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Design of an RFID-based positioning system for safety of personnel in nuclear facilities

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***Abstract*—Modern nuclear energy facilities are built with safety as a top priority. One of the main requirements of these installations is the control of the radiation doses received by workers or visitors. In the work presented here we propose a Local Positioning System based upon Radiofrequency Identification technology (termed RFID-LPS), which permits to determine and trace the physical location of all the staff in the facilities by means of radiofrequency (RF) signals exchanged between an emitter tag carried by the user and a set of receivers placed in known locations of the facility. The system is designed considering two distinctive features of the future facility IFMIF-DONES (International Fusion Materials Irradiation Facility-DEMO Oriented Neutron Source): the high attenuation of the RF signals due to the building construction, and the expected ionizing radiation received by the electronic components, which could decrease their operating lifetime. The proposed system is based on RFID technology, as it is easy to deploy and robust, and may include component shielding to allow devices to resist the radiation levels expected in key areas of IFMIF-DONES (between 10 μGy/h and 100 mGy/h). We expect that the RFID-LPS system, complemented with other conventional access control systems such as access cards, will increase the safety of the personnel in IFMIF-DONES, monitoring and quantifying their exposition to radiation in an efficient way.**

***Index Terms*—RFID technology, nuclear facilities, indoor positioning, radiation resistant electronics**

I. INTRODUCTION

Large scale energy production by means of controlled nuclear fusion has been a desirable goal for the past decades. Due to still unsolved technical difficulties, the construction of a nuclear fusion reactor with gain factor larger than unity has not been achieved yet. However, there are numerous intermediate facilities built for experimentation and development of new materials and systems involved in a future nuclear fusion reactor.

One of the prototypes being designed at the moment is DEMO (Demonstration Power Plant), which represents an evolution of other previous prototypes like ITER (International Thermonuclear Experimental Reactor). It is estimated that the deuterium-tritium fusion reactions occurring in DEMO [1] will generate neutron fluxes in the range $1-5\times10^{18}$ m/s^2, with 14.1 MeV of maximum energy. The interaction between these neutrons and the materials of the reactor walls and other structures produces a structural damage on the construction that must be addressed.

In order to study the interaction of high energy neutrons with matter and to construct structures which are sufficiently resistant to nuclear radiation, intermediate facilities such as IFMIF-DONES (International Fusion Materials Irradiation Facility – DEMO Oriented Neutron Source) are being currently designed. IFMIF-DONES is basically a neutron source where the conditions expected at DEMO will be reproduced. The city of Granada (Spain) is supported by the EUROfusion consortium to host the future IFMIF-DONES facility, which is expected to start its operation in 2029, according to the roadmap elaborated by the European Strategy Forum on Research Infrastructures (ESFRI).

A. *Description of IFMIF-DONES*

The dimensions of the main building of the IFMIF-DONES facility are 158 × 75 m, and it consists of four floors: two basement floors and two floors above ground level. The first basement floor holds the most important part of the facility, the Test Cell, where the neutrons are generated by the interaction of deuterons with a lithium flux. The Test Cell dimensions are $2.8\times4\times5.8$ m.

For facilities where significant radiation levels are expected, it is mandatory to perform an Occupational Radiation Exposure (ORE) analysis, in order to calculate the radiation doses received by the workers during their permanence in the plant. A summary of ORE-determined levels for IFMIF-DONES is shown in table I, which is color-coded for easy reference.

Areas marked as white, blue or green usually pose no risk for the workers. However, in the yellow areas, the presence of workers is allowed during a specified time, for example for maintenance tasks [2]; in the orange-colored areas, human presence is only allowed for a very short time; and in the red areas no human presence is allowed at any time.

In order to contain the ionizing radiation generated during operation of the reactor, the IFMIF-DONES facility will be heavily shielded with reinforced concrete and additional

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Area		Colour code	Radiation dose
Not restricted		White	$< 0.5\mu$Sv/h
Supervised		Blue	$< 3\mu$Sv/h
Controlled	Free access	Green	$< 10\mu$Sv/h
	Regulated access	Yellow	$<$ 1 mSv/h
	Restricted access	Orange	$<$ 100 mSv/h
	Prohibited	Red	$\geq$ 100 mSv/h

Table I: Classification of the expected radiation levels in IFMIF-DONES, established by the Euratom directive 2013/59 for the protection against ionizing radiation exposure risks.

