ScandiNova

TRAINING RF SYSTEMS: THE RF DIGITIZER

RF diagnostics and protection of the klystron

Roger Karlsson

THE RF DIGITIZER

- RF Digitizers are available for both klystron modulators and magnetron modulators.
- The RF Digitizer for klystron modulators is more versatile than the RF Digitizer for magnetron modulators.
- The RF Digitizer for klystron modulators is available in two frequency bands with identical functionality:
  - 50 MHz to 8 GHz (Hittite HMC713LP3E)
  - 8 GHz to 12 GHz (Analog Devices HMC948LP3E, 1 to 23 GHz)
- Only the RF Digitizer for klystron modualtors will be treated here. This presentation is based on the calibration document shown here.
- Once the RF Digitizer for klystron modulators is understood, the RF Digitizer for magnetron modulators can be easily understood.

ScandiNova

Document name					
INSTRUCTION, Calibration of the RF Digitizer					
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Calibration of the RF Digitizer

Abstract

This document describes the ScandiNova RF Digitizer intended for use in klystron pulse modulators with the ScandiCAT control system. It contains instructions for how the RF Digitizer should be calibrated under different conditions and constraints such as klystron rating, waveguide directional coupler attenuation, and parameters/specifications of equipment supplied by ScandiNova that are included as part of the customer purchase order. The RF digitizer provides measurements of the waveguide forward and reflected (reverse) RF power, the Voltage Standing Wave Ratio (VSWR), and RF pulse length. All of these values are presented on the Graphical User Interface (GUI) of the pulse modulator. The klystron drive power can also be shown as a signal proportional to the output power of the RF Amplifier, which drives the klystron. Taking into account the loss of the klystron drive cable, this signal is then calibrated so the proper drive power is displayed on the GUI. A reflected power interlock is also provided that can be set according to the klystron manufacturers maximum reflected power specification. When the maximum reflected power threshold is exceeded the interlock is tripped and the RF Digitizer rapidly switches the Enable signal for the RF Amplifier from +5 V to 0 V. This opens an RF Switch that removes RF drive power and thus klystron RF output within about 0.1 µs. RF Amplifiers delivered as an integrated part of ScandiNova's pulse modulators have this RF Switch incorporated. With the data from the RF Digitizer the modulator can also be configured to interlock when the VSWR becomes too high. This can be used to identify reflections and turn off the pulsing even at power levels lower than the maximum power.

It is important to be aware of that the RF Digitizer only works for pulsed signals

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Page:

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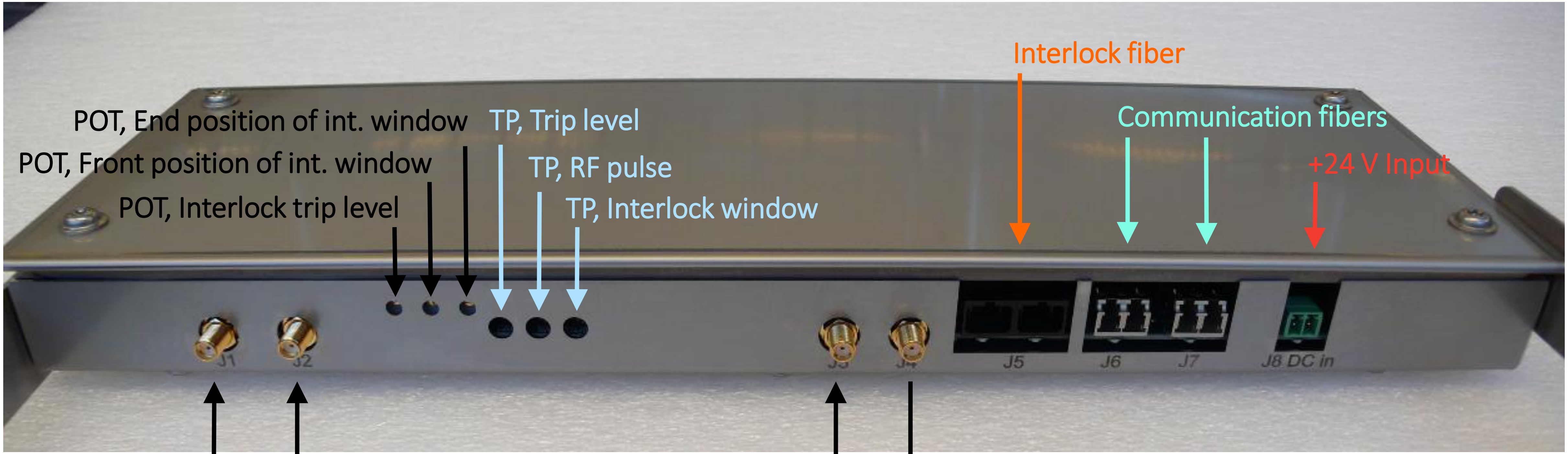
BASIC OVERVIEW OF THE RF DIGITIZER

RFDU – RF Digitizer Unit
Adapted with mounting brackets for 19” cabinets

BASIC OVERVIEW OF THE RF DIGITIZER



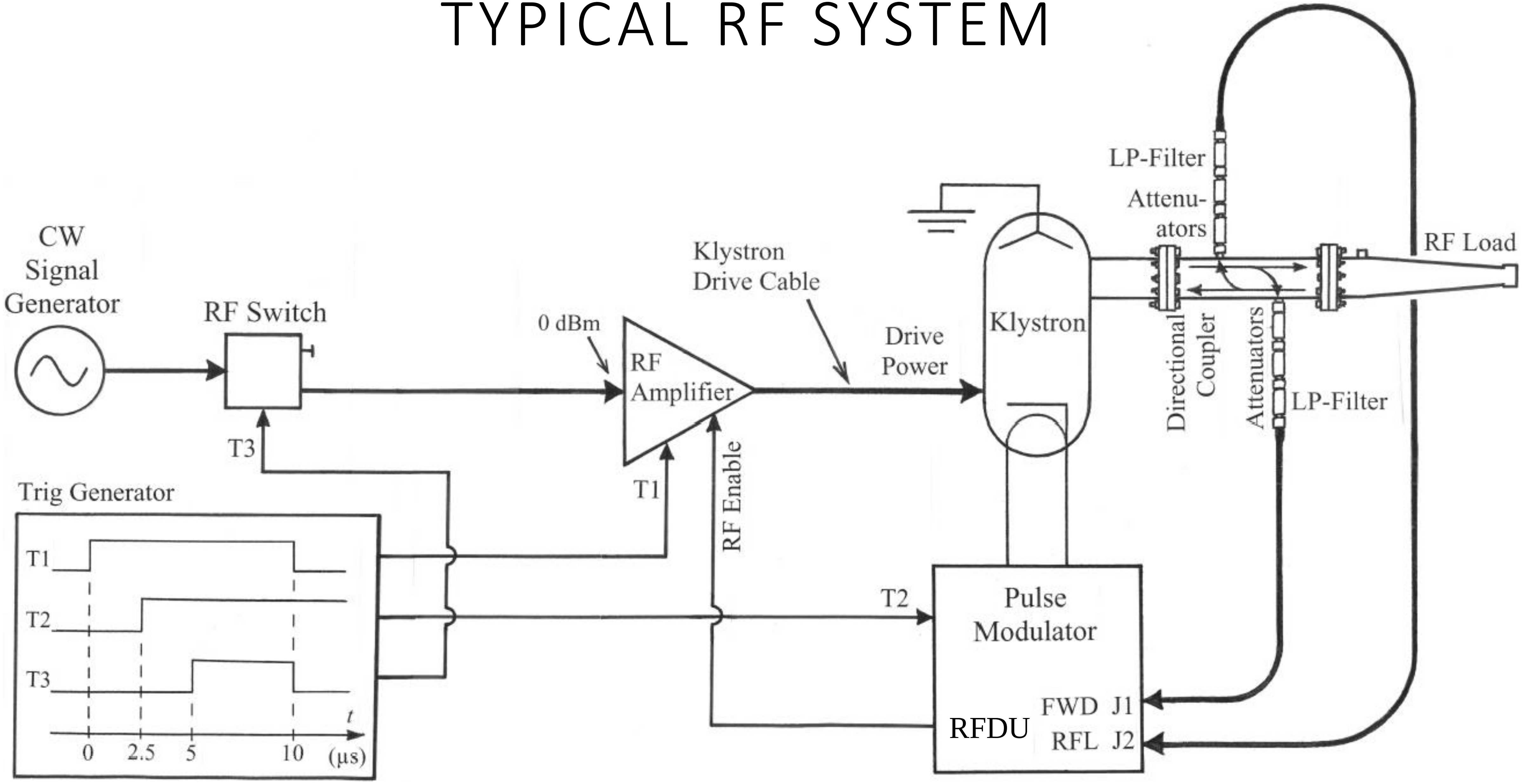
Forward
RF Input

Reflected (reverse)
RF Input

Electric Trig
(not used)

+5 V Enable signal to fast RF
Switch inside the RF Amplifier.
Reflected power Interlock!

TYPICAL RF SYSTEM



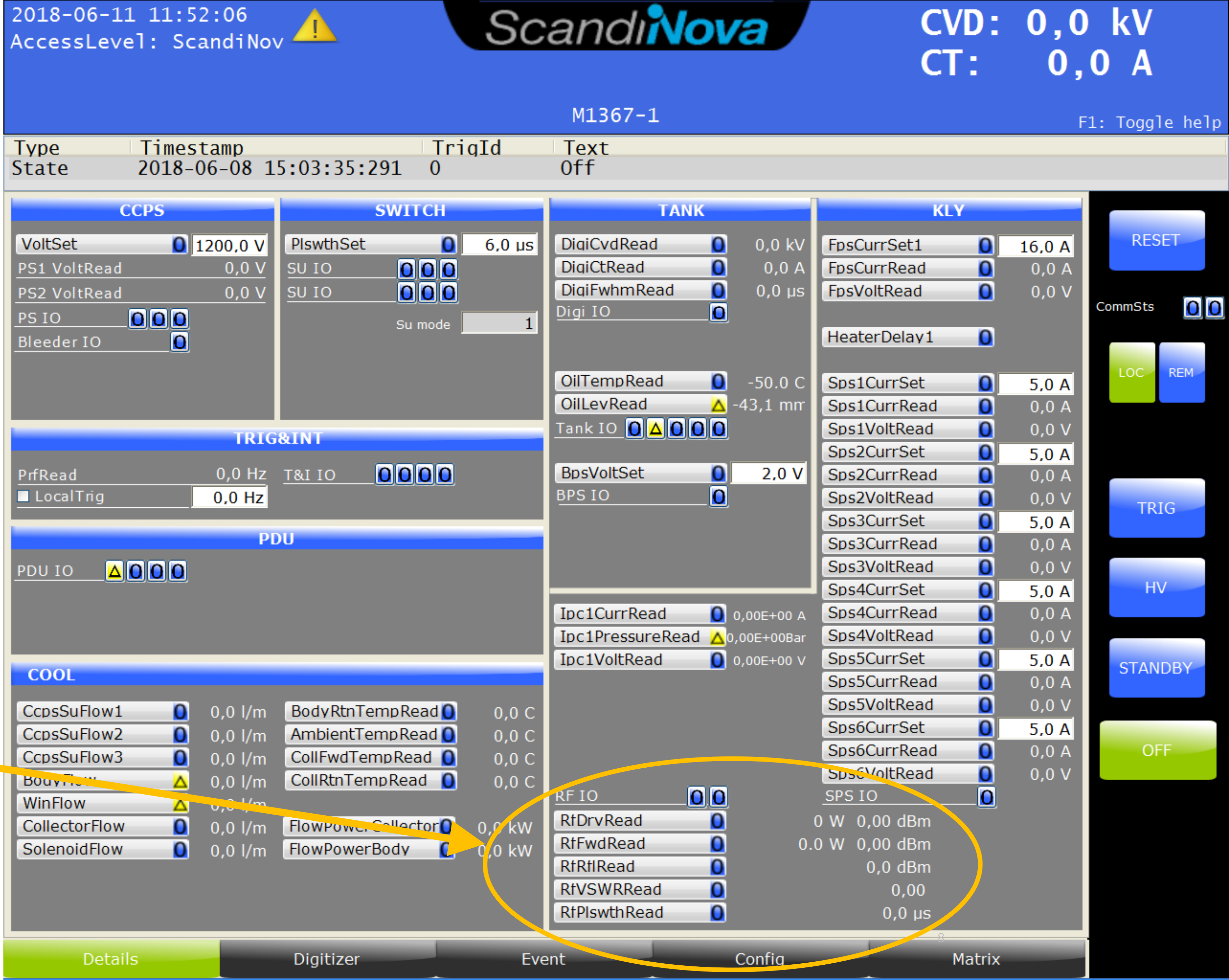
SETTING UP THE SYSTEM

- Pulse modulator GUI
- Klystron drive power
- RF Digitizer settings
  - Adjustment of potentiometers
  - Setting sampling position and sampling length
- RF Digitizer calibration
  - Forward RF power: choise of attenuators and calibration of Forward power
  - Reflected RF power: choise of attenuators and calibration of Reflected power
  - Reflected power interlock
  - VSWR interlock
  - Klystron drive power
  - RF pulse length

