

Software Package “RP Q-switch” for Calculations on Q-switching

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1 Introduction

The software package **RP Q-switch** has been developed by RP Photonics Consulting GmbH, <http://www.rp-photonics.com/>. It can be used for calculations on actively or passively Q-switched lasers, and of spiking phenomena in continuous-wave lasers. Based on given parameters of the laser cavity and the gain medium, it numerically simulates the evolution of the laser power and calculates the parameters of generated pulses. Input and output of parameters is done via a convenient form, so that it is very easy for new users to get started. In addition, one can generate graphical output (e.g. gain and losses vs. time), and write tabulated data to a file. Both graphics and tabulated output are very flexible concerning what is plotted or listed.

RP Q-switch has been developed for designers of actively or passively Q-switched lasers, and can also be used for educational purposes in a development team. Typical questions to be addressed with **RP Q-switch** are:

- Is the experimentally observed performance of my Q-switched laser (including pulse energy and duration, double pulsing, etc.) in agreement with theoretical expectations?
- If not, which deviations of parameters could explain that?
- What are the prospects for better performance resulting from considered design changes?
- Is my Q switch fast enough, and is its hold-off sufficient? If not, how much better would it have to be to solve my problems?
- Is it possible to find a laser design which gives me three times shorter pulses? What limits the achievable pulse duration?
- Can I get improved frequency doubling conversion efficiency by inserting a frequency doubler in the laser cavity? To which extent will this make the pulses longer? Which value of low-intensity conversion efficiency (in %/W) will be ideal?

The software allows answering such questions in a faster and more reliable way than with experiments. It thus can help to optimize the laser performance and speed up the process of understanding and solving problems while potential saving a lot of expenses.

RP Q-switch is also quite versatile. For example, it can handle

- modulators with finite switching time
- slow or fast saturable absorbers
- four-level or quasi-three-level gain media
- various formats for modulation of the pump power
- intracavity frequency doubling

This software is designed for use on a personal computer (PC) with the operating system Windows 2000, Windows NT or Windows XP. The requirements in terms of performance and memory are moderate and should be easily fulfilled by an up-to-date PC. However, it is recommended that the screen resolution of the monitor is not smaller than 1064 x 768 points.

It is well possible that the software can be used e.g. on a Linux system with Windows emulation software. However, this has not been tested by RP Photonics.

The terms and conditions for use of this software are not subject of this software description, but of a separate license agreement. Note that the license fee includes up to eight hours of additional support, which can be used to clarify any issues which might remain after studying this documentation.

2 Installation

This simulation package is based on the program **RP CAS** of RP Photonics. This means that **RP CAS** has to be installed before **RP Q-switch** can be used. Therefore, the installation procedure consists of two simple parts, which are described in the following.

2.1 Installation of the Program RP CAS

The installation package contains the file **RP_CAS_setup.exe**. Copy this file to the PC and execute it. The installer program will lead you through the simple procedure. You may just confirm the suggested settings, or modify e.g. the folder in which the program will be installed. The installer also associates the file extension **.def** with the **RP CAS** program. This means that **RP CAS** will be started e.g. when you double-click a **.def** file in the Windows Explorer.

2.2 Installation of the Package RP Q-switch

If you obtained the software by e-mail, extract the content of the zip file **RP_Q-switch.zip** from the installation package to a folder on your PC. The name of this folder may e.g. be **My documents\Lasers\Q-switching simulations**.

If you are installing the software from a CD, these files are not packed into a zip file, but stored separately in the folder **RP Q-switch**. Simply copy these files to a folder on your PC, as mentioned above.

The two **.def** files are examples for parameter sets to be used with the model:

- **Actively qs laser.def**: model for an actively Q-switched Nd:YAG laser
- **Passively qs laser.def**: model for a passively Q-switched Nd:YAG laser

By double-clicking on such a file in the Windows Explorer, you start **RP CAS** to open the program's main form with the given parameter set. For making your own model, it is recommended to use a copy of one of the **.def** files and choose the filename to describe the specific situation.

If different users work with the software on the same PC, they need to install **RP CAS** only once, but may copy the **RP Q-switch** package to different folders in order to keep their files separated. This may also be useful if one user is working on different projects. If different folders are used, the graphics settings (e.g. axis ranges) and alike are also kept separate.

2.3 Removing the Software

For removing the program **RP CAS**, you can use the usual Windows deinstallation procedure. For example, with an English version of Windows XP, you can go to the Start menu, select "Set Program Access and Defaults", then "Change or Remove Programs", click on **RP CAS** in the list, and click on "Remove".

Removing the **RP Q-switch** package does not require a deinstallation procedure – simply delete the corresponding folder.

3 Principle of the Model

3.1 Cavity Setup

Within this model, the cavity of the considered laser can contain various components which modify the circulating laser power in different ways: an output coupler (O), a laser gain medium (G), a saturable absorber for passive Q switching (A), a modulator for active Q switching (Q), and components with parasitic linear losses (P). Fig. 1 shows this schematically. The program allows to define an arbitrary order of the components. For example, the order “OQGPGQ” is visualized in the following figure:

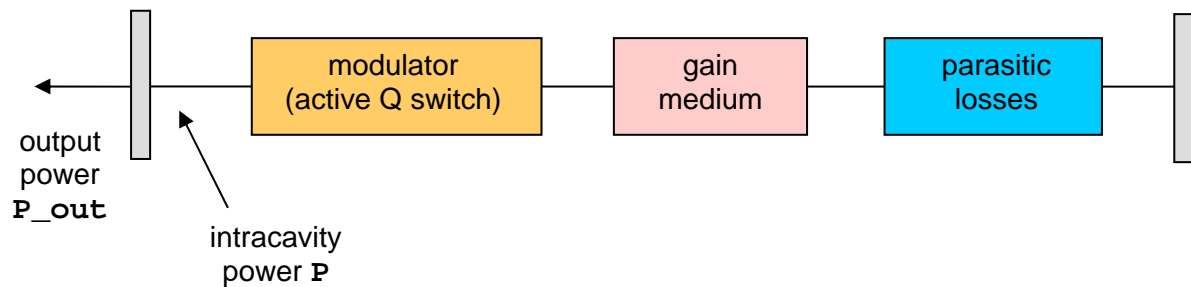


Fig. 1: Schematic setup of the laser cavity as assumed in the RP Q-switch model. The order of components has been assumed to be “OQGPGQ”. The mirror on the right side is a high reflector without any influence on the power.

The basic rules are:

- The first component always has to be the output coupler mirror (O). The intracavity power P is taken to be the power *before* the light hits the output coupler. The output power is then $P_{out} = T_{out} * P$. The output coupler (O) should normally appear only once in the list, except if it is a folding mirror in a standing-wave cavity.
- The other components (Q, G, P) are applied in the order in which they are specified. In the given case “OQGPGQ”, we have the output coupler, Q switch (in this case a modulator), gain medium, parasitic loss, gain medium, Q switch. Note that we do not list “O” again at the end, because the next reflection at the output coupler is considered to belong to the next cavity round trip. Also note that the parasitic losses are applied only once per round trip in our example; this means that the losses per round trip (rather than per single pass) must be specified.

