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Reconstruction of Neutron Energy Spectra in Z-pinch Fusion Experiments

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1 Current situation of the studied problem

This thesis deals with the experiments in Z-pinches and in the discharges of the dense plasma focus. A pinch is defined as plasma configuration in which an electric current generates an azimuthal magnetic field that has the ability to confine the plasma. The prefix "Z" was added in the 1950s to distinguish that electric current passes along the pinch axis – conventionally referred to the z-axis. If the light nuclei are presented in the high temperature plasma of Z-pinches or plasma foci, the fusion reactions can occur. Nowadays, the most examined fusion reaction is the reaction of the deuterium atoms. This work is limited to the deuterium fusion reactions, especially to the $D(d,n)^3He$ fusion reaction – see eq. (1). However, the described principles could be applied in the various fusion experiments, for example, experiments with the deuterium-tritium mixture, i.e. $T(d,n)^4He$ fusion reaction.

$$\mathrm{D} + \mathrm{D} \;\rightarrow\; \mathrm{n}(2.45\ \mathrm{MeV}) +^3 \mathrm{He}(0.8\ \mathrm{MeV}). \tag{1}$$

Eq. (1) shows that the product of the reaction is also neutron which can be use as a diagnostic tool. The reason is that the neutron does not interact with electric and magnetic fields and it can be measured outside the experimental vessel. Only the neutron interaction with the matter, i.e. neutron scattering on the walls of experimental vessel and air, should be included into the precise measurement.

1.1 Neutron diagnostics

By means of neutron diagnostics we are able to identify parameters of the ions in the Z-pinch fusion plasma. Concretely, it could help us to recognize how the ions, deuterons in case of the $D(d,n)^3He$ reaction, were accelerated. Nowadays, there are two general models of the ion acceleration and subsequent production of neutrons, (i) beam-target models and (ii) thermonuclear models, are proposed. The vindication of the thermonuclear mechanism of a neutron production is essential for the production of electricity in some of Z-pinch facilities in the future. For that reason, a precise neutron diagnostics especially the one determining the neutron energy spectra is required. The most significant characteristics of a neutron energy spectrum are: (i) the mean value of neutron energy, whose value should be about 2.45 MeV for the thermonuclear mechanism of a neutron production, (ii) a neutron energy spectrum width and (iii) neutron emission anisotropy. The width of the neutron spectrum based on plasma temperature kT_i should be $E_{\rm n}(\text{keV}) = 82.5\sqrt{kT_i}(\text{keV})$ [1] for the maxwellian plasma and thermonuclear mechanism of a neutron production.

There are many experimental approaches or methods for determining the energies of the neutrons produced in a burst, i.e. neutron energy spectra measurements or neutron spectroscopy methods. However, the method with a relatively high energy resolution in the relatively small range of neutron energies is required. The TOF methods seam to be the most suitable to fulfill these requirements.

1.1.1 Time-of-flight measurement

The time-of-flight (TOF) measurements of the neutron energy spectra were applied immediately after the discovery of the neutron. An experimental setup used in these experiments was formed only by one time-resolved neutron detector, e.g. a fast plastic scintillator with a fast photomultiplier tube, see Fig. 1. We will call these methods as "basic TOF methods".

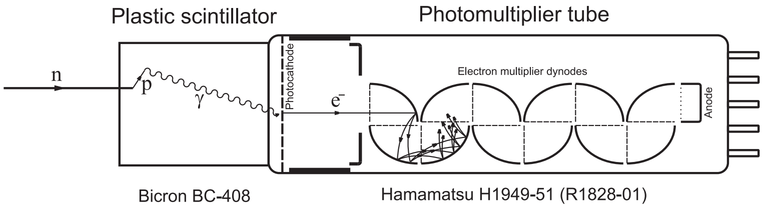

Figure 1: Two main parts of the scintillation detector – a scintillator and PMT.

If the reconstruction method uses more TOF signals from more TOF detectors, then such a method is called an "extended TOF method".

1.1.2 Extended time-of-flight methods

The basic TOF methods cannot be used for the sources characterized by a long duration of the neutron emission when compared to the neutron time-of-flight from the source to the detector. For this class of experiments, a new kind of methods was designed and for the first time presented in Ref. [2]. This kind of TOF methods can determine an energy spectra with a time resolution based on the measurement of a neutron pulse by several detectors. These detectors should be placed in a line at different distances from the neutron source.