Established Individual Dose	
Maximum per year	$\leq$ 5 mSv/year
Average per year	$\leq$ 2 mSv/year
Maximum per year (limbs)	$\leq$ 50 mSv/year
Maximum per working shift	$\leq$ 0.5 mSv/day
Limit for safe handling	$\leq$ 650 μSv/hour

Table II: Occupational radiation exposures for the IFMIF-DONES workers during the machine operation, established by Euratom directive 2013/59 (Protection against dangers from exposition to ionizing radiation).

materials. Considering the preliminary floorplans, the IFMIF-DONES Consortium has performed a simulation based in neutronics models to calculate the expected radiation doses in the building, both during machine operation and in the shutdown periods (maintenance) [3]. The goal of this process is to classify the different zones of the facility according to radiological criteria and the expected radiation doses. Fig. 1 shows a layout drawing of the first floor of the main building in IFMIF-DONES facility [4], with the effective dose expected in each of its rooms.

B. *Scope and motivation of the present work*

Safety is the most stringent requirement on the design and operation of any modern nuclear facility. There are two main requisites: to ensure the confinement of radioactive materials in any event and to guarantee that the radiation dose received by workers complies with regulation limits. This last requisite is the goal of the present work. As seen previously, the normal operation of the IFMIF-DONES reactor will result in some areas of the facility becoming constantly exposed to radiation. Thus, it must be monitored that the workers or visitors of the installation will not receive daily or accumulated radiation doses higher than the safety levels established by regulating bodies, and summarized in table II.

The control of the personnel in the different areas of the facility can be achieved by several methods: using cards or personal access codes, for instance. Alternatively, in the present work we propose a design of a local positioning system (which we term RFID-LPS), based in radiofrequency identification technology, which is appropriate for its use in nuclear fusion facilities, and which can determine the location of workers or visitors of IFMIF-DONES facility at any time with room-level accuracy. Such system can be used, for example, to stop irradiation experiments if a person is detected in any of the hazardous areas. By processing the logged positioning data during extended periods of time, the system can also determine the total radiation dose received by the users from their work in the facility.

The areas of interest for the application of the RFID-LPS system are those with controlled access, where it is feasible that the workers could exceed the maximum radiation doses per day or per year given in table II in prolonged stays in those areas. The prohibited areas are not considered as no personnel is allowed in any situation. Considering this, the RFID-LPS system deployed in such areas must be able to withstand radiation levels between 10 μSv and 100 mSv per hour.

In this context, the local positioning system (RFID-LPS) proposed in this work can be useful for its application in the following situations:

- To determine the location of the staff in the building and, particularly, in the areas with controlled access, when radiation experiments are being performed.
- To monitor the maintenance operations of the areas with limited access.
- To estimate the total radiation dose received by the staff for longer periods of time (per month or per year), according to the time spent in different areas.

The two main issues that differentiate the RFID-LPS proposed in this work from a “conventional” indoor localization system, and that must be considered to guarantee its reliability in IFMIF-DONES are: the effect on RF propagation of the heavy shielding design of the facilities (treated in section II) and the degradation of the electronic components due to the effects of radiation (seen in section III). Finally, section IV presents a preliminary design of the RFID-LPS system as would be used in the facilities.

II. EFFECT OF THE BUILDING SHIELDING IN THE RF SIGNALS USING FOR PERSONAL LOCATION

The most common architecture for indoor localization systems is based on the transmission of radiofrequency (RF) signals between an emitting beacon, carried by the person to be localized, and a set of receivers installed at known points in the facility [5] (in other systems, the placement of emitter and receiver beacons is reversed). In this way, the location of the person can be estimated by the intensity of the received signals or, for RF technologies which support it, by direct measurement of the transmission time. This simple setup can be further refined with the help of pedestrian dead reckoning and map-matching techniques [6].

RF-based localization performs best in relatively free-obstacle spaces, such as shopping centers, transport stations or even office areas with thin partition walls. Nuclear facilities, however, are heavily shielded during their construction in order to contain the ionizing radiation. The main rooms in IFMIF-DONES will be separated by walls of reinforced concrete of 1.5 m thickness. These materials also cause a considerable attenuation of the RF signals used for the estimation of the localization [7].

