RC20 RESISTIVE COUPLER

FOR NPG SERIES NANOSECOND

PULSE GENERATORS

USER MANUAL

V2.0 of February 07, 2023

Megaimpulse Ltd. contact information

Address:	28 Polytechnicheskaya str., St. Petersburg, 194021 Russia
www:	http://www.megaimpulse.com
e-mail:	mp@power.ioffe.rssi.ru
fax:	+7-812-297-3145

CONTENTS

RC20 resistive coupler allows the precise measurement of high voltage nanosecond pulses, including applied to (incident) and reflected from the load, calculation of their energies and total energy balance of the discharge, as well as estimation of the pulse voltage on the load and pulse current. Therefore, comprehensive information about the discharge can be obtained.

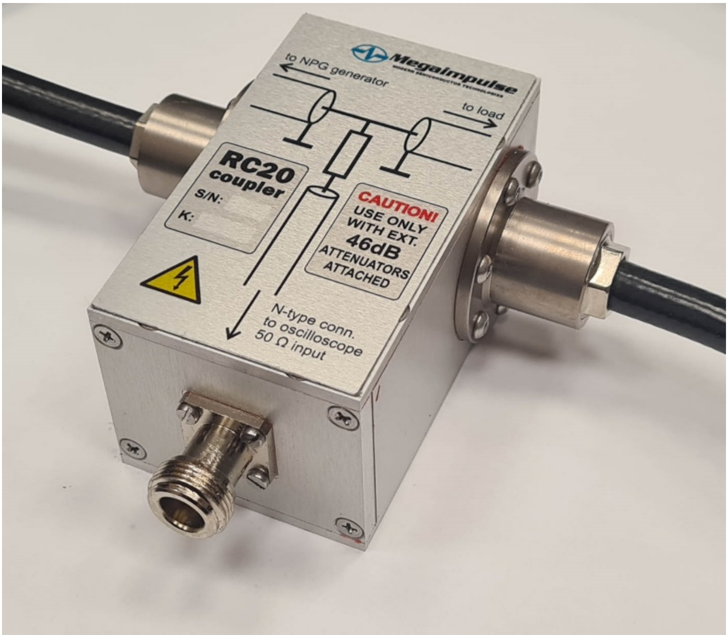


Fig. 1. RC20 resistive coupler with two attached HV coaxial cables of 5 meters in length each.

PACKAGE CONTENT

Please check the package for the following items:

- RC20 resistive coupler with two attached HV coaxial cables of 5 meters in length each;
- 6 dB attenuator with N-type connectors;
- 20 dB attenuator with N-type connectors;
- 3 meters in length semirigid coaxial cable assembly with N-type and SMA connectors;
- 20 dB attenuator with SMA connectors;
- SMA-to-BNC adapter.

SAFETY MANUAL

Electrical safety

- RC20 resistive coupler is designed for the precise measurement of nanosecond high-voltage pulses. Please be very careful while working with high-voltage equipment, and operate by qualified personnel only.
- Improper use may result in electric shock, strong electromagnetic interference, or damage to other electronic equipment.
- The signal from the coupler should be registered by an oscilloscope. Please ground the oscilloscope obligatory, and divide the signal from the coupler down to a safe level by 46 dB attenuators.
- It is strongly prohibited to connect or disconnect the coupler to or from the system while the HV pulse generator is turned on, as well as leave the N-type connector of the coupler open, i.e. without attached attenuators. Inevitable arcing across the open N-type connector may damage it.

Operation safety

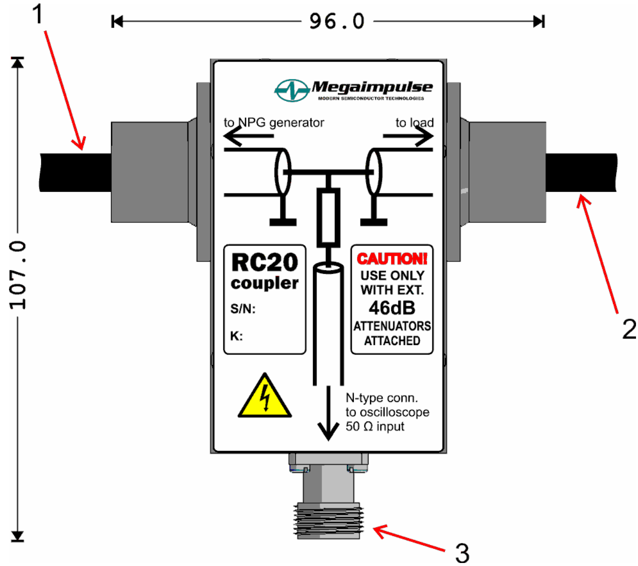
- Please read this manual before installing and using the coupler.
- Make sure that all the cables are applicable and undamaged. All the connectors should be clean, dry, and free from dust and dirt.
- The coupler should operate in normal laboratory conditions. Please, avoid dust, humidity, and temperature extremes.
- Please, if you encounter any technical problems with the coupler, then contact Megaimpulse Ltd. Do not try to repair it by yourself.