The order of the optical components is not important as long as each effect is relatively weak, i.e., for lasers where gain and losses per round trip are small. One may then somewhat speed up the calculation e.g. by using the gain medium (G) only once but doubling the number of passes through it in the parameters of the gain (see section 3.4.1). For situations with high gain and high losses, however, the order of components does matter.

Effects which are neglected in the underlying model are:

- Accumulation of population in levels other than the upper laser level and the ground state.

- Upconversion losses, energy exchange processes, and alike, are not considered. However, a general reduction of pumping efficiency can be assumed.
- The upper-state lifetime should be large compared to the cavity round-trip time. (This condition is well fulfilled for nearly all solid state lasers, particularly for those used for Q switching.)
- In quasi-three-level lasers, the gain medium changes its shape when the excitation level changes. Therefore, the optical spectrum (including the average wavelength) might change during pulse build-up. This effect can not be included in the model.
- The optical bandwidth and mode structure is not considered. Thus, e.g. mode beating and spatial hole burning effects are not reproduced by the model.
- For saturable absorbers, some simple model is used, which does e.g. not include excited-state absorption.

3.2 Dynamical Variables

The dynamical variables of the model are the following:

- \mathbf{P} = intracavity power
- $\mathbf{I_g}$ = fractional excitation of the gain medium. The range is 0..1; for example, 1 would mean that all laser-active ions are in the upper laser level.
- $\mathbf{I_a}$ = fractional excitation of the saturable absorber (range: 0..1), assuming that it is a slow absorber. (For fast absorbers, this quantity is not relevant.) For example, the absorption is fully saturated if $\mathbf{I_a} = 1$.

The corresponding initial values, which are specified by the user, are $\mathbf{P0}$, $\mathbf{I_g0}$ and $\mathbf{I_a0}$.

3.3 General Structure

The software calculates the evolution of the above listed dynamical variables, starting with given initial values which are assumed to hold for the starting time $t = 0$. The temporal evolution is always done by applying the effects of all intracavity optical components in the given sequence for each cavity round trip. After such a round trip, one obtains a new set of values \mathbf{P} , $\mathbf{I_g}$ and $\mathbf{I_a}$. The software can either store these values after each round trip, or only every n round trips (see the variable \mathbf{dt} in section 3.4.2). The number of simulated round trips is automatically determined by the number of pulses to be calculated (see the variable $\mathbf{pulse_no}$ in section 3.4.2) or by the maximum time argument of functions like $\mathbf{P(t)}$ or $\mathbf{I_g(t)}$ (see section 3.5).

3.4 Description of Parameters

The temporal evolution of the dynamical variables depends on a number of parameters, which are all explained in the following.

3.4.1 Parameters of the Gain Medium

The parameters of the laser gain medium are not shown in the main form, but in an additional form which can be opened from the main form by pressing the function key F2:

The screenshot shows a software window titled "CAS RP Q-switch.cas Actively qs laser.def" with a menu bar (File, Edit, Calc, Options, Help) and a toolbar. The main area is titled "Parameters of the Gain Medium" and contains the following fields:

Wavelength of operation:	$l_s =$	<input type="text" value="1064 nm"/>	
Pump wavelength:	$l_p =$	<input type="text" value="808 nm"/>	
Length:	$L_g =$	<input type="text" value="5 mm"/>	
Dopant concentration:	$N_d =$	<input type="text" value="80e24 /m^3"/>	
Mode area:	$A_g =$	<input type="text" value="80e-9 m^2"/>	<input type="text" value="w g = 160 μm"/>
Cross-sections:	$\sigma_{s_em} =$	<input type="text" value="28 pm^2"/>	$\sigma_{s_abs} =$ <input type="text" value="0 pm^2"/>
	$\sigma_{p_abs} =$	<input type="text" value="5 pm^2"/>	$\sigma_{p_em} =$ <input type="text" value="0 pm^2"/>
Overlap factors:	$\xi_p =$	<input type="text" value="100%"/>	$\xi_s =$ <input type="text" value="100%"/>
Number of passes:	$N_p =$	<input type="text" value="1"/> (pump)	
	$N_s =$	<input type="text" value="1"/> (signal)	
Fluorescence lifetime:	$\tau_g =$	<input type="text" value="230 μs"/>	
Power efficiency:	$\eta_g =$	<input type="text" value="100%"/>	
	{ added stored energy / absorbed pump energy }		
Minimum power:	$P_{min} =$	<input type="text" value="1 nW"/>	
Fully inverted gain:	$G_{max} =$	<input type="text" value="73.1e3 = 48.6 dB"/>	
Pump saturation power:	$P_{sat_p} =$	<input type="text" value="17.1 W"/>	
Ground-state pump absorption:		<input type="text" value="86.5% = 8.69 dB"/>	
Saturation energy:	$E_{sat_g} =$	<input type="text" value="533 μJ"/>	
Saturation power:	$P_{sat_g} =$	<input type="text" value="2.32 W"/>	

At the bottom, a status line reads: l_s : emission wavelength of the laser

The white fields are input fields, while the gray fields display calculated outputs. The meaning of the input fields is explained with the text in front or behind, and in addition (for most fields) in some detail in the status line (at the bottom of the form) for the active field (i.e., for the one in which the cursor is).

Some additional comments:

- The underlying model describes saturation of the laser gain as well as pump saturation. For example, the reduction of pump absorption as a consequence of ground state depletion is fully included.
- All cross sections are specified in units of $\text{pm}^2 = (10^{-12} \text{ m})^2 = 10^{-24} \text{ m}^2$.
- The overlap factors ξ_s and ξ_p indicate how strong the interaction is compared to a situation where the optical field has a top-hat profile (i.e., a constant intensity within the given beam radius, and no intensity outside). For Gaussian beams in a bulk laser, which stay fully within the doped region, the overlap factors are 1. For fibers, they are smaller than 1 according to the fraction of the field intensity propagating outside the doped fiber core (assuming an undoped fiber cladding). This has the same effect as a reduction of the corresponding cross sections.

