MUNI
FI

Faculty of Informatics
Masaryk University

# Spectrometric systems for mixed field of gamma radiation and neutrons

Habilitation Thesis
(Collection of Articles)

Zdeněk Matěj

October 2019
Brno, Czech Republic

# Abstract

Devices working with ionizing radiation are nowadays used in many areas. It is not only the energy industry, but also there are, for example, many therapeutical and diagnostical procedures in medicine that use this kind of radiation. Many research laboratories try hard to describe and simulate the behavior of these devices in relation to their functionality and to the safety of the personnel using it. Devices generating neutron radiation are of special concern. This is common for example at cyclotrons producing radiopharmaceuticals. This kind of radiation is accompanied by gamma radiation and it is not possible to measure it independently in wider energy intervals. Thus it is important to focus on methods and algorithms that enable us to suitably distinguish individual radiation components and evaluate them independently. There are several methods to measure neutron radiation, e.g. activation analysis, Bonner spheres, proportional counters, time of flight, etc. The quality of the output of separation methods depends on the quality of the input. This data can be obtained in varying quality nowadays. If we concentrate on the energy range of neutrons produced in nuclear reactors, the range is approximately 0.5 to 20 MeV. For the best results, it is necessary to design and manufacture the whole spectrometric system together with its various modules from scratch. It is also necessary to validate and verify individual methods and algorithms used. However, these procedures cannot be performed only with generated or simulated data, it is important to use neutron sources that are well defined using statistical methods (for example reference fields).

The aim of this work is to acquaint the reader with research results in the area of the design of individual modules and algorithms for spectrometric systems, including examples of validation and verification with real experiments on nuclear facilities. This work also deals with the hardware and software design of the spectrometric system.

This work is structured as a collection of selected academic publications supplemented with introductory commentaries that provide necessary context. It is divided into two parts. The first part focuses on the description of the spectrometric system, methods, algorithms, and tools that we devised for the spectrometric system for mixed radiation fields. The second part describes improvements of individual algorithms and modules all the way to the verification and validation of the spectrometric chain, including hardware and software tools.



**Keywords:** Spectrometry, neutron, gamma ray, two-prametric, digitalization.

## Abstrakt

Zařízení pracující s ionizujícím zářením se v dnešní době používají v mnoha odvětvích. Nejedná se jen o energetiku, ale například i v medicíně je dnes mnoho postupů spjato s nutností využívat těchto záření. Mnohá vědecká pracoviště se snaží co nejlépe popsat a simulovat chování těchto zařízení vzhledem ke kvalitě funkce samotné ale i k bezpečnosti používání a ochrany obsluhy. Velký problém spočívá především u zařízení generující neutronové záření. Toto záření totiž vzniká velmi často zároveň s gama zářením a není možno ho měřit samostatně pro větší energetické rozsahy. Proto je nutné se zaměřit na metody a algoritmy, které nám umožní nějakým způsobem oddělit jednotlivé složky záření a ty dále vyhodnocovat samostatně. Možností a metod, jak měřit neutronová spektra je více. Například metody aktivační analýzy, Bonerovy sféry, proporcionální detektory, Time of Flight atd. Kvalita výsledků z separačních metod a algoritmů velmi závisí na kvalitě vstupních dat. Tyto data lze dnes získat mnoha způsoby v různé kvalitě. Pokud se zaměříme na energetické rozsahy neutronů, které jsou často spojovány s jadernými reaktory, pak uvažujeme rozsah od 0,5 až 20 MeV. Pro co možná nejlepší výsledky v této oblasti je však nutné celý spektrometrický systém pro tato směsná pole neutronů a gama záření navrhnout a vyrobit nový i se všemi moduly. Při tvorbě takového systému je nutné validovat a verifikovat jednotlivé algoritmy a moduly. Tyto procesy však není možné provádět jen s generovanými nebo simulovanými daty, ale je nutné použití zdrojů neutronů, které jsou dobře popsané a spočítané pomocí statistických metod.

Cílem práce je seznámit čtenáře s výzkumnými výsledky v oblasti návrhu jednotlivých modulů a algoritmů pro spektrometrické systémy. Součástí práce jsou ukázky jejich validace a verifikace s reálnými experimenty na jaderných zařízeních. Zároveň se práce věnuje i problematice návrhu spektroskopického systému po softwarové i hardwarové stránce.

Práce je strukturovaná jako kolekce vybraných vědeckých publikací doplněných o úvodní komentář, který poskytuje k výsledkům potřebný kontext. Práce je rozdělena na dvě základní části. První část je zaměřena na popis spektrometrického systému, metod, algoritmů a nástrojů, které jsme navrhli pro spektrometrické systémy pracujících ve směsných polích záření. Druhá část obsahuje popis vylepšení jednotlivých částí algoritmů a modulů až po verifikaci a validaci spektrometrického řetězce včetně softwarových a hardwarových nástrojů.


**Klíčová slova:** Spektrometrie, neutron, gama záření, dvoj-parametrický, digitalizace

## Acknowledgements

I would like to thank my wife Lenka and the whole family for their support and understanding in solving their work and research tasks. I would also like to thank my long-time trainer Vaclav Prenosil for his patience and for providing expert knowledge and advice. I would also like to thank František Cvachovec for his professional guidance and much valuable experience. Both are a great role model for me.

I also thank my colleagues at or outside the university. Especially also to my colleague Michal Košťál, who supports professional knowledge from other fields than just informatics. Thank you.

*Zdeněk Matěj*

# Contents

# Part I

# Commentary

# Chapter 1

# Introduction

Spectrometric systems for mixed fields of neutrons and gamma rays are indispensable for most experimental research activities in the fields such as neutron spectroscopy and other experiments with ionizing radiation, e.g. at research nuclear reactors or particle accelerators (examples [2], [23], [29]). Such systems usually consist of many different independent parts that allow changing the configuration and parameters of the system depending on the requirements of the experiment. Precise knowledge of neutron spectra is necessary to estimate the lifetime of nuclear devices or to evaluate experiments.

First and foremost, the spectrometric system contains a detector, which may be plastic, liquid etc. These types of detectors have beedn known for decades. Incident neutrons and gamma rays interact with the molecules of the detector and weak intensity scintillation photons are generated.The detector is connected with photomultiplier which transforms scintillation photons into electric charge. The output impulse is obtained by the integration of this charge at the output impedance of the PMT. There it needs to be adjusted and processed. In analog systems, this processing was done with integration, derivative and delay lines . With digital systems impulses are sampled and digitized and transformed into vectors. These are further processed digitally. An example of the spectrometric system is presented in Figure 1.1.

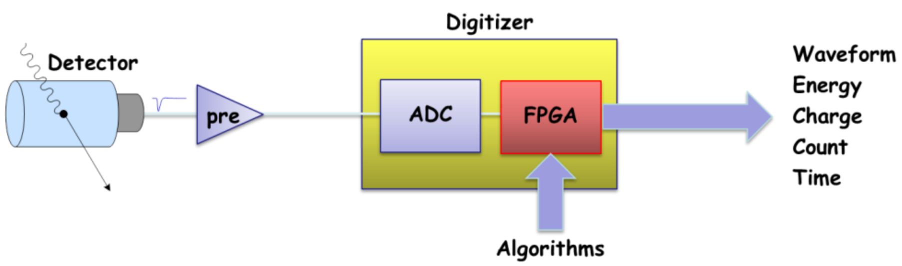


Figure 1.1: Spektrometric system based on digital technology. [3]

One of the problems when measuring neutrons are the detectors themselves. With scintillation detectors, it is not possible to measure only neutrons for the energy range above 0.5 MeV. They are sensitive to gamma photons as well. The results would be affected by this depending on the intensity and energy of this secondary field. With digital systems, it is possible to better separate these components and evaluate them independently. The evaluation itself is not a trivial problem either. We cannot estimate the results simply on the ratio of these components. We must incorporate the energy of incident particles into our analysis. There are several ways to evaluate the type and energy of the particle. Since there is pressure to decrease the acquisition times and we want to process a significant particle count per second we should consider methods and algorithms that can do it very fast with minimum delays. The problem is not just algorithms but the whole design of the spectrometric system. This design affects the parameters of input data and thus the quality of its function.

Especially with the introduction of digital systems many of these disadvantages were eliminated [25]. However, the limitations posed by the physical principles of detectors remain. Even modern scintillation materials remain sensitive to more types of radiation [28], [26]. The stilbene scintillation material is still considered to be the best for neutron energy range 1 – 20 MeV [31]. The evaluation of the data from these detectors is a necessary step in the validation and verification of the separation algorithms. Measured neutron spectra are evaluated in our case by deconvolution of proton response spectra by Maximum Likelihood Estimation [5].