TECHNICAL SPECIFICATION

Maximum HV pulse amplitude	**20 kV**
Maximum average power in HV cable	**120 W**
Pulse polarity	**Any**
Rise time (transient response)	**1.5 ns**
Nominal pulse voltage attenuation of RC20 coupler RC20 with 46 dB attenuators	 **1:50 (34 dB) *)** **1:10000 (80 dB)**
Impedance and length of HV cables	**75 Ohm, 5 m + 5 m**
Output connector to the oscilloscope	**N-type, 50 Ohm impedance**
The delay between the incident and reflected pulses	**approx. 50 ns, depending on the coax cable length as well as the length of the wires to the load and load dimensions**
Pulse amplitude attenuation coefficient: per 1 meter of HV coaxial cable per 5 meters of HV coaxial cable	 **k_1 = 1:1.0061** **k_5 = 1:1.031**
Energy loss in dB and attenuation coefficient: per 1 meter of HV coaxial cable per 5 meters of HV coaxial cable per 10 meters of HV coaxial cable	 **0.053 dB / k_1^2 = 1:1.0123** **0.265 dB / k_5^2 = 1:1.063** **0.53 dB / k_{10}^2 = 1:1.13**
Size (for reference only)	**107 x 96 x 46 mm^3**

*) the exact measured attenuation values are written on the coupler front label and in the testing protocol.

➔ **To prevent damage to the coupler do not exceed the maximum pulse amplitude and average power in HV coaxial cable.**



* All the dimensions are in mm and are given for the reference only

Fig. 2. The drawing of RC20 resistive coupler.

1 - HV coaxial cable to the NPG generator. The length is 5 meters; cable impedance is 75 Ohm. Standard 75 Ohm coaxial connector is installed on the generator's side.

2 - HV coaxial cable to the load. The length is 5 meters; cable impedance is 75 Ohm.

3 - N-type connector to the oscilloscope. Impedance of the output is 50 Ohm.

ASSEMBLING AND PUTTING INTO OPERATION

➔ **Please follow the next steps. It will help to prevent damage to the equipment and personnel injury.**

Step 1.

Unpack the package and check the presence of the following items:

- RC20 resistive coupler with two attached 5 m HV coaxial cables;
- 6 dB attenuator with N-type connectors;
- 20 dB attenuator with N-type connectors;
- 3 m semirigid coaxial cable assembly with N-type and SMA connectors;
- 20 dB attenuator with SMA connectors;
- SMA-to-BNC adapter.

Step 2.

Assemble the attenuators, measurement cable, and adapter in the following order:

- 6 dB N-type attenuator;
- 20 dB N-type attenuator;
- 3 m semirigid coaxial cable assembly with N-type and SMA connectors;
- 20 dB SMA attenuator;
- SMA-to-BNC adapter.

Attach them to the output N-type connector of the coupler as is shown in Fig.4. It is important to keep this order for the best signal-to-noise ratio and to prevent damage to the coupler in case of a lost connection in the cable assembly.

➔ **To prevent contacts damage, please hold the attenuator body fixed and rotate the nut only when you attach the attenuator to the coupler.**

➔ **It is strictly forbidden to apply HV pulses without the attenuators attached.**

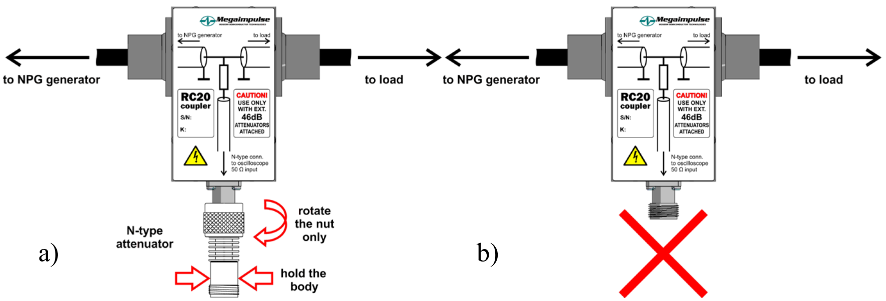


Fig.3. a) when you attach the attenuators please hold the body fixed and rotate the nut only;
b) it is strictly forbidden to apply HV pulses without the attenuators attached.

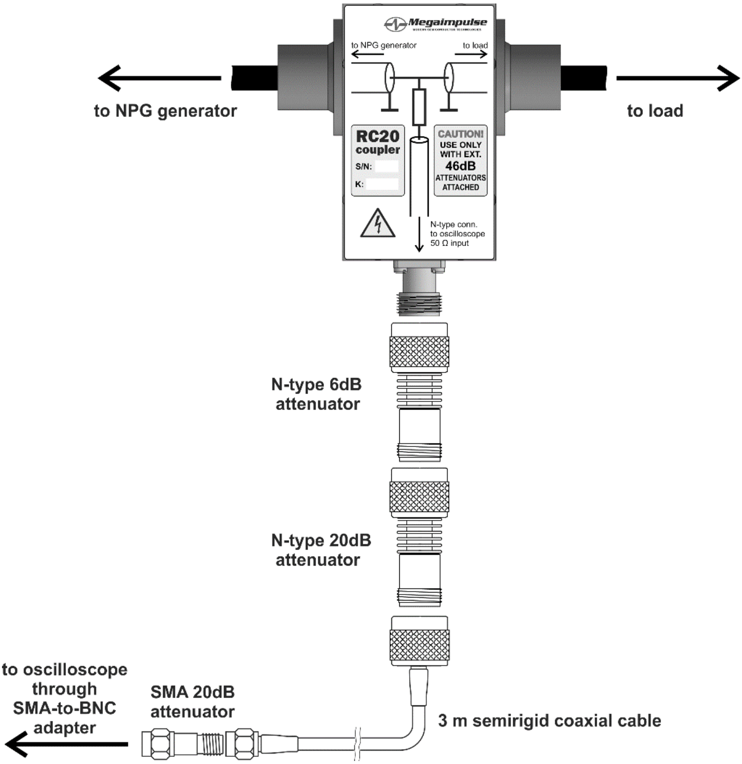


Fig.4. RC20 resistive coupler assembling and connection.

