DEVELOPMENT OF ADVANCED NEUTRON INDUCED PROMPT GAMMA-RAY ANALYSIS SYSTEM FOR SURVEY OF ANTI-PERSONNEL MINES

T. Iguchi[1], J. Kawarabayashi[1], K. Watanabe[1], K. Nishimura[2], T. Handa[2] and H. Sawamura[2]
[1] Nagoya University, Nagoya, Japan; [2] Computer Software Development Co.,Ltd. Tokyo, Japan

Abstract: An advanced neutron induced prompt gamma ray analysis system has been designed for detection and localization of anti-personnel landmines. The system consists of an improved Cockcroft-Walton type accelerator neutron source using DD fusion reaction and multi-functional gamma ray spectrometers combining a compact multi-Compton gamma camera based on stacked BGO scintillators to deduce the incident direction of 10.8 MeV gamma rays from nitrogen included in landmines and a high purity Germanium detector for good energy resolution measurement to identify the elemental ratio peculiar to landmines. An outline of the design results including some performance tests for the prototype components is presented, which also gives an expectation that the present system could detect a landmine of 30g TNT explosive buried at a depth of 20 cm in a 1m square area within 10 minutes and locate it with the spatial resolution around ± 15 cm in FWHM, through Monte-Carlo neutron and gamma ray transport calculation.

Introduction: An advanced neutron induced prompt gamma ray analysis (NPGA) system for detection and location of anti-personnel land mines (APM)s is now under development, supported by R&D programs for humanitarian demining of MEXT in Japan[1]. The NPGA system consists of a compact pulsed neutron generator and prompt gamma ray sensors. Since explosives used in APM are rich in nitrogen(N) content, neutron capture reaction of N, resulting in the emission of 10.8 MeV characteristic gamma rays, is used for its detection. At present, we are aiming at the detectability for a landmine corresponding to 30g TNT explosive buried at a depth of 20 cm in 1m square area within 10 minutes. To realize this target performance, we have designed an improved Cockcroft-Walton type accelerator neutron source using DD fusion reaction and also multi-functional gamma ray spectrometers combining a compact multi-Compton gamma camera based on stacked BGO scintillators to deduce the incident direction of 10.8 MeV gamma rays from N and a high purity Germanium(HPGE) diode detector for good energy resolution measurement to identify the elemental ratio peculiar to APM.

This paper presents an outline of the NPGA system design including some performance test results for the prototype components and also refers to expectation of the performance on the APM detection and location through Monte-Carlo neutron and gamma ray transport calculation.

Results: The neutron generator for design improvement consists of a high-density ion source called as the helicon plasma source[2], high voltage accelerator used 13 laminated layers of combinations ring-shaped insulator and electrodes, a target with heat pipes to remove heat produced by collision of ion beams, evacuating system and high voltage feedthrough. The maximum acceleration voltage is designed at 130 kV for compactness and light weight of the system. In this case, the neutron energy produced from DD reactions is 2.8 MeV at maximum and the neutron intensity is expected around 2×10^8 n/s in time average under accelerating deuterium ion beam current of 30mA in pulsed operation (duty ratio 10%) and 3mA in CW operation. The neutron production from DD reaction is about two orders smaller than that from DT reaction often used, but is advantageous to obtain a better signal-to-noise ratio on the selective detection of the characteristic gamma rays from neutron capture reaction of N due to the lower neutron energy and strong anisotropy of the neutron emission profile.

The performance test of the helicon plasma ion source was made to verify the stable operation on ion beam extraction up to 30mA in pulsed mode. The results have shown that the plasma density of 5×10^{12} cm^{-3} was achieved at an RF power of 2 kW with a frequency of 13.4 MHz and hydrogen gas pressure of 2.85 mTorr by using the pulse-modulated RF with the pulse width of 0.5ms and the duty ratio of 10%, while, in a preliminary experiment to extract an ion beam from the present ion source, the beam current of 14.4 mA was observed at an RF power of 900W with good proportionality of the beam current to the RF power.

To make design consideration of the accelerator tube and target system, several analyses on the structure materials, configuration, heat removal and cooling have been made mainly through two kinds of simulation; one is for a beam trajectory simulation from the extraction electrode to the target with the IGUN simulator[3], and the other for a thermal conducting simulation from the target through heat pipes with the ABAQUS simulator[4]. Fig.1 shows a design solution for the present neutron generator, which can meet the target performance together with compactness and good maintenance.

