POLITECNICO
MILANO 1863

SCUOLA DI INGEGNERIA INDUSTRIALE
E DELL'INFORMAZIONE

Executive Summary of the Thesis

Validation and Characterization of an Extended Range Neutron Detector: Design of a Control Network and Software for Multi-Device Management

Laurea Magistrale in Nuclear Engineering - Ingegneria Nucleare

Author: Margherita Morriello

Advisor: Prof. Stefano Luigi Maria Giulini Castiglione Agosteo

Co-advisors: Ing. Michele Ferrarini, Dott. Francesco Bonforte

Academic year: 2023-2024

---

1. Introduction

The National Center for Oncological Hadrontherapy (CNAO) hosts a synchrotron for proton and carbon ion therapy and is expanding to include a BNCT facility and a proton therapy unit with a rotating gantry. Future upgrades will enable the synchrotron to accelerate ions like He, Li, O, and Fe for both therapeutic and experimental purposes. To ensure safety, robust neutron field monitoring is essential for managing radiation from processes as beam injection, extraction, and target interactions. CNAO's radiation protection team plans to implement a continuous monitoring system by strategically placing multiple detectors across the center. A key element of this system is a cost-effective REM counter, based on a Microstructured Semiconductor Neutron Detector (MSND) [3].

This experimental thesis assess two primary goals. The first is the design and implementation of an integrated network and software system for the real-time control and monitoring of multiple neutron detection devices deployed within the facility. This multi-device management system is designed to improve operational efficiency and the reliability of neutron dose monitoring across various facility locations. The second aim focuses on the characterization and validation of the extended-range neutron detector, which involves evaluating its calibration, linearity, and performance in diverse radiation environments.

2. The Detector

The DOMINO neutron detector, utilizing Microstructured Semiconductor Neutron Detector (MSND) technology, provides an efficient, compact, and selective solution for neutron detection. By integrating microstructures within a silicon substrate filled with neutron-reactive material such as ^{6}LiF, the MSND design significantly enhances neutron absorption and detection efficiency, making it a viable alternative to ^{3}He-based systems. The detector is housed in a spherical polyethylene moderator, with additional lead and cadmium elements, as shown in Figure 1. The DOMINO detector interfaces with a Raspberry Pi Model 4 via GPIO pins for efficient data collection and real-time display on the Raspberry Pi. Initially, a Python-based graphical user interface was developed for

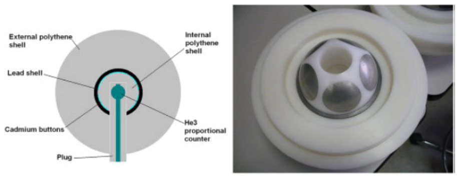


Figure 1: Design of detector moderator.

single-detector control, allowing users to start and stop measurements [1]. However, to satisfy the requirements established by CNAO's radiation protection group, this thesis developed a centralized software solution for managing multiple detectors across the center.

3. Network and Software Development

A network and control software have been developed to facilitate the centralized management of multiple MSND detectors for real-time neutron dose monitoring. Additionally, modifications have been made to the existing counting code written in C to reduced memory footprint.

3.1. CNAO Network

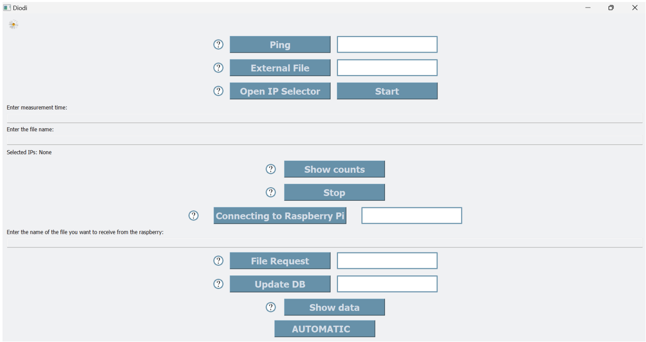
To support CNAO's expansion, an advanced monitoring system has been implemented. Multiple MSND detectors will be strategically placed throughout the facility at key locations, selected based on structural considerations and critical areas.
To enable centralized control, a Local Area Network (LAN) will be established using network switches to connect the Raspberry Pi units to a central PC via Ethernet using the TCP/IP protocol. This network infrastructure will facilitate reliable data transmission and enable remote management of the monitoring devices.