Step 3.

Connect the HV cables to the NPG-series pulse generator and to the load as well as connect RC20 to the oscilloscope.

Set the input impedance of the oscilloscope to 50 Ohm.

Set the external attenuation to 1:10000 or, which is more correct, to the exact attenuation value specified in the testing protocol. Alternatively, it is possible to calculate the pulse amplitude manually by setting the external attenuation 1:1. It is recommended to set the vertical scale to 5 kV/div in the first case or to 500 mV per division in the second.

Set the horizontal scale to 10 ns per division.

Step 4.

Turn on the generator and register the incident and reflected pulse waveforms by the oscilloscope.

THEORY OF THE OPERATION

RC20 resistive coupler allows the precise measurement of the output pulse waveform of NPG-series HV pulse generators (incident pulse for the load), as well as the pulse waveform reflected from the load. To prevent distortion, the nanosecond pulses, similar to high-frequency signals, should be transmitted from a generator to load through high-frequency transmission lines, for example, coaxial cables. Most of NPG generators have 75 Ohm impedance output coaxial connector and operate with HV coaxial cables having 75 Ohm impedance as well. According to basic principles of HF transmission lines, the pulse energy can be absorbed by the load completely in the case of ideal impedance matching only, i.e. if the load impedance is fixed and equal to the cable impedance. Unfortunately, this is impossible in the discharge applications. The impedance of the discharge gap changes from a high before the breakdown down to typically less than one Ohm after it. Part of the pulse energy inevitably reflects from the load and travels back to the generator. RC20 coupler is a measurement tool of the incident and reflected pulse waveforms, which allows us to calculate the energy of both pulses, and therefore, determine the energy balance or energy efficiency of the discharge. In addition, the evaluation of the pulse voltage on the load and pulse current is possible.

Let us consider the basic relationships between the incident and reflected pulses as well as RC20 operation principles in more detail. The reflection coefficient Γ which is defined as a ratio of the reflected V_R and incident V_I signals is equal to:

$$\Gamma \equiv \frac{V_R}{V_I} = \frac{Z_{LOAD} - Z_{CABLE}}{Z_{LOAD} + Z_{CABLE}} \qquad [1]$$

, where
Z_{LOAD} is the impedance of the load;
Z_{CABLE} is the impedance of the cable.

According to equation [1], if the load impedance Z_{LOAD} is higher than Z_{CABLE}, then Γ is within 0…1 and the reflected pulse has the same polarity. If the load impedance is lower than Z_{CABLE}, then Γ is within -1…0 and the reflected pulse has opposite polarity. Γ = 1 and Γ = -1 in two extreme cases of open or short load, and the reflected pulse amplitude is equal to the incident one.

The pulse voltage on the load V_{LOAD} and pulse current I_{LOAD} are equal to:

$$V_{LOAD} = V_I + V_R \qquad [2]$$

$$I_{LOAD} = I_I - I_R = (V_I - V_R) \,/\, Z_{CABLE} \qquad [3]$$

If the load impedance Z_{LOAD} is higher than Z_{CABLE}, then the reflected pulse has the same polarity, pulse voltage amplitude on the load is equal to the sum of the incident and reflected pulses, i.e. higher than the incident one, and the pulse current through the load is the incident pulse current minus the reflected one, i.e. lower than the incident pulse current (see Fig.5).

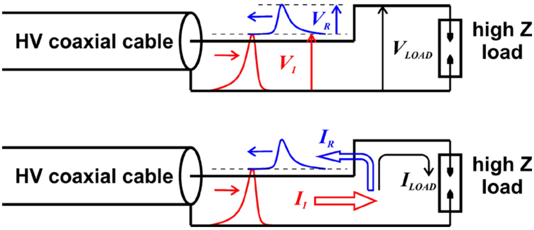


Fig.5. Pulse voltage on the load and pulse current in the case of high impedance load. The incident pulse is marked by red, reflected one by blue; the propagation directions of both pulses are pointed by the arrows.

If the load impedance Z_{LOAD} is lower than Z_{CABLE}, then the reflected pulse has reversed polarity. Equations [2] and [3] are also applicable. The pulse voltage on the load is lower than the incident one, but the pulse current through the load is higher (see Fig.6).

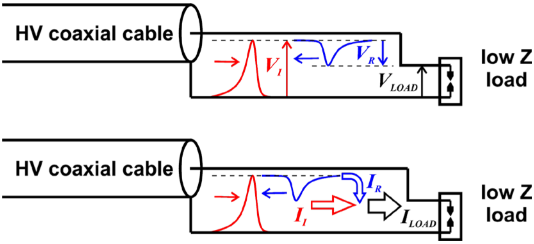


Fig.6. Pulse voltage on the load and pulse current in the case of low impedance load. The incident pulse is marked by red, reflected one by blue; the propagation directions of both pulses are pointed by the arrows.

The pulse energy can be calculated from its waveform measured in the cable by the following equation:

$$E = \int \frac{V^2(t)}{Z_{CABLE}} dt \qquad [4]$$

, where
$V(t)$ is the captured waveform of the incident $V_I(t)$ or reflected $V_R(t)$ pulse;
Z_{CABLE} = 75 Ohm is the cable impedance.

