



Development and performance of the thin-foil proton recoil spectrometer for ITER plasma diagnostics

J. Dankowski^{a,*}, J. Bielecki^a, J. Bładek^a, S. Conroy^b, B. Coriton^d, G. Croci^c, D. Dworaka^a, G. Ericsson^b, J. Eriksson^b, A. Wójcik-Gargula^a, A. Hjalmarsson^b, A. Jardin^a, R. Kantor^a, A. Kovalev^d, K. Król^a, A. Kulińska^a, A. Kurowski^a, G. Mariano^d, R. Mehrara^a, D. Morawski^a, M. Rebai^c, M. Scholz^a, F. Scioscioli^c, M. Tardocchi^c, G. Tracz^a, M. Turzański^a, U. Wiącek^a

^a Institute of Nuclear Physics Polish Academy of Sciences, Radzikowskiego 152, PL 31342, Krakow, Poland

^b Department of Physics and Astronomy, Uppsala University, Lägerhyddsvägen 1 75237, Uppsala, Sweden

^c Istituto per la Scienza e Tecnologia dei Plasmi, via Cozzi 53, Milano, Italy

^d ITER Organization, Route de Vinon-sur-Verdon, CS 90 046, 13067St. Paul Lez Durance Cedex, France

ARTICLE INFO

Keywords:

High resolution neutron spectrometer
Plasma diagnostics
Fusion
ITER
magnetic field
MCNP

ABSTRACT

High Resolution Neutron Spectrometer (HRNS) is one of the essential plasma diagnostics of ITER, whose operational role is the neutronic measurement of the n_t/n_d ratio in a plasma core. Coexisting with the other ITER diagnostics makes it a powerful tool for efficient and precise plasma diagnostics. The main goal of this work is to present the operating principles and key challenges associated with the High Resolution Neutron Spectrometer in ITER, with a particular focus on the Thin-Foil Proton Recoil (TPR) Spectrometer. The complexity of ITER tokamak brings with it many variables that had not been considered of primary importance until now, such as the magnetic field or high temperature in the detector region.

1. Introduction

For years, the ITER project has been bringing progress in many fields of science and technology. Plasma diagnostics planned within the project, especially those crucial in terms of machine protection, safety and control, are entering the advanced design phase. One example of such diagnostics is the HRNS system, whose main task is to measure the fuel ion ratio n_t/n_d in the plasma core, complementing other ITER diagnostics measuring the same parameter but in the peripheral regions of the deuterium - tritium (DT) plasma.

The HRNS is dedicated to measuring time-resolved neutron spectra for both DD and DT plasmas, providing mainly the determination of the fuel ion ratio in the plasma core for a wide range of ITER operational scenarios in fusion power. Moreover, as a supplementary function, HRNS provides information on the ion temperature, confined alpha particles, and fast ions in real time [1].

In its current form, the HRNS system consists of a set of non-magnetic neutron spectrometers located in the equatorial port cell. #01. From this location, the system will observe the ITER plasma through a single, near-radial line of sight (LOS) with a 100 mm outer diameter opening in the

first wall [2]. Due to its complex design, the system is divided into two sections to optimally utilize the available neutron flux: “high-power” neutron spectrometers at the front and “low-power” neutron spectrometers at the rear. This solution also serves to distance the sensitive ToFs scintillators with Photo Multiplier Tubes far from the strong magnetic field of up to 150 mT.

The HRNS system consists of four spectrometers:

- Thin-foil Proton Recoil (TPR);
- Neutron Diamond Detector (NDD);
- Forward Time-of-Flight (FTOF);
- Backscattering Time-of-Flight (BTOF).

2. Features of the HRNS detection system

To achieve the ITER requirements on uncertainty of n_t/n_d better than 20 %, the HRNS must be able to operate over a large dynamic range of fusion power. For this purpose, the system consists of a set of four neutron spectrometers installed along the LOS, as presented in Fig. 1. The first spectrometer in the system, the so-called Thin-foil Proton

* Corresponding author.

