Universität Hamburg

Synchrotron Research Institute

German-Armenian Joint Practical Course
on Accelerator Physics

Radiofrequency Techniques in Accelerators

Introduction to RF Measurement and Techniques, Concepts and Essentials

Supervisor: Dr. Ashot Vardanyan

Federal Foreign Office

Supported by the German Federal Foreign Office under Kapitel 0504, Titel 68713

YEREVAN, ARMENIA
2019

Contents

Introduction 3
Experiments 3
RF Measurements Laboratory 4
Test Stands and Tasks 6
Test stand 1, 2. 6
Test stand 3, 4. 6
Test stand 5. 7
Test stand 6. 7
Test stand 7. 7
Working Schedule 8
Modern Measurement Devices and Tools 8
Power meters 9
Network analyzer 9
Smith Chart 9
Basic Definitions of RF Measurements (Terminology) 10
dB 10
dBm. 10
Power 11
Average Power 11
Pulse Power 11
Peak Power Definitions: 12
Amplifier 12
Gain: 12
Output power: 12
Bandwidth and flatness: 13
Third-order intercept point: 15
Appendix 1. S-parameters 16
Appendix 2. Smith Chart 17
Appendix 3. Bead Pull Measurements 19
Tuning 20
Supporting Materials 21
References 22

Introduction

In this course, you will receive basic knowledge of RF measurement techniques and will acquire practical skills of working on RF components and state-of-the-art equipment widely used in the RF community in general, particularly in accelerators. You will learn the RF terminology and its main components, characteristics and applications, mainly the methods applying modular equipment and measurement possibilities. The learning program will include two main measurements performed on seven experimental stands. These type of measurements are used not only in accelerator technology, but also in many other fields, for example in telecommunications. Measurement results will be discussed and interpreted in small groups using data charts and diagrams in RF terminology. The gained knowledge and practical skills will be consolidated with the help of exercises and tests. During the course, you will become familiar with the Vector Network Analyzer, Spectrum analyzer, different types of Power meters and other modern equipment.

Experiments

The possible applications and the importance of the corresponding measurement will be discussed in the introduction part to each test stand separately. Designed exercises, which include the test descriptions and interpretation of the output of each test stand, consist of the following parts:

- Short theory introduction,
- Terminology,
- Used equipment,
- Used components,
- Equipment calibration and tuning.

At the end of the program, individual evaluation of each student will take place according to the provided scale.

RF Measurements Laboratory

The RF Measurements Laboratory consists of seven measurement stands, where up to 10 students can simultaneously perform different experiments. The “Cavity tuning Test stand” for “Bead-pull measurement” will be located on the separate desk in the center of the room.

The Laboratory is equipped with state-of-the-art devices from “Rohde & Schwarz”:

1. **VNA 14** up to 14 GHz Vector Network Analyzer
    a. With calibration kit **ZV-Z235**
    b. Cavity tuning test stand for Bead-pull measurement
2. **FPL1000-** one instrument for multiple applications up to 7,5 GHz:
    a. Spectrum analysis: spurious, narrowband resolution bandwidth down to 1 Hz, spectrogram measurements to display the spectrum versus time, trace zoom function
    b. Signal analysis of analog and digitally modulated signals: harmonic distortions, third-order intercept point, AM modulation depth
    c. Power measurements with power sensors: two NRP Z211 sensors are available
    d. Gated sweep for accurate display of pulsed signals: one NRP Z81 sensor is available
    e. Noise figure and gain measurements, signal-to-noise ratio

3. **FPC1500** 3 in 1 device:
    a. Spectrum analyzer: from 5 kHz to 3 GHz range, with RBW settings down to 1 Hz.
    b. Network analyzer: S11 reflection measurements, Smith chart and DTF features
    c. Signal generator: with independent signal source, CW within the frequency range, or in a coupled mode to follow the center frequency setting of the spectrum analyzer mode
4. Two**HMF2525**Arbitrary Function Generator:
    a. Frequency range: 10µHz to 25 MHz
    b. Waveform modes: sine, square, pulse, triangle, ramp and arbitrary waveforms (incl. standard curves: white noise, pink noise, cardiac, exponential rise and fall, etc.)
    c. Modulation modes: AM, FM, pulse, PWM, FSK (internal and external)
    d. Arbitrary waveform generator: 250MSa/s, 14bit, 256kSa
    e. Easily create your own waveforms using standard PC software
5. **SMC100A** Signal Generator
    a. Frequency range 9 kHz to 1.1 GHz or 3.2 GHz with output level of typ. > +17 dBm
    b. Analog modulation modes (AM/FM/φM/pulse) integrated as standard
    c. Power measurements with power sensors: two **NRP Z211** sensors are available.
6. Two **RTB2002**Oscilloscopes: 10-in-1 oscilloscope 1. Oscilloscope, 2.Logic analyzer, 3.Protocol analyzer, 4.Waveform and pattern generator, 5. Digital voltmeter, 6.Frequency analysis mode (FFT), 7. Mask test, 8. History and segmented memory mode, 9. Low-frequency response - Bode plot,10. Amplitude profile.

