

POLITECNICO DI TORINO

Master's Degree in Automotive Engineering



Master's Degree Thesis

Setup and Measurement of Electromagnetic Fields on Vehicles for Medium-High Capacity Public Transport with Focus on AIMD Compliance Limits

Tutors

Prof. Guido Lombardi
Eng. Marco Aimo-Boot
Mr. Matteo Perrone

Candidate

Antonio GUAGLIANO

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Abstract

The aim of this thesis is to demonstrate that IVECO buses are safe for all passengers, including the most vulnerable individuals, such as those with AIMDs. During this process, it was fundamental to define first what are the regulations dedicated to automotive sector, possibly dedicated to buses, and those dedicated to AIMDs. The review and identification of the relevant standards and exposure limits were essential to define a reliable and repeatable measurement methodology. This analysis highlighted several significant weaknesses in the current regulatory framework. The combination of an outdated regulatory framework and the significant improvements in technology and scientific understating highlights the need for a revised regulatory approach. This thesis introduces a structured proposal for a dedicated assessment standard, intended to support both regulatory development and industrial best practice of buses environment, giving an example of a real EMF measurement test report

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1 Introduction

1.1 Emissions

During the last thirty years, the automotive engineering focused its attention to the reduction of emissions of carbon anhydride (CO_2), carbon monoxide (CO), unburned hydrocarbons (HC), nitrogen oxides (NO_x), and particulate matter (PM), products of the fuel combustion inside the internal combustion engines (ICEs). For this purpose, the engineers have driven the improvement of the ICEs itself and the development of new devices capable of destroying these products.

Regarding improvements at the ICE level, one of the most effective solutions to reduce emissions is a proper engine calibration. Nowadays, this process is carried out during the engine design phase, often with the help of virtual methodologies and software tools capable of simultaneously considering multiple parameters, such as the start of injection (SOI), start of combustion (SOC), end of injection (EOI), end of combustion (EOC), the amount of fuel injected, the exhaust gas recirculation (EGR) rate, valve timing (VVT) and air fuel ratio (λ) all controlled by the electronic control unit (ECU) depending on engine speed [1].

Other solutions external to the engines are additional devices that, positioned after the exhaust valve, reduce the emissions by acting directly on the undesired molecule. Depending on the type of fuel, and consequently on the type of engine, the emissions and the mitigation systems change.

Some emission control systems are common to both spark ignition (SI) and compression ignition (CI) engines. A notable example is the EGR system, which reduces emissions by recirculating a portion of the exhaust gases back into the intake, lowering the combustion temperature and thus limiting NO_x formation. EGR also plays a role in λ calibration by influencing the air-fuel mixture.

$$\lambda = \frac{\frac{\text{air}}{\text{fuel}}}{\frac{\text{air}}{\text{fuel}}_{\text{stoichiometric}}} \quad (1)$$

Another system used in both engine types is the particulate filter, specifically, the diesel particulate filter (DPF) for diesel engines and the gasoline particulate filter (GPF) for gasoline direct injection (GDI) engines. These filters physically trap solid particulate matter while allowing gaseous components to pass through. Interestingly, the accumulation of particulates can initially enhance filtration efficiency, but once the filter reaches saturation, the ECU triggers the so-called regeneration phase. This phase increases exhaust gas temperature to burn off the accumulated soot. However, it also temporarily increases fuel consumption compared to standard operating conditions.

The typical emissions produced by SI engines include CO , HC and NO . The most effective aftertreatment system for SI engines is the three-way catalyst (TWC), which, when operating under stoichiometric conditions ($\lambda \approx 1$) is capable of simultaneously reducing all three pollutants._x

However, its efficiency varies depending on the air-fuel ratio: in rich mixtures ($\lambda < 1$), the TWC is more effective at reducing NO_x but less efficient in oxidizing CO and HC; conversely, in lean mixtures ($\lambda > 1$), CO and HC conversion improves, while NO_x reduction becomes less effective (**Figure 1**).

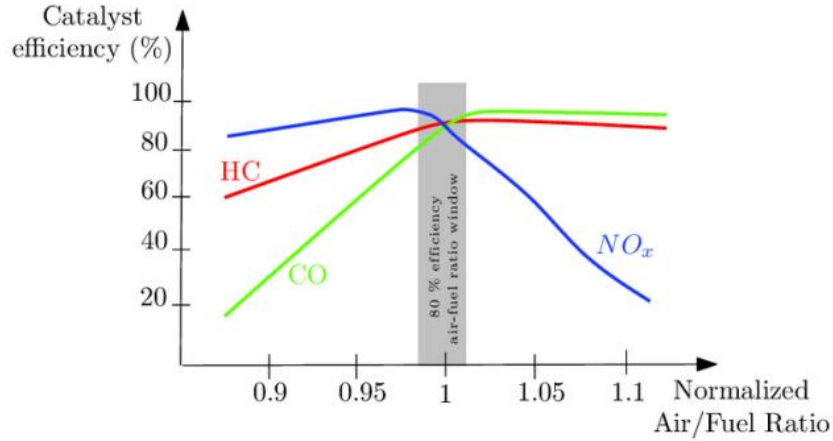


Figure 1: Three-way catalytic converter efficiency [2].

In traditional SI engines the only TWC is enough to meet the regulations, while the complex aftertreatment system for a GDI engine is represented in **Figure 2**.

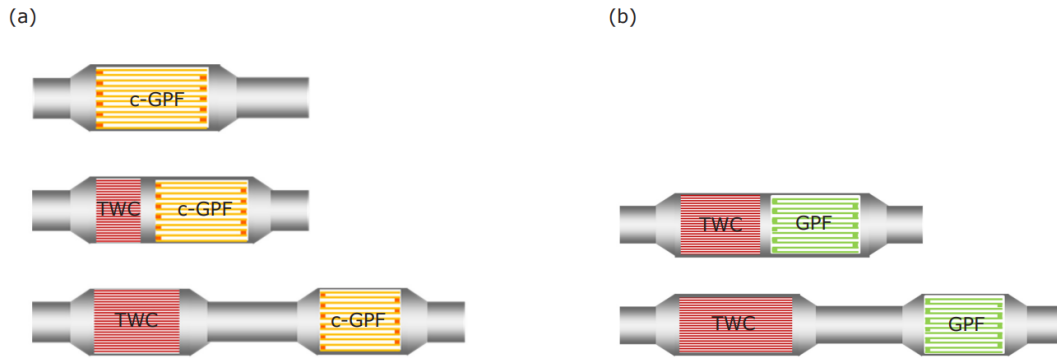


Figure 2: Light-duty gasoline system architecture with GPF. Various option shown, broadly classified into: (a) TWC-coated c-GPF and (b) GPF systems for filtration only [3].

The case of CI engines is different. Although the main pollutants, CO, HC and NO_x , are the same as in SI engines, CI engines typically emit significant higher levels of NO_x and PM due to their high combustion temperature and lean operating conditions.

The reduction of particulate matter is achieved by using the DPF in which, compared to the GPF used in SI engines, soot accumulation is more severe, requiring more frequent regeneration phases to prevent filter saturation.

The reduction of CO, HC and a portion of NO_x is carried out by the diesel oxidation catalyst (DOC), which oxidizes CO and HC into CO_2 and H_2O , and converts part of NO into NO_2 .

The production of NO_2 is intentionally favoured because it enhances the passive regeneration of the DPF.

However, the DOC alone is not sufficient to meet modern NO_x emissions standards. Therefore, an additional aftertreatment system is employed: the selective catalyst reduction (SCR) system, which uses a urea-based solution (AdBlue) and a catalytic substrate (commonly based on vanadium, zeolites, or platinum group metals) to convert NO_x into nitrogen (N_2) and water. To prevent excess ammonia (NH_3) from escaping the tailpipe, an Ammonia Slip Catalyst (ASC) is often installed downstream of the SCR to remove residual NH_3 , ensuring full compliance with emissions limits [4].

All the systems are placed in such a way that the global efficiency is the highest possible. Each device reaches its best efficiency at a certain temperature, for this reason the sequence of each aftertreatment system is DOC-DPF-SCR-ASC as represented in **Figure 3**.

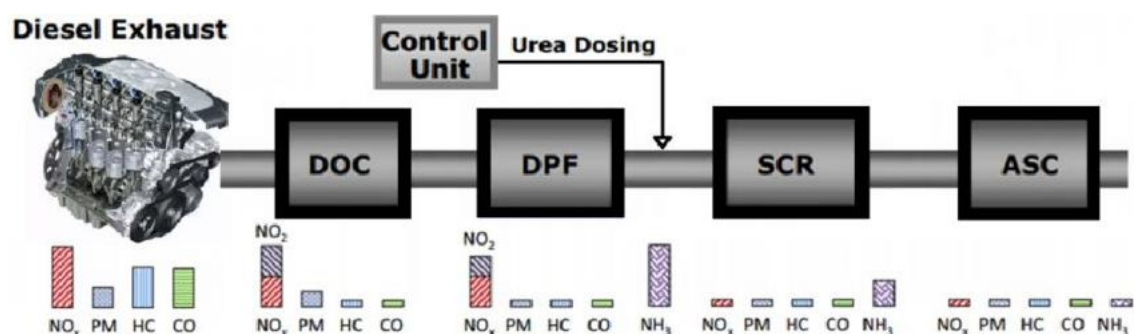


Figure 3: The standard diesel Euro VI aftertreatment system [5].

1.2 New engines

All the aftertreatment systems do not completely solve the problem of the pollutant emissions; they only reduce their amount. Therefore, engineers are striving to develop “zero emissions” vehicles, by creating new powertrain technologies.

Within the field of the ICEs, current research focuses on hydrogen engines. This category is not strictly a “zero emission” solution because, although carbon atoms are not involved in the combustion process, the high combustion temperatures can lead to the formation of NO_x , necessitating dedicated aftertreatment systems.

However, hydrogen is not only used in ICEs. A promising yet challenging technology under development is the Fuel Cell Electric Vehicle (FCEV), in which the hydrogen (H_2) is split into 2H^+ ions and two electrons (2e^-). The 2H^+ ions react with oxygen (O_2) from the air, while the two electrons travel through an external circuit, generating electric current. This process is made possible by an electrolytic membrane that allows the hydrogen protons to pass through while forcing the electrons to flow through an external circuit [6] [7].

Nowadays, the leading solutions for low-emission (hybrid) and zero-emission (fully electric) vehicles are electrified powertrains. These vehicles are equipped with electric motors composed of permanent magnets and coils, which together generate rotational motion of the shaft. Every day, new models employing this technology are gaining ground in the automotive market. [8]

Electric propulsion is now used not only in cars, but also in bicycles, motorcycles, heavy-duty vehicles, medium-to-high capacity public transport vehicles and even high-performance sports cars (Formula-E is a prime example of electric motorsport at the maximum level).

The electric alternative offers several advantages: rapid acceleration, regenerative braking, reduced emissions, and lower noise levels. From an economic perspective, electricity is also generally cheaper than conventional fuels. However, the main drawback remains long recharging time.

1.3 New challenge – Electromagnetic compatibility

The result of this ongoing process of electrification is the significant reduction of ICEs emissions, but the increase in another kind of emission, the Electromagnetic emissions. These emissions were present also in the traditional ICEs vehicles (the simple rolling of the wheels generates electromagnetic fields), but in the electric vehicles, especially in the charging phases, the electromagnetic emissions are particularly severe, in particular in fast-charging [9].

These emissions, unlike those from internal combustion engines, pose different types of challenges, challenges that the field of Electromagnetic Compatibility (EMC) seeks to understand and address. The main problems are the immunity and the emission. Immunity is the capability of a device to normally operate even if the electromagnetic fields generated by other components impinge on it. Obviously, any device is not immune to every kind of electromagnetic perturbation, for this reason it is important to identify the environment in which the device is called upon to work [10].

The environment is influenced by the electromagnetic emissions of the devices, so it is important that the totality of the emissions is not harmful to the other devices and, in some cases, for the humans [11].

As reported by the ICNIRP (International Commission on Non-Ionizing Radiation Protection) Guidelines of 1998 [12], there are three mechanisms of interaction between electromagnetic fields (EMFs) and living matter:

- coupling to low-frequency electric fields;
- coupling to low-frequency magnetic fields;
- absorption of energy from electromagnetic fields at higher frequencies.

During the interaction between time-varying electric fields with human body, electric current arises, electric dipoles are formed, and the already existing dipoles reorient themselves. The intensity of these phenomena depends on the electrical properties of the body or tissue. In fact, the conductivity, the permeability and the permittivity depend on the tissues and on the frequency of the field. Electric field external to the body induces a surface charge by causing induced currents and its distribution depends on the body geometry and position with respect to the field.

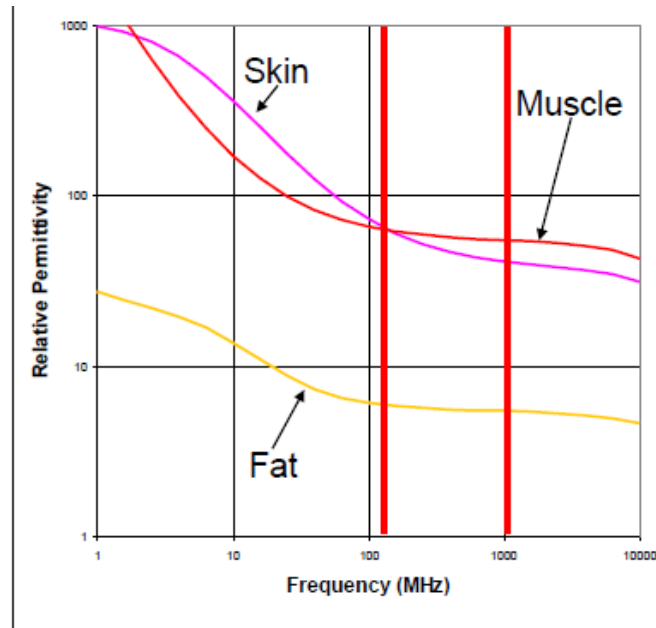


Figure 4: Relative Permittivity vs. Frequency for various body tissue types [13].

For what concerns the coupling with low-frequency magnetic fields, the interaction with the human body results in induced electric fields and circulating electric currents (**Figure 5**).

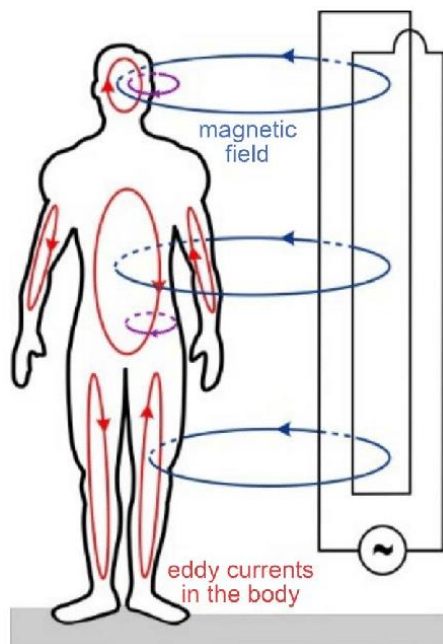


Figure 5: Eddy currents in human body caused by low-frequency magnetic field [14].

The intensity is proportional to the radius loop, greater is the radius greater is the intensity. The path of induced currents is related to the tissue, and being the body not electrically homogeneous, it is different in any part of the body. These two cases are negligible from the absorption energy point of view, but it becomes crucial when high-frequency

electromagnetic fields (above 100 kHz) are taken into account. The indicator for the absorbed energy at high frequency is the SAR (specific absorption rate) that is directly proportional to the electrical conductivity of the tissue and to square of the root-mean-square value of the electric field, and inversely proportional to the mass density of the tissue. [12]

To better explain the level of absorption it is important to divide the electromagnetic field in four ranges [12]:

- frequencies from 100 kHz up to 20 MHz, at which the absorption in the trunk decreases rapidly with decreasing frequency. Significant absorption may occur in the neck and legs;
- frequencies from 20 MHz up to 300 MHz, at which relatively high absorption can occur in the whole body, and to even higher values if partial body resonances are considered (e.g. head);
- frequencies from 300 MHz up to 10 GHz, at which significant local, non-uniform absorption occurs;
- frequencies above 10 GHz, at which energy absorption occurs primarily at the body surface.

Another coupling mechanism is the indirect one. Also in this case, it is necessary to talk about two different categories of indirect coupling mechanism:

- contact currents (human body enters in contact with an object at a different electric potential);
- coupling of electromagnetic fields to medical devices, worn by or implanted in, an individual [12].

As explained in the *Non-binding guide to good practice for implementing Directive 2013/35/EU* [15], the health effects and risks associated with electromagnetic fields are classified as either direct effects and indirect effects.

The direct effects are those caused by the exposure of a human to an electromagnetic field. There are two kinds of direct effects, health effects, permanent effects still present after the end of the exposure, and sensory effects, transient effects that stop when the exposure is removed. Direct effects are vertigo and nausea for static magnetic fields, effects on organs, nerves and muscles (up to 100 kHz), heating up of all body or portion of it (equal or higher than 10 MHz), effects on nerves and muscles and heating up caused by intermediate frequencies (100 kHz – 10 MHz).

Indirect effects are caused by the presence of conductive objects within an electromagnetic field (EMF), which may harm individuals who come into contact with them. Those effects are interferences with electronic medical devices, interferences with active implantable medical devices (AIMD), interferences with medical devices worn on body (insulin injectors), interferences with passive implantable medical devices (PIMD), effects on metallic splinters, tattoos, body piercing and body art, propulsive risk of not fixed ferromagnetic objects, accidental primer of detonators, primer of blazes caused by

inflammable objects, electric sparks or burns due to contact currents when a person touches a conductor element inside an electromagnetic field and one of them is not grounded.

To prevent any health effect, many organizations in the world gave advice to nations and populations. The most important is the already mentioned ICNIRP, but it is not the only one. Many states embraced the Guidelines of the ICNIRP and inspired by them, imposed restrictions and laws on the infrastructures, workers and companies for the protection of the population itself.

Among them, at the European level, the most prominent are the *Council Recommendations of 12 July 1999* and the *Directive 2013/35/EU of the European Parliament and of the Council of 26 June 2013*. As is readily observable, these regulations are somewhat outdated, yet they remain in effect to this day. Over time, all sectors have progressively aligned with these standards. However, in the current context of increasing and continuous electrification, complying with such constraints presents a growing challenge and can no longer be taken for granted. The automotive sector also, as one of the industries most heavily engaged in electrification, is also confronting this challenge.

The automotive industry is not dedicated only to private customers, but it is also comprehensive of the commercial vehicles branch. But if a personal vehicle can be easily adapted to the necessities of its owner, this is not so simple for commercial vehicles, often bought by an employer and given to its employees or used by public community.

Let us now consider the buses. They can be considered commercial vehicles, where a wide variety of persons enter inside it. Men, women, children, young and old and each one individual is distinct from the others. This means that these vehicles are products aimed at everyone and at every kind of person, and this is a strength from the commercial point of view, but at the same time it is a weakness because each vehicle must respect the restrictions imposed by law, also for the most critical cases. To that purpose, it is fundamental to know what the most vulnerable individuals are. At first glance, one might think of children, but this is not the case.

The discussion previously addressed the issue of indirect effects and there it is possible to find the weakest and the most critical elements, also more than the biological tissues, the medical devices. They can be classified in two categories: PIMD, as prostheses, screw, metallic plates, and AIMD as implantable insulin microinjector or the cochlear implant. Their interaction with electromagnetic fields requires particular attention, as it may cause significant harm to users.

The effects are different based on the type of medical device. Passive medical devices inside electromagnetic fields could move causing indirect effects harmful to humans, but the worst case are the indirect effects that affect AIMD. Among them the most sensitive to electromagnetic fields are pacemakers. Principal risks are the suppression of the stimulation, spurious stimulation and shifting to security mode [16], potentially life-threatening for individuals with implants (**Figure 6**).

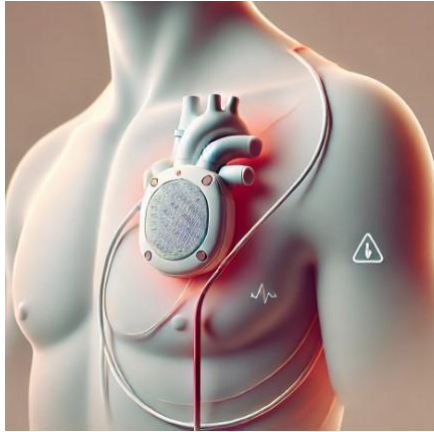


Figure 6: Representation of warning in pacemaker [17].

The restrictions currently in effect consider also these kinds of problems, and impose additional limit values of electromagnetic fields, discretizing the occupational exposure and public exposure. This is particularly relevant in the automotive sector, especially for buses and other vehicles prone to public transports. In such vehicles, pacemakers may be present in both passengers and drivers (or other personnel) who could remain inside the vehicle for extended periods of time.

2 Aim of the thesis

After discussing the risks associated with electromagnetic fields (both direct and indirect effects), users may feel uncertain or concerned about the safety of using such vehicles, especially if they are electric and/or large, like buses.

The scope of the thesis is to demonstrate that the buses produced by IVECO Group are in compliance with the regulations above mentioned and that their products are of high quality so that they can claim they serve as models to be followed even by their competitors.

It is important to define and follow a clear methodology that complies with relevant regulations, in order to ensure the validity and reliability of the process.

The first step consisted in identifying the current regulations and legal limits established by institutions, to define precise constraints for the measured values.

The relevant regulations cover not only exposure limits, but also for the measurement setup. Adhering to established standards is essential to ensure accurate and reliable measurements. In this step, it is also important to verify that the measurement device and its setup are capable of ensuring the performance required by the standards.

Once having set up the tools, the measurement values are recorded and compared to the limits of before.

These values are expected to already comply with the imposed limits, while any deviation from them will provide an indication of the product's quality and safety.

This study is not only important for assessing the safety of electromagnetic emissions from IVECO's buses, but also for evaluating the adequacy of current procedures and standards. In the automotive sector, several regulatory gaps still exist. While specific standards have already been defined for conventional cars, commercial and heavy-duty vehicles, such as buses, are still lacking in this regard. Therefore, a secondary task of this thesis is to provide guidance and recommendations that may support the development of new, dedicated standards for buses, and potentially for the other vehicle categories as well. During the thesis activity, for this purpose, a proactive dialog with EU-JRC and local ARPA is started.

3 The phenomenon of electromagnetic fields

The previous chapters addressed electromagnetic (EM) emissions without discussing their physical meaning. Electromagnetic fields are wave phenomena that propagate through space and are described by Maxwell's equations. Although not easily solvable, they constitute a fundamental tool for the design of electronic devices, with applications concerning both emissions and susceptibility.

3.1 Maxwell's equation

Although commonly referred to as Maxwell's equations, their development was the result of contribution from several physicists prior to Maxwell. There are four equations: Gauss's laws (for the electric field and magnetic field), Faraday-Neumann-Lenz's law (electric field circulation) and Ampère-Maxwell's law (magnetic field circulation). They have two forms, a differential one and an integral one. Their differential form is presented later:

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}; \quad \nabla \cdot \mathbf{B} = 0; \quad \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}; \quad \nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t} \quad (2)$$

3.1.1 First Gauss's law – electric field

The flux of the $\mathbf{E}$ field through the surface $d\Sigma$ is the scalar quantity [18]

$$d\Phi(\mathbf{E}) = \mathbf{E} \cdot \mathbf{u}_n d\Sigma = E \cos(\theta) d\Sigma = \mathbf{E}_n \cdot d\mathbf{\Sigma} \quad (3)$$

where $\mathbf{u}_n$ is the unit vector normal to the surface and θ is the angle between the $\mathbf{E}$ field and $\mathbf{u}_n$ (Figure 7).

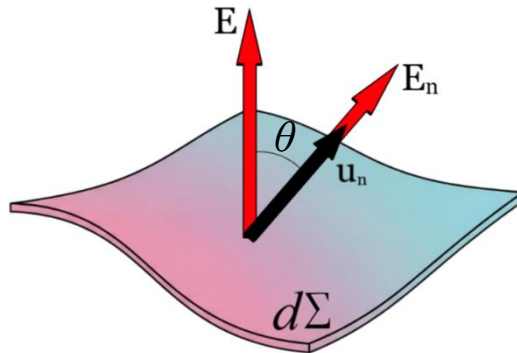


Figure 7: Electric field flux through an infinitesimal surface $d\Sigma$.

