C.2 GEOMETRY OF EXPERIMENTAL HALL, COLLIMATOR AND DETECTION SETUPS

The ELI-NP experimental hall configuration including the γ-ray collimator and beam dump was implemented in the Geant4 simulation code. The experimental setups proposed by the GANT workgroup were implemented in a flexible manner, allowing the investigation of various geometries and combinations of detectors and shielding layers.

Here we present the experimental hall, collimator system, beam dump and detection arrays structure and possible configurations.

C.2.1 EXPERIMENTAL HALL

The structure of the ELI-NP building along the high energy γ-ray beam line was implemented in the following manner:

- A 1.5 meters thick brick wall between the accelerator hall and the collimator + gamma diagnostic hall. The wall is placed at 2.58 meters from the interaction point. The gamma beam passes the wall through a 1.1 cm aperture beam duct.
- The main gamma ray beam collimator, placed at 8.9 meters from the interaction point. The collimation system will be presented in the following section.
- A 1 meter thick radioprotection heavy concrete wall placed after the collimator, at 9.68 meters from the interaction point. The gamma beam passes the wall through a 0.7 cm aperture beam duct.
- A 1.5 meters thick brick wall between the collimator + gamma diagnostic hall and the E7 experimental hall. The wall is placed at 16.47 meters from the interaction point. The gamma beam passes the wall through a 1.1 cm aperture beam duct.
- The E8 experimental hall including the gamma ray beam dump and the experimental setups. The beam dump and the experimental setups will be discussed at length in the following sections. All the E8 lateral walls, the ceiling and the floor have been implemented in the code for a thorough investigation of the scattering effects, especially for neutrons. The hall is 27.58 meters from the interaction point. The lateral wall and the floor are 2 meters thick while the ceiling is 1.5 meters thick. The gamma beam passes the wall through a 3. cm aperture beam duct.

Schematic views of the experimental hall geometry implemented in the Geant4 simulation code are represented in Figures C.24.a,b. While the E8 experimental hall can be filled with either air or vacuum, the rest of the experimental hall is under vacuum.

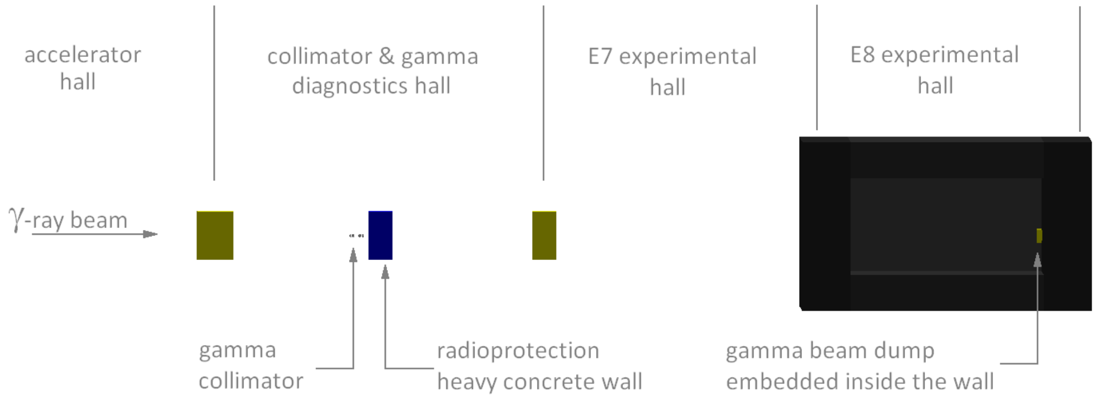


Figure C.24.a Schematic view of the ELI-NP experimental hall implemented in the Geant4 code. A lateral wall of the experimental hall has been removed for better visualization.

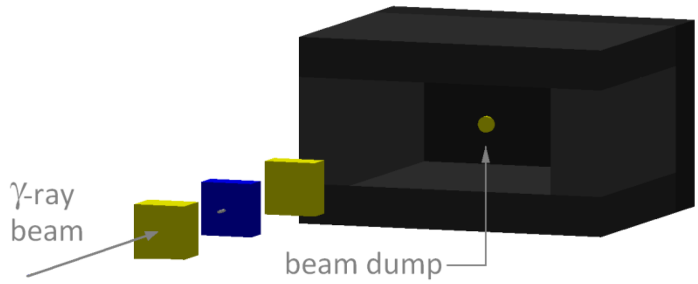


Figure C.24.b Same as Figure C.24.a, but from an upstream perspective. The front wall of the experimental hall has been removed for better visualization.

C.2.2 COLLIMATOR

The γ-ray beam ELI-NP collimator will consist of a system of tunable aperture slits. Each slit is composed of two tungsten blocks (see Figure C.25.a) encased in an aluminum frame (see Figure C.25.b). The dimensions of the tungsten blocks as well as the aperture are free input parameter. The collimator system consists in sets of such tungsten slits, where the number of slit sets and the distances between the sets and between the slits inside each set are free input parameters (see Figures C.25.d,e). One set is composed of N_{slits} stacked slits, each of them rotated in the transverse beam plane with an angle $\Delta\varphi$ with respect to the previous slit (see Figure C.25.c). The individual rotation angle $\Delta\varphi$ is obtained as the ratio between the total angular span covered by the slits from one collimator set and the number of rotations, namely: $\Delta\varphi = \varphi_{set} / (N_{slit} - 1)$, where N_{slit} and φ_{set} are free input parameters.

