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M. Francucci, M. Ferri De Collibus, F. Angelini, F. Belli, S. Cesaroni

Abstract
ITER's (International Thermonuclear Experimental Reactor) Radial Neutron Camera (RNC), together with the Vertical Neutron Camera, aims to provide, through reconstruction techniques applied to integrated neutron fluxes, the time-resolved measurement of neutron flux profile generated during the fusion plasma production process. Specifically, neutron emissivity should be measured by the RNC, i.e. the neutrons emitted per unit time and volume. The RNC consists of two subsystems, the RNC In-Port and the RNC Ex-Port, located inside and outside the Equatorial Gate Plug #01, respectively. This report presents and discusses the studies performed and results obtained for the design of the ITER RNC focusing on an optical system for the calibration of photomultiplier neutron detectors. The latter will be installed in the Ex-Port part for time-resolved measurement of neutron flux. These activities were carried out within the framework of a collaboration agreement between the ENEA NUC-TECFIS-DIM and NUC-FUSEN-DIA laboratories on the topic: "Sviluppo di una diagnostica ottica per ITER Radial Neutron Camera" ("Development of an optical diagnostics for ITER Radial Neutron Camera") which is part of the F4E (Fusion for Energy) activities assigned to ENEA (grant SG07).

Keywords: *Radial Neutron Camera, ITER, neutron flux, laser, optical fiber, splitter, PMT.*

Riassunto
La Radial Neutron Camera (RNC) di ITER (International Thermonuclear Experimental Reactor), insieme alla Vertical Neutron Camera, ha come obiettivo quello di fornire, attraverso tecniche di ricostruzione applicate ai flussi di neutroni integrati, la misura risolta nel tempo del profilo del flusso neutronico generato durante il processo di produzione del plasma fusionistico. Più esattamente, con l'RNC si vuole valutare l'emissività neutronica, ovvero i neutroni emessi per unità di tempo e di volume. L'RNC è composto da due sottosistemi: l'RNC In-Port e l'RNC Ex-Port situati, rispettivamente, all'interno e all'esterno del Plug della Porta Equatoriale #01. In questo rapporto si presentano e discutono gli studi effettuati e i risultati ottenuti per la progettazione della ITER RNC focalizzandosi su un sistema ottico per la calibrazione di rivelatori neutronici a fotomoltiplicatore. Questi saranno infatti installati nella parte Ex-Port per la misura risolta nel tempo del flusso neutronico. Tali attività sono state effettuate nell'ambito di un accordo di collaborazione tra i laboratori ENEA NUC-TECFIS-DIM e NUC-FUSEN-DIA sul tema: "Sviluppo di una diagnostica ottica per ITER Radial Neutron Camera" che rientra nell'ambito delle attività di F4E (Fusione for Energy) assegnate ad ENEA (grant SG07).

SUMMARY

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La Radial Neutron Camera (RNC) di ITER (International Thermonuclear Experimental Reactor), insieme alla Vertical Neutron Camera, ha come obiettivo quello di fornire, attraverso tecniche di ricostruzione applicate ai flussi di neutroni integrati, la misura risolta nel tempo del profilo del flusso neutronico generato durante il processo di produzione del plasma fusionistico. Più esattamente, con l'RNC si vuole valutare l'emissività neutronica, ovvero i neutroni emessi per unità di tempo e di volume. L'RNC è composto da due sottosistemi: l'RNC In-Port e l'RNC Ex-Port situati, rispettivamente, all'interno e all'esterno del Plug della Porta Equatoriale #01. In questo rapporto si presentano e discutono gli studi effettuati e i risultati ottenuti per la progettazione della ITER RNC focalizzandosi su un sistema ottico per la calibrazione di rivelatori neutronici a fotomoltiplicatore. Questi saranno infatti installati nella parte Ex-Port per la misura risolta nel tempo del flusso neutronico. Tali attività sono state effettuate nell'ambito di un accordo di collaborazione tra i laboratori ENEA NUC-TECFIS-DIM e NUC-FUSEN-DIA sul tema: "Sviluppo di una diagnostica ottica per ITER Radial Neutron Camera" che rientra nell'ambito delle attività di F4E (Fusione for Energy) assegnate ad ENEA (grant SG07).

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ITER's (International Thermonuclear Experimental Reactor) Radial Neutron Camera (RNC), together with the Vertical Neutron Camera, aims to provide, through reconstruction techniques applied to integrated neutron fluxes, the time-resolved measurement of neutron flux profile generated during the fusion plasma production process. Specifically, neutron emissivity should be measured by the RNC, i.e. the neutrons emitted per unit time and volume. The RNC consists of two subsystems, the RNC In-Port and the RNC Ex-Port, located inside and outside the Equatorial Gate Plug #01, respectively. This report presents and discusses the studies performed and results obtained for the design of the ITER RNC focusing on an optical system for the calibration of photomultiplier neutron detectors. The latter will be installed in the Ex-Port part for time-resolved measurement of neutron flux. These activities were carried out within the framework of a collaboration agreement between the ENEA NUC-TECFIS-DIM and NUC-FUSEN-DIA laboratories on the topic: "Sviluppo di una diagnostica ottica per ITER Radial Neutron Camera" ("Development of an optical diagnostics for ITER Radial Neutron Camera") which is part of the F4E (Fusion for Energy) activities assigned to ENEA (grant SG07).

Keywords: Radial Neutron Camera, ITER, neutron flux, laser, optical fiber, splitter, PMT.

1. INTRODUCTION

Within the framework of the F4E (Fusion for Energy) activities assigned to ENEA (grant SG07), a collaboration agreement was started between the NUC-TECFIS-DIM and NUC-FUSEN-DIA laboratories on the topic: "Sviluppo di una diagnostica ottica per ITER Radial Neutron Camera" ("Development of an optical diagnostics for ITER Radial Neutron Camera") under which several activities were carried out aimed at the design of the ITER Radial Neutron Camera (RNC) [1], [2], [3], [4], [5], [6]), including one relative to the development of an optical diagnostic system for the calibration of photomultiplier neutron detectors that will be installed in the Ex-Port part of the RNC.

The two ENEA laboratories have already successfully co-operated regarding the IVVS (In Vessel Viewing and ranging System) projects for JET (Joint European Torus) and ITER.

Specifically, under these projects, an Amplitude Modulation (AM) incoherent laser scanner system was developed for 3D imaging able to provide simultaneously viewing and ranging images with very high accuracy and resolution (of the order of 1 mm at a distance of 10 m) of even large-scale real scenes.

This system, called IVVS, was developed for viewing in hostile environments, particularly inside fusion machines, such as JET and ITER, or even in fission reactors. The IVVS has demonstrated the feasibility of using laser radar sensors for viewing and ranging inside the vessel of nuclear reactors to detect any damage or erosion on the vessel walls due to plasma produced during the fusion process [7, 8, 9, 10, 11, 12], and visualized by high-resolution 3D images.

The ITER's RNC, together with the Vertical Neutron Camera (VNC) [13], aims to provide, through reconstruction techniques applied to integrated neutron fluxes, the time-resolved measurement of the neutron flux profile generated during the phase of fusion plasma production and, more precisely, the neutron emissivity, i.e., neutrons emitted per time and volume unit.

The RNC consists of two subsystems, the RNC In-Port and the RNC Ex-Port, located inside and outside of the Plug of the Equatorial Port #01, respectively. The In-Port subsystem, which recently underwent a Final Design Review, is at a more advanced design stage than the Ex-Port subsystem. In the latter, scintillator detectors (plastic and He_4 gas) coupled with PhotoMultiplier Tubes (PMTs) are to be installed, for whose gain correction the calibration system presented in this report is required.

The objective of this report is to present the specifications of the radiation-resistant (hard-rad) optical fibers, those of the light source, and the laboratory tests required to achieve the correct gain correction of the PMTs coupled with scintillator detectors located in the 16 lines-of-sight (LOS) of the RNC Ex-Port, which form the calibration system of the neutron detectors. Since there are two detectors for each LOS, a total of 32 optical fibers interposed between the light source and the detectors will be required for optical signal transmission.

Being light sources are generally non-radiation-resistant components, they must be located in an area outside of the tokamak bio-shield, which, in this case, was identified in the Diagnostic Building of the ITER complex. The optical reference signal of the light source must be transmitted to the detectors along a fiber path through areas subject to radiation (up to 1 MGy integrated dose). Hence, there is a need to use hard-rad optical fibers in the visible light region where PMT detectors are sensitive.