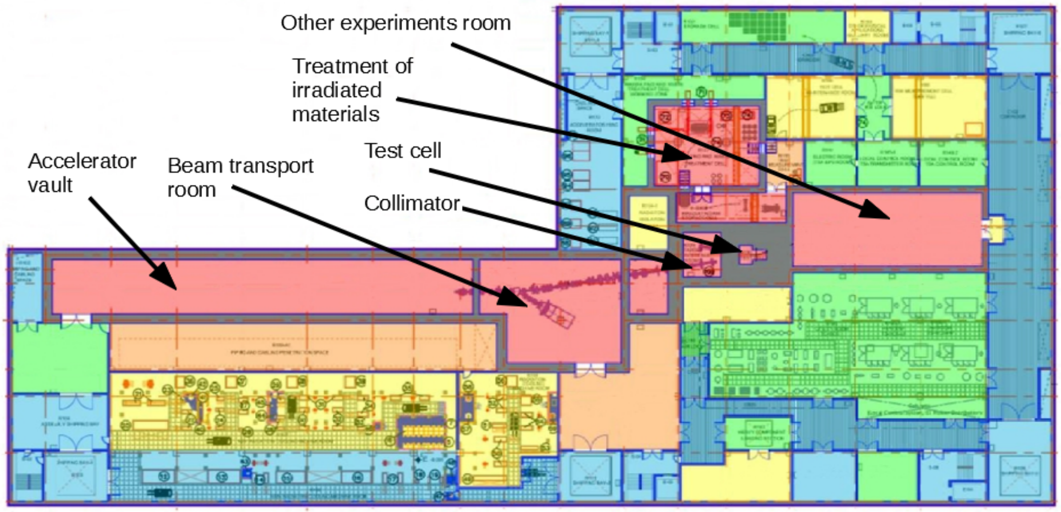

Figure 1: Expected radiation levels in the first basement floor of the IFMIF-DONES facility, during the machine operation, following the classification of table I (after [4]).

The propagation of RF signals in indoor spaces can be studied with ray-tracing simulation algorithms [8], using the experimentally measured dielectric constants for common building materials can be found in [9]. As an example, in Fig. 2 we show a simulation of RF propagation in an indoor environment; the top image corresponds to a building with light partitions (such as an office), and the bottom image corresponding to an equivalent building but with thicker, concrete walls. In the areas colored in dark blue, the intensity of the RF signals decreases below the detection threshold of the receiver, producing shadow zones where the users could go undetected by the localization system.

Normally, RF-based indoor localization systems are designed so that users are visible to several RF receivers simultaneously, and the localization can be estimated by the combination of the different received signals (using the trilateration algorithm, fingerprinting, etc.) [6]. In the case of IFMIF-DONES, this would require the deployment of a considerable amount of RF readers, due to the attenuation of the signals mentioned above. Consequently, we choose a system architecture which ensures the robust detection of users in the facility at least to room-level, instead of trying to determine their accurate location. More details of the proposed design will be provided in section IV, after discussing the degradation of the components in RF devices due to radiation exposure.

III. DEGRADATION OF ELECTRONIC COMPONENTS DUE TO RADIATION

The second important issue about the design of the localization system for IFMIF-DONES is the degradation of the electronic components due to the ionizing radiation existing in the areas of deployment of the system. The effects of radiation in electronic circuits has been widely studied, as it is relevant in aeronautics (particularly for military aircrafts flying at high altitudes), space industry (satellites for civil or military applications) and nuclear facilities [11].

The radiation generated in the experiments performed in IFMIF-DONES is composed mainly of gamma rays and neutrons. Both types of radiation remain in the background, with intensities decaying with time and, in contrast to other ionizing particles, travel long distances through air. Thus, very high radiation levels are expected in the surroundings of the Test Cell [12]–[14].

A. *State of the art*

The interaction between the radiation generated in nuclear processes and semiconductor materials takes place by two main mechanisms. Heavy particles, like neutrons, generate damage by direct collisions with the lattice atoms [15]. On the other hand, high energy gamma radiation causes ionization, which may provoke glitches in the operation of the semiconductor device, but also a cumulative permanent damage, depending on both the radiation energy and the total radiation dose received by the material [16]. The work here presented focuses in gamma radiation, which is the main expected cause of electronics damage in the areas where the RFID-LPS system would be deployed.