E-mail address: jan.dankowski@ifj.edu.pl (J. Dankowski).

Recoil (TPR) spectrometer positioned 19 m away from the tokamak centre, is suited for high fusion power conditions and uses thin polyethylene (PE) foils as neutron-proton converters [3]. The energy of a recoil proton is related to the neutron energy by the equation:

$$E_p = E_n \cos(\theta)^2$$

Where θ is the scattering angle. By analysing the spectrum of protons reaching the detector at the θ angle, it will be possible to determine the temperature of the ions in the plasma [4]. Each of the three TPR detectors consists of two silicon sensors with different thicknesses to work in $\Delta E-E$ configuration. This type of configuration allows measurement of proton recoil from the PE converter while eliminating protons that will be produced from the TPR volume. Additionally, the thickness of the detectors was selected so that the signal from protons emitted at the converter is recorded in both detectors, assuming that the interesting energy range for the TPR is 8–15 MeV. The number of TPR detectors proposed in the design is related to the analysis of measurement uncertainty n_t/n_d for this spectrometer. The uncertainty is at the level of 17 % for three TPR detectors, whereas for comparison with one TPR detector, this uncertainty is at the level of 30 %. The influence of polyethylene foils on the neutron flux and energy spectrum can be neglected.

The next spectrometer is the Neutron Diamond Detector (NDD), located 21 m from the tokamak centre, behind the TPR vacuum chamber [5]. The NDD is designed for high and intermediate power values and features pixel segmentation to enhance its count rate capability. This device, designed as a mosaic high-purity Chemical Vapour Deposition (CVD) diamond detector, can measure spectrometric signal created by fast neutrons with energy above 6.2 MeV thanks to a nuclear reaction on carbon atoms, $^{12}\text{C}(n,\alpha)^9\text{Be}$.

The back-scattering time-of-flight spectrometer (BToF) follows, embedded within a shared geometry along with the forward time-of-flight spectrometer (FToF) in a second cuboid structure. Positioned at 23 m from the tokamak centre, the FToF spectrometer is used for low tritium densities and pure deuterium operations. Both the BToF and FToF spectrometers employ segmented detectors to improve count rate capabilities [1]. The neutron time-of-flight measurement method applicable for both spectrometers is based on the linear correlation of the time of flight t_{TOF} required for a fast neutron to travel a known distance L , in this case between the detector T_0 and a detector located at distance L by the equation:

$$E_n = \frac{1}{2}m_n v_n^2 = \frac{1}{2}m_n \left(\frac{L}{t_{\text{TOF}}}\right)^2$$

where m_n is the mass of neutron.

The operational range in fusion power of each HRNS system, to achieve an uncertainty in n_t/n_d better than 20 % with a time resolution of 100 ms, is shown in Fig. 3.

Fig. 2

This arrangement of four spectrometers ensures that the HRNS system can meet the ITER measurement requirements across the entire fusion power range. The operational limits and performance are modelled for plasma ion temperatures of 10 keV and 20 keV. While the NDD design is based on calculations due to limited experimental data on diamond detectors in high-power fusion environments, the system as a whole is expected to meet ITER requirements.

3. Preliminary TPR signal modelling

A numerical code has been developed using a dataset of SRIM/TRIM simulation results [6] and the $1\text{H}(n, \text{elastic})$ cross-section values obtained from the JENDL/HE-2007 dataset of the JANIS database [7], to model neutron-proton conversion in the polyethylene (PE) foils, trajectories of protons and their detection in the silicon detectors. Several simulations were compared with a Geant4 [8] model of the PE-Si system, giving similar results.

For calculation, it was assumed that the TPR spectrometer consists of three identical detector sets and identical three polyethylene foils placed one behind the other along the line of sight (LOS). A circular polyethylene (PE) foil with a diameter of 20 mm and a thickness of 100 μm , acting as a proton-neutron converter, is placed in a neutron beam. Protons emitted from one foil are detected by one set of silicon ring detectors (with an inner radius of 24 mm and an outer radius of 48 mm) placed at a distance of 330 mm from the converter (PE) foil. All three detector sets, together with dedicated foils, are placed in a cylindrical vacuum chamber, maintaining a pressure of 10^{-3} – 10^{-5} mbar. The thicknesses of ΔE and E detectors are 500 and 1500 μm , respectively.

