

# User Guide

**Novoptel**

EPS1000 Polarization Scrambler/Transformer



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## Revision history

Version	Date	Remarks	Author
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0.1.1	30.08.2012	Draft version	B. Koch
0.1.2	15.04.2013	Description of external voltage allocation (Registers 50...65)	B. Koch
0.1.3	23.07.2013	Support of multiple wavelength bands	B. Koch
0.1.4	07.05.2014	Description of PDL measurements	B. Koch
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0.1.6	26.06.2015	Updates due to GUI rev. 1.4.2.0	B. Koch

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Rear panel

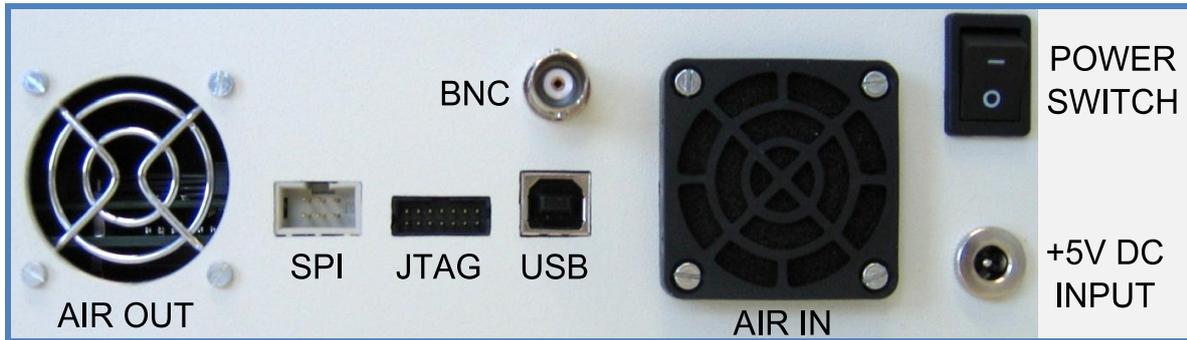


Fig. 1: EPS1000 rear panel

Operation of the instrument via front control panel

Power the instrument with the provided power supply and switch it on. The scrambler firmware provides a cyclic menu, which is shown on the LCD or OLED display. The menu structure is

WELCOME
QWP0
QWP1
QWP2
HWP
QWP3
QWP4
QWP5
Optical Frequency
Wavelength Band

Menu points QWP0 and QWP5 are missing in scrambler configurations with only four quarter wave plates. The menu point *Wavelength Band* is missing if the scrambler supports only a single wavelength band. The control buttons *UP* and *DOWN* let you to navigate through the menu. The control buttons *LEFT* and *RIGHT* changes a selected setting or selects a decimal place, which can afterwards be changed with the buttons *UP* and *DOWN*.

For each wave plate, you can choose between *DISABLED*, *FORWARD* and *BACKWARD* operation of the wave plate and set the desired rotating speed. For the quarterwave plates, rotation speed is given in in rad/s between 0 and +999,999.99 rad/s. For the halfwave plate, it is in krad/s between 0 und 20,000.00 krad/s.

The range for the optical frequency is at least C and L band, usually 182.9 THz (1639.1 nm) to 198.5 THz (1510.3 nm).

## Operation of the instrument via graphical user interface

The instrument communicates by a USB I.C.FT232R from FTDI (Future Technology Devices International Limited, <http://www.ftdichip.com>).

The Novoptel EPS1000 Graphical User Interface (= GUI) is compiled on a Microsoft Windows 7 64 Bit system with .NET Framework 4.5.1 installed.

### Installing the USB driver

Execute the installation program of the provided USB driver (*CDM20814\_Setup.exe*). You will find more detailed information about the driver at <http://www.ftdichip.com/Support/Documents/InstallGuides.htm>.

### Connecting the instrument

After the driver is installed successfully, connect PC and instrument using the provided USB cable. Wait until Windows has recognized the USB device and shown an acknowledgement message. Power the instrument with the provided power supply and switch it on.

### Installing the GUI

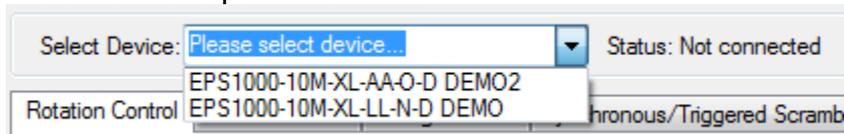
Execute *setup.exe* in the folder *EPS1000\_GUI*. Follow the instructions of the installation dialogue.

### First steps with the GUI

The software launches automatically after installation. If you want to launch the software later manually, select *Programs\Novoptel\EPS1000* from the Windows Start Menu.

#### Selecting one of the attached instruments

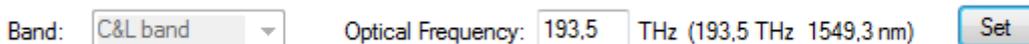
If you have attached only one Novoptel polarization scrambler/transformer, the GUI automatically selects this one. If you have attached more than one instrument, select the desired one from the drop-down menu.



Subsequently, you can launch further instances of the GUI and connect them to further instruments.

#### Setting the optical frequency

Type the optical frequency in THz with up to one position after decimal point into the field besides *Optical Frequency*.



The valid range is at least C and L band, usually 182.9 THz (1639.1 nm) to 198.5 THz (1510.3 nm). Click the button *Set*. Retardations of the halfwave plate is fine-tuned to the given optical frequency.

## Setting the rotation speed

The polarization scrambler provides six (or four) quarterwave plates and one halfwave plate, each with adjustable rotation speed. For the quarterwave plates, rotation speed is given in rad/s between 0 and 999,999.99 rad/s. For the halfwave plate, it is in krad/s between 0 and 20,000.00 krad/s. The given values correspond to the polarization changing speed when generating rotating linear polarization. This is the case with circular polarization at the input of a quarterwave plate or linear polarization at the input of a halfwave plate.

The wave plates are depicted among each other in the sequence in which they are traversed by the light. Type the desired speed with up to two positions after decimal point into the box beside the wave plates. To obtain a uniform distribution of the polarization states on the Poincaré sphere, the speeds of the waveplates should be incommensurate with each other.

