NUCLEAR PHYSICS AND ELEMENTARY PARTICLES

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DISTRIBUTION OF THE BEAM DENSITY AT THE TARGET OF SUBCRITICAL FACILITY "NEUTRON SOURCE"*

I.M. Karnaukhov, A.Yu. Zelinsky
National Science Center "Kharkov Institute of Physics and Technology", Kharkiv, Ukraine
E-mail: zelinsky@kipt.kharkov.ua

NSC KIPT subcritical facility "Neutron Source" uses rectangular tungsten or uranium target of 64×64 mm top cross-section. To generate maximum neutron flux, prevent overheating of the target and reduce thermal stress during the facility power operation one should provide uniform electron beam distribution at the target top surface. During the facility design three different possibilities of electron beam density redistribution above the target surface were considered. These were the fast beam scanning with two dimensional scanning magnets; the method of uniform beam distribution formation with linear focusing elements (dipole and quadrupole magnets) and nonlinear focusing elements (octupole magnets), when final required rectangular beam shape with homogeneous beam density is formed at target; and combined method, when one forms the small rectangular beam with homogeneous beam density distribution and scan it over the target surface with scanning magnets. In the paper the all three methods are considered and discussed taking into account the layout of the transportation channel of NSC KIPT subcritical facility "Neutron Source". For the first stage of the facility start-up and pilot operation the fast scanning method was chosen, realised and tested. The results of the beam distribution measurements over the surface of the target during the facility adjustment and start up are presented.

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INTRODUCTION

In National Science Center "Kharkov Institute of Physics and Technology" (NSC KIPT, Kharkov, Ukraine) a neutron source based on the subcritical assembly driven by electron linear accelerator was designed, constructed and is under physical start up [1, 2]. The neutron source is a hybrid facility. The main facility components are an electron linear accelerator, a system for electron beam transportation from linear accelerator to the target, neutron production target, subcritical assembly, biological shield, neutron channels and auxiliary supporting systems. Photonuclear reactions, induced by hard electromagnetic radiation emerging at retarding of the beam of relativistic electrons in the target from heavy element, are used to generate source neutrons. Two options of the target material supposed to be used: tungsten and natural uranium. Energy of electrons in driving beam is 100 MeV. It is expected that facility will provide neutron flux of about 2.4×10^{13} neutron/s. All activity is supported by Argon National Laboratory, Chicago, USA.

100 MeV/100 kW electron linear accelerator was designed by NSC KIPT and IHEP, Beijing, China [3], manufactured in IHEP, delivered to NSC KIPT, installed, put in operation and adjusted for the facility physical start up [4].

To generate maximum neutron flux without overheating of the target and with minor thermal stress the uniform electron beam distribution at the target surface should be provided along with accurate beam transportation through the transportation channel.

1. LAYOUT OF THE FACILITY AND TRANSPORTATION CHANNEL

The layout of the facility is shown in Fig. 1. The linear accelerator is installed at the second floor of the neutron source building. In such configuration the transportation channel is quite simple but meets the requirements:

- transportation of the high current electron beam from the driving linear accelerator to the subcritical assembly without particle losses;
- electron beam distribution size at the subcritical assembly target should be of about ±32 mm in both transversal directions;
- electron beam density distribution at the target should be uniform.

The lattice of the transportation channel is shown in Fig. 2. Two 45° vertical sector bending magnets of 0.51 m radius, B1 and B2 are used to bend the beam from the linac to the target. A quadrupole (Q11) is placed at the middle point of the arc to compensate the dispersion. A triplet (Q6, Q7, and Q8) and another two quadrupoles (Q9, Q10) are used to form the beam size on the target. Because of the uncertainty of the beam twiss parameters at the linac exit, the triplet is also used for the emittance measurement together with the profile monitor PR3 by the quadrupole scanning method. The distance between the last bending magnet B2 and the target is about 2.5 m.