Input par.	Unit	Observations
2	#	Nb. of slit sets
5.	cm	Distance between slit sets
6	#	Nb. of slits in one set
180	deg	Angle span of slits in a set
0. 90.	deg	Phi angle of the first slit in each set
1.	cm	Distance between slits
3. 4. 6.	cm	Thickness, width and length of a lead block
0.05	cm	Slit aperture
2.	cm	Maximum slit opening

0.5	cm	Thickness of slit frame

Table C.7 Input file for construction of a collimation system using the Geant4 simulation code.

For all our simulations we used two sets of six 1.8 cm thick slits and a total angular span of 180 degree per set, therefore each slit was rotated with 36 degrees with respect to the previous one. An input file containing the input parameters required for constructing a collimation system using the Geant4 code and explanations is listed in Table C.7.

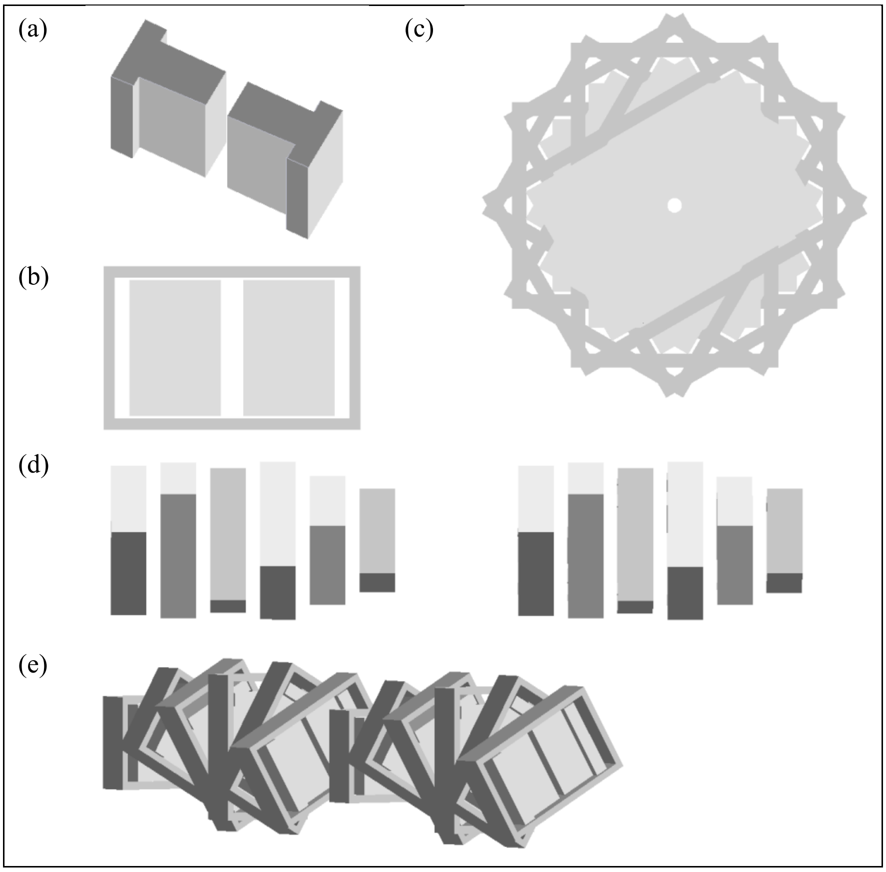


Figure C.25 Schematic representations of: (a) one slit composed of two tungsten blocks, (b) one slit inside the aluminium frame, (c) a set of slits view from the perspective of the γ-ray beam, (d) and (e) two sets of slits from different perspectives.

C.2.3 GAMMA RAY BEAM DUMP

The gamma ray beam dump implemented in the Geant4 simulation code has a two layers structure and is composed of lead and paraffin moderator. Schematic representations of the collimator with and without the outer moderator paraffin layer are represented in Figures C.26.a,b. The beam dump is embedded in the back wall of the E8 experimental hall, as can be seen in the Figures C.24.a,b. The gamma ray beam enters the collimator through a shaft of 2.5 cm diameter and 60 cm length and hits the inner layer of lead absorbent, as represented in Figure C.26.c. Photons and charged radiation are stopped in the inner lead layer. The neutrons created in the lead absorbent are moderated in the outer layer of paraffin moderator.

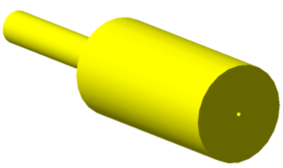


Figure 4.2.26.a Schematic view of the E8 gamma ray beam dump. The yellow material represents the parrafin neutron moderator. Also the beam gap opening can be seen.

