Radio Frequency Generator for Driving Electrodynamic Multipoles

Version 3-15CF

User Manual

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Safety Information

- The device may be installed and used by authorized and instructed personnel only. Read this manual carefully before installing and using the device. Always follow the safety notes and warnings in this manual.
- The device is designed for indoor dry laboratory use only. Before powering the device on, it must acclimatize to the ambient temperature to avoid moisture condensation. This is especially relevant after transport.
- Do not operate the device if it is damaged or not functioning properly. Never use damaged cables or accessories.
- To avoid damage, connect the line cord to a properly wired and grounded receptacle only. Be sure that the mains voltage and the fuse rating match the device specification. Never operate the device during thunderstorms.
- Never use corrosive or abrasive cleaning agents or polishes, avoid the use of organic solvents. If necessary, clean the device with a soft damp cloth. Make sure that the device is completely dry and free from contaminants before powering it on.

! **Warning:** The radio frequency generator is an electronic device that is sensitive to electrostatic electricity. While handling the generator, the ESD (*electrostatic discharge*) protection rules must be kept in mind.

Technical Data

Characteristics

- compact radio frequency (RF) generator
- symmetrical output voltage with DC bias
- digital enable control
- analog RF voltage control
- metallic case for DN100CF flange mount
- two fans and two air outlets for optimal forced cooling

Mains Supply

- universal line input: 90 – 255 V, 47 – 63 Hz
- power consumption:
  standby (generator deactivated): <5 VA, 3.5 VA typ.
  operation (RF enabled): <10 VA, 5 VA typ.
  maximum (fan maximum): <15 VA, 10 VA typ.
- main fuses: T 2.0 A (slow acting, size ø5x20 mm)
- mains connection (*Line Input*):
  IEC inlet with EMC filter and integrated fuse holder

RF Power Supply

- connectors: two banana safety sockets (*RF Power +/–*)
- voltage: 0 – 50 V typical, see test protocol
- current consumption: < 2 A typ., see test protocol

RF Output

- two electrical feedthroughs on the DN100CF flange
- frequency: given by the resonance frequency of the output circuitry,
  see test protocol
- amplitude: continuously variable by the power supply voltage,
  see test protocol

Security

- interlock loop (*Enable*):
  BNC socket ot the front panel
  signal level: TTL, internal pull-up to +5 V: 20 kΩ
  polarity: short circuit disables the generator

- over- and undertemperature protection:
  - temperature sensor at generator's heat sink
  - overtemperature threshold: +60°C
  - undertemperature threshold: +10°C

Fan Control

- linear temperature regulation
- minimum speed: below +30°C
- maximum speed: above +55°C

Bias Voltage

- connector: BNC socket (*DC Bias*)
- allowable voltage range: ±50 V typ., see test protocol
- internal serial resistance: 10 kΩ typ., see test protocol

Monitoring

- connectors: two BNC sockets (*Monitor 1*, *Monitor 2*)
- type: capacitive voltage divider
- output capacitance: 5 nF typ.
- attenuation: 1:100 typ.

Device State

- indicator: multicolor LED (*Driver Power*)
- color coding:
  - standby (disabled): yellow
  - active: green
  - overtemperature: red
  - undertemperature: blue
  - fan failure: cyan

General

- metallic case:
  - height and width: 239.5 mm, depth: 226.5 mm
  - total height with air filters: 260.5 mm
  - total width with air filters: 257.5 mm
  - outer surfaces: clear anodized, inner surfaces: chromated

- forced cooling:
  two 120 mm fans with air filters on the top and bottom panels
  two 120 mm air outlets with air filters on the side panels
  temperature-dependent control
  monitored fan operation, warning in the event of a fan failure
- allowable temperature range for device operation: +10...+40°C
- weight: 6.4 kg typ. (incl. flange), see test protocol
- cleaning: use damp cloth only, avoid use of organic solvents

Shipment Contents

- radio frequency generator RFG50CF
- flange DN100CF with two electrical feedthroughs
- set of capacitors for frequency adjustment
- line cord (universal IEC mains lead, length 1.8 m)
- user manual in electronic form

Quick Setup Guide

! **Warning:** The generator can produce lethal voltages, please note the following before powering it on:

- The device must be properly grounded **before** the mains voltage is applied. The device is intended to be mounted on a flange of a vacuum apparatus and grounded to it. Check the ground resistance in case of any doubts.
- The output circuit must be connected by short wires with sufficiently low impedance, please do not neglect skin effect. The generator produces high-amplitude, high-frequency voltages. If not properly connected and grounded, it may cause RF emissions with a high intensity that may interfere with other devices. Thin output wires with a high inductance will not provide a sufficient connection between the output transformer and the load. This may lead to high-frequency oscillations at the transformer output accompanied by high-amplitude voltage peaks at the MOSFETs of the power stage. This may limit the amplitude of the output voltage or even damage the power stage.
- The device has been adjusted to the frequency and load specified by the customer. For the exact test conditions, see the test protocol provided with the device. When the device is put into operation, compare the supply values with the test protocol and do not proceed if there is a significant difference.

Connect the mains to the IEC inlet *Line Input* on the front panel (see Fig. 1) via a standard line cord with the universal IEC mains lead. Turn the device on via the switch integrated into the IEC inlet. The LED indicator *Driver Power* should change color several times and, after the startup sequence finishes, it should light up green — this indicates that the device is enabled. Short the BNC socket *Enable* with a 50 Ω terminator or apply a logical 0 to the input in another way. The LED indicator should change to yellow, indicating that the generator is disabled.

! **Warning:** If the LED indicator has any other color, see the section "Technical Data" for an explanation of the indicated states and consult the section "Troubleshooting". Do not proceed until the failure has been resolved.

If the device works as expected, turn it off again and disconnect it from the mains. Mount it to the flange and connect the electrodes to the outputs. Short the BNC socket *DC Bias* with a 50 Ω terminator, connect the mains and turn the device on. Open the short circuit at the BNC socket *Enable* and verify that the LED *Driver Power* lights up green. Connect the DC power supply unit to the banana safety sockets *RF Power +* and *RF Power –*, paying attention to the polarity.

! **Warning:** If a DC voltage with a wrong polarity is connected, the generator will limit the voltage to less than 1 V and will consume as much current as the current limit of the DC power supply unit allows. Be sure to initially set a low current limit to prevent an overload in case of an error.

Connect an oscilloscope to the BNC sockets *Monitor 1* and *Monitor 2* via two short (no longer than 1 m) coaxial cables. Increase the voltage of the DC power supply unit slowly and observe the output signals with the oscilloscope. Compare the values with the data from the test protocol.

! **Warning:** Every time the DC power supply unit is operated, its current limit should be set to a value only slightly larger than the expected current value from the test certificate. A good strategy is to set the desired voltage and then increase the current limit until the set voltage is reached. If the current consumption is significantly higher than expected, do not proceed and consult the section "Troubleshooting".

Description

General

The device is a radio frequency (RF) generator with an external power supply unit for its power stage. It produces two harmonic signals phase-shifted by 180°. It is self-tuning, i.e. it automatically runs at the optimum working frequency close to the resonance frequency of the output circuitry. A temperature sensor monitors the temperature of the power semiconductors and shuts down the device if a critical temperature is reached. The device is fit into an approximately cube-shaped metallic box (edge length about 23 cm). The front panel is shown in