Fig. 3 presents the expected proton energy deposition in the ΔE - E silicon detectors for an incident DT neutron spectrum resulting from a thermal plasma with $T_i = 20$ keV. To investigate the TPR performance in deriving n_t/n_d several plasma scenarios have been studied. A reference

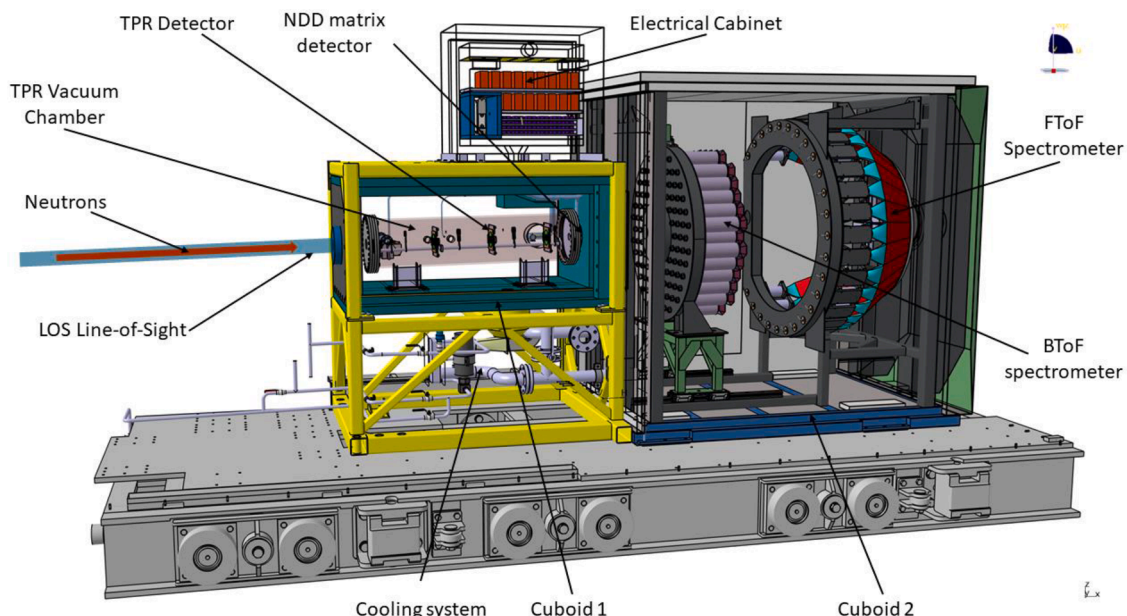


Fig. 1. HRNS System with four neutron spectrometers (TPR, NDD, FToF and BToF) located on the Port Cell Support Structure (PCSS) in Equatorial Port #01.