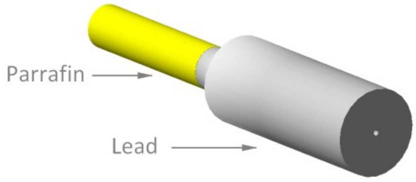


Figure 4.2.26.b Schematic view of the E8 gamma ray beam dump. The lateral parrafin neutron moderator is removed here. The grey material represents the lead radiation absorbant.

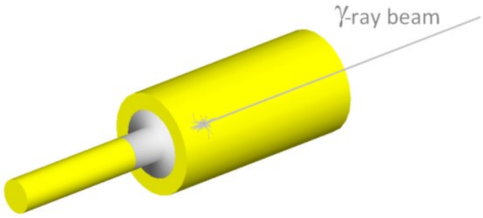


Figure 4.2.26.c Schematic view of the E8 gamma ray beam dump. A pencil-like γ-ray beam is stopped in the beam dump and the length of the central beam gap can be observed in the figure.

The precise dimensions of each of the beam dumps components are listed in Figure C.27.

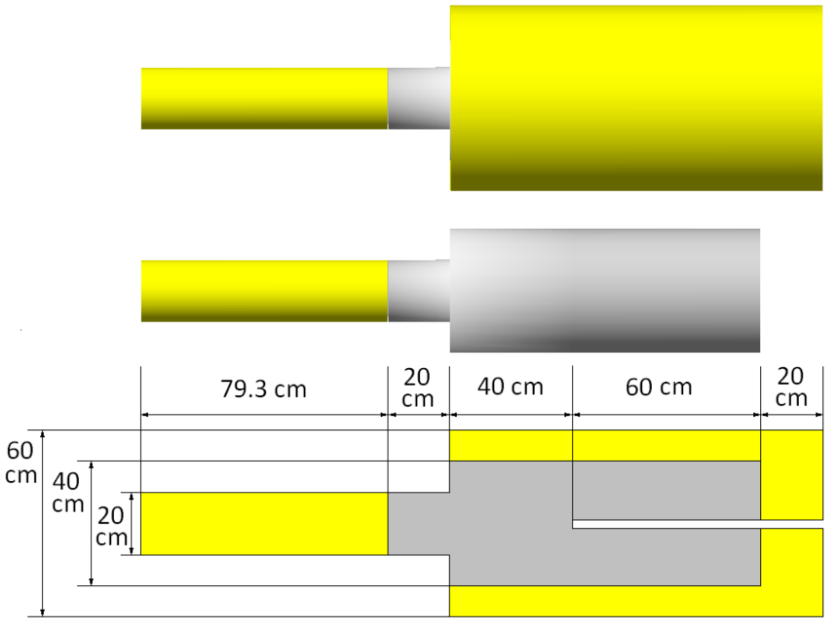


Figure C.27 Schematic view of the E8 gamma ray beam dump. The beam dump is represented with the outer moderator layer (top image) and without it (middle image). Also the precise dimensions of each component of the beam dump are present in the bottom image.

C.2.4 4Π NEUTRON DETECTOR

Photoneutron cross sections will be measured at ELI-NP using the 4π neutron detector by the "slowing down" method. The reaction neutrons emitted with energies up to several MeV, depending on the nucleus and γ-ray beam energy, are moderated in a polyethylene block and recorded by neutron counters placed in concentric rings around the beam axis. Neutrons induce nuclear reactions in the counters and the charged reaction products, collected using an electric field, generate the detector signal. Because no information on the energy of the neutrons can be obtained from the signal, the ring ratio method is employed for determining the average energy of the neutron evaporation spectra.

Our studies on the 4π neutron detector were focused on finding optimum geometries to satisfy the following requirements:
- High neutron detection efficiency;

- Flat dependency neutron detection efficiency;
- Minimal pile-up effects induced by the pulsed time structure of the ELI-NP gamma beam;
- Good neutron – gamma discrimination properties in very high fluxes of gamma radiation;
- Minimal effects given by the background radiation scattered from the walls of the experimental hall and from the beam dump.

Because the development of the neutron detector implied a highly iterative procedure in search of the best working parameters, a very flexible and user friendly method of constructing the setup geometry was implemented in the simulation code.