*Work supported by ANL, Chicago, USA contract #9J-30123…
#gohar@anl.gov

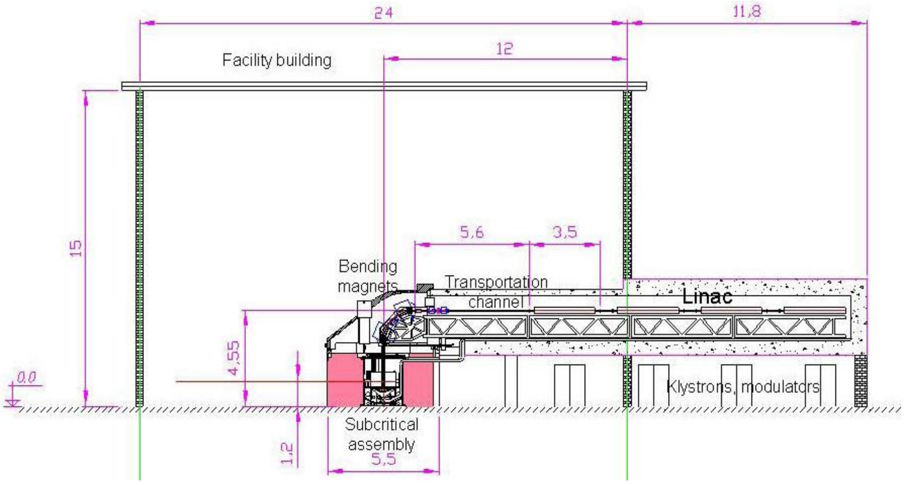

Fig. 1. Layout of the NSC KIPT neutron source

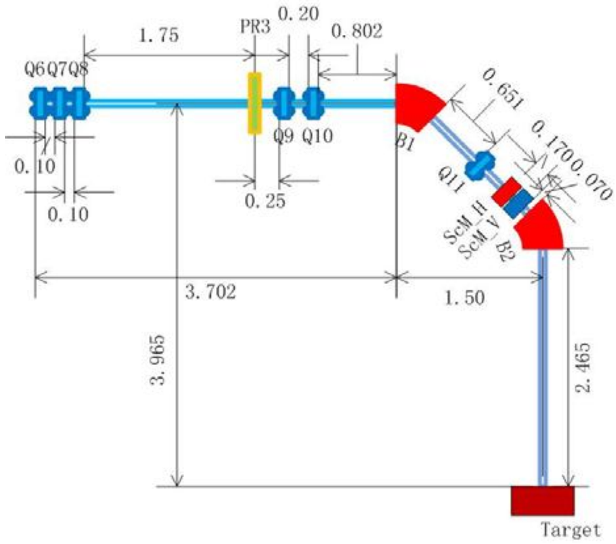

Fig. 2. Layout of the transportation channel

Fig. 3 shows the beta functions and dispersion function along the transportation channel calculated with MAD code with the assumption that ε = 0.5 mm·mrad, β = 10 m, and α = 0 at the target. Fig. 4 is the MAD calculation results assumed β = 55 m at the target. Such results show flexibility of the lattice and opportunity to readjust the lattice for the beam size variation at the target.

2. SIMULATION OF THE ALIGNMENT AND FIELD ERRORS

For the simulations of the alignment errors effect it was supposed that the electron beam at the entrance of the transportation channel has Gaussian beam density distribution functions in both horizontal and vertical directions with the same RMS sizes (1 mm and 1 mrad) and with energy spread of 2%.

The following RMS alignment error values and magnetic field installation errors were used for all transportation channel electromagnetic elements that are quadruple lenses and bending magnets:

- Transversal position displacement is 200 µm;
- Angle rotations in three planes are 0.2 mrad;
- RMS relative field errors are equal to 10^{-4}.

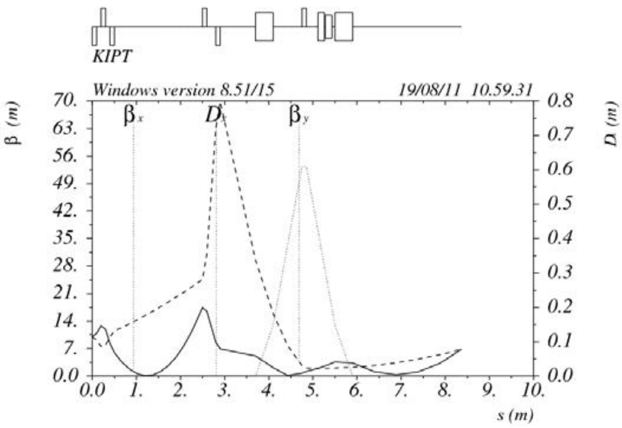

Fig. 3. Beta functions and dispersion function along the transportation channel with β=10 m at the target

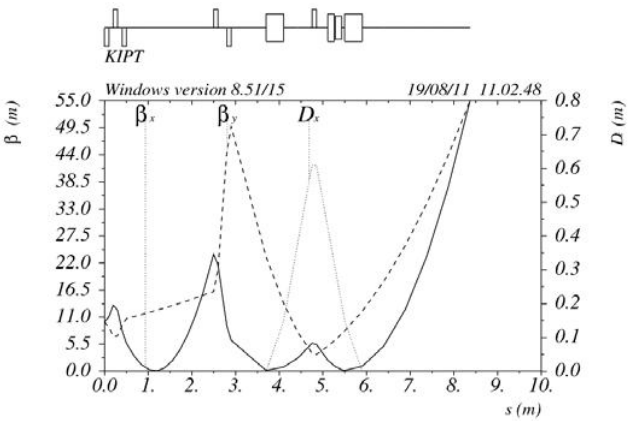

Fig. 4. Beta functions and dispersion along the transportation channel with β=55 m at the target

Fig. 5 shows the results of RMS beam position displacement calculations made with MAD code and with error values mentioned above.

