POSTECH
POHANG UNIVERSITY OF SCIENCE AND TECHNOLOGY

미래기반 가속기 전문인력양성 사업단

특론: 가속기 실험실습 I

(NUCE719P-01/PHYS715P-01, 정모세)

eLABs 시설을 이용한 빔운전 및 RF/빔진단 기초 2 (부제: RF 기초 1)

정모세

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Introduction

- In general, charged particles are focused and bent by use of magnets, and accelerated by use of electromagnetic waves in cavities.

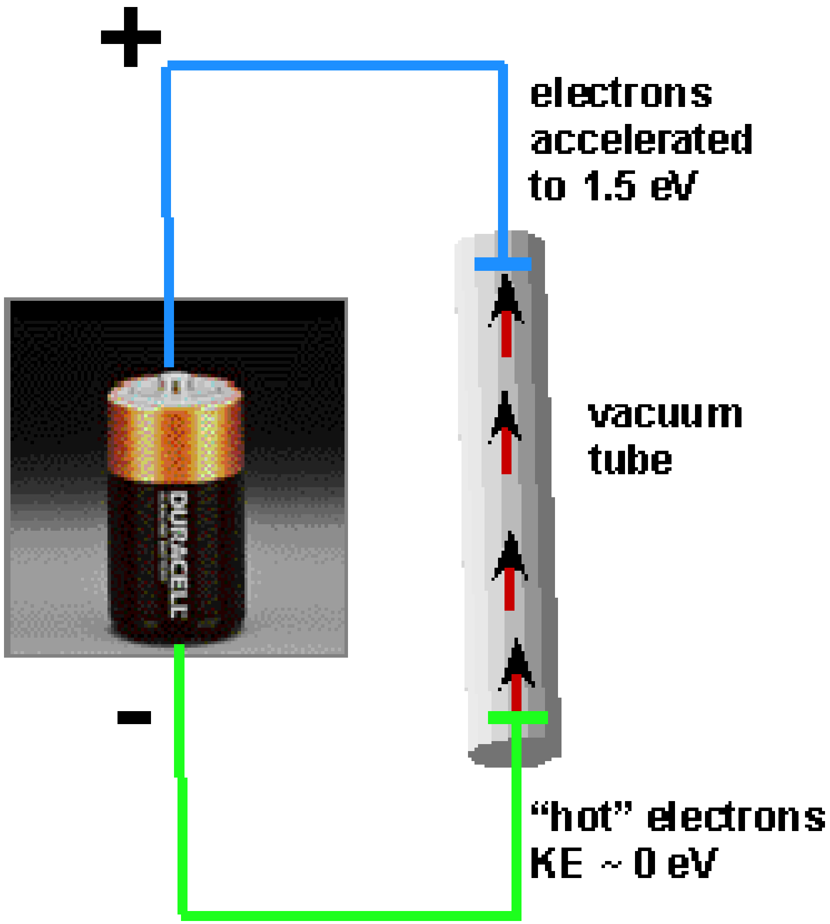
$$\mathbf{F} = q\mathbf{E} = q\left(-\nabla\phi - \frac{\partial \mathbf{A}}{\partial t}\right)$$

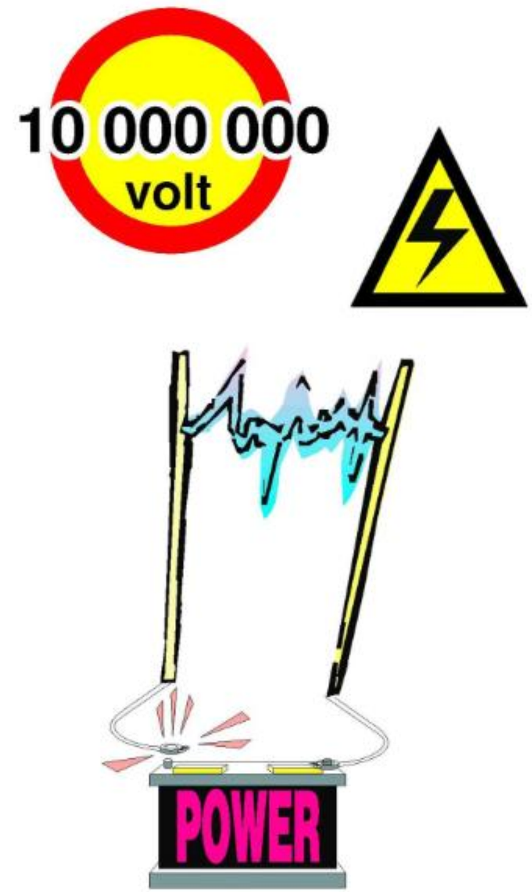
- DC acceleration is limited by high-voltage sparking and breakdown. It is very difficult to produce DC voltages more than a few million volts.

- RF accelerators bypass this limitation by applying a harmonic time-varying electric field to the beam, which is localized into bunches, such that the bunches always arrive when the field has the correct polarity (phase) for acceleration.

- The beam is accelerated within electromagnetic-cavity structures, in which a particular electromagnetic mode is excited from a high-frequency external power source.

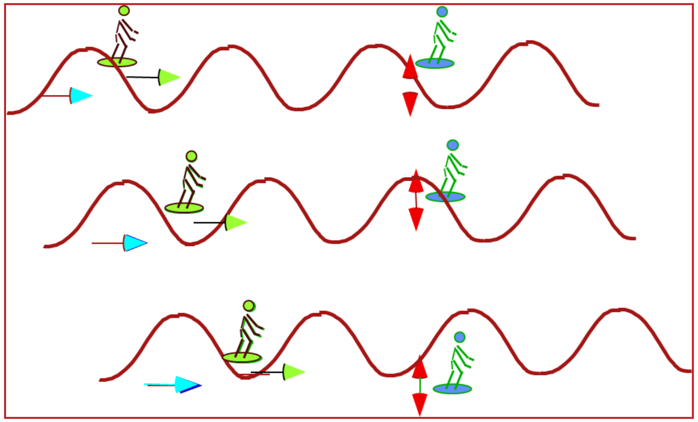
DC Acceleration





RF Acceleration

입자속도~파동속도 입자속도<< 파동속도



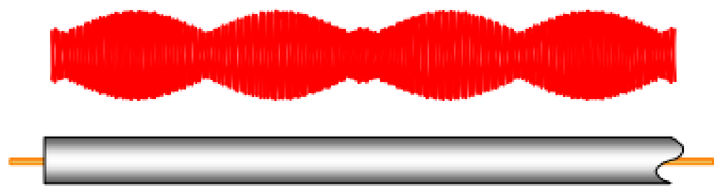
Low and High frequencies

Low frequencies

- wavelengths > > wire length
- current (I) travels down wires easily for efficient power transmission
- measured voltage and current not dependent on position along wire

펄스의 rise time 이 신호의 cable 통과 시간 보다 아주 느릴 때

Freq.	Wavelength
60 Hz	5000 km
10 MHz	30 m
1 GHz	30 cm
40 GHz	7.5 mm
100 GHz	3 mm

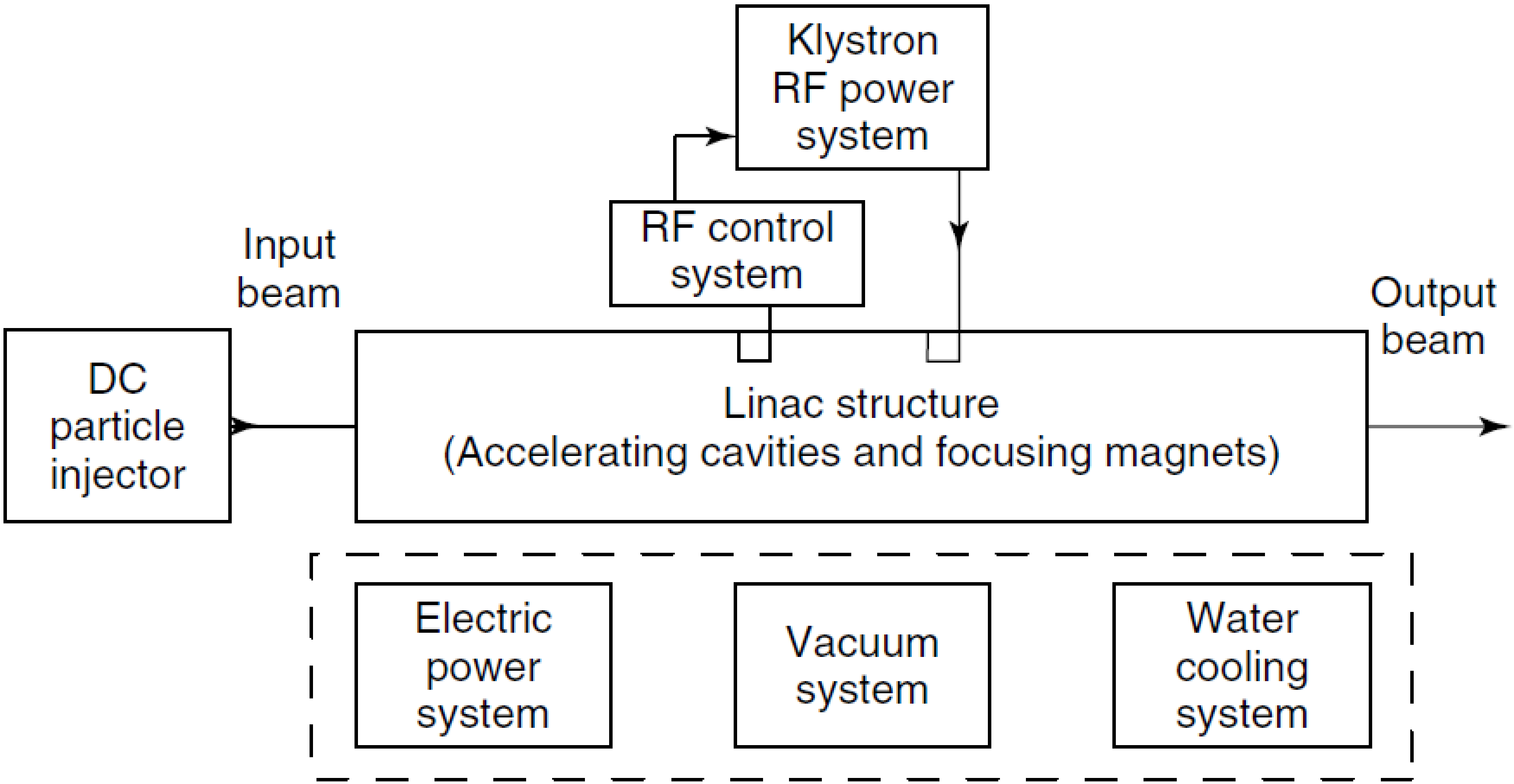


High frequencies

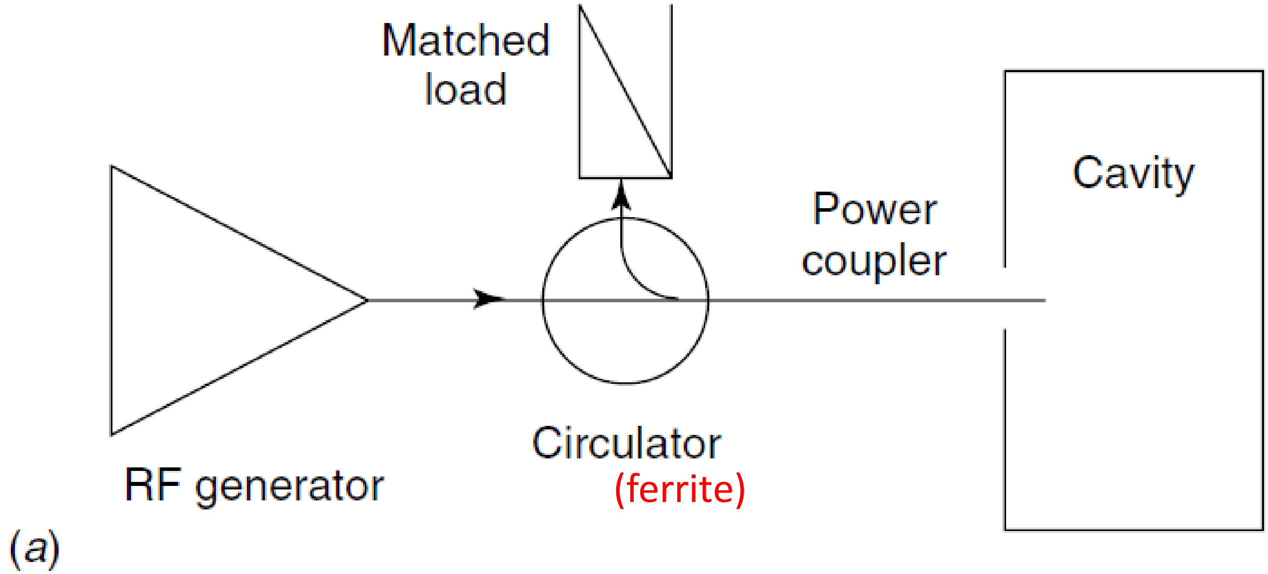
- wavelength ≈ or < < length of transmission medium
- need transmission lines for efficient power transmission
- matching to characteristic impedance (Z_0) is very important for low reflection and maximum power transfer
- measured envelope voltage dependent on position along line