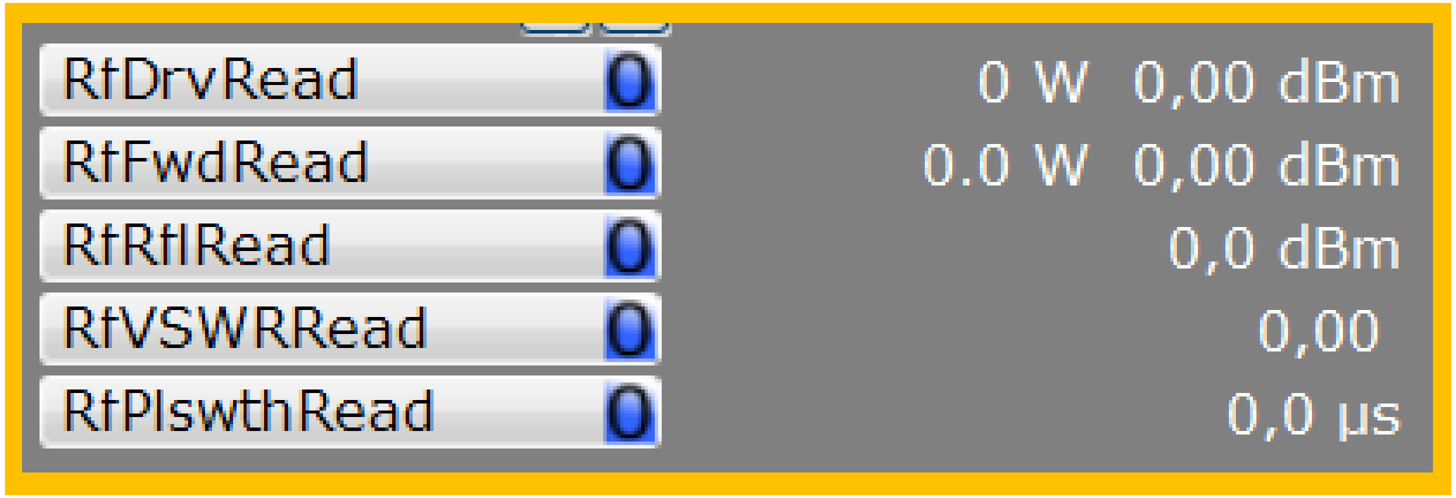
PULSE MODULATOR GUI

PULSE MODULATOR GUI

RF parameters

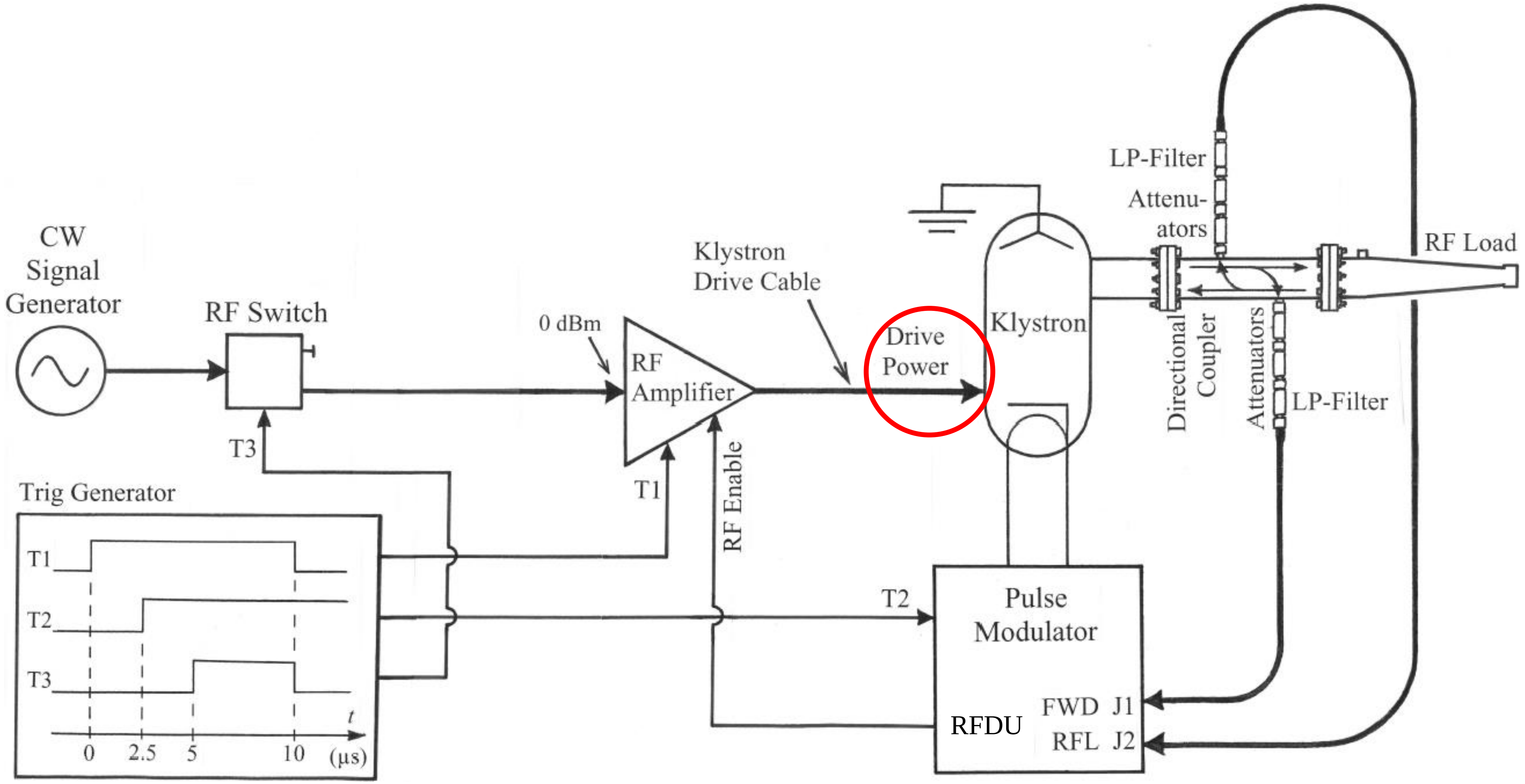


PULSE MODULATOR GUI



- **RfDrvRead:** Klystron drive power, P_{drive} (Watt and dBm)
- **RfFwdRead:** Klystron output power, P_{FWD} (MWatt and dBm)
- **RfRflRead:** Reflected RF power, P_{RFL}, travelling back to the klystron (dBm)
- **RfVSWRRead:** Voltage Standing Wave Ratio, VSWR
- **RfPlswthRead:** RF pulse length (µs)

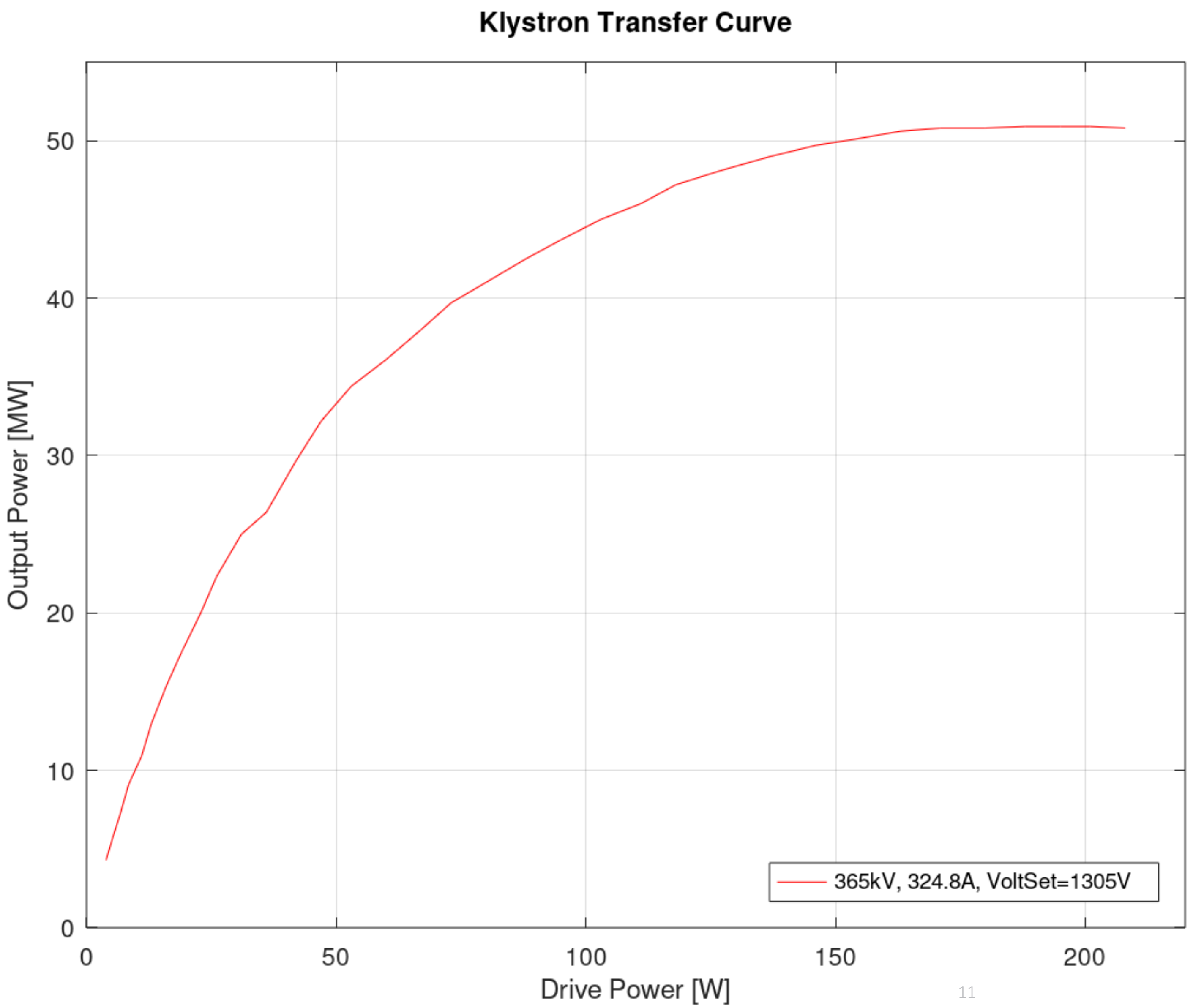
KLYSTRON DRIVE POWER



KLYSTRON DRIVE POWER

- The klystron drive power is specified in the FAT protocol from the klystron manufacturer.

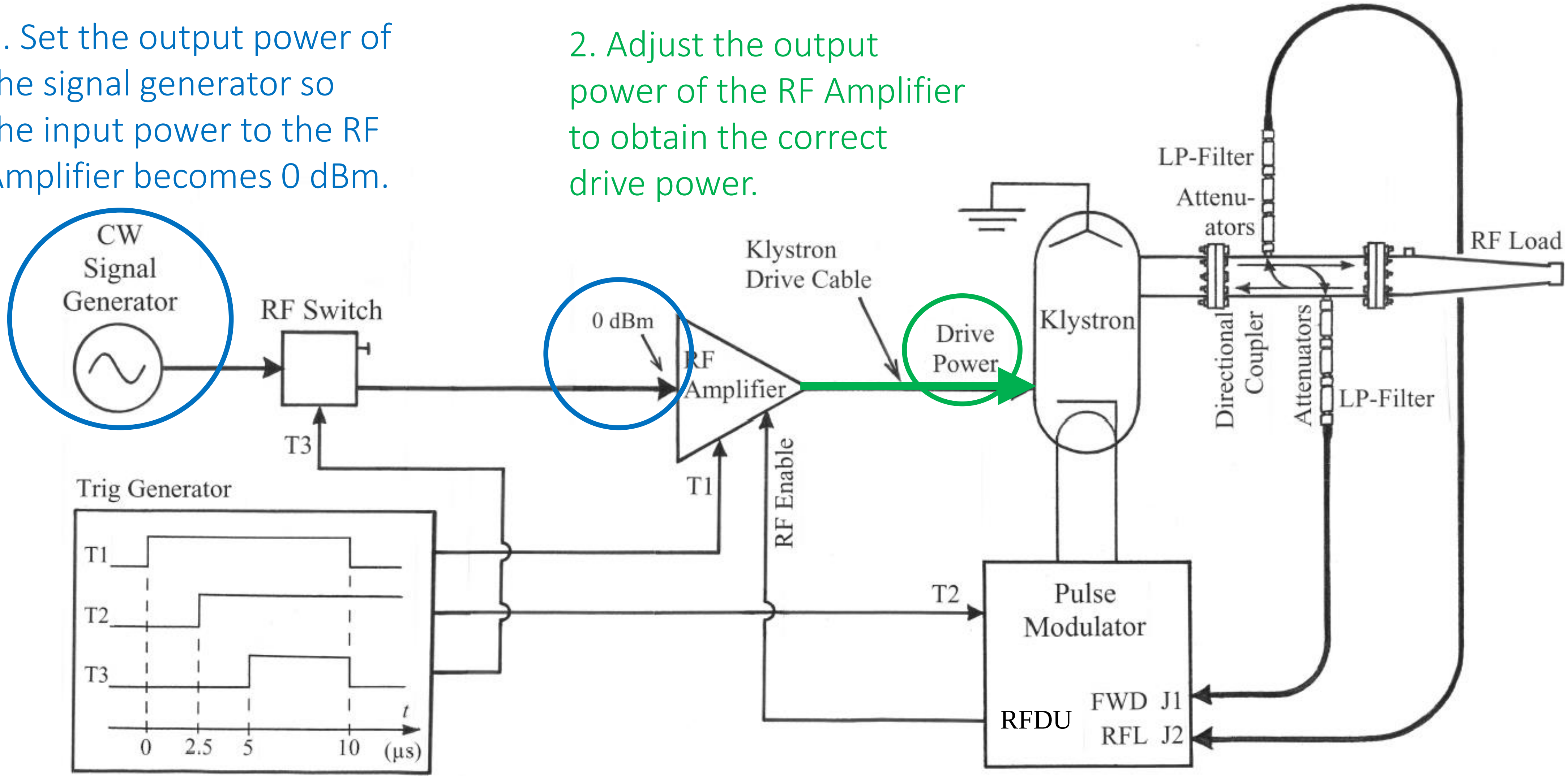
- Alternatively, the drive power can be estimated from the klystron transfer curve.



