Mini-Circuits®

RFS-G90G93750X+ Quick Start Guide AN-60-145

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1. Introduction

This document is a quick start guide for the Mini-Circuits RFS-G90G93750X+ high power signal source and amplifier. The RFS-G90G93750X+ is a solid state connectorized 750W signal source and amplifier module which can be used in a wide range of industrial, scientific, and medical applications in the 902-928 MHz ISM band.

The amplifier contains a microcontroller that actively monitors the PA and support circuitry to ensure proper operation and provides protection to the unit for any extreme operating conditions. The ISC, RFS, and RFX series can be operated by sending text commands over their serial interface(s). These commands are part of a non-proprietary command protocol made to be both legible by humans and suitable for process automation through software. The serial command set enables users to get started quickly and communicate directly with RFS-G90G93750X+ using nothing more than a standard USB cable and PC

2. Overview

2.1 Safety

This PA is capable of delivering high levels of RF power while consuming up to 1.5kW of DC power. All connections internally are shielded, but extreme care should be taken by the user to avoid any exposed DC connections and use high quality shielded RF interconnects. Direct handling of the unit during operation is not recommended

2.2 Block Diagram

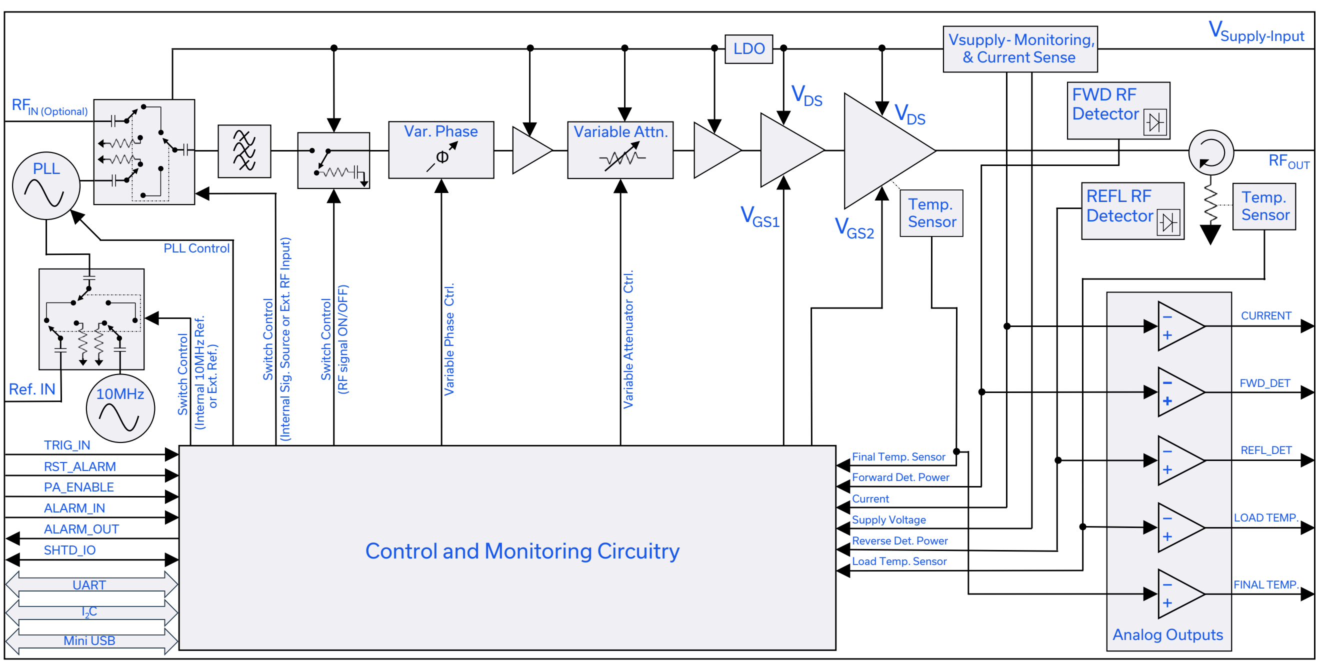


Figure 1. Block diagram of the RFS-G90G93750X+

Electrical Specifications and Ratings

Operational rating details, such as range of acceptable VDD levels or RF input power, are provided by the device Datasheet. It is the intent of this document to get the user up and running quickly, so this guide will refer to general use only.

Functional Description

The RFS-G90G93750X+ is a full RF Energy (RFS) generator and amplifier subsystem that includes a PLL, input switch, variable attenuators and phase shifter, power amplifier, circulator, and control/monitoring/protection circuitry in a single module. All functions needed to monitor and control the RFS-G90G93750X+ are accessible through the serial command set and communication with the units is made over the Mini-USB connector (Ctrl2). In addition to the serial interface, the RFS-G90G93750X+ offers several functions through dedicated pins on the 30-pin connector (Ctrl1) to interface the unit into a larger system. A full description of these pins is included in the datasheet.

3. Heat Sink Mounting

3.1 Importance of the Heat Sink

The RFS-G90G93750X+ generates and dissipate a significant amount of power. At the nominal operating mode of 750W output and assuming 60% efficiency, 500W of heat is dissipated in the amplifier. Mini-Circuits provides the RFS-G90G93750X+ as an amplifier pallet "without a heat sink" leaving the end-user to decide what type of cooling they want to use. Do not attempt to operate the RFS-G90G93750X+ without a heat sink attached to it.

It is important to remember the 500W dissipated power is a best-case scenario where little to no power is reflected back into the amplifier. In reality, the RF load could he very reflective and up to 750W of RF power could be absorbed by the internal power termination for a total of 1250W dissipated power. This is the reason why a water-cooled heat sink is required to remove the heat from the unit and keep it below 60°C (maximum recommended operating temperature). Otherwise, the amplifier will get too hot, the built-in protection alarms will be activated and the power amplifier will shut itself down.

If the user is sure the unit will operate with little to no RF power reflected at the output, then, the power dissipated is to remain at around 500W. In this case, an air-cooled heat-sink with low thermal resistivity and high velocity fan can be used. For more information on a high-performance air-cooled heat sink solution, please contact the Mini-Circuits application team.

There are 12 mounting holes on the RFS-G90G93750X+ to assemble the unit on top of a heatsink. Eleven holes are located beneath the shield cover and one hole is accessible outside the shield (see top section of Figure 2).