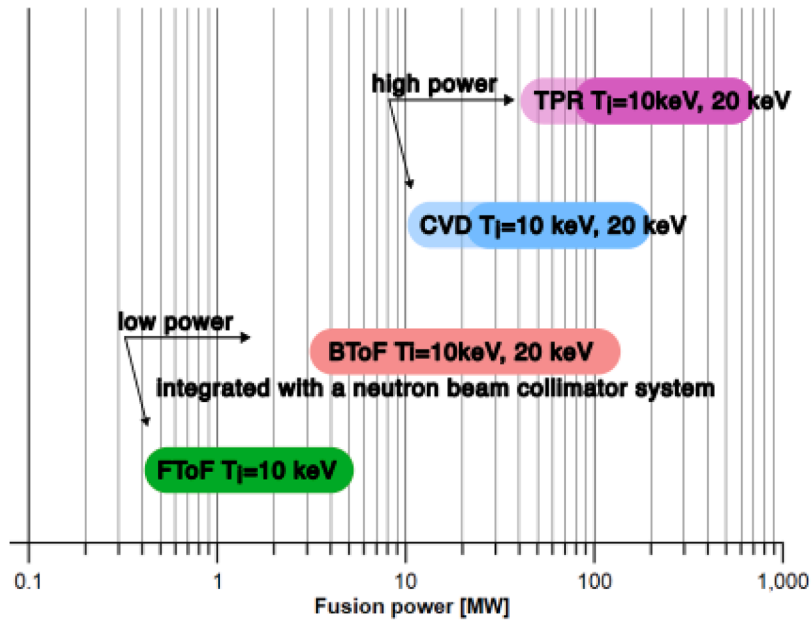


Fig. 2. The operating range of each HRNS spectrometer is due to the fusion power [MW]. The operating range presented takes into account plasma scenarios for different ion temperatures, and in the case of BTof and FToF, the operating range is related to the use of a collimator with a different diameter.

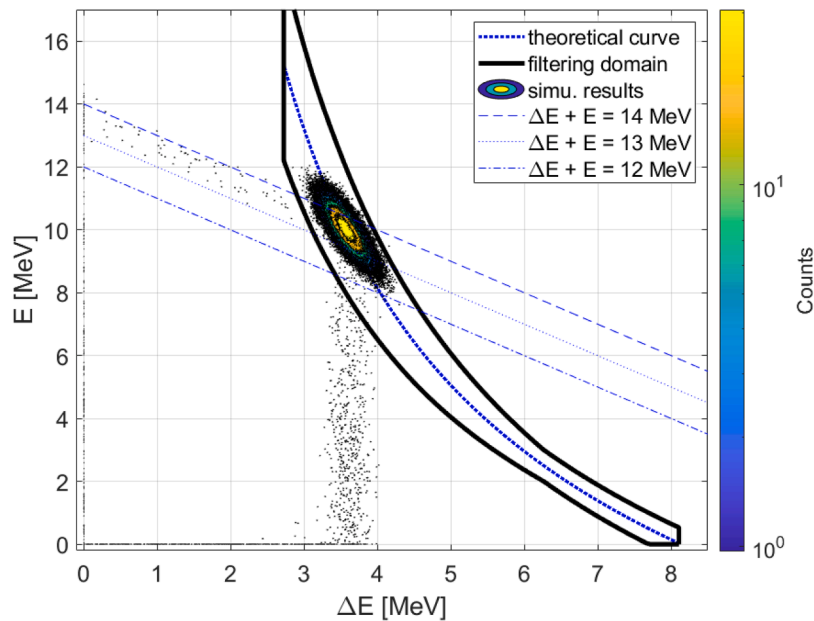


Fig. 3. $\Delta E - E$ diagram of proton energy absorption in silicon detectors of the TPR for a DT neutron spectrum resulting from a thermal plasma with $T_i = 20$ keV.

scenario has been chosen and is based on the 410 MW 2nd ITER plasma scenario (S2) as given in [1]. This scenario was chosen since the associated fuel ion distributions in energy and pitch angle are provided in a format suitable for the analysis tools available.

The main useful signal, as presented in Fig. 3, is around ($\Delta E = 3.8$ MeV, $E = 10$ MeV). Counts outside of the filtering domain correspond to protons reaching or escaping the silicon volume from the side of the detector.

According to the magnetic field distribution maps in the tokamak area, the HRNS system is located in a place where the magnetic field can be at a level of up to 150 mT. For this reason, calculations are being carried out to determine the influence on HRNS subsystems (TPR, CVD, FToF and BTof).

The influence of the magnetic field on TPR measurements is

illustrated in Fig. 4. The main impact of the magnetic field is the deflection of proton trajectories. It should be noted here that only the component of the magnetic field perpendicular to the TPR axis has a significant impact on the proton trajectories. It leads to different impact positions and angles on the silicon detectors, which generate errors in the reconstruction of the most probable scattering angle and slightly distort the $\Delta E - E$ diagram. Therefore, it can degrade the ultimate neutron energy resolution of the TPR system. Preliminary calculations seem to show that adding a magnetic shielding that would decrease the field below 30 - 50 mT would allow for a negligible impact of the magnetic field on the reconstruction process. A trade-off between the magnetic shielding material, thickness and the TPR measurement performance will be found based on HRNS and ITER requirements.