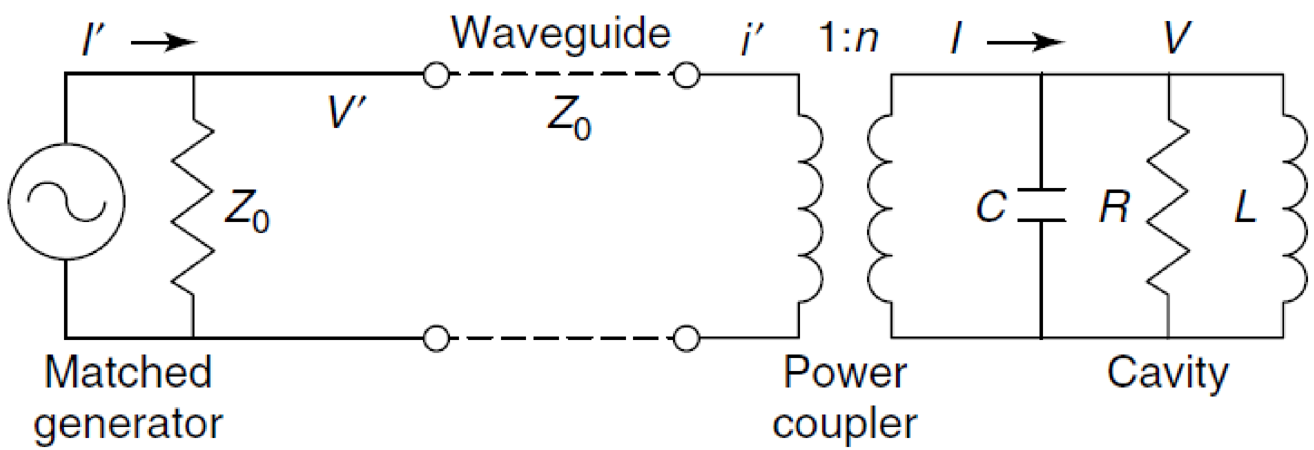
펄스의 rise time 이 신호의 cable 통과 시간 보다 아주 빠를 때

Block Diagram of RF Accelerator

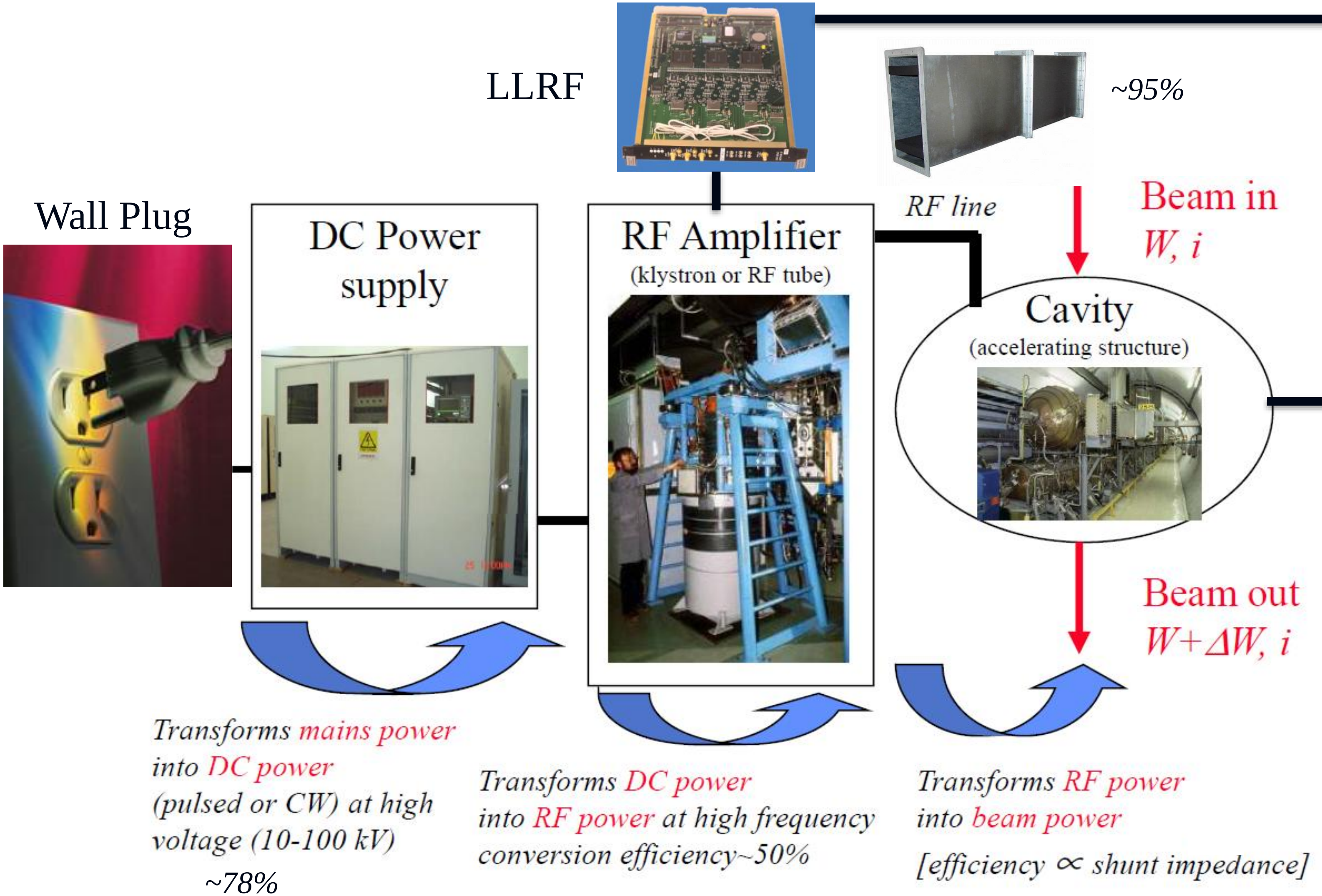


Circuit Diagram of RF Accelerator

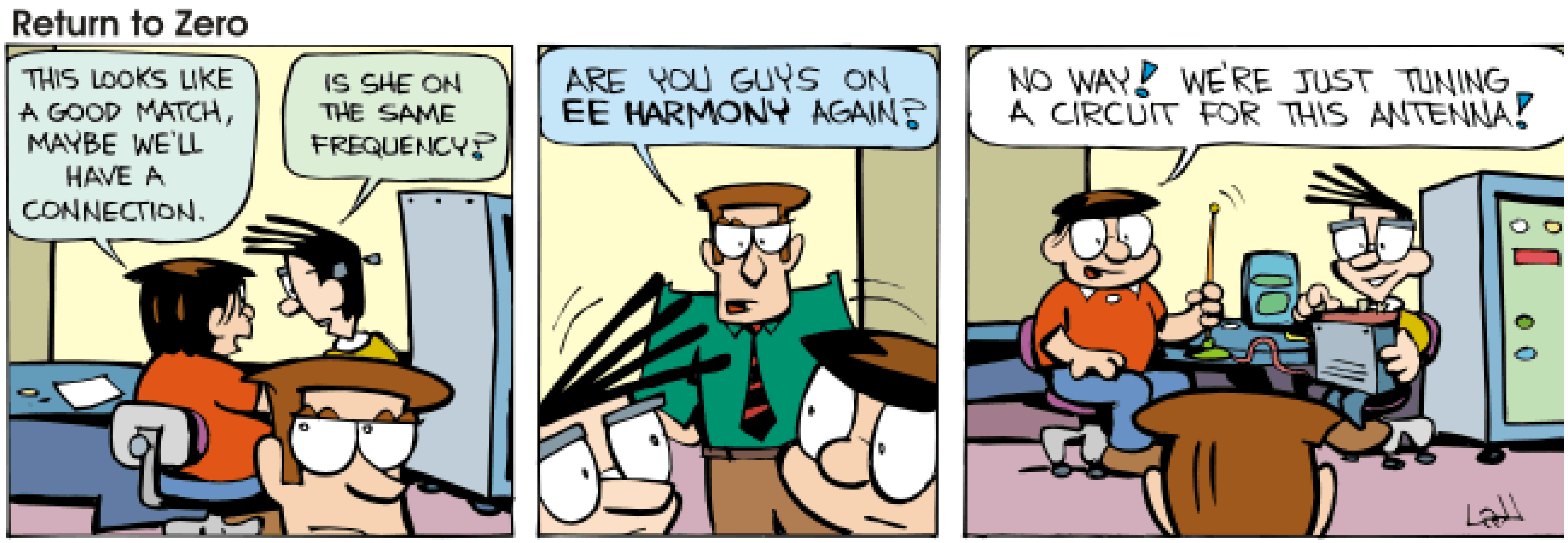




Real Pictures of RF Accelerator

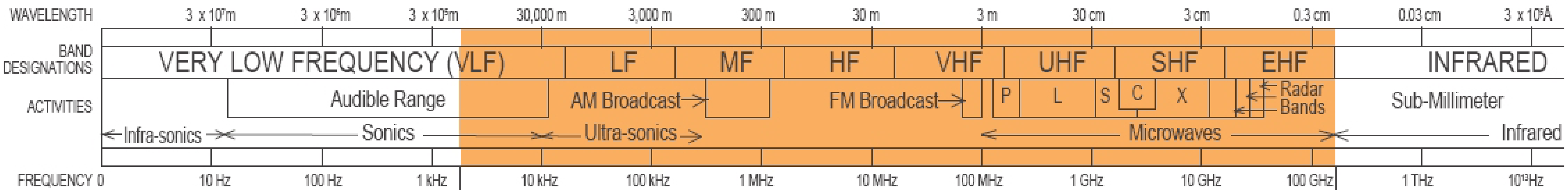


Building Blocks of RF Systems



Hertz (Hz)

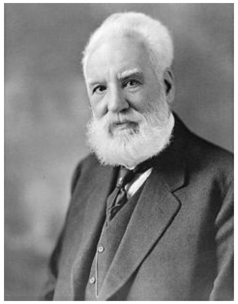
Heinrich Rudolf Hertz



From: US Department of Commerce
FCC Frequency Allocation Chart

IEEE Band	Frequency Range	Origin of Name	Wavelength in free space (centimeters)
L	1 to 2 GHz	L for "long" wave.	30.0 to 15.0
S	2 to 4 GHz	S for "short" wave	15 to 7.5
C	4 to 8 GHz	C for "compromise" between S and X band.	7.5 to 3.8
X	8 to 12 GHz	Used in WW II for fire control, X for cross (as in crosshair).	3.8 to 2.5
Ku	12 to 18 GHz	Ku for "kurz-under".	2.5 to 1.7
K	18 to 26 GHz	German "kurz" means short, yet another reference to short wavelength.	1.7 to 1.1
Ka	26 to 40 GHz	Ka for "kurz-above".	1.1 to 0.75
V	40 to 75 GHz	V for "very" high frequency band (not to be confused with VHF).	0.75 to 0.40
W	75 to 110 GHz	W follows V in the alphabet.	0.40 to 0.27

decibel (dB)



Alexander Graham Bell

- Means of expressing large values via a logarithmic ratio.

$$\mathrm{dB} = 10 \times \log_{10}\left(\frac{P_2}{P_1}\right)$$

- In RF and microwave systems, typical power and voltage ratios are expressed in dB.

$$\mathrm{dB} = 10 \times \log_{10}\left(\frac{V_2^2/R}{V_1^2/R}\right) = 20 \times \log_{10}\left(\frac{V_2}{V_1}\right)$$

- Sometimes, reference power is normalized to 1 mW.

$$\mathrm{dBm} = 10 \times \log_{10}\left(\frac{P}{1\ \mathrm{mW}}\right)$$

- Attenuation is

$$\mathrm{Attenuation\ (dB)} = 10 \times \log_{10}\left(\frac{\mathrm{Input\ power\ (W)}}{\mathrm{Output\ power\ (W)}}\right)$$

dB	power ratio	amplitude ratio
100	10 000 000 000	100 000
90	1 000 000 000	31 623
80	100 000 000	10 000
70	10 000 000	3 162
60	1 000 000	1 000
50	100 000	316 .2
40	10 000	100
30	1 000	31 .62
20	100	10
10	10	3 .162
6	3 .981	1 .995 (~2)
3	1 .995 (~2)	1 .413
1	1 .259	1 .122
0	1	1
−1	0 .794	0 .891
−3	0 .501 (~1/2)	0 .708
−6	0 .251	0 .501 (~1/2)
−10	0 .1	0 .316 2
−20	0 .01	0 .1
−30	0 .001	0 .031 62
−40	0 .000 1	0 .01
−50	0 .000 01	0 .003 162
−60	0 .000 001	0 .001
−70	0 .000 000 1	0 .000 316 2
−80	0 .000 000 01	0 .000 1
−90	0 .000 000 001	0 .000 031 62
−100	0 .000 000 000 1	0 .000 01

Connectors

Typically supports frequencies up to **11 GHz**

Type N

APC 7

TNC

BNC

Typically supports up to **4 GHz**

SMA

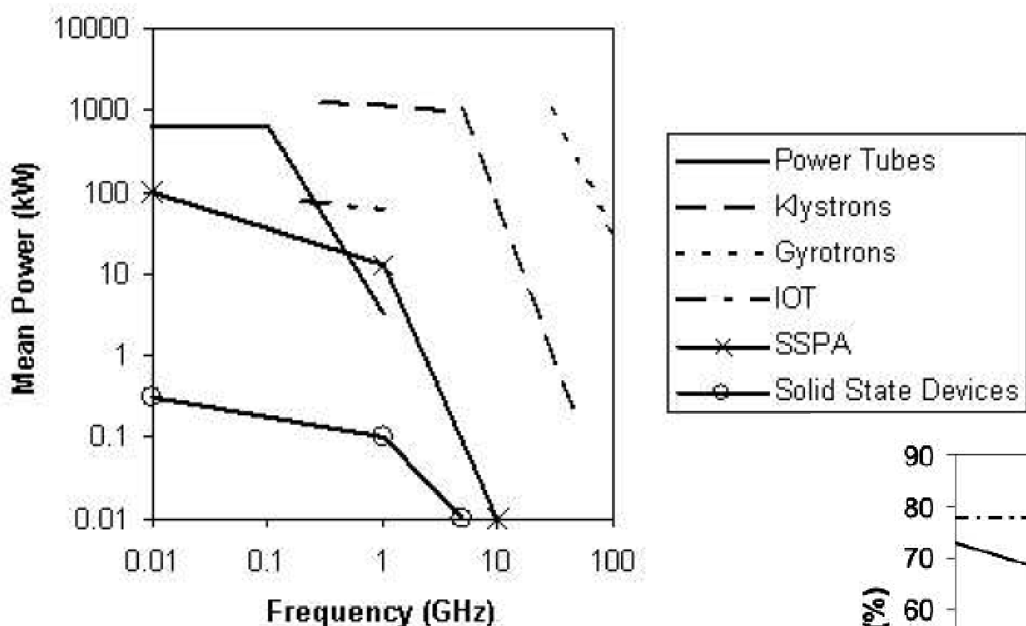
Connector used for high-frequency signal transmission (Typically up to 18 GHz)

Lemo

Ideal for compact applications requiring high performance.