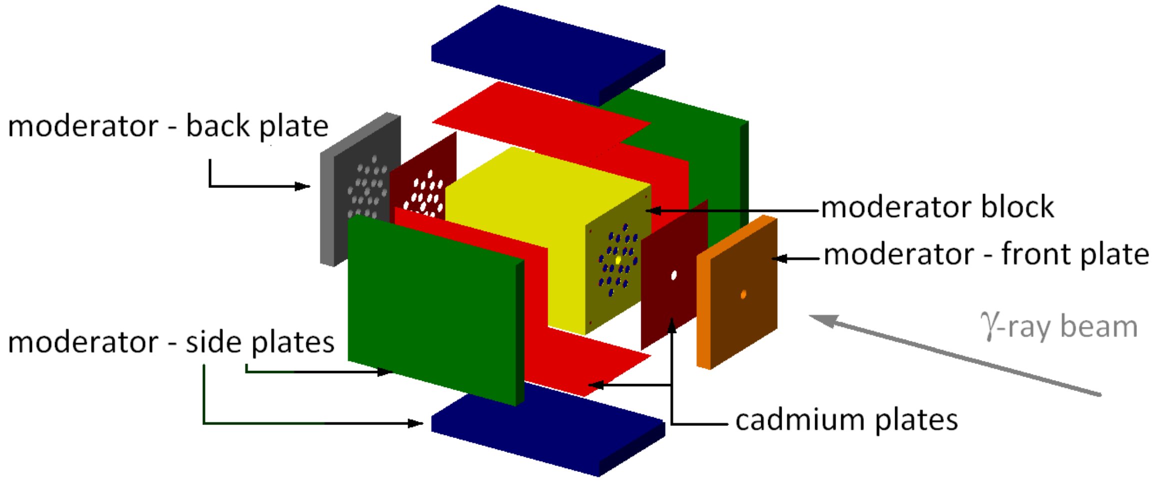


Figure C.28 Schematic image of the 4π neutron detector structure. Additional space has been added between the components for a better visualization the main detector structure. The moderator front, back and lateral plates, the cadmium plates and the main moderator block are marked in the image. Also the direction of the incident gamma ray beam is represented.

The neutron detector is composed of a moderator block of fixed length of 50 cm along the beam axis in which up to three rings of neutron counters can be embedded. The neutron counter shape (cylindrical), dimensions (55 cm length and 2.5 cm diameter) and casing (0.4 mm thick stainless steel) are fixed. Layers of 0.5 mm thick cadmium and 10 cm thick polyethylene plates are placed on the lateral, front and rear side of the moderator block for stopping background neutrons from entering the detector. The structure of the neutron detector is represented in Figure C.28.

Keeping the above mentioned parameters fixed, the detection geometry can be easily configured by varying the following free input parameters:
- Number of neutron counter rings, which can be varied from 1 to 3.
- Ring radii, represented by the distance from the center of the moderator to the center of the counters from each ring.
- Number of counters per ring.
- Moderator size in the transverse plane related to the beam axis. When increasing the ring radii, the moderator size must be increased correspondingly to ensure neutrons which go beyond the outer ring can be backscattered in the moderator material outside of the outer ring.
- Type, pressure and sensitive isotope enrichment of the gas contained inside the neutron counters. Two types of materials are implemented:

- Mixture of ^3He and CO_2 gas. Sensitive isotope: ^3He.
- BF_3 gas. Sensitive isotope: ^{10}B.

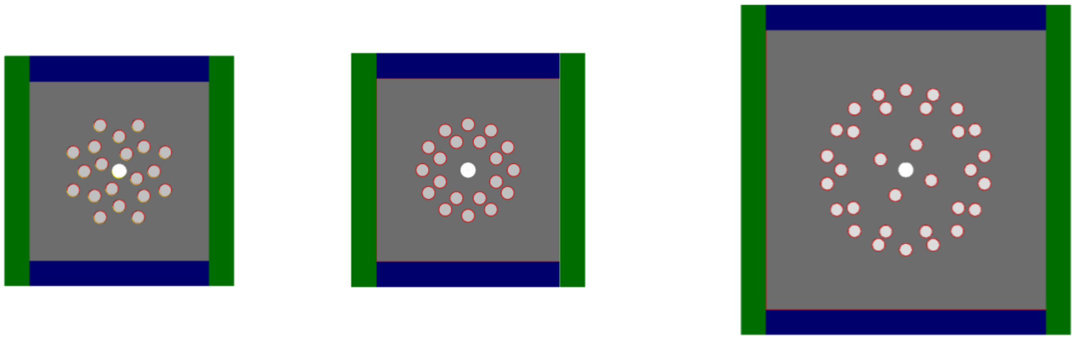


Figure C.29 Schematic images of different configurations for the 4π neutron detector, where the beam is coming out of the paper through the central gap in the detector. Left image: high efficiency configuration presently used, with 4, 8 and 8 counters on the inner, middle and outer rings, respectively; Middle image: example of a two rings detector with 8 detectors on the inner ring and 12 on the outer one; Right image: example of a flat efficiency configuration with three rings of 4, 10 and 18 counters on the inner, middle and outer rings, respectively.

Examples of detection geometries are displayed in Figure C.29. The left image represents the high efficiency 4π neutron detector currently in use at the NewSUBARU facility. It consists of three rings of 4, 8 and 8 counters placed at 3.8, 7 and 10 cm, respectively, from the beam axis. The middle image represents a detector with two rings of 8 and 12 counters placed at 6 and 9 cm from the beam axis. The right image represents a flat efficiency detector developed for (g,xn) cross section measurements. It contains three rings of 4, 10 and 18 counters placed at 5.5, 13 and 16 cm, respectively, from the beam axis. The flat efficiency detector will be discussed in a following section. The neutron block is 36 cm wide for the first two illustrated cases, while for the third case is 56 cm wide. A geometry input file is shown in Table C.8, including the input commands with possible input parameters and observations.