There is a significant amount of literature dealing with spectrometric systems [9]. They often do not contain enough information to evaluate the quality of the system itself. My research and experiments show the possibilities of our spectrometric system in nuclear experiments and certify to its functionality.

## 1.1 Focus of the thesis

This work focuses on summarizing my results from the area of algorithm and method design for the spectrometric system. In cooperation with colleagues working in the area of nuclear and neutron physics, we were able to validate and verify the system during several nuclear experiments. The results were published in enclosed publications. Most of these results were published in renowned physical journals as experiments with real data are the best proof of the quality of the separation and evaluation algorithms. The publishing of these algorithms would not be enough and real experiments are very valuable. Journals and conferences focused on physical research are the most suitable for publishing this kind of results.

In the accompanying text, I first introduce to the reader the area of spectrometric systems and then I focus on the methods, algorithms, and tools we designed for mixed field spectrometric systems. Then I describe the validation and verification of the system including the software and hardware tools. This work is partially a follow-up and an expansion to my dissertation thesis that described the basic digitization of the neutron/gamma mixed field spectrometric system [24]. The spectrometric system designed was based on this thesis and received very good reviews from the physical community (for example International Atomic Energy Agency).

## 1.2 Thesis structure

This text is divided into different parts based on my work on various modules of the spectrometric system.

The first part of chapter 2 describes methods, algorithms, and tools that we designed for mixed field spectrometric systems. The second part focuses on data processing and evaluation.

Chapter 3 contains the description of method and algorithm improvements of various system parts. It also cover verification and validation of the spectrometric chain including software and hardware tools.

Finally, chapter 4 discusses possibilities of future work and development of the spectrometric system and summarizes achieved results. The collection of publications is attached to the end of this work.

# Chapter 2

# Spectrometry of mixed field neutrons and gamma radiation

There are several challenges in the area of mixed field spectrometry. The first one is the choice of a suitable detector based on the studied energy range of neutrons or gamma photons. The research in the area of detectors is closely connected with spectrometric systems. It depends on the desired parameters and the arrangement of the system.

The spectrometric system is a chain beginning from the detector and ending with the software for the evaluation. Depending on the chosen detector suitable components and algorithms are selected. The desired physical quantity is the spectral neutron flux density or gamma flux density. It is not desirable to evaluate the individual components only but the whole system.

The second task is the choice of suitable electronics. Firstly, it is important to achieve the best possible linearity of the output signal based on input signal. This is a challenge for not only component manufacturers but also for research groups [27]. The output signal is then processed. In the past this was done with analog systems however, this approach was abandoned and fast analog-digital converters are used instead. Good knowledge of signal characteristics is needed for this approach. Nevertheless analog parts are still present and cannot be completely avoided. The signal needs to be adjusted to achieve the best input for ADC (Figure 2.1).

After the ADC conversion, digital values need to be preprocessed and evaluated. An example of this evaluation is displayed in Figure 2.2. This is done in digital circuits. Fast processors or field-programmable gate arrays are most commonly used. It is important to realize that tens of gigabits per second are being processed here. The evaluation is the final step.

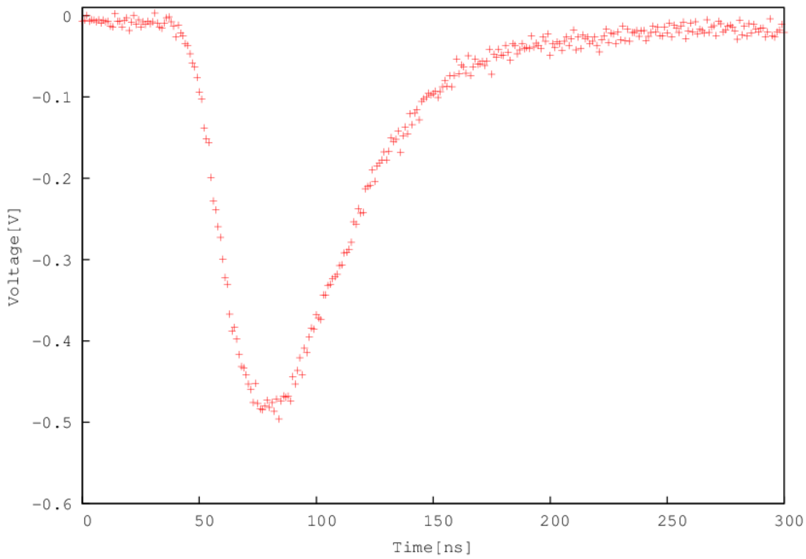


Figure 2.1: The output signal form the spectrometric detector. [24]

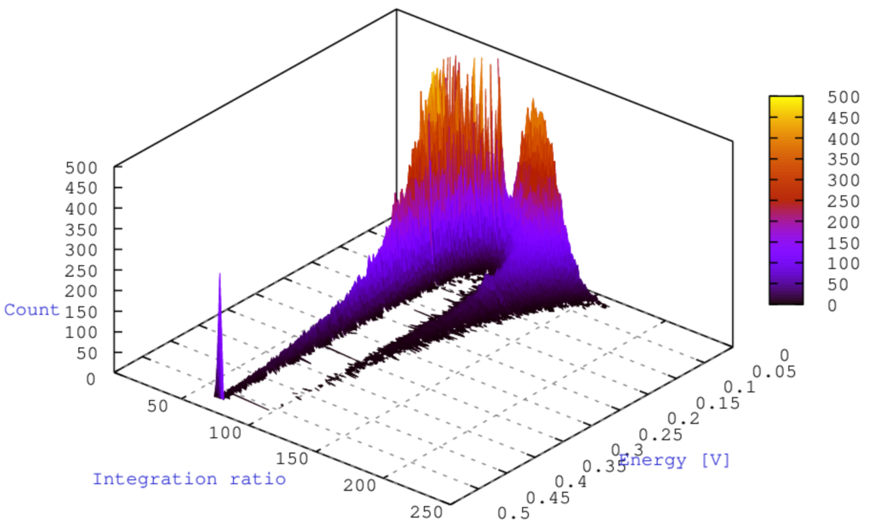


Figure 2.2: The output after filtration and separation algorithms. [24]

## 2.1 Data processing

As was mentioned before, the results need to be evaluated to all the processing. It is thus difficult to simulate or test individual components. The whole system needs to be used. Measured neutron spectra are evaluated by deconvolution of proton response spectra by Maximum Likelihood Estimation [5].

There is a great variety of algorithms for impulse separation [20] [8] [4] [21]. Some of them work in the time domain, others in the frequency domain [22]. I researched the choice of the best algorithm in my dissertation thesis. The result was that the best algorithms for fast data processing are those based on charge comparison. These algorithms work with the information calculated from the integral of the selected part of the impulse and their ratios.

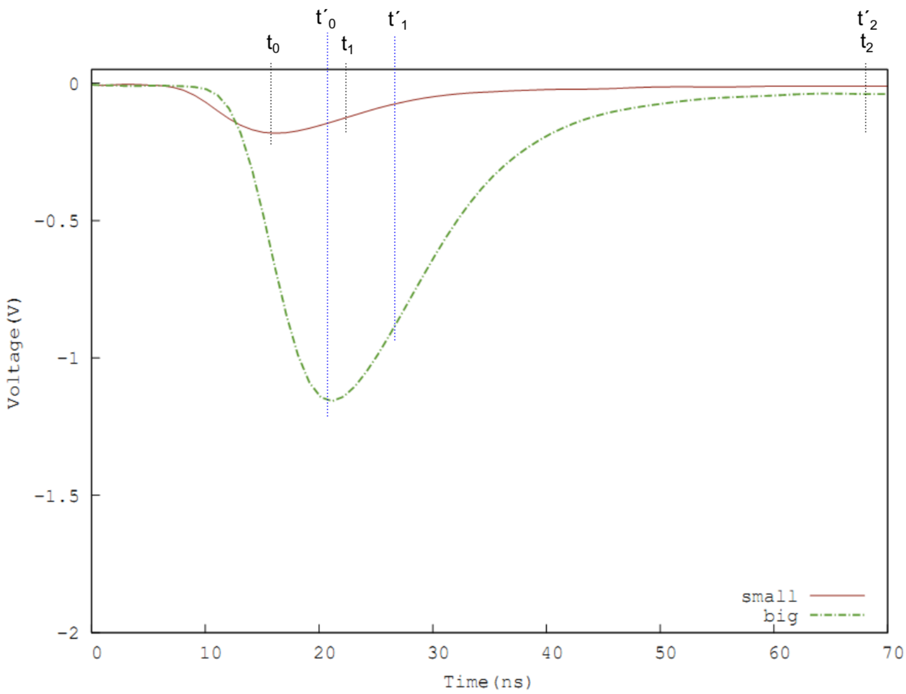


Figure 2.3: The output after filtration and separation algorithms. [24]

