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Design Solutions for the Upgrade of the JET Tangential Gamma-Ray Spectrometer

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ABSTRACT.

The JET Tangential Gamma-Ray Spectrometer (TGRS) is an essential diagnostics for fast particle studies. Following a series of changes in the configuration of this diagnostics and in order to provide conditions for future high fusion power studies a conceptual design for the upgrade of the JET TGRS has been carried out. The main design target is 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. A complex system of collimators and shields for both the neutron and gamma radiations define the spectrometer field of view. Two tandem collimators determine the field of view through the tokamak plasma. The entrance aperture to the penetration in the JET Torus Hall south wall is defined by a neutron shield. Two gamma-ray shields together with the existing concrete collimator determine the field of view at the Bismuth Germanate (BGO) gamma-ray detector. One of the gamma-ray shields (with an embedded neutron attenuator) can be remotely moved in and out of the detector line of sight thus providing flexibility in definition of the neutron and gamma-ray fields at the BGO detector. Neutron attenuators using lithium hydride (LiH) with natural isotopic composition (that meets the requirements for gamma-ray transparency) could provide the necessary attenuation factors (approximately 10^4 for the 2.45MeV neutrons and 10^2 for the 14.1MeV neutrons). A hot pressing technology has been proposed for the construction of the lithium hydride attenuators. The performance of a simplified geometry TGRS has been evaluated by preliminary neutron and photon transport calculations and the results show that the design parameters could 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, neutral beam injector 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], [3]. The applicability of gammaray diagnostics to high performance deuterium and deuteriumtritium 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). Design solutions aimed at fulfilling such requirements have been developed for two major components of the JET gamma-ray diagnostics: the 2D gamma-ray camera [4] and the gamma-ray spectrometer with a quasi-tangential line of sight.

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 [2]. 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, inside a long (2650mm) cylindrical (300mm diameter) boronated concrete collimator, behind the high resolution x-ray crystal spectrometer (the KX1 x-ray spectrometer). Two polyethylene neutron attenuators with a diameter of 150mm and a length of 250mm are inserted in the concrete collimator in front of the BGO detector. An additional 500mm long dump of polyethylene is placed behind the BGO scintillation detector. This is followed towards the end of the concrete collimator by a 1000mm long steel dump, the collimator being closed at its external end by a 500mm diameter and 1000mm length concrete plug. Additional polyethylene attenuators (equivalent thickness of about 300mm) are situated outside, in front of the concrete collimator. It is considered 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 a X-ray camera (the KJ5 radiation shield, Figure 1.a) has served as a precollimator before the JET 2004 shutdown. The analysis done within the TGRS upgrade conceptual design 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 (huge cut 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.

2. CONCEPTUAL DESIGN OF THE UPGRADED JET TANGENTIAL GAMMA-RAY SPECTROMETER. OVERALL SYSTEM

The field-of-view of the upgraded JET Tangential Gamma-Ray Spectrometer (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 Figure 1(b). It contains the following main components: front collimator, rear collimator, neutron shield, gamma-ray shield and neutron attenuators.

A CAD (CATIA [5]) model of the full TGRS system is presented in Figure 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.

A. TGRS UPGRADE MAIN COMPONENTS.

The main components of the new TGRS diagnostics configuration, as presented schematically in Figure 1(b), have been developed to provide the functions defined in what follows.

Front collimator.

The front collimator defines the spectrometer field of view at the plasma side of the line-ofsight.

Its dimensions (outer diameter and length) have been determined in terms of 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.

Rear collimator.

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 (E_{max} ~14.1MeV) and gamma radiation (E_{max} ~5MeV). The rear collimator is made up of polyethylene plates for the neutron collimation and lead plates for the gamma-ray collimation. The two collimators are designed to work in a tandem configuration.

Neutron shield.

