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ABSTRACT

The Tangential Gamma-Ray Spectrometer (TGRS) of the JET tokamak fusion facility is an important diagnostics for investigating the fast particle evolution. A well defined field of view for the TGRS diagnostics is essential for its proper operation and this is to be determined by a rather complex system of collimators and shields both for the neutron and gamma radiations. A conceptual design for this system has been carried out with the main design target set to maximize the signal-to-background ratio at the spectrometer detector, the ratio being defined in terms of the plasma emitted gamma radiation and the gamma-ray background. As a first phase of the TGRS diagnostics upgrade a set of two tandem collimators has been designed with the aim of determining a quasi-tangential field of view through JET tokamak plasmas. A modular design of the tandem system has been developed in order to allow for the construction of different configurations for deuterium and deuterium-tritium discharges. The internal structure of the collimators consists of nuclear grade lead and high density polyethylene slabs arranged in an optimized pattern. The performance of a simplified geometry of the tandem collimator configuration has been evaluated by neutron and photon transport calculations and the numerical results show that the design parameters can be attained.

1. INTRODUCTION

Gamma-ray emission of tokamak plasmas is the result of the interaction of fast ions (fusion reaction products, including alpha particles, NBI ions, ICRH-accelerated ions) with main plasma impurities (e.g., carbon, beryllium). Gamma-ray diagnostics involve both gamma-ray imaging (cameras) and gamma-ray spectrometry (spectrometers). For the JET tokamak, gamma-ray diagnostics have been used to provide information on the characteristics of the fast ion population in plasmas [1, 2]. The applicability of gamma-ray diagnostics to high performance deuterium and deuterium-tritium JET discharges is strongly dependent on the fulfillment of rather strict requirements for the definition and characterization of the neutron and gamma radiation fields (detector field of view, radiation shielding and attenuation, parasitic gamma-ray sources). The JET Tangential Gamma-Ray Spectrometer (TGRS) has a horizontal (quasi-tangential) line of sight that crosses the JET plasma from the octant 8 vacuum port to the octant 3 vacuum port. The TGRS diagnostics uses a calibrated bismuth germanate (BGO) scintillation detector which has a diameter of 75mm and a height of 75mm. It is located in a shielded bunker, behind the high resolution x-ray crystal spectrometer (the KX1 x-ray spectrometer). It is estimated that the BGO detector line of sight lies in a horizontal plane about 30 cm below the JET plasma magnetic axis.

The field of view of the JET TGRS diagnostics has never been clearly defined. The radiation shield of an X-ray camera (the KJ5 radiation shield, Figure 1) has served as a pre-collimator before the JET 2004 shutdown.

The analysis done within the TGRS upgrade conceptual design [3] has shown that the KJ5 radiation shield has operated as a proper pre-collimator only along the vertical (radial) direction. Along the horizontal (toroidal) direction it allowed wide regions of unwanted gamma-ray sources to be seen by the gamma-ray detector. These included both plasma and neutron-induced parasitic gamma-ray sources. During the JET 2004 shutdown the KJ5 radiation shield was removed from the vicinity of the machine port at Octant 8. The quality of the physics information from the TGRS diagnostics has been dramatically reduced by an increase in background events (strong degradation in signal to background ratio plus the lack of the definition of any field-of-view) to the extent that the experimental data has now a considerably reduced physics value.

The field-of-view of the upgraded JET TGRS diagnostics is defined by a system of collimators and shields (for both the neutron and the gamma rays).

The neutron flux at the gamma-ray detector position is to be reduced by a set of three lithium hydride (LiH) attenuators: two fixed and one movable. The upgraded TGRS configuration developed during the conceptual design phase is shown schematically in Fig.1(bottom). It contains the following main components: front collimator, rear collimator, neutron shield, gamma-ray shield and neutron attenuators. A CAD model of the full TGRS system is presented in Fig.2. It shows a mid-plane cross section of the full TGRS line of sight together with zoomed-in cross sections of the main components.

As a first phase of the TGRS upgrade, the first two components, the front and rear collimators, have been designed to work in tandem and are being constructed.