3.2 Outline Drawing

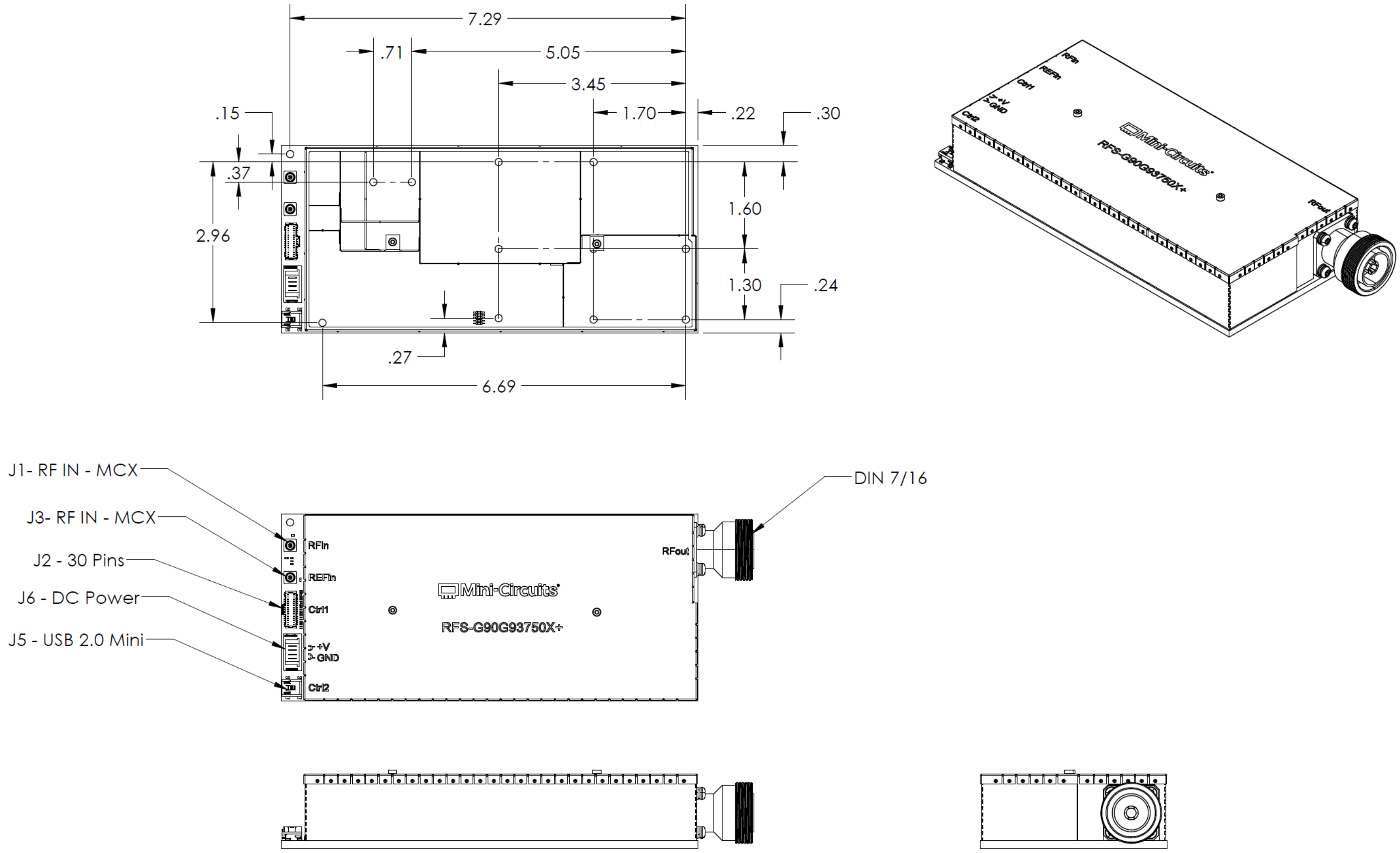


Figure 2. Outline drawing of RFS-G90G93750X+ and assembly holes location.

4. Quick Start Guide

4.1 Required hardware

The following hardware are required to test the unit:

- A computer operating under Windows or Linux.
- An appropriate RF load capable of handling a minimum of 800W of output power.
- A power supply capable of 50V / 1.5kW of DC power.
- An external 10MHz reference signal generator (Signal generator mode only, Optional).
- An external RF signal source (902-928MHz, Max. Pout ≈ 3dBm, Amplifier mode only).

Additionally, the following accessories are required to interface the hardware together:

- USB A – USB-mini cable (Mini-Circuits P/N: MUSB-CBL-3+ or equivalent).
- 7/16-M to 7/16-M RF Cable (Pasternack PE3C7593-50CM 101 or equivalent).
- DC Power supply cable (Samtec P/N UMPC-04-L-16-M-XX.X).
- BNC to MCX-M (Amphenol RF 095-850-303-024 or equivalent, required to interface the external 10MHz reference signal generator).
- SMA to MCX-M (Mini-Circuits Cable P/N FL086-12SMMCR+ or equivalent, required to interface the RF signal source).

Finally, the Mini-Circuits GUI is required on the computer to control the RF Generator / Amplifier. This GUI is developed for integration with touch displays or with a PC and mouse and is available for download on Windows or Linux.

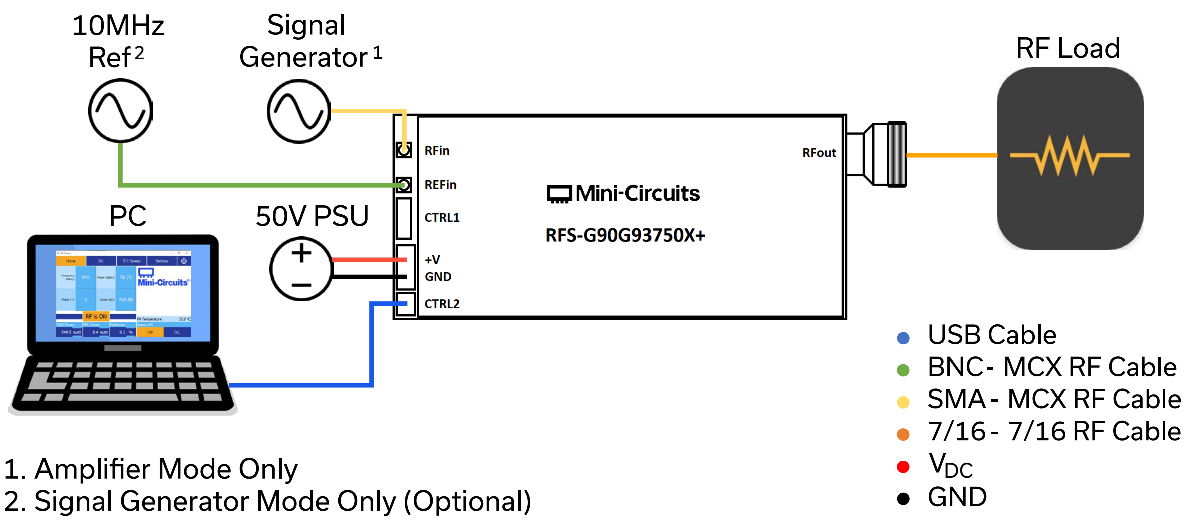


Figure 3. System Assembly Diagram

4.2 Power Up Sequencing

It is recommended to connect the USB port first to power-up the control and monitoring circuit of the RFS-G90G93750X+ before the +50V DC power is applied.

4.3 LED Status Indication

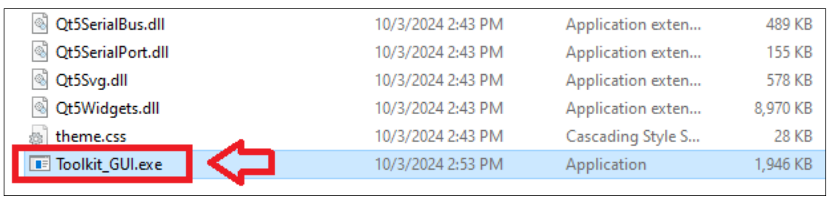
The external LED Status indication is used for quick identification of unit status. The table below indicates the different colors and their meaning.

LED Color	Description
Red	RF line-up is powered-up and active
Blue	USB port is active
Yellow (blinking)	Unit micro-controller is powered-up and active

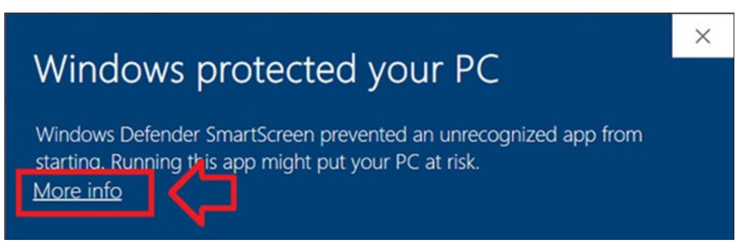
4.4 Set up and run GUI

Windows

Download the GUI first (RF Energy Software Download - Mini Circuits).
1. Simply unzip/extract the files to the desired destination folder.
2. In the extracted folder find the executable 'Toolkit_GUI' and double-click it to start the program.



Windows Defender may prevent the application from running. To grant permission to run the application do the following:
a. Press "More Info".
b. Press the "Run anyway" button that appears at the bottom.