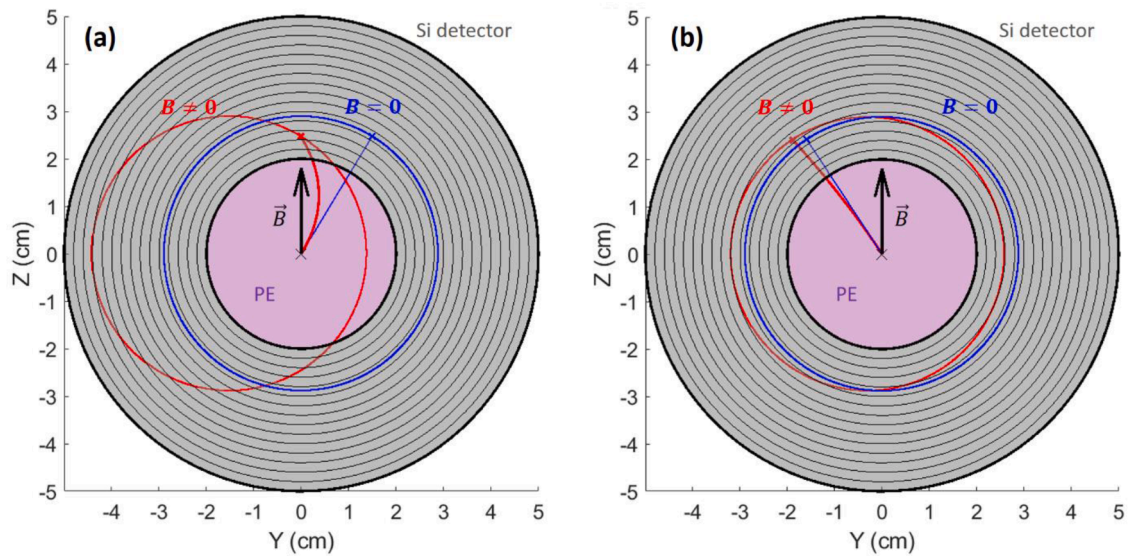


Fig. 4. Spot of proton trajectories on TPR silicon detectors, assuming (for illustration purposes) 14 MeV protons originating from the centre of the PE foil with a scattering angle θ of 5° , under a perpendicular magnetic field of (a) 150 mT and (b) 30 mT.

4. Preliminary neutronic calculation for HRNS system

The MCNP [9] calculations outlined in this work propose the optimal thickness of the radiation shielding around the system to adhere to ITER, HRNS and ALARA requirements. The subsequent phase of MCNP calculations refines the radiation shielding to match the final system configuration during the preliminary design phase. The HRNS system adheres to established dimensions and total mass constraints alongside the integrator port and the 55.Q1 system.

The current design of the HRNS features a simplified geometry comprising two Cuboids enveloped by radiation shielding, intended to minimize the dose from fast neutrons entering the system via the LOS of the HRNS. Additionally, the shielding aims to mitigate background levels resulting from radiation scattering across the entire volume of EQ1. Considering fire safety requirements and seismic risks associated with the project, polyethylene has been identified as a high-risk material due to its low fire hazard parameters. Therefore, efforts were made to find a material with shielding properties, such as polyethylene, but with much better technical parameters, especially in terms of fire resistance. At this stage of the project, all calculations that are carried out assume a new material called SWX-277 [10].

Since SWX 277 is a soft material that provides geometric stability,

the base of the shielding is attached to a 3 mm thick steel frame. In the current model, a 10 cm thick SWX material has been assumed.

The current configuration presented in Fig. 5 includes two cuboids and a shielded cabinet for electronic devices.

