# Bunch length measurement with RF and microwave signals

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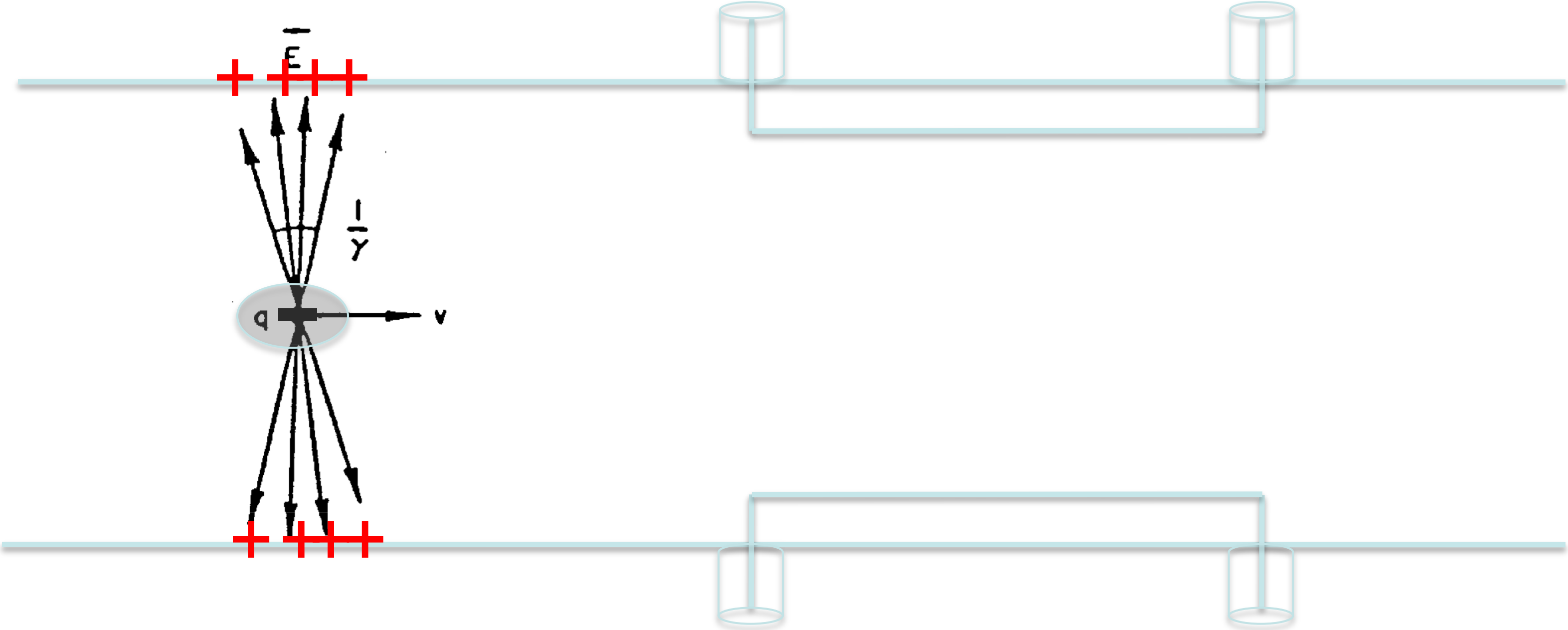
# Overview

- RF and microwave pickups are common on accelerators, mainly for sensing transverse position.
- What are the limitations on bunch length measurement using RF/ microwave signals?
- Many techniques are analogous to what is done at optical frequencies.

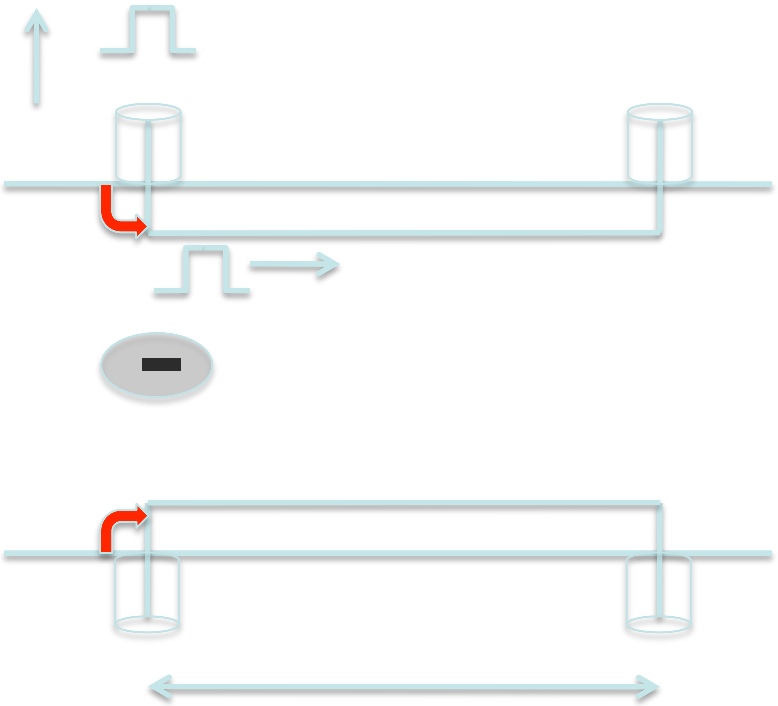
# Beam Image Current

- For relativistic beams, the EM fields are flattened to an opening angle of 1/γ, approximating a TEM wave.
- Image current flows on the inner surface of the beam pipe.
- A beam pickup (PU) intercepts some fraction of the image current



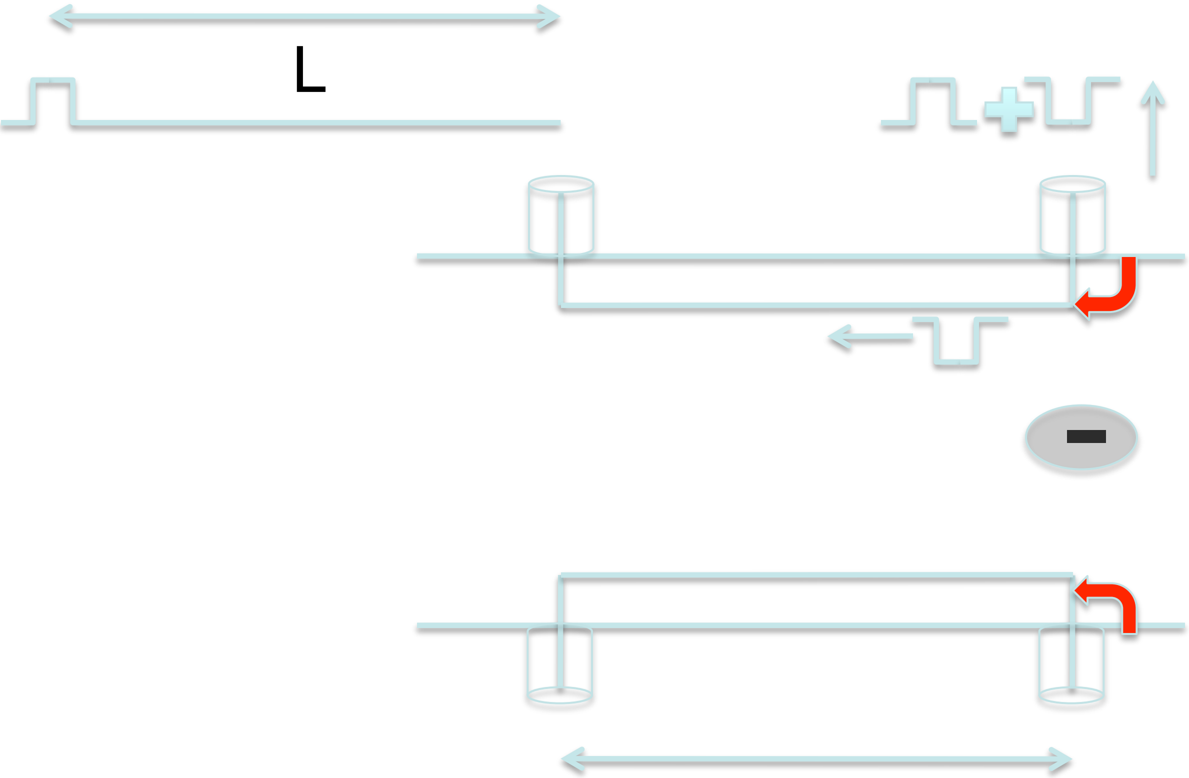
# Stripline as a Pickup

- Beam passes upstream port of PU
  - – Induced voltage at gap
  - – If stripline impedance is matched to upstream output port, half of pulse exits port, the other half travels downstream. For vacuum, pulses moves at c.