CW Power Sources

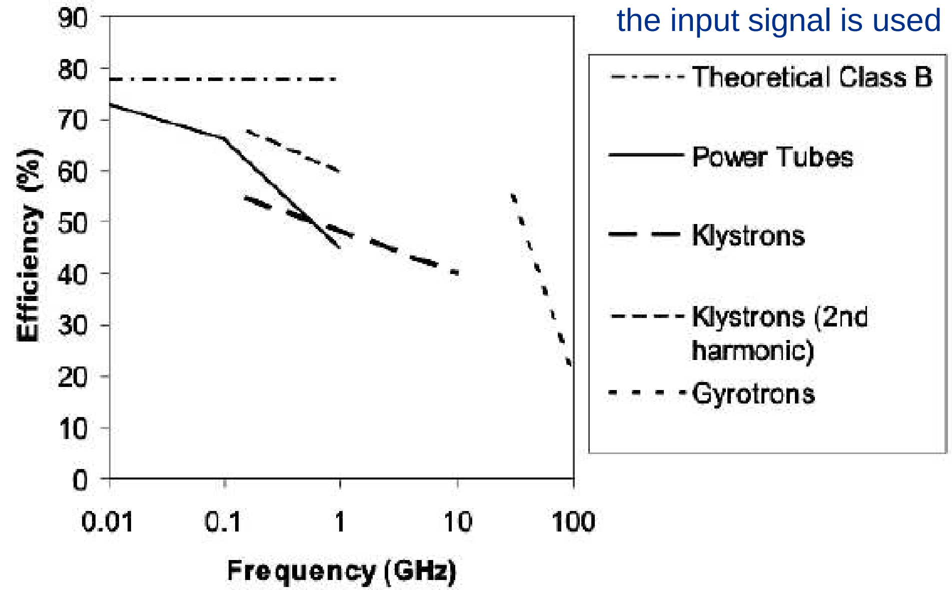
- The two main categories are solid-state devices and vacuum tubes.



IOT: Inductive Output Tube

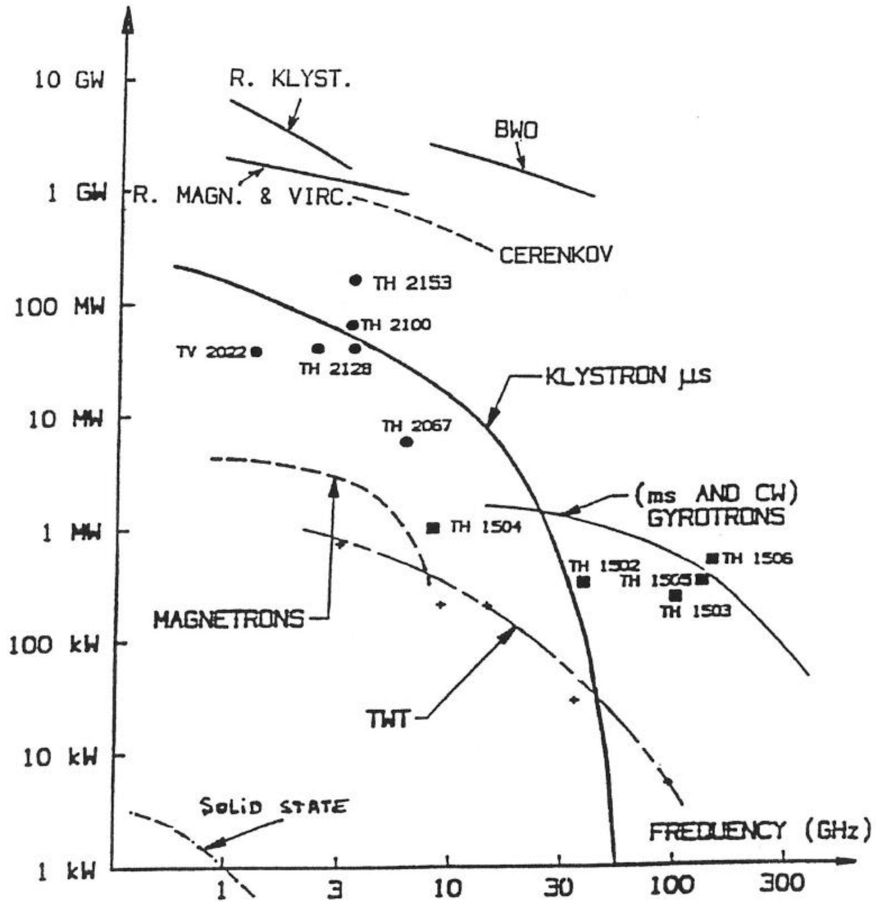
SSPA: Solid State Power Amplifier

Class B PA: 50% of the input signal is used



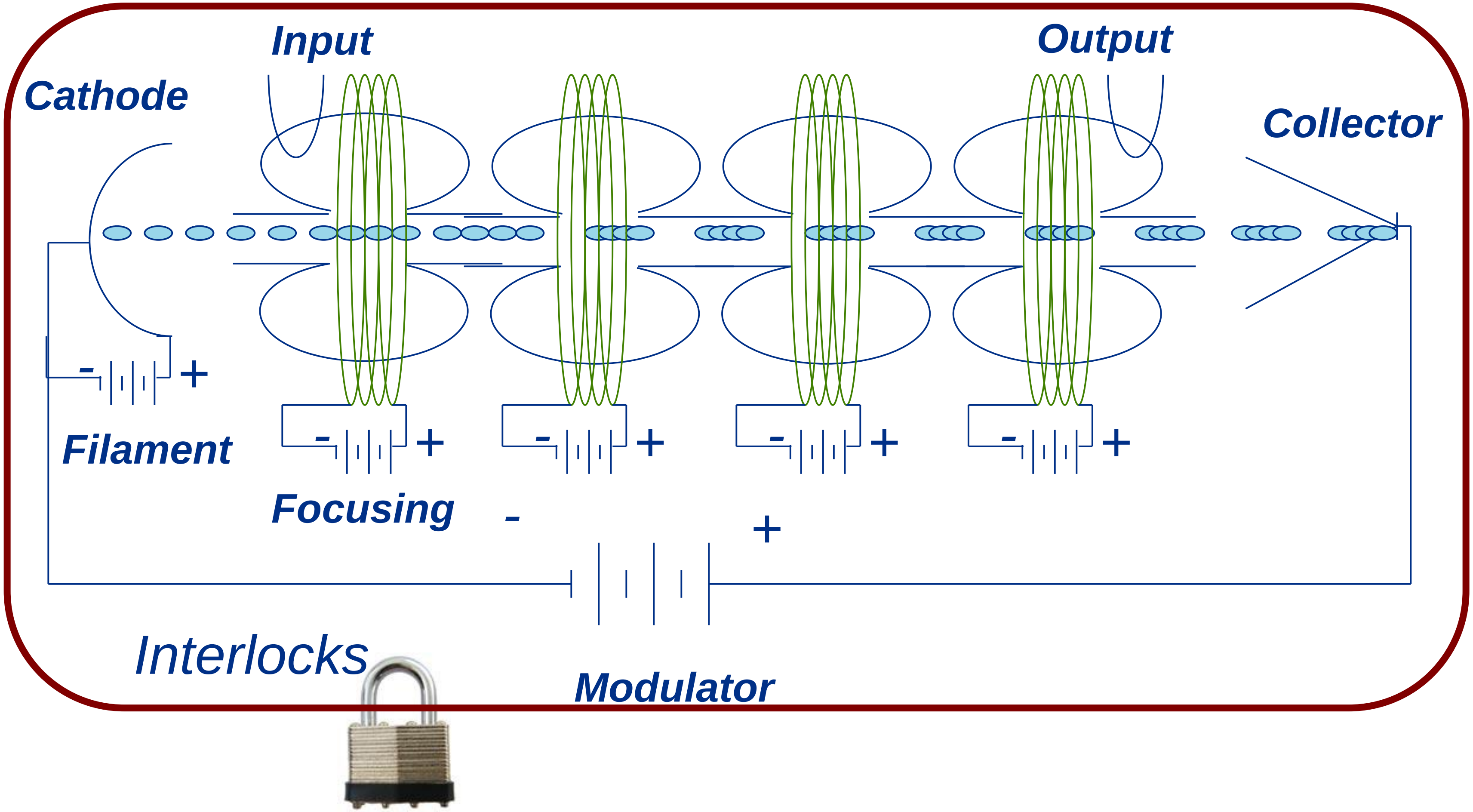
Pulsed Power Sources

- Klystrons (>350 MHz) for electron linacs and modern proton linacs. RF distribution via waveguides.
- RF tube (<400 MHz) or solid state amplifiers for proton and heavy ion linacs. RF distribution via coaxial lines.



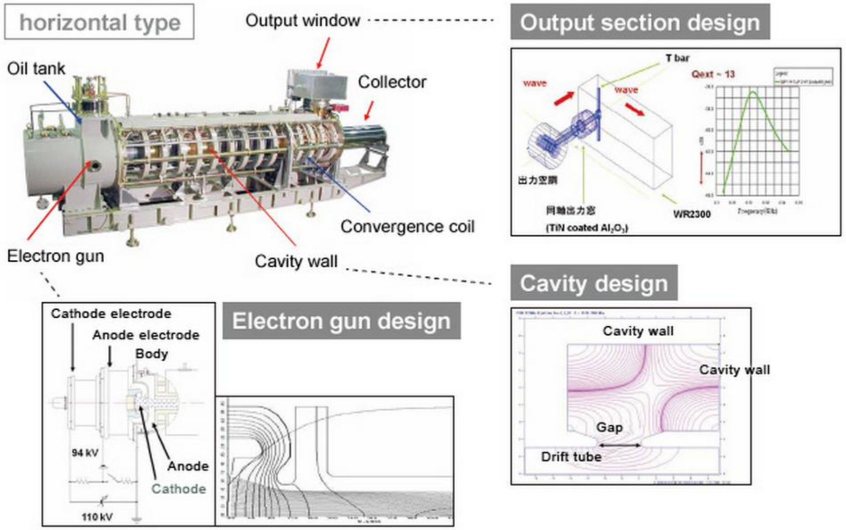
Typical Klystron Operation

- Decelerator: Amplify RF signals by converting the kinetic energy in a DC electron beam into radio frequency power. (velocity modulation → bunching)

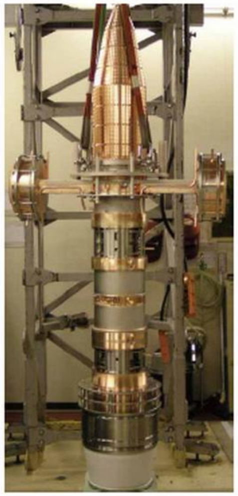


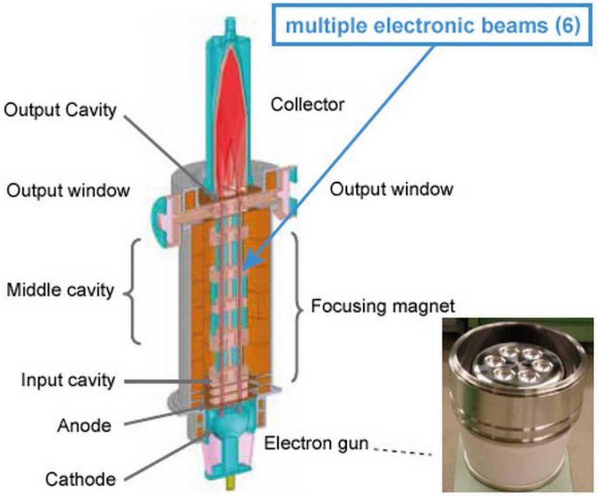
Typical Klystron Parameters

- Power Gain — 40-60 dB (10^4-10^6)
- Power — 10^3 to 10^7 Watts
- Duty Cycle — Continuous or Pulsed
- Frequency — Hundreds MHz to Tens GHz
- Bandwidth — 1%
- Efficiency — 50%
- Cathode Volts — 10's to 100's of kilovolts
- Klystron Life — 10,000-100,000 hours



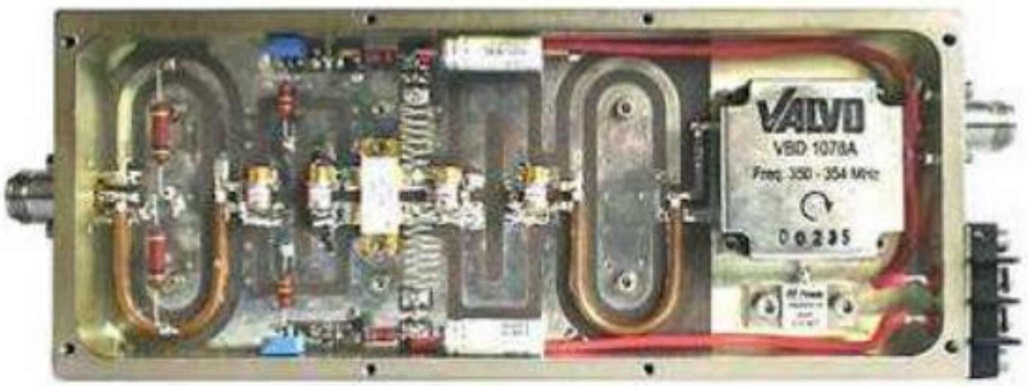
Toshiba



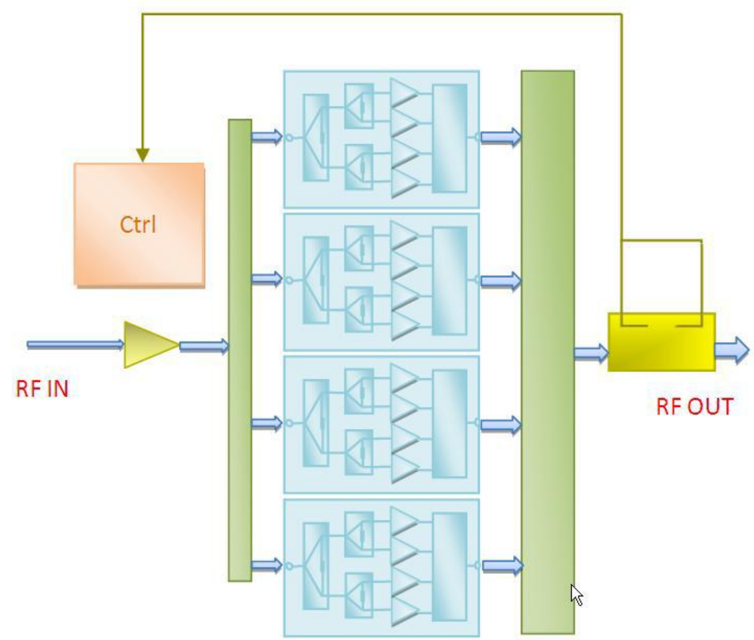


Typical Solid State Module

- Solid state amplifiers are based on transistors instead of vacuum electron tubes as active device.