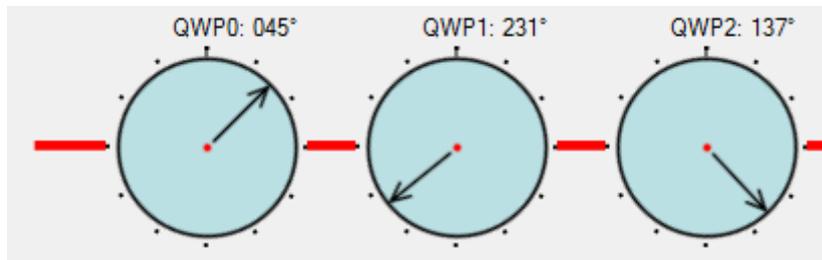
QWP2:  rad/s (999999,99 rad/s)

HWP:  krad/s (20000,00 krad/s)

Click the button *Set*. Select the rotation direction by clicking “*Forward*” or “*Backward*”.

## Setting a certain state of polarization

This function allows setting a fixed state of polarization or adjusting the input- and output polarization of a rotating wave plate. Select the tab *Position Control*. Each wave plate is depicted as a rotary knob. An arrow marks the orientation of the wave plate. The orientation is shown above the wave plate in degrees.



To rotate the wave plate, click on one knob and move the mouse with pressed mouse button around the center of the knob. In case that the wave plate was configured to rotate with a given speed, it will be halted automatically. You can start the rotation again using the tab *Rotation Control*.

## Store and load a configuration

You can save and recall up to ten configurations. Both rotating speeds and fixed positions of all wave plates are considered thereby.

Load Configuration:

Save Configuration:

Click on a numbered button beside *Save Configuration* to save the configuration to one of the memory locations. Click on a button beside *Load Configuration* to recall a configuration from a memory location. Unused memory locations are faded out. Instances of the Software which are launched in parallel share the memory locations.

## Operation of the instrument using Matlab®

The USB driver (CDM20814\_Setup.exe) has to be installed on your system and the scrambler needs to be connected using a USB cable.

### Access the USB driver

Matlab needs a header file like *ftd2xx.h* from FTDI to access the driver. Novoptel provides the header version *matftd2xx.h*, in which the data types are modified to become compatible with current Matlab versions.

You will find help about communicating to a driver at <http://www.mathworks.com/help/techdoc/ref/loadlibrary.html>

The different functions of the driver can be seen from the header file. Information about each function is provided at <http://www.ftdichip.com/Support/Knowledgebase/index.html>

Example Matlab scripts for USB data transfer are available from Novoptel upon request.

### USB Settings

The following settings have to be applied within Matlab (or other programs) to enable USB communication:

<b>Baud Rate</b>	230400 baud
<b>Word Length</b>	8 Bits
<b>Stop Bits</b>	1 Bit
<b>Parity</b>	0 Bit

To speed up sequential read and write operations, we recommend setting:

<b>USB Latency Timer</b>	2 ms
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### Transfer protocol

The polarization scrambler is controlled by reading from and writing to USB registers. The register address line is 12 bits wide, while each register stores 16 bits. All communication is initiated by the USB host, e.g. the Matlab program.

Writing to a register uses a 9 byte data packet. Each byte represents an ASCII-coded character. The packet starts with the ASCII-character "W" and ends with the ASCII-code for *carriage return*.

#### Send write data packet

„W“	A(2)	A(1)	A(0)	D(3)	D(2)	D(1)	D(0)	^CR
-----	------	------	------	------	------	------	------	-----

The 12 bit register address A is sent using 3 bytes, each containing the ASCII-character of the hexadecimal numbers 0 to F which represents the 4 bit nibble. The character of the most significant nibble is sent first. The 16 bit data, which should be written into the register, is sent with 4 bytes using the same coding as the register address.

Reading data from a register requires the host to send a *request data* packet to the instrument. The packet starts with the ASCII-character “R”, followed by the register address coded the same way as in *write data* packets.

### Send *request data* packet

„R“	A(2)	A(1)	A(0)	„0“	„0“	„0“	„0“	^CR
-----	------	------	------	-----	-----	-----	-----	-----

After receiving the *request data* packet, the instrument sends the requested data packet to the host:

D(3)	D(2)	D(1)	D(0)	CR
------	------	------	------	----

### USB registers

The following table describes all USB register used to control the scrambler:

Register address	Bit(s)	Read/ Write	Function
0	0	R/W	HWP rotation enable(1) or disable (0)
	1	R/W	HWP direction backward(1) or forward(0)
1	0	R/W	QWP0 rotation enable(1) or disable (0)
	1	R/W	QWP0 direction backward(1) or forward(0)
2	0	R/W	QWP1 rotation enable(1) or disable (0)
	1	R/W	QWP1 direction backward(1) or forward(0)
3	0	R/W	QWP2 rotation enable(1) or disable (0)
	1	R/W	QWP2 direction backward(1) or forward(0)
4	0	R/W	QWP3 rotation enable(1) or disable (0)
	1	R/W	QWP3 direction backward(1) or forward(0)
5	0	R/W	QWP4 rotation enable(1) or disable (0)
	1	R/W	QWP4 direction backward(1) or forward(0)
6	0	R/W	QWP5 rotation enable(1) or disable (0)
	1	R/W	QWP5 direction backward(1) or forward(0)
9	15..0	R/W	HWP rotation speed Bits 15..0 <sup>(1)</sup>
10	15..0	R/W	HWP rotation speed Bits 31..16 <sup>(1)</sup>
11	15..0	R/W	QWP0 rotation speed Bits 15..0 <sup>(2)</sup>
12	15..0	R/W	QWP0 rotation speed Bits 31..16 <sup>(2)</sup>
13	15..0	R/W	QWP1 rotation speed Bits 15..0 <sup>(2)</sup>
14	15..0	R/W	QWP1 rotation speed Bits 31..16 <sup>(2)</sup>
15	15..0	R/W	QWP2 rotation speed Bits 15..0 <sup>(2)</sup>
16	15..0	R/W	QWP2 rotation speed Bits 31..16 <sup>(2)</sup>
17	15..0	R/W	QWP3 rotation speed Bits 15..0 <sup>(2)</sup>
18	15..0	R/W	QWP3 rotation speed Bits 31..16 <sup>(2)</sup>
19	15..0	R/W	QWP4 rotation speed Bits 15..0 <sup>(2)</sup>
20	15..0	R/W	QWP4 rotation speed Bits 31..16 <sup>(2)</sup>
21	15..0	R/W	QWP5 rotation speed Bits 15..0 <sup>(2)</sup>
22	15..0	R/W	QWP5 rotation speed Bits 31..16 <sup>(2)</sup>

