Electrical Energy
Conversion and
Power Systems

Universidad
de Oviedo

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Introduction and General Concepts

Electromagnetic Interference

- **Electromagnetic compatibility** (EMC) is the branch of electrical sciences that studies the unintentional generation, propagation and reception of electromagnetic energy with reference to the unwanted effects (Electromagnetic interference or EMI) that such energy may induce.

- EMC aims to ensure that equipment items or systems will not interfere with or prevent each other's correct operation through spurious emission and absorption of EMI

- **EMS: Susceptibility (immunity) aspect**
- **EMI: Emission aspect**

Typical areas

Programmable electronic systems with digital buses

They generate interference and present susceptibility problems

Interference in radio reception.

Electromagnetic disturbances in the AC grid

Harmonics, overvoltage, voltage fluctuations.

Power electronic equipment. Power supplies.

Central locking. It can be activated with a cell phone.

Cash register. Carpet on the flooe may give rise to errors.

Medical electronic systems

Radar for missile detection in the HMS Sheffield

During the Falklands war the Sheffield was sunk by an EXOCET missile from Argentina air force because of the interference produced by the communication system in the radar.

Examples

Crash of a "TORNADO" fighter aircraft of the German Air Force at Rosenheim, caused by the fields emitted by "Radio Free Europe".

- Crashes of the "Blackhawk" helicopter of the USA Navy (>100 by rumour), caused by susceptibility of onboard electronics to electro magnetic fields.

A nuclear power plant goes on alert status when turbine control valves spontaneously close

Sheffield was sunk by an EXOCET missile from Argentina air force because of the interferences produced by the communication system in the radar

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Examples

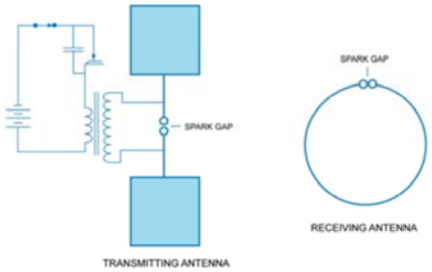
In 1996, TWA Flight 800 bound from New York to Paris exploded over the ocean shortly after take-off. After a lengthy investigation that involved salvaging and reconstructing major portions of the aircraft, it was concluded that the most probable cause of the explosion was a spark in the center wing fuel tank that ignited the air/fuel mixture. This spark was likely the direct result of a large voltage transient, possibly a power line transient or electrostatic discharge.

A study, published in 2008 by researchers from Amsterdam, showed that electromagnetic interference from RFID devices also had the potential to cause critical care medical equipment to malfunction.

A Brief History of EMC

In the late 1880's, the German physicist Heinrich Hertz performed experiments that demonstrated the phenomenon of radio wave propagation, thus confirming the theory published by James Clerk Maxwell two decades earlier.

The spark excitation created an oscillating current on the rods resulting in electromagnetic radiation near the resonant frequency of the antenna



A Brief History of EMC

In **1895**, Guglielmo Marconi developed the wireless telegraph, the first communications device to convey information using radio waves.

In **1899**, the Navy initiated the first shipboard tests of the wireless telegraph. While the tests were successful in many ways, the Navy was unable to operate two transmitters simultaneously.

This early electromagnetic compatibility problem came to be referred to as Radio Frequency Interference (RFI).

In **1904**, Theodore Roosevelt signed an executive order empowering the Department of Commerce to regulate all private radio stations and the Navy to regulate all government stations

1912 invention of the vacuum tube oscillator in and the super heterodyne receiver in 1918

The period from about **1925 to 1950** is known as the golden age of broadcasting. The number of radios proliferated, so did the electromagnetic compatibility problems

A Brief History of EMC

In the **1940's** many new types of radio transmitters and receivers were developed for use during World War II. Radio signals were not only used for communication, but also to locate ships and planes (RADAR) and to jam enemy radio communications. Because of the immediate need, this equipment was hurriedly installed on ships and planes, resulting in severe EMC problems.

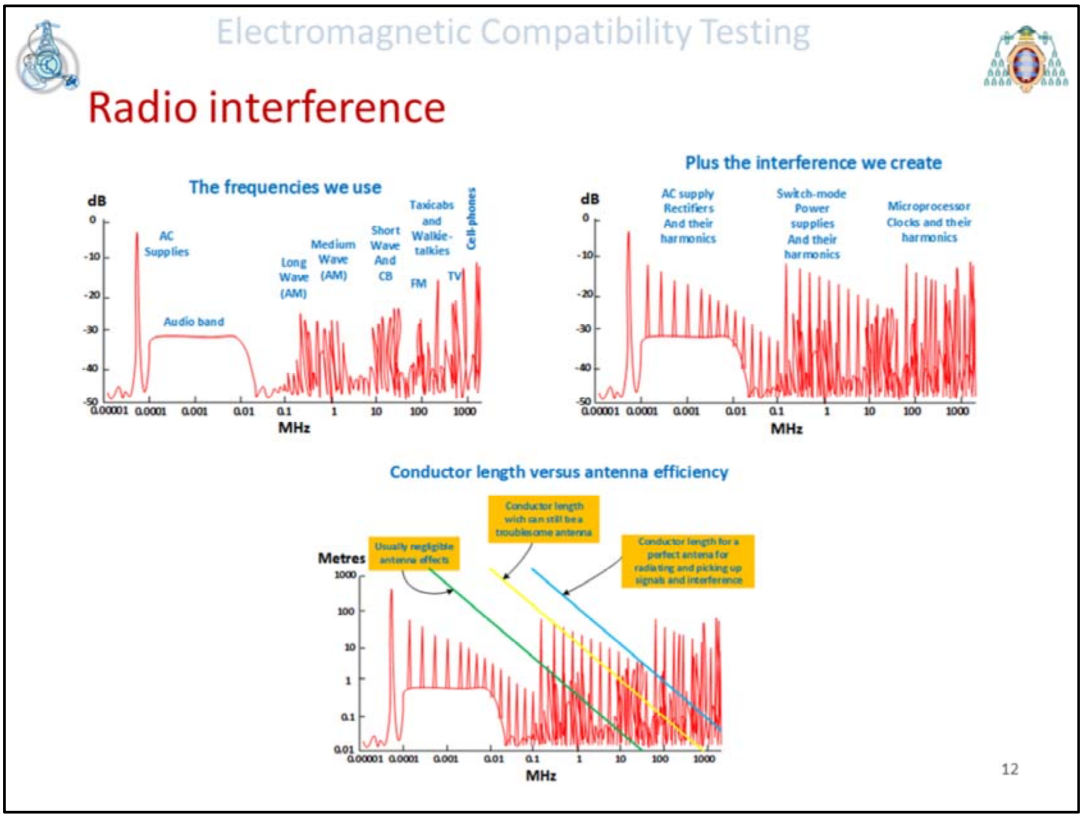
Experiences with electromagnetic compatibility problems during the war prompted the development of the first joint Army-Navy RFI standard, JAN-I-225, "Radio Interference Measurement," published in 1945

In **1954**, the first Armour Research Foundation Conference on Radio Frequency Interference was held.

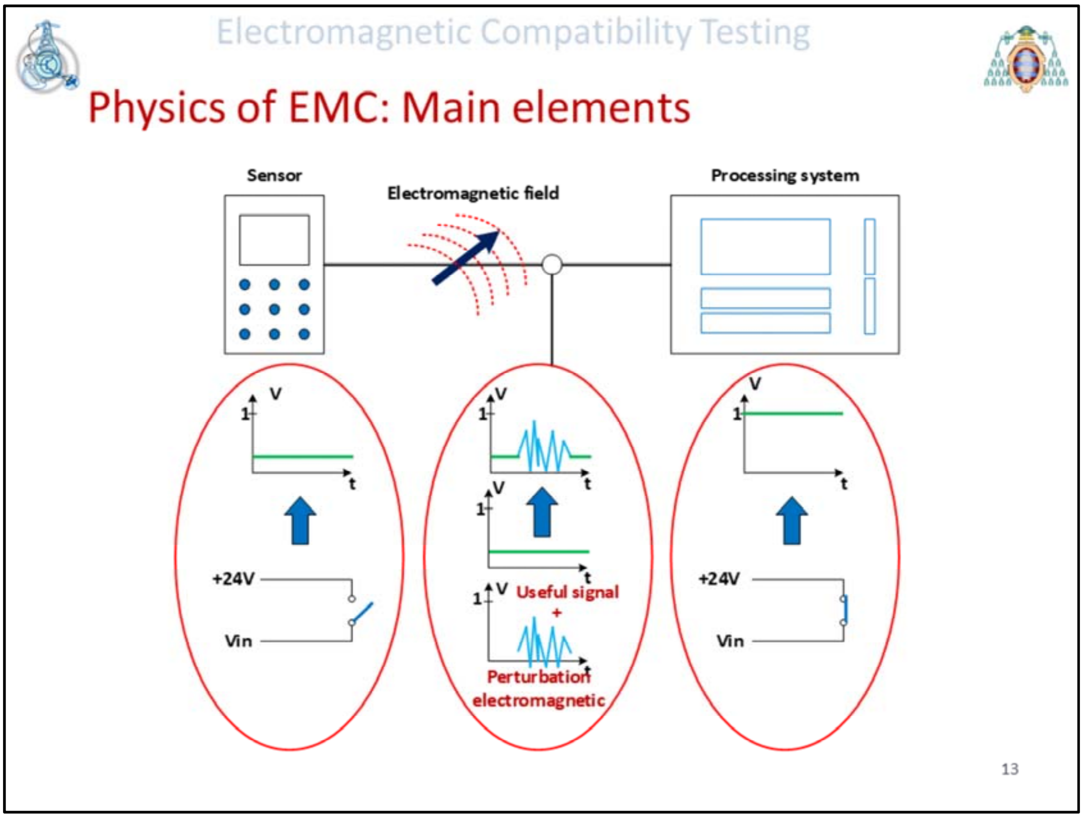
During the **60's and 70's**, the term RFI was gradually substituted by the more general term EMI or Electromagnetic Interference, since not all interference problems occurred at radio frequencies

1980's regulations placed limits on the electromagnetic emissions from *computing devices*.

In the **1990's**, the European Union adopted EMC regulations

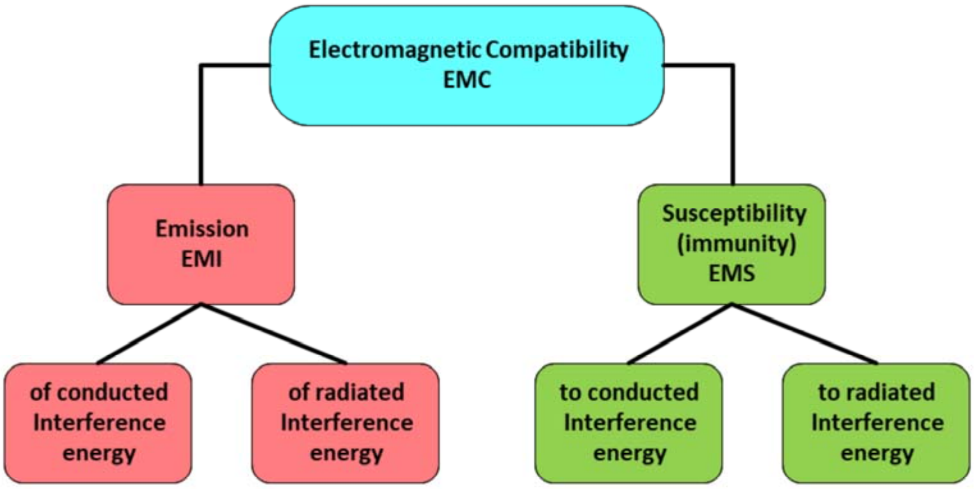


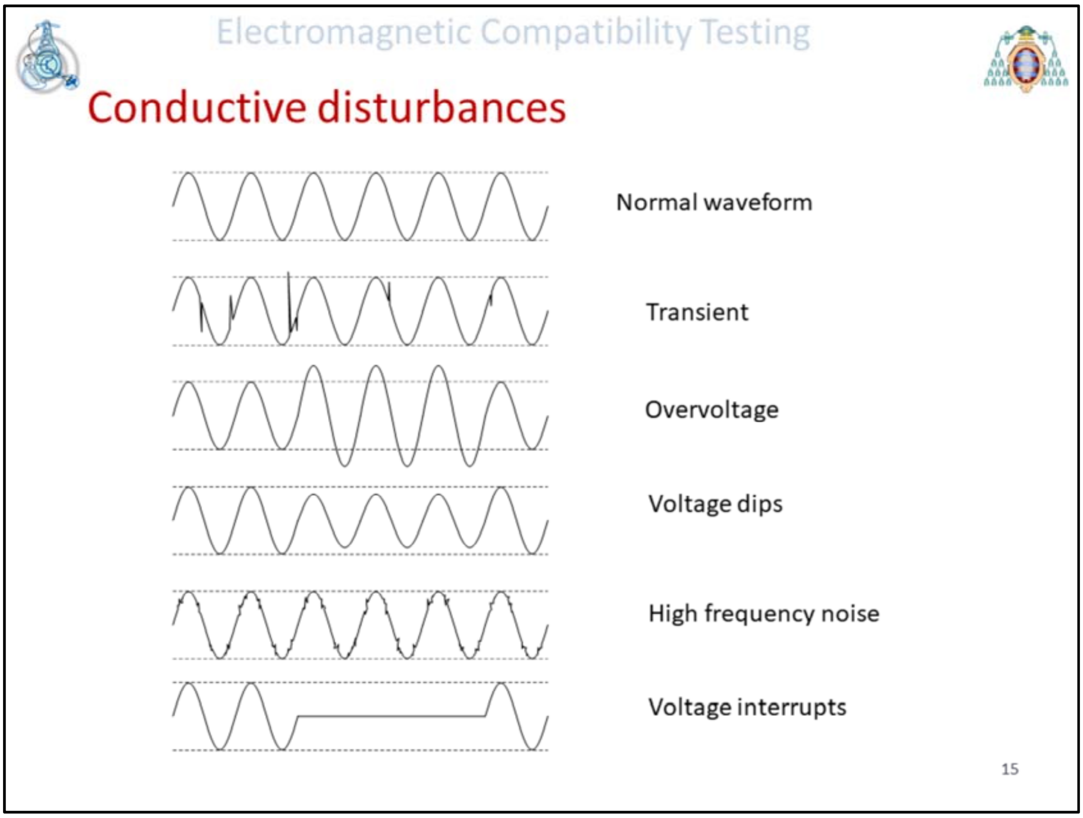
Some of the sources of interference come from communication emissions. A conductor can act as an antenna, for this the length of said conductor has to be an integral multiple of the half-wavelength



Electromagnetic fields can introduce noisy signals in conductors and cause malfunction of other electronic systems