The flux on a finite surface can be obtained by a surface integral as follows

$$\Phi(\mathbf{E}) = \int_{\Sigma} \mathbf{E} \cdot \mathbf{u}_n d\Sigma \quad (4)$$

And if the surface is closed

$$\Phi(\mathbf{E}) = \oint_{\Sigma} \mathbf{E} \cdot \mathbf{u}_n d\Sigma \quad (5)$$

So, Gauss's law for electrostatic field states:

The flux of the electrostatic field $\mathbf{E}$ produced by a system of charges through a closed surface is equal to the algebraic sum of the electric charges contained within the surface, divided by ϵ_0 [18].

$$\Phi(\mathbf{E}) = \oint \mathbf{E} \cdot \mathbf{u}_n d\Sigma = \frac{\sum_i q_i}{\epsilon_0} \quad (6)$$

This law is the first of Maxwell's equations set, where q_i denotes a distribution of discrete charges, generalizable as in (2) where it is defined a volumetric charge density ρ .

3.1.2 Second Gauss's law – magnetic field

Similarly to the previous law, the magnetic field through an infinitesimal surface can be written as [17]:

$$d\Phi(\mathbf{B}) = \mathbf{B} \cdot \mathbf{u}_n d\Sigma \quad (7)$$

and for a closed surface:

$$\Phi(\mathbf{B}) = \oint \mathbf{B} \cdot \mathbf{u}_n d\Sigma \quad (8)$$

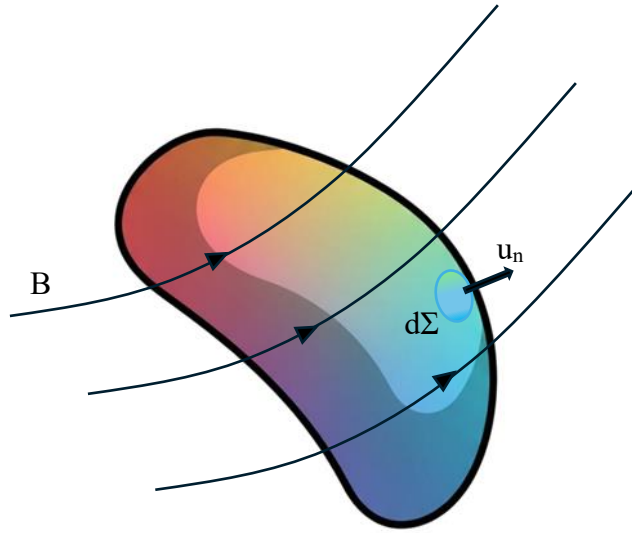


Figure 8: Flux of magnetic field through a closed surface.

Studies of the magnetic field show that its field lines have neither a beginning nor an end, and along them the direction of $\mathbf{B}$ remains constant. As a consequence, each line of $\mathbf{B}$ entering a closed surface must necessarily exit it (**Figure 8**), and the magnitude of the entering flux must be equal to the exiting one. This implies that the total flux must be zero [18].

$$\Phi(\mathbf{B}) = \oint \mathbf{B} \cdot \mathbf{u}_n d\Sigma = 0 \quad (9)$$

In fact, the Gauss's law for magnetic field states:

The flux of the magnetic field $\mathbf{B}$ through a closed surface is always zero [18]. This fact, in connection with Gauss's law, is further supported by the absence of isolated magnetic charges, unlike electric charges.

3.1.3 Faraday-Neumann-Lenz's law – electromagnetic induction

The Faraday-Neumann-Lenz's law states:

Whenever the magnetic flux $\Phi(\mathbf{B})$ linked with a circuit varies with time, an electromotive force (emf) is induced in the circuit, equal to the negative time derivative of the flux [18].

$$emf = - \frac{d\Phi(\mathbf{B})}{dt} \quad (10)$$

Assuming R the circuit resistance, the current that flows through is:

$$i = \frac{emf}{R} = -\frac{1}{R} \cdot \frac{d\Phi(\mathbf{B})}{dt} \quad (11)$$

Considering also the electromotive force as:

$$emf = \oint \mathbf{E}_i \cdot d\mathbf{s} \quad (12)$$

where E_i is the induced electric field, it is possible to write:

$$emf = \oint \mathbf{E}_i \cdot d\mathbf{s} = -\frac{d\Phi(\mathbf{B})}{dt} \quad (13)$$

The sign minus is the contribute of the physicist Lenz. It is fundamental from the physical point of view of the entire law. It means that the emf is always in opposition to the variation of the magnetic flux. In conclusion, the Lenz law states:

The effect of the induced electromotive force is always such as to oppose the cause that generated it; therefore, the electromotive force that arises in the circuit produces an induced current whose magnetic effects oppose the variations of the flux $\Phi(\mathbf{B})$ linked with the circuit itself [18].

3.1.4 Ampère-Maxwell's law

The Ampère's law is valid for the magnetic field in particular in vacuum [18]:

$$\oint \mathbf{B} \cdot d\mathbf{s} = \mu_0 i_c \quad (14)$$

where i_c is the current that flows through the considered surface and its product with the magnetic permeability is the circulation of the magnetic flux generalizable with the current density $\mathbf{J}$ as in (2).

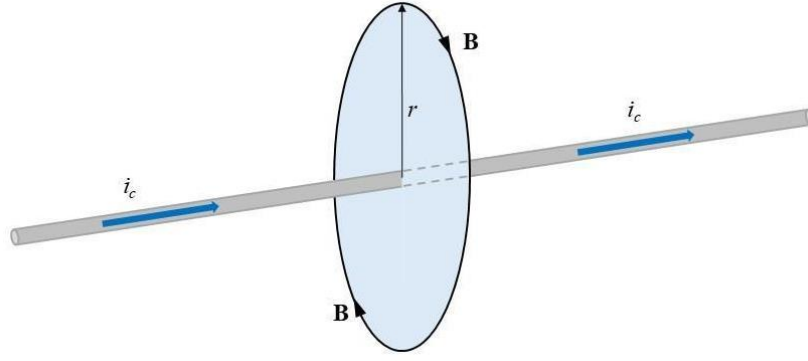


Figure 9: Ampère's law representation.

This law is satisfied when the current i_c is supported by conductor (**Figure 9**).

When the electromagnetic phenomenon with time-variation is present in a conductive system with discontinuities (for example in the plates of a capacitor as in **Figure 10**), the Ampère law is not valid anymore [18].

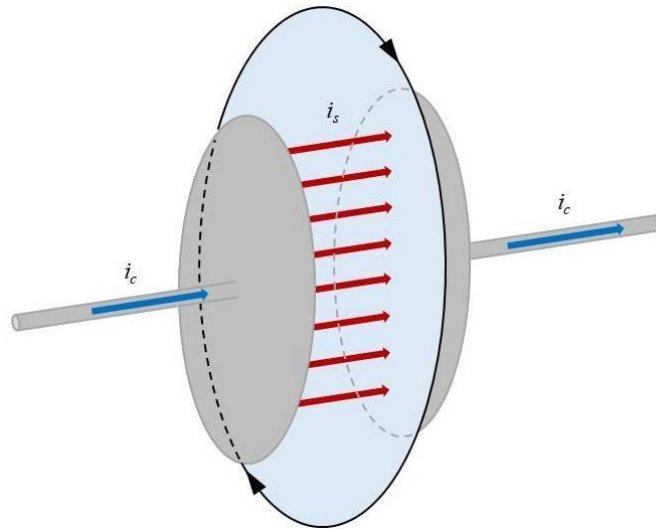


Figure 10: Ampère-Maxwell's law representation.

Maxwell's contribution was fundamental, because he noticed that it was necessary to introduce an additional term regarding the displacement current i_s . With this addition, Ampère's law became Ampère-Maxwell's law that in vacuum presents the following form[18].

$$\oint \mathbf{B} \cdot d\mathbf{s} = \mu_0 \left(i_c + \varepsilon_0 \frac{d\Phi(\mathbf{E})}{dt} \right) \quad (15)$$

where:

$$i_s = \varepsilon_0 \frac{d\Phi(\mathbf{E})}{dt} \quad (16)$$

3.1.5 Electromagnetic waves

These four laws make up the set of Maxwell's equations (2), that in vacuum (without charges and currents) can be written in integral form with respect to differential form reported at (2) as [18]:

$$\begin{aligned} I) \oint \mathbf{E} \cdot \mathbf{u}_n d\Sigma &= 0, \quad II) \oint \mathbf{B} \cdot \mathbf{u}_n d\Sigma = 0, \\ III) \oint \mathbf{E} \cdot d\mathbf{s} &= -\frac{d\Phi(\mathbf{B})}{dt}, \quad IV) \oint \mathbf{B} \cdot d\mathbf{s} = \varepsilon_0 \mu_0 \frac{d\Phi(\mathbf{E})}{dt} \end{aligned} \quad (17)$$

From this set, Maxwell was able to predict the wave nature of the electromagnetic fields.

With proper considerations, the equations solution can be written in sinusoidal form, as waves, and/or as composition of waves.

If electromagnetic fields propagate through space as waves, their characteristics can be described using typical parameters such as wavelength, period and frequency.

Particularly the wavelength λ is the distance between two consecutive wave crests of a monochromatic, the period T is the time interval between two consecutive wave crests, while the frequency f is the inverse of the period. **Figure 11** represents a monochromatic wave of the electric field $\mathbf{E}$, which similarly describes the behaviour of the magnetic field $\mathbf{B}$.

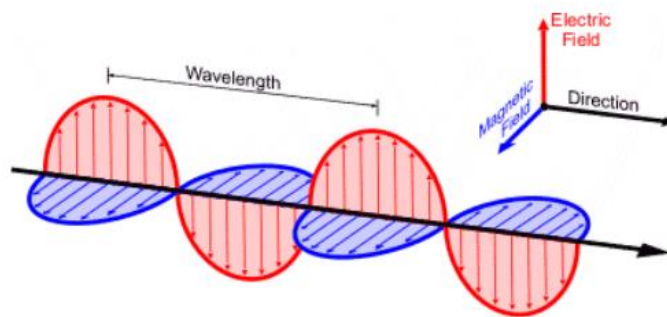


Figure 11: Electromagnetic wave [19].

From the set of equations (17) it is clear that electric field $\mathbf{E}$ and the magnetic field $\mathbf{B}$ can not be separated when time variations are relevant: whenever an electric field $\mathbf{E}$ is present, a magnetic field $\mathbf{B}$ is also present, and vice versa. For this reason, they are referred to as electromagnetic fields and electromagnetic waves, as the two fields are coupled.

As fundamental solution of equations (17), when time variation are relevant we consider the monochromatic uniform plane wave whose properties are [18]:

- $\mathbf{E}$ and $\mathbf{B}$ propagate at the same speed $c = \sqrt{1/(\varepsilon_0 \cdot \mu_0)} \approx 3 \cdot 10^8 \text{ m/s}$;
- the magnitudes of the fields are correlated with the relationship $B = E/c$;
- $\mathbf{E}$ and $\mathbf{B}$ are orthogonal to each other and to the direction of propagation: the electromagnetic waves are transversal waves and for them the concept of polarization is significant;
- the direction of the vectorial product $\mathbf{E} \times \mathbf{B}$ defines the direction of the propagation given by $\mathbf{c}$;
- the electromagnetic waves are subject to the principle of superposition; this is a general property that arises from the fact that in equations (17) $\mathbf{E}$ and $\mathbf{B}$ are linear.

Exploiting these property we can represent any electromagnetic fields in terms of plane wave spectrum [18].

$$u_e = \frac{1}{2} \varepsilon_0 E^2 \quad , \quad u_m = \frac{1}{2\mu_0} B^2 \quad (18)$$

u_e is the electric field energy and u_m is the magnetic field energy. Exploiting this property we can represent any electromagnetic fields in terms of plane wave spectrum. E^2 and H^2 are the square modulus respectively of $\mathbf{E}$ and $\mathbf{H}$. The total energy is given by the sum of the energies of the electric field and the magnetic field.

$$u = u_e + u_m \quad (19)$$

For what concern the transport of energy it is defined by the Poynting vector $\mathbf{S}$.

$$\mathbf{S} = \frac{1}{\mu_0} \mathbf{E} \times \mathbf{B} \quad (20)$$

This one is the energy flux, the power per unit area carried by the wave. i.e. energy flows through a specific area per unit of time, including the information on the direct flow as it is a vector quantity

3.2 Shielding of electromagnetic fields

It is possible that the emissions of a device are so high that they exceed the limits imposed, leading to non-compliance with the regulations. The most effective solution to prevent this problem, when the device can not be modified, is *shielding*. The term *shielding* refers to the technique of enclosing the device within a metallic box, thereby fully containing it. The main purposes of shielding are two [20]:

- to prevent the emissions of the shielded device, or part of them, from radiating beyond the enclosure. This ensures compliance with the regulatory limits (**Figure 12a**);
- to prevent the emitted radiation from coupling with other devices, thereby avoiding interference or malfunction of the entire system of devices (**Figure 12b**).

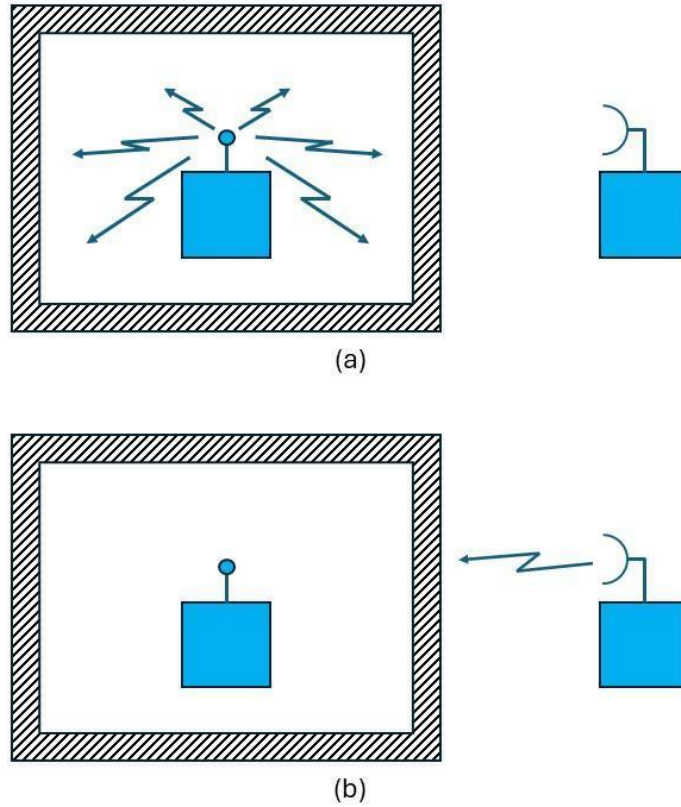


Figure 12: Shielding.

An important parameter is the shielding efficiency (SE). It is the ratio between the magnitude of the incident electromagnetic field on the shield and the magnitude of the electromagnetic field transmitted through the shield. The shielding efficiency is defined in dB and for the electric field it is [20]:

$$SE = 20 \cdot \log_{10} \left| \frac{E_i}{E_t} \right| \quad (21)$$

Similarly, for the magnetic field it is

$$SE = 20 \log_{10} \left| \frac{H_i}{H_t} \right| \quad (22)$$

If the source of the electromagnetic field is close to the shield the efficiencies for the electric field and for the magnetic field are not the same, however usually the reference efficiency is the one expressed in (21).

In case of ray propagation, let's consider the **Figure 13**

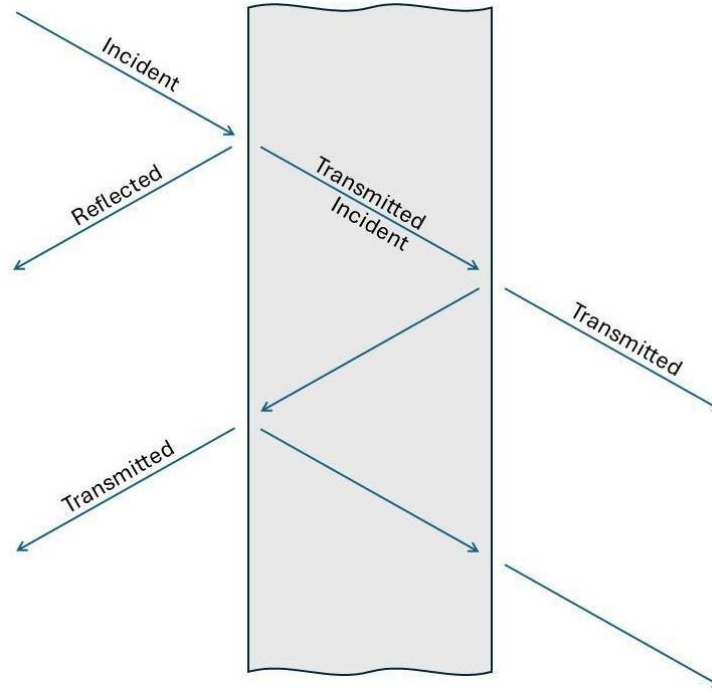


Figure 13: Multiple reflections within a shield that exemplifies a ray propagation.

Several phenomena reduce the electromagnetic field during its transmission through the shield. The proportion of the incident electromagnetic field that is reflected depends on the reflection coefficient of the shield (in **Figure 13** the “Reflected” arrow on the left). The proportion of the electromagnetic field that propagates through the shield is referred to as the “Transmitted” field. The transmitted field after the first wall becomes incident on the second interface of the shield, where part of it is reflected back inside the shield and the remaining portion is transmitted outside. Similarly, the reflected portion inside the shield returns to the first wall, where is again partially transmitted within the shield and partially transmitted outside. The multiple reflections inside the two interfaces of the shield reduce drastically the emissions also because the material of the shield is conductive and the amplitude of the wave is attenuated of a factor $e^{-\alpha}$, where α is the attenuation constant of the material. This phenomenon is called *absorption losses* [20]. Finally, the shielding efficiency can be divided in the contribution of three phenomena: *reflection loss* R , *absorption loss* A and *multiple reflection loss* M

$$SE_{dB} = R_{dB} + A_{dB} + M_{dB} \quad (23)$$

3.2.1 Shielding of electromagnetic fields at low frequencies

It is important to underline that the mechanisms described before have different relevance depending on the type of field and the distance of the source and operational frequency, as the phenomena change according to the electric distance. For sources located far from the shield, reflection loss is the predominant mechanism at low-frequencies, while absorption loss becomes dominant at high-frequencies. In the case of sources close to the shield, a distinction between electric and magnetic fields is necessary. For nearby electric field sources, as previous stated, reflection loss prevails at low frequencies, whereas absorption loss prevails at high frequencies. For nearby magnetic field sources, absorption loss is the dominant mechanism across all frequencies. However, at low frequencies this mechanism is very weak, which makes it necessary to adopt different shielding strategies [20].

There are two main strategies to mitigate low-frequency magnetic fields:

- diverting the magnetic flux using materials with high magnetic reluctance;
- generating an opposing magnetic flux by applying the Faraday's law (the short-circuited loop method).

However, two factors could worsen the shielding efficiency of the first technique:

- the permeability of ferromagnetic materials decreases when the frequency increases;
- the permeability of ferromagnetic materials decreases when the intensity of the magnetic field increases.

For these reasons, the producers of ferromagnetic materials give the value of the relative permeability at a given low frequency, so that is the maximum permeability for that material [20].

So, it is important to establish first the value of the magnetic field to mitigate and successively choose the most appropriate material of the shielding.

Often to avoid the saturation, the shielding is made of two shields, one with a low value of μ_r and high saturation threshold to reduce the incident magnetic field, and the other with a high value of μ_r and a lower saturation threshold.

3.2.2 Effect of openings

Sometimes shielding must include openings for practical reasons, such as cooling the device. To avoid a significant reduction in shielding effectiveness, these openings are made numerous and small, rather than a single large hole. This is because the induced currents generate magnetic fields that oppose the magnetic field to be mitigated. If the hole is large and singular, the direction of the induced currents would be altered, and the induced magnetic field would be less effective, thereby reducing the shielding efficiency. Since the exact direction of the induced currents cannot be known, a large number of small holes is preferred.

Access panels are also necessary, which inevitably create some gaps. If the length of these gaps is much greater than their thickness and is of the same order of magnitude as the relevant wavelength, they can act as a *slotted antenna*, according to Babinet's principle. To prevent this, multiple screws are positioned close together around the cover, and in some cases metallic gaskets are used to seal the gaps and operational frequencies, as the phenomena change according to electric distance [20].

4 Standard and exposure limits

Once the nature of electromagnetic fields has been clarified, and the mechanisms by which their propagation can be reduced through shielding have been understood, it is essential to define the threshold values that must not be exceeded.

As previously outlined in Chapter 1, ICNIRP has carried out extensive studies with the objective of defining safe levels of human exposure to electromagnetic fields. The results of this research activity is a set of internationally recognised guidelines, which provide scientifically based recommendations aimed at ensuring the protection of the general population and of the workers who may be exposed in specific environments. These guidelines establish threshold values of exposure, above which there is a risk that electromagnetic fields may produce harmful biological or health effects on the exposed individuals. Consequently, they represent the reference framework within which measurements and evaluations must be conducted, and they form the benchmark against which the compliance of any practical case is assessed.

4.1 ICNIRP 1998

Chronologically speaking, the first article is the “*Guidelines for limiting exposure to time-varying electric, magnetic and electromagnetic fields (up to 300 GHz)*” [12]. Its aim is to establish guidelines and exposure limits to prevent any health effects. The article make difference between direct effects, effects caused directly by electromagnetic fields (EMFs) on human tissues, and indirect effects, caused by the exposure of objects that successively damage the human by the contact with them.

Another distinction concerns the classes of guidance. The *basic restrictions* are based on established health effects, and they are current density (**J**), specific energy absorption rate (SAR), and power density (S). These are values inside the human body, so they cannot be measured in individuals. The *reference levels* are those values provided for practical assessment. They are electric field strength (**E**), magnetic field strength (**H**), magnetic flux density (**B**), power density (**S**) and current flowing through the limbs (**I_L**). The indirect effect quantities are contact current (**I_C**) and specific energy absorption (SA). Compliance with reference levels ensures compliance with basic restrictions [12].

Regarding the quantities, the units of measure, electric field **E** is expressed in volts over meters (V m^{-1}), magnetic field **H** is expressed in ampere over meter (A m^{-1}), magnetic flux density **B** in tesla (T). Being **H** and **B** correlated by the expression:

$$\mathbf{B} = \mu \mathbf{H} \quad (24)$$

where μ is the magnetic permeability, (μ is the ratio between the relative magnetic permeability μ_R over the magnetic permeability in vacuum μ_0) just one between $\mathbf{B}$ or $\mathbf{H}$ is enough to describe the magnetic field.

The power density $|\mathbf{S}|$ is related to $\mathbf{E}$ (rms) and $\mathbf{H}$ (rms) by the expression:

$$|\mathbf{S}| = E \times H = |\mathbf{E}|^2/377 = 377 \cdot |\mathbf{H}|^2 \quad (25)$$

The value of 377 ohm is the vacuum impedance.

Similarly to magnetic field and magnetic flux, the internal electric field and current density are related by the equation:

$$\mathbf{J} = \sigma \mathbf{E} \quad (26)$$

where σ is the electrical conductivity of the medium [12].

The coupling mechanisms are already explained in Chapter 1. Instead, the attention is focused on another important section of the document, “Biological basis for limiting exposure”. Another distinction is established between frequencies up to 100 kHz and frequency from 100 kHz up to 300 GHz.

In these sections the results of biological (both on animals and human volunteers) experiments are recorded[12]. At low frequencies there are no significative data that could demonstrate the correlation between carcinogenesis and electromagnetic exposure, with the possible exception of mammary tumours. A threshold of 10 mA m⁻² up to 1 kHz is reported for the current density that could cause minor effects on nervous system functions, while the exposure to extreme low frequency (ELF) fields causes the appearance of visual phosphenes and minor heart rate, but without the association with long-term risks[12].