25	15..0	R/W	Optical Frequency Index I <sup>(3)</sup>
40	15..0	R/W	HWP position Index I <sup>(4)</sup>
41	15..0	R/W	QWP0 position index I <sup>(4)</sup>
42	15..0	R/W	QWP1 position index I <sup>(4)</sup>
43	15..0	R/W	QWP2 position index I <sup>(4)</sup>
44	15..0	R/W	QWP3 position index I <sup>(4)</sup>
45	15..0	R/W	QWP4 position index I <sup>(4)</sup>
46	15..0	R/W	QWP5 position index I <sup>(4)</sup>
47	15..0	R/W	Table Dwell Time (multiples of 40 ns) as stored in the table, Bits 15..0
48	15..0	R/W	Table Dwell Time (multiples of 40 ns) as stored in the table, Bits 31..16
50	13..0	R/W	LiNbO <sub>3</sub> section 1 electrode 1 voltage <sup>(5)</sup>
51	13..0	R/W	LiNbO <sub>3</sub> section 1 electrode 2 voltage <sup>(5)</sup>
52	13..0	R/W	LiNbO <sub>3</sub> section 2 electrode 1 voltage <sup>(5)</sup>
53	13..0	R/W	LiNbO <sub>3</sub> section 2 electrode 2 voltage <sup>(5)</sup>
54	13..0	R/W	LiNbO <sub>3</sub> section 3 electrode 1 voltage <sup>(5)</sup>
55	13..0	R/W	LiNbO <sub>3</sub> section 3 electrode 2 voltage <sup>(5)</sup>
56	13..0	R/W	LiNbO <sub>3</sub> section 4 electrode 1 voltage <sup>(5)</sup>
57	13..0	R/W	LiNbO <sub>3</sub> section 4 electrode 2 voltage <sup>(5)</sup>
58	13..0	R/W	LiNbO <sub>3</sub> section 5 electrode 1 voltage <sup>(5)</sup>
59	13..0	R/W	LiNbO <sub>3</sub> section 5 electrode 2 voltage <sup>(5)</sup>
60	13..0	R/W	LiNbO <sub>3</sub> section 6 electrode 1 voltage <sup>(5)</sup>
61	13..0	R/W	LiNbO <sub>3</sub> section 6 electrode 2 voltage <sup>(5)</sup>
62	13..0	R/W	LiNbO <sub>3</sub> section 7 electrode 1 voltage <sup>(5)</sup>
63	13..0	R/W	LiNbO <sub>3</sub> section 7 electrode 2 voltage <sup>(5)</sup>
64	13..0	R/W	LiNbO <sub>3</sub> section 8 electrode 1 voltage <sup>(5)</sup>
65	13..0	R/W	LiNbO <sub>3</sub> section 8 electrode 2 voltage <sup>(5)</sup>
84	15..0	R	Firmware version
91	15..0	R	Serial Number
123	15..0	R	Dark current of ADC sample (optional photodetector)
124	15..0	R	Optical power at upper ADC range limit in $\mu$ W
126	1	R/W	(1) automatic or (0) manual switching between two optional photodetectors
	0	R/W	Manual switch position or polarity of automatic switching according to Bit 1
128	15..0	R	Integer part of ADC sample
129	9..0	R/W	Averaging Time Exponent (ATE) for ADC sampling
130	15..0	R/W	Address of internal sampling memory
131	15..0	R	Data-Out of internal sampling memory
132	0	R/W	Triggered WP rotation enable (1) or disable (0)
133	15..0	R	Fractional part of ADC sample, frozen at each reading of register 128
134	15..0	R/W	Memory stop-address for measurements (max.2 <sup>16</sup> -1)
135	15..0	R	Next sampling memory address bits 15..0
136	15..0	R/W	Measurement delay in multiples of 20 ns <sup>(6)</sup>
137	15..0	R/W	Memory Averaging Time Exponent (MEMATE) for memory trigger <sup>(6)</sup>

138	2..0	R/W	Control of optional electrical switches <sup>(6)</sup>
139	0	R	Next sampling memory address bit 16 <sup>(6)</sup>
140	15..0	R/W	Number of cycles to be skipped during measurements <sup>(6)</sup>
141	3..0	R/W	With a value A in this register, 2 <sup>A</sup> samples will be stored per waveplate position <sup>(6)</sup>
150	0	R/W	(0): Define WP rotation speed by registers in rad/s (1): Define WP rotation speed by rotations per 10.7s
151	15..0	R/W	HWP rotations per 10.7 s
152	15..0	R/W	QWP0 rotations per 10.7 s
153	15..0	R/W	QWP1 rotations per 10.7 s
154	15..0	R/W	QWP2 rotations per 10.7 s
155	15..0	R/W	QWP3 rotations per 10.7 s
156	15..0	R/W	QWP4 rotations per 10.7 s
157	15..0	R/W	QWP5 rotations per 10.7 s
219	9..0	R/W	Table memory input address
220	0	R/W	Enable (1) or disable (0) continuous table execution
221	0	W	Table memory write trigger. Must be reset to "0"!
224	0	R/W	External trigger input enabled (1) or disabled (0)
225	1	R/W	Enable (1) or disable (0) trigger by ATE counter
	0	R/W	Enable (1) or disable (0) internal trigger counter
227	0	W	Any write to this register will launch 1 trigger event (manual trigger)
228	9..0	R/W	Length of current table in table memory
229	0	R/W	Fixed waveplate positions are defined by registers (0) or by table memory (1)
230	15..0	R/W	HWP position index table memory input
231	15..0	R/W	QWP0 position index table memory input
232	15..0	R/W	QWP1 position index table memory input
233	15..0	R/W	QWP2 position index table memory input
234	15..0	R/W	QWP3 position index table memory input
235	15..0	R/W	QWP4 position index table memory input
236	15..0	R/W	QWP5 position index table memory input
237	15..0	R/W	Table Dwell Time (multiples of 40 ns) to be stored in the table, Bits 15..0
238	15..0	R/W	Table Dwell Time (multiples of 40 ns) to be stored in the table, Bits 31..16
250	15..0	R/W	LiNbO <sub>3</sub> section 1 electrode 1 voltage table memory
251	15..0	R/W	LiNbO <sub>3</sub> section 1 electrode 2 voltage table memory
252	15..0	R/W	LiNbO <sub>3</sub> section 2 electrode 1 voltage table memory
253	15..0	R/W	LiNbO <sub>3</sub> section 2 electrode 2 voltage table memory
254	15..0	R/W	LiNbO <sub>3</sub> section 3 electrode 1 voltage table memory
255	15..0	R/W	LiNbO <sub>3</sub> section 3 electrode 2 voltage table memory
256	15..0	R/W	LiNbO <sub>3</sub> section 4 electrode 1 voltage table memory
257	15..0	R/W	LiNbO <sub>3</sub> section 4 electrode 2 voltage table memory
258	15..0	R/W	LiNbO <sub>3</sub> section 5 electrode 1 voltage table memory
259	15..0	R/W	LiNbO <sub>3</sub> section 5 electrode 2 voltage table memory
260	15..0	R/W	LiNbO <sub>3</sub> section 6 electrode 1 voltage table memory