Pulse shape discrimination $D$ is realized by an integration method which in principle lies in comparison of the area limited by part of a trailing edge of the measured response $Q_1$ with the area limited by the whole response $Q_2$. $Q_1$ and $Q_2$ areas are the integrals over time are expressed in Equation 2.1 and their illustration is shown in Figure 2.3.

$$Q_1 = \int_{t_1}^{t_2} U(t)dt, Q_2 = \int_{t_0}^{t_2} U(t)dt, D = \frac{Q_1}{Q_2} \tag{2.1}$$

Charge $Q_1$ is determined by an area limited by the course of response within time interval $t_1$ , $t_2$. This method numerates charge $Q_2$ determined by an area that is limited by the course of response within firmly defined times $t_0$ and $t_2$. Times $t_0$ and $t_2$ are parameters dependent on parameters of the measuring apparatus. Time $t_2$ is defined as the time of the end of response. In this way, it is possible to eliminate the classification mistakes caused by dependency of the response shape on its amplitude. The implemented integration method has linear computational complexity and therefore it is suitable for online measurement with a high number of impulses per second. The second parameter of the spectrometric system is the energy of the detected particle. The energy is evaluated from the integral of the whole response.

## Contributions

In the past years, Ihave been mostly working on the development of the software tools for measured data evaluation. I focused on algorithms for filtration and visualization.

Since 2014, together with my colleagues, we have been developing spectrometric software Figure 2.4 that contains a lot of tools for filtration, visualization, and evaluation of spectrometric data. It allows for comfortable online or offline data evaluation and presents an interface for setting up the spectrometer parameters. These parameters affect the measuring range and allow for the best impulse separation. Additionally, the software visualizes the measured data in real-time and enables the calibration of the system. Response function matrices can be added and used to evaluate spectra. For example this allowed us to evaluate the photon spectrum from medical cyclotron (IBA [[6]]).

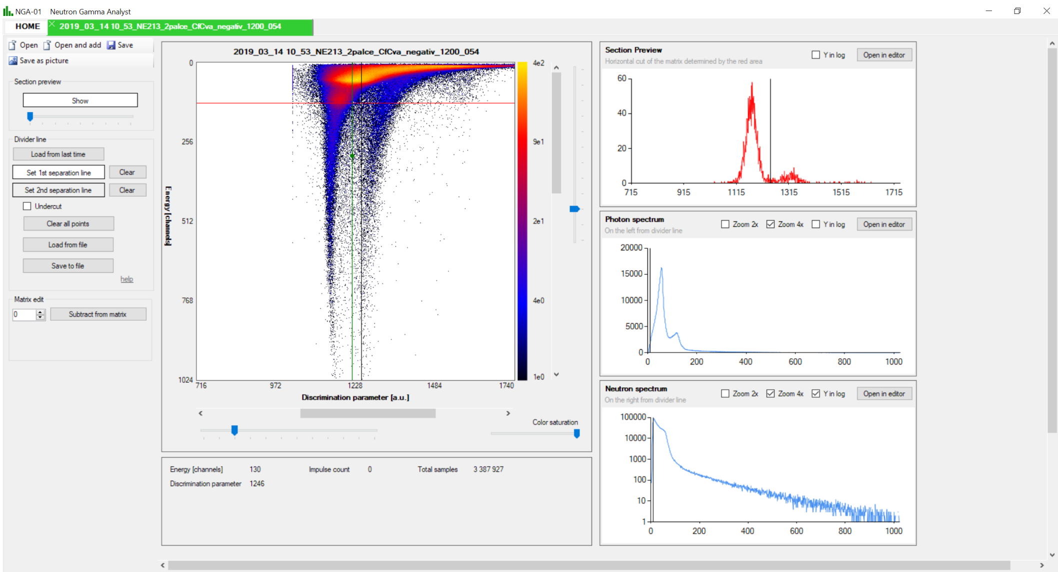


Figure 2.4: Software for data processing (Author)

The first results of the development of the spectrometric software were obtained with a plastic scintillator while measuring monoenergetic neutrons generated at the Van de Graff accelerator. This accelerator is well described and the expected results are known. These measurements brought us a lot of new information and most of all showed us the disadvantages of current algorithms. A great benefit was the test of our system on real data. This paper [7] was the first from a collection created in cooperation with the research department of the VF, a.s. company. It proved that the spectrometric system concept is a correct approach and its development will continue.

## Articles in Collection

[7] A. Jančář, Z. Kopecký, J. Dressler, M. Veškrna, Z. Matěj, C. Granja, and M. Solar. Pulse-shape discrimination of the new plastic scintillators in neutron–gamma mixed field using fast digitizer card. *Radiation Physics and Chemistry*, 116:60 – 64, 2015

I cooperated on the design of the separation algorithm and wrote the part of the text. Contribution 15%.

# Chapter 3

# Enhancement of the spectrometric system

Enhancement of the spectrometric systems shows an important step in improving the functionality of the spectrometric system Figure 3.1 and of its parts. Besides the improvement of the separation method, we focused on enhancing the linearity and stability of the whole system. The challenge is not only the individual measurements and evaluations but also the repeatability of experiments and long term stability of the results.


Figure 3.1: NGA-01 spectrometric system (Author)

## Contributions

The presented paper [17] demonstrates the utilization of the spectrometric system while measuring at well-defined research reactor LR-0. Since it focuses on the area of the development of the new generation of nuclear reactors it gained many citations. The measured results are compared with the calculated ones. In this paper we verified the capability of the apparatus in the real running reactor in cooperation with Research Center Řež. Based on these measurements the analog parts of signal wires were adjusted and thus the maximum count rate per second was increased from 100 000 impulses per second to 300 000 impulses per second. My contribution was in the research of the analog technologies and the adjustment of preamplifier parameters to improve the behavior of the system. The increase in the impulse count rate was one of the main reasons to use digital technologies. The operation of nuclear facilities is expensive and higher throughput of a measuring apparatus allows for shorter measuring periods. Besides that every nuclear device has some minimum particle flux rate at its proximity which is determined by its construction and usage. Examples of facilities with high flux rates are active zone of nuclear reactors or areas in close proximity to particle accelerators. Here measuring apparatus with lower throughput cannot be used at all. The verification was done in a specifically adjusted active zone of the research reactor LR-0.

## Articles in Collection

[17] M. Košťál, M. Veškrna, F. Cvachovec, B. Jánský, E. Novák, V. Rypar, J. Milčák, E. Losa, F. Mravec, Z. Matěj, J. Rejchrt, B. Forget, and S. Harper. Comparison of fast neutron spectra in graphite and flina salt inserted in well-defined core assembled in lr-0 reactor. *Annals of Nuclear Energy*, 83:216 – 225, 2015

I cooperated on the design of the separation algorithm and filtration methods and wrote the part of the text. Contribution 10%.

## 3.1 Methods and algorithms

Applicable algorithms for the neutron/gamma separation were mentioned in section ??. I described the selection of a suitable method previously in my dissertation thesis. However the research shows that there is a space for further improvements. For example with the setup of suitable parameters for the separation algorithm it is possible to achieve better result especially in the lower energy parts of the spectrum (Figure 3.2). Many changes do not occur only in the algorithm itself but to the whole measuring chain.