At high frequencies, the most evident effect to extended exposure (about 30 minutes), is the increase of body temperature of about 1°C, damaging temporarily the thermoregulation. For what concerns the indirect effects, when the contact with metallic objects exposed to electromagnetic fields occurs, the contact currents that arises could cause burns or other injuries. For these effects, different threshold levels have been identified. Specifically, the SAR threshold level associated to direct effect is 4 W kg⁻¹. For contact currents, values in the range of 25-40 mA are considered as the perception threshold, 30-55 mA correspond to the pain threshold and currents exceeding 50 mA can result in severe burns [12].

The last distinction present in the document is the occupational and the general public exposure. The distinction is made because the workers are trained to take appropriate precautions. Instead, the general public comprises all ages individuals who could have every kind of health status. Often the general public is unaware of their exposure to EMF, so the limits imposed are more restrictive [12].

4.1.1 Exposure limits

Table 1: Basic restrictions for time-varying electric and magnetic fields for frequencies up to 10 GHz^a [12].

Exposure characteristics	Frequency range	Current density for head and trunk (mA m ⁻²) (rms)	Whole-body average SAR (W kg ⁻¹)	Localized SAR (head and trunk) (W kg ⁻¹)	Localized SAR (limbs) (W kg ⁻¹)
Occupational exposure	Up to 1 Hz	40	-	-	-
	1 – 4 Hz	40/ <i>f</i>	-	-	-
	4 Hz – 1 kHz	10	-	-	-
	1 – 100 kHz	<i>f</i> /100	-	-	-
	100 kHz – 10 MHz	<i>f</i> /100	0.4	10	20
	10 MHz – 10 GHz	-	0.4	10	20
General public exposure	Up to 1 Hz	8	-	-	-
	1 – 4 Hz	8/ <i>f</i>	-	-	-
	4 Hz – 1 kHz	2	-	-	-
	1 – 100 kHz	<i>f</i> /500	-	-	-
	100 kHz – 10 MHz	<i>f</i> /500	0.08	2	4
	10 MHz – 10 GHz	-	0.08	2	4

^aNote:

1. *f* is the frequency in Hz.
2. Because of electrical inhomogeneity of the body, current densities should be averaged over a cross-section of 1 cm² perpendicular to the current direction.
3. For frequencies up to 100 kHz, peak current density values can be obtained by multiplying the rms value by $\sqrt{2}$ (~1.414). For pulses of duration t_p the equivalent frequency to apply in the basic restrictions should be calculated as $f = 1/(2t_p)$.
4. For frequencies up to 100 kHz and for pulsed magnetic fields, the maximum current density associated with the pulses can be calculated from the rise/fall times and the maximum rate of change of magnetic flux density. The induced current density can then be compared with the appropriate basic restriction.
5. All SAR values are to be averaged over any 6-min period.
6. Localized SAR averaging mass in any 10 g of contiguous tissue; the maximum SAR so obtained should be the value used for the estimation of exposure.
7. For pulses of duration t_p the equivalent frequency to apply in the basic restrictions should be calculated as $f = 1/(2t_p)$. Additionally, for pulses exposures in the frequency range 0.3 to 10 GHz and for localized exposure of the head, in order to limit or avoid auditory effects caused by thermoelastic expansion, an additional basic restriction is recommended. This is that the SA should not exceed 10 mJ kg⁻¹ for workers and 2 mJ kg⁻¹ for the general public, averaged over 10 g tissue.

Table 2: Basic restrictions for power density for frequencies between 10 and 300 GHz^a [12].

Exposure characteristics	Power density (W m ⁻²)
Occupational exposure	50
General public	10

^aNote:

1. Power densities are to be averaged over any 20 cm² of exposed area and any 68/ $f^{1.05}$ -min period (where f is in GHz) to compensate for progressively shorter penetration depth as the frequency increases.
2. Spatial maximum power densities, averaged over 1 cm², should not exceed 20 times the values above.

Table 3: Reference levels for occupational exposure to time-varying electric and magnetic fields (unperturbed rms values)^a [12].

Frequency range	E-field strength (V m ⁻¹)	H-field strength (A m ⁻¹)	B-field (μT)	Equivalent plane wave power density S_{eq} (W m ⁻²)
Up to 1 Hz	-	1,63 x 10 ⁵	2 x 10 ⁵	-
1 – 8 Hz	20.000	1,63 x 10 ⁵ / f^2	2 x 10 ⁵ / f^2	-
8 – 25 Hz	20.000	2 x 10 ⁴ / f	2,5 x 10 ⁴ / f	-
0,025-0,82 kHz	500/ f	20/ f	25/ f	-
0,82-65 kHz	610	24,4	30,7	-
0,065 – 1 MHz	610	1,6/ f	2,0/ f	-
1 – 10 MHz	610/ f	1,6/ f	2,0/ f	-
10 – 400 MHz	61	0,16	0,2	10
400 – 2.000 MHz	3/ $f^{1/2}$	0,008/ $f^{1/2}$	0,01/ $f^{1/2}$	$f/40$
2 – 300 GHz	137	0,36	0,45	50

^aNote:

1. f as indicated in the frequency range column.
2. Provided that basic restrictions are met and adverse indirect effects can be excluded, field strength values can be exceeded.
3. For frequencies between 100 kHz and 10 GHz, S_{eq} , E^2 , H^2 , and B^2 are to be averaged over any 6-min period.
4. For frequencies up to 100 kHz, peak current density values can be obtained by multiplying the rms value by $\sqrt{2}$ (~1.414). For pulses of duration t_p the equivalent frequency to apply in the basic restrictions should be calculated as $f = 1/(2t_p)$.
5. For peak values at frequencies exceeding 100 kHz see **Figure 14** and **Figure 15**. Between 100 kHz and 10 MHz, peak values for the field strengths are obtained by interpolation from the 1,5-fold peak at 100 kHz to the 32-fold peak at 10 MHz. For frequencies exceeding 10 MHz it is suggested that the peak equivalent plane wave power density, as averaged over the pulse width, does not exceed 1.000 times the S_{eq} restrictions, or that the field strength does not exceed 32 times the field strength exposure levels given in the table.
6. For frequencies exceeding 10 GHz, S_{eq} , E^2 , H^2 , and B^2 are to be averaged over any 68/ $f^{1.05}$ -min period (f in GHz).
7. No E-field value is provided for frequencies < 1 Hz, which are effectively static fields. Perceptions of surface electric charges will not occur at field strengths less than 25 kVm⁻¹. Spark discharges causing stress or annoyance should be avoided.

Table 4: Reference levels for general public exposure to time-varying electric and magnetic fields (unperturbed rms values)^a [12].

Frequency range	E-field strength (V m ⁻¹)	H-field strength (A m ⁻¹)	B-field (μT)	Equivalent plane wave power density S_{eq} (W m ⁻²)
Up to 1 Hz	-	3,2 x 10 ⁴	4 x 10 ⁴	-
1 – 8 Hz	10.000	3,2 x 10 ⁴ / f^2	4 x 10 ⁴ / f^2	-
8 – 25 Hz	10.000	4.000/ f	5.000/ f	-
0.025-0.8 kHz	250/ f	4/ f	5/ f	-
0.8-3 kHz	250/ f	5	6,25	-
3 – 150 kHz	87	5	6,25	-
0,15 – 1 MHz	87	0,73/ f	0,92/ f	-
1 – 10 MHz	87/ $f^{1/2}$	0,73/ f	0,92/ f	-
10 – 400 MHz	28	0,073	0,092	2
400 – 2.000 MHz	1,375/ $f^{1/2}$	0,0037/ $f^{1/2}$	0,0046/ $f^{1/2}$	$f/200$
2 – 300 GHz	61	0,16	0,20	10

^aNote:

1. f as indicated in the frequency range column.
2. Provided that basic restrictions are met and adverse indirect effects can be excluded, field strength values can be exceeded.
3. For frequencies between 100 kHz and 10 GHz, S_{eq} , E^2 , H^2 , and B^2 are to be averaged over any 6-min period.
4. For frequencies up to 100 kHz, peak current density values can be obtained by multiplying the rms value by $\sqrt{2}$ (~1.414). For pulses of duration t_p the equivalent frequency to apply in the basic restrictions should be calculated as $f = 1/(2t_p)$.
5. For peak values at frequencies exceeding 100 kHz see **Figure 14** and **Figure 15**. Between 100 kHz and 10 MHz, peak values for the field strengths are obtained by interpolation from the 1,5-fold peak at 100 kHz to the 32-fold peak at 10 MHz. For frequencies exceeding 10 MHz it is suggested that the peak equivalent plane wave power density, as averaged over the pulse width, does not exceed 1.000 times the S_{eq} restrictions, or that the field strength does not exceed 32 times the field strength exposure levels given in the table.
6. For frequencies exceeding 10 GHz, S_{eq} , E^2 , H^2 , and B^2 are to be averaged over any $68/f^{1,05}$ -min period (f in GHz).
7. No E-field value is provided for frequencies < 1 Hz, which are effectively static fields. Perceptions of surface electric charges will not occur at field strengths less than 25 kV m⁻¹. Spark discharges causing stress or annoyance should be avoided.

Up to 1 kHz, the general public reference levels (**Table 4**) for electric field are the middle of the occupational values (**Table 3**), to prevent adverse indirect effects for more than 90% of the exposed individuals. Up to 100 kHz, the general public reference levels (**Table 4**) for magnetic fields are scaled of a factor of 5 below the occupational values (**Table 3**). In the range 100 kHz – 10 MHz, the magnetic field does not contribute significantly to the risk of injuries, so the limitation is more pronounced for the electric fields. From 10 MHz up to 10 GHz the scaling factor between general public reference levels (**Table 4**) and occupational levels (**Table 3**) both for electric and magnetic fields is of 2.2, the square root of 5. The square root is used to relate the field strength to the power density. In 10 – 300 GHz range the scale factor is equal to 5 [12].

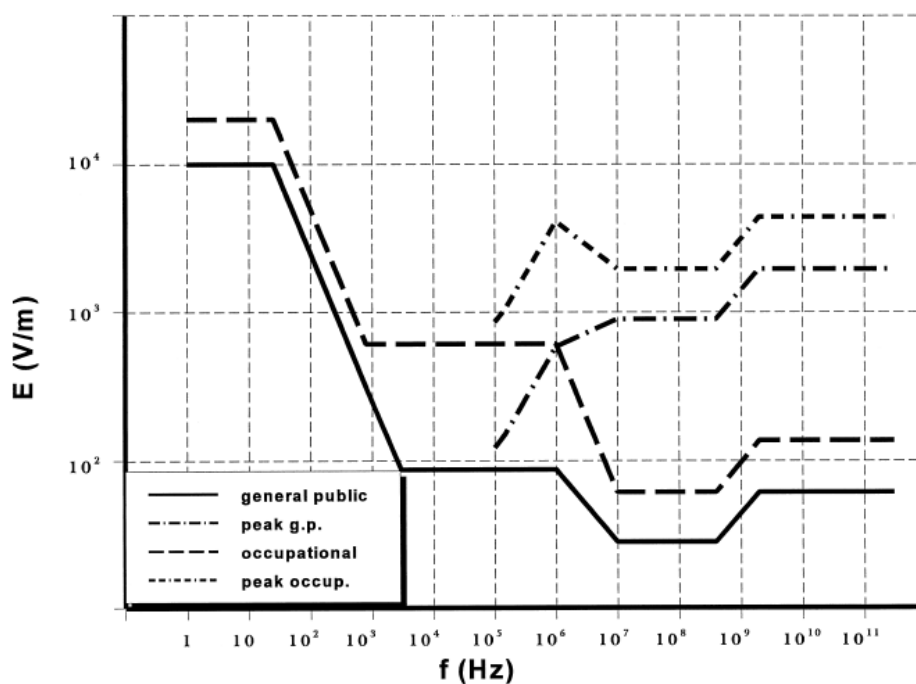


Figure 14: Reference levels for exposure to time varying electric fields (compare Table 3 and Table 4) [12].

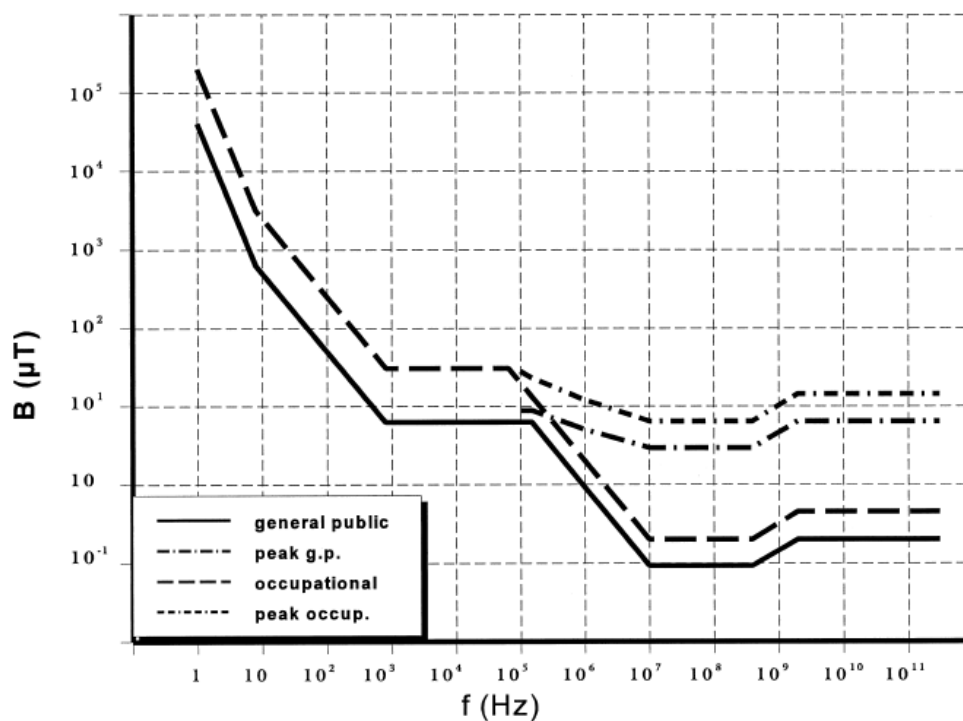


Figure 15: Reference levels for exposure to time varying magnetic fields (compare Table 3 and Table 4) [12].

Table 5: Reference levels for time varying contact currents from conductive objects^a [12].

Exposure characteristics	Frequency range	Maximum contact current (mA)
Occupational exposure	up to 2,5 kHz	1,0
	2,5 – 100 kHz	0,4 f
	100 kHz – 110 MHz	40
General public exposure	up to 2,5 kHz	0,5
	2,5 – 100 kHz	0,2 f
	100 kHz – 110 MHz	20

^aNote:

f is the frequency in kHz.

Up to 110 MHz the reference levels for contact current (**Table 5**) are given to avoid shock and burn hazards. The scale factor of 2 between occupational exposure and general public exposure is due to the fact that the adult men can tolerate about the 50% of currents more than children and about the 67% more than the adult women [12].

Table 6: Reference levels for current induced in any limb at frequencies between 10 and 110 MHz^a [12].

Exposure characteristics	Current (mA)
Occupational exposure	100
General public	45

^aNote:

1. The public reference level is equal to the occupational reference level divided by $\sqrt{5}$.
2. For compliance with the basic restriction on localized SAR, the square root of the time-averaged value of the square of the induced current over any 6-min period forms the basis of the reference levels.

From 10 MHz up to 110 MHz, reference levels ensure values of current below the basic restriction on localized SAR [12].

4.1.2 Simultaneous exposure to multiple frequency fields

In case of simultaneous exposure, the effects of different fields are additive, so they must be evaluated by using the following equations.

For electrical stimulation up to 10 MHz, the current densities should be added according to:

$$\sum_{i=1 \text{ Hz}}^{10 \text{ MHz}} \frac{J_i}{J_{L,i}} \leq 1 \quad (27)$$

For thermal effects, over 100 kHz, SAR and power densities should be added as:

$$\sum_{i=100 \text{ kHz}}^{10 \text{ GHz}} \frac{SAR_i}{SAR_L} + \sum_{i>10 \text{ GHz}}^{300 \text{ Hz}} \frac{S_i}{S_L} \leq 1 \quad (28)$$

where:

J_i is the current density induced at frequency i ;

$J_{L,i}$ is induced current density restriction at frequency i , as given in **Table 1**;

SAR_i is the SAR caused by exposure at frequency i ;

SAR_L is the SAR limit given in **Table 1**;

S_i is the power density at frequency i .

S_L is the power density limit given in **Table 2** [12].

These equations refer to basic restrictions. For practical issues, the equations to be considered are the following (reference levels equations):

$$\sum_{i=1 \text{ Hz}}^{1 \text{ MHz}} \frac{E_i}{E_{L,i}} + \sum_{i>1 \text{ MHz}}^{10 \text{ MHz}} \frac{E_i}{a} \leq 1 \quad (29)$$

and

$$\sum_{j=1 \text{ Hz}}^{65 \text{ kHz}} \frac{H_j}{H_{L,j}} + \sum_{j>65 \text{ kHz}}^{10 \text{ MHz}} \frac{H_j}{b} \leq 1 \quad (30)$$

where:

E_i is the electric field strength at frequency i ;

$E_{L,i}$ is the electric field reference level from **Table 3** and **Table 4**;

H_j is the magnetic field strength at frequency j ;

$H_{L,j}$ is the magnetic field reference level from **Table 3** and **Table 4**;

a is equal to 610 V m^{-1} for occupational exposure and 87 V m^{-1} for general public exposure;
 b is equal to $24,4 \text{ A m}^{-1}$ ($30,7 \mu\text{T}$) for occupational exposure and 5 A m^{-1} ($6,25 \mu\text{T}$) for general public exposure [12].

The constants a and b should not be mixed with thermal considerations (high frequency exposure). For that purpose the equations to use are:

$$\sum_{i=100 \text{ kHz}}^{1 \text{ MHz}} \left(\frac{E_i}{c} \right)^2 + \sum_{i>1 \text{ MHz}}^{300 \text{ GHz}} \left(\frac{E_i}{E_{L,i}} \right)^2 \leq 1 \quad (31)$$

$$\sum_{j=100 \text{ kHz}}^{1 \text{ MHz}} \left(\frac{H_j}{d} \right)^2 + \sum_{j>1 \text{ MHz}}^{300 \text{ GHz}} \left(\frac{H_j}{H_{L,j}} \right)^2 \leq 1 \quad (32)$$

where:

E_i is the electric field strength at frequency i ;

$E_{L,i}$ is the electric field reference level from **Table 3** and **Table 4**;

H_j is the magnetic field strength at frequency j ;

$H_{L,j}$ is the magnetic field reference level from **Table 3** and **Table 4**;

c is equal to $610/f \text{ V m}^{-1}$ (f in MHz) for occupational exposure and $87/f^{1/2} \text{ V m}^{-1}$ for general public exposure;

d is equal to $1,6/f \text{ A m}^{-1}$ (f in MHz) for occupational exposure and $0,73/f \text{ V m}^{-1}$ for general public exposure [12];

For limb current and contact current, respectively, the following requirements should be applied:

$$\sum_{k=10 \text{ MHz}}^{110 \text{ MHz}} \left(\frac{I_k}{I_{L,k}} \right)^2 \leq 1 \quad , \quad \sum_{n=1 \text{ Hz}}^{10 \text{ MHz}} \frac{I_n}{I_{C,n}} \leq 1 \quad , \quad \sum_{n=100 \text{ kHz}}^{110 \text{ MHz}} \left(\frac{I_n}{I_{C,n}} \right)^2 \leq 1 \quad (33)$$

where:

I_k is the limb current component at frequency k ;

$I_{L,k}$ is the reference level of limb current (see **Table 5**);

I_n is the contact current component at frequency n ;

$I_{C,n}$ is the reference level of contact current at frequency n (see **Table 6**).

These summations are the worst-case condition, so they are more restrictive than the reference levels [12].

4.2 ICNIRP 2009

The document entitled “*ICNIRP Guidelines on limits of exposure to static magnetic fields*” [19], is specifically dedicated to the study and regulation of static fields ($f < 1$ Hz), as the title itself suggests. This domain had already been studied in the previous *ICNIRP Guidelines* published in 1994. However, the updated version was released in order to incorporate the progress achieved through the numerous scientific studies conducted in the following years.

4.2.1 Exposure limits

As seen in ICNIRP 1998, the distinction between occupational exposure and general public exposure occurs also in this document.

For occupational exposure, the head and trunk value should not exceed the peak of 2 T of magnetic flux density. It can reach 8 T only in case of controlled environment and appropriate work practices to control induced effects or for limbs exposure [21].

Above 2 T transient effects have been observed (vertigo, nausea or phosphenes), without any evidence of irreversible health effects, for this reason the limit imposed is to prevent these unpleasant effects.

For general public exposure, the limit suggested is 400 mT to prevent any kind of injuries, but, since the possibility of exposure of people with implanted electronic devices medical devices (AIMD) or implants containing ferromagnetic materials, the limit of 0,5 mT [21] is suggested.

These limits that are summarized in **Table 7** are those considered for the assessment in next chapters, in particular the more restrictive value for AIMD.

Table 7: Limits of exposure^a to static magnetic fields [21].

Exposure characteristics	Magnetic flux density
Occupational^b	
Exposure of head and trunk	2 T
Exposure of limbs ^c	8 T
General public^d	
Exposure of any part of the body	400 mT

- ICNIRP recommends that these limits should be viewed operationally as spatial peak exposure limits.
- For specific work applications, exposure up to 8 T can be justified, if the environment is controlled and appropriate work practices are implemented to control movement-induced effects.
- Not enough information is available on which to base exposure limits beyond 8 T.
- Because of potential indirect adverse effects, ICNIRP recognizes that practical policies need to be implemented to prevent inadvertent harmful exposure of persons with implanted medical devices and implants containing ferromagnetic materials, and danger from flying objects, which can lead to much lower restriction levels such as 0,5 mT.

4.3 ICNIRP 2010

Following the 2009 ICNIRP Guidelines model, the 2010 ICNIRP Guidelines is a document specifically dedicated to the study of a defined low-frequency range. The fully title of this publication is “*Guidelines for Limiting Exposure to Time-Varying Electric and Magnetic Fields (1 Hz to 100 kHz)*”[22]. In this document, both direct and indirect effects of exposure to such fields were analysed in depth. On the basis of these investigations, exposure limits were established, taking into consideration several critical aspects of human health (neuroendocrine system, neurodegenerative disorders, cardiovascular health, reproduction and development), exactly as done in previous documents [22].

4.3.1 Exposure limits

Regarding basic restrictions (**Table 8**), the threshold value of internal electric field in the range 10 – 25 Hz is 50 mV m^{-1} . Below this value effects as phosphenes or other transient effects on brain function are avoided. Above 400 Hz and below 3 kHz the threshold value becomes of 4 V m^{-1} . The restriction factor between occupational and general public exposure is equal to 5 up to 1 kHz and it becomes equal to 2 for higher frequencies. The restrictions are different for head, due to effects on central nervous system (CNS) and peripheral nervous system (PNS). For all body values, the scaling factor is equal to 2 for all frequencies. All the values are resumed in **Table 8**. Some values in range from 100 kHz up to 10 MHz will be present in that section. They are related to radiofrequency EMF that could stimulate the nervous system [22].

Table 8: Basic restrictions for human exposure to time-varying electric and magnetic fields [22].

Exposure characteristics	Frequency range	Internal electric field (V m ⁻¹)
Occupational exposure		
CNS tissue of the head	1 – 10 Hz	0,5/ f
	10 – 25 Hz	0,05
	25 – 400 Hz	$2 \times 10^{-3}f$
	400 Hz – 3 kHz	0,8
	3 kHz – 10 MHz	$2,7 \times 10^{-4}f$
All tissues of head and body	1 Hz – 3 kHz	0,8
	3 kHz – 10 MHz	$2,7 \times 10^{-4}f$
General public exposure		
CNS tissue of the head	1 – 10 Hz	0,1/ f
	10 – 25 Hz	0,01
	25 – 1000 Hz	$4 \times 10^{-4}f$
	1 – 3 kHz	0,4
	3 kHz – 10 MHz	$1,35 \times 10^{-4}f$
All tissues of head and body	1 Hz – 3 kHz	0,4
	3 kHz – 10 MHz	$1,35 \times 10^{-4}f$

Notes:

- f is the frequency in Hz.
- All values are rms.
- In the frequency range above 100 kHz, radio frequency basic restrictions need to be considered additionally.

