# DIAMINE (Detection and Imaging of Anti-personnel Landmines by Neutron Backscattering Technique)

Giancarlo Nebbia and the DIAMINE* Consortium

*Abstract*—**DIAMINE is a project in the field of Humanitarian Demining developped in the frame of the IST of the European Union 5th Framework Program. The problem of detection of minimum metal content mines is approached with the use of a hand-held sensor based on the detection of low energy backscattered neutrons during irradiation of the soil with a radioactive neutron source. Such a device should be sensitive to low atomic number elements present both in the explosive and in the plastic case of the mine. Coupling with a metal detector to provide a double sensor in a single searching unit is considered.**

*Index Terms*—**Humanitarian demining, imaging, neutron backscattering.**

## INTRODUCTION

THE DIAMINE project considers primarily the problem of demining in the Balkan region where a strong efficiency improvement of the current demining operations is needed. The reported productivity of a single demining team (usually made of 6 operators and eventually 2 dogs) is presently limited to about 300-400 m$^2$ per day for commercial organisations. The safety issue is also a very important one considering that to the present rate of landmine victims in the civil population one must add a large number of accidents in the demining teams (about 6/Km$^2$) [1]. With reference to the Balkan region recent statistics [2] point out that the most dangerous types of mines are PROM-1, MRUD, PMR-3 and TMR-P6. Small AP mines like PMA3 and PMA1 are reported to be buried at an average depth of 90 mm. From the detection point of view , mines having a sufficiently high metal content (about 54% of the total) are easily identified by metal detectors while the reamining 46% low metal content mines represent a serious threat for the safety of the demining teams and a time consuming task to be challenged. In the DIAMINE project the assumption is that new landmine detection technologies are basically known and must be developed and integrated to produce a prototype close to the industrial production standards. The goal of the project is to develop a prototype of a hand-held landmine detector making use the neutron backscattering technique (NBT), equipped with ancillary sensors like a detector-to-soil distance sensor .The principle of operation of a NBT sensor is rather simple : a source of fast neutrons , i.e. a $^{252}$Cf radioactive source with a neutron average energy of about 2 MeV, is set close to the ground and irradiates the soil to be investigated. The fast 2 MeV neutrons have the desirable property of being a highly penetrating radiation and can then probe a layer of soil of few tens of centimeters. Fast neutrons will undergo scattering processes with all the elemets of the soil in the inspected region and will be scattered bakwards to the source with a probability inversely proportional to the atomic number of the scatterer, moreover the residual energy lost by the neutrons will be also inversely proportional to the atomic number of the scatterer. It is thus clear that a high rate of low energy (thermal to epithermal) backscattered neutrons will indicate the presence of a low atomic number item buried in the soil. It is then expected that the

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explosive and the plastic case of landmines (which both display a high hydrogen content) will produce such a “signal” that one should be able to distinguish from the soil background by means of a detection system rather insensitive to fast neutrons and gamma rays and with a high sensitivity for the thermal and/or epithermal component of the neutron spectrum.

It is envisaged that the NBT sensor will be used to scan the suspect area in connection with a metal detector survey in order to produce a coupled information to the operator , one based on the presence of a “metal anomaly” a second one based on a “hydrogen anomaly” thus reducing the false alarm rate due to metal clutter. Furthermore an NBT based sensor should greately enhance the efficiency for the detection of minimum metal content landmines.

## STATUS OF THE PROJECT

### A. *Monte Carlo calculations*

A first part of the DIAMINE working program concerns the simulation of neutron transmission and scattering in the bulk soil medium and the response to backscattered neutrons of different kinds of detector assemblies. By means of Monte Carlo codes run independently in two different institutes (Bari and Bratislava) one has proceeded to a strict cross validation of the results for a given input set.