The absorbed by the load energy E_{LOAD} can be easily calculated from the energies of the incident E_I and reflected E_R pulses:

$$E_{LOAD} = E_I - E_R - E_{LOSS} \qquad [5]$$

Of course, the energy loss E_{LOSS} in cables should be taken into account for the precise calculation of E_{LOAD}. This question will be discussed in the next chapter in more detail. RC20 operation in case of low and high impedance loads are schematically shown in Fig.7 and Fig.8.

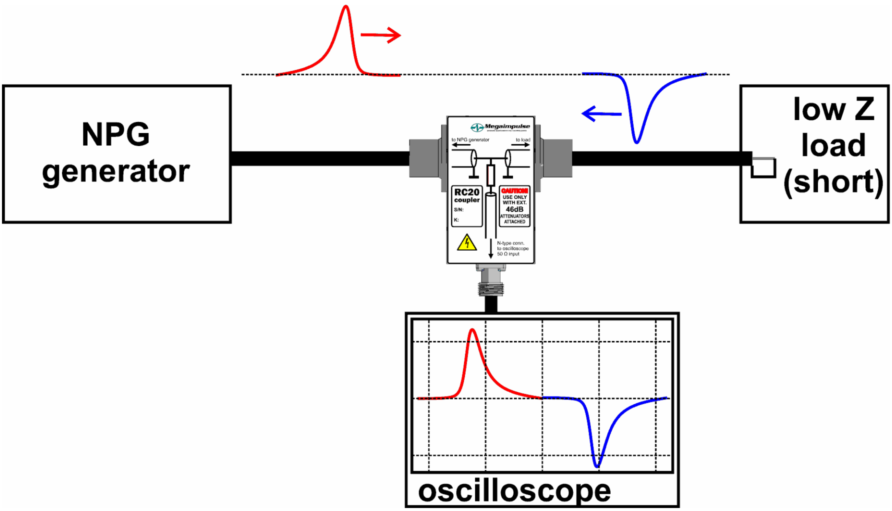


Fig. 7. The incident (red) and reflected (blue) pulses for short or low-impedance load. The reflected pulse has reversed polarity. The propagation directions of the incident and reflected pulses are pointed by the arrows.

The operation in the case of short or low-impedance load is shown in Fig.7. The reversed polarity of the reflected pulse clearly indicates the load impedance is lower than the cable impedance Z_{CABLE} = 75 Ohm. The registered by oscilloscope delay between the incident and reflected pulses is equal to the propagation time from the coupler to the load and back. The specific propagation time along HV coaxial cable is about 5 ns per meter, which gives ca. 50 ns of delay in cable in both directions plus the propagation delay in cable-to-load wires and the load itself. The exact delay should be measured in each particular application.

The high-impedance load operation is shown in Fig.8. The reflected pulse polarity is unchanged. The delay between pulses is the same, i.e. ca. 50 ns.

The operation with the discharge load is schematically shown in Fig.9. Before the breakdown the impedance of the discharge gap is high and the reflected pulse has the same polarity. After the breakdown the impedance drops dramatically, and the polarity changes. Similarly, the waveforms allow to calculate the incident and reflected pulse energies (eq. [4]), calculate the energy which goes into the discharge (eq. [5]), as well as estimate the pulse voltage on the load and pulse current (eq. [2] and [3]).

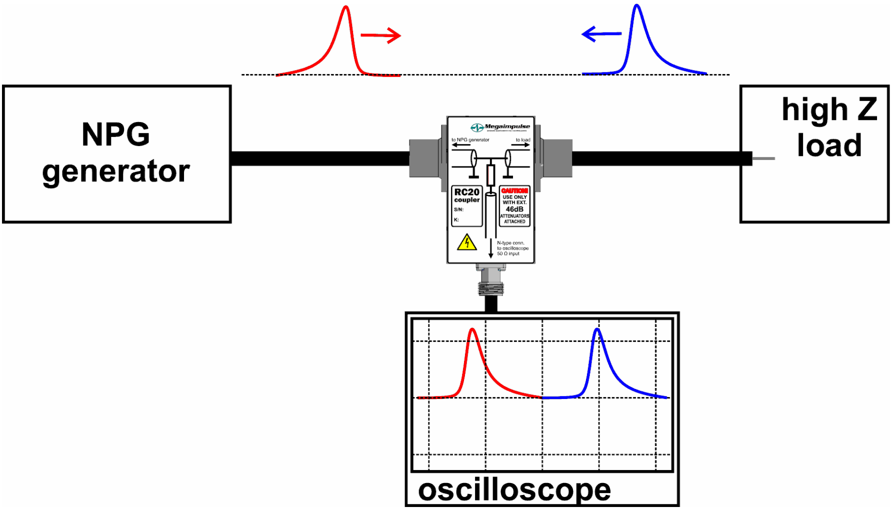


Fig. 8. The incident (red) and reflected (blue) pulses for high-impedance load or open cable. The reflected pulse has the same polarity. The propagation directions of the incident and reflected pulses are pointed by the arrows.