7. Two Educational Kits **FPC-Z10:** Upconverter path, Downconverter path, Power supply, Calibration Kit, DC/DC converter, IQ Modulator/ Demodulator, Adjustable Local Oscillator.

8. Two Educational Kits **DSB:**
    a. More than 7 modes of operations
    b. In total more than 30 exercises available from R&S

Test Stands and Tasks

The equipment available and the tasks foreseen at the different test stands are the following:

Test stand 1, 2.

Oscilloscope RTB 2002 with DSP board (Digital Signal Processing Kit)

- Mode 1: Audio, ANA, PWM, I2C - 7 exercises
- Mode2: ANA, LIN bus - 2 exercises
- Mode3: Audio, ANA, PWM, I2C - 4 exercises
- Mode4: Digital Stimulus Board - 4 exercises
- Mode5: Signal and trigger - 2 exercises
- Mode6: CAN bus - 2 exercises
- Mode7: Power Ripple - 2 exercises

Test stand 3, 4.

Spectrum Analyzer FPC1500 and FPL1000with FPC-Z10 board (Digital Signal Processing Kit)

- Designed to showcase different RF measurements in a lab environment.
- Two signal processing paths, up- and a down-converter (85 - 2700 MHz)
- attenuator with variable signal attenuation
- amplifier with a gain of approx. 18 dB at 836.5 MHz

- bandpass filter with a 3 dB bandwidth of approx. 20 MHz at 836.5 MHz
- mixing stage to up- or down-convert the signal
- I/Q modulator or demodulator

Test stand 5.

Signal GeneratorSMC100A

- Broad power spectrum 9 kHz to 3.2 GHz, is suitable for EMC applications, with output level of typ. > +17 dBm
- Full set of standard features. The analog AM, FM, φM and pulse modulation modes are integrated in the instrument as standard. An internal modulation and pulse generator supplies the required modulation signals.
- Power measurements with power sensors: two NRP Z211 sensors are available.

Test stand 6.

Analyzer **ZVB14**

- Becoming familiar with the Vector Network Analyzer
- Calibration of the Vector Network Analyzer: ZV-Z235
- Navigation in the Smith Chart [Appendix 2].
- 4-port S-parameter measurements for different RF-components [Appendix 1].

Test stand 7.

Bead pull measurements with VNA ZVB14, cavity tuning

- Calibration of the Vector Network Analyzer
- Tuning of the prototype of CANDLE 50MeV upgrade 7-cell cavity [Appendix 3].

All described experiments (measurements) performed on these test stands are more or less connected to accelerators, but the most related and closest to our field of study and also scientifically more interesting are the ones performed with Vector Network Analyzers. The lecture notes “Cavities” [W. Hillert] will serve as a theoretical basis for the last two experiments. It is highly recommended that, before the start of this practical work, students are familiar with the material mentioned above.

Working Schedule

It is planned to have a learning course with duration of 5 working days and working schedule as presented below:

- On the first day, the students will get familiar with the RF terminology, will perform simple experiments on 1st to 5th test stands; and will gain experience in working with modern equipment in intuitive learning-by-doing mode.
- On the second day, a short lecture will be given to introduce the main characterizing parameters of cavities, VNA measurement possibilities and Smith chart navigation. On the second half of the day, the students will perform the experiment on the 6th test stand, herewith getting prepared for the 7th test by doing VNA calibration and preliminary measurements such as cavity resonant frequency, quality factor and shunt impedance measurements, as well as S-parameter measurements for different RF components.
- On the 3rd day, the bead-pull measurement for the 7-cell prototype of CANDLE 50 MeV upgrade cavity will be performed. Though time consuming, cavity tuning will be completed as well during this day.
- On the 4th day, we will summarize the knowledge gained while performing the experiments and measurements, and the students will start working on their presentation.
- On the second half of the 5th day, the students will present their presentations, which will serve as a basis for the final assessment.

Modern Measurement Devices and Tools

For the characterization of components, systems and signals in the radiofrequency (RF) and microwave ranges, several dedicated and graphical instruments are in use [1 - 4].

Power meters

The power meter plays an important role in the measurement chain of acquiring a signal, reacting to the signal, and finally producing an understandable output.

Network analyzer

The network analyzer will be introduced which has become extremely versatile, powerful and indispensable tool for RF signal analysis. Thanks to its methods the measuring the transmission or reflection coefficients became very easy. Network analyzers require sophisticated calibration procedures, which are now indispensable form any measurement applications.

The main capabilities of VNAs:

- Gain, attenuation, and distortion,
- Phase and group delay,
- Pulsed RF measurements,
- Non-linear measurements of active and passive devices,
- Multi-port and differential measurements,
- Load-pull and harmonic load-pull.

Smith Chart

The Smith Chart is a graph of the reflection coefficient in the polar plane. Phillip H. Smith invented this chart in the 1930s. With the help of the Smith Chartit is very easy to convert impedances to reflection coefficients and vice versa [Appendix 2], [W.Hillert, p28]. The Smith chart is a very valuable and important tool that facilitates the interpretation of S-parameter measurements. The students will gain knowledge on navigating inside the chart.