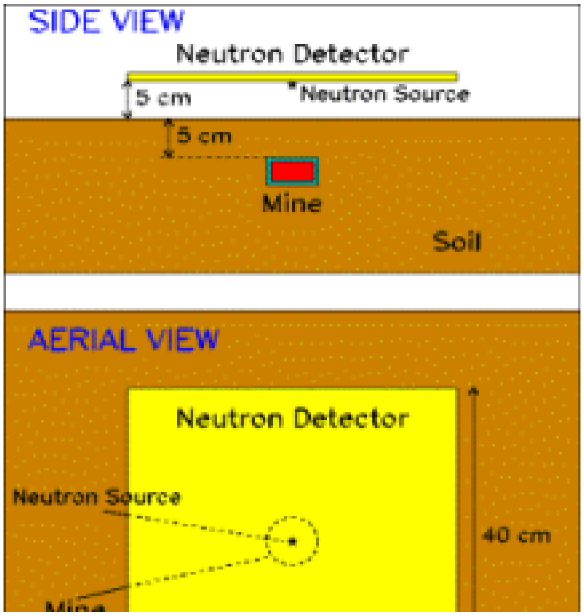

Fig. 1

The geometry of the inspected area (fig. 1) has been fixed in a box of 100 x 100 x 50 $cm^3$ of soil whose elemental composition was taken from an average measured in different locations in the Balkan area as described below. Moreover a number of calculations were performed introducing different values of soil moisture using informations also coming from direct soil moisture measurements performed in Croatia. Mine types PMA-2 and TMA-3 were used to verify the rate of backscattered neutrons compared to the undisturbed soil background.

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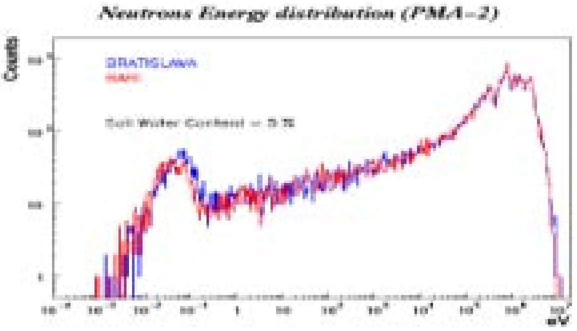


Fig. 2

Backscattered neutron spectra have been then calculated variating all the above described parameters and were plotted as seen by an ideal detector of 40 x 40 $cm^2$ positioned at 5 cm from the soil surface, an example of such spectrum calculated by the two groups is shown in fig. 2. First it can be seen from the plot that the two spectra match rather well, secondly one should notice the large bump in the yield around thermal and epithermal energy of the backscattered neutrons, this feature is of paramount importance for the definition of the detector characteristics. The second batch of simulations have dealt with the definition of the neutron detector itself, geometry has been more realistically defined as a square surface of 20 x 20 $cm^2$, thickness and structural details of the detector have been varied in order to provide an overall view of the detector's performances under different options. Details on the detector's parameters will be given on a separate paragraph.

### *B. Soil moisture measurements*

The knowledge of the quantity of water per unit volume and/or per unit weight is a very important issue since the spectral shape and intensity of the backscattered neutron flux strongly depend on the average atomic number of the irradiated area. Hydrogen atoms in water molecules will indeed produce a rather severe background noise if one is seeking a signal related to the hydrogen content of the explosive and the mine casing, as a consequence one has to study carefully the moisture concentration in the different kinds of soil present in the mine affected areas.

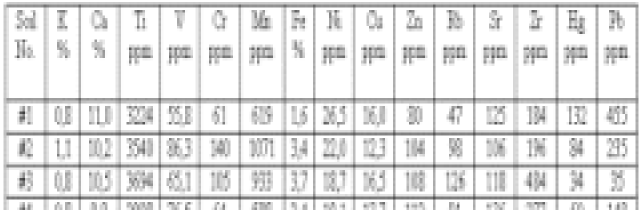
For these reasons a large campaign of soil characterisation has been performed in a number of different sites in the Croatia territory in areas neighbouring minefields. The map of such locations is shown in fig. 3.

Fig. 3

The red dots in the figure represent eleven sites where the soil misture has been measured locally, moreover soil samples were collected from the same locations and taken to the Institute Rudjer Boskovic in Zagreb for further analysis.

In situ measurements of the soil moisture have been performed by means of a radiofrequency electromagnetic profile probe that determines the volume percent of water in the soil at different depths (from surface to 40 cm deep in 10 cm steps) by measuring the dielectric constant of the medium surrounding the probe head. Two rotations of 120° of the probe head provided three readings for all locations at each depth in order to average out possible anisotropies in the moisture distribution even in the small soil volume (about 1.5 liters) checked by the probe.