A neutron shield to be installed on the south wall of the JET Torus Hall has the function of defining an aperture at the entrance of the wall penetration. In this way the neutron interaction with the penetration material is avoided and the structure and composition of the filling material (silica grout) in the wall penetration is no longer involved in the neutron-photon transport calculations. The dimensions of the neutron shield have been chosen as follows:

- Inner diameter: determined by the minimum value allowed by the wall penetration pipe (extension of the KX1 flight tube, see Figure 2);
- Length: determined by the requirement of providing an attenuation factor of ~10^2 for the 14.1MeV neutrons;
- Outer diameter: determined by the radial extension of the neutron field seen by the BGO detector beyond the rear collimator. The neutron shield is to be constructed from polyethylene plates.

Gamma-ray shield.

The gamma-ray shield has the purpose of reducing to a minimum the flux of the parasitic gamma radiation reaching the BGO detector. This background radiation will be generated by the interaction of the fast neutron flux with the components inside the KX1 bunker (especially those of the KX1 x-ray spectrometer, Figure 1(b). The dimensions of the gamma-ray shield have been determined by the geometry of the field-of-view in front of the BGO concrete collimator as well as the dimensions of the external neutron attenuator which the shield is going to accommodate. The gamma-ray shield is designed to be constructed from cast lead.

Neutron attenuators.

The neutron attenuators have the aim of reducing the neutron flux at the gamma-ray detector position. Three attenuators are to be used for this purpose: two fixed and one movable. Lithium hydride with natural isotopic composition is to be used as the attenuating material. The dimensions of the attenuators have been determined by the diameter of the BGO detector and by the necessary total thickness of material (LiH) to obtain the following attenuation factors: 10^4 for 2.45 MeV neutrons, and 10^2 for 14.1 MeV neutrons.

B. TGRS DESIGN PROCEDURE.

The development of the conceptual design solutions for the TGRS upgrade has been done through the following iterating procedure:

- Estimation of necessary materials and thicknesses to provide the required attenuation factors for neutrons and gamma-rays;
- Evaluation of available space and determination of the positions of the collimators and shields;
- Estimation of outer diameter and thickness for the collimators and shields;
- CAD (CATIA) model for the new TGRS configuration
- Simplified TGRS model for the neutron-photon transport (MCNP [6]) calculations
- Update of the CATIA model based on the results of the MCNP calculations

This iterating procedure provided the final conceptual design solutions for the new TGRS configuration. Further improvement of the design is to be done only after a detailed evaluation of the neutronics performance of the proposed configuration is completed. This can be done during the following design phase (scheme design) using both the updated CATIA model and more detailed MCNP calculations.

3. CONCEPTUAL DESIGN SOLUTIONS DEVELOPED FOR THE MAIN COMPONENTS OF THE TGRS DIAGNOSTICS UPGRADE

A number of conceptual design solutions have been developed for each of the main components of the TGRS diagnostics upgrade. The solutions have been evaluated at various stages of the concept development and a set of recommended designs have been selected to be further developed at the level of scheme design. The objects to be described are ordered from the tokamak machine outwards: front collimator, rear collimator, neutron shield, gamma-ray shield and neutron attenuators. Regarding the materials selected for the casings and supports for the above components, the selection was done based on properties, behavior during manufacture and service life. These materials are: INCONEL 600, SS316L and aluminum alloy.

A. CONCEPTUAL DESIGN FOR THE FRONT COLLIMATOR

The final design solution for the front collimator is that of the so-called “revolving modules”. The main components of the revolving front collimator (Figure 3) are: front module (first module), rear module (second module), positioning (rotating or revolving) support, active collimating materials.

B. CONCEPTUAL DESIGN FOR THE REAR COLLIMATOR

The main components of the rear collimator are shown in Figure 4: rear collimator assembly (cylindrical shape), support assembly (semi-cylindrical halves) and pole support. The rear collimator assembly is divided into halves to permit installation, its axis coinciding with that of KX1 flight tube.

C. CONCEPTUAL DESIGN FOR THE NEUTRON SHIELD

The main components of the neutron shield are shown in Figure 5: casing (two halves), support (two halves) and a support platform. The casing comprises two identical semicylindrical parts joint together around the KX1 flight tube, each part being filled with semi-circular polyethylene slabs.