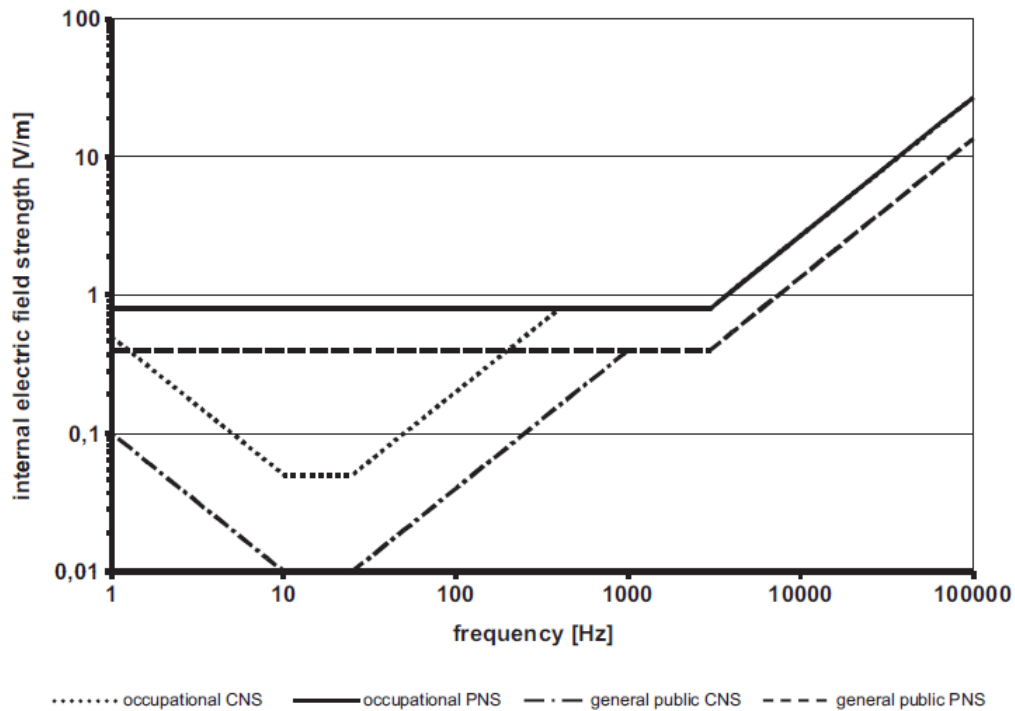


Figure 16: Basic restrictions for general public and occupational exposure in terms of internal electric field strength concerning CNS and PNS effects [22].

As in previous documents, the reference levels are derived through mathematical modelling of the basic restrictions, providing the maximum protection [22].

Table 9: Reference levels for occupational exposure to time-varying electric and magnetic fields (unperturbed rms values) [22].

Frequency range	E-field strength E (kV m ⁻¹)	Magnetic field strength H (A m ⁻¹)	Magnetic flux density B (T)
1 – 8 Hz	20	$1,63 \times 10^5 / f^2$	$0,2 / f^2$
8 – 25 Hz	20	$2 \times 10^4 / f$	$2,5 \times 10^{-2} / f$
25 – 300 Hz	$5 \times 10^2 / f$	8×10^2	1×10^{-3}
300 Hz – 3 kHz	$5 \times 10^2 / f$	$2,4 \times 10^5 / f$	$0,3 / f$
3 kHz – 10 MHz	$1,7 \times 10^{-1}$	80	1×10^{-4}

Notes:

- f in Hz.
- See separate sections below for advice on non-sinusoidal and multiple frequency exposure.
- In the frequency range above 100 kHz, radio frequency basic restrictions need to be considered additionally.

Table 10: Reference levels for general public exposure to time-varying electric and magnetic fields (unperturbed rms values) [22].

Frequency range	E-field strength E (kV m ⁻¹)	Magnetic field strength H (A m ⁻¹)	Magnetic flux density B (T)
1 – 8 Hz	5	$3,2 \times 10^4/f^2$	$4 \times 10^{-2}/f^2$
8 – 25 Hz	5	$4 \times 10^3/f$	$5 \times 10^{-3}/f$
25 – 50 Hz	5	$1,6 \times 10^2$	2×10^{-4}
50 – 400 Hz	$2,5 \times 10^2/f$	$1,6 \times 10^2$	2×10^{-4}
400 Hz – 3 kHz	$2,5 \times 10^2/f$	$6,4 \times 10^4/f$	$8 \times 10^{-2}/f$
3 kHz – 10 MHz	$8,3 \times 10^{-2}$	21	$2,7 \times 10^{-5}$

Notes:

- f in Hz.
- See separate sections below for advice on non-sinusoidal and multiple frequency exposure.
- In the frequency range above 100 kHz, radio frequency basic restrictions need to be considered additionally.

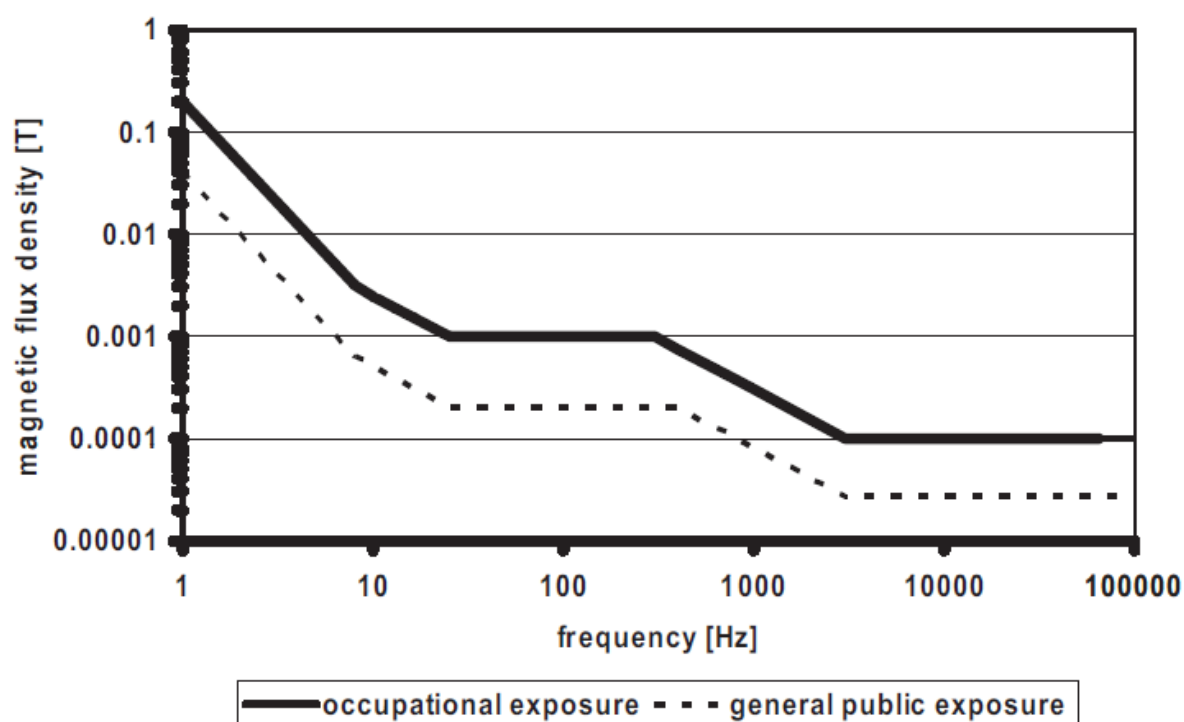


Figure 17: Reference levels for exposure to time-varying magnetic fields (compare Table 9 and Table 10) [22].

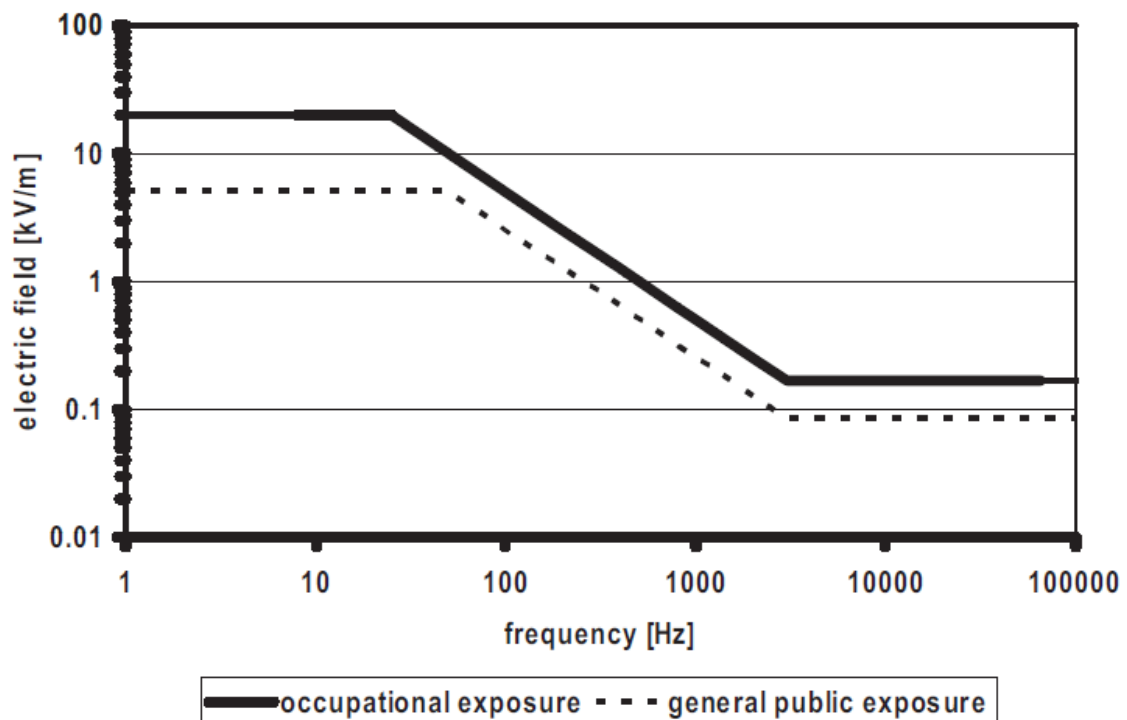


Figure 18: Reference levels for exposure to time-varying electric fields (compare **Table 9** and **Table 10**) [22].

For contact currents the considerations are the same with respect to those of previous guidelines. For this reason, only the table will be provided.

Table 11: Reference levels for time-varying contact currents from conductive objects [22].

Exposure characteristics	Frequency range	Maximum contact current (mA)
Occupational exposure	up to 2,5 kHz	1,0
	2,5 – 100 kHz	$0,4f$
	100 kHz – 10 MHz	40
General public exposure	up to 2,5 kHz	0,5
	2,5 – 100 kHz	$0,2f$
	100 kHz – 10 MHz	20

Note: f is the frequency in kHz

4.3.2 Simultaneous exposure to multiple frequency fields

As before the exposure to fields of different fields, these exposures are additive. For internal electric fields should be applied:

$$\sum_{j=1 \text{ Hz}}^{10 \text{ MHz}} \frac{E_{i,j}}{E_{L,j}} \leq 1 \quad (34)$$

For practical purposes the equations to be considered are:

$$\sum_{j=1 \text{ Hz}}^{10 \text{ MHz}} \frac{E_j}{E_{R,j}} \leq 1 \quad (35)$$

$$\sum_{j=1 \text{ Hz}}^{10 \text{ MHz}} \frac{H_j}{H_{R,j}} \leq 1 \quad (36)$$

where:

E_j is the electric field strength at frequency j ;

$E_{R,j}$ is the electric field strength reference level at frequency j as given in **Table 9** and **Table 10**;

H_j is the magnetic field strength at frequency j ;

$H_{R,j}$ the magnetic field strength reference level at frequency j as given in **Table 9** and **Table 10** [22].

For limb current:

$$\sum_{j=1 \text{ Hz}}^{10 \text{ MHz}} \frac{I_j}{I_{L,j}} \leq 1 \quad (37)$$

where I_j is the contact current component at frequency j , and $I_{L,j}$ is the reference level of the contact current at frequency j as given in **Table 11** [22].

4.4 ICNIRP 2020

The last frequency range studied by ICNIRP is present in this document, “*Guidelines for Limiting Exposure to Electromagnetic Fields (100 kHz to 300 GHz)*” [23]. The frequency range 100 kHz – 10 MHz was previously analysed but only the radiofrequency point of view, here is repropose but for different health effects not caused on nerve stimulation. All the other preliminary remarks are the same as in the other documents.

4.4.1 Exposure limits

The difference between ICNIRP 2020’s basic restrictions and the others is that two tables are given for different averaging intervals, ≥ 6 min and > 0 to < 6 min.

Table 12: Basic restrictions for electromagnetic field exposure from 100 kHz to 300 GHz, for averaging intervals ≥ 6 min^a [23].

Exposure scenario	Frequency range	Whole-body average SAR (W kg ⁻¹)	Local Head/Torso SAR (W kg ⁻¹)	Local Limb SAR (W kg ⁻¹)	Local S _{ab} (W m ⁻²)
Occupational	100 kHz to 6 GHz	0,4	10	20	NA
	> 6 to 300 GHz	0,4	NA	NA	100
General public	100 kHz to 6 GHz	0,08	2	4	NA
	> 6 to 300 GHz	0,08	NA	NA	20

^aNote:

1. “NA” signifies “not applicable” and does not need to be taken into account when determining compliance.
2. Whole-body average SAR is to be averaged over 30 min.
3. Local SAR and S_{ab} exposures are to be averaged over 6 min.
4. Local SAR is to be averaged over a 10 g cubic mass.
5. Local S_{ab} is to be averaged over a square 4 cm² surface area of the body. Above 30 GHz, an additional constraint is imposed, such that exposure averaged over a square 1 cm² surface area of the body is restricted to two times that of the 4 cm² restriction.

Table 13: Basic restrictions for electromagnetic field exposure from 100 kHz to 300 GHz, for integrating intervals > 0 to < 6 min^a [23].

Exposure scenario	Frequency range	Local Head/Torso SAR (W kg ⁻¹)	Local Limb SAR (W kg ⁻¹)	Local U _{ab} (kJ m ⁻²)
Occupational	100 kHz to 400 MHz	NA	NA	NA
	> 400 MHz to 6 GHz	3,6[0,05 + 0,95($t/360$) ^{0,5}]	7,2[0,025 + 0,975($t/360$) ^{0,5}]	NA
	> 6 to 300 GHz	NA	NA	36[0,05 + 0,95($t/360$) ^{0,5}]
General public	100 kHz to 400 MHz	NA	NA	NA
	> 400 MHz to 6 GHz	0,72[0,05 + 0,95($t/360$) ^{0,5}]	1,44[0,025 + 0,975($t/360$) ^{0,5}]	NA
	> 6 to 300 GHz	NA	NA	7,2[0,05 + 0,95($t/360$) ^{0,5}]

^aNote:

1. “NA” signifies “not applicable” and does not need to be taken into account when determining compliance.
2. t is time in seconds, and restrictions must be satisfied for all values of t between > 0 and < 360 s, regardless of the temporal characteristics of the exposure itself.
3. Local SA is to be averaged over a 10 g cubic mass.
4. Local U_{ab} is to be averaged over a square 4 cm² surface area of the body. Above 30 GHz, an additional constraint is imposed, such that exposure averaged over a square 1 cm² surface area of the body is restricted to 72[0,025+0,975($t/360$)^{0,5}] for occupational and 14,4[0,025+0,975($t/360$)^{0,5}] for general public exposure.
5. Exposure from any pulse, group of pulses, or subgroup of pulses in a train, as well as from the summation of exposures (including non-pulsed EMFs), delivered in t s, must not exceed these levels.

Table 14: Basic restrictions for electromagnetic field exposure from 100 kHz to 10 MHz, for peak spatial values^a [23].

Exposure scenario	Frequency range	Induced electric field; E _{ind} (V m ⁻¹)
Occupational	100 kHz to 10 MHz	2,70 x 10 ⁻⁴ f
General public	100 kHz to 10 MHz	1,35 x 10 ⁻⁴ f

^aNote:

1. f is frequency in Hz.
2. Restriction values relate to any region of the body, and are to be averaged as root mean square (rms) values over 2 mm x 2 mm x 2 mm contiguous tissue (as specified in ICNIRP 2010).

For practical purposes, the guidelines also provide a series of tables and graphs in which the reference levels are summarised. These are not arbitrary values but are the result of both computational simulations and experimental measurements. They are defined in such a way as to guarantee the same protection level of the basic restrictions, or in many cases even greater than. These values are calculated by assuming worst-case boundary conditions, thereby ensuring compliance with the limits already mentioned.

Table 15: Reference levels for exposure, averaged over 30 min and the whole body, to electromagnetic fields from 100 kHz to 300 GHz (unperturbed rms values)^a [23].

Exposure scenario	Frequency range	Incident E-field strength; E_{inc} (V m ⁻¹)	Incident H-field strength; H_{inc} (A m ⁻¹)	Incident power density; S_{inc} (W m ⁻²)
Occupational	0,1 – 30 MHz	$660/f_M^{0,7}$	$4,9/f_M$	NA
	> 30 – 400 MHz	61	0,16	10
	> 400 – 2000 MHz	$3f_M^{0,5}$	$0,008f_M^{0,5}$	$f_M/40$
	> 2 – 300 GHz	NA	NA	50
General public	0,1 – 30 MHz	$3000/f_M^{0,7}$	$2,2/f_M$	NA
	> 30 – 400 MHz	27,7	0,073	2
	> 400 – 2000 MHz	$1,375f_M^{0,5}$	$0,0037f_M^{0,5}$	$f_M/200$
	> 2 – 300 GHz	NA	NA	10

^aNote:

1. “NA” signifies “not applicable” and does not need to be taken into account when determining compliance.
2. f_M is frequency in MHz.
3. S_{inc} , E_{inc} and H_{inc} are to be averaged over 30 min, over the whole-body space. Temporal and spatial averaging of each of E_{inc} and H_{inc} must be conducted by averaging over the relevant square values.
4. For frequencies of 100 kHz to 30 MHz, regardless of the far-field/near-field zone distinctions, compliance is demonstrated if neither E_{inc} or H_{inc} exceeds the above reference level values.
5. For frequencies of > 30 MHz to 2 GHz: (a) within the far-field zone: compliance is demonstrated if either S_{inc} , E_{inc} or H_{inc} , does not exceed the above reference level values (only one is required); S_{eq} may be substituted for S_{inc} ; (b) within the radiative near-field zone, compliance is demonstrated if either S_{inc} , or both E_{inc} and H_{inc} , does not exceed the above reference level values; and (c) within the reactive near-field zone: compliance is demonstrated if both E_{inc} and H_{inc} do not exceed the above reference values; S_{inc} cannot be used to demonstrate compliance, and so basic restrictions must be assessed.
6. For frequencies of > 2 GHz to 300 GHz: (a) within the far-field zone: compliance is demonstrated if S_{inc} does not exceed the above reference level values; S_{eq} may be substituted for S_{inc} ; (b) within the radiative near-field zone, compliance is demonstrated if S_{inc} does not exceed the above reference level values; and (c) within the reactive near-field zone, reference levels cannot be used to determine compliance, and so basic restrictions must be assessed.

Table 16: Reference levels for local exposure, averaged over 6 min, to electromagnetic fields from 100 kHz to 300 GHz (unperturbed rms values)^a [23].

Exposure scenario	Frequency range	Incident E-field strength; E_{inc} (V m ⁻¹)	Incident H-field strength; H_{inc} (A m ⁻¹)	Incident power density; S_{inc} (W m ⁻²)
Occupational	0,1 – 30 MHz	$1504/f_M^{0,7}$	$10,8f_M$	NA
	> 30 – 400 MHz	139	0,36	50
	> 400 – 2000 MHz	$10,58f_M^{0,43}$	$0,0274f_M^{0,43}$	$0,29f_M^{0,86}$
	> 2 – 6 GHz	NA	NA	200
	> 6 – < 300 GHz	NA	NA	$275/f_G^{0,177}$
	300 GHz	NA	NA	100
General public	0,1 – 30 MHz	$671/f_M^{0,7}$	$4,9/f_M$	NA
	> 30 – 400 MHz	62	0,163	10
	> 400 – 2000 MHz	$4,72f_M^{0,43}$	$0,0123f_M^{0,43}$	$0,058f_M^{0,86}$
	> 2 – 6 GHz	NA	NA	40
	> 6 – < 300 GHz	NA	NA	$55/f_G^{0,177}$
	300 GHz	NA	NA	20

^aNote:

1. “NA” signifies “not applicable” and does not need to be taken into account when determining compliance.
2. f_M is frequency in MHz; f_G is frequency in GHz.
3. S_{inc} , E_{inc} and H_{inc} are to be averaged over 6 min, over the relevant projected body space. Temporal and spatial averaging of each of E_{inc} and H_{inc} must be conducted by averaging over the relevant square values.
4. For frequencies of 100 kHz to 30 MHz, regardless of the far-field/near-field zone distinctions, compliance is demonstrated if neither peak spatial E_{inc} or peak spatial H_{inc} , over the projected whole-body space, exceeds the above reference level values.
5. For frequencies of > 30 MHz to 6 GHz: (a) within the far-field zone, compliance is demonstrated if one of peak spatial S_{inc} , E_{inc} or H_{inc} , over the projected whole-body space, does not exceed the above reference level values (only one is required); S_{eq} may be substituted for S_{inc} ; (b) within the radiative near-field zone, compliance is demonstrated if either peak spatial S_{inc} , or both peak spatial E_{inc} and H_{inc} , over the projected whole-body space, does not exceed the above reference level values; and (c) within the reactive near-field zone: compliance is demonstrated if both E_{inc} and H_{inc} do not exceed the above reference values; S_{inc} cannot be used to demonstrate compliance; for frequencies > 2 GHz, reference levels cannot be used to determine compliance, and so basic restrictions must be assessed.
6. For frequencies of > 6 GHz to 300 GHz: (a) within the far-field zone, compliance is demonstrated if S_{inc} , averaged over a square 4 cm² projected body surface space, does not exceed the above reference level values; S_{eq} may be substituted for S_{inc} ; (b) within the radiative near-field zone, compliance is demonstrated if S_{inc} , averaged over a square 4 cm² projected body surface space, does not exceed the above reference level values; and (c) within the reactive near-field zone reference levels cannot be used to determine compliance, and so basic restrictions must be assessed.
7. For frequencies of > 30 GHz to 300 GHz, exposure averaged over a square 1 cm² projected body surface space must not exceed twice that of the square 4 cm² restrictions.