The effect of radiation in a material depends on two factors. The first is the absorbed dose, defined as the amount of energy deposited per unit mass (measured in J/kg or Grays, Gy). Sometimes, the effective dose (measured in Sieverts, Sv), which measures the biological effect of radiation, is used. Both units are related by a conversion factor that evaluates the effect of ionizing radiation in human organs and tissues [17]. For gamma radiation, the weighting factor is usually taken as

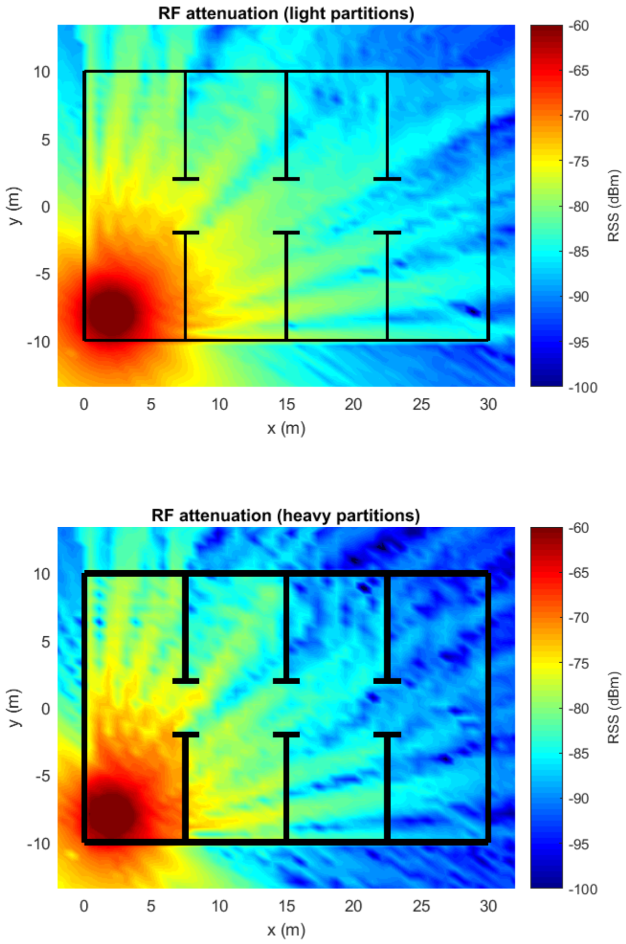

Figure 2: Simulation of the RF signals attenuation in an indoor environment with thin walls (top) and with reinforced concrete walls (bottom). The emitting RF source is in the lower-left corner. The simulation has been produced with an RF ray-tracing software [10].

one, so the radiation absorbed dose in Gy is equivalent to the effective dose in Sv.

The second factor for assessing the radiation damage to electronic devices is the dose rate (Gy per unit time). Experiments have determined that some semiconductor materials show better tolerance to high dose rates than to lower ones [18]. This somehow counter-intuitive result is explained by the annealing effects at high radiation dose rates, in which thermal processes compensate part of the damage generated in the structure of the material [19].

In table III, it is shown a summary of the results obtained from the literature on semiconductor devices (mostly RFID devices) exposed to gamma radiation. As it can be observed, RFID devices can resist without failure a total dose of about 300 Gy with very low radiation dose rates, in the range from 200 μG/h to 20 mGy/h. However, these devices could resist higher total radiation doses using greater radiation dose rates, around 1 Gy/s. This behaviour has also been observed in other semiconductor devices, such as Arduino boards [20].

The authors of [23] found that RFID devices could resist up to 50 Gy without failure, and that when the dose reached 240 Gy most devices stopped working. At the radiation dose rates they used (20 mGy/h), this restricts the lifetime of devices to about four months, which was increased up to three years by the use of shielding [25].

B. *Radiation experiments on RFID devices*

Based on the state of the art provided above, we have planned a batch of experiments to establish the resistance of RFID devices to gamma radiation. Our objective is reaching the doses that cause component failure as reported in the literature. Experiments will be carried out in the CIEMAT (Spanish Research Center in Energy, Environment and Technology), where there are different facilities for gamma irradiation.

