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Visualization of the process of neutron-physical calculation of a nuclear reactor

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Abstract

This article describes a computer program for visualization of the process of solving the diffusion equation by the source iteration method. This method is used in the overwhelming majority of software systems for calculation of VVER and RBMK reactors. This program allows you to visually demonstrate the process of obtaining the neutron field micro- and macrostructure (macrofield) in course of the iterative solution of the equation. Visualization of the iterative process allowed us to establish the fact of the rapid appearance of the microstructure of the solution at the first iterations and the slow appearance of the macrofield of the neutron flux density. This fact made it possible to propose a new approach for solving the diffusion equation, namely, to extract the low-frequency component from the initial data of macroscopic interaction cross sections using digital filtering methods; then initially perform the calculation with filtered macroconstants on a coarse grid, and finally on a fine grid.

The studies have shown that the calculation of reactor is accelerated several times even on a one-dimensional model, which means that when solving a three-dimensional problem, the solution speed will increase by orders of magnitude. This is important when solving optimization problems and «online» calculating emergency situations.

Keywords: nuclear reactor, neutron flux density, neutron-physical calculation, source iteration method, macrofield, low-pass filter.

1. Introduction

Nowadays, when performing the neutron-physical calculation of a nuclear reactor (NPC), classical methods such as, for example, the Monte Carlo method[1], the Vladimirov characteristic method[2], the S_n – Carlson method[3], and others[4] can be used. However, due to its effectiveness and relatively simple implementation, the method of iteration of sources has become the most widespread one [5,6]. Applying it during the NPC using difference schemes, the multigroup diffusion equation is iteratively solved

$$-\nabla(D_k(\vec{r})\nabla\Phi_k(\vec{r}))+\Sigma_{ad_k}(\vec{r})\Phi_k(\vec{r})-\frac{1}{K_{эф}}\chi_k\sum_{l=1}^{M}(\nu_f\Sigma_f)_l(\vec{r})\Phi_l(\vec{r})-\sum_{l=1}^{k-1}\Sigma_{l\to k}(\vec{r})\Phi(\vec{r})=0 \quad , \quad (1)$$

where:

$\Phi_k(\vec{r})$ - neutron flux density of k-group in point with coordinate $\vec{r}$;

$D_k(\vec{r})$ - neutron diffusion coefficient of k-group;

$\Sigma_{ad_k}(\vec{r})$ - total macroscopic cross section of neutron absorption and neutron scattering of k-group;

$K_{эф}$ - effective neutron multiplication coefficient;

χ_k - neutron fraction of k-group in fission neutrons;

$\Sigma_{fk}(\vec{r})$ - macroscopic neutron fission cross section of k-group;

ν_f - average number of fission neutrons per absorbed neutron;

$\Sigma_{l\to k}(\vec{r})$ - macroscopic neutron scattering cross section of l-group into k-group;

M- number of neutron energy groups.

The purpose of the calculation is to determine the eigen-value $K_{эф}$ and neutron flux density $\Phi_k(\vec{r})$. With the usual calculation accuracy $K_{эф}$ (of the order of 10-5) the number of iterations, depending on the structure of the core and its size, can reach several hundreds and even thousands. Since the NPC is repeatedly performed in solving various problems of design and operation of reactors, in two- and three-dimensional cases, the cost of computer time for its implementation is significant, which complicates the operational solution of many optimization and forecast problems.

Thus, the task of reducing the execution time of the NPC is still relevant. To solve it, this paper proposes to visualize the iterative process in order to identify its characteristic features, accounting for which would allow to create new NPC algorithms with a noticeable decrease of calculation time in future.

2. Visualization software modules

To perform the neutron-physical calculation of the core, a basic program is written in which the method of iteration of sources is implemented. Using this method, the neutron diffusion equation (1) is solved numerically.