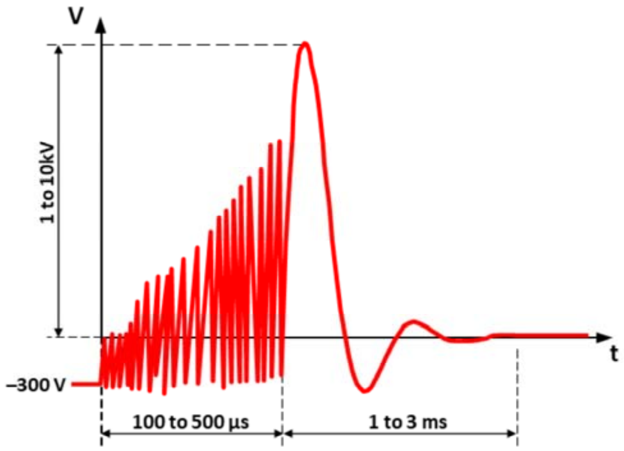
Categories of EMC





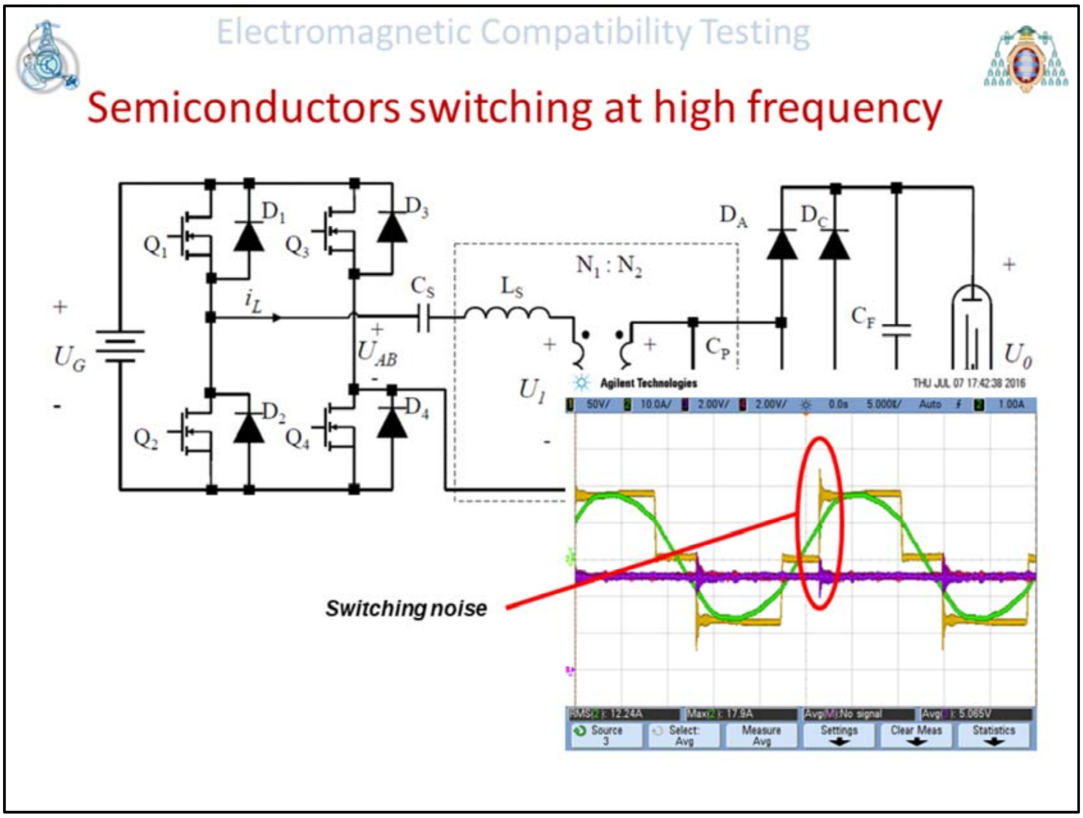
Some of the types of disturbances that we can find in the AC grid

Typical interference

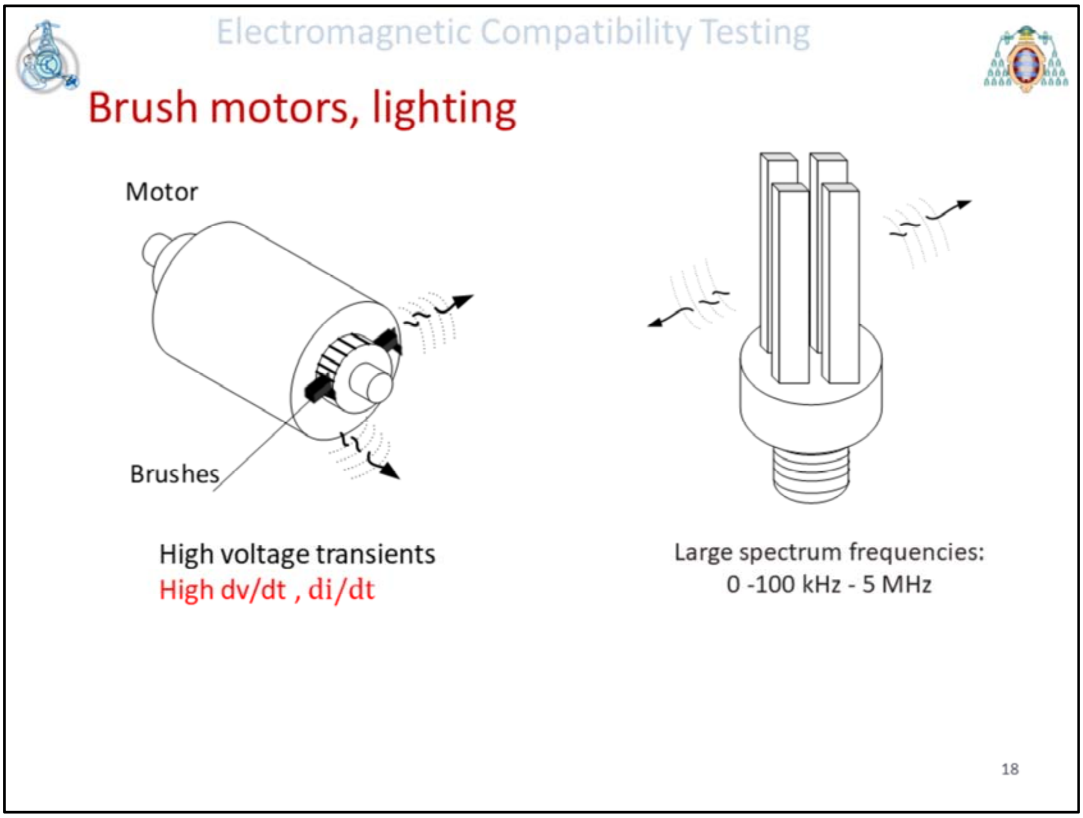


Voltage across the contacts of a mechanical switch
During the turn-on process (9 A)

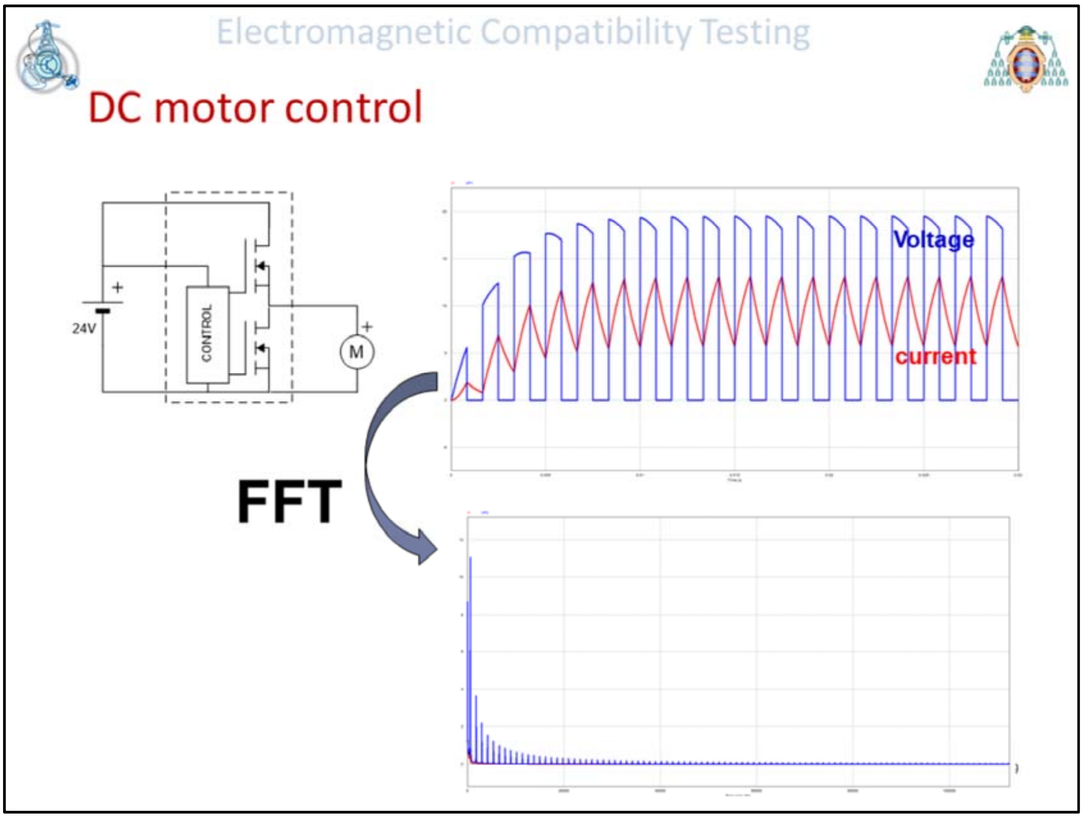
Radiated and conducted emissions in the band kHz-Mhz



Semiconductor commutations also generate high-frequency oscillations that are conducted and radiated by cables

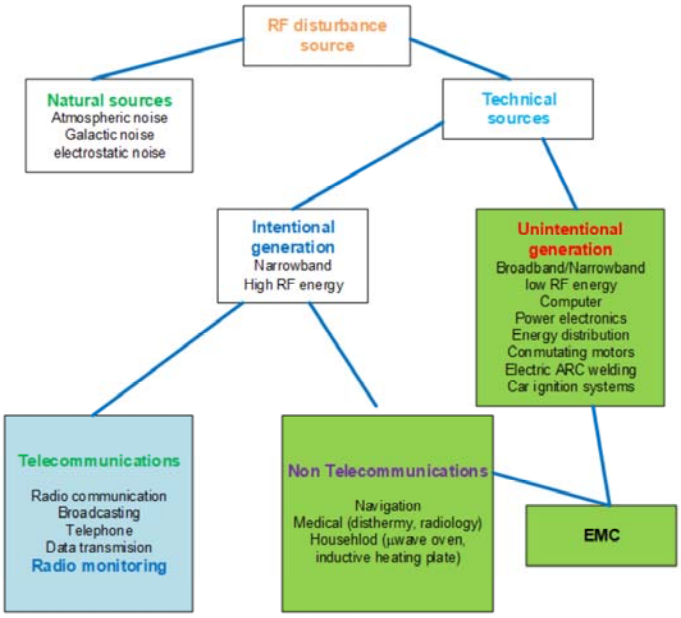


Voltage or current variations are the two key aspects in the generation of electromagnetic noise.



In this example, a PWM control of the speed of a DC motor is observed. The generated harmonic content reaches very high frequency values

RF disturbance source



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Electromagnetic Compatibility Testing

Solar Interference

- **2012 Solar Maximum**
  - 11-year solar cycles
  - Flight routes over north pole changed
- **Solar Storm of 1859**
- **March 1989 Solar Storm**
  - X-class solar flare
  - Power outage in Quebec
  - Communications with some satellites disrupted for hours
- **Other potential issues**
  - Spacecraft communication
  - Induced currents on underground piping
  - HF radio interference

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We can also find sources of electromagnetic noise of natural origin

Interference at 2.4 GHz

- Why use 2.4GHz?
  - Part of the ISM (Industrial, Scientific and Medical) Band
  - No license needed to design devices in this range
  - FCC (Federal Communications Commission-USA) originally designated 2.4-2.483 GHz band for microwave ovens

- Devices and protocols that operate in this band
  - Cordless telephones
  - Baby monitors
  - Bluetooth
  - Wi-Fi 802.11b and 802.11g wireless devices (most routers)
  - Wireless cameras and controllers

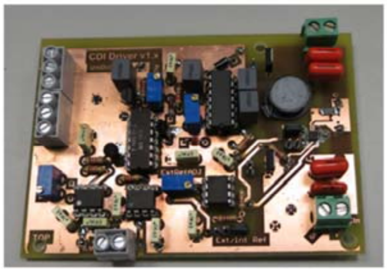
Cellular Device Interference

- Airplanes
  - No proven scientific basis for banning cell phone use on airplanes
  - FAA, FCC, and aircraft OEMs are unwilling to spend money to do testing
  - Ban on cell phone use errs on the side of caution
- Medical Equipment
  - 2007 Mayo Clinic study showed that phones have no negative effect on medical equipment
  - FDA has developed standards for pacemaker OEMs to ensure safety

OEMs: Original Equipment Manufacturer
FDA: food and Drugs administration

Power Converters

- Capacitive, Inductive, and Resistive loads
- Caused by sudden load changes
- Found in many household items
  - Computers, phone chargers, TVs, etc.



Power converters are very widespread elements that incorporate components capable of generating electric and magnetic fields varying at high frequency and can thereforebecome a source of electromagnetic noise

EMC 89/336/CEE Directive (25-5-1989)

The EMC Directive (89/336/EEC) is primarily concerned with removing trade barriers in the area of electromagnetic compatibility and, being a total harmonization directive, it replaces national provisions where they previously existed.

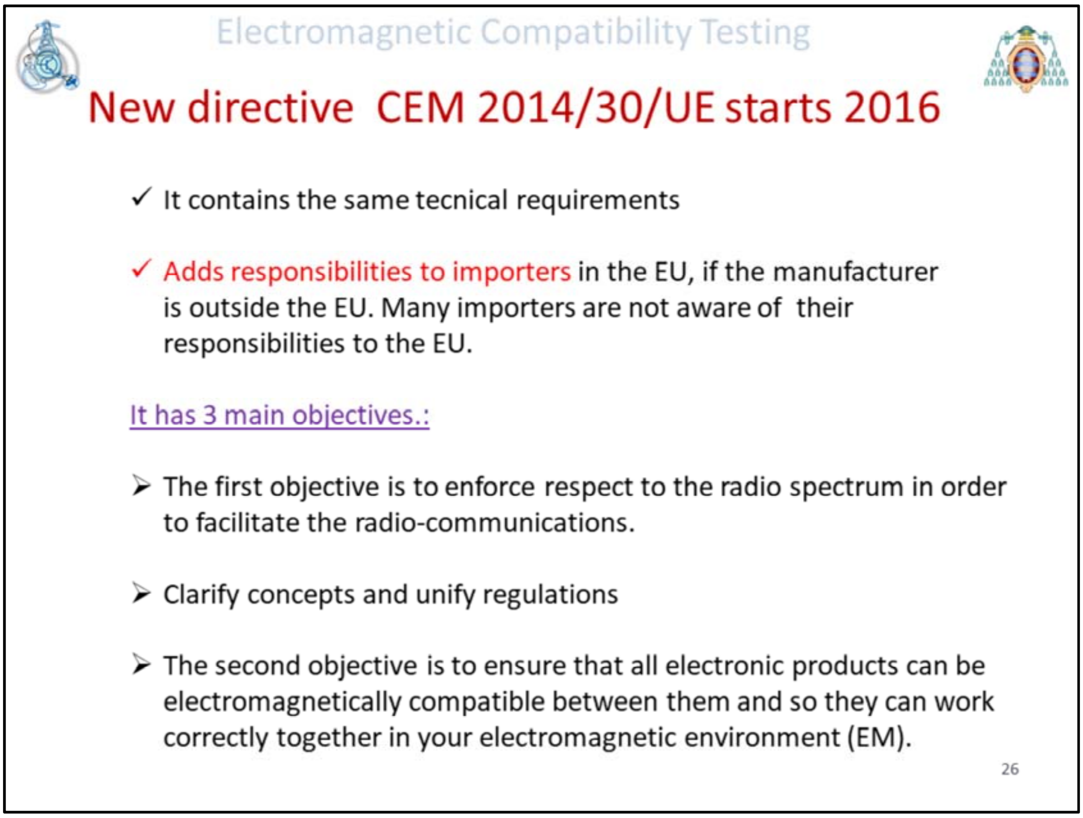
Mandatory essential requirements :

Provide test, methods and limits:

Limits for the interferences are defined
The apparatus have to show a required immunity level
(components are outside of the regulation)
(PC targets have to fulfil it)

Responsibility

The manufacturer is fully responsible of guaranteeing a correct operation.