KLYSTRON DRIVE POWER

1. Set the output power of the signal generator so the input power to the RF Amplifier becomes 0 dBm.

2. Adjust the output power of the RF Amplifier to obtain the correct drive power.

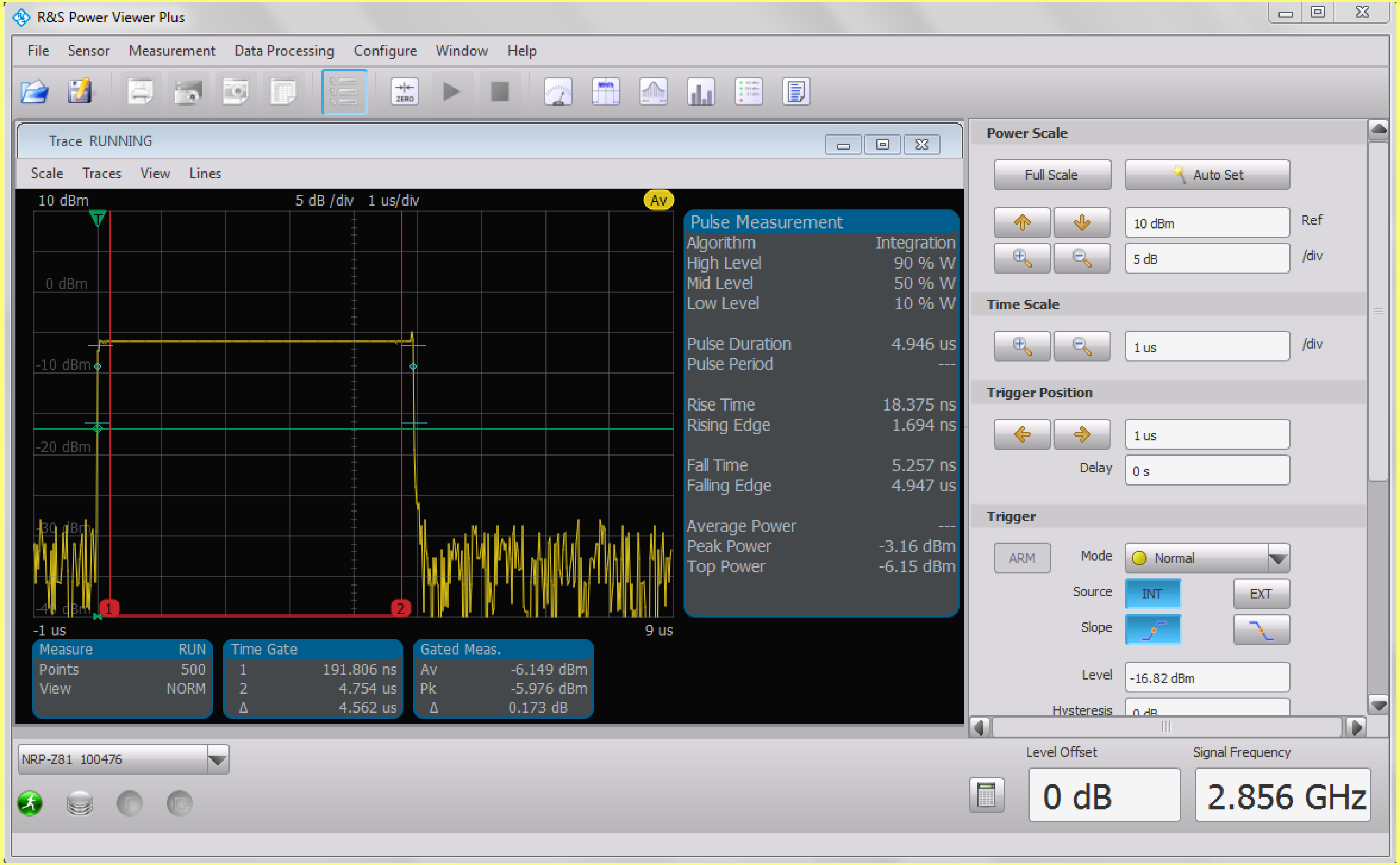


NOTE: RF Amplifier output power ≠ klystron drive power

EXTRA: RF POWER SENSOR

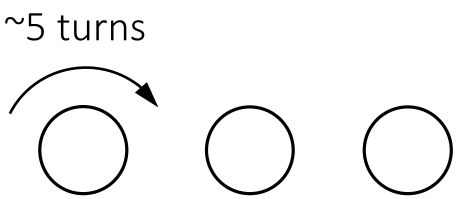
R&S NRP-Z81 Pulsed Power Sensor

- 18 GHz
- –60 dBm to +20 dBm

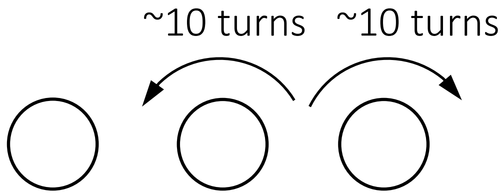


RF DIGITIZER SETTINGS

Adjustment of potentiometers



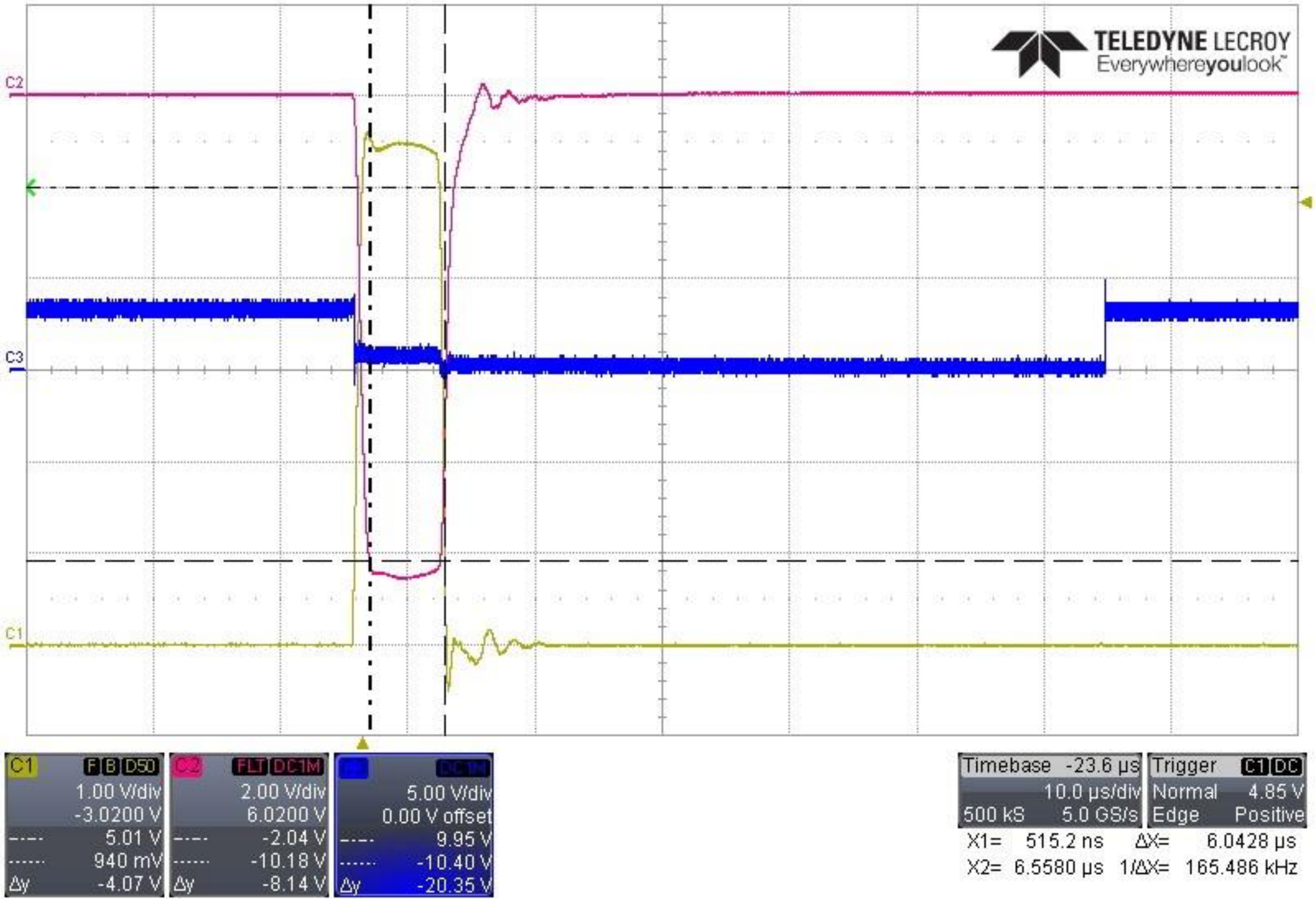
Increase the reflected power interlock level. Needed in order to be able to calibrate the reflected RF power, otherwise an interlock will be generated.



Set the interlock window as wide as possible.

RF DIGITIZER SETTINGS

Interlock window



Yellow: Modulator current pulse.

Red: Modulator voltage pulse.

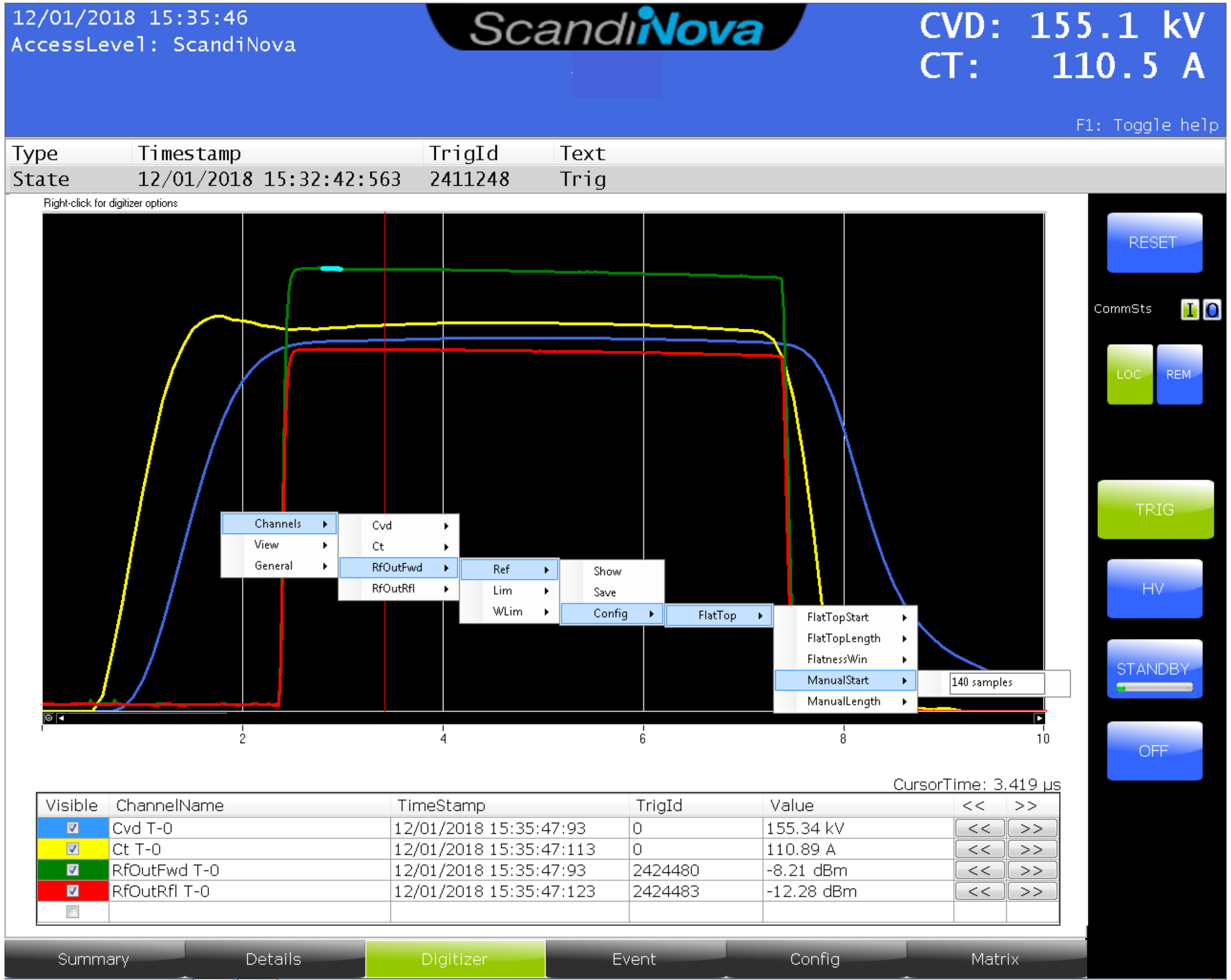
Blue: Interlock window, stretching almost 60 µs.

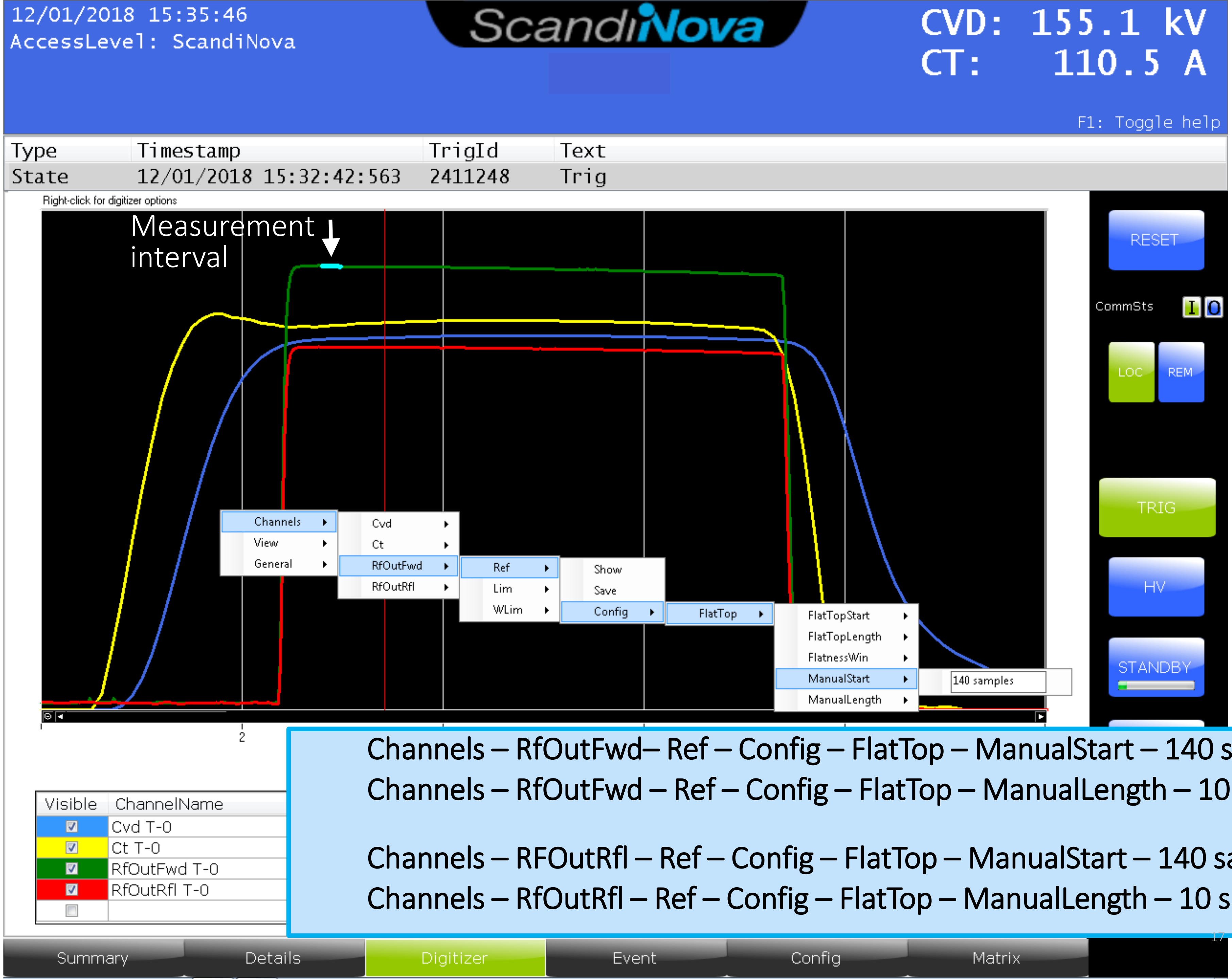
Time scale: 10 µs/div.

RF DIGITIZER SETTINGS

Setting sampling position and sampling length

Right-click in the Digitizer view



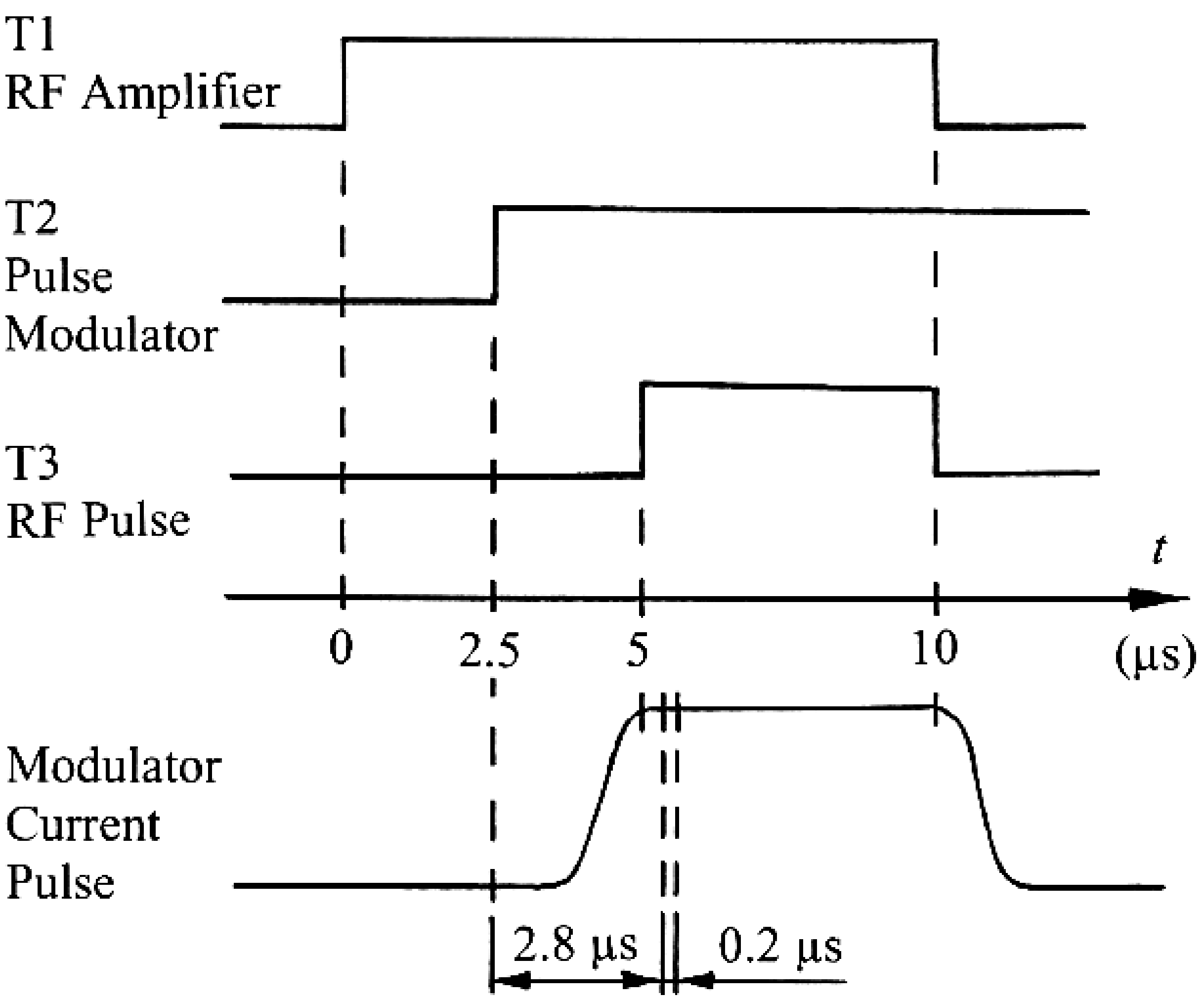


Channels – RfOutFwd– Ref – Config – FlatTop – ManualStart – 140 samples
Channels – RfOutFwd – Ref – Config – FlatTop – ManualLength – 10 samples

Channels – RFOutRfl – Ref – Config – FlatTop – ManualStart – 140 samples
Channels – RfOutRfl – Ref – Config – FlatTop – ManualLength – 10 samples