261	15..0	R/W	LiNbO <sub>3</sub> section 6 electrode 2 voltage table memory
262	15..0	R/W	LiNbO <sub>3</sub> section 7 electrode 1 voltage table memory
263	15..0	R/W	LiNbO <sub>3</sub> section 7 electrode 2 voltage table memory
264	15..0	R/W	LiNbO <sub>3</sub> section 8 electrode 1 voltage table memory
265	15..0	R/W	LiNbO <sub>3</sub> section 8 electrode 2 voltage table memory

(1) The HWP rotation speed index I (32 bit integer) is calculated from the nominal HWP rotation speed SHWP (in krad/s) by  $I = \text{round}(\text{SHWP} \cdot 100)$ .

(2) The QWP rotation speed index I (32 bit integer) is calculated from the nominal QWP rotation speed SQWP (in rad/s) by  $I = \text{round}(\text{SQWP} \cdot 100)$ .

(3) The optical frequency index I is calculated from the optical frequency F (in THz) by  $I = \text{round}(F \cdot 10 \cdot 1829)$ .

(4) The position index I is calculated from Position P (in degrees) by  $I = \text{round}(P \cdot 65536 / 360)$ .

(5) Only applicable since firmware 1.0.2.0

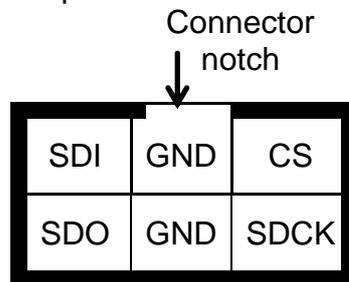
(6) Only applicable since firmware 1.0.6.0

## Operation of the instrument using other programs

The USB vendor <http://www.ftdichip.com/Support/Knowledgebase/index.html> provides examples for USB access using other programs, for example LabVIEW®. A rudimental example of a LabVIEW-VI (virtual instrument) is available from Novoptel upon request.

## Operation of the instrument using SPI

All USB registers can also accessed by SPI. The SPI interface allows communication with a simpler protocol and shorter delays than USB. The SPI connector at the backside of the device provides the following connection:



Transmission starts with falling edge of CS and ends with rising edge of CS. After falling edge of CS, the command is transmitted. SDI is sampled with rising edge of SCK. Maximum SCK frequency is 500 kHz. Command and data word length is 16 bit each. MSB of command and data word is sent first, LSB last. If a valid *register read* (RDREG) command is received, the SDO output register shifts with falling edge of SCK to transmit the requested data word. Otherwise SDO remains in high impedance state. Data transfer to the device continues directly after transmitting a *register write* (WRREG) command.

### Serial interface (SPI) commands

Command	Code	Data	Function
RDREG	0XXXh	OUT	Read register XXXh (for definition see <i>USB section</i> )
WRREG	1XXXh	IN	Write register XXXh (for definition see <i>USB section</i> )

**Serial interface (SPI) timing**

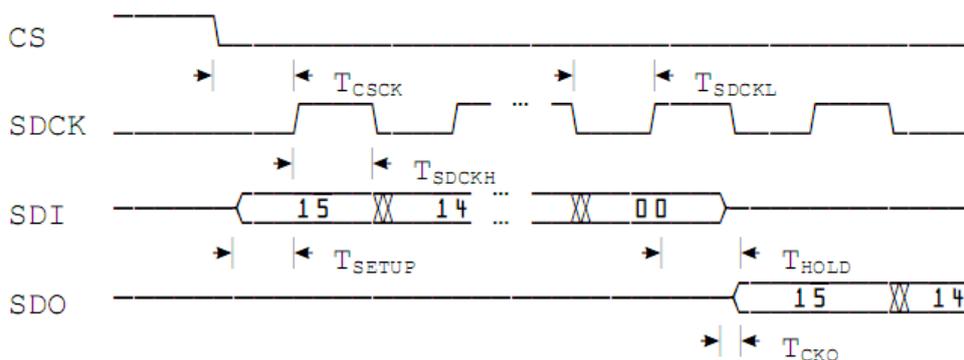


Fig. 2: Timing of SPI port.

Symbol	Description	Min	Max	Units
T <sub>CSCK</sub>	CS low to SDCK high	120	–	ns
T <sub>CKCS</sub>	SDCK low to CS high	120	–	ns
T <sub>SDCKL</sub>	SDCKL low time	1	–	µs
T <sub>SDCKH</sub>	SDCKL high time	1	–	µs
T <sub>SETUP</sub>	SDI egde to SDCK high (setup time)	30	–	ns
T <sub>HOLD</sub>	SDCK to SDI edge (hold time)	30	–	ns
T <sub>CKO</sub>	SDCK edge to stable SDO	–	100	ns

**Firmware upgrade**

Via the JTAG port the user can upgrade the firmware, if ever needed. Note that the upgrading firmware must be obtained from Novoptel on a per-module basis because the firmware is encrypted and authenticated.

The schematic and timing of the JTAG port correspond to that detailed in Spartan-3 Generation Configuration User Guide UG332 (v1.6) October 26, 2009 from Xilinx ([www.xilinx.com](http://www.xilinx.com)).