Fig. 2 shows an example of the propagation of a long duration neutron burst through the free space and its simultaneous measurement by several detectors with the time resolution at distances 0 m, 2 m, 5 m and 10 m. The

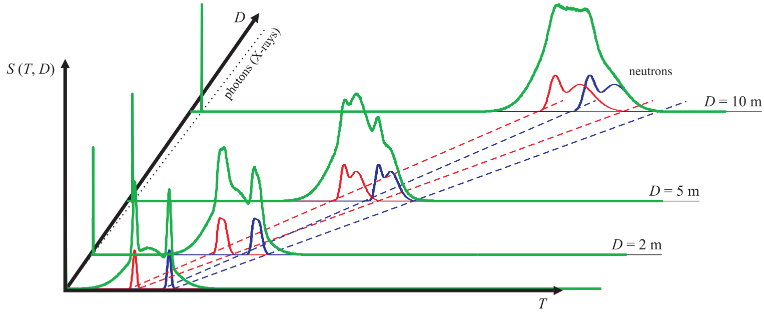

Figure 2: Propagation of a long duration neutron burst through the free space (green signals). Two elementary short pulses (red and blue) are indicated to show the superposition of spectra of neutrons which were emitted at various times. The signals were normalized to the same height.

dashed lines represent the propagation of two neutron pulses, which were emitted at various times, to denote the superposition of the energy spectra.

From the point of view of experiments and data processing, extended TOF methods are more difficult than the basic TOF methods but they have the advantage of providing more detailed information about the time-resolved neutron energy spectrum.

1.1.3 Reconstruction of the energy spectra from TOF signals

The aim is to reconstruct the probability density function, i.e. the neutron time-resolved energy spectrum or time evolution of the energy spectrum, $f(t, E)$. The relation between $f(t, E)$ and the neutron TOF signal $S(T, D)$ is

$$S(T, D) \propto \int_{t1}^{t2} \int_{E1}^{E2} f(t, E)\, \delta \left(t - T + \frac{D}{\sqrt{2E/m_{\mathrm{n}}}} \right) dE\, dt, \tag{2}$$

where T is the neutron detection time, t is the neutron emission time and t_1, t_2, E_1, E_2 define the reconstruction domain.

As it was suggested earlier by Schmidt and Herold [3], the reconstruction of the time-resolved energy spectra can be treated as a tomographic problem by changing the energy scale E into the reciprocal velocity scale $q = \sqrt{m_{\mathrm{n}}/2E}$. The correspondence between the physical variables t, q and the tomographic imaging geometry is defined as

$$\mathrm{cotg}(\theta) = \frac{t_2 - t_1}{q_2 - q_1} \cdot \frac{1}{D}, \tag{3}$$

where θ is the angle of the line of sight. According to relation (3), the detector distance D determines the line of sight.

1.1.4 Reconstruction methods

The reconstruction of the time-resolved neutron energy spectrum with a limited data set is an inverse ill-defined problem. There are several theoretical approaches for the development of algorithms, such as a numerical solution of the first kind of Fredholm-type integral [2], the reconstruction by the Laplace transformation [3], convolution and backprojection, Monte Carlo backprojection (MCBP), Analog Monte Carlo reconstruction method (AMCRT)[4], Algebraic reconstruction technique (ART), Maximum entropy (ME) method, minimum Fisher information algorithm, constrained optimization, optimization by a Genetic algorithm (GA) [5] and Maximum a posteriori (MAP) method.

The methods reconstruction by convolution and backprojection, MCBP, AMCRT, ART and ME were evaluated in Ref. [6]. According to this paper the AMCRT gives the best results.

2 The aims of the doctoral thesis

The initial aim of this work was the application of a known extended TOF method for the reconstruction of the time-resolved energy spectra of neutrons produced during the deuterium fusion experiments at the plasma focus facility PF-1000 at IPPLM in Warsaw.

The extensive neutron TOF diagnostics was build during years 2005 and 2007. At the same time, the idea of a simultaneous usage of the neutron detectors in two opposite directions was suggested by Prof. Pavel Kubeš. Thus, the second aim was assigned: To consider a proposal with simultaneous usage of the neutron detectors in two opposite directions of the neutron detection and to adapt the reconstruction method in case of fusion experiments with deuterium.

Since other fusion experiments were performed on the pulse power generator S-300 at RRC KI in Moscow, the third aim was assigned: To adapt the extended TOF reconstruction method to the experimental conditions in S-300 facility – a small number of neutron detectors and relatively short accessible distances for the neutron measurements.

3 Working method

This section deals with the description of the method used for the reconstruction of the neutron energy spectra from Z-pinch fusion experiments. The improvement of the reconstruction method including two opposite directions of the neutron detection is also mentioned.

3.1 Analog Monte Carlo reconstruction technique

The following paragraphs describe the reconstruction of the neutron energy spectra by the extended TOF method which uses the Monte Carlo technique – the Analog Monte Carlo reconstruction technique (AMCRT). This technique was published in Ref. [4]. The basic reconstruction algorithm consists of the two following steps.