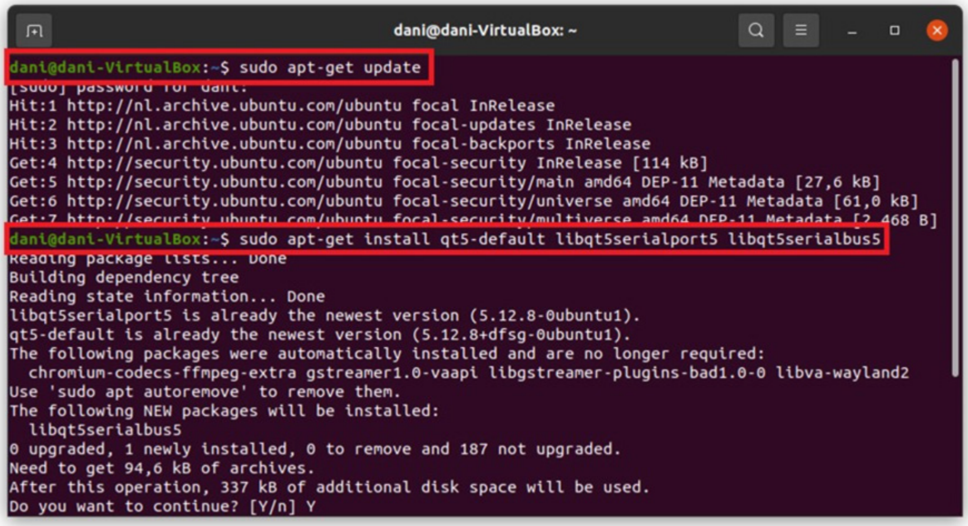


Linux

1. Simply unzip/extract the files to the desired destination folder on the Linux system.
2. Open a terminal (CTRL + ALT + T) and install the necessary dependencies

Input the following lines:
- sudo apt-get update
- sudo apt-get install qt5-default libqt5serialport5 libqt5serialbus5

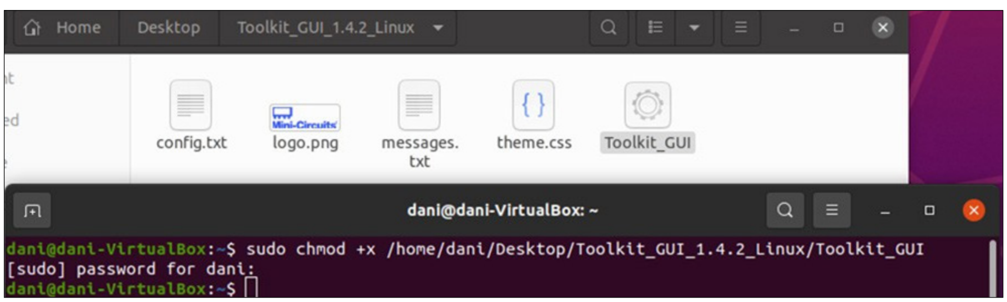
Note: This step requires internet access.
Note: Linux may request permission to do these actions. Provide 'Y' to approve.
Note: Some Linux distributions may use a different packet manager than 'apt-get'.



3. In the extracted folder locate the file 'Toolkit_GUI'.

In the terminal application use the 'chmod' function to grant run permission to the GUI application:

- sudo chmod +x /path/to/Toolkit_GUI

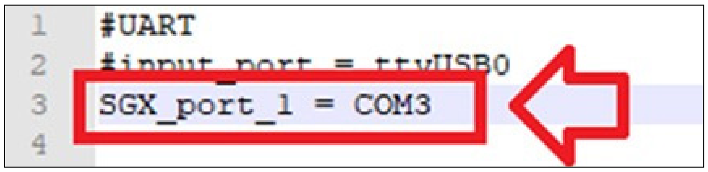


4. Double-click 'Toolkit_GUI' to start the program.

4.5 (Optional) Configure communication port

By default, the application should automatically detect the hardware communication port at which the signal generator is plugged in. If, for whatever reason the application cannot find the signal generator board, it can be forced to use a specific port by editing the program's configuration file.

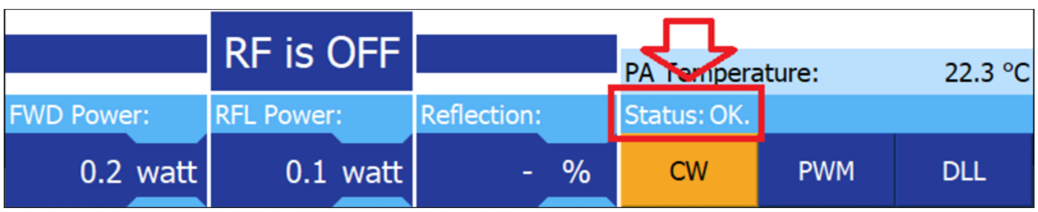
1. In the folder where the software was extracted, find and open the file 'config.txt'.
2. Inside the config.txt file, find the entry 'SGX_port_1' and uncomment it by removing the '#' in front, then provide a valid port name for the signal generator board.



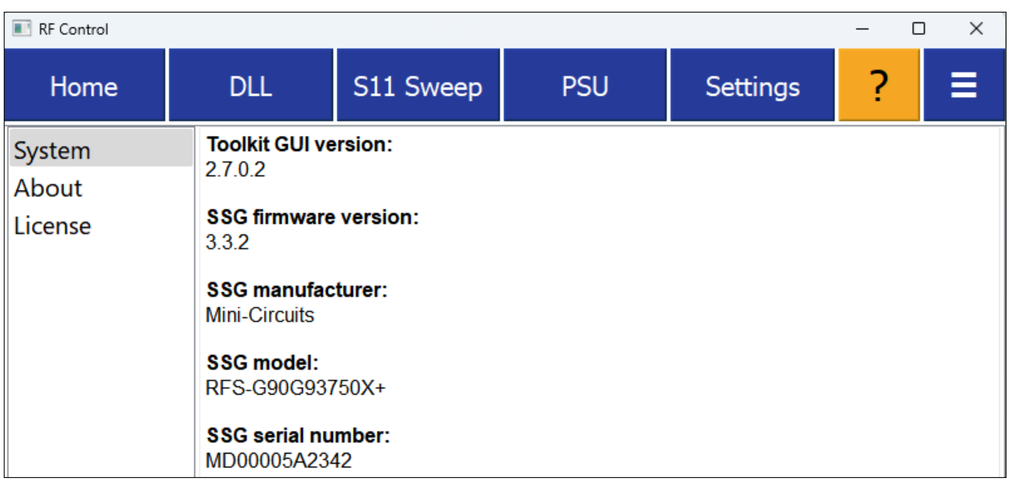
Note: The device's port name can be found using Window's Device Manager or by looking at the Linux' / dev/ directory. For detailed instructions, see section "5.2 Set up communication".
Automatic port detection can be re-enabled again by commenting out the line with a '#'.

4.6 Check system status

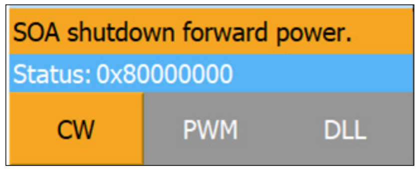
Before continuing to the RF application activity, take a moment to become familiarized with some of GUI's features. In the 'Home' menu take a look at the status bar in the lower right area of the GUI to see if there are any error.



In the 'Settings' menu, take a look at the bottom row to see the version of the signal generator board's firmware, serial number as well as the version of the GUI software.



In this case, the GUI version is 2.7.2.0, the firmware version on the RFS-G90G93750X+ is v3.3.2 and there are no pending errors. If there was an error, it would be displayed on the GUI above the Status line:



The GUI automatically attempts to clear errors. If any errors persist, that means there is an ongoing problem with the setup that must be resolved before continuing.

4.7 Find the best frequency for RF energy delivery

Now you have the GUI installed you will want to run your first application. During an RF heating process, the user wants to make sure that the available RF energy is used optimally to heat up the load (the chosen material). In a typical application, this is not a trivial thing to do: The frequency where energy is effectively transferred into the load is called the "match" and needs to be determined. A good match means most of the RF energy is absorbed by the load, whereas a bad match means a large portion of the energy is reflected back into the RF generator system.