2. DESIGN OF THE TANDEM COLLIMATORS FOR THE TANGENTIAL GAMMA-RAY SPECTROMETER.

2.1 DESIGN CONSTRAINTS AND BOUNDARY CONDITIONS

The tandem collimators had to be designed in order to fulfil the following constraints:

- Space available for the two tandem collimators (front and rear collimators).
- Constraints with respect to the KX1 flight tube (see Fig.2). The tandem collimators were designed with a clearance of 10 mm to the unshielded KX1 flight tube. The design solutions for the tandem collimators were determined by the requirement that the KX1 flight tube should not be opened or changed for their installation or removal.
- Constraints with respect to the nearby equipments

2.2 FUNCTIONAL REQUIREMENTS

The main aim of the tandem collimators is to provide a proper collimation for the gamma-ray (BGO) detector of the tangential gamma-ray spectrometer, with a well-defined field of view at the plasma end of the diagnostics line-of-sight. The collimation system should at the same time improve the signal-to-background ratio at the detector end of the line-of-sight. The field-of-view (FoV) defined by the tandem collimators within the JET vacuum vessel is shown in Fig.3. It extends from the Octant 8 vacuum port (entrance) to the Octant 3 vacuum port (exit).

In order to fulfil these requirements the tandem collimators should:

- Provide an adequate neutron and gamma-ray shielding factor. A value of at least 102 is usually required for this factor
- Reduce as much as possible any parasitic gamma-ray sources which may fall within the spectrometer field-of-view.

2.3 OPERATING REQUIREMENTS

The tandem collimators will operate under the conditions provided by the JET Torus Hall environment. One particular requirement for the tandem collimators use is that the KX1 flight tube (Figure 2) should not be opened or changed for their installation or removal.

The main components of the new TGRS diagnostics configuration, as presented schematically in Fig. 1 - bottom, have been developed to provide the functions defined in what follows and are ordered from the tokamak machine outwards:

The front collimator defines the spectrometer field of view at the plasma side of the line-of-sight. Its dimensions (outer diameter and length) have been determined taking into account the available space in front of the JET Octant 8 vacuum port. The front collimator acts as a shield for both the neutron and gamma radiation. It uses polyethylene plates for the neutron collimation and lead plates for the gamma-ray collimation, Fig.4(left).

The rear collimator defines (by its external diameter) the radial extension of the shielded field seen by the bismuth germanate (BGO) gamma-ray detector. The thickness of the rear collimator is determined by the necessary amount of material needed to shield the BGO detector from parasitic neutron (Emax ~14.1 MeV) and gamma radiation (Emax ~5 MeV). The rear collimator is made up of polyethylene plates for the neutron collimation and lead plates for the gamma-ray collimation, Fig. 4.

3. EVALUATION OF RADIATION (NEUTRON AND PHOTON) PERFORMANCE OF THE TANDEM COLLIMATORS

The radiation performance of the tandem collimators was evaluated by means of Monte Carlo numerical simulations using the MCNP-5 code. A simplified geometry with point (neutron and photon) sources, irradiating the collimators within a defined solid angle and detectors placed behind the collimators, was used. In this geometry the numerical simulations provided the following physical quantities at the detector positions:

- integrated neutron and photon fluxes
- neutron and photon spectra

The shielding characteristics of the tandem collimators are defined in terms of a shielding factor, which is the ratio of the radiation fluxes in two detectors: one placed on the axis of the system and another placed behind the collimators, at a mid-radius position.

3.1 MCNP CONFIGURATION

The configuration used for the Monte Carlo simulations has the following components (Fig.5):

A point neutron source placed at the intersection of the collimator axis with the (vertical projection of) magnetic axis. This is at a distance of 4.5 m from the front face of the front collimator.

A point photon (gamma-ray) source placed at the intersection of the collimator axis with a plane perpendicular to the surface of the inner wall guard limiter in Octant 2. This is at a distance of 6.8 m from the front face of the front collimator.

The front collimator made up of 12 alternating polyethylene (thickness 40 mm) and lead (thickness 10mm) plates. A polyethylene plate is placed at the front face of the front collimator.

Two detectors behind the front collimator, with their centre in a plane at a distance of 50mm behind the rear face of the collimator. One detector (D11) is placed on the collimator axis, and the other (D12) is placed at the mid-radius of the collimator (216mm from the axis).

The rear collimator made up of 12 alternating polyethylene (thickness 40mm) and lead (thickness 10mm) plates. The rear collimator has an additional 10 mm lead plate at the rear face. A polyethylene plate is placed at the front face of the rear collimator.