3.1.1 First step of the AMCRT

Without any detailed knowledge of time evolution and energy distribution, the events, when the neutrons occur with the given and time, are sampled by a uniform random density function in the plane $f(t, q)$ at the source position[1]. After that, the algorithm tests if the event is detectable on all used detectors. This is mathematically expressed by fulfilling the following conditions for all detectors j at distances D_j

$$\begin{aligned} T_{j,\min} < T_j = t + D_j q < T_{j,\max}\,, \\ S_j(D_j, T = t + D_j q) \geq S_{j,\min}\,(D_j, T), \end{aligned} \tag{4}$$

where $T_{j,\min}$ is the time of the fastest neutron detection from the reconstructed spectra, i.e. a neutron produced with the highest energy in the earliest time, and $T_{j,\max}$ is the time of the slowest neutron, i.e. a neutron produced with the lowest energy in the latest time, for the detector j at a given distance D_j. The threshold $S_{j,\min}\,(D_j, T)$ is taken as a detection level, where it is equal to zero for the numerical testing or it does not equal to zero for the computation with noised experimental data.

If the events satisfied, i.e. passed the test, it is accepted and the corresponding element in the reconstructed spectrum is increased by one unit, and the corresponding sample in each detector is decreased by one unit, i.e. each neutron the TOF signal $S_j(T, D)$ is changed. The first step of the

[1] The dependence between the reciprocal velocity q and energy E is $q = \sqrt{m_\mathrm{n}/2E}$, where m_n is a neutron mass.

reconstruction process stops when a lot of events have not passed the test. A stop condition can vary, for example, when the defined ratio between the number of accepted events and the total number of the recorded events has been reached.

3.1.2 Second step of the AMCRT

At first, the reconstructed spectrum $f(t,q)$ obtained after the first step is used to generate the bivariate distribution function. Then, the second step almost follows the algorithm described at the first step. The difference is in the sampling of events. Events are not sampled by a uniform random generation but they are now governed by the joint bivariate distribution function. The second step is iterated in order to obtain a maximum reconstruction efficiency factor.

3.2 Improvement of the reconstruction method

The formulation of the reconstruction technique as a tomographic problem and later results from numerical tests indicate that the methods could give better results when we use signals from detectors which are placed in two opposite directions of the neutron detection. This approach improves the reconstruction because there is available wider choice of possibilities of angles of view. Fig. 3 shows the difference between the reconstruction from the detector signals in one direction, where only the first and third quadrants of the reconstruction domain are accessible, and the reconstruction with the signals from two opposite directions, where all quadrants of the reconstruction domain are accessible.

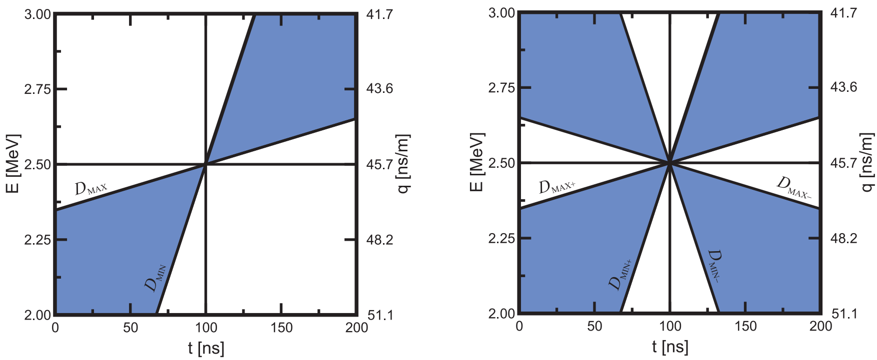

Figure 3: Reconstruction plane, i.e. a time-resolved energy spectrum, with the angles of the direction of sight for the minimum and maximum distances of the detectors.

If we want to employ neutron signals from two opposite directions of the neutron detection, we must assume that a sufficient number of neutrons which can be detected in both directions have been produced. The process of the reconstruction is as follows: (i) We randomly select the time of production t of one neutron and its energy in one direction – we will mark this energy as E_{n}^{+}, i.e. we create the event, and we test whether this neutron is detectable on all detectors in one direction. This point is the same as the one during the reconstruction with the signals from one direction. (ii) After that, we will test the additional neutron at all signals in the opposite direction. This neutron is produced at the same time t but with different energy – we will mark this energy as E_{n}^{-}. In other words, we assume that for each realized $\mathrm{D(d,n)^3He}$ fusion reaction where the neutron with the angle ϑ and with the energy E_{n}^{+} has been produced, another reaction with the same initial conditions (time t and energy of the collided deuteron E_{d}) occurs. However, the outgoing neutron from the second reaction is produced in the opposite direction $\vartheta + 180°$ and with energy E_{n}^{-}. All above mentioned facts imply that we must find a neutron energy E_{n}^{-} only from the knowledge of energy E_{n}^{+}. In the following text, we will use the term "the transformation of the neutron energy". In addition, we must examine the probability of the production of neutrons in an opposite direction. We will use term "the anisotropy of the neutron fluxes".