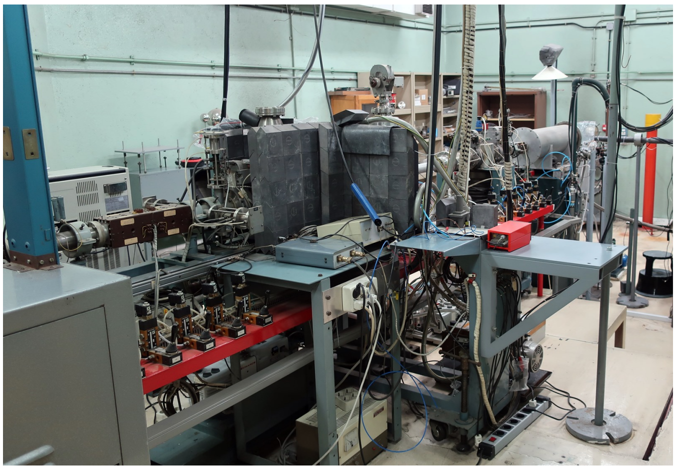

Figure 3: Image of the Van de Graaff electron accelerator located in CIEMAT.

To have an approximation of the total dose required to cause damage to the RFID tags, we used a Van de Graaff electron accelerator, shown in Fig. 3. This machine can create a flux of electrons with energy of 2 MeV, which impacts in a target with an area of 20×20 cm^2, producing ionization rates as high as 10^4 Gy/s. Electron and gamma radiation produce similar damage in semiconductor devices, although in the former case the ionization of the material is a direct process and in the second ionization is indirect.

In Fig. 4 we show an outline of the experiment. RFID tags are emitting their identification RF signals during irradiation, which are received by an RFID reader placed close by in an instrumentation rack protected by lead blocks. The reader antennas are placed outside of the metal protection and connected to the reader by a 2 meters long RG58 cable. The reader is connected by a 20 m long USB cable to the USB port of a computer situated in the control room. In the computer, RFID readings are registered in real time, until the tags fail. We used active RFID tags made by RFCode (Fig. 5), with an emitting rate of 1 Hz.

Table III: Resistance to radiation of electronic components, obtained from the literature. We show the total dose at which components stopped working, and the dose rate, if specified in the paper.

Research group	Dose rate	Total dose	Comments
Tsai et al. (2008) [21]	200 μGy/h	300 Sv	Regulatory dose rate limit on the surface of a type B packaging
Teraura et al. (2013) [22]	-	215 Gy	Low energy gamma radiation
Teraura et al. (2013) [22]	-	4000 Gy	High energy gamma radiation
Teraura et al. (2015) [23]	20 mGy/h	350 Gy	Low energy gamma radiation
Teraura et al. (2015) [23]	-	2500-5000 Gy	High energy gamma radiation
Coloma (2020) [20]	1-5 Gy/s	800 Gy	Arduino Uno tests
Violette (2014) [24]	0.33 Gy/s	600 Gy	Arduino Uno tests

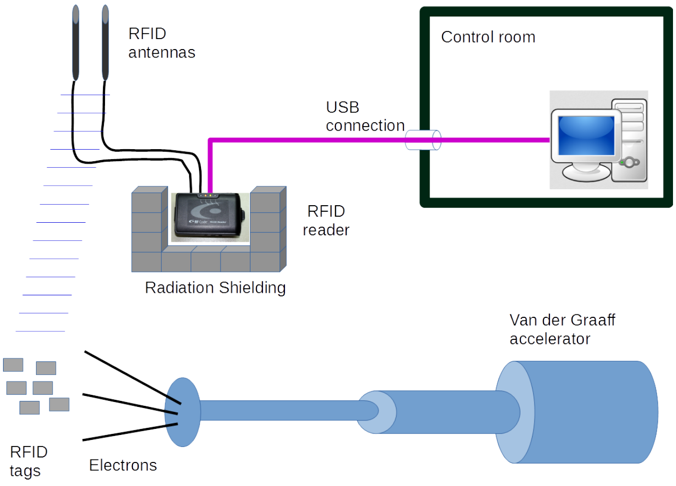

Figure 4: Experiment to test the resistance of RFID tags to electron radiation with the Van de Graaff accelerator.

Figure 5: RFID reader (left) and tag used in the irradiation experiments, from the RFCode company.

Tags were irradiated in batches of ten, arranged in a plate put in front of the electron beam, at a distance where the electron flux is approximately uniform across the irradiated area (Fig. 6). For the experiments, the plastic cover of the tags is removed, since it would attenuate the electron flux (however, it would have no effect on gamma radiation).

The irradiation took place in two steps. For 1 hour the tags were irradiated with an approximate dose rate of 45 mGy/s. After this time, all tags continued to function normally, so a second hour was programmed but the dose rate was increased to 90 mGy/s. In this case, all the components stopped working before the end of this irradiation.