2. ACTIVITIES FOR ITER RNC

To achieve the purposes set in the design of an optical system for calibration of photomultiplier neutron detectors in the Ex-Port part of the ITER RNC, the following activities were performed:

1) analysis of the problem and identification of possible solutions to be adopted based on the use of one or more light sources and hard-rad optical fibers with their related coupling systems;
2) identifying of the specifications of the light source (LED, laser) best suited for the design purpose;
3) proper simulations related to the optical path from the light source to the detector;
4) laboratory tests of specific components to be used for the Ex-Port optical diagnostics of the ITER RNC.

3. PROBLEM ANALYSIS

Regarding item 1) of section 2, a study of the attenuation of the optical calibration signal of the detection system, traveling by optical fiber with a length of about 290 m from the reference light source (LED or laser) to the detector, was specifically carried out. Several problems were encountered during this study, which are listed below:

a) light sources are generally non-radiation-resistant devices;
b) optical reference signal must be transmitted from light source to detectors in an environment subject to uneven radiation doses (up to a maximum of 1 MGy) through radiation-resistant (hard-rad) optical fibers with a length of hundreds of meters (precisely about 290 m);
c) hard-rad optical fibers introduce a non-negligible attenuation factor (Radiation Induced Attenuation, RIA), which depends on the absorbed dose, the wavelength of transmitted light, and the fiber length;
d) radiation emitted by the light source, transmitted by optical fibers to the detectors, will necessarily be in the visible range, being PMTs most sensitive in this spectral region, although hard-rad optical fibers are usually optimized for signal transmission in the near-IR or IR wavelength range (≥ 850 nm);
e) spectral response of PMT detectors for ITER RNC is peaked around 450 nm;
f) visible light has a remarkable attenuation factor when propagating in optical fiber compared with infrared radiation because of the effect of color centers.

Concerning item a), the found solution was initially to place the light source (LED or laser) inside the ITER Diagnostic Building, which is located outside the zone subject to irradiation although at a considerable distance (about 290 m) from the detection system consisting of 32 detectors.
Recently, as an alternative solution to the previous one, the feasibility of placing the light source in an area much closer to the detection system (about 7 m -8 m away in the PCSS area of ITER) is being evaluated, so reducing the attenuation of the light signal.
Regarding items c), d), e), and f), a good compromise was found between the wavelength of light source to be used, RIA, and the spectral response of the PMT detectors, which consists of using visible light around 520 nm (green). In this area of the visible, the RIA has relatively low values (Figure 1) and the spectral response of the identified PMT detectors, which are the Hamamatsu H6153-70 (R5946) or, alternatively, the Hamamatsu R10754-07-M16 detectors, is very good. More specifically, the PMT Hamamatsu H6153-70 (R5946) has a sensitivity of 0.05 A/W and a quantum efficiency of about 15% (Figure 5).

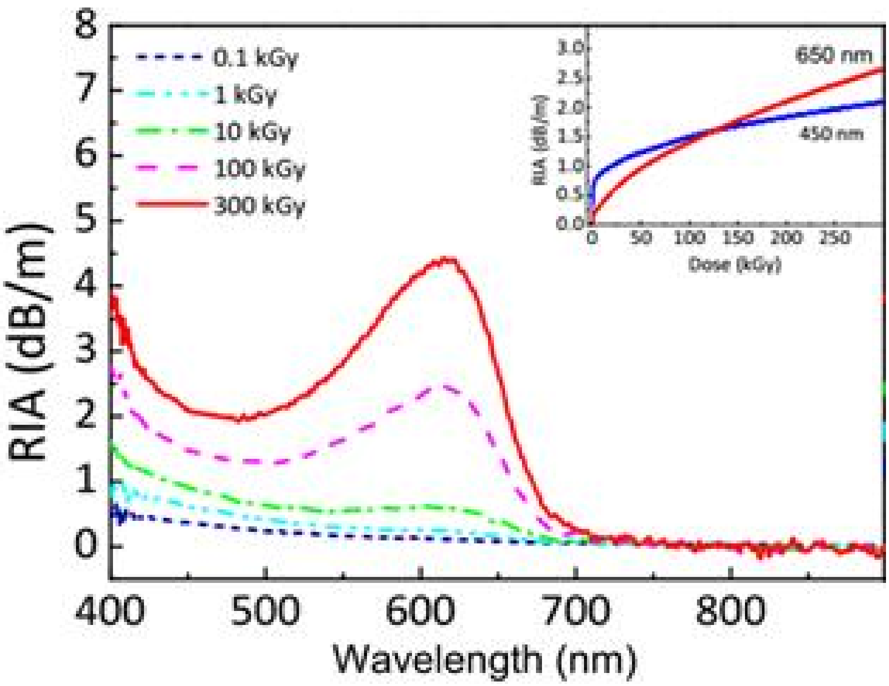


Figure 1. RIA trend as a function of wavelength for a high OH optical fiber irradiated with different radiation doses [14]. The inset shows the trend of RIA by varying the absorbed dose at 450 nm and 650 nm, where the RIA behavior is nearly linear.

Regarding items b) and e), various studies and market surveys were carried out on available hard-rad optical fiber systems that allow minimizing the attenuation of the optical signal in the visible spectral range. As a result of this investigation, the Polymicro's (now Molex) QP600 component was identified as the best hard-rad optical fiber for signal transmission, which, unfortunately, is currently discontinued.

However, the characteristics of the optical fibers transmitting signal from the light source to the detector, which will actually be used, should be similar to those of the QP600 optical fiber to ensure efficient signal transmission. These characteristics are summarized in the Table 1 [15].

Cumulated dose	***Up to 20 kGy***	***1 MGy***
RIA (dB/m) @ 520 nm	≤ 0.1	≤ 1

Table 1. RIA at 520 nm for the QP600 (Polymicro, now Molex) optical fiber irradiated at different values of cumulative doses.

The possibility of using integrated optical devices to control the optical power transmitted to the detectors was also evaluated, though these elements introduce an additional power loss factor into the optical path. This solution is described in detail in the section 7.

The scheme of the fiber path of the light signal emitted from the light source to reach the detection system is shown in Figure 2. The values of radiation doses to which the optical fiber is subjected in the various zones of the optical path are also highlighted. These values were derived from MCNP (Monte-Carlo N-Particle Radiation Transport Code) calculations based on the radiation maps of ITER [16].

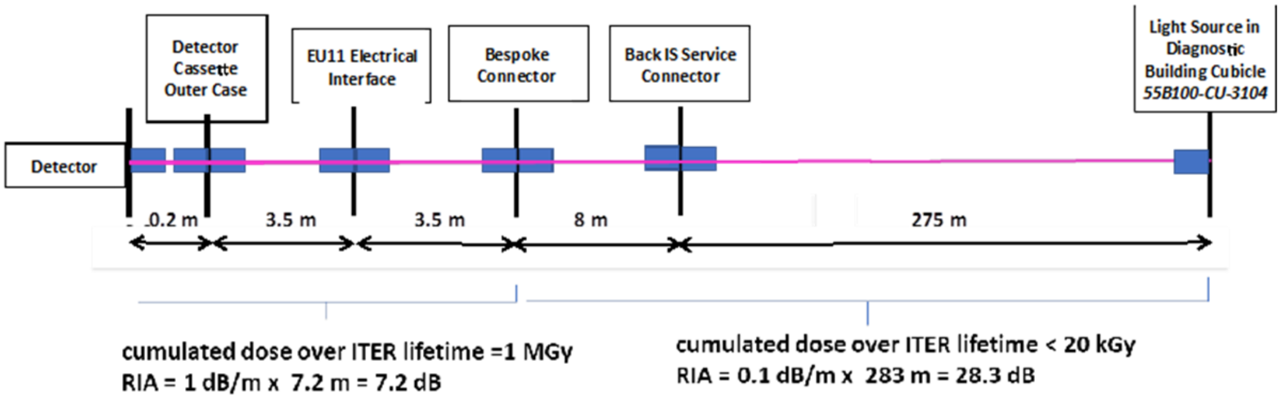


Figure 2. Scheme of the fiber optic path (Ex-Port part of ITER RNC) of the optical signal from the light source located in Diagnostic Building Cubicle 55B100-CU-3104 to the detector (PMT) placed in the Detector In Port Interspace with the corresponding radiation doses absorbed during the path.