A neutron source was defined in front of the entrance to the HRNS system as a source on the surface with a diameter equal to 3.3 cm with the same probability of emission from each point on the assumed source surface. The neutron beam was collimated and emitted parallel to the x-axis. The energy distribution of neutrons was defined based on data taken from the ITER C-model. Using the presented model, the radiation conditions in both cuboids were calculated. Using Mesh Tally, the space distribution maps of neutrons and gamma fluxes, and biological and silicon absorbed dose rates, were obtained. The results were calculated with relative errors below 10 %. The examples of the neutron flux and total silicon absorbed dose rate maps for HRNS are shown in Figs. 6 and 7.

For ITER, high neutron and gamma radiation fluxes may pose a potential problem related to the selection of appropriate components that will ultimately be used to construct diagnostic systems, which is especially important for devices that will operate during the D-D and D-T campaigns [11]. The total neutron emission for the ITER campaign is estimated to range from a minimum of 10^{14} n·s⁻¹ in the

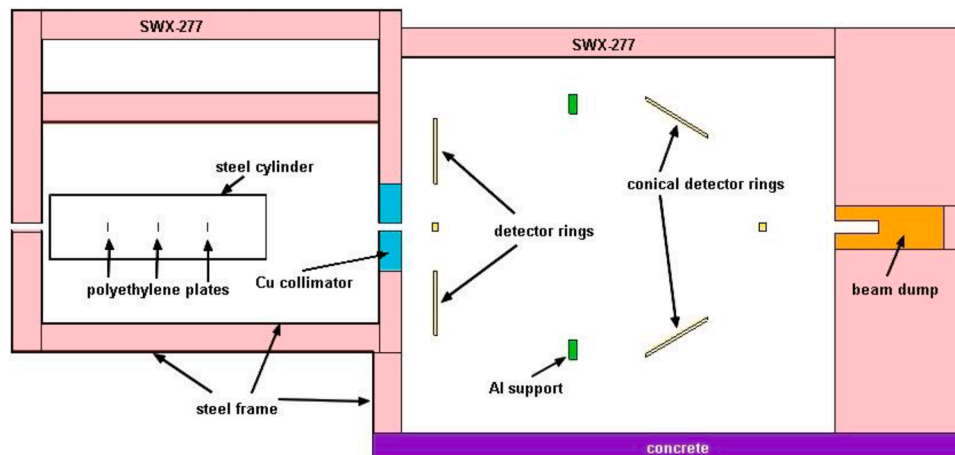


Fig. 5. Vertical cross-section of the current MCNP model used in the simulations. The detectors are of cylindrical symmetry.

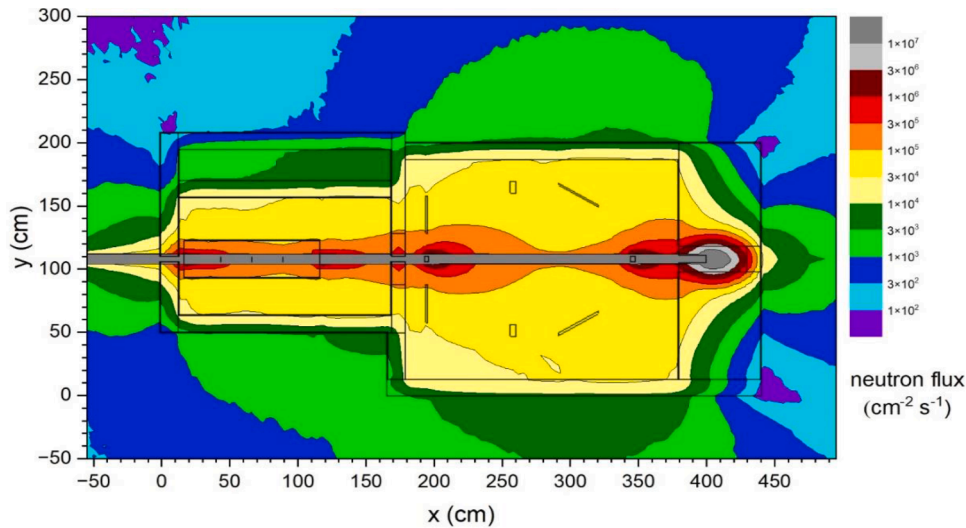


Fig. 6. Neutron Flux in HRNS – vertical view.