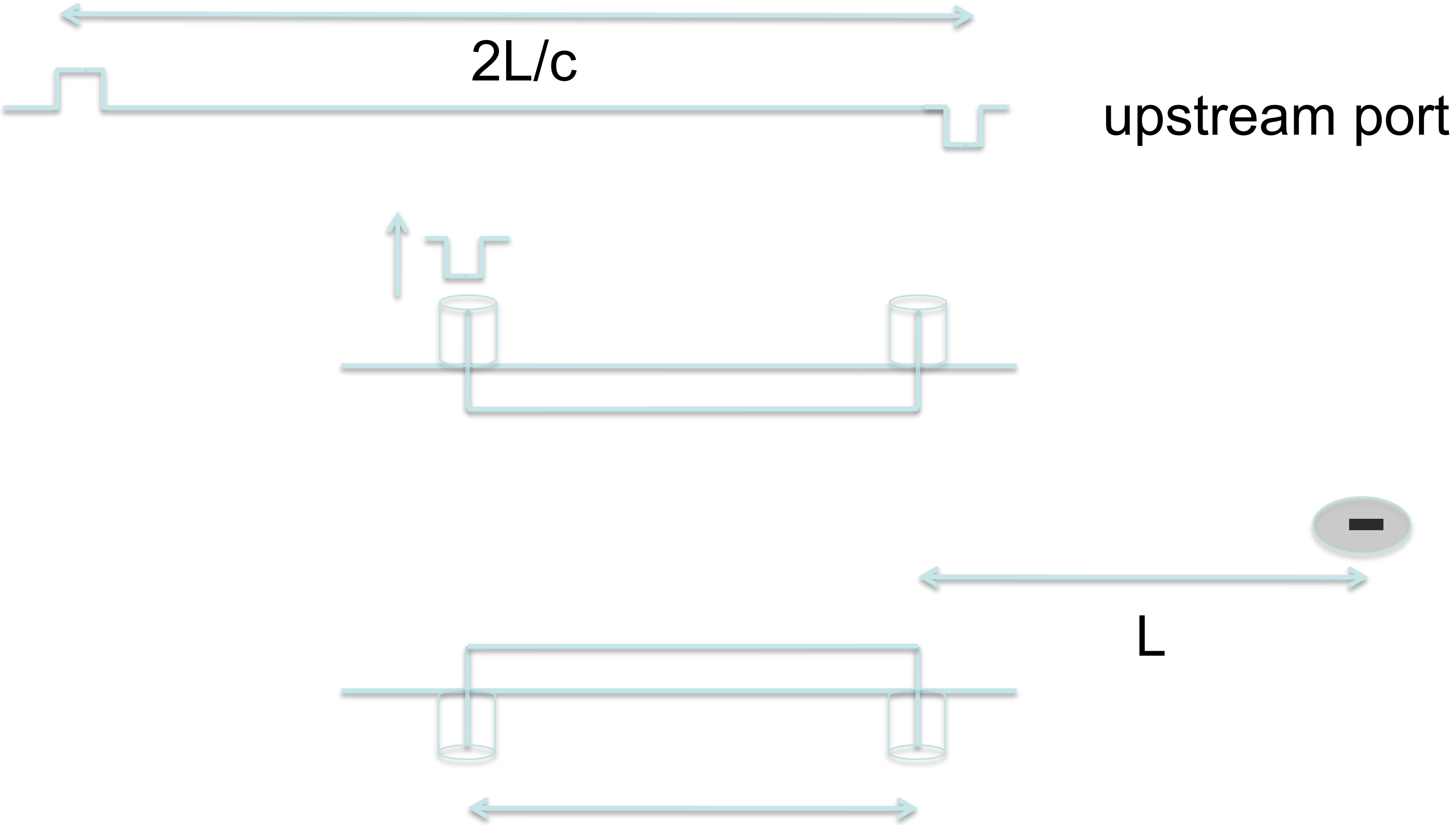
# Stripline as a Pickup

- Beam passes downstream port of PU
    - Induced voltage at gap (opposite polarity to upstream port)
    - If stripline impedance is matched to downstream output port, half of pulse cancels pulse from upstream port, the other half travels upstream and is observed at upstream port at a time 2L/c.



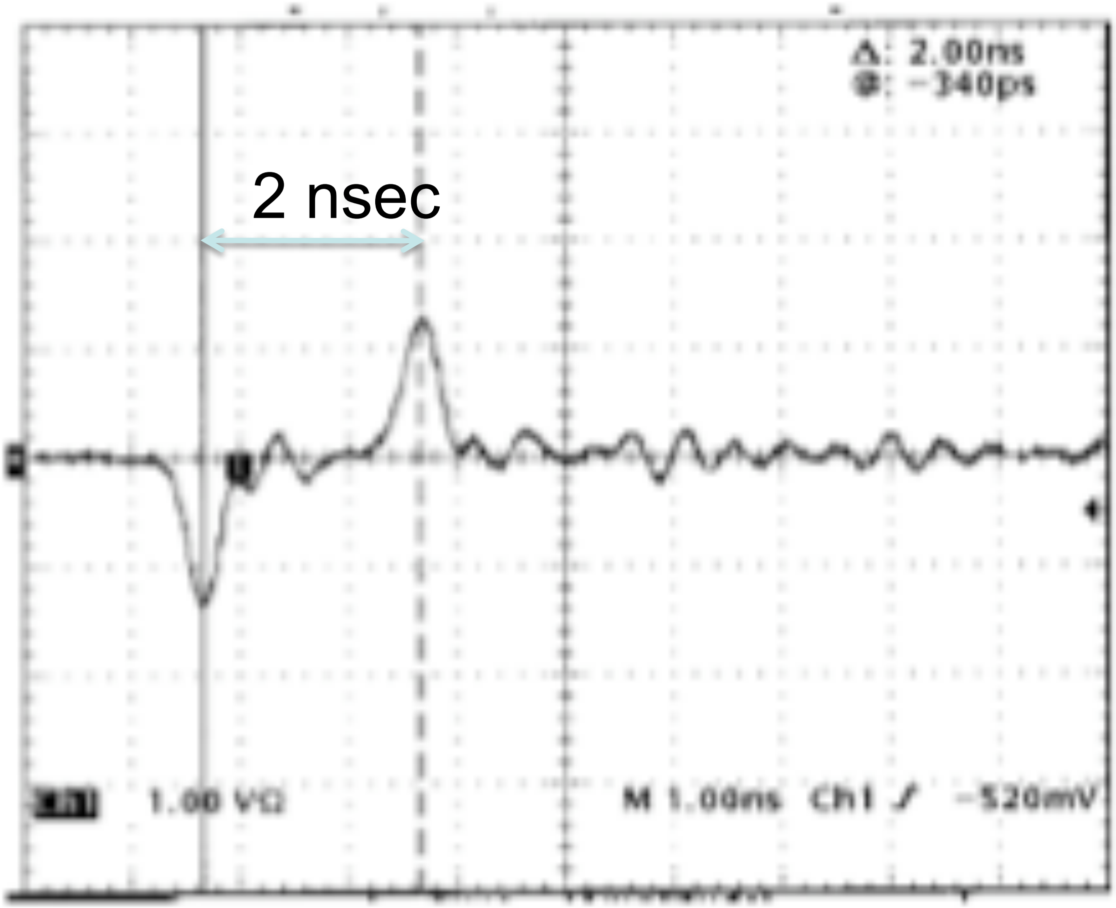
# Stripline as Pickup

- The downstream pulse exits through the upstream port at a time 2L/c. No signal from downstream port (ideal case)



# Example Signals

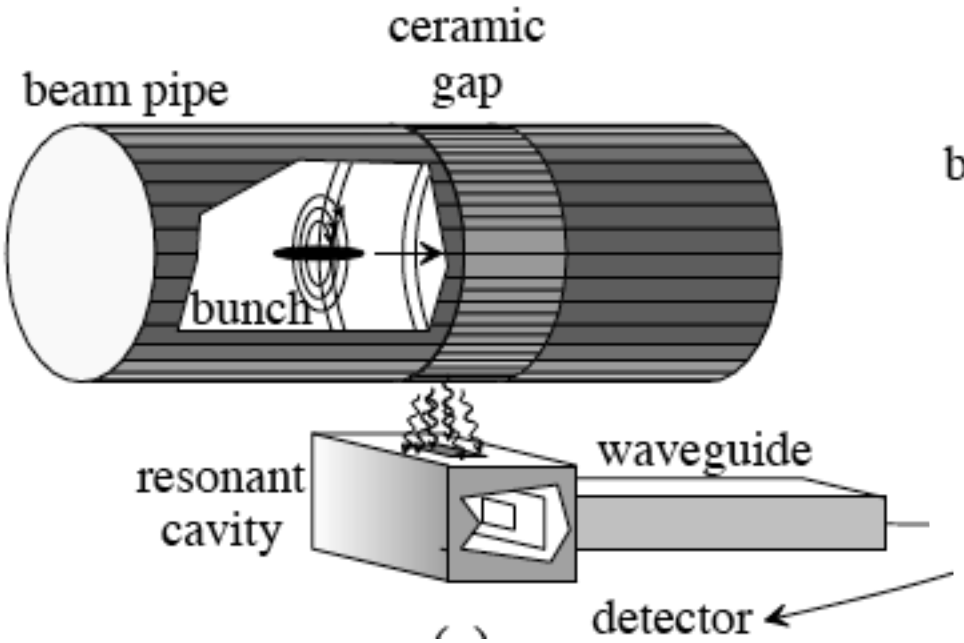
- Advanced Light Source stripline. Signal at the upstream port. Kicker length is 1 nsec (30 cm)

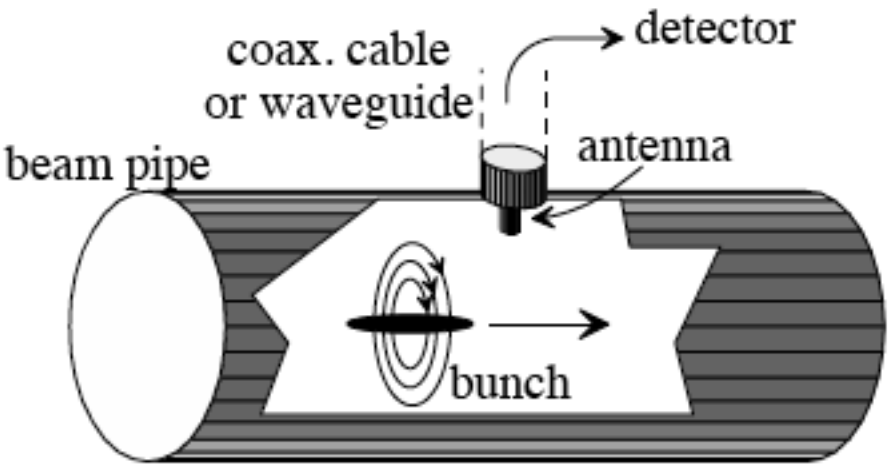


2 nsec

# Ceramic Gap

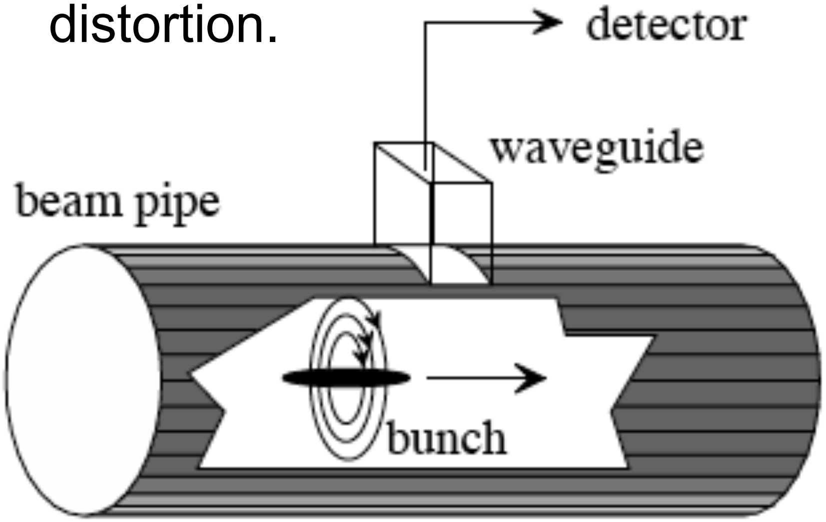
- Bunch passes by a ceramic gap in the vacuum chamber, its field radiates from the gap into a cavity and then into a waveguide leading to a detector.
- The cavity resonates at a fixed frequency and the signal can be detected by using either a diode detector or a bolometer. Several (and different) resonance boxes can be installed giving the possibility to measure the amplitude at several frequencies.