Two detectors behind the rear collimator, with their centre in a plane at a distance of 50 mm behind the rear face of the collimator. One detector (D21) is placed on the collimator axis, and the other (D22) is placed at the mid-radius of the rear collimator (403.5mm from the axis).

In order to reduce the computation time (a typical run takes about 48 hours) the propagation space was limited to a reduced solid angle. Its value is 5 times the angle subtended by the front face of the front collimator. A number of $2x10^9$ particles were propagated.

3.2 SIMULATION RESULTS AND ANALYSIS

The energy distribution of the neutrons reaching the detectors was calculated in 8 energy bins. The energy distribution obtained in the D22 detector is shown in Figure 6. Neutron spectra at locations D21 and D22 are presented together with the spectra of photons induced by neutron capture.

The shielding characteristics of the tandem collimators are defined in terms of a shielding factor, which is the ratio of the radiation fluxes in the two detectors placed behind the collimators. Table 1 presents the shielding factor D1/D2 for MCNP runs as follows:

The analysis demonstrates that the tandem collimators produce very good values for the shielding factor, both for neutrons and for the parasitic gamma-ray sources.

The influence of changing the material of last two layers of the rear collimator was also assessed. Polyethylene was replaced by borated polyethylene in order to reduce the flux of photons generated by neutron capture. Neutrons and photons spectra are presented in Fig.6 and the shielding factors are listed in Table 2.

The 9MeV gamma-ray line corresponds to the most intense nickel neutron capture gamma-ray line expected to be emitted by the INCONEL support of the inner wall guard limiter. For its propagation the energy distribution of the photons reaching the detectors is calculated in 10 energy bins. The photon energy distribution is shown in Fig. 7 and the shielding factors are presented in Table 3. It can be seen from this figure that the transmission of the 9 MeV photons through the tandem collimator structure has been reduced by at least two orders of magnitude.

CONCLUSIONS

A set of two collimators designed to work as tandem was - designed for the JET TGRS. It provides for the TGRS detector a well defined field of view at the plasma end of the line-of-sight thus allowing a better scientific exploitation of the diagnostics compared to the previous configuration.

The final collimator configuration developed for deuterium discharges provides shielding factors of about 250 for 2.45MeV neutrons, 100 for neutron-capture photons induced within the collimation structure and about 450 for a parasitic gamma-ray line of 9 MeV. When two polyethylene collimation plates are replaced by two boronated polyethylene plates a substantial increase (×2.5) is obtained in the n-capture photon shielding factor. It is thus highly recommended to include such boronated plates in the structure of the rear collimator in spite of the increase in cost.

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D1/D2	Front collimator	Rear collimator
n	19 ± 1	246 ± 5
(n, γ)	5 ± 1	96 ± 14

Table 1: The neutron shielding factor

D1/D2	Rear collimator
n	305 ± 22
(n, γ)	243 ± 68

Table 2: The neutron shielding factor after changing the material of last two layers of the rear collimator

D1/D2	Front collimator	Rear collimator
γ	45 ± 1	464 ± 50

Table 3:The shielding factor for 9 MeV γ -ray line.