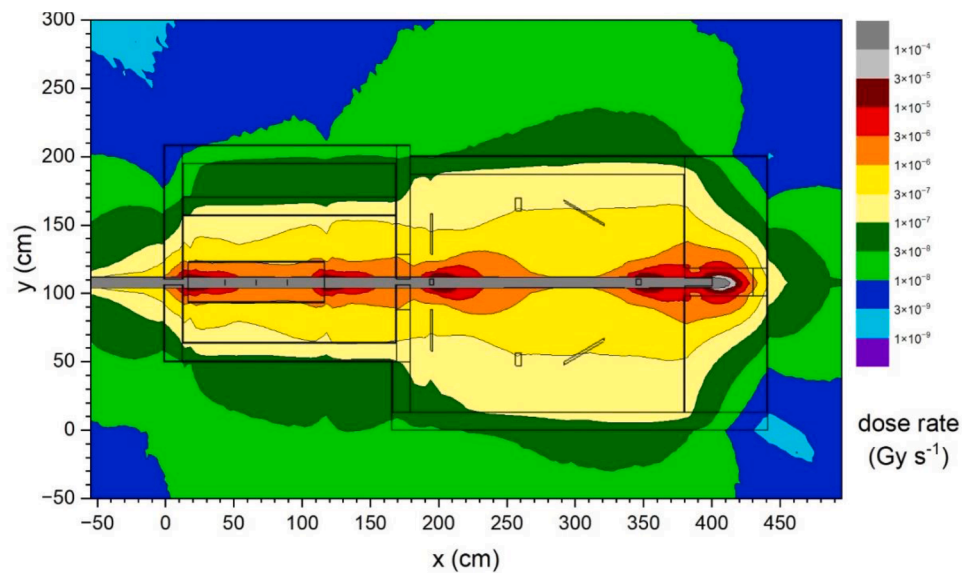


Fig. 7. Total silicon absorbed dose rate in HRNS – vertical view.

deuterium-deuterium (D-D) phase to a maximum of $7.5 \cdot 10^{20} \text{ n} \cdot \text{s}^{-1}$ in the D-T phase [12]. For the HRNS system, some of the electronic devices (preamplifiers and controllers) will be placed in the Port Cell, as close as possible to the TPR and diamond detectors, to minimize issues with an additional electric capacitance of the measurement system. In the bio-shield space for EQ01, the neutron flux ranges from approximately $3 \cdot 10^7 \text{ n} \cdot \text{s}^{-1} \cdot \text{cm}^{-2}$ to $10^8 \text{ n} \cdot \text{s}^{-1} \cdot \text{cm}^{-2}$.

The results presented in this section are a starting point for future analyses related to the appropriate selection of electronics that will work in the PC area. The map of the total silicon absorbed dose rate in HRNS is presented in Fig. 6. From the ITER lifetime point of view ($2 \cdot 10^7 \text{ s}$), the total fast neutron (above 1 MeV) fluence in the volume above cuboid 1 is approximately $3.1 \cdot 10^{10} \text{ n} \cdot \text{cm}^{-2}$ to $9.3 \cdot 10^{11} \text{ n} \cdot \text{cm}^{-2}$, and the dose absorbed by silicon from plasma radiation has a maximum value corresponding to several Gy. If electronics are operated in a radiation environment without any shielding close to the TPR system, they would be at greater risk of radiation damage and, as a result, the HRNS system would lose its operational capacity.

ITER, as a nuclear facility, has strictly defined rules related to radiation safety. One of these rules is an alert thresholds on radiation

conditions for electronic items according to which each electronics located in the tokamak building must be protected from radiation so that the total ionising dose is not greater than 1 Gy, Total neutron fluence (1 MeV Si equivalent) is not greater than 10^8 n/cm^2 and total neutron flux $< 10 \text{ n/cm}^2/\text{s}$. If the conditions are not met, a mitigation plan must be presented.

