. Repeat the same procedure of bottom heat source temperature setting by the group "COLD" – see items B-F for the bottom heat source "COLD".

Press the button "Set" of the "HOT".



- J. The temperature indicator flashing will start showing the preset temperature of the bottom heat source.

The setting can be changed by the arrows up/down.

After setting the desired temperature, press "Set".



- K. The temperature indicator shows the current temperature.

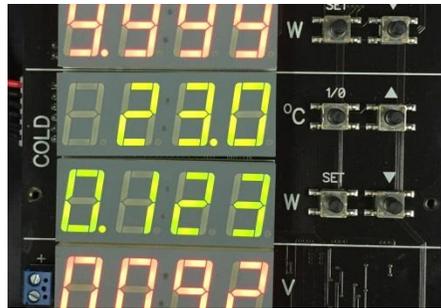
The index "H" (Hold) before temperature readings indicates that the heat source is turned off.



- L. Switch on the heat source "1/0".

The index "H" disappears. The temperature indicator shows the actual temperature reaching the desired value.

Temperature steadying takes time - a few minutes.



- M. Wait for the temperature values of both heat sources achieving the steady state.

The overall temperature difference is the difference of the top and bottom steady-state temperatures.

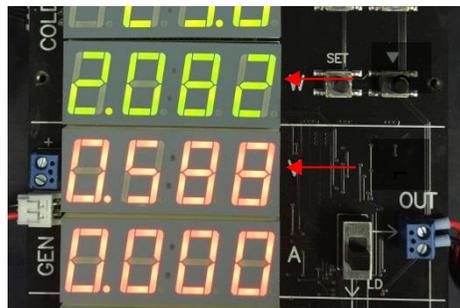
In the case shown

$$\Delta T = (45 - 25)^\circ\text{C} = 20^\circ\text{C}.$$



- N. In the steady state the heat flux indicator of the group "COLD" displays the heat flux through the sample thermoelectric generator.

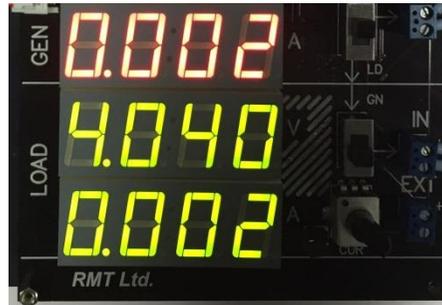
The voltage indicator of the group "GEN" shows the thermal e.m.f. of tested the thermoelectric generator under these conditions (at the temperature difference



given).

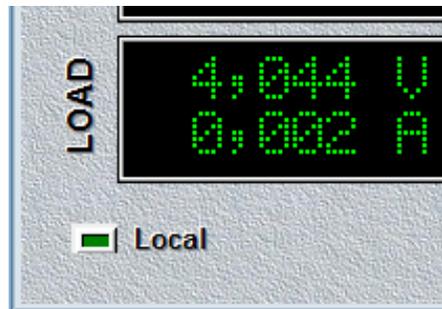
- O. The group LOAD indicator shows the standard voltage at the output of the DC/DC converter board.

The voltage 4.0 V indicates that the converter is in the operational mode. The input voltage from the thermoelectric generator made the converter start up and get the standard voltage (for charging an accumulator or supercapacitor).



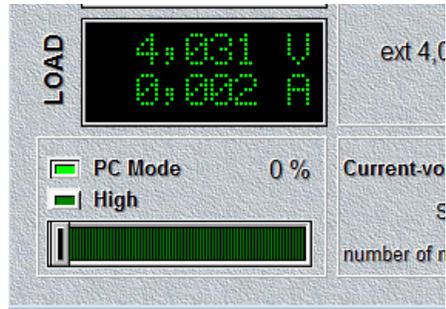
More information on the system operation is displayed in the main window of the running software TEGLab.

- P. To control the Development Kit by your computer, click on the button "Local".



Q. The additional control elements are open.

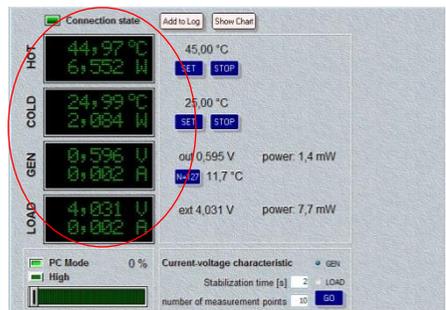
The button switches to the status "PC Mode" meaning control of the advanced settings from the computer (see below).