3.2. Advanced Software Version

The visualization software, displayed in Figure 2, has been developed using Python, utilizing the PyQt5 library. The software allows the management of multiple Raspberry Pi devices from a single computer, provided they are connected to the same network. Each Raspberry Pi is assigned a unique IP address, which identifies each device individually. Consequently, each computer will be connected to a series of IP addresses, the number of which depends on the ports available on the switch. The software offers the following capabilities:

- Network functionality verification;
- Initiating and halting measurements;
- Requesting and retrieving files from the Raspberry Pi devices;
- Creating and displaying the database.

These features are linked to specific buttons. The software also monitors system performance, logging each operation and its result in a text file.



Enter measurement time:

Enter the file name:

Selected IPs: None

Enter the name of the file you want to receive from the raspberry:

Figure 2: View of the graphical user interface.

Network functionality verification
To ensure the functionality and reliability of the system, two distinct monitoring functions have been implemented.
The first is the **"Ping"** function, developed to continuously monitor the connection status between the Raspberry Pi devices and the central PC. This functionality is essential, as the detectors will be used to monitor dose levels. Thus, the ability to verify connection and system integrity in real time is crucial. The implementation of the ping function allows for the prompt identification of any disruptions or communication issues.
The second function is designed to verify the presence and non-emptiness of a critical file named **"File_Esterno"**. This file can be modified by the user whenever a new detector needs to be added or replaced, characterized by a different IP address and calibration coefficient. It is essential to ensure that the data within this file are not deleted, as its integrity is crucial for the proper functioning of the entire system, particularly for the creation of the database.

Initiating and halting measurements
The system has been developed to enable users to easily start and stop measurements across

multiple devices while providing real-time visualization of the collected data. The following critical functionalities have been integrated into the interface:

- **Device Selection**: Users can choose which Raspberry Pi to use for the measurement.
- **Measurement Duration**: The interface allows users to specify the duration of the measurement.
- **File Naming**: Users can assign a name to the file that will be created on the Raspberry Pi during the measurement.
- **Measurement Initialization**: Once the device and settings are selected, users can start the measurement process.
- **Real-Time Data Visualization**: The interface includes real-time visualization of the data being collected.
- **Measurement Termination**: Users have the option to stop the measurement at any time.

Requesting and retrieving files from the Raspberry Pi devices

The system also ensures data storage and the creation of a database for easy visualization and archiving. To meet these needs, a function was created to first establish a connection between the Raspberry Pi devices and the master PC. Once the connection is established, users can request files from the different Raspberry Pi units by clicking the **"File Request"** button in the GUI. The requested files are then collected and stored in a designated folder on the PC. Additionally, users can request past measurement files simply by entering the desired file name in the GUI text box. This process streamlines data management, making it easier to organize and analyze collected data without the need for manual file copying from the Raspberry Pi devices.

Creating and displaying the database

After retrieving and saving the files in a designated directory, the **"Update Database"** button is used to create a comprehensive database using SQL. This process organizes data from both the measurement files and the "File_Esterno", which contains additional details such as the Raspberry Pi's IP address, the position in the facility, and calibration coefficient. The resulting database stores key information, including IP addresses, timestamps, dates, integral counts, calibration coefficients, and the total dose.

Once the database is created, the **"Show Data"** button allows users to convert it into an Excel file, which is then automatically opened for easy review. This seamless process simplifies the visualization and analysis of the data, providing quick and convenient access to all relevant information for further evaluation.