Measurements of soil moisture have been carried out on a weekly basis in most locations year round, this is important since it gives us a detailed information on the soil characteristics as a function of seasonal and precipitation conditions. In order to input the information on soil misture into the Monte Carlo simulation to infer its influence on the neutron backscattering process one has to transform the volume percent information obtained directly from the field measurements into mass percent. This has been done by determining the precise elemental composition of the soil samples using XRF laboratory techniques, the results of such analysis are shown in the table of fig. 4.



| Soil No. | K % | Ca % | Ti ppm | V ppm | Cr ppm | Mn ppm | Fe % | Ni ppm | Cu ppm | Zn ppm | Rb ppm | Sr ppm | Zr ppm | Hg ppm | Pb ppm |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| #1 | 0,8 | 11,0 | 3224 | 55,8 | 61 | 609 | 1,6 | 26,5 | 16,0 | 80 | 47 | 125 | 184 | 132 | 405 |
| #2 | 1,1 | 10,2 | 3540 | 86,3 | 140 | 1071 | 3,4 | 22,0 | 12,3 | 104 | 98 | 106 | 196 | 84 | 235 |
| #3 | 0,8 | 10,5 | 3694 | 65,1 | 105 | 933 | 3,7 | 18,7 | 16,5 | 108 | 126 | 118 | 404 | 34 | 35 |

Fig. 4

In order to have a confirmation of the local measurements the samples of soil collected in the various sites were sealed into air tight containers and transported to the laboratory where hygrometric determinations have been performed by gravitometric methods.

The results of such investigations led to a rather precise knowledge of the moisture content of a layer of soil about 40 cm thick for different soil types, at different locations in the territory of Croatia and at differents times of year . One can thus appreciate the variations of background problems due to water concentration in the soil that appear to be strongly dependent on the soil composition . From fig. 5 one can see for example results for a clay based soil located close to a river bank in the region of Slavonia for a period of about seven months.

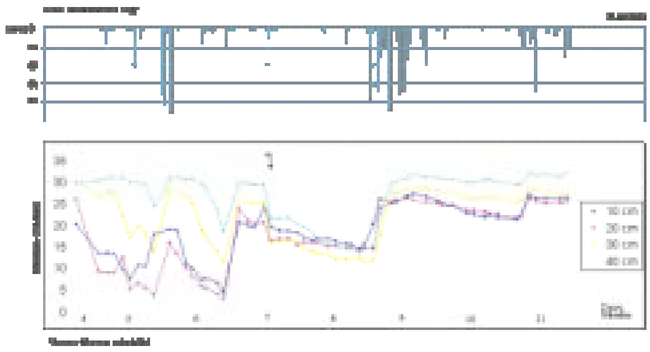


Fig. 5

In the upper panel is represented the rainfall in centimeters on a daily basis, the lower panel shows the soil moisture mass percent measurements at different depths. One can see that for this kind of soil the average water content is rather variable during the rainy spring season and groups around a value of about 20% during the summer to rise up sharply to about 30% after the heavy rainfalls of the fall.

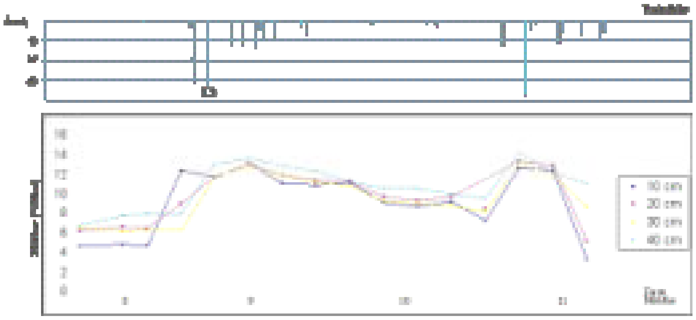


Fig 6

A rather different behavior can be seen in the results shown in fig. 6 relative to a sand based soil located in a coastal area near the city of Zadar. In this case the high draining power of the sandy soil gives an overall lower value of the moisture content between 8-13% for most seasons and with little dependence on the rainfall intensity.