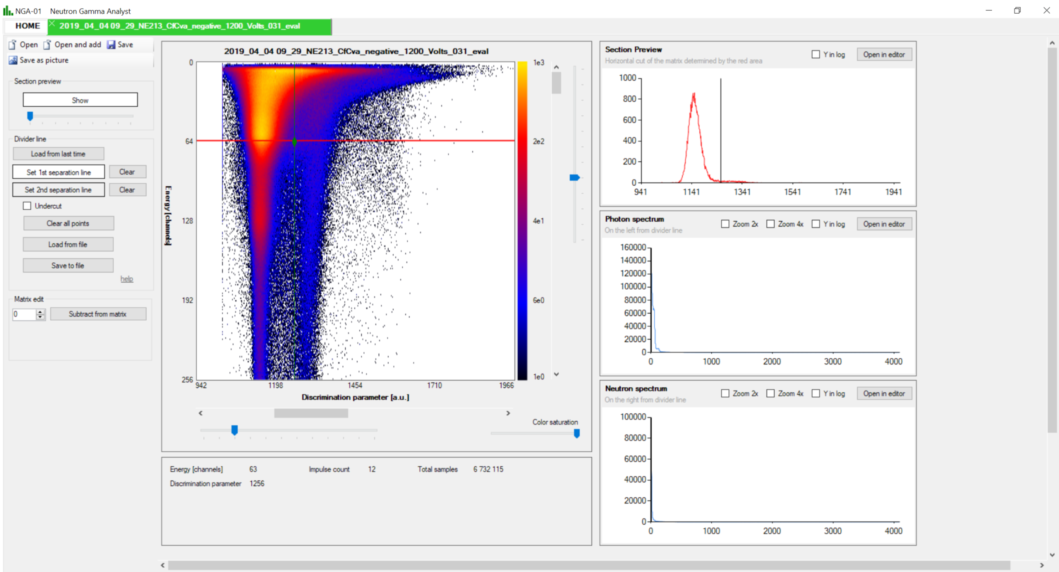


Figure 3.2: Spectrum - demonstration (red line) of problematic areas in the separation of individual areas of the spectrum (two separate “trousers”). At this point it is not possible to separate the other parts of the spectrum. (Author)

For this reason, there are algorithms at the low level of processing that improve the quality of the data. DC filtering algorithms belong to this category. The elimination of this component improves the determination of the energy parameter. This component can be removed by subtraction of the offset determined before the arrival of the impulse. Our research showed that this needs to be done before each impulse to minimize the effect of previous impulses. Another algorithm is the high-frequency noise filter. We experimented with several kernel filters as low-pass filters, but the moving average filter seems to work the best for us. In case of the FD-11 spectrometric system this needs to be done with the data rate of 24 Gbit per second. That means that these algorithms need to be implemented directly into the FPGA.

Another crucial algorithm that has to be implemented directly in the FPGA is the separation algorithm. Figure 3.3 shows the parameters that need to be set up correctly.

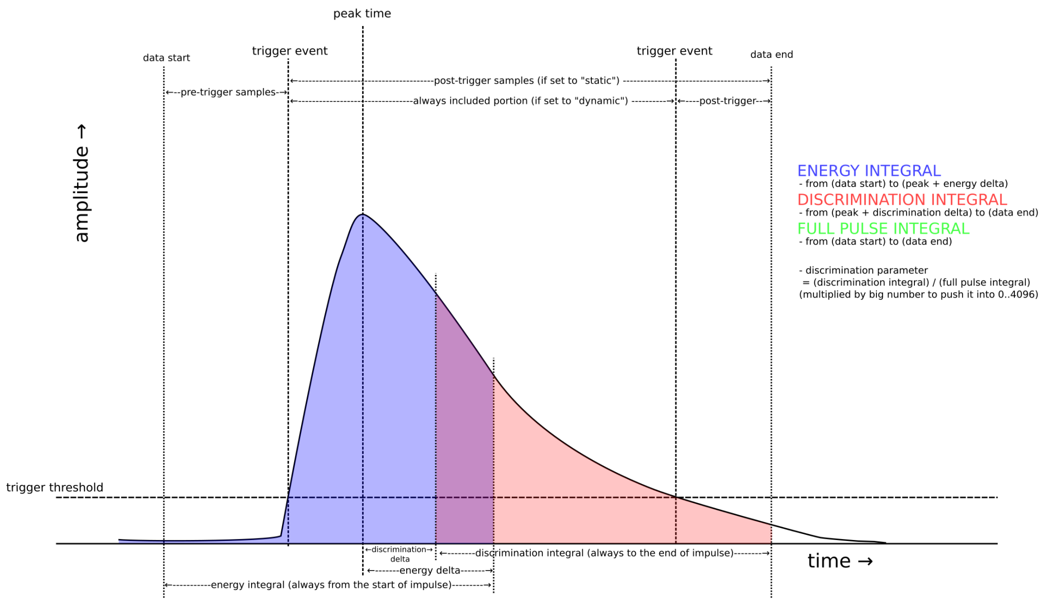


Figure 3.3: Integration method - parameters for NGA-01 (FD-11). (Author)

The digital signal $i(t_o)$ from the ADC (Figure 3.4) is filtered by a software low-pass averaging filter. It is necessary to solve the problem related with the DC coupling offset voltage from the output of the photomultiplier. For this purpose, the normal voltage level (zero voltage, $V_{out}$) is calculated as 3.1. This algorithm processes the sampled signal $iV_{out}$) before each triggered impulse in the time $t_t$, and averages 50 registered samples computing the value of $i_{out}$. In order not to count part of the measured pulse, the average is calculated by 20 samples before the triggered time tt. Before the discrimination of the neutrons and gamma pulses the $V_{out}$ value is subtracted from all samples.

$$V_{out} = (\sum_{t_t-70}^{t_t-20} i(t_o))/50 \tag{3.1}$$

The discrimination algorithm works with two parameters. The first parameter of the spectrometric system is the type of the detected particle (impulse). For this purpose, pulse shape discrimination is used. The computational complexity of the implemented integration method is linear, and therefore, it is suitable for online measurements processing a high number of impulses per second.

$$E = \int_{t_2}^{t_t-16} i(t)dt \tag{3.2}$$

The second parameter (E), of the spectrometric system, is the energy of the detected

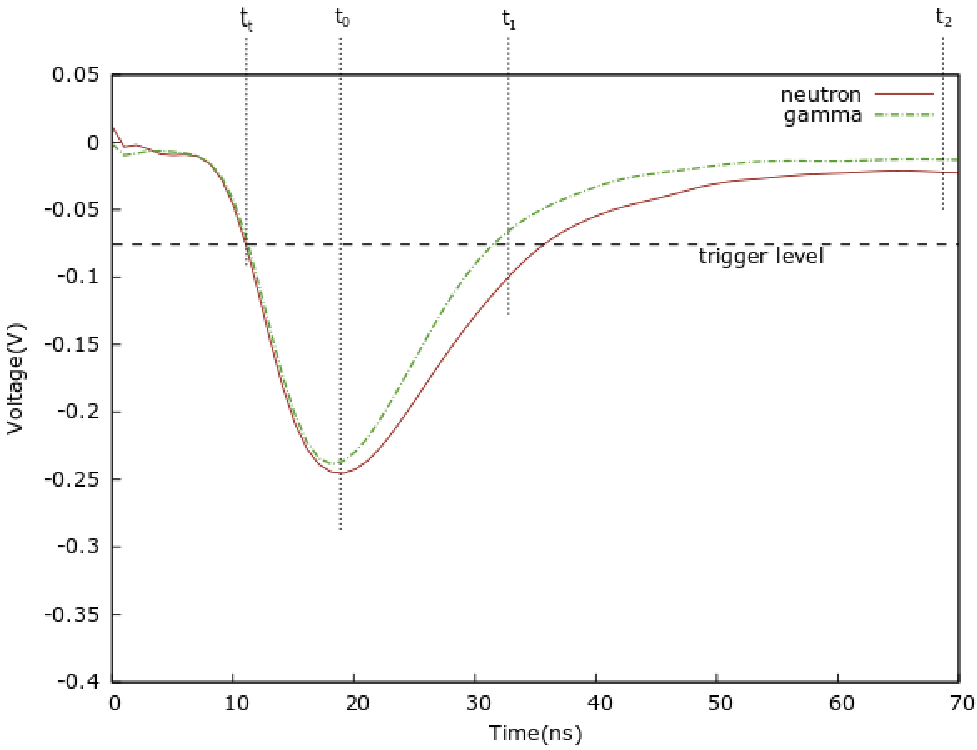


Figure 3.4: Output signal $i(t_o)$ from detector - parameters for algorithms (Author)

particle. The energy is evaluated from the integral 3.2 of the whole response where $t_t$ is time when the impulse was triggered. As is shown in (Figure 3.4) the impulse begins before the time $t_t$, therefore, the lower limit of the integration is set to $t_t - 16$ to cover the whole area of energy range.