3.3. Counting program

This thesis presents modifications to the existing counting code aimed at enhancing data handling capabilities by transitioning from a text file format to a binary format. This shift reduces memory usage, as binary files can store numerical data more compactly than the larger ASCII representation utilized in text files. Additionally, the updated code organizes the output files into a designated directory on the Raspberry Pi, which streamlines file management. To ensure ease of access and interpretation of the recorded data, a C program was developed to convert the binary files back into text format, facilitating straightforward analysis.

3.4. Measurements at CNAO

To validate the functionality of the software and the accuracy of the radiation detectors, two one-hour measurements were conducted at the CNAO laboratory using an Am-Be source and three different rem counters. The detectors were positioned 100 cm from the Am-Be source. After completing the measurements, the radiation dose recorded by the MSND system was compared with the dose predicted by FLUKA simulations.

Meas. Number	IP Address	MSND Int. Counts [counts/h]	Calibration Coeff. [nSv/count]	MSND Dose Rate [μSv/h]
1	169.254.168.17	2336	1.34	3.13
1	169.254.89.134	2667	1.07	2.89
1	169.254.128.219	2872	1.18	3.38
2	169.254.168.17	2355	1.34	3.15
2	169.254.89.134	2659	1.07	2.84
2	169.254.128.219	2822	1.18	3.32

Table 1: Results of the measurements conducted in the laboratory.

The results of the FLUKA simulation indicated a dose of 2.99 µSv/h at 100 cm from the source.

As shown in Table 1, the recorded doses closely aligned with the expected values, staying within a 30% margin of uncertainty, accounting for measurement errors and geometric factors. This comparison confirmed the proper operation of the network architecture and control software, while further validating the functionality of the detector.

4. Characterization and Validation of the detector

To characterize the REM counter, experimental campaigns were conducted to assess its linearity and calibrate extended-REM counters at the Czech Metrology Institute (CMI), a leading center for the calibration of radiation detection instruments. Additionally, dose response measurements were carried out in mixed radiation fields at the CERN-EU Reference Field (CERF), which simulates the radiation environments typical of high-energy hadron accelerators.

4.1. Calibration coefficient evaluation

The primary goal of these measurements was to determine the calibration coefficient, k, which converts recorded counts to dose in nSv. Measurements were conducted with an Am-Be source at a certified dose rate of $36 \pm 1.66\,\mu$Sv/h, with detectors positioned 50 cm from the source. The calibration coefficient for MSNDs was calculated as:

$$k = \frac{H^*(10)}{\text{counts}}$$

where $H^*(10)$ is the ambient dose equivalent, integrated over the measurement time t. Calibration across eight detectors produced an average coefficient of 1.29 nSv/count.

4.2. Linearity test

The secondary goal of the experiment was to evaluate the linearity of the detector, which was tested using an Am-Be source. Measurements were conducted at various distances from the source, ranging from 15 to 150 cm, which corresponded to reference dose rates between 0.13 mSv/h and 13 mSv/h. The evaluation of linearity involved integrating the recorded counts and the reference doses over a defined measurement time t. The results are summarized in Figure 3. Both systematic and statistical uncertainties were considered for the real and ideal responses, with uncertainties combined quadratically to ensure a thorough assessment of measurement accuracy. Analysis of the data revealed that the detector maintains linearity up to approximately 3 mSv/h. Although this limit may seem low compared to traditional neutron detectors, it aligns well with the operational requirements of this specific detector.

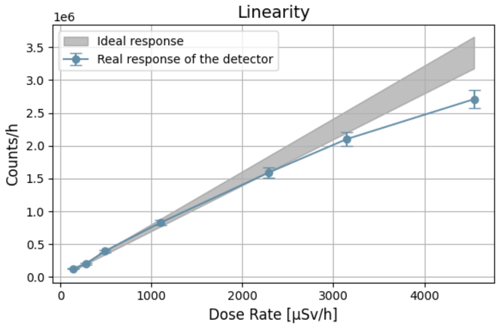


Figure 3: Plot of the linearity test; the shaded gray area represents the ideal response with a propagated uncertainty of 7%.