One can also notice a rather different dependence on the depth for the two kinds of soil investigated.

### C. *The NBT detector*

In order to define the optimum characteristics of a neutron detector designed to satisfy the boundary conditions of the DIAMINE project one has to consider a number of possible options and different parameters according to the following requirements:

The detector has to be light weight , an investigation performed among the actual users of demining equipment yielded a maximum weight of about 2 kilograms for the detector head.

The detector must have minimum sensitivity to all radiations except low energy (thermal and epithermal) neutrons. Since the NBT sensor has to be a hand held device the only possible source of neutrons that can be used to irradiate the ground is a small sealed radioactive neutron source which, in our case , was chosen to be a $^{252}$Cf source embedded into a ceramic nugget enclosed into a small stainless steel vessel. Such a source emits fast neutrons (about 2 MeV average energy) and gamma rays with a typical statistical spectrum with a high energy tail. The NBT counter must then be essentially "transparent" to such emission and to all gamma radiation produced in reactions induced by the neutron flux in the vicinity the detector's head.

The active area of the detector has to be large enough to guarantee a reasonable detection efficiency given the limitation of the neutron source intensity due to radiation safety restrictions. An active surface of about 20 x 20 cm$^2$ has been envisaged for the NBT counter.

In order to allow the capability of making an image of the detected target one should provide the NBT sensor with a segmentation (about 2 cm) in two orthogonal dimensions that would render it position sensitive . This will enable the device to analyze the flux of slow neutrons originating from an extended target and to produce an image of the inspected area with a pixel size of 2 x 2 cm$^2$.

The detector must be mechanically robust for field use, radiation resistant, low cost and low maintenance.

Since the NBT sensor must be integrated with a metal detector one should carefully choose the materials, in particular one should keep the metal content at a minimum.

All of the above requirements have been considered in the definition of the possible options for the NBT sensor head, a R&D program has been carried out on four kinds of detectors: a lithium loaded thin sheet scintillating glass, two Resistive Plate Chamber (RPC) devices with thermal neutron converters, and a Multi Wire Proportional Chamber (MWPC) also with thermal neutron conversion plates.

Scintillating glasses offer an attractive possibility to build large area position sensitive thermal neutron detectors, usually they are made on a glass basis doped with a suitable converter material containing isotopes like $^6$Li, $^{10}$B or $^{nat}$Gd. The efficiency of such scintillators is directly proportional to the concentration of converter atoms which is comparatively low in doped glass scintillators. In order to maximize the converter concentration to obtain a high efficiency for thermal neutron detection we used a new scintillation material based on $LiPO_3$ . The advantage is that the converter (Li in this case) is a constituent of the glass itself, moreover all constituents of the scintillator are low atomic number elements thus minimizing the efficiency for gamma ray detection. In order to increase the light output Bi atoms have been added as an activator with different concentrations in the range 0.5 – 2 %. At the Institute of Physiscs SAS of the Univerity of Bratislava a number of samples of $LiPO_3$ were produced in the form of circular plates with diameter of about 20 mm and thickness of 3 mm, several series of samples (almost 50 pieces) with different concentrations of activators (both BGO and $Bi_2O_3$) were prepared and tested. After the first tests additional light element oxides ($B_2O$) were added to reduce hygroscopicity of the compound to ensure stability for field use. The maximum of the light response for $LiPO_3$ is expected around 680 nm , therefore a photomultiplier tube with extended red sensitivity was used for the tests. The response of different samples to gamma rays from $^{60}$Co , $^{137}$Cs , alfa particles from $^{241}$Am and moderated neutrons from a Pu-Be neutron source was measured coupling directly the photomultiplier tube to the glass without a ligh guide. The response to gamma rays does not show any important structure corresponding to a full energy peak , they rather show a continuous distribution associated to an extended Compton component.