RF DIGITIZER SETTINGS

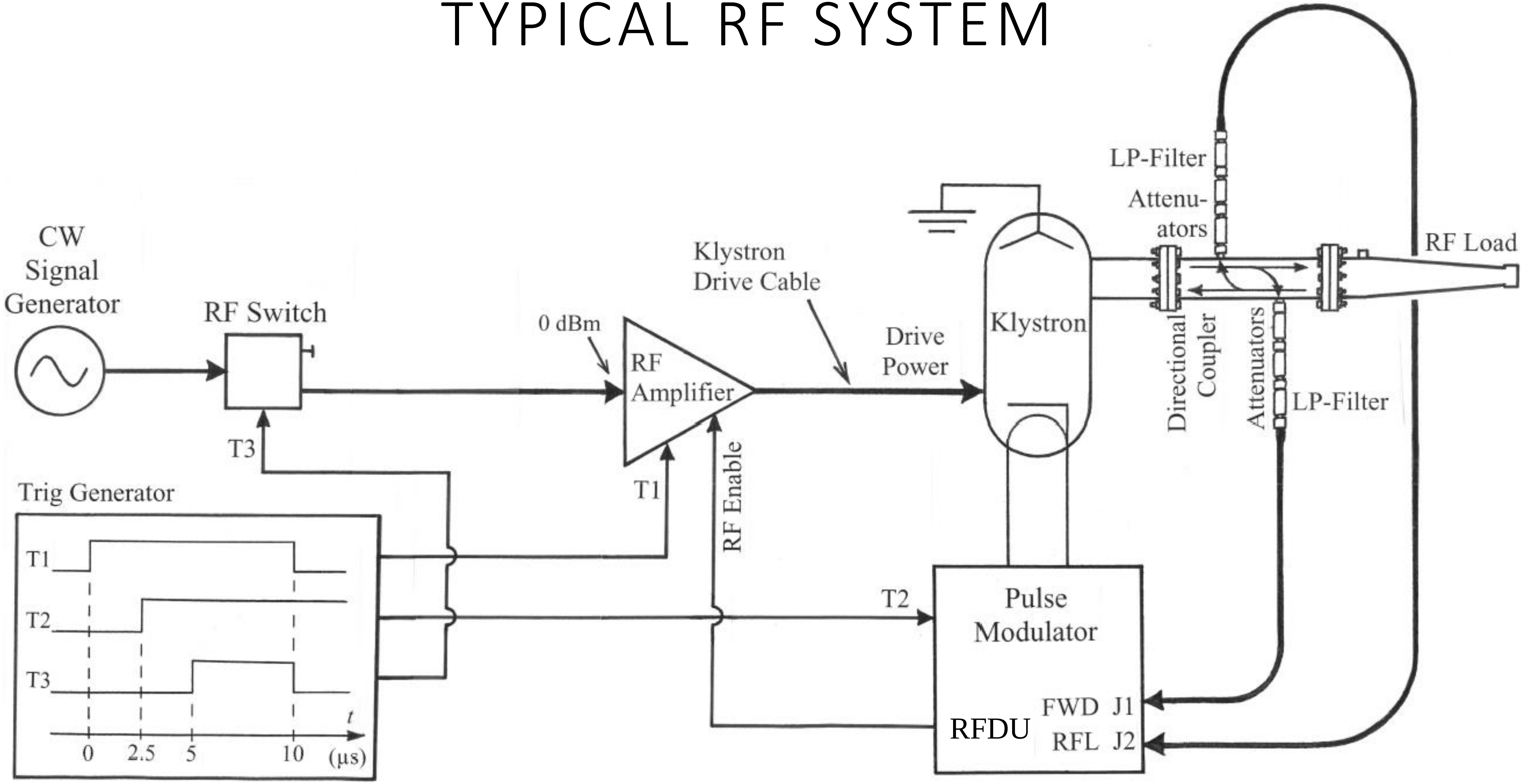
Setting sampling position and sampling length



ManualStart:
140 samples × 20 ns/sample = 2.8 μs

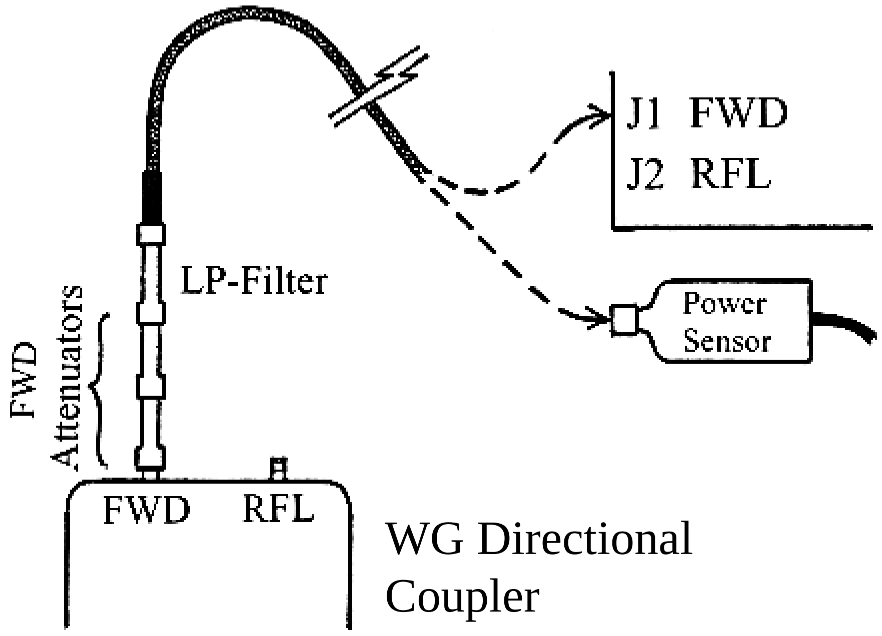
ManualLength:
10 samples × 20 ns/sample = 0.2 μs

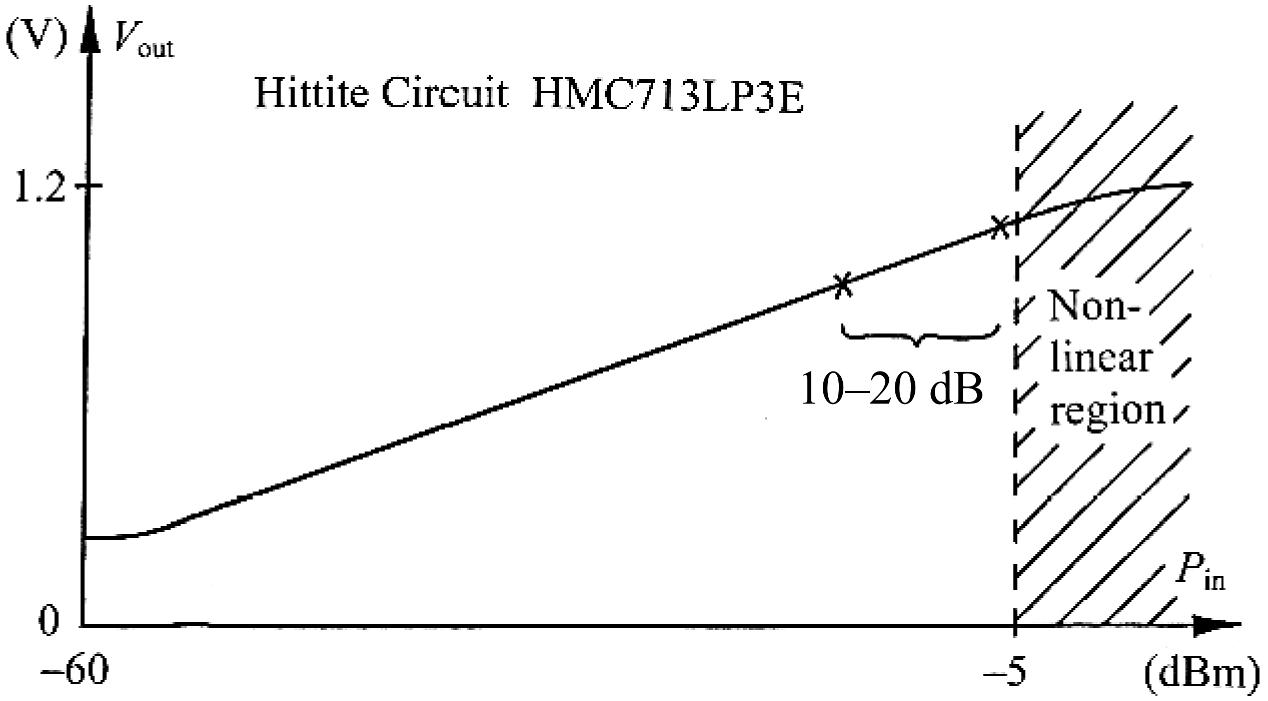
TYPICAL RF SYSTEM



RF DIGITIZER CALIBRATION: FORWARD RF POWER

Selection of attenuators

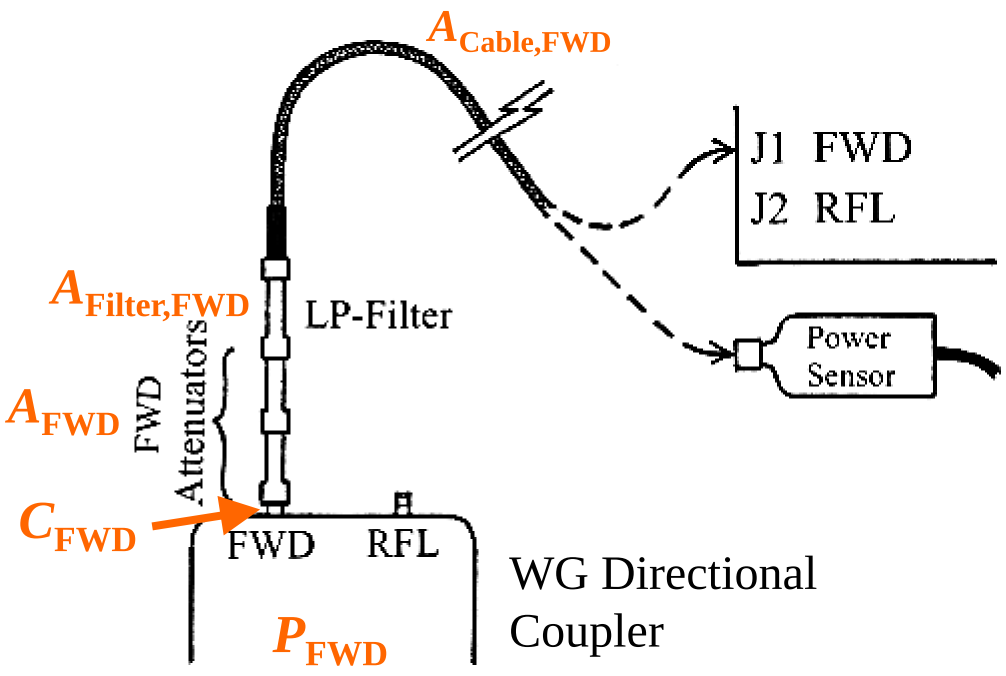




- The RF circuits inside the RFDU becomes non-linear above –5 dBm.
- Select the forward attenuators so the input power to the RF Digitizer becomes < –5 dBm.

RF DIGITIZER CALIBRATION: FORWARD RF POWER

Selection of attenuators



- Move from the WG along the RF path to the input of the RF Digitizer:

$$P_{FWD} - C_{FWD} - A_{FWD} - A_{Filter,FWD} - A_{Cable,FWD} < -5 \text{ dBm}$$

- Solve for A_{FWD}, the attenuation needed for Forward power.
- Select attenuator values so that the their sum will be larger than A_{FWD}

P_{FWD} = WG forward power = klystron output power
C_{FWD} = Coupling of forward port of directional coupler
A_{FWD} = Attenuation of the sought attenuators
$A_{Filter,FWD}$ = Attenuation of a possible LP-filter
$A_{Cable,FWD}$ = Attenuation of the cable to the RF Digitizer

RF DIGITIZER CALIBRATION: FORWARD RF POWER

Selection of attenuators

Example 1: Determine the attenuation that should be placed at the forward port of the waveguide directional coupler for a system with the following characteristics:
Klystron output RF power = 10.0 MW,
forward coupling of the directional coupler = 60.52 dB,
passband attenuation of a LP-filter for the forward port = 0.40 dB,
attenuation of the RF cable connecting to the RF Digitizer = 2.60 dB.
Also, consider the power requirements of the attenuators to be selected.

Solution: The klystron output RF power of 10.0 MW corresponds to

$$P_{FWD} = 10 \log_{10}(10.0\ \text{MW}/1\ \text{mW})\ \text{dBm} = 100.00\ \text{dBm}$$

Inserting the values in the inequality on the previous page gives

$$100.00\ \text{dBm} - 60.52\ \text{dB} - A_{FWD} - 0.40\ \text{dB} - 2.60\ \text{dB} < -5\ \text{dBm}$$

This gives the forward attenuation

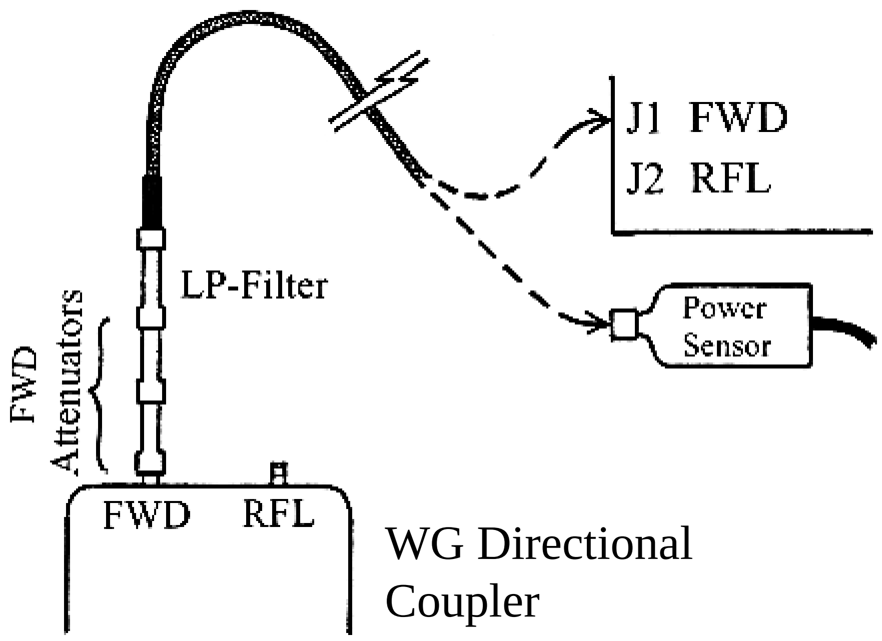
$$A_{FWD} > 41.48\ \text{dB}$$

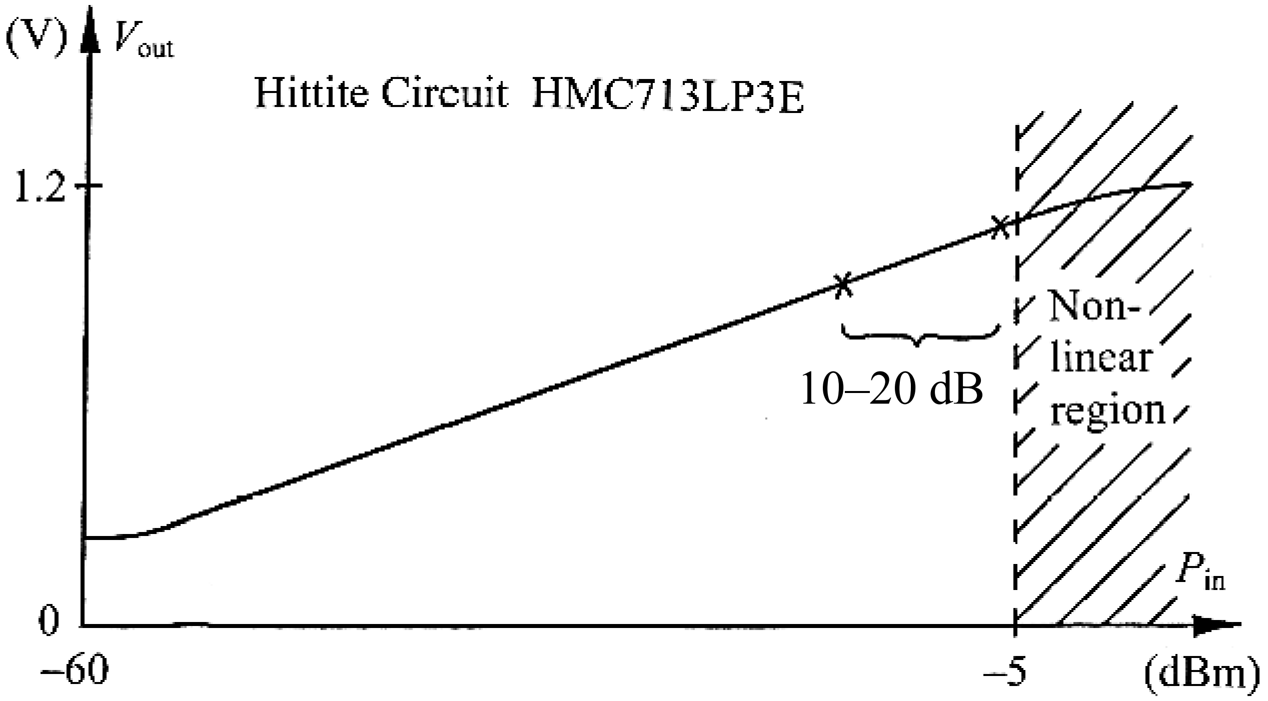
Select $A_{FWD} = 43$ dB, which can be implemented as *e.g.* 3 dB + 40 dB or as 3 dB + 10 dB + 30 dB, depending on availability of attenuator values.

The power handling capability of the attenuators should also be considered. They will be exposed by a peak RF power of 100.00 dBm – 60.52 dB = 39.48 dBm = 8.9 W. The average power will be substantially less, typically 0.001 times the peak power. Anyway, the power handling capability of the attenuators should not be too low. It is recommended that at least 2 W attenuators be used.