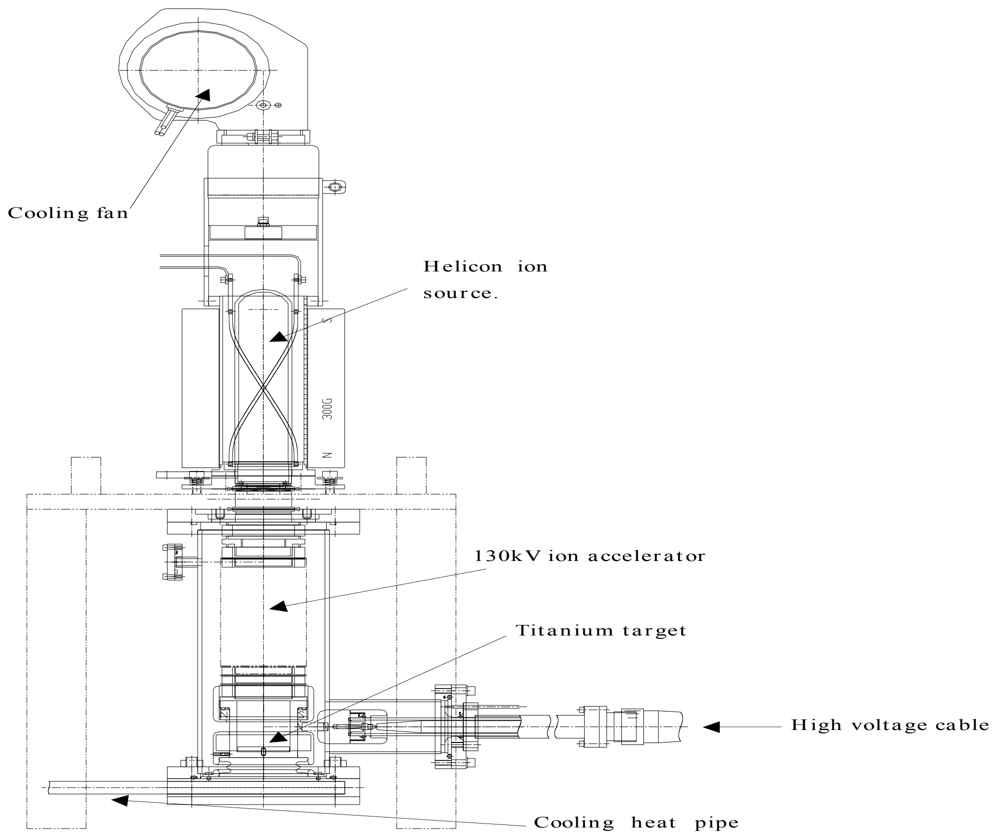


Fig. 1 Schematic view of the neutron generator.

As for the design of multi-functional gamma ray spectrometers, we have adopted a new idea of a compact multi-Compton gamma camera based on stacked BGO scintillators to locate an APM by deducing the incident direction of neutron capture γ-rays of 10.8MeV from N included in the APM. The configuration of a detector unit of the multi-Compton gamma camera is shown in Fig. 2. It consists of 5.4mm×5.4mm×150mm BGO scintillatior rods stacked into an 8×8 array and two multi-anode photomultiplier tubes (MAPMTs) mounted at both ends of the scintillator stack. This detector unit can measure three-dimensional position and intensity of scintillations produced through Compton multiple scattering interactions between incident high energy gamma rays and electrons in the sensitive region, where each BGO rod with rough lateral surface preparation and Teflon tape wrapping operates independently without crosstalk between the neighbouring rods. Therefore, the two-dimensional position of scintillation on the square cross section of the detector unit can be determined by identifying the scintillation emitting BGO rod with the MAPMTs, while the scintillation position in the longitudinal direction of the BGO rod can be determined from the light output ratios at both ends of the BGO rod under an assumption of exponential decay of scintillation photons with their traveling distance in the BGO scintillator. We can also obtain energy information deposited by incident gamma rays onto the BGO rod from the scintillation light intensity.

