RF Engineering
RF Measurements

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Outline and Objectives

- **Overview of RF measurement instruments**
  - **Oscilloscope, spectrum analyzer (SA), signal (FFT) analyzer, slotted measurement line, vector network analyzer (VNA)**
- **Reflection measurement with the slotted coaxial air-line**
- **The super-heterodyne receiver principle**
  - **Modulation, down-conversion, mixer, spectrum analyzer block schematics**
- **S-parameter measurements**
  - **Simple measurement setup, VNA block schematics**
  - **VNA calibration**
  - **Synthetic pulse measurements with the VNA**
  - **Measurement example 1: pillbox resonator characterization**
    - Equivalent circuit parameters, Q-factor measurement in the Smith-chart, *Slater*'s theorem, bead-pull measurement
  - **Measurement example 2: beam coupling impedance**
    - Stretched-wire measurement of the longitudinal coupling impedance

Please note the references to the JUAS proceedings!

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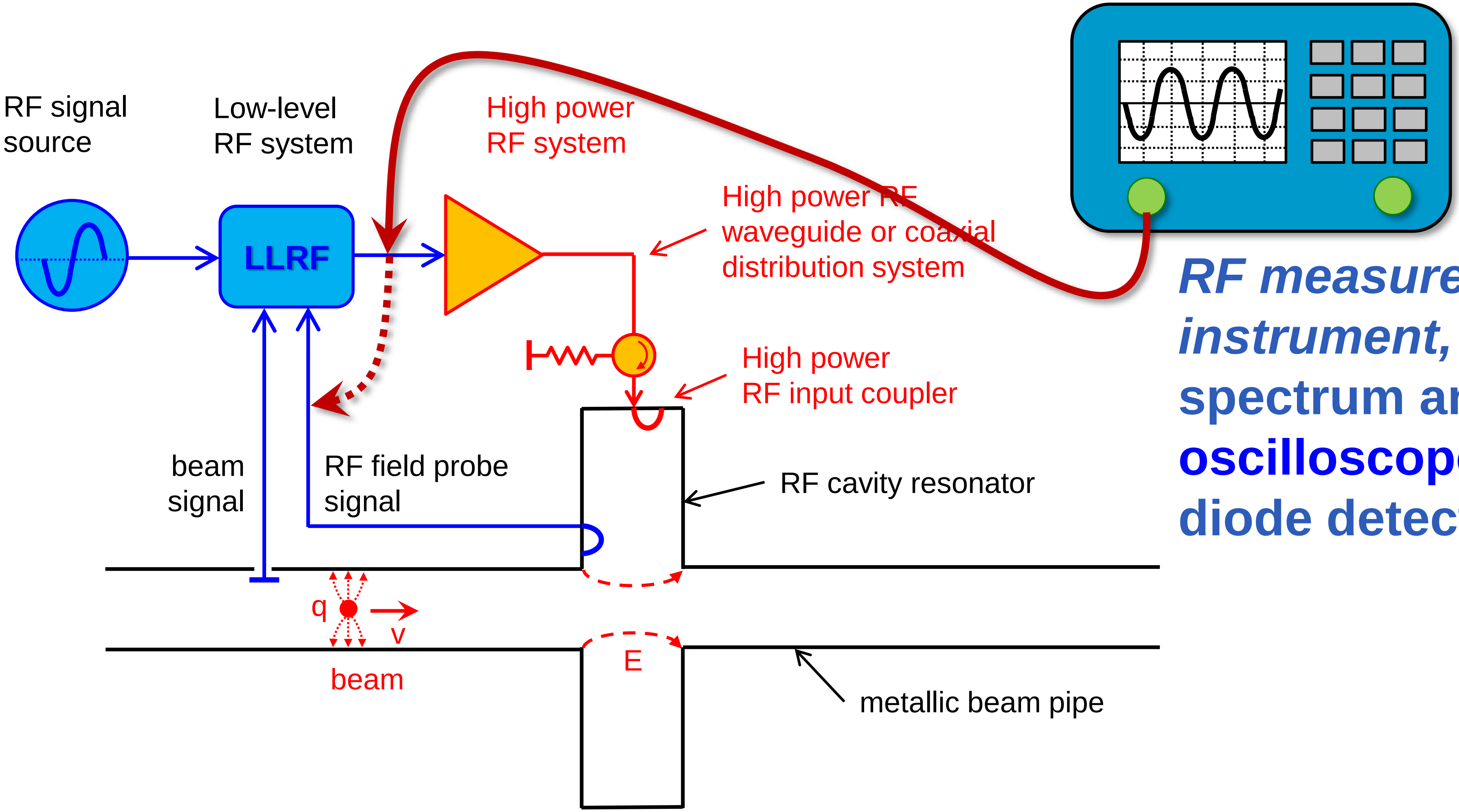
II.2.x.y.z, p. nnn

RF Measurements



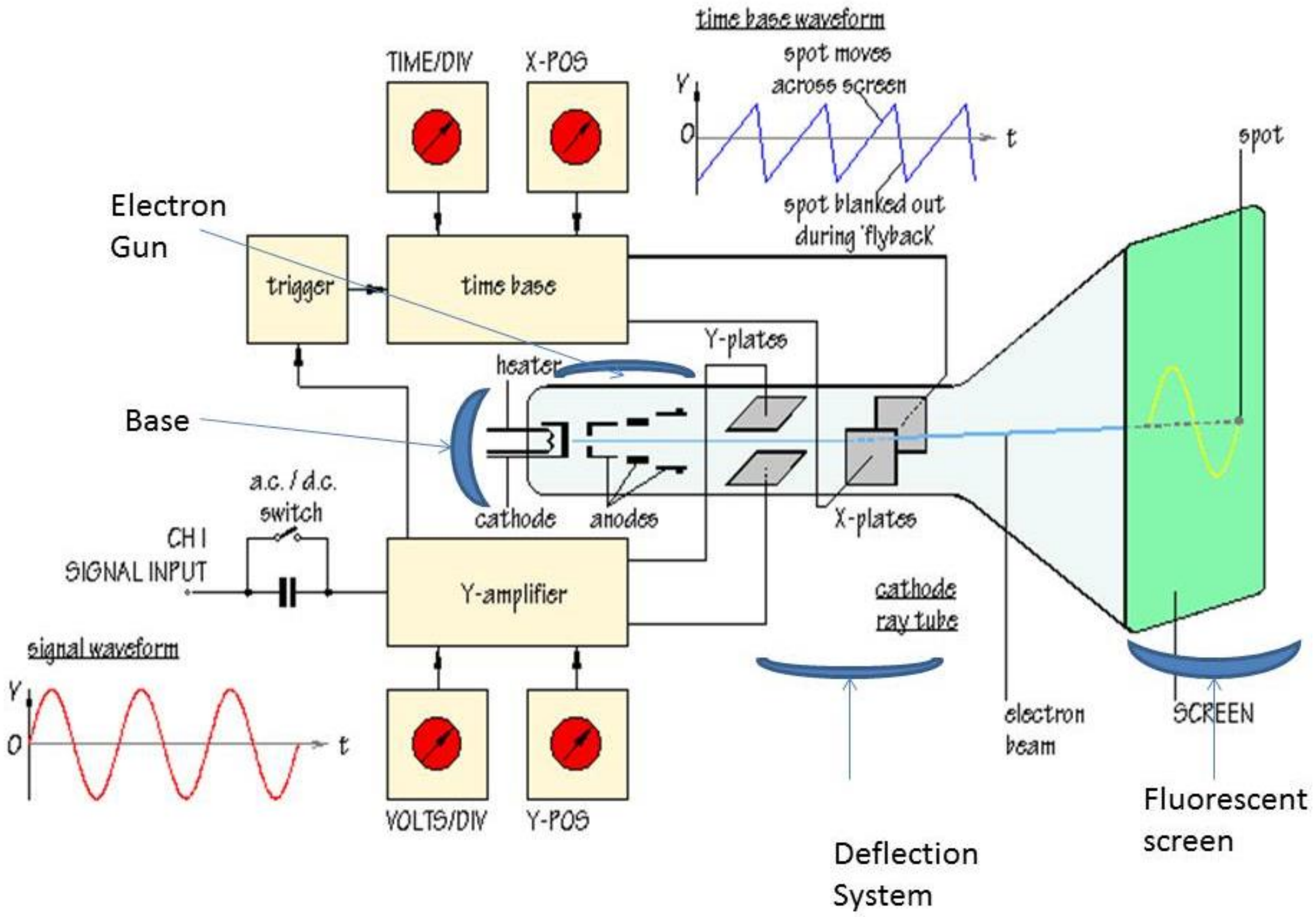
RF measurement instrument, e.g.:
spectrum analyzer,
oscilloscope,
diode detector, etc.

RF Measurement Methods (1)

There are different options to observe RF signals
Here some typical measurement tools:

- **Oscilloscope: to observe signals as time-domain waveform**
  - **periodic signals**
  - **burst and transient signals with arbitrary waveforms**
  - **application: direct observation of signals from a beam pick-up, from a test generator, or from other sources**
  - **visualizes the shape of a waveform, etc.**
  - **limited performance for the evaluation of non-linear effects.**

Cathode Ray Tube (CRT) Oscilloscope

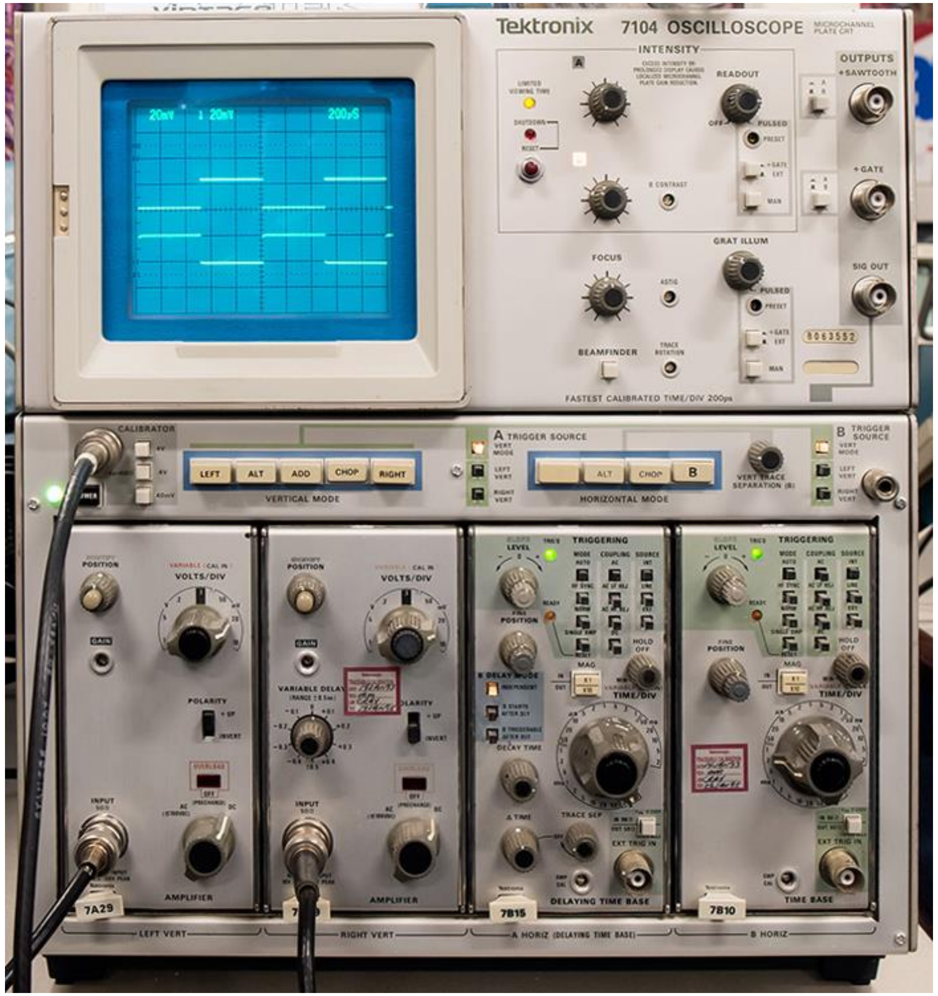


Electron Gun

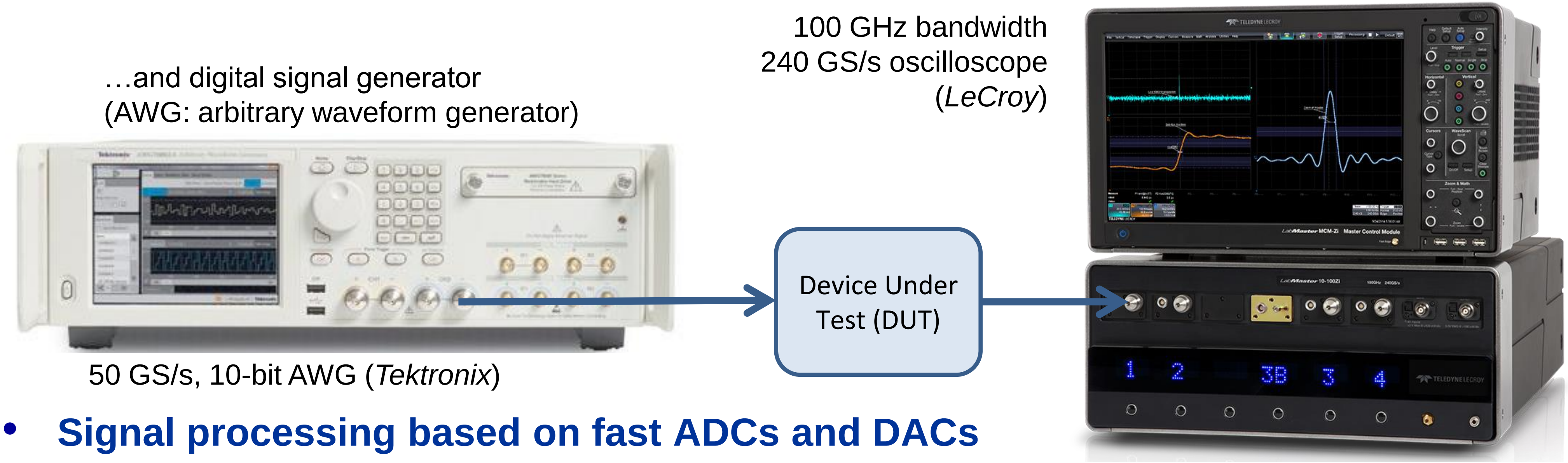
Base

Deflection System

Fluorescent screen



Today: Digital Storage Oscilloscope (DSO)



…and digital signal generator
(AWG: arbitrary waveform generator)