3.2.1 Transformation of the neutron energy

The transformation of the neutron energy is based on kinematics of the binary fusion system and it has been applied specifically to the $\mathrm{D(d,n)^3He}$ fusion reaction. The energy of the outgoing neutron from the $\mathrm{D(d,n)^3He}$ reaction depends on the energy of the collision deuteron and the angle ϑ between the deuteron and the neutron. Since we never know the trajectory of the collided deuteron, i.e. angle ϑ, the energy of neutron which has arisen in opposite direction E_{n}^{-} is calculated by means of the component of the deuteron kinetic energy $E_{\mathrm{d}} \cos^2 \vartheta$. It can be formally written as

$$E_{\mathrm{n}}^{+} \;\rightarrow\; E_{\mathrm{d}} \cos^2 \vartheta \;\rightarrow\; E_{\mathrm{n}}^{-}. \tag{5}$$

This dependence was derived from the kinematics of the binary fusion system, where we assume that the energy of the collided deuteron E_{d} is much smaller, usually bellow 300 keV, than the released energy Q from the $\mathrm{D(d,n)^3He}$ reaction ($Q = 3.27$ MeV). The derived dependence is the following

$$E_\mathrm{d} \cos^2 \vartheta \approx \frac{(m_\mathrm{n} + m_\mathrm{He})^2}{m_\mathrm{d} m_\mathrm{n}} \left(\sqrt{E_\mathrm{n}} - \sqrt{\frac{m_\mathrm{He} Q}{m_\mathrm{n} + m_\mathrm{He}}} \right)^2 , \qquad (6)$$

where m_He is mass of ^{3}He atom and m_d is mass of deuteron.

3.2.2 Anisotropy of the neutron fluxes

The neutron emission anisotropy for the opposite directions was calculated as the ratio of differential cross-sections for chosen angles $\vartheta = 0°$ and $\vartheta = 180°$. The values of the differential cross-section of the D(d,n)^{3}He reaction were taken from a nuclear data in Ref. [7].

4 Results

4.1 Possibilities of the program Neutrons

The reconstruction program "Neutrons", which implemented AMCRT, can reconstruct time-resolved neutron energy spectra from several neutron TOF signals. The program Neutrons can use TOF signals both from one direction and from two opposite directions of the neutron detection. The program provides a time-resolved energy spectrum with a relatively high energy resolution. Moreover, it can also calculate the component of the kinetic energy of the deuterons producing fusion neutrons.

The reconstruction program Neutrons brought many promising results:

- The reconstruction of the energy spectra from two opposite directions of the neutron detection provided much better results than the reconstruction from one direction only. The reason is that the "rhomboid artifact" was eliminated.
- The influence of scattered neutrons can be partially eliminated by using two opposite directions of the neutron detection.
- The way how to determine the time of the neutron production.
- The special procedure for processing the data from the fusion experiments on a S-300 pulse power generator was found and described.
- The optimal setting of the input parameters of the program Neutrons such as a number of events, reconstruction steps and reconstruction rounds was suggested.

- The proposal of the whole neutron TOF diagnostic setup for the reconstruction of the time-resolved neutron energy spectra in Z-pinch fusion experiments was shown.

- The procedure for the determination of the energy resolution of the reconstruction method AMCRT and the determination of the uncertainty was found.

4.2 Results obtained during PF-1000 experiments

This section demonstrates how the program Neutrons was used to process the experimental data. The PF-1000 facility is a plasma focus which operates at the Institute of Plasma Physics and Laser Microfusion in Warsaw. Typical initial parameters of the experiments were: charging voltage of 27 kV and a pressure of the deuterium gas of 465 Pa. The PF-1000 provided a maximal current level up to 1.9 MA. The neutron TOF diagnostics consisted of nine detectors placed in the z-axis at distances from 84 m to 7 m in two opposite directions and one detector which was placed at 7 m in the a radial direction.

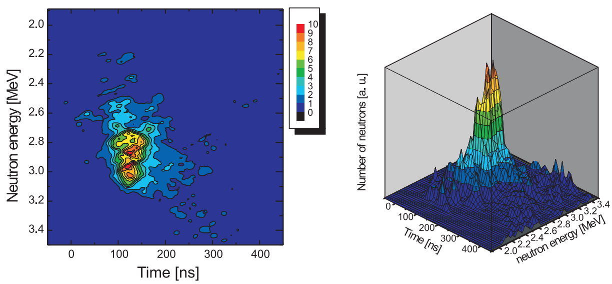

Figure 4: Reconstructed time-resolved neutron energy spectrum in downstream direction (shot No. 6540).

An example of the reconstructed neutron energy spectrum in a downstream direction (shot No. 6540) is shown in Figs. 4 and 5. The peak of the reconstructed energy spectra in a downstream direction was 2.84 MeV whose width was 500 keV (FWHM). The corresponding component of the kinetic energy of deuterons producing fusion neutrons is shown in Fig. 6 – the minus sign corresponds to the energy component in an upstream direction.