## Contributions

The presented papers demonstrate continuous research in the area of the selection of the best separation algorithm. The summary is in the paper [1] which uses the knowledge and data from the spectrometric system and discusses the results from selected algorithms. Results are compared using the Figure of merit method. The next paper [12] shows the improvement of filter algorithms. The moving average filter was used and with the right selection of parameters the ±10 % deviation from calculated values was achieved. This result was obtained thanks to the well-defined model of the active zone of LR-0 reactor. This work was a significant contribution to the so-called benchmark of the reactor configuration and to the establishment of the reference neutron field. Such field can serve to support other experiments and publications. Thanks to this work the LR-0 reactor becomes a unique facility for the development of spectrometric systems.

The results achieved due to improved filtration parameters are described also in the paper [16] which uses our methods in mixed fields with high count rates where a lot of impulse superpositions are present. In this paper, the spectrometric system was tested and verified in a special configuration near the LVR-15 reactor that contained silicon and lead filters. In this experiment, we were again able to compare measured results with calculated ones and thus verify them.

My contribution to these publications was in the research and tuning of the integration method parameters including the noise characteristics of individual components and the application of this knowledge in the readjustment of components between each other. The results are compared with calculations and simulations. The results and recommendations are again published in physical journals.

## Articles in Collection

[1] M. Amiri, V. Přenosil, F. Cvachovec, Z. Matěj, and F. Mravec. Quick algorithms for real-time discrimination of neutrons and gamma rays. *Journal of Radioanalytical and Nuclear Chemistry*, 303:583–599, Jan 2015

I cooperated on the design of the separation algorithm and wrote the part of the text. Contribution 20%.

[12] M. Košťál, Z. Matěj, F. Cvachovec, V. Rypar, E. Losa, J. Rejchrt, F. Mravec, and M. Veškrna. Measurement and calculation of fast neutron and gamma spectra in well defined cores in lr-0 reactor. *Applied Radiation and Isotopes*, 120:45 – 50, 2017

I cooperated on the design of the separation algorithm and wrote the part of the text. Contribution 35%.

[16] M. Košťál, M. Schulc, J. Šoltés, E. Losa, L. Viererbl, Z. Matěj, F. Cvachovec, and V. Rypar. Measurements of neutron transport of well defined silicon filtered beam in

lead. *Applied Radiation and Isotopes*, 142:160 – 166, 2018

I cooperated on the design of the algorithm and wrote the part of the text. Contribution 15%.

## 3.2 Detectors

Detectors themselves have a big influence on the parameters of the spectrometric system. The research in this area is difficult and long term. It requires knowledge from physics, electronics, and computer science. We have been working in this area in cooperation with University of Defense, Czech Academy of Sciences, VF, a.s. and Research Center Řež for quite some time.

The problem is to find the best detector parameters depending on the detector material and consequent processing. This affects the parameters of the signal entering the integration method algorithm and can increase, especially for smaller amplitudes, inaccuracies when separating impulses. The first step is the choice of scintillation material. Each of the tested ones has its advantages and disadvantages. Considering the separation properties the best one is stilbene. But as it is a crystal that holds together thanks to Van der Waals forces, it is very fragile, which limits its size and causes its anisotropy. This limits us for certain experiments, for example if we need to detect small radiation sources we need large detection volume. Not just for these reasons we need to focus on other materials as well. Plastic scintillators (e.g. EJ-299-33A) or liquid scintillators (NE-213) are popular.

Another step is the selection of a suitable photomultiplier. Commercially available PMTs are usually used (ET, Hamamatsu). The noise characteristics need to be considered as well as sensitivity of the photocathode to needed wavelengths. The correct range guarantees good synergy with the detector.

A necessary step for the proper functionality of the photomultiplier is the selection of the right voltage divider. PMT manufacturers have to consider this as well. It is a complex problem with a wide variety of parameters.

Complementary circuits that can be added to the detector serve to improve parameters and the stability of the system. It is important to realize that long term stability and repeatability of experiments is also very important as they can last for several days.

## Contributions

In the area of detectors, I focused on the development of individual parts. Having selected the selection of the right PMT I experimented with the development of my own voltage dividers that distribute high voltage between dynodes. First I tested passive dividers that are usually provided by PMT manufacturers. From Figure 3.5 it is obvious that the linearity of the output based on count rate is far from good.

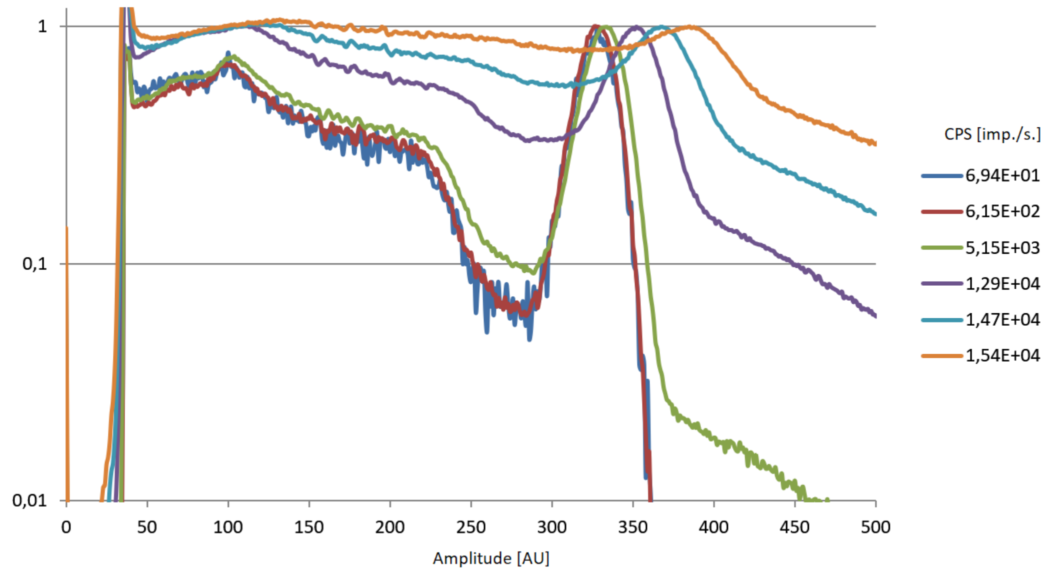


Figure 3.5: Output spectrum from source Cs-137 and detector NaI(Tl) from testing linearity with the passive voltage divider. (Author)

There has been a significant improvement with a newly developed active divider using MOSFET transistors (Figure 3.6). It achieves better linearity for high count rates but also for different impulse amplitudes. Results were described in the paper [13].

During the development of the active divider, we also developed a method for testing of linearity of the apparatus together with the PMT and the divider. For the validation test of the system without a detector, an impulse generator is needed. For the testing of PMT a method and apparatus were developed that generates short light impulses with properties of scintillation flashes. It is necessary to be able to adjust the parameters of these flashes and thus influence the count rate and amplitude of generated photons. With this device, we are able to test the linearity of the whole system and to detect any non-linearity of the scintillation detector. This device was tested and it helped us to improve the apparatus parameters which allowed us to better assess individual scintillators [14].

With this device, we focused on the testing of temperature dependencies as well. The

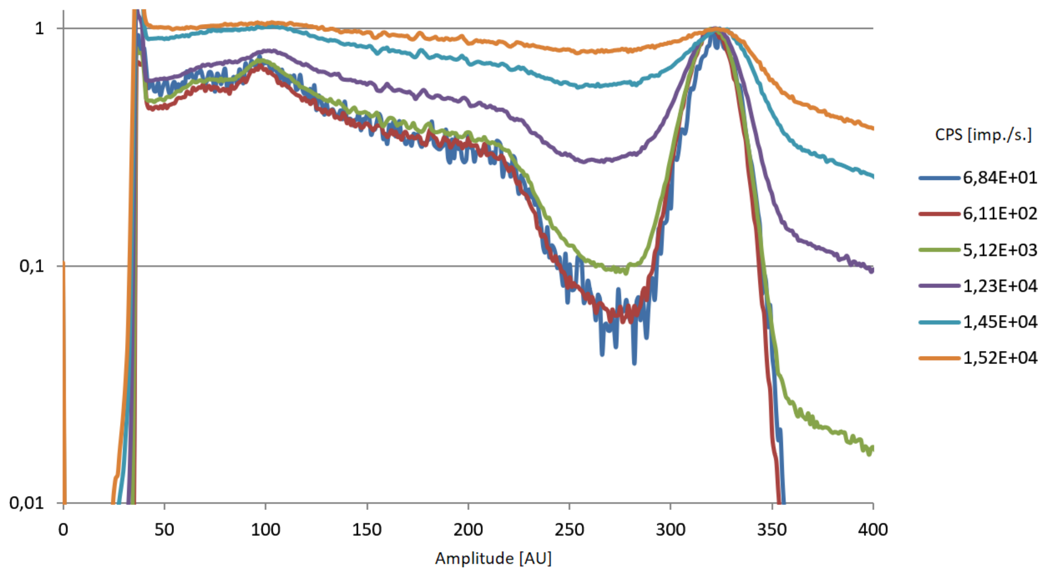


Figure 3.6: Output spectrum from source Cs-137 and detector NaI(Tl) from testing linearity with the active voltage divider based on MOS-FET tranzistors. (Author)

results are not particularly favorable with respect to the long term stability. Temperature variations during the measurement cause significant changes in the quality of the impulse separation (Figure 3.7).