Before starting the calculations, the user has an opportunity to form a heterogeneous active zone, consisting of separate homogeneous zones. To do this, a graphical interface was created (Fig. 1), with which you can set both the number and width of zones into which the reactor core is divided, and the parameters of each zone necessary for calculating the neutron field (diffusion coefficient D, absorption macroscopic section $\sum_a$ and fission macroscopic section $\sum_f$). The basic program performs NPC for user-defined reactor core parameters. At the end of the calculations, the distribution of the neutron flux density in the nuclear reactor and the effective neutron multiplication coefficient $K_{эф}$ are displayed showing the criticality level of the reactor. The program also provides the output of the number of iterations and machine clocks to evaluate the effectiveness of the algorithm implemented in it.

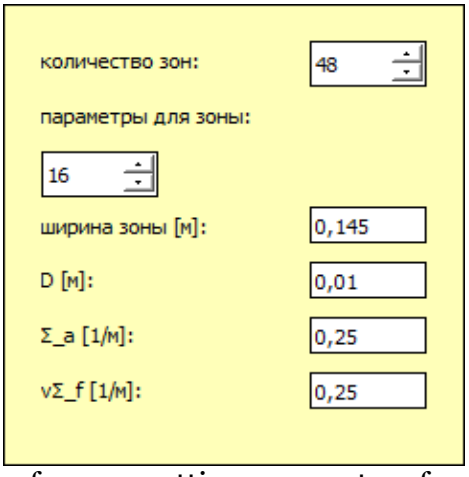

Fig. 1. Interface for user setting parameters for reactor zones.

During the visualization, the basic NFR program was supplemented with three modules, two of which directly visualize the process of calculating the neutron field, and the third uses a digital low-pass filter to perform accelerated calculation of the reactor using a modified algorithm.

2.1 Neutron field profile visualization module

The source iteration method is an iterative algorithm in which the neutron field is recalculated at each iteration until it is finally calculated with a given accuracy. The module for visualizing the neutron field profile created in this work visually displays the calculation process itself, namely, it shows in the animation mode how the neutron field profile changes at each iteration and how its micro- and macrostructure changes:

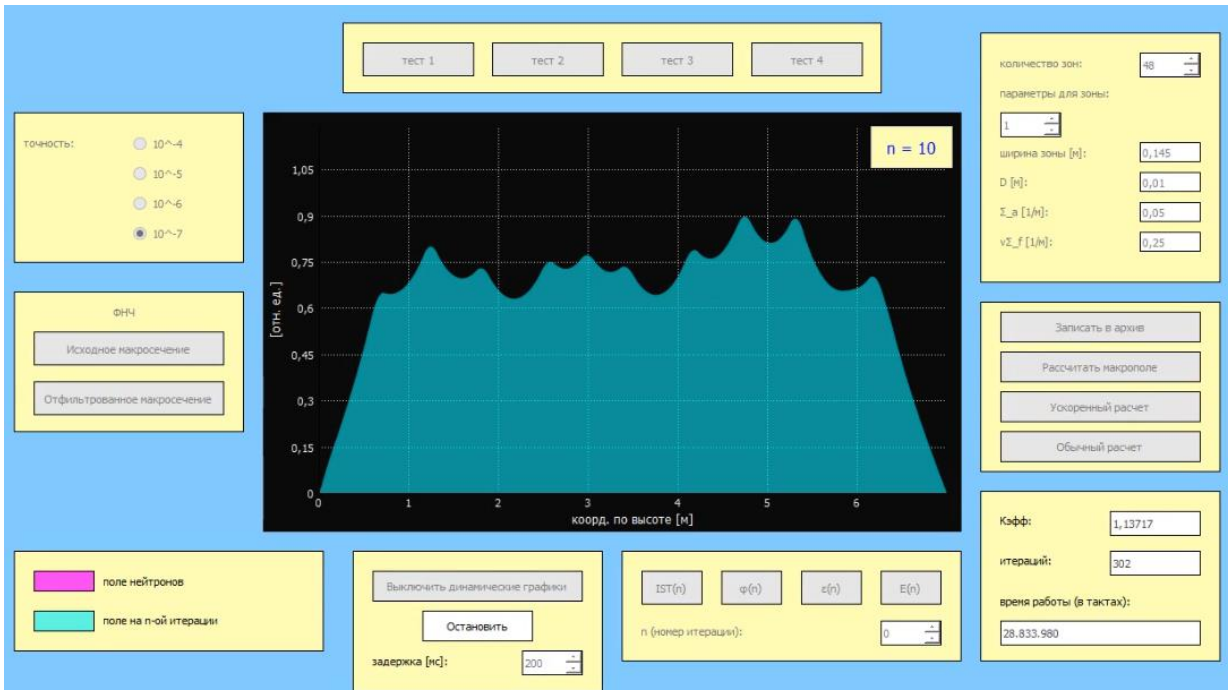

Fig. 2. Changes in the neutron field profile at each iteration of the NPC (n is the iteration number).

The above animation allows to observe the dynamics of changes in the neutron field during the NPC. Already the first iterations show how local peaks and dips in the neutron field — the so-called microstructure — are clearly manifested. However, the global skewness (macro-field) almost coincides with the given initial approximation (constant).

Visualization of subsequent iterations shows that the microstructure remains practically unchanged, while the macro-field gradually changes and only after several hundred iterations almost stops changing.

Thus, the module for visualizing the neutron field profile created in this work visually displays the calculation process itself, namely, it shows in the animation mode that during the NPC the microstructure of the neutron field is established very quickly, unlike the macro-field, the calculation of which accounts for the majority of subsequent iterations.

2.2 Visualization module for the spectral composition of errors of the NPC

For a more detailed presentation of the features of calculating the neutron macro-field, a module for visualizing the spectral composition of errors of the NPC was created. If we take the neutron field obtained at the last iteration as the true solution, then this module allows you to see how the error changes during the calculation depending on the harmonic number

and iteration number, where the error is the modulus of the difference between the true solution and the solution obtained at the current iteration:

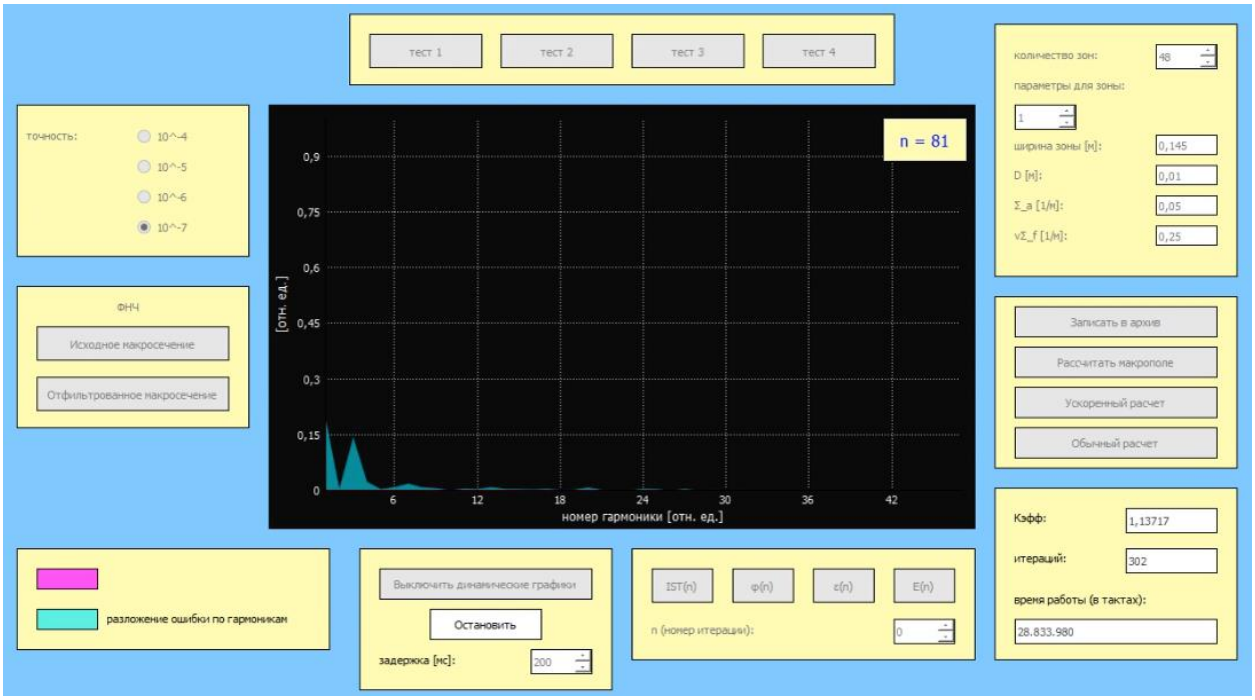

Fig. 3. Changes in the spectral composition of the errors of the NPC at each iteration (n is the number of iterations).

This animation shows how, when conducting NPC, the spectral composition of physical calculation errors at each iteration changes. Already at the first iterations, it is seen that the largest error modulus is observed at the lower harmonics (1-8 harmonics), which correspond to the macrostructure of the neutron field. In this case, the higher harmonics, which correspond to the microstructure, almost do not contain errors.

Further iterations show that the low-frequency component of the error decreases rather slowly, which was also demonstrated by the previous module: most of the iterations accounted for the change in the macro-field.

The above results of the second visualization module allow us to establish the main reason for the slow convergence of the NPC, as well as to draw the following conclusion: if we form the initial approximation of the neutron field, consisting of the first 6-8 low-frequency harmonics corresponding to the real neutron macro-field in the reactor, we can significantly accelerate the NPC, since when it is performed, the main time expenditure falls on the calculation of the macro-field.

2.3 Neutron field macrostructure visualization module

The next stage of the work was to search for a way to find such an initial approximation of a neutron macro-field with a limited spectrum, in which its profile would practically not differ from the real one. The idea was suggested that the spectrum of macro-constants (according to Fourier) is related to the spectrum of the neutron field profile in the reactor core[7]. The essence of the idea is that to isolate the macro field, it is enough to only take into account the low-frequency component of the arrays of macro constants (D[i], $\sum_a[i]$, $\sum_f[i]$, where i is number of zone).

To check it, the third visualization module was written, which allows filtering, that is, smoothing macro-constants with a high-precision digital low-pass filter, followed by displaying the results of NPC with smoothed macro-constants.

At the beginning of the operation of this module, macro-constant values set by the user for each zone are supplied to its input. Macro-constants are digitally processed using a high-

precision low-pass filter with a specially selected cutoff frequency ω_{cp}. As a result of digital filtering in arrays of macro-constants, all frequency components above ω_{cp} (in our case ω_{cp} approximately coincides with the 6th harmonic). To illustrate the operation of the digital filter, figures 4 and 5 show the initial and filtered absorption macroscopic cross sections. $\sum_a$:

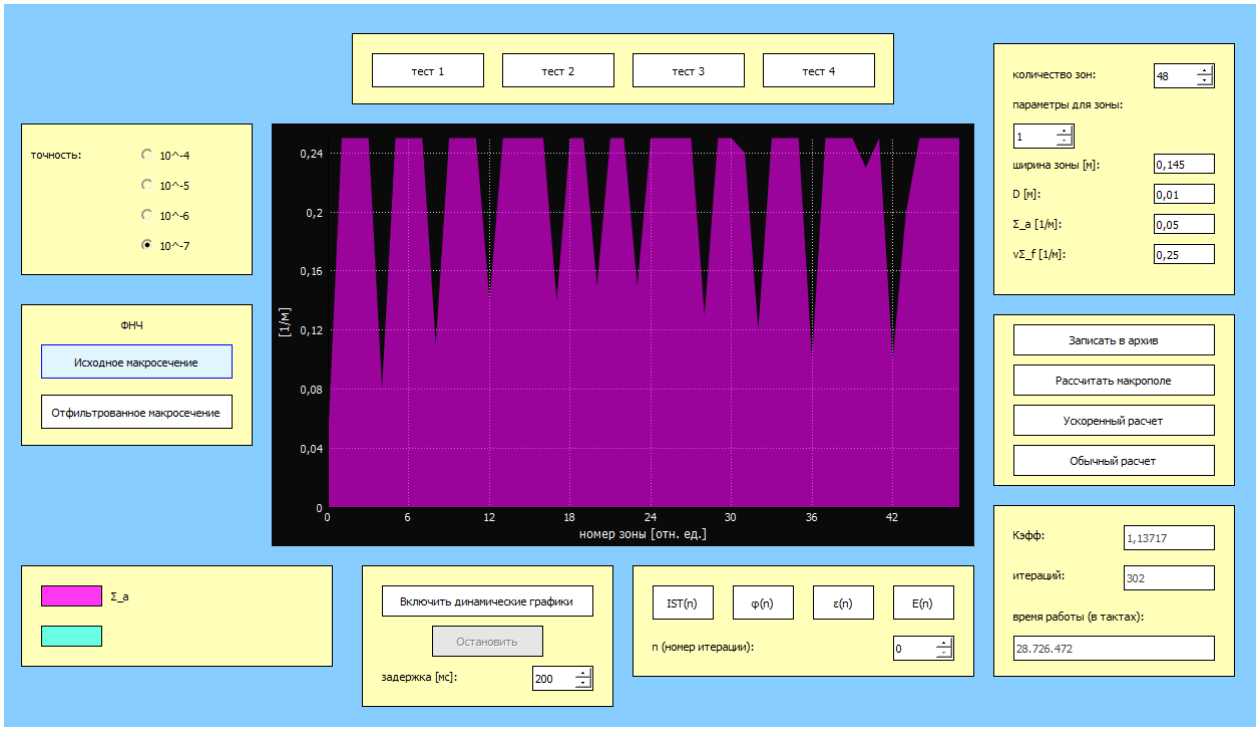

Fig. 4. Initial absorption macroscopic cross section $\sum_a$.