A match can be expressed in different ways depending on the units used to measure RF power. When measuring the power using dBm, the match is expressed as 'S_{11}':

$$S_{11} = (P_{RFL} - P_{FWD})$$

Here, S_{11} is expressed in dB, and the powers P_{FWD} and P_{RFL} are expressed in dBm.

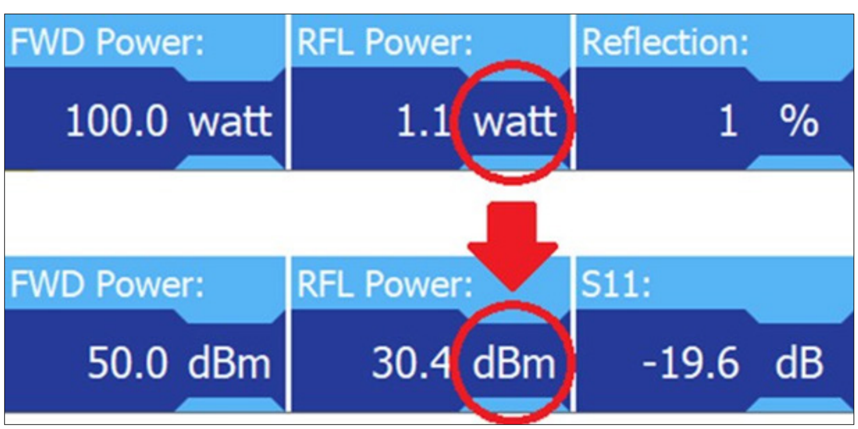
A lower value of S_{11}, the better. For example, a value of about -13dB would indicate that approximately 95% of the forward RF power is used in the cavity and only 5% is reflected.

When measuring the power using watts the match is expressed as "Reflection":

$$Reflection = (P_{RFL} / P_{FWD})$$

The reflection has a value typically between 0 and 1, and is expressed as a percentage (%). The powers P_{FWD} and P_{RFL} are expressed in watt. The closer the reflection is to 0%, the better.

The GUI displays forward power, reflected power and reflection (%) or S_{11} (dB) in the lower left corner. Switching units (watt <-> dBm) is done by clicking the 'unit' button of any of the three displayed parameters:



Though this information is very useful, it is not sufficient to properly optimize the process. To find out the frequency at which to heat (i.e., the match), a frequency sweep should be performed to assess the S_{11} parameter across a pre-defined frequency band. This is done by briefly using low RF power and determining the S_{11} parameter at various frequencies over a given frequency range. The resulting data can be formatted into a graph that provides insight into the possible match within the tested frequency range (Figure 4).
In the example graph below, a 'minimum' S_{11} point can be seen around the 911MHz range, this is the frequency where the reflection is closest to 0 and the RF energy delivery into the load/process would be the most efficient.

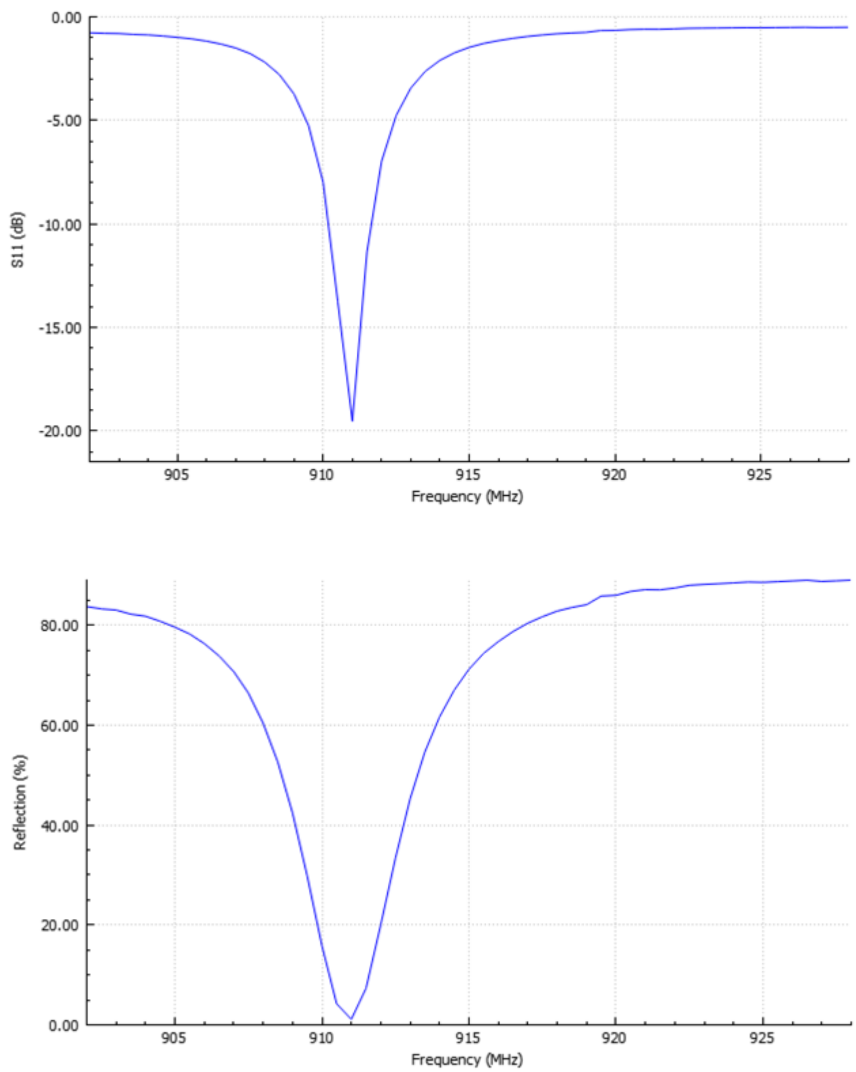
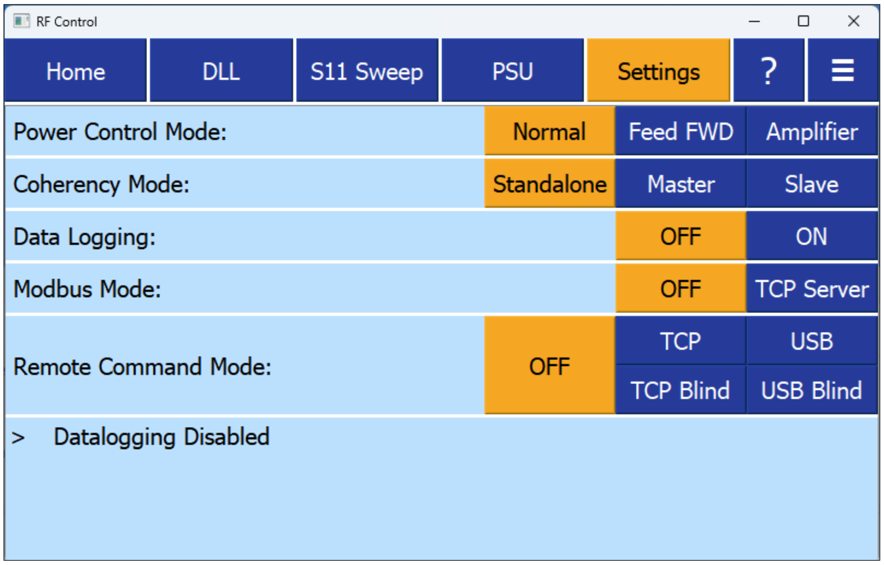