100 GHz bandwidth
240 GS/s oscilloscope
(*LeCroy*)

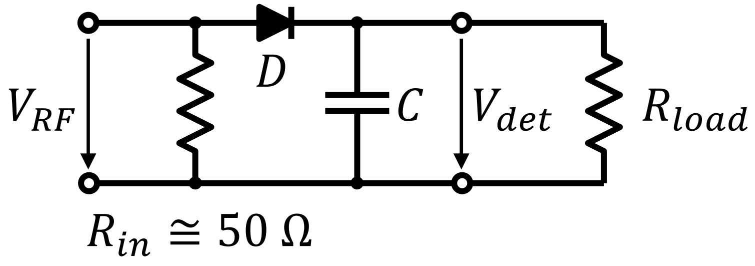
Device Under Test (DUT)

50 GS/s, 10-bit AWG (*Tektronix*)

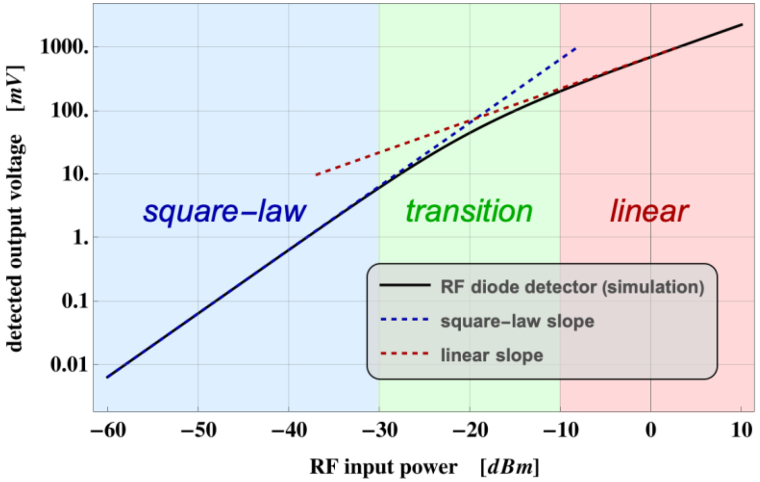
- **Signal processing based on fast ADCs and DACs**
  - **Similar “look and feel” as analog oscilloscopes, but better performance**
    - 8…12-bit multi-GS/s ADCs, still, be aware of aliasing effects!
    - Fast sampling oscilloscope require sufficient memory resources.
- **AWG or pulse generator & digital oscilloscope: Time-domain (TD) test setup**
  - **Device under test (DUT) characterization and trouble shooting**
    - Impulse, step, or arbitrary waveform (e.g., beam signal) as stimulus signal
    - High impedance probe for measurements on the printed circuit board (PCB)

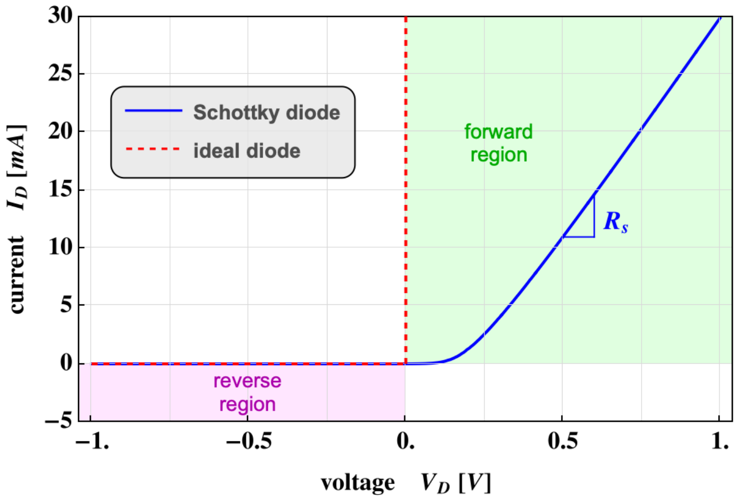
RF Measurements Methods (2)

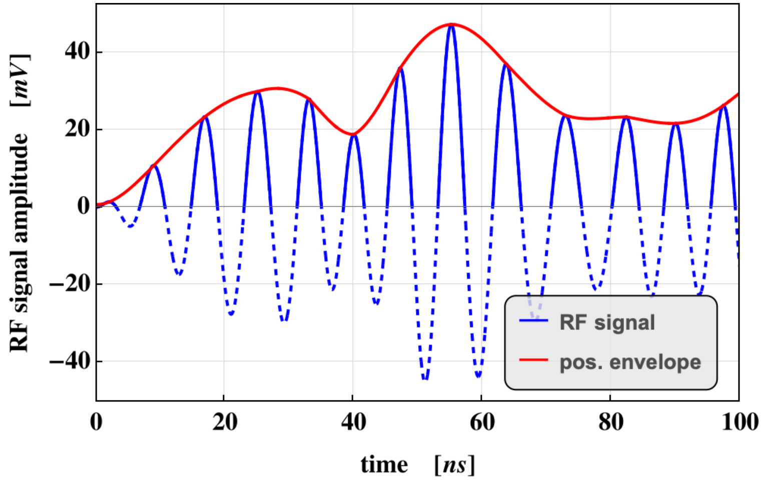
- **RF detection (Schottky) diode (RF power meter)**
  - **Supplies a rectified (video) output signal proportional to the RF signal level**
  - **Delivers no frequency or phase information, but operates over a very broad frequency range few MHz to many GHz, and up to ~60 dB dynamic range.**



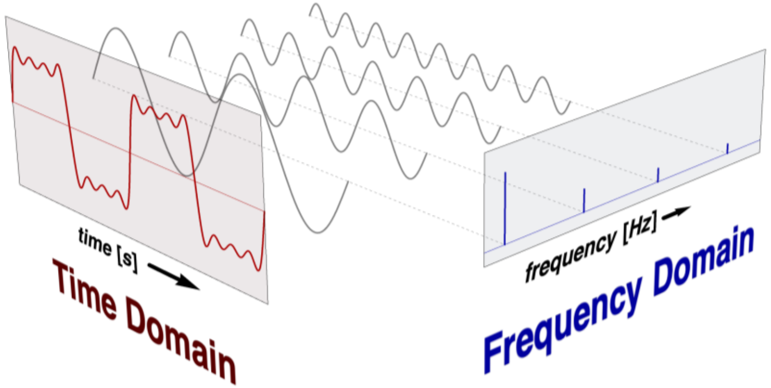
$$I_D = I_S\left(e^{\frac{V_D - I_D R_S}{nV_T}} - 1\right)$$







RF Measurements Methods (3)



- **Spectrum analyzer: to observe signals in a “frequency-domain like” fashion**
  - **sweeps in equidistant steps through a given frequency range**
  - **application: observation of spectrum from the beam, or from a signal generator or RF source, or the spectrum emitted from an antenna to locate EMI issues in the accelerator tunnel, etc.**
    - ➢ Also, DUT characterization in the laboratory, e.g., noise figure measurement on amplifiers (requires a noise source), intermodulation measurements on amplifiers (requires two RF generators).
  - **Requires periodic signals**
  - **Assumes time-invariance of the measurement object (DUT) throughout the frequency sweep**
  - **Large dynamic range!**

RF Measurements Methods (4)

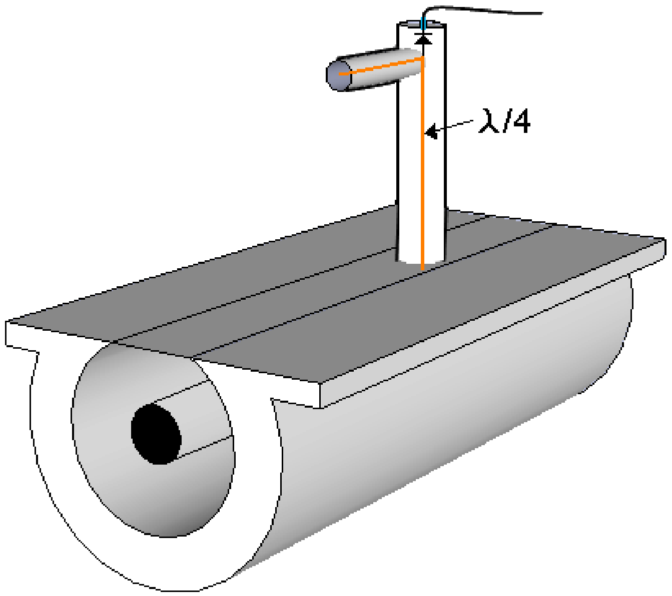
- **Vector signal analyzer (VSA), sometimes called FFT analyzer**
  - **Acquires the RF signal, after down-conversion to an intermediate (IF) signal, in time-domain by fast sampling**
  - **Further numerical treatment in digital signal processors (DSPs)**
  - **Spectrum calculated using Fast Fourier Transform (FFT)**
  - **Combines features of an oscilloscope and a spectrum analyzer: Signals can be observed directly in time-domain, or in a frequency-domain like fashion**
  - **Contrary to the SA, also the spectrum of non-periodic signals and transients can be measured**
  - **Application: Observation of tune sidebands, transient behavior of a phase locked loop, single pass beam signal spectrum, etc.**
  - **Digital oscilloscopes and FFT analyzers share similar technologies, i.e., fast sampling and digital signal processing, and therefore can provide similar measurement options**
    - ➢ The digital oscilloscope directly digitizes the RF signal → limited dynamic range, large instantaneous bandwidth
    - ➢ The FFT analyzer digitizes the down-converted IF signal → large dynamic range, but (still) limited instantaneous bandwidth

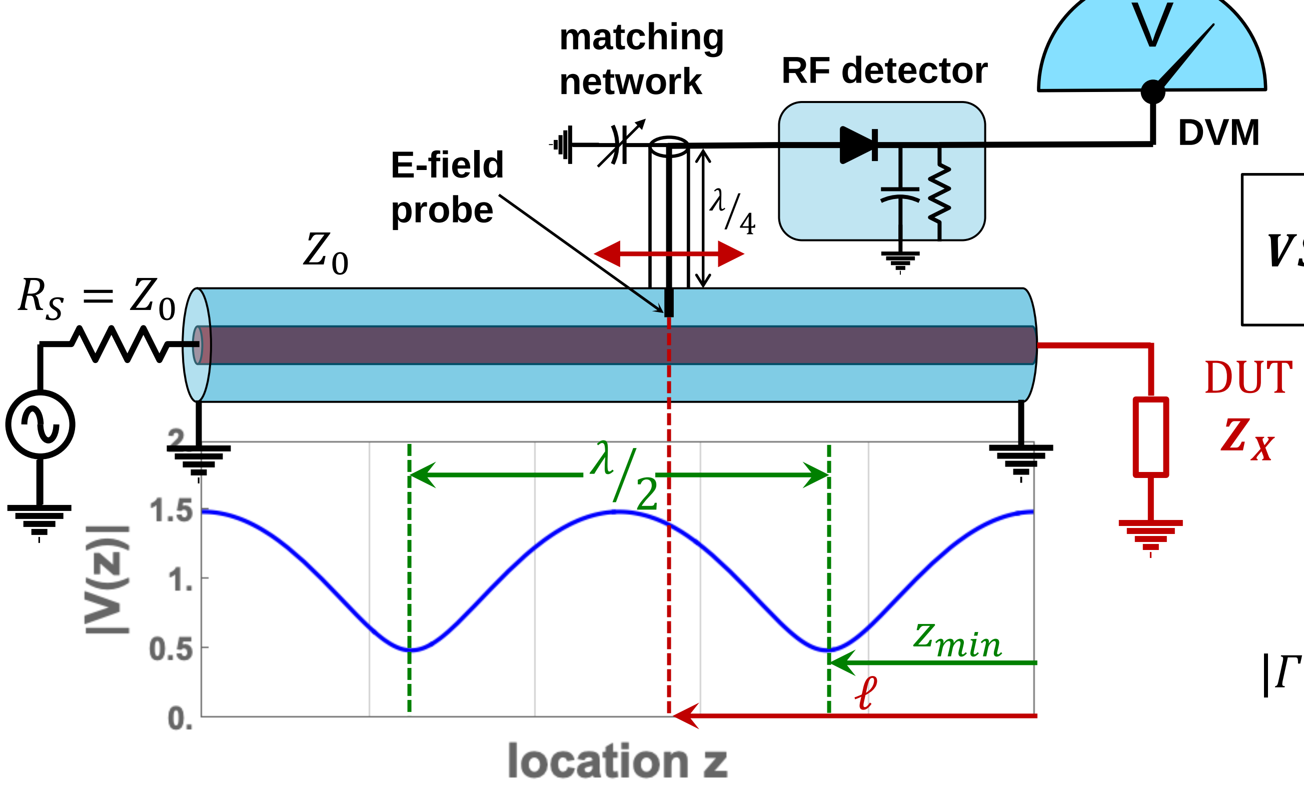
RF Measurements Methods (5)

Tools to characterize RF components and sub-systems:

- **Slotted coaxial (or waveguide) measurement transmission-line**
  - **For study and illustration purposes only –
not anymore used in today's RF laboratory environment.**
- **Vector Network Analyzer (VNA)**
  - **Combines the functions of a vector spectrum analyzer (FFT analyzer), a RF sweep generator, and a S-parameter test set (directional coupler)**
  - **Excites a *Device Under Test* (DUT, e.g., circuit, antenna, amplifier, etc.) network at a given sinusoidal *continuous wave* (CW) frequency, and measures the response in magnitude and phase => determines the S-parameters**
  - **Covers a selectable frequency range by measuring step-by-step at subsequent frequency points (like a spectrum analyzer, again requires the DUT to be time-invariant!)**
  - **Applications: characterization of passive and active RF components, *Time Domain Reflectometry* (TDR) by Fourier transformation of the reflection response, etc.**
    - ➢ Also, power sweep measurements (1 dB compression point),
4-port VNAs enable virtual ports: e.g., single-ended / differential port DUT characterization.
  - **The VNA is the most versatile and comprehensive tool in the RF laboratory!**

Reflection (VSWR) Measurement





$$\boxed{VSWR = \frac{|V_{max}|}{|V_{min}|}}$$

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

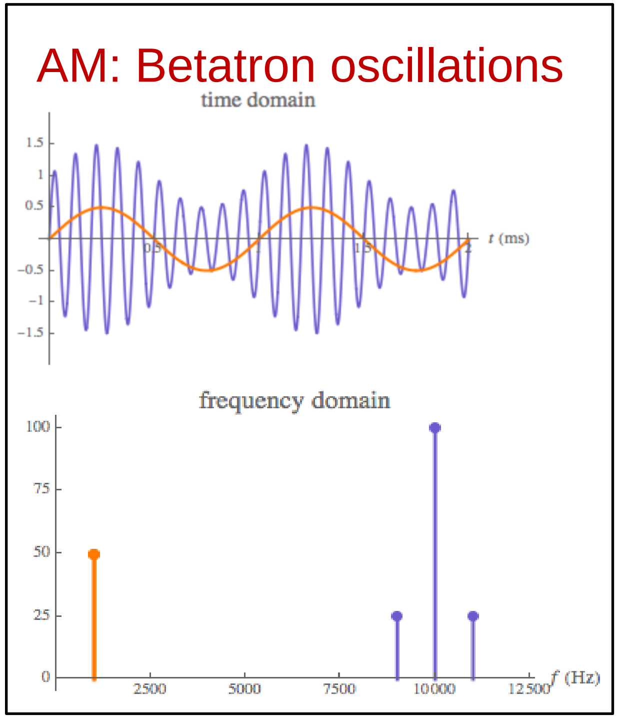
$$\angle\Gamma = \frac{4\pi}{\lambda} z_{min} - \pi$$