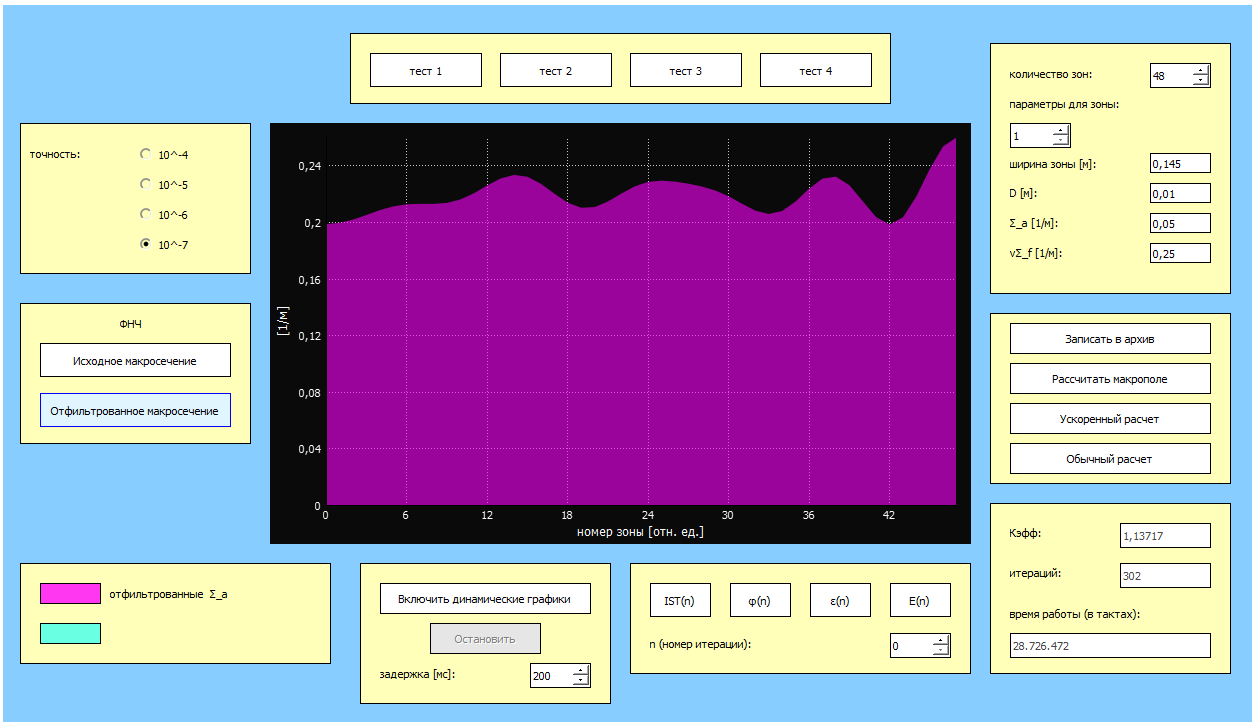

Fig. 5. Filtered absorption macroscopic cross section $\sum_a$.

Further on, with the obtained filtered macro-constants, the neutron field is calculated on a coarse grid, which is an order of magnitude faster than the calculation on a fine grid. The result is a macro-field, the profile of which is almost no different from the real one (Fig. 6):