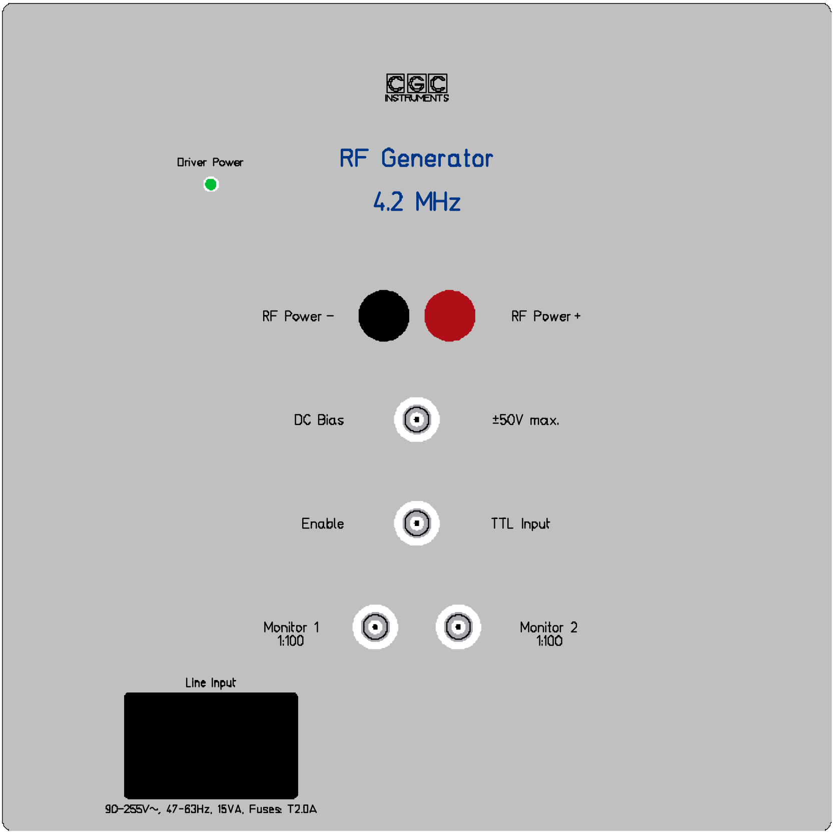

Fig. 1. The front panel of the RF generator.

Fig. 1.

Device Function

The design of the device is based on the concept from reference [1], but the circuit diagram has been significantly improved to obtain better parameters and stable RF signals. This third generation of the RF generators uses a field programmable gate array (FPGA) to integrate all control and supervision functionality. The FPGA makes it possible to implement a sophisticated device control and reach optimal parameters under any conditions.

The sinusoidal output voltages are produced by an RF transformer (*TR* in Fig. 2). Its secondary winding acts as a resonance circuit together with the capacitance at the output leads *RF1* and *RF2*. The device excites oscillations in this circuit at a frequency close to the electrical resonance. The operation close to the electrical resonance frequency and the symmetric circuit design provide sinusoidal output voltages with a high amplitude and an excellent spectral purity.

Together with the inductance of the secondary winding of the transformer *TR*, the capacitance at the output leads *RF1* and *RF2* sets the resonance frequency. Therefore, it indirectly determines the output

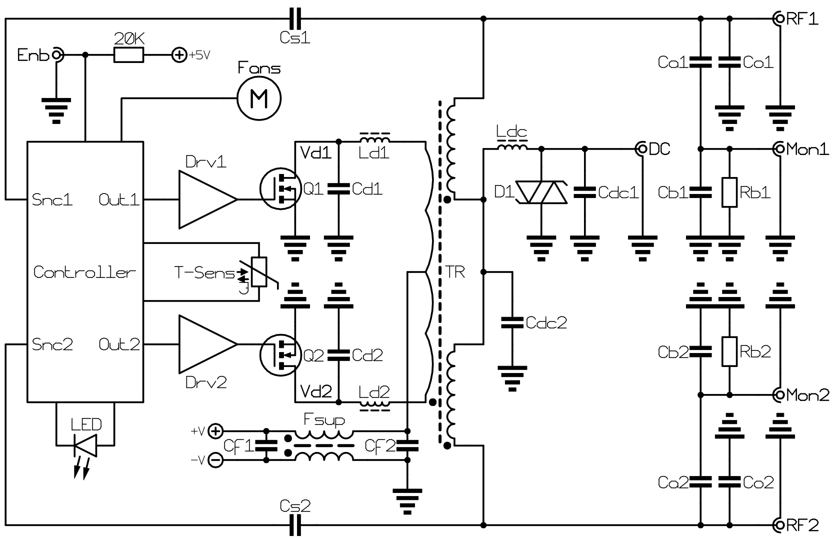

Fig. 2. Simplified circuit diagram of the generator.

frequency. The capacitance consists of the capacitance of the external load including the connection cable and of the internal capacitance. The latter is made up of the capacitors *Co1/2* and *Ca1/2* as well as the capacitance of the transformer *TR* and the internal stray capacitance. The capacitors *Co1/2* are adjusted in the factory to obtain the desired output frequency. The user may exchange them if the connected electrodes have a different capacitance than expected or if the electrode hardware has been changed and/or the operating frequency differs from the desired value. Consult the section "Troubleshooting" for more details.

The input connector *DC* (BNC socket *DC Bias* on the front panel, see Fig. 1) defines the DC potential of the RF output leads *RF1* and *RF2*. The DC voltage is applied to the outputs via the coil *Ldc* and the secondary winding of the transformer *TR*. The capacitors *Cdc1* and *Cdc2* together with the coil *Ldc* filter the RF signal from the transformer so that only a small residual RF amplitude is present at the DC input *DC*. The diode *D1* provides overvoltage protection of the DC input. It limits the DC voltage so that the connected capacitors cannot be overloaded even if the DC input is disconnected and electron or ion currents charge the electrodes connected to the outputs *RF1* and *RF2*. Note that in the real circuit, the coil *Ldc* is a serial combination of a coil and a resistor, both result in the typical serial resistance of 10 kΩ (see section "Technical Data").