- The factors **N_p** and **N_s** can describe multiple passes of the pump or laser radiation through the gain medium. For example, **N_s = 2** means that the laser radiation passes the gain medium twice for each “G” in the list of optical components. This has the effect of doubling the laser gain and reducing the effective saturation energy and saturation power by a factor of two.
- The model is suitable for four-level lasers (with **sigma_s_abs = 0** and **sigma_p_em = 0**) as well as for quasi-three-level lasers. In the latter case, **sigma_s_abs** describes absorption at the signal (laser) wavelength, and **sigma_p_em** stimulated emission at the pump wavelength.
- Parasitic losses of the gain medium (not to be confused with parasitic losses in the cavity) can be taken into account with the factor **eta_g**, specifying which fraction of the absorbed pump photons which contribute to the population of the upper laser level. Alternatively, simple quenching can be modeled by using a reduced fluorescence lifetime. A possible extension (which could be implemented by RP Photonics) would be to make the fluorescence lifetime (the decay rate) dependent on the excitation level to simulate increased upconversion losses for high excitation.
- Numerically, the intracavity power is not allowed to get below the value **P_min** (directly after the gain medium). This simulates the spontaneous emission into the laser mode, from which the pulse formation starts when then gain exceeds the losses. (Mathematically, the amplification of zero initial power would always leave the power at zero.) The appropriate value of **P_min** could be estimated from the parameters of the gain medium, but is in most cases very uncritical, so that a very rough estimate is normally sufficient for practical purposes.

The following quantities are some outputs, which can be used e.g. for diagnostic purposes:

- **G_max** is the power amplification factor of the gain medium for full excitation. Note, however, that full excitation can be reached only for pump powers far above the pump saturation power (see below) and if the emission cross section at the pump wavelength is zero.
- **P_sat_p** is the pump saturation power, i.e., the pump power for which the pump absorption is reduced to one half its unbleached value, assuming that no lasing takes place.
- Ground-state pump absorption: this shows the level of pump absorption assuming that all laser-active ions are in the ground state.
- **E_sat_g** is the pump saturation energy, i.e., the energy of an incident short pump pulse which would reduce the pump absorption to 1/e of its initial value.
- **P_sat_g** is the saturation power of the gain medium at the laser wavelength, i.e., the intracavity laser power for which the laser gain is reduced to one half its small-signal value (assuming a constant pump rate, i.e., a pump power well below the pump saturation power). For a four-level laser gain medium, an intracavity laser power equal to **P_sat_g** is reached when the pump power is twice the threshold pump power.

3.4.2 Other Parameters

All other parameters of the laser can be edited in the main form:

RP Q-switch: Numerical Simulation of Q-switching Dynamics
 RP Photonics Consulting GmbH, www.rp-photonics.com

Operation Conditions

Pump power: $P_p = 1 \text{ W}$
 Modulation: **none** (dropdown) Amplitude: 0 W Frequency: 10 kHz
 Duty cyc.: 20% Phase: 0°

Initial conditions: $P_0 = 0 \text{ W}$ (intracavity power)
 Excitation of gain: $I_{g0} = 0\%$ 0 J Mode: **manual** (dropdown)
 Excitation of abs.: $I_{a0} = 0\%$ 0 J

Laser Parameters

Output coupler: $T_{out} = 10\%$ Parasitic loss = 0% = 0.0 dB
 Cavity frequency: $f_{cav} = 500 \text{ MHz}$ Round-trip time: 2 ns
 Component order: **00GPGQ** (e.g. 00GPGQ)

Active Q Switch

Repetition rate: $f_{rep} = 20 \text{ kHz}$ (0 = Q switch is always in low-loss state)
 Timing phase: $ph_{qs} = 0^\circ$ Opening time: $ot_{qs} = 10 \mu\text{s}$
 Switching time: $\tau_{qs} = 500 \text{ ns}$ (10% to 90%)
 Loss: $l_{qs_hi} = 60\%$ = 4.0 dB $l_{qs_lo} = 1\%$ = 0.0 dB

Amplifier Stages

Number of amplifier stages: $N_{amps} = 0$ (edit parameters with F3..F5)

Numerical Parameters

Temporal step size: $dt = 10 \text{ ns}$ Max. no steps: 400000
 Maximum temporal range: 4 ms Calculated so far: $302 \mu\text{s}$

Pulse Parameters

Number of output pulse to be analyzed: **laser output** (dropdown) $pulse_no = 5$ (0 = none)
 Peak power: 125 W Pulse energy: $21.2 \mu\text{J}$
 Pulse duration: 150 ns Pulse position: $302 \mu\text{s}$

F1 = documentation, Shift-F1 = help on field, F2 = edit parameters of gain medium

Most of the parameters are sufficiently well explained by the content of the form and the context-sensitive texts in the status line at the bottom. Some additional comments:

- Various modulation formats can be chosen for the pump power:
 - none: the pump power stays constant at the level specified above (P_p), independent of the other parameters
 - sinusoidal: sinusoidal modulation
 - rectangular: the pump power is $P_p \pm A_p$; the duty cycle dc_p specifies the percentage of time within a cycle in which the power has the higher value. For $ph_p = 0$, a period with the higher power begins at $t = 0$.
 - triangular: the varies linearly between $P_p - A_p$ and $P_p + A_p$ (with constant speed)

- saw_tooth: the power ramps up linearly from $P_p - A_p$ to $P_p + A_p$ and then instantly back to $P_p - A_p$.

Note that the phase **dc_p** is relevant only for rectangular modulation. For checking the pump modulation, one can display the values **P_p(t)** in a graph.

- The fields to the right of those for **I_g0** and **I_a0** show the corresponding stored energies. The field “Mode” has three possible values:
 - “manual”: set the initial value of **I_g0** manually by entering its value into the corresponding input field. You may e.g. set this to zero if at $t = 0$ there is no energy stored in the gain medium.
 - “ss blocked cavity”: if this is chosen, the software automatically sets the initial value of **I_g0** to the value which is reached in the steady state when the cavity is blocked, i.e., no lasing can occur. The first calculated pulse then has the parameters which can be achieved by pumping the gain medium for a long time before starting the Q switch. (Later pulses may have lower energies, if the energy in the gain medium can not fully recover in the time between two pulses.) The calculated value of **I_g0** is then displayed in the corresponding input field, and it depends on the pump power and on various parameters of the gain medium (cross sections, doping density, length and mode area, upper-state lifetime, etc.). It basically arises from a (numerically calculated) balance between energy added to the gain medium by the pump source and energy lost via spontaneous emission.
 - “ss lasing”: with this setting, the initial value of **I_g0** is automatically set to the value which is reached in the steady state when the Q switch is always open (i.e., in the low-loss state). This option is allowed only when no saturable absorber is in the cavity.
- The output field **I_g0_b** shows the steady-state value of the fractional excitation of the gain medium when the cavity is blocked so that lasing is prevented. One may use this value for **I_g0** to simulate a case where the pump power has been switched on long before starting the Q-switching cycle.
- The field “Component order” determines which optical elements occur in the laser cavity, and in which order (see section 3.1). For example, enter “OGQPQG”, if the light field sees the output coupler, gain medium, Q switch, parasitic losses, Q switch, and gain medium, in this order. In case of some inconsistencies, corresponding error messages are displayed in the field to right of the component order field.
- The panel “Active Q switch” is only displayed if the field “Component order” (see above) contains a “Q” (for “Q switch”).

The active Q switch has several parameters:

- The repetition rate **f_rep** is the number of Q-switching cycles per second. The Q switch can be deactivated by setting the repetition rate to 0; it will then always be in the low-loss state.
- The timing phase **ph_qs** determines in which state the Q switch is at $t = 0$, the start of the simulation: if this phase is zero, a time interval with low loss (see below) just starts at $t = 0$. Positive values of **ph_qs** indicate a time delay.