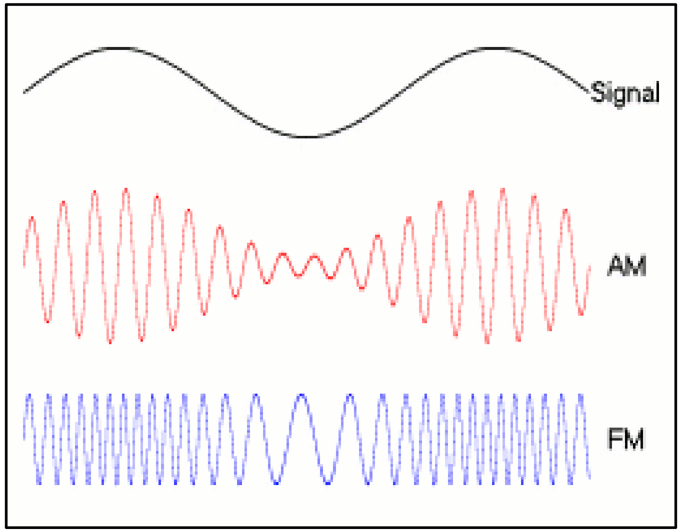
$$\boxed{Z_x = Z_0 \frac{1 - \Gamma}{1 + \Gamma}}$$

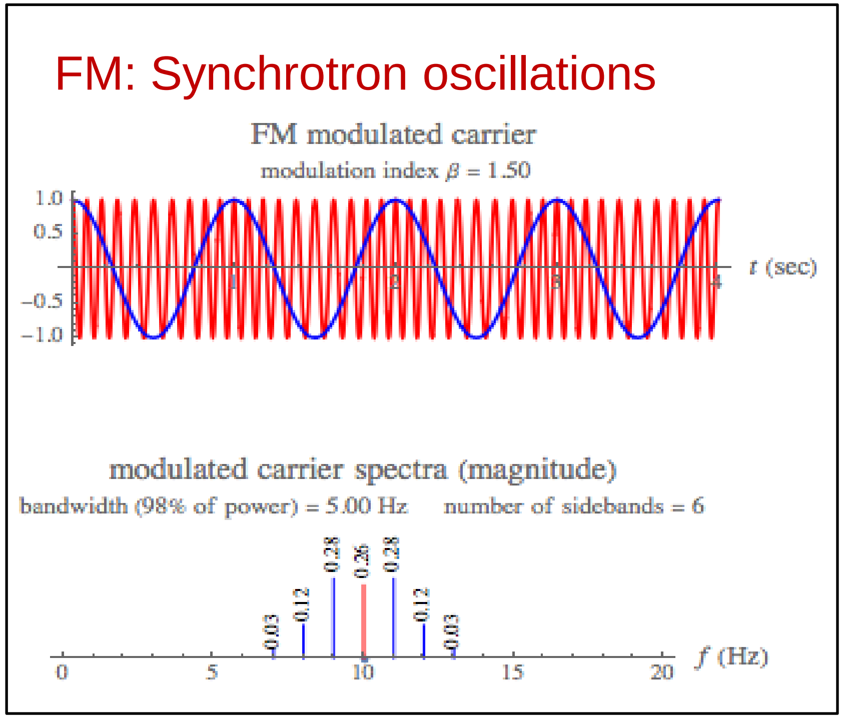
- **Slotted coaxial air-line is used as standing wave detector**
  - **Probes the radial electric field along the slotted line.**
  - **Measurement of E-field minima's E_{min} and maxima's E_{max} with a diode detector, thus detect $|V_{min}|$ and $|V_{max}|$ along the line.**
  - **Evaluate the reflection coefficient Γ of a DUT of unknown Z_X at the end of the line**

RF Signals & Modulation, without Math!

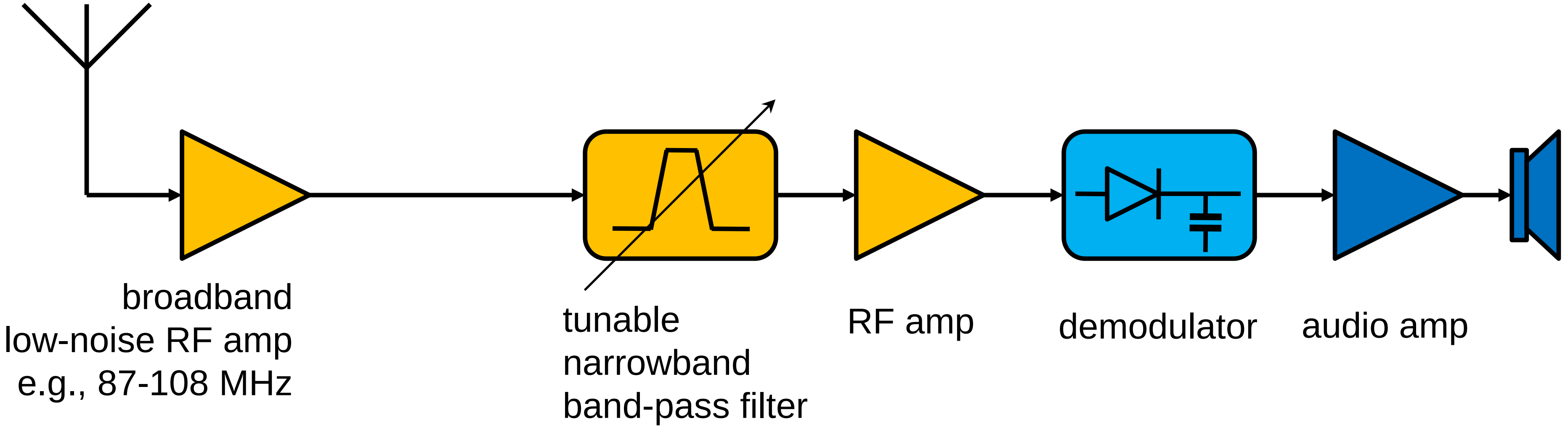
- **RF signals are continuous wave (CW),sinusoidal signals**
  - **Often, a high frequency carrier is modulated with low frequency information**
  - **Modulation appears “naturally” in ring accelerators as:**
    - ➢ Modulation is also provided through the LLRF system to the accelerating structures


AM: Betatron oscillations




FM: Synchrotron oscillations

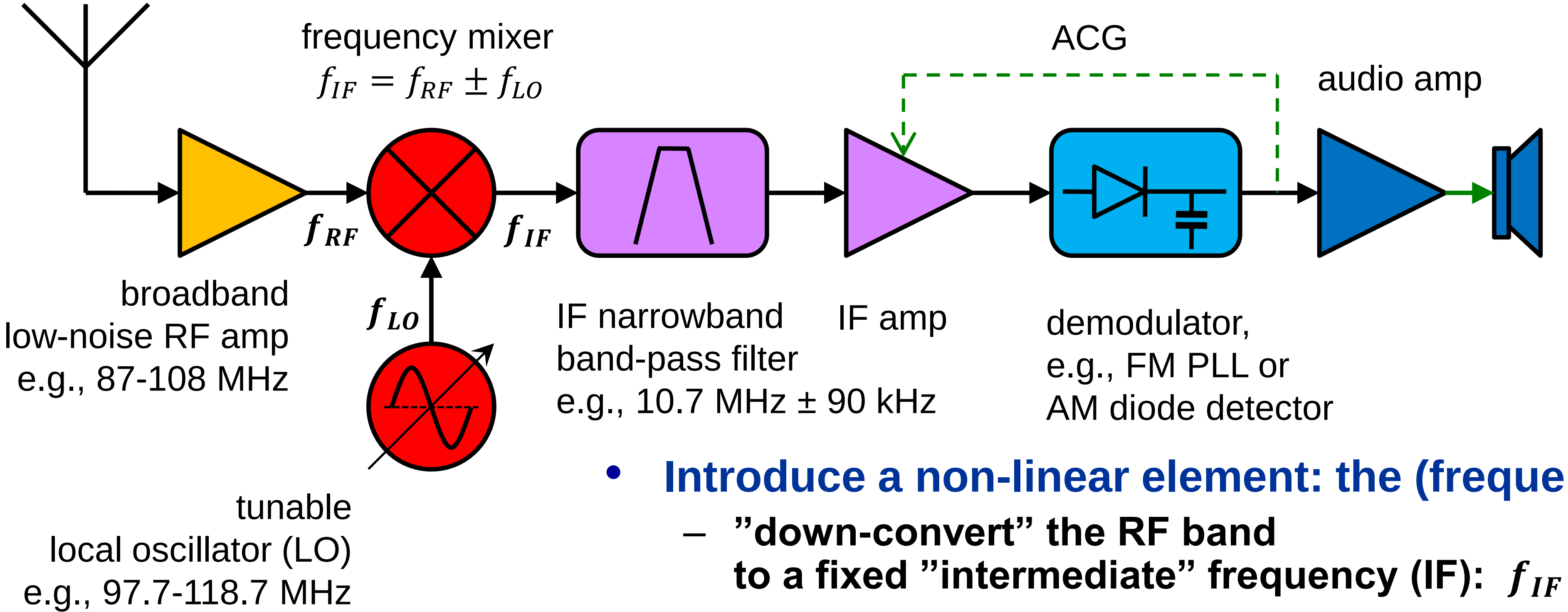
A (too) simple Radio Receiver



- **…or: How does a ”traditional” analog radio works?**
  - **It was, and still is, difficult to make precisely tunable narrowband, band-pass filters for high frequencies (~100 MHz)!!**
  - **high frequency low-noise amplifiers are expensive!**
  - **high frequency demodulators are not trivial.**

  - **direct detection of radio and RF signals is challenging!**

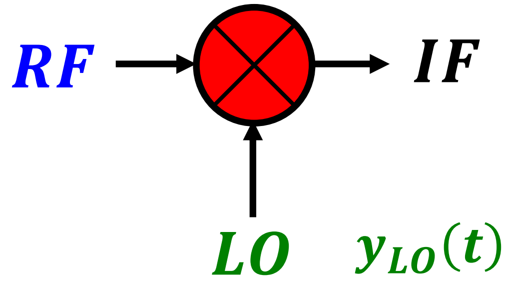
The Super-Heterodyne Receiver



- **Introduce a non-linear element: the (frequency) mixer!**
  - **”down-convert” the RF band to a fixed ”intermediate” frequency (IF): $f_{IF} = f_{RF} \pm f_{LO}$**
  - **requires a tunable local oscillator (LO)**
  - **well manageable IF section:**
    - narrowband band-pass filter(s) (BPF) and amplifier(s)
  - **RF telecommunication standard**
  - **Often multiple mixing stages are used in modern RF instruments, e.g., spectrum and network analyzers**

The RF Mixer as Down-Converter

$y_{RF}(t) = A_{RF}\sin(\omega_{RF}t + \varphi_{RF})$



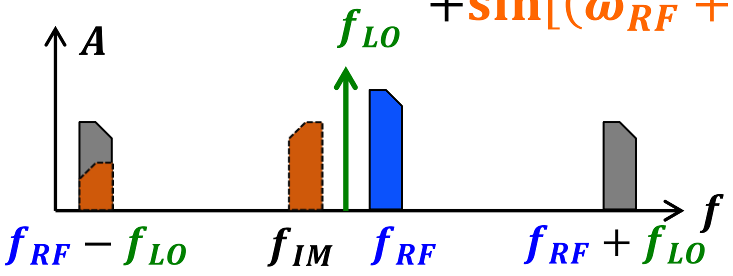
$y_{IF}(t) = y_{RF}(t)\,y_{LO}(t)$

$y_{LO}(t) = A_{LO}\sin(\omega_{LO}t + \varphi_{LO})$

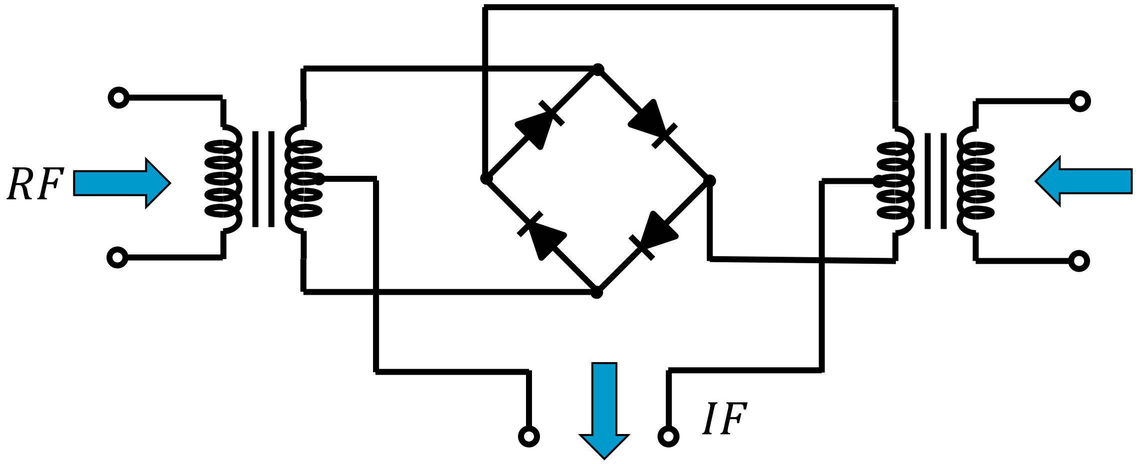
- **Ideal mixer:** $\boxed{f_{IF} = f_{RF} \pm f_{LO}}$

$$y_{IF}(t) = \frac{1}{2}A_{LO}A_{RF}\{\sin[(\omega_{RF} - \omega_{LO})t + (\varphi_{RF} - \varphi_{LO})]$$ upper sideband

$$+\sin[(\omega_{RF} + \omega_{LO})t + (\varphi_{RF} + \varphi_{LO})]\}$$ **lower sideband** (also called “base-band”)