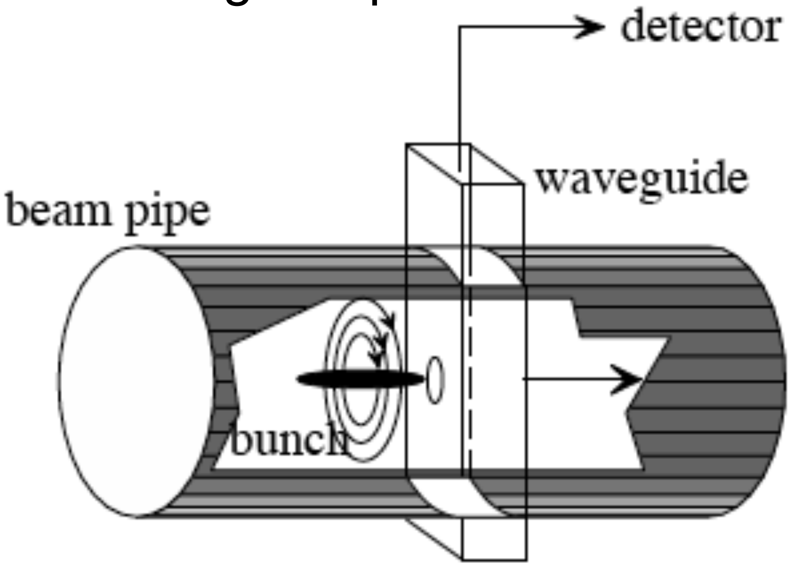




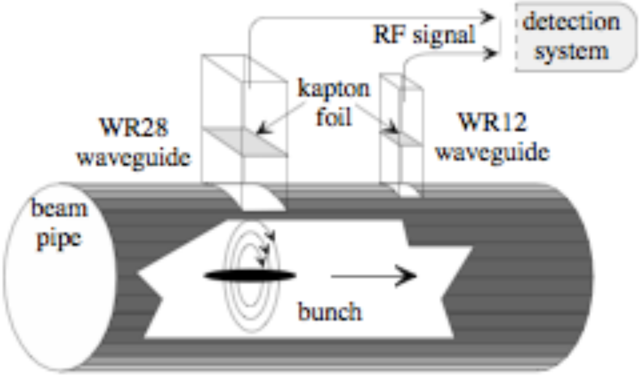
# Waveguide coupling

- Direct coupling of the beam fields into waveguide provides less distortion.





- Different size waveguides can be used to couple different frequency bands.



# Waveguide signal transmission

- Signals usually transmitted in TE01 mode.
- Waveguide attenuation acceptable for frequencies from 10-100 GHz

Surface impedance of the waveguide wall

$$Z_m = \frac{1+j}{\sigma\delta_s} \qquad \text{where } R_m = (\sigma\delta_s)^{-1}$$

$$\delta_s = (2/\omega\mu\sigma)^{1/2}$$

$$-\frac{\partial P}{\partial z} = P_l = 2\alpha P_0 e^{-2\alpha z} = 2\alpha P$$

$$\alpha = \frac{P_l}{2P} = \frac{R_m \oint_C \vec{J}\cdot\vec{J}^* \, dl}{2Z \int \vec{H}\cdot\vec{H}^* \, dS}$$

$$\alpha = \frac{R_m}{ab\beta_{10}k_0 Z_0}(2bk_{c,10}^2 + ak_0^2)^2 \ \frac{\text{Np}}{\text{m}}$$

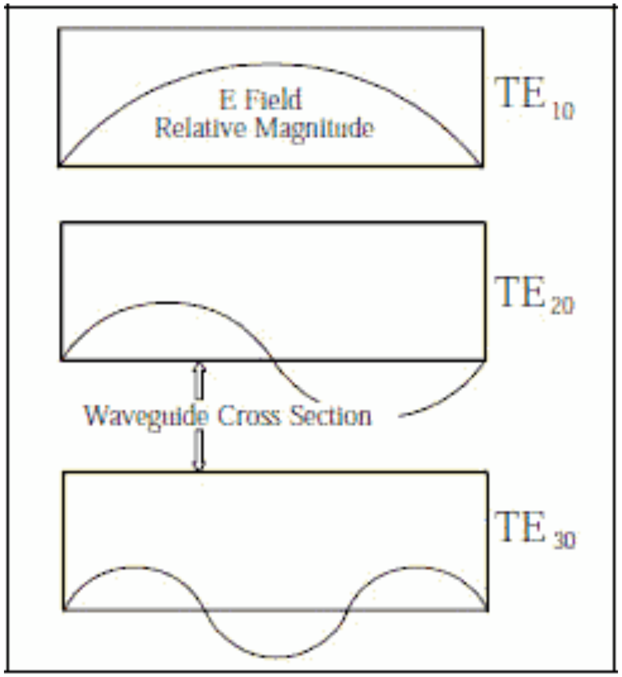
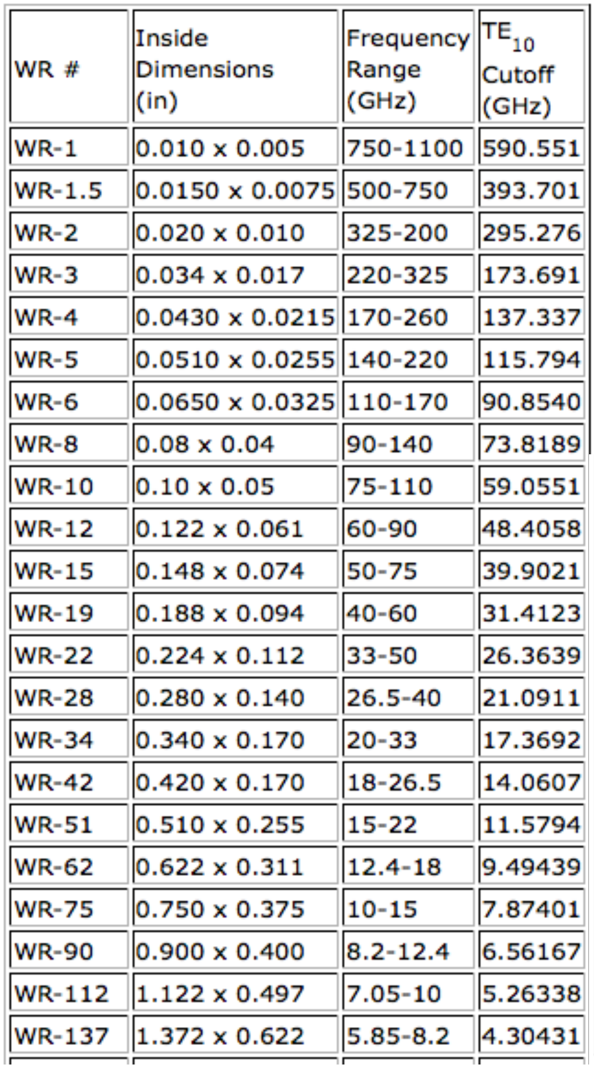
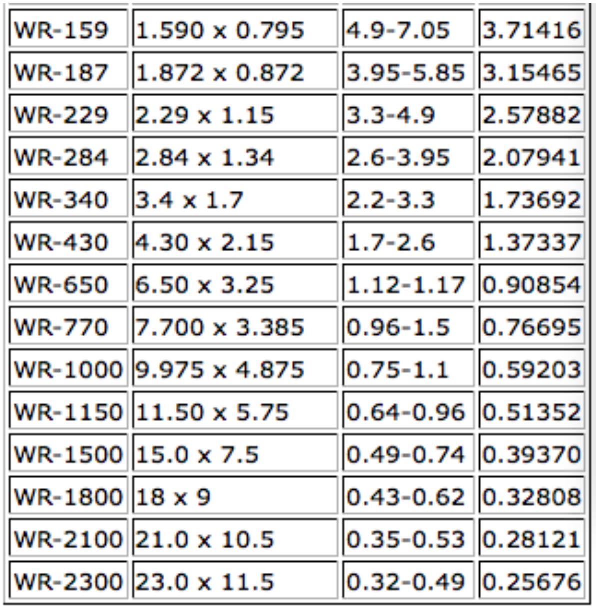


**Figure 2.** TE modes

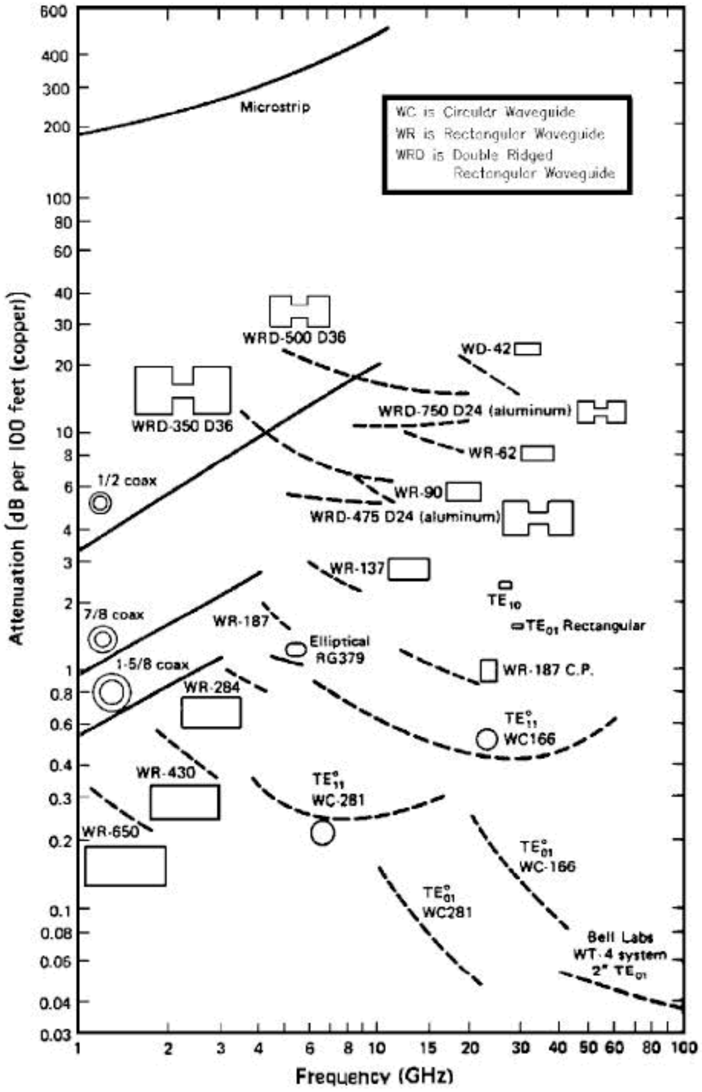
$$k_{c,nm} = \left[\left(\frac{n\pi}{a}\right)^2 + \left(\frac{m\pi}{b}\right)^2\right]^{1/2}$$