The presented results indicate that the use of shielding for the electric cabinet is not sufficient due to the high neutron flux. For this reason, work is being carried out on increasing the shielding in this area as well as defining a mitigation plan for the preamplifiers that will be located in this cabinet.

5. Conclusions

The High Resolution Neutron Spectrometer (HRNS) system is designed to demonstrate the capability to measure the fuel ion ratio (n_t/n_d) in ITER plasma core with an uncertainty of $< 20 \%$ and a time resolution of 100 ms. Its multi-spectrometer configuration ensures comprehensive coverage across main DT ITER plasma scenarios, from low to high-power deuterium-tritium phases. The preliminary design

indicates that the thin-foil proton recoil spectrometer (TPR) and the rest of the HRNS detectors can effectively function under specific conditions related to large radiation and EM fields. Preliminary MCNP calculations show the viability of electronic components in the radiation environment over the ITER operational lifetime, with shielding ensuring minimal risk of radiation damage. The preliminary MCNP calculations showed that the current shielding of the area where the electronics are located does not fully meet the requirements of ITER. The results of the studies show that in the next phase of the project, it is necessary to focus on developing other solutions for the electronics in the port cell. Certainly, an appropriate maintenance plan should be prepared, as another shielding material should be considered to reduce the neutron flux in this area.

CRediT authorship contribution statement

J. Dankowski: Writing – original draft, Methodology, Investigation, Conceptualization. **J. Bielecki:** Data curation. **J. Bładek:** Data curation. **S. Conroy:** Resources. **B. Coriton:** Resources. **G. Croci:** Resources. **D. Dworaka:** Data curation. **G. Ericsson:** Resources. **J. Eriksson:** Resources. **A. Wójcik-Gargula:** Data curation. **A. Hjalmarsson:** Conceptualization. **A. Jardin:** Investigation. **R. Kantor:** Software, Methodology. **A. Kovalev:** Resources. **K. Król:** Resources. **A. Kulińska:** Resources. **A. Kurowski:** Resources. **G. Mariano:** Software. **R. Mehrara:** Software. **D. Morawski:** Software. **M. Rebai:** Resources. **M. Scholz:** Conceptualization. **F. Scioscioli:** Resources. **M. Tardocchi:** Resources. **G. Tracz:** Resources. **M. Turzański:** Resources. **U. Wiącek:** Resources, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was done as part of a project co-financed by ITER Organization, France and the Polish Ministry of Science and Higher Education under the program entitled “International Projects Co-financed”

The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

Data availability

No data was used for the research described in the article.

References

- [1] M. Scholz, et al., *Nucl. Fusion* 59 (2019) 065001.
- [2] L. Bertalot, et al., *J. Fusion Energ.* 38 (2019) 283–290.
- [3] B. Marcinkevicius, et al., *Rev. Sci. Instrum.* 89 (2018) 101107.
- [4] G. Ericsson, *EFDA–JET–CP* (10) (2012), 03/12.
- [5] C. Hellesen, et al., *Nucl. Fusion* 57 (2017) 066021.
- [6] J. Ziegler, et al., *NIM B* 268 (11) (2010) 1818–1823.
- [7] Y. Watanabe, et al., *J. Korean Phys. Soc.* 59 (2) (2011) 1040–1045.
- [8] J. Allison, et al., *Nucl. Instrum. Methods Phys. Res. A* 835 (2016) 186–225.
- [9] M.E. Rising, et al., *MCNP® Code Version 6.3.0, Los Alamos National Laboratory Tech. Rep.*, 1, LA-UR-22-33103, Rev. 2023.
- [10] <https://www.shieldwerx.com>.
- [11] M. Dapena, et al., *Fus. Eng. Des.* 86 (6–8) (2011) 1204–1208.
- [12] F. Moro, et al., *IEEE Trans. Plasma Sci.* 50 (11) (2022) 4150–4156.