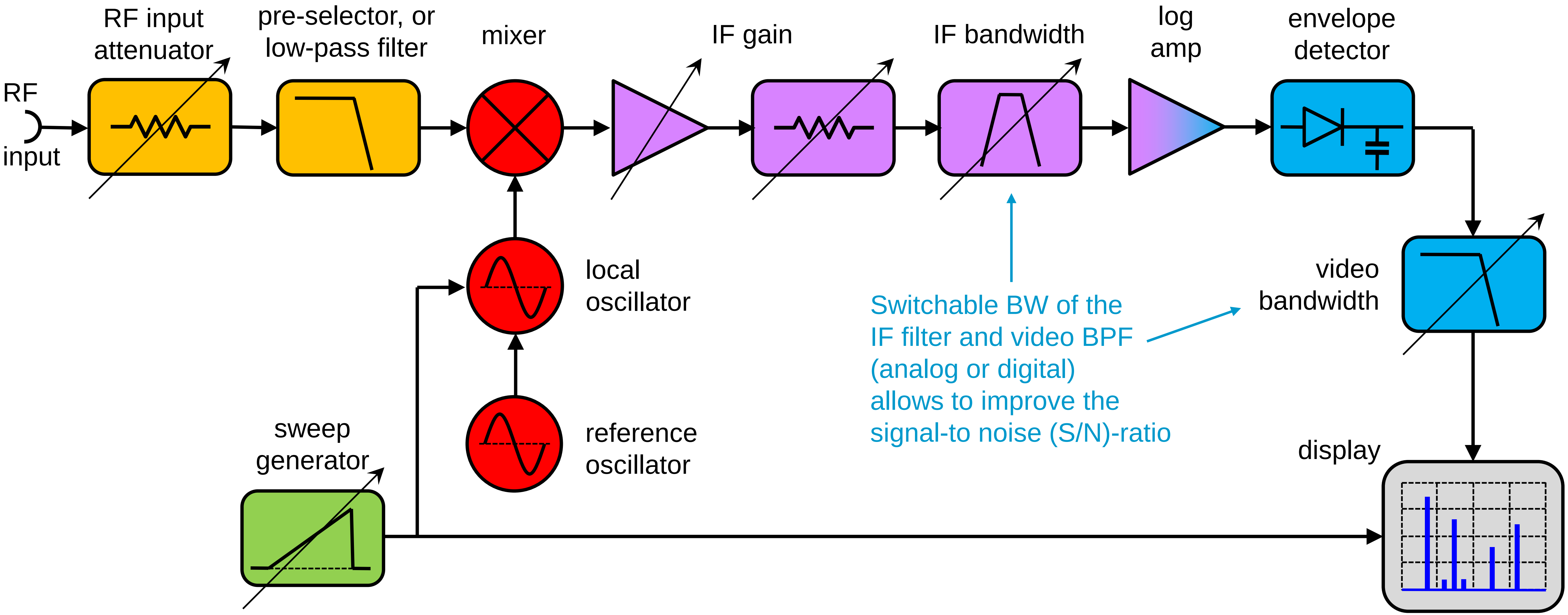
- **The mixer is based on non-linear circuit elements**
  - e.g., the diode, popular is the **double-balanced mixer**



- **Frequency conversion**
  - $f_{RF} \neq f_{LO}$: heterodyne receiver
  - $f_{RF} = f_{LO}$: homodyne, demodulator
- **Real-world mixer:** $f_{IF} = mf_{RF} \pm nf_{LO}$
  - Image frequency: $f_{IM} = f_{LO} - f_{IF}$

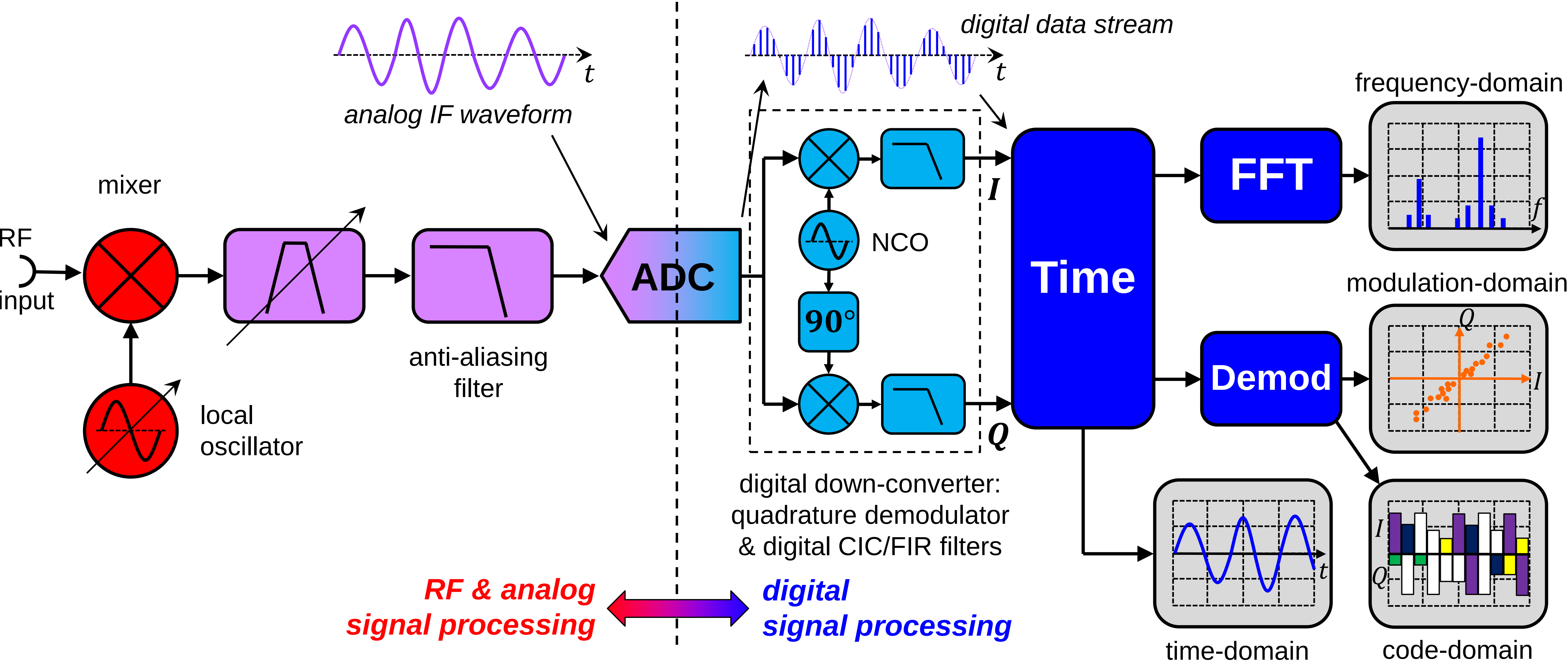
Simplified Spectrum Analyzer

- **based on the super-heterodyne principle**



Switchable BW of the IF filter and video BPF (analog or digital) allows to improve the signal-to noise (S/N)-ratio

Vector Signal Analyzer (VSA) or FFT Analyzer



analog IF waveform

t

digital data stream

t

RF
input

mixer

local
oscillator

anti-aliasing
filter

ADC

NCO

90°

I

Q

Time

FFT

Demod

frequency-domain

f

modulation-domain

Q

I

time-domain

t

code-domain

I

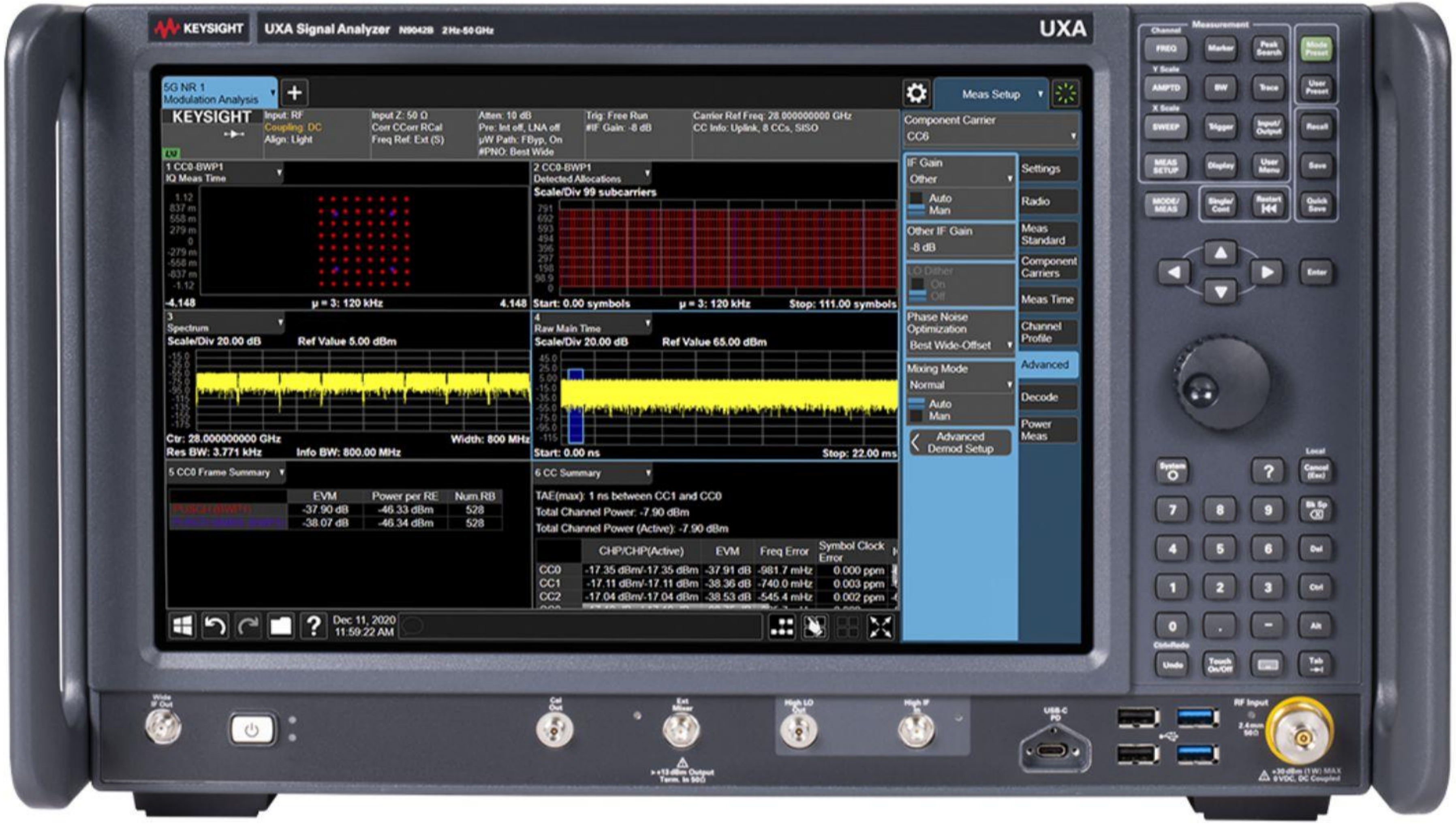
Q

digital down-converter:
quadrature demodulator
& digital CIC/FIR filters

RF & analog
signal processing

digital
signal processing

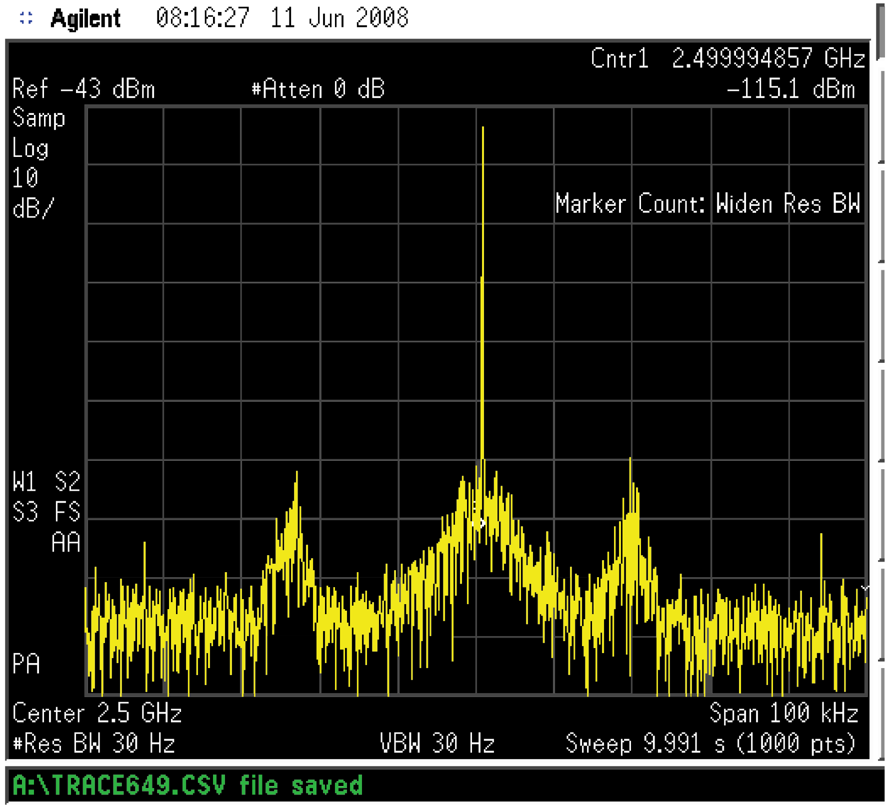
Modern Spectrum (RF Signal) Analyzer



Example: E-cloud investigation in the SPS

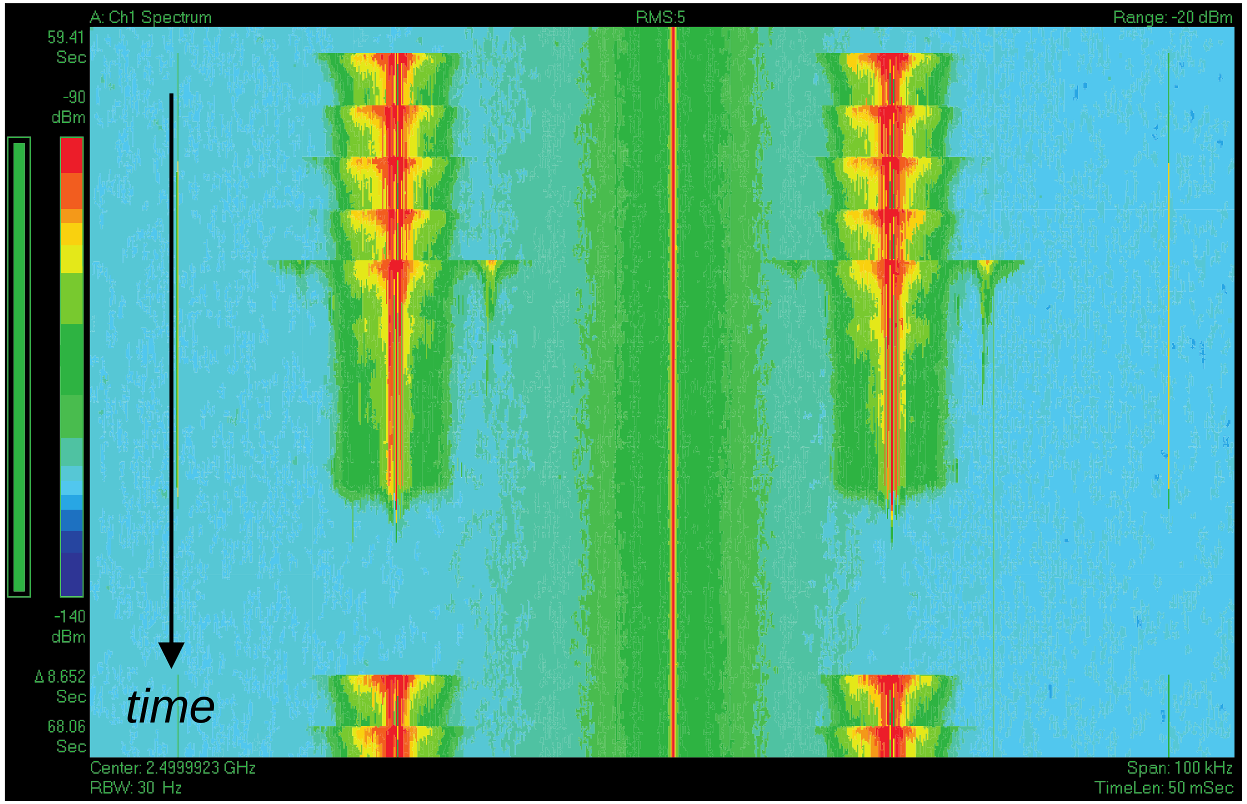
- **Electron cloud beam studies in the SPS (CERN) –** courtesy *F. Caspers*