Occupational

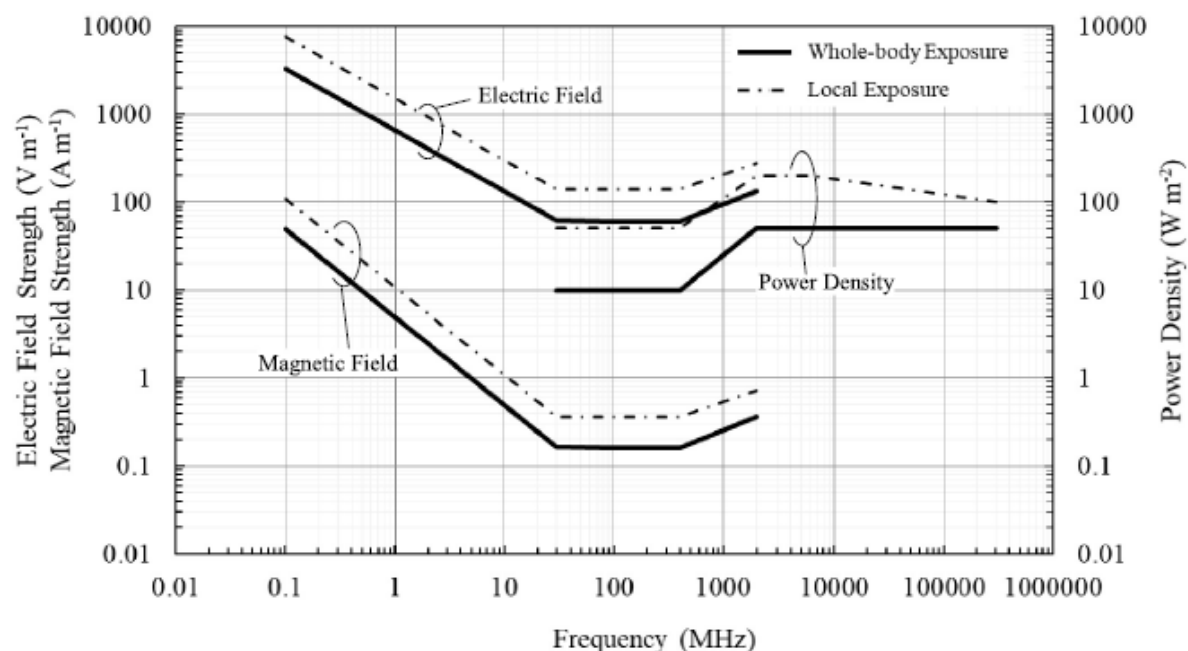


Figure 19: Reference levels for time averaged occupational exposure of ≥ 6 min, to electromagnetic fields from 100 kHz to 300 GHz (unperturbed rms values; see **Table 15** and **Table 16** for full specifications) [23].

General Public

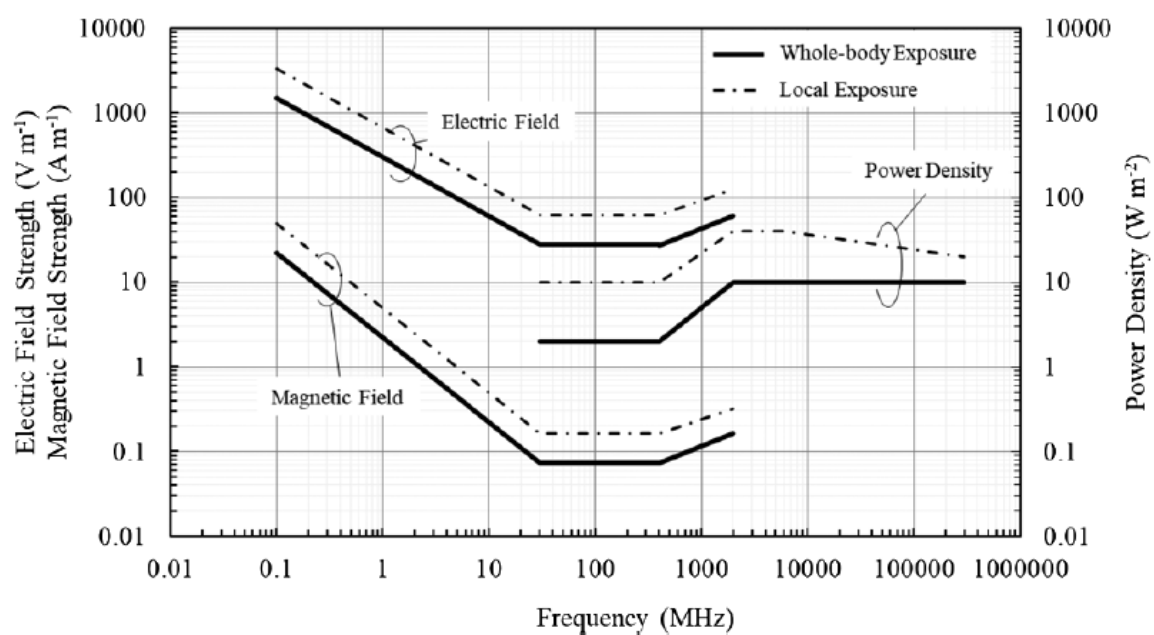


Figure 20: Reference levels for time averaged general public exposures of ≥ 6 min, to electromagnetic fields from 100 kHz to 300 GHz (unperturbed rms values; see **Table 15** and **Table 16** for full specifications) [23].

Table 17: Reference levels for local exposure, integrated over intervals of between > 0 and < 6 minutes, to electromagnetic fields from 100 kHz to 300 GHz (unperturbed rms values)^a [23].

Exposure scenario	Frequency range	Incident energy density; U_{inc} (kJ m ⁻²)
Occupational	100 kHz – 400 MHz	NA
	> 400 – 2000 MHz	$0,29f_M^{0,86} \times 0,36[0,05+0,95(t/360)^{0,5}]$
	> 2 – 6 GHz	$200 \times 0,36[0,05+0,95(t/360)^{0,5}]$
	> 6 – < 300 GHz	$275/f_G^{0,177} \times 0,36[0,05+0,95(t/360)^{0,5}]$
	300 GHz	$100 \times 0,36[0,05+0,95(t/360)^{0,5}]$
General public	100 kHz – 400 MHz	NA
	> 400 – 2000 MHz	$0,058f_M^{0,86} \times 0,36[0,05+0,95(t/360)^{0,5}]$
	> 2 – 6 GHz	$40 \times 0,36[0,05+0,95(t/360)^{0,5}]$
	> 6 – < 300 GHz	$0,55/f_G^{0,177} \times 0,36[0,05+0,95(t/360)^{0,5}]$
	300 GHz	$20 \times 0,36[0,05+0,95(t/360)^{0,5}]$

^aNote:

1. “NA” signifies “not applicable” and does not need to be taken into account when determining compliance.
2. f_M is frequency in MHz; f_G is frequency in GHz. t is time interval in seconds, such that exposure from any pulse, group of pulses, or subgroup of pulses in a train, as well as from the summation of exposure (including non-pulsed EMFs), delivered in t seconds, must not exceed these reference level values.
3. U_{inc} is to be calculated over time t , over the relevant projected body space.
4. For frequencies of 100 kHz to 400 MHz, > 0 to < 6 min restrictions are not required and so reference levels have not been set.
5. For frequencies of > 400 MHz to 6 GHz: (a) within the far-field zone: compliance is demonstrated if peak spatial U_{inc} , over the projected whole-body space, does not exceed the above reference level values; U_{eq} may be substituted for U_{inc} ; (b) within the radiative near-field zone, compliance is demonstrated if peak spatial U_{inc} , over the projected whole-body space, does not exceed the above reference level values; and (c) within the reactive near-field zone, reference levels cannot be used to determine compliance, and so basic restrictions must be assessed.
6. For frequencies of > 6 GHz to 300 GHz: (a) within the far-field or radiative zone, compliance is demonstrated if U_{inc} , averaged over a square 4 cm² projected body surface space, does not exceed the above reference level values; (b) within the reactive near-field zone, reference levels cannot be used to determine compliance, and so basic restrictions must be assessed.
7. For frequencies of > 30 GHz to 300 GHz: exposure averaged over a square 1 cm² projected body surface space must not exceed $275/f_G^{0,177} \times 0,72[0,025+0,975(t/360)^{0,5}]$ kJ m⁻² for occupational and $55/f_G^{0,177} \times 0,72[0,025+0,975(t/360)^{0,5}]$ kJ m⁻² for general public exposure.

Table 18: Reference levels for local exposure to electromagnetic fields from 100 kHz to 10 MHz (unperturbed rms values), for peak values^a [23].

Exposure scenario	Frequency range	Incident E-field strength; E_{inc} (V m ⁻¹)	Incident H-field strength; H_{inc} (A m ⁻¹)
Occupational	100 kHz – 10 MHz	170	80
General public	100 kHz – 10 MHz	83	21

^aNote:

Regardless of the far-field/near-field zone distinction, compliance is demonstrated if neither peak spatial E_{inc} or peak spatial H_{inc} over the projected whole-body space, exceeds the above reference level values.

Table 19: Reference levels for current induced in any limb, averaged over 6 min, at frequencies from 100 kHz to 110 MHz^a [23].

Exposure scenario	Frequency range	Electric current; I (mA)
Occupational	100 kHz – 110 MHz	100
General public	100 kHz – 110 MHz	45

^aNote:

1. Current intensity values must be determined by averaging over the relevant square values.
2. Limb current intensity must be evaluated separately for each limb.
3. Limb current reference levels are not provided for any other frequency range.
4. Limb current reference levels are only required for cases where the human body is not electrically isolated from a ground plane.

4.4.2 Simultaneous exposure to multiple frequency fields

In simultaneous exposure section, the difference is between basic restrictions and reference levels, but also for exposure intervals < 6 min and ≥ 6 min.

Starting from the basic restrictions for intervals ≥ 6 min, SAR should be added according to:

$$\sum_{i=100 \text{ kHz}}^{300 \text{ GHz}} \frac{SAR_i}{SAR_{BR}} \leq 1 \quad (38)$$

where:

SAR_i is the whole-body average SAR levels at frequency i ;

SAR_{BR} is the whole-body average SAR basic restrictions given in **Table 12** [23].

For local exposure, values should be added as follows:

$$\sum_{i=100 \text{ kHz}}^{6 \text{ GHz}} \frac{SAR_i}{SAR_{BR}} + \sum_{i>6 \text{ GHz}}^{30 \text{ GHz}} \frac{S_{ab,4cm,i}}{S_{ab,4cm,BR}} + \sum_{i>30 \text{ GHz}}^{300 \text{ GHz}} \text{MAX} \left\{ \left(\frac{S_{ab,4cm,i}}{S_{ab,4cm,BR}} \right), \left(\frac{S_{ab,1cm,i}}{S_{ab,1cm,BR}} \right) \right\} \leq 1 \quad (39)$$

where:

SAR_i is the local SAR level at frequency i ;

SAR_{BR} is the local SAR basic restriction given in **Table 12**;

$S_{ab,4cm,i}$ is the 4 cm² absorbed power density level at frequency i ;

$S_{ab,4cm,i}$ is the 4 cm² absorbed power density basic restriction given in **Table 12**;

$S_{ab,1cm,i}$ is the 1 cm² absorbed power density level at frequency i ;

$S_{ab,1cm,i}$ is the 1 cm² absorbed power density basic restriction given in **Table 12** [223];

The corresponding reference levels whole-body equations for interval ≥ 6 min are:

$$\begin{aligned}
& \sum_{i=100 \text{ kHz}}^{30 \text{ MHz}} \left\{ \left(\frac{E_{inc,i}}{E_{inc,RL,i}} \right)^2 + \left(\frac{H_{inc,i}}{H_{inc,RL,i}} \right)^2 \right\} \\
& + \sum_{i>30 \text{ MHz}}^{2 \text{ GHz}} \text{MAX} \left\{ \left(\frac{E_{inc,i}}{E_{inc,RL,i}} \right)^2, \left(\frac{H_{inc,i}}{H_{inc,RL,i}} \right)^2, \left(\frac{S_{inc,i}}{S_{inc,RL,i}} \right) \right\} \\
& + \sum_{i>2 \text{ GHz}}^{300 \text{ GHz}} \left(\frac{S_{inc,i}}{S_{inc,RL}} \right) \leq 1
\end{aligned} \tag{40}$$

where:

$E_{inc,i}$ is the whole-body average incident electric field strength at frequency i ;

$E_{inc,RL}$ is the whole-body average incident electric field strength reference level given in **Table 15**, at frequency i ;

$H_{inc,i}$ is the whole-body average incident magnetic field strength at frequency i ;

$H_{inc,RL,i}$ is the whole-body average incident magnetic field strength reference level given in **Table 15**, at frequency i ;

$S_{inc,i}$ is the whole-body average incident power density at frequency i ;

$S_{inc,RL,i}$ is the whole-body average incident power density reference level given in **Table 15**, at frequency i [23];

And for local exposure the equation to consider is:

$$\begin{aligned}
& \sum_{i=100 \text{ kHz}}^{30 \text{ MHz}} \text{MAX} \left\{ \left(\frac{E_{inc,i}}{E_{inc,RL,i}} \right)^2, \left(\frac{H_{inc,i}}{H_{inc,RL,i}} \right)^2 \right\} \\
& + \sum_{i>30 \text{ MHz}}^{2 \text{ GHz}} \text{MAX} \left\{ \left(\frac{E_{inc,i}}{E_{inc,RL,i}} \right)^2, \left(\frac{H_{inc,i}}{H_{inc,RL,i}} \right)^2, \left(\frac{S_{inc,i}}{S_{inc,RL,i}} \right) \right\} \\
& + \sum_{i>2 \text{ GHz}}^{6 \text{ GHz}} \left(\frac{S_{inc,i}}{S_{inc,RL,i}} \right) + \sum_{i>6 \text{ GHz}}^{30 \text{ GHz}} \left(\frac{S_{inc,4cm,i}}{S_{inc,4cm,RL,i}} \right) \\
& + \sum_{i>30 \text{ GHz}} \text{MAX} \left\{ \left(\frac{S_{inc,4cm,i}}{S_{inc,4cm,RL,i}} \right), \left(\frac{S_{inc,1cm,i}}{S_{inc,1cm,RL,i}} \right) \right\} \leq 1
\end{aligned} \tag{41}$$

where:

$E_{inc,i}$ is the local incident electric field strength at frequency i ;

$E_{inc,RL}$ is the local incident electric field strength reference level given in **Table 16**, at frequency i ;

$H_{inc,i}$ is the local incident magnetic field strength at frequency i ;

$H_{inc,RL,i}$ is the local incident magnetic field strength reference level given in **Table 16**, at frequency i ;

$S_{inc,i}$ is the local incident power density at frequency i ;

$S_{inc,RL,i}$ is the local incident power density reference level given in **Table 16**, at frequency i [23].

Finally, the equation for limb current reference level is:

$$\sum_{i=100 \text{ kHz}}^{110 \text{ MHz}} \left(\frac{I_i}{I_{RL}} \right)^2 \leq 1 \quad (42)$$

where:

I_i is the limb current component at frequency i ;

I_{RL} is the limb current reference level value from **Table 19** [23].

Similar approach for intervals < 6 min. Basic restrictions equation is:

$$\begin{aligned} & \sum_{i=100 \text{ kHz}}^{400 \text{ MHz}} \int_t \frac{SAR_i(t)}{360 \times SAR_{BR}} dt + \sum_{i>400 \text{ MHz}}^{6 \text{ GHz}} \frac{SA_i(t)}{SA_{BR}(t)} + \sum_{i>6 \text{ GHz}}^{30 \text{ GHz}} \frac{U_{ab,4cm,i}(t)}{U_{ab,4cm,BR}(t)} \\ & + \sum_{i>30 \text{ GHz}}^{300 \text{ GHz}} MAX \left\{ \left(\frac{U_{ab,4cm,i}(t)}{U_{ab,4cm,BR}(t)} \right), \left(\frac{U_{ab,1cm,i}(t)}{U_{ab,1cm,BR}(t)} \right) \right\} \leq 1 \end{aligned} \quad (43)$$

where:

$SAR_i(t)$ is the local SAR level at frequency i over time t ;

$SAR_{BR}(t)$ is the local SAR basic restriction given in **Table 12**, over time t .

$SA_i(t)$ is the local SA level at frequency i over time t ;

$SA_{BR}(t)$ is the local SA basic restriction given in **Table 13**, over time t ;

$U_{ab,4cm,i}(t)$ is the 4 cm² absorbed power density level at frequency i , over time t ;

$U_{ab,4cm,BR}(t)$ is the 4 cm² absorbed power density basic restriction given in **Table 13**, over time t ;

$U_{ab,1cm,i}(t)$ is the 1 cm² absorbed power density level at frequency i , over time t ;

$U_{ab,1cm,BR}(t)$ is the 1 cm² absorbed power density basic restriction given in **Table 13**, over time t [23];

For reference levels and for intervals < 6 min, the equation is:

$$\begin{aligned}
& \sum_{i>100 \text{ kHz}}^{30 \text{ MHz}} \text{MAX} \left\{ \left(\int_t \frac{E_{inc,i}^2(t)}{360 * E_{inc,RL,i}^2} dt \right), \left(\int_t \frac{H_{inc,i}^2(t)}{360 * H_{inc,RL,i}^2} dt \right) \right\} \\
& + \sum_{i>30 \text{ MHz}}^{400 \text{ MHz}} \text{MAX} \left\{ \left(\int_t \frac{E_{inc,i}^2(t)}{360 * E_{inc,RL,i}^2} dt \right), \left(\int_t \frac{H_{inc,i}^2(t)}{360 * H_{inc,RL,i}^2} dt \right), \left(\int_t \frac{S_{inc,i}(t)}{360 * S_{inc,RL,i}} dt \right) \right\} \\
& + \sum_{i>400 \text{ MHz}}^{6 \text{ GHz}} \frac{U_{inc,i}(t)}{U_{inc,RL,i}(t)} + \sum_{i=6 \text{ GHz}}^{30 \text{ GHz}} \frac{U_{inc,4cm,i}(t)}{U_{inc,4cm,RL,i}(t)} \\
& + \sum_{i>30 \text{ GHz}}^{300 \text{ GHz}} \text{MAX} \left\{ \left(\frac{U_{inc,4cm,i}(t)}{U_{inc,4cm,RL,i}(t)} \right), \left(\frac{U_{inc,1cm,i}(t)}{U_{inc,1cm,RL,i}(t)} \right) \right\} \leq 1 \quad (44)
\end{aligned}$$

where:

$E_{inc,i}(t)$ is the local Einc level over time t , at frequency i ;

$E_{inc,RL,i}(t)$ is the local Einc reference level given in **Table 16**, at frequency i ;

$H_{inc,i}(t)$ is the local Hinc level over time t , at frequency i ;

$H_{inc,RL,i}(t)$ is the local Hinc reference level given in **Table 16**, at frequency i ;

$S_{inc,i}(t)$ is the local Sinc level over time t , at frequency i ;

$S_{inc,RL,i}(t)$ is the local Sinc reference level given in **Table 16**, at frequency i ;

$U_{inc,i}(t)$ is the incident energy density level over time t , at frequency i ;

$U_{inc,RL,i}(t)$ is the incident energy density reference level given in **Table 17**, at frequency i ;

$U_{inc,4cm,i}(t)$ is the 4 cm² incident energy density level over time t , at frequency i ;

$U_{inc,4cm,RL,i}(t)$ is the 4 cm² incident energy density reference level given in **Table 17**, at frequency i ;

$U_{inc,1cm,i}(t)$ is the 1 cm² incident energy density level over time t , at frequency i ;

$U_{inc,1cm,RL,i}(t)$ is the 1 cm² incident energy density reference level given in **Table 17**, at frequency i [23];

4.5 Council Recommendation of 12 July 1999

This document differs from ICNIRP 1998 primarily in terms of inclusivity. In particular, it emphasizes the need to safeguard categories of individuals who may be more vulnerable to electromagnetic fields. As explicitly stated:

Community measures were introduced to encourage improvements in the safety and health at work of pregnant workers and workers who have recently given birth or are breastfeeding which oblige, inter alia, employers to assess activities which involve a specific risk of exposure to non-ionising radiation [24].

Whereas the occupational exposure levels defined in the previous chapters were based on the model of a healthy adult male, the limits applicable to the general public also take into account groups such as pregnant women and children. In this context, the European Council, through the document “*Council Recommendation of 12 July 1999 on the limitation of exposure of the general public to electromagnetic fields (0 Hz to 300 GHz)*” [24] introduced the reference limits previously. Furthermore, this document retains the same distinction between basic restrictions and reference levels as originally proposed by ICNIRP. The table of values has the same general public exposure levels of ICNIRP, but are resumed in only two tables:

Table 20: Basic restrictions for electric, magnetic and electromagnetic fields (0 Hz to 300 GHz) [24].

Frequency range	Magnetic flux density (mT)	Current density (mA/m ²) (rms)	Whole body average SAR (W/kg)	Localized SAR (head and trunk) (W/kg)	Localized SAR (limbs) (W/kg)	Power density, S (W/m ²)
0 Hz	40	-	-	-	-	-
> 0 – 1 Hz	-	8	-	-	-	-
1 – 4 Hz	-	8/f	-	-	-	-
4 – 1000 Hz	-	2	-	-	-	-
1000 Hz – 100 kHz	-	f/500	-	-	-	-
100 kHz – 10 MHz	-	f/500	0,08	2	4	-
10 MHz – 10 GHz	-	-	0,08	2	4	-
10 – 300 GHz	-	-	-	-	-	10

Notes:

1. f is the frequency in Hz.
2. The basic restriction on the current density is intended to protect against acute exposure effects on central nervous system tissues in the head trunk of the body and includes a safety factor. The basic restrictions for ELF fields are based on established adverse effects on the central nervous system. Such acute effects are essentially instantaneous and there is no scientific justification to modify the basic restrictions for exposure of short duration. However, since the basic restrictions refers to adverse effects on the central nervous system, this basic restriction may permit higher current densities in body tissues other than the central nervous system under the same exposure conditions.
3. Because of electrical inhomogeneity of the body, current densities should be averaged over a cross section of 1 cm² perpendicular to the current direction.
4. For frequencies up to 100 kHz, peak current density values can be obtained by multiplying the rms value by $\sqrt{2}$ (~1,414). For pulses of duration t_p the equivalent frequency to apply in the basic restrictions should be calculated as $f = 1/(2t_p)$.
5. For frequencies up to 100 kHz and for pulsed magnetic fields, the maximum current density associated with the pulses can be calculated from the rise/fall times and the maximum rate of change of magnetic flux density. The induced current density can then be compared with the appropriate basic restriction.
6. All SAR values are to be averaged over any six-minute period.
7. Localised SAR averaging mass is any 10g of contiguous tissue; the maximum SAR so obtained should be the value used for the estimation of exposure. These 10g of tissue are intended to be a mass of contiguous tissue with nearly homogeneous electrical properties. In specifying a contiguous mass of tissue, it is recognised that this concept can be used in computational dosimetry but may present difficulties for direct physical measurement. A simple geometry such as cubic tissue mass can be used provided that the calculated dosimetric quantities have conservative values relative to the exposure guidelines.
8. For pulses of duration t_p the equivalent frequency to apply in the basic restrictions should be calculated as $f = 1/(2t_p)$. Additionally, for pulsed exposures, in the frequency range 0,3 to 10 GHz and for localised exposure of the head, in order to limit and avoid auditory effects caused by thermoelastic expansion, an additional basic restriction is recommended. This is that the SA should not exceed 2mJ kg⁻¹ averaged over 10g of tissue.

Table 21: Reference levels for electric, magnetic and electromagnetic fields (0 Hz to 300 GHz, unperturbed rms values) [24].

Frequency range	E-field strength (V/m)	H-field strength (A/m)	B-field (μT)	Equivalent plane wave power density S_{eq} (W/m^2)
0 – 1 Hz	-	$3,2 \times 10^4$	4×10^4	-
1 – 8 Hz	10000	$3,2 \times 10^4$	$4 \times 10^4/f^2$	-
8 – 25 Hz	10000	$4000/f$	$5000/f$	-
0,025 – 0,8 kHz	$250/f$	$4/f$	$5/f$	-
0,8 – 3 kHz	$250/f$	5	6,25	-
3 – 150 kHz	87	5	6,25	-
0,15 – 1 MHz	87	$0,73/f$	$0,92/f$	-
1 – 10 MHz	$87/f^{1/2}$	$0,73/f$	$0,92/f$	-
10 – 400 MHz	28	0,073	0,092	2
400 – 2000 MHz	$1,375 f^{1/2}$	$0,0037 f^{1/2}$	$0,0046 f^{1/2}$	$f/200$
2 – 300 GHz	61	0,16	0,20	10

Notes:

1. f as indicated in the frequency range column.
2. For frequencies between 100 kHz and 10 GHz, S_{eq} , E^2 , H^2 , and B^2 are to be averaged over any six-minute period.
3. For frequencies exceeding 10 GHz, S_{eq} , E^2 , H^2 , and B^2 are to be averaged over any $68/f^{1,05}$ -minute period (f in GHz).
4. No E-field value is provided for frequencies < 1 Hz, which are effectively static electric fields. For most people the annoying perception of surface electric charges will not occur at field strength less than 25 kV/m. Spark discharges causing stress or annoyance should be avoided.