- 330 W module
- 352 or 500 MHz, different devices
- 1 transistor/pallet
- 1 circulator/transistor
- © Synchrotron SOLEIL - Ti Ruan



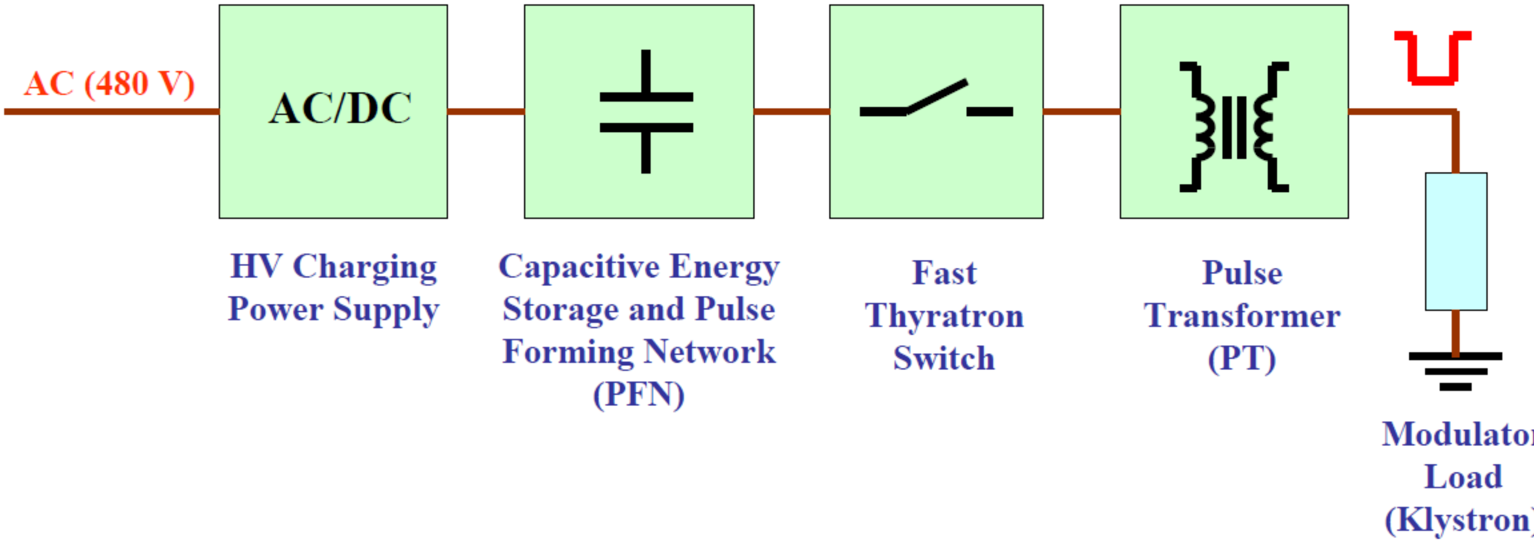
Typical Solid State Parameters

- Power Gain 20-70 dB (10^2-10^7)
- Power 10^3 to 10^5 Watts
- Duty Cycle Continuous or Pulsed
- Frequency 1 MHz to 2 GHz
- Bandwidth few % to decades %
- Efficiency 10-50%
- Supply Volts 20-50 volts DC
- Life time 10,000-200,000 hours

Bruker

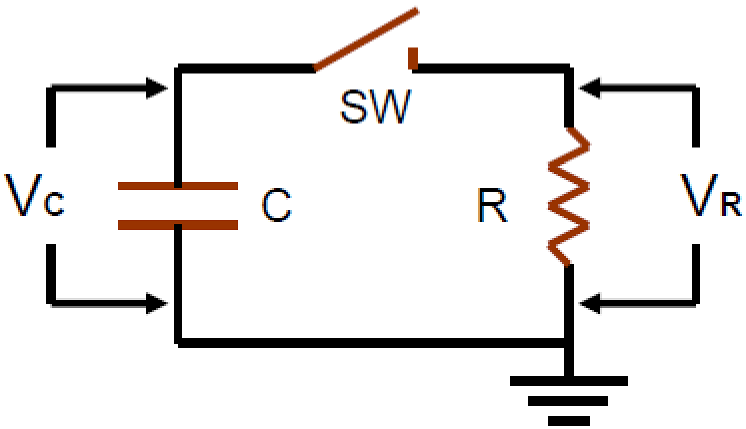
Modulator

- The modulators are locally and remotely controlled pulse generators that supply high-voltage pulses required for proper operation of high-power pulsed RF amplifiers.

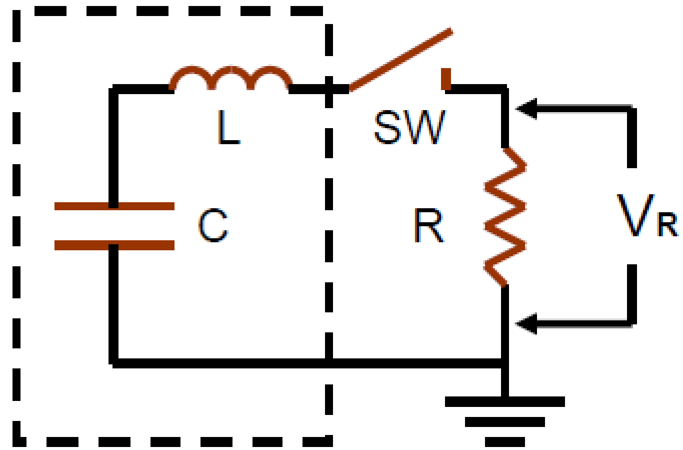


Pulse Forming

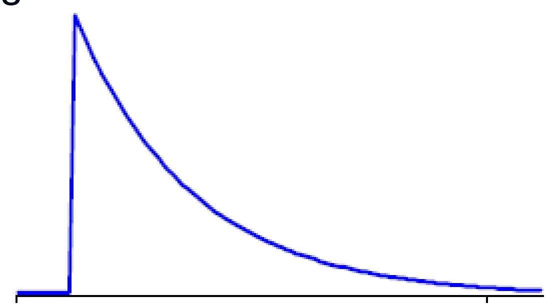
Fast/High current switch

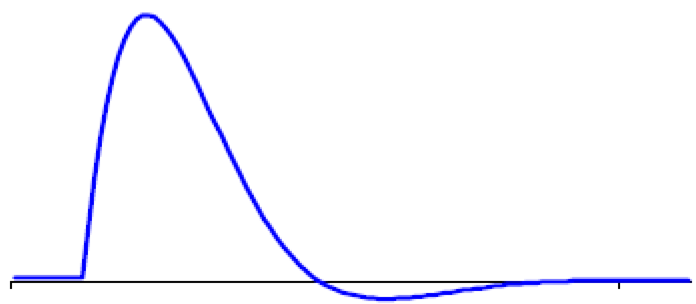


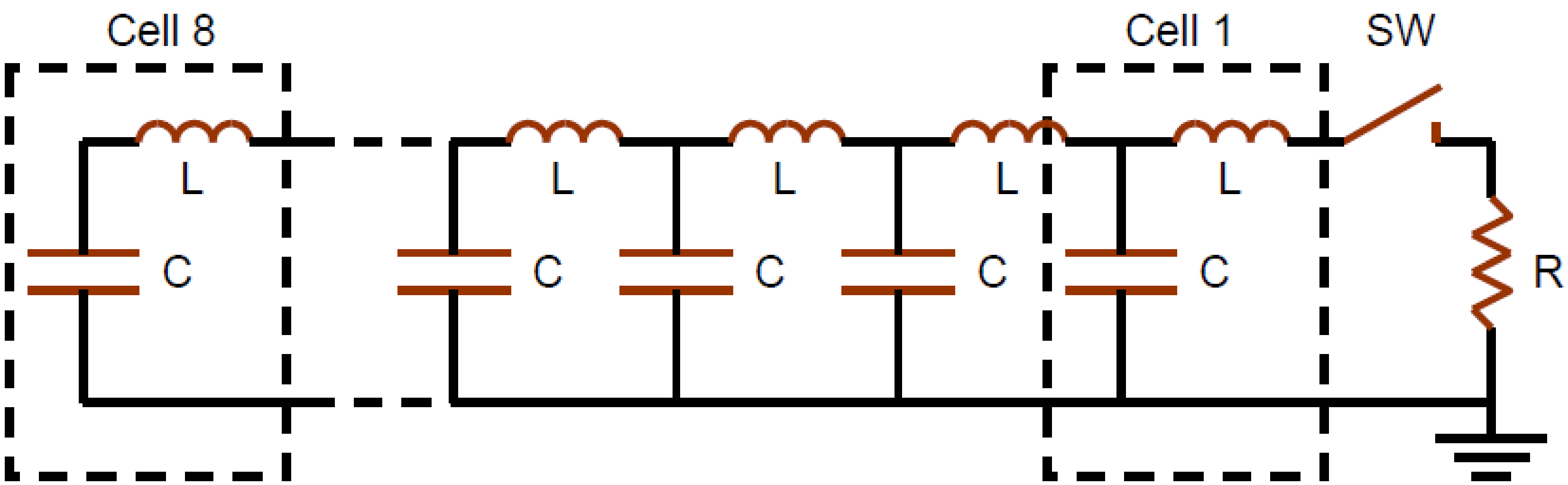
The Cell

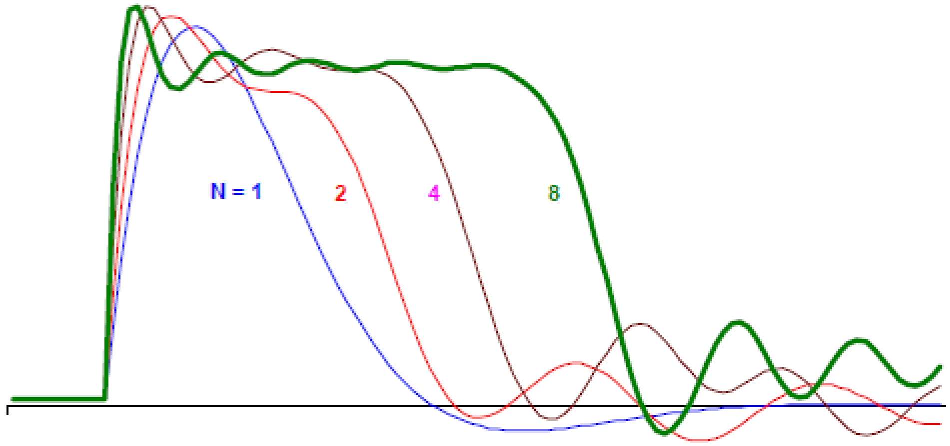


Fast/High current switch



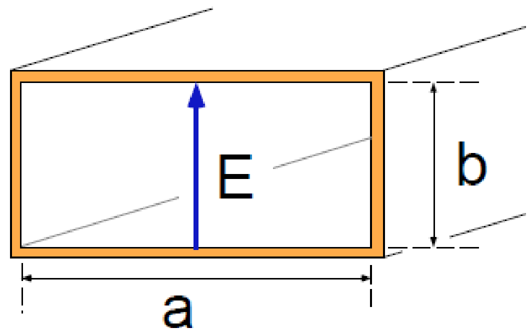


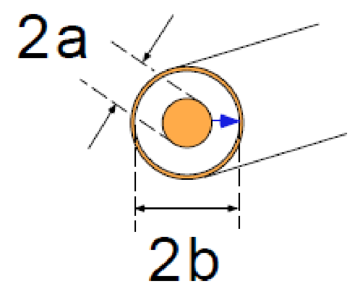

Cell 8
Cell 1
SW
L
L
L
L
L
C
C
C
C
C
R

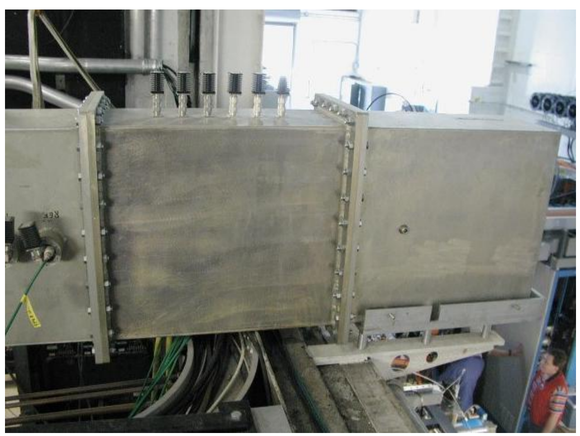

N = 1
2
4
8

Power Transmission

- Transmission lines transmit RF power from one point to another with minimum loss and external radiation of energy.
- Two common types: Rectangular waveguide type / Coaxial type