R. The indications of the indicators in the program repeat those of the indicators on the control board.

However, there are some differences.

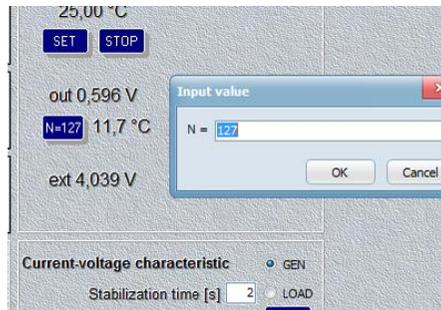
The values of the heat flux indicators on the board are limited to one digit of integer. Therefore, the maximum displayed value is 9.999. The corresponding indicator in the program TEGLab is free of this drawback and shows the true value even if it exceeds 9.999. The program also indicates a sign (direction) of the heat flux.



- S. The software also enables calculating operating temperature difference on the sides of the generator ΔT_w .

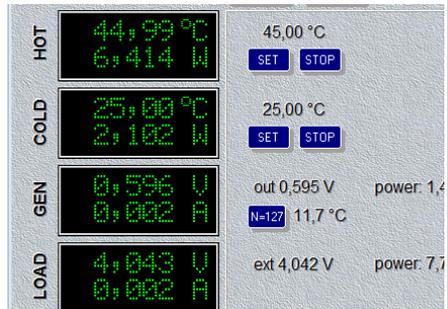
For that, it is necessary:

- Press the button "N="
- Specify the number of pairs of elements of the generator tested.
- "OK"



- A. By the approximate value of thermal e.m.f. per elements pair, the program calculates and displays the value of the working temperature difference ΔT_w on the generator. This value is always less than the total temperature difference ΔT .

The difference ($\Delta T - \Delta T_w$) is thermal loss on the interfaces – contacts of the heat sources with the tested generator.



- B. In the example above (A-Q) the operation of the thermoelectric generator with DC/DC converter is checked at given top and bottom temperatures.

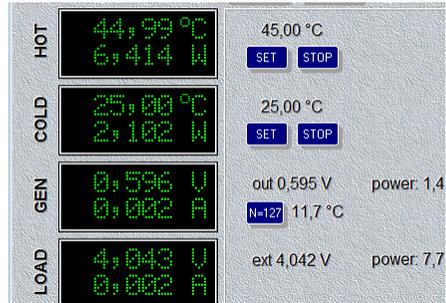
The generator at a given temperature difference produces thermal e.m.f., displayed on the indicators of the control board (L) and of the program TEGLab (O).

To test the thermoelectric generator at different temperatures, it

is necessary to repeat items A-Q for other temperature conditions.

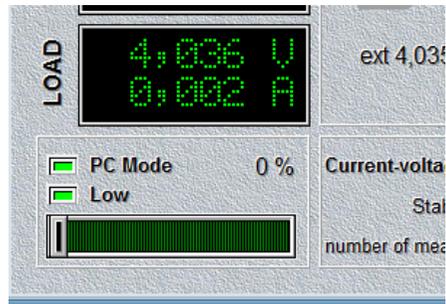
1.14 Current-Voltage Characteristic with DC/DC Converter

- D. Repeat the actions of the items A-Q of the Section "Checking the Circuit of Thermoelectric Generator with DC/DC converter".



- E. Set the range of workloads by the button Low/High.

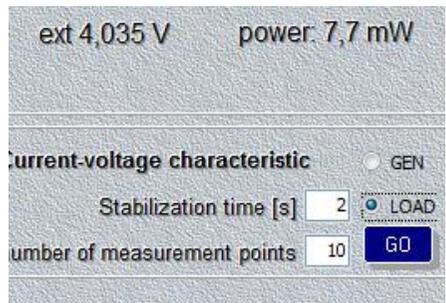
- In the case "High" the load will be set in the range of current – 0...90 mA
- In the case "Low" the load will be set in the range of current – 0...5 mA



- F. Set the following parameters of the current-voltage characteristic (CVC):