Following graphs in Figs. 7 and 8 show dependence of the mean energy and FWHM of the reconstructed energy spectra on the total neutron yield

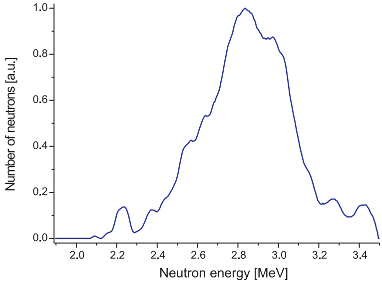

Figure 5: Neutron energy spectrum received by an integration of time-resolved energy spectrum from Fig. 4 (shot No. 6540).

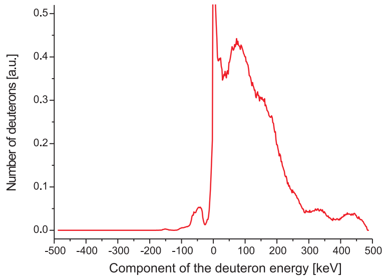

Figure 6: Probability function of the kinetic energy component (in axial directions) of deuterons producing fusion neutrons (shot No. 6540).

in all 12 processed shots (year 2006). The neutron yield was measured by the silver activation counters.

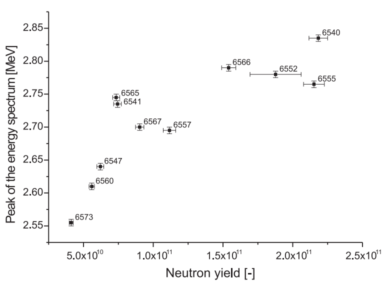

Figure 7: Dependence of the mean energy of the reconstructed energy spectrum on the total neutron yield.

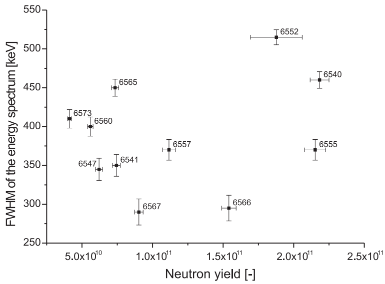

Figure 8: Dependence of the FWHM of the reconstructed energy spectrum on the total neutron yield.

4.3 Results obtained during S-300 experiments

The S-300 facility is a pulse power generator located at the RRC Kurchatov Institute in Moscow. The basic parameters of the generator are: charging voltage $U_0 = (40 \div 60)$kV, bank energy $E_0 = (100 \div 300)$kJ, current rise time $T_{10\% \div 90\%} = 100$ ns, maximal current level up to 2 MA.

Only the results from the experiments with deuterium gas-puff (year 2009) are shown in this statement. The parameters of the gas-puff were: solid fill with about 40 mm in a diameter, linear density up to 50 μg cm^{-1} and the separation between the cathode and the anode was 11 mm or 20 mm. The neutron TOF diagnostics setup, see Fig. 9, include 11 neutron and hard X-ray detectors. Four axial, i.e. end-on, detectors were located at

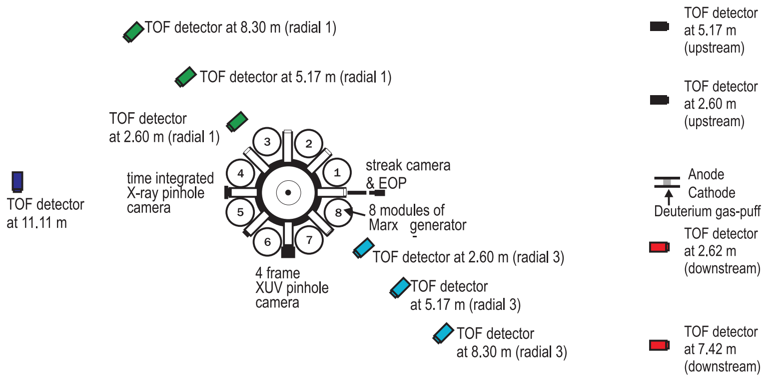

Figure 9: S-300 device – a schematic diagram of the diagnostic setup (left: end-on view, right: side-on view) with 11 time-resolved hard X-ray and neutron detectors (September 2009).

the distances of −5.17 m and −2.60 m (the minus sign means upstream, i.e. behind the anode), 2.62 m and 7.42 m (downstream, behind the cathode).Six radial, i.e. side-on, detectors were positioned in the line at the distances of −8.30 m, −5.17 m, −2.60 m, 2.60 m, 5.17 m and 8.30 m from the Z-pinch plasma. The last detector was positioned to the most distant accessible place at the distance of 11.11 m in the experimental room.

