PASSIVE AND ACTIVE SHIELDING AGAINST ELECTROMAGNETIC RADIATION

by

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In nuclear physics experiments, it is very important to isolate the measured quantities from electromagnetic noise. Without this possibility, it is impossible to obtain usable experimental results since natural electromagnetic noise can be several orders of magnitude larger than the measured magnitude. In order to enable such measurements, it is necessary to eliminate electromagnetic noise from the experimental procedure. This is achieved by shielding against electromagnetic radiation. In this paper, experiments were performed to protect a room from electromagnetic noise. By applying all known methods of shielding against electromagnetic radiation, it was concluded that the room can be protected from the electrical component, but it is impossible to protect it from the magnetic component of electromagnetic radiation.

Key words: electromagnetic field, shielding, pulse voltage, shiede material

INTRODUCTION

The increasing degree of miniaturization of electronic components and assemblies, accompanied by an increase in electromagnetic contamination by high – frequency (non – ionizing and ionizing) low – intensity electromagnetic fields, imposes the need to measure low – intensity magnetic fields. Such measurements are carried out in rooms with the lowest possible level of the surrounding magnetic field. The unwanted magnetic field from the environment is called magnetic noise, and it originates from natural sources (the Earth's magnetic field, solar wind, *etc.*) as well as from fields that are a consequence of technical and telecommunication devices. Urban environments have numerous sources of magnetic noise, such as vehicles whose operation is accompanied by overvoltages that generate fast magnetic fields. One of the main sources of slow magnetic fields is the 50 Hz network with its higher harmonics [1, 2].

An example of sensitive measurement, which is performed in magnetically shielded rooms, is the recording of the field of biological currents of the human brain, heart, *etc*. In standard laboratory conditions, magnetic noise exceeds biological fields by several orders of magnitude, which makes reliable measurements difficult. Therefore, so-called magnetically quiet rooms with significantly attenuated magnetic noise are being built in the institutions intended for performing these measurements [3].

Minimization of external magnetic fields is also required in laboratories where physical experiments are performed. The following examples are given:
- laboratories for the calibration of sensitive induction meters used in space programs,
- electron microscopes whose magnetic lenses are sensitive to the level of the external magnetic field,
- elementary particle spectrometers and detectors where beams of charged particles pass through vacuum channels, and
- in applications of high-energy physics with energy implantation in fusion plasma by nanosecond electron beams.

When the volume to be shielded is relatively small then a magnetic shield from superconducting walls whose operation is based on the Meissner effect can in principle be applied. Superconducting protection is used in some physical experiments, but it is not used in laboratory rooms. However, there is interest in superconducting protection on future flights in order to protect personnel exposed to cosmic radiation consisting of high-energy charged particles.

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One of the aspects of the electromagnetic protection is the field reduction in the vicinity of strong electromagnetic sources that may interfere with or prevent the operation of nearby sensitive electronic systems. An example are the rooms of medical institutions in which magnetic resonance imaging is used. Massive superconducting magnets that generate an induction greater than 1 T are shielded by a ferromagnetic shield, which prevents the influence on the other instrumentation. Among household appliances, a strong source of electromagnetic radiation is a microwave oven that is lined with an effective protective cage. Loudspeaker magnets are also shielded so that the scattered flux does not interfere with the operation of cathode-ray tubes and other equipment. In computers, mobile phones and other electronic devices, sensitive modules are shielded in order to protect against emission antennas or voltage modules [4, 5].

There are two principles to protect the area of the magnetic field: passive and active. Passive shielding is most often used, which consists of shielding the space with sheets of conductive and ferromagnetic materials. When passive shielding is not sufficient, an active shielding is also performed by a system of electrical windings placed around the protected rooms. By means of an induction sensor and a feedback system, the windings are supplied with currents that generate a field of the same strength but in the opposite direction from the outside, which leads to cancellation. When constructing a room with record low induction, both passive and active shielding is applied at the same time [6, 7].

Most of the available research was performed with alternating voltage of a defined frequency. The aim of this paper is to measure the qualitative effects of protection against pulsed electromagnetic fields. The measurement parameter is the frequency of the highest harmonic of the pulse voltage. These measurements were performed on the basis of methods developed by the authors [8-10].