# Waveguide specifications

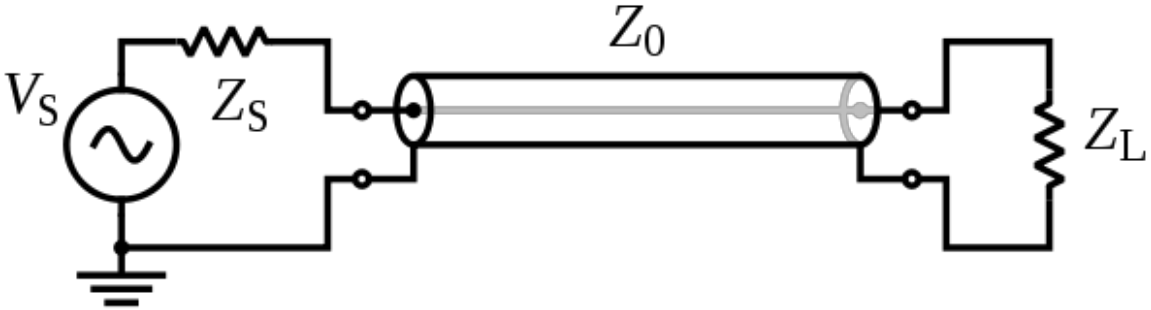
| WR # | Inside Dimensions (in) | Frequency Range (GHz) | TE$_{10}$ Cutoff (GHz) |
|---|---|---|---|
| WR-1 | 0.010 x 0.005 | 750-1100 | 590.551 |
| WR-1.5 | 0.0150 x 0.0075 | 500-750 | 393.701 |
| WR-2 | 0.020 x 0.010 | 325-200 | 295.276 |
| WR-3 | 0.034 x 0.017 | 220-325 | 173.691 |
| WR-4 | 0.0430 x 0.0215 | 170-260 | 137.337 |
| WR-5 | 0.0510 x 0.0255 | 140-220 | 115.794 |
| WR-6 | 0.0650 x 0.0325 | 110-170 | 90.8540 |
| WR-8 | 0.08 x 0.04 | 90-140 | 73.8189 |
| WR-10 | 0.10 x 0.05 | 75-110 | 59.0551 |
| WR-12 | 0.122 x 0.061 | 60-90 | 48.4058 |
| WR-15 | 0.148 x 0.074 | 50-75 | 39.9021 |
| WR-19 | 0.188 x 0.094 | 40-60 | 31.4123 |
| WR-22 | 0.224 x 0.112 | 33-50 | 26.3639 |
| WR-28 | 0.280 x 0.140 | 26.5-40 | 21.0911 |
| WR-34 | 0.340 x 0.170 | 20-33 | 17.3692 |
| WR-42 | 0.420 x 0.170 | 18-26.5 | 14.0607 |
| WR-51 | 0.510 x 0.255 | 15-22 | 11.5794 |
| WR-62 | 0.622 x 0.311 | 12.4-18 | 9.49439 |
| WR-75 | 0.750 x 0.375 | 10-15 | 7.87401 |
| WR-90 | 0.900 x 0.400 | 8.2-12.4 | 6.56167 |
| WR-112 | 1.122 x 0.497 | 7.05-10 | 5.26338 |
| WR-137 | 1.372 x 0.622 | 5.85-8.2 | 4.30431 |
| WR-159 | 1.590 x 0.795 | 4.9-7.05 | 3.71416 |
| WR-187 | 1.872 x 0.872 | 3.95-5.85 | 3.15465 |
| WR-229 | 2.29 x 1.15 | 3.3-4.9 | 2.57882 |
| WR-284 | 2.84 x 1.34 | 2.6-3.95 | 2.07941 |
| WR-340 | 3.4 x 1.7 | 2.2-3.3 | 1.73692 |
| WR-430 | 4.30 x 2.15 | 1.7-2.6 | 1.37337 |
| WR-650 | 6.50 x 3.25 | 1.12-1.17 | 0.90854 |
| WR-770 | 7.700 x 3.385 | 0.96-1.5 | 0.76695 |
| WR-1000 | 9.975 x 4.875 | 0.75-1.1 | 0.59203 |
| WR-1150 | 11.50 x 5.75 | 0.64-0.96 | 0.51352 |
| WR-1500 | 15.0 x 7.5 | 0.49-0.74 | 0.39370 |
| WR-1800 | 18 x 9 | 0.43-0.62 | 0.32808 |
| WR-2100 | 21.0 x 10.5 | 0.35-0.53 | 0.28121 |
| WR-2300 | 23.0 x 11.5 | 0.32-0.49 | 0.25676 |

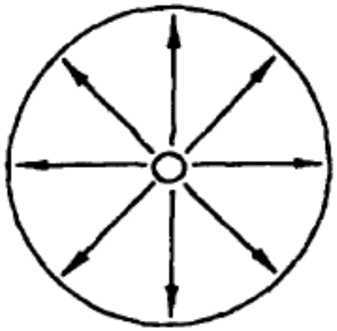
- Rectangular waveguides are available over a broad frequency range.



# Coaxial waveguides

- Convenient and flexible
- Usually contains a polyethylene dielectric
- Typically configured with 50 Ohm impedance





END VIEW OF COAXIAL CABLE

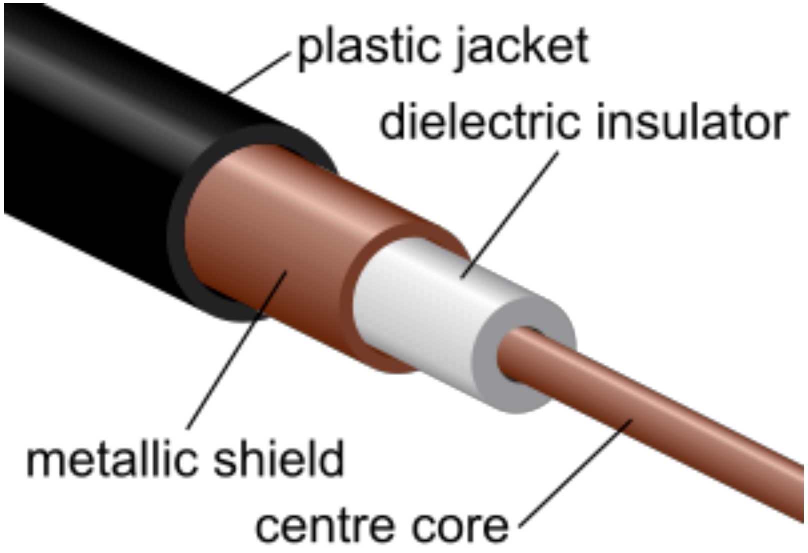
$$Z_0 = \frac{1}{2\pi}\sqrt{\frac{\mu}{\epsilon}}\ln\frac{D}{d} \approx \frac{138\Omega}{\sqrt{\epsilon_r}}\log_{10}\frac{D}{d}$$

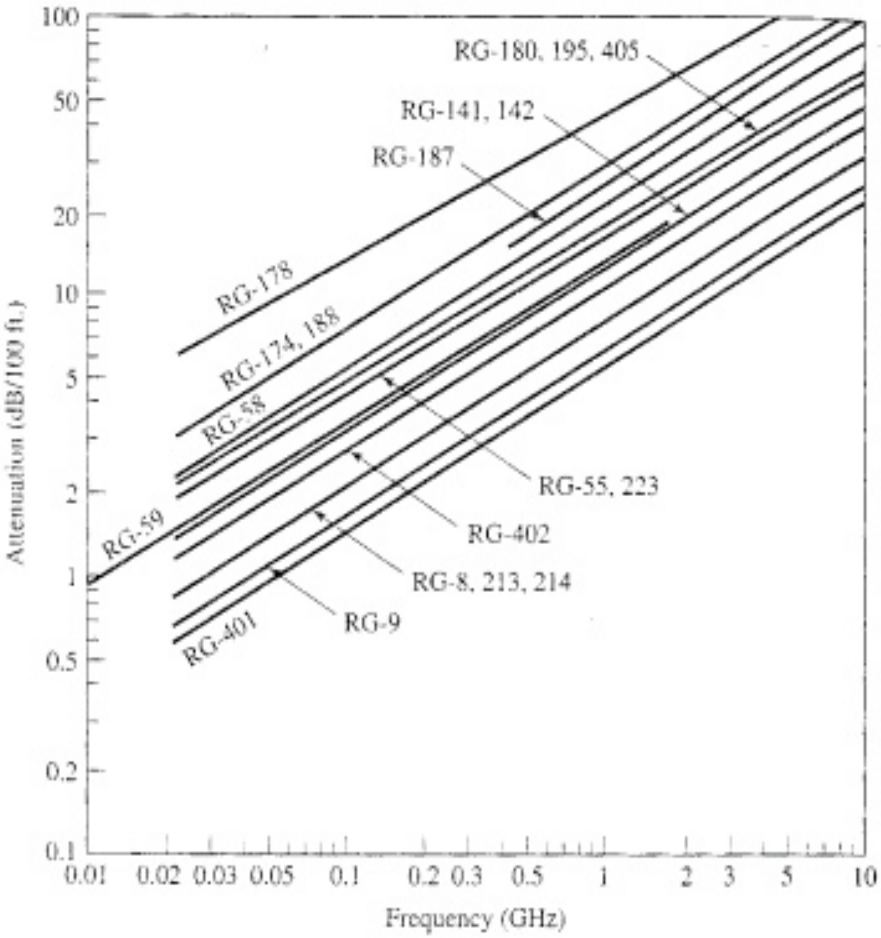
- Bandwidth from DC to cutoff frequency of next available mode ($TE_{01}$) (one wavelength inside dielectric.
- Loss in resistance of center conductor and shield (skin effect) and heating of dielectric.
- Loss increases with frequency.

$$f_c = \frac{1}{\pi(\frac{D+d}{2})\sqrt{\mu\epsilon}} = \frac{c}{\pi(\frac{D+d}{2})\sqrt{\mu_r\epsilon_r}}$$