Fig. 7

On the other hand the response to 5.5 MeV alpha particles as well as to thermal neutrons shows a characteristic structure due, in the latter case, to charged particles produced in the reaction $^{6}\mathrm{Li} + n \rightarrow \alpha + {}^{3}\mathrm{H}$. In fig. 7 are shown the responses to different radiations of various samples of scintillators for increasing concentrations of activator. The blue and green spectrua are relative to gamma ray signals from $^{60}$Co and $^{137}$Cs sources respectively, the black one is relative to direct alpha irradiation from $^{241}$Am, and finally the red spectrum is relative to charged particle signals from Am-Be neutron conversion . The position sensitivity has not been studied insofar with a large area $LiPO_3$ scintillator, nevertheless we have investigated this possibility using a plastic scintillator that has a light output similar to $LiPO_3$. The size of the plastic sheet was 20 x 30 x 0.5 cm$^3$ , and it was coupled to the photomultiplier tube via lucite trapezoidal light guides ending with optical fiber bundles. The light was thus collected from the edge of the two opposite shorter sides of the sheet and the pulse height of the photomultiplier tubes were recorded simultaneously during the irradiation of the plastic sheet with a collimated $^{241}$Am alpha particle source. The pulse amplitude was found to be proportional to the distance of the source from the edge according to the light attenuation law and gave a position resolution of few centimeters that could be further improved coating the optical links with reflective paint.

In order to satisfy the requirements described above for the NBT characteristics and performances the next option that was considered involved the use of gas filled counters. Such a choice is interesting since the amount of active material (gas) of the detector can be tuned to render the counter sensitivity adequate to the kind of radiation of interest, moreover the detector components are all rather inexpensive and easy to replace. RPC based gaseous detectors were designed and tested in different configurations : the first one consists in a double gap geometry counter operated in streamer mode with a 15 μm thick Gd converter placed between the two gaps.

The total active thickness of the detector is about 100 μm , the electrodes are made of metallized mylar foils 10 to 20 μm thick stretched on G10 frames, a Gd foil packed onto a 1.5 μm mylar foil allows, according to estimates based on an accurate MonteCarlo simulation, a detection efficiency for thermal neutrons of about 33 %.

About 10 small scale different prototypes have been built and tested in different configurations. First results indicate that the detectors work satisfactorily but show a problem of limited lifetime probably due to charge accumulation on the electrodes because of the mylar high resistivity. The second RPC configuration considered consisted in a single gap counter made with bakelite or glass electrodes used also as thermal neutron converters. The choice of converting material was between boron and lithium , both emitting alpha particles after thermal neutron capture, the former was chosen for the better chemical properties in the operation in a gaseous environment . Monte Carlo simulations have been performed to define the optimum thickness of the boron coating taking into account the spectrum of the backscattered neutrons and the self-absorption of alphas in the converter. A number of tests on deposition of boron have been performed on 10 x 10 cm$^2$ samples using different isotopic compositions and chemical forms. Two different deposition techniques have been investigated , electron gun evaporation and magnetron sputtering , in order to check on the deposition temperature that could eventually damage irreversibly the substrate changing its electrical properties. Sputtering on bakelite indeed resulted in a low quality adhesion of the boron layer onto the substrate, while this technique results adequate for deposition on glass.