- The opening time **ot_qs** is the width of the time interval in which the Q switch is in the low-loss state. (If this time is longer than the repetition period, the Q switch is assumed to be in the low-loss state at all times.)
- The switching time is **tau_qs**; it is the time required for getting from 10% to 90% of the loss change. (At the nominal switching time, half of the loss change is assumed to have happened.) A value of zero means instantaneous switching.
- Finally, one can specify the losses in the low- and the high-loss state. A perfect Q switch would have **l_qs_lo** = 0% and **l_qs_hi** = 100%. Realistic values are e.g. **l_qs_lo** = 1% and **l_qs_hi** = 60%.
- The panel “Passive Q switch” is only displayed if the field “Component order” (see above) contains an “A” (for “absorber”). Therefore, it is missing in the screen shot shown above.

The saturable absorber can be a fast or slow one. A fast absorber is one which instantly adjusts its attenuation properties to the current intracavity power, without any delays. In contrast to that, a slow absorber is one which requires some time (more than a cavity round-trip time) to reach its equilibrium. In any case, **loss_a** (formula symbol l_a) is the power loss caused by the absorber in its unsaturated state. For high optical powers, the losses approaches zero. (Any nonsaturable losses have to be treated separately as parasitic losses in the cavity settings.)

- For a fast absorber, one specifies the saturation power **P_sat_a** and sets **E_sat_a** to zero. The power is then attenuated according to $P \rightarrow P \cdot \left(1 - \frac{l_a}{1 + P/P_{\text{sat,a}}}\right)$. This means that the losses are reduced to one half the unbleached losses when the intracavity power equals the saturation power.

The equation is actually in agreement with a simple absorber model only for l_a well below 1. If this is undesirable, one may use several “A” in the list of intracavity components with correspondingly smaller l_a .

- Conversely, for a slow absorber one has to specify the saturation energy **E_sat_a** and the recovery time **tau_a** while setting **P_sat_a** to zero. The saturation energy can be calculated from the photon energy, the absorption cross section, and the mode area in the absorber: $E_{\text{sat,a}} = \frac{h\nu}{\sigma_{\text{abs}}} A_a$, or one half this value if there is a double pass through the absorber without two “A” occurring in the list of optical components. For Cr⁴⁺:YAG, a frequently used saturable absorber material, one can use $\sigma_{\text{abs}} \approx 5 \cdot 10^{-18} \text{ cm}^2$ and $\tau_a = 3.5 \mu\text{s}$.

The optical power is attenuated according to $P \rightarrow P \cdot \exp(-q)$, and the absorption evolves according to $\frac{dq}{dt} = -\frac{q - q_0}{\tau_a} - \frac{(1 - \exp(-q))P}{E_{\text{sat,a}}}$ with $q_0 = -\ln(1 - l_a)$. The numerical treatment actually has the variable I_a , which determines q as

$q = q_0(1 - I_a)$: for $I_a = 1$, the absorption is fully bleached. Without light field, I_a decays with the time constant τ_a (**tau_a**).

All these equations are correct for small or large I_a .

- The panel “Frequency Doubler” is only displayed if the field “Component order” (see above) contains an “F”. Therefore, it is missing in the screen shot shown above.

The input field “**gamma_fd**” allows to enter the conversion efficiency of the device per Watt of intracavity power in the low-conversion regime. The program uses a simple model to describe the saturation of the conversion efficiency at high powers: the conversion efficiency for an intracavity power **P** is

$$\mathbf{eta_fd} = \tanh(\sqrt{\mathbf{gamma_fd} * \mathbf{P}})^2$$

so that the conversion efficiency approaches 100% for high powers, without ever exceeding this value. (sqrt() means the square root.) For small intensities, the efficiency is approximately **gamma_fd*****P**.

The frequency-doubled power can be retrieved with the functions **P2(t)** and **P2_ip(t)** (see section 3.5).

Note that the simple model used may fail in special situations where the phase-matching band-width of the frequency doubler is very small, so that the laser may “escape” the nonlinear losses to some extent by oscillating on a slightly different wavelength.

- In the main form, one can determine the number of external amplifier stages. The parameters of these must be specified in separate forms, available with the function keys F3 (for the first amplifier) to F5 (for the third one).
- The numerical step size **dt** can be equal to the cavity round-trip time (i.e., the inverse of the cavity frequency **f_cav**), or an integer multiple of that. In the latter case, the available memory allows to investigate a larger time range. This is appropriate for cases where the pulse duration is much longer than the cavity round-trip time. In other cases, the propagation of power and stored energies remains correct, but the stored data may miss out short pulses, so that the graphically displayed pulse profile as well as the displayed pulse parameters may not be accurate. As a rule of thumb, make sure that **dt** stays well below the expected pulse duration.
- The field to the right of that for **dt** contains the maximum number of steps **N_max**. This value times **dt** is the maximum temporal range over which the simulation can be done. This value (displayed to the right of **N_max**) should not be higher than necessary in order to limit the computation time, particularly in cases where no pulses are formed and the simulation runs through the full range in the search for pulses. The maximum allowed value for **N_max** is one million.

In extreme cases with a very high number of cavity round trips per Q-switching cycle, the software may not be able to simulate the full temporal range of a Q-switching cycle because of the storage limitations. One can then still simulate the pulse formation by setting the initial values so that a pulse occurs not too long after $t = 0$.

The displayed outputs are as follows:

- The following quantities apply to one pulse which can be the intracavity pulse, the laser output pulse, the frequency-doubled pulse (if an intracavity frequency doubler is used), or the pulse after the external amplifier(s). Also, one can select the number of the pulse with the variable **pulse_no**, counting from the start of the simulation; for example, **pulse_no** = 2 delivers the second pulse. The program will automatically do as many temporal steps (see above) as required to find this pulse, unless this would take more than the maximum number **N_max** of steps (see above). When a laser runs continuously (e.g. with no Q switch) or below threshold, the program may run into this limit in the search for a pulse. As this may take some time, one may temporarily switch off this search for a pulse by setting **pulse_no** to 0.
- The displayed pulse properties are the peak power (**P_pk**), the pulse energy (**E_p**), the full width half maximum pulse duration (**tau_p**), and the temporal pulse position (**t_p**). (The corresponding variable names are indicated because these are required to plot such quantities, see section 4.3). These values will be set to 0 if **pulse_no** is 0.

Note that due to the discrete nature of steps, short pulses (with durations of only a few steps) can have an inaccuracy of a few percent in the displayed duration.

- Near the bottom of the form, there is a field with a line for warnings, which are displayed if certain inputs appear to be inconsistent or outside the usual ranges. For example, a warning will appear if a nonzero modulation depth of a saturable absorber are specified, but the list of optical components contains no “A”. This field is hidden if no warnings are there. For space reasons, only one warning can be displayed.