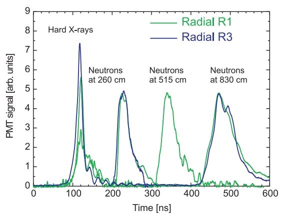

Figure 10: Side-on TOF signals shifted by the TOF of X-rays, shot No. 090922.

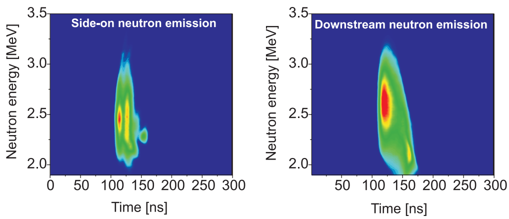

Figure 11: Neutron energy spectra in the side-on (radial) and end-on (axial) directions, shot No. 090922.

The received time-resolved neutron energy spectra reconstructed from TOF signals, see Fig. 10, are displayed in the Figs. 11 and 12. In the downstream direction, the mean neutron energy was (2.60 ± 0.08)MeV with a (700 ± 200)keV width. In the side-on directions, the mean neutron energy was (2.40 ± 0.05)MeV and the width of the neutron spectra was (600 ± 150)keV. The probability density functions of the end-on and side-on components of the kinetic energy of reacting deuterons can be seen in Fig. 13. It can be clearly seen that most of the fusion neutrons were produced by the deuterons with the kinetic energy component below 300 keV. It agrees with the fact that the maximum neutron energies of about 3.2 MeV both in the side-on and end-on directions are observed.

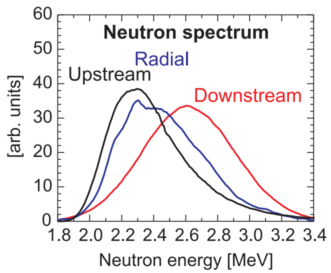

Figure 12: Time-integrated neutron energy spectra, shot No. 090922.

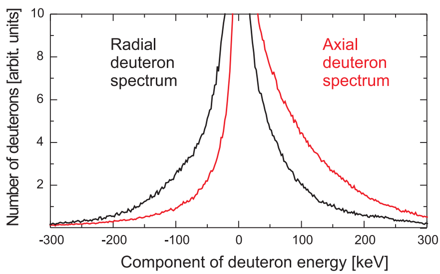

Figure 13: Kinetic energy components of reacting deuterons, shot No. 090922. The plus and minus signs of kinetic energy component reflect the direction of a deuteron velocity.

5 Summary, conclusions and future prospects

5.1 Summary

The application of any known extended time-of-flight (TOF) method for the reconstruction of time-resolved energy spectra of neutrons which were produced during the deuterium fusion experiments in Z-pinches was assigned as the first aim of this thesis. The Analog Monte Carlo reconstruction technique (AMCRT) was chosen as the most appropriate for the reaching this aim. The reconstruction program "Neutrons" which implemented this method was written. Further, the demonstration of this method in data processing from the PF-1000 experiments was shown.

Following the second aim the reconstruction method was enriched as follows. Two opposite directions of the neutron detection were examined using several detectors. The improvement of the method was performed for deuterium Z-pinch experiments, where the kinematics of a fusion binary system and nuclear data of the $D(d,n)^3He$ reaction were taken into account. The application and advantages of this improved method were also shown in the experimental data processing.

The adaptation of the reconstruction method on experimental conditions at an S-300 pulse power generator was specified as the last target of the thesis. The special procedure of data processing from S-300 experiments was designed. Furthermore, the additional program for the preparation of an initial probability function which was necessary for a special procedure was created. This additional program was also used for the preparation of the data both for the numerical testing and "half-manual" estimation of the energy spectra based on the comparison of the measured TOF signals by the signals which were generated from the entered probability function, i.e. a time-resolved energy spectrum.

On the basis of the above mentioned facts, the author believes that all assigned aims have been fulfilled. The reconstruction program Neutrons, which implemented AMCRT, or a program Neutrons-testing were used in the following articles [8, 9, 10, 11, 12, 13, 14, 15] and conference proceedings [20, 21, 22, 23, 24, 25].

5.2 Conclusions

The first conclusion obtained immediately after programming and testing one of the published reconstruction technique (an AMCRT) was that the reconstruction of the energy spectra from one direction of the neutron detection provide the results with a "rhomboid artifact" [14]. According to this conclusion, the reconstruction method was improved and this artifact was eliminated by placing the detectors in two opposite directions. In addition, another advantage was find out during the numerical testing with scattered neutrons: the reconstruction from two opposite directions eliminated the influence of the scattered neutrons.

The second conclusion was obtained during the numerical testing, where the optimal setting of the input parameters of the reconstruction program was examined. These optimal values of the parameters were: (i) A recommended number of reconstruction rounds lies in the range of 3 – 5. (ii) A recommended number of reconstruction steps is too high for the program to finish up the reconstruction round by itself. (iii) A recommended number of events was ranging from 2 to 8, in average, per one bin of an energy spectrum. It corresponds to 1×10^5 events for energy spectrum with 250×242 bins.