# Coaxial Signal transmission

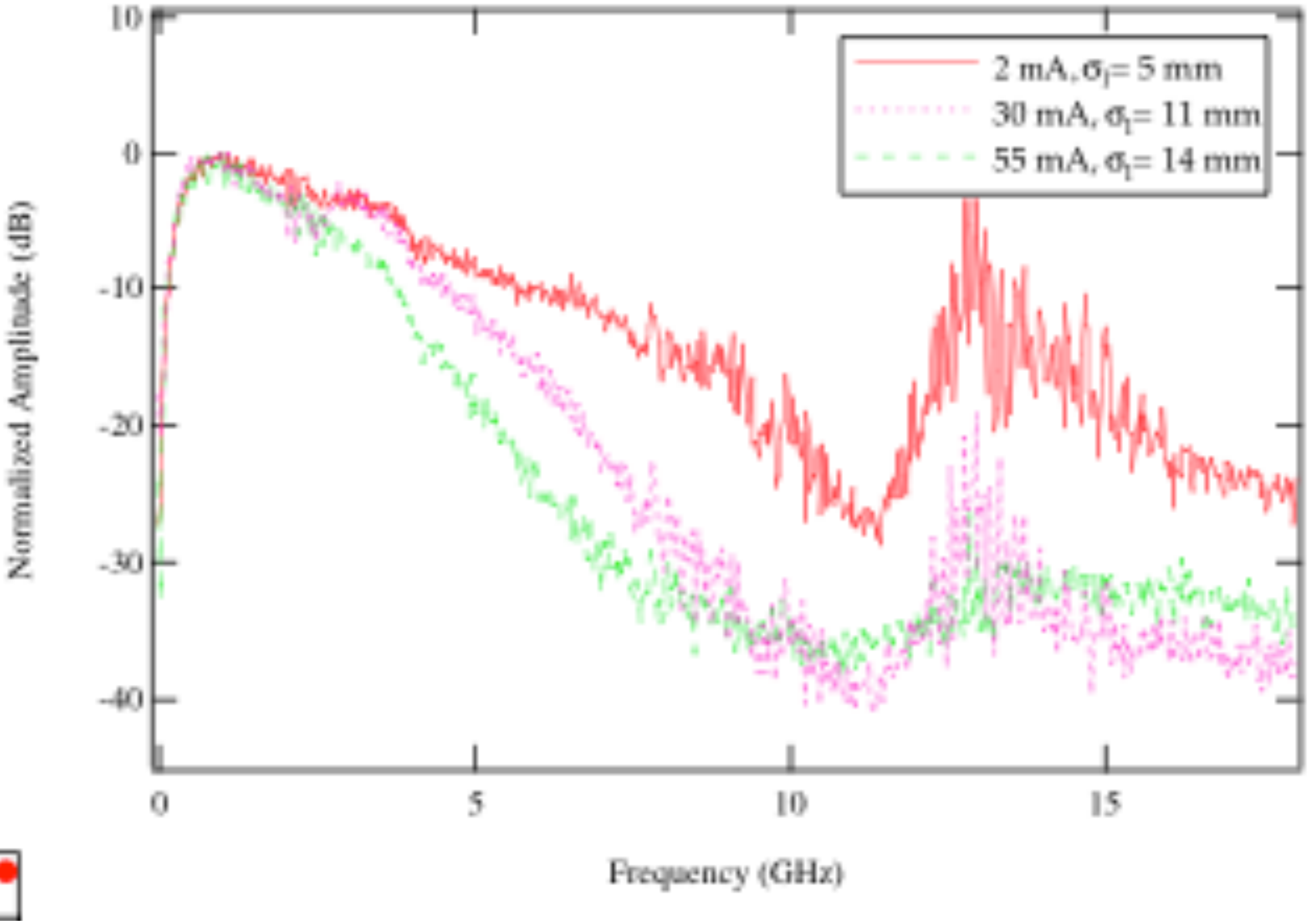
- Coaxial cable





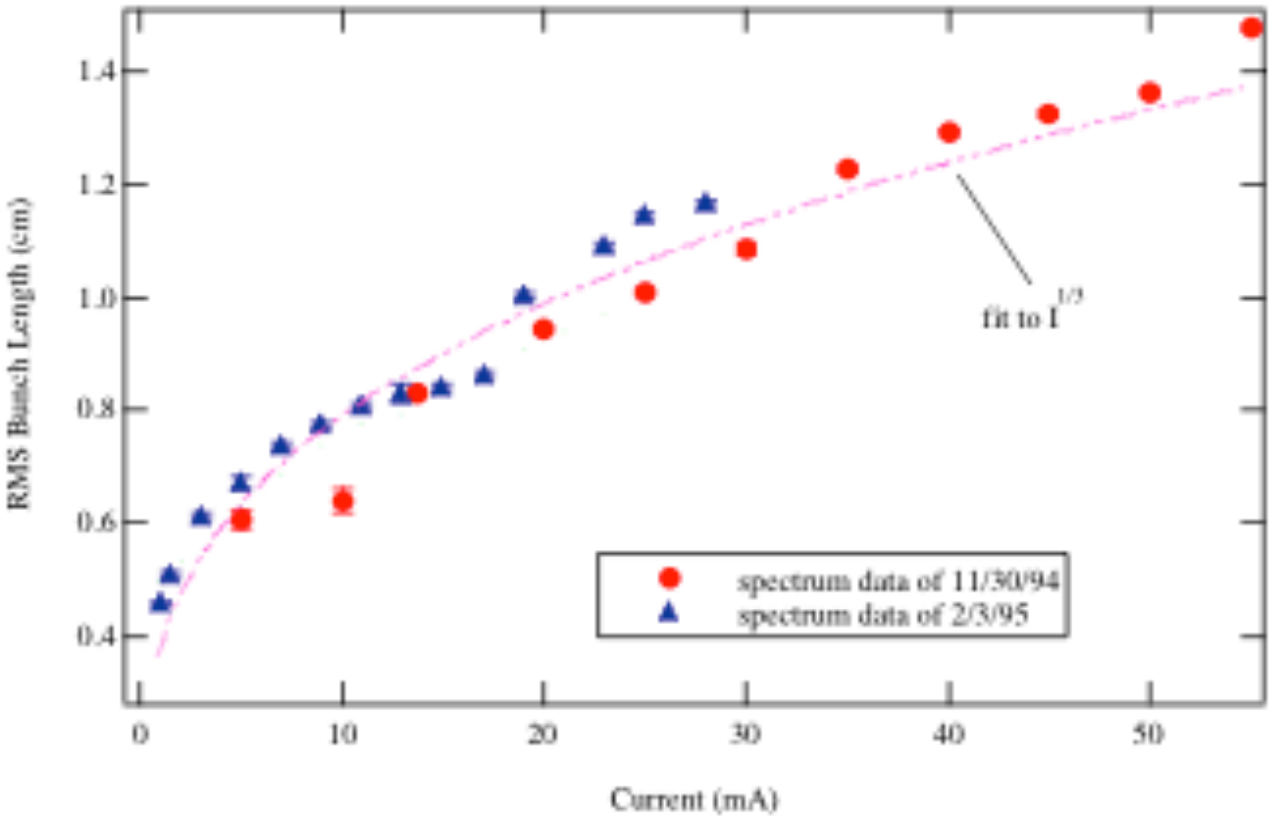
# Example: Broadband BPM spectrum

- Measure spectrum from single BPM button.
- Use 10 meters of high quality coaxial cable



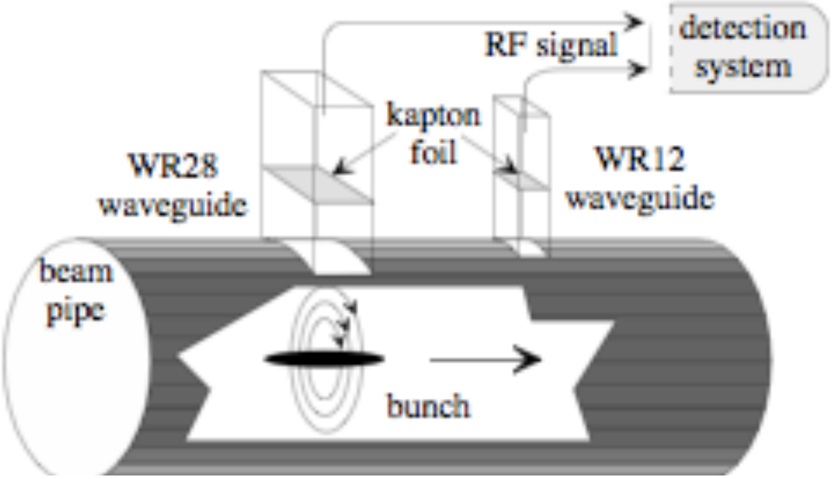
# Bunch length from BPM spectrum

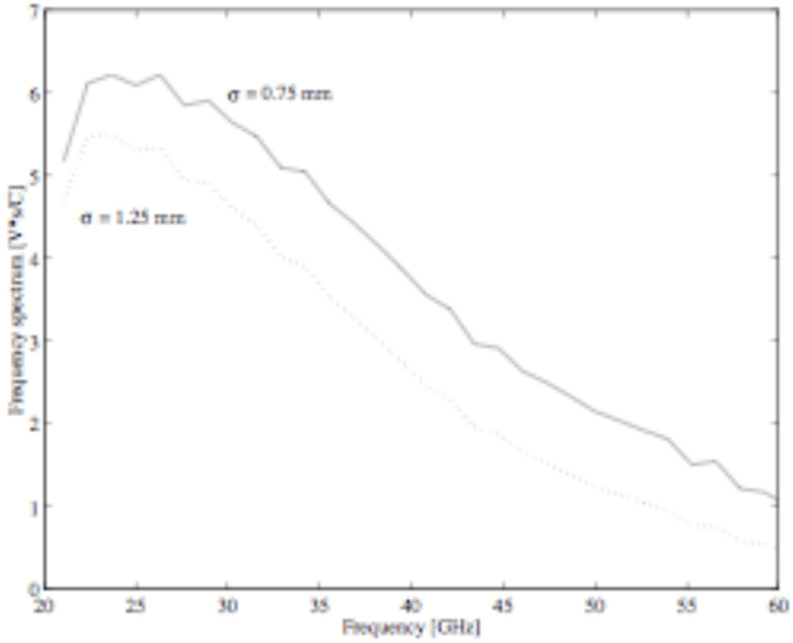
- Normalize measured spectrum to zero current spectrum. Assume Gaussian distribution.



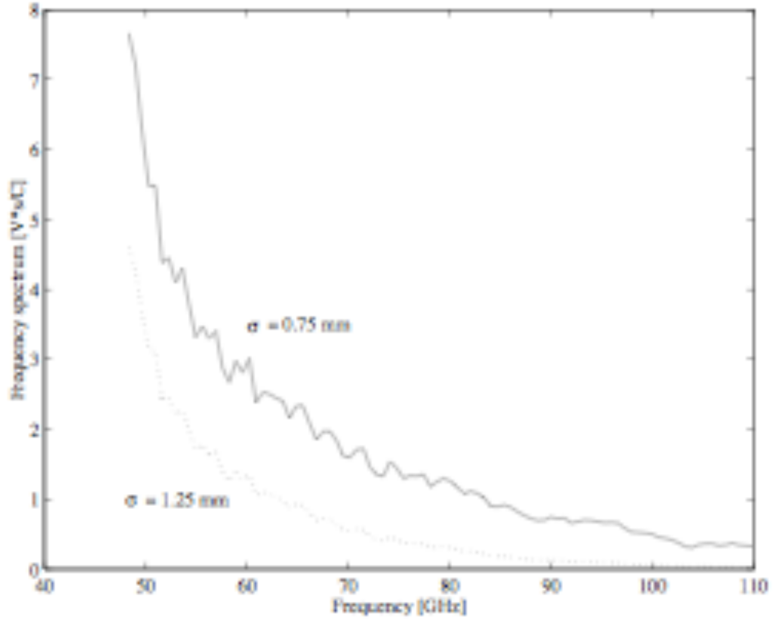
# Microwave bunch signals

- Try to extract beam signals up to 100 GHz
- Use two size WGs





(a) WR28



(b) WR12

# High frequency spectrum analysis

- Use a heterdyne receiver to mix signals to detectable frequency band.

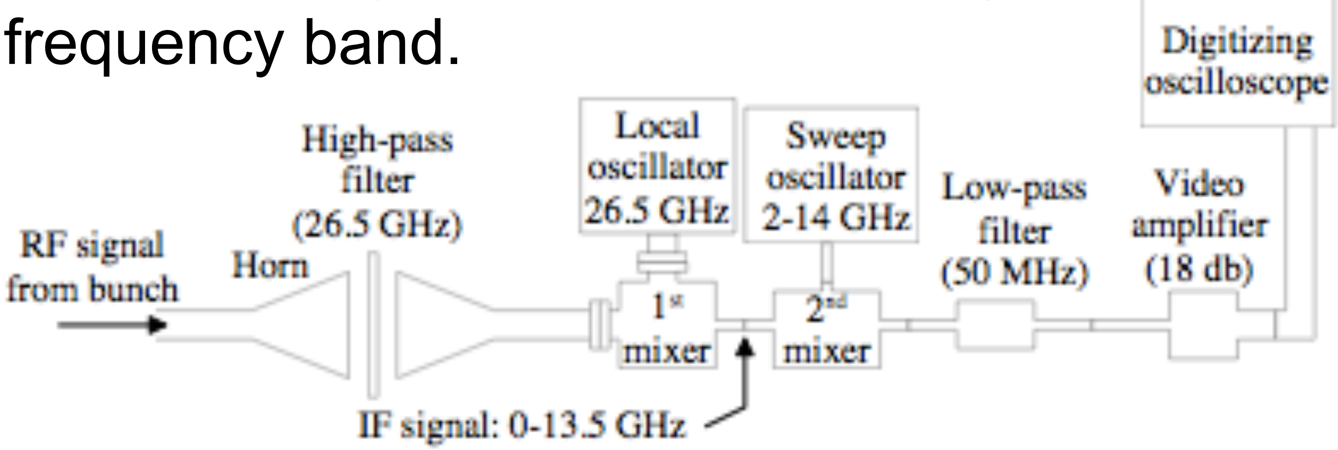


Figure 3.18: Schematic representation of the two-mixer detection system.