high-resolution measurement
of the detected beam signal



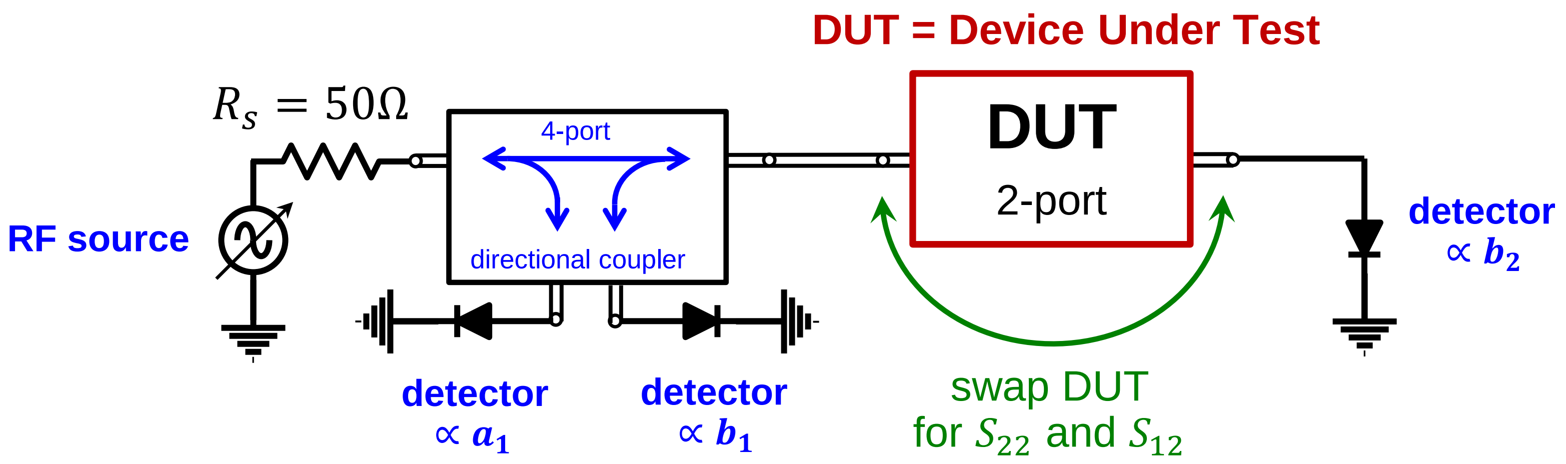
```
Agilent   08:16:27  11 Jun 2008
                                    Cntr1  2.499994857 GHz
Ref -43 dBm          #Atten 0 dB              -115.1 dBm
Samp
Log
10
dB/
                                    Marker Count: Widen Res BW
W1  S2
S3  FS
    AA

PA
Center 2.5 GHz                                Span 100 kHz
#Res BW 30 Hz              VBW 30 Hz   Sweep 9.991 s (1000 pts)
A:\TRACE649.CSV file saved
```

color-coded spectogram display
of 200 measurement traces



```
A: Ch1 Spectrum                 RMS:5                 Range: -20 dBm
Center: 2.4999923 GHz                                 Span: 100 kHz
RBW: 30  Hz                                           TimeLen: 50 mSec
```

How to measure S-Parameters?



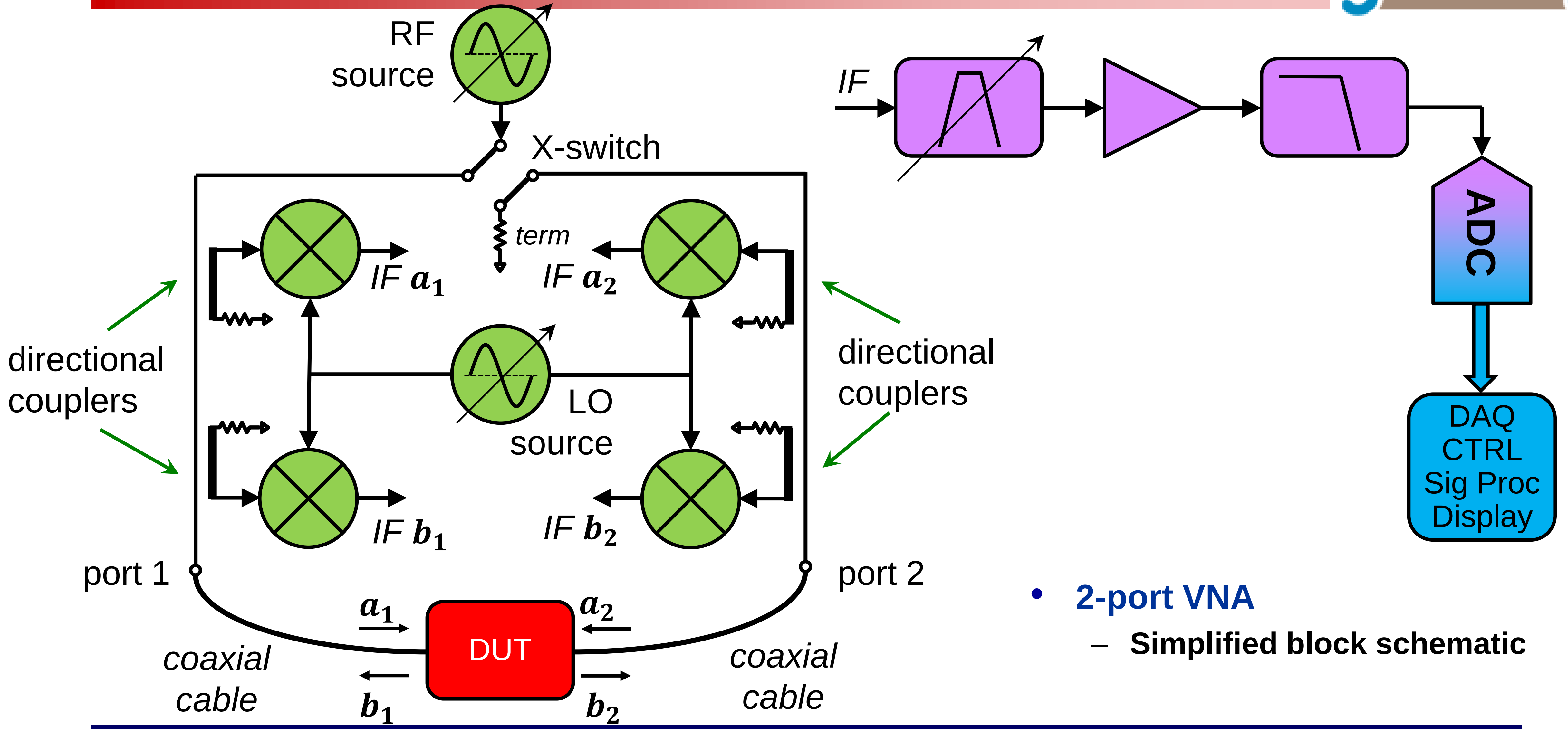
- **Performed in the "frequency domain"**
  - **Single or swept frequency generator, stand-alone or as part of a VNA or SA**
  - **Requires a directional coupler and RF detector(s) or receiver(s)**
- **Evaluate S_{11} and S_{21} of a 2-port DUT**
  - **Ensure $a_2 = 0$, i.e., the detector at port 2 offers a well-matched impedance**
  - **Measure incident wave a_1 and reflected wave b_1 at the directional coupler ports and compute for each frequency**
  - **Measure transmitted wave b_2 at DUT port 2 and compute**

$$S_{11} = \left.\frac{b_1}{a_1}\right|_{a_2=0}$$

$$S_{21} = \left.\frac{b_2}{a_1}\right|_{a_2=0}$$

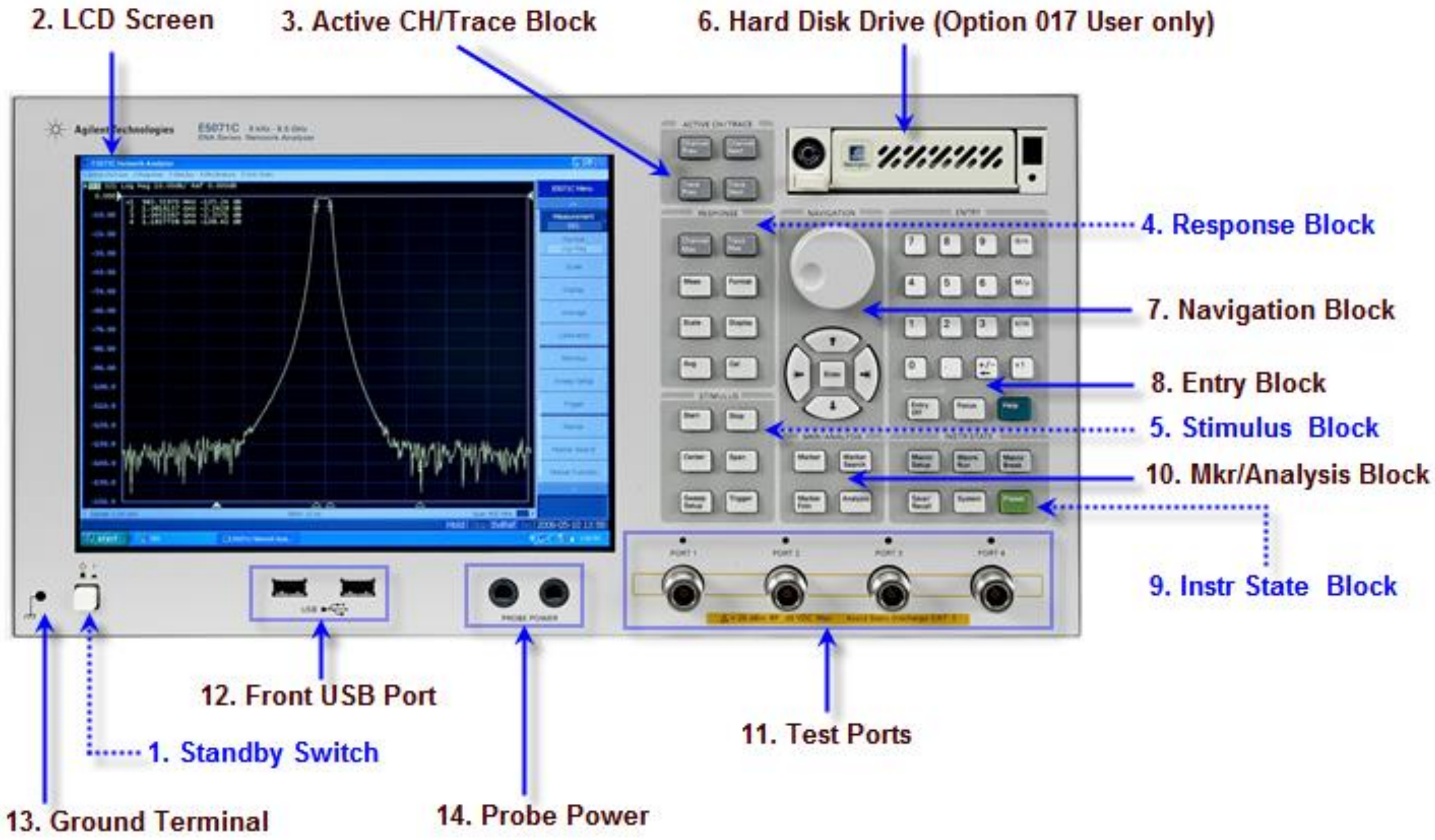
- **Evaluate S_{22} and S_{12} of the 2-port DUT**
  - **Perform the same methodology as above by exchanging the measurement equipment on the DUT ports**

The Vector Network Analyzer (VNA)



- **2-port VNA**
  - **Simplified block schematic**

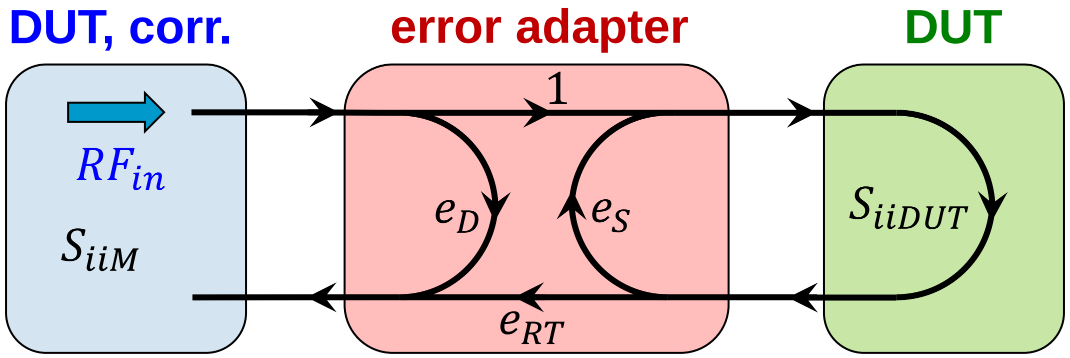
Fun with the VNA!