Figure 4. S11 (dB) vs frequency & Reflection (%) vs Frequency

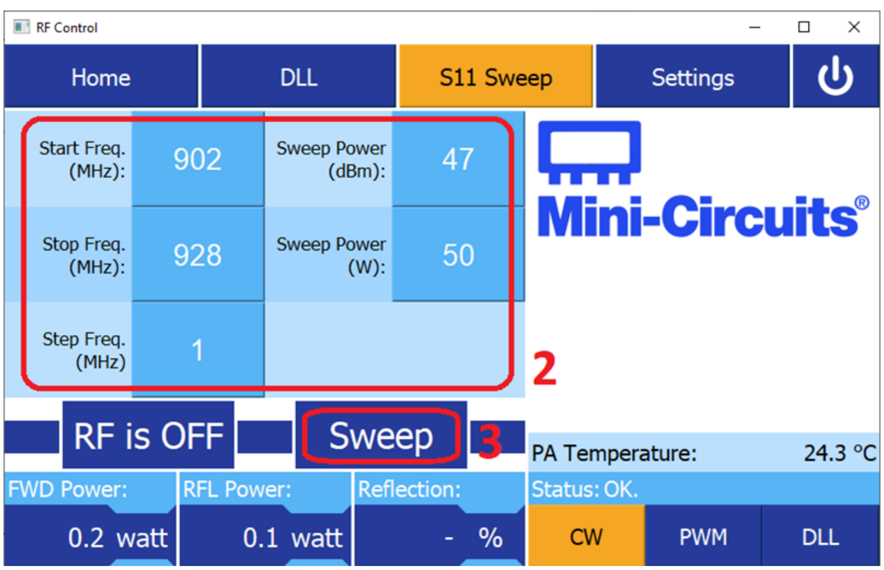
Note: During the execution of a frequency sweep, reflected power will be generated at all mismatched frequencies; it is therefore best to perform the frequency sweep at a lower power than what is intended to be used for the actual heating process to avoid stressing the RF generator. Another reason to use low power is that the user does not want to already process the load during this characterization phase. Typical values of 5-10% of the intended processing power are recommended to be used for the characterization sweep(s). The RFS-G90G93750X+ signal generator supports frequencies in the 902 – 928 MHz range.

In the following example, an S_{11} frequency sweep is performed at 50 watts, in the 902 – 928 MHz range, with a step size of 0.5MHz:

1. Click on the "Settings" Tab, then select the following options:
   a. Power Control Mode: "Normal".
   b. Coherency Mode: Choose "Slave" if you are using an external 10MHz reference signal. Otherwise, select "Standalone".



2. Click on the "S11 Sweep" Tab. Configure the sweep with the parameters below:
   a. Start-Stop-Step Frequency: 902-928-1 MHz
   b. Sweep Power: 47dBm (or 50W)



3. Press on "Sweep" button.

4. After performing a sweep, the GUI outputs the sweep data as a graph (see Figure 5 below). The lowest point in the graph represents the best match. In this case, the minimum is at 920MHz, where the reflection is roughly 1%.

Note: To return to previous page of the sweep menu, press the 'back' button in the top left.

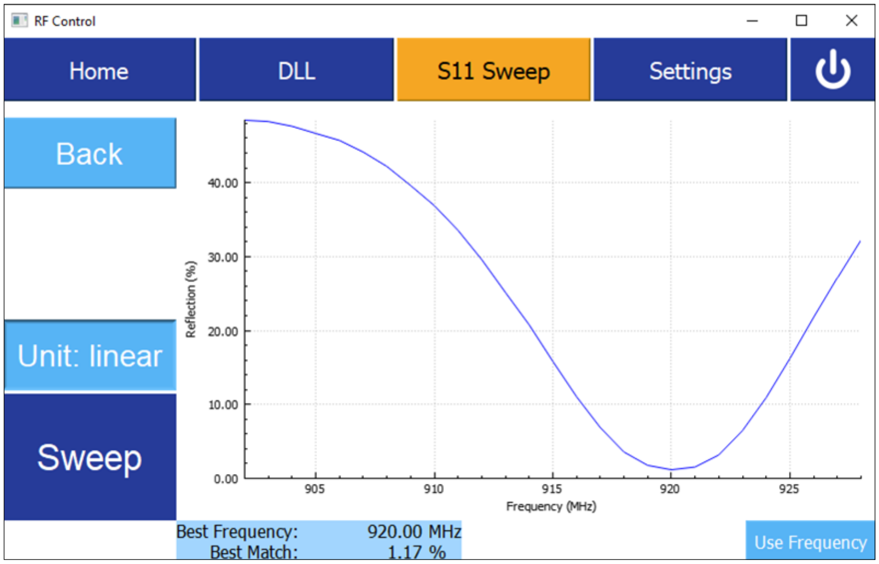
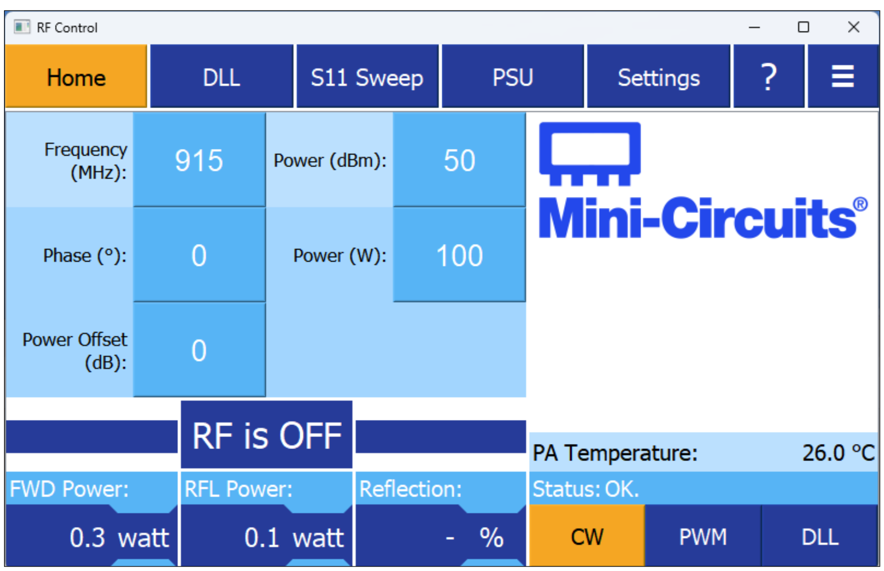


Figure 5. Resulting reflection (%) graph from the sweep just defined

Now that the best match frequency has been found, the RF generator may now be configured for heating.

5. Click on the "Home" Tab.
   a. Set Frequency to 920MHz (per value found in the "S11 Sweep").
   b. Set Power to 58.75dBm (or 750W).

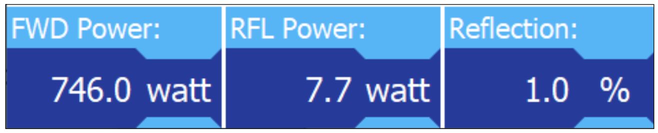


6. With the right frequency and power configured, the RF output may now be switched on. Press the RF ON/OFF button to enable RF

Note: Before turning on the RF output, ensure the RF cannot leak from the cavity.

4.8 Use the digital locked loop (DLL) to track the best match frequency real time

The material in the cavity is now being heated at the optimized frequency.



The GUI displays a forward power of 746W, a reflected power of 7.7W and a reflection value of 1.0%, meaning the material is absorbing some 738W of RF energy. This is in line with the earlier sweep measurement.

4.9 Use the digital locked loop (DLL) to track the best match frequency

As the material continues to heat, its physical properties may start changing. Changes to the load can affect the quality of the match: the best match frequency will shift to a different value. It is more than likely that after a while the match is no longer optimal, and the load reflects too much energy back into the system. Obviously, this is not a desirable situation. To avoid straining the system with a poor match, turn off RF output for the time being.

Conveniently, the RFS-G90G93750X+ board provides a method that tracks the processing frequency as the match changes over time: this is called the "digital locked loop" (DLL). The next few paragraphs describe the usage of this DLL feature. Perform an S_{11} frequency sweep to determine the starting frequency for the DLL algorithm.