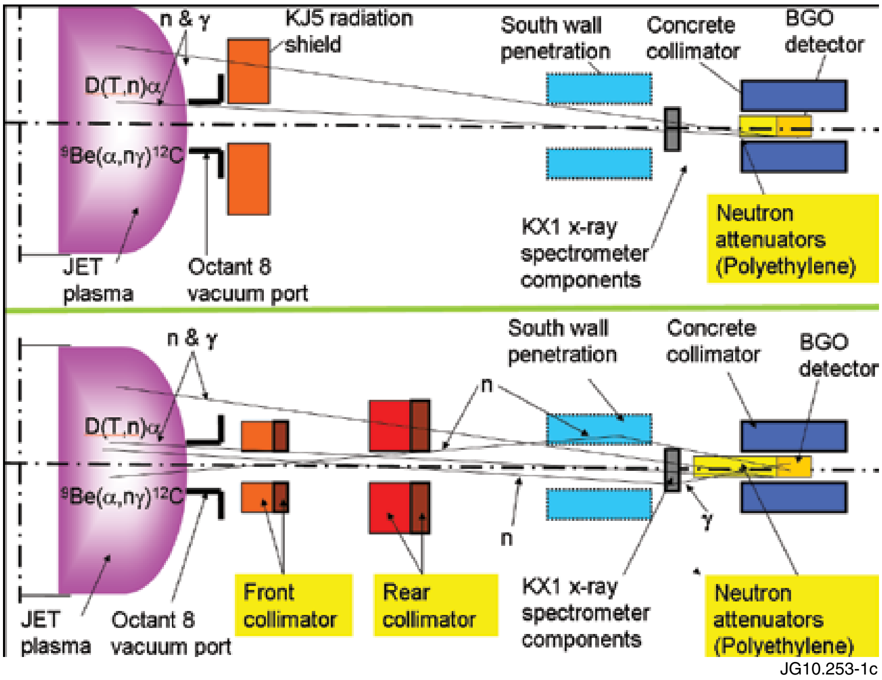

Figure 1: Tangential gamma-ray spectrometer. Schematic representation of the full system: old configuration (top) and upgraded configuration (bottom).

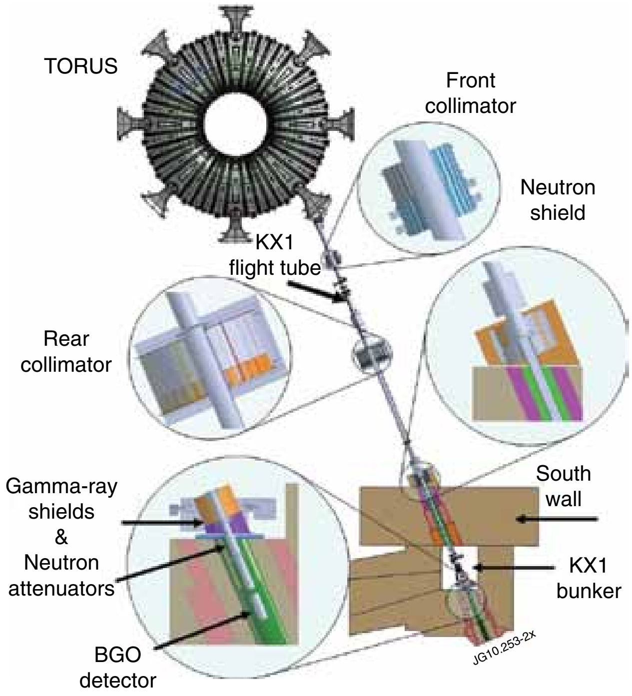

Figure 2: CAD (CATIA) model for the TGRS system. Mid-plane cross section

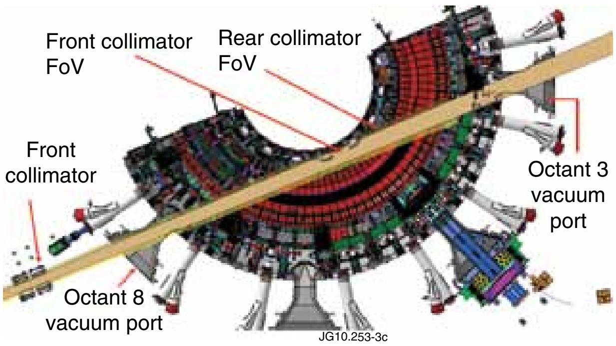

Figure 3: JET Tokamak mid-plane section showing the collimators fields of view.