- value of stabilization time before the measurement,
- number of points on the current-voltage characteristic

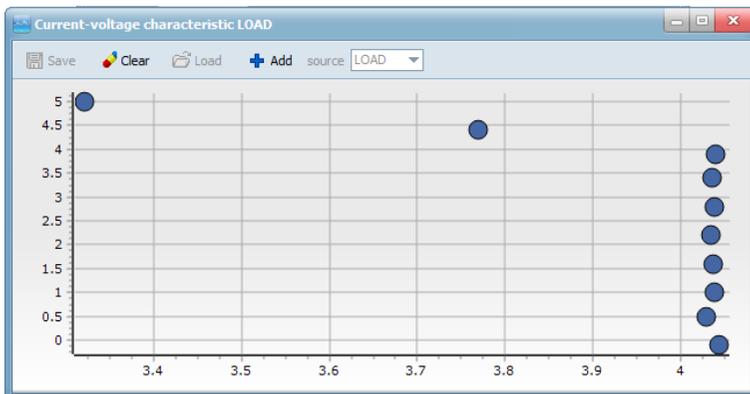
Or use the software defaults (2 seconds and



10 points).

The switch must be in the position "LOAD"-measuring current-voltage characteristic of the generator. Choose the connection of the load to the generator by the switches on the board: the top switch - up; the top switch – down.

- G. Press the button "GO". The current-voltage characteristic window will appear and the real-time CVC will start plotting: on the X axis - the DC/DC converter voltage, on the Y axis – the load current.



Example of CVC of DC/DC converter

The CVC of DC/DC converter has a characteristic threshold appearance:

- From the zero load up to a certain threshold current (in the example 4 mA), the converter voltage is a fixed operational value 4.0V.

- By increasing the voltage above the threshold, the signal from the thermoelectric generator is not enough for the DC/DC converter stable operation, and the output voltage sharply drops.

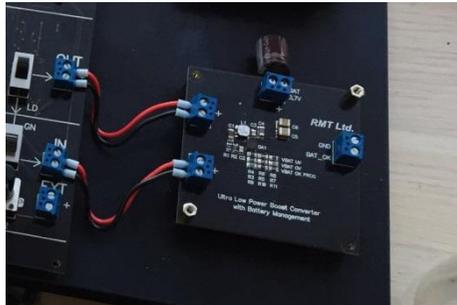
Thus, in this example, the selected operating conditions of the thermoelectric generator ($T_{\text{hot}} = 45 \text{ }^{\circ}\text{C}$, $T_{\text{cold}} = 25 \text{ }^{\circ}\text{C}$ and at the operating temperature difference $\Delta T_w = 11,7 \text{ }^{\circ}\text{C}$) the maximum output power of the device is 16 mW (= 4 mA x 4 V).

1.15 Connection/replacement of DC/DC Converter Board

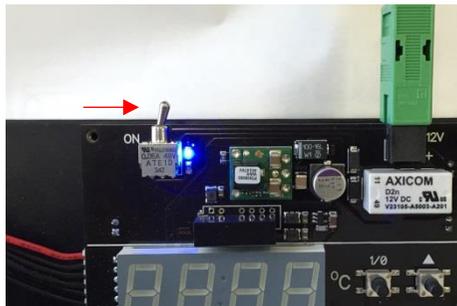
In the Thermoelectric Generator Development Kit the pre-installed DC/DC converter board is located in the lower right corner of the test bench.

It is one of the two boards of the Kit (Section "**Delivery Kit**").

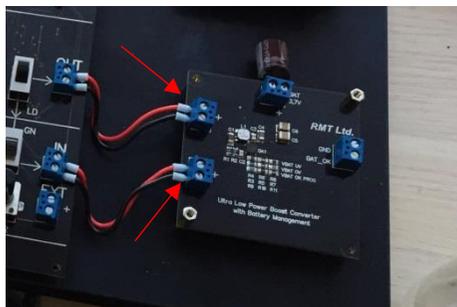
The procedure for replacing a board of the DC/DC converter is the following.