Table 22: Reference levels for contact currents from conductive objects (f in kHz) [24].

Frequency range	Maximum contact current (mA)
0 Hz – 2,5 kHz	0,5
2,5 kHz – 100 kHz	$0,2 f$
100 kHz – 110 MHz	20

For the frequency range 10 MHz to 110 MHz, a reference level of 45 mA in terms of current through any limb is recommended. This is intended to limit the localised SAR over any six-minute period.

4.5.1 Exposure from sources with multiple frequencies

The basic restrictions equations are the same of ICNIRP 1998 (27) and (28).

The reference level equations are slightly different and more restrictive.

$$\sum_{i=1}^{1 \text{ MHz}} \frac{E_i}{E_{L,i}} + \sum_{i>1 \text{ MHz}}^{10 \text{ MHz}} \frac{E_i}{a} \leq 1 \quad (45)$$

$$\sum_{j=1}^{150 \text{ kHz}} \frac{H_j}{H_{L,j}} + \sum_{j>150 \text{ kHz}}^{10 \text{ MHz}} \frac{H_j}{b} \leq 1 \quad (46)$$

where:

E_i is the electric field strength at frequency i ;

$E_{L,i}$ is the electric field reference level from **Table 21**;

H_j is the magnetic field strength at frequency j ;

$H_{L,j}$ is the magnetic field reference level from **Table 21**;

a is 87 V/m and b is 5 A/m (6,25 μ T) [24].

4.6 Directive 2013/35/EU

This document is one of the most important because it is one of the first document that tries to protect the workers.

The approach is similar to the ICNIRP. It is possible to compare the ICNIRP's basic restrictions with 2013/35/EU's ELVs (exposure limit values) and the reference levels with ALs (action levels).

ELVs are established on the basis of “*scientifically well-established short-term and acute direct effects*”. They are divided into two different categories, health effects ELVs (above which workers might be subjected to adverse health effects) and sensory effects ELVs (above which workers may be subjected to transient sensory perceptions) [25]. They are referred to values as SAR or internal electric fields that are difficult to measure.

ALs are given for practical purposes because they are quite simple to measure, and their compliance guarantees the compliance with ELVs.

ALs are divided into “low ALs” and “high ALs” that have different meaning if referred to electric or magnetic fields. For electric fields they are related to specific protection and to prevention respectively. For magnetic fields low ALs are related to sensory effects ELVs, while high ALs are related to health effects ELVs.

4.6.1 Exposure limits – non-thermal effects

The limits suggested will be reported starting from ELVs and with an incremental frequency order.

Table 23: ELVs for external magnetic flux density (B_0) from 0 to 1 Hz [25].

Sensory effects ELVs	
Normal working conditions	2 T
Localised limbs exposure	8 T
Health effects ELVs	
Controlled working conditions	8 T

As can be seen in **Table 23**, the limits imposed for static magnetic fields are comparable to those presented in **Table 7**. However, since they specifically concern workers, the reference values are those established for a healthy adult male. In next tables will be possible to see the values related to persons wearing AIMD.

Table 24: Health effects ELVs for internal electric field strength from 1 Hz to 10 MHz [25].

Frequency range	Health effects ELVs
$1 \text{ Hz} \leq f \leq 3 \text{ kHz}$	$1,1 \text{ Vm}^{-1}$ (peak)
$3 \text{ kHz} \leq f \leq 10 \text{ MHz}$	$3,8 \times 10^{-4} f \text{ Vm}^{-1}$ (peak)

Notes:

1. f is the frequency expressed in hertz (Hz).
2. The health effects ELVs for internal electric field are spatial peak values in the entire body of the exposed subject.
3. The ELVs are peak values in time which are equal to Root-Mean-Square (RMS) values multiplied by $\sqrt{2}$ for sinusoidal fields. In the case of non-sinusoidal fields, exposure evaluation carried out in accordance with Article 4 shall be based on the weighted peak method (filtering in time domain), explained in the practical guides referred to in Article 14 but other scientifically proven and validated exposure evaluation procedures can be applied, provided that they lead to approximately equivalent and comparable results.

This table is up to 10 MHz because the exposure is to the entire non-thermal frequency range, while the sensory effects provided in **Table 25** show a narrower frequency range (above 400 Hz there are not sensory effects).

Table 25: Sensory effects ELVs for internal electric field strength from 1 to 400 Hz [25].

Frequency range	Sensory effects ELVs
$1 \leq f \leq 10 \text{ Hz}$	$0,7/f \text{ Vm}^{-1}$ (peak)
$10 \leq f \leq 25 \text{ Hz}$	$0,07 \text{ Vm}^{-1}$ (peak)
$25 \leq f \leq 400 \text{ Hz}$	$0,0028 f \text{ Vm}^{-1}$ (peak)

Notes: see **Table 24**

Since the non-thermal effects occurs below 10 MHz, higher frequency ranges ELVs will be provided in next paragraph, consequently the following tables will refer to ALs. As previously explained, there will be low ALs and high ALs, with different meaning depending on the nature of the field (electric or magnetic).

Table 26: ALs for magnetic flux density (B_0) of static magnetic fields, from 0 to 1 Hz [25].

Hazards	ALs(B_0)
Interference with active implanted devices, e.g. cardiac pacemakers	0,5 mT
Attraction and projectile risk in the field of high field strength sources (> 100 mT)	3 mT

Table 27: ALs for contact current I_C [25].

Frequency	ALs(I_C) steady state contact current [mA] (RMS)
up to 2,5 kHz	1,0
$2,5 \leq f < 100$ kHz	0,4 f
$100 \leq f \leq 10000$ kHz	40

Notes:

f is the frequency expressed in kHz.

Table 28: ALs for exposure to electric fields from 1 Hz to 10 MHz [25].

Frequency range	Electric field strength Low ALs(E) [Vm^{-1}] (RMS)	Electric field strength High ALs(E) [Vm^{-1}] (RMS)
$1 \leq f < 25$ Hz	$2,0 \times 10^4$	$2,0 \times 10^4$
$25 \text{ Hz} \leq f < 50$ Hz	$5,0 \times 10^5/f$	$2,0 \times 10^4$
$50 \text{ Hz} \leq f < 1,64$ kHz	$5,0 \times 10^5/f$	$1,0 \times 10^6/f$
$1,64 \text{ kHz} \leq f < 3$ kHz	$5,0 \times 10^5/f$	$6,1 \times 10^2$
$3 \text{ kHz} \leq f \leq 10$ MHz	$1,7 \times 10^2$	$6,1 \times 10^2$

Notes:

1. f is the frequency expressed in hertz (Hz).
2. The low ALs (E) and high ALs (E) are the Root-Mean-Square (RMS) values of the electric field strength which are equal to the peak values divided by $\sqrt{2}$ for sinusoidal fields. In the case of non-sinusoidal fields, the exposure evaluation carried out in accordance with Article 4 shall be based on the weighted peak method (filtering in time domain), explained in the practical guides referred to in Article 14, but other scientifically proven and validated exposure evaluation procedures can be applied, provided that they lead to approximately equivalent and comparable results.
3. ALs represent maximum calculated or measured values at the workers' body position. This results in a conservative exposure assessment and automatic compliance with ELVs in all non-uniform exposure conditions. In order to simplify the assessment of compliance with ELVs, carried out in accordance with Article 4, in specific non-uniform conditions, criteria for the spatial averaging of measured fields based on established dosimetry will be laid down in the practical guides referred to in Article 14. In the case of very localised source within a distance of a few centimetres from the body, the induced electric fields shall be dosimetrically, case by case.

Table 29: ALs for exposure to magnetic fields from 1 Hz to 10 MHz [25].

Frequency range	Magnetic flux density low ALs(B) [μ T] (RMS)	Magnetic flux density High ALs(B) [μ T] (RMS)	Magnetic flux density ALs for exposure of limbs to a localised magnetic field [μ T] (RMS)
$1 \leq f < 8$ Hz	$2,0 \times 10^5/f^2$	$3,0 \times 10^5/f$	$9,0 \times 10^5/f$
$8 \leq f < 25$ Hz	$2,5 \times 10^4/f$	$3,0 \times 10^5/f$	$9,0 \times 10^5/f$
$25 \leq f < 300$ Hz	$1,0 \times 10^3$	$3,0 \times 10^5/f$	$9,0 \times 10^5/f$
$300 \text{ Hz} \leq f < 3 \text{ kHz}$	$3,0 \times 10^5/f$	$3,0 \times 10^5/f$	$9,0 \times 10^5/f$
$3 \text{ kHz} \leq f \leq 10 \text{ MHz}$	$1,0 \times 10^2$	$1,0 \times 10^2$	$3,0 \times 10^2$

Notes: see **Table 28**

4.6.2 Exposure limits – thermal effects

Thermal effects occur above 100 kHz, so from **Table 30** up to **Table 34** will be focused on the frequency range between 100 kHz and 300 GHz

Table 30: Health effects ELVs for exposure to electromagnetic fields from 100 kHz to 6 GHz [25].

Health effects ELVs	SAR values averaged over any six-minute period
ELVs related to whole body heat stress expressed as averaged SAR in the body	$0,4 \text{ Wkg}^{-1}$
ELVs related to localised heat stress in head and trunk expressed as localised SAR in the body	10 Wkg^{-1}
ELVs related to localised heat stress in the limbs expressed as localised SAR in the limbs	20 Wkg^{-1}

Note: Localised SAR averaging mass is any 10 g of contiguous tissue; the maximum SAR so obtained should be the value used for estimating exposure. This 10 g of tissue is intended to be a mass of contiguous tissue with roughly homogeneous electrical properties. In specifying a contiguous mass of tissue, it is recognised that this concept may be used in computational dosimetry but may present difficulties for direct physical measurements. A simple geometry, such as cubic or spheric tissue mass, can be used.

Table 31: Sensory effects ELVs for exposure to electromagnetic fields from 0,3 to 6 GHz [25].

Frequency range	Localised specific energy absorption (SA)
$0,3 \leq f \leq 6 \text{ GHz}$	10 mJkg^{-1}

Note: Localised SA averaging mass is 10 g of tissue.

Table 32: Health effects ELVs for exposure to electromagnetic fields from 6 to 300 GHz [25].

Frequency range	Health effects ELVs related to power density
$6 \leq f \leq 300 \text{ GHz}$	50 Wm^{-2}

Note: The power density shall be averaged over any 20 cm^2 of exposed area. Spatial maximum power densities over 1 cm^2 should not exceed 20 times the value of 50 Wm^{-2} . Power densities from 6 to 10 GHz are to be averaged over any six-minute period. Above 10 GHz, the power density shall be averaged over any $68/f^{1,05}$ -minute period (where f is the frequency in GHz) to compensate for progressively shorter penetration depth, as the frequency increases.

Table 33: ALs for steady state contact currents and induced limb currents [25].

Frequency range	Steady state contact current, ALs(I _c) [mA] (RMS)	Induced limb current in any limb, ALs(I _l) [mA] (RMS)
$100 \text{ kHz} \leq f < 10 \text{ MHz}$	40	-
$10 \leq f \leq 110 \text{ MHz}$	40	100

Note: $[\text{ALs(I}_l)]^2$ is to be averaged over a six-minute period.

Table 34: ALs for exposure to electric and magnetic fields from 100 kHz to 300 GHz [25].

Frequency range	Electric field strength ALs(E) [Vm^{-1}] (RMS)	Magnetic flux density ALs(B) [μT] (RMS)	Power density ALs(S) [Wm^{-2}]
$100 \text{ kHz} \leq f < 1 \text{ MHz}$	$6,1 \times 10^2$	$2,0 \times 10^6/f$	-
$1 \leq f < 10 \text{ MHz}$	$6,1 \times 10^8/f$	$2,0 \times 10^6/f$	-
$10 \leq f < 400 \text{ MHz}$	61	0,2	-
$400 \text{ MHz} \leq f < 2 \text{ GHz}$	$3 \times 10^{-3} f^{1/2}$	$1,0 \times 10^{-5} f^{1/2}$	-
$2 \leq f < 6 \text{ GHz}$	$1,4 \times 10^2$	$4,5 \times 10^{-1}$	-
$6 \leq f \leq 300 \text{ GHz}$	$1,4 \times 10^2$	$4,5 \times 10^{-1}$	50

Notes:

1. f is the frequency expressed in hertz (Hz)
2. $[\text{ALs(E)}]^2$ and $[\text{ALs(B)}]^2$ are to be averaged over six-minute period. For RF pulses, the peak power density averaged over the pulse width shall not exceed 1000 times the respective ALs(S) value. For multi-frequency fields, the analysis shall be based on summation, as explained in the practical guides referred to Article 14.
3. ALs(E) and ALs(B) represent maximum calculated or measured values at the workers' body position. This results in a conservative exposure assessment and automatic compliance with ELVs in all non-uniform exposure conditions. In order to simplify the assessment of compliance with ELVs, carried out in accordance with Article 4, in specific non-uniform conditions, criteria for the spatial averaging of measured fields based on established dosimetry will be laid down in the practical guides referred to in Article 14. In the case of a very localised source within a distance of few centimetres from the body, compliance with ELVs shall be dosimetrically, case by case.

4.7 D. P. C. M. 8 July 2003

This is the legislative framework specifically introduced within the Italian territory. In the tables reported below, the first aspect that should be highlighted concerns the exposure range: for frequencies between 100 kHz and 300 GHz, specific values are prescribed, while for frequencies below 100 kHz no limits are established. Nevertheless, the limits set by the Italian regulation are more restrictive than those recommended by ICNIRP and previously discussed.

Another relevant difference compared to the ICNIRP guidelines lies in the definition of the limits themselves. The law provides three separate tables, all referring to the same frequency range but assigning different exposure values according to the corresponding “*quality level*”. This distinction introduces a further degree of stringency in the evaluation exposure conditions [26].

There are two *DPCM of 8 July 2003*, and only the second one, *DPCM of 8 July 2003 Bis*, is devoted to exposure from power distribution systems operating at the frequency of 50 Hz, defining safety distances and allowable exposure durations.

4.7.1 Exposure limits

As anticipated, there are not basic restrictions and reference levels, but “Limiti di esposizione” (Exposure limits), “Valori di attenzione” (Attention values), “Obiettivi di qualità” (Quality tasks), however these values play a similar role.

- Limiti di esposizione: values that must not be exceeded.
- Valori di attenzione: caution values to prevent any long-term effects. Related to buildings, with permanence periods equal or higher to four hours, and their external zones.
- Obiettivi di qualità: values with the aim of the progressive decrease of exposure levels, averaged in 6 minutes.

Table 35: Table with “Limiti di esposizione” [26].

Limiti di esposizione			
Frequency range	Electric field strength E (V/m)	Magnetic field strength H (A/m)	Power density D (W/m ²)
$0,1 < f \leq 3$ MHz	60	0,2	-
$3 < f \leq 3000$ MHz	20	0,05	1
$3 < f \leq 300$ GHz	40	0,01	4

Table 36: Table with “Valori di attenzione” [26].

Valori di attenzione			
Frequency range	Electric field strength E (V/m)	Magnetic field strength H (A/m)	Power density D (W/m ²)
0,1 MHz < f ≤ 300 GHz	6	0,016	0,10 (3 MHz – 300 GHz)

Table 37: Table with “Obiettivi di qualità” [26].

Obiettvi di qualità			
Frequency range	Electric field strength E (V/m)	Magnetic field strength H (A/m)	Power density D (W/m ²)
0,1 MHz < f ≤ 300 GHz	6	0,016	0,10 (3 MHz – 300 GHz)

In 2023, with the law 214/2023 the limit of E field was increased up to 15 V/m, however these values play a similar role [27].

Compared to other limits imposed in European Union, Italy has the most restrictive values together with other few countries as Switzerland.

4.7.2 Multiple exposure

Assessment of multiple exposure is quite difficult due to the complexity of the equations. They are the following:

$$C_i = \frac{E_i^2}{L_i^2} \quad \text{or for frequency } f > 3 \text{ MHz} \quad C_i = \frac{D_i}{D_{Li}} \quad (47)$$

where:

E_i is the i-th source;

L_i is the corresponding limit in **Table 35**, **Table 36** or **Table 37**;

D_i is the power density of the source;

D_{Li} is the corresponding power density limit in **Table 35**, **Table 36** or **Table 37** [26].

If the sum:

$$C = \sum_i C_i > 1 \quad (48)$$

The exposure limits are not satisfied, and one or more E_i must be reduced. [26]

In that case, the contributes C_j that singularly overcome the value 1 are named R_j . To each of the corresponding signals E_j a reduction coefficient β_j must be applied to.

$$\beta_j^2 R_j = 0,8 \rightarrow \beta_j = \sqrt{\frac{0,8}{R_j}} = \sqrt{\frac{0,8 * L_j^2}{E_j^2}} \text{ and } E_{jR} = \beta_j E_j \quad (49)$$

If the sum:

$$C = \sum_p C_p + \sum_j \frac{E_{jR}^2}{L_j^2} > 1 \quad \text{where } (p + j = i) \quad (50)$$

The various signals must be reduced in such a way that $C \leq 0,8$ with the aim of a higher general public protection.

From the set of the contributions to be normalized, the signals giving a contribution lower than 1/100 must be excluded, conventionally indicated with the expression:

$$\sum_k A_k \quad (51)$$

Considering $n + k = p$, the equation (52)

$$C = \sum_p C_p + \sum_j \frac{E_{jR}^2}{L_j^2} > 1 \quad (52)$$

where $p + j = i$ can be write as:

$$C = \sum_n \frac{E_n^2}{L_n^2} + \sum_k A_k + \sum_j \frac{E_{jR}^2}{L_j^2} > 1 \quad (53)$$

By imposing to the (53) $C = 0,8$; $E_{nR} = \alpha E_n$; $E_{jRR} = \alpha E_{jR}$ and being α the reduction coefficient and E_{nR} and E_{jRR} the new values, reduced to compliance, of the electric fields, it is obtained:

$$0,8 = \sum_n \frac{E_{nR}^2}{L_n^2} + \sum_k A_k + \sum_j \frac{E_{jRR}^2}{L_R^2} = \sum_n \frac{\alpha^2 E_n^2}{L_n^2} + \sum_k A_k + \sum_j \frac{\alpha^2 E_{jR}^2}{L_R^2} \quad (54)$$

from which:

$$0,8 - \sum_k A_k = \alpha^2 \left(\sum_n \frac{E_n^2}{L_n^2} + \sum_j \frac{E_{jR}^2}{L_j^2} \right) \quad (55)$$

$$\alpha = \sqrt{\frac{0,8 - \sum_k A_k}{\sum_n \frac{E_n^2}{L_n^2} + \sum_j \frac{E_{jR}^2}{L_j^2}}} = \sqrt{\frac{0,8 - \sum_k A_k}{\sum_n \frac{E_n^2}{L_n^2} + \sum_j \frac{\beta_j^2 E_j^2}{L_j^2}}} \quad (56)$$

[26].

In 2012, with *Law n. 221/2012*, the averaging period was changed from 6 minutes to 24-h mean value

4.8 ACGIH TLVs and BEIs

With regard to the suggested exposure limits, the American Conference of Governmental Industrial Hygienists threshold limit values and biological exposure indices (ACGIH TLVs and BEIs) are generally not more restrictive than those proposed by ICNIRP, with the exception of a single specific case. Certain models of cardiac pacemakers have been shown to be particularly susceptible to interference from magnetic flux densities at power frequencies (50-60 Hz) as low as 0,1 mT. For this reason, it is recommended that the exposure individuals wearing cardiac pacemakers, or similar electronic medical devices, be maintained at or below 0,1 mT when exposed to 50-60 Hz magnetic fields. This precaution is intended to prevent malfunctions or disruptions in the normal operation of such devices, thereby ensuring the safety of vulnerable individuals [28].

4.9 Summary of the lowest limit values

For both practical and considerations and quality assurance purposes, it is essential to comply with the most restrictive values previously mentioned, in particular for exposure of vulnerable individuals in public and occupational areas as identified by the scope of this thesis, and in particular workers and travellers with AIMD in public transportation. Since these values are drawn from different tables, the following table represents a combined set containing the most restrictive limits.

Table 38: Summary table of most restrictive values.

Frequency range	Electric field strength E (V/m)	Magnetic field strength H (A/m)	Magnetic flux density B (μ T)	Power density (W/m ²)
0-1 Hz	-	$3,2 \times 10^4$	5×10^2	-
1 – 8 Hz	10000	$3,2 \times 10^4$	$4 \times 10^4/f^2$	-
8 – 25 Hz	10000	$4000/f$	$5000/f$	-
25 - 50 Hz	$250/f$	$4/f$	$5/f$	-
50 – 60 Hz	$250/f$	$4/f$	$5/f$	-
0,06 – 0,8 kHz	$250/f$	$4/f$	$5/f$	-
0,8 – 3 kHz	$250/f$	5	6,25	-
3 – 100 kHz	87	5	6,25	-
100 – 150 kHz	6	0,016	6,25	-
0,15 – 3 MHz	6	0,016	$0,92/f$	-
0,003 – 300 GHz	6	0,016	$0,92/f$	0,10

Note:

1. f as indicated in the frequency range column.
2. Provided that basic restrictions are met and adverse indirect effects can be excluded, field strength values can be exceeded.
3. For frequencies between 100 kHz and 10 GHz, S_{eq} , E^2 , H^2 , and B^2 are to be averaged over any 6-min period.
4. For frequencies up to 100 kHz, peak current density values can be obtained by multiplying the rms value by $\sqrt{2}$ (~ 1.414). For pulses of duration t_p the equivalent frequency to apply in the basic restrictions should be calculated as $f = 1/(2t_p)$.

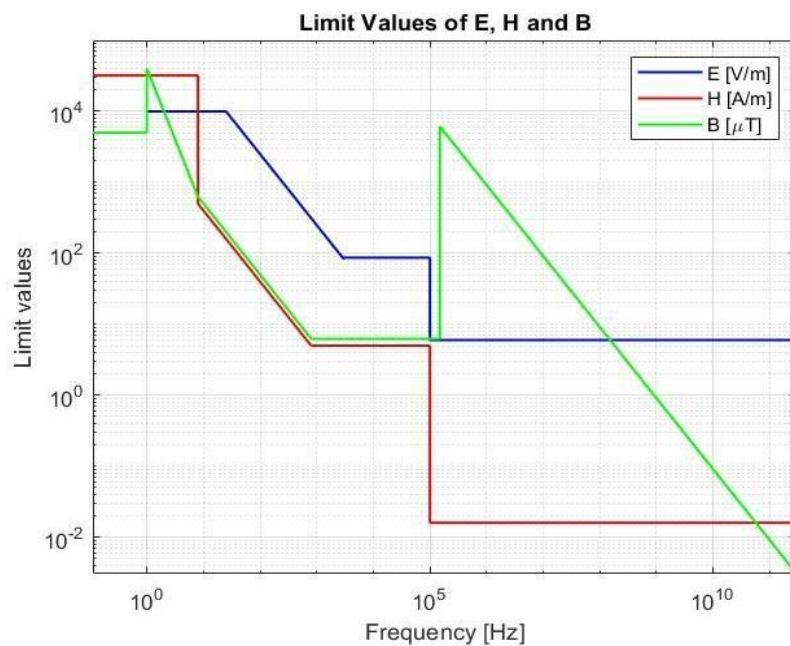


Figure 21: Most restrictive limit values (Table 38: Summary table of most restrictive values).

5 AIMDs regulations

Throughout all the chapters, the topics of direct and indirect effects have repeatedly emerged, together with the static magnetic field exposure limit of 0,5 mT. In particular, indirect effects have been described as those arising from the interaction of EMFs with objects, which may in turn pose risks to individuals who come into contact with them. Among these special, attention must be given to objects that remain in continuous contact with the human body: implanted medical devices.