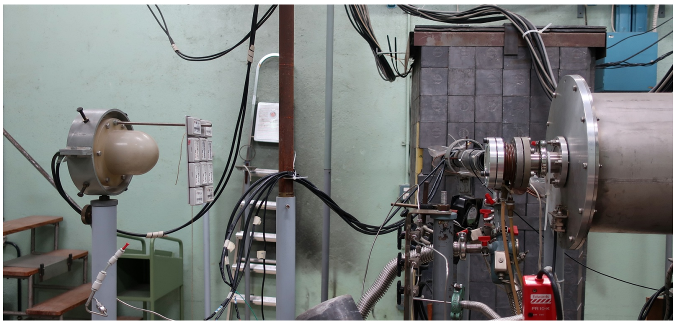

Figure 6: Arrangement of the batch of RFID tags in front of the output of the van de Graaff accelerator.

Total received radiation doses were computed from the time elapsed until component malfunction. In figure 7 we compare our results with those obtained by Teraura [23]. Results are qualitatively similar, although the dose rates are very different (20 mGy/h in their case, and between 18-90 mGy/s in ours).

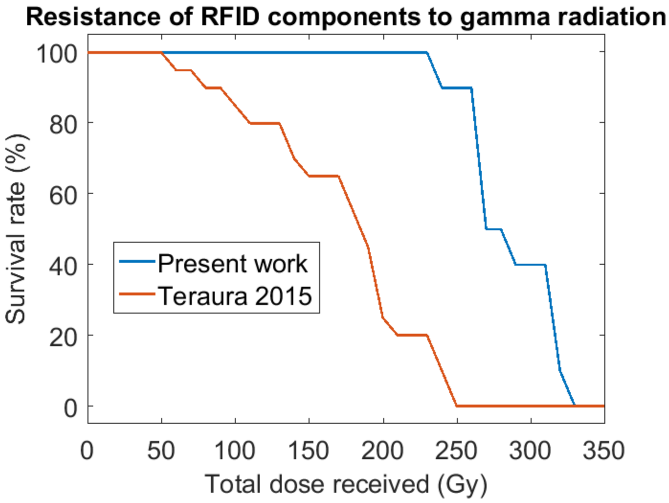

Figure 7: Comparison of experimental results of irradiation of RFID tags with the van de Graaff accelerator with those from reference [23].

With this we can draw some preliminary ideas of the applicability of RFID technology to the installations of IFMIF-

DONES. In controlled areas with free or regulated access (see table I), radiation levels are so low that the RFID components would last several years; only in restricted or prohibited access areas the radiation would cause component failure within months of operation.

The last aspect investigated in this experiment is whether irradiation increases transmission failures between RFID tags and readers. Under normal circumstances, a reader does not receive every single emission made by the tags, due to multiple phenomena (signal attenuation, self-interference by multipath, mutual interference with other tags, etc). In our setup, the number of missed detections was about 0.2 %. This did not increase when the tags were irradiated. Our conclusion is that, at the dose rates used in our experiment, irradiation does not affect the operation of the device until accumulated damage physically destroys it.

C. Future experiments on RFID devices

In a second experiment we plan to use a gamma irradiation facility (see Fig. 8), which is a pool that contains different ^{60}Co sources placed at its bottom, and is filled with water to act as a biological shield. The electronic devices to be irradiated are placed inside a watertight cylindrical sample holder, and then lowered into the pool to bring them near the radioactive sources. The kind of sources used and their proximity determines the dose rate.

With this facility we can irradiate RFID tags with a dose rate of 2 Gy/h for a week, to achieve a total dose similar to that of the first experiment. However, compared with the van de Graaff experiment, the container with the RFID tags has to be extracted periodically (for example, daily) from the pool and opened, to check if the devices remain operative, as the attenuation caused by the 5 meters of water (the depth of the pool) makes the reading of the tags impossible while submerged in water.

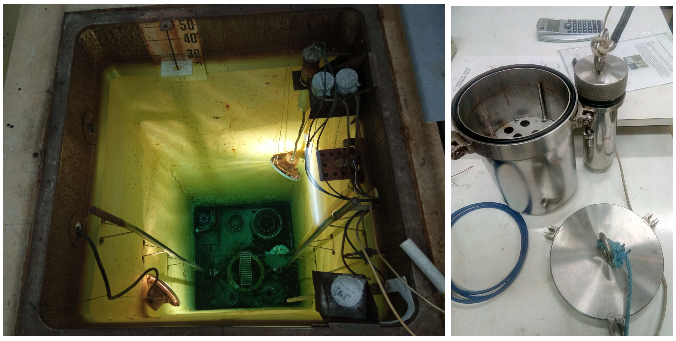

Figure 8: Image of the pool facility for gamma irradiation at CIEMAT (left), and sample holder to bring the electronic devices close to the radioactive sources (right).