4.3. Measurements at CERF facility

The CERF facility simulates mixed radiation fields similar to those encountered near high-energy hadron accelerators. Dose measurements can be performed on two different roofs: a concrete roof, with ambient dose equivalent rates ranging from 5 to 250 μSv/h, and an iron roof, with dose rates between 18 and 360 μSv/h. These values are well below the detector's saturation threshold of 3 mSv/h. An example of the detector positioning for dose measurements is shown in Figure 4.

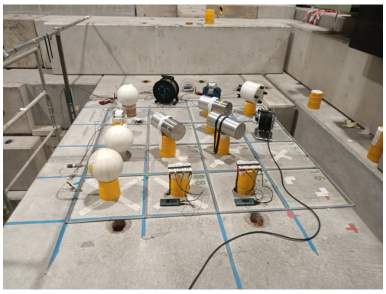


Figure 4: Positions available on the concrete top.

The collected data were analyzed, focusing on a comparison between the dose measured by the MSND and the dose values calculated using FLUKA, alongside the ionization chamber (IC) counts provided by the CERF radioprotection team. Specifically, the dose rate for the REM counters was determined by applying calibration coeffiecients obtained at the CMI facility to the counts recorded by the MSND. In contrast, the FLUKA dose rate was derived by multiplying the reference FLUKA values at each measurement position by the IC counts reported by the facility team, [2]. The data analysis indicated a consistent underestimation by the detector compared to the FLUKA-calculated values, with an average underestimation of 9% for the concrete top measurements and 30% for the iron top measurements. This underestimation, can be attributed to the different neutron emissions from the iron top. These emissions occur within an energy range where the rem counter is known to underestimate the ICRP coefficients.

5. Experimental Campaigns at CNAO

The measurements at CNAO aimed to validate the newly developed radiation monitoring system and the individual detectors.

The first set of measurements was conducted in Treatment Room 3 to test the functionality of individual detectors within a typical treatment field, using a phantom to simulate a patient.

The second set of measurements was conducted to verify the functionality of the network and control software in managing multiple devices simultaneously. The results confirmed that both the detectors and the integrated system are highly suitable for continuous monitoring at CNAO. In particular, the developed system meets the requirements, especially its ability to perform extended measurements, ensuring reliable and continuous monitoring.

5.1. Measurements in treatment room three

Measurements were carried out in treatment room 3, where a head-shaped and a torso-shaped phantom were irradiated with proton beams at energies ranging from 60 to 230 MeV, delivering a 1 Gy dose, replicating clinical treatment conditions. The primary objective was to evaluate the performance of the individual detectors under realistic therapy scenarios. The detectors were positioned around the phantoms at various angles to measure the angular distribution of neutrons, which were generated by interactions between the proton beam, the phantoms, and the surrounding room elements. Results show that the highest neutron dose was recorded at 0°, in line with the primary beam direction, indicating that secondary neutron production is largely concentrated along the beam path. The larger torso phantom exhibited significantly higher dose values at 0° compared to the head phantom, likely due to its greater volume and cross-sectional area, which enhances neutron production. A comparison of dose measurements obtained from WENDI detectors and MSNDs highlighted generally consistent results, validating the MSND's reliability under these experimental conditions, as shown in Figures 5 and 6. However, discrepancies were observed due to variations in detector design and material composition, affecting interactions with heavy charged particles.

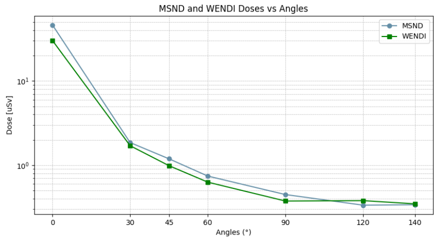


Figure 5: Angular dose distribution of MSND and WENDI detectors for torso phantom.