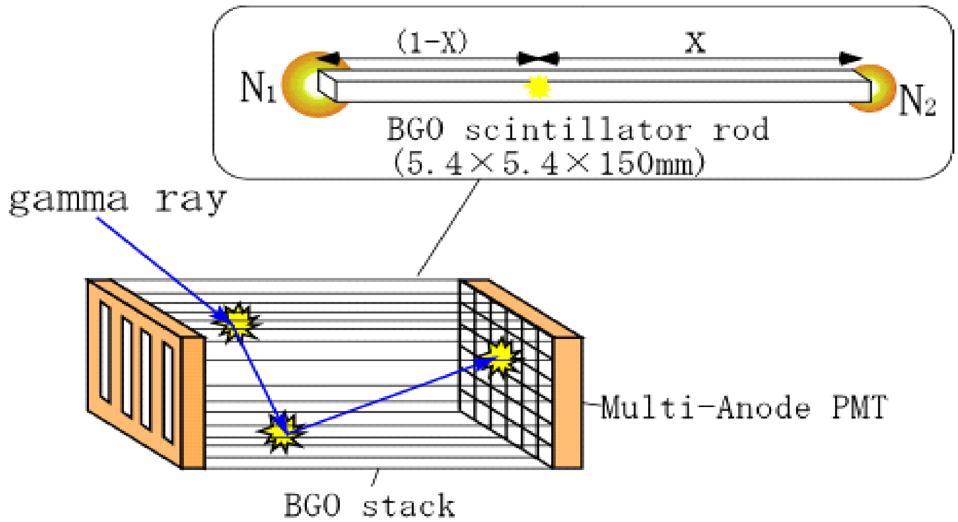


Fig.2 Configuration of a detector unit of multi-Compton gamma camera based on stacked BGO scintillators

By measuring these three-dimensional position and energy of Compton multiple scattering gamma rays inside the BGO scintillator stack, we can estimate the incident direction of the gamma rays without any collimation from the following principle;

As shown in Fig.3, we consider that an incident gamma ray into the detector encounters Compton scattering with the scattered angle θ and the imparting energy E_1 at the first interaction point, and then deposits its remaining energy E_2 at the succeeding scattering and/or captured points. The positions of the first two interactions define a vector which lies along the direction of the scattered gamma ray. The scattered angle θ is given by;

$$\cos\theta = 1 + m_0c^2\left(\frac{1}{E_0} - \frac{1}{E_2}\right) \quad ,$$

where m_0c^2 is the rest mass of the electron and E_0 is the incident gamma ray energy (E_0=E_1+E_2). The above equation means that the direction of the incident gamma ray is restricted on the cone with an axis along the direction of the scattered gamma ray, an apex at the first interaction point and a vertical angle θ. Therefore, we can estimate the location of the gamma ray source of a specific energy E_0 from the intersection of multiple cones defined by several gamma ray Compton scattering events, which are deduced from the measurement of three-dimensional position and energy of multiple Compton scattering gamma rays inside the detector.

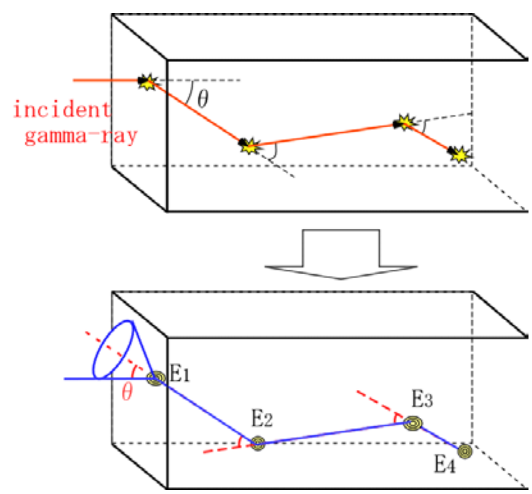


Fig.3 Multiple Compton scattering process

To realize this signal processing, we have designed and constructed a prototype circuit with commercial ASIC for reading out the multichannel signals of MAPMT (HAMAMATSU H8500) in coincidence. The ASIC (Ideas ASA ; VA32_HDR11+TA32CG) chip used is a 32 channel charge sensitive preamplifier-shaper circuit with low noise, low power and high dynamic range, and also has the capability of simultaneous sample and hold, multiplexed analogue readout and calibration function. By using 662 keV gamma rays emitted from a ^{137}Cs source, we have made preliminary performance tests for the prototype system illustrated in Fig.4, and confirmed that the spatial and energy resolutions are around 35mm and 20% in FWHM, respectively, along the longitudinal direction of a single BGO rod.