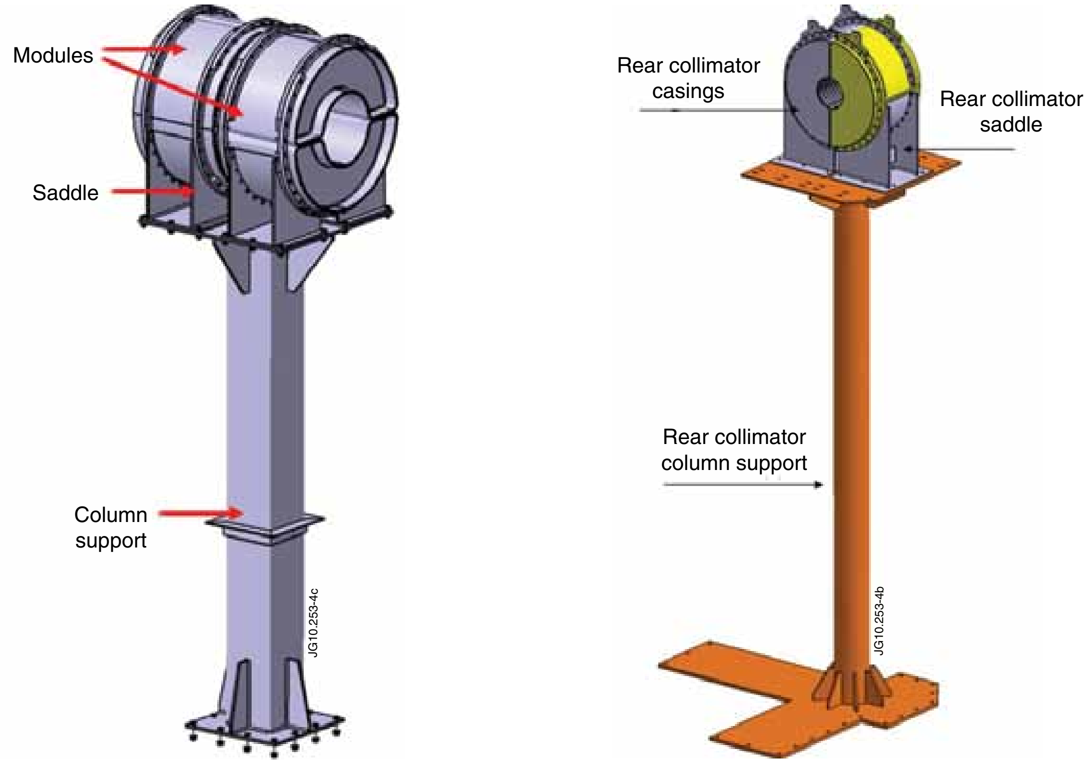

Figure 4: Front (left) & Rear Collimator (right) - main components

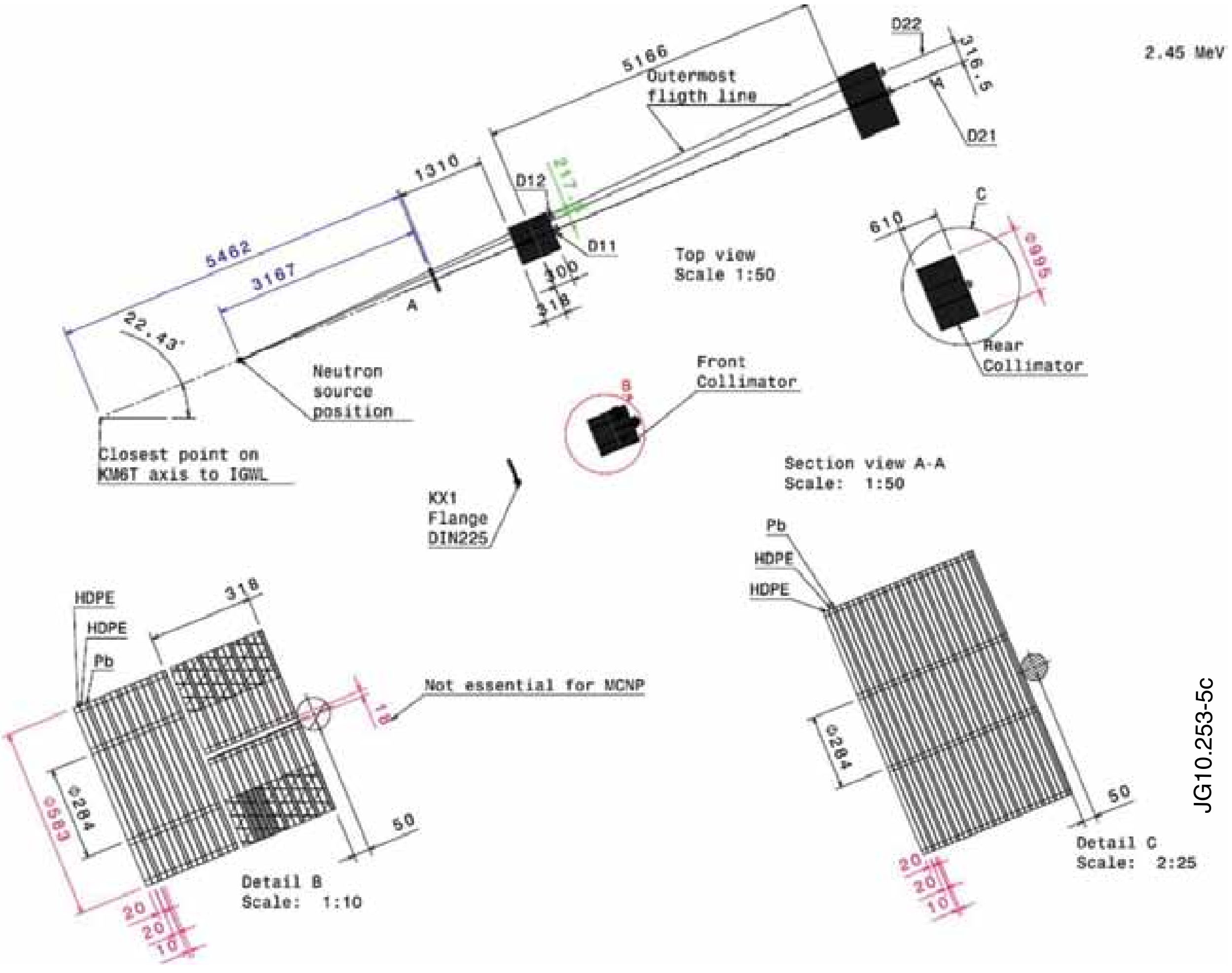