The control unit (*Controller* in Fig. 2) of the device is based on an FPGA. It senses the RF voltages via the capacitors *Cs1* and *Cs2* and produces the control signals for the drivers *Drv1* and *Drv2* that drive the gates of the MOSFETs *Q1* and *Q2*. The MOSFETs form a push-pull class E RF end stage, i.e. they operate with so-called soft switching (activating the MOSFETs in the time periods where no significant drain voltage is present) to reduce switching losses. The primary circuitry contains the capacitors *Cd1* and *Cd2* as well as the inductors *Ld1* and *Ld2*, they optimize the signal waveforms at the MOSFET drains and enable the soft switching.

The voltage for supplying the power stage is applied externally to the terminals *+V* and *–V* (banana safety sockets *RF Power +* and *RF Power –* on the front panel, see Fig. 1). The voltage is filtered by the filter *Fsup* and the capacitors *Cf1* and *Cf2*. The magnitude of the applied voltage determines the output amplitude. For detailed information about the conversion ratio and the current consumption, see the test protocol of the specific device.

The device monitors the temperature of the heat sink onto which the MOSFETs are mounted via the sensor *T-Sens*. If the measured temperature exceeds a certain value, the device is disabled to prevent additional heating. The device is also disabled if the temperature is too low and moisture condensation can occur.

The device is equipped with an enable input *Enb* (BNC socket *Enable* on the front panel, see Fig. 1) that accepts TTL levels. It can be used to turn off the RF if, for instance, the connected ion trap has to be emptied or if the vacuum pressure is not sufficiently low to safely operate the connected electrodes. The input is equipped with an internal pull-up resistor to +5 V of 20 kΩ, i.e. if the terminal is left open, the resistor sets a logical 1 at the input that enables the device. If the terminal is shorted — either directly or by a 50 Ω terminator — the device is disabled by the resulting logical 0 at the input. Note that if the device is disabled, the oscillations in the output circuitry do not stop immediately but their amplitude decreases exponentially. The duration of the ringing at the output is given by the electrical quality of the output circuitry and may take many tens of periods. Similarly, the RF voltage does not start up instantly and several RF periods are typically required to reach the desired amplitude.

To check the RF output voltages, two monitor outputs *Mon1* and *Mon2* (BNC sockets *Monitor 1* and *Monitor 2* on the front panel, see Fig. 1) are available. Their voltages are gained by passive capacitive filters formed by the capacitors *Ca1*/*2* and *Cb1*/*2*. The attenuation ratio is given by the ratios *Cax*/*Cbx*, the typical value is 1:100. The output capacitance is given by the capacitors *Cb1* and *Cb2*, the typical values are 5–10 nF. The resistors *Rb1* and *Rb2* with a typical resistance of 10 MΩ set the DC component at the monitor outputs to zero and prevent accidental charging of the terminals. The monitor circuitry and the used component values make it possible to connect an oscilloscope to the monitor outputs via conventional coaxial cables without losing the precision. A typical 1 m long coaxial cable has a capacitance of about 100 pF, this causes a systematic error of only 1–2%.

Terminals

For the mains connection, an IEC inlet *Line Input* (see Fig. 1) with an EMC filter and integrated fuse holder and switch is located on the front panel. Use a standard line cord with the universal IEC mains lead to connect the device to the mains. To replace the fuse, remove the line cord and open the fuse holder. Insert the new fuse(s), close the fuse holder, and connect the line cord back to the IEC inlet.

For supplying the power stage, i.e. for adjusting the output amplitude, an adjustable DC power supply unit should be connected to the banana safety sockets *RF Power +* and *RF Power –*. Consult the test certificate of the device to look up the voltage and current values required to achieve the desired RF amplitude. Note that if the device is disabled or not powered on, the current consumption of the power stage is almost zero, it usually does not exceed 1 mA. Therefore, it is safe to apply the external DC power supply to the power stage even if the device is turned off.