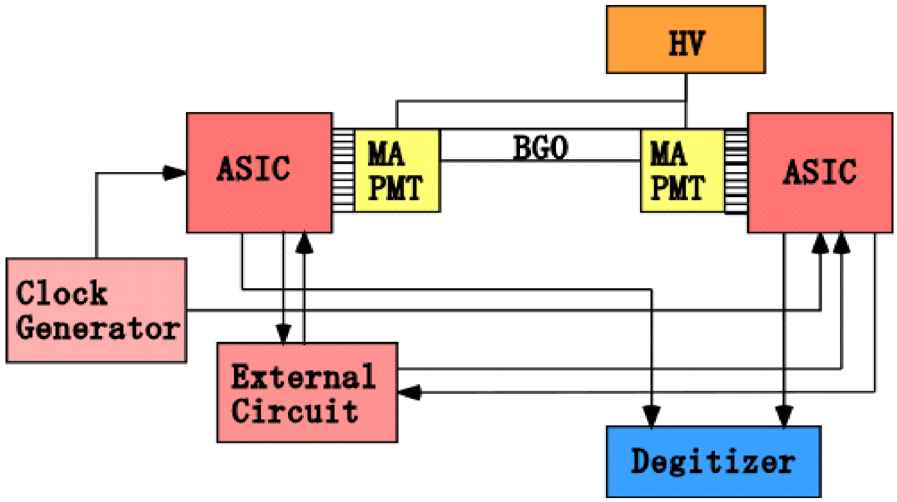


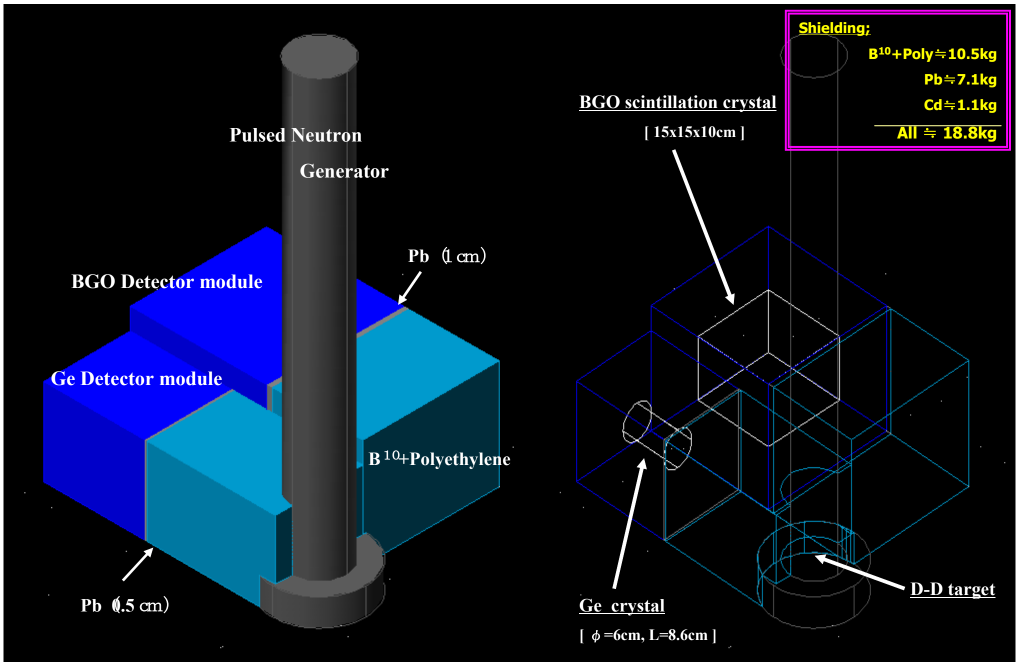
Fig.4 Prototype signal processing system for multi-Compton gamma camera based on stacked BGO scintillators

As the multi-functional gamma ray spectrometers for the NPGA, we are planning to use 6 detector units of the 8x8 stacked BGO scintillator rods to enhance the detection efficiency of 10.8 MeV gamma ray up to 50%, combined with a commercially available and portable HPGE detector with a relative efficiency of 150% for good energy resolution measurement to identify the elemental ratio peculiar to APM.