RF DIGITIZER CALIBRATION: FORWARD RF POWER

Calibration of forward RF power

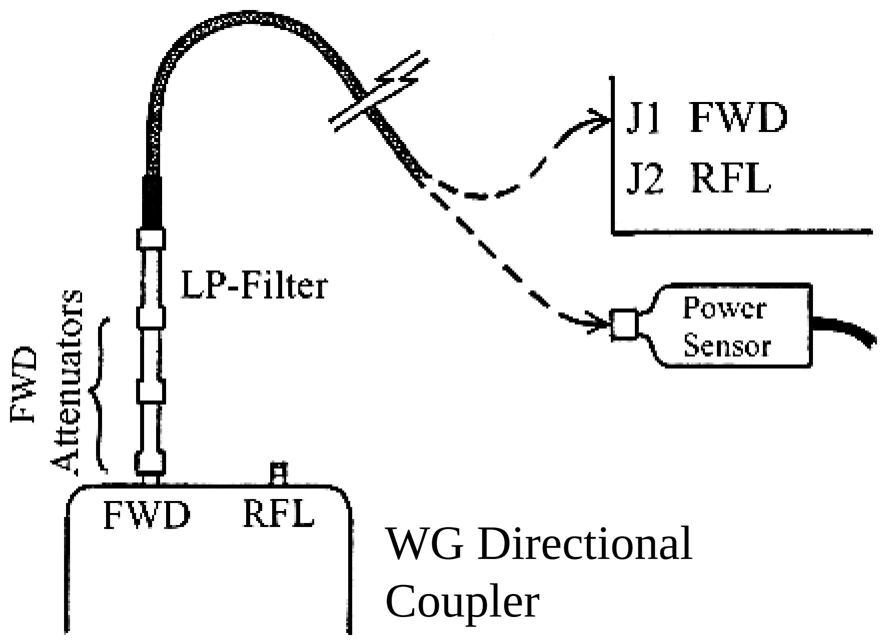


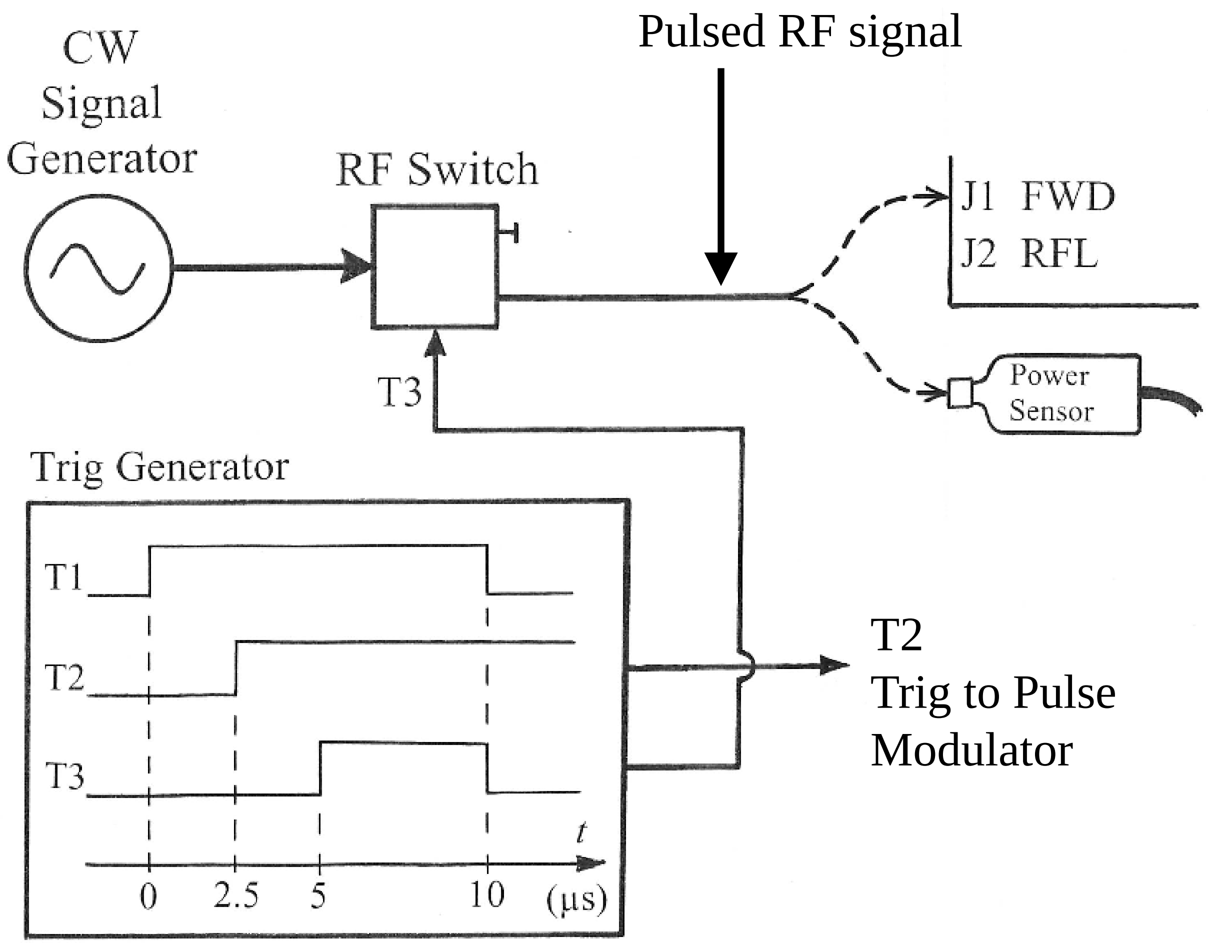


- Select the first calibration point just below –5 dBm and the second 10–20 dB lower. Measure the RF power with *e.g.* a power sensor.
- Use *well-known* attenuator(s) to set the power level of the second calibration point. Don't use the power sensor at this very low power level!

RF DIGITIZER CALIBRATION: FORWARD RF POWER

Calibration of forward RF power: calibration source



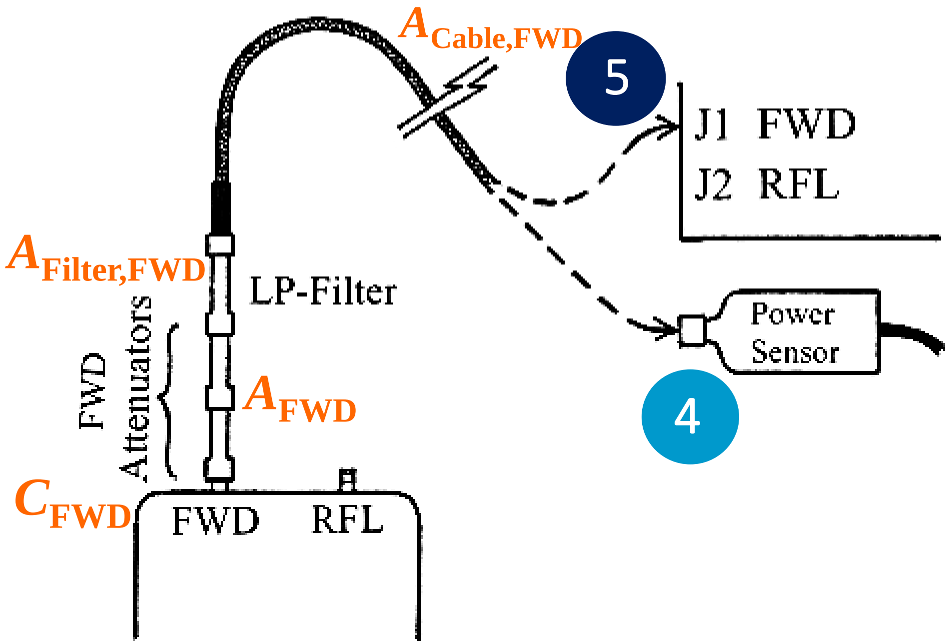


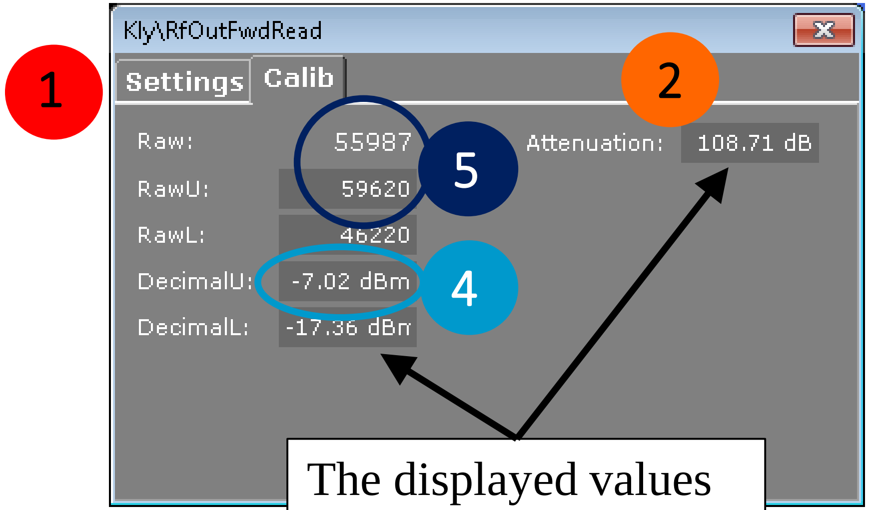
Calibration source:

- Use either the RF power from the forward port of the WG directional coupler or
- Use a signal generator to create the pulsed RF signal of power <≈ –5 dBm

NOTE: The input signals to the RF Digitizer **must be pulsed**!

RF DIGITIZER CALIBRATION: FORWARD RF POWER





The displayed values are just examples.

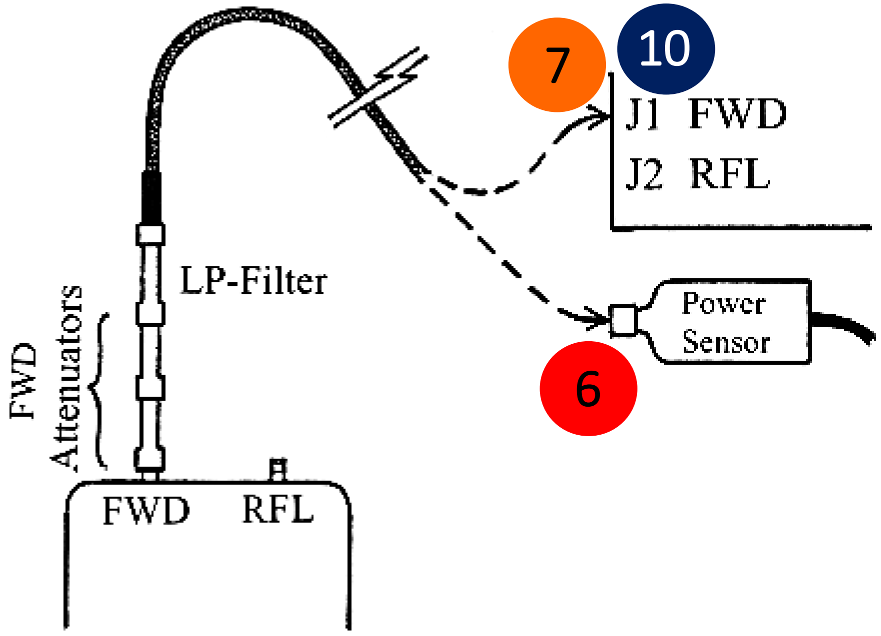
Prior to the calibration the RF Digitizer should have been powered on for at least four hours so it is warmed up.

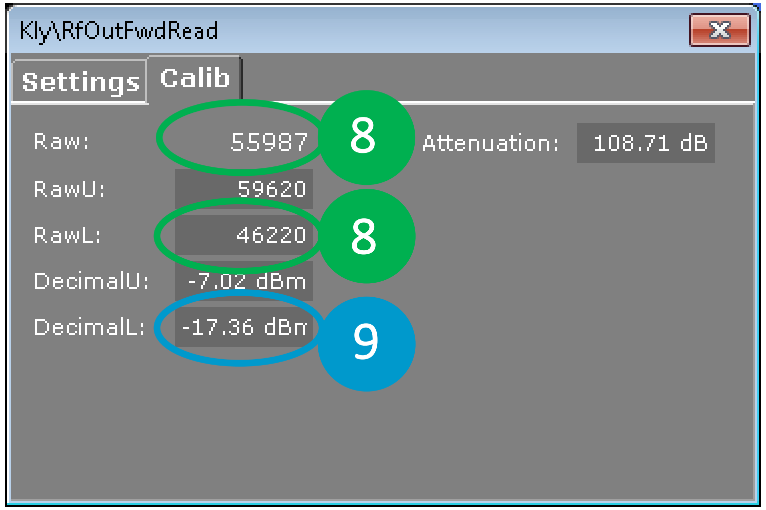
1. Open the **Settings/Calib** tab by clicking on **RfFwdRead** on the GUI. Select the **Calib** tab.
2. Sum the attenuation from the WG directional coupler all the way to the input of the RF Digitizer:

   $$\text{Total Attenuation} = C_{\mathrm{FWD}} + A_{\mathrm{FWD}} + A_{\mathrm{Filter,FWD}} + A_{\mathrm{Cable,FWD}}$$

   Insert the sum in the "**Attenuation**" field in the calib tab.
3. Regardless of calibration source, pulse the modulator at a repetition rate of typically 5–10 pps.
4. Measure the RF power to be inserted on input J1 on the RF Digitizer with *e.g.* a (pulsed) power sensor. Insert the value in dBm as **DecimalU**.
5. Connect the RF Cable to input **J1** on the RF Digitizer and read the displayed **Raw** value. Insert an average of this **Raw** value as **RawU**.

RF DIGITIZER CALIBRATION: FORWARD RF POWER





Continued…

6. Measure the RF power again with the power sensor.
7. Connect an attenuator of 10 dB or 20 dB with an *exactly* known attenuation at **J1** on the RF Digitizer and then the RF Cable. If a value between 10 dB and 20 dB is desired, a combination of well-known attenuators may be used.
8. Estimate the displayed **Raw** value and insert it in the Calib tab as **RawL**.
9. For **DecimalL**, insert the value measured in Step 6 (or in step 4) minus the *exact* value of the attenuator(s) that was used. Do not attempt to measure this very low power with the power sensor!
10. Remove the extra attenuator(s) and connect the RF Cable back to **J1**.

Finished! The GUI should now display the correct RF power.

Comment: The pulsing may be stopped between each of the steps described above.

RF DIGITIZER CALIBRATION: REFLECTED RF POWER

Selection of attenuators

The maximally allowed Voltage Standing Wave Ratio (VSWR) is listed in the klystron specification. Usually the value is 1.4:1 or 1.5:1. From $\mathrm{VSWR}_{\mathrm{max}}$ the level of maximally allowed reflections can be calculated.

1. Use the $\mathrm{VSWR}_{\mathrm{max}}$ to calculate the magnitude of the Voltage Reflection Coefficient, $|\Gamma|$:

$$|\Gamma| = \frac{\mathrm{VSWR}-1}{\mathrm{VSWR}+1}$$

2. Calculate the corresponding Return Loss, RL:

$$\mathrm{RL} = -20\log_{10}(|\Gamma|)$$

3. The Return Loss is the difference (in dB) between the Forward RF power and the Reflected RF power, $\mathrm{RL} = P_{\mathrm{FWD}} - P_{\mathrm{RFL}}$
4. $\mathrm{VSWR}_{\mathrm{max}}$ gives the minimum RL, *i.e.* the smallest allowed difference between the Forward- and Reflected RF powers. In case the Reflected power becomes larger the modulator reflected power interlock must trip.