High pass filter made with holy plate.

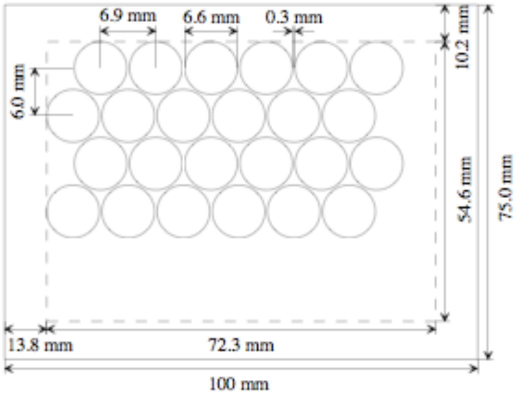
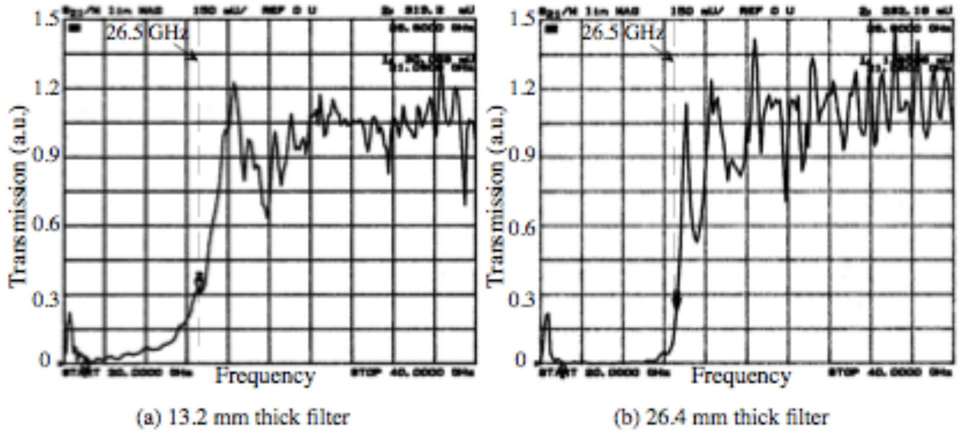


Figure 3.23: Design of a filter with a cut-off frequency of 26.5 GHz.

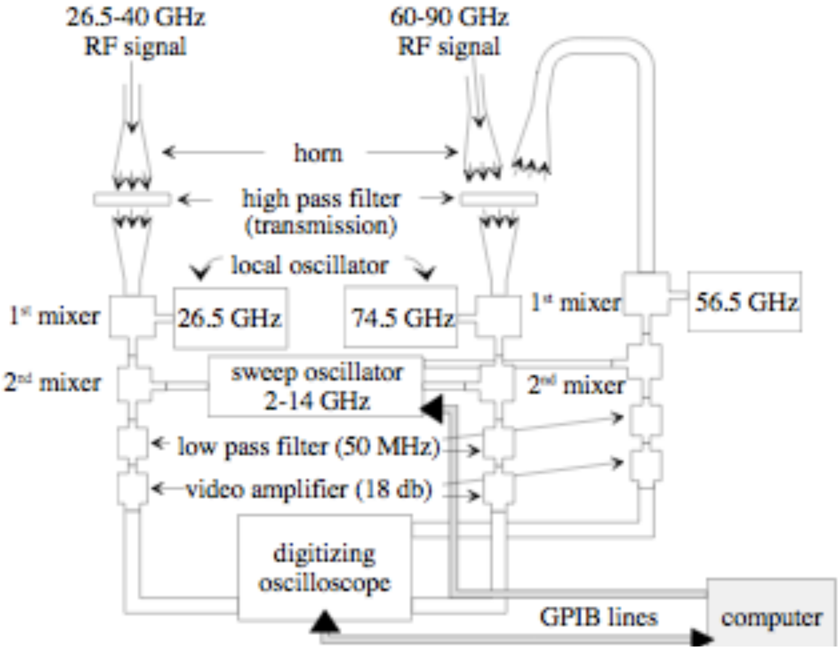


(a) 13.2 mm thick filter

(b) 26.4 mm thick filter

Figure 3.24: Transmission spectrum.

# Measurements



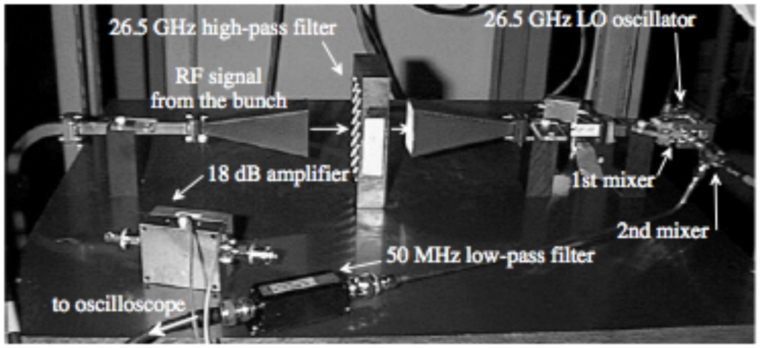


Figure 4.12: View of the $K_a$ band processing set-up.

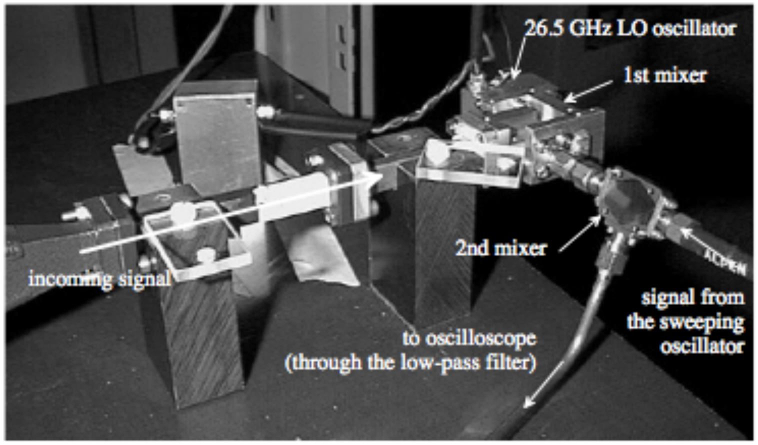
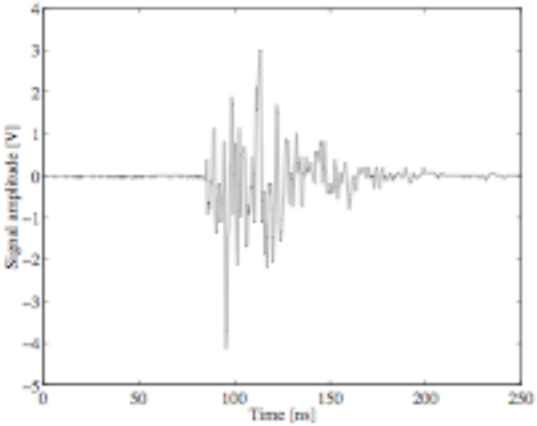
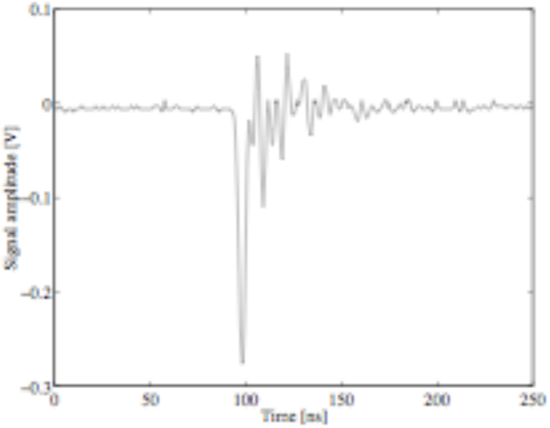


Figure 4.13: Closer view of the $K_a$ band mixers.

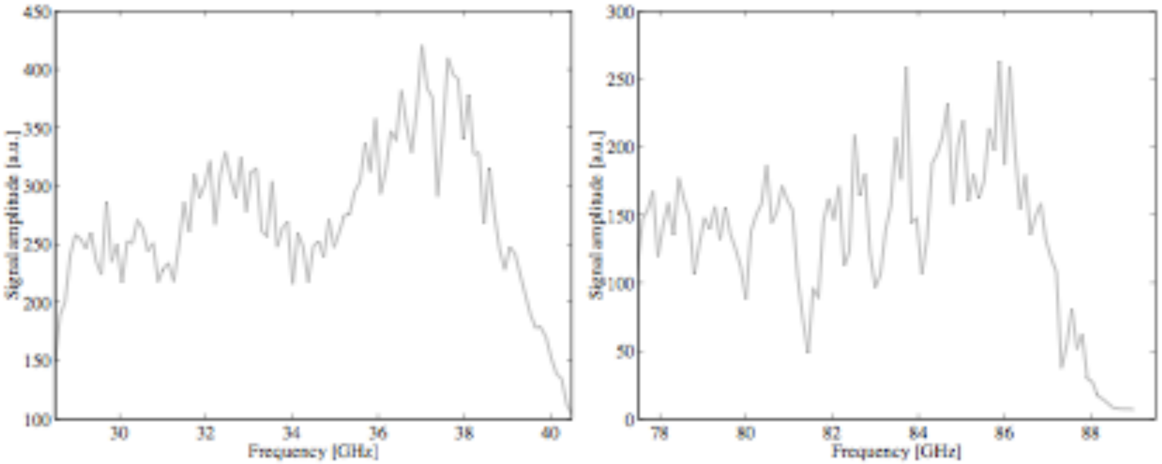


(a) Signal at 30 GHz



(b) Signal at 60 GHz

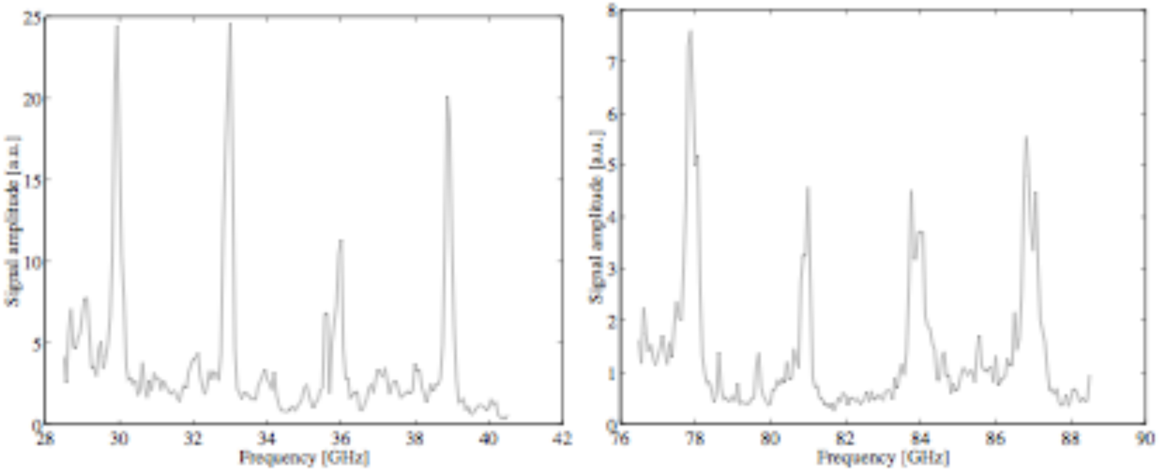
# Measurements



(a) $K_a$ band.