MAGNETICALLY SHIELDED ROOMS

Michael Faraday is credited with inventing the first effective protection against electromagnetic fields (where the mentioned protection refers primarily to electric fields). The protective system, the so-called Faraday cage, is a room surrounded by a thick wire mesh or conductive sheet metal. Modern Faraday cages are mostly lined with a high-conductivity aluminum sheet. In addition to electric fields, the cages also protect against radio frequency electromagnetic fields. An alternating magnetic field perpendicular to the conductive plate induces eddy currents in it, which create a field in the opposite direction from the incident one. On the surface of the plate the currents have the highest densities, J_0, which decrease with increasing depth, h, according to the exponential law

$$J(h) \quad J_0 \mathrm{e}^{\; h/\delta} \tag{1}$$

where δ is a constant called the depth of penetration and is equal to the depth at which the density decreases $e = 2.72$ times

$$\delta \quad \frac{1}{\sqrt{\pi f \mu \sigma}} \tag{2}$$

where f is the frequency, μ – the magnetic permeability, and σ – the specific conductance. Equation (1) shows that with increasing depth the current density decreases but still does not reach zero. As with some similar exponential laws, at depths five to ten times greater than δ, the electromagnetic wave can be considered to be completely absorbed (*i.e.*, all its energy is converted into heat) [11, 12].

It is known that the losses due to eddy currents are proportional to the square of the frequency. This means that as the frequency decreases, the protection efficiency drops sharply. The lower limit of the frequency range of a radio signal is considered $f_1 = 100$ kHz. Pure aluminum, as the most commonly used protective layer, has a specific conductance 35 $\mathrm{MSm^{-1}}$. This means that

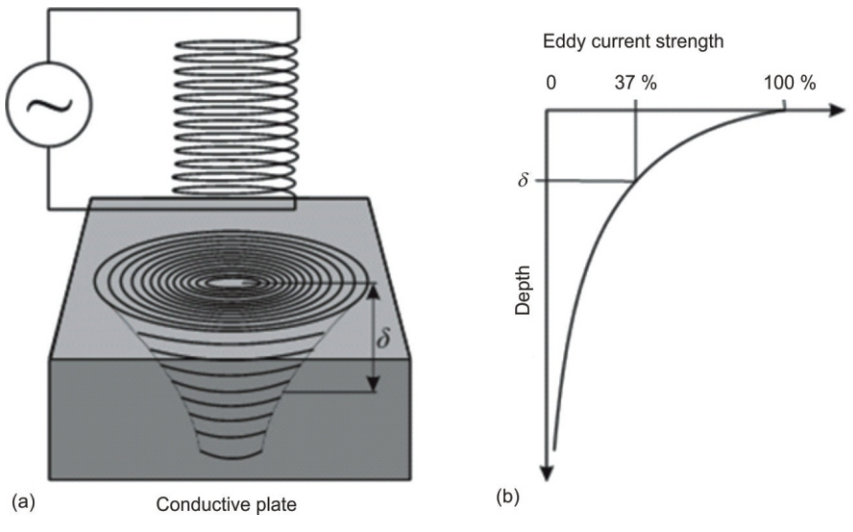

Figure 1. An explanation of protection against electromagnetic waves: (a) absorption due to eddy currents and (b) exponential law of decreasing current amplitude

at 100 kHz the penetration depth is δ mm. Attenuation of this electromagnetic wave 1000 times is achieved by aluminum sheet thickness H = 3.3 mm. In preparing the cage it is necessary to prevent the penetration of the field through the component edges, cracks and openings such as doors, electrical installations, installations for plumbing, air conditioning, *etc*. Small openings are particularly critical in the case of high frequency electromagnetic waves with submillimetre wavelengths [13, 14].

At lower frequencies, the protection of the eddy current principle is becoming inefficient. In the case of a steady field, such as the Earth's field, aluminum plates do not provide any protection. Protective layers of ferromagnetic materials are used to suppress low frequency magnetic fields.

Protection against permanent and slow-changing magnetic fields differs significantly in relation to protection against electric and electromagnetic fields. The steady magnetic field cannot be absorbed or weakened by converting it into heat as with electromagnetic waves. The fundamental property of magnetic induction is that there is no source. The lines of magnetic induction *come out* of one pole of the magnet and reach the other through the magnet (they close in on themselves). It is only possible to change the shape of the magnetic field lines, *i. e.* flux direction, by changing the local magnetic resistance. Protection against slow- changing magnetic fields is reminiscent of protection in hydrology – a river flow that cannot be stopped is diverted by canals so that water bypasses the place being protected.