4. RESULTS: LIGHT SOURCE

Concerning item 2) of section 2, the specifications that the light source must have to generate an efficient optical calibration signal of the detection system were defined.
By the JET experience in which a LED light source was used [17], for a valid reference signal of the detection system to be produced that is well distinguishable from the signal generated by the neutron and gamma flux, the light source must be present the following features:

I) light emission at the wavelength of 520 nm (green), which is not the ideal wavelength as a function of RIA and sensitivity of PMT detectors, but it is the best compromise between these latter and the emission wavelengths of commercially available sources with the below-listed characteristics (items from II to VIII);

II) optical fiber output (pigtailed);

III) pulsed operation mode;

IV) pulse width (duration) between 50 ns and 100 ns (adjustable, preferably 50 ns);

V) adjustable pulse shape (preferably rectangular/Gaussian);

VI) Pulse Repetition Rate (PRR) varying between 1 kHz and 2 kHz (adjustable, preferably 1 kHz);

VII) pulse power higher than 60 mW (adjustable);

VIII) stability of the pulse, both in amplitude (power) and in width (duration) < 7%.

Based on these specifications and the carried out simulations (section 5), the most suitable light source was identified by a laser, which, compared to an LED device, is characterized by more efficient optical fiber coupling and higher optical emission power, coupled with the efficient tuning of optoelectronic parameters such as pulse duration and shape, PRR, and optical emission power.
To this end, an accurate market survey was conducted through which the suitable laser source for the specific optical diagnostics of the ITER's Ex-Port RNC was defined. This source (Figure 3) is represented by the custom pigtailed laser diode system of the Aerodiode (model 520LD-2) with the the SHAPER driver operating at a wavelength of 520 nm. It is coupled with the Thorlabs 460HP single-mode output optical fiber (2 m length) with FC/PC connector, and it is characterized by the ability to generate Gaussian (or other desired shapes) pulses with FWHM (Full Width Half Maximum) around 50 ns (adjustable). It is also able to emit output power from the optical fiber up to 75 mW (adjustable) [18].

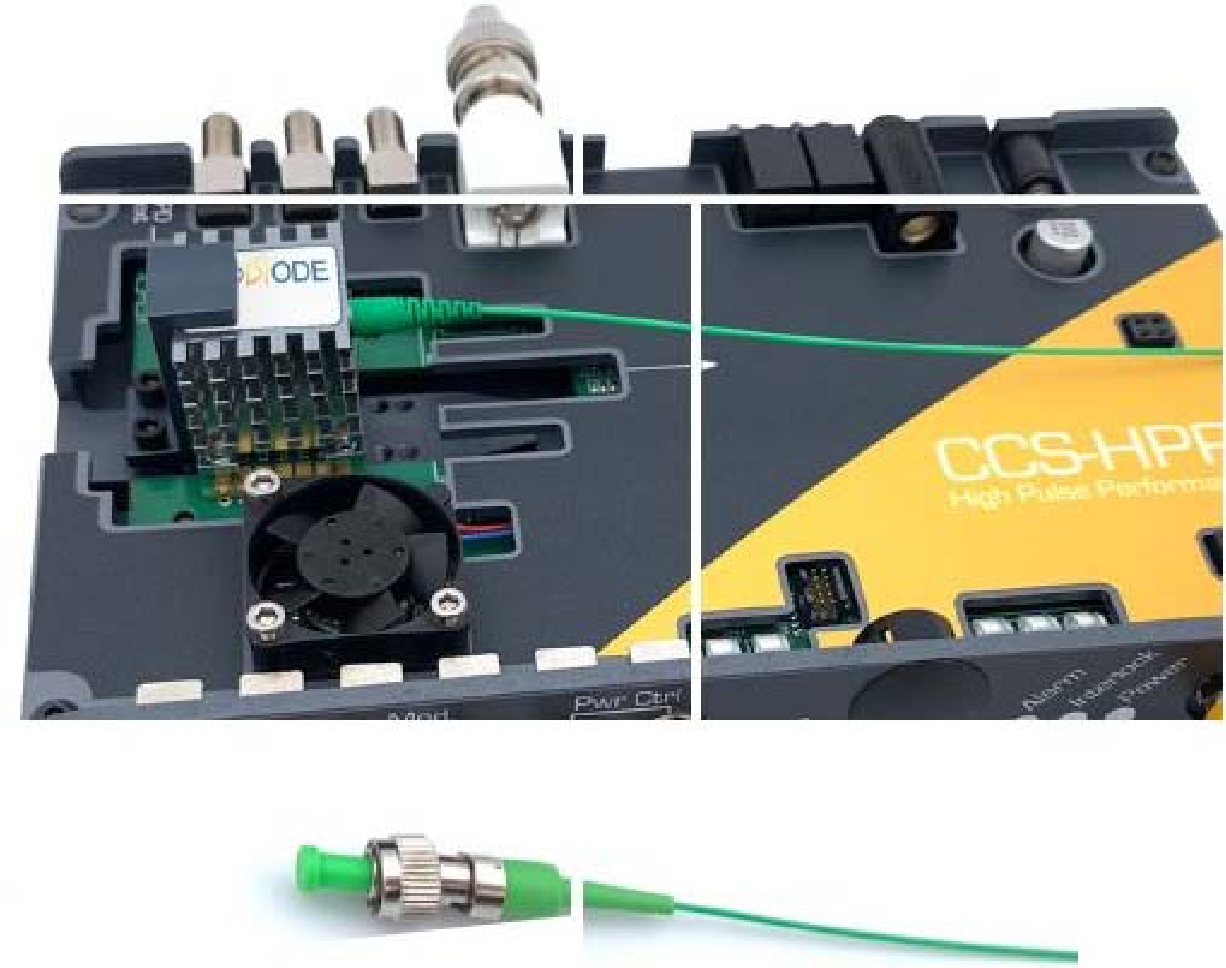


Figure 3. Custom Aerodiode model 520LD-2 pigtailed laser diode source with relative driver and single-mode output optical fiber for the calibration optical system of photomultiplier neutron detectors of the ITER RNC.

The commercial Aerodiode laser source (520 nm, 75 mW) is classified by the manufacturer as CLASS 4 according to EN 60825. Since in the optical scheme of the ITER RNC it is expected that the light emitted by the laser source will be divided over 32 channels (each of which corresponds to a detection channel with a fiber-optic path such as the one shown in Figure 2), the presence of a 1:32 splitter to be placed in the neighborhood of the laser source, operating in our case at 520 nm, is also necessary.

Although, despite a thorough market survey, a 1:32 splitter could not be found directly, an alternative (commercial and low-cost) solution was nevertheless found represented by the splitter TN532R5F1 532nm ± 15 nm 1x2 Narrowband Fiber Optic Coupler and the splitter TWQ560HF 560nm ± 50 nm 1x4 Wideband Fiber Optic Coupler, both supplied by the Thorlabs company.

The two splitters, despite being centered at 532 nm and 560 nm, respectively, are still characterized by a bandwidth (± 15 nm and ± 50 nm, respectively) sufficient to cover even the emission wavelength of the Aerodiode laser source.

The use of the multiple TN532R5F1 and TWQ560HF Thorlabs splitters, in a suitable cascade combination, will allow the 1:32 splitting condition of laser beam to be realized. An example of how this layout can be realized in practice is shown in Figure 4. Particularly, the pigtailed laser source (Aerodiode in our case) and a series of cascading beam splitters (1 x 2 and 1 x 4 splitters), that form "the laser system", are respectively highlighted.