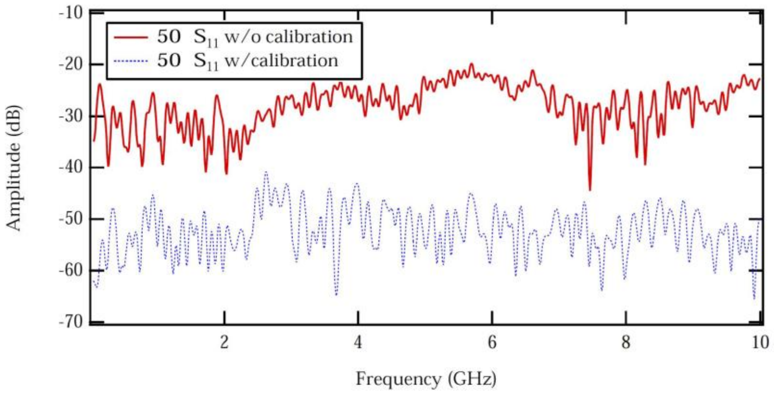
- The “*look and feel”* between VNAs vary between manufacturers and models
  - Concepts and operation is still very similar

VNA Calibration (1)

- Calibration is not necessary for pure frequency or phase measurements
- Before calibrating the VNA measurement setup, perform a brief measurement and chose appropriate VNA settings:
  - Frequency range (center, span or start, stop)
  - Number of frequency points
    - Can be sometimes increased by rearranging the VNA memory (# of channels)
  - IF filter bandwidth
  - Output power level
- Calibrate the setup, preferable with an electronic calibration system if more than 2 ports are used!
  - Each port and combination needs to be calibrated, with the cables attached
  - Choose the appropriate connector type and sex
  - The instrument establishes a correction matrix and displays the ”CAL” status.



VNA Calibration (2)

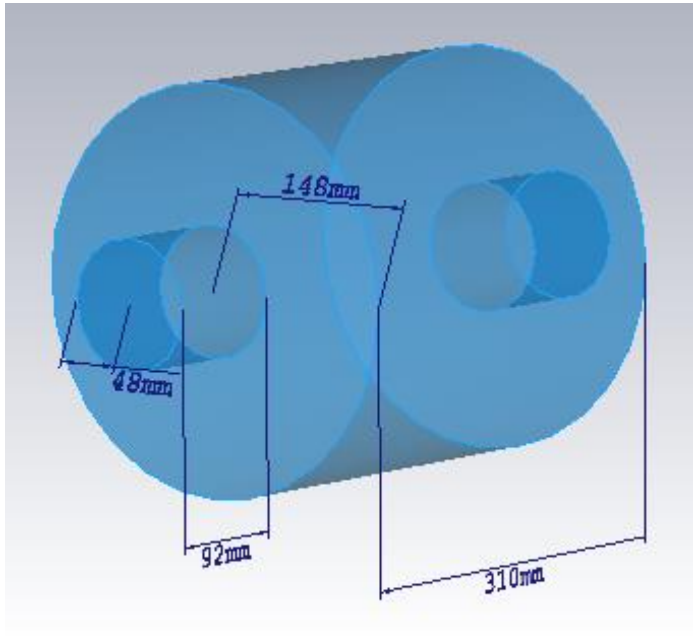


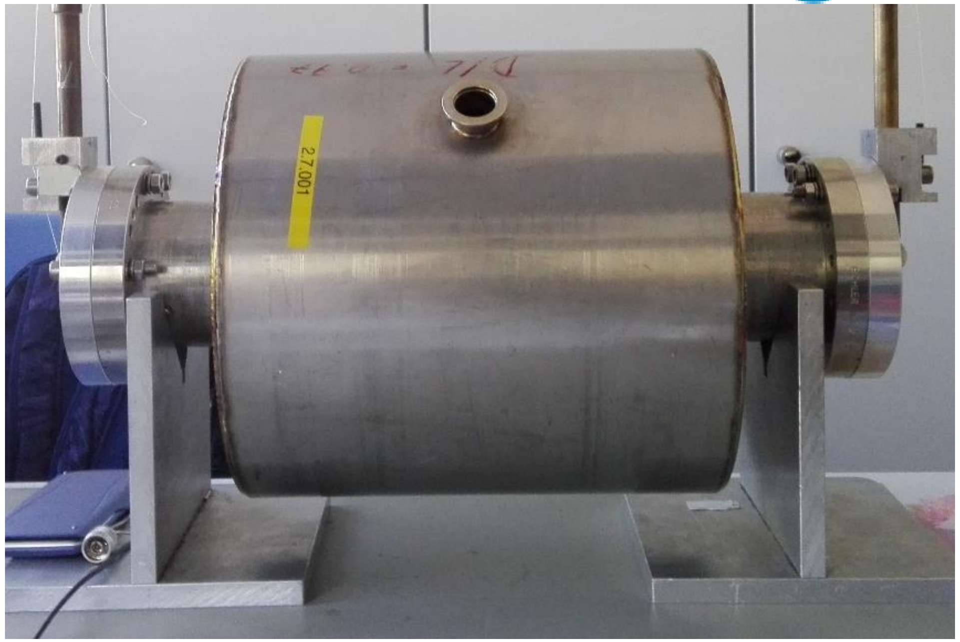
- Calibration improves the measurement performance
  - Return loss improvement by typically 20 dB. Enables mdB accuracy measurements!
  - Full 2-port or 4-port calibration with manual calibration kits is prone to errors, better use electronic calibration systems.
  - Changing VNA settings after calibration will cause the instrument to inter- and extrapolate, and the calibration status becomes uncertain!
- Cables need to be included in the calibration!
  - However, changing coaxial connector types usually not!
  - Special VNA cables allows the adaption of different connector types and sex, without requiring a re-calibration of the setup!

RF Measurement Instrument Features

- **Modern VNAs (SAs, oscilloscopes, etc. as well) have many “features”**
- **Hardware features, e.g.**
  - **Automatic calibration system, down to DC**
  - **4 and more ports**
  - **Additional 2nd source, for downconverter / mixer measurements**
  - **Integrated spectrum analyzer function**
- **Software, control and data post processing options, e.g.**
  - **Far too many to list all**
  - **Sweep options, e.g., lin., log., segmented, in frequency or power**
  - **iDFT (or iFFT), gating**
  - **TDR, TDT for BP or LP step or impulse, segmented (advanced) TDR**
    - Only for linear, time-invariant systems!
  - **Port extension, virtual ports (4-port VNA), Z_{0e}, Z_{0o} characterization, virtual baluns, etc.**
  - **Data transformations, e.g., $\Gamma \Rightarrow Z$**
  - **Noise figure measurements**
  - **Measurements following telecommunication standards**

An Example – Pillbox* TM_{010} Eigenmode

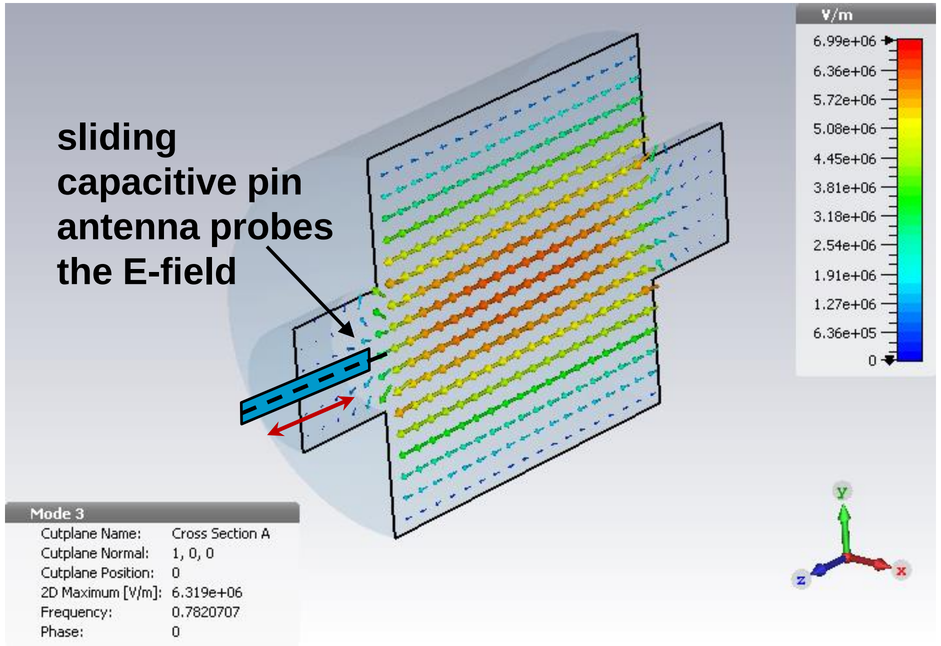




- **Characterize the accelerating TM_{010} mode of a cylindrical cavity with beam ports**
  - **The TM_{010} does not have to be the lowest frequency mode**
- **Compare the measured values of f_{res}, Q_0 and R/Q**
  - **with an analytical analysis of a perfect cylinder (no beam ports)**
  - **with a numerical analysis**

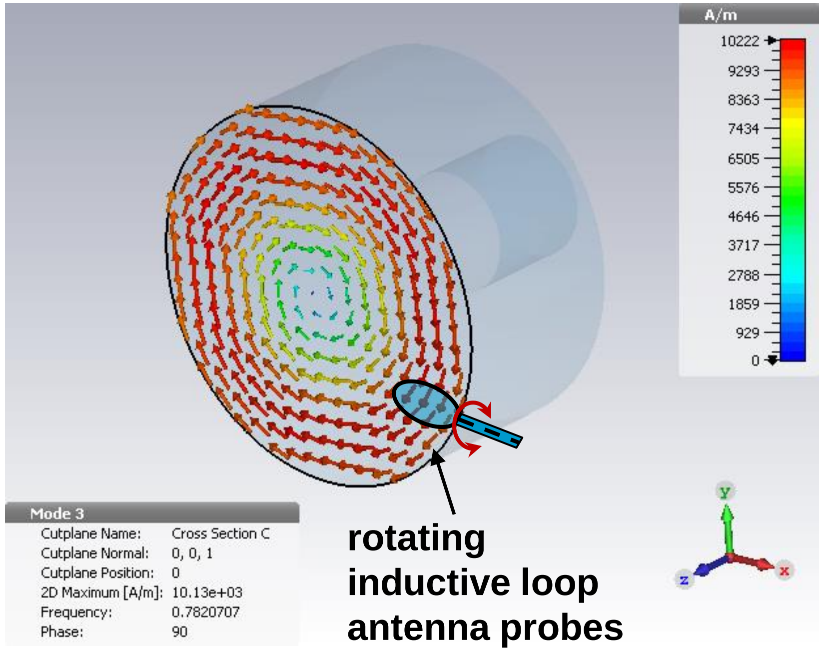
* normal conducting!

Excite the Modes while Measuring S_{11}



sliding capacitive pin antenna probes the E-field

Mode 3
Cutplane Name: Cross Section A
Cutplane Normal: 1, 0, 0
Cutplane Position: 0
2D Maximum [V/m]: 6.319e+06
Frequency: 0.7820707
Phase: 0

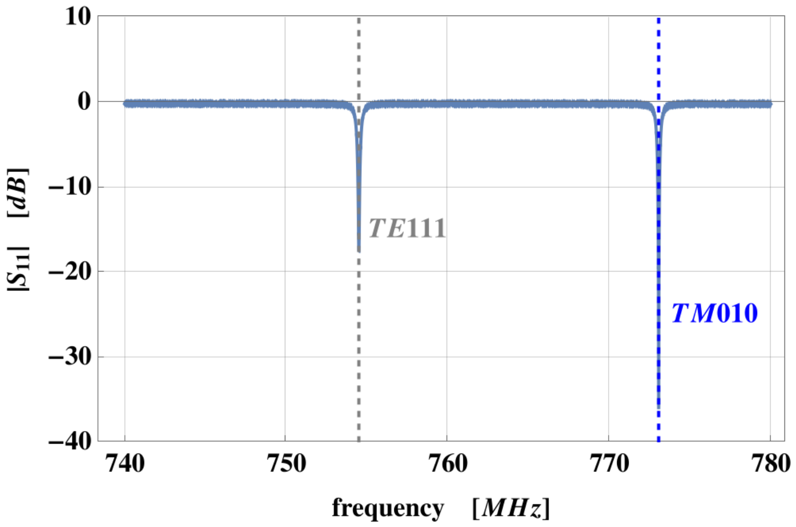


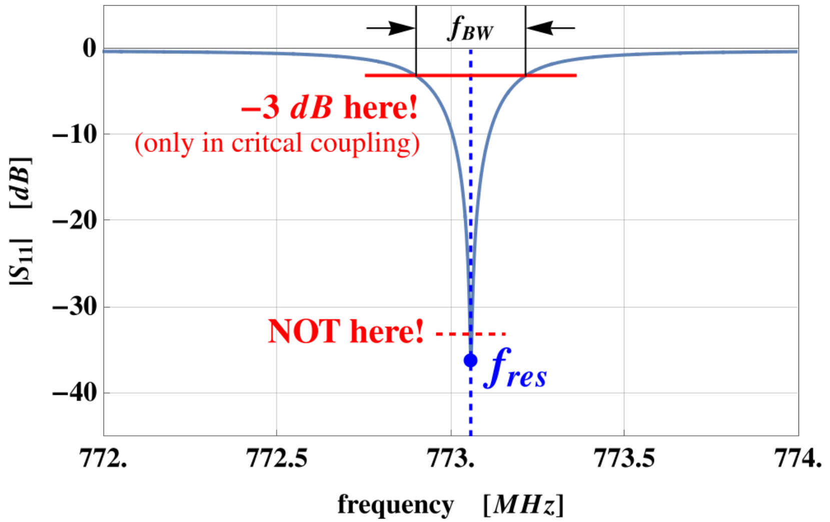
Mode 3
Cutplane Name: Cross Section C
Cutplane Normal: 0, 0, 1
Cutplane Position: 0
2D Maximum [A/m]: 10.13e+03
Frequency: 0.7820707
Phase: 90