Basic Definitions of RF Measurements (Terminology)

dB

In many cases, such as gain or attenuation measurement, the ratio of two powers, or relative power, is frequently the desired quantity rather than absolute power. Relative power is the ratio of one power level, P, to some other level or reference level, P_{ref}. The ratio is dimensionless since the units of both the numerator and denominator are watts. Relative power is usually expressed in decibels (dB) defined as:

$$dB = 10\ lg(P/P_{ref})$$

The use of dB has two advantages. First, the range of numbers commonly used is more compact; for example +60 dB to -150 dB is more concise than 10^6 to 10^{-15}. The second advantage is apparent when it is necessary to find the gain of several cascaded devices. Multiplication of numeric gain is then replaced by the addition of the power gain in dB for each device.

dBm.

The formula for dBm is similar to dB except the denominator, P_{ref} is always one milliwatt:

$$dB = 10\ lg(P/1mW)$$

In this expression, P is expressed in milliwatts and is the only variable, so dBm is used as a measure of absolute power (see Figure 1).

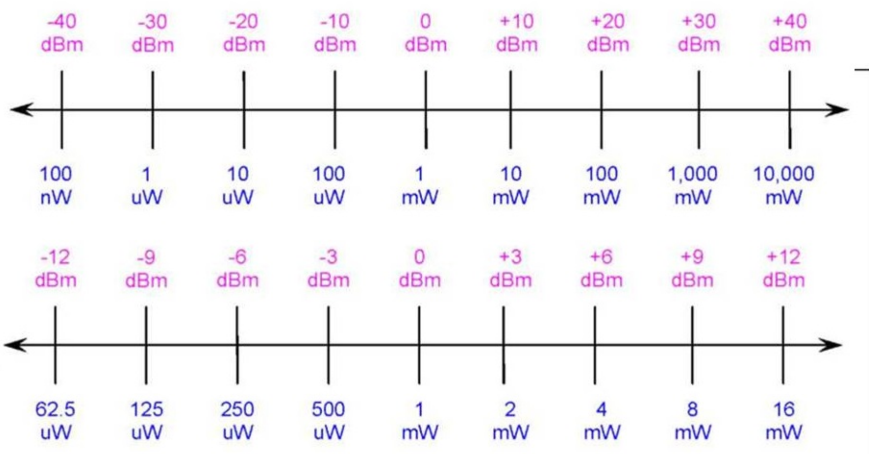


Figure 1. dBm to Watt conversion chart.

Power

Power is the most frequently measured RF quantity. The term “average power” is very popular and is used to specify almost all RF and microwave systems. The terms “pulse power” and “peak envelope power” are more pertinent to radar and navigation systems. In elementary theory, power is defined as the product of voltage and current. However, for an AC voltage cycle, the product $V \times I$ varies during the cycle. A sinusoidal generator, for example, produces a sinusoidal current as expected:

$$V = V_0 \sin \omega t,\ I = I_0 \sin \omega t,$$

but the product of voltage and current:

$$V * I = \frac{V_0 I_0}{2} - \frac{V_0 I_0}{2} \sin 2\omega t$$

has a DC term as well as a component at twice the generator frequency. The word “power,” as most commonly used, refers to that DC component of the power product.

Average Power

Average power means that the energy transfer rate is to be averaged over many periods of the lowest frequency involved. For a CW signal, the lowest frequency and highest frequency are the same, so average power and power are the same. For an amplitude modulated wave, the power must be averaged over many periods of the modulation component of the signal as well.

Pulse Power

For pulse power, the energy transfer rate is averaged over the pulse width. Pulse width is considered to be the time between the 50 percent risetime/falltime amplitude points. The definition of pulse power has been extended since the early days of microwave to be:

$$Pp = P_{avg} / \text{Duty Cycle}$$

where duty cycle is the pulse width times the repetition frequency.

Peak Power Definitions:

The following definitions are illustrated in Figure 2.

- **Rise time -** usually 10 and 90 percent of pulse-top amplitude.
- **Fall time -** same as rise time measured on the last transition.
- **Pulse width -** measured at the mesial level; normally taken as the 50% power level.
- **Duty cycle -** measured pulse duration divided by the pulse repetition period.
- **Peak power -** the highest point of power in the waveform.

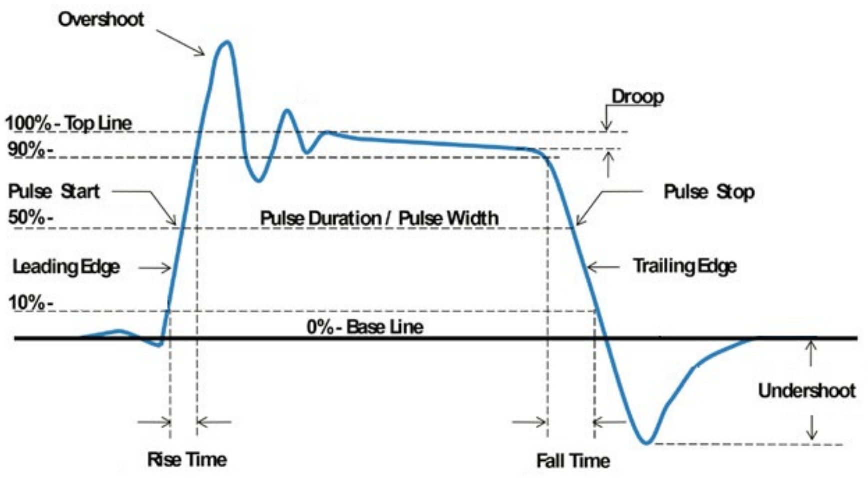


Figure 2. **Main definitions for Peak Power**

Amplifier

Gain:

This is simply the amplifier's signal output compared to the signal input—usually stated in decibels.