As a conclusion of this section, we have outlined the total dose required to make the RFID components which will be used in the localization system stop working, which is approximately in line with that found by previous research. However, we note that due to the limitations of the experimental procedures available to us, these total doses will be achieved at much higher dose rates that those that would be found in IFMIF-DONES (i.e., operation time will be reduced), so the results must be taken with precaution.

IV. DESIGN CONSIDERATIONS FOR AN RFID-LPS SYSTEM OPERATIVE IN IFMIF-DONES

From what has been set out in the previous sections, a design for the personnel localization system for its use in the IFMIF-DONES facility is proposed.

A. Choice of the RF locating technology

As it was previously mentioned, there are several types of signals that could be used in the design of an indoor localization system: acoustic/ultrasonic, infrared and radio frequency (RF) waves, the latter being the most common and versatile found in literature. Within the RF signals, IEEE 802.11 (wifi) y 802.15 (Bluetooth) protocols are very common, as well as 802.15.4 (Zigbee), ultra wide band (UWB) and radio frequency identification (RFID).

The localization system here proposed for the IFMIF-DONES facility is based on RFID technology, since it is simple to deploy and configure, requires little maintenance and is usually highly reliable. Active RFID technology (with battery-powered tags) can be used for several months or even years without requiring a battery change. While RFID is normally aimed at logistics and item tracking applications, it has found widespread use for personal indoor localization purposes [26]. Indeed, our own experience with RFID-based indoor positioning, whether as a standalone technology or combined with inertial sensors or map-matching [27], [28] has been very satisfactory. While RFID-based localization might not be very precise, as previously exposed, detection reliability, ease of deployment and system ruggedness are more important requirements than positioning accuracy for this particular situation. Apart from these reasons, RFID technology has been previously used in nuclear facilities for maintenance tasks [29], equipment tracking [23] or management of nuclear materials [21].

B. System architecture

The proposed system consists of three components, which are schematically shown in figure 9:

- A set of active RFID tags. Workers or visitors of the facility are given an identifier tag which is registered in a database; the tag emits an identification code regularly (typically every few seconds).
- A network of RFID tag readers located at known locations in the facility. For each tag signal reception, the reader registers the ID, the reception time, the received signal strength (RSS), and other additional data that can be programmed in the tag.
- A master computer which manages the network of RFID readers and registers the acquired data in real time.

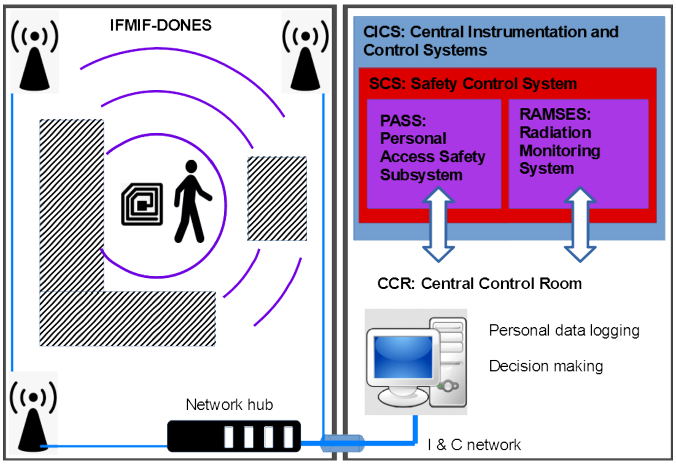

Figure 9: The architecture for the proposed RFID-LPS system: at the left, one of the monitored rooms and the deployed RFID readers; at the right, the central control room with the system of data registration and decision making, and the integration of the RFID-LPS system with the Central Instrumentation and Control Systems (CICS) of IFMIF-DONES.

Although modern RFID systems permit wireless connections with the master computer, a wired connection will be more reliable given the shielding characteristics of the IFMIF-DONES facility, using the communication networks (Ethernet and optical fiber) already planned for the building.