Implantable medical devices can be divided into two main categories: non-active implantable medical devices (for example, prostheses or dental implants) and active implantable medical devices or AIMD, (such as pacemakers or drug delivery injectors) so called due to their energy source that is different from one produced by human body (battery or electric stimulation). The discussion will focus primarily on the second category, as these devices are particularly susceptible to the influence of EMFs due to their reliance on electronic components and electrical functionality. It is therefore appropriate to provide a clear definition of what AIMDs are. The first formal classification of AIMDs was introduced in Council Directive 90/385/EEC [29] in 1990, which was later replaced by Regulation (EU) 2017/745 – Medical Device Regulation (MDR) [30].

Active Implantable Medical Device: any active medical device which is intended to be totally or partially introduced, surgically or medically, into the human body or by medical intervention into a natural orifice, and which is intended to remain after the procedure [29].

As with all electronic and medical devices, AIMD must strictly comply with specific regulations and technical standards. These regulatory frameworks are designed to ensure that patients are adequately protected from potential injuries and malfunctions that could arise both from the normal operation of the device and from external factors, such as the EMFs. Compliance is therefore a fundamental prerequisite, not only for the certification and market access of AIMD, but also for guaranteeing their long-term safety and reliability in clinical use.

5.1 EU 2017/745 MDR

The purpose of this Regulation is to govern in European Union, through state-of-the-art standards, the placing on the market of medical devices intended for human use. A device may be placed on the market only if it is with the provisions set out in this Regulation.

In the context of this study, particular attention will be given to the following chapters, as they contain requirements directly or indirectly related to the EMC of AIMDs:

- Article 10 – General obligations of manufacturers;
- Article 61 – Clinical evaluation;
- Article 104 – Role and support of the Medical Device Coordination Group (MDCG);
- Article 120 – Transitional provisions from the previous directives to the MDR;
- Annex I – General safety and performance requirements;

5.1.1 Article 10: General obligations of manufacturers

Article 10 establishes the general obligations that manufacturers must comply with before placing a medical device on the market or putting it into service. Manufacturers are required to design and produce their devices in accordance with the Regulation, ensuring safety, performance, and conformity to state-of-the-art requirements.

They must establish and maintain a risk management system and conduct a clinical evaluation including post-market clinical follow-up activities. A technical documentation set must be prepared and kept up to date to demonstrate conformity with the Regulation.

Manufacturers are also required to draw up an EU Declaration of Conformity and affix the CE marking once compliance has been demonstrated. They must implement the Unique Device Identification (UDI) system and ensure the registration of devices and economic operators.

All relevant documentation, including technical files, declarations of conformity, and certificates, must be retained for at least ten years after the last device has been placed on the market, or fifteen years in the case of implantable devices. Moreover, manufacturers must maintain procedures ensuring the ongoing conformity of serial production, even after regulatory or technical changes.

Finally, they are required to implement and maintain a Quality Management System (QMS) suitable for the risk class and nature of the device, ensuring continuous compliance with the MDR's essential requirements for safety and performance [30].

5.1.2 Article 61: Clinical evaluation

Article 61 establishes that compliance with the general safety and performance requirements must be demonstrated through sufficient clinical evidence regarding the risks, benefits, and performance of the medical device.

The manufacturer is required to justify the level of clinical evidence appropriate to the device's characteristics and intended purpose, and to conduct and document a clinical evaluation following a scientifically valid methodology.

The clinical evaluation shall include:

- a critical analysis of relevant scientific literature;
- a critical evaluation of the results from available clinical investigations;
- an analysis of alternative therapeutic options, where applicable.

For implantable and class III devices (class III devices are AIMDs intended to remain inside the human body for long periods, where any malfunction could pose a significant risk to the patient), clinical investigations are generally mandatory, unless equivalence with an already marketed device can be demonstrated and adequately supported by sufficient clinical evidence of the original device.

An alternative approach may be applied for devices where clinical data are not appropriate, provided that this choice is duly justified through risk management and supported by non-clinical data (e.g. laboratory or pre-clinical tests). However, this exemption does not apply to implantable or class III devices.

The clinical evaluation is a continuous process throughout the entire clinical life cycle of the device. New clinical data and post-market clinical follow-up (PMFC) information must be integrated and used to update the Clinical Evaluation Report (CER).

All results, evidence, and conclusions derived from the clinical evaluation process must be documented in the Clinical Evaluation Report, which forms an integral part of the device's technical documentation [30].

5.1.3 Article 104: Role and support of the Medical Device Coordination Group (MDCG)

Article 104 outlines the European Commission's role in supporting the cooperation between national competent authorities under the Medical Device Regulation (MDR).

Specifically, it mandates that the Commission to:

- facilitate the functioning of cooperation among national competent authorities;
- organize exchanges of experience between these authorities;
- provide technical, scientific, and logistical support to the Medical Device Coordination Group (MDCG) and its subgroups;
- organize and participate in MDCG meetings and ensure appropriate follow-up actions.

This support is essential for ensuring consistent implementation and enforcement of the MDR across the European Union [30].

5.1.4 Article 120: Transitional provisions from the previous directives to the MDR

Article 120 outlines the transitional provisions applicable to medical devices already placed on the market under Directive 93/42/EEC or Directive 90/385/EEC before the full application of the MDR. Key points include:

- devices compliant with the previous directives may continue to be placed on the market until 26 May 2024, provided they continue to meet their original conformity assessment requirements;
- certificates issued under the old directives remain valid until their expiry, but in no case late than 26 May 2024;
- manufacturers must ensure ongoing compliance with vigilance and post-market surveillance obligations under the MDR;
- the transitional provisions are meant to provide sufficient time for manufacturers to adapt their devices and documentation to the MDR requirements without disrupting market availability [30].

5.1.5 Annex I – General safety and performance requirements

Annex I specifies the general safety and performance requirements that all medical devices must meet to ensure they are safe and perform as intended throughout their life cycle. Key points include:

1. Risk Management – Devices must be designed and manufactured to reduce risks as far as possible, taking into account the generally acknowledged state-of-the-art.
2. Chemical, Physical, and Biological Properties – Devices must be safe with respect to chemical composition, physical design, and biological interactions.
3. Infection and Microbial Contamination - Devices must be designed to minimise the risk of infection or microbial contamination.
4. Design and Manufacturing- Devices must be designed and manufactured according to quality management principles to ensure consistent performance.
5. Protection Against Radiation and Electromagnetic Disturbances – Devices must not expose users or patients to unacceptable electromagnetic or other radiations, and must be designed to function correctly in the presence of electromagnetic disturbances.
6. Performance and Safety Verification – Devices must achieve their intended purpose without compromising safety.
7. Information Supplied by the Manufacturer – Adequate instructions and information must accompany the device to ensure safe use.

Point 5 constitutes the case study of the thesis. Document [30] outlines the requirements that AIMDs must meet. These devices must not expose the patient to leakage currents or to overheating caused by external sources, with EMFs being the main contributor, and they must minimise or eliminate risks associated with medical procedures, such as the use of defibrillators.

These requirements apply to all stages of a device’s lifecycle, including design, production, storage, distribution and disposal [30].

5.2 ISO 14117:2019

One of the key reference documents that specifies the requirements for testing AIMDs is ISO 14117, most recently revised in 2019. This standard provides detailed methodologies for evaluating the EMC of AIMDs, with particular attention to the safety and functional reliability of such devices in the presence of electromagnetic disturbances. The frequency ranges covered by the standard are $0 \text{ Hz} \leq f < 385 \text{ MHz}$ and $385 \text{ MHz} \leq f \leq 3000 \text{ MHz}$ [16]. The susceptibility of AIMDs to electromagnetic interference is already well established. However, it is essential to emphasise that these devices are implanted within the human body. For this reason, they “*shall not create an unacceptable risk for patients because of susceptibility to electrical influences due to external EM fields, whether through malfunction of the device, damage to the device, heating of the device, or by causing local increase of induced electrical current density within the patient*” [16]. To ensure this, AIMDs are subjected to extensive testing, and all such tests must be successfully passed before the devices can be placed on the market.

The requirements for the tests described in this section are defined by the standard *EN 45502-2-1* [31], while the detailed procedures for performing these tests are provided

by *ISO 14117* [16]. For this reason, the compliance requirements for the device are summarized at the end of each test description.

5.2.1 Induced lead current

The first test present in the document concerns the “induced lead current” in which the device is stimulated by two different test signals at different voltage and frequency (1 V with a frequency swept over the range 16,6 Hz to 20 kHz and a sinusoidal carrier signal at 500 kHz with a modulation at 130 Hz and maximum voltage of 2 V). The elements needed for the test are:

- an oscilloscope to measure the induced electrical current;
- a test signal generator;
- a tissue equivalent interface that emulates the human body;
- a low-pass filter;
- a device under test (DUT).

All elements are connected to the equivalent tissue, and the connection of DUT with the tissue depends on the kind of the device (there are four groups, from “a” to “d”). The voltage will be evaluated at the connection point between the filter and the tissue and divided by 232 Ω for test signal 1 and by 82 Ω for test signal 2. The current values must be below 50 μ A for test signal 1 and below 50 μ A x (f/1 kHz) for test signal 2 [3].

5.2.2 Protection from persisting malfunction attributable to ambient electromagnetic fields

The devices must be constructed so that it is difficult that EMFs cause persisting malfunctions also after the end of the exposure.

In this case, two separate tests are required: the first covering the frequency range from 16,6 Hz to 10 MHz, and the second covering the frequency range from 10 MHz to 385 MHz (this second test will not be addressed, as the corresponding frequency lies outside the scope of the present study).

For the first test, the typical setup consists of an oscilloscope, a test signal generator, and a tissue equivalent interface. All devices are properly connected to the equivalent tissue. The applied test signal is a continuous sinusoidal waveform, swept across the frequency range of 16,6 Hz to 10 MHz at a rate of one decade per minute.

The amplitude of the test signal for the common mode test is defined as follows:

- 1 V for 16,6 Hz $\leq$ f $\leq$ 20 kHz
- 1 V x (f/20 kHz) for 20 kHz $\leq$ f $\leq$ 140 kHz
- 7 V x (f/140 kHz)^{0,1624} for 140 kHz $\leq$ f $\leq$ 10 MHz

The test is considered passed if the AIMD, properly connected to the tissue equivalent interface, operates in the same way both with and without the application of the test signal [16].

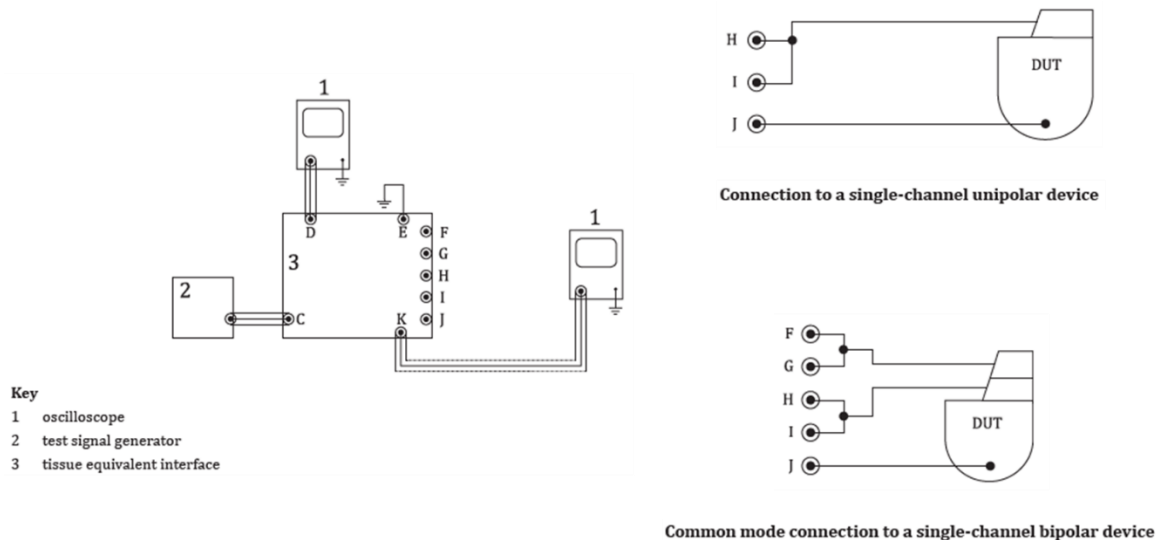


Figure 21: Protection from persisting malfunction attributable to ambient electromagnetic fields setup [16].

5.2.3 Protection from malfunction caused by temporary exposure to CW (continuous wave) sources

Also in this case, the device must be designed and constructed in such a way that temporary exposure to CW EMFs is unlikely to result in malfunction or performance degradation.

The tested frequency range goes from 16,6 Hz up to 167 kHz. The equipment consists in an oscilloscope, a test signal generator, a tissue equivalent interface and an inhibition generator.

The test signal must be a continuous sinusoidal applied for at least four different well-spaced frequencies per decade in the range before mentioned. Its amplitude must slowly increase from zero to a maximum of 1 V.

The device is in compliance with the regulation if:

- a) *either the pacemaker continues to operate as set while the test conditions are varied as required; or*
- b) *for pacing devices incorporating a defined interference mode:*
 - if while increasing the test signal amplitude the device transitions from its set mode to its interference mode when the test signal amplitude is increased by no more than 6 dB, or;*
 - if while increasing the test signal amplitude the device transitions from its set mode to its interference mode, the time between either*
 - *delivery of a pacing pulse, or*

- *inhibition of pacing due to sensing of the simulated heart signal, is no more than two preset intervals [16].*

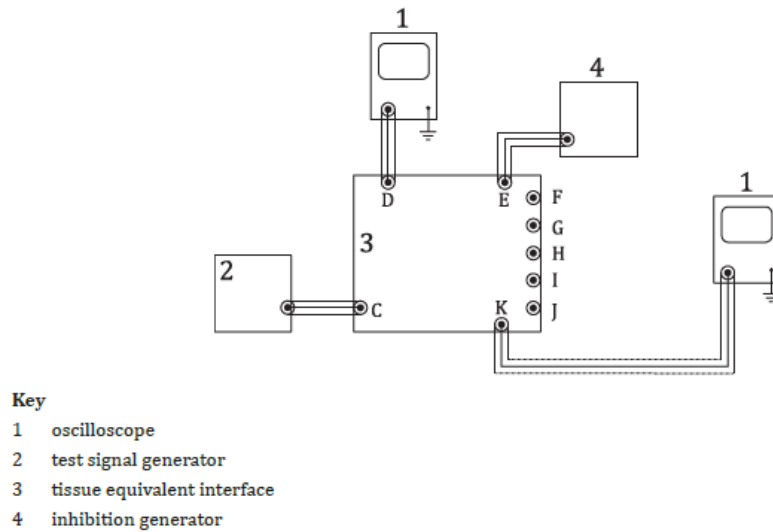


Figure 22: Test setup to characterize DUT performance while subject to interference [16].

5.2.4 Protection from sensing EMI as cardiac signals

This test is carried out across three different frequency ranges: 16,6 Hz to 150 kHz, 150 kHz to 10 MHz, 10 MHz to 385 MHz. As already stated in previous sections, the last frequency range will not be discussed, as it lies outside the scope of this work.

For the first frequency range (16,6 Hz to 150 kHz), the experimental setup consists of a tissue-equivalent interface, two oscilloscopes, an inhibition signal generator and a test signal generator.

Two different test signals are generated:

1. a continuous sinusoidal waveform with a frequency between 16,6 Hz and 1 kHz. It is essential that the test includes the specific frequencies of 16,6 Hz, 50 Hz, 60 Hz, and 100 Hz.
2. a burst-modulated signal of approximately 100 ms duration, with a frequency between 1 kHz and 150 kHz.

For both types of test signals, the peak-to-peak amplitude shall be:

- 2 mV for $16,6 \text{ Hz} \leq f \leq 1 \text{ kHz}$;
- $2 \text{ mV} \times (f/1 \text{ kHz})^2$ for $1 \text{ kHz} \leq f \leq 3 \text{ kHz}$;
- $6 \text{ mV} \times (f/1 \text{ kHz})$ for $3 \text{ kHz} \leq f \leq 150 \text{ kHz}$.

Compliance is confirmed if the AIMD consistently operates in its prescribed mode under all conditions, both in the absence of the test signal and during its application [3].

For the second frequency range (150 kHz to 10 MHz), the test equipment is identical to that used for the first range.

The applied test signal consists of a modulated waveform between the specified frequency range. The burst duration shall be of 100 ms, with a burst-to-burst interval of $700 \text{ ms} \pm 50 \text{ ms}$.

The peak-to-peak amplitude of the test signal shall be defined as follows:

- $6 \text{ mV} \times (f/1 \text{ kHz})$ for $150 \text{ kHz} \leq f \leq 167 \text{ kHz}$;
- 1 V for $167 \text{ kHz} \leq f \leq 1 \text{ MHz}$;
- $1 \text{ V} \times (f/1 \text{ MHz})$ for $1 \text{ MHz} \leq f \leq 10 \text{ MHz}$.

Compliance is confirmed if the AIMD consistently operates in its prescribed mode under all test conditions, both in the absence of the modulated signal and during its application [16].

5.2.5 Protection from static magnetic fields of flux density up to 1 mT

The device must be immune to static magnetic fields with flux densities not exceeding 1 mT.

The required equipment consists of an inhibition generator, an oscilloscope, two resistors ($51 \text{ k}\Omega \pm 1 \%$ and $500 \text{ }\Omega \pm 1 \%$), and a field coil capable of generating a uniform magnetic field with a flux density of up to $1 \text{ mT} \pm 0,1 \text{ mT}$.

The lower-value resistor is connected to one terminal, while the test signal is injected into the same terminal through the higher-value resistor.

Compliance is confirmed if the AIMD remains inhibited for the entire duration of the applied magnetic field.

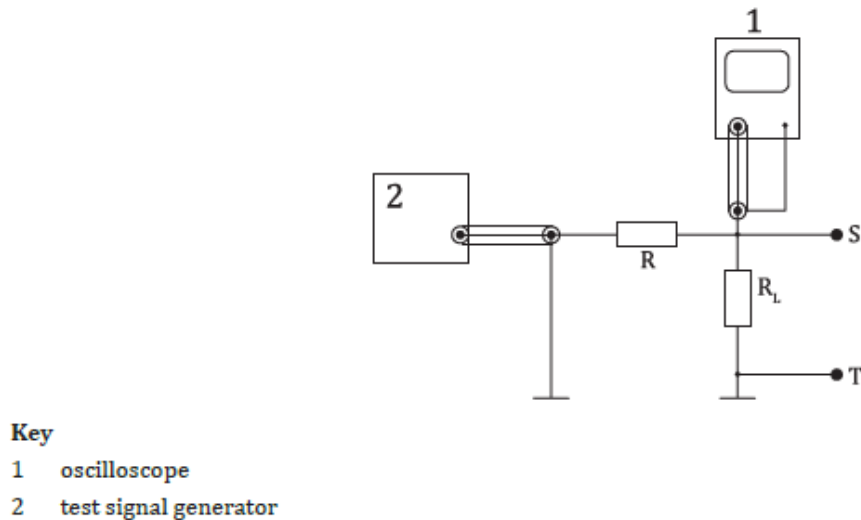


Figure 23: Test setup for magnetostatic measurements [16].

5.2.6 Protection from static magnetic field of flux density up to 50 mT

The device, after the end of the exposure to static fields up to 50 mT, must guarantee its normal working functionality.

The equipment required for this test consists of a coil capable of generating a uniform magnetic field with a flux density of up to $50 \text{ mT} \pm 5 \text{ mT}$.

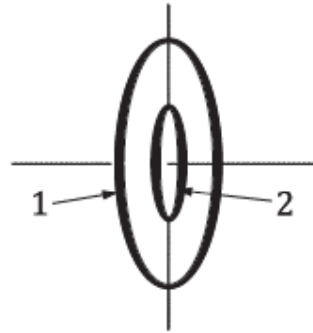
During the test, the device shall be slowly positioned at the centre the coil once the magnetic field has been activated. After an exposure of at least 15 seconds, the AIMD shall be slowly removed from the test position. The procedure is repeated for each of the three orthogonal axes of the test coil.

Compliance with the regulation is confirmed if, after removal from the magnetic field exposure, the AIMD operates normally and shows no deviation from its pre-test performance [16].

5.2.7 Protection from AC magnetic field exposure in the range of 1 kHz to 140 kHz

All the AIMDs shall be constructed in such a way that their functionality is not compromised after removal from exposure to a magnetic field.

The equipment required for the test includes: a radiating coil with a diameter of at least 12 cm and at least 50% larger than the greatest linear dimension of the AIMD; a calibration coil with a diameter of no more than 4 cm; a signal generator to energize the radiating coil.



Key

- 1 radiating loop
- 2 field monitoring loop

Figure 24: Loop configuration for varying magnetic field test [16].

The test magnetic field shall be modulated according to the following conditions:

- 150 A/m for $1 \text{ kHz} \leq f \leq 100 \text{ kHz}$;
- $150 \text{ A/m} \times (100 \text{ kHz} / f)$ for $100 \text{ kHz} \leq f \leq 140 \text{ kHz}$.

The signal levels applied to the radiating coil are determined using the calibration coil. The magnetic field is produced at the centre of the radiating coil. After removing the calibration coil, the AIMD shall be positioned so that its centre coincides with the calibration point of maximum field intensity. The test must then be performed along the three orthogonal axes of the AIMD, each aligned with the axis of the radiating coil.

Compliance is confirmed if, after exposure, the AIMD continues to operate normally and shows no alteration compared to its pre-test performances [16].

The last test described in the standard is the “*Test requirements for the frequency range of $385 \text{ MHz} \leq f \leq 3000 \text{ MHz}$* ”. However, this test will not be discussed in the present work, as the corresponding frequency range falls outside the scope of interest.

6 EMF assessment standardization and Test Report

The current automotive standards for exposure to EMF assessment are mainly focused on passenger cars, while for buses no assessment standards have been released. EU and international automotive regulations, such as UNECE Regulation 10, focus exclusively on vehicle homologation and therefore on electromagnetic compatibility (EMC) requirements to ensure the correct and reliable operation of systems and subsystems in vehicles. Manufacturers comply with these regulatory obligations, but again only with regard to automotive EMC aspects. On the contrary, we note that exposure standards on vehicles do not impact on homologation at present time as reported by EU-JRC.

From this gap, the necessity of a clear and well-defined assessment approach arises for the exposure in vehicles, particularly for manufacturers who must ensure to their customers safe products for all types of passengers, also the most vulnerable.

To address this blank, this chapter proposes an appropriate methodology for processing the EMF exposure assessment and generating the corresponding test report. A case study developed in collaboration with IVECO will be provided to explain better the proposed approach.

6.1 Automotive standards

There are two main documents that help the process of EMF exposure assessment, one for the passenger car (IEC 62764-1) and one for the railway environment (EN 50500). Being buses a mixture of both vehicles, they will be both taken into account in the standardization process.

6.1.1 IEC 62764-1: 2022

The full title of IEC 62764-1 is “*Measurement procedures of magnetic field levels generated by electronic and electrical equipment in the automotive environment with respect to human exposure – Part 1: Low-frequency magnetic fields*”. For exposure point of view, this standard is precisely aligned with the objective of this thesis; however, it is limited to passenger cars only.

The first fundamental guideline provided by the standard concerns the test site. The assessment must be performed in an environment where the background magnetic field level remains below 10% of the limit values specified for the measurement volumes. As a result, the test area must be free from any external magnetic fields interference. The test can be performed both indoor and outdoor (in the case of an outdoor track, the slope must be in the range of $\pm 2\%$). Dynamometer and roller bench may be used if it rotates all the wheels of the vehicle [32].

The other fundamental section is the vehicle set-up. The points to guarantee are:

- all seats, if adjustable, must be at the centre horizontal position and at the lowest vertical position;
- the rearmost seats, if adjustable, in their rearmost position;
- the headrest fully retracted;

- all seats except for the rearmost seats, if adjustable, approximately 15° back from the vertical;
- all seats backs of the rearmost seats, if adjustable, fully titled backwards;
- the steering wheel in its centre position both horizontally and vertically [32].

Regarding the measurement points, the document requires the assessment of all the regions accessible to the driver or passengers, both inside and outside the vehicle. The internal accessible regions are illustrated in the **Figure 26**.