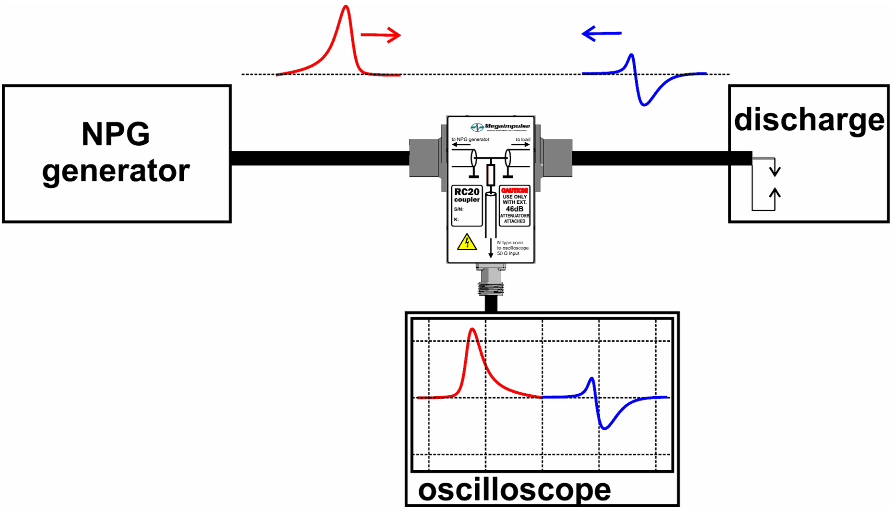


Fig. 9. The incident (red) and reflected (blue) pulses for the discharge load. The reflected pulse changes the polarity from positive to negative, which indicates high impedance of the load before the breakdown and low after it. The propagation directions of the incident and reflected pulses are pointed by the arrows.

As an example, the oscillograms of the incident and reflected waveforms for the first and the second pulses in a burst registered by RC20 coupler in case of 1 mm gap discharge at ambient pressure are shown in Fig.10 and Fig.11. The pulse-to-pulse interval within a burst is 10 μs (100 kHz repetition rate). One can see for the second pulse; the discharge occurs when the amplitude is much lower because of the presence in the gap of the excited products from the previous discharge.

➔ **It is recommended to use the oscilloscope with 1 GHz bandwidth and 10 GS/s or more.**

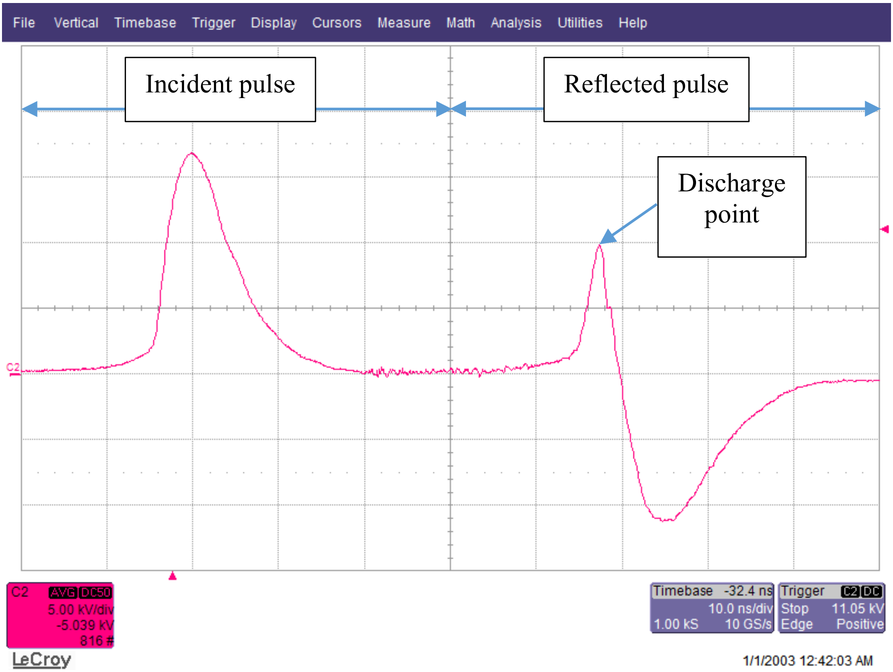


Fig. 10. The incident and reflected waveforms of the first pulse in a burst for 1 mm gap discharge. The reflected pulse changes the polarity after the gap breakdown. The discharge point is marked by arrow.
The scales are 5 kV/div and 10 ns/div.