Following the theory, numerical tests and experience, the optimal experimental arrangement of the neutron TOF diagnostics for the reconstruction of time-resolved neutron energy spectra and the determination of kinetic energy components of the deuterons producing fusion neutrons in Z-pinch experiments was proposed. The recommendations are as follows: The experimental setup should consist of 12 neutron detectors which should be organized in two lines, i.e. one radial line and one axial line; each line consisting of 6 detectors, where two opposite directions in each line should be used. The rules for detector the placement in each direction was also described.

In the reconstruction process of the neutron energy spectra, we were able to partially eliminate the negative role of scattered neutrons by our newly developed method, i.e. using two opposite direction of a neutron detection. Nevertheless, there was a need to eliminate scattered neutrons as much as possible. Therefore, we recommend to apply other known techniques: (i) by neutron shielding in the directions where the neutrons were not detected and (ii) to evaluate the neutron scattering by an MCNP code for the given facility precisely and to include it in the reconstruction of the neutron energy spectra.

The fifth important finding was that the AMCRT strongly depends on the selection of the probability function for generating random events during the first reconstruction step. On the one hand, this fact was applied during a special methodology of data processing from the S-300 experiments. On the other hand, the unsuitable choice of the initial probability function can destroy the whole reconstruction process. Thus, the uniform initial probability function is recommended in case of experiments with a sufficient number of detectors in one line and carefully selected a non-uniform initial probability function in case of a small number of detectors.

The reconstruction program "Neutrons" implementing the AMCRT was tested by many numerical tests. Based on the results from all these tests, we can conclude that the reconstruction program provides results in a sufficient quality.

The described TOF diagnostics and reconstruction method were used in Z-pinch fusion experiments in big facilities PF-1000 and S-300. The peak current up to 2 MA was obtained in our experiments, where the total neutron yield reached 5×10^{11} in case of PF-1000 experiments, and 6×10^{10} in case of S-300 experiments. More detailed description of the production mechanism of the fusion neutrons is one of the most important goal in our Z-pinch fusion experiments. All results, particularly, reconstructed energy spectra with a high resolution, i.e. the values of the peak of energy spectra and the energy spectra FWHM, provide the information about a non-thermal production of the neutrons from Z-pinches in more detail.

5.3 Future perspectives

Nowadays, we do not know if the application of Z-pinches is the right approach for the construction of the future fusion reactor. However, thanks to the relatively small costs of a Z-pinch facility with respect to other facilities such as a big laser system or a tokamak, Z-pinches offer many future applications. Except for the applications described in the second chapter, Z-pinches can be used: (i) for the preparation, testing and calibration of the fast neutron diagnostic tools, (ii) as a source of fast neutrons and (iii) for studying the processes, e.g. the production mechanism of the fusion neutrons. In all these applications, a precise neutron diagnostics, especially, the diagnostics with high resolution will be required in the future.

Several improvements of the reconstruction of neutron energy spectra were demonstrated by the program Neutrons. These improvements can be also applied in the future with the implementation of some other reconstruction techniques.

The described reconstruction program "Neutrons" and program "Neutrons-testing" were already applied in the data processing from the Z-pinch fusion experiments at a current level up to 2 MA, i.e. PF-1000 and S-300 experiments. The future prospects are expected after using the programs in the following experimental campaigns on these facilities and during scheduled experiments in another facility GIT-12 at Tomsk, where the peak current reaches 2.5 MA.

Finally, the imperfection of the reconstruction technique and the possibility of its suppression are presented. The important imperfection is the fact that the reconstruction program can not uncover such small details in orders of units of percent. The small details are important especially in searching the thermonuclear neutrons produced during the Z-pinch experiments at a low current level, i.e. up to 2 MA. The potential improvement is expected after the application of some optimization techniques such as Genetic algorithms.

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Response and reviews

The list of the candidate's works relating to the doctoral thesis with the number of responses, i.e. citations, recorded in the Web of Science® (WoS). The list does not include auto-citations and cross-citations.

Work [9], co-author, times cited: 1.
Work [10], co-author, times cited: 3.
Work [12], co-author, times cited: 1.
Work [14], main author, times cited: 2.
Work [16], co-author, times cited: 2.
Work [19], co-author, times cited: 1.

H-index without auto-citations and cross-citations: 2.

The total number of citations on the candidate's works according to the WoS: 61.

H-index according to the WoS: 5.

Résumé

The main goal of this thesis is determining energy spectra of fast neutrons produced in a relatively short burst from tens to hundreds of nanoseconds. Typical sources of the neutrons of such parameters are, for example, hot dense Z-pinch fusion plasma or fusion discharges of the dense plasma focus. The time-of-flight (TOF) diagnostic method has been chosen to achieve the goals of this thesis. The diagnostic setup of TOF measurements consists of several neutron time-resolved detectors placed in one line at different distances from a neutron source.