## Synchronous/triggered Waveplate Rotation

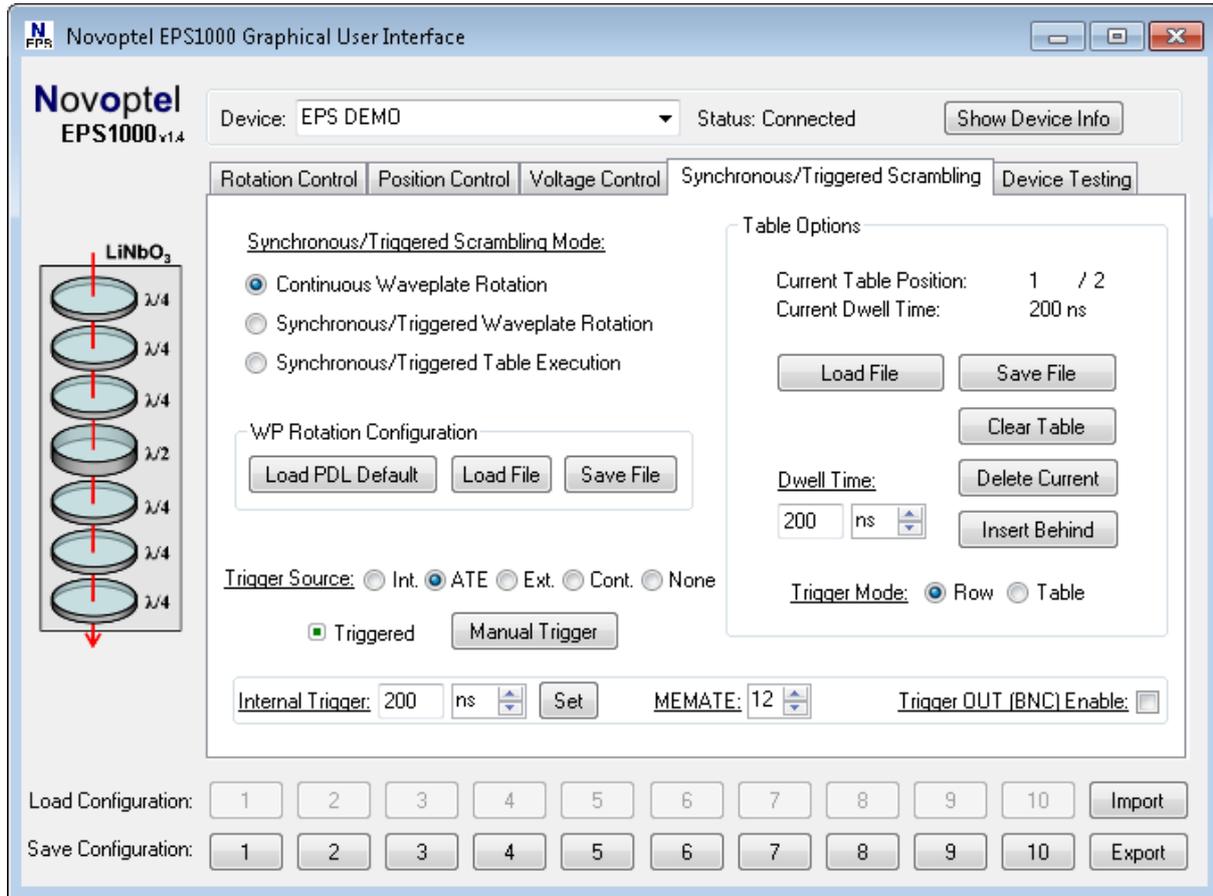


Fig. 3: “Synchronous/Triggered Scrambling” tab

In normal scrambling mode, waveplates are rotated continuously. Quasi-steady polarization changes are thereby achieved. For some applications, the polarization should be fixed for a defined time interval to allow accurate SOP sampling within it. This can be done with the synchronous/triggered waveplate rotation function: The waveplates will be kept rotating internally, but the corresponding electrode voltages will be updated only upon a trigger event.

### Trigger Source

Several different trigger sources are available:

**Manual:** Trigger events can be manually released by pushing the *Manual Trigger* button.

**Internal:** The scrambler is triggered by an internal clock. The *Internal Trigger Period* can be adjusted in multiples of 40 ns. Minimum *Internal Trigger Period* is 200 ns

**ATE:** Internal trigger synchronous to the averaging time of the optional photodetector. The trigger event will be launched every  $80 \text{ ns} \cdot 2^{\text{MEMATE}}$ .

**External:** Triggering by a LVCMOS33 (0 V / +3.3 V) signal that is applied to the BNC connector at the rear panel of the device.

**Continuous:** Only applicable for synchronous/triggered table execution: The scrambling table is executed continuously.

The internal triggers can optionally be fed out to the BNC connector at the rear panel of the device if the box *Trigger (OUT) BNC* is activated.

The complete synchronous/triggered waveplate rotation configuration can be stored to and loaded from text files. The text files simply contain the values of registers 40...46, 9...22, 0...6, 150...156 and 157, each register value in a new line. For a better understanding of these registers, please refer to Application Note 2: "Automated PDL Measurement with EPS1000". A default configuration for PDL measurements can be loaded by pressing the *Load PDL Default* button.

## Synchronous/triggered Table Execution

The scrambler can put all waveplates to arbitrary positions or even put all electrode voltages to specified values which are stored in a table. Each row of the table contains the positions of the 7 waveplates, followed by the 16 corresponding electrode voltages and a dwell time (= subsequent delay) in nanoseconds. The dwell time must be a multiple of 40 ns. Minimum dwell time is 200 ns.

Tables can be created using the GUI. They can be stored to and loaded from a file. This way, tables can also be generated by an external program and, afterwards, loaded into the scrambler. For a better understanding of the corresponding registers, please also refer to Application Note 2.

There are two basic trigger modes, row or table:

### ***Row Trigger Mode***

In row trigger mode, the rows of the stored table are executed one-by-one upon a trigger event. After the last table row, the counter starts over from the first table row.

### ***Table Trigger Mode***

In table trigger mode, the scrambler starts over from the first table entry upon every trigger. Subsequent rows are executed after the dwell time delay specified in each row. After the last table row, the row counter is halted until the next trigger event occurs.

In *Row Trigger Mode* the *Internal Trigger Period* must be chosen at least as long as the longest *Dwell Time*. In *Table Trigger Mode* the *Internal Trigger Period* must be chosen at least as long as the sum of all *Dwell Times*.

## PDL measurement

Polarization-dependent loss (PDL) can be measured by Muellermatrix evaluation with Novoptel's polarimeter PM1000 and the EPS1000. In contrast, **non-polarimetric** methods for PDL (and loss) measurement are covered here.

The EPS1000 can optionally be equipped with a photodetector for measuring the optical power of an applied signal. How PDL can be measured with direct EPS1000 register access (enabling also the usage of external photodetectors) is described in Application Note 2: "Automated PDL Measurement with EPS1000". PDL measurement with the GUI (= Novoptel EPS1000 graphical user interface) is described in the following.

We recommend

- either the **extinction method**, i.e. the searching of polarizations with maximum and minimum transmission,

- or the **scrambling method**. This requires a sequence of polarizations states, whose correlation matrix of normalized Stokes vectors is 1/3 times the identity matrix. Such a sequence is applied to the device under test (DUT) and the output power  $P$  is measured for each applied polarization state. Maximum and minimum output power are given by  $\langle P \rangle \pm \sqrt{3}\sigma_P$ . The PDL in dB is given by  $10\log_{10}\left(\frac{\langle P \rangle + \sqrt{3}\sigma_P}{\langle P \rangle - \sqrt{3}\sigma_P}\right)$ .