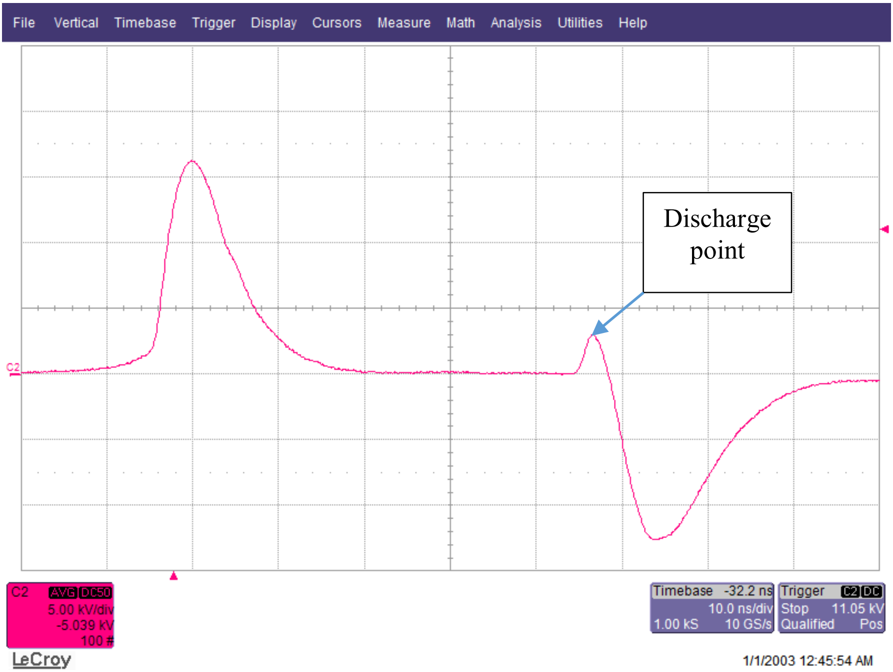


Fig. 11. The incident and reflected waveforms of the second pulse in a burst for 1 mm gap discharge. The discharge occurs at much lower voltage. The scales are 5 kV/div and 10 ns/div.

ENERGY LOSS IN A CABLE
CALCULATION OF THE ENERGY BALANCE

Unfortunately, significant energy loss occurs in HV cable during the pulse transfer, and this loss should be considered when you calculate the energy balance. The measured energy loss (for the NPG pulse) on one meter of new HV cable is equal to 0.053 dB which corresponds to attenuation coefficient k_1^2 = 1:1.0123. It means the pulse energy decreases by 1.0123 times while the pulse travels along one meter of HV cable. The cable length between RC20 coupler and the load is 5 meters. Therefore, the energy loss on 5 meters of travel is 0.265 dB, or the attenuation coefficient is k_5^2 = 1:1.063. The same attenuation occurs while the pulse travels back from the load to the coupler, and the total attenuation is $k_{10}^2 = k_5^2 \times k_5^2$ = 1:1.13. Generally speaking, the energy loss depends on the frequency. The curve presented in Fig.12 is taken from the HV cable datasheet. According to the information from the manufacturer, the energy loss may increase up to two times due to cable aging, i.e. degradation of the insulator and oxidation of the cable braid.

Therefore, it is reasonable to check the cable loss at least once per year. Please increase the gap up to the discharge is eliminated completely. The incident and reflected pulse waveforms should be similar to Fig.13. The incident pulse energy divided by the reflected energy gives k_{10}^2 coefficient.

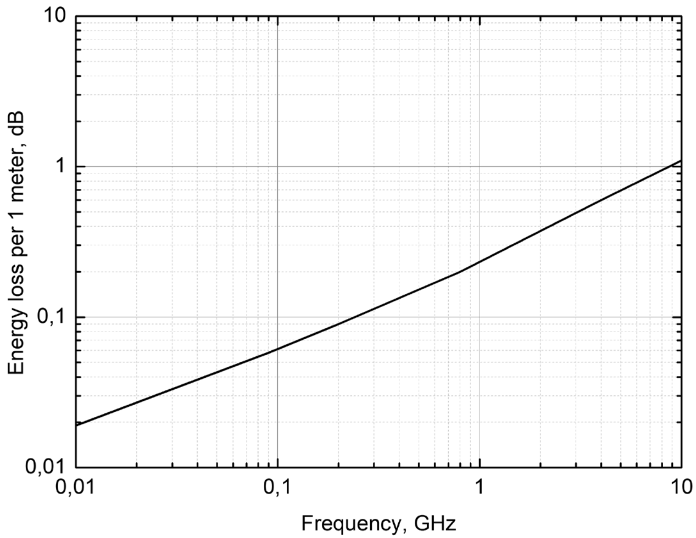


Fig.12. The energy loss per one meter of HV coaxial cable depending on the frequency.

Let us estimate the energy balance based on the captured incident and reflected pulse waveforms shown in Fig. 10.

Calculated from the waveform the incident pulse energy is 24.026 mJ (eq.[4], integral from 0 ns to 50 ns of the oscillogram). The pulse energy is attenuated by 1.063 times while it travels from the coupler to the load. Therefore, the energy of the pulse applied to the load is 24.026/1.063≈22.60 mJ.

The reflected pulse energy is 16.163 mJ (eq.[4], integral from 50 ns to 100 ns). And again, it is attenuated by 1.063 times while the pulse travels from the load to RC20 coupler. Therefore, we should multiply the registered energy of the reflected pulse by 1.063 to get the real reflected pulse energy 16.163*1.063≈17.18 mJ.

Total energy balance:

Energy of the incident pulse applied to the load	22.60 mJ
Energy of the reflected pulse from the load	17.18 mJ
Energy that goes into the discharge	22.60 - 17.18 = 5.42 mJ

One can see that only 24% of the pulse energy goes into the discharge, and most of the pulse energy reflects back.

The energy balance calculation for the second pulse in a burst (Fig.11) gives the following results:

Energy of the incident pulse applied to the load	20.99 mJ
Energy of the reflected pulse from the load	19.01 mJ
Energy that goes into the discharge	20.99 - 19.01 = 1.98 mJ

9.4% only of the second pulse energy goes into the discharge. The quite low efficiency is explained by the very low impedance of the gap.

EVALUATION OF THE PULSE VOLTAGE ON THE LOAD AND THE PULSE CURRENT

RC20 can help to evaluate the pulse voltage on the load and the pulse current. At first, the exact delay between the incident and reflected pulses should be measured. It depends on the cable length as well as on the length of the connecting wires and discharge electrodes. Please increase the gap between electrodes so the discharge is eliminated completely. The pulse energy is reflected back from the load in this case, and the reflected pulse waveform should be similar to the incident one. The typical oscillogram of the incident and reflected pulses is shown in Fig.13, where the pulse-to-pulse delay is measured by the interval between two peaks.