This thesis also describes the improvement of the TOF methods by placing the detectors on both sides of the source, i.e. the neutrons are detected in the opposite directions. TOF diagnostic data was obtained from plasma focus fusion experiments in a PF-1000 facility in Warsaw and Z-pinch fusion experiments an a pulse power generator S-300 in Moscow. The data was processed by our newly developed program Neutrons, which was successfully evaluated by a great number of numerical tests. The program implemented the Analog Monte Carlo reconstruction technique (AMCRT) used for the reconstruction of the neutron energy spectra. The reconstruction also considered following phenomena as: (i) the influence of the time properties of the neutron detector, (ii) the dependence of the scintillator light output on the neutron energy, (iii) the reconstruction from a small number of neutron TOF signals and (iv) the influence of scattered neutrons.

In case of PF-1000 experiments – plasma focus discharges in deuterium gas, typical parameters of the neutron emission were the neutron yield up to 10^{11} neutrons/shot and the duration of the neutron emission from 100 ns to 500 ns. The reconstructed energy spectra in a downstream direction had the width (FWHM) in the range of 280 keV – 520 keV, where the peaks of neutron energy spectra were located in the range of 2.55 MeV – 2.85 MeV. In case of S-300 experiments – the implosion of a conical wire array onto a deuterated fiber and the implosion of a deuterium gas-puff, typical parameters of the neutron emission were the neutron yield from 1×10^9 up to 6×10^{10} neutrons/shot and the duration of the neutron emission from 30 ns to 100 ns. The peak of the reconstructed energy spectra in a downstream direction was typically of about 2.6 MeV with about a 500 keV width (FWHM) and in a radial direction the peak showed the energy of about 2.4 MeV whose width was about a 500 keV (FWHM).

On the basis of the reconstructed energy spectra, the acceleration mechanism of the ions and the production mechanism of the neutrons in a fusion plasma were discussed.

Resumé

Hlavní náplní této práce je rekonstrukce energetických spekter rychlých neutronů, které jsou produkovány v relativně krátkém pulsu od několika desítek po stovky nanosekund. Takovéto neutronové pulsy mohou být generovány například fúzními reakcemi v horkém hustém Z-pinčovém plazmatu nebo při výbojích plazmatického fokusu v deutériu. Energetická spektra jsou rekonstruována time-of-flight metodou, tj. metodou, která je založena na měření doby letu částic – neutronů. Rekonstrukce je provedena za použití neutronových signálů, které jsou měřeny několika detektory umístěnými v různých vzdálenostech od zdroje neutronů.

V této doktorské práci je též popsáno vylepšení TOF metody použité při rekonstrukci energetického spektra z TOF signálů změřených z protilehlého směru detekce. Při rekonstrukci byly zohledněny další důležité aspekty, jako například: (i) vliv časových vlastností detektoru, (ii) vliv závislosti odezvy scintilátoru na energii detekovaného neutronu, (iii) rekonstrukce energetických spekter z malého počtu TOF signálů a (iv) vliv rozptýlených neutronů.

Rekonstrukce energetických spekter byla provedena analogovou Monte Carlo rekonstrukční technikou (AMCRT). Možnosti a plná funkčnost nově vyvinutého programu Neutrons, který implementuje AMCRT, byly prokázány pomocí numerických testů a předvedeny také při zpracování dat z fúzních experimentů na plazmatickém fokusu PF-1000 ve Varšavě a na generátoru proudového pulsu S-300 v Moskvě.

V experimentech na zařízení PF-1000, vytvářející plazmatický fokus v plynném deuteriu, byly změřeny následující parametry neutronové emise: neutronový zisk až 10^{11} neutronů/výstřel a délka emise neutronů od 100 ns do 500 ns. Rekonstruovaná energetická spektra neutronů ve směru downstream měla následující parametry: pološířku v rozmezí od 280 keV do 520 keV a maximum energetického spektra v intervalu od 2.55 MeV do 2.85 MeV. V experimentech na zařízení S-300, kde byla zkoumána imploze kónického pole drátků na deuterizované vlákno a imploze deuteriového gas-puffu, byly změřeny neutronové zisky v rozsahu od 1×10^9 do 6×10^{10} neutronů/výstřel a délka emise neutronů od 30 ns do 100 ns. Rekonstruovaná energetická spektra neutronů měla ve směru downstream typické hodnoty pološířky 500 keV, v maximu obvykle okolo hodnoty 2.6 MeV; v radiálním směru pak měla obvykle pološířku 500 keV, v maximu obvykle okolo energie 2.4 MeV.

Na základě rekonstruovaných energetických spekter byly diskutovány způsoby urychlení iontů a produkce neutronů ve fúzním plazmatu.