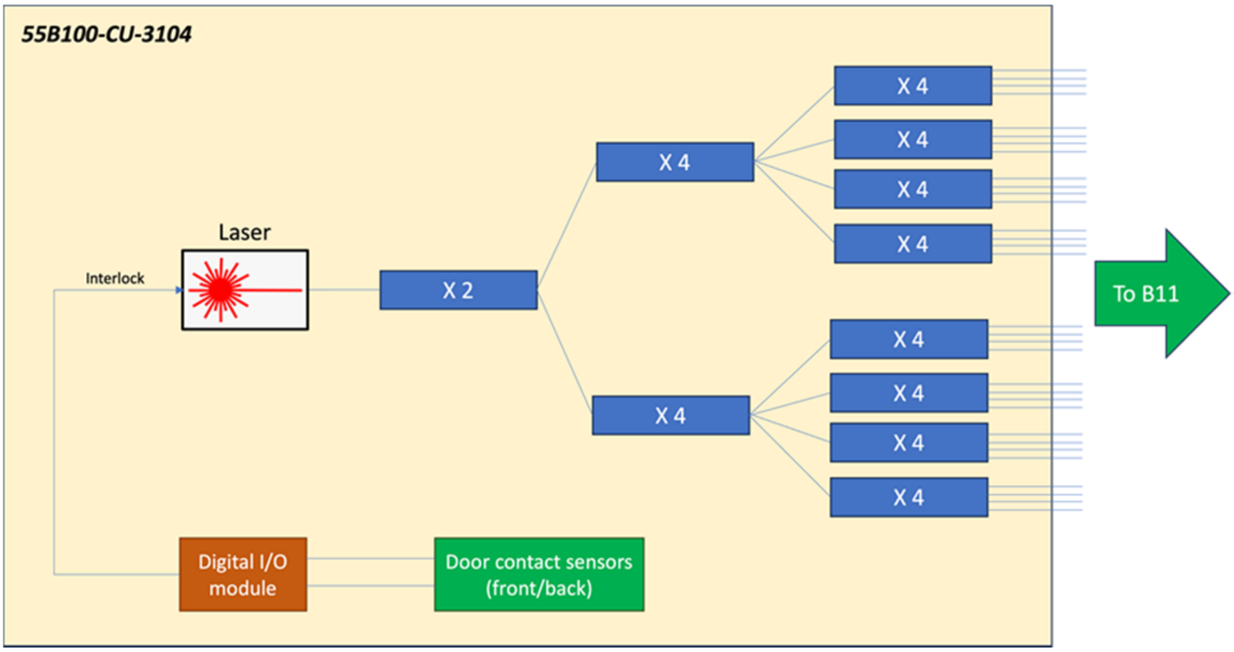


Figure 4. Scheme of the pigtailed laser system enclosed in the dedicated 55B100-CU-3104 cubicle of the ITER Diagnostic Building, when using the R10754-07-M16 Hamamatsu PMT (only a laser source is required).

Referring to Figure 4, the Thorlabs TN532R5F1 (1 x 2) and TWQ560HF (1 x 4) splitters introduce a signal attenuation on each channel of 3.7 dB and 7.7 dB, respectively, and both use the Thorlabs 460HP optical fiber, thus ensuring optimal coupling with the pigtailed laser source.

The same applies to the FC/PC connector chosen for the 460HP optical fiber, which is the same as that used for the input and output optical fibers of the two Thorlabs splitters, thus ensuring minimization of losses of the optical power emitted by the Aerodiode laser source.

In the optical path between the laser system and detectors, multimode hard-rad (HR) optical fibers with a 50-μm core are to be coupled with the single-mode output fibers of the laser system to transmit effectively the light signal to the detectors. Since the core diameter of multimode optical fibers (HR) is about 10 times larger than that of single-mode ones, the optical power loss is negligible.

Regarding the laser source and beam splitters, they are expected to be enclosed in a compact, light-tight environment. The light signal should be transmitted by optical fibers along a protected path to the detectors. The laser system will be installed in a suitably dedicated standard ITER cubicle (55B100-CU-3104) located in the B74 Diagnostic Building. The optical fibers transmit the signal directly from this cubicle to the detection cassettes located in the Port Interspace of the RNC Ex-Port. In the detection cassettes, each fiber (HR) is connected directly to each detection module, where the optical signal is captured by PMT.

5. RESULTS: MATLAB SIMULATIONS

About point 3) of section 2, appropriate calculation codes were developed in the Matlab environment, such as PMT_optical_power_electrical_signal_v4.m and later versions and associated Windows and Mac executables, to simulate the performance of the system for the Ex-Port specific optical diagnostics of ITER RNC. In particular, the optical power of the light source and that received by a single PMT detector required to achieve the correct gain correction for neutron detection are evaluated.

For the codes developed in Matlab, the maximum optical emission power at 520 nm of the pulsed laser source of 75 mW (which is the maximum fiber-optic output power of the Aerodiode 520LD-2 laser source) and the characteristics (at 520 nm) of the Hamamatsu H6153-70 (R5946) PMT, which are the same as those of the ITER's He_4 prototype detector, were used as a reference [19]. It has a sensitivity of 0.05 A/W and a gain (@ 2100 V - max supply 2300 V) of 1.5 x 10^6, derived from the Hamamatsu datasheet curves shown in Figure 5 [20].

The various power losses suffered by the laser beam along the optical path from the light source to the single detector were also taken into account. More specifically, the following transmission and/or attenuation factors were considered:

a) transmission of splitter system for each single channel;
b) coupling between pigtailed laser system and HR multimode optical fiber carrying optical signal to detectors;
c) transmission of connections along fiber-optic path between light source and detector;
d) attenuation of optical power due to several fiber sections irradiated with different doses of radiation (Figure 2);
e) coupling between multimode optical fiber and single PMT detector.

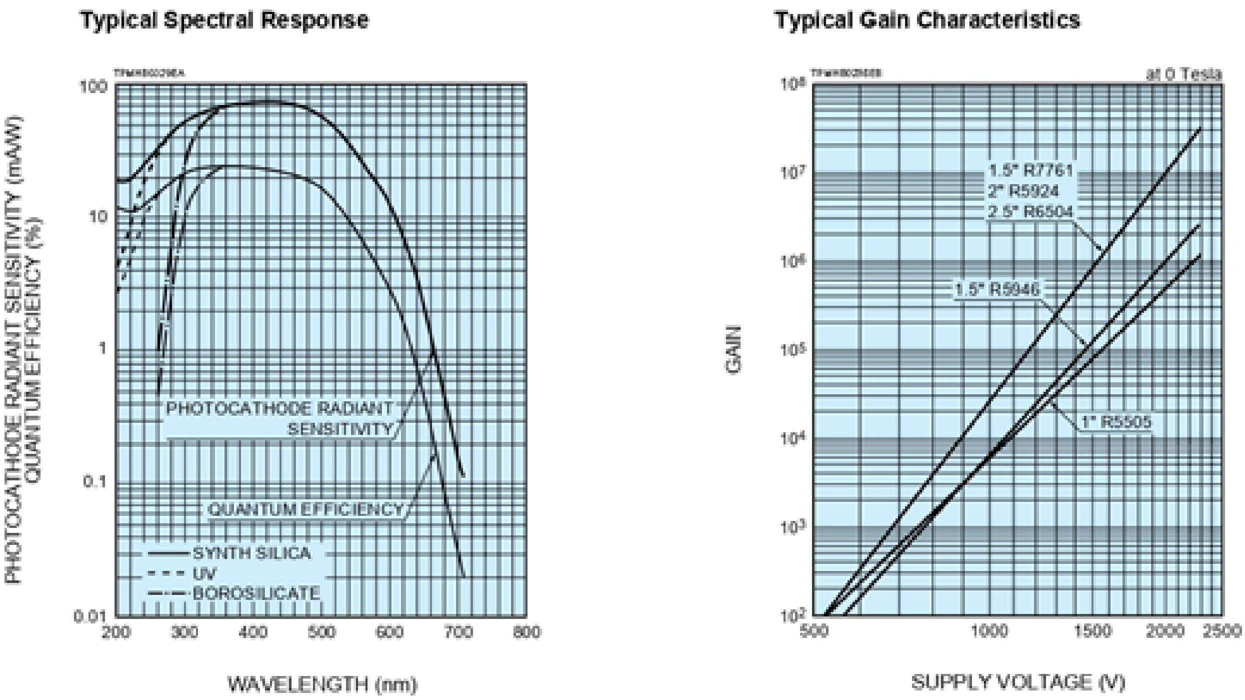


Figure 5. Typical spectral response curves versus wavelength and gain versus supply voltage for the Hamamatsu H6153-70 (R5946) PMT detector.