In principle, the magnetic field cannot be ideally permanent (*i. e.* completely established) because that would mean that both the strength and the direction of the field have the same value for an indefinite period of time, which is practically impossible. The attenuation diagram of the magnetic field is given as a function of frequency. Fields that are considered permanent in practice have a frequency range of approximately 0.01 Hz to 0.1 Hz [15, 16].

Magnetic shielding is achieved by coating the walls of the room with panels of ferromagnetic material of high permeability. The best form of protected volume is spherical, but such a form is rarely used in practice. The cylindrical shape is another favorable shape, but for practical reasons, most of the protected rooms are shaped like a square. Sharp edges represent places with weaker protection, so the edges are rounded and additionally protected [17].

As mentioned earlier, the magnetic flux is distributed in such a way that the total magnetic resistance is minimal. Most of the flux is directed along the ferromagnetic walls and a smaller part through the protected space. The field strength in the protected volume can be reduced but not to zero. By increasing the number of protected layers that are embedded in each other, an increased reduction of the field is achieved. The reduction has an asymptotic character which means that, regardless of the number of layers, the field inside the room cannot be reduced to zero [18].

The principle of passive shielding of a square-shaped room is illustrated in fig. 2. The electromagnetic and magnetic fields have vertical directions. The outer layer, which acts as a Faraday cage, consists of aluminum sheet thickness 5 mm. This metal sheet stops the electric field and absorbs high frequency telecommunication electromagnetic waves.

Two layers of ferromagnetic walls are used to reduce the strength of the low frequency magnetic field. The first ferromagnetic layer *attracts* a significant part of the lines of magnetic induction, *i. e.* a significant portion of the incident flux closes over the walls of the outer layer. A weakened magnetic field falls on the inner ferromagnetic cage, from which again a significant part is directed through the walls, and a smaller part penetrates the room. In this way, the field inside the volume becomes weakened many times over. As an electrical analogy of magnetic field attenuation by a large number of protective ferromagnetic layers, fig.

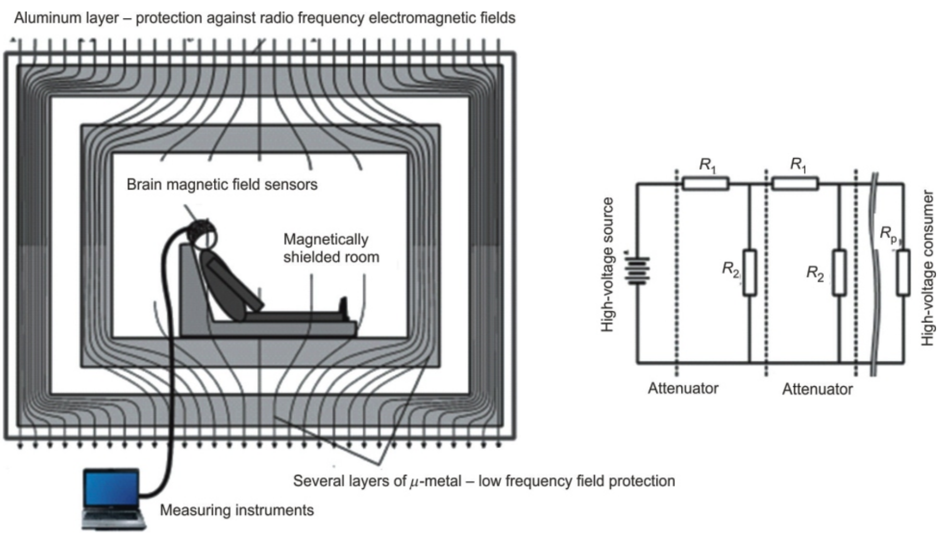

Figure 2. (a) Passive (multilayer) shielding method of the room and (b) an equivalent protection scheme using a multiple electrical voltage attenuator, [1]

2(b) shows a multi-stage voltage attenuator consisting of several series-connected voltage dividers. Each divider further weakens the input voltage which still does not become zero [19].

The ferromagnetic protective material is expected to have high permeability, a low coercive magnetic field, and low magnetic loss as much as possible (narrow hysteresis cycle). The best existing material of this type is an alloy called μ-metal developed in 1923 in order to improve the characteristics of telecommunication underwater cables. In its composition, μ-metal contains 77 % nickel, 16 % iron and a smaller percentage of copper, chromium and molybdenum. The relative permeability of μ-metals and some other similar alloys ranges up to 200 000. This data refers to the steepest part of the $B(H)$ characteristic where H is the magnetic field strength.