The solution is the development of additional components to the detector. A new generation of the detector contains thermal stabilization of the scintillator and PMT and precise thermal regulators. This way we achieved thermal stability of the whole detector probe with a temperature above the usual thermal variance. This again enhances linearity and repeatability of measurements.

Another important addition was a magnetic shield. As our experiments showed at least two layers of shielding are needed. This knowledge is important for the separation algorithm parameters. Now i is not necessary to compensate for the physical artifacts of the detector and we can focus on the separation itself. Detectors improved this way led to a publication [10] where we measured the mixed field at the training reactor VR-1 .

My contribution to these publications was the research of the linearity of components and the development of active dividers. Thanks to the modification and the development of own procedures of testing I achieved significant improvement in the results of the system. Experiments were performed in various nuclear facilities that prove the stability of the system in various environments. The validation was done by comparison with independently calculated results. The uniqueness of these results was confirmed by having a patent granted. Furthermore the quality of results is supported by paper [18] which compares calculations

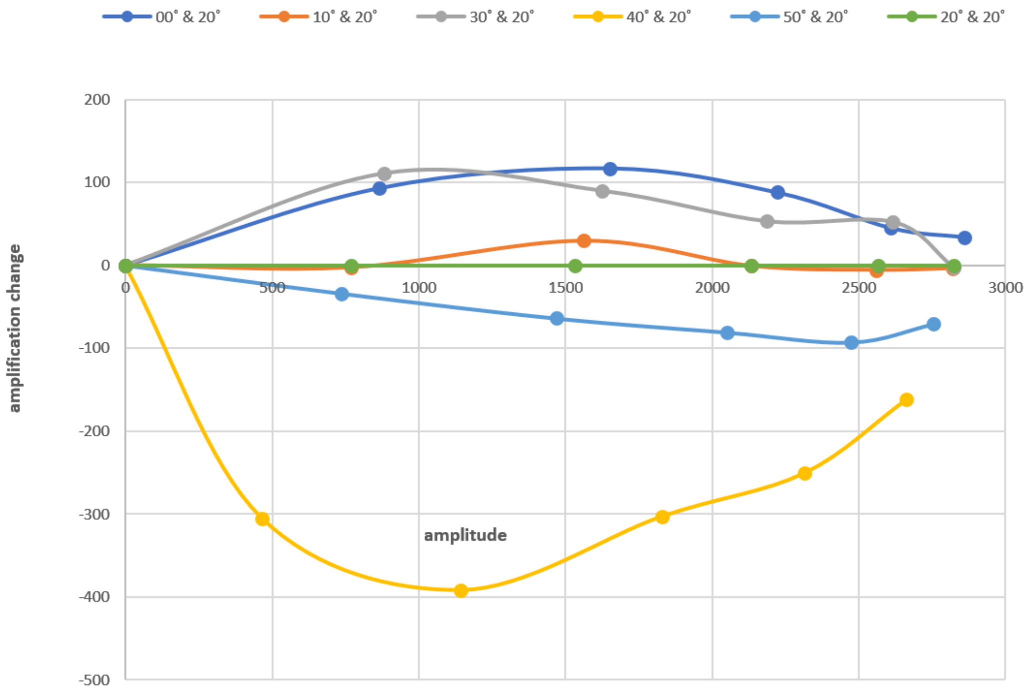


Figure 3.7: Dependence of measured pulse amplitude on change of temperature and light intensity of test LED. (Author)

with spectra measured at LVR-15 reactor from output channel HK-1 moderated by 1-meter thick pure silicon filter.

## Articles in Collection

[14] M. Košťál, J. Šoltés, L. Viererbl, Z. Matěj, F. Cvachovec, V. Rypar, and E. Losa. Measurement of neutron spectra in a silicon filtered neutron beam using stilbene detectors at the lvr-15 research reactor. *Applied Radiation and Isotopes*, 128:41 – 48, 2017

I cooperated on the design of the active divider and wrote the part of the text. Contribution 20%.

[13] M. Košťál, Z. Matěj, E. Losa, O. Huml, M. Štefánik, F. Cvachovec, M. Schulc, B. Jánský, E. Novák, D. Harutyunyan, and V. Rypar. On similarity of various reactor spectra and 235u prompt fission neutron spectrum. *Applied Radiation and Isotopes*, 135:83 – 91, 2018

I cooperated on the design of the separation algorithms and wrote the part of the text. Contribution 30%.

[10] M. Košťál, E. Losa, Z. Matěj, V. Juříček, D. Harutyunyan, O. Huml, M. Štefánik, F. Cvachovec, F. Mravec, M. Schulc, T. Czakoj, and V. Rypar. Characterization of mixed n/g beam of the vr-1 reactor. *Annals of Nuclear Energy*, 122:69 – 78, 2018

I cooperated on the developing of magnetic shieldeling and wrote the part of the text. Contribution 15%.

[18] M. Kostal, Z. Matej, F. Mravec, F. Cvachovec, M. Schulc, V. Juricek, V. Rypar, J. Soltes, E. Losa, and L. Viererbl. Testing of Scintillation Detectors in Quasi-Monoenergetic Neutron Spectra in a Silicon Filtered Neutron Beam at the LVR-15 Research Reactor. *JOURNAL OF NUCLEAR ENGINEERING AND RADIATION SCIENCE*, 5(3), jun 2019

I cooperated on the design of the separation algorithms and wrote the part of the text. Contribution 20%.

## 3.3 Validation and verification

Spectrometric system validation is a complicated task. Well-Defined radiation sources are needed for comparison of the results. Validation is done by a comparison with models calculated using the data from nuclear libraries. Worldwide efforts are undertaken to obtain the most reliable data for these libraries leads to our effort to verify and specify them. This is essential for the development of new types of reactors and facilities.

### Contributions

On the basis of the previous research in the area of filtration, separation and evaluation algorithms, it is possible to validate and verify the spectrometric system with various calculations and experiments. In this area, we focused on the reactor model VVER-1000. These reactors are used, for example, in Temelín nuclear power plant. A model of this reactor vessel is part of the research reactor LR-0. There we can perform well-defined experiments which consequently allow us to verify the functionality of our algorithms and the whole system. Results can be found in papers [19] and [15]. These experiments were supported by experiments with activation analysis.

A great improvement in the stability and parameters of the system were demonstrated in paper [11]. These results were obtained at the particle accelerator that serves mostly for the production of radiopharmaceuticals for medical facilities. It shows that with a properly configured system it is possible to measure in the proximity of facilities that generate a lot of interference and still obtain good results.

My contribution to these publications was the development and correct setup of parameters for the separation algorithm. A significant contribution was also the change in the determination of energy. This consist of the correct identification of the integration part to calculate the impulse energy.

## Articles in Collection

[19] M. Košt'ál, E. Losa, M. Schulc, J. Šimon, D. Harut, V. Klupák, T. Czakoj, V. Juříček, Z. Matěj, F. Cvachovec, and V. Rypar. The effect of local power increase on neutron flux in internal parts of the vver-1000 mock-up in lr-0 reactor. *Annals of Nuclear Energy*, 121:567 – 576, 2018

I cooperated on the design of the algorithm and wrote the part of the text. Contribution 15%.

[15] M. Košťál, V. Rypar, E. Losa, D. Harut, M. Schulc, V. Klupák, Z. Matěj, F. Cvachovec, B. Jánský, E. Novák, T. Czakoj, V. Juříček, and S. Zaritsky. The influence of core power distribution on neutron flux density behind a pressure vessel of a vver-1000 mock up in lr-0 reactor. *Applied Radiation and Isotopes*, 142:12 – 21, 2018

I cooperated on the design of the algorithm and wrote the part of the text. Contribution 15%.