From simulations using Matlab computational codes, it was found that the optical input power to the single Hamamatsu H6153-70 (R5946) PMT detector, required to produce an output signal from the detector (terminated at 50 ohm) of the order of 1 V, is about 0.27 μW. Taking into account the attenuation factor (6000) derived for an irradiated RNC Ex-Port fiber, it was deduced that the power of the laser pulse at the input of each single HR optical fiber of the 32 ones expected, needed to have 0.27 μW on the single PMT, is 1.6 mW.

Considering the 75 mW output power of the Aerodiode laser, splitting the signal into 16 channels (using a 1x4 splitter followed by another 1x4 splitter at each output) and taking into account the splitter attenuation, the value of 2.1 mW is obtained at the input of each fiber. From this result, it follows that two laser sources would be required for the detector calibration optical system.

Therefore, based on the Matlab simulations performed, it was verified that two Aerodiode 520LD-2 laser sources are fit for purpose, i.e., capable of emitting sufficient optical power to generate a 1 V signal on the single PMT (with a tolerance on the maximum optical power emitted by laser of about 20%). This ensures the generation of a valid reference signal for correct neutron detection of the ITER RNC.

Since the production of the Hamamatsu H6153-70 (R5946) PMT is not guaranteed by the company for a long time, an alternative solution represented by the Hamamatsu R10754-07-M16 PMT was also considered. The latter is characterized at 520nm by a sensitivity of 0.04 A/W and a gain of 5×10^6 at a supply voltage of 2350 V (maximum supply value 2700 V). In this case, it was obtained that the optical input power to the single PMT detector, required to produce an output signal from the detector (terminated at 50 ohm) of the order of 1V, is about 0.12 μW. This corresponds to having an input optical signal to the single approximately 290 m-long hard-rad fiber of 0.72 mW (taking into account the attenuation factor of about 6000 due to the single HR optical fiber).

Contrary to the use of the Hamamatsu H6153-70 (R5946) PMT detector, which requires two Aerodiode laser sources to produce an effective reference signal for proper neutron detection of the ITER RNC, the advantage of using the Hamamatsu R10754-07-M16 PMT is that only one Aerodiode laser source can be employed (Figure 4), whose emitted beam can be split into 32 channels while maintaining sufficient power, with a significant advantage in terms of cost reduction and spatial sizes [21].

It was also considered that within the PCSS area of ITER (e.g., within the EU21 shielded cabinet that houses the RNC preamplifiers) there may be space available (not yet allocated by ITER) to accommodate the laser source system.

This area would be close to the "Bespoke Connector" (Figure 2) and, in this case, the HR fibers would only be subject to an RIA value of 7.2 dB. Using a single laser unit (Figure 4) followed by a 1 x 2 splitter and two stages of 1 x 4 splitters (e.g. Thorlabs ones, with a total attenuation of 19.1 dB), the signal attenuation would be 26.3 dB (equivalent to attenuation factor of 427).

Taking into account four interconnections along the optical path of the laser beam, which would introduce an additional attenuation factor of 1.52, the final attenuation factor would be about 650. In this case, considering the optical output signal of the Aerodiode laser with a power of 75 mW, the final signal obtained at the input of the PMT detectors would be 115 μW, much higher than what is required to produce a valid reference signal for proper neutron detection of the ITER RNC.

On the other hand, in the case of using an LED source with an emitting power of 60μW (we would need 32 LEDs in total, one for each detection channel), taking into account only the RIA of the HR fiber of 7.2 dB (attenuation factor of about 5.25) and the interconnections (attenuation factor of 1.52), the final attenuation factor would be about 8, resulting in a final input signal to the PMT detectors of about 7.5 μW, again more than sufficient for our purposes. However, two factors make the laser system more suitable than the LED for the purpose in question: I) the price (about 20 k€ for the laser versus 36 k€ for the LED system); II) the space required in the PCSS area.

In fact, each of the four 10-channel LED driver modules that could be used as an alternative light source to the laser is a 240x180x100 mm^3 box, and each of the 32 LEDs that would be used is housed inside 50x60x15 mm^3 boxes, which constitute a much larger footprint volume than that is required to accommodate a laser source such as the Aerodiode one with its 208x100x37 mm^3 driver (Figure 3).

Concerning the laser system (light source with its driver and with beam splitters), Figure 6, Figure 7, and Figure 8 show examples of various possible configurations for different regions available to host such a system.

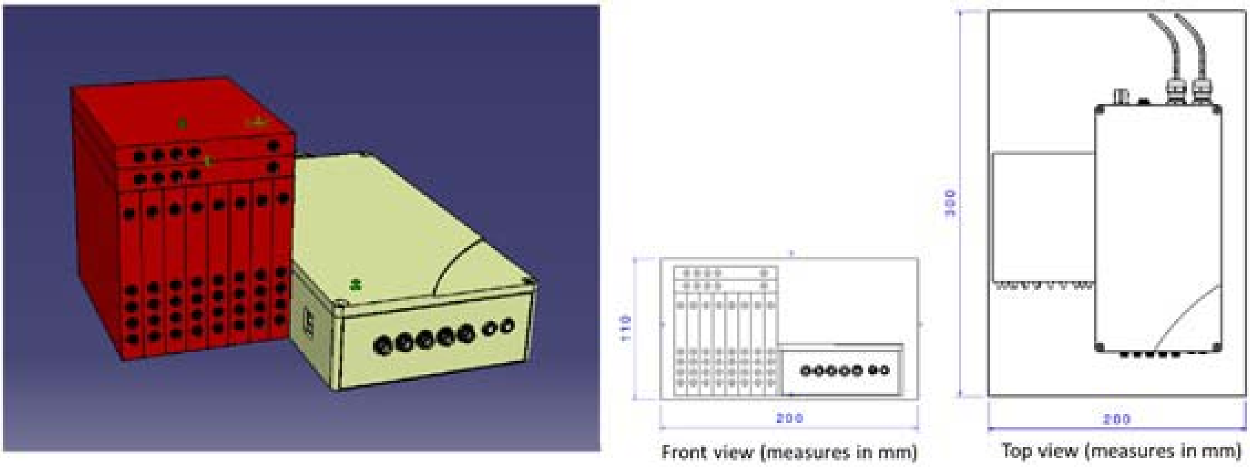


Figure 6. *First possible spatial configuration for the laser system (source + driver + splitter).*

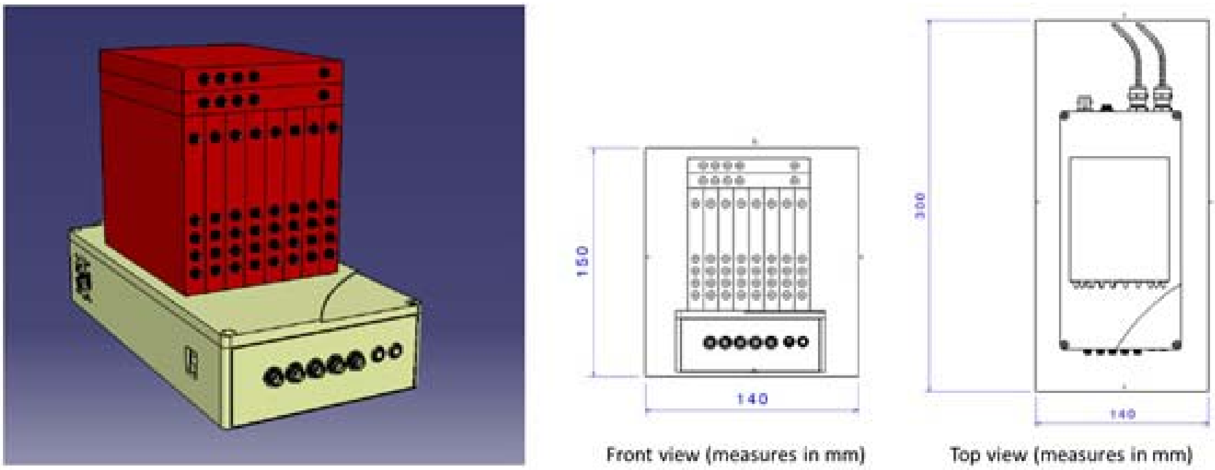


Figure 7. *Second possible spatial configuration for the laser system (source + driver + splitter).*