Power gain in decibels is defined as:

$$10\lg\left(\frac{P_{out}}{P_{in}}\right)[dB]$$

Output power:

Output power usually is stated in dBm at the **1 dB compression point**. This is the output level at which the amplifier gain is reduced by 1 dB from the small-signal gain (see Figure 3). At this point, the amplifier has deviated from the linear I/O relationship and – as the input signal levels are increased beyond this point – distortion products start to rise rapidly.

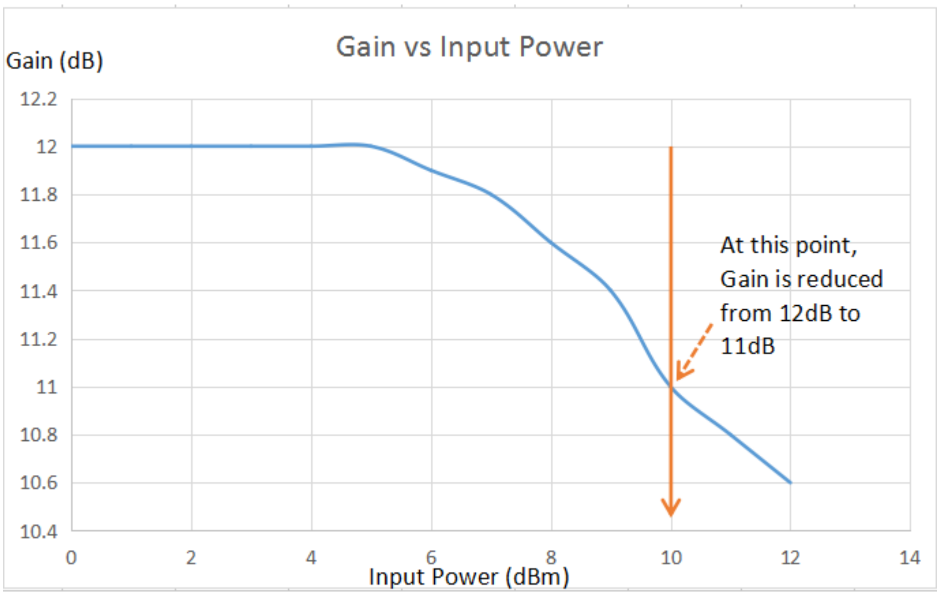


Figure 3. 1 dB compression point - Gain is reduced from 12dB to 11dB

Bandwidth and flatness:

The bandwidth of an amplifier usually is stated in terms of half-power points or points at which the power is diminished by 3 dB (see Figure 4). The flatness is usually stated as ±n dB from frequency X to frequency Y (flatness is the ripple amplitude for given frequency range). For example, the gain and flatness of an amplifier may be stated as 20 dB, ±1.5 dB, from 20 MHz to 150 MHz.

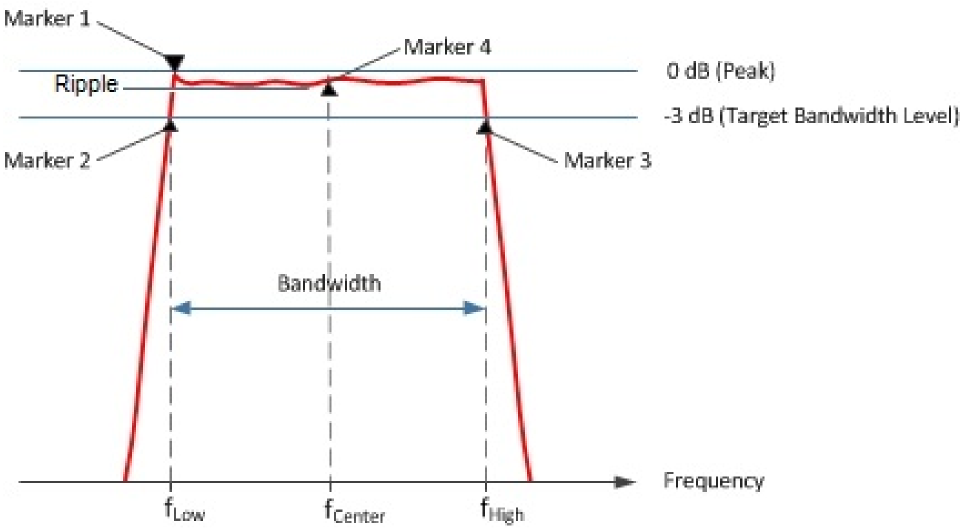


Figure 4. Definition of bandwidth and flatness.