Note that further calculated quantities can be investigated using graphics (section 4.3) or tabulated data (see section 4.4).

3.5 Description of Functions

For graphical output (sections 4.3) or tabulated output (section 4.4), one may also use the following functions defined in **RP Q-switch**:

- **P(t)** is the intracavity power vs. time, and **P_out(t) = T_out * P(t)** the laser output power.
- **P_p(t)** is the pump power vs. time.
- **P2(t)** is the frequency-doubled power. (If “F” occurs several times in the component order, the value corresponding to its last occurrence is taken.)
- **I_g(t)** and **I_a(t)** are the fractional excitation levels of the gain medium and the (slow) saturable absorber, respectively. (For a fast absorber, or no absorber at all, **I_a(t)** is not relevant.)
- **g(I)** is the gain coefficient, and **G(I) = exp(g(I))** is the power amplification factor for a given value of the excitation level **I_g** of the gain medium. One may e.g. plot **g(I_g(t))** or **G(I_g_ip(t))** vs. **t**. Note that these gain values correspond to one of the “G” in the component order (see section 3.1); for example, the round-trip gain coefficient is **2 * g(I_g(t))** if there are two “G”.

- $P_{ip}(t)$ is the linearly interpolated version of $P(t)$, showing a smooth temporal variation rather than steps with a temporal resolution of dt . In an analogous fashion, $P2_{ip}(t)$, $I_{g_{ip}}(t)$ and $I_{a_{ip}}(t)$ are defined.
- $P_{max}(t, T)$, $P_{out_{max}}(t, T)$ and $P2_{max}(t, T)$ are the maximum intracavity, output and second-harmonic power, respectively, within a temporal range of width T around the time t . These functions can be convenient for plotting: one can set T to a value in the order of the temporal resolution of the plot in order to avoid “missing” of some pulse maxima.
- The power after the external amplifiers can be retrieved with the function $P_{amp}(t)$. The functions $I_{amp1}(t)$ to $I_{amp3}(t)$ deliver the time-dependent inversion levels of the amplifier stages. Interpolated versions are $P_{amp_{ip}}(t)$, $I_{amp1_{ip}}(t)$, etc.
- $l_{qs}(t)$ is the time-dependent loss (0..1) of the Q switch.
- $l_{abs}(t)$ is the time-dependent loss (0..1) of the saturable absorber.

Apart from these functions, one may use a large number of standard functions, such as $\sin(x)$, $\cos(x)$, $\tan(x)$, $\cot(x)$, $\text{sqr}(x)$ (square), $\text{sqrt}(x)$ (square root), $\exp(x)$, $\ln(x)$, $\lg(x)$, etc.; RP Photonics can explain more functions if required for sophisticated plots.

The use of all these functions allows to generate graphical outputs in a very flexible way. Section 4.3 gives some examples.

4 Handling of the Software

4.1 Parameter Sets

As already indicated in section 2.2, the user can have an arbitrary number of parameter sets associated with the **RP Q-switch** software. Each parameter set contains all input values corresponding e.g. to a given configuration of a laser. Parameter sets are stored in files with the extension **.def**, which (apart from the input values) contain a reference to the worksheet with which they are used. In this case, the worksheet is always stored in the file **RP Q-switch.cas**, which contains the definition of the main form as well as the used equations.

One can create additional parameter files either in the Windows Explorer (by copying existing files to others with different names, but still the same filename extension), or in the **RP CAS** program with “File/Save as”.

4.2 Using the Input/Output Form

As previously mentioned, the white rectangular fields are input fields. One can change an input value by typing a new value and pressing the Return key. It is often convenient to increase or decrease input values by fixed steps using Ctrl-F9/F10 (course steps), Ctrl-F7/F8 (smaller steps), Ctrl-F5/F6 (still smaller), etc. In any case, the outputs will be recalculated as soon as an input is modified¹. The output fields are displayed in a darker gray while the calculation is ongoing.

With the function key F1, you can display this documentation file, provided that your computer has a program installed for displaying PDF files (e.g. the free Adobe Acrobat Reader). F2 shows the form for editing the parameters of the gain medium.

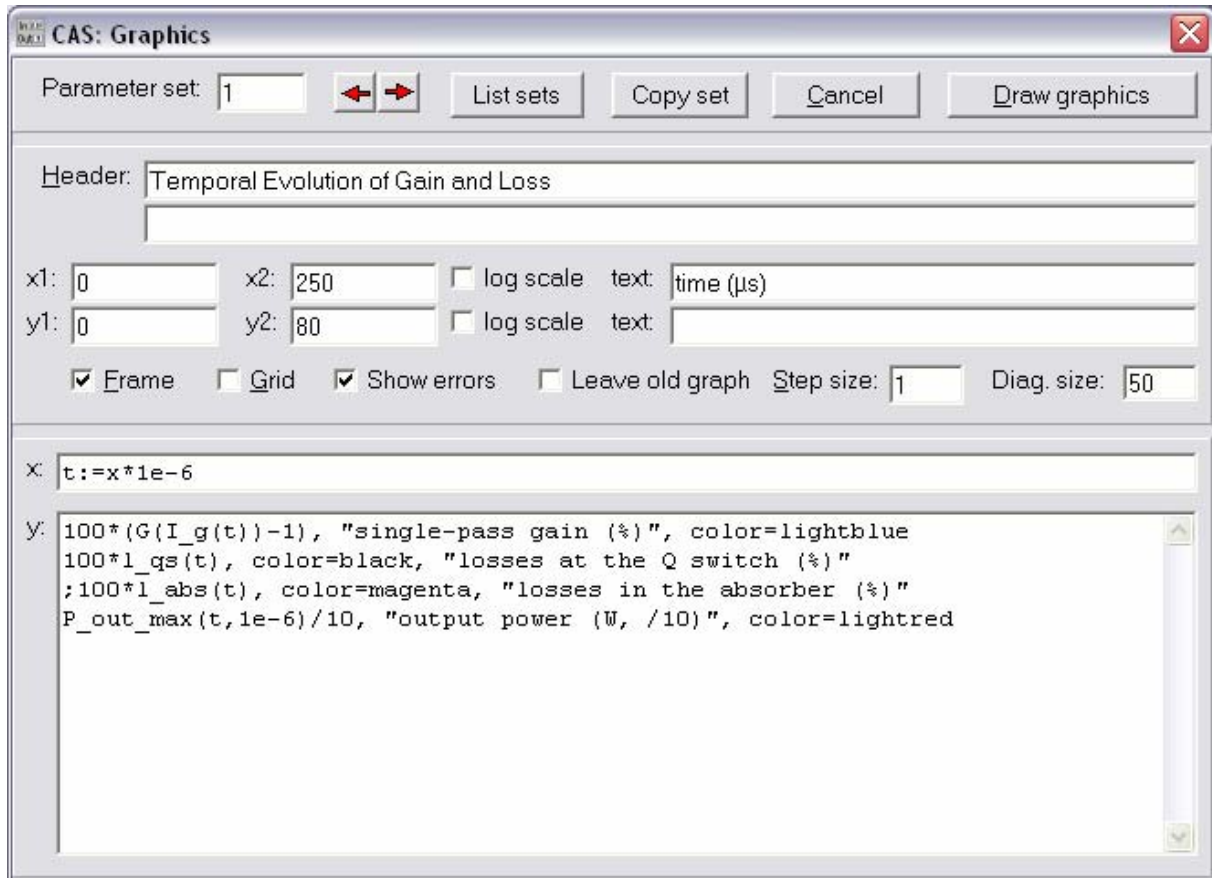
¹ The **RP CAS** program actually analyzes the dependencies so that only those values are recalculated which are affected by the change of an input value.