Electromagnetic Compatibility Testing
New directive CEM 2014/30/UE starts 2016
✓ It contains the same tecnical requirements
✓ Adds responsibilities to importers in the EU, if the manufacturer is outside the EU. Many importers are not aware of their responsibilities to the EU.
It has 3 main objectives.:
➢ The first objective is to enforce respect to the radio spectrum in order to facilitate the radio-communications.
➢ Clarify concepts and unify regulations
➢ The second objective is to ensure that all electronic products can be electromagnetically compatible between them and so they can work correctly together in your electromagnetic environment (EM).
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Six different families

Product families:

- Residential, commercial
- Industrial
- Transport
- Electrical Grid
- Special
- Equipment for telecommunications

Product standards have priority over general ones.

Classes of Regulations

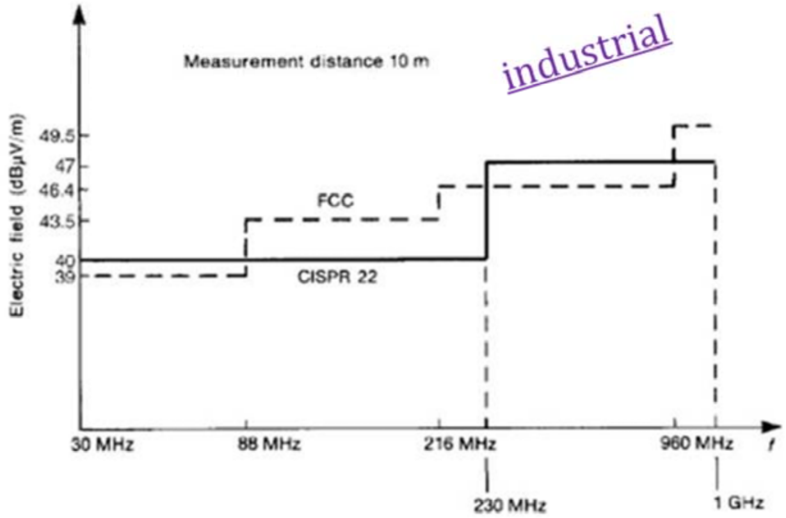
- Class A

"A computing device that is marketed for use in a commercial, industrial, or business environment."

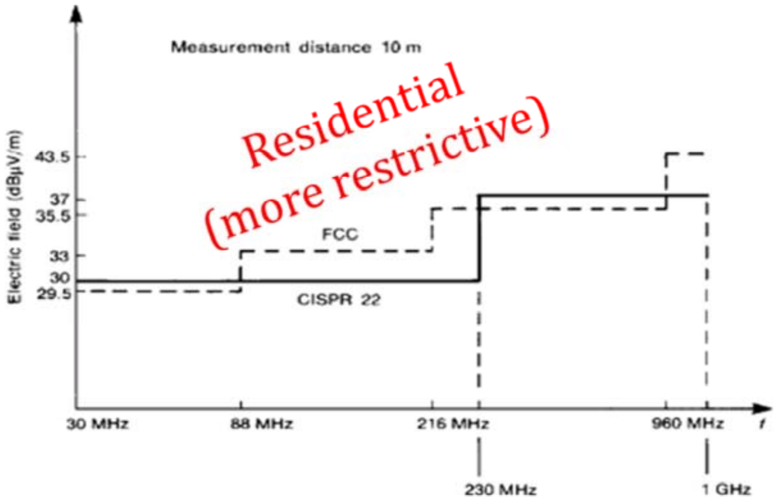
- Class B

"A computing device that is marketed for use in a residential environment, notwithstanding use in a commercial business

FCC and CISPR Class A



FCC and CISPR Class B (residential)



What the standards said?

- The country where they should be observed
- The type of device
- The procedure and equipment for the tests
- Maximum interference limits

Self-certification!!!!

CE marking, and standards

International

IEC- (International Electrotechnical Commision) www.iec.ch

Main committees:
TC77→ IEC 1000
CISPR→CISPR XX

EU

CENELEC- (European Committee for Electrotechnical Standardization)

Main committees :
TC110→ EN50 XXX
EN55 XXX
EN60 XXX

CE - Conformité Européenne
European Conformity

EN 6XXXX = IEC XXXX

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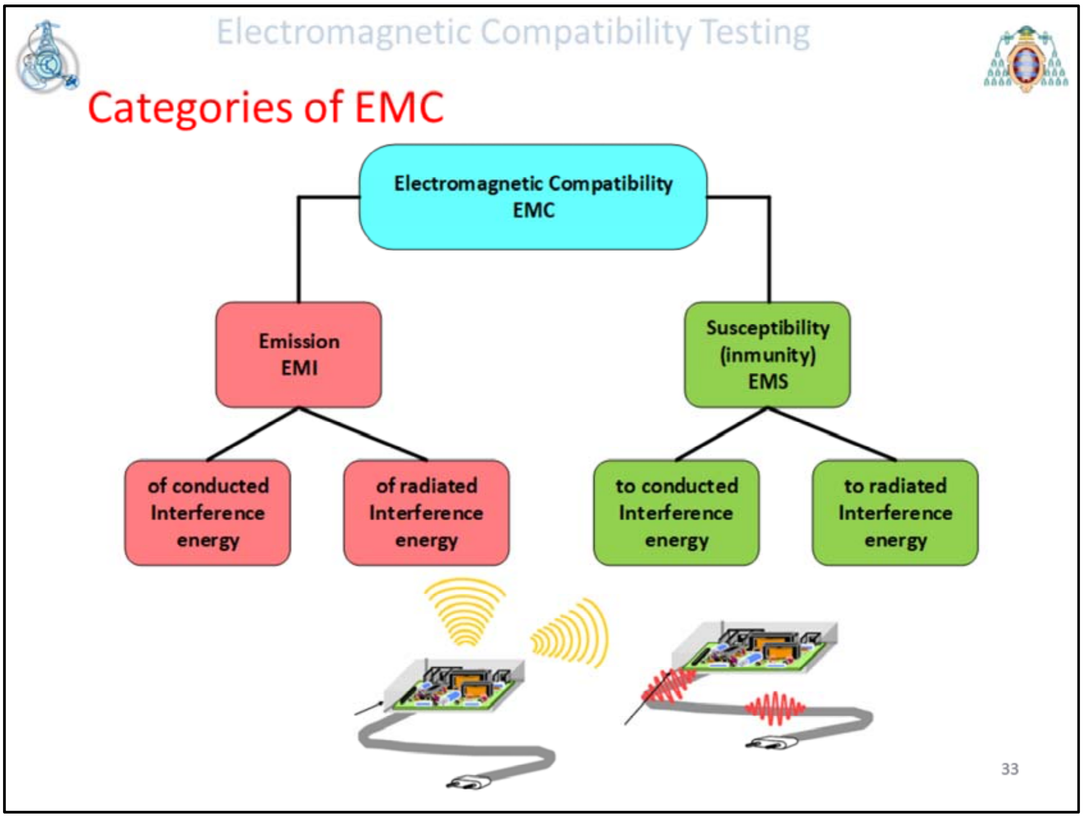
Electromagnetic Compatibility Testing
Categories of EMC
Electromagnetic Compatibility
EMC
Emission
EMI
Susceptibility
(inmunity)
EMS
of conducted
Interference
energy
of radiated
Interference
energy
to conducted
Interference
energy
to radiated
Interference
energy
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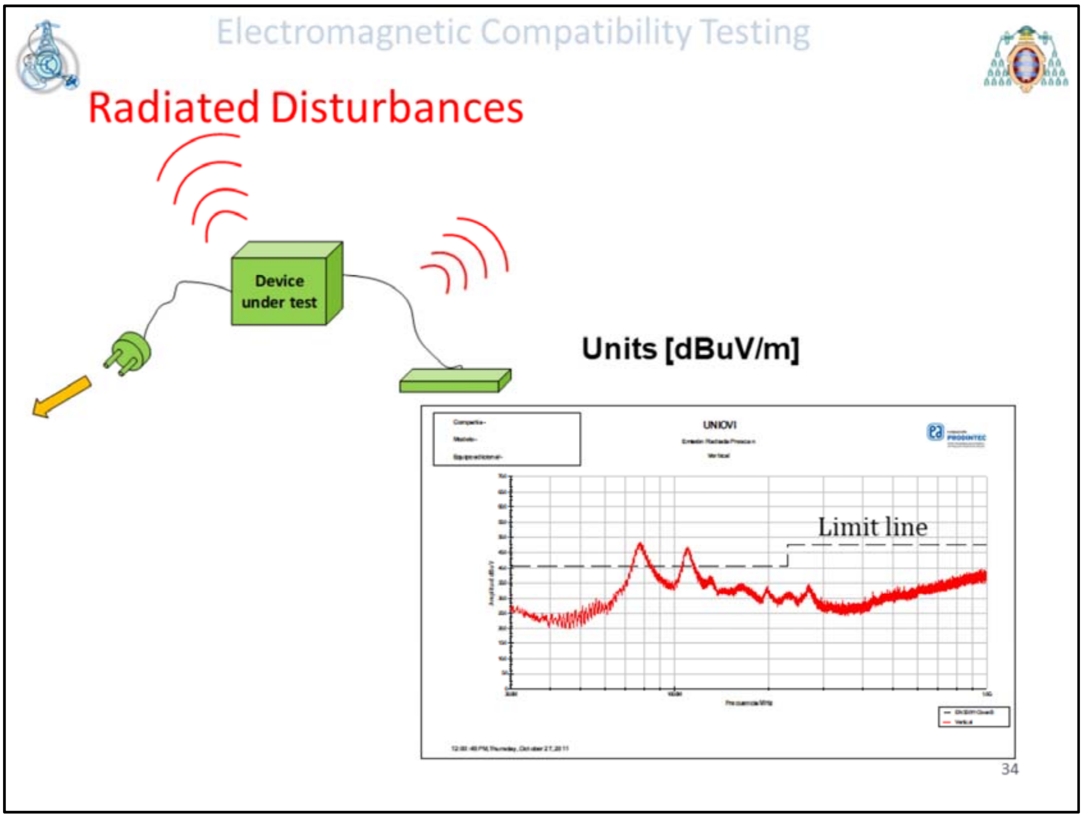
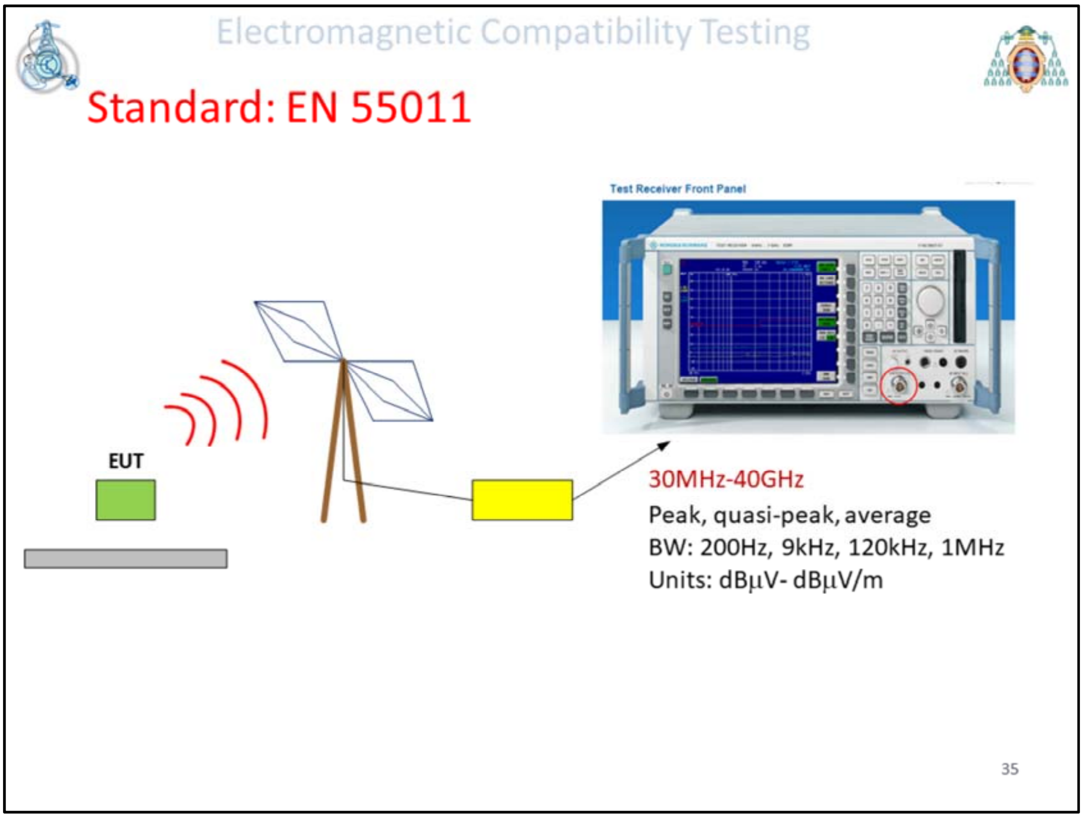
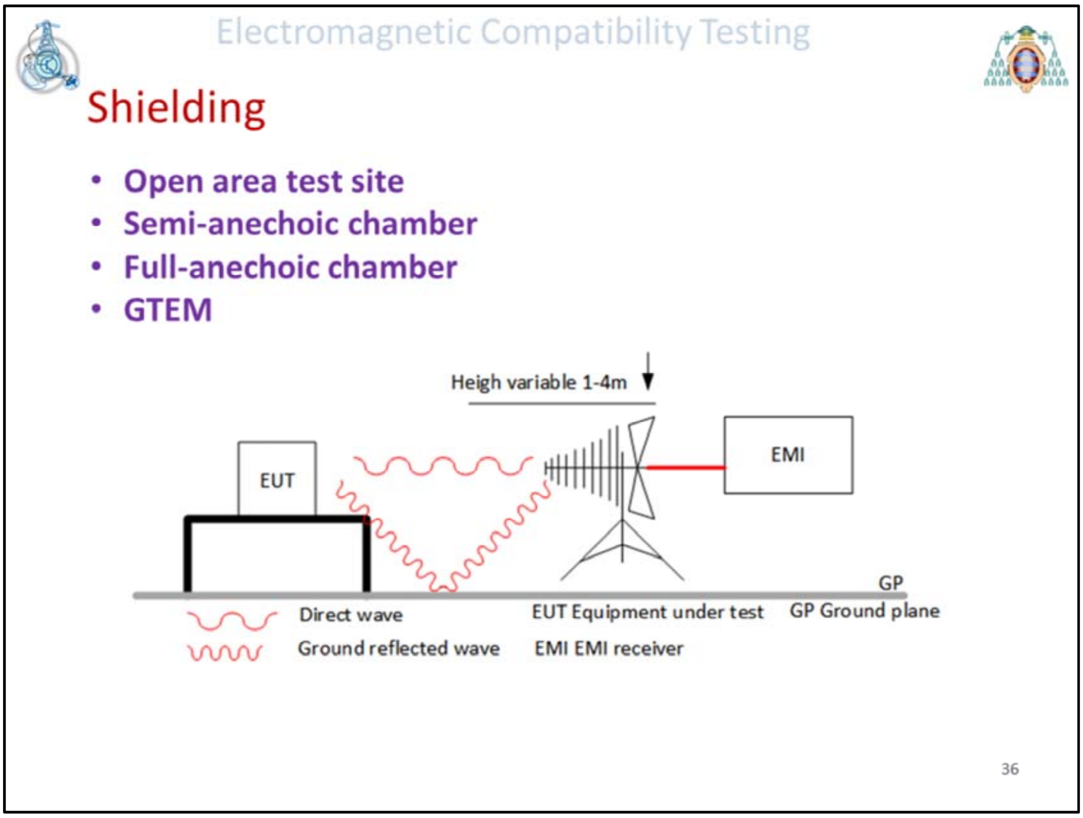