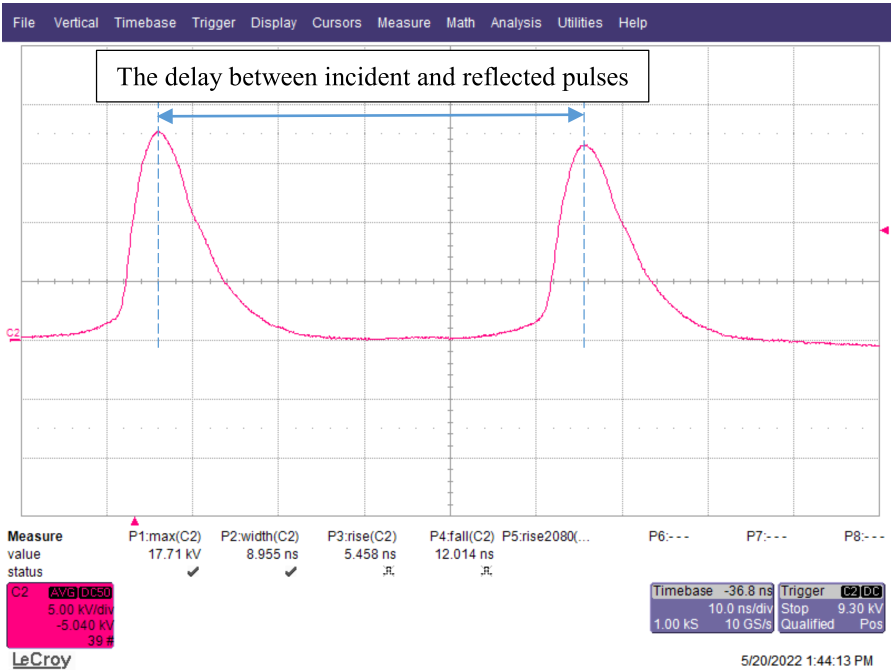


Fig.13. Measurement of the delay between incident and reflected pulses. The scales are 5 kV/div and 10 ns/div.

Let us evaluate the pulse voltage on the load and pulse current for the oscillogram in Fig.10. According to eq.[2] and eq.[3], and taking into account the pulse-to-pulse delay, the voltage on the load and the current are equal to:

$$V_{LOAD} = V_I(t) + V_R(t - delay) \quad [6]$$

$$I_{LOAD} = (V_I(t) - V_R(t - delay))/Z_{CABLE} \quad [7]$$

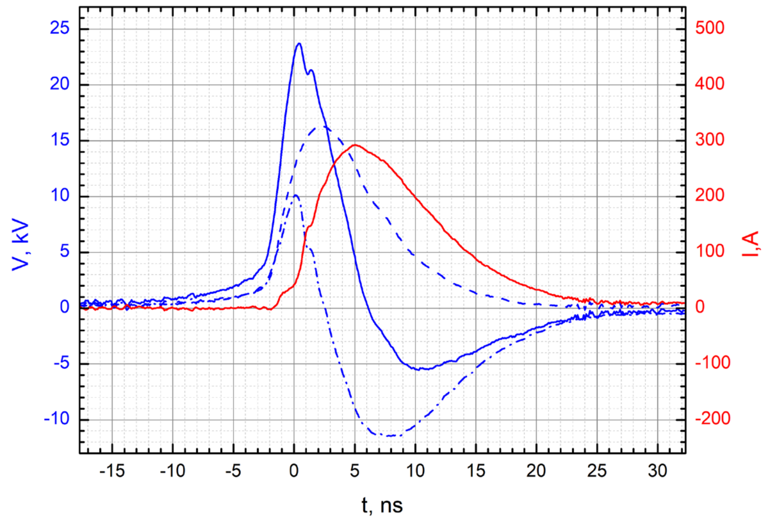


Fig.14. Calculation of the pulse voltage on the discharge and pulse current:
blue solid line – calculated pulse voltage on the discharge,
red solid line – calculated pulse current through the discharge,
blue dash line – incident pulse $V_I(t)$ divided by 1.031 (k_5),
blue dash-dot line – reflected pulse $V_R(t\text{-}delay)$ multiplied by 1.031 (k_5).

Special attention should be taken to the stray parameters of the load. The equivalent electrical circuit of the discharge reactor is shown in Fig.15, where L_{STRAY} is the stray inductance of the wires between the coaxial cable and the electrodes as well as the electrodes itself, C_{STRAY} is the stray capacitance of the discharge gap, and R_{PLASMA} is non-linear resistance of the plasma.

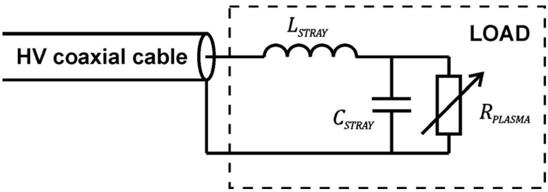


Fig.15. The equivalent electrical circuit of the discharge reactor.

C_{STRAY} can be made as low as 1 pF and below, which results in its minor influence. Indeed, the current through C_{STRAY} is equal to:

$$I = C_{STRAY} \frac{dU}{dt} \qquad [8]$$

The typical voltage rise rate of NPG generators is 5 kV/ns, which gives the estimation of the pulse current through C_{STRAY} about 5 amperes while the total current through the discharge is equal to a few hundred amperes.