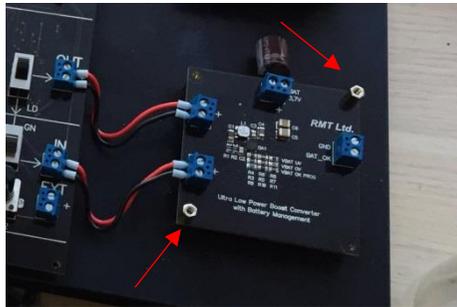
- A. **! Before connecting/replacing the DC/DC converter board, make sure that the control board is switched off. The toggle switch is in the "off" position.**



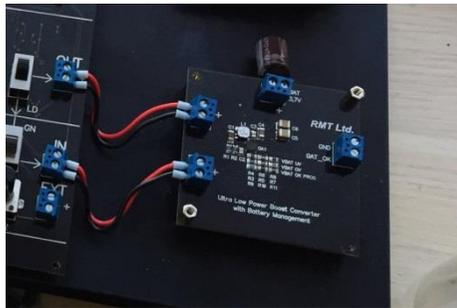
- B. Use a screwdriver to release the wires "IN" and "OUT" from the terminal on the board of the DC/DC converter.



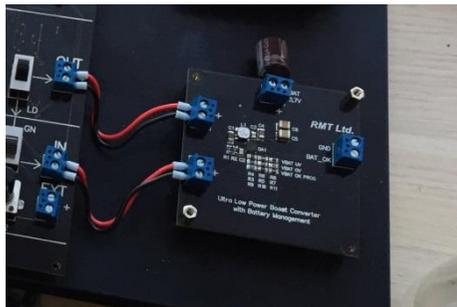
- C. Using a wrench, unscrew the screws fixing the board to the test bench. Remove the board.



- D. Place another board of the DC/DC converter on the seat.
E. Tighten the mounting screws.



- F. Connect respectively: the wires "IN" to the input of the DC/DC converter, the wires "OUT" to the output of the DC/DC converter.



! Observe the polarity markings on the board and the color of the wires (red - "+").

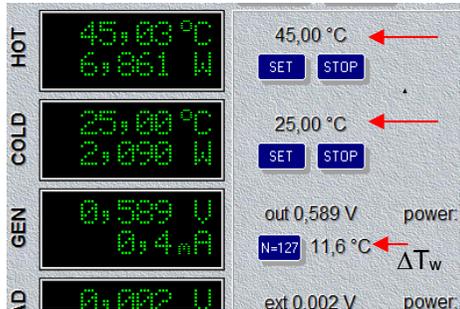
1.16 Load Capacity of Thermoelectric Generator

In the section "Checking Serviceability of Thermoelectric Generator Circuit" it is only the ability of the thermoelectric generator to generate thermoelectric power for a given temperature difference that is checked.

The generator can perform useful work if there is a load connected.

In this section, the load capacity of the thermoelectric generator is checked.

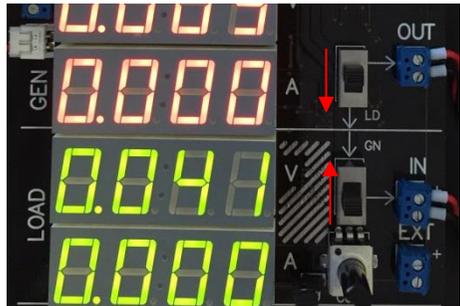
- A. Repeat fully the procedure of checking the thermoelectric generator ("Checking Serviceability of Thermoelectric Generator Circuit") items A-Q.



- B. Turn the switch of the group GEN to the position "down".

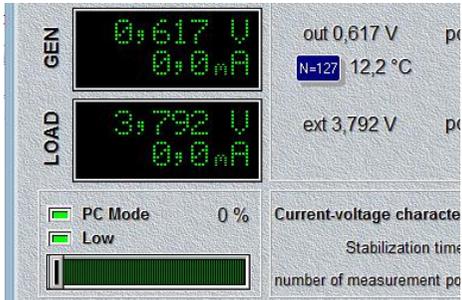
- C. Turn the switch of the group LOAD to the position "up".

Thus, the commutation "Generator to internal load" is provided (Section "Wiring Diagram", Table 1)

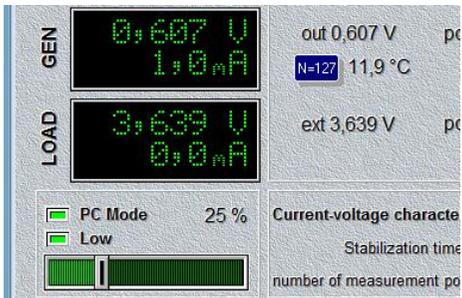


D. In the main window of the software TEGLab set the load switch in the position High or Low:

- In case "High" the load is set in the range of currents – 0...100 mA
- In case "Low" load is set in the range of currents – 0...5 mA.