D. CONCEPTUAL DESIGN FOR THE GAMMA-RAY SHIELD

The two gamma-ray shields (one fixed and the other one movable, Figure 6), are located inside the KX1 bunker, close to the entrance of concrete collimator containing the BGO gamma-ray detector. The shield is composed of two cylindrical parts one of them cut an angle of 22.5 degrees to be fixed on the wall, and it has a central hole to accommodate the protruding part of the first section of the neutron attenuator assembly. The other shield part is placed on mobile support that executes a vertical translation (between the parking and working locations) of minimum 400mm driven by an electrical motor. The axis of the shield coincides with that of KX1 flight tube. The shielding material is lead, cast into cylindrical forms

E. CONCEPTUAL DESIGN FOR THE NEUTRON ATTENUATORS

The TGRS neutron attenuators will be constructed by encapsulation of LiH discs inside a metal casing (Figure 7). A hot pressing technology was proposed for the production of the LiH discs. The all-metal casings are designed as vacuum tight enclosures using Ultra-High Vacuum (UHV) technology.

4. RADIATION (NEUTRON & PHOTON) ANALYSIS OF THE UPGRADED TANGENTIAL GAMMA-RAY SPECTROMETER

The TGRS neutron and photon transport calculation model used the MCNP [6] code and was constructed starting from its 3D CAD (CATIA) drawings as illustrated in Figure 8. A much simplified TGRS configuration which does not contain some important elements of the full system (e.g., it does not contain the neutron and gamma-ray shields) was used to produce the MCNP model.

As an example of the numerical results, the efficiency of the TGRS collimator configuration was evaluated by calculating the particle flux at a specified line-of-sight location (cell 33 in Figure 8) with and without the collimators (i.e., collimators replaced by air). The results are presented in Figure 9, and show that the front collimator does not modify significantly the shape of the neutron spectrum while producing an attenuation factor of approximately 7.

A first estimate for the overall performance of the full system for the simplified TGRS model has shown that the neutron attenuation factor is $\sim 1.5 \times 10^4$ with a 0.1MeV cut-off in the MCNP calculation, and $\sim 3.7 \times 10^4$, without cut-off. The attenuation factor for the plasma-emitted gamma-rays is ~20.

CONCLUSIONS

A major upgrade has been proposed for the JET Tangential Gamma-Ray Spectrometer (TGRS) with the aim of providing adequate conditions for gamma-ray measurements in future experimental campaigns involving high power DD and DT discharges. A complex system consisting of radiation collimators, shields and attenuators has been developed up to the conceptual design level.

On a shorter term the upgraded configuration should provide the necessary conditions to regain the capability of this essential diagnostics for fast particle physics studies of JET plasmas.

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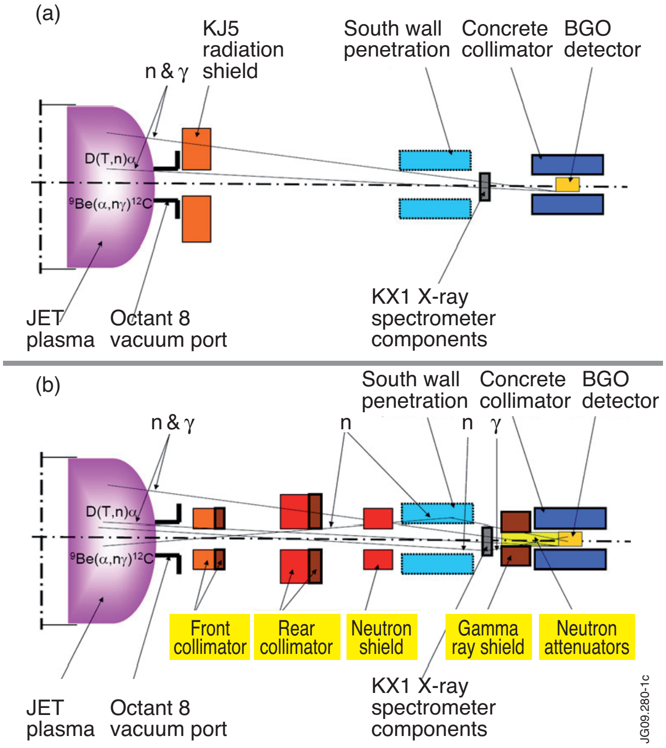