Figure 5: Configuration used for the Monte Carlo simulations

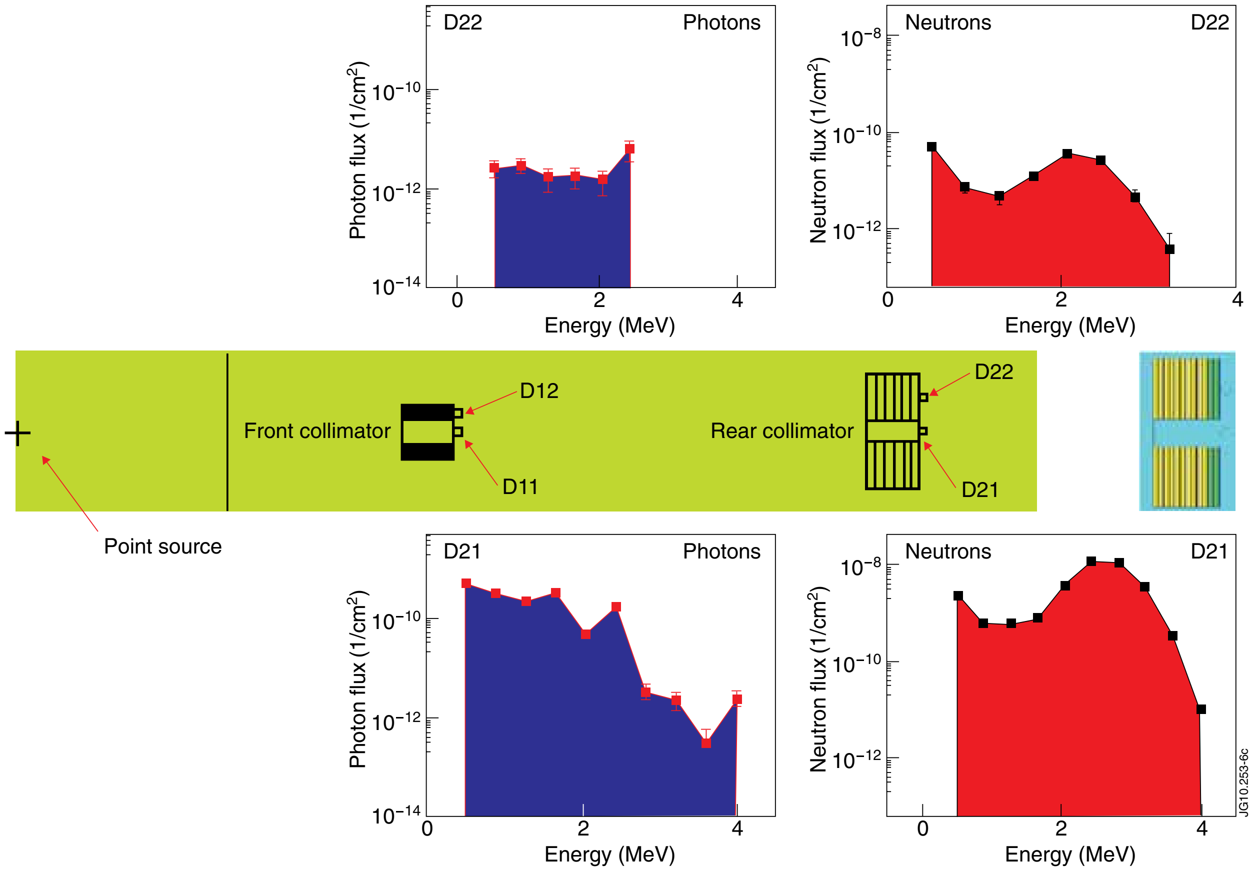

Figure 6: Simulation results - neutron and photon