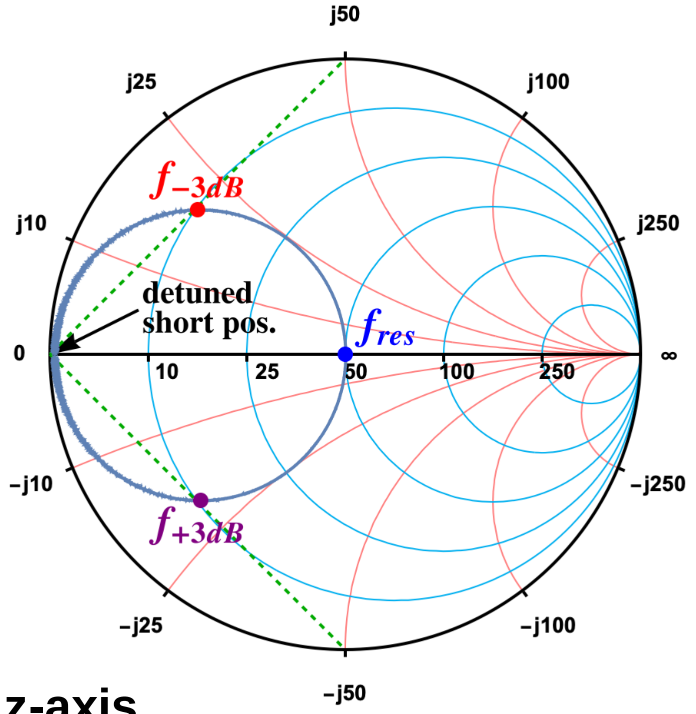
rotating inductive loop antenna probes the H-field

- S_{11} measurement with tunable coupling antenna
  - – E-field on z-axis using a capacitive coupling pin
    - ➢ Center pin, e.g., of semi-rigid coaxial cable
  - – H-field on the cavity rim using an inductive coupling loop
    - ➢ Bend the center conductor to a closed loop connected to ground

Measurement of Frequency and Q-value

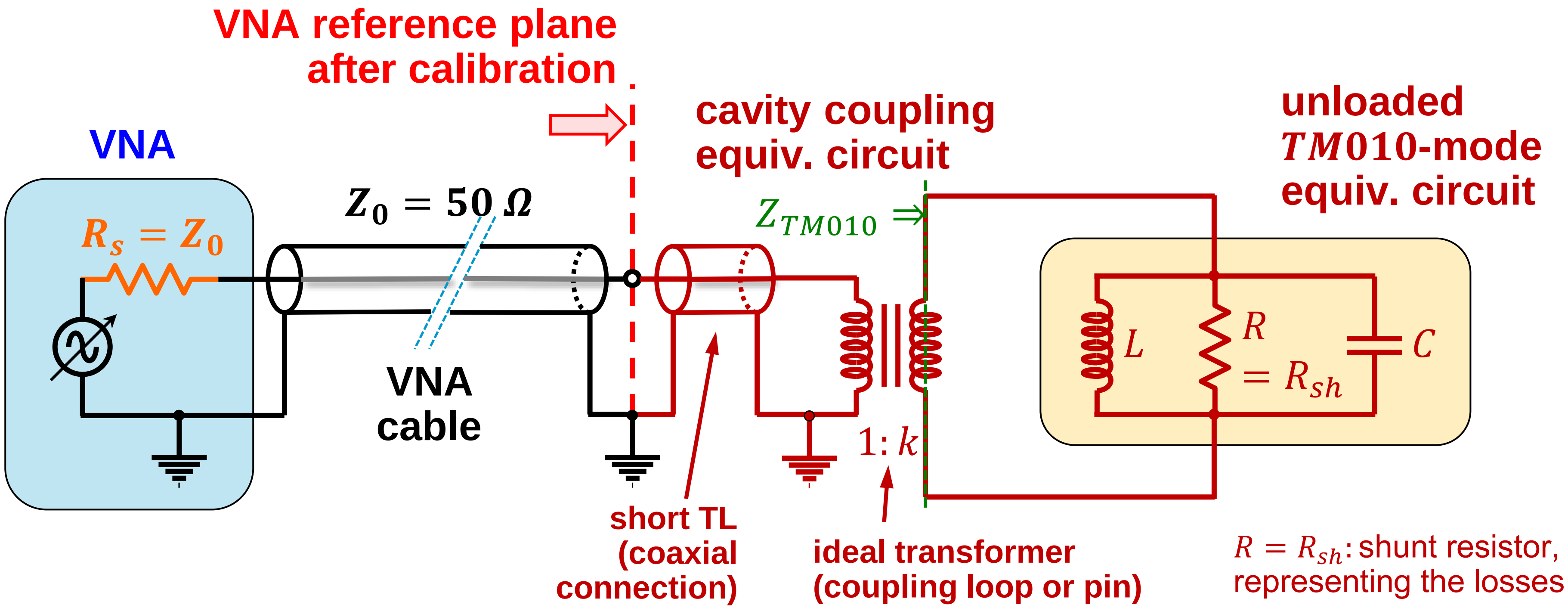






- Identify the correct (TM_{010}) mode frequency
  - Introduce a small perturbation, e.g., metallic rod or wire on the z-axis, and observe the shift of the mode frequencies
- Calibrate the VNA and measure S_{11}
  - Tune the coupling loop for critical coupling
  - Display the resonant circle in the *Smith* chart using enough points!

The Equivalent Circuit of a Resonant Mode



VNA reference plane after calibration

VNA

$R_s = Z_0$

$Z_0 = 50\ \Omega$

VNA cable

cavity coupling equiv. circuit

$Z_{TM010} \Rightarrow$

unloaded $TM010$-mode equiv. circuit

L

$R = R_{sh}$

C

$1\!:\!k$

short TL (coaxial connection)

ideal transformer (coupling loop or pin)

$R = R_{sh}$: shunt resistor, representing the losses of the resonator

we have resonance condition, when: $\omega L = \frac{1}{\omega C}$

at resonance: $Z_{TM010} = R$

→ resonance frequency: $\omega_{res} = 2\pi f_{res} = \frac{1}{LC} \Longrightarrow \boxed{f_{res} = \frac{1}{2\pi\sqrt{LC}}}$

Useful Formulas of the Equivalent Circuit

- **Characteristic impedance "R over Q"**

$$X = \frac{R}{Q} = \omega_{res} L = \frac{1}{\omega_{res} C} = \sqrt{L/C}$$

- **Stored energy at resonance**

$$U = U_e + U_m = \frac{1}{4}|V_C|^2 C + \frac{1}{4}|I_L|^2 L$$

V_C ... Voltage at the capacitor

I_L … Current in the inductor

- **Dissipated power**

$$P = \frac{V^2}{2\,R}$$

- **Q-factor**

$$Q = \frac{R}{X} = \frac{\omega_{res}\,U}{P}$$

U ... stored energy

P ... dissipated power over 1 period

- **Shunt impedance (circuit definition)**

$$R = \frac{V^2}{2\,P}$$

$$\boxed{\frac{R}{Q} = \frac{V^2}{2\omega_{res}\,U}}$$

- **Tuning sensitivity**

$$\frac{\Delta f}{f} = \frac{1}{2}\,\frac{\Delta C}{C} = -\frac{1}{2}\,\frac{\Delta L}{L}$$

- **Coupling parameter (shunt impedance over generator or feeder impedance)**

$$k^2 = \frac{R}{R_{input}}$$

tune for critical coupling

The Quality Factor (Q-Factor)

- The quality (Q) factor of a resonant circuit is defined as ratio of the stored energy U over the energy dissipated P in one oscillation cycle:

$$\boxed{Q = 2\pi \frac{\text{energy stored}}{\text{energy dissipated in 1 cycle}} = \frac{\omega_{res} U}{P}}$$

- The Q-factor of an impedance loaded resonator:
  - Q_0: unloaded Q-value of the unperturbed system
  - Q_L: loaded Q-value, e.g., measured with the impedance of the connected generator
  - Q_{ext}: external Q-factor, representing the effects of the external circuit (generator and coupling circuit)

$$\boxed{\frac{1}{Q_L} = \frac{1}{Q_0} + \frac{1}{Q_{ext}}}$$

tune k for critical coupling:

$$Q_0 = Q_{ext}$$

$$\Rightarrow Q_0 = 2\, Q_L$$

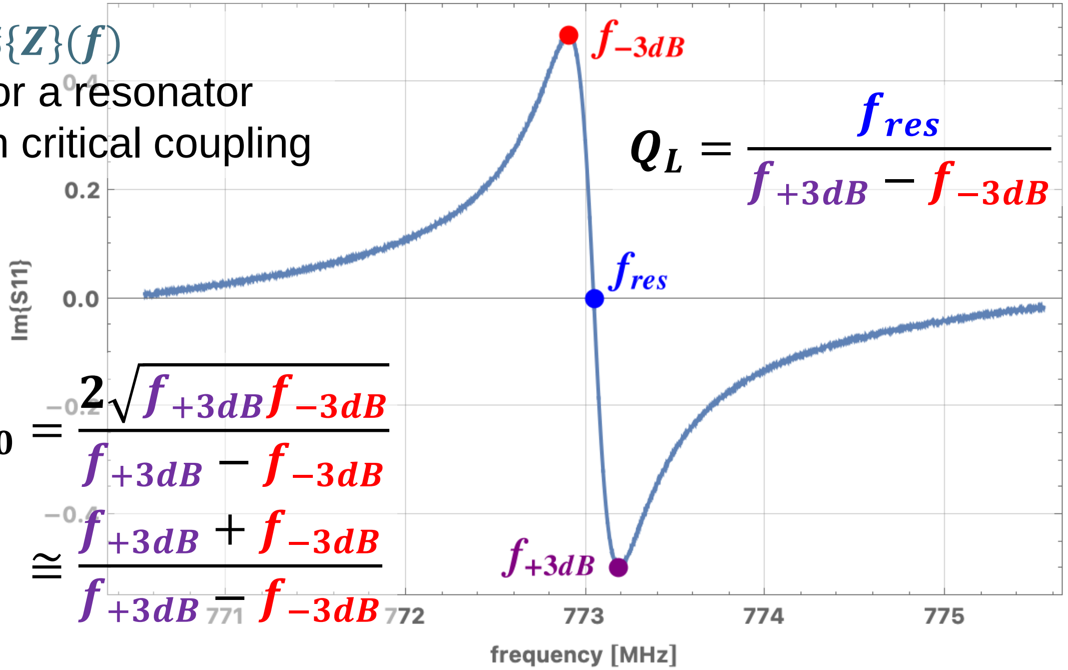
with Q_L being our measured Q-value

- Q-factor and bandwidth
  - This is how we actually "measure" the Q-factor!

$$\boxed{Q = \frac{f_{res}}{f_{BW}}}$$

with: $f_{BW} = f_{+3dB} - f_{-3dB}$

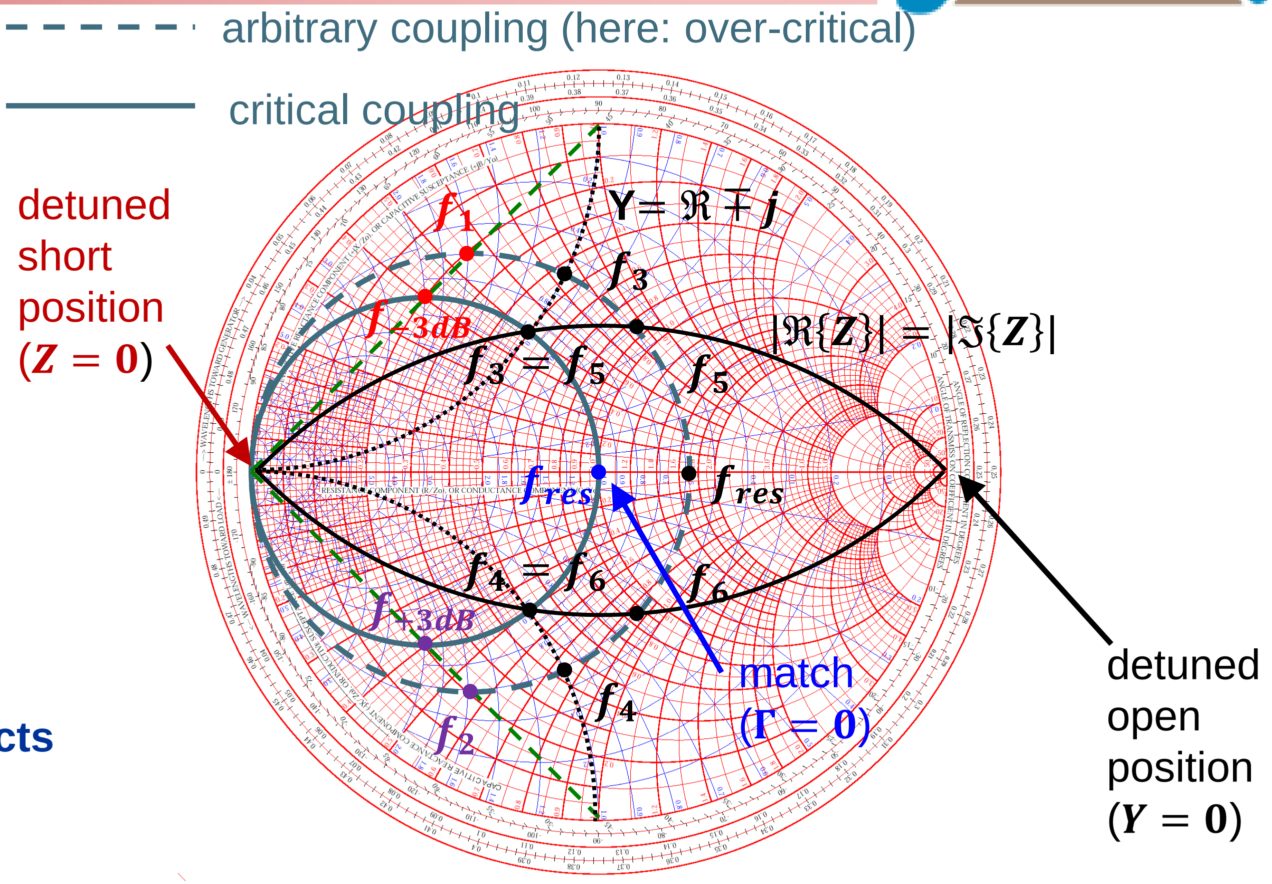
Q-factor from S_{11} Measurement



$\Im\{Z\}(f)$
for a resonator
in critical coupling

$$Q_L = \frac{f_{res}}{f_{+3dB} - f_{-3dB}}$$

$$Q_0 = \frac{2\sqrt{f_{+3dB} f_{-3dB}}}{f_{+3dB} - f_{-3dB}} \cong \frac{f_{+3dB} + f_{-3dB}}{f_{+3dB} - f_{-3dB}}$$



- **Correct for the uncompensated transmission-line effects between calibration reference and the coupling loop**
  - **Electrical length adjustment: ”straight” $\Im\{Z\}(f)$**
- **Adjust the locus circle to the detuned short location**
  - **Phase offset**
- **Verify no evanescent fields penetrating outside the beam ports**
  - **i.e., no frequency shifts if the boundaries at the beam ports are altered**