Figure 1: Tangential gamma-ray spectrometer Schematic representation of the full system. 1(a): old configuration; 1(b): upgraded configuration

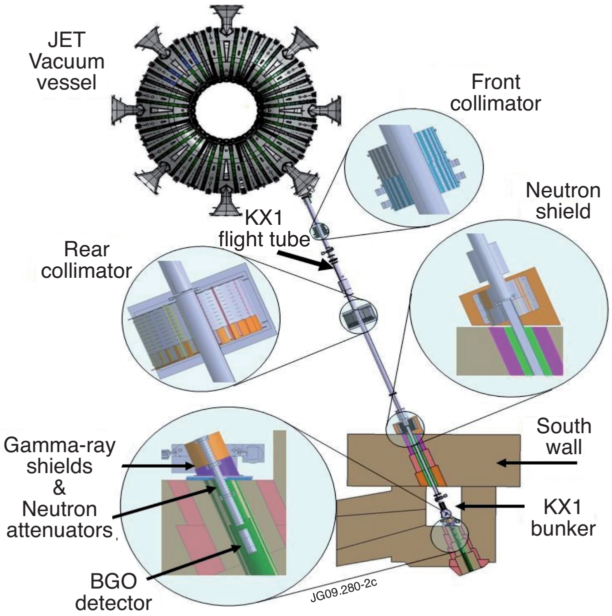

*Figure 2: CAD (CATIA) model for the TGRS system. Mid-plane crosss*section

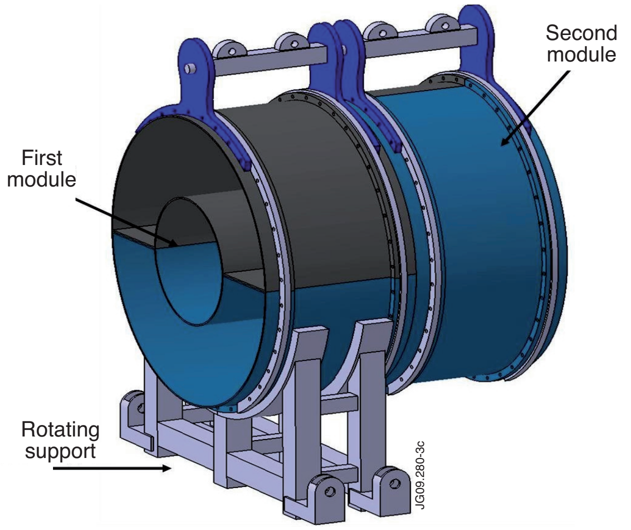

Figure 3: Complete front collimator (collimating materials removed for clarity)