Command	**Input value**	**Observations**
`/eli/det/setSDPercentage`	p_s	Set the sensitive isotope enrichment in the counters; $p_s = 0 – 100$ %
`/eli/det/setSDMaterial`	^{3}He_gas BF_3_gas	Set the type of material in the counter. Two materials implemented: ^{3}He_gas: mixture of ^3He and CO_2 gas, where the sensitive isotope is ^3He; BF_3_gas: pure BF_3 gas, where the sensitive isotope is ^{10}B.
`/eli/det/setSDPressure`	*p* units	Set total pressure of gas inside counters. - units: any pressure unit accepted by Geant4.
`/eli/det/setModeratorSize`	*l* units	Set the transverse size of the moderator block. The transverse profile of the moderator is a square, so only one side must be given as input. - units: any length unit accepted by Geant4.
`/eli/det/setNumberOfRings`	1, 2 or 3	Set number of counter rings, from 1 to 3.

/eli/geometry/SetRadius1	l_1 units	Set distance between the center of the beam gap and the center of each counter placed in Ring1. - units: any length unit accepted by Geant4.
/eli/geometry/SetRadius2	l_2 units	Set distance between the center of the beam gap and the center of each counter placed in the Ring2. - units: any length unit accepted by Geant4.
/eli/geometry/SetRadius3	l_3 units	Set distance between the center of the beam gap and the center of each counter placed in the Ring3. - units: any length unit accepted by Geant4.
eli/geometry/SetNumber1	#1	Set the number of counters in Ring1.
eli/geometry/SetNumber2	#2	Set the number of counters in Ring2.
eli/geometry/SetNumber3	#3	Set the number of counters in Ring3.
/eli/geometry/SetPhase1	φ_1	Polar angle φ for the first counter on Ring1.
/eli/geometry/SetPhase2	φ_2	Polar angle φ for the first counter on Ring2.
/eli/geometry/SetPhase3	φ_3	Polar angle φ for the first counter on Ring3.

Table C.8 Input file for construction of a 4π neutron detector using the Geant4 simulation code.

Figure C.30 represents the neutron detector inside the E8 experimental hall.The neutron detector is placed in the vicinity of the beam dump because upstream will be placed the large NRF and ELIGANT detection arrays. Therefore a thorough investigation of the beam dump is necessary to minimize the contribution of radiation scattered from it.

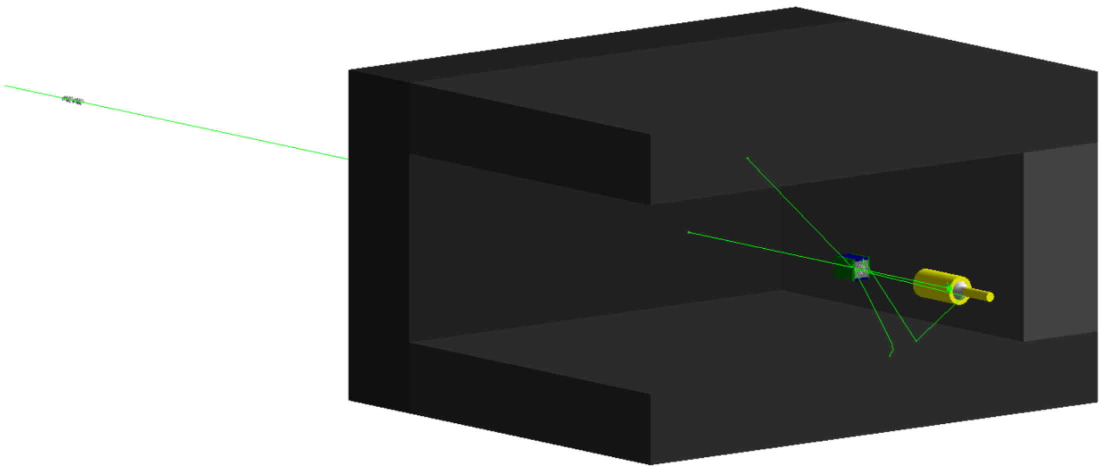


Figure C.30 Schematic view of the 4π neutron detector placed inside the E8 experimental hall, as implemented in the Geant4 code. A lateral and the back walls of the experimental hall have been removed for better visualization.

C.2.5 GAMMA AND NEUTRON DETECTION ARRAY

Experimental studies on the structure of the GDR, PDR and MDR will be performed at ELI-NP employing γ-ray spectroscopy and neutron time of flight measurements with a mixed array of scintillators. We present here the:

- Type and structure of detectors; Two types of detectors were implemented in the Geant4 simulation code: $LaBr_3$ / $CeBr_3$ scintillation crystals for γ-ray detection and BC501A liquid scintillator neutron detectors;

- Method of constructing custom detection arrays;
- Structure of test arrays used for investigation of angular anisotropy emission of reaction products and beam related background;
- Geometric configuration proposed for the ELI-GANT detection system;
- Additional polarimeter configuration for studies on parity of nuclear excited levels implemented in the Geant4 simulation code.