RF DIGITIZER CALIBRATION: REFLECTED RF POWER

Selection of attenuators

Continued…

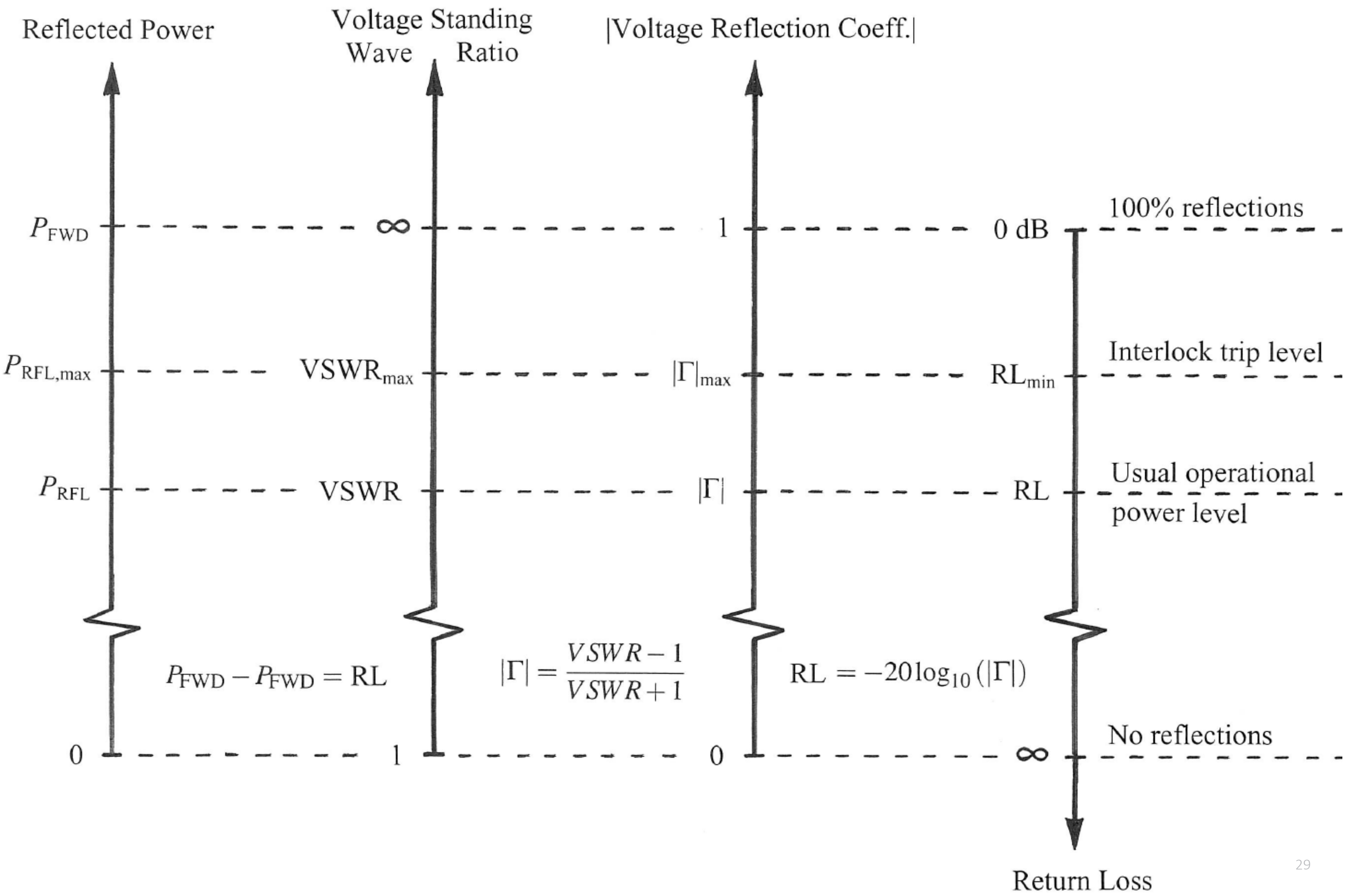
5. At the reflected power interlock trip level the power incident to J2 on the RF Digitizer should not exceed –5 dBm. This gives the inequality:

$$P_{\mathrm{FWD}} - \mathrm{RL}_{\mathrm{min}} - C_{\mathrm{RFL}} - A_{\mathrm{RFL}} - A_{\mathrm{Filter,RFL}} - A_{\mathrm{Cable,RFL}} < -5\ \mathrm{dBm}$$

   Note that $P_{\mathrm{FWD}} - \mathrm{RL}_{\mathrm{min}} = P_{\mathrm{RFL,max}}$ which is the interlock level for reflected power.

6. Solve the inequality for A_{RFL} and select the attenuators.

RF DIGITIZER CALIBRATION: REFLECTED RF POWER



RF DIGITIZER CALIBRATION: REFLECTED RF POWER

Selection of attenuators

Example 2: For the same system as in Example 1, determine the attenuation needed at the reflected port of the waveguide directional coupler when the maximum VSWR of the klystron is 1.4:1,
klystron output power = 10.0 MW,
reflected (or reverse) coupling of the waveguide directional coupler = 60.54 dB,
passband attenuation of the LP-filter for the reflected port = 0.41 dB,
and attenuation of the RF cable connecting to the RF Digitizer = 2.59 dB.

Solution: The magnitude of the voltage reflection coefficient becomes $|\Gamma| = (1.4 - 1)/(1.4 + 1) = 0.4/2.4 = 1/6$. The minimum difference between the forward power and the reflected power, or minimum Return Loss becomes $RL_{min} = -20\log_{10}(|1/6|) = 15.56$ dB. In order to have a small margin, we select $RL_{min} = 16$ dB. Since the klystron output power of 10.0 MW is equal to 100.00 dBm, the inequality above becomes:

$$100.00 \text{ dBm} - 16.0 \text{ dB} - 60.64 \text{ dB} - A_{RFL} - 0.41 \text{ dB} - 2.59 \text{ dB} < -5 \text{ dBm}$$

This give the attenuation

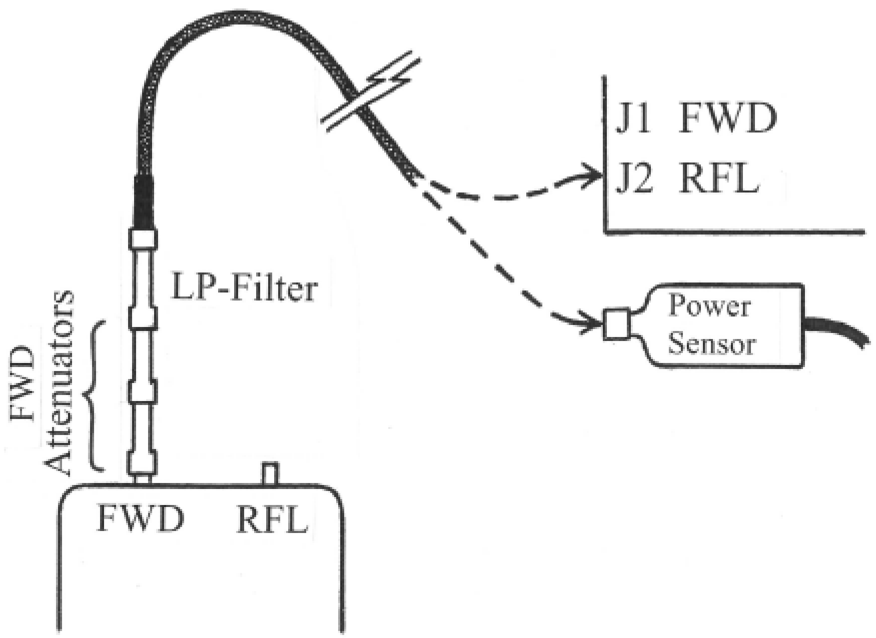
$$A_{RFL} > 25.36 \text{ dB}$$

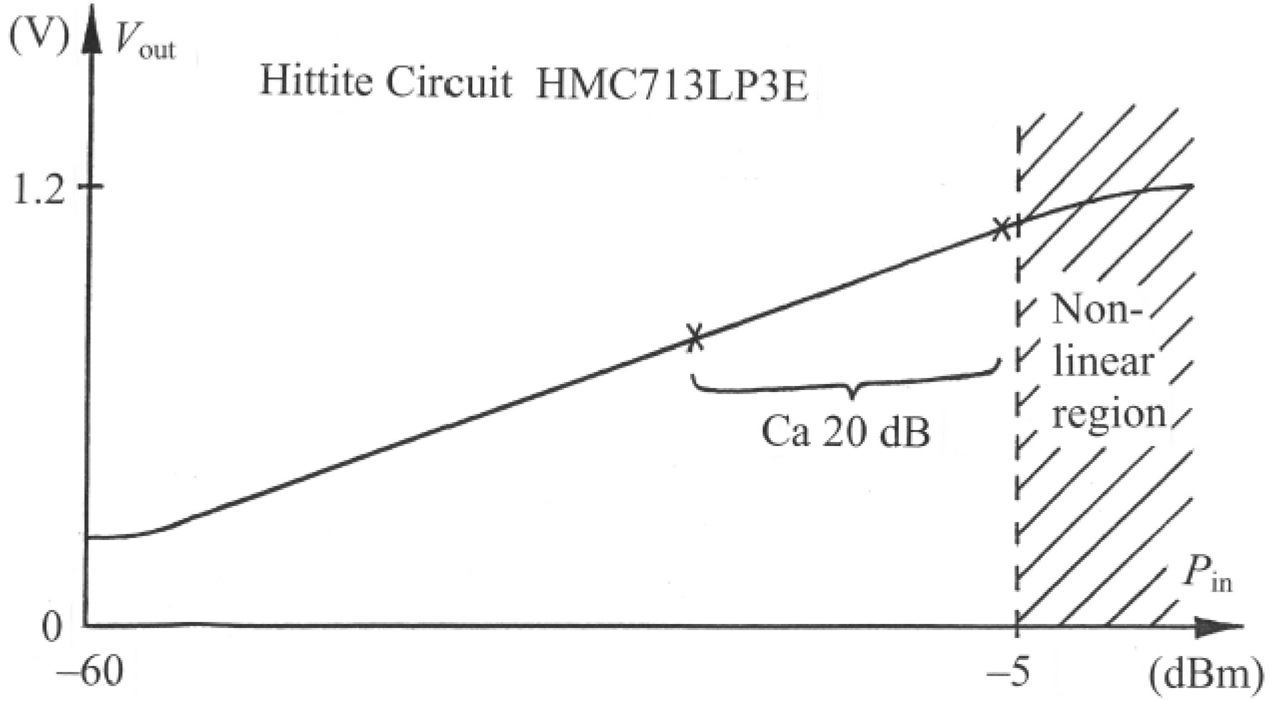
Select $A_{RFL} = 26$ dB which can be implemented as the sum of two attenuators at 6 dB and 20 dB. (Another choice would be to select $A_{RFL} = 30$ dB, which may be implemented as one attenuator at 30 dB, or with two at values 10 dB and 20 dB.)

■

RF DIGITIZER CALIBRATION: REFLECTED RF POWER

Calibration of reflected RF power

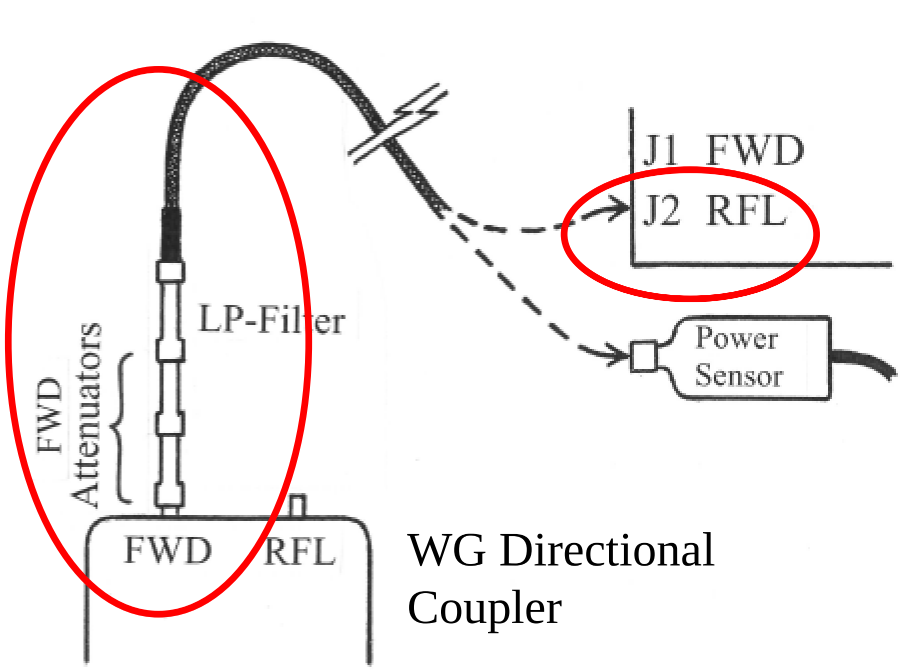


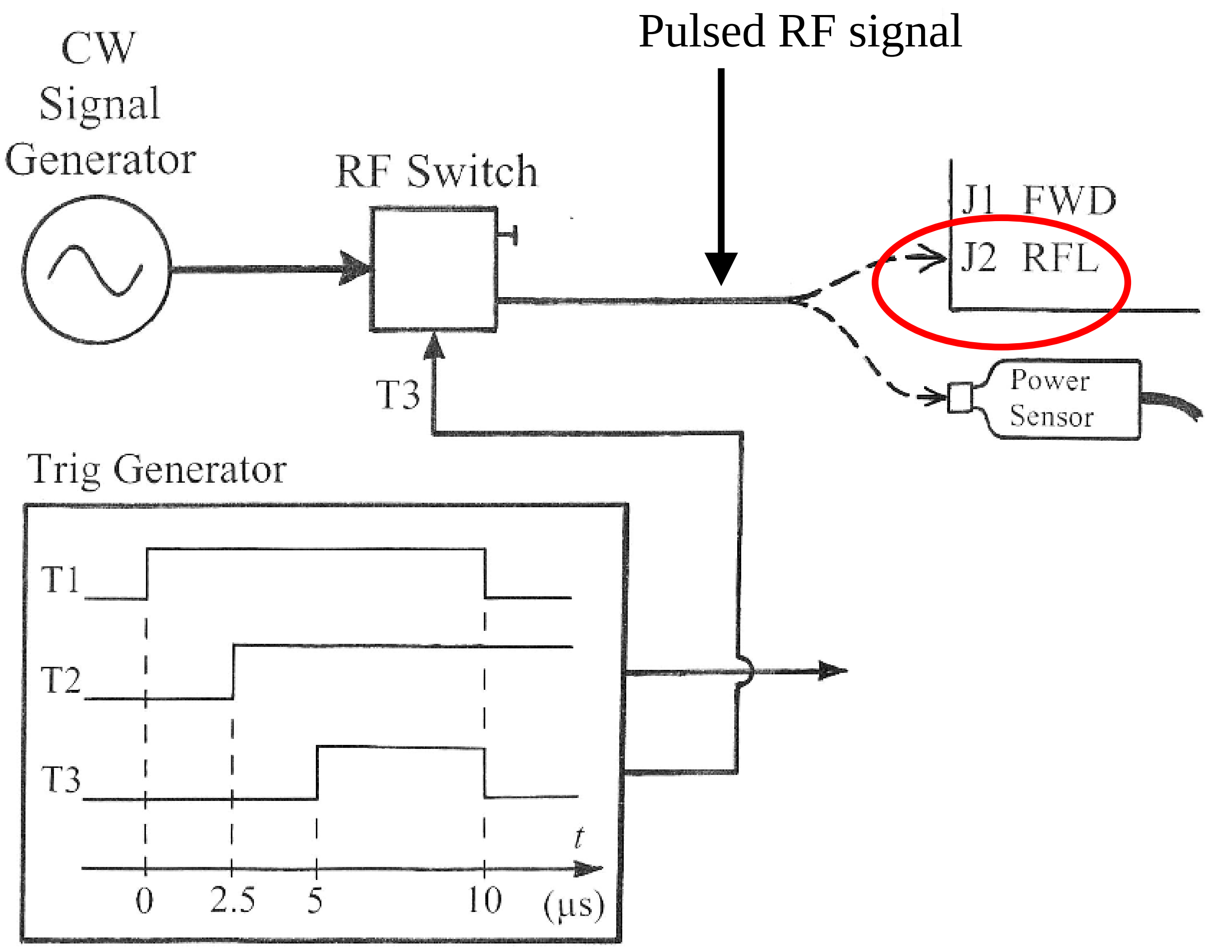


- Select the first calibration point just below –5 dBm and the second 20 dB lower. Measure the RF power with *e.g.* a power sensor.
- Use *well-known* attenuator(s) to set the power level of the second calibration point. Don't use the power sensor at this very low power level!