(b) E band

Figure 4.9: Raw frequency spectrum for a single bunch.

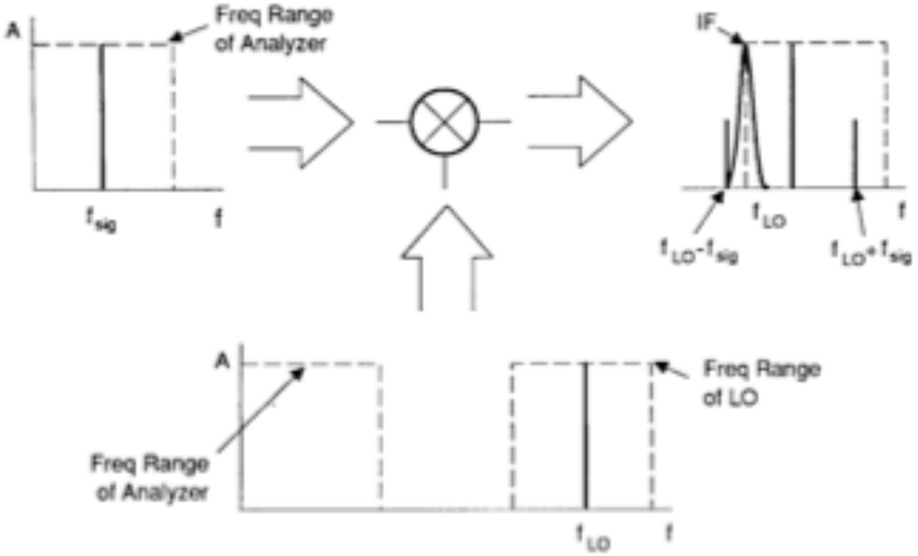


(a) $K_a$ band.

(b) E band

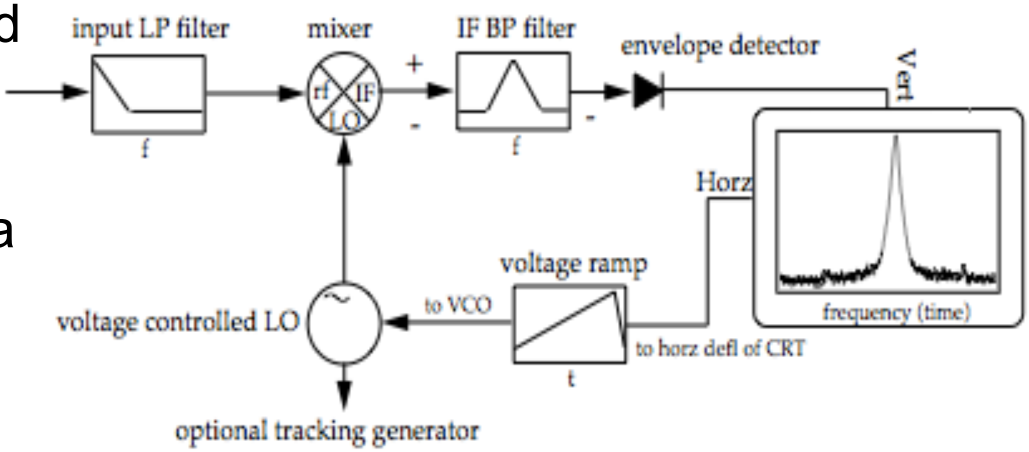
Figure 4.10: Raw frequency spectrum for a train of bunches.

# Heterodyne Spectrum Analysis

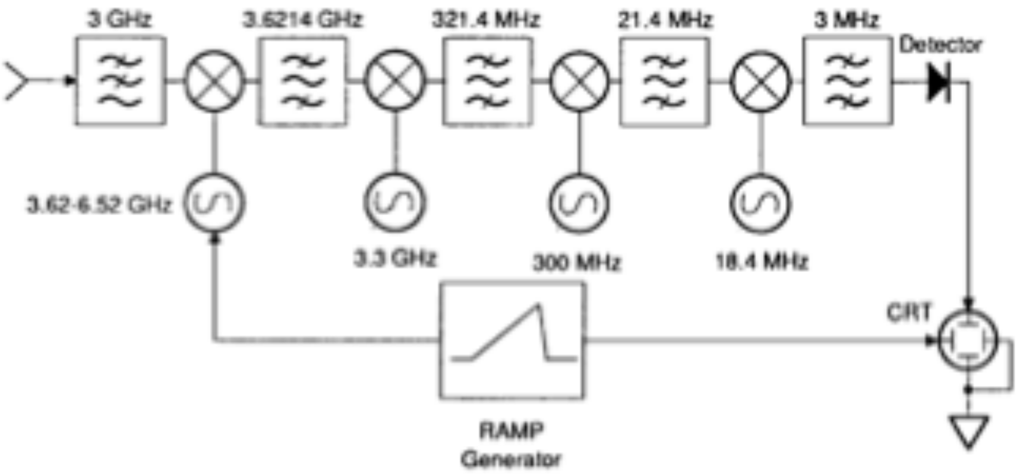


- Heterodyne receivers mix the signal to lower intermediate frequency where it is filtered and processed. Sweeping the LO frequency allows processing over a wide frequency range.

- The IF signal is bandpass filtered to reduce noise
- The envelope of the IF signal drives the vertical deflection on a CRT.
- The Voltage ramp to the VCO sweeps the horizontal axis.

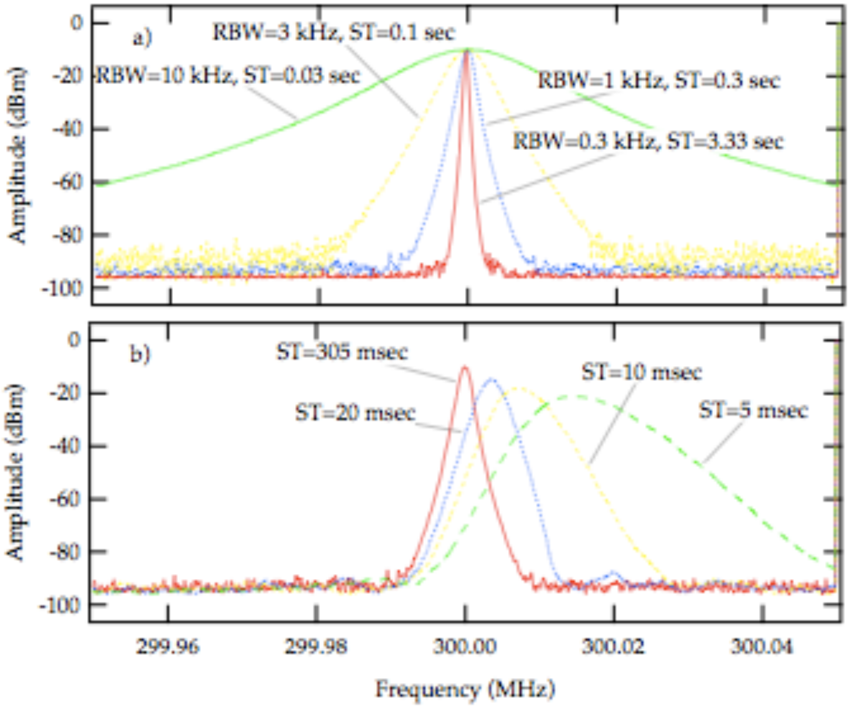


# Spectrum Analyzer: RBW and Sweep Time



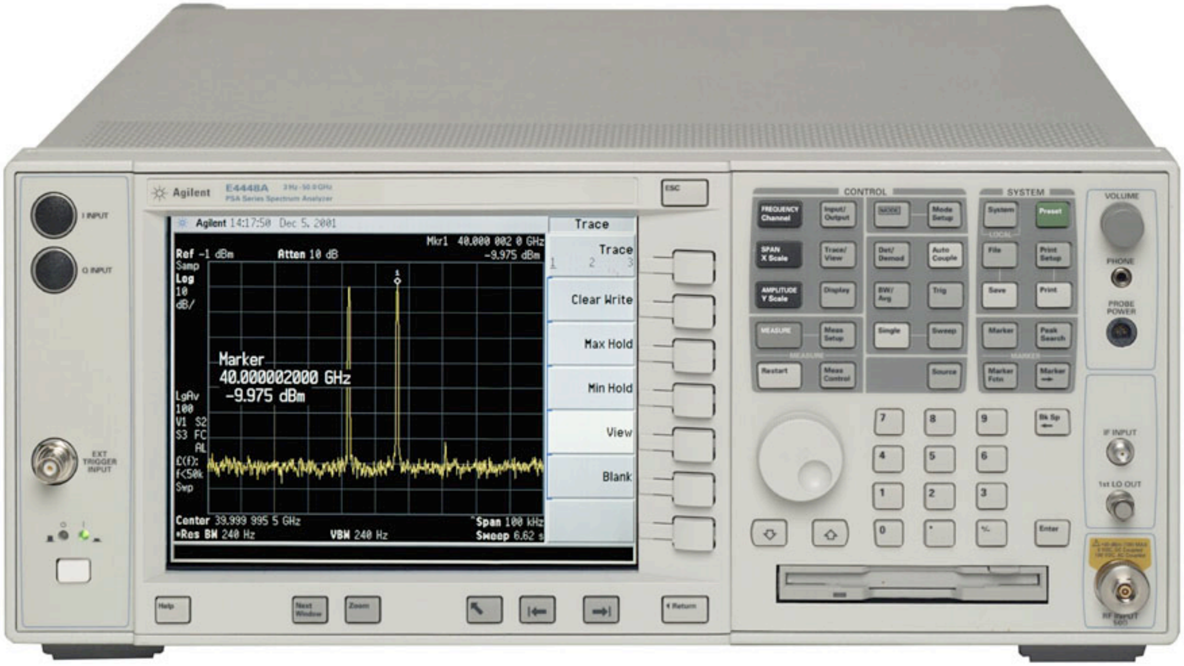
- Most SPAs use multistage filters to achieve high performance

- The SPA measures only the average amplitude of the signal at given frequency.
- The sweep time is typically adjusted to match the risetime of the selected resolution bandwidth filter.