The emission test shows the electromagnetic field that the equipment under test (EUT) generates. This emission cannot exceed the limit line imposed by the regulation



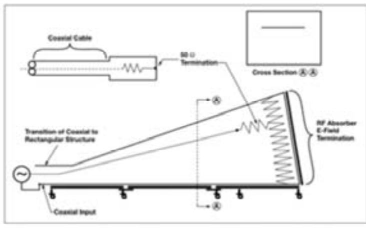
The equipment necessary to carry out the emission test are: the receiver, the antenna and a place free of environmental noise so as not to contaminate the measurement

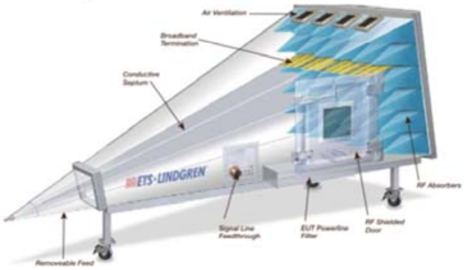


This type of tests are carried out in shielded chambers

GTEM

Electrically, the GTEM is an extension of a 50-ohm transmission line





The TEM waves have a field impedance of 377 ohms, the same as free space.
The intensity of the field is directly proportional to the power input and the distance of the septum to the outer conductor (floor)

Images obtained from catalog

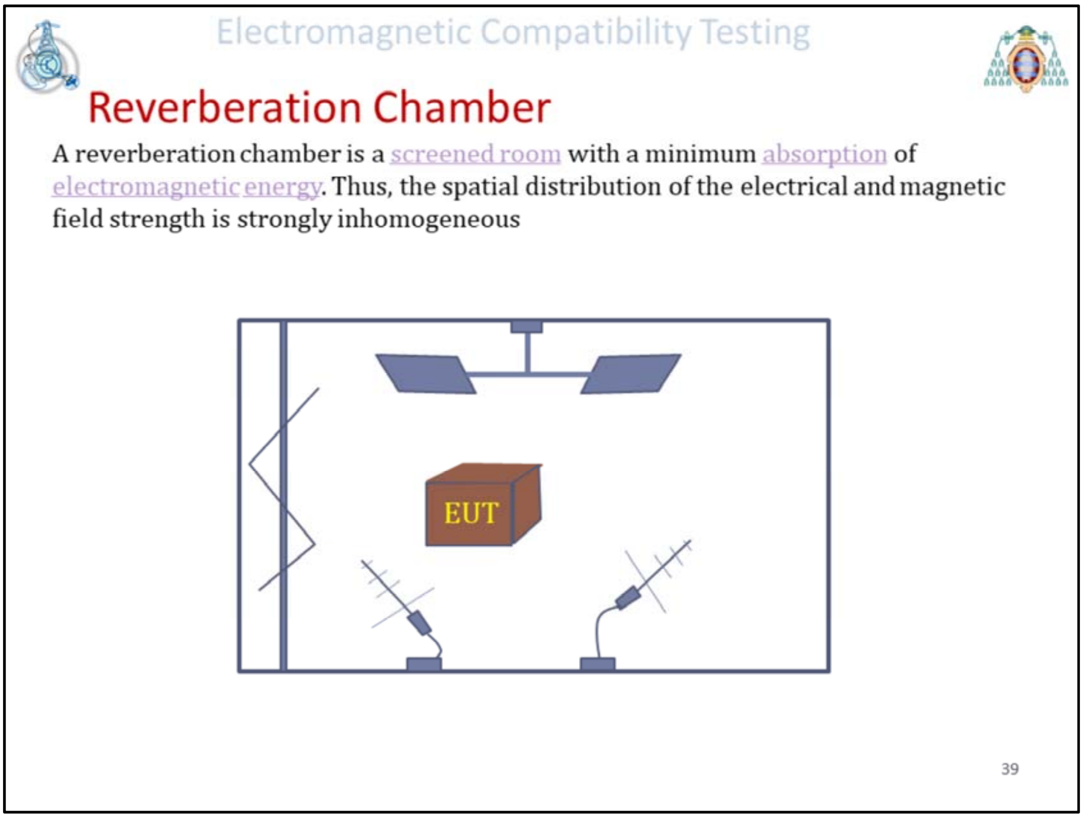
GTEM

Benefits

- Can be used to make both Radiated Emissions (RE) and Radiated Immunity (RI) measurements
- Creates high field strengths with relatively modest power input
- Generates fields that are typically homogeneous and uniform
- Operates over a very broad frequency range
- Requires no antennas, antenna setup, or stopping for band breaks
- Provides 50 ohm characteristic impedance
- Requires no facility resources other than power

Problems:

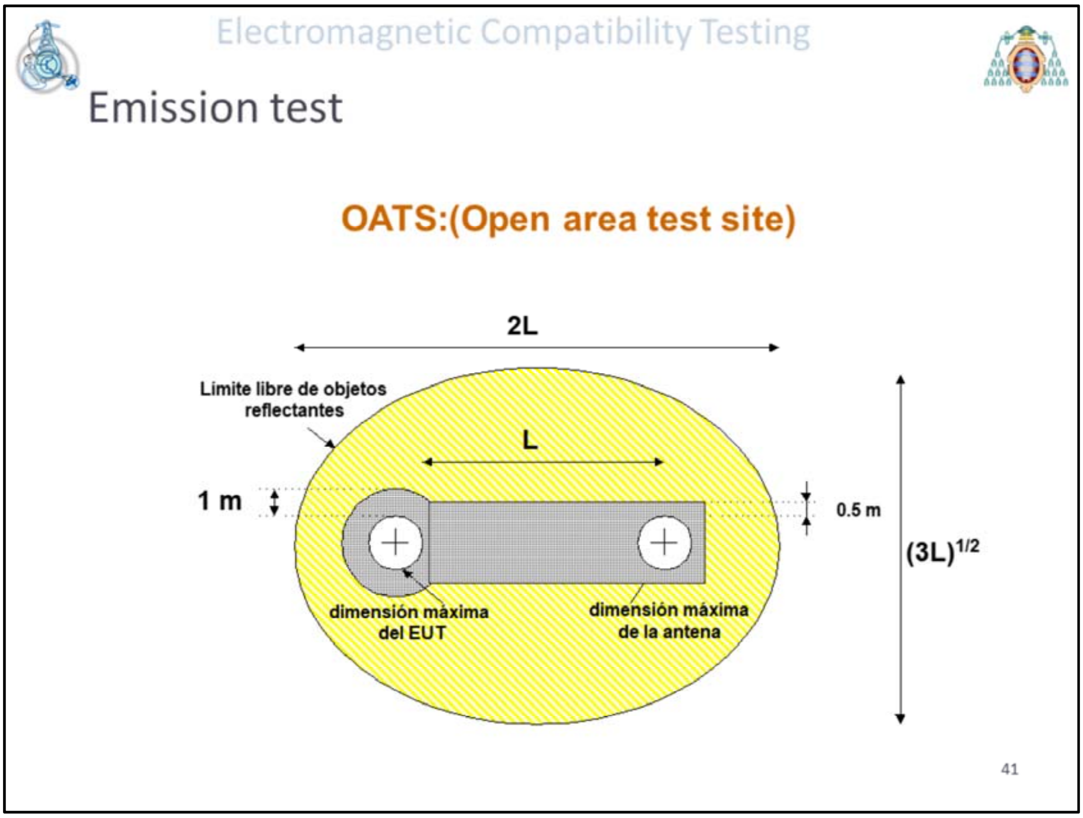
Test Volume
Uniformity Along Cell
Positioning



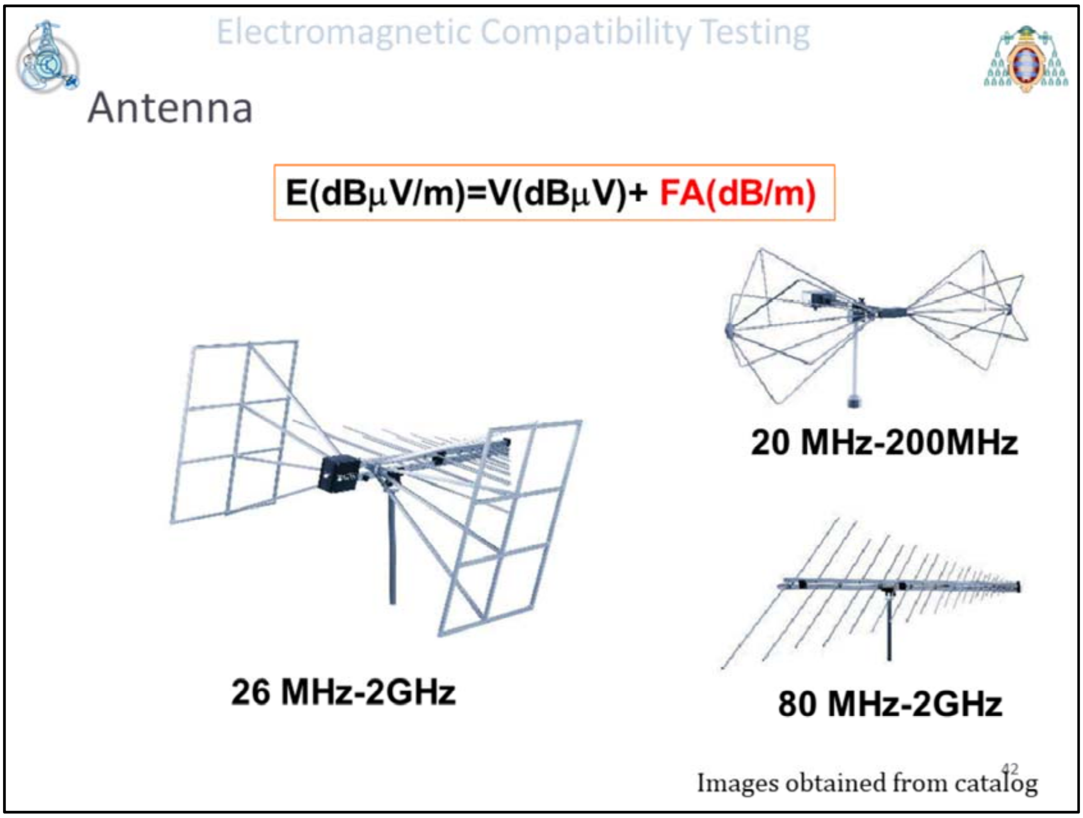
This type of chambers are not usually used to perform radiated emission measurements and do not appear in the regulations in this regard.

The image shows a full anechoic chamber and the equipment under test. This type of chamber has the walls, the roof and the floor completely covered by ferrites and absorbents. Reflections that can influence the measure are thus avoided. Only the direct emission of the equipment under test will be measured.

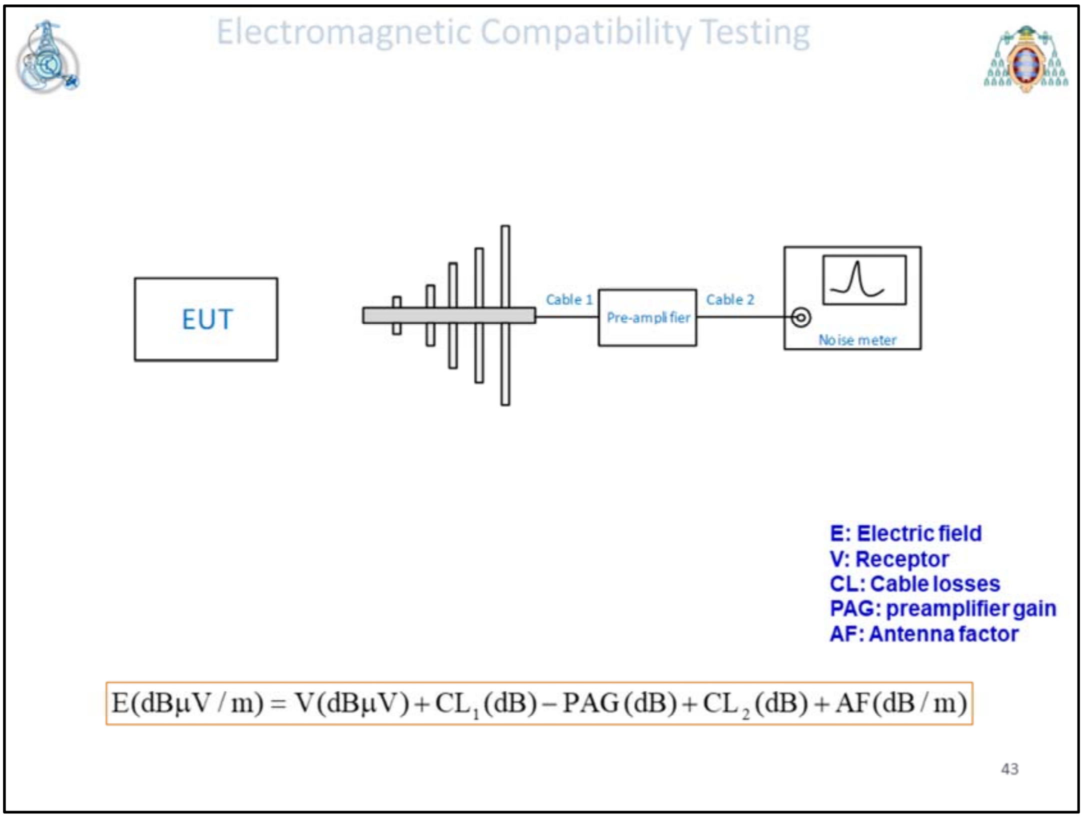
In semi-anechoic chambers the floor is a metal plate connected to the ground. This type of chambers allows reflection on the ground and therefore the measurement is affected by said reflections. It is the chamber defined by the regulations



Distances inside the chamber are defined by the regulations.



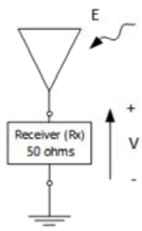
The Antenna Factor (FA) is the parameter that allows to know the electromagnetic field that the antenna receives from the voltage signal that it provides.



$$E(dB\mu V/m) = V(dB\mu V) + CL_1(dB) - PAG(dB) + CL_2(dB) + AF(dB/m)$$

To determine the existing electromagnetic field, we must take into account the antenna factor and the attenuation introduced by the rest of the elements of the system: cables, pre-amplifier, etc.