RF DIGITIZER CALIBRATION: REFLECTED RF POWER

Calibration of reflected RF power: calibration source



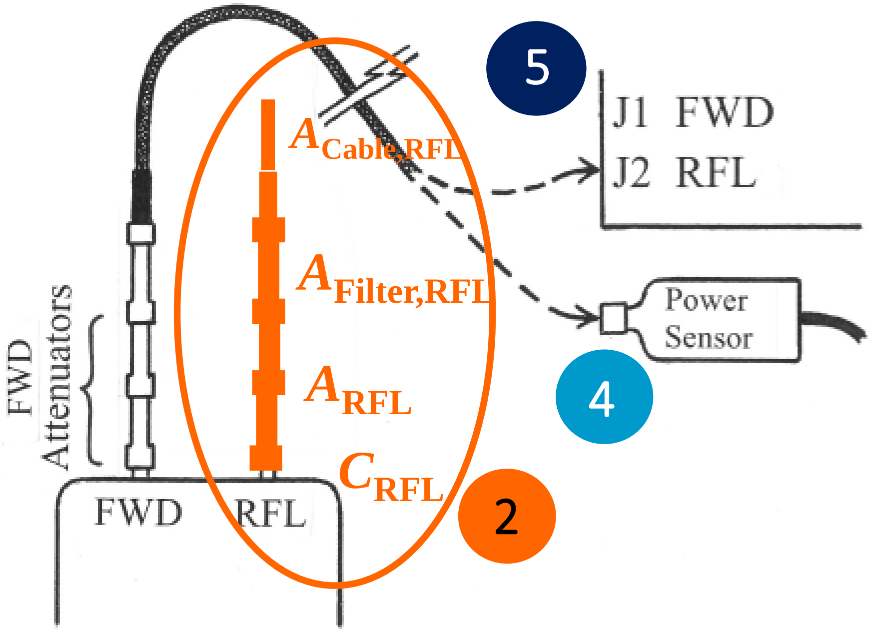


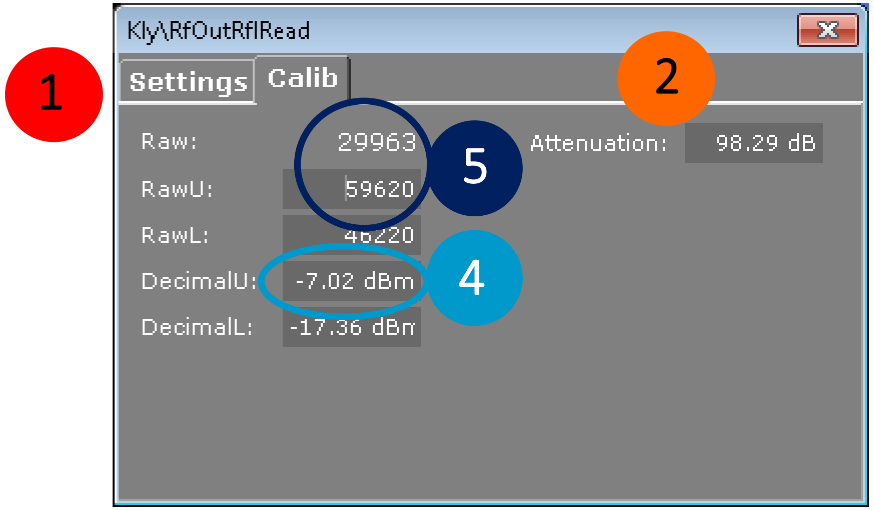
Calibration source:

- Use either the RF power from the forward port of the WG directional coupler with the forward attenuators, filter, and cable, or
- Use a signal generator to create the pulsed RF signal of power <≈ –5 dBm

NOTE: The input signals to the RF Digitizer **must be pulsed**!

RF DIGITIZER CALIBRATION: REFLECTED RF POWER



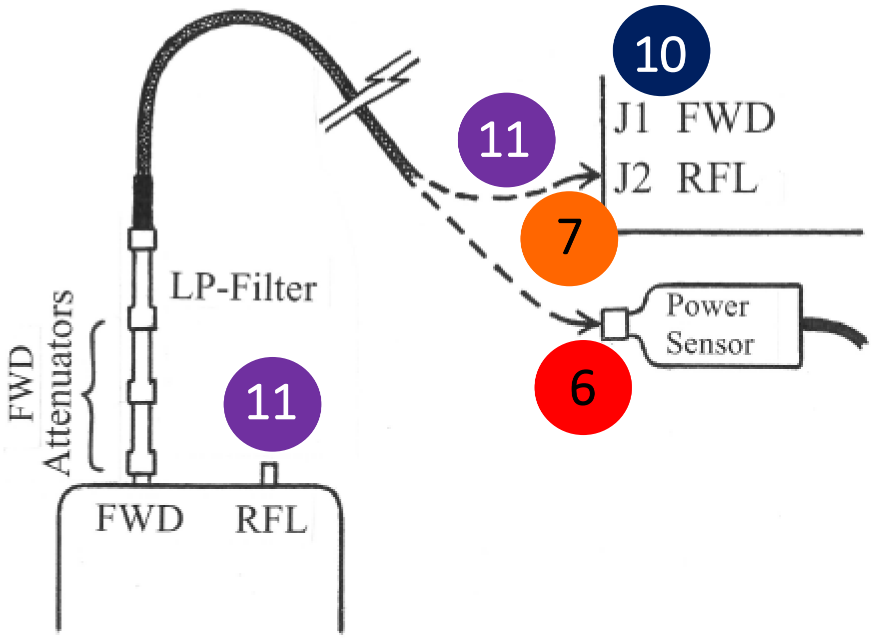


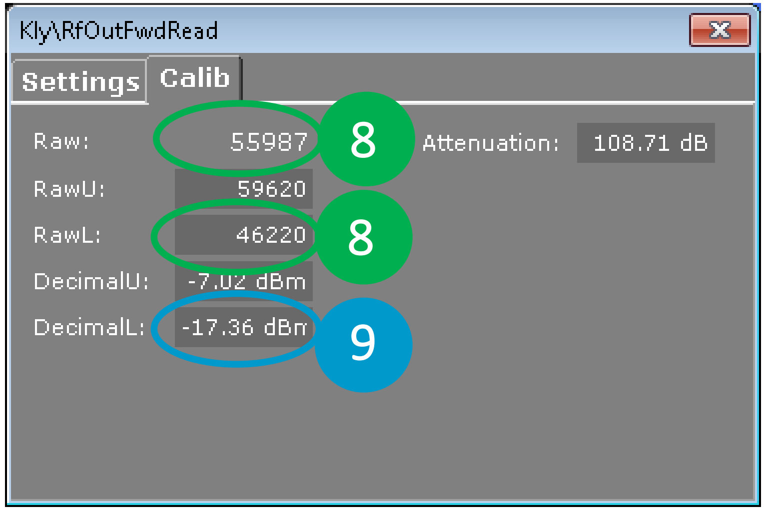
1. Open the **Settings/Calib** tab by clicking on **RfRflRead** on the GUI. Select the **Calib** tab.
2. Sum the **Reflected** attenuation from the WG directional coupler all the way to the input of the Rf Digitizer:

   $$\text{Total Attenuation} = C_{\text{RFL}} + A_{\text{RFL}} + A_{\text{Filter,RFL}} + A_{\text{Cable,RFL}}$$

   Insert the sum in the "**Attenuation**" field in the calib tab.
3. Regardless of calibration source, pulse the modulator at a repetition rate of typically 5–10 pps.
4. Measure the RF power to be inserted on input J2 on the RF Digitizer with *e.g.* a (pulsed) power sensor. Insert the value in dBm as **DecimalU**.
5. Connect the RF Cable to input **J2** on the RF Digitizer and read the displayed **Raw** value. Insert an average of this **Raw** value as **RawU**.

RF DIGITIZER CALIBRATION: REFLECTED RF POWER





Continued…

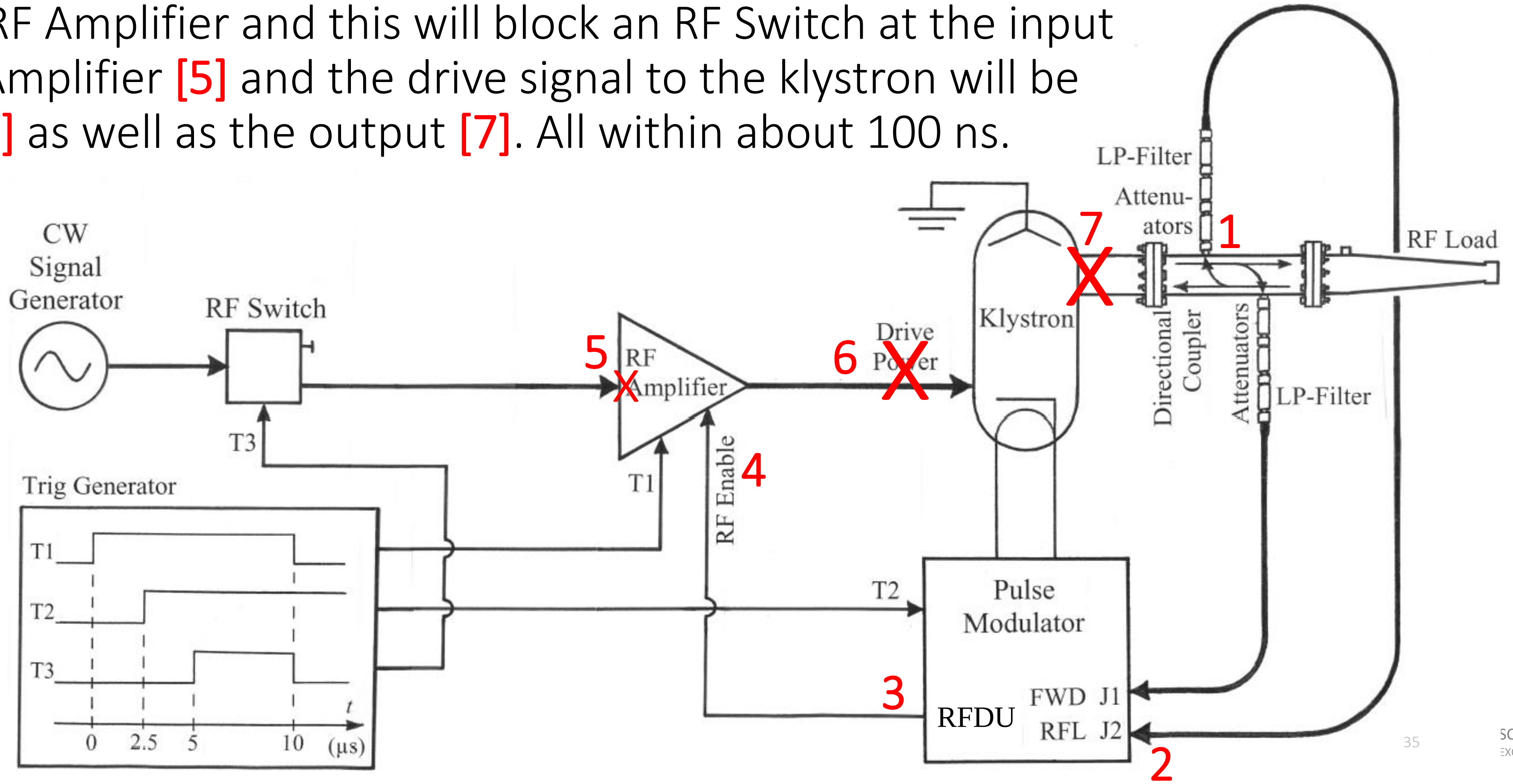
6. Measure the RF power again with the power sensor.
7. Connect an attenuator of 20 dB with an *exactly* known attenuation at **J2** of the RF Digitizer and then the RF Cable.
8. Estimate the displayed **Raw** value and insert it in the Calib tab as **RawL**.
9. For **DecimalL**, insert the value measured in Step 6 (or in step 4) minus the *exact* value of the attenuator that was used. Do not attempt to measure this very low power with the power sensor!
10. Remove the extra attenuator and connect the **Forward** RF Cable back to **J1**.
11. Connect the **Reflected** attenuators and LP-Filter to the **Reflected** port of the directional coupler and the **Reflected cable** to **J2** on the RF Digitizer.

Finished! The GUI should display the correct Reflected RF power.

Comment: The pulsing may be stopped between each of the steps described above.

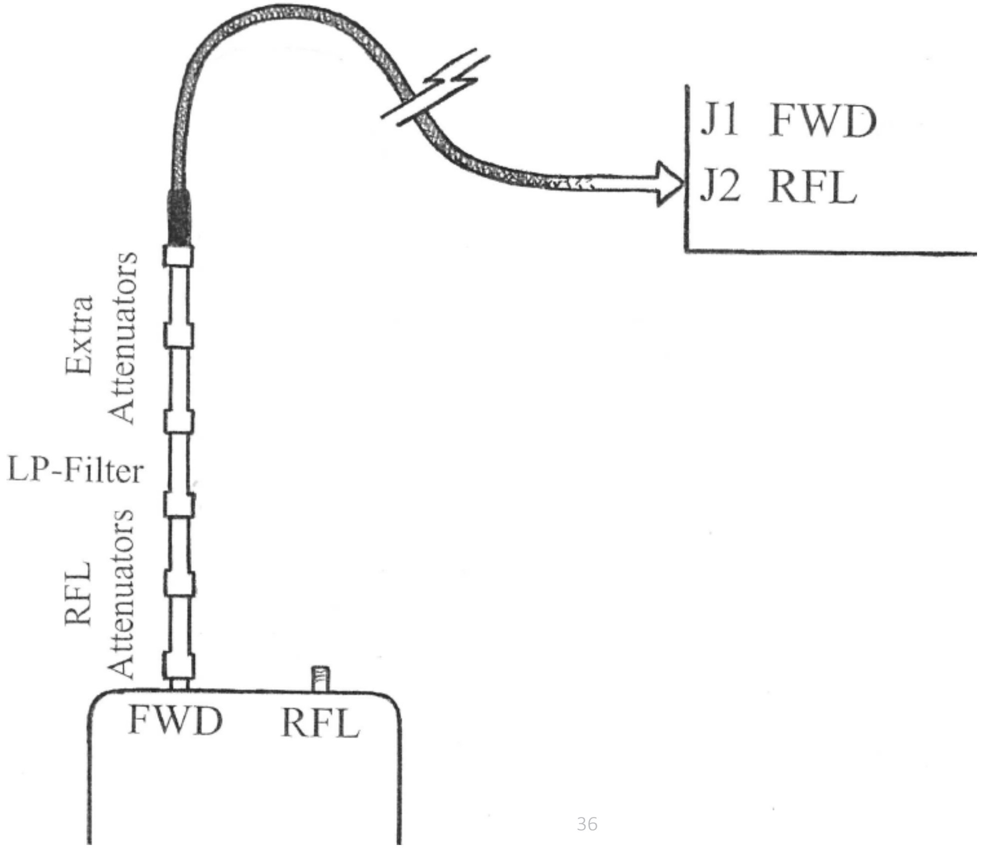
RF DIGITIZER CALIBRATION: REFLECTED POWER INTERLOCK

In case the reflected power inside the WG becomes too high [1] it will be sensed by the RF Digitizer at input J2 [2]. The RF Digitizer will switch the output from 5V to 0V [3] changing the Enable signal [4] to the RF Amplifier and this will block an RF Switch at the input of the RF Amplifier [5] and the drive signal to the klystron will be stopped [6] as well as the output [7]. All within about 100 ns.

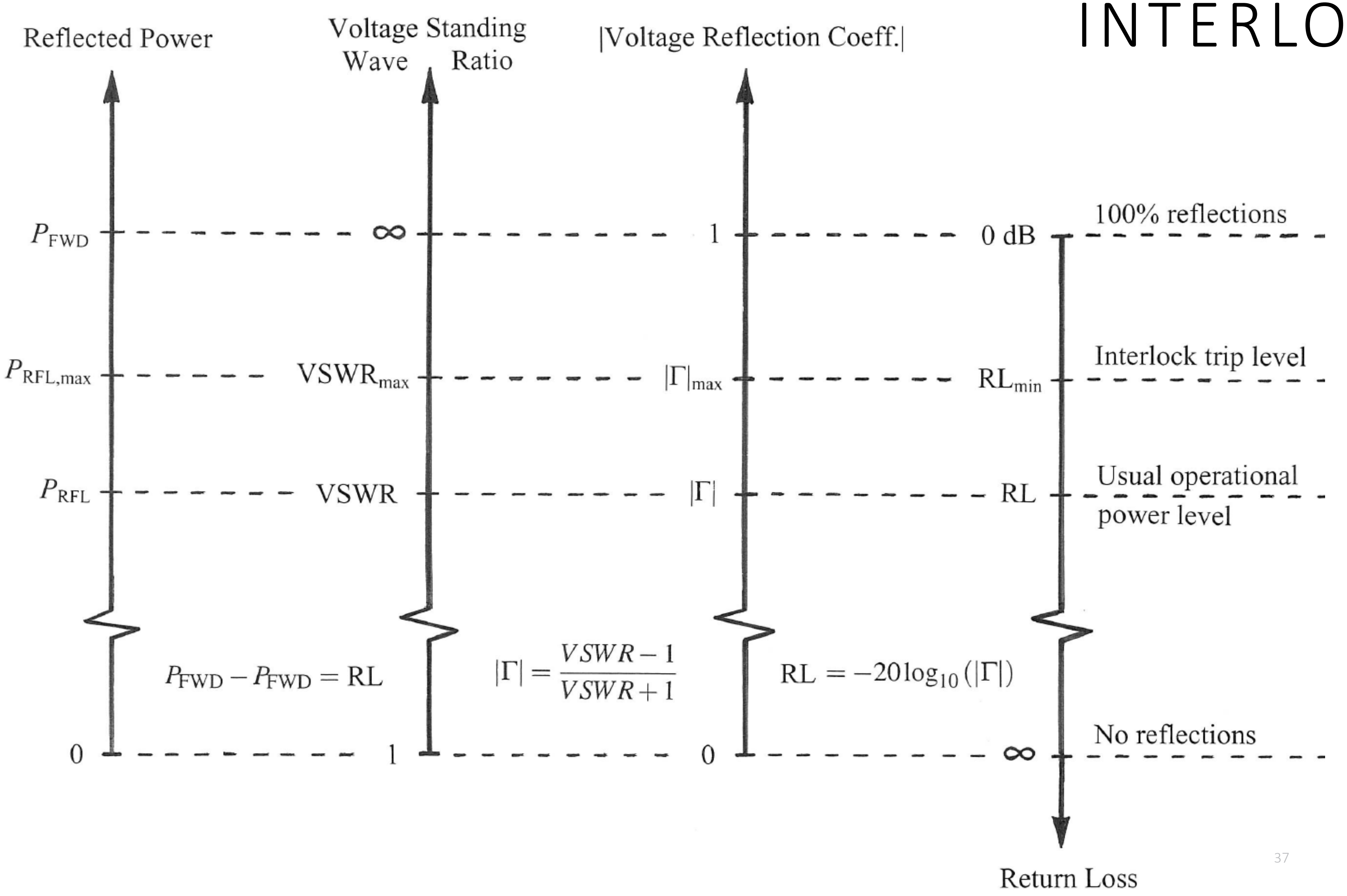


RF DIGITIZER CALIBRATION: REFLECTED POWER INTERLOCK

- At full RF output power from the klystron the modulator must interlock when the reflections reach above the level of RL_{min} below the Forward power.
- This interlock power level will remain the same also if the Forward power is reduced.
- The interlock level refers to the Forward power and we can use the Forward power as reference when we set the interlock.
- The Forward power is available at the directional coupler port for **Forward** power.
- Use the attenuators, the LP-filter, and the cable for **Reflected** power.
- Add extra attenuation of value RL_{min}.