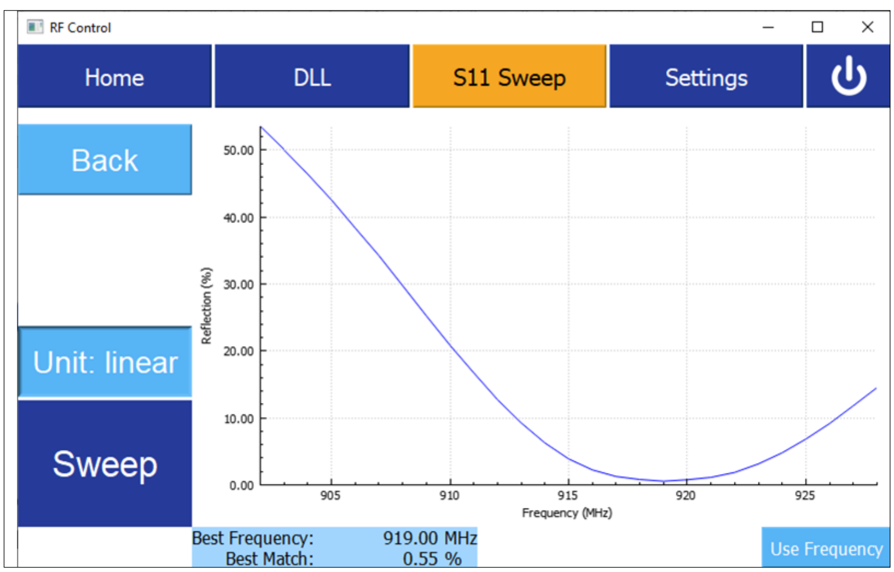
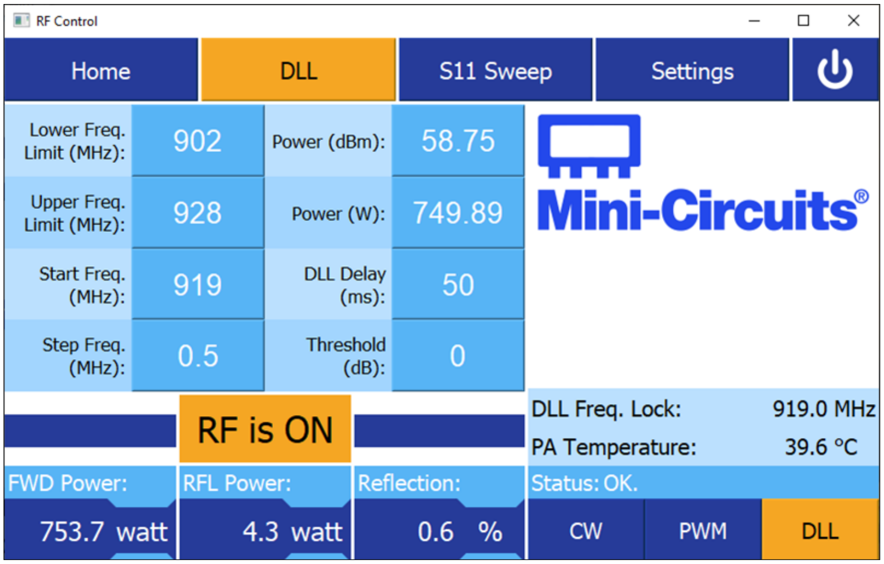


Figure 6. Resulting reflection (%) graph to setup the DLL starting frequency

The sweep indicates the best match frequency has shifted towards 919MHz, where the reflection value is less than 1%.

To enable the real time tracking, we will enable the DLL algorithm to do the frequency tracking for us.

1. Go to the DLL menu
2. Configure the start frequency to 919 MHz
3. Press the DLL enable button in the bottom right corner of the GUI to turn on the DLL.
4. Enable RF output.



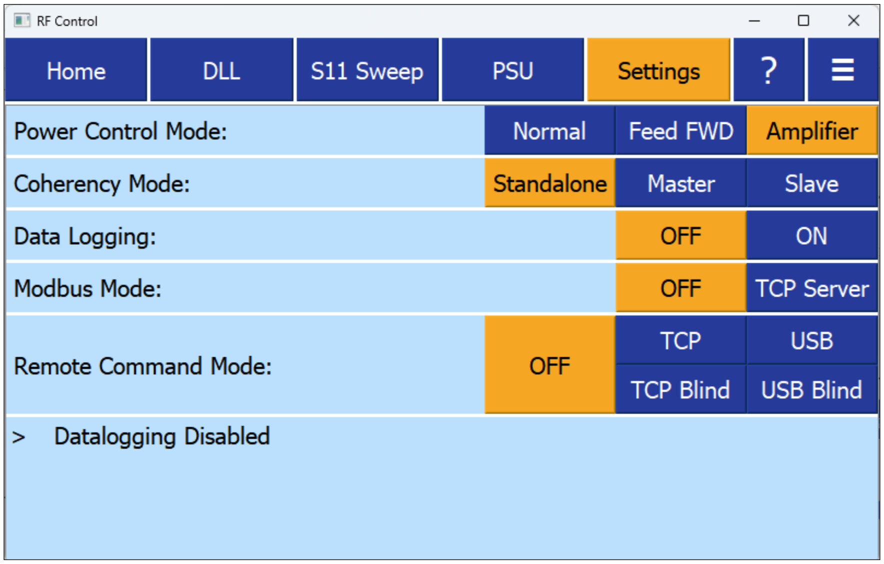
The DLL is now enabled and is tracking the optimum S_{11} frequency as the material heats.
The currently used (locked-) frequency for the DLL can be viewed live on the right side of the GUI in the 'DLL Freq. Lock' bar (or alternatively at the frequency parameter in the home menu).

With the frequency optimized, the chosen material will be processed as per the user requirements. Of course, the exact timing of this process depends on the size of the material and the RF power used and needs to be determined in by the user.

4.10 RF Amplifier mode

If the users want to incorporate the RFS-G90G93750X+ into a system where an external signal generator is already available, then the unit can be used as a Power Amplifier. To enable Power Amplifier mode:

1. Click on the "Settings" Tab, then select the following options:
   a. Power Control Mode: "Amplifier".



Click on the "Home" Tab.

a. Set Frequency so it matches the frequency you are expecting to inject in the amplifier

   The internal power sensor is frequency dependent, so matching this frequency value to the real operating frequency will improve the measurement accuracy. In this example, we will set the value to 915 MHz.

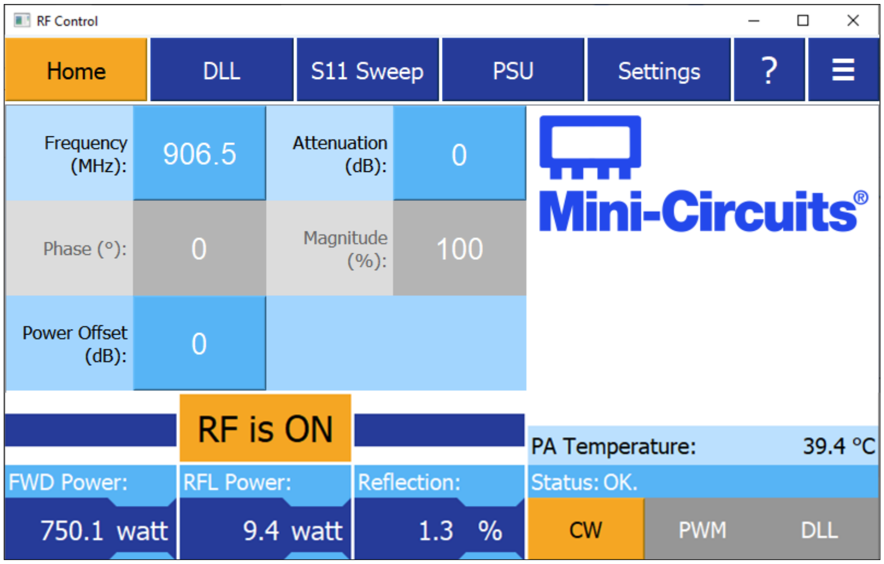
b. Set attenuation to 0dB.