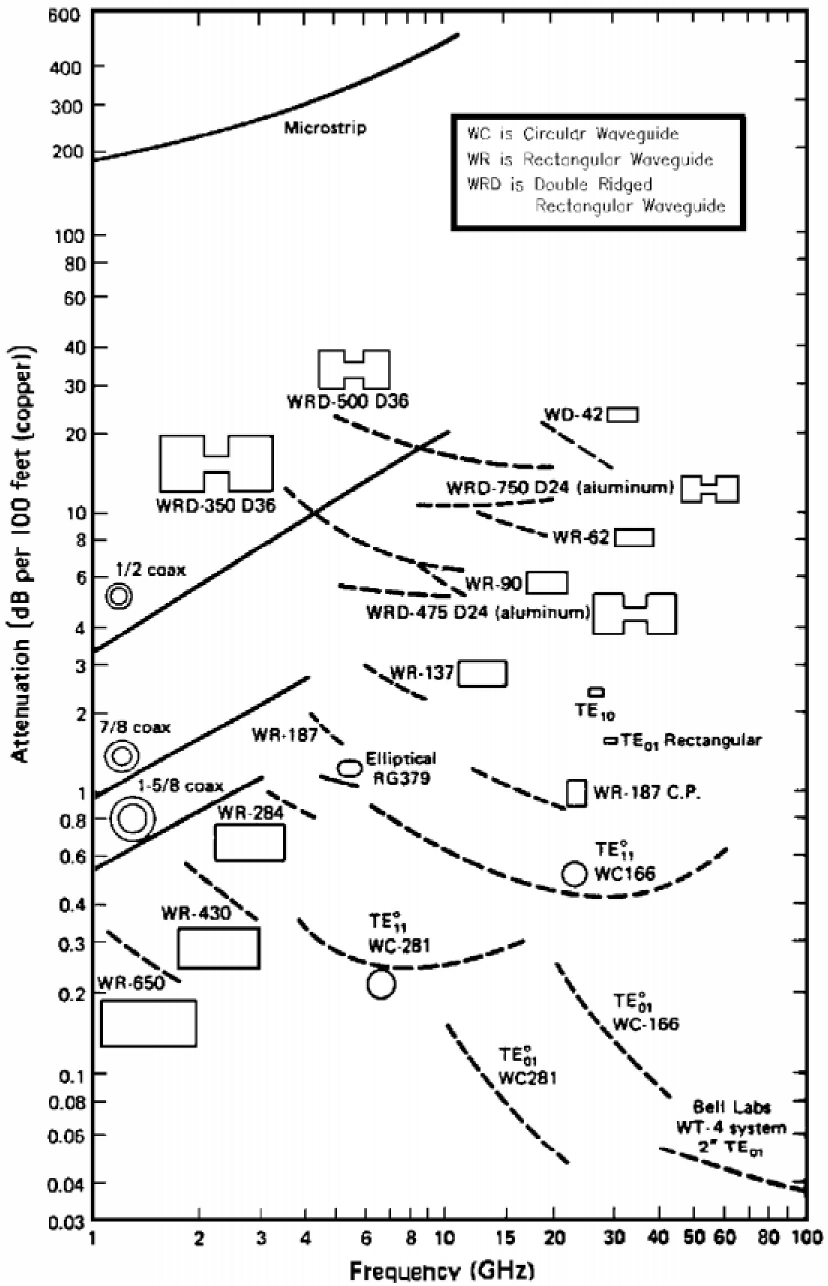


Rigid line

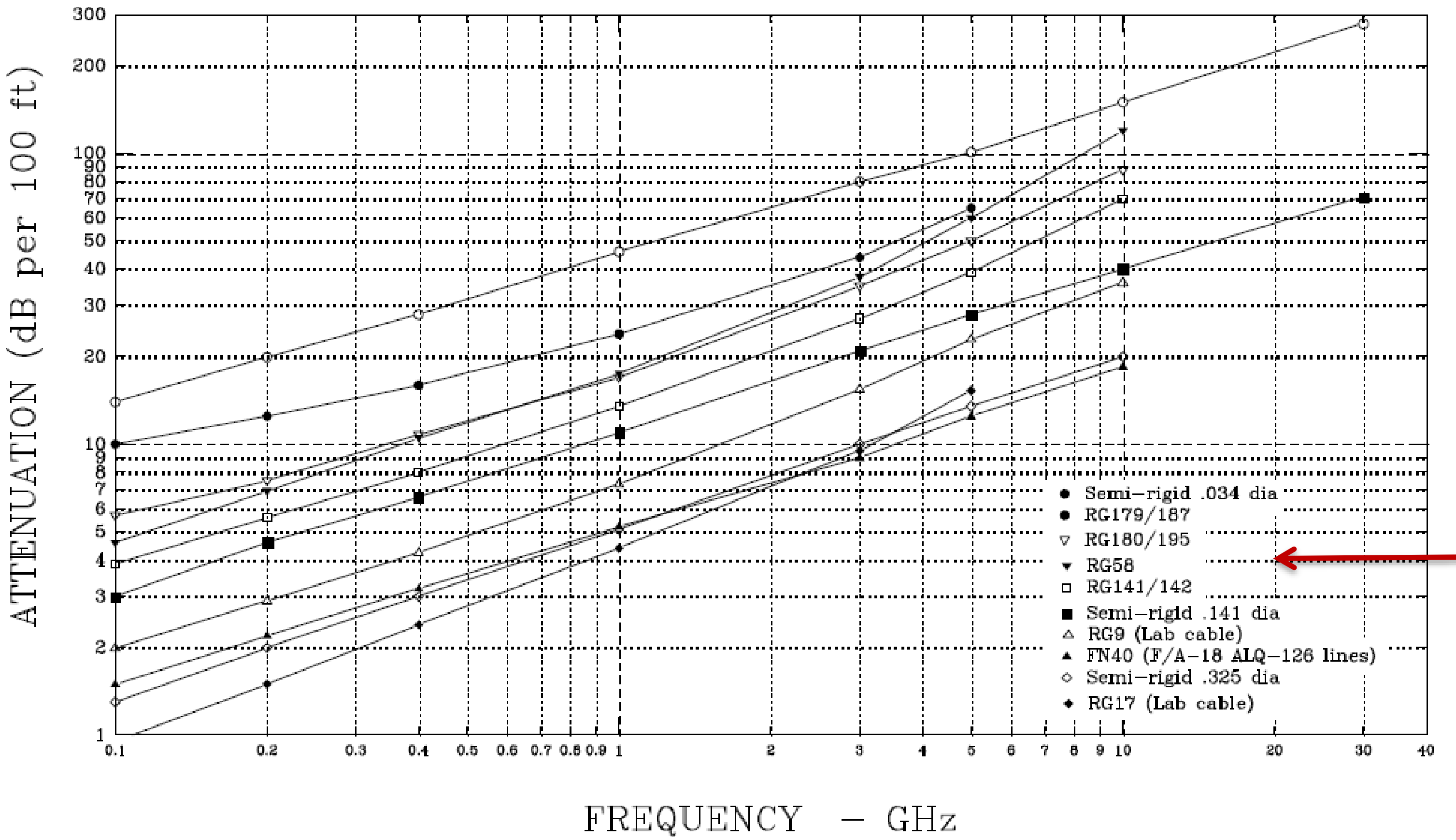
Hard line (Heliax)

- Commonly used rectangular waveguides have an aspect ratio b/a of ~ 0.5.

6.50''


Microstrip
WC is Circular Waveguide
WR is Rectangular Waveguide
WRD is Double Ridged Rectangular Waveguide
WRD-500 D36
WD-42
WRD-350 D36
WRD-750 D24 (aluminum)
WR-62
1/2 coax
WR-90
WRD-475 D24 (aluminum)
WR-137
TE10
TE01 Rectangular
7/8 coax
WR-187
Elliptical
RG379
1-5/8 coax
WR-187 C.P.
WR-284
TE°11
WC166
WR-430
TE°11
WC-281
WR-650
TE°01
WC-166
TE°01
WC281
Bell Labs
WT-4 system
2" TE01
Attenuation (dB per 100 feet (copper))
Frequency (GHz)
600
400
300
200
100
80
60
40
30
20
10
8
6
4
3
2
1
0.8
0.6
0.4
0.3
0.2
0.1
0.08
0.06
0.04
0.03
1
2
3
4
6
8
10
15
20
30
40
50
60
80
100

- Coaxial cable is used for frequencies up to about 400 MHz and down to DC and waveguide at higher frequencies, where the loss is less than coaxial cable.



Velocity of Propagation in a Coaxial Line

- Typically, a coaxial cable will have a dielectric with relative dielectric constant ϵ_r between the inner and outer conductor, where $\epsilon_r = 1$ for vacuum, and $\epsilon_r = 2.29$ for a typical polyethylene-insulated cable.

$$Z_0 = \frac{1}{\sqrt{\epsilon_r}} 60 \ln\left(\frac{b}{a}\right) \qquad v_{ph} = \frac{c}{\sqrt{\epsilon_r}}$$

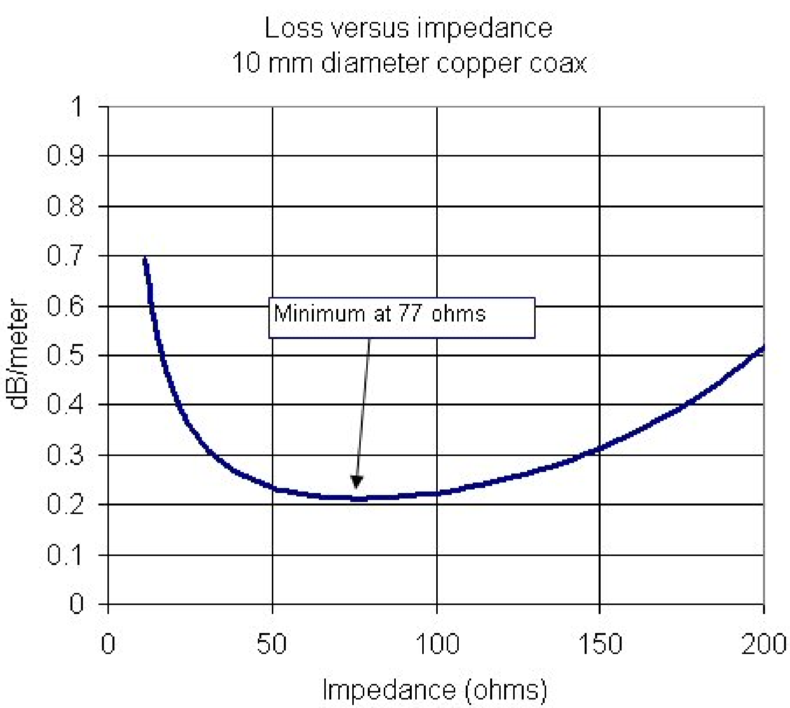
- For a polyethylene-insulated coaxial cable, the propagation velocity is roughly 2/3 the speed of light:

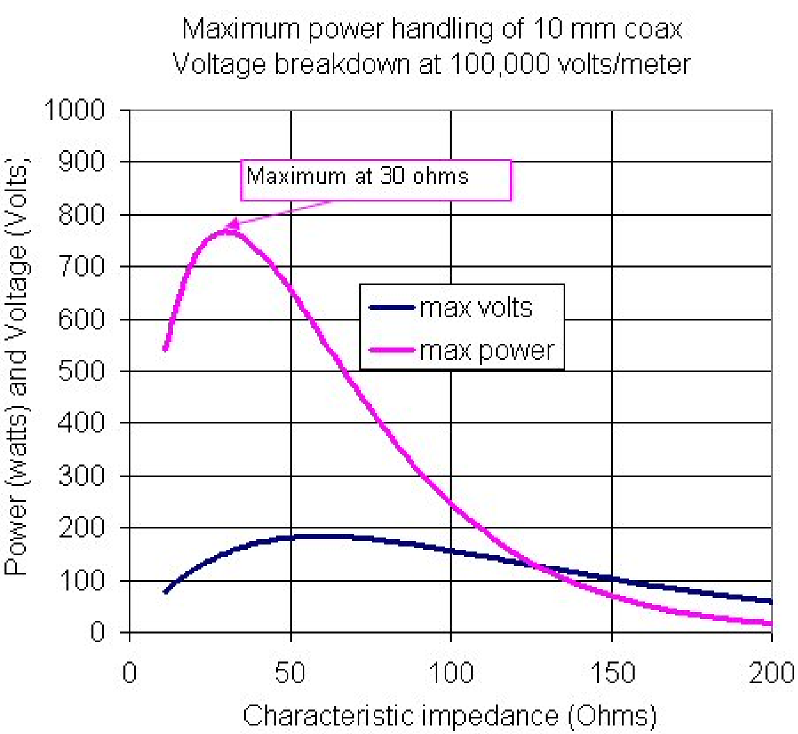
$$v_{ph} = 0.66c$$

Ex] 1 nsec time delay in RG58 cable: ~ 19.8 cm

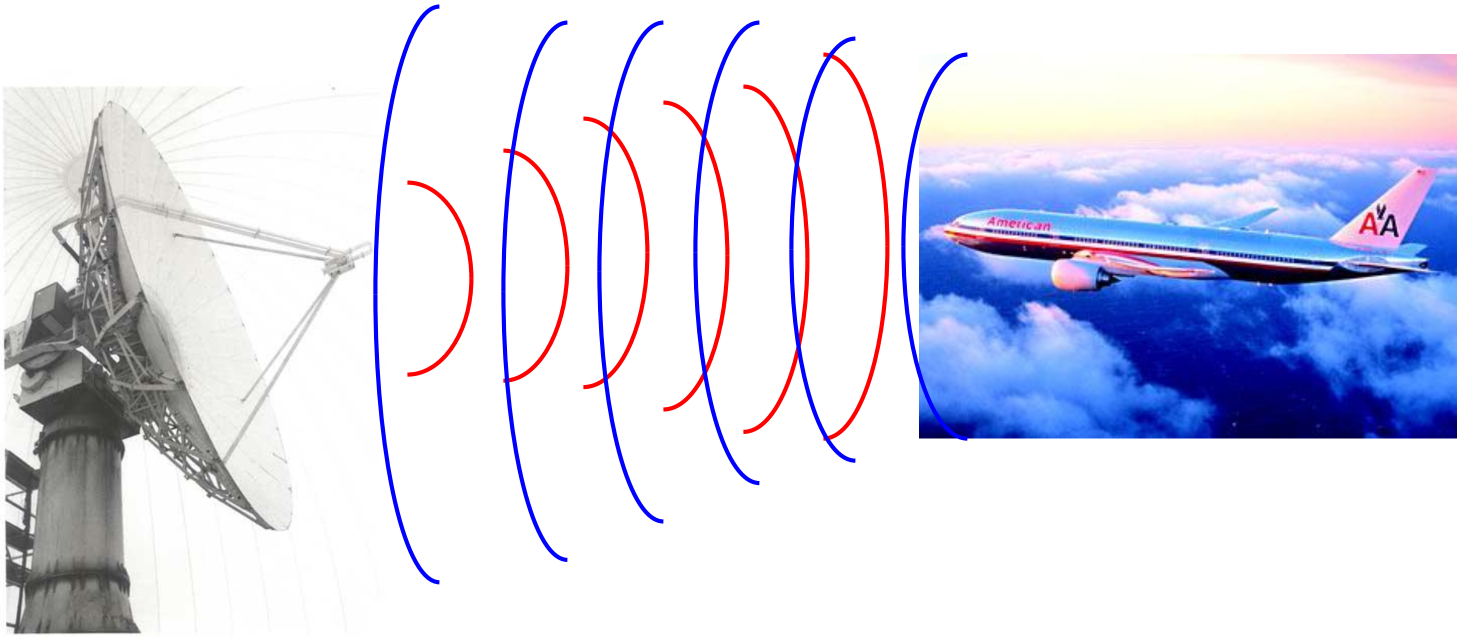
Why 50 Ohms ?

- The arithmetic mean between 30 ohms (best power handling) and 77 ohms (lowest loss) is 53.5, the geometric mean is 48 ohms. Thus the choice of 50 ohms is a compromise between power handling capability and signal loss per unit length, for air dielectric.

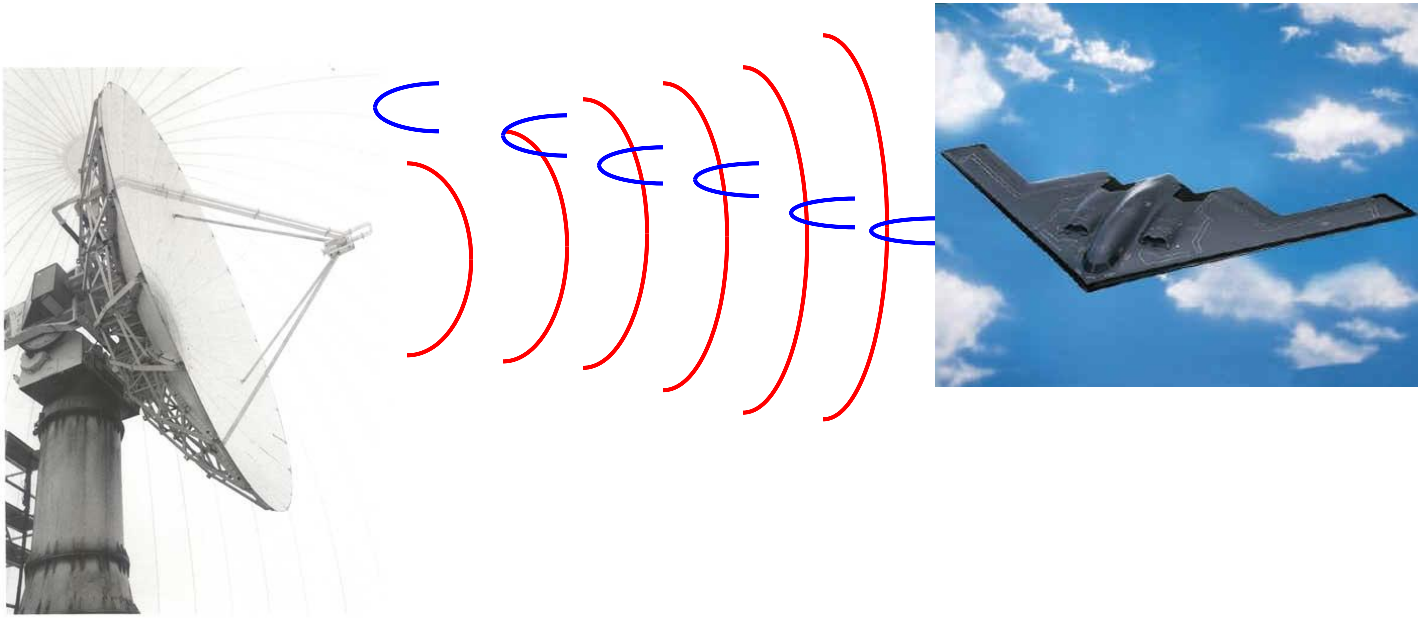




Impedance Matching



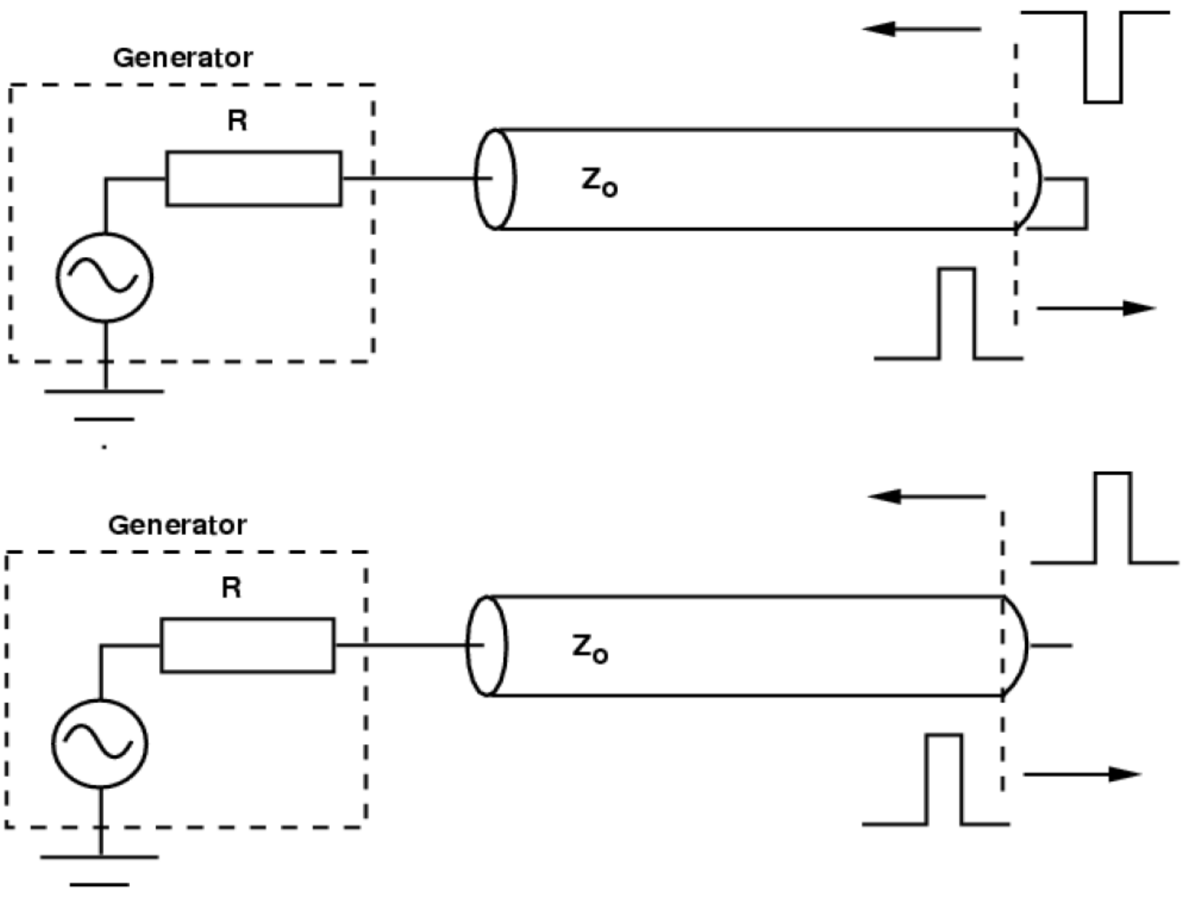
Radar works due to poor matching



Better matching (absorption) with the Stealth !

Reflection Coefficient

- Note that the generator has an internal impedance R. If $R = Z_0$, the returning pulse is completely absorbed in the generator (Matched generator).



Short ($Z_L = 0$)

$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0} = \frac{\beta_c - 1}{\beta_c + 1}$$

Open ($Z_L \to \infty$)

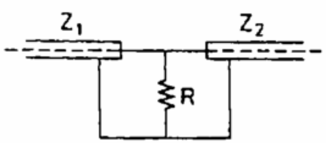
Simple Matching

Example 13.1 A signal is to be sent from a coaxial cable of impedance Z_1 into another coaxial cable of impedance Z_2. What termination scheme should be used in order to avoid reflections?

Two cases arise:

a) $Z_1 < Z_2$

Here the impedance which cable 1 sees must be reduced. This implies adding a resistance R in parallel to cable 2, i.e.,



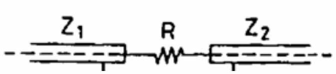
Since the combination must equal Z_1 we find

$$\frac{RZ_2}{R+Z_2} = Z_1$$

$$R = \frac{Z_1 Z_2}{Z_2 - Z_1}.$$

b) $Z_1 > Z_2$

Since the impedance seen by cable 1 must be increased, we add a resistance R in series.



Then,

$$Z_2 + R = Z_1 \Rightarrow R = Z_1 - Z_2.$$

Some other possible situations which often arise are summarized in Table 13.2 along with the termination scheme to be used.

Table 13.2. Cable termination schemes

Cable impedance = Z_c

Source		*Load*	*Termination scheme*
$Z_s = Z_c$	Z_c	$Z_L = Z_c$	No termination necessary
$Z_s = Z_c$	Z_c	$Z_L > Z_c$	Receiving end; parallel $R = Z_c/(1 - Z_c/Z_L)$
$Z_s = Z_c$	Z_c	$Z_L < Z_c$	Receiving end; series $R = Z_c - Z_L$
$Z_s < Z_c$	Z_c	$Z_L = Z_c$	Sending end; series $R = Z_c - Z_s$
$Z_s > Z_c$	Z_c	$Z_L = Z_c$	Sending end; parallel $R = Z_c/(1 - Z_c/Z_s)$

Combinations of the above situations may also arise in which case an appropriate combination of termination schemes may be used, e.g.,

$Z_s < Z_c$	Z_c	$Z_L > Z_c$	Receiving end; parallel $R = Z_c/(1 - Z_c/Z_L)$ with sending end; series $R = Z_c - Z_s$