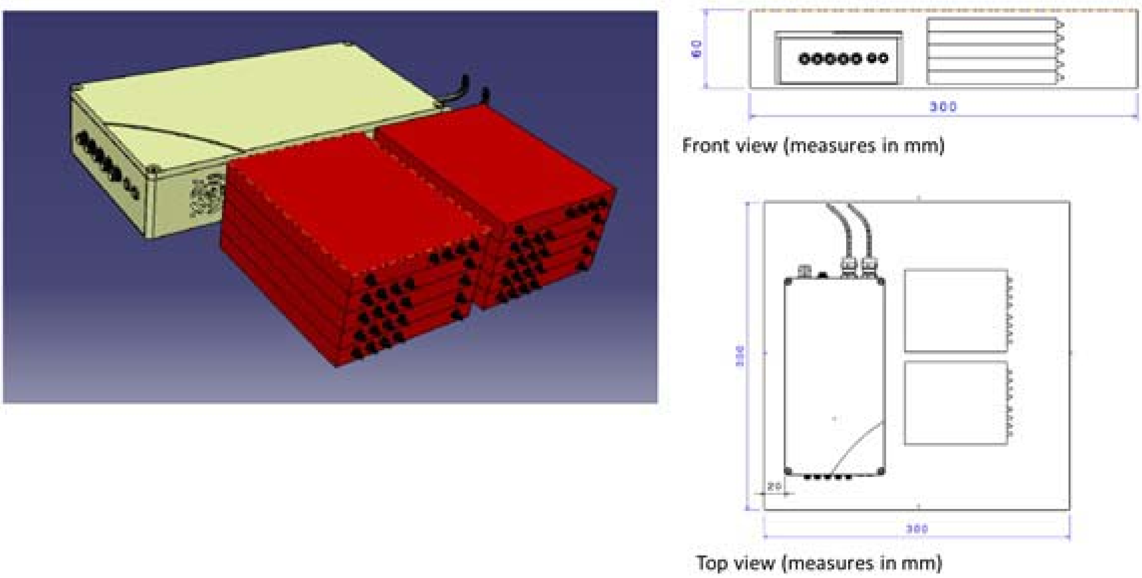


Figure 8. *Third possible spatial configuration for the laser system (source + driver + splitter).*

In Figure 6, Figure 7, and Figure 8, the yellow module represents the integrated driver of the Aerodiode laser, including the power supply and driver control cables, while the red modules are the 1 x 4 beam splitters. The 1 x 2 splitter is not shown in the above figures because it is simply a split cable. However, some free space has been left to accommodate the fibers and connectors.
Since we have no information on the radiation resistance of the laser system (nor on the LED system), though their possible location could be in the ITER PCSS, which is an environment subject to integrated radiation doses of up to 1 MGy, the possible effects of radiation on these systems were neglected in the analysis presented.

6. RESULTS: LABORATORY TESTS

With regard to the laboratory tests of the specific components to be used for the Ex-Port optical diagnostics of the ITER RNC (item 4, section 2), preliminary tests were carried out in the Neutron Diagnostics laboratory at the ENEA research center in Frascati (Rome).
These tests were performed by using devices available in the center's laboratories, including the Quantel Centurion plus laser source emitting pulses at 532 nm (green) with energy of 18 mJ, width of 8 ns, repetition rate up to 100 Hz, and beam divergence of 7 mrad.
Confirming what was already predicted with Matlab simulations, laboratory tests have established that the use of a laser source is preferable compared to the use of an LED source for the development of the experimental layout of the above diagnostics, taking into account the required optoelectronic parameters (power, duration, shape and repetition frequency of the pulse, section 4).
In fact, measuring the optical output power of the commercial high-power 151033GS03000 LED (Würth Elektronik, λ = 520 nm, 18000 mcd @ 25 mA) with Thorlabs' S121C powermeter, supplied at the maximum available current, was found to be 60 μW, which is insufficient compared to the value of 0.72 mW required for the set purposes. Although more powerful LEDs (up to 100 mW) are available on the market, they have the problem that the pulse width (usually of the order of tens of μs) cannot be adjusted as desired and therefore cannot reach the value of 50 ns — 100 ns required for proper neutron detection by ITER RNC.
Moreover, the problem of coupling between LED source and optical fiber (particularly single-mode one) must also be considered, which further reduces the value of the power that can be effectively transmitted. Therefore, with respect to an appropriately selected laser such as the Aerodiode one, an LED light source is not a suitable solution for the correct calibration of photomultiplier neutron detectors in order to obtain proper neutron detection.
In terms of amplitude and pulse width stability (see requirements listed in the section 4), the results achieved by the Quantel Centurion laser were no better than those obtained by using LED source. More precisely, for the former a pulse amplitude stability of 10% was measured compared to a value of 6% for LED source, while for the total energy (integral) of the signal a stability of 7% was achieved for the laser versus a value of 3% for LED. This occurred because the Centurion source is a power laser and, therefore, is not optimal in terms of the stability of emitted energy. This necessitated the purchase of the Aerodiode laser system for further verification and validation tests of the expected requirements.

7. OPTOELECTRONIC DEVICES FOR ATTENUATION CONTROL OF HARD-RAD OPTICALFIBERS

In the optical system for calibration of photomultiplier neutron detectors for time-resolved measurement of neutron flux proposed for the ITER RNC, the use of a multimode hard-rad optical fiber is planned to transmit the optical reference signal from the light source (laser) to the detection

system. This signal is needed to calibrate the single detector (PMT) during the detection phase of gamma rays and neutrons produced by the ITER plasma.
In this section, some working hypotheses are evaluated to control the time variation of the attenuation coefficient (i.e. RIA) of multimode hard-rad optical fibers due to the integrated absorbed dose of gamma radiation and high neutron fluxes.
The optimal solution would be to take a portion of the optical power before inserting the fiber into the detector and to perform a measurement of change over time of the optical power of the signal transmitted in the fiber.
Unfortunately, due to the available space and the presence of radiation in the area of interest, it is not possible to realize an experimental layout that can include both external optical elements (lenses and mirrors) and PIN diodes or APD (Avalanche PhotoDiode) detectors in the visible range.
The direct signal at the photomultiplier (PMT) cannot provide meaningful information about the attenuation (RIA) of hard-rad optical fibers and its possible variation with time, because this signal is also affected by the variation of the detector characteristics (e.g. gain and quantum efficiency) by varying the radiation dose to which it is exposed.
The choice of using "integrated" optoelectronic components such as circulators or beam splitters is therefore essential. Specifically, the proposed component for the experimental layout in terms of RIA control turns out to be the commercial TM50R2S1B beam splitter, manufactured by Thorlabs, categorized as 1x2 Step Index Multimode Fiber Optic Couplers.
More specifically, the device is a multimode (low OH) optical fiber with a core of 50 μm and a numerical aperture of 0.22, operating as a 1x2 splitter in the 400 nm — 2200 nm spectral range. Various couplings are provided for such a device between the two separate optical output fibers (50:50, 75:25, 90:10, 99:1) with SMA or FC/PC connectors.
Unfortunately, as a commercial product, no data is available on its behavior in environments exposed to radiation. On the other hand, the used optical fibers can have both low and high OH content, and, similarly to the hard-rad fibers that will be used in the RNC diagnostics, both are fluorine doped.
For the sake of completeness, the typical attenuation curve of the FG050LGA fiber at low OH content as a function of wavelength is shown in Figure 9, which is similar to the attenuation curve of the hard-rad fiber expected for the ITER RNC's optical diagnostics, while the specifications of the TM50R2S1B splitter with a 90:10 splitting ratio and SMA905 connectors are depicted in Figure 10.
Thus, the experimental layout includes two equal hard-rad fibers with the same optical path from the "cabinet" (where the laser is expected to be placed) to the photomultiplier and the relative return path, after connection to the splitter, with a reference detector for optical power measurement.
In the absence of experimental data on the behavior of the splitter in the presence of radiation, and assuming that it is not possible to use a custom-made hard-rad product that would be the optimal solution, as a first hypothesis it can be assumed that the irradiation effect may be negligible considering that its length (80 cm) is considerably less than that of the two round-trip hard-rad optical fibers.
In the case of the presence of fairly easy access and compatibility with the doses of radiation actually present, it may be considered to replace only the irradiated splitter with a new one at regular time intervals to obtain reliable attenuation data. Moreover, the range of possible coupling ratio values (up to 99:1) allows the splitter to be used even under conditions of high attenuation of the optical signal.
These considerations are based on the assumption that the optical power measured in the reference channel is sufficient to be detected, which depends on the optical configuration used (one or two laser sources, optimal coupling ratio, type of detectors used, etc.).