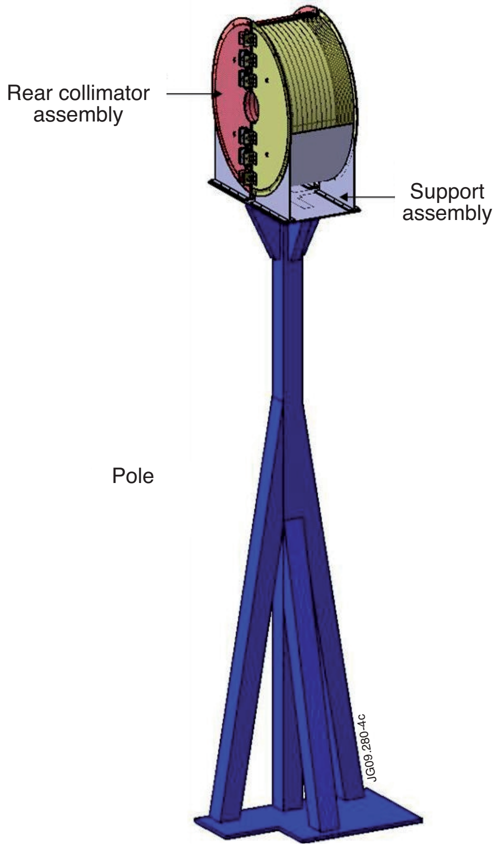

Figure 4: Rear collimator - overall view

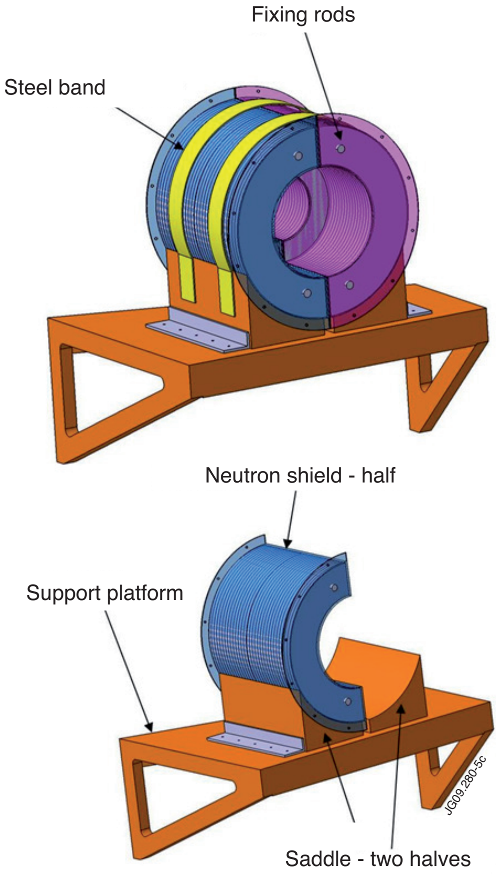

Figure 5: Main components of the neutron shield

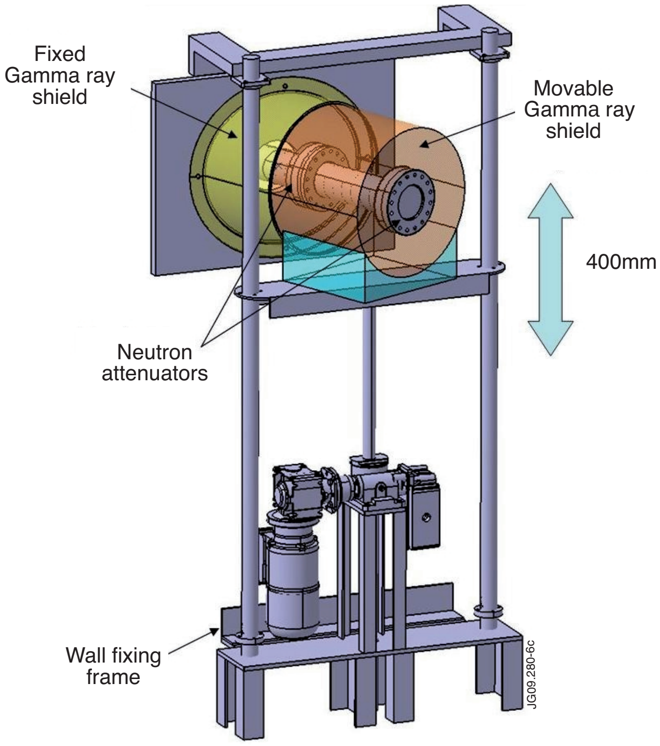

Figure 6: Overall view of the gamma-ray shield assembly. Vertical translation between working (up) and parking position (down) is shown.

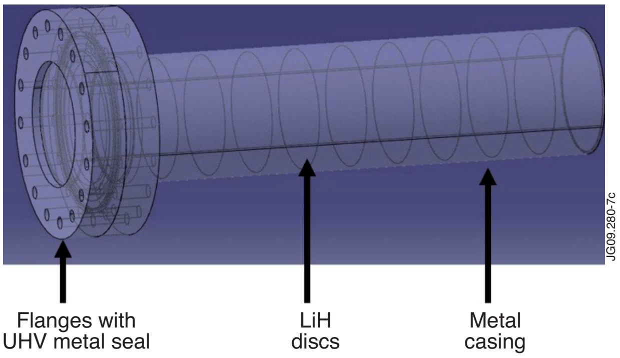

Figure 7 Neutron attenuator casing (all-metal sealing).