   The assumption here is the amplifier output power is controlled by changing the magnitude of the input power.

   Optionally, the user could also inject a fixed input power and use the variable attenuator to control the output power.

   In all cases, at 0dB of attenuation, an input power of approximately 0dBm should be sufficient to obtain approximately 750W of output power.

c. Turn on the RF output (RF ON/OFF button), ensure the RF cannot leak from the cavity. This turns on the RF switches in the amplifier chain to let the signal through.



The amplifier is now enabled and outputs approximately 750W or RF power.

5. Quick Start (Serial Terminal Interface)

The entire process of the quick start will be repeated now, but this time using the terminal emulator program 'PuTTY' instead. The scenario is the same as before (See chapter "2 Quick Start (GUI)") except for the software used.
When using the command language to control the RFS-G90G93750X+, the user has the option to create and save their own individual recipes to support their specific applications.

5.1 Assemble the hardware

The physical requirements and the assembly of the components are the same as before (See section "4.1 Required hardware"), however instead of the Mini-Circuits GUI, the unit command set is used to operate the generator. This is achieved by using the terminal emulator program PuTTY.

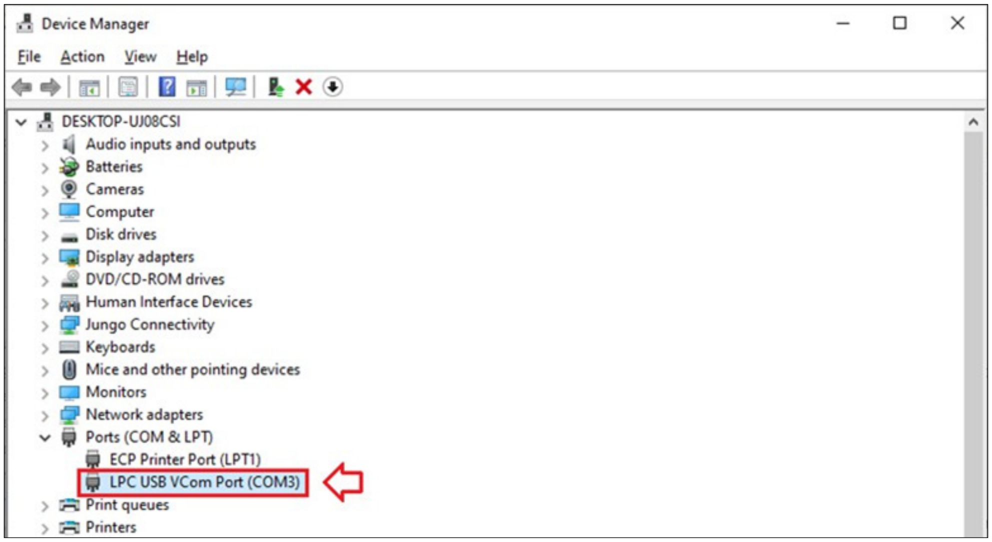
1. PuTTY SSH and telnet client free open-source software
- Windows download available here: https://www.chiark.greenend.org.uk/~sgtatham/putty/latest.html
- Linux variants available through the package manager.

2. Download example (Debian):
- sudo aptitude install putty
- Additional information available here: https://www.ssh.com/academy/ssh/putty/linux

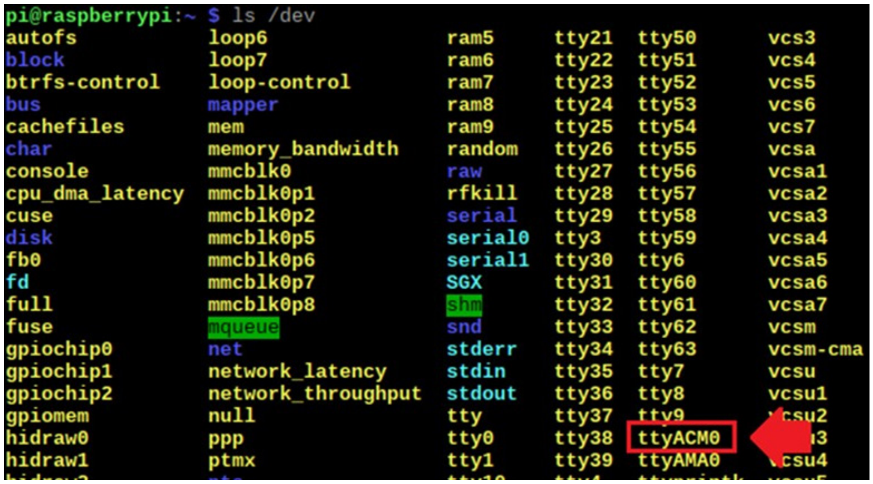
5.2 Set up communication

1. Plug the RFS-G90G93750X+ board into the PC using a mini-USB cable.
2. Find the port name of the device

Windows:
Open the 'Device Manager' in Windows and find the port name of your device. It will show up as an 'LPC USB VCOM Port', followed by the port name.

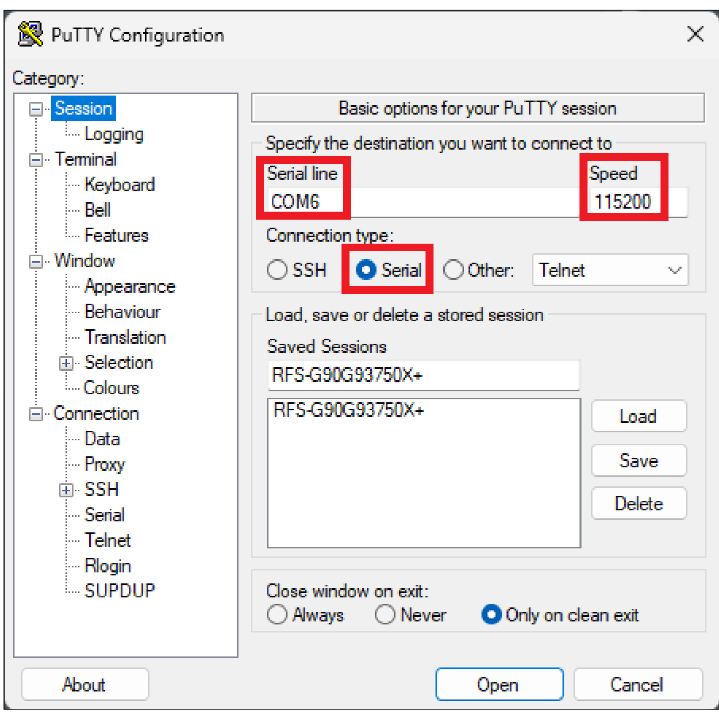


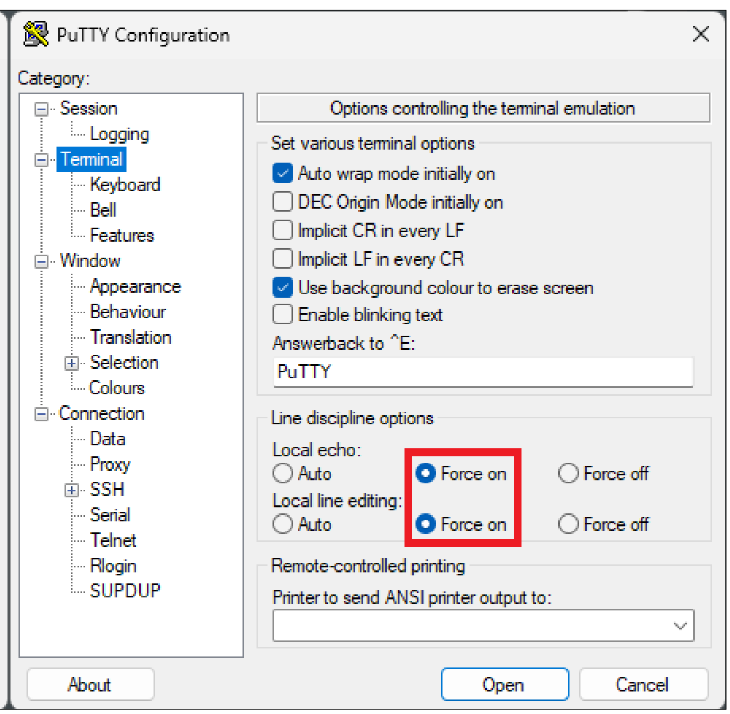
Linux:
Open a terminal (CTRL + ALT + T) and use the "ls /dev" command to view available devices. The signal generator board should appear as a 'ttyACM' device followed by a number.