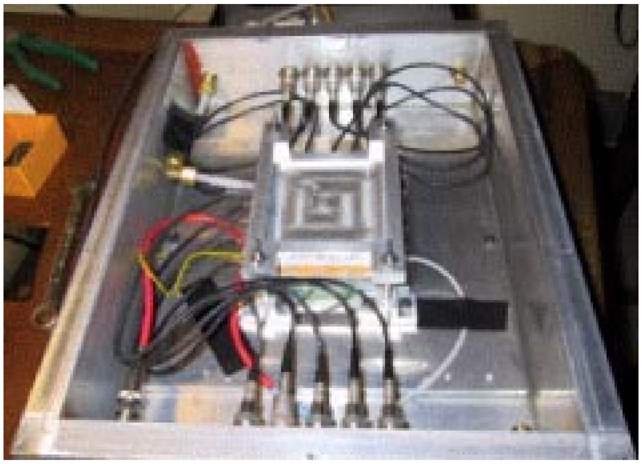


Fig. 9

All electrodes with different boron deposition have been tested in laboratory conditions with a moderated neutron source to verify the effective alpha particle yield with calibrated alpha counters and gave satisfactory results in agreement with the predictions from Monte Carlo calculations within the stastistical errors. Preliminary tests on the detection of alpha particles in a realistic RPC configuration have proven very promising using a subset of selected electrodes , in fact the signal quality is such that one could operate the RPC at a lower than nominal voltage thus reducing the background noise due to minimum ionizing particles. Fig. 9 shows a picture of the testing vessel in wich the actual structure of the RPC has been installed to allow easy replacement of different electrode configurations.Tests were performed as well on the gas mixture to be employed for alpha particle detection, in fact a more suitable mixture compared to the traditional one ( 50 % Ar + 41 % $C_2H_2F_4$ + 8 % $C_4H_{10}$ + 1 % $SF_6$) might allow to operate the detector at an even lower voltage thus allowing a better separation between the alpha particle signal and the cosmic rays background. Yet another test on the filling gas has been performed in view of a field use of the detector that has been successfully operated in a stationary mode (without gas flow) without any appreciable degradation of the signal for at least 5-6 hours. Finally the option of rendering the detector position sensitive in two dimensions is being studied through a strip segmentation of the electrodes.The fourth option for the NBT detector consists of a Multi Wire Proportional Chamber (MWPC) adapted for the detection of thermal neutrons whose general layout is shown in fig. 10.

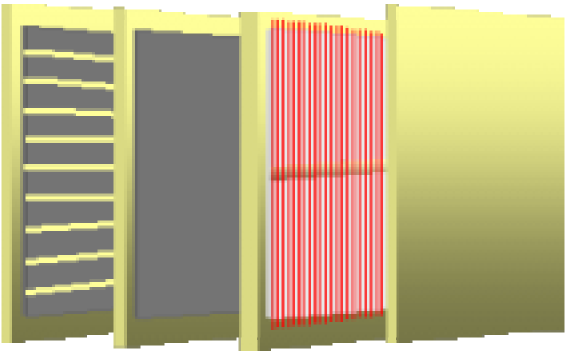


Fig. 10

The first element on the right of the figure is a G10 plate 20 x 20 cm$^2$ coated with an evaporation of 2-3 μm of boron as a converter, the second electrode is a grid of gold-plated tungsten wires of 20 µm diameter with a spacing of 2 mm grounded through suitable resistors. The wire mesh is supported in the middle by a rim which is part of the electrode structure in order to minimize undesired effects due to vibrations and to increase the robustness of the mesh itself. The third electrode is a cathode which is operated at about 3000 Volts to establish the electric field. This electrode is also coated with a boron layer of 2-3 µm that doubles the conversion efficiency of the device. The fourth electrode is made of a series of photoengraved strips (on a G10 substrate) orthogonal to the wires direction that give a position information through the induced signals. To obtain position information along the other axis the wires of the mesh have been shorted in groups of ten and each group has a separate read out . The overall weight of the structure is about 600 grams and the metal content is about 14 grams.

The detector has been tested inside an aluminimu sealed vessel (fig. 11) to allow flexibility in changing electrodes, gas pressure etc.

Fig. 11

Alpha particles from a $^{241}$Am source and a gas filling mixture of 85 % Ar + 15 % $CO_2$ at atmospheric pressure have been used for the tests. A very accurate monitoring of the signal degrading with time has been performed in order to verify the impact of gas ageing on the detector performances, it has thus been demonstrated that the counter can operate without gas flow for at least 8 hours.

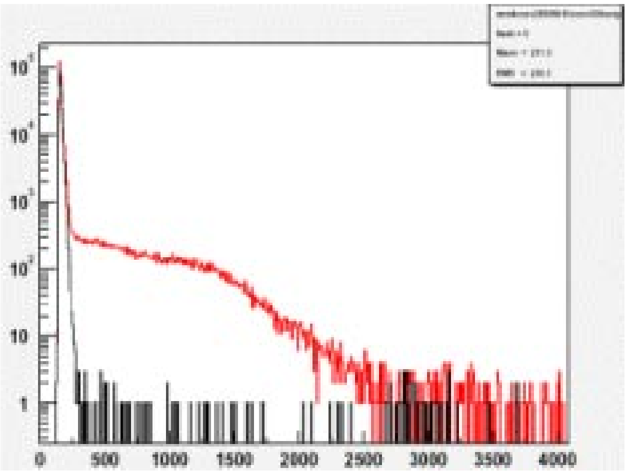


Fig. 12

A test programme on the neutron conversion and detection efficiency has been carried out changing the detector's parameters like the thickness of the boron layer, the electric field and the geometry of the electrodes using a calibrated thermal neutron flux provided by a moderated $^{252}$Cf sealed source.