Here  $\langle P \rangle$  is the mean output power and  $\sigma_P$  is the standard deviation of  $P$ . Examples for such polarization state sequences are the corners of diamond, cube and other polyhedrons, which can be stored in and executed from a table (see above), or simply equidistributed polarizations. PDL measurement with the scrambling method and equidistributed polarizations is fully supported by the *Synchronous/Triggered Waveplate Rotation* feature in the GUI.

### ***PDL measurement with the extinction method***

The EPS1000 GUI provides a function for searching maximum and minimum transmission. Only if the EPS1000 is equipped with a photodetector, the tab *Device Testing* (Fig. 4) will appear in GUI. The value of the current optical power sample is shown in a yellow bar.

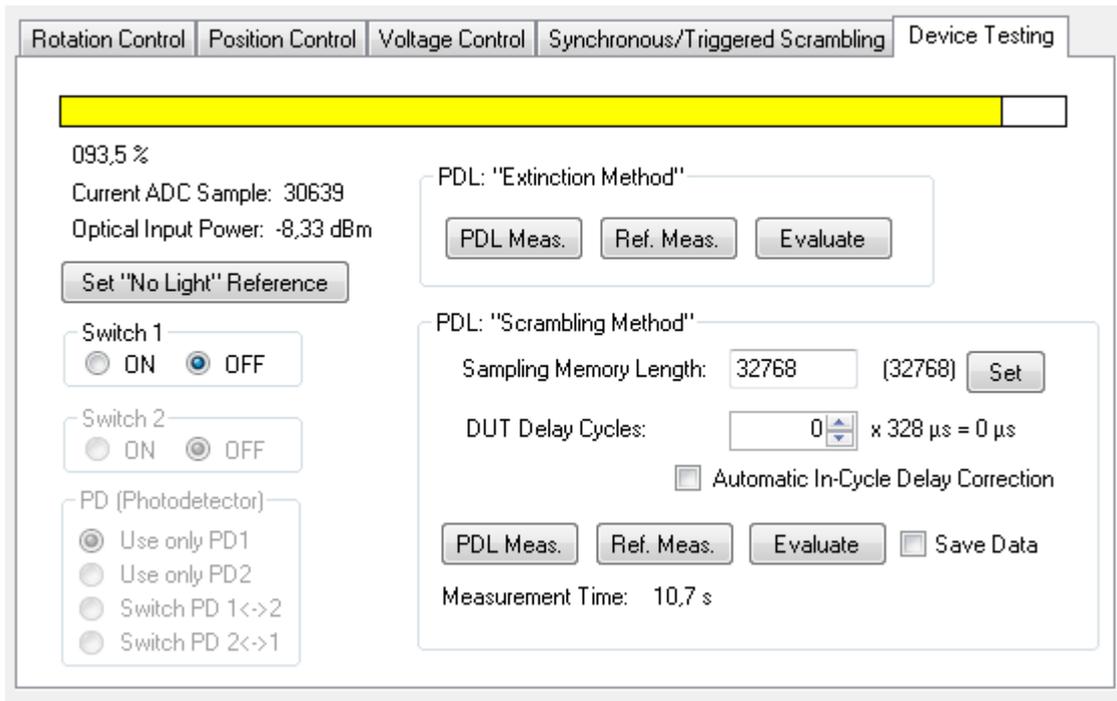


Fig. 4: “Device Testing” tab, for PDL measurement

1. Turn off the optical signal and press *Set “No Light” Ref.* to store the current sample as the new dark current reference for the following measurements.
2. Turn on the optical signal. Place the DUT between scrambler output and power meter input for the PDL measurement *PDL. Meas.* A new window will open.

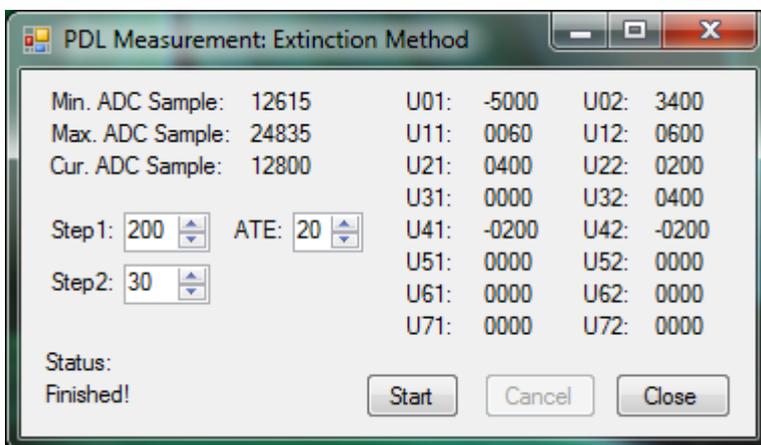


Fig. 5: Search for minimum and maximum transmission

3. Pressing *Start* in the new window will initiate the minimum and maximum transmission search. The EPS1000 modulates the 16 voltages U01 to U72 one after the other and gets a voltage set for minimum and maximum transmission. This is conducted twice: Once with modulation step size defined in the *Step 1* box and once with step size defined in the *Step 2* box. The averaging of the measurement can be defined in the *ATE* box. After the two voltage sets and the ADC samples at minimum and maximum transmission have been found, press *Close*.

4. Connect the scrambler output and power meter input with a patch cord and press *Ref. Meas* for the reference measurement. The voltage sets found for minimum and maximum transmission will now be applied again subsequently, and the two corresponding new ADC samples will be stored for reference. Provided that the input polarization to the EPS1000 did not change since the PDL measurement, this task allows subtracting PDL of the EPS1000 from the previously measured PDL of the DUT.

This reference measurement is not mandatory. If it is not undertaken then it will be assumed that the EPS1000 has no PDL. In that case, just PDL, but no minimum loss and no mean loss, will be displayed during the evaluation 5.

5. Press *Evaluate* to get

- mean loss (for equidistributed input polarizations),
  - minimum loss (for the best transmitted polarization) and
  - PDL
- of the DUT.