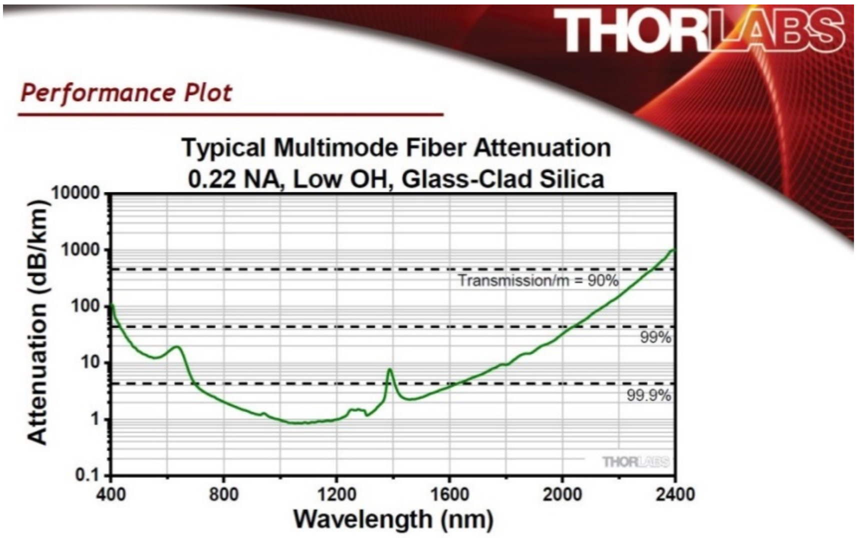
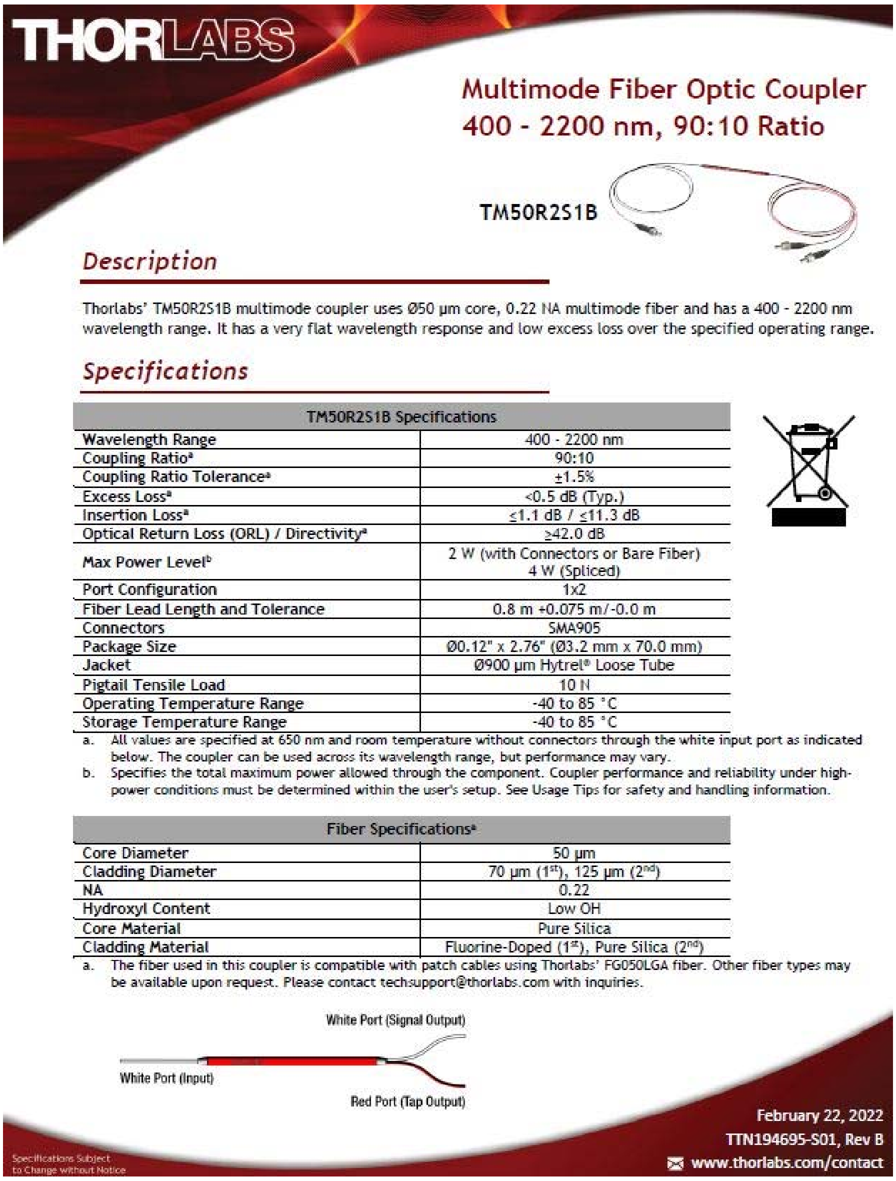


Figure 9. Typical attenuation curve of the FG050LGA multimode optical fiber as a function of wavelength.


THORLABS

Multimode Fiber Optic Coupler
400 - 2200 nm, 90:10 Ratio

TM50R2S1B

Description

Thorlabs' TM50R2S1B multimode coupler uses Ø50 µm core, 0.22 NA multimode fiber and has a 400 - 2200 nm wavelength range. It has a very flat wavelength response and low excess loss over the specified operating range.

Specifications

TM50R2S1B Specifications	
Wavelength Range	400 - 2200 nm
Coupling Ratio[a]	90:10
Coupling Ratio Tolerance[a]	±1.5%
Excess Loss[a]	<0.5 dB (Typ.)
Insertion Loss[a]	≤1.1 dB / ≤11.3 dB
Optical Return Loss (ORL) / Directivity[a]	≥42.0 dB
Max Power Level[b]	2 W (with Connectors or Bare Fiber) 4 W (Spliced)
Port Configuration	1x2
Fiber Lead Length and Tolerance	0.8 m +0.075 m/-0.0 m
Connectors	SMA905
Package Size	Ø0.12" x 2.76" (Ø3.2 mm x 70.0 mm)
Jacket	Ø900 µm Hytrel® Loose Tube
Pigtail Tensile Load	10 N
Operating Temperature Range	-40 to 85 °C
Storage Temperature Range	-40 to 85 °C

a. All values are specified at 650 nm and room temperature without connectors through the white input port as indicated below. The coupler can be used across its wavelength range, but performance may vary.
b. Specifies the total maximum power allowed through the component. Coupler performance and reliability under high-power conditions must be determined within the user's setup. See Usage Tips for safety and handling information.

Fiber Specifications[a]	
Core Diameter	50 µm
Cladding Diameter	70 µm (1st), 125 µm (2nd)
NA	0.22
Hydroxyl Content	Low OH
Core Material	Pure Silica
Cladding Material	Fluorine-Doped (1st), Pure Silica (2nd)

a. The fiber used in this coupler is compatible with patch cables using Thorlabs' FG050LGA fiber. Other fiber types may be available upon request. Please contact techsupport@thorlabs.com with inquiries.

White Port (Signal Output)
White Port (Input)
Red Port (Tap Output)

Specifications Subject to Change without Notice

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TTN194695-S01, Rev B
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Figure 10. Specifications of the Thorlabs TM50R2S1B multimode splitter with a 90:10 splitting ratio and SMA905 connectors.

8. CONCLUSIONS

Within the F4E actions assigned to ENEA (Grant SG07), several research activities aimed at designing the ITER RNC were carried out. More exactly, some of these activities, which are also part of the collaboration agreement between the ENEA NUC-TECFIS-DIM and NUC-FUSEN-DIA laboratories on the topic: "Sviluppo di una diagnostica ottica per ITER Radial Neutron Camera" ("Development of an optical diagnostics for ITER Radial Neutron Camera"), focused on the development of an optical system for the calibration of photomultiplier neutron detectors that will be installed in the Ex-Port part of the ITER RNC.

The performed activities allowed to identify the specifications of the radiation-resistant (hard-rad) optical fibers and those of the light source necessary to obtain the correct gain correction of the PMTs of the scintillator detection system located in the 16 lines of sight (LOS) of the Ex-Port ITER RNC. The detectors will be equal to 32 (as well as the transmission optical fibers) since two detectors are present for each LOS.