$LaBr_3$ and $CeBr_3$ scintillation crystals for γ-ray detection

Cylindrical scintillation crystals of variable length, radius and material can be used for the construction of arrays. Two types of scintillator materials have been implemented in the code: lanthanum bromide ($LaBr_3$) and cerium bromide ($CeBr_3$). The cylindrical scintillation crystal is encased in 1 mm thick aluminium.

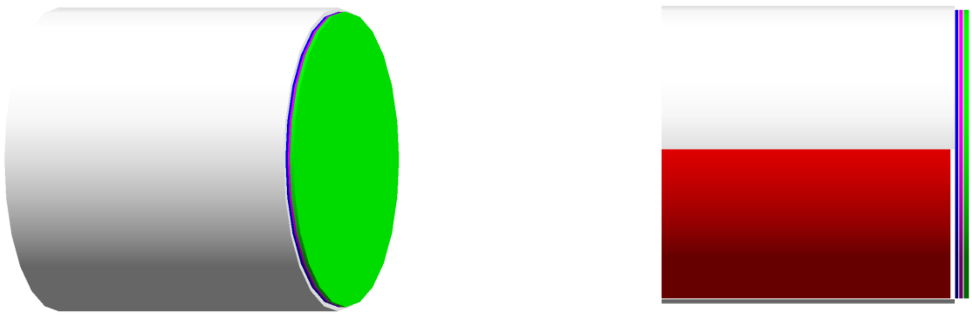


Figure C.31 Schematic view of a γ-ray scintillation detector implemented in the Geant4 code.

Left image: the crystal is placed in a 1 mm thick aluminium case (white) and three absorbents have been placed in front of it.

Right image: a part of the aluminium case is removed for a better visualization of the crystal inside. Also three absorbent materials are placed in front of the crystal.

Up to three absorbent plates can be placed in front of each of the detectors. The number of absorbents and the material and width of each plate are free input parameters. The absorbent material must be chosen from the library of materials defined in the Geant4 simulation code. The configuration of absorbents investigated up to now is the following:
- First absorbent: 0.5 mm thick copper absorbent;
- Second absorbent: 0.5 mm thick cadmium plate;
- Third absorbent: 1.0 mm thick lead plate.

Schematic views of a cylindrical γ-ray scintillation detector are represented in Figure C.31. The materials with the highest atomic numbers are placed first in the path of the radiation entering the detector. The first lead plate is meant to stop the incident electrons and positrons. The cadmium plate is placed to attenuate the X-rays emitted by the lead atoms and also the bremsstrahlung radiation emitted by the electrons and positrons in the lead plate. The material closest to the detector has the lowest atomic number and must further attenuate deceleration radiation produced by the charged particles in the plates and also the X-rays emitted by the cadmium atoms.

A γ-ray detector geometry input file is shown in Table C.9, including the input commands with possible input parameters and observations.

BC501A liquid scintillator neutron detectors

Material and dimensions for the BC501A neutron scintillation detectors are fixed in the Geant4 simulation code and cannot be modified by input commands. The scintillation material is composed of 9.2% hydrogen and 90.8% carbon and has a density of 0.874 g/cm^3. The scintillation crystal is a cylinder of 20 cm diameter and 5 cm thickness. The light guide is implemented as a glass full cylinder and also the photomultiplier as an empty glass cylinder. The detector is placed inside a 1 mm thick aluminium casing shaped as to accommodate also a voltage divider, although the voltage divider is not implemented in the simulation code yet.

Input Command	**Input value**	**Observations**
`/eli/det/setBromideMaterial`	LaBr3 CeBr3	Set the material for the scintillation detector. Two types of sensitive materials implemented in the code: $LaBr_3$ and $CeBr_3$
`/eli/det/setDetectorRadius`	*r*	Set radius of scintillation crystal
`/eli/det/setDetectorLength`	*l*	Set length of scintillation crystal
`/eli/det/setLaAtten1_Placement`	*true* *false*	Place (*true*) or not (*false*) **an attenuator** in front of the γ-ray scintillation detectors.
`/eli/det/setLaAtten1_Thickness`	*h1* units	Set the thickness of the first attenuator. - units: any length unit accepted by Geant4
`/eli/det/setLaAtten1_Material`	*m1*	Set the material for the first attenuator.
`/eli/det/setLaAtten2_Placement`	*true* *false*	Place (*true*) or not (*false*) **a second attenuator** in front of the γ-ray scintillation detectors.
`/eli/det/setLaAtten2_Thickness`	*h2* units	Set the thickness of the second attenuator. - units: any length unit accepted by Geant4
`/eli/det/setLaAtten2_Material`	*m2*	Set the material for the second attenuator.
`/eli/det/setLaAtten3_Placement`	*true* *false*	Place (*true*) or not (*false*) **a third attenuator** in front of the γ-ray scintillation detectors.
`/eli/det/setLaAtten3_Thickness`	*h3* units	Set the thickness of the third attenuator. - units: any length unit accepted by Geant4
`/eli/det/setLaAtten3_Material`	*m3*	Set the material for the third attenuator.

Table C.9 Input file for construction of γ-ray scintillation detectors using the Geant4 simulation code.