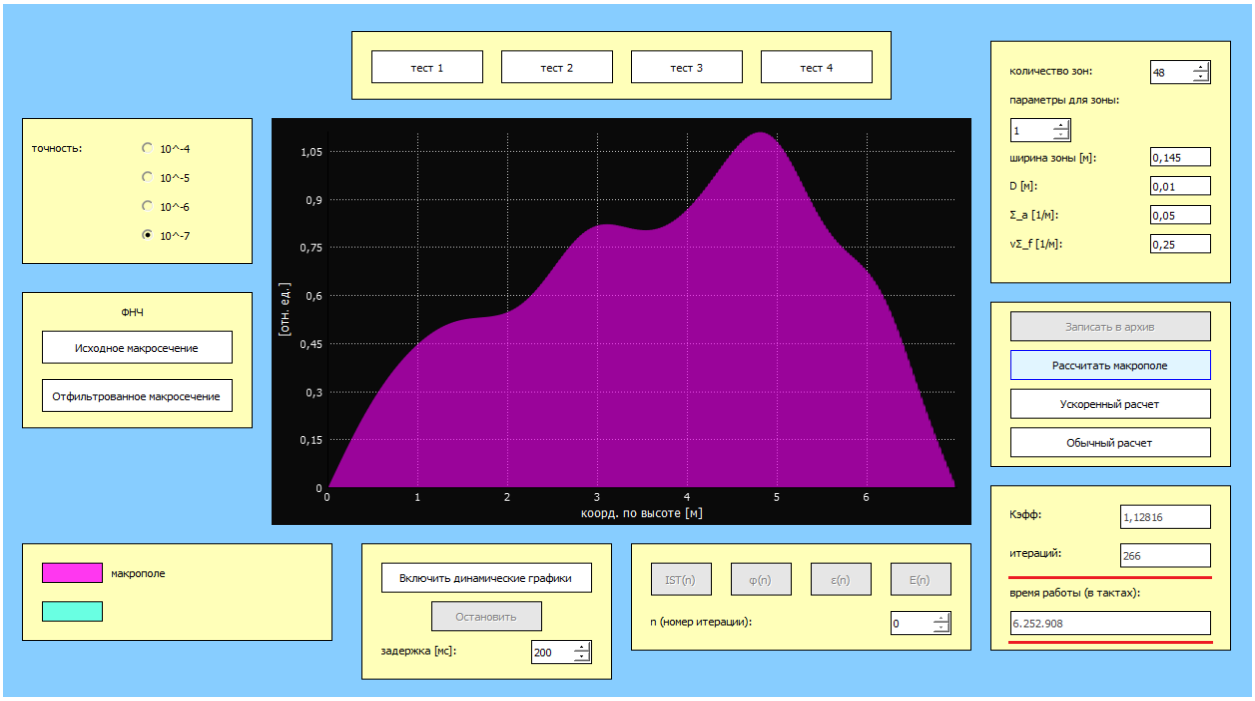

Fig. 6. Calculated neutron macro-field.

The neutron macro-field calculated on a coarse grid is subsequently used as an initial approximation when performing NPC on a fine grid with initial macro-constants. At the same time, the total time costs are reduced several times in comparison with the usual use of the basic program and amount to only 10 million measures against 28.8 million, as shown in fig. 7 and fig. 8.

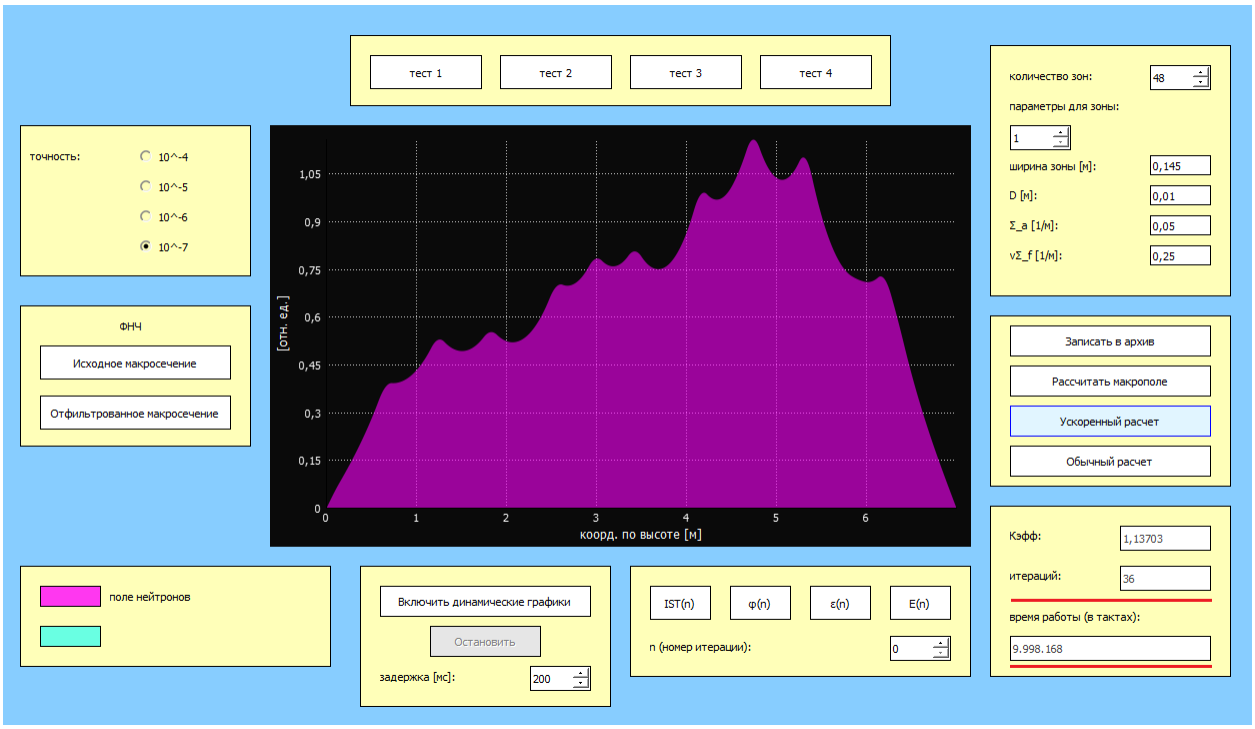

Fig. 7. Neutron field profile obtained by accelerated calculation.