[11] M. Košťál, E. Losa, M. Schulc, J. Šimon, Z. Matěj, M. Antoš, Šimon Vadják, M. Cuhra, F. Cvachovec, F. Mravec, F. Brijar, T. Czakoj, and V. Rypar. The methodology of characterization of neutron leakage field from pet production cyclotron for experimental purposes. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 942:162374, 2019

I cooperated on the design of the algorithm and wrote the part of the text. Contribution 15%.

# Chapter 4

# Conclusion and future work

My research contribution to the field of spectrometric systems in the past 10 years is in the determination and tuning of the methods and algorithms for the proper functionality of the system. The parameters of algorithms were tuned with the emphasis on the repeatability of measurements and usability of the whole system. A big improvement was done by the selection of correct separation parameters. This research area is wide because of the complexity of the whole system and a necessity to tune individual components that are dependent on each other.

My contributions consist of several parts. Using the previously described system one can perform measurements in nuclear facilities with different scintillation materials. With this system, we were able to characterize the reference field of a special zone of experimental reactor LR-0. This enables other experiments to build on this result, for example, to test new technologies and materials for the IV. Generation of nuclear reactors, as shown by publications. Another important contribution of this research is the fact that our experiments helped to specify better certain data in nuclear data libraries IRDFF-II [30]. It also enables the development and testing of new types of neutron radiation detectors. There is only 17 neutron reference field in the world, and only 5 of them are suitable for the testing of techniques for scintillation detectors. This shows the importance of these results. Based on these results nuclear devices and reactors are simulated.

Thanks to the knowledge we gained from our research we continue to develop our own liquid and plastic scintillation materials. This material provides us with new research opportunities in the radiation mixed fields. Following the research of this new material, I am also developing a spectrometric system for the energy interval 50 keV to 1 MeV using proportional counters.

Besides the measurement at the LR-0 reactor, we tested our apparatus at the training reactor VR-1. This was the first characterization of neutron and gamma spectra in this reactor. It should be stated that the device I developed characterized the neutron and in certain cases photon field at all three Czech research reactors.

Most of the presented papers were created in close cooperation with several excellent Czech workplaces (CVR, CVUT, UO). The consequence of this cooperation was the testing of algorithms and several development stages of our system on real experiments. This also explains why presented publications were published in journals of nuclear physics. These papers would not be created without research in the fields of spectrometric systems and computer science .

The research in this area can continue in several different directions. It will be interesting to focus on machine learning algorithms that can be implemented for field-programmable gate arrays nowadays. Another partial research can focus on automatization of evaluation without constant control from human operators. This part is already in progress and is being tested in Research Center Řež. Another step is the automatization of calibration and runtime function tests. Implementation of tested algorithms into smaller devices also possesses a great future challenge. This can be useful for example near cyclotrons.

Current research in the area of scintillation detector tries to enable the transfer of scintillation photons through optical fibers commonly used in telecommunications. This would enable the utilization of the spectrometric system at large reactors or near powerful accelerators.

# Bibliography

[1] M. Amiri, V. Přenosil, F. Cvachovec, Z. Matěj, and F. Mravec. Quick algorithms for real-time discrimination of neutrons and gamma rays. *Journal of Radioanalytical and Nuclear Chemistry*, 303:583–599, Jan 2015.

[2] R. Bedogni, C. Domingo, K. Amgarou, M. De-San-Pedro, A. Esposito, A. Gentile, and A. Pola. Spectrometry of 50 and 100mev quasi monochromatic neutron fields with extended range bonner spheres. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 746:59 – 63, 2014.

[3] CAEN. *CAEN Digitizer overview [online]*. 2019 [cit. 2019-11-01].

[4] Z. Caoa, L. Millera, and M. Bucknerb. *Implementation of dynamic bias for neutron–photon pulse shape discrimination by using neural network classifiers*. Nuclear Instruments and Methods in Physics Research Section A, 1998.

[5] J. Cvachovec and F. Cvachovec. Maximum likelihood estimation of a neutron spectrum and associated uncertainties. *Advances in Military Technology*, 3(2):67–79, 2008. cited By 19.

[6] IBA. *IBA Cyclone [online]*. 2019 [cit. 2019-11-01].

[7] A. Jančář, Z. Kopecký, J. Dressler, M. Veškrna, Z. Matěj, C. Granja, and M. Solar. Pulse-shape discrimination of the new plastic scintillators in neutron–gamma mixed field using fast digitizer card. *Radiation Physics and Chemistry*, 116:60 – 64, 2015.

[8] S. Jastaniah and P. J. Sellin. *Digital techniquesfor n/g pulse shape discrimination and capture-gate neutron spectroscopy using liquid scintillators*. Nuclear Instruments and Methods in Physics Research A, 2003.

[9] A. Klix, M. Angelone, U. Fischer, and M. Pillon. Fast neutron and gamma-ray spectra measurements with a ne-213 spectrometer in the fng copper benchmark experiment. *Fusion Engineering and Design*, 109-111:309 – 314, 2016. Proceedings of the 12th International Symposium on Fusion Nuclear Technology-12 (ISFNT-12).

[10] M. Košťál, E. Losa, Z. Matěj, V. Juříček, D. Harutyunyan, O. Huml, M. Štefánik, F. Cvachovec, F. Mravec, M. Schulc, T. Czakoj, and V. Rypar. Characterization of mixed n/g beam of the vr-1 reactor. *Annals of Nuclear Energy*, 122:69 – 78, 2018.

[11] M. Košťál, E. Losa, M. Schulc, J. Šimon, Z. Matěj, M. Antoš, Šimon Vadják, M. Cuhra, F. Cvachovec, F. Mravec, F. Brijar, T. Czakoj, and V. Rypar. The methodology of characterization of neutron leakage field from pet production cyclotron for experimental purposes. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 942:162374, 2019.

[12] M. Košťál, Z. Matěj, F. Cvachovec, V. Rypar, E. Losa, J. Rejchrt, F. Mravec, and M. Veškrna. Measurement and calculation of fast neutron and gamma spectra in well defined cores in lr-0 reactor. *Applied Radiation and Isotopes*, 120:45 – 50, 2017.

[13] M. Košťál, Z. Matěj, E. Losa, O. Huml, M. Štefánik, F. Cvachovec, M. Schulc, B. Jánský, E. Novák, D. Harutyunyan, and V. Rypar. On similarity of various reactor spectra and 235u prompt fission neutron spectrum. *Applied Radiation and Isotopes*, 135:83 – 91, 2018.

[14] M. Košťál, J. Šoltés, L. Viererbl, Z. Matěj, F. Cvachovec, V. Rypar, and E. Losa. Measurement of neutron spectra in a silicon filtered neutron beam using stilbene detectors at the lvr-15 research reactor. *Applied Radiation and Isotopes*, 128:41 – 48, 2017.

[15] M. Košťál, V. Rypar, E. Losa, D. Harut, M. Schulc, V. Klupák, Z. Matěj, F. Cvachovec, B. Jánský, E. Novák, T. Czakoj, V. Juříček, and S. Zaritsky. The influence of core power distribution on neutron flux density behind a pressure vessel of a vver-1000 mock up in lr-0 reactor. *Applied Radiation and Isotopes*, 142:12 – 21, 2018.

[16] M. Košťál, M. Schulc, J. Šoltés, E. Losa, L. Viererbl, Z. Matěj, F. Cvachovec, and V. Rypar. Measurements of neutron transport of well defined silicon filtered beam in lead. *Applied Radiation and Isotopes*, 142:160 – 166, 2018.

[17] M. Košťál, M. Veškrna, F. Cvachovec, B. Jánský, E. Novák, V. Rypar, J. Milčák, E. Losa, F. Mravec, Z. Matěj, J. Rejchrt, B. Forget, and S. Harper. Comparison of fast neutron spectra in graphite and flina salt inserted in well-defined core assembled in lr-0 reactor. *Annals of Nuclear Energy*, 83:216 – 225, 2015.

[18] M. Kostal, Z. Matej, F. Mravec, F. Cvachovec, M. Schulc, V. Juricek, V. Rypar, J. Soltes, E. Losa, and L. Viererbl. Testing of Scintillation Detectors in Quasi-Monoenergetic Neutron Spectra in a Silicon Filtered Neutron Beam at the LVR-15 Research Reactor. *JOURNAL OF NUCLEAR ENGINEERING AND RADIATION SCIENCE*, 5(3), jun 2019.