With the function key Shift-F1, you can display some text explaining the input or output field in which the cursor currently is located. For most of the fields, such texts are defined.

If some outputs can not be calculated for some reason, “???” will be displayed in the corresponding field. In such cases, check your input values, and consider that e.g. pulse parameters may be undefined if the laser runs continuously, or a pulse is not emitted within the maximum allowed temporal range.

4.3 Preparation of Graphical Output

With the menu "Calc/Graphics" (or by pressing the shortcut Ctrl-G in the main form) one can open another form for generating graphical output:



On the top panel, you can select one of 99 parameter sets; each one allows to generate a different kind of graph. **RP Q-switch** comes with 9 predefined graphs, which the user may complement with additional ones.

Each graphics parameter set (containing the settings of the form) is stored in a separate file, e.g. **RP Q-switch.c01** for parameter set number 1. These settings are common for all data parameter sets (see section 4.1).

On the panel in the middle of the form, you can determine the properties of the coordinate system. (Note that mathematical expressions can be used instead of simple numerical values for the axis ranges.)

Some other settings:

- “Frame”: draws a coordinate system as a frame instead of just two axes.

- “Grid”: draws grid lines.
- “Show errors”: any numerical errors which occur when a graph is prepared are displayed in a window.
- “Leave old graph”: draws new graphs on top of any old graphs (in an already existing graphics window), so that changes become apparent.
- “Step size” (in pixels): defines in which steps in the horizontal direction the program calculates function values for graphs. The value 1 gives the most precise graphs, but larger values lead to faster execution.

Note that it is allowed to enter mathematical expressions into the numerical fields. For example, you may use **1.1*P_pk** for the maximum y value in a plot of the output power vs. time of a pulse, so that the scaling of the graph automatically adapts to the calculated peak power.

Finally, the bottom panel, containing the fields **x:** and **y:**, determines what is plotted. There are three possibilities for plotting:

- Showing a graph of a given function or of a variable which is recalculated in the worksheet (typically one of the variables displayed in an output field). Here, in the field **y:** one specifies an expression which typically depends on the variable **x**, or on another variable as specified in the **x:** field above. For example, one may
 - plot **P(t)** (field **y:**) versus **t** (field **x:**)
 - plot **E_p*f_rep** (pulse energy times repetition rate = average power) versus **P_p** (pump power) or **f_rep** (repetition rate)
(Note that the program will automatically recalculate **E_p** as **P_p** is changed in the graph; at the end, the original values from the form are restored.)

After the expression, one can append several options (after commas), e.g. **color=lightred** (to change the graph color), **style=dotted** (can be **solid**, **dotted**, **dashed**, **fdashed**, or **dotdashed**), **width=3** (for increased thickness of the curves), or a text in double quotes (for a label). Several graphs can be defined in subsequent lines of the **y:** field.

- Showing a parametric graph:

Example: **@ t:=0 to 100e-9 step dt, g(t), P(t), color=magenta.**
Here, the parameter **t** runs through some given range, and the following two expressions determine the x and y coordinates of the points to be plotted (and connected with lines). The plotted functions may of course depend on output fields of the worksheet, assuming that these depend on the parameter **t**.

- Plotting numerical data (e.g. measured data) for comparison with simulated data:

Example: **file="measured.dat", row=3, marker="r", color=lightred**

Here, the given file should contain at least four columns of numbers, where the first is by default interpreted as **x**, and the following ones are **y1**, **y2**, **y3**, etc. As markers for the data points, rectangles are used (or e.g. triangles with **marker="t"**). The option **row=3** means that **y3** is plotted versus **x**. More flexibility is achieved with something like

```
file="test.dat",      show      (10*y1,y2/y3),      marker="r"  
where y2/y3 is plotted versus 10*y1 with rectangles.
```

The available colors are listed in the table below. They are actually predefined variables with values between 0 and 15; you may use these numbers instead of the color names.

0 = black	8 = darkgray
1 = blue	9 = lightblue
2 = green	10 = lightgreen
3 = cyan	11 = lightcyan
4 = red	12 = lightred
5 = magenta	13 = lightmagenta
6 = brown	14 = yellow
7 = lightgray	15 = white

Any expressions used for plotting can also refer to the variables **CS_x1**, **CS_x2**, **CS_y1**, and **CS_y2**, which specify the axis ranges of the coordinate system. This can be used e.g. to scale a curve to the full axis range.

If all settings are done, press the "Draw Graphics" button on the top panel to generate the graph.

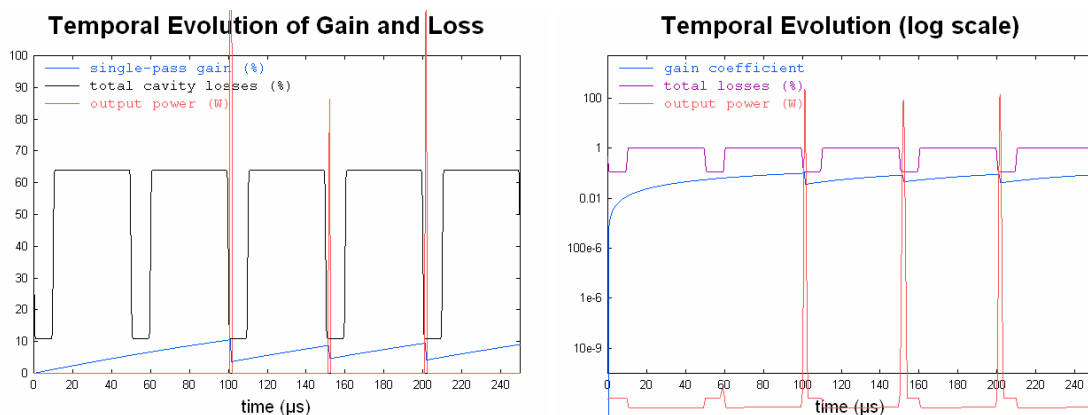
When you have changed some parameters in the main form, you can update all graphs in already existing graphics windows with "**Calc/Update all graphs**" (Ctrl-U).