The μ-metal alloy represents one of the softest magnetic materials. The magnetic characteristics are isotropic, have a slightly pronounced magnetostriction and the μ-metal is suitable for plastic mechanical processing which does not disturb the magnetic characteristics. The remanent induction of μ-metal ranges from 0.4 T to 0.6 T. The coercive field is very small and amounts to 0.5 Am^{-1}. The ferromagnetic layer is supplied with a special winding for demagnetization, which reduces the remanent induction to zero [20].

When analyzing the magnetic shielding, it must be noted that the ferromagnetic material is completely demagnetized and is located in the initial part of the B-H characteristic, which is characterized by a small slope. In this mode of operation, the magnetic permeability is significantly lower than on the steep part of the characteristic. The relative differential permeability of μ-metal at small fields is 13 000 which is only 10 % of the maximum declared value.

With a larger number of ferromagnetic layers, the protection factor increases. However, this complicates the manufacture and increases the consumption of expensive materials, including μ-metal. The best magnetically shielded room in the world is located in the PTB Institute in Berlin, and it consists of seven layers of μ-metal and one layer of aluminum. The mass of μ-metal consumed is 24 T. The useful volume of the chamber is 9 times smaller than the outside [21].

Active magnetic shielding is used as a supplement to the passive shielding system with the aim of further reducing magnetic noise, especially at some frequencies where the efficiency of the passive system is the weakest. The active shielding consists of a triaxial Helmholtz coil system of circular or square shape (Helmholtz cube). The geometry of the cube has an advantage due to the larger internal volume with the same external dimensions of the system.

To help these pairs of mutually coupled pairs, the following magnetic fields are generated B_x, B_y, and B_z. The windings are powered from automatically regulated current sources, fig. 3. In the feedback circuit of the regulator, as induction sensors, magnetometers with core saturation are used, which represent the most sensitive field meters. The resulting field generated by the windings has the same strength but opposite direction from the corresponding components of the external field. Due to the behavior of the field, the passively shielding room is located in a space with significantly attenuated magnetic noise, which further reduces the internal field. The total attenuation of the combined passive and active shielding are additive on the decibel scale [22].

Each Helmholtz coil is twofold. It consists of two separate coils where one is made of thicker and the other of thinner wire. The coils of thicker wire are supplied with a constant DC current of higher strength I_{0x}, I_{0y}, and I_{0z} whose field cancels the mean value of the local Earth's field B_0. The coils of thinner wire are supplied with a weaker, time-varying current I_x, I_y, and I_z from automatic current regulators, which cancels the variable component of magnetic noise $B(t)$.

It should be noted that the space for protection against magnetic fields should be extremely stable in the static (mechanical) sense.

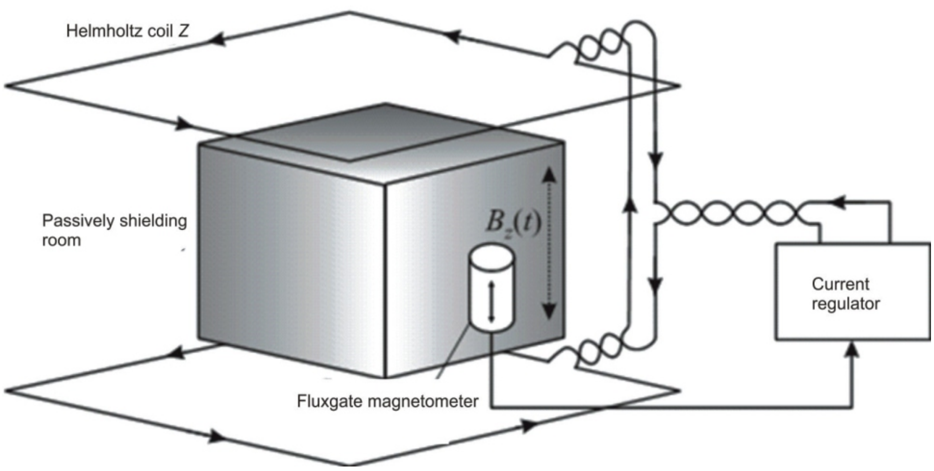

Figure 3. An explanation of the magnetically shielded room: automatic current generation of Helmholtz coils for variable induction compensations B_z(t)

The shielding methods presented above are given to explain the protection method applied in the experiment. Even with less μ-metal used in the experiment the achieved level of protection was enough to obtain useful qualitative results.