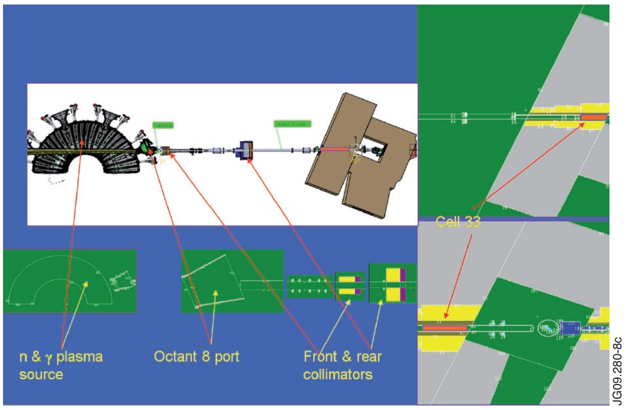

Figure 8: The MCNP model for the TGRS based on the CATIA model; Upper left: CATIA model; Lower left: MCNP configuration; Right: details for cell 33 (wall penetration).

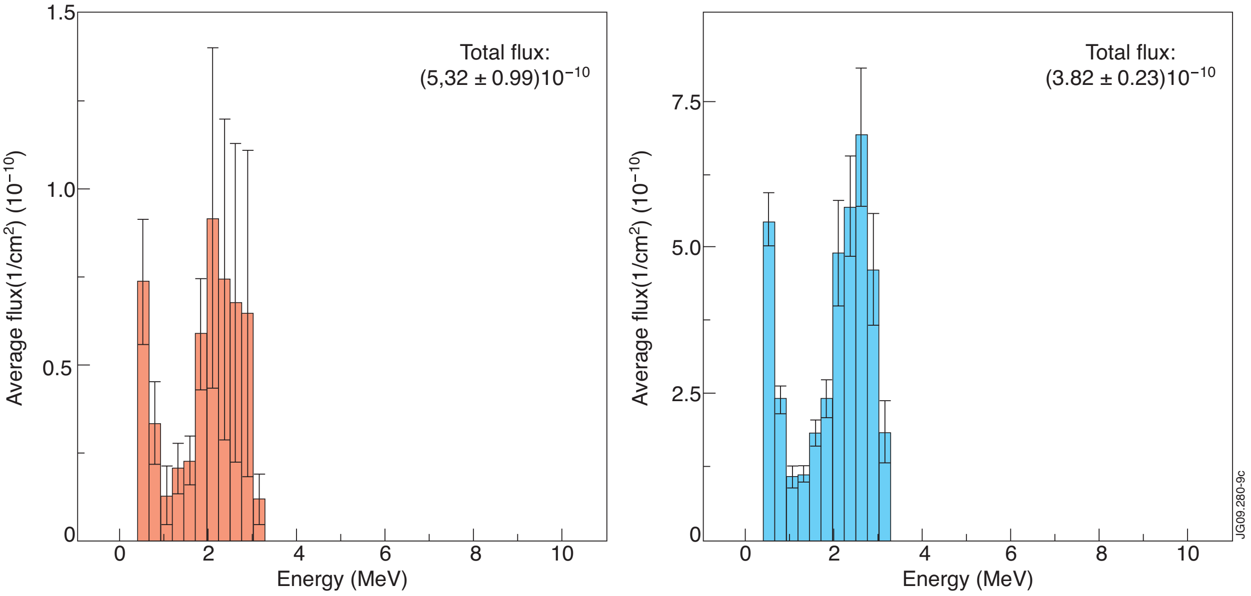

Figure 9: Average neutron flux in cell 33 (see Figure 8) with (left) and without collimators (right)