Frequency marker points in the *Smith* chart:
$f_{1,2}$ (f_{-3dB}, f_{+3dB}): $|\Im\{S_{11}\}| = max.$ to calculate Q_L
$f_{3,4}$: $Y = \Re \mp j$ to calculate Q_{ext}
$f_{5,6}$: $|\Re\{Z\}| = |\Im\{Z\}|$ to calculate Q_0

R/Q Measurement – *Slater*'s Theorem

- **Remember from the equivalent circuit:**

$$\frac{R}{Q} = \frac{V_{acc}^2 \big/ 2P_d}{\omega_{res} U \big/ P_d} = \frac{V_{acc}^2}{2\omega_{res} U} \qquad \text{with:} \qquad V_{acc} = \left| \int E_z(z) \overbrace{\cos\left(\frac{\omega z}{\beta c_0}\right)}^{\text{transit time related}} dz \right|$$

  - V_{acc} is based on the integrated longitudinal E-field component E_z along the z-axis ($x = y = 0$)
- **Based on Slater's perturbation theorem:**

$$\frac{\Delta f}{f_{res}} = \frac{1}{U}\left[\mu_0 \left(k_{\parallel}^H |H_{\parallel}|^2 + k_{\perp}^H |H_{\perp}|^2\right) - \varepsilon_0 \left(k_{\parallel}^E |E_{\parallel}|^2 + k_{\perp}^E |E_{\perp}|^2\right)\right]$$

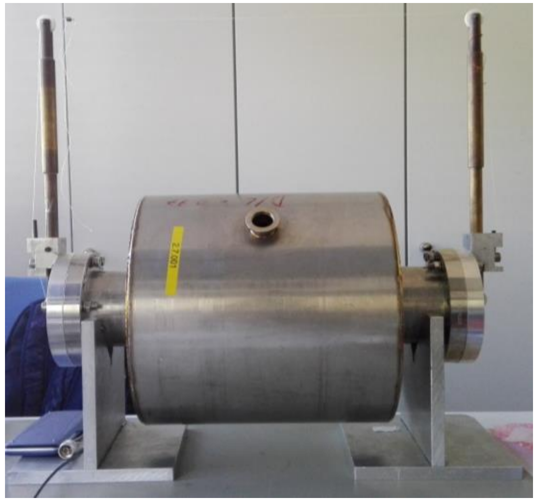
  - Resonance frequency shift due to a small perturbation object, expressed in longitudinal and transverse E and H field components
  - k: coefficients proportional to the electric or magnetic polarizability of the perturbation object (here: only $k_{\parallel}^E$ for a longitudinal metallic object)
- **E-field characterization along the z-axis**

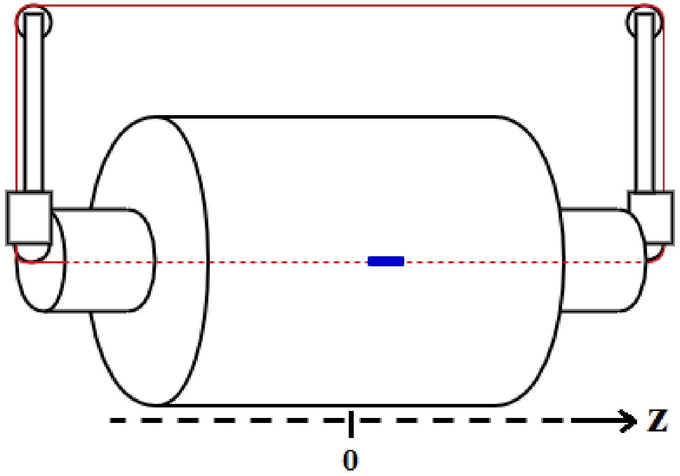
$$E(z) = E_{\parallel}(z) = \sqrt{U \frac{\Delta f(z)}{f_{res}} \cdot \frac{-1}{k_{\parallel}^E \varepsilon_0}}$$

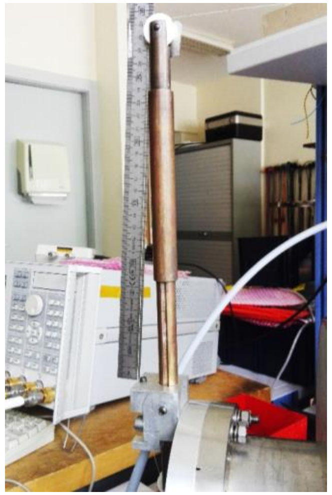
with: $k_{\parallel}^E = \frac{\pi}{3} l^3 \left[\sinh^{-1}\left(\frac{2}{3\pi}\frac{l}{a}\right)\right]^{-1}$

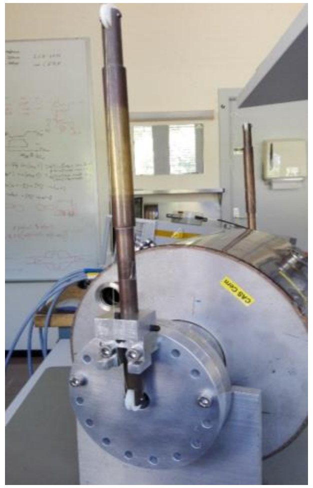
(metallic ellipsoid, e.g., syringe needle of half length l and radius a)

R/Q Measurement - Bead Pull Method









- **E-field characterization by evaluating**
  - **The frequency shift Δf (S_{11} reflection measurement with a single probe) or**
  - **The phase shift ϕ at f_{res} (S_{21} transmission measurement with 2 probes)**

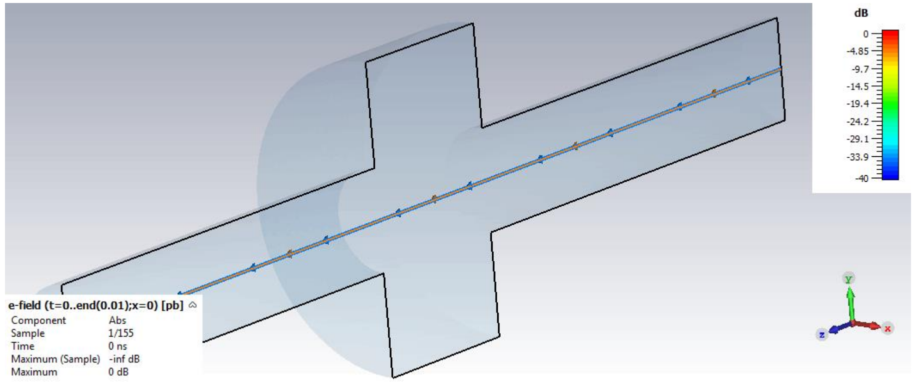
$$\frac{\Delta f}{f_{res}} = \frac{1}{2\,Q_0} \tan \phi$$

- **Exercise with a manual bead-pull through a known cavity**
  - **requires: fishing wire, syringe needle, ruler and VNA**
  - **Compare the measured E_z at the maximum f or ϕ shift (in the center of the cavity) with the theoretical estimation (e.g., numerical computed value)**

Beam Coupling Impedance

- **The wake potential**
  - Lorenz force on q_2 by the wake field of q_1:

$$\vec{F} = \frac{d\vec{p}}{dt} = q_2\left(\vec{E} + c_0\vec{e}_z \times \vec{B}\right)$$

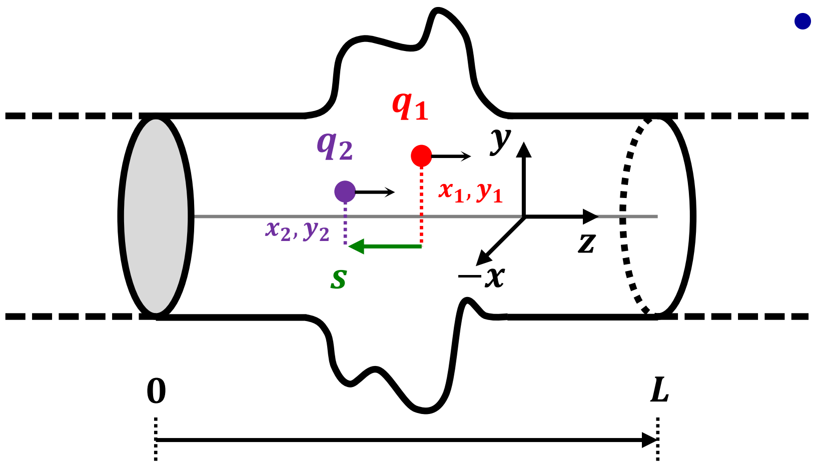


e-field (t=0..end(0.01);x=0) [pb]

Component Abs
Sample 1/155
Time 0 ns
Maximum (Sample) -inf dB
Maximum 0 dB

  - Wake potential of a structure, e.g., a discontinuity driven by q_1

$$\vec{w}(x_1, y_1, x_2, y_2, s) = \frac{1}{q_1}\int_{-\infty\ (\text{or } 0)}^{+\infty\ (\text{or} L)} dz\left[\vec{E}(x_2, y_2, z, t) + c_0\vec{e}_z \times \vec{B}(x_2, y_2, z, t)\right]_{t=(s+z)/c}$$

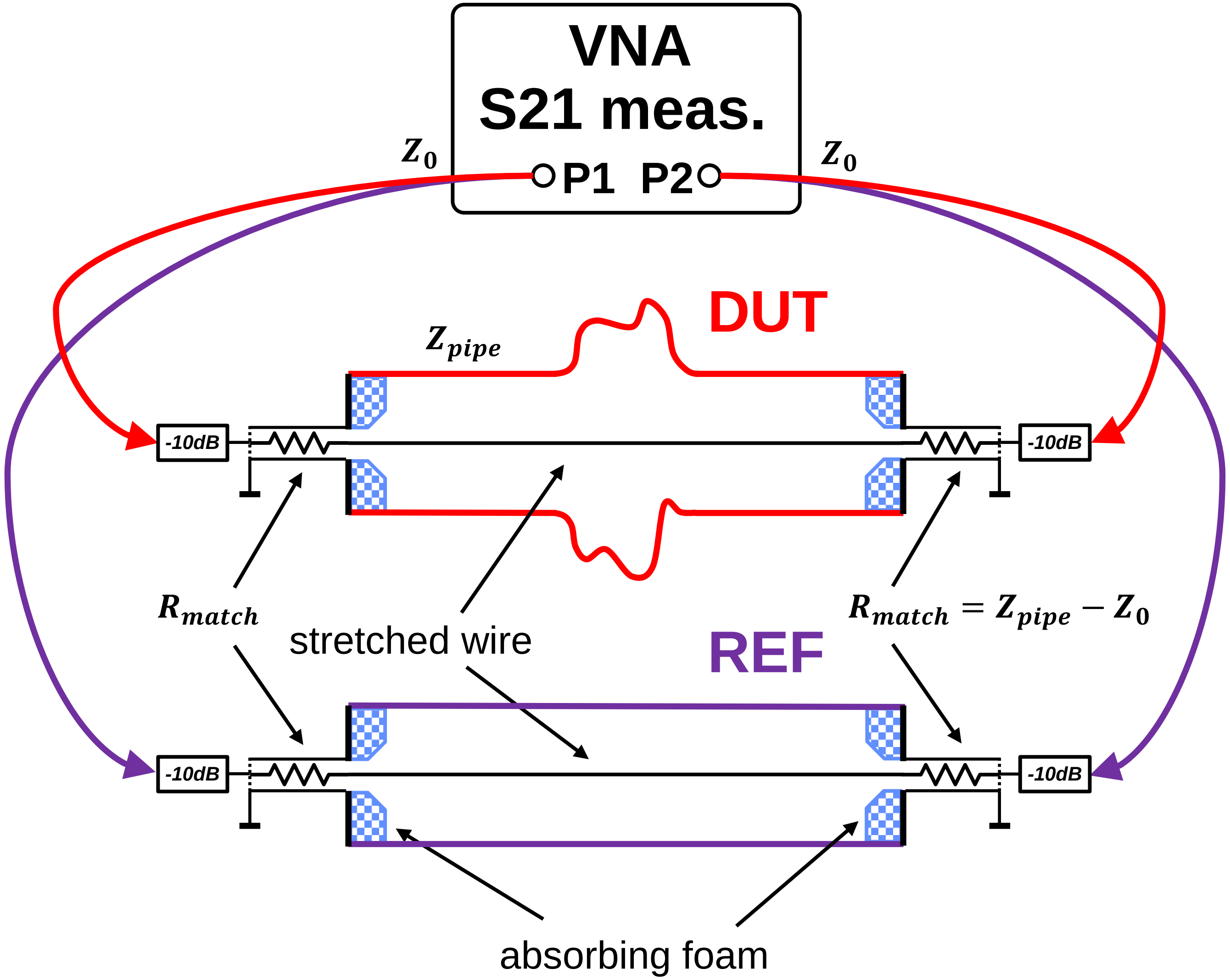


- **Beam coupling impedance**
  - Frequency domain representation of the wake potential

$$Z(x_1, y_1, x_2, y_2, \omega) = -\frac{1}{c_0}\int_{-\infty}^{+\infty} ds\,\vec{w}(x_1, y_1, x_2, y_2, s)e^{-j\omega s/c_0}$$

  - Can be decomposed in longitudinal $Z_{\parallel}$ and transverse $Z_{\perp}$ components (*Panofsky-Wenzel* theorem)
  - Resonant structures, i^{th} mode: $R_{sh,i} = Z_{\parallel,i} = \dfrac{2k_{loss,i}Q_i}{\omega_i}$

Stretched-Wire $Z_{\parallel}$ Measurement



- **Formulas:**
  - **Normalized electrical length:** $\Theta = 2\pi \frac{L}{\lambda}$
  - **Lumped impedance formula**

$$Z_{\parallel} = 2Z_{pipe} \frac{1 - S_{21}}{S_{21}} \qquad \begin{array}{l} \Theta \leq 1 \\ L < D_{pipe} \end{array}$$

  - **Log formula**

$$Z_{\parallel} = -2Z_{pipe} \ln S_{21}$$

  - **Improved log formula**

$$\boxed{Z_{\parallel} = -2Z_{pipe} \ln S_{21} \left(1 + j \frac{\ln S_{21}}{2\Theta}\right)}$$

  - **Transmission coefficient**

$$\boxed{S_{21} = \frac{S_{21,DUT}}{S_{21,REF}}}$$

  - **Circular beam pipe impedance**

$$Z_{pipe} = \frac{\eta_0}{2\pi\sqrt{\varepsilon_r}} \ln \frac{D}{d} \cong 60\ \Omega \ln \frac{D_{pipe}}{d_{wire}}$$

Summary

- **No summary, just**

Thank you!