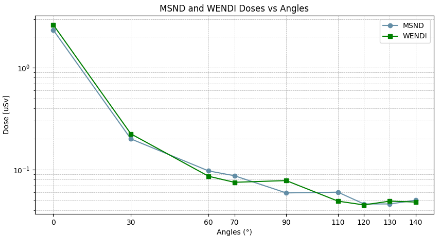


Figure 6: Angular dose distribution of MSND and WENDI detectors for head phantom.

5.2. Measurements in the XPR

In collaboration with the CREMA project, the experimental measurements in the XPR room aimed to validate the neutron dose monitoring system developed in this thesis under realistic operational conditions. This testing evaluated both immediate performance and long-term stability to confirm the system's suitability for continuous dose monitoring.

The measurements were conducted over two nights, starting with three short-duration tests using both proton and carbon ion beams, followed by a continuous four-day measurement period. The setup was irradiated with proton beams at an energy of 227.2 MeV and carbon ion beams with energies ranging from 300 to 400 MeV/u. These beams interacted with the setup components, resulting in the production of a neutron field. This field was monitored by five MSND detectors and one WENDI detector. The MSND detectors were placed at varying angles (100°–170°) and distances (2–4 m) from the irradiation point to capture spatial dose variations, with the WENDI detector positioned at 90° and 4.2 m as a benchmark. The results demonstrated consistency in dose measurements between MSND and WENDI detectors, with dose values decreasing as the angle from the source increased, validating the system's accuracy. The extended measurement confirmed the stability of the network and software over time, including continuous data collection, storage, and analysis. Data retrieval, database organization, and visualization processes were smoothly managed, verifying the system's robustness and operational readiness for continuous neutron dose monitoring applications.

6. Conclusions

This thesis presents the development of a continuous neutron monitoring system at CNAO, designed to support the expansion of the facility. The system integrates network and control software for the MSND-based REM counters, enabling real-time monitoring of ambient neutron doses and beam losses across the facility. The software allows users to remotely control measurements, visualize data, and store results in a centralized database. It enables simple and simultaneous control of multiple devices, ensuring efficient management across the facility.

Data from the CMI and CERF facilities were analyzed to determine the calibration factor and evaluate the performance of the REM counter. At CMI, an average calibration coefficient of 1.29 ± nSv/count was determined using the Am-Be source, and linearity tests identified a saturation dose rate of approximately 3 mSv/h, confirming the REM counter's suitability for beam loss monitoring. Data from CERF revealed a slight underestimation of dose in high-energy neutron fields, a known behavior in REM counters generally calibrated with Am-Be or ^{252}Cf sources, which peak at 1-10 MeV.

Two validation experiments were conducted at CNAO to fully assess the detectors and monitoring network. In the first, individual detectors were tested. The MSND measurements were compared to WENDI detectors, showing consistent results, validating the reliability of the MSND. The second experiment focused on verifying the entire monitoring system in the Experimental Room. Proton and carbon ion beams were used, with multiple measurements conducted to test both short- and long-term functionality. Despite the influence of complex room geometry, the results closely aligned with WENDI data, confirming the system's robustness. After four days of continuous operation, the system's data were successfully retrieved, stored, and analyzed, demonstrating its capability to autonomously monitor and manage data over extended periods.

In conclusion, the developed system effectively monitors ambient dose levels and beam losses across the CNAO facility, providing real-time feedback and efficient data management. It enables simultaneous monitoring of multiple detectors, even at distant locations, and operates autonomously for extended periods, ensuring accurate and timely data for ongoing research and facility operations.

References

[1] Francesco Bonforte. Radiation physics and experimental characterization of the radiation fields produced by a heavy ion accelerator for medical applications. 2024.

[2] F Pozzi and M Silari. The cern-eu high-energy reference field (cerf) facility: New fluka reference values of spectral fluences, present and newly proposed operational quantities. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 979:164477, 2020.

[3] Rotunda Scientific Technologies. Microstructured semiconductor neutron detector, 2021.