Usually, the influence of L_{STRAY} is much higher. Exactly the stray inductance is responsible for the negative half-wave of the calculated voltage pulse on the load in Fig.14 at t = 6 ns and after.

RC20 allows us to measure L_{STRAY} precisely, which may be useful for the discharge simulation. In addition, changing the stray parameters can help to adjust the pulse waveform on the load. Please short-circuit the discharge gap. The load becomes just inductive, and the oscillogram should be similar to the typical one shown in Fig. 16.

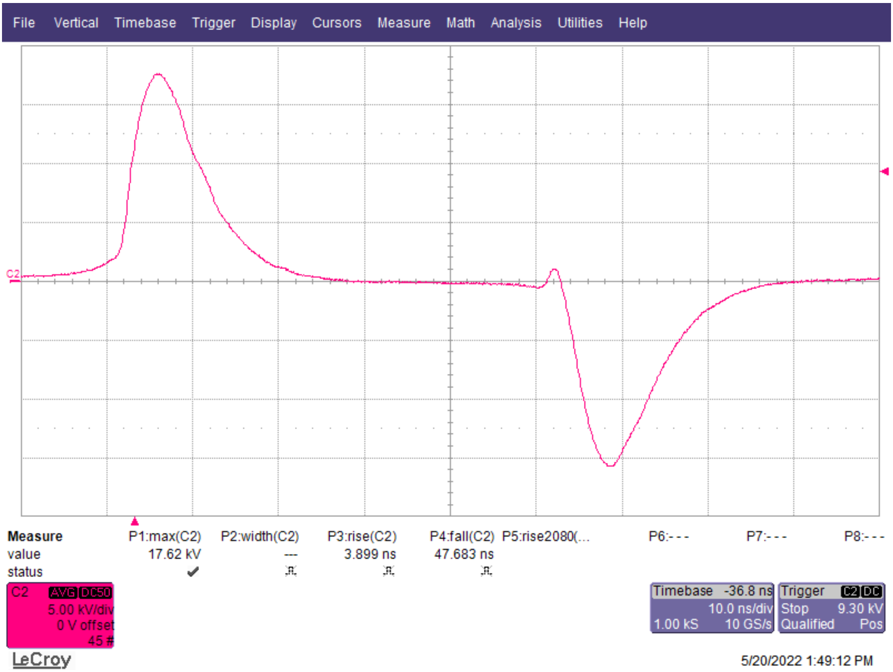


Fig. 16. The oscillogram of the incident and reflected pulses when the discharge gap is shorted. The scales are 5 kV/div and 10 ns/div.

The voltage on the inductance, is equal to:

$$U = L \frac{dI}{dt} \qquad [9]$$

Therefore, the inductance can be calculated from the voltage pulse and the first derivative of the current pulse (see Fig.17).

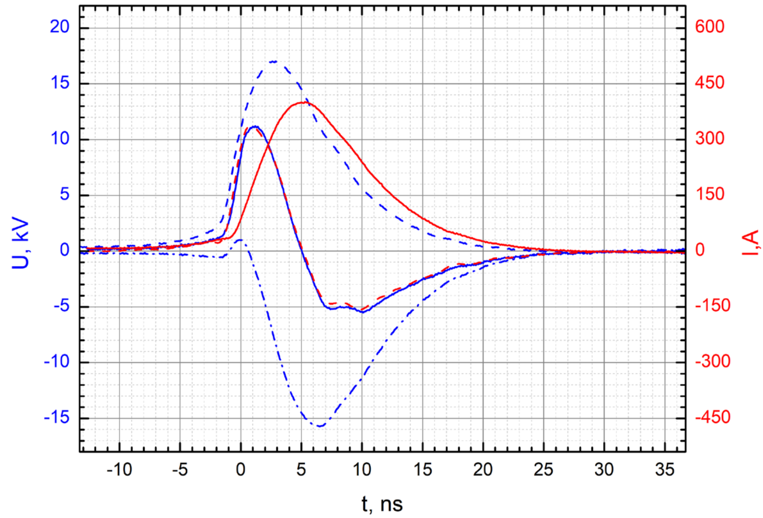


Fig.17. Calculation of the stray inductance of the discharge chamber:
blue dash line – incident pulse *$V_I(t)$* divided by 1.031 (k_5),
blue dash-dot line – reflected pulse *$V_R(t\text{-}delay)$* multiplied by 1.031 (k_5),
blue solid line – calculated pulse voltage on the load,
red solid line – calculated pulse current through the load,
red dash line – 1st derivative of the current pulse multiplied by 122.7 nH.

One can see good agreement between the voltage pulse on the load and 1st derivative of the current pulse. The calculated stray inductance in this experiment is 122.7 nH.

RC20 coupler registers the pulse waveform reflected from the load which consists of the discharge gap itself, stray capacitance, and stray inductance of the wires/electrodes. The calculated pulse voltage is not exactly the voltage on the gap, one should consider the stray parameters too. It is important to keep the electrode system as compact as possible and wires short. All the above calculations were made with the assumption of a compact load. The size of the load should be much less than the pulse front duration (3 ns) multiplied by the speed of light, i.e. significantly less than 1 meter. The large-size load with distributed stray parameters results in multiple or spread reflections which makes the interpretation of the results much more complicated.

WARRANTY

Please see your sales agreement to determine the warranty period and condition. Removing the warranty seals and labels terminates the warranty.