The Stability of an amplifier is a very important specification figure. The stability factor should be listed in the specification sheet as a Rollett K factor. If the K factor is greater than 1, the amplifier is said to be unconditionally stable under all load conditions. If the K factor is less than 1, the amplifier may become very unstable under certain load conditions. Calculating the stability factor (K): The Rollett stability, or K factor, can be computed from the S-parameters (see Appendix 1). Following equation can be used to calculate the K factor of a specific amplifier to see if it would be unconditionally stable.

$$K = \frac{1-|S_{11}|^2-|S_{22}|^2+|\Delta|^2}{2\,|S_{12}S_{21}|}, \text{ where } \Delta = S_{11}S_{22} - S_{12}S_{21}$$

When K-factor > 1 while delta is < 1, the amplifier is unconditionally stable for any load.

Impedance: For communication work in a 50-ohm system, the amplifier should be designed for 50-ohm impedance (often a real industry normalized value, such as 50Ω, 75Ω or other standard).

Noise figure is usually stated in decibels. For example, an amplifier noise figure might be stated as 5 dB. If the signal-to-noise ratio at the input to such an amplifier is 30 dB and the noise figure is 5 dB, then the signal-to-noise ratio at the output of the amplifier is 25 dB. The signal-to-noise ratio is degraded by an amount equal to the noise figure of the amplifier (see Figure 5).

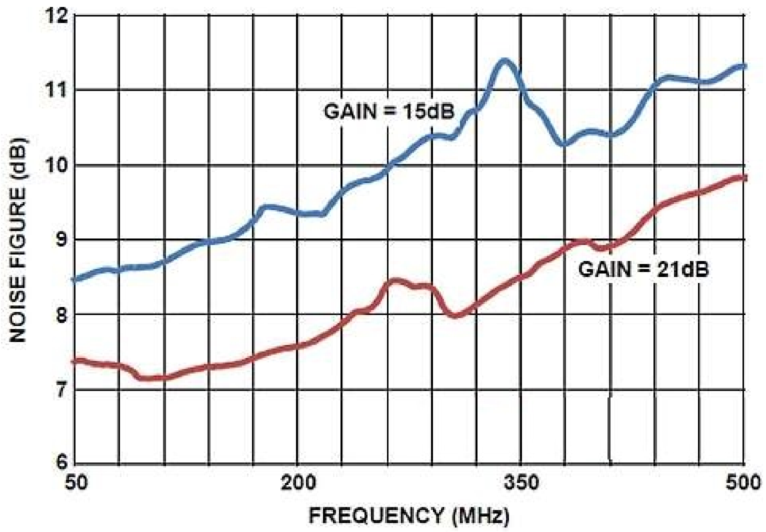


Figure 5. The noise figure of two different amplifiers

Third-order intercept point:

This specification figure is an indication of how well the amplifier performs under strong signal conditions. This is usually specified in terms of dBm, or decibels referenced to 1mW (see Figure 6). For example, an amplifier's specification for TOI (third-order intercept) might be listed as +15 dBm. The higher this figure, the better the strong signal performance, but the amplifier cost rises accordingly.