Antenna Factor

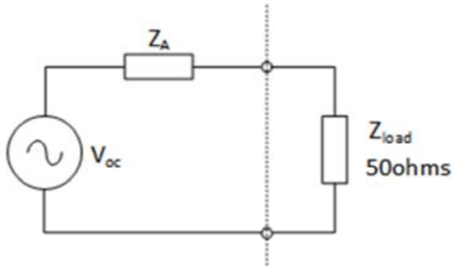


$$AF = \frac{E}{V}$$ In decibels:

$$AF_{dBm^{-1}} = E_{dBV/_m} - V_{dBV} = E_{dB\mu V/_m} - V_{dB\mu V}$$

magnetic field antenna

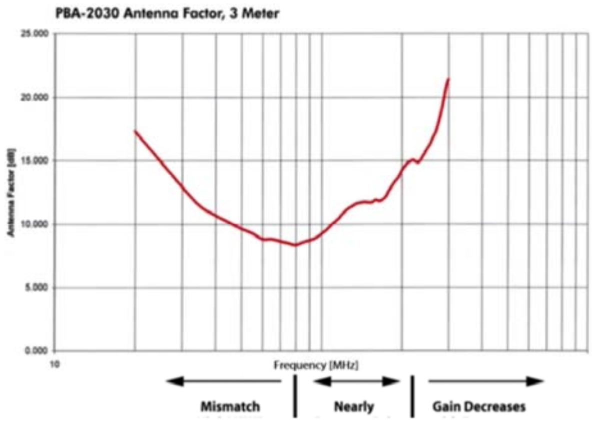
$$AF^{magnetic} = \frac{H_{incident}}{V_{received}} \quad [siemens/m]$$



$$V_{received} = \frac{V_{oc} \cdot Z_{load}}{Z_{load} + Z_A}$$

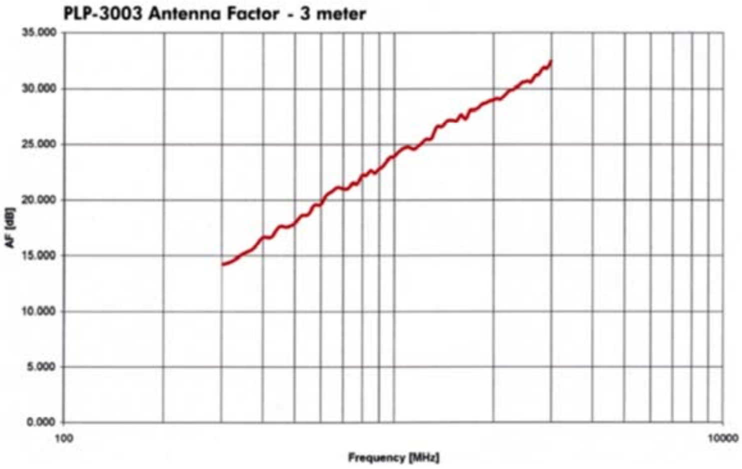
If the antenna produces 0.5V with E=1V/m then: AF=20log(1/0.5)=6dB/m

Antenna factor-Biconical Antenna



Images obtained from catalog

Antenna factor-Log Periodic Antenna



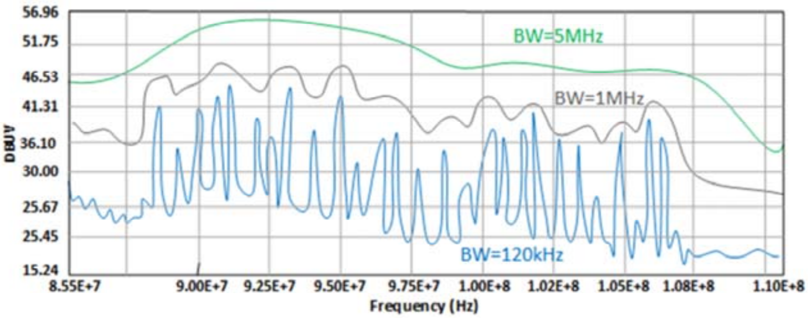
Images obtained from catalog

Bandwidth resolution (RBW)

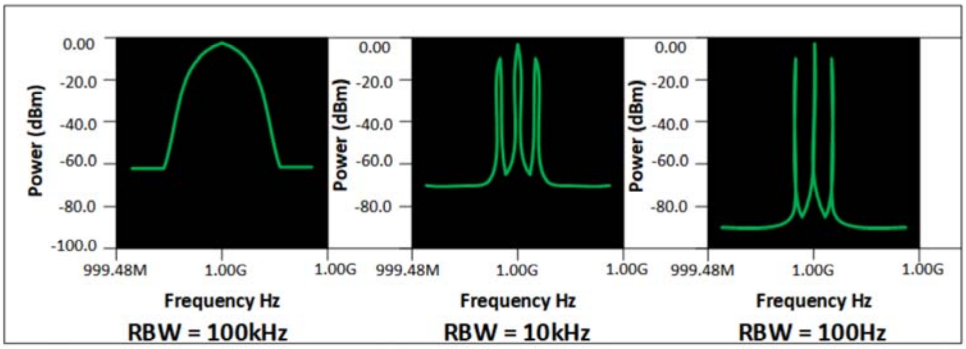
Allows the discrimination of signals with closely spaced frequency componentes.
Decreasing the RBW filter decreases the measured noise floor.

10kHz 150kHz 30MHz 1GHz

200 Hz 9 kHz 120 kHz



The resolution bandwidth (RBW) determines the smallest frequency that can be resolved. The following graphs represent the same signal with varying RBW.



The smaller RBW, on the right, has much finer resolution, which allows the sidebands to be visible. Finer resolution requires a longer acquisition time.

<u>Larger RBW</u>

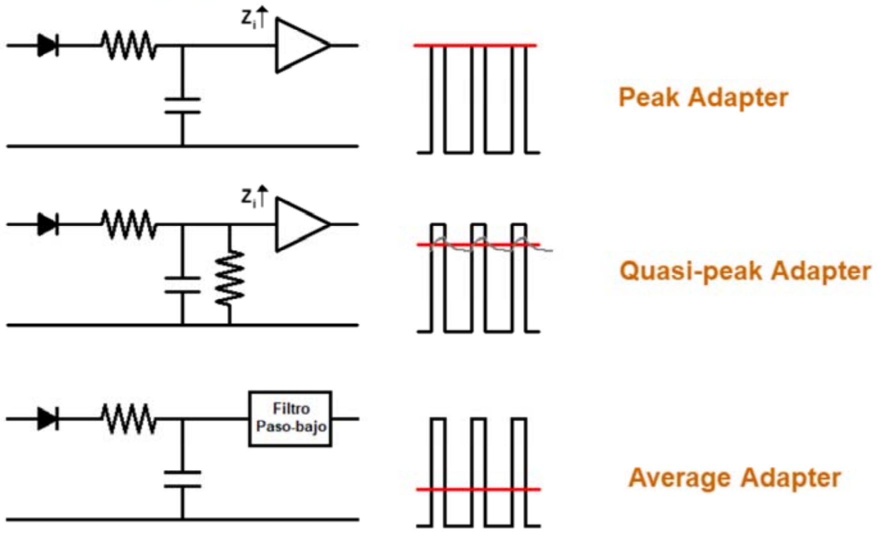
Smaller FFT size; fewer samples; requires less acquisition and computation time; often unable to resolve two closely spaced tones in a spectrum.

<u>Smaller RBW</u>

Larger FFT size; more samples; requires more acquisition and computation time; tones are easily resolved.

Detectors

This was originally done because the quasi-peak detector was believed to better indicate the subjective annoyance level experienced by a listener hearing impulsive interference to an AM radio station



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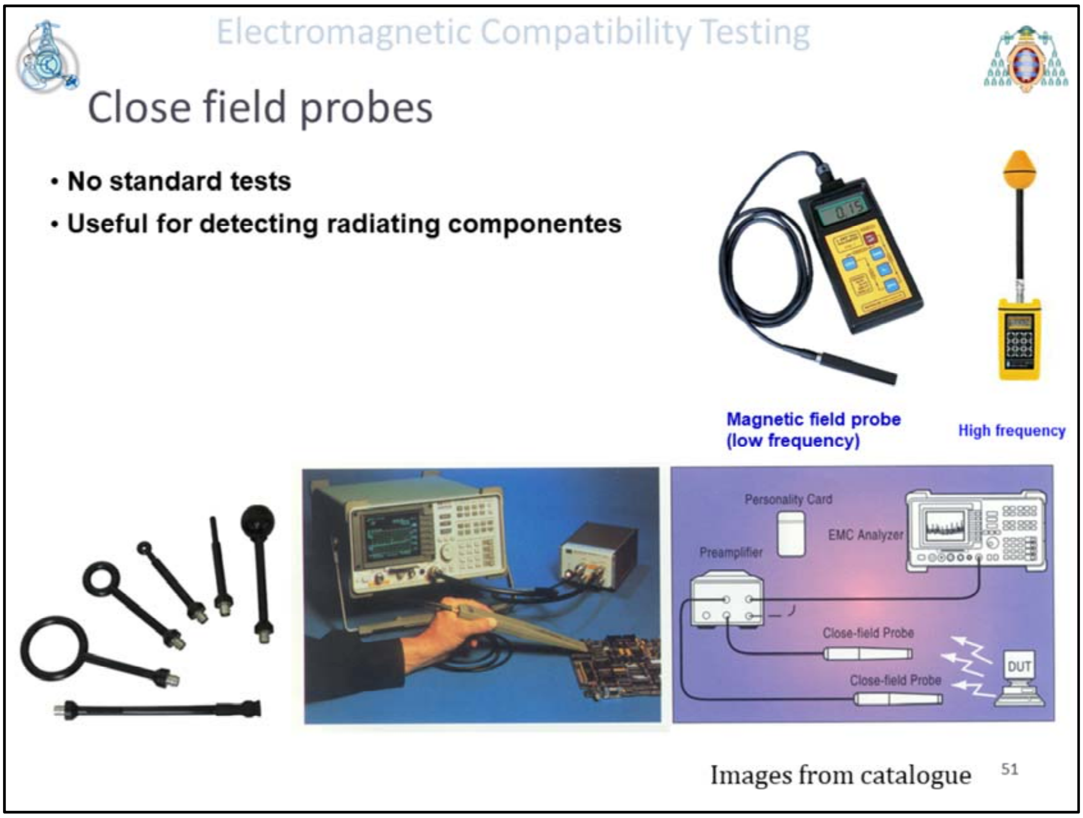
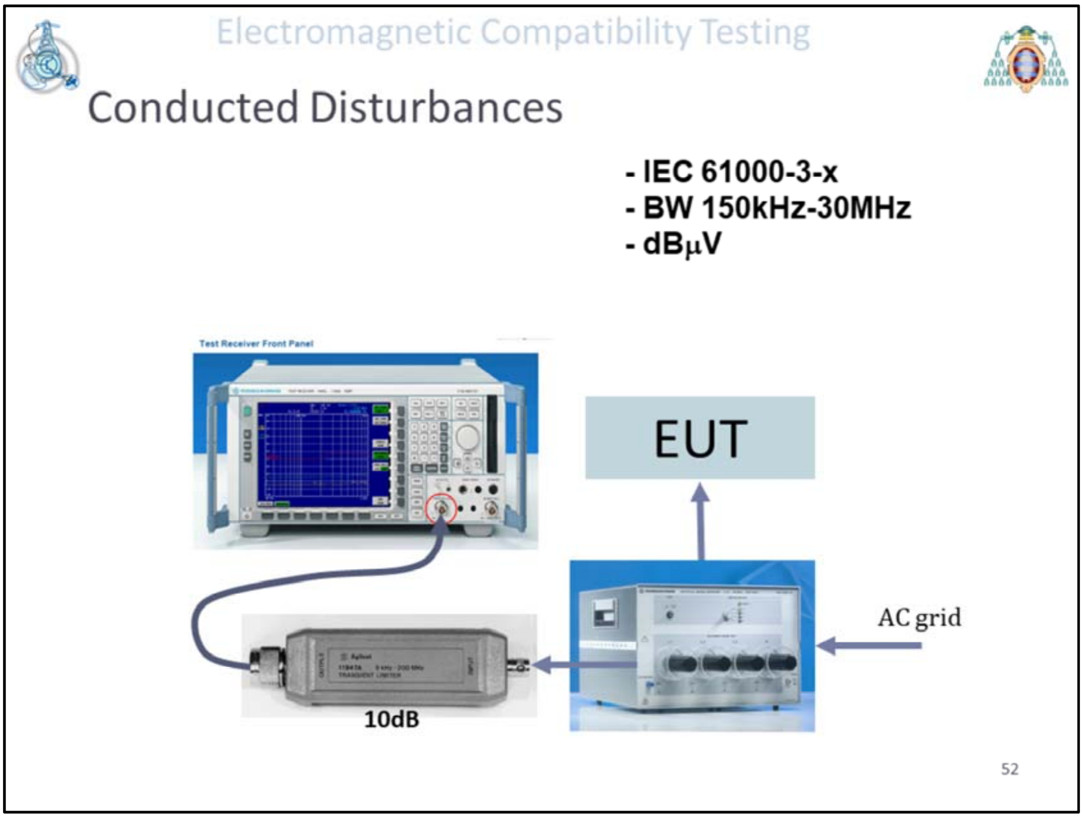
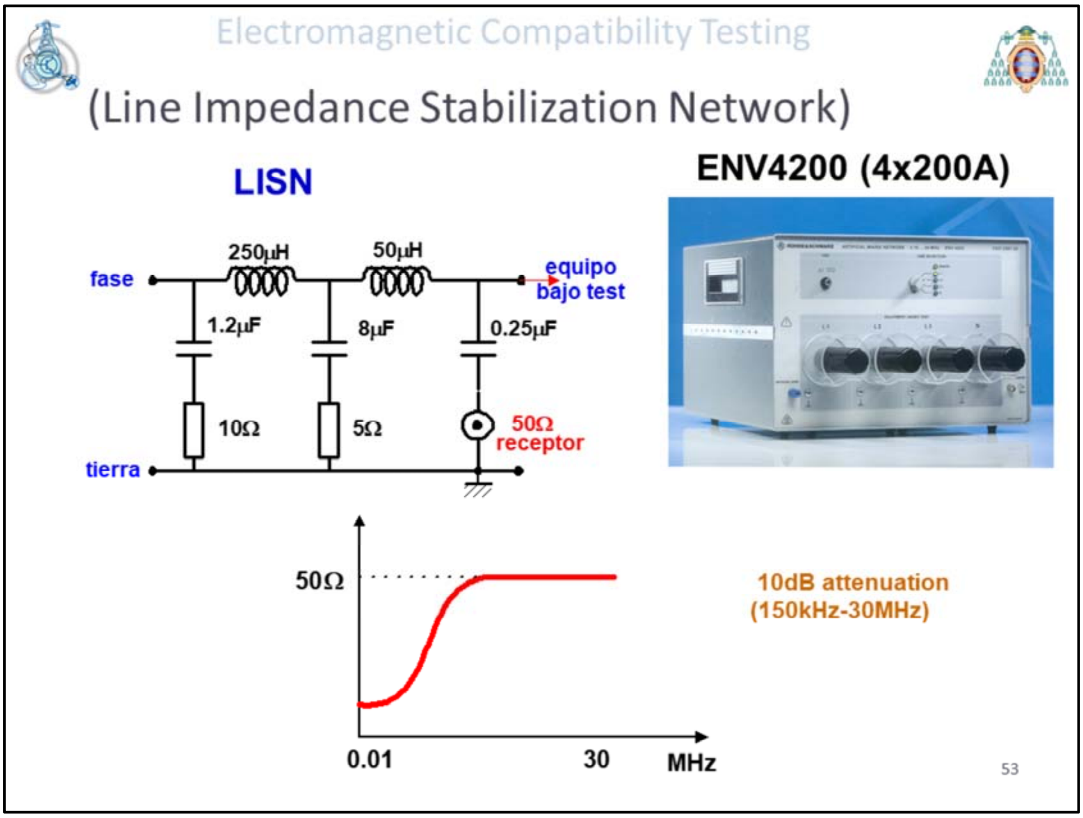
EMC equipment



Near field probes allow you to identify the components that are electromagnetically noisier



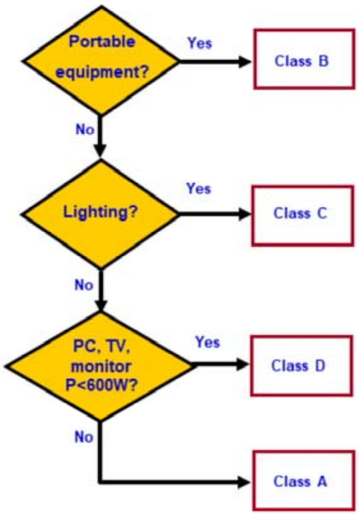
To carry out a conducted emission test, the receiver and a Line Impedance Stabilization Network (LISN) are needed. Normally a limiter is incorporated that attenuates the signal (typically by 10dB)



The LISN is formed by passive elements and aims to guarantee an impedance of 50 ohms throughout all the bandwidth considered.