The same system of shielding materials as for the γ-ray detectors is used. Images of a BC501A neutron scintillation detector are shown in Figure C.32. A neutron detector geometry input file is shown in Table C.10, including the input commands with possible input parameters and observations.

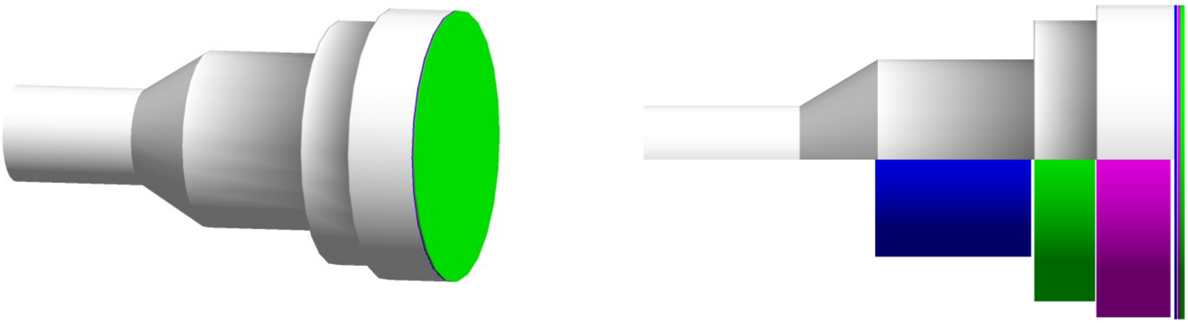


Figure C.32 Schematic view of a BC501A neutron scintillation detector implemented in the Geant4 code.

Left image: the sensitive material, light guide and photomultiplier are placed in a 1 mm thick aluminium case (white) and three absorbents have been placed in front of the sensitive material.

Right image: a part of the aluminium case is removed for a better visualization of the components inside. Also three absorbent materials are placed in front of the detector.

Input Command	**Input value**	**Observations**
`/eli/det/setNeAtten1_Placement`	*true* *false*	Place (*true*) or not (*false*) **an attenuator** in front of the neutron liquid scintillation detectors.
`/eli/det/setNeAtten1_Thickness`	*h1* units	Set the thickness of the first attenuator. - units: any length unit accepted by Geant4
`/eli/det/setNeAtten1_Material`	*m1*	Set the material for the first attenuator.
`/eli/det/setNeAtten2_Placement`	*true* *false*	Place (*true*) or not (*false*) **a second attenuator** in front of the neutron liquid scintillation detectors.
`/eli/det/setNeAtten2_Thickness`	*h2* units	Set the thickness of the second attenuator. - units: any length unit accepted by Geant4
`/eli/det/setNeAtten2_Material`	*m2*	Set the material for the second attenuator.
`/eli/det/setNeAtten3_Placement`	*true* *false*	Place (*true*) or not (*false*) **a third attenuator** in front of the neutron liquid scintillation detectors.
`/eli/det/setNeAtten3_Thickness`	*h3* units	Set the thickness of the third attenuator. - units: any length unit accepted by Geant4
`/eli/det/setNeAtten3_Material`	*m3*	Set the material for the third attenuator.

Table C.10 Input file for construction of neutron liquid scintillation detectors using the Geant4 simulation code.

Detection array construction method

The two types of detectors described above may be placed in a wide variety of configurations inside the E8 experimental hall using the Geant4 code. We will present here the method for constructing a mixed setup geometry.

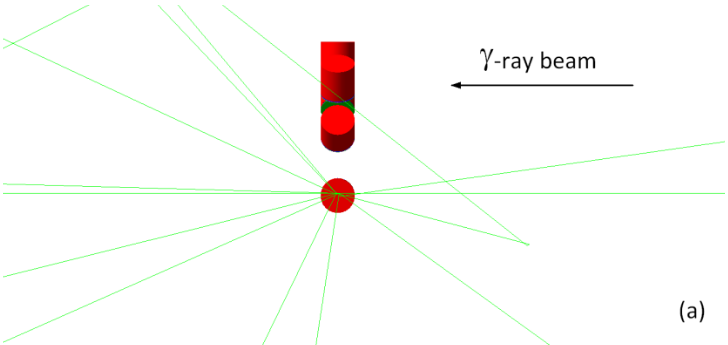
Detectors are placed in rings around a symmetry axis given by the gamma ray beam axis. Each detector is facing the target position represented by the center of the array.
- The number of rings must be provided in the input file.
- For each ring must be provided in the input:
  - The polar angle θ between the beam axis and the longitudinal axis of a detector on that ring must be specified.
  - The number of detectors.
  - Polar angle φ corresponding to the first detector.
  - Polar angle Δφ between detectors.

The input command lines explained above for one type of detectors (gamma or neutron) are:

N_{rings}

θ^i N^i_{det} φ^i $\Delta\varphi^i$

where N_{rings} is the number of rings and θ^i, N^i_{det}, φ^i, $\Delta\varphi^i$ are the i_{th} ring polar angle theta, number of detectors, polar angle phi for the first detector on the ring and polar angle phi between detectors on the ring.