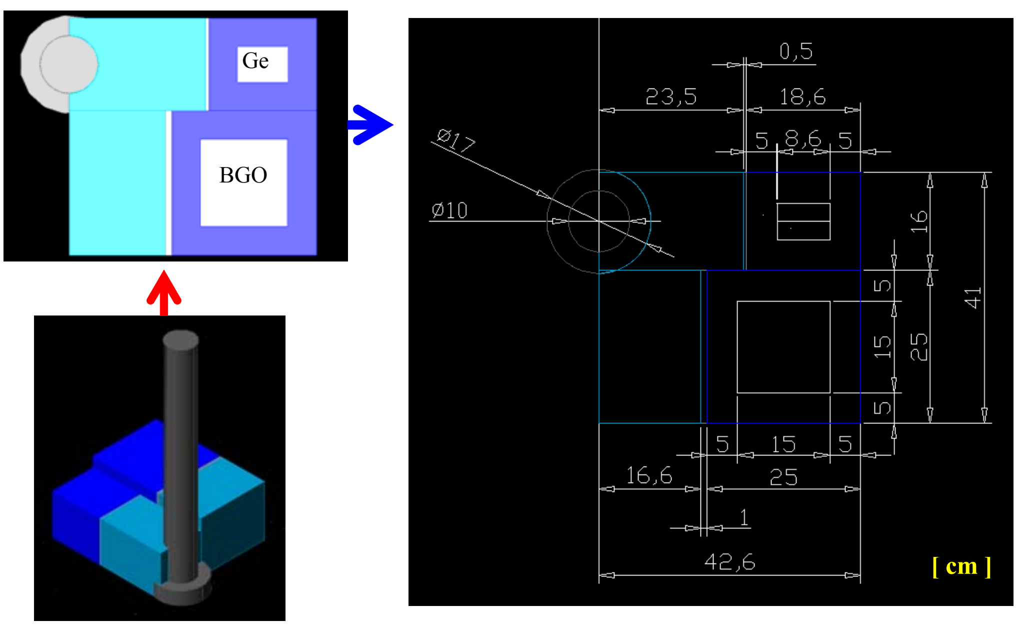
Discussion: We have tried a system integration between the neutron generator and the multi-functional gamma ray spectrometers through neutron and gamma ray transport calculation with the Monte Carlo code MCNP-4C[5]. To optimize the signal-to-noise ratio for the gamma ray sensors and the system size (or weight), the extensive parametric survey calculation has been made on the system configuration including the detector shielding. Figs.5(a) and (b) show one of the results on the system configuration optimized by trial and error, where the total system can be housed in the space of 45 cm wide x 55cm long x 85cm high with the weight less than 200 kg. When the distance between the neutron source and the ground surface is set up at 10cm and the time gate for gamma ray measurement from 300 μs to 1000 μs for 100 μs burst width and 1000 μs intervals of the neutron pulses, the calculation has also suggested that the present system could count more than 110 signals in 10 minutes for 10.8MeV gamma rays produced from an APM of 30g TNT explosive buried at a depth of 20 cm in 1m square of laterite soils.

We have also checked the applicability of the compact multi-Compton gamma camera based on stacked BGO scintillators to the APM location through simulation of the interaction process of 10.8 MeV gamma rays inside the detector with the EGS-4 code[6]. Reflecting the basic performance (i.e. spatial and energy resolutions) obtained from the preliminary experiment, Fig.6 gives an example of the simulation results deducing the incident direction of 10.8MeV gamma rays from N included in an APM (2cm square x 1cm thick), which are located at 20 cm depth, and at the center and 20cm apart from the center in a 1m square area, respectively.

From this result, we have confirmed that it would be possible to roughly identify the location of 10.8 MeV gamma ray sources (or N content profiles) with the spatial resolution around ± 15 cm in FWHM at a depth of 20 cm in a 1m square area.