RF Devices for Matching

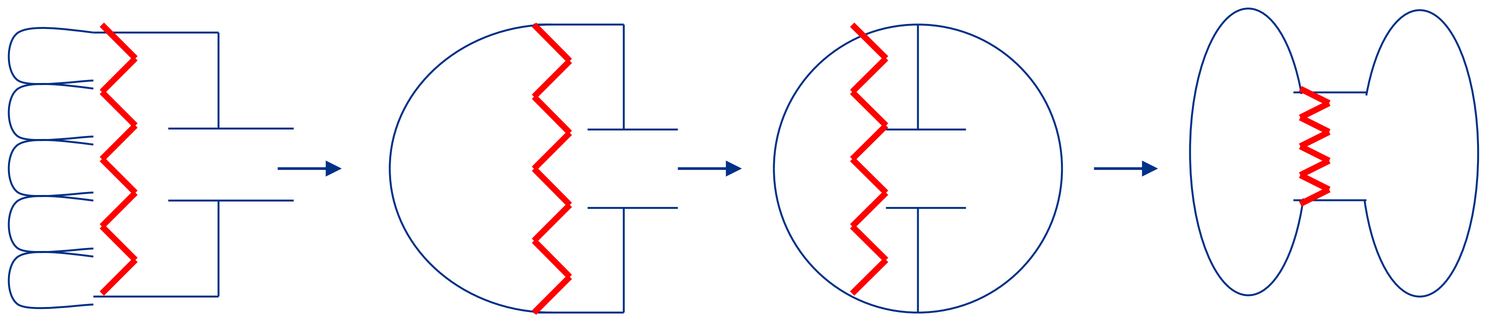
Directional Coupler

Three Stub Tuners

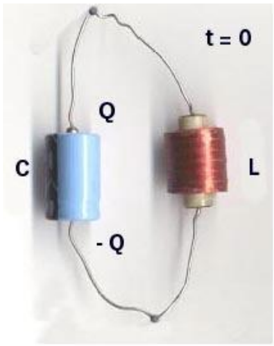
Circulator/Isolator

Waveguide Load

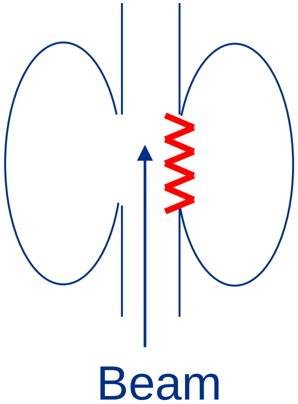
LC Circuit to RF Cavity



Shunt
Impedance



$$\omega = 2\pi f = \frac{1}{\sqrt{LC}}$$



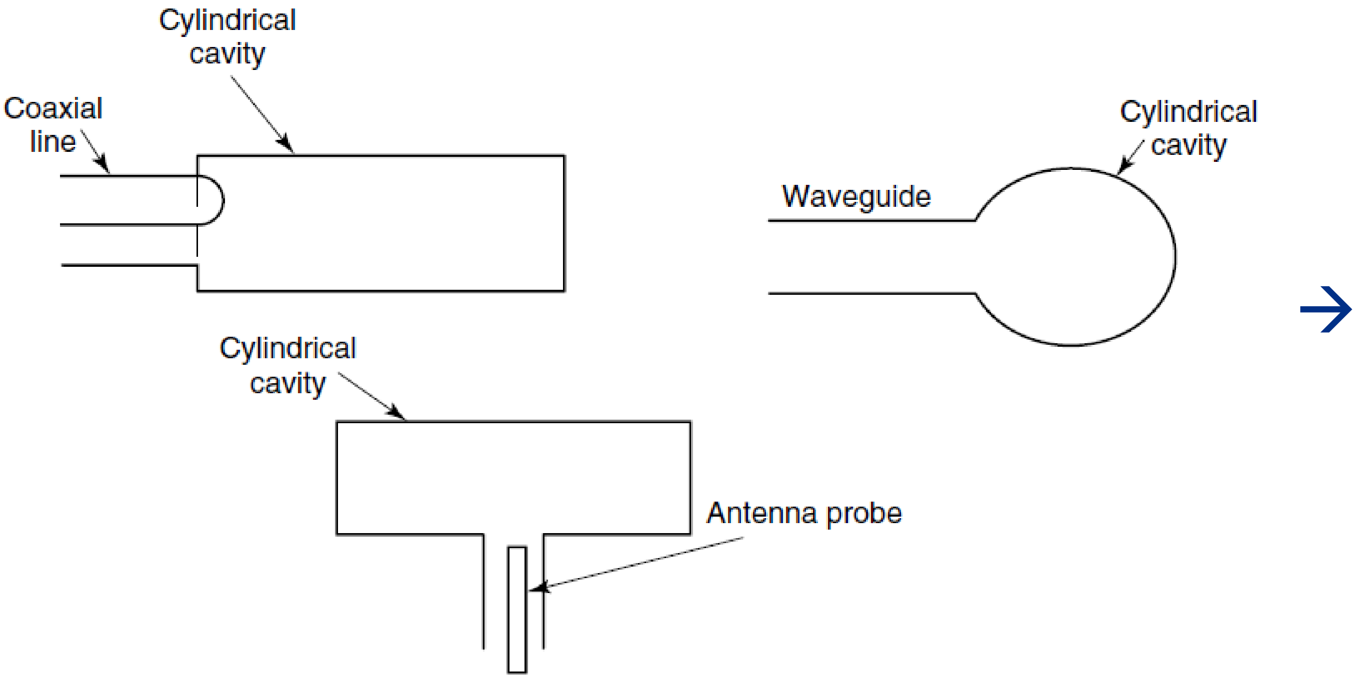
$$r_s = \frac{V_0^2}{P}$$

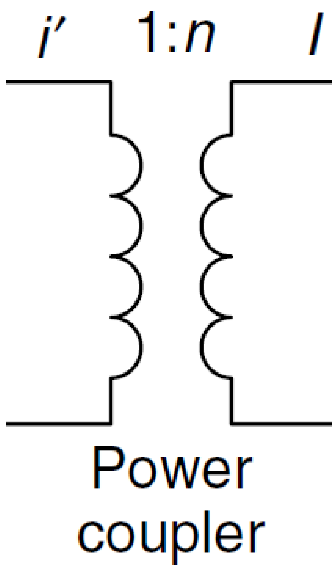
Effectiveness of producing an axial voltage for a given power dissipated

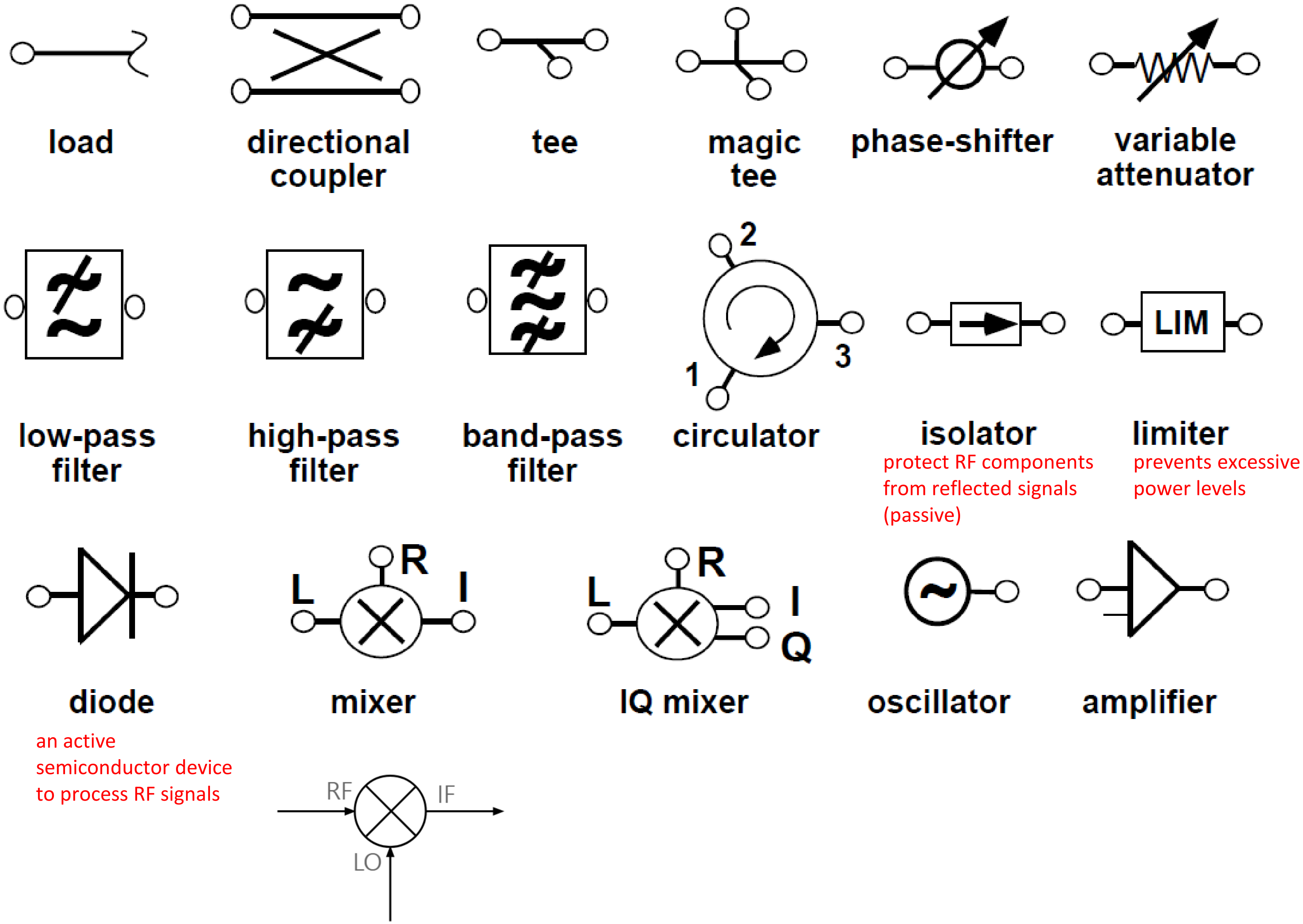
Methods of Coupling to Cavities

- The coupling mechanism and the waveguide are represented by a transformer with a turns ratio of 1:*n.*

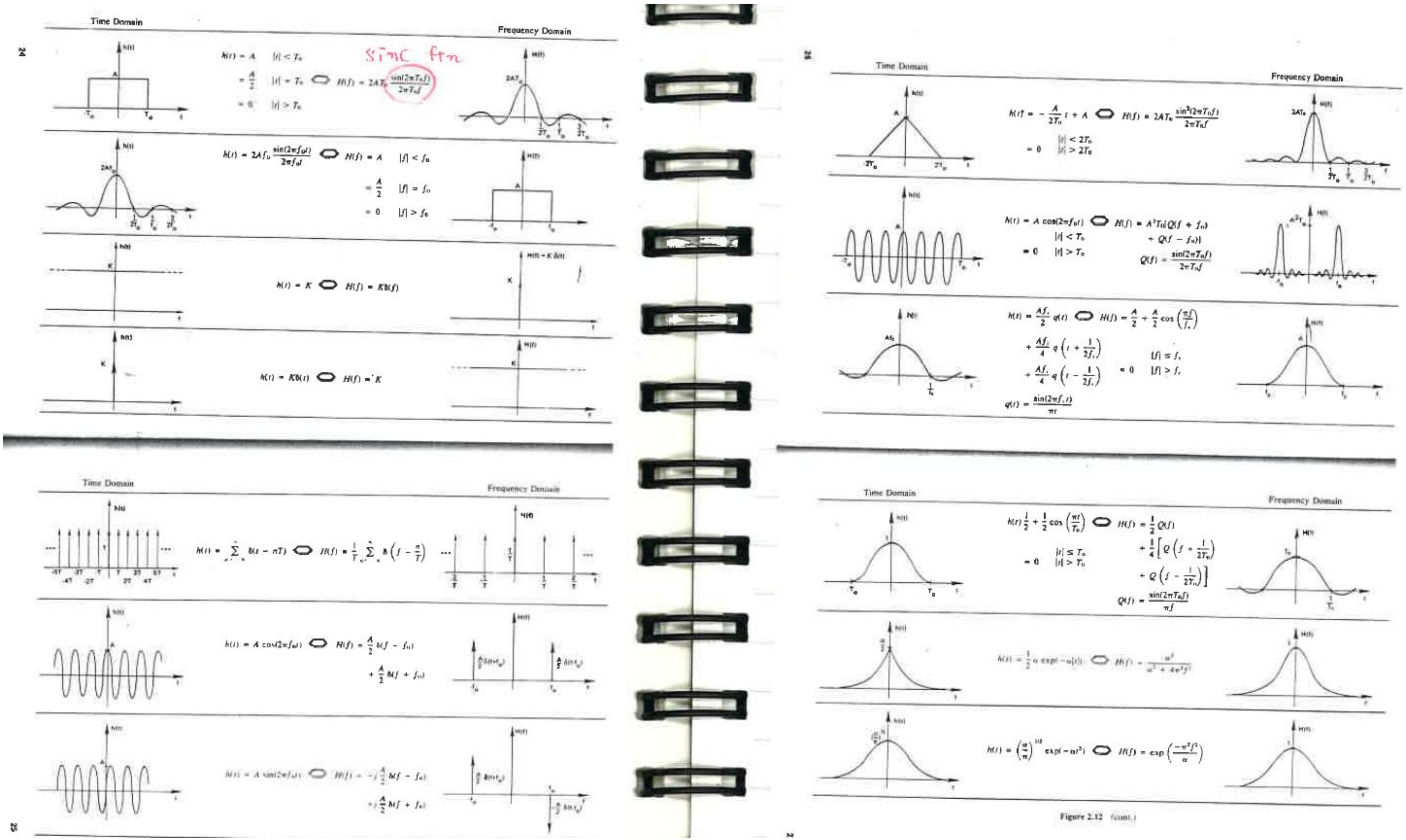
$$\frac{V'}{V} = \frac{i}{i'} = \frac{1}{n}$$