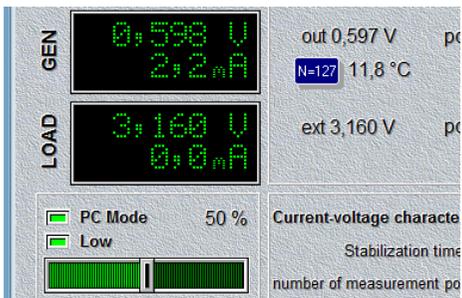


E. By the slider set the load as a percentage of the maximum value for the range given, using the readings in %.



F. The operational load current and the corresponding value of the input load voltage will be displayed in the group of indicators GEN.

It will be seen that with increasing load (current) voltage decreases. It is the behavior of the generator current-voltage characteristics (see the Section "Current-Voltage Characteristic of



Thermoelectric Generator").

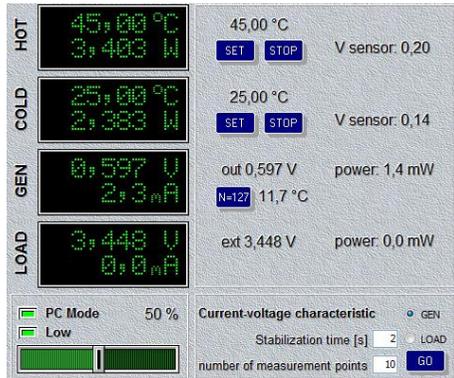
- G. It is also useful to calculate the generator efficiency.

This value is given in the main window of the software.

The value of efficiency at a steady temperature difference (T_{hot} and T_{cold}) is calculated as:

$$n = \frac{Q}{U \times I} \%$$

Here Q is the value given by the heat flux indicator of the group COLD, U and I are the readings of the indicators of the group GEN.



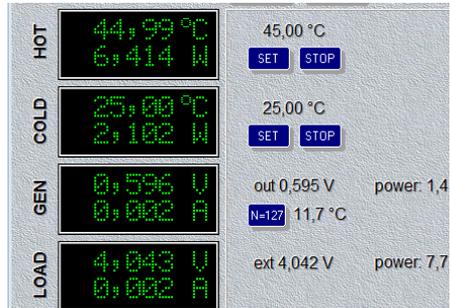
1.17 Load Capacity with DC/DC Converter

In the section "Checking Circuit of Thermoelectric Generator with DC/DC Converter" we only check the thermoelectric generator ability to generate thermal e.m.f. for a given temperature difference.

The generator circuit can carry out useful work only in case the current is supplied to the output DC/DC converter load connected.

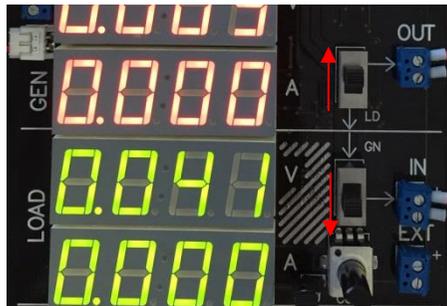
In this section the load capacity of the thermoelectric generator circuit with DC/DC converter is checked.

- H. Repeat the full procedure of checking thermoelectric generator (see "**Checking Circuit of Thermoelectric Generator with DC/DC Converter**"), items A-T.

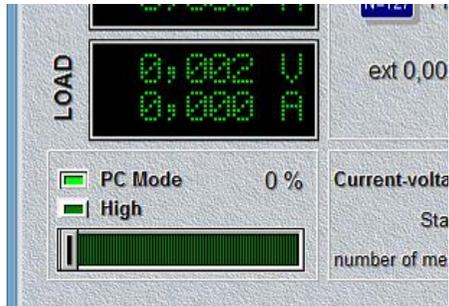


- I. Turn the switch of the group GEN to the position "up".
- J. Turn the switch of the group LOAD to the position "down".