(a) Bird's-eye view



(b) Plane view

Fig.5 Optimized system configuration among the neutron generator, gamma ray sensors and the detector shielding

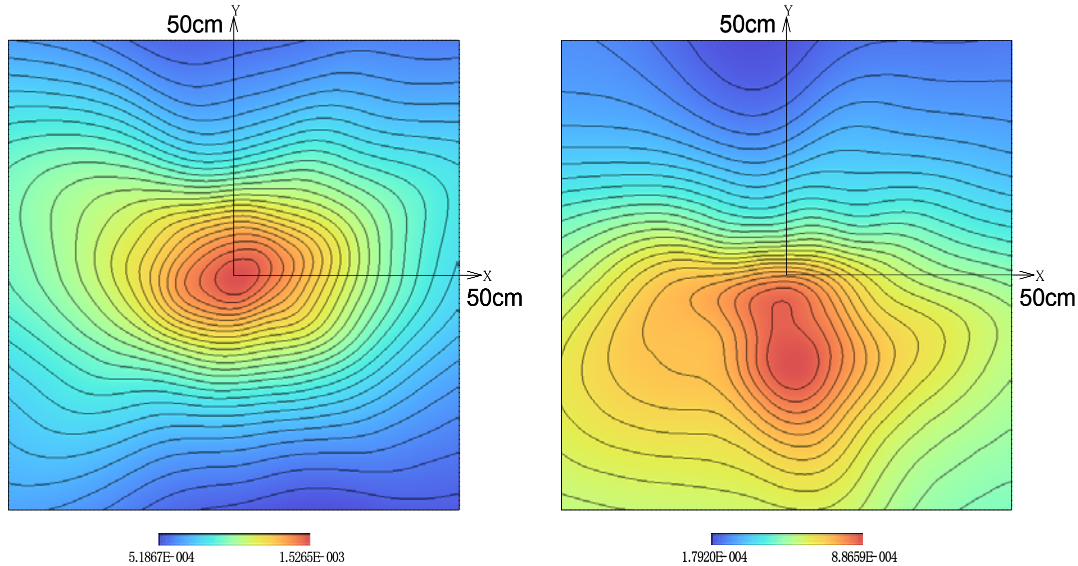


Fig.6 Deduced images for the incident direction of 10.8MeV gamma rays from N of an APM (2cm square x 1cm thick) located at 20 cm depth, and at the center (left) and 20cm apart from the center (right) in a 1m square area, respectively.

Conclusions: We have designed an advanced NPGA system for detection and location of APMs, which consists of an improved Cockcroft-Walton type accelerator neutron source using DD fusion reaction and multi-functional gamma ray spectrometers combining a compact multi-Compton gamma camera based on stacked BGO scintillators to deduce the incident gamma ray direction and a HPGE detector for good energy resolution measurement. Through preliminary performance tests for the prototype components and Monte-Carlo neutron and/or gamma ray transport calculations, we have demonstrated that the present NPGA system could detect an APM of 30g TNT explosive buried at a depth of 20 cm in 1m square of laterite soils within 10 minutes, and locate it with the spatial resolution around ± 15 cm in FWHM. However, it is necessary to make experimental checks on the signal-to-noise ratio of the gamma ray sensors. In parallel with the development of the full system, we are now trying to do mock-up experiments on the APM detection with the DD neutron based NPGA.

References: [1] http://www.mext.go.jp/english/news/2002/05/020602.htm
[2] M. Nisoa, Y. Sakawa and T. Shoji, "Compact High-Density Plasma Source Produced by Using Standing Helicon Waves", Jpn. J. Appl. Phys., Vol.38, L777-L779 (1999).
[3] R.Becker, "New Features in the Simulation of Ion Extraction with IGUN",Proc. EPAC98, Stockholm, Sweden (1998).
[4] Hibbit, Karlsson and Sorensen Inc.,"ABAQUS/Standard User's Manuals, Version 6.1." Pawtucket, RI, USA (2000).
[5] J.F.Briesmeister (Ed.), "A General Monte Carlo N-Particle Transport Code-Version 4C", LA-13709-M (2000).
[6] W.R.Nelson, H.Hirayama and D.W.O.Rogers,"The EGS4 Code System", SLAC-265 (1985).