! **Warning:** Use a DC power supply unit with an adjustable current limit and set it to a value only minimally larger (not more than +20%) than the current value specified in the test certificate. If the current consumption is larger than expected, check the output signals with an oscilloscope. The most likely cause is a wrong connection of the electrodes, or their capacitance is different to the value the device was adjusted for in the factory. Consult the section "Troubleshooting" for more details. If the output signals have the expected form, i.e. they have a sinusoidal shape and the frequency matches the nominal value, try to increase the current limit. However, values 20% larger or more are suspect and the distributor or the manufacturer should be contacted for further instructions if the reason cannot be identified.

The terminal *DC Bias* is a BNC socket to which an external DC voltage can be applied. This voltage determines the DC component of the RF output signals and usually sets the potential on the axis of the connected ion trap or ion guide. The input can be shorted by a 50 Ω terminator if no DC voltage is applied. The input should not be left open since ion or electron currents to the connected electrodes can charge them and lead to unpredictable DC potentials. However, even under these conditions, operating the device is still safe since the input is equipped with an overvoltage protection (diode *D1* in Fig. 2) that prevents that the DC voltage from reaching voltages that could damage the used components.

The terminal *Enable* is a BNC socket that can be used to enable or disable the RF output. If it is left open or if a logic level 1 is applied, the device is enabled and harmonic signals are generated on the RF outputs. If the terminal is shorted or if a logic level 0 is applied, the device is disabled and no RF is generated. Note that a common 50 Ω BNC terminator can be used for shorting.

The terminals *Monitor 1* and *Monitor 2* are BNC sockets that provide output signals attenuated by the specified ratio. The typical attenuation is 1:100, an oscilloscope can be connected directly via conventional 50 Ω coaxial cables. The cable length should not exceed 1 m, otherwise a systematic error of several % will be introduced into the monitoring signals.

The RF outputs are connected directly to the electrical feedthroughs on the vacuum flange DN100CF onto which the device is mounted. The connection can be disassembled if the generator needs to be removed from the flange (see Fig. 3), e.g. if the vacuum chamber should be baked out at temperatures higher than about 100°C.

Installation And Operation

! Before powering on the device, read the user manual thoroughly.

The device is intended to be mounted on a flange of a vacuum apparatus. It requires a space of at least 27 × 27 × 30 cm^3 (width × height × depth). The installation space must be kept dry and the temperature and humidity within the range specified in the section "Technical Data". Note that, depending on the amplitude of the output voltage, the device produces heat during operation. Avoid exposing the device to direct sunlight since this may significantly increase the device temperature. High device temperatures may lead to increased noise from the running fans or even a thermal shutdown if the heat sink approaches the shutdown temperature (see section "Technical Data"). Ensure that the vacuum apparatus can carry the weight of the generator specified in the test protocol.

During operation, only the front panel of the RF generator has to be accessible. The device can operate in any position; however, the air inlets on the top and bottom panels as well as the air outlets on the side panels must not be covered or obstructed. They must have access to sufficiently cool air for active cooling of the device. Inspect and clean the air filters regularly. Furthermore, use a vacuum cleaner to

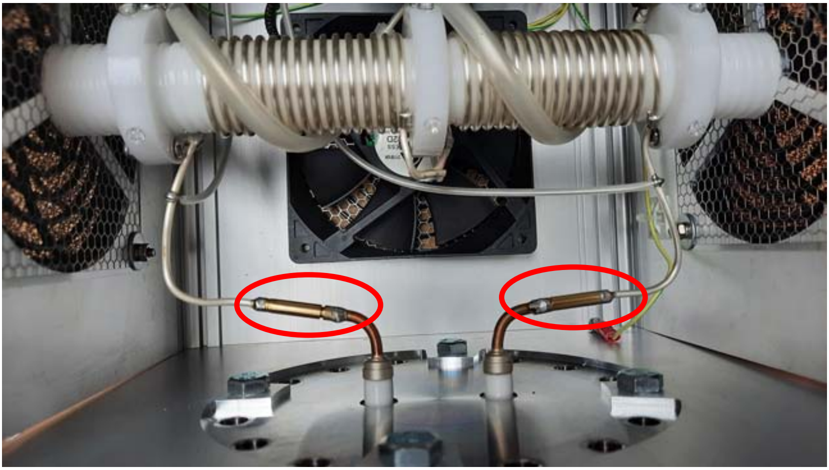

Fig. 3. View of the generator's RF terminals and the vacuum flange DN100CF with the electrical feedthroughs.
The red circles mark the output terminals.

remove dust from the filters and the fans in the device housing. Large dust layers substantially lower the cooling power (the device may overheat if the air filters are extremely dirty). The lifetime of dirty fans can also be significantly shorter.