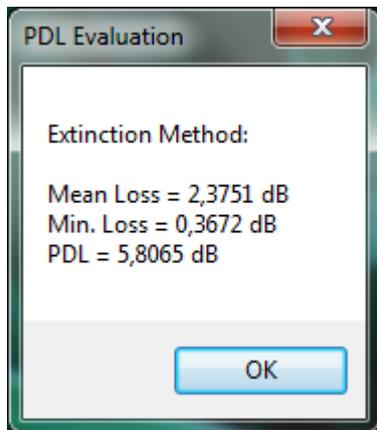


Fig. 6: Result of PDL measurement with extinction method

For example, an ideal polarizer has a minimum loss of 0 dB, a mean loss of 3 dB and a PDL of  $\infty$  dB.

Before device testing the yellow bar allows choosing a suitable optical power. If the maximum measured power during device testing is 100% – overflow falsifies results! – or is <50% – low values decrease accuracy! – then a warning will be issued to the user.

### ***PDL measurement with the scrambling method***

For PDL measurement with the scrambling method and triggered waveplate rotation, the following 3 steps are required:

1. Apply initial waveplate positions in *Position Control* tab and desired rotation speeds in *Rotation Control* tab. A useful example is given in Fig 7.

Waveplate	Turns	Steps	Start at
QWP0	$2^2$	$2^{13}$	1/48
QWP1	$2^6$	$2^9$	3/48
QWP2	$2^{10}$	$2^5$	5/48
HWP	$2^{12}$	$2^3$	0
QWP3	$2^8$	$2^7$	7/48
QWP4	$2^4$	$2^{11}$	9/48
QWP5	$2^0$	$2^{15}$	11/48

Fig. 7: Number of waveplate turns (in each measurement), number of steps per turn and starting positions (referred to 1 electric period).

Turns \* Steps = *Sampling Memory Length* (= number of samples) =  $2^{15}$

All QWP and HWP speeds are different. Each QWP is rotated in 4 steps per turn or electrical period. The HWP is rotated in 8 steps per turn.

The averaging time exponent ATE refers to the optional photodetector in the EPS1000. It sets the averaging or measurement time as  $80\text{ns} * 2^{\text{ATE}}$ . For an exemplary ATE = 11 the averaging time is  $2^{11} * 80 \text{ ns} = 163.84 \mu\text{s}$ . The memory trigger period defined by MEMATE = 12 is always twice as long,  $2^{12} * 80 \text{ ns}$ . It is  $327.68 \mu\text{s}$  in our example. For a *Sampling Memory Length* =  $2^{15}$  one measurement hence takes 10.7 s.

Needed physical, nominal rotation speeds (with "Turns" taken from Fig. 7) are

$$\text{QWP speed} = 2 * \pi / ( 2 * 80\text{ns} * 2^{\text{ATE}} * \textit{Sampling Memory Length} ) * \text{Turns},$$

$$\text{HWP speed} = 2 * 2 * \pi / ( 2 * 80\text{ns} * 2^{\text{ATE}} * \textit{Sampling Memory Length} ) * \text{Turns},$$

or

$$\text{QWP speed} = 2 * \pi / \text{Steps} / ( 2 * 80\text{ns} * 2^{\text{ATE}} ),$$

$$\text{HWP speed} = 2 * 2 * \pi / \text{Steps} / ( 2 * 80\text{ns} * 2^{\text{ATE}} ).$$

The need for doubled speed setting of the HWP compared to the QWP comes from the EPS1000 rotation speed definition: The nominal scrambling speed values are those achieved with rotating linear output polarization, i.e. for circular input polarization of a QWP and linear input polarization of a HWP.

Rotation speeds according to Fig. 7 are shown in Fig. 8, for ATE = 11 set in the *Rotation Control* tab. In the *Position Control* tab, the waveplate positions are adjusted to match the starting positions multiplied by  $360^\circ$ . Alternatively to the manual rotation speeds and positions setting, a configuration file can be loaded in the *WP Rotation Configuration* section on the "Synchronous/Triggered Scrambling" tab. A default configuration for PDL measurements with ATE=11 (MEMATE=12) and *Sampling Memory Length* =  $2^{15}$  can be loaded by pressing the *Load PDL Default* button.

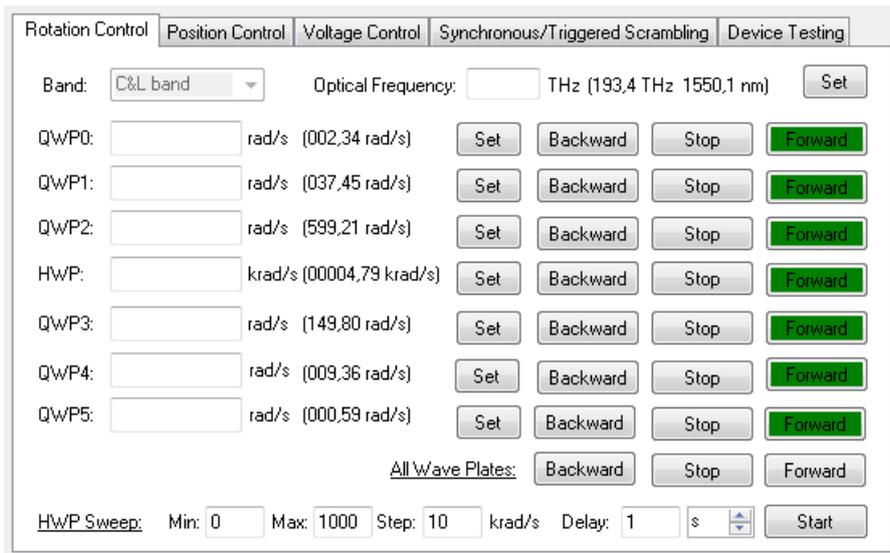


Fig. 8: Setting waveplate rotation speeds for PDL measurement (ATE = 11)

2. Enable *Synchronous/Triggered Waveplate Rotation* in the *Synchronous/Triggered Scrambling* tab. Set *Trigger Source* to *ATE* and specify the desired MEMATE value.