3. Open PuTTY on your PC and provide the necessary information for the connection with the device. It is highly recommended to configure the settings 'Local echo' and 'Local line editing' to 'Force on'.

Note: Linux requires the full path to the port (e.g., "/dev/ttyACM0").





Save the session, so that it won't need to be reconfigured again in the future and press 'Open' to start a connection with the RFS-G90G93750X+ board.

A blank terminal window will pop up.

5.3 Check system status

Before applying RF, take a moment to gather some data about the system to verify proper functioning:
1. Send the $VER command to view the firmware version of the RFS-G90G93750X+ board.
2. Send the $ST command to check if there are any errors.

```
$VER,1
$VER,1,Mini-Circuits,3,2,0,October 4, 2024,13:19:00
$ST,1
$ST,1,0,0
```

In this case, the firmware version is V3.2.0 and there are no errors pending.

If the $ST command were to return an error value (for example "$ST,1,0,100000000"), use the $ERRC command to reset errors, then send $ST again to see if the errors did not reappear.

```
$ST,1
$ST,1,0,100000000
$ERRC,1
$ERRC,1,OK
$ST,1
$ST,1,0,0
```

If any errors persist, that means there is an ongoing problem with the setup that must be resolved before continuing. All error/warning codes are explained in the "Command set manual".

5.4 Find the best frequency for RF energy delivery

During an RF heating process, the user wants to make sure that the available RF energy is used optimally to heat up the load (the chosen material). The frequency where energy is effectively transferred into the load is called a "match" and needs to be determined. A good match means most of the RF energy is absorbed by the load, whereas a bad match means a large portion of the energy is reflected back into the RF generator system.

To find out the best frequency at which to heat (i.e. a good match), a frequency sweep should be performed to assess the S_{11} parameter across a pre-defined frequency band.

The RFS-G90G93750X+ small signal generator supports frequencies in the 902 – 928 MHz range.

In the example below, an S_{11} frequency sweep is performed at 50 watts, in the 902 – 928 MHz range, with a step size of 2MHz.

- Use the $SWP command to perform an S_{11} frequency sweep in watts.

```
$SWP,1,902,928,2,47,0            Input
$SWP,1,902.0,51.913,0.88731
$SWP,1,904.0,53.159,0.72901
$SWP,1,906.0,54.267,0.58777
$SWP,1,908.0,55.665,0.45160
$SWP,1,910.0,56.779,0.36385
$SWP,1,912.0,58.190,0.29536
$SWP,1,914.0,58.863,0.25963      Response
$SWP,1,916.0,60.737,0.23481
$SWP,1,918.0,62.021,0.26059
$SWP,1,920.0,63.159,0.30638
$SWP,1,922.0,64.771,0.40781
$SWP,1,924.0,65.928,0.58574
$SWP,1,926.0,67.413,0.85533
$SWP,1,928.0,68.756,1.26527
$SWP,1,OK
```

The command ($SWP,1,902,928,2,47,0) returns forward and reflected RF powers in watts at 2MHz intervals, which show that the match is best around 916MHz. At that frequency the reflection is only around 0.4% of the forward power (0.220W / 58.8W = 0.0037 → 0.4%).

Note: For the sake of this guide, a large step size is used in the sweep to keep the resulting data easy to work with. Under normal circumstances a smaller step size like 0.5MHz is recommended as it would yield a better resolution along the frequency axis.

Now that the best match frequency has been found, the frequency of the RFS-G90G93750X+ board needs to be changed to 920MHz.

- Use the $FCS command to set the frequency to 920MHz.

```
$FCS,1,920
$FCS,1,OK
```

5.5 Configure power

For this example, the material will be heated with the maximum available power. The Mini-Circuits RFS-G90G93750X+ PA is a 750W model, so 750W output power will be used.

- Use the $PWRS command to set the power to 750W.

```
$PWRS,1,750
$PWRS,1,OK
```

5.6 Start heating

With the right frequency and power configured, the RF output may now be switched on. Note: Before turning on the RF output, ensure the RF cannot leak from the cavity.

- Use the $ECS command to turn on RF output.

```
$ECS,1,1
$ECS,1,1,OK
```

The material is now being heated. According to the 0.4% reflection value calculated in the earlier step, the load is absorbing some 750W of RF energy and reflecting around 3W back into the RF system. This can be monitored on the fly using the $PPG command:

- Use the $PPG command to get live power measurements.

```
$PPG,1
$PPG,1,748.49046,1.62326
$PPG,1
$PPG,1,748.33409,1.61694
$PPG,1
$PPG,1,748.12561,1.60434
$PPG,1
$PPG,1,747.91714,1.59805
```

The measurements align with expectations: 748W forward power is emitted, 1.6W is reflected back, 746W is absorbed by the load.

5.7 Use the digital locked loop to track the best match frequency

As the material continues to heat, its physical properties will start changing. Changes to the load can affect the matching conditions: the best match frequency will shift to a different value. It is more than likely that after a while the match is no longer optimal, and the load reflects too much energy back into the RF generator. Obviously, this is not a desirable situation.

- To avoid straining the system with a poor match, turn off the RF output for the time being.

```
$ECS,1,0
$ECS,1,0,OK
```

The available DLL tracking algorithm resolves the issue.

- Perform an S_{11} frequency sweep to determine the starting frequency for the DLL algorithm.

```
$SWP,1,902,928,2,47,0
$SWP,1,902.0,51.913,0.88731
$SWP,1,904.0,53.159,0.72901
$SWP,1,906.0,54.267,0.58777
$SWP,1,908.0,55.665,0.45160
$SWP,1,910.0,56.779,0.36385
$SWP,1,912.0,58.190,0.29536
$SWP,1,914.0,58.863,0.25963
$SWP,1,916.0,60.737,0.23481
$SWP,1,918.0,62.021,0.26059
$SWP,1,920.0,63.159,0.30638
$SWP,1,922.0,64.771,0.40781
$SWP,1,924.0,65.928,0.58574
$SWP,1,926.0,67.413,0.85533
$SWP,1,928.0,68.756,1.26527
$SWP,1,OK
```

Input (first line); Response (remaining lines)

The sweep indicates the best match frequency has shifted towards 916MHz, where the reflection value is a mere 0.4% (0.234W / 60.7W = 0.0038 → 0.4%). Please note that the reflection at the previously configured 920MHz has increased to 0.5% in the meantime.

Going forward, the DLL algorithm will do the frequency tracking:

- Use the $DLCS command to configure DLL to start tracking at 916MHz (at the best-known match).
- Use the $DLES command to turn on DLL.
- Use the $ECS command to turn on RF output again.

```
$DLCS,1,902,928,916,0.5,20,100
$DLCS,1,OK
$DLES,1,1
$DLES,1,OK
$ECS,1,1
$ECS,1,1,OK
```

Input (red dots); Response (blue dots)

The DLL is now enabled and is tracking the optimum S_{11} frequency as the material heats. The momentarily used (locked-) frequency for DLL can be viewed using the frequency get command.

- Use the $FCG command to view the frequency as it changes over time

```
$FCG,1
$FCG,1,915.5
$FCG,1
$FCG,1,915.0
$FCG,1
$FCG,1,914.5
$FCG,1
$FCG,1,914.5
```

This shows the DLL is tracking the match downward in frequency as the best match frequency continues to shift over time.

Finish:
While DLL is active, the power transfer toward the load is maximized throughout the heating process.