The background due to fast neutrons and gamma rays originating from the $^{252}$Cf source has been measured to verify the level of "transparency" of the detector to such radiations. The red spectrum of fig. 12 represents the signal amplitude distribution when the fast neutrons produced by the source have been properly thermalized, while the black spectrum refers to the signal amplitude distribution when the bare source is in contact with the detector showing that a simple linear threshold on the signal amplitude is able to discriminate the low energy neutron component.

## CONCLUSIONS

The testing phase of the NBT detector has been successfully carried out considering the diferent options described above, the most promising technique seems to be the MWPC one, nevertheless development and tests on RPC and $LiPO_3$ glass will continue until the complete optimization has been achieved. In all cases the possibility of providing a hit distribution information in two dimensions has been seriously considered in order to provide an imaging capability of the DIAMINE sensor.

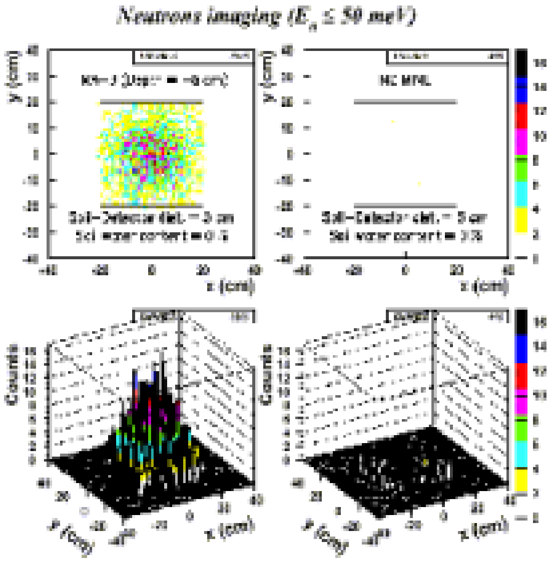


Fig 13

To this end a number of Monte Carlo simulations have been performed under various conditions to assess , at least theoretically, the capability of reaching a significative image of the buried object.

An example of such calculations is shown in fig. 13, in the right side of the figure the upper panel represents the distribution of hits due to backscattered neutrons on a 40 x 40 $cm^2$ detector positioned at 5 cm from the ground surface after a 10 seconds irradiation of the soil with a $^{252}Cf$ source delivering $10^5$ neutrons/second . The lower panel on the same side is a 3D image of the same. In the left side of the figure the same analysis is done but with a TMA3 antitank mine buried at 5 cm under the ground surface. The relative humidity of the soil in this calculation was fixed at 5 %. As it can be seen a clear image of the buried mine is possible under these conditions where a well distinguishable image of the object stands out of the background. Many different such calculations have been performed changing type of mine, depth, irradiation time and soil moisture in order to verify the theoretical limits of the imaging capability.

Tests on the compatibility of the NBT sensor head with a metal detector have been carried out for most components , satisfactory results have been reached after modifications on the materials and electrode geometry have been applied.

The front-end electronics have been designed and partly realized and tested following criteria of compactness, light weight, low power consumption and robustness for use on the field. At the same time the Man-Machine-Interface has been designed both in its hardware and software components following the same criteria . Such unit will proceed to self calibrate the system , evaluate the local background level and pre-process the data coming from the NBT sensor to yield a simple signal (e.g. a variable intensity beeper) to the operator.

Finally, since the instrument includes a $^{252}Cf$ radioactive source, an evaluation of the dose received by the operator during the use of the sensors gives an upper limit of about 660 hours/year of use (i.e. 26 working weeks of 5 days per week at 5 hours per day) to stay within the limits imposed for non professionally exposed personnel.

* The DIAMINE Consortium is composed as follows :

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