[19] M. Košt'ál, E. Losa, M. Schulc, J. Šimon, D. Harut, V. Klupák, T. Czakoj, V. Juříček, Z. Matěj, F. Cvachovec, and V. Rypar. The effect of local power increase on neutron flux

in internal parts of the vver-1000 mock-up in lr-0 reactor. *Annals of Nuclear Energy*, 121:567 – 576, 2018.

[20] G. Liu, M. D. Aspinall, X. Ma, and M. J. Joyce. *Pulse shape analysis of liquid scintillators for neutron studie.* Nuclear Instruments and Methods in Physics Research Section A, 2002.

[21] G. Liu, M. D. Aspinall, X. Ma, and M. J. Joyce. *An investigation of the digital discrimination of neutrons and Ît rays with organic scintillation detectors using an artificial neural network.* Nuclear Instruments and Methods in Physics Research Section A, 2009.

[22] G. Liu, M. J. Joyce, X. Ma, and M. D. Aspinall. *A Digital Method for the Discrimination of Neutrons and Rays With Organic Scintillation Detectors Using Frequency Gradient Analysis.* IEEE Transactions on Nuclear Science, 2010.

[23] G. Lövestam, M. Hult, A. Fessler, J. Gasparro, P. Kockerols, K. Okkinga, H. Tagziria, F. Vanhavere, and J. E. Wieslander. Neutron fluence spectrometry using disk activation. *Radiation Measurements*, 44(1):72 – 79, 2009.

[24] Z. Matěj. Digitalization of spectometric system for mixed field of fast neutrons and gamma radiation. *disertation work*, 2014.

[25] B. Ošmera, F. Cvachovec, J. Kyncl, and V. Smutný. Measurement and calculation of the fast-neutron and photon spectra from the core boundary to the biological shielding in the wwer-1000 reactor model. *Radiation Protection Dosimetry*, 115(1-4):92–94, 2005. cited By 1.

[26] I. Pawełczak, S. Ouedraogo, A. Glenn, R. Wurtz, and L. Nakae. Studies of neutron-$\gamma$ pulse shape discrimination in ej-309 liquid scintillator using charge integration method. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 711:21 – 26, 2013.

[27] V. Popov. Design and study of photomultiplier pulse-shaping amplifier powered by the current flowing through a voltage divider. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 505(1):316 – 319, 2003. Proceedings of the tenth Symposium on Radiation Measurements and Applications.

[28] P. Roy, K. Banerjee, A. Saha, C. Bhattacharya, J. Meena, P. Bhaskar, S. Mukhopadhyay, and S. Bhattacharya. Detailed investigation on the possibility of using ej-299-33a plastic scintillator for fast neutron spectroscopy in large scale experiments. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 901:198 – 202, 2018.

[29] D. Thomas. Neutron spectrometry. *Radiation Measurements*, 45(10):1178 – 1185, 2010. PROCEEDINGS OF THE 11TH SYMPOSIUM ON NEUTRON AND ION DOSIMETRY.

[30] A. Trkov, P. J. Griffin, S. P. Simakov, L. R. Greenwood, K. I. Zolotarev, R. Capote, D. L. Aldama, V. Chechev, C. Destouches, A. C. Kahler, C. Konno, M. Koštál, M. Majerle, E. Malambu, M. Ohta, V. G. Pronyaev, V. Radulović, S. Sato, M. Schulc, E. Šimečková, I. Vavtar, J. Wagemans, M. White, and H. Yashima. *IRDFF-II: A New Neutron Metrology Library.* 2019.

[31] R. Weldon, J. Mueller, C. Lynch, P. Schuster, S. Hedges, C. Awe, L. Li, P. Barbeau, and J. Mattingly. High-precision characterization of the neutron light output of stilbene along the directions of maximum and minimum response. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 927:313 – 319, 2019.

# Part II

# Collection of Articles

# Appendix A

# Journal articles

This appendix contains the total of 12 research articles that were selected as the representatives of my contributions within the studied research field. The fulltexts of the articles are inserted into the appendix of the printed version of this thesis[1] and referenced via the article numbers assigned in the list below.

**Article A:** A. Jančář, Z. Kopecký, J. Dressler, M. Veškrna, Z. Matěj, C. Granja, and M. Solar. Pulse-shape discrimination of the new plastic scintillators in neutron–gamma mixed field using fast digitizer card. *Radiation Physics and Chemistry*, 116:60 – 64, 2015

**Article B:** M. Košťál, M. Veškrna, F. Cvachovec, B. Jánský, E. Novák, V. Rypar, J. Milčák, E. Losa, F. Mravec, Z. Matěj, J. Rejchrt, B. Forget, and S. Harper. Comparison of fast neutron spectra in graphite and flina salt inserted in well-defined core assembled in lr-0 reactor. *Annals of Nuclear Energy*, 83:216 – 225, 2015

**Article C:** M. Amiri, V. Přenosil, F. Cvachovec, Z. Matěj, and F. Mravec. Quick algorithms for real-time discrimination of neutrons and gamma rays. *Journal of Radioanalytical and Nuclear Chemistry*, 303:583–599, Jan 2015

**Article D:** M. Košťál, Z. Matěj, F. Cvachovec, V. Rypar, E. Losa, J. Rejchrt, F. Mravec, and M. Veškrna. Measurement and calculation of fast neutron and gamma spectra in well defined cores in lr-0 reactor. *Applied Radiation and Isotopes*, 120:45 – 50, 2017

**Article E:** M. Košťál, M. Schulc, J. Šoltés, E. Losa, L. Viererbl, Z. Matěj, F. Cvachovec, and V. Rypar. Measurements of neutron transport of well defined silicon filtered beam in lead. *Applied Radiation and Isotopes*, 142:160 – 166, 2018

[1]The fulltexts of the articles are excluded from the publicly available electronic version of this text to avoid copyright violation.

**Article F:** M. Košťál, J. Šoltés, L. Viererbl, Z. Matěj, F. Cvachovec, V. Rypar, and E. Losa. Measurement of neutron spectra in a silicon filtered neutron beam using stilbene detectors at the lvr-15 research reactor. *Applied Radiation and Isotopes*, 128:41 – 48, 2017

**Article G:** M. Košťál, Z. Matěj, E. Losa, O. Huml, M. Štefánik, F. Cvachovec, M. Schulc, B. Jánský, E. Novák, D. Harutyunyan, and V. Rypar. On similarity of various reactor spectra and 235u prompt fission neutron spectrum. *Applied Radiation and Isotopes*, 135:83 – 91, 2018

**Article H:** M. Košťál, E. Losa, Z. Matěj, V. Juříček, D. Harutyunyan, O. Huml, M. Štefánik, F. Cvachovec, F. Mravec, M. Schulc, T. Czakoj, and V. Rypar. Characterization of mixed n/g beam of the vr-1 reactor. *Annals of Nuclear Energy*, 122:69 – 78, 2018

**Article I:** M. Kostal, Z. Matej, F. Mravec, F. Cvachovec, M. Schulc, V. Juricek, V. Rypar, J. Soltes, E. Losa, and L. Viererbl. Testing of Scintillation Detectors in Quasi-Monoenergetic Neutron Spectra in a Silicon Filtered Neutron Beam at the LVR-15 Research Reactor. *JOURNAL OF NUCLEAR ENGINEERING AND RADIATION SCIENCE*, 5(3), jun 2019

**Article J:** M. Košt'ál, E. Losa, M. Schulc, J. Šimon, D. Harut, V. Klupák, T. Czakoj, V. Juříček, Z. Matěj, F. Cvachovec, and V. Rypar. The effect of local power increase on neutron flux in internal parts of the vver-1000 mock-up in lr-0 reactor. *Annals of Nuclear Energy*, 121:567 – 576, 2018

**Article K:** M. Košťál, V. Rypar, E. Losa, D. Harut, M. Schulc, V. Klupák, Z. Matěj, F. Cvachovec, B. Jánský, E. Novák, T. Czakoj, V. Juříček, and S. Zaritsky. The influence of core power distribution on neutron flux density behind a pressure vessel of a vver-1000 mock up in lr-0 reactor. *Applied Radiation and Isotopes*, 142:12 – 21, 2018

**Article L:** M. Košťál, E. Losa, M. Schulc, J. Šimon, Z. Matěj, M. Antoš, Šimon Vadják, M. Cuhra, F. Cvachovec, F. Mravec, F. Brijar, T. Czakoj, and V. Rypar. The methodology of characterization of neutron leakage field from pet production cyclotron for experimental purposes. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 942:162374, 2019