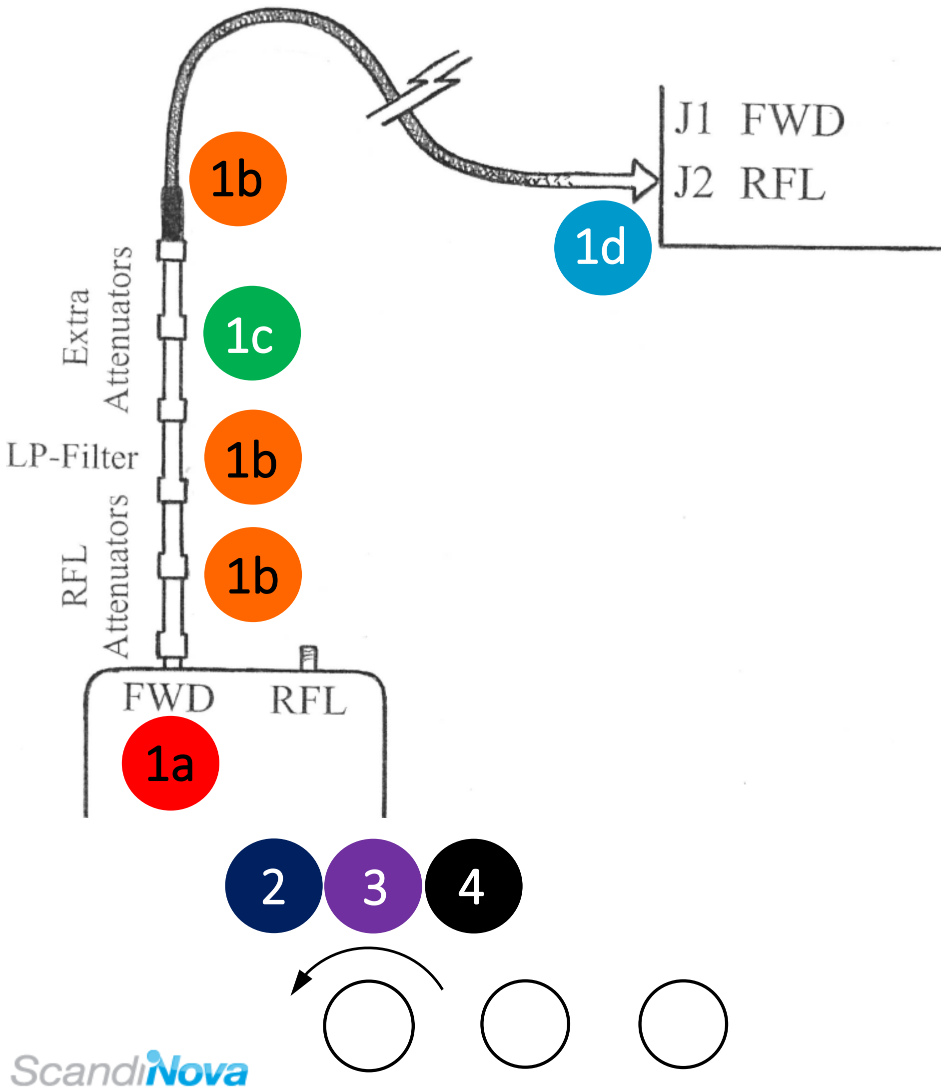


RF DIGITIZER CALIBRATION: REFLECTED POWER INTERLOCK



RF DIGITIZER CALIBRATION: REFLECTED POWER INTERLOCK

Calibration procedure



1. Connect according to the figure:
   a) Use the **Forward** port of the directional coupler
   b) Connect the attenuators, LP-filter, and cable for **Reflected** power.
   c) Add extra attenuation of value RL_{min}
   d) Connect the cable to **J2** on the RF Digitizer
2. Pulse the modualtor with RF and turn the left-most potentiometer in the counterclockwise direction until the modulator interlocks.
3. Turn the potentiometer slightly back in the clock-wise direction to be able to reset the interlock and start the modulator again.
4. Fine-tune the interlock level by turning the potentiometer again slowly in the counterclock wise until the modulator interlocks. The reflected interlock is now properly set.
5. Remove the extra attenuation and put back the sets of Forward- and Reflected components at their proper place.

RF DIGITIZER CALIBRATION: REFLECTED POWER INTERLOCK

Example 3:

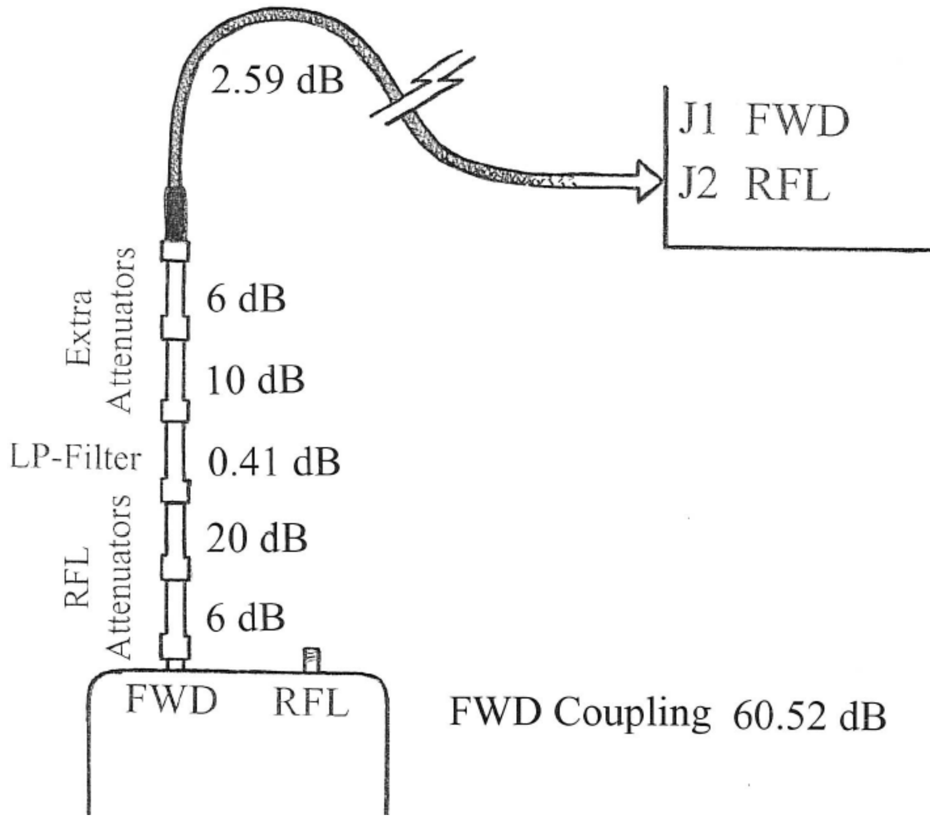
For the same system as in Example 1 and **Example 2**, elaborate the procedure to set the reflected power interlock at the correct level. Also, determine the approximate input power level to connector J2 on the RF Digitizer during the setting of the interlock.

Solution:

In Example 2, we had $VSWR_{max}$ = 1.4:1. This gave a minimum Return Loss, of 15.56 dB, which we rounded off to 16 dB to obtain a small margin. Since we want the reflected power interlock to trip when the power at connector J2 on the RF Digitizer is just below −5 dBm, the inequality in Subsection 8.1 specifies how the connection should be made. We start with the waveguide power of 100.00 dBm and use the forward port of the directional coupler at a coupling value of 60.52 dB (see Example 1). Since the power will be RL_{min} lower than the forward power, we subtract 16 dB. Then we have the attenuators for reflected power (26 dB according to Example 2), the LP-filter (0.41 dB) and the RF cable (2.59 dB) to connect to J2 on the RF Digitizer. With values inserted we obtain the RF power at J2:

$$100.00 \text{ dBm} - 16.0 \text{ dB} - 60.64 \text{ dB} - 26 \text{ dB} - 0.41 \text{ dB} - 2.59 \text{ dB} = -5.64 \text{ dBm}$$

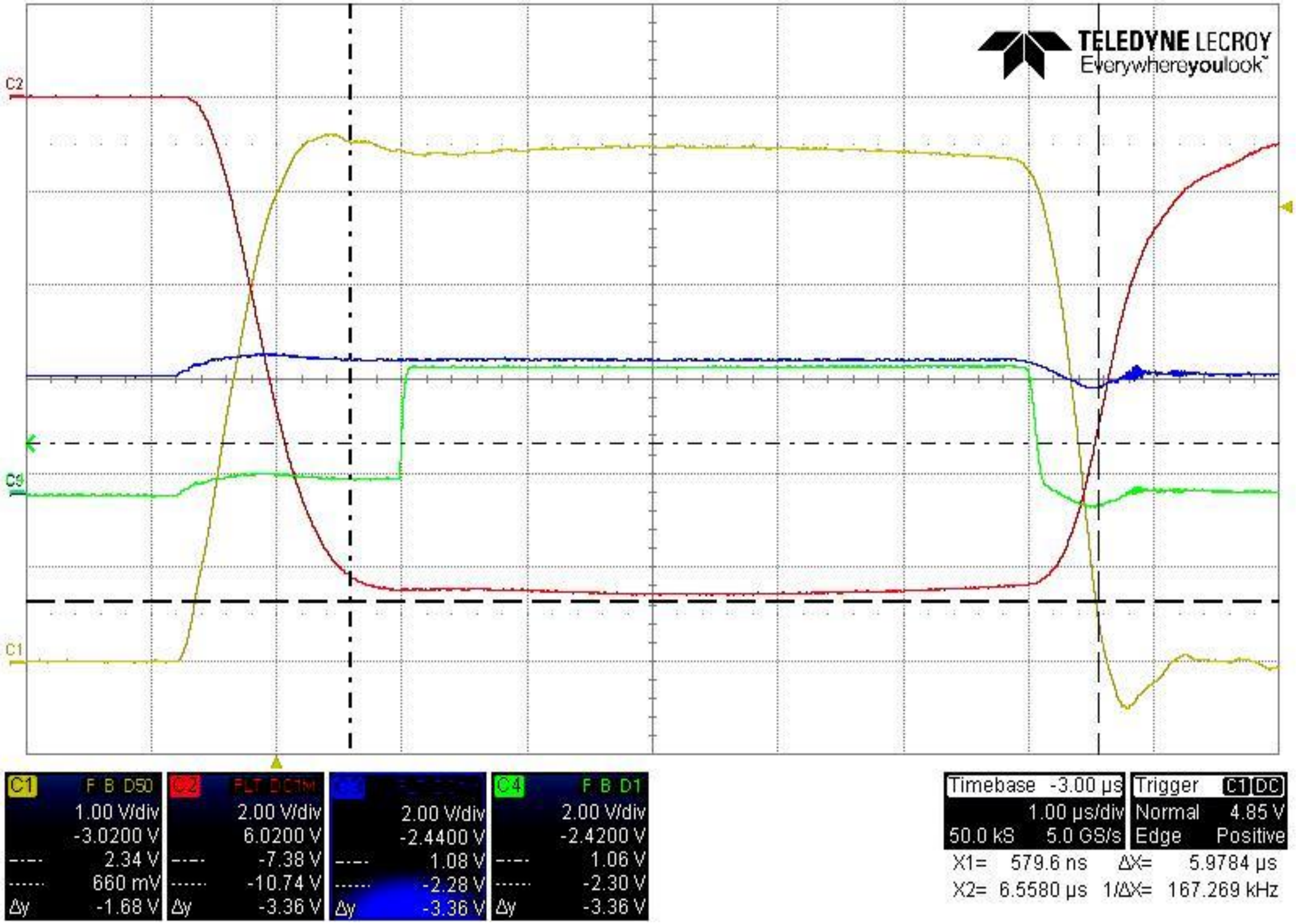
Note that the 16 dB extra attenuation is placed as the second term in the inequality. The connection is illustrated in Figure



Connection to set the reflected power interlock. The directional coupler port for *forward* power is used together with the attenuators, the LP-filter, and the RF cable for *reflected* power, and in this case 16 dB extra attenuation to reach the correct interlock trip power level 16 dB below the forward power.

RF DIGITIZER CALIBRATION: REFLECTED POWER INTERLOCK

Interlock trip level



Yellow: Modulator current pulse

Red: Modulator voltage pulse

Blue: Interlock trip level (measured at the left-most TP)

Green: RF pulse (measured at the middle TP)

RF DIGITIZER CALIBRATION: VSWR INTERLOCK

- Independent of the reflected power interlock, which trips at an absolute power level, the modulator can be set to interlock when the VSWR exceeds the maximally allowed value, regardless of the absolute power level.
- This can be used to interlock the modualtor at a certain VSWR when the modulator is operating at a power level less than the maximum power.
- The VSWR interlock only works during the number of samples set by ManualLength, while the reflected power interlock works over the whole interlock window.
- On the GUI, click on RfVSWRRead to open the Setting tab.
- Only HLim (High Limit) and WHLim (Warning High Limit) are available.
- Set Hlim = $\mathrm{VSWR}_{\mathrm{max}}$
- Set WHLim = $\mathrm{VSWR}_{\mathrm{max}} - 0.1$
- In case of Example 2, we would set Hlim = 1.40 and WHLim = 1.30.

RF DIGITIZER CALIBRATION: KLYSTRON DRIVE POWER

- The RF Amplifier outputs a detector voltage signal proportional to its output power. This voltage signal can be used to calibrate the klystron drive power on the GUI. This step does actually not involve the RF Digitizer.
- When the klystron drive power has been properly set, perform the following steps:

a) On the GUI, click on **RfDrvRead** to open the Settings/Calib tab. Select the Calib tab.

b) Set the “Cable Attenuation” field equal to zero. IMPORTANT! Otherwise the calibration will not be correct!

c) Make sure all the components for Forward power are properly connected between the Forward port of the directional coupler and J1 on the RF Digitizer.

d) Pulse the modulator at a rep. rate of typically 50 pps and a pulse length of >2 µs. Open the Calib tab and insert the Raw value as **RawU** and the already known drive power as **DecimalU**.

e) Select the lower calibration point as zero and insert **RawL = 0** and **DecimalL = 0.00 dBm**.

f) Insert the attenuation of the drive cable in the “Cable Attenuation” field. The GUI will now display the correct drive power.

RF DIGITIZER CALIBRATION: RF PULSE LENGTH

- On the GUI, click on **RfPlswthRead** to open the Settings/Calib tab.
- With the Forward power connected to J1 on the RF Digitizer, set an RF pulse length and perform the calibartion of **RawU** and **DecimalU** in the usual way.
- Select the lower calibration point as zero and insert the values **RawL = 0** and **DecimalL = 0.00 µs**.
- For a 5.0 µs long RF pulse, typical calibration values are

RawU = 5040

RawL = 0

DecimalU = 5.00 µs

DecimalL = 0.00 µs

THE END

THANKS FOR LISTENING!