If the RF generator was shipped with a mounted vacuum flange and connected RF terminals (see Fig. 3), the flange must be removed prior to the installation of the device. To gain access to the flange and the terminals, the device cover plate has to be removed: Unfasten the four M3 screws that hold the cover plate in place (two on the front and two on the rear panel) and remove it. The cover plate with the mounted fan is connected to the device with a grounding wire and the fan cable, it can only be completely removed if both cables are disconnected.

Carefully open the connectors connecting the RF outputs to the electrical feedthroughs on the vacuum flange (see red circles in Fig. 3).

! Make sure that only the silver-coated wires and not the electrical feedthroughs are mechanically stressed.

! Do not touch the silver-coated wires or the chromated inner surfaces of the device case with bare fingers since the coating will be chemically affected and lose its high electric conductivity.

Unfasten the four M8 screws fixing the vacuum flange to the rear plate and remove the flange. Mount it to the vacuum apparatus with the gasket of choice. Be sure to insert only the remaining 12 screws and leave the four screws for fixing the generator unused. Mount the generator case to the vacuum flange and tighten all its 16 screws.

Connect the RF outputs to the electrical feedthroughs on the vacuum flange, do not mechanically stress them. Connect the cables of the cover plate (the grounding wire and the fan cable) to the device. Attach the cover plate to the case and tighten the four M3 screws.

Connect the electrodes to the vacuum side of the electrical feedthroughs. Use thick silver-coated round or flat wires to minimize the skin effect and reduce losses. Keep the capacitance of the wires against ground and against each other low by keeping the spacing as large as possible. Use sufficiently large clamps to connect the wires to the electrical feedthroughs. Note that all parts of the output circuitry have to conduct large RF currents, often several Amps or even more than 10 A. Depending on the operating frequency, such currents require conductors with a large surface to minimize losses and prevent heating by the RF.

To power the device, a power mains socket with proper grounding is required. Check the voltage rating on the front panel before connecting the line cord and powering on the device.

! **Warning:** Supplying the device with a voltage outside the specification may permanently damage the device.

Follow the instructions in the section "Quick Setup Guide". Consult the remaining parts of the manual if the device behaves differently to this description. Should that not resolve the problem, contact the distributor or the manufacturer.

Troubleshooting

If the LED indicator *Driver Power* does not light up, check the line connection and the fuses integrated in the IEC inlet *Line Input* on the front panel (see Fig. 1). If the fuses are broken, check the voltage rating of the device and the applied line voltage. If the failure occurs again, contact the distributor or the manufacturer.

If the LED indicator *Driver Power* does not light up green or yellow, but a different color is displayed, this indicates that either the device has overheated (red), the device temperature is too low (blue), or one of the fans is not running properly (cyan, see section "Technical Data"). In case of an over- or undertemperature, let the device acclimatize to the room temperature. Also make sure that the room temperature is within the allowable range (see section "Technical Data").

In case of a fan failure, the generator should not be operated since the cooling may not be sufficient. Locate the defective fan and remove the

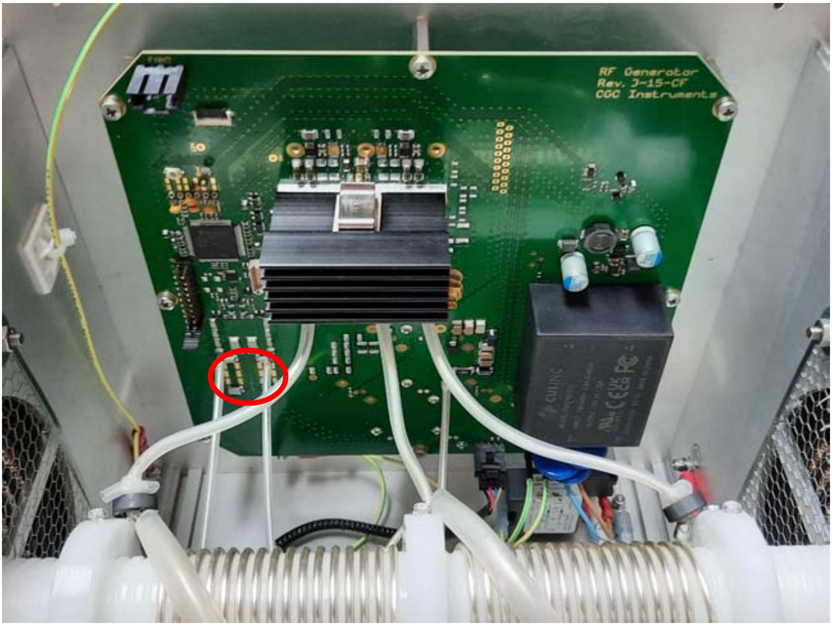

Fig. 4. View of the generator's printed circuit board.
The red circle marks the capacitors *Co1* and *Co2* for adjusting the resonance frequency of the output circuit.