Electromagnetic Compatibility Testing

Limits for harmonic current emissions EN 6100-3-2



Maximum Current injected to the grid

Harmonic	Class A [A]	Class D [mA/W]
3	2.3	3.4
5	1.14	1.9
7	0.77	1.0
9	0.40	0.5
11	0.33	0.35
13	0.21	0.296
$15 \leq n \leq 39$	2.25/n	3.85/n

In class A, the values are absolute [A]
In class D, they are relative values [mA/W]

Clase D is more restrictived with low power <500W

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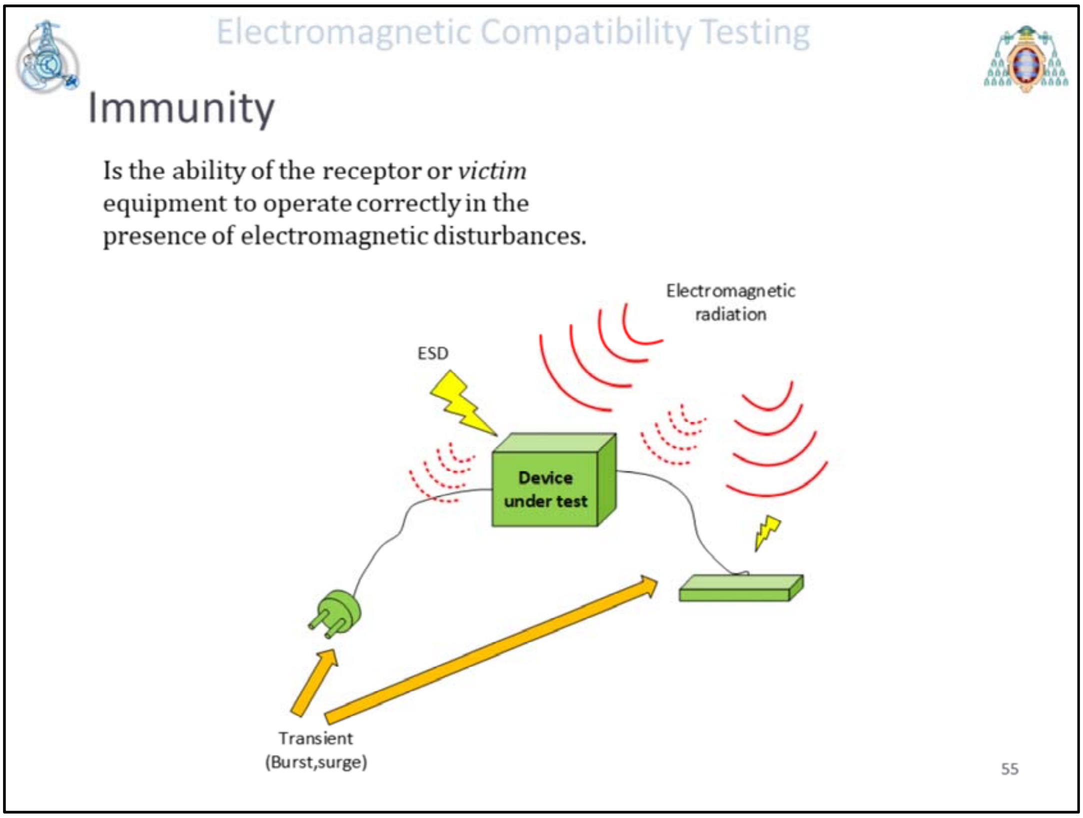
The low-frequency current harmonics test is defined for several types of devices. Depending on the type, the maximum achievable value changes.



Immunity tests are intended to verify the correct functioning of equipment when subjected to electromagnetic disturbances (conducted or emmitted)

Electromagnetic Compatibility Testing

Aptitude criteria

Results of the test:

- A: Normal operation after the test

- B: Temporary degradation or loss of function or performance, which is self-recoverable

- C: Temporary degradation or loss of function or performance, which requires operator intervention or system reset

- D: The equipment doesn’t work after the test

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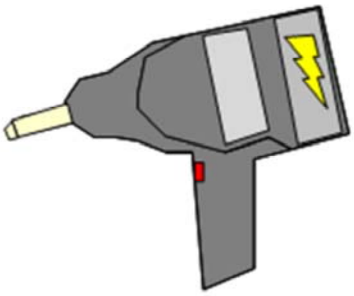
The results of the test are classified according to the aptitude criteria: A, B, C, D. The standard defines what criteria must be met depending on the type of circuit being tested (medical, industrial, safety, etc.). For example, a safety system must maintain its correct functioning during the test, therefore it must comply with criterion A

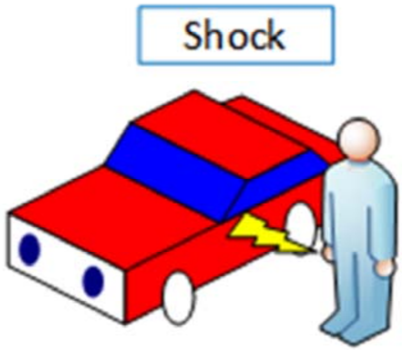
Electrostatic discharge immunity test. ESD

- **EN 61000-4-2**

ESD is the abrupt release of charge from one object (often a person) to another.

Electronic products are tested for ESD immunity to ensure their continued reliable operation if subjected to realistic levels of ESD after being placed in service





ESD

Test levels

Contact discharge		Air discharge	
Level	Test voltage kv	Level	Test voltage
1	2	1	2
2	4	2	4
3	6	3	8
4	8	4	15
x[1)]	Special	x[1)]	Special

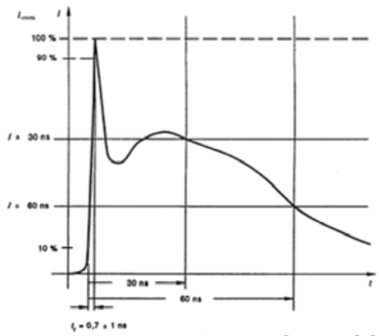
[1)] "x" is an open level . The level has to be specified in the dedicated equipment specification .
If higher voltages than those shown are specified , special test equipment may be needed .

ESD

Tabla 2
Parámetros de forma de onda

Nivel	Tensión indicada kV	Primera cresta de la corriente de descarga ± 10% A	Tiempo de subida t_r con el interruptor de descarga ns	Corriente (± 30%) a 30 ns A	Corriente (± 30%) a 60 ns A
1	2	7,5	0,7 a 1	4	2
2	4	15	0,7 a 1	8	4
3	6	22,5	0,7 a 1	12	6
4	8	30	0,7 a 1	16	8

Waveform



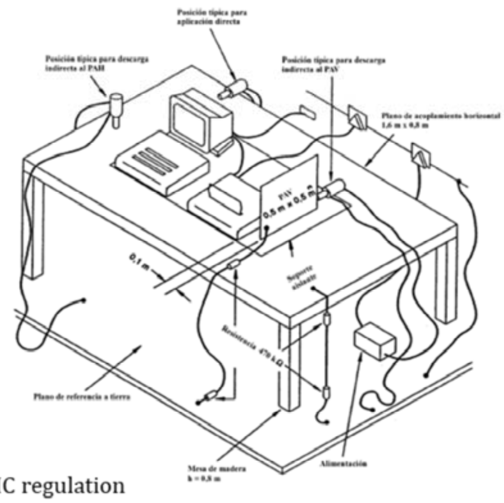
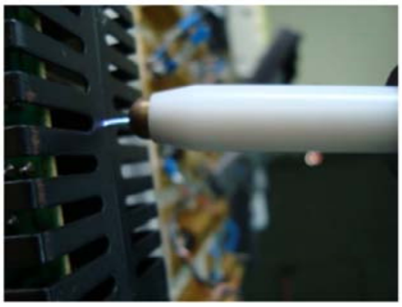
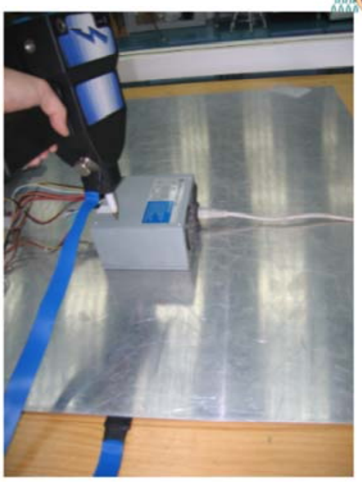


Image obtained from EMC regulation

ESD





Where should the test be applied?

- In isolated areas
- Keyboards
- LCD
- Any point not connected directly to ground that can be touched by a person

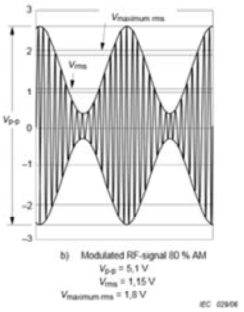
Electromagnetic Compatibility Testing

Radiated, radio-frequency, electromagnetic field immunity test EN 61000-4-3

Emisiones "intencionadas"

radiodifusión	LW / MW / SW	10 V/m
televisión	VHF / UHF	1 V/m
radar	UHF / SHF	1 kV/m
transmisores móviles		10 - 100 V/m

Frequencies: 80MHz-1GHz



Level	Test field strength V/m
1	1
2	3
3	10
x	Special
NOTE – x is an open test level. This level nay be given in the Product specification.	

This signal is 80% amplitude modulated with 1-kHz sinewave.

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In this test, equipment is radiated with a carrier modulated 80% in amplitude with a 1-kHz wave. The bandwidth to analyze goes from 80MHz to 1GHz

Test configuration

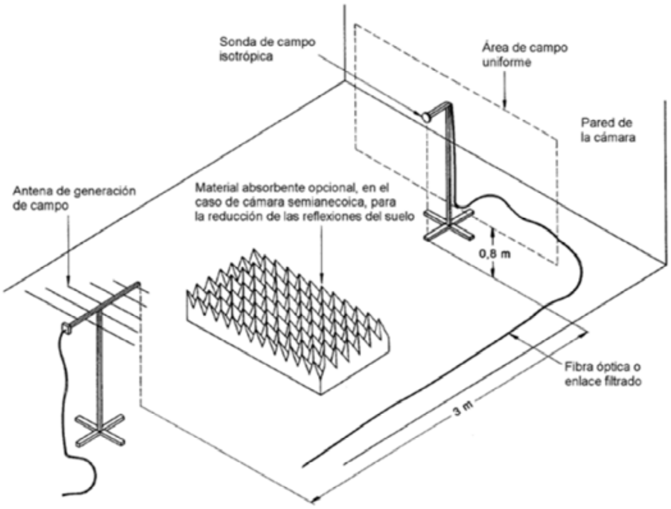
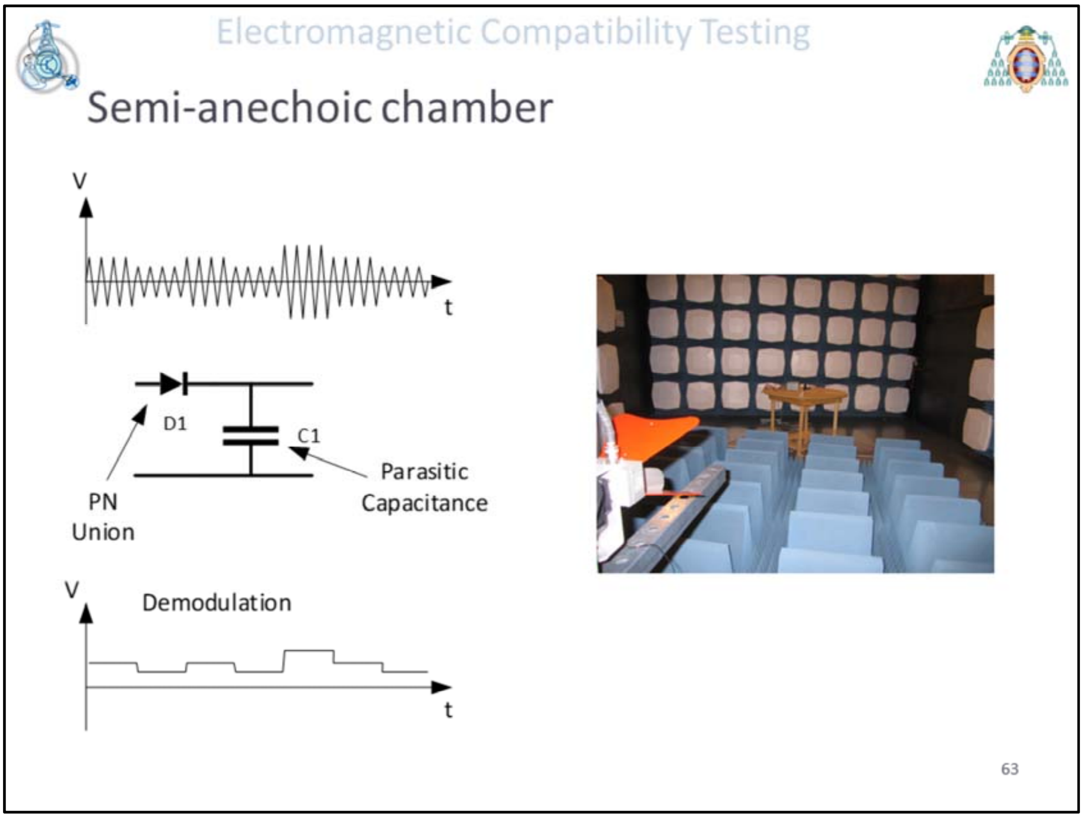
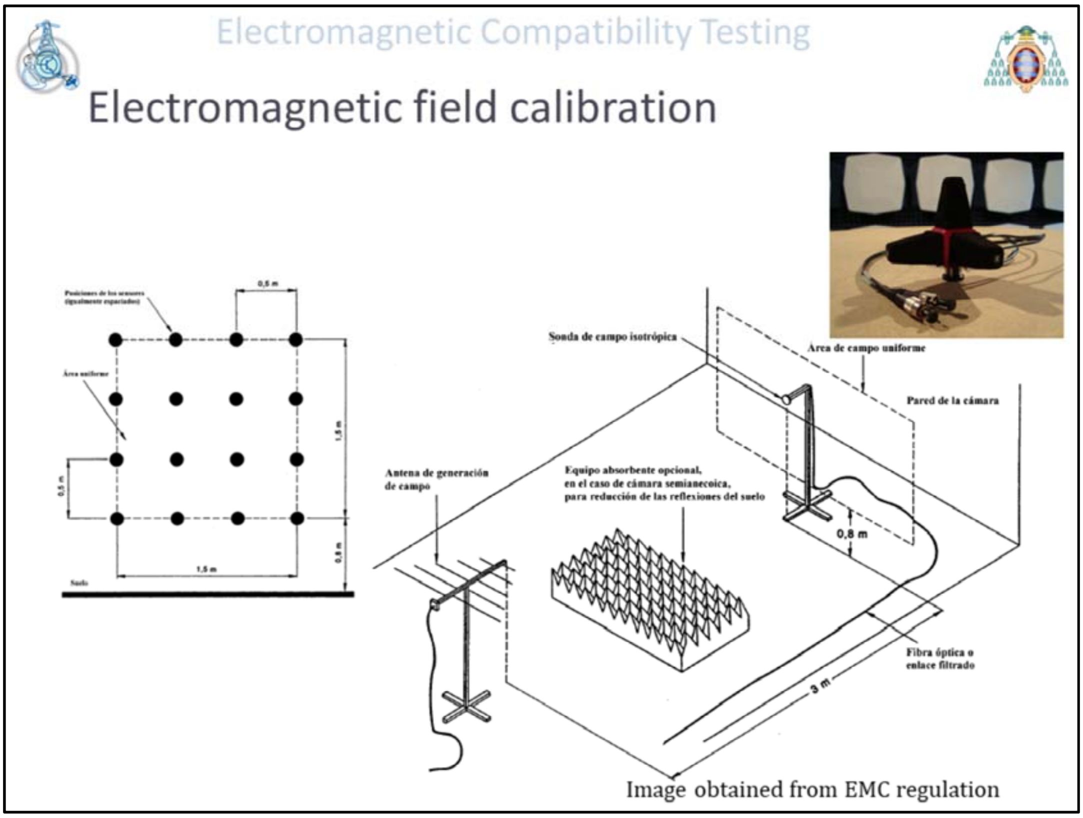


Image obtained from EMC regulation



The modulated wave with which the equipment is radiated can be easily demodulated by the presence of a diode and parasitic capacitances that can lead to a peak detector



To carry out the calibration of the test, field probes such as the one in the photo are used. The probe is placed in the position occupied by the EUT and the calibration process is started by radiating the probe, which sends the information of the field amplitude to the control system in order to increase the radiation until the one specified by the standard is reached. This process is done for each frequency considered.