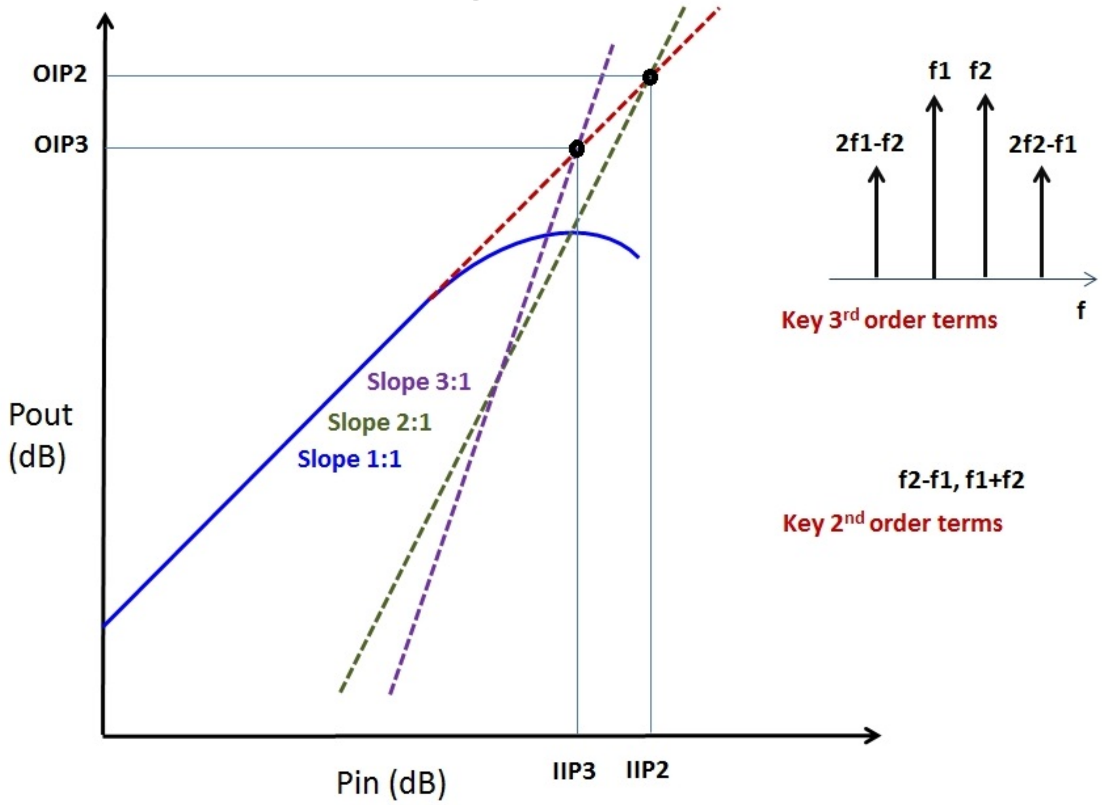


Figure 6. Second and third order intercept points

In contrast to the second order non-linearity, the third order effect of the amplifier creates some additional, unwanted frequencies *2 f1 – f2* and *2 f2 – f1* at the output of the amplifier. These frequencies can be too close to the wanted output *f1* and *f2,* their cannot be removed easily by filtering.

Appendix 1. S-parameters

A key assumption when making measurements is that networks can be completely characterized by quantities measured at the network terminals (ports) regardless of the contents of the networks. Once the parameters of a network have been determined, its behavior in any external environment can be predicted. At low frequencies, typical choices of network parameters to be measured and handled are Z-parameters or Y-parameters, i.e. the impedance or admittance matrix, respectively.

In microwave design, S-parameters are the natural choice because they are easier to measure and work with at high frequencies than other kinds of parameters. They are conceptually simple, analytically convenient, and capable of providing a great insight into a measurement or design problem[1]. Similarly, when light interacts with a lens, and a part of the light incident is reflected while the rest is transmitted, scattering parameters present the reflection and transmission of voltage waves through an electrical network.

The operation of a two-port device, such as an amplifier, can be described by the use of four S-parameters designated as S_{11}, S_{12}, S_{21} and S_{22}. The subscripts indicate where the signal is measured and where the signal is injected. The input port is designated as port 1, and the output port as port 2. The first subscript indicates the port of measurement. The second subscript indicates the port where the signal is injected.

For $\mathbf{S_{11}}$, the signal is measured at the input, and the signal is injected at the input. This is a measure of the **return loss at the input**.

For $\mathbf{S_{12}}$, the signal is measured at the input and injected at the output. Thus, this is a measure of the **isolation of the amplifier between the output and input**.

For $\mathbf{S_{21}}$, the signal is measured at the output port and injected at the input port. This is a measure of the **gain of the amplifier**.

For $\mathbf{S_{22}}$, the signal is measured and injected at the output port. This is a measure of the **return loss at the output port**.

[1] In the early 1950s Rohde & Schwarz released the first VNA they called a "Z-g-diagraph", capable of measuring magnitude and phase of S-parameters up to 300 MHz. In 1954 the Z-g-diagraph reached frequencies of 2.4 GHz

Appendix 2. Smith Chart

A Smith chart is a circular plot with a lot of interlaced circles on it. When used correctly, matching impedances, with apparent complicated structures, can be made without any computation. The only effort required is the reading and following of values along the circles.

The Smith chart is a polar plot of the complex reflection coefficient Γ or defined as the 1-port scattering parameter s or $\mathbf{s_{11}}$.

A Smith chart is developed by examining the load where the impedance must be matched. Instead of considering its impedance directly, you express its reflection coefficient Γ, which is used to characterize a load. The reflection coefficient is defined as the ratio between the reflected voltage wave and the incident voltage wave and defined as:

$$\Gamma = \frac{V_{Refl}}{V_{Inc}} = \frac{Z_L - Z_0}{Z_L + Z_0} = \Gamma_{Re} + j\Gamma_{Im}$$

The amount of reflected signal from the load is dependent on the degree of mismatch between the source impedance and the load impedance.

In order to reduce the number of unknown parameters, we will normalize it tothe characteristic impedance Z_0 (is often a real industry normalized value, such as 50Ω,75Ω or other standard). The normalized load impedance z defined as:

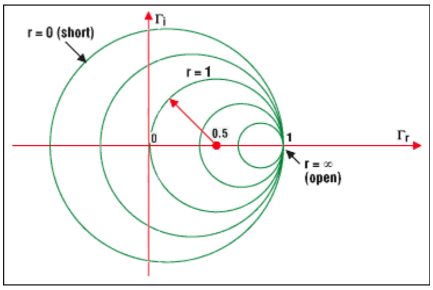
$$z = \frac{Z_L}{Z_0} = \frac{R + jX}{Z_0} = r + jx$$

With this simplification, we can rewrite the normalized load impedance z components as: $z = r + jx = \frac{1+\Gamma_L}{1-\Gamma_L} = \frac{1+\Gamma_{Re}+j\Gamma_{Im}}{1-\Gamma_{Re}-j\Gamma_{Im}}$ where $r = \frac{1-\Gamma_{Re}{}^2-\Gamma_{Im}{}^2}{1+\Gamma_{Re}{}^2-2\,\Gamma_{Re}+\Gamma_{Im}{}^2}$

By setting the real parts and the imaginary parts of equation for normalized load impedance z equal (eliminating x) and after simple manipulations theequation can be rewritten to

$$\left(\Gamma_{Re} - \frac{r}{r+1}\right)^2 + \Gamma_{Im}{}^2 = \left(\frac{1}{1+r}\right)^2$$

This equation is a relationship in the form of a parametric equation $(x - a)^2 + (y - b)^2 = R^2$ in the complex plane (Γ_{re}, Γ_{im}) of a circle centered at the coordinates [r/(r + 1), 0] and having a radius of 1/(1 + r).