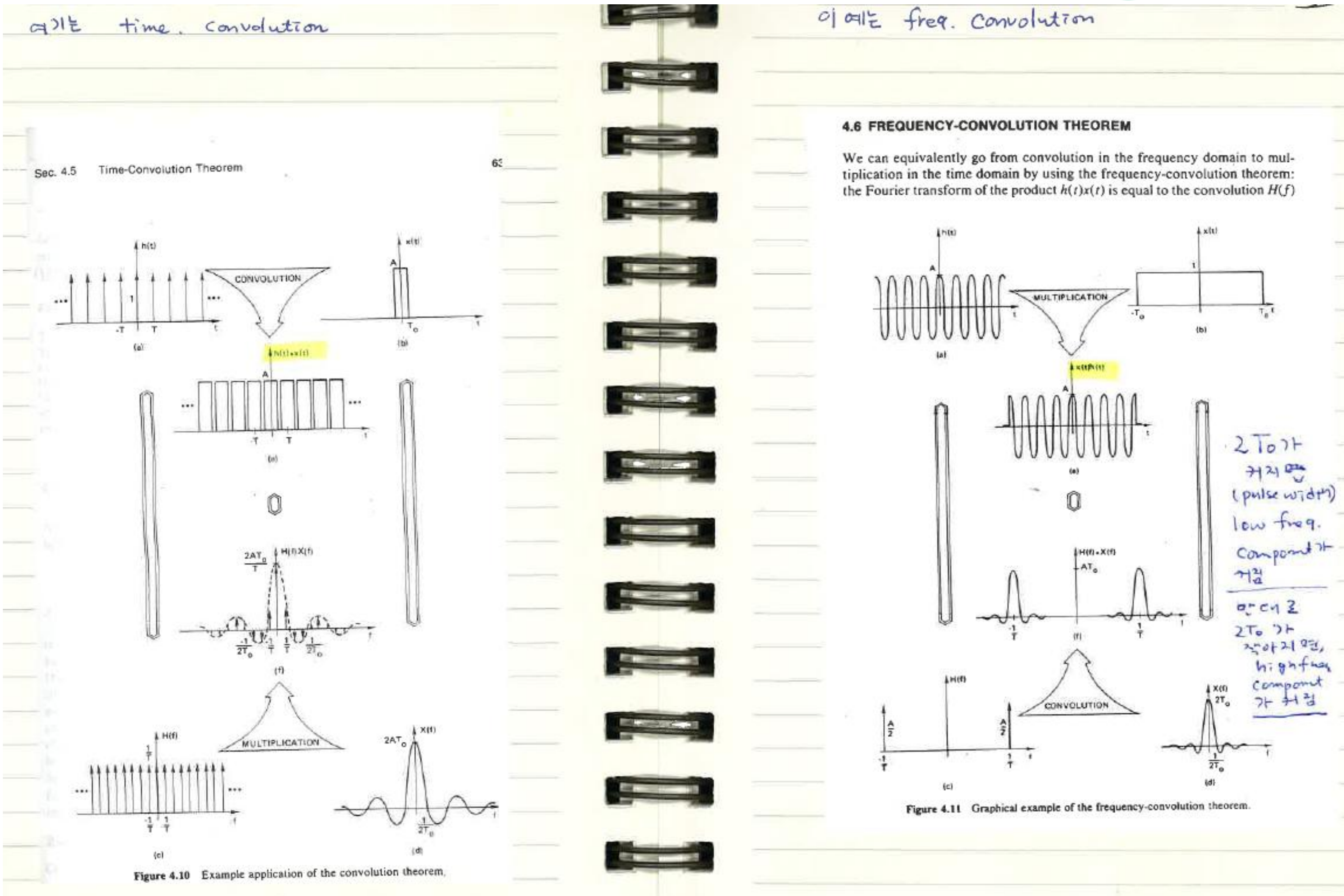



load
directional coupler
tee
magic tee
phase-shifter
variable attenuator
low-pass filter
high-pass filter
band-pass filter
2
3
1
circulator
LIM
isolator
protect RF components from reflected signals (passive)
limiter
prevents excessive power levels
R
L
I
R
L
I
Q
diode
an active semiconductor device to process RF signals
mixer
IQ mixer
oscillator
amplifier
RF
IF
LO

Time vs Frequency

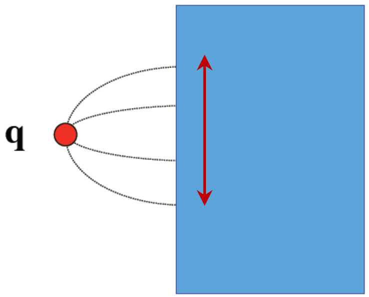


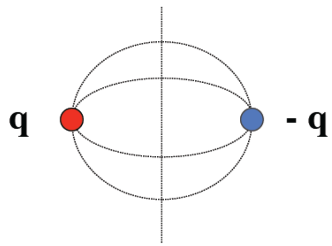
Time vs Frequency



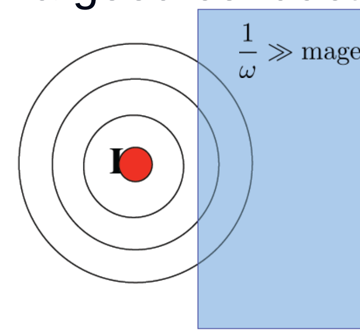
Boundary Conditions

- Electric field near a good conductor:



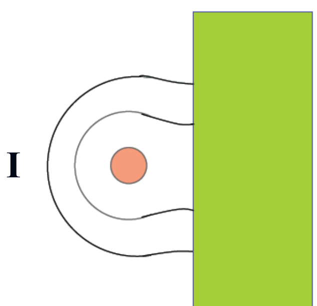


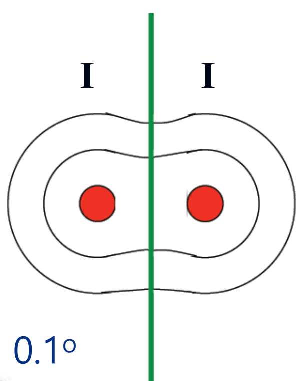
- Static magnetic field near $\mu_r \approx 1$(even in the case of a good conductor)

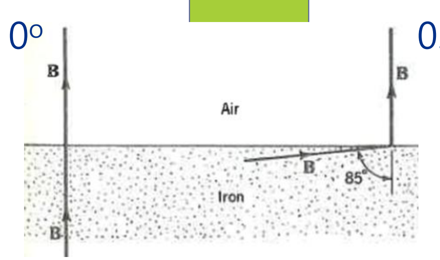


$$\frac{1}{\omega} \gg \text{magentic diffusion time} = \frac{4d^2\sigma\mu}{\pi^2}$$

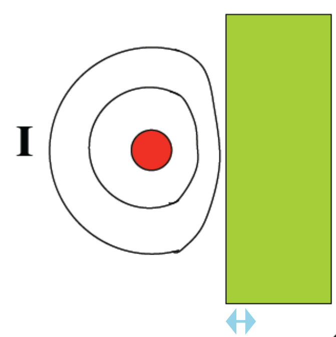
- Static magnetic field near $\mu_r \gg 1$(i.e., ferromagnetic material)

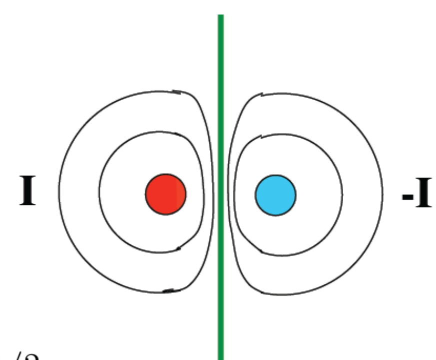






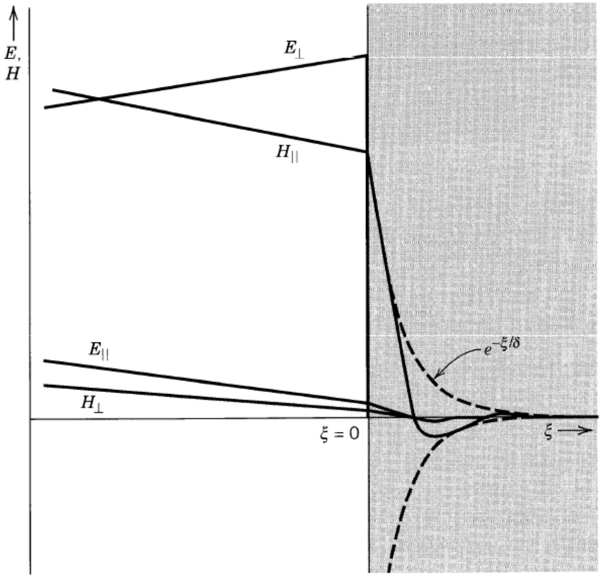
- Time-varying magnetic field near a good conductor (i.e., small skin depth):





$$\delta = \left(\frac{2}{\mu\omega\sigma}\right)^{1/2}$$

BCs determine Modes



We commonly classify the solutions to the wave equation in the following types:

1) TEM modes
Waves that contain neither electric nor magnetic field in the direction of propagation. The name transverse electromagnetic mode arises from the fact that all of the fields lie entirely in the transverse plane. They are the usual transmission line waves along a multiconductor guide.

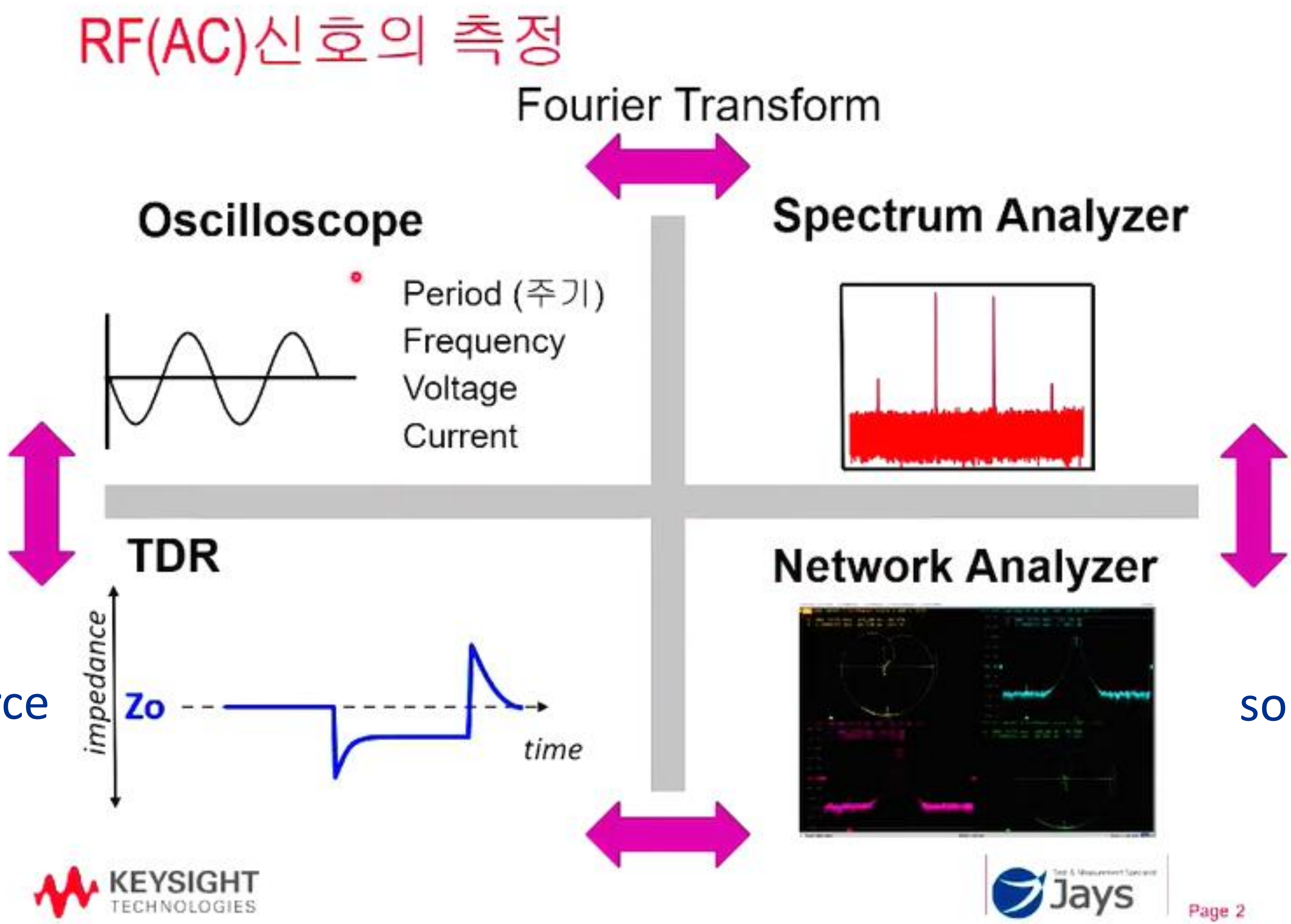
2) TM modes
Waves that contain electric field but no magnetic field in the direction of propagation. Also known as E, or electric, waves.

3) TE modes
Waves that contain magnetic field but no electric field in the direction of propagation. Also known as H, or magnetic, waves.

4) Hybrid modes
Boundary conditions require all field components, may often be considered a coupling of TE and TM modes by the boundary conditions. Common in structures with "complex" 3-dimensional geometry.

RF Measurements

source



source

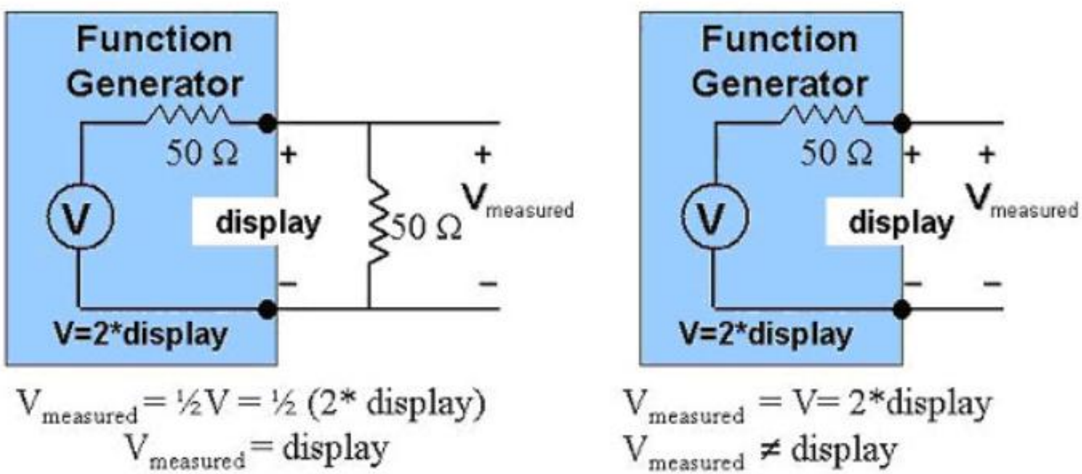
Function/Signal/Waveform/Pulse Generator

Why your function generator outputs twice the programmed voltage

PDF

The default setting for Keysight function generators is to display the desired voltage as though terminated into a 50 Ohm load. When a high impedance device, such as an oscilloscope is used to measure the output of the function generator, the waveform appears to be twice the voltage set on the display of the oscilloscope.

Some oscilloscopes can change their input impedance from standard high impedance to a 50 Ohm termination. Another solution is to add a 50 Ohm feed through (Keysight part number: 0960-0301) to the end of the BNC cable.



Function generators tend to be signal generators that focus on low frequency, but with very flexible waveforms.
Signal generator is a more generic term, but would frequently refer to RF or audio frequency sine wave generators that are designed to generate signals with very high spectral purity and stable frequency and amplitude.