Electromagnetic Compatibility Testing

Low-frequency magnetic field immunity test

Regulation EN 61000-4-8

Table 1-Test levels for continuous field

Level	Magnetic field strength A/m
1	1
2	3
3	10
4	30
5	100
x[1]	special

NOTES
1 – "x" is an open level. This level can be given in the product specification.

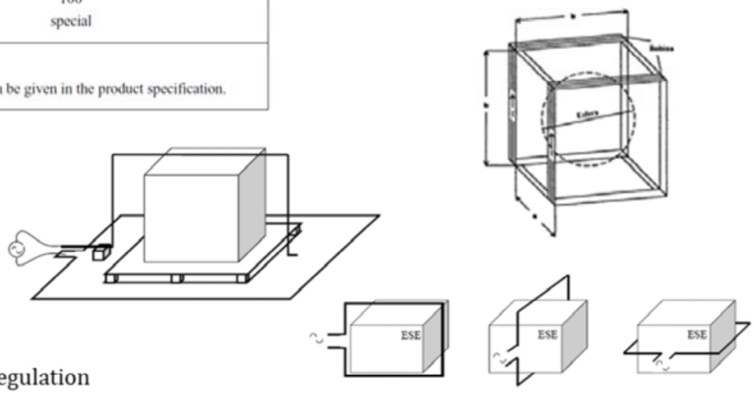
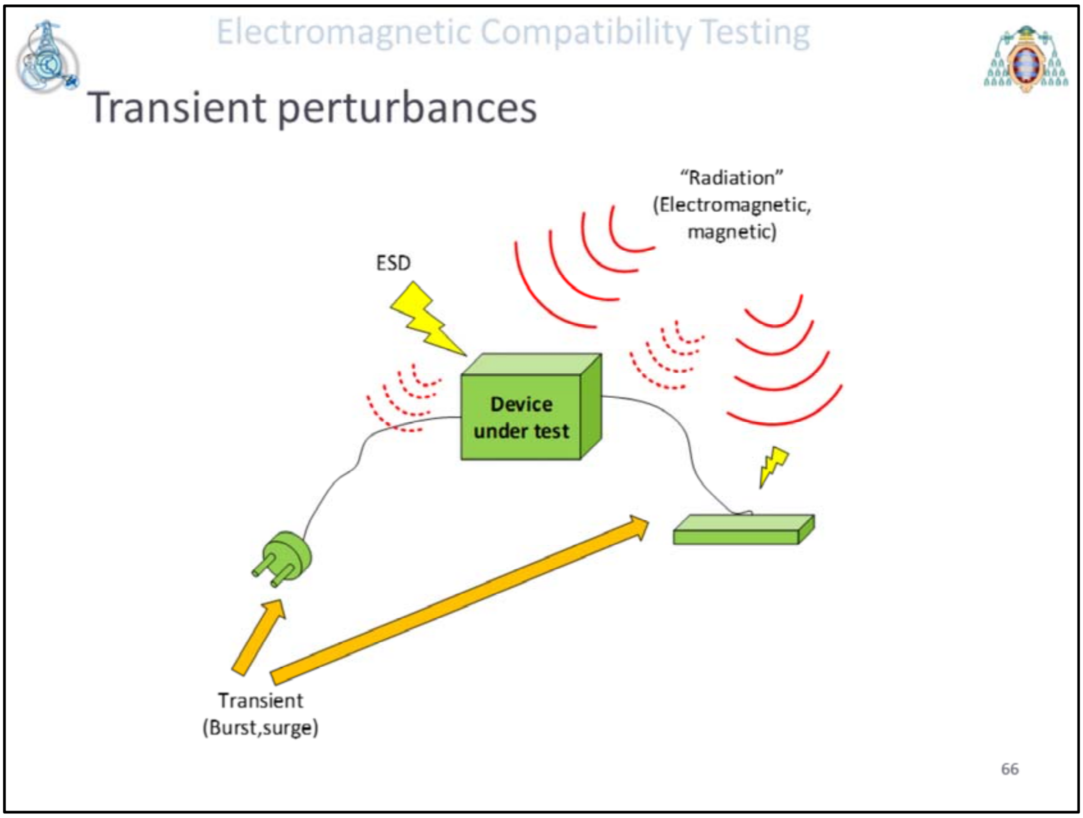
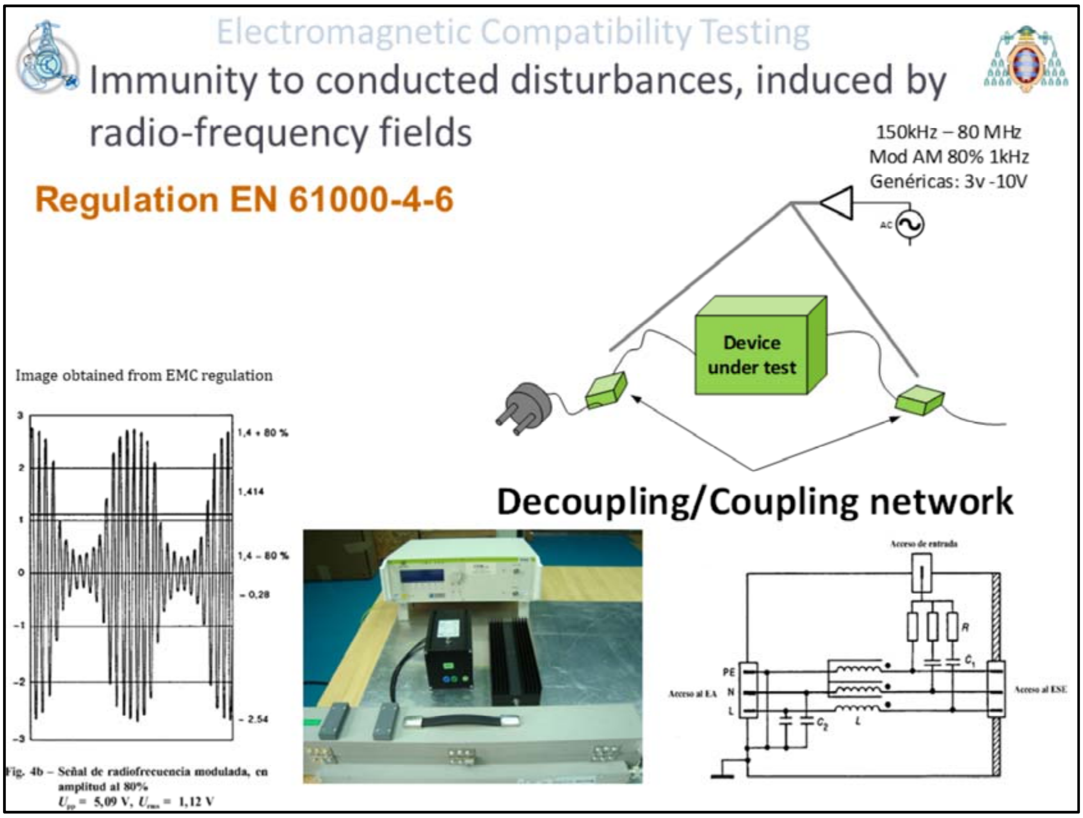


Image obtained from EMC regulation

In this test, a specified current is injected through the antenna to obtain the magnetic field defined in the regulation



There are several tests that cause transient disturbances, both radiated and conducted, in the equipment,

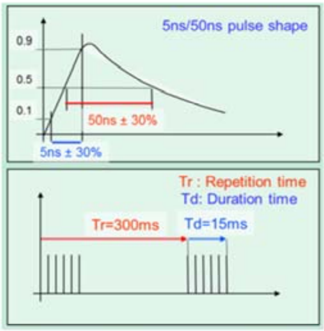


This test injects in the cables (supply lines, communication, etc.) a carrier that varies from 150kHz to 30MHz modulated in amplitude 80% with a modulator of 1kHz.

The injection of the noise signal is achieved through a decoupling / coupling network. The decoupling / coupling network contains a coupling capacitor and a coil in series with the conductors that acts as a filter to prevent the noise signal from reaching other equipment connected to the same conductors

Electrical fast transient/burst immunity test

Regulation EN 61000-4-4



Test levels

Open-circuit output test voltage (±10 %) and repetition rate of the impulses (±20 %)				
Level	On power supply port, PE		On I/O (Input/Output) signal, data and control ports	
	Voltage peak kV	Repetition rate kHz	Voltage peak kV	Repetition rate kHz
1	0.5	5	0.25	5
2	1	5	0.5	5
3	2	5	1	5
4	4	2.5	2	5
x[1)]	Special	Special	Special	Special

[1)] "x" is an open level. The level has to be specified in the dedicated equipment specification.

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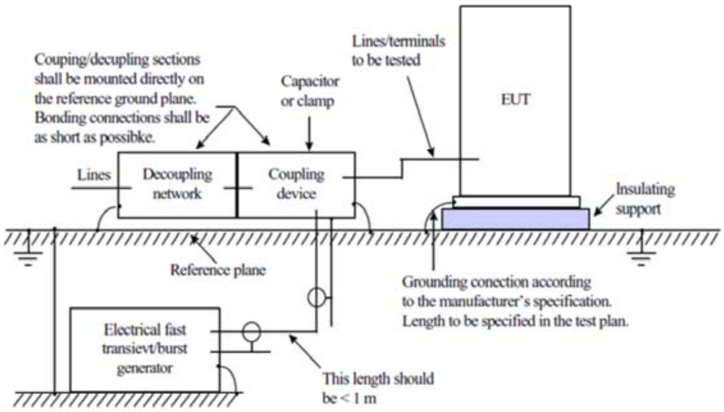
Image obtained from EMC regulation

This type of tests are destructive if the equipment under test does not incorporate a device such as avaristor or transil. Several over-voltages are applied whose duration and number is defined by the standard. The amplitude of the overvoltage is defined through 4 levels plus a special one.

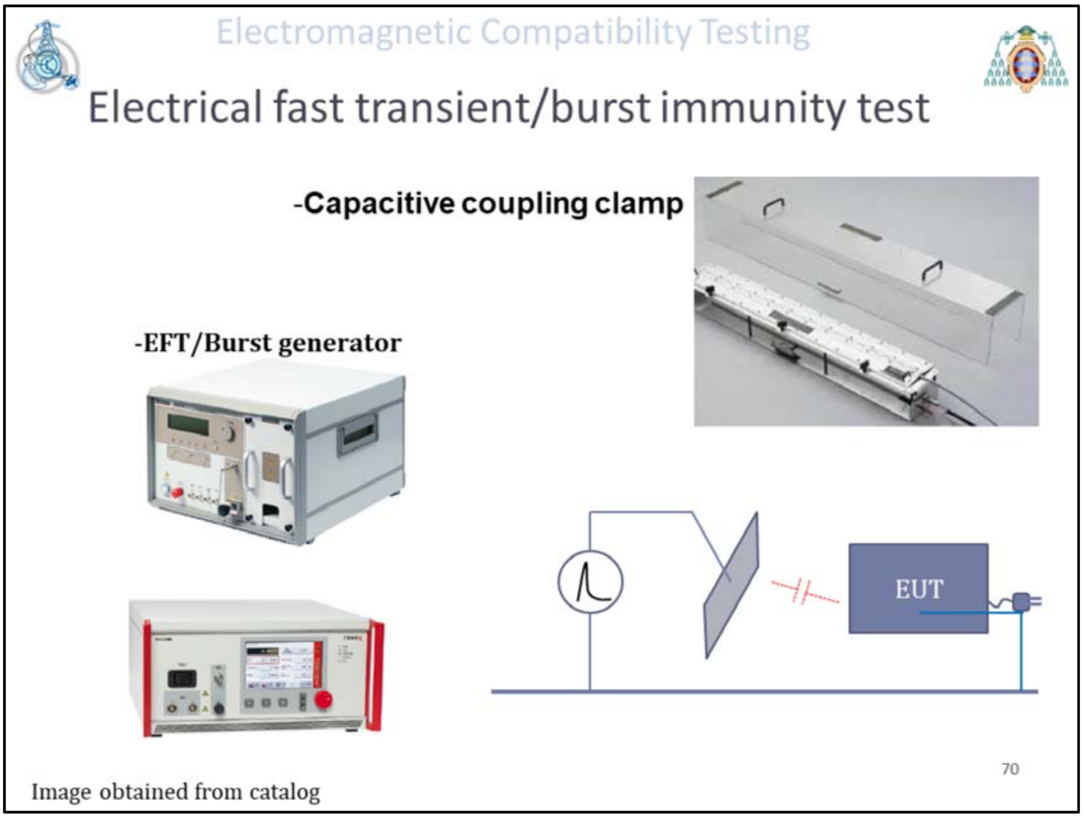
Electrical fast transient/burst immunity test

Equipment
- **Capacitive coupling clamp**
- **Coupling / Decoupling Network**
- **Burst generator**

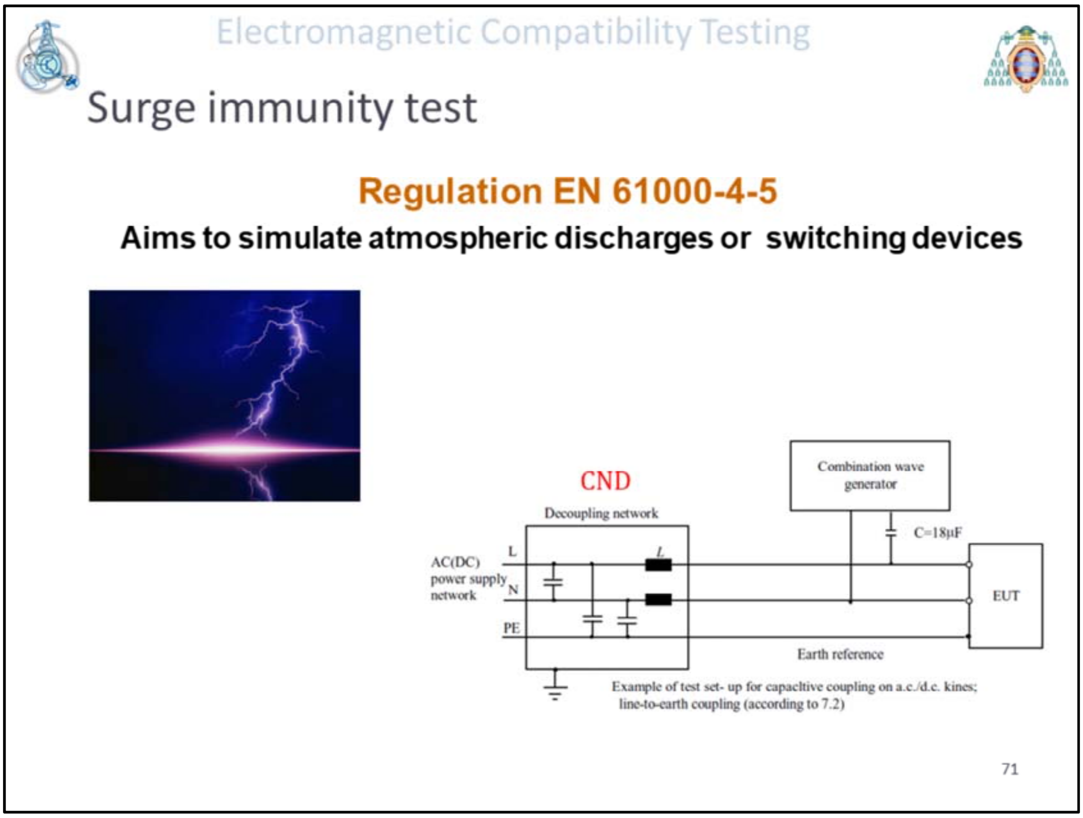


Block-diagram for electrical fast transient/burst immunity test

Image obtained from EMC regulation



The use of capacitive clamps facilitates the interconnection of equipment and the application of surges regardless of the type of cable used.