respective cover plate. The fans are mounted on the top and bottom cover plates which can be removed by unfastening the four M3 screws fixing the respective plate (two on the front and two on the rear panel). The cover plate can then be detached and the fan replaced. Contact the distributor or the manufacturer for information on how to obtain the replacement parts.

If the operating frequency differs from the desired value, if the output signals do not have a sinusoidal waveform or are not symmetric, or if the current consumption is larger than expected, i.e. the current consumption does not correspond to the data from the test protocol, the output circuitry has to be checked and/or the output capacitance has to be adjusted.

The most likely cause for strongly asymmetric output signals is a short circuit in the output circuitry. Discharges can also result in asymmetric signals, they can further degrade the signal shape and limit the amplitude. The typical symptom is a strongly increasing current consumption at higher amplitudes.

If the device does not operate at the desired frequency or if the output signals show a small asymmetry, the most likely cause is a wrong output capacitance. The output capacitance consists of the capacitance of the external load (the electrode system, including the connection wires or cables), the internal capacitance from the capacitors *Co1/2* and *Ca1/2*, as well as the internal capacitance of the RF generator. The capacitors *Co1* and *Co2* (see Fig. 4) are adjusted for the desired output frequency in the factory. Check the test protocol for the set values.

! In case of any discrepancy between the observed supply voltage and current and the values given in the test protocol, be extremely careful when increasing the supply voltage of the power stage. If the generator does not behave similarly to the data in the test protocol, the load capacitance is most probably incorrect and the device may easily be overloaded. If the device is operated at higher supply voltages of the output power stage and consumes excessive current to reach a certain output amplitude, it may be permanently damaged. Be sure not to exceed a supply power of 10–20 W in order to prevent any damage if the device does not behave according to the test protocol.

The resonance frequency of an LC circuit is given by the following equation:

$f_R = 1 / \left(2\pi\sqrt{L \cdot C}\right)$,

where L is the inductance and C the capacitance of the circuit. From this, the following difference formula can be derived:

$\Delta C / C = -2\, \Delta f_R / f_R$.

This implies that for a 1% increase of the frequency, the capacitance has to be decreased by about 2%. Knowing the approximate output capacitance and the current output frequency makes it possible to estimate the approximate capacitance difference that will be required to reach the desired frequency.

To implement such changes, the built-in capacitors *Co1* and *Co2* have to be replaced or additional capacitors have to be installed. To gain access to the built-in capacitors, the device cover plate has to be removed: Unfasten the four M3 screws (two on the front and two on the rear panel) that hold the cover plate in place and remove it. Disconnect the grounding wire and the fan cable to be able to remove the cover plate completely. The capacitors *Co1* and *Co2* are located on the printed circuit board (see Fig. 4). For each RF output, a total of four SMT (surface-mounted technology) capacitors can be installed. Remove the installed ones and/or install new ones and measure the operating frequency again. Note that the cover plate also has a minor influence on the operating frequency. Be sure to also measure the operating frequency with the removed cover plate to reflect this influence.

! Be sure to use high-voltage, high-quality capacitors that are able to withstand the high output voltage and frequency. Preferably, the capacitors supplied together with the device should be used. Contact the distributor or the manufacturer for information on how to obtain additional ones.

If the operating frequency equals the desired value but the signal is not symmetric, the capacitors at the RF output with the larger amplitude have to be increased and the capacitors at the opposite output have to be decreased. In contrast to the resonance frequency, the symmetry is a linear function of the capacitance. This implies that a 1% difference between the capacitors will introduce a 1% asymmetry.

If the operating frequency and the symmetry have been adjusted, the printed circuit board should be cleaned and protected by a suitable varnish to provide the required isolation. When failing to do so, discharges may occur at high output amplitudes that may destroy the printed circuit board.

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