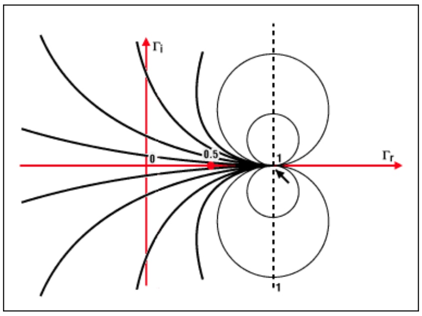


The points situated on a circle are all the impedances characterized by a same real impedance part value. For example, the circle, r = 1, is centered at the coordinates (0.5, 0) and has a radius of 0.5. It includes the point (0, 0), which is the reflection zero point (**the load is matched with the characteristic impedance**). A short circuit, as a load, presents a circle centered at the coordinate (0, 0) and has a radius of 1. For an open-circuit load, the circle degenerates to a single point (centered at 1, 0 and with a radius of 0). This corresponds to a maximum reflection coefficient of 1, at which the entire incident wave is reflected totally.

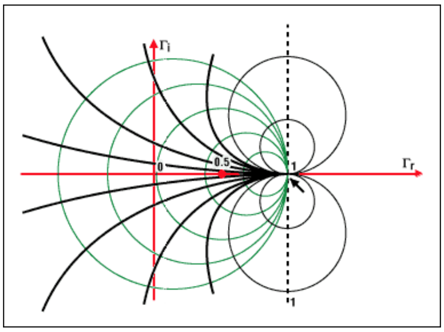
Doing the same manipulation but now (eliminating r) for the x component theequation can be rewritten to

$$(\Gamma_{Re}-1)^2+\left(\Gamma_{Im}-\frac{1}{x}\right)^2=\left(\frac{1}{x}\right)^2$$

Again, is a parametric equation of the type $(x - a)^2 + (y - b)^2 = R^2$ in the complex plane (Γ_{re}, Γ_{im}) of a circle centered at the coordinates (1, 1/x) and having a radius of 1/x.



The points situated on a circle are all the impedances characterized by a same imaginary impedance part value x. For example, the circle × = 1 is centered at coordinate (1, 1) and has a radius of 1. All circles (constant x) include the point (1, 0). Differing with the real part circles, x can be positive or negative. This explains the duplicate mirrored circles at the bottom side of the complex plane. All the circle centers are placed on the vertical axis, intersecting the point 1.



To complete our Smith chart, we superimpose the two circles' families. It can then be seen that all of the circles of one family will intersect all of the circles of the other family. Knowing the impedance, in the form of r + jx, the corresponding reflection coefficient can be determined. It is only necessary to find the intersection point of the two circles corresponding to the values r and x.

Among the most important conditions that should be noted are:

- All the circles have one same, unique intersecting point at the coordinate (1, 0)
- The zero Ω circle where there is no resistance (r = 0) is the largest one
- The infinite resistor circle is reduced to one point at (1, 0)

- There should be no negative resistance. If one (or more) should occur, we will be faced with the possibility of oscillatory conditions.
- Another resistance value can be chosen by simply selecting another circle corresponding to the new value.

Appendix 3. Bead Pull Measurements

For measuring the electric and magnetic fields within the resonator (preferably on the axis) antennas are unsuitable because the necessary cables would alter the field distribution in the resonator.

Bead-Pull RF field measurements are used in evaluating the field distribution inside a resonant structure and in tuning them to obtain the required field parameters.

The Bead-Pull system consists of a small dielectric or metallic bead being pulled through a cavity while the Network Analyzer is used to take the RF measurements.

The small impurity (a dielectric or conducting object) which slightly distorts the field,is inserted into the resonator causing a shift in the resonant frequency ($\omega_0 \rightarrow \omega$) and at constant excitation with ω_0 changing the reflection coefficient S (here - S_{11}). Both (ω or S) can be measured and used for calculating the fields.

The Bead-Pull method is based on the classical Slater perturbation theory which states that if any resonant cavity is perturbed by a small bead, its resonant frequency shifts from the original frequency. This frequency shift is proportional to the combination of the squared amplitudes of the electrical and magnetic fields at the location of the bead. This relationship is given by equation:

$$\frac{\omega_0^2 - \omega^2}{\omega^2} \cong 2\frac{\Delta\omega}{\omega_0}$$

see [W.Hillert, p36]

From this equation, we realize that, if the magnetic field is zero (which is the case along the center of the cavity), the electric field is directly proportional to the change in resonant frequency. Therefore, if the change in resonant frequency is known, the electric field can be determined by moving the bead along a line in the cavity.

For the resonant frequency measurements, VNA takes the data at a given point a number of times specified by the user and averages them for better measurements.

The GUI displays the measurements on the screen and converts them into the desired format.