induced energy distributions

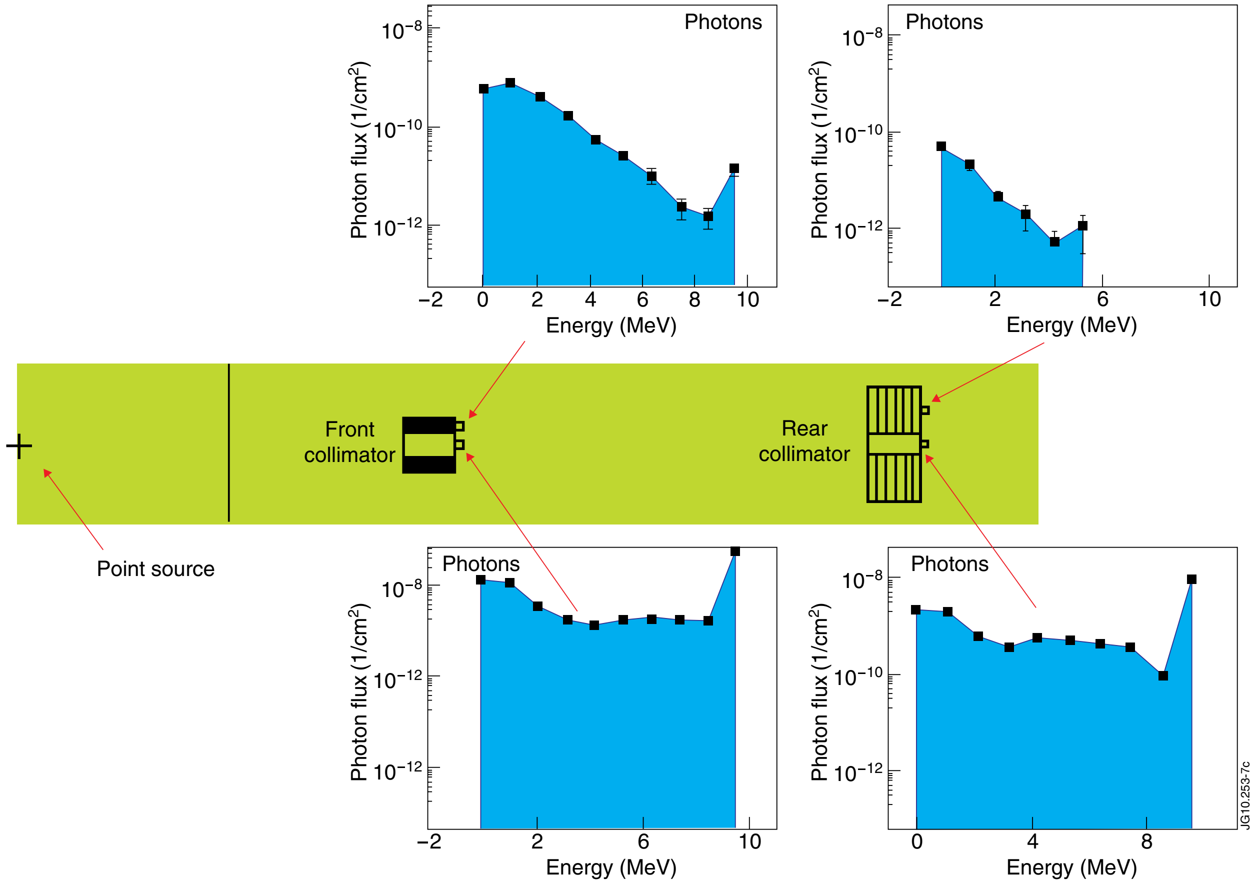

Figure 7: Simulation results - neutron and photon induced energy distributions.