EXPERIMENT

The measuring instrumentation is closed in a chamber protected from electromagnetic radiation such as a well-made Faraday cage which provides satisfactory protection from the electrical component of the field. However, the problem is the protection from the magnetic component, *i. e*. the possibility of its accurate measurement. This problem occurs especially in experiments of high-energy physics, where an electronic pulse of width of the order of ns (nanoseconds) is implanted in the plasma in order to heat it (fusion experiments). For that purpose, an experiment of measuring fast pulses was conceived and performed.

The basis of the experiment was a commercial Faraday cage of protection greater than 100 dB, fig. 4. Within that Faraday cage, the measuring equipment was placed in passive and active shielding chambers against the magnetic field. The passive and active shielding chambers were made with limited quantities of μ-metals (in accordance with the budget of the experiment) so that the obtained results should be interpreted qualitatively according to the principles set out in the previous chapter. The passive and active shielding chambers were of the dismantling type.

The Faraday cage was galvanically separated from the outside so that the measurement results were protected from induced noise (this is especially important at high speeds of applied pulse voltages since then even the shortest parts of wire structures must be treated as circuits with widespread parameters).

Sources of fast pulse voltages were:

– Classic Marx generator at switching mode 250/2500 μs.
– Classic Marx generator set to atmospheric voltage 1.2/50 μs.
– Marx generator set to pulse voltage 0.2/10 μs (generator without output capacitor), fig. 5.

Figure 4. Commercial Faraday cage

Figure 5. Marx generator set to pulse voltage 0.2/10 μs

– Cable generator pulse rise rate 0.5 ns.

The pulse generators were connected via a fast voltage divider by a non-galvanic connection to the oscilloscope and other instruments in the Faraday cage. The applied fast divider had an SF6 insulated high voltage capacitor, a mica low voltage capacitor and a 50 waveguide termination resistor (all connections were minimized to the maximum possible).

As a measuring instrument, a 10 GHz digital oscilloscope and a control 500 MHz analog oscilloscope were used, as well as a commercial system for measuring the magnetic field with a semiconductor magnetically resistant sensor.

The experiment consisted of recording the pulse voltage after 100 pulses with a one-minute break between two consecutive strokes. Recording was performed with each of the following high voltage sources using:

– only the Faraday cage,
– the Faraday cage and passive shielding, and
– the Faraday cage, passive and active shielding.

Using statistical, analytical and Monte Carlo methods, the measurement uncertainty of the measuring procedure was about 10 % [16].

The experimentally obtained results were statistically processed. As a measure of the effect of protection against electromagnetic radiation, the taken difference is between the obtained responses of the measuring instruments expressed by the surfaces between them in electrical voltage – time and magnetic voltage – time. The identity of the measurement signals was previously determined using a *U*-test with a statistical unreliability of 3 % [23].

RESULTS AND DISCUSSION

Figure 6 shows the curve obtained by the above mentioned high voltage sources. Table 1 shows the differences between the obtained responses expressed by surfaces in the electrical plane voltage-time. From

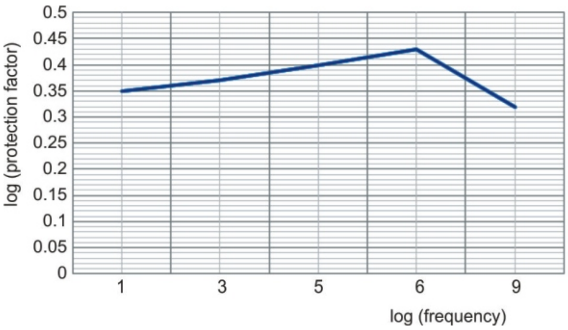

Figure 6. Dependence of the protection factor on the electrical component of the electromagnetic field (log – log diagram)

Table 1. Protection factors of the passive shielding chamber

Frequency [Hz]	Protection factor	Attenuation [dB]
<0.1	60	25
1	500	34
10	1000	45
$10\text{-}10^6$	1000	45
$10^6\text{-}10^9$	550	35