In the Bead-Pull GUI one can set the parameters of the Step Motor (start and stop coordinates, and the velocity/number of steps in one cycle), then pushing start button the program calls the Network Analyzer to take the measurements until step motor reaches the end coordinate.

Once it reaches the stop position, all the data is collected into a spreadsheet file placed in user specified location with a defined name including time/date stamp. Finally, it moves the bead back to the start position.

During the measurements the students can follow the results displayed on the Network Analyzer, and be assured that the program reads the measurements from the VNA.

Tuning

The 7-cell prototype of CANDLE 50MeV upgrade cavity will be adjusted to designed parameters during experiment. In order to provide synchronism with the beam, the phase advance of each cell needs to be adjusted to its nominal parameters by pushing or pulling the specially designed tuners; hence, the adjustment process is called tuning.

The ΔS_{11} will be measured via a bead-pull measurement. The change of input reflection will be recorded and electrical field component will be calculated. During tuning process, a few measurements will be repeated to guarantee a good reproducibility, corresponding to an amplitude variation below ±1.0% and a phase variation below ±0.5°.

Polar plot of real, imaginary part and absolute of ΔS_{11} will be plotted before and after tuning as shown in Figure 7.

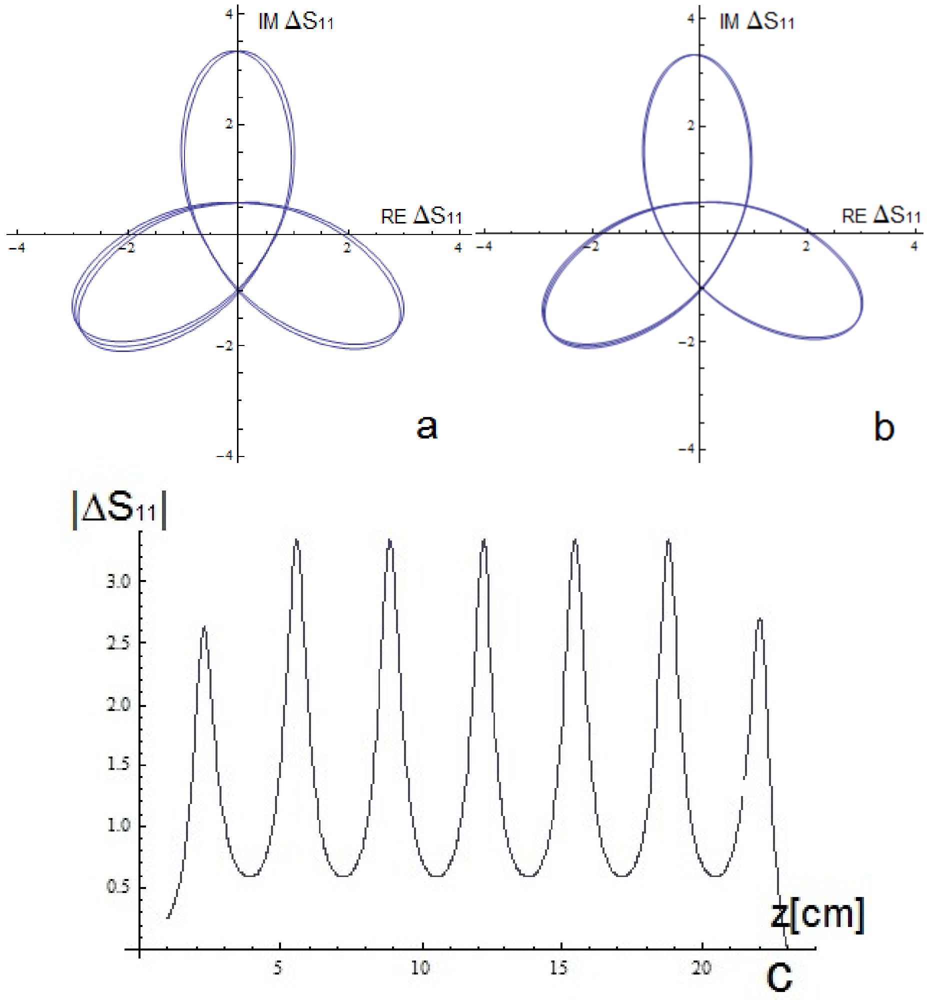


Figure 7. Polar plot of real, imaginary part a) before tuning, b) after tuning and c) absolute of $\Delta \boldsymbol{S_{11}}$ after tuning

After few steps of tuning the phase advance per cell of all 7 regular cells will be in average within 120°±1° (instead of 120°±5° or more) so the tuning can be finished.

Supporting Materials

W. Hillert "Hohlraumresonatoren/Cavities" Lecture notes PDF file will be provided

References

1. V. Teppati, A. Ferrero, M. Sayed. "Modern RF and Microwave Measurement Techniques" 2013
2. F. Caspers, RF engineering basic concepts: S-parameters, CERN-2011-007, pp. 67-93
3. P. Smith, Electronic Applications of the Smith Chart. Noble Publishing, Atlanta, 2000, ISBN 1-884932-39-8
4. M. Hiebel, Fundamentals of Vector Network Analysis R&S, Munchen, 2007, ISBN 3939837067