Predefined Graphics

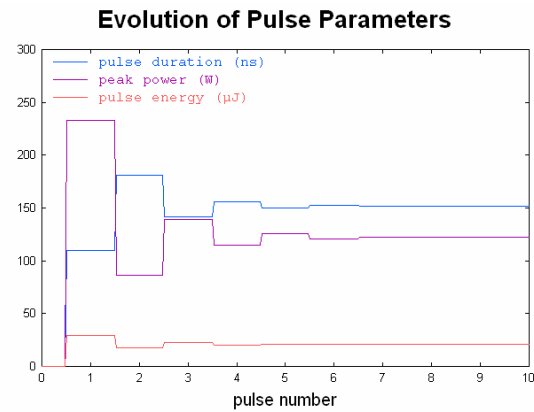
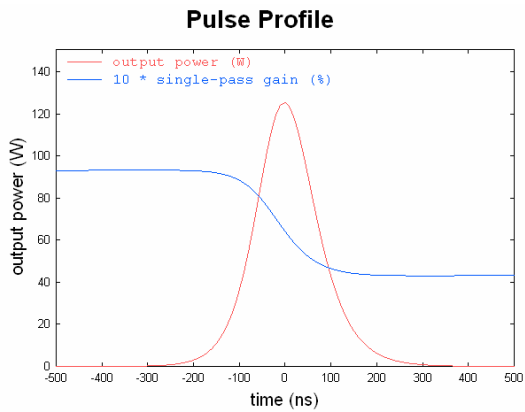
In the following, some graphics parameter sets are described which have been predefined in the **RP Q-switch** package. They all apply to an actively Q-switched Nd:YAG laser. Its settings are those displayed in the screen shots in the previous sections.

- Graph 1: temporal evolution of gain and losses.

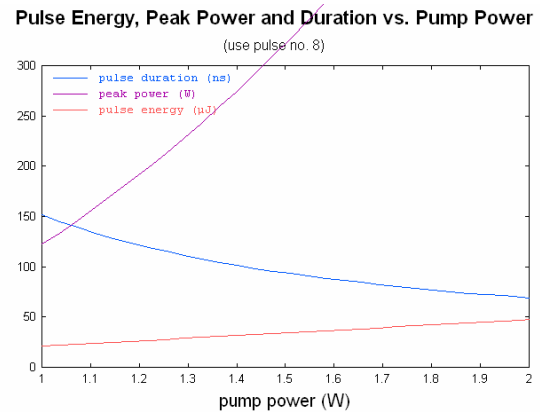
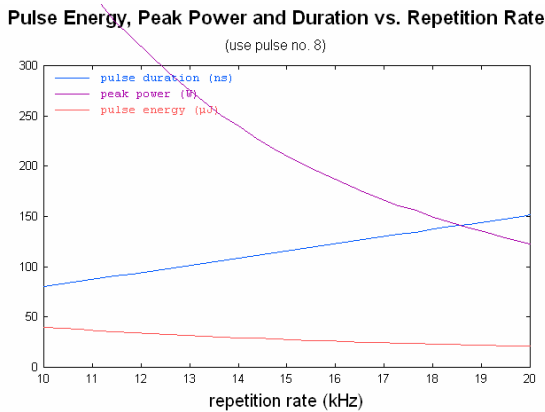
For a given parameter set, this graph shows how the gain and losses evolve over time.



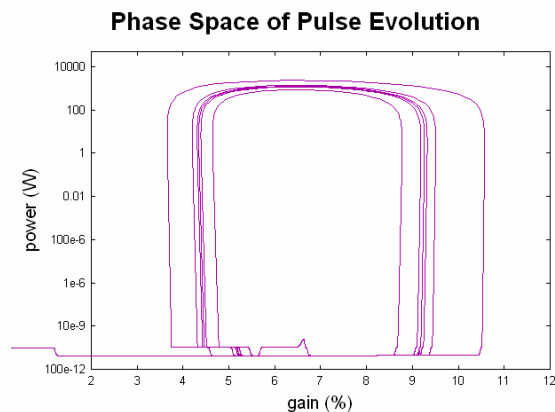
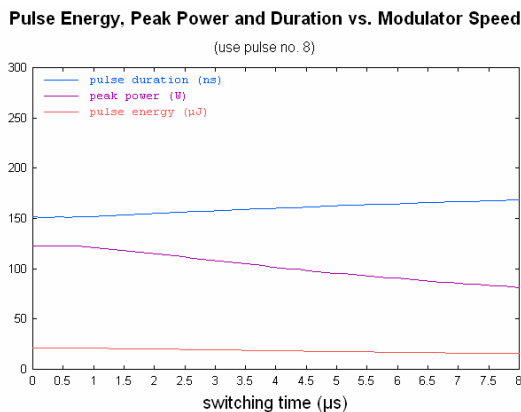
- Graph 2: temporal evolution, logarithmic scale. This shows more about the pulse build-up.
- Graph 3: profile of the pulse which was selected with the variable **pulse_no** in the main form (see section 3.4.2). This is basically a magnified portion of graph 1.



- Graph 4: evolution of pulse parameters (after switching on the pump power).
- Graph 5: pulse energy, peak power and duration vs. repetition rate of the Q switch. Such graphs can take somewhat more computation time (e.g. several minutes), because for every repetition rate the whole pulse evolution has to be recalculated.



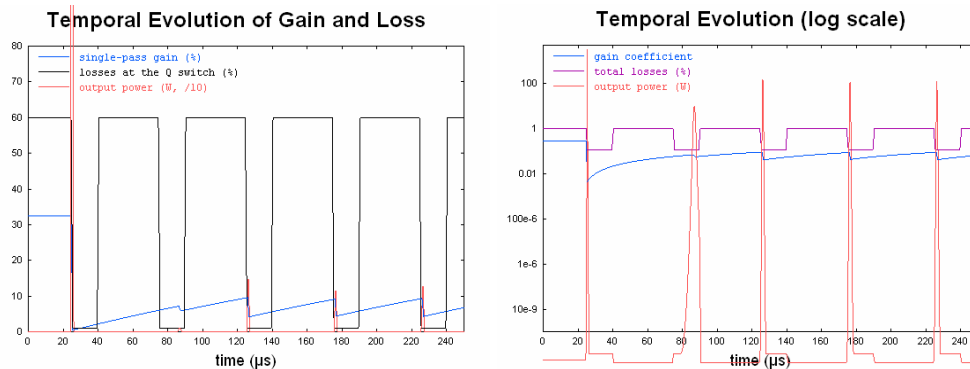
- Graph 6: pulse energy, peak power and pulse duration vs. pump power.
If such a graph shows unexpected results, such as e.g. a sudden drop of pulse energy, study this behavior by looking at graph 1 or 2 (for the corresponding pump power): it may e.g. occur as a result of multiple pulsing, if the low-loss time of the Q switch is too long.
- Graph 7: pulse energy, peak power and pulse duration vs. switching speed of the modulator.



- Graph 8: pulse evolution in phase space. This is a parametric plot, showing how laser gain and intracavity power evolve with time.