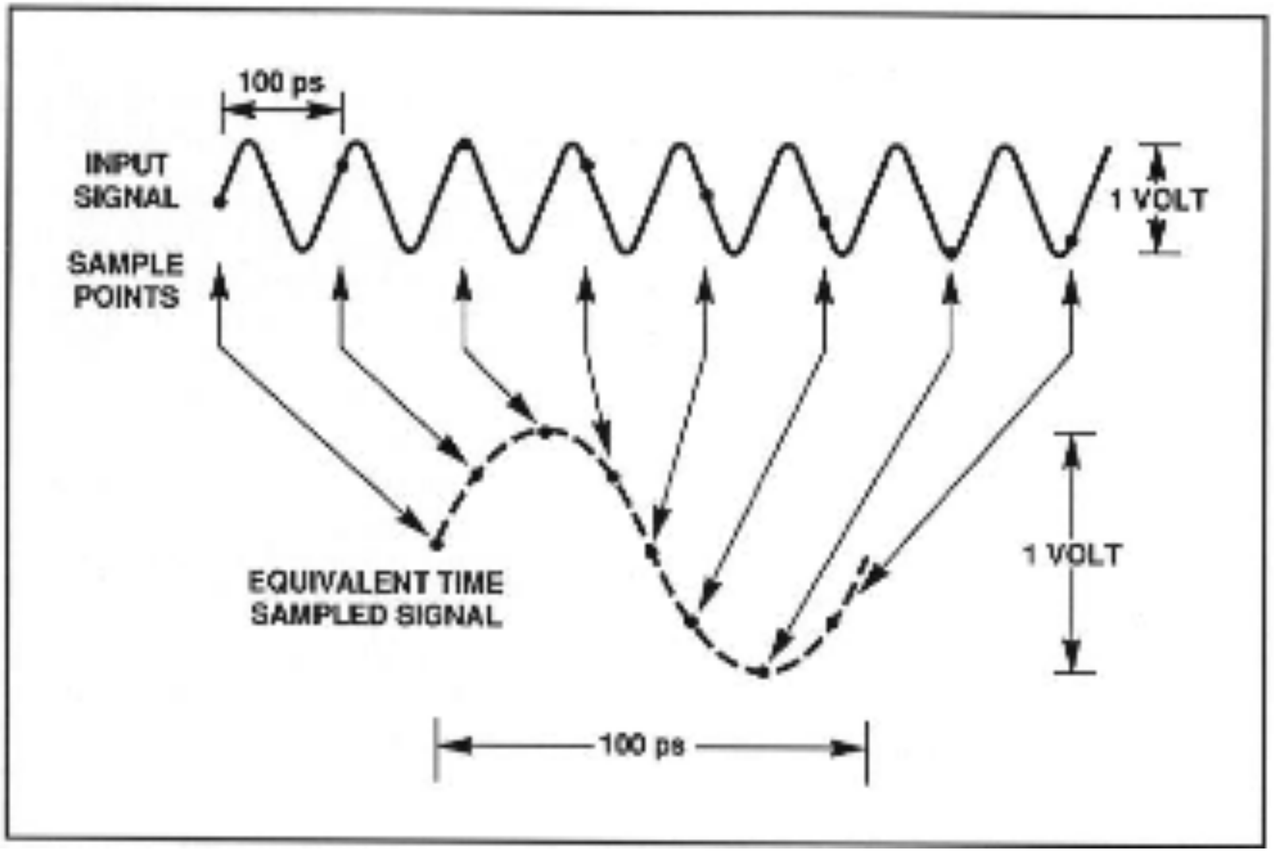
# Commercial SPAs available up to 50 GHz

- The Agilent E4448A PSA high-performance spectrum analyzer measures and monitors complex RF, microwave, and millimeter-wave signals up to 50 GHz. With optional external mixing, the frequency coverage expands to 110 GHz with the Agilent external mixer, and to 325 GHz with other vendors' mixers

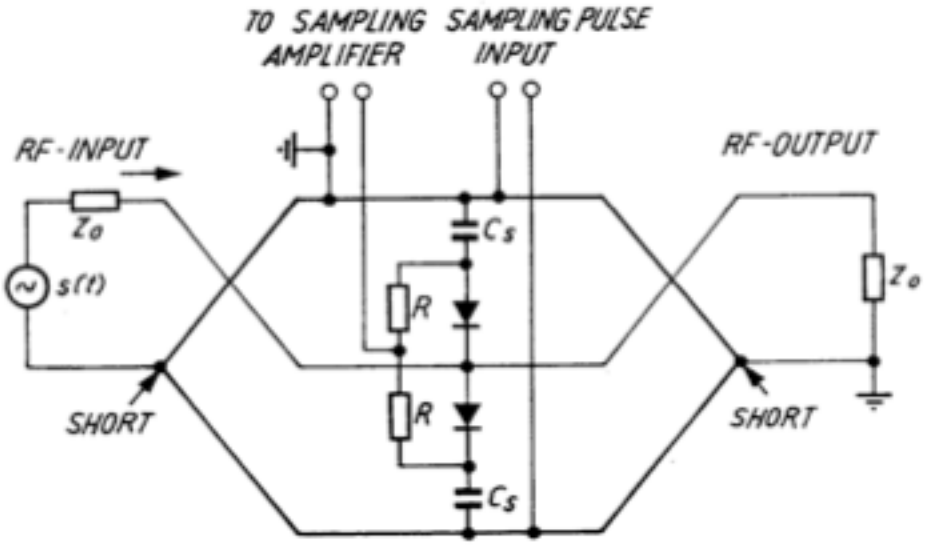


# Sampling scope

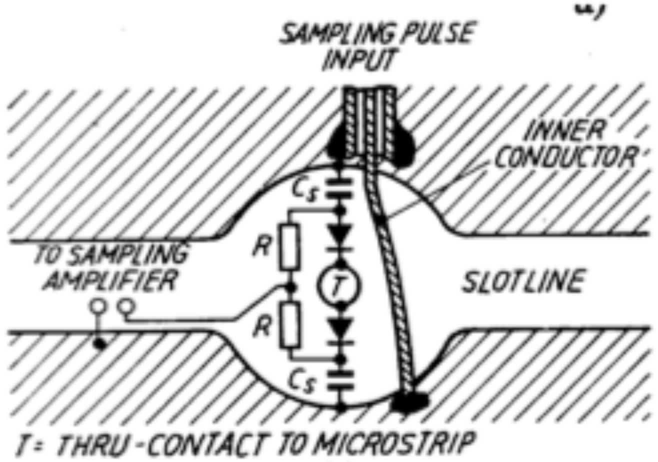
- Sampling scopes use a nonlinear gate to sample the waveform of a periodic signal.
- Allows much higher bandwidths than real-time scopes.

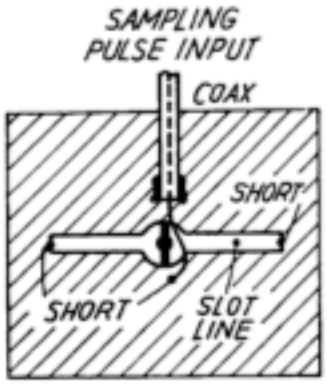


# Sampling Head



a)

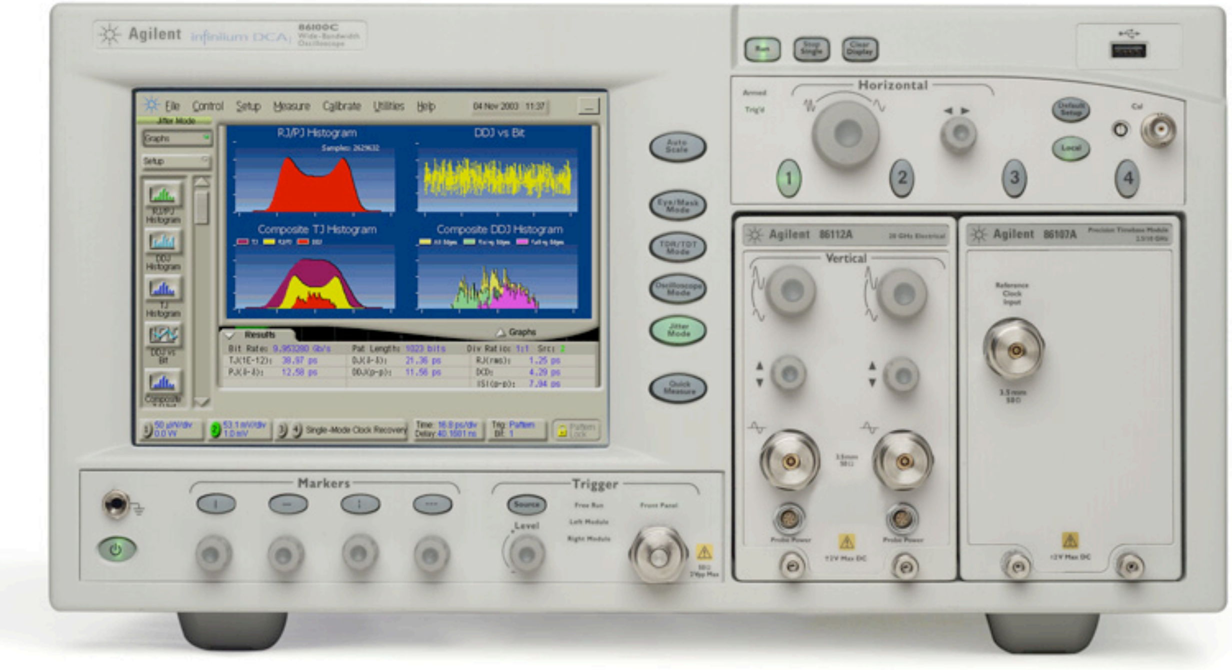




c)

- Sampling pulse allows diodes to conduct.
- Sampling capacitor is charged by signal during “on” time.
- Sampling capacitor read our during “off” period.
- Bandwidth determined by time width of sampling pulse.

# Commercial RF Sampling scopes



- 86100C DCA-J
- Electrical bandwidth from 12 to over 80 GHz
- A high-precision Time Domain Reflectometer (TDR) for measuring both impedance and s-parameters

# Optical Sampling Scopes

- Same principle as an RF scope, but using optical signals
- Input is an 1.5 micron optical signal (on fiber) modulated with up to 500 GHz signals.
- Sampling head (or gate) uses nonlinear optical material (diode)
  - 1 picosecond sampling resolution
  - Low sampling jitter <100fs
  - Very high bandwidth >500GHz
  - High signal sensitivity
  - Low polarization dependency
  - Software clock recovery without external clock
  - Real-time algorithm with fast refresh rate
  - Total bit-rate independent with tunable sampling rates
  - Data modulation formt independent
  - External clock-in option available