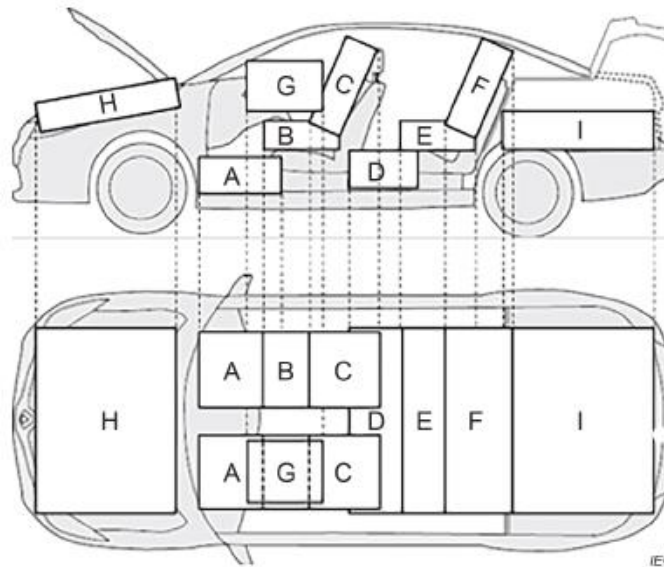


Figure 26: Example of test volumes taking account of all body parts for a left-hand drive vehicle [32].

The regions to measure are the head and trunk region, the upper leg region, the lower leg region, and in addition for the driver the hand region. The EMFs must be measured also in the baggage compartment and the motor compartment, where accessible. Outside the vehicle, it is important to evaluate the external areas around the vehicle perimeter [32].

It is also important to ensure a distance from any part of the vehicle and the centre of the probe of 20 cm, and of 6,5 cm for seats only. Regarding the probe itself, it must comply with the *IEC 61786-1* [33].

Vehicles work at different operating conditions and, depending on their status, the emitted EMFs are different in intensity and in frequencies. For this reason, the assessment must occur in all the possible conditions. They are:

- stationary mode;
- driving mode (at constant speed);
- dynamic mode (acceleration and deceleration phases);
- plug-in charging mode (only for hybrid and electric vehicles).

In stationary mode, the vehicle must be at idle with transmission disengaged or ready to drive, depending on the propulsion and on the transmission. The parking brake must be enabled, doors closed, the seats in position defined above and with all the electrical device turned on (A/C, lights, ...). In case of hybrid electric vehicles (HEV) or battery electric vehicles (BEV), the state of charge (SOC) must be higher than 20%. In other operating conditions, the vehicle configuration is more or less the same, the only difference is the transmission to make the vehicle moving. In driving mode the speed must be equal to 40 ± 8 km/h (cruise control can be used) and in case of hybrid vehicles the assessment shall be performed both in single mode (with both internal combustion engine (ICE) and electric motor) and in two separate modes (only with ICE propulsion and only with electric propulsion mode). If the vehicle is not able to reach the required speed, its maximum speed must be chosen. In dynamic mode the vehicle is accelerating from 0 km/h up to 90 km/h with at least $2,5 \text{ m/s}^2$ between 10 km/h and 75 km/h. The same performances must be guaranteed for the deceleration phase. If the vehicle is not able to perform these accelerations, its maximum acceleration and speed must be used, and these values must be specified in the test report. In plug-in charging mode the SOC, must be below the 20%, with vehicle and all the electrical equipment switched off, and the cable must be attached to the vehicle as showed in **Figure 27** [32].

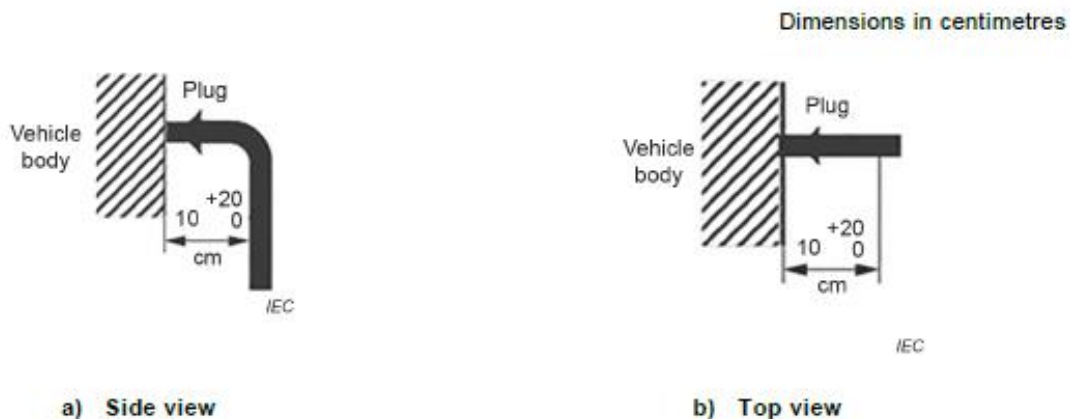


Figure 27: Plug-in charging cable positioning [32].

The test report must contain the details of the vehicle set-up for each mode, highlighting any deviation from the recommended settings.

For driving mode, it is necessary to report the engine speed and the maximum speed reached.

For dynamic mode, the values of maximum speed and acceleration must be specified and the values of SOC at the beginning and at the end of the test.

All the details of the environment and all the details that make the assessment repeatable must be reported [32].

6.1.2 EN 50500: 2008 + A1: 2015

As previously mentioned, and as its full title suggest, this document focuses on the railway environment: “*Measurement procedures of magnetic field levels generated by electronic and electrical apparatus in the railway environment with respect to human exposure*”.

Even though the standard is intended for railway applications, it is relevant to buses mainly for two aspects: in public-transport buses, as in trams, passengers may remain standing. For this reason, the measurement probe should be positioned at two different heights, 0,9 m and 1,5 m above the floor level; the test report must include the environmental conditions in detail [34].

6.2 Proposed standard for EMF assessment on buses

The absence of a precise procedure for the electromagnetic fields (EMF) exposure assessment on buses creates significant challenges for manufacturers, who must determine whether their products are in compliance with safety regulations and ensure adequate protection for passengers, in particular the vulnerable ones like travellers and workers with AIMD in public transportation. Although the above-mentioned documents do not specifically address buses EMF exposure assessment, they represent a suitable basis for the development of a dedicated standard.

6.2.1 Test site

A standardized process must take into account the test site in which the measurement is performed. It is necessary to indicate first of all the atmospheric conditions (temperature and relative humidity) of the site, and the background EMF level must be below 10% of the levels of the specified requirements EMF levels[32]. The test can be performed indoor and outdoor, and if outdoor track is used, the slope must be in the range $\pm 2\%$.

6.2.2 Measurement points of the vehicle

The points to measure are those corresponding to the most vulnerable exposed parts of the human body, so the head, the trunk for all passengers, in particular the vulnerable ones like travellers and workers with AIMD in public transport, and also the hands and lower legs for the driver as showed in **Figure 26**.

If for a passenger car is possible to measure all these areas for each passenger by measuring about 20 points, measure the same points for all bus's passengers is impossible, because the measurement points increase up to about 200 points. Furthermore, not all the buses are equal to each other, in fact on the public transport buses the passenger can be stay standing, increasing the occupied area in terms of volume to measure. For this reason, the suggestion is to divide the bus in areas, established by the manufacturer and justified by the positioning of the equipment (e.g. the engine is positioned 50 cm on the right with respect to the centre of the bus, so the area of measurement on the right side of the bus will be smaller). An example of division is showed in **Figure 28**.



Figure 28: Measurement areas on IVECO e-way bus (picture given by IVECO GROUP).

The subdivision shown in **Figure 28** is intended to divide the different areas and avoid the need to measure hundreds of points. In this way, a single measurement point can represent the entire area, positioned approximately at its centre and at a height of about 150 cm, to represent both seated and standing passengers.

Another important aspect is that the areas to be measured are located both inside and outside the vehicle. By labelling the external zones with Roman numerals, it becomes easier to distinguish them from the internal ones.

6.2.3 Measurement technique

To ensure a repeatable and reliable measurement, the probe must comply with the *IEC 61786-1* [33], it must not be fixed in the space during the assessment and the duration of the recording must be enough and in accordance with the reference regulations (e.g. 6 min. recording for ICNIRP 1998 standard).

6.2.4 Measurement procedure

Since vehicles work in many different conditions, it is important that the setup represents all of them and possibly in the worst-case condition. To reach this task, the EMF must be evaluated when the vehicle is in:

- stationary mode (vehicle stopped);
- driving mode (constant speed);
- dynamic mode (acceleration and deceleration phases);
- plug-in charging mode (only BEVs and Plug-in hybrid vehicles).

It is important to address all the cases to detect the potential abnormalities of the vehicle. The starting vehicle setup should be equal for all the cases. The bus must have:

- the passenger seats not inclined;
- the steering wheel in its centre position;
- the driver seats in its lowest vertical position [32];

During the stationary mode it is important that all the electrical equipment must be switched on, the transmission in neutral position and the engine at idle or ready to drive. The doors should remain closed, as well as all the other openings such as windows, hoods and similar components.

While the load on the vehicle is not relevant in stationary mode, in driving and dynamic modes the vehicle must be fully loaded to simulate the worst-case exposure scenario. For BEV and hybrid vehicles the SOC must be higher than 20%.

During the driving mode test the vehicle speed must be of 40 ± 8 km/h (cruise control can be used) [32].

More complex is the dynamic mode. It is divided into two phases, the acceleration phase and the deceleration phase. For the first phase the vehicle must accelerate from 0 to 90 km/h performing an acceleration of at least $2,5 \text{ m/s}^2$ between 10 km/h and 75 km/h. Vice versa during the deceleration phase, the vehicle shall start from 90 km/h and reach the 0 km/h, performing a deceleration of at least $2,5 \text{ m/s}^2$ between 75 km/h and 10 km/h. If the vehicle is not able to perform the test guaranteeing these conditions, the maximum vehicle speed will be considered at the end of the acceleration phase and at the beginning of the deceleration phase; the maximum acceleration must be performed. The new speed and acceleration must be specified in the test report [32]. If during the static and driving mode it is possible to measure the EMF for long periods, the dynamic mode is very short. For this reason, the value to take into account is the highest registered during the single phases.

The last mode is the plug-in charging mode. The starting SOC must be lower than 20% and the recharging cable must be inserted as showed in **Figure 27**, the vehicle must be with the key off and all the electrical equipment switched off [32].

The measurement points are different for each phase. The points indicated in **Figure 26** are valid for stationary mode. The same points, excepted for the those outside the vehicle, are valid for driving and stationary mode. The points inside and outside the vehicle, and the points around the plug are valid for plug-in charging mode.

6.3 Test report

The test report must be prepared in accordance with *IEC 62311:2020* [35]. The test location, environmental conditions, equipment used, and the vehicle model shall be specified. Regarding the reported data, the use of weighted peak values is recommended, as they provide a more representative evaluation than the absolute values. The applicable standards referenced during the assessment must also be included in the report.

6.4 IVECO test report

6.4.1 Environmental conditions

Data taken from Italian Air Force Institute:

Temperature: 18°C

Relative humidity: 70%

Bus model: IVECO eway – electric bus

Background Magnetic field: 2,598% (wrt 1999 Recommendation - Public exposure)

6.4.2 Acquisition points

Areas inside the vehicle (see **Figure 28**) are called with numbers from 1 to 7, while the external points called with Roman numerals.

6.4.3 Reference standard

The reference standard used is the *Council Recommendation of 1999*, with limits imposed in **Table 21** [24].

6.4.4 Device

The measurement was performed by Wavecontrol SMP2 + WP400 probe.

This combination of devices ensures variable log time from 0,5 seconds to 6 minutes, more than 1 million samples of memory and the possibility to compare the measure with many standards (ICNIRP guidelines, Council Recommendation, 2013/35/EU and other, both for public and worker exposure). The frequency range measurable is between 1 Hz up to 400 kHz.

The mode used is the weighted peak because the best and the most accurate according to the IEC 61786-2, in particular for 2013/35/EU.

6.4.5 Probe position

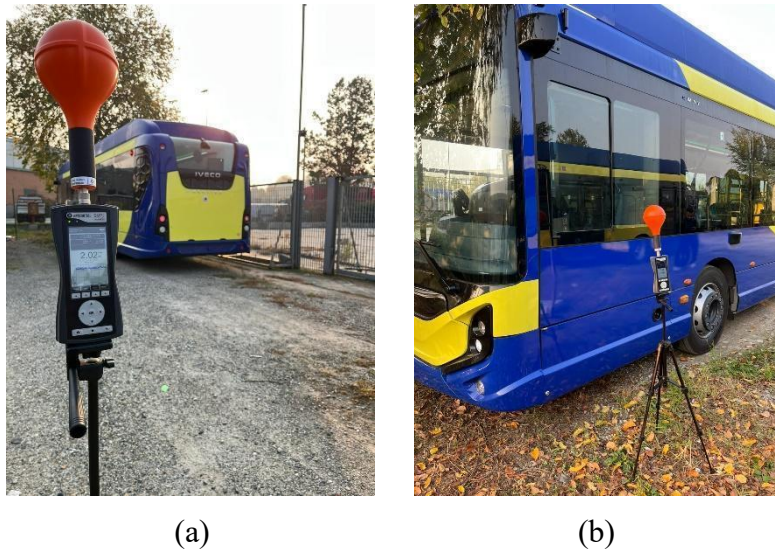


Figure 29: a) Probe position for environmental background magnetic field; b) Probe position for point IV.

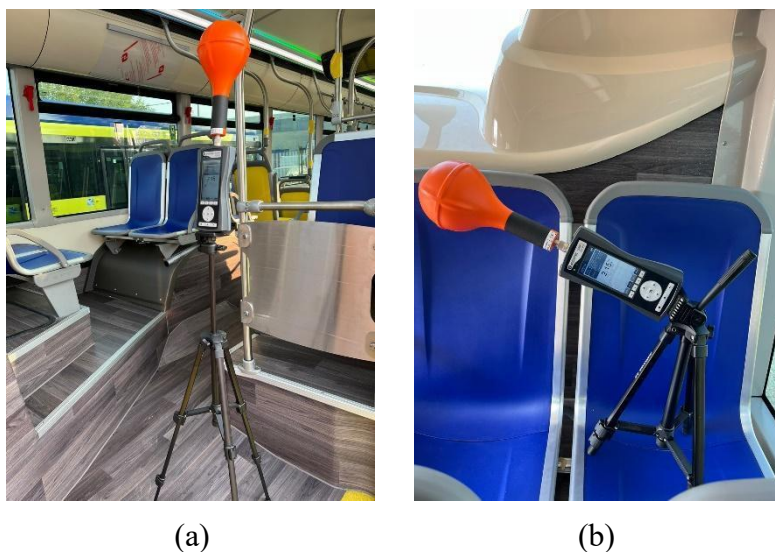


Figure 30: a) Probe position for point 7; b) Probe position for point 8.



(a)



(b)

Figure 31: a) Probe position for point 4; b) Probe position for point 2.



(a)



(b)

Figure 32: Probe position for point 1 (trunk); b) Probe position for point 1 (head).

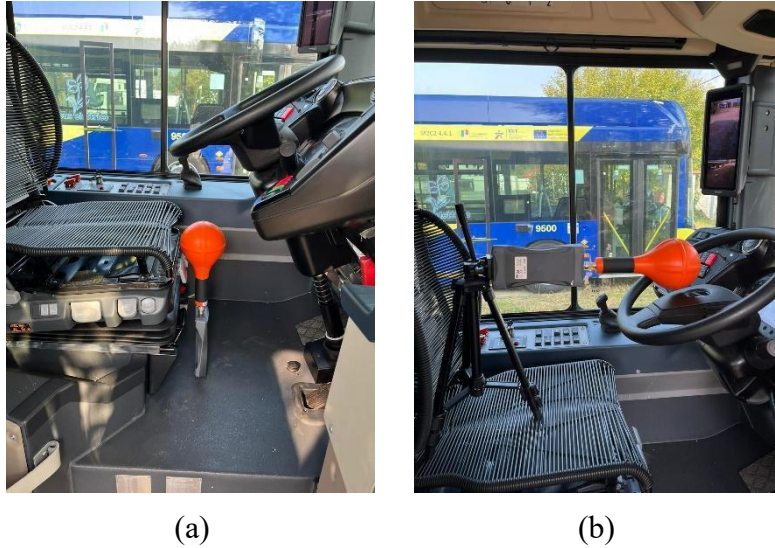


Figure 33: a) Probe position for point 1 (legs); b) Probe position for point 1 (hands).

6.4.6 Bus conditions

In this measurement campaign the bus was in stationary mode, but the doors were kept opened. The other cases were performed by IVECO in another campaign that will not be discussed in this thesis. Only the points discussed in figures from **Figure 29** to **Figure 33** were assessed, due to the results of the previous campaign and the not critical conditions of the test case.

6.4.7 Results

Background magnetic field was assessed both outside and inside the vehicle, but only at the centre of the bus and the results are around the 2% of the *Council Recommendation of 1999*. These data make the test site appropriate for measurement.

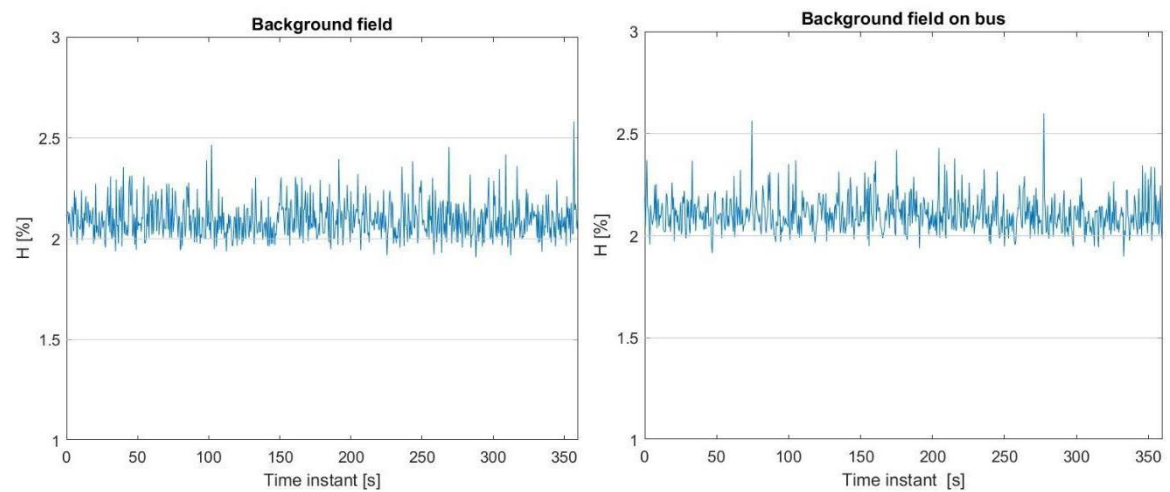


Figure 34: Background magnetic field (weighted peak).

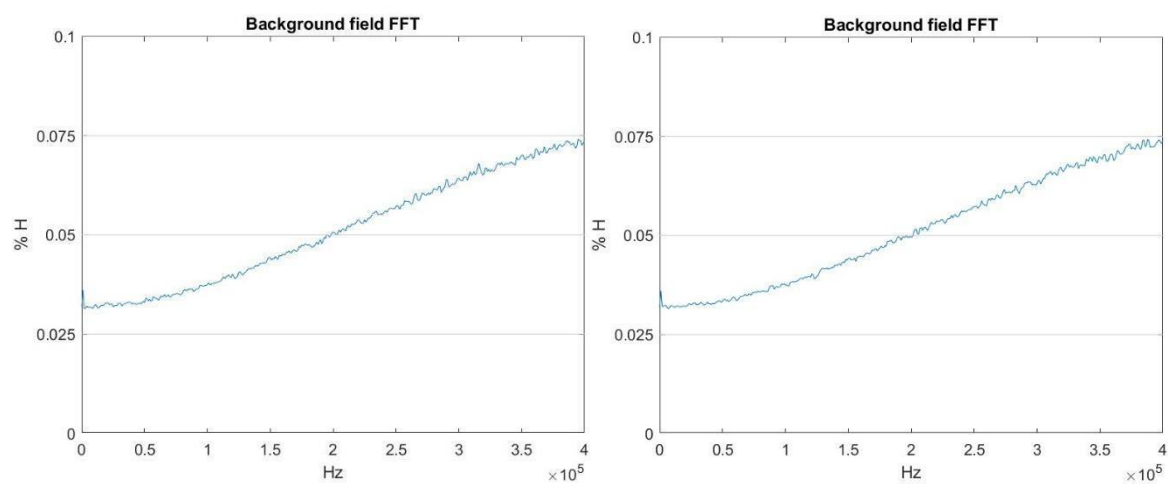


Figure 35: Background magnetic field FFT.

Table 40: Measurement results table.

Acquisition points	Electric field E [%]	Magnetic field H [%]
	Frequency range (1 Hz – 400 kHz)	Frequency range (1 Hz – 400 kHz)
	Council Recommendation of 1999	Council Recommendation of 1999
	Public exposure	Public exposure
Point 1 (Driver's trunk)	1,903 %	5,207 %
Driver head	1,863 %	5,750 %
Driver hands	1,885 %	3,842 %
Driver legs	1,894 %	3,797 %
Point 2	2,004 %	3,038 %
Point 4	1,898 %	2,520 %
Point 7	1, 867 %	2,534 %
Point 8	2,049 %	2,871 %
Point IV	1,872 %	2,907 %

7 Conclusion

The purpose of this thesis is to demonstrate the quality of IVECO buses from the electromagnetic exposures point of view, ensuring a safe product for all passengers, including workers and passengers who wear active implantable medical devices (AIMDs).

Starting from the documentation phase, it became evident that, from the perspective of AIMDs, the specific regulatory limits address only static magnetic fields. Both the ICNIRP 2009 guidelines and the EU Directive 2013/35/EU set a limit of 0.50 mT for such devices. For other frequency ranges, no dedicated exposure limits are defined for AIMD users, as AIMD manufacturers are required to guarantee device immunity for field levels below the ICNIRP reference values. To enhance compliance with the requirements and ensure a higher level of safety, it is advisable to apply a safety factor of 5 with respect to the actual limits, specifically in sectors or situations involving individuals wearing AIMDs.

The equipment used during the test was not capable of measuring static magnetic fields. Nevertheless, the EMF levels recorded in the measurable frequency range (1 Hz to 400 kHz) under static vehicle conditions were significantly lower than the applicable exposure limits. This result indicates that, within the tested configuration, the vehicle provides a robust level of electromagnetic safety.

Another key objective, which emerged during the documentation phase, is to establish well-defined assessment approaches, as existing standards and regulations do not provide adequate guidance on exposure in public transportation.

The combination of an outdated regulatory framework, based on the 1999 Council Recommendation and the ICNIRP 1998 guidelines, and the significant improvements in technology and scientific understating highlights the need for a revised regulatory approach. A modernised framework should reflect the improved immunity levels of contemporary devices, while maintaining an appropriate safety margin to prevent any potential AIMD malfunctions.

This regulatory gap is also evident in the EMC homologation phase. In fact, the approval process focuses exclusively on the high-frequency range, which is intended to ensure the proper functioning of all electronic systems within the vehicle. However, it does not take into account the human safety aspect related to low-frequency EMF exposure. From the discussion held with the EU JRC, which contributes to defining the practical implementation of existing regulations, it emerged that this is the current situation in the EU. However, they expressed strong interest in the efforts being made by manufacturers and other organisations to develop exposure assessment criteria for vehicles and public transport systems.

In this scenario, the role of Original Equipment Manufacturers (OEMs) could include proposing a new measurement standard, as they possess the most comprehensive knowledge of the appropriate and reliable methods for operating their products. Another potential area of development involves enhanced EMF screening or evaluating alternative vehicle battery-charging strategies that may prove safer and more efficient than current methods. In the future, this could pose the attention in-transit recharging during passenger boarding and alighting, allowing the vehicle to operate for longer periods and travel extended distances, thereby reducing energy consumption and lowering environmental emissions.

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