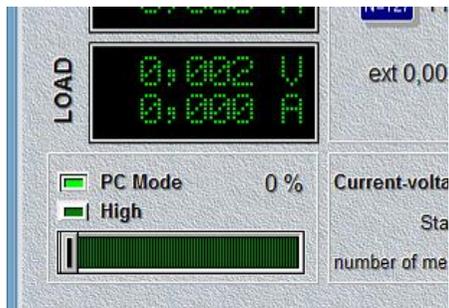
Thus, the commutation "Generator to DC/DC converter and internal load" is done (Section "**Wiring Diagram**").



- K. In the main window of the software TEGLab click the load switch in the position Low.

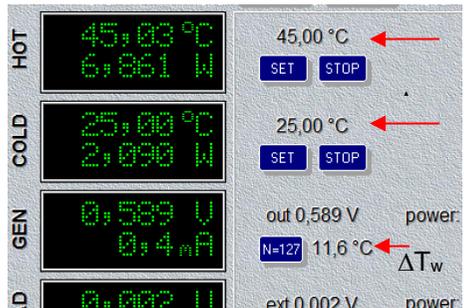


- L. By the slider set the load as a percentage of the load as a percentage of the maximum value for the range given, using the readings in %.



- M. The operational load current and the corresponding value of the input load voltage will be displayed in the group of indicators LOAD.

It will be seen that up to a certain load current (for given temperature conditions) the DC/DC converter provides stable voltage supply. However, above a certain threshold, the voltage drops sharply. The DC/DC converter is out of the operating mode.



It is the behavior of the generator current-voltage characteristic (see the Section "Current-Voltage Characteristic of Thermoelectric Generator with Dc/DC converter").

- N. It is also useful to calculate the generator efficiency.

This value is given in the main window of the software.

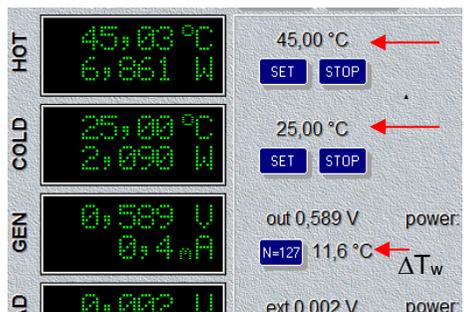
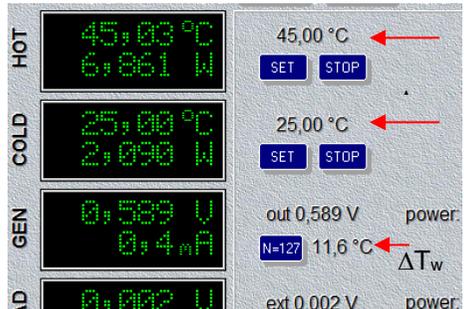
The value of efficiency at a steady temperature difference (T_{hot} and T_{cold}) is calculated as:

$$n = \frac{Q}{U \times I} \%$$

Here Q is the value given by the heat flux indicator of the group COLD, U and I are the readings of the indicators of the group GEN.

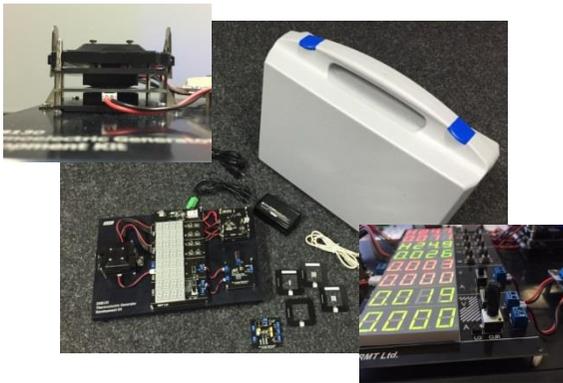
- O. The value of DC/DC converter efficiency can be estimated additionally. This value is also displayed in the main window.

The DC/DC converter efficiency is calculated as:



$$\eta_{DC/DC} = \frac{U_{GEN} \times I_{GEN}}{U_{LOAD} \times I_{LOAD}} \%$$

Here in the numerator of the fraction there are current and voltage at the input of the converter (from the generator). In the denominator there are current and voltage on the load (output of the DC/DC converter).



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