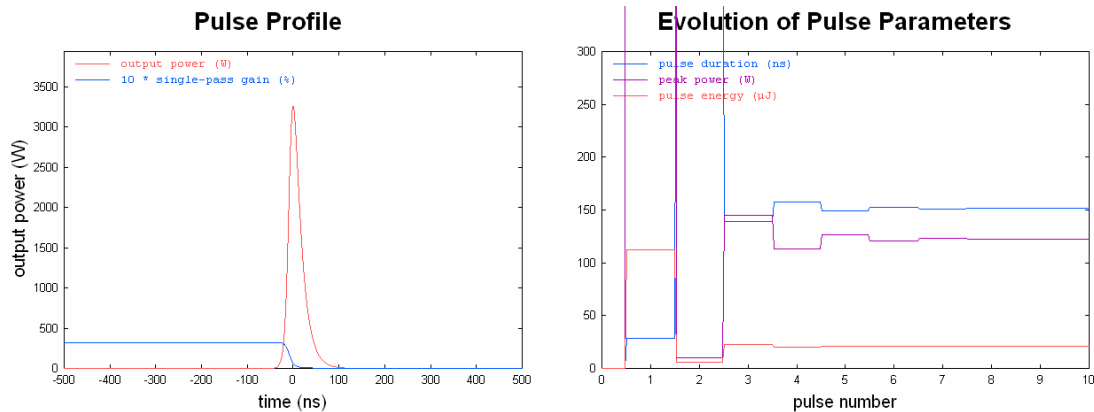
In the following, most of these graphs are shown for a modified case where the “Mode” field is set to “ss blocked cavity” (instead of “manual”, as above). Because the first pulse develops rather fast, the switching time of the modulator was reduced from 500 ns to 200 ns. Also, the phase of the Q switch (**ph_qs**) is set to 180° so that the first pulse is fired shortly after half a cycle period, rather than shortly after $t = 0$:

- Graphs 1 and 2: temporal evolution of gain and losses.



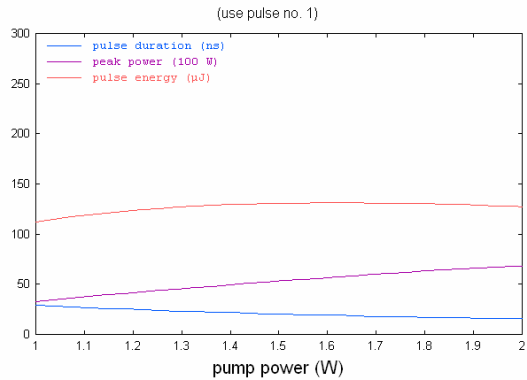
The first pulse is now stronger, and the second one weaker than those in the steady state of the Q-switched laser. This is because the first pulse extracts a lot of energy from the gain medium, which can not be fully replenished within the short time to the next pulse. Graph 2 also shows that the gain stays constant before the first pulse, as it should, because it has been calculated to be at the steady-state value.

- Graph 3: profile of the first pulse. (The powers have been divided by 100 in order to show both power and stored energy on reasonable scales.) The energy extraction is nearly complete in this case.



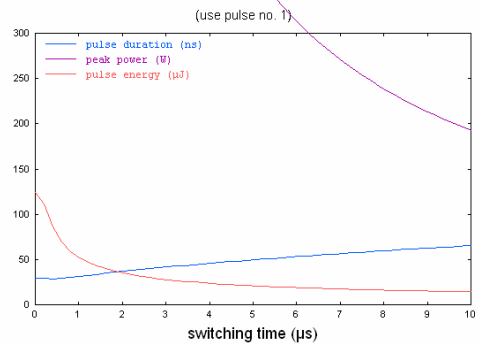
- Graph 4: evolution of pulse parameters. The scale is the same as above in order to show that the parameters converge to the same values as before, but the parameters of the first pulse are off the scale.
- Graph 6: pulse energy, peak power and pulse duration vs. pump power. For too high pump powers, the pulse energy decreases again, because for the given switching speed of the modulator the loss at the modulator increases for decreasing pulse build-up time.

Pulse Energy, Peak Power and Duration vs. Pump Power

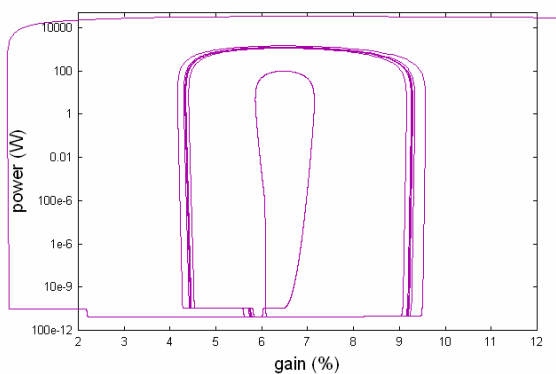


- Graph 7: pulse energy, peak power and pulse duration vs. switching speed of the modulator. Graph 8: pulse evolution in phase space, again with the same scale as before.

Pulse Energy, Peak Power and Duration vs. Modulator Speed



Phase Space of Pulse Evolution



The user can easily prepare additional graphs by defining new graphics parameter sets. The easiest way is to set the number of the new parameter set (see section 4.3) and then press the “Copy set” button to copy an already existing parameter set in order to modify this.

4.4 Creating Tabulated Output

With the menu "Calc/Make a table" (or by pressing the shortcut Ctrl-T in the main form) you can open another form which you can use to generate tabulated output:

As for graphical output, you can have up to 99 different parameter sets, each one creating a different type of table. Each parameter set is stored in a separate file, e.g. **RP Q-switch.t01**. As an example, there is one predefined parameter set for the **RP Q-switch** package, which lists various performance data (pulse energy, peak power, pulse duration) vs. pump power, providing an output file like

```
1.0, 13.3175, 50.7422, 232.107
1.2, 17.8102, 90.6245, 173.729
1.4, 22.431, 144.023, 137.695
1.6, 26.1731, 195.507, 118.357
1.8, 29.9091, 253.961, 103.934
2.0, 36.0735, 370.937, 85.8815
```

In the form for tabulated output, you have to fill out at least the following fields:

- The name of a variable ("Var 1") and a range for this variable (from ... to ... step).
- A list of expressions, defining one line of output for each value of the variable.

By default, the output will be shown in a window on the screen. You can also save the output to a text file by specifying its name.

A second variable (together with a range) can be specified; the value of this will run through the given range once for every value of the first variable.

One or two header lines can be written to the output before the calculated lines. The header lines can contain calculated text in brackets [], or otherwise will be stored exactly as entered.

If “Show errors” is checked, any numerical errors which occur when a table is prepared are displayed in a window.

5 Support

The license fee for **RP Q-switch** includes some amount of support via e-mail or telephone. Consult the license agreement for details. If you need such support, contact RP Photonics via e-mail to Paschotta@rp-photonics.com or telephone to +41 44 201 02 60.