The surge test simulates the burst test but with different amplitudes and times in the download. In this case it is a single pulse applied, although the procedure is identical.

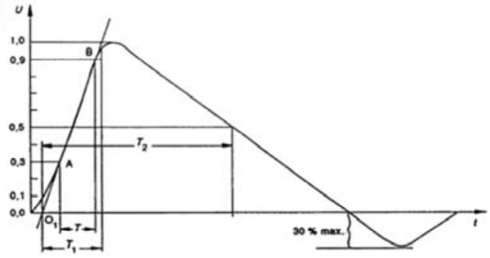
Surge inmunity test

Table 1-Test levels

Level	Open-circuit test voltage ±10 % kV
1	0.5
2	1.0
3	2.0
4	4.0
x	Special
NOTE - x is an open class . The level can be specified in the product specification .	

Tr/Th 1,2/50 µs

1 pulse/min

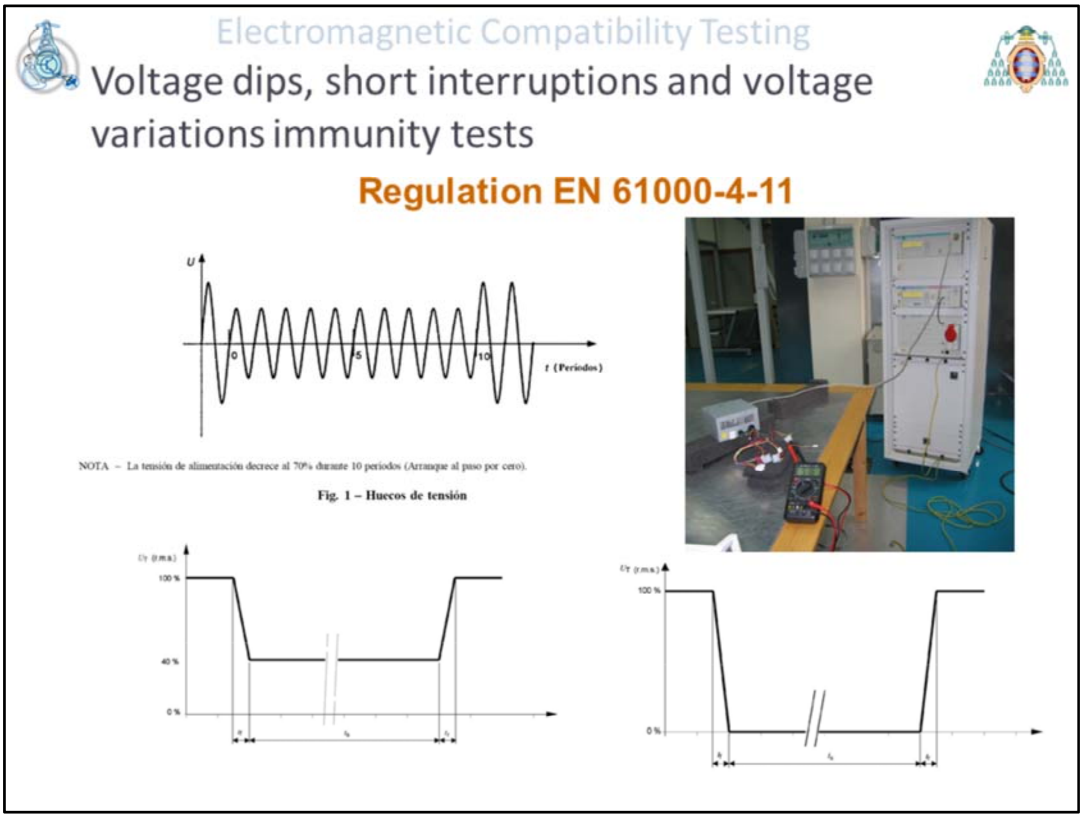


Duración del frente $T_1 = 1{,}67 \times T = 1{,}2\ \mu s \pm 30\%$

Tiempo transcurrido hasta el valor mitad $T_2 = 50\ \mu s \pm 20\%$

Image obtained from EMC regulation

Fig. 2 – Forma de onda de la tensión a circuito abierto (1,2/50 µs) (definición de la forma de onda de acuerdo con CEI 60-1)



This test evaluates the correct functioning of the equipment during short interruptions or voltage dips. Normally the capacities present in the power supplies provide enough energy to maintain the correct operation during the test.

Human exposure

Humans can be exposed to electromagnetic fields from the following:

- High voltage and/or high current cables
- High current transformers
- Microwave ovens
- Radar transmitters
- Medical magnetic imaging
- Mobile/cellular telephones and transmitter masts
- TV and radio transmitters

Current Amperes	Physiological Phenomena	Effect on Man
< 0.001	None	Imperceptible
0.001	Perception Threshold	Mild Sensation
0.003	Pain Threshold	Painful Sensation
0.010	Paralysis Threshold of Arms and Hands	Person cannot release grip; if no grip, victim may be thrown clear. Tighter grip because of paralysis may allow more current to flow; may be fatal.
0.030	Respiratory Paralysis	Stoppage of breathing, frequently fatal.
0.075	Fibrillation Threshold	Heart action uncoordinated, probably fatal.
4.000	Heart Paralysis Threshold	Heart stops on current passage, normally restarts when current interrupted.
5.000	Tissue Burning	Not fatal unless vital organs are burned

Health

Electricity is used everywhere

Whenever electricity flows, both electric and magnetic fields are produced

Since the late 1970s, questions have been raised whether exposure to these extremely low frequency (ELF) electric and magnetic fields (EMF) produces adverse health consequences.

Non-ionizing (or non-ionising) **radiation** refers to any type of electromagnetic radiation that does not carry enough energy per quantum to ionize atoms or molecules—that is, to completely remove an electron from an atom or molecule. Instead of producing charged ions when passing through matter, the electromagnetic radiation has sufficient energy only for exciting the movement of an electron to a higher energy state

Electric and Magnetic Fields

Electric fields arise from electric charges. They are measured in volts per metre (V/m)

Magnetic fields arise from the motion of electric charges (i.e. a current). They are expressed in tesla (T), or more commonly in millitesla (mT) or microtesla (μT).

In some countries another unit called the gauss, (G), is commonly used (10,000 G = 1 T).

They are not shielded by most common materials, and easily pass through them.

Both types of fields are strongest close to the source and diminish with distance

Electricity Frequencies

Most electric power operates at a frequency of 50 or 60 hertz (Hz).

The magnetic field values can be of the order of a few hundred microteslas (100μT)

Underneath power lines, magnetic fields can be about 20 μT and electric fields can be several thousand volts per metre.

However, average residential power frequency magnetic fields in homes are much lower - about 0.07 μT in Europe and 0.11 μT in North America.

Mean values of the electric field in the home are up to several tens of volts per metre (10V/m)

Dosimetric quantity (Units)

- At low frequency range **of 300 Hz to 1 MHz**, currents are induced in the body that may influence the biological systems. They may interfere with the normal information processing capabilities of the *central nervous System*.
  The relevant dosimetric quantity in this frequency range is the current density, expressed in **A/m²**
- In the frequency range of **100 kHz to 10 GHz**, the absorption of electromagnetic energy leads to generation of *heat*, and heat tolerance is the limiting factor.
  The appropriate dosimetric quantity in this frequency range is the Specific **Energy Absorption Rate (SAR)** expressed in units of **W/kg.**
- In the frequency range of **6 – 300 GHz**, the energy from the electromagnetic fields is increasingly being dissipated at the body surface, resulting mainly in *heating of the skin*. Limits are referred to **W/m²**

Limits from World Health Organization

Table 1.1- Basic Restrictions for Instantaneous Spatial peak current density in the Head and Trunk

Exposure Category	Frequency Range	Current Density in head and trunk in (mA/m^2 rms)
Occupational	3 kHz-10 MHz	10 x f
General Public	3 kHz-10 MHz	2 x f

Note(s):

a. *f is the frequency in kHz.*
b. *Because of the electrical in homogeneity of the body, current densities must be averaged over a circular cross-section of 1 cm^2 perpendicular to the current direction.*
c. *For pulsed magnetic field exposures spanning frequencies up to 100 kHz, the maximum current density associated with the pulses can be calculated from the maximum rate of change of magnetic flux density using Faraday's law of induction.*

Table 1.4- Basic restrictions for Incident Power Density

Exposure Category	Frequency Range	Time averaged Power density (W/m^2)	Instantaneous Power density (W/m^2)
Occupational	6 GHz - 300 GHz	50	50 000
General Public	6 GHz - 300 GHz	10	10 000

Note(s):

a. *Power densities may be averaged over an area no larger than 20 cm^2 in the shape of a square.*
b. *Spatial maximum time averaged power densities, spatially averaged over 1 cm^2, and must not exceed 20 times the time-averaged values above.*
c. *For determination of time-averaged values at frequencies below 10 GHz, an averaging time of six applies and for frequencies above 10 GHz an averaging time of $68/f^{1.05}$ minutes (where f is in GHz) must be used. This approach compensates for progressively shorter penetration depth as the frequency increases.*

Table 1.2- Basic restrictions for whole body average and Spatial Peak SAR

Exposure Category	Frequency Range	Whole Body averaged SAR (W/kg)	Spatial Peak SAR in head & trunk (W/kg)	Spatial peak SAR in limbs (W/kg)
Occupational	100 kHz – 6 GHz	0.4	10	20
General Public	100 kHz – 6 GHz	0.08	2	4

Note(s):

a. *A 6-minute averaging period must be applied to all SAR values.*
b. *Spatial peak SAR averaging mass is any 10 g of contiguous tissue in the shape of a cube.*

Limits

Table 1.5- Reference Levels for Time averaged Exposure to RMS Electric and Magnetic Fields (Unperturbed Fields)

Exposure Category	Frequency Range	E-field Strength (V/m rms)	H-field Strength (A/m rms)	Equivalent Plane Wave Power Density S_{eq} (W/m^2)
Occupational	100 kHz – 1 MHz	614	1.63 / f	—
	1 MHz – 10 MHz	614 / f	1.63 / f	$1000 / f^2$ *(see note d)*
	10 MHz – 400 MHz	61.4	0.163	10 *(see note d)*
	400 MHz – 2 GHz	$3.07 \times f^{0.5}$	$0.00814 \times f^{0.5}$	f / 40
	2 GHz – 300 GHz	137	0.364	50
General Public	100 kHz – 150 kHz	86.8	4.86	—
	150 kHz – 1 MHz	86.8	0.729/ f	—
	1 MHz – 10 MHz	$86.8 / f^{0.5}$	0.729 / f	—
	10 MHz – 400 MHz	27.4	0.0729	2 *(see note e)*
	400 MHz – 2 GHz	$1.37 \times f^{0.5}$	$0.00364 \times f^{0.5}$	f / 200
	2 GHz – 300 GHz	61.4	0.163	10

Note(s):

a. *f is the frequency in MHz.*

b. *For frequencies between 100 kHz and 10 GHz, S_{eq}, E^2 and H^2 must be averaged over any 6-minute period.*

c. *For frequencies exceeding 10 GHz, S_{eq}, E^2 and H^2 must be averaged over any $\frac{9.6*10^4}{f^{1.05}}$ minute period.*

d. *For occupational exposure, E and H reference levels of Table 1.5 are given in plane wave ratio at frequencies greater than or equal to 1 MHz. However, for many occupational exposure situations, equivalent plane wave power density is not an appropriate metric if "far field" exposure conditions do not apply. Survey meters may be calibrated in terms of W/m^2, but both E and H will generally require independent measurement and evaluation if measured in the near field.*

e. *For public exposure E and H reference levels of Table 1.5 are given in plane wave ratio at frequencies greater than or equal to 10 MHz. However, equivalent plane wave power density is not an appropriate metric if "far field" exposure conditions do not apply. Survey meters may be calibrated in terms of W/m^2, but both E and H will generally require independent measurement and evaluation if measured in the near field.*

Exposure limits for non-ionizing radiation. Singh, D.K. ; Electron. & Radar Dev. Establ., Bangalore, India

Limits

Recommendation:

Magnetic field (occupational): 50/60 Hz up to 0.5 mT during 8h and 5mT short exposure 2 hours.

Maximum Electric field 10 and 30 kV/m.

The limit during ***24 hours*** for general public is fixed in:
E=600V/m and B=0,1 mT.

People with pacemakers
Limits/10

IEEE Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 GHz

ICNIRP (*International Commission for on Ionizing Radiation Protection*)

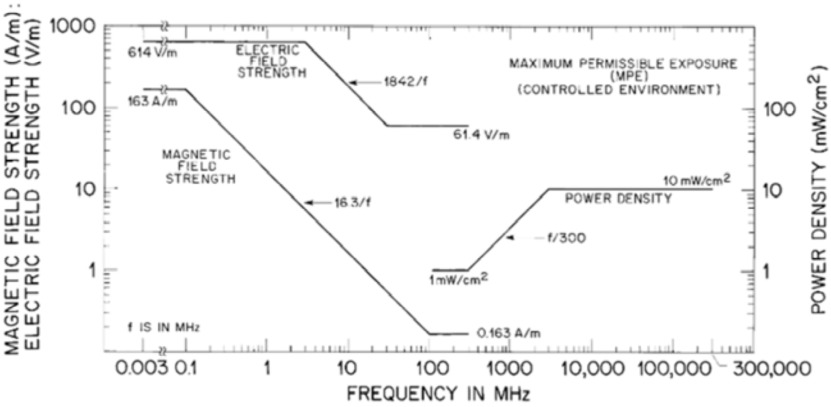


Figure E.2—Graphic representation of maximum permissible exposure in terms of fields and power density for a controlled environment