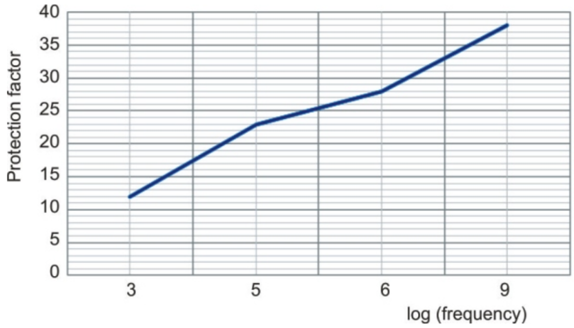

Figure 7. Dependence of the protection factor on the magnetic component of the electromagnetic field (lin – log diagram)

Table 2. Protection factors for permanent magnetic fields

Protected chamber	Number of ferromagnetic layers	Protection factor
Made chamber	1	20
Made chamber	3	40
Made chamber	5	45
Commercial chamber	5	1500
PTB Berlin	7	75000

fig. 6 one cannot see that the introduction of passive and active magnetic shielding in the Faraday cage contributes significantly to the results obtained.

However, as the pulse rate increases, this difference increases, as can be seen from tab. 1, but this increase is within the expressed measurement uncertainty (although the effect is expected).

A completely different result is registered by a magnetic measuring instrument. Depending on the speed of the high-voltage pulse, there is a significant deviation of the results, fig. 7, tab. 2.

These deviations are most pronounced at high frequencies of the magnetic field, and negligible at lower frequencies (almost completely ignored at a permanent magnetic field). These deviations are not within the expressed measurement uncertainty.

Based on the obtained results and taking into account the production quality of the passive and active shielding against the magnetic field, it can be concluded that the pulse shape of the electronic fusion generator cannot be completely and accurately measured (or reproduced) in three-layer protection chambers. For protection greater than 100 dB, the Faraday cage is completely satisfactory for the measurement of the electric component of the electromagnetic field. However, due to the nonlinearity of the hysteresis, the magnetic component is not transmitted with satisfactory linearity. By developing into harmonics, the magnetic component would be transferred (by an inverse mathematical operation) with large deviations from the actual value. These deviations would give an unrealistically large value of the magnetic component of the field at low (zero) frequencies. Although this result could not affect modern experiments in high-energy physics, it is interesting because it is the permanent component of the magnetic field of the electron pulse (in a negligible amount) that is superimposed with the permanent magnetic field needed to hold the fusion plasma in magnetic bottles.

CONCLUSIONS

Based on the obtained results, which may not be the most quantitatively accurate, it can be concluded that the precise measurements of fast pulse waves of an electromagnetic field are not possible. Since the measurements were aimed at assessing the possibility of avoiding jitter on-line measurements in high-energy physics experiments, it can be argued with certainty that it is difficult feasible and only from this aspect. The trigger system also introduces problems here, which should synchronously fire eight or more electronic cannons with a power of 1.25 TW (per cannon) with a width of 5 ns. For this reason, based on these results, it can be concluded that in the process of injecting electron beam energy the total power will never be obtained as a simple sum of the power of individual pulses. However, the resolution of the electric component of the field is more important for these types of research and the result is more successful.

Our opinion is that further investigations and investments in magnetic shielding would be economically (and time) inexpedient and unreasonable.

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AUTHORS' CONTRIBUTIONS

S. B. Djekić proposed the idea for the experiment which was carried out by D. V. Brajović, D. P. Nikezić, U. R. Ramadani, and S. B. Djekić. All authors analyzed the results and participated in the preparation of the final version of the manuscript under supervision and guidelines of N. M. Kartalović.

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ПАСИВНА И АКТИВНА ЗАШТИТА ОД ЕЛЕКРОМАГНЕТНОГ ЗРАЧЕЊА

У експериментима нуклеарне физике веома је важно изоловати мерене величине од електромагнетног шума. Без тога, немогуће је добити употребљиве експерименталне резултате пошто природни електромагнетни шум може да буде више редова јачи од мерене величине. Да би се омогућила таква мерења потребно је елиминисати електромагнетни шум из експерименталног поступка. То се постиже заштитом од електромагнетног шума. Применом свих познатих метода заштите од електромагнетног зрачења закључено је да је простор могуће заштитити од електричне компоненте, а немогуће заштитити од магнетне компоненте електромагнетног зрачења.

Кључне речи: електромагнетно поље, заштита, импулсни напон, заштитни материјал