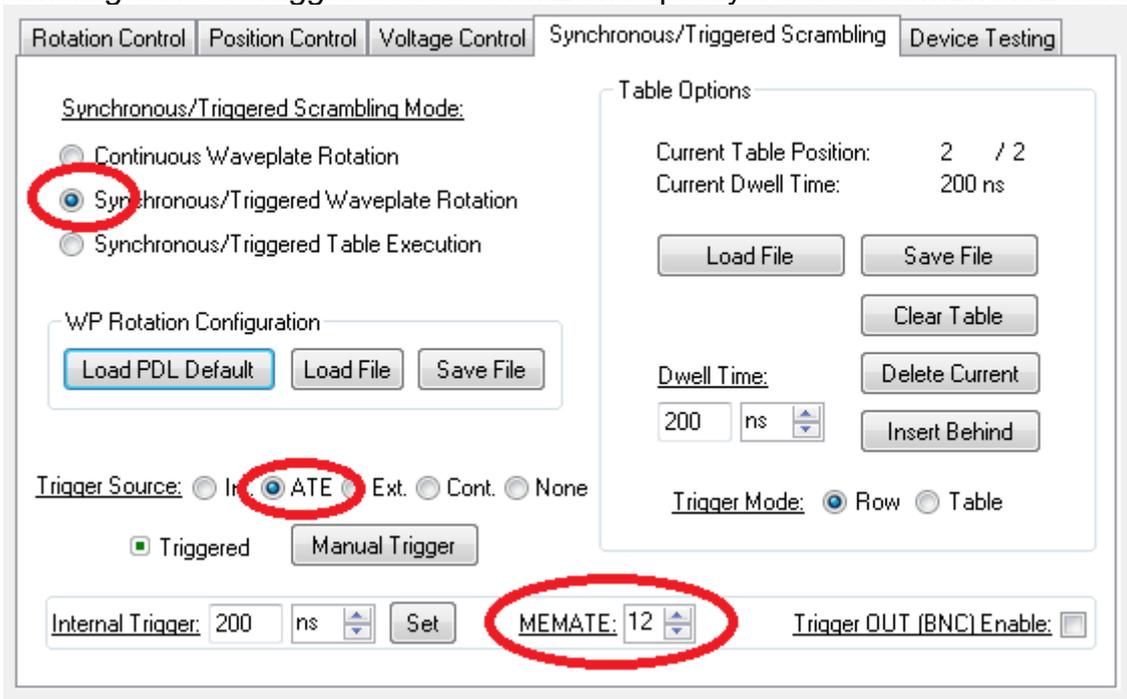


Fig. 9: *Synchronous/Triggered Scrambling* tab, for PDL measurement

3. Measure the reference without light as described in the previous section. Specify the *Sampling Memory Length* to 32768 ( $= 2^{15}$ ) for the example of Fig. 7. Place the DUT between scrambler output and power meter input for the PDL measurement *PDL Meas.* Then replace the DUT with a patchcord for the reference measurement *Ref. Meas.*

After both measurements are finished, Press *Evaluate* to get a summary of the DUT's PDL as well as it's mean and minimum insertion loss as described in the previous

section. Optionally *Save Data* can previously be activated to store the measured samples in two text files for analysis by other programs like Matlab™.

The EPS1000 can be optionally equipped with one or more electrical output signals that can be switched between 0V and 5V. This allows to control an external optical switch for selecting DUT and reference measurement by clicking on ON and OFF in the fields *Switch 1* and *Switch 2* in Fig. 4. If the EPS1000 is not equipped with this output(s), the corresponding fields are disabled.

With firmware 1.0.6.0 (release 15.06.2015) or later, the EPS1000 can consider any delay induced by the DUT. The delay must be estimated at least as accurate as one waveplate trigger period. The delay is set to a multiple of the waveplate trigger period. Any residual fractional delay is ignored in this setting. If it is nonzero it must be corrected. This residual (nonnegative) fractional delay can be automatically corrected. For this purpose, four measurements, each delayed with respect to the previous by 1/4 of the trigger period, will be taken. Two of these measurements will be taken at once by storing 2 samples per waveplate position. Thereby a doubled memory length is needed. Since a wrong delay will result in a lowered PDL value, the GUI automatically selects the one of the four measurements that leads to the highest PDL value.

## External electrode voltage allocation

Since firmware 1.0.2.0 (release 15.04.2013), the EPS1000 allows external allocation of the 16 LiNbO<sub>3</sub> electrode voltages via USB or SPI. This increases flexibility when searching for a defined polarization state: 16 instead of 7 degrees of freedom are thereby provided. The external voltage setting overwrites any rotation or position setting of the corresponding waveplate when writing to one of the registers 50 to 65, see register description. The voltage value is given as an unsigned integer with an offset of 8192. Positive integers generate positive voltages. The register value is limited to 8192±6000, referring to a voltage range from -48V to +48V. In the GUI, the offset is not shown.

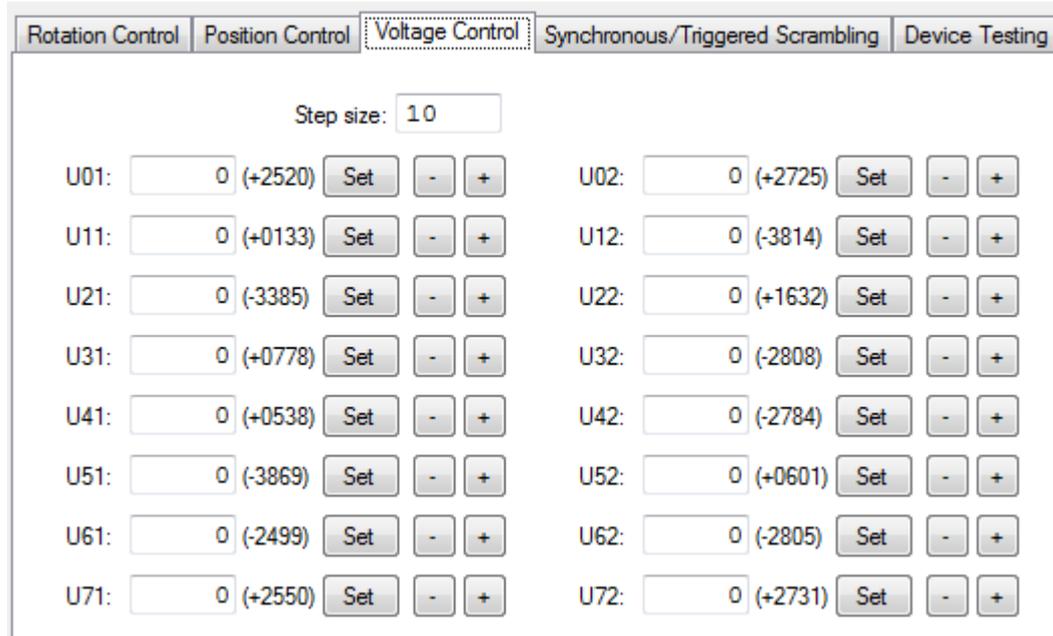


Fig. 10: Allocation of registers corresponding to 16 electrode voltages.

The given value is written into the digital-to-analog converter (DAC) directly after it appears in the register. When using SPI, the delay between the last SPI command bit and the internal DAC complete output flag is <100 ns. Initial electrooptic response is typically obtained in <100 ns more.