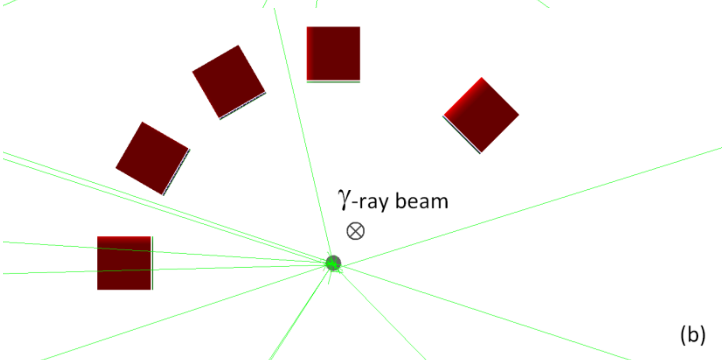


Figure C.33 Configuration of LaBr₃ detectors in one ring for θ = 90º with 5 detectors at φ angles: 0º, 30º, 60º, 90º and 135º. The configuration is defined in the input file as:

```
2
90. 4   0. 30.
90. 1 135.  0.
```

(a) the array is viewed as we look transversal to the gamma ray beam.

(b) the array is viewed from the interaction point along the beam.

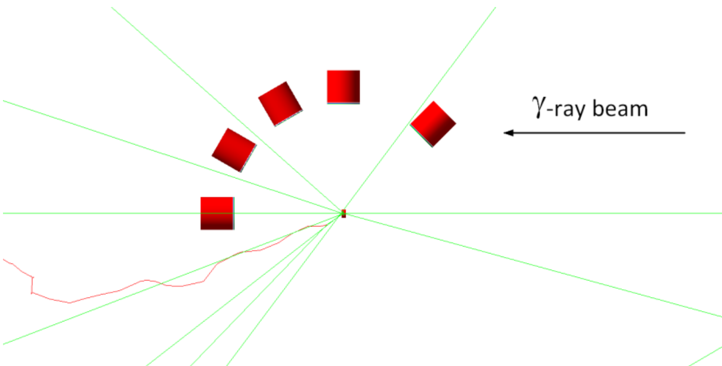


Figure C.34 Configuration of $LaBr_3$ detectors in 5 rings for θ = 0º, 30º, 60º, 90º and 135º, each with 1 detectors at φ angle of 90º. The configuration is defined in the input file as:

```
5
 0.  1   90.  0.
30.  1   90.  0.
60.  1   90.  0.
```

```
 90.   1    90.   0.
135.   1    90.   0.
```

The array is viewed as we look transversal to the gamma ray beam.

The gamma and neutron detectors configurations must be given separately. After constructing the geometry around the beam axis, the whole array can be rotated around the *x*, *y* and *z* axis in the gamma ray beam coordinate system.

Figures C.33 and C.34 present simple schematic views of detection arrays to exemplify the construction method.

Configuration of test detection array

A test detection array was used for the investigation of angular anisotropy emission of reaction products and beam related background. The configuration is displayed in Figure 4.2.35. The configuration consists of 5 rings of detectors:
- $\theta_1 = 37^o$, 4 detectors;
- $\theta_2 = 63^o$, 8 detectors;
- $\theta_3 = 90^o$, 12 detectors;
- $\theta_4 = (180 - 63)^o = 117^o$, 8 detectors;
- $\theta_5 = (180 - 37)^o = 143^o$, 4 detectors.

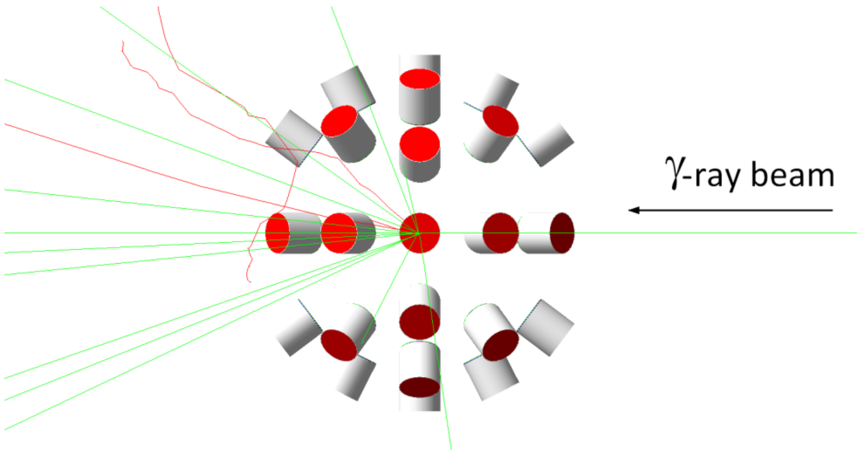


Figure C.35 Test detection array implemented in the Geant4 simulation code.

This configuration was employed for:
- gamma and neutron anisotropy studies;
- beam related background studies. Because the array is constructed symmetrically around the beam axis, detector responses and incident spectra on detectors placed in the same ring can be added to increase statistics;
- studies on the angular detector positions in the experimental setup;
- studies on attenuators to be placed in front of the detectors.