The transmitter location can be obtained from the information of the received signal strength (RSS) by the readers, considering the path loss law for the RSS [30]. Typical positioning accuracies of several meters can be achieved by this method, depending on the density of deployed readers and the complexity of the areas where they are installed. In practice, and given the compartmentalization of the IFMIF-DONES facility, we prefer to determine reliably the presence of a person in a specific area rather than knowing their exact location (the so called symbolic localization). The described configuration of RFID-LPS is termed a *centralized* architecture, as there is a central node (master computer) with the information of the localization of every user.

C. Distribution of RFID readers

As stated previously, RFID readers must be deployed in the different rooms of IFMIF-DONES guaranteeing location coverage in all of them. In order to achieve this for a large facility, we will perform a computer optimization process comprised of two stages: modelling indoor RF propagation and optimization of beacon locations. RF indoor propagation can be studied with empirical methods (such as log-distance, Okumura-Hata, Motley-Keenan or COST231) or more precise deterministic techniques (FDTD or ray-tracing) [8], depending on the desired accuracy, information about the environment and computation time.

The optimization process is multiobjective, and normally performed with a compromise between coverage, accuracy and number of beacons used. One such approach is presented in [31] for the optimization of beacon layout in an acoustic positioning system, considering signal blockage by walls and the floorplan of the building. Heuristic methods provide a good compromise between computation time and optimization results [32].

D. Protection of components against radiation

A demonstration prototype of the RFID-LPS system will be designed using standard technology offered by the RFID manufacturers. Although some RFID equipment is designed to operate in 'harsh' conditions, this usually refers to adverse environmental conditions such as humidity, extreme temperatures, etc. As far as we know, no RFID radiation resistant devices are available commercially. Consequently, one future task for our work is the design of a shield which would protect the sensitive components of the RFID readers [11].

E. Integration of the proposed RFID-LPS within the Central Instrumentation and Control systems of IFMIF-DONES

IFMIF-DONES is composed of five major groups of systems [1]: one of these is the Central instrumentation and control system (CICS), in which the proposed RFID-LPS would be integrated. Within this hierarchy, CICS is composed of three components: Control Data Access and Communications (CODAC), Machine Protection System (MPS) and Safety Control System (SCS).

SCS is designed to implement all the protection functions concerning the plant personnel and environment. Among them we find [33]:

- The Plant Safety Subsystem (PSS), dedicated to the detection of plant events and the activation of actuators to avoid potential risks.
- The Occupational Safety Subsystem (OSS), which provides protection to people against conventional hazards (electric, toxicological, physical, criogenical, etc).
- Personal Access Safety Subsystem (PASS), ensuring safety of people in specific areas which may be dangerous; for example, stopping ongoing experiments if an intrusion is detecting, defining and granting access permissions depending on the current activity of the plant,etc.
- Radiation Monitoring System for the Environment and Safety (RAMSES), designed to keep the radiation doses received by workers as low as possible, and in any case below the limits prescribed by the authorities.

The described RFID-LPS system would be probably included in the PASS and RAMSES subsystems. At the present time, these subsystems are only specified generically within the IFMIF-DONES design.

The RFID-LPS system would make use of the communication networks contemplated for IFMIF-DONES (high-speed Ethernet and optical fiber). Supervision and decision making would be done in the Control Central Room (CCR), the place which unifies all these tasks in the IFMIF-DONES facilities. The system must be designed to operate in a distributed way and obviously in real-time; besides this, IFMIF-DONES favours the use of open-source programming tools.

V. CONCLUSIONS

In the present work we have discussed the design of a local positioning system based in radiofrequency identification (RFID) technology for its use in nuclear facilities such as IFMIF-DONES. In this type of environment two issues have to be considered: the attenuation of the RF signals caused by the building structure itself, and the exposure of the device components to ionizing radiation, which affects their operational lifetime.

An architecture for personal localization through RF identification technology (RFID-LPS) is proposed, based in a set of readers deployed in the area of interest, and active tags which are carried by the users. Taking into account that the proposed system will operate in the controlled access areas of DONES, where typical radiation levels of approximately of 10 mGy/h are expected, the preliminary studies found in literature show that the RF readers could have a lifetime of several months, although it could possibly be improved with appropriate shielding of the devices.

As further work, more experiments will be performed with RFID components in order to reliably determine their lifetime and a proof-of-concept test of the system will be carried out in conditions resembling those of the IFMIF-DONES facility.

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