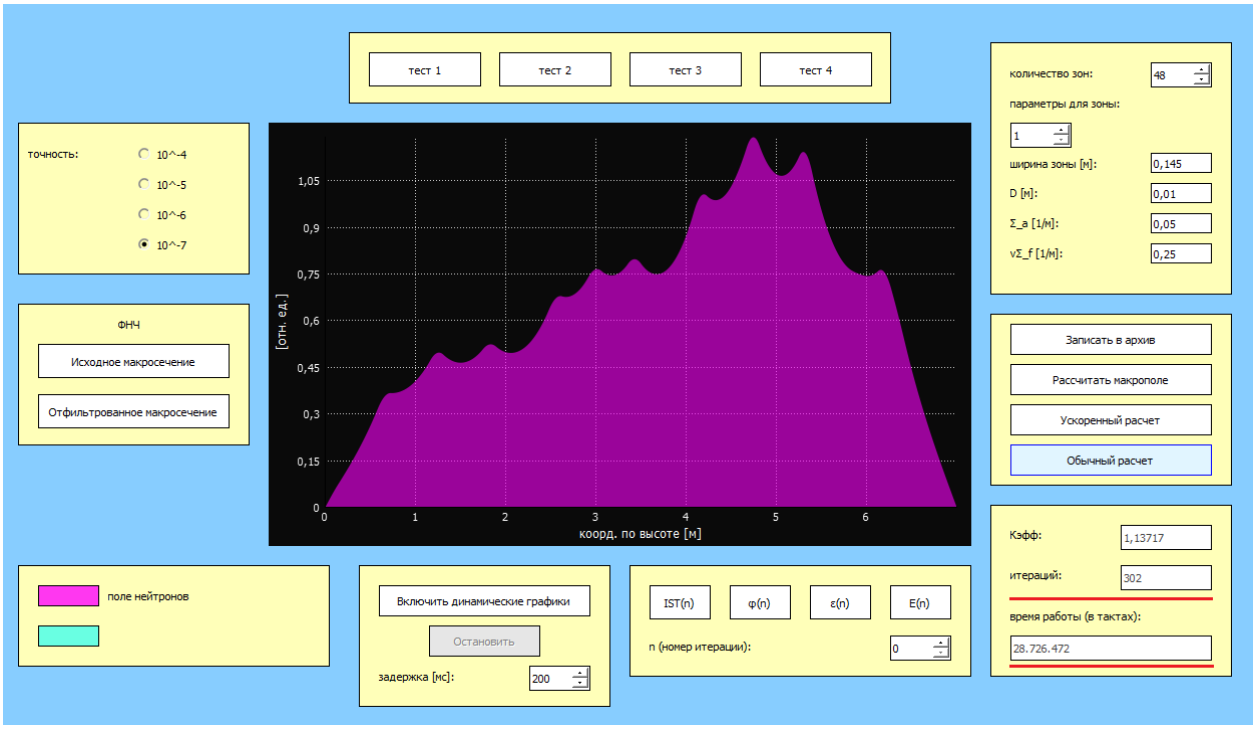

Fig. 8. The neutron field profile obtained by usual calculation.

Thus, the use of this module confirmed the validity of the idea of the relationship between the macroscopic constants spectra and the neutron field profile of the reactor and the sufficiency of using the first 6-8 harmonics of the neutron field as an initial approximation for accelerating NPC.

3. Conclusion

As a result of using the three visualization modules of the iterative process of neutron-physical calculation of the reactor presented in this work, its characteristic features were revealed, accounting for which allowed us to create a new NPC algorithm with a noticeable decrease of calculation time[8].

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