Based on these specifications, the most suitable light source and optical fibers for the purpose were identified. Specifically, the Aerodiode's custom pigtailed laser diode system (model 520LD-2) with the SHAPER driver operating at a wavelength of 520 nm was chosen. It is coupled to the Thorlabs 460HP single-mode output optical fiber (length 2m) via an FC/PC connector. This laser source is characterized by the ability to generate Gaussian pulses (or any other desired shape) with an FWHM of around 50 ns (adjustable) and it is capable of emitting an output power from the optical fiber up to 75 mW (adjustable).

Regarding the hard-rad optical fibers for signal transmission from the light source to the detectors, which will be installed in an ITER environment exposed to radiation doses up to 1 MGy, it has been established that they will be multimodal (to ensure an optimal signal transmission) with a core of 50μm — 100 μm. The fibers have similar characteristics to the QP600 from Polymicro (now Molex, Table 1), currently discontinued, to minimize attenuation of the optical signal along the path between the light source and detector.

Since the receiving system consists of 32 detection channels, the light beam emitted by the laser source will be split into 32 channels, traveling for each of them by optical fiber to reach the corresponding detector. Despite a careful market survey, it was not possible to find a direct 1:32 splitter. So, an alternative (commercial and low cost) solution was identified represented by the TN532R5F1 532nm ± 15 nm 1x2 Narrowband Fiber Optic Coupler splitter and the TWQ560HF 560nm ± 50 nm 1x4 Wideband Fiber Optic Coupler splitter, both supplied by Thorlabs.

The use of multiple Thorlabs TN532R5F1 and TWQ560HF splitters in a suitable cascade combination, as shown in the scheme of Figure 4, will allow the 1:32 splitting condition of the starting laser beam to be realized.

The Aerodiode laser source and the splitters identified as suitable for the set purpose are "non-hard-rad" components. They will therefore be located in an appropriate ITER area which, in this specific case, has been identified in the Diagnostic Building (cubicle 55B100-CU-3104) of the tokamak complex. The optical reference signal will be transmitted to the detectors along a fiber-optic path of about 290m passing different irradiated zones (up to 1 MGy cumulative dose).

An alternative solution to the one just mentioned has also been identified, which is to place the Aerodiode laser source and the splitters as close as possible to the detectors, thus reducing the fiber optical path of the light signal emitted by the source and its attenuation.

Specifically, this alternative solution consists of placing the laser source and the splitters in the ITER PCSS area, for example inside the EU21 shielded cabinet which houses the RNC preamplifiers and is

located at a distance of about 7 m - 8 m from the detectors, where there would be available a space (currently not yet assigned by ITER) to be used for this purpose which would be located next to the "Bespoke Connector" (Figure 2).
Concerning the amplitude and width (duration) stability of the light pulse (requirements reported in section 4), the Quantel Centurion laser source used for preliminary laboratory tests did not permit to achieve results better than those obtainable by using an LED source.
This occurred because the Centurion source is a power laser and therefore not optimal in terms of stability of emitted energy. In fact, for the former a pulse amplitude stability of 10% was measured versus a value of 6% for the LED source, while for pulse total energy an integral stability of 7% for the laser versus a value of 3% of the LED was observed.
Finally, although the results obtained are not optimal since the laser used is not specifically adapted for achieving the set purposes and optimal performances, a significant margin of improvement is expected as soon as the Aerodiode source will be available which has characteristics that guarantee the achievement of the design requirements of the optical diagnostic system of the ITER RNC with a pulse stability of about 1%.

9. PROSPECTIVES/FUTURE TESTS

Once the Aerodiode laser source (520 nm, 75 mW) is available in our laboratories, experimental tests will be carried out to verify source performances, its correct operation, and that of the entire acquisition chain, as well as verify the emission characteristics of the source requested in section 4. More precisely, the laboratory tests scheduled are the following:

1) measurement of the optical output power of the Aerodiode 520LD-2 laser source coupled with the Thorlabs 460HP single-mode optical fiber (length 2m) and with the iXblue IXF-RAD-MMGI-50-125-020-PI optical fiber (length 1.5m, chosen as comparison fiber with the Thorlabs 460HP one) using a proper powermeter such as the Thorlabs S121C one. The purposes of the tests are:
    a) check the stability of the optical output power of laser pulse, which must be <7%;
    b) evaluate the minimum and maximum output available power by regulating the laser diode current (required for test 2), i.e. the value range in which it is possible to vary the laser power.
2) Measurements of the signal obtained with the Hamamatsu H6153-70 (R5946) photomultiplier, operating at 2100 V, and the Xilinx X6-400M DAQ acquisition card (sampling rate 400 MS/s, resolution 14-bit). The purposes of the tests are:
    a) check the ability to adjust the repetition frequency (PRR) of laser pulses, which must be 1 kHz, and the stability in terms of PRR values;
    b) verify the ability to adjust the shape and width (duration) of the laser pulse (value required of FWHM of 50 ns) and their stability, which must be <7%.
3) Verify the correct operation of the laser chain and the detection system. In particular, since the PMT reference signal must be used during neutron/gamma measurements by RNC, it is important that it does not interfere with other signals, including those due to radiations. The example reported in Figure 11 shows a separation plot between neutron/gamma signal and PMT reference one due to the light pulses of the source (LED in the case of the example) obtained with the Charge Comparison Method (CCM) [22],where the integrals of the signals are reported

on the x-axis, while the ratios of the short/long integrals according to the CCM are shown on the y-axis. The PMT reference signal is clearly distinguishable in the lower right corner of the plot.

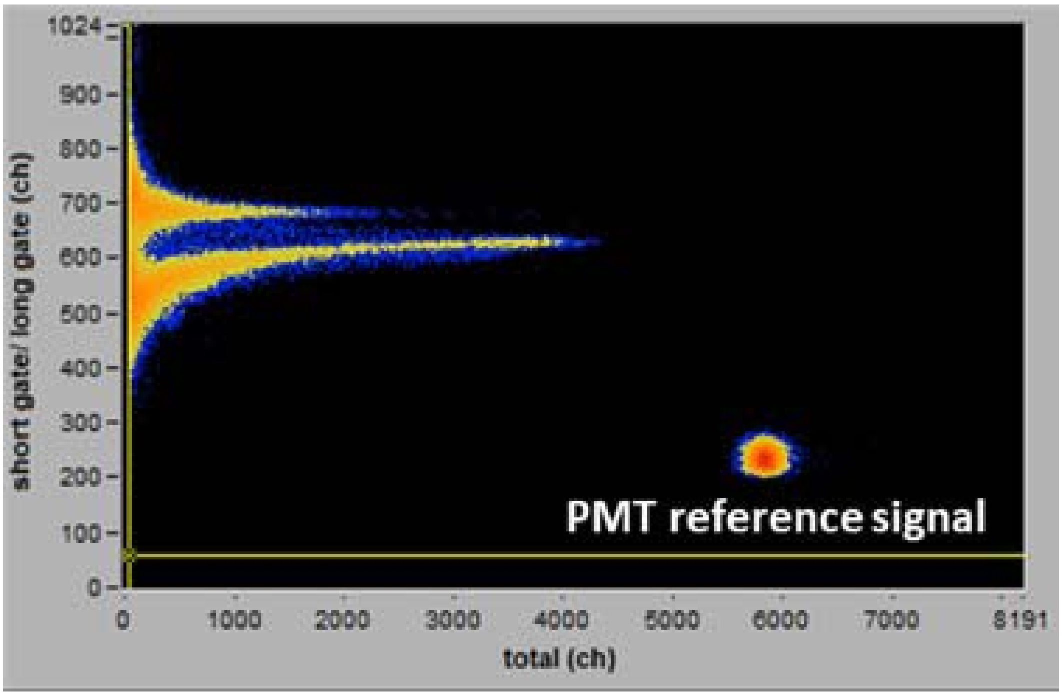

Figure 11.. Example of neutron/gamma signals recorded together with the PMT reference signal. The latter is well distinguishable from the neutron/gamma signals.

4) Repeat tests 1a), 2b), and 3) by using the He_4 detector prototype to compare the results with those obtained by using the Hamamatsu H6153-70 (R5946) photomultiplier.

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