As one can see in Fig. 5 the RMS beam position displacement in the horizontal plane is about 2 mm at the beam position monitor M and about 14 mm at the neuron generating target. The RMS beam position displacement in the vertical plane is about 3.5 mm at the neutron generating target and about 1.5 mm at the beam monitor M.

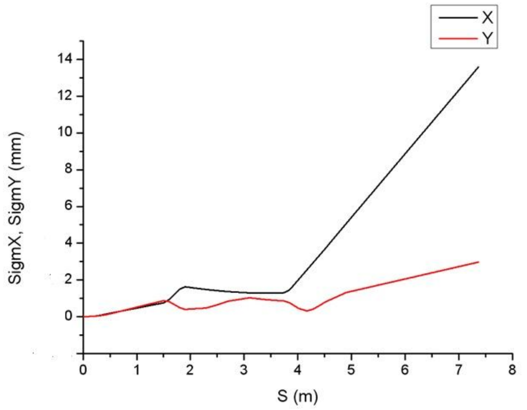

Fig. 5. RMS beam position displacement along transportation channel

As it is clear the transportation channel lattice has serious sensitivity of beam position and size to the alignment errors of the channel magnetic elements [5]. The reason of the effect is the high gradients of the quadrupole lenses of final triplet and doublet. To reduce such sensitivity the focusing strength was decreased. That allowed to focus electron beam at the neutron-generating target in 3×3 mm spot during electron beam tuning [4] and further during the facility start up. The beam tuning was performed by two doublets Q6, Q8, and Q9, Q10. Quadrupole lens Q7 was switched off.

3. ELECTRON BEAM UNIFORMITY AT THE TARGET

Three different ways to provide uniform electron beam distribution at the target surface were considered during design of the transportation channel such as:

- the fast beam scanning with two dimensional scanning magnets;
- the method of uniform beam distribution formation with linear focusing elements (dipole and quadrupole magnets) and nonlinear focusing elements (octupole magnets), when final required rectangular beam shape with homogeneous beam density is formed at target;
- combined method, when one forms the small rectangular beam with homogeneous beam density distribution and scan it over the target surface with scanning magnets.

SCANNING SYSTEM

The scanning system which consists of two deflection magnets (ScM_H and ScM_V) is placed before B2 (see Fig. 2). The scanning angles are determined by the transportation matrix from the scanning magnets to the target. The horizontal and vertical deflection angles change from -10 to 10 mrad and -24 to 24 mrad to spread the beam pulses on the target evenly, as it is shown in Fig. 6. The beam repetition rate is 625 Hz. According to the strength settings in Fig. 7, the scanning magnets deflect these beam pulses to 625 different places in a second, which means there are 25 horizontal and 25 vertical steps. Because of the beam pulse time interval is very short (1.6 ms), the changing frequency of one magnet should be 12.5 Hz with saw-tooth waveform (blue line in Fig. 7. The anther magnet strength changes with multi-step (see red line in Fig. 7) with step ≤1.6 ms.

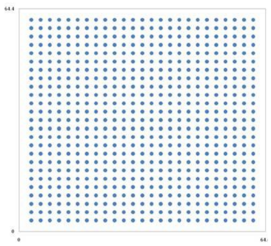

Fig. 6. Beam pulses distribution on the target

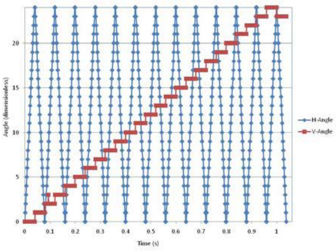

Fig. 7. Scanning magnets strength settings in a second

The scanning method determines the distance between the nearest two beam pulse positions on the target. The selection of the beam size is very important to increase the beam density uniformity on the target. On the assumption the beam having a Gaussian density profile, the distance between the beam pulse positions on the target should be (0.73…~1.72) σ, where σ is the RMS beam size. The beam density uniformity can reach 1% at most regions of the target. Fig. 8 shows difference of the beam density at a corner of the target with different pulse position gap. According to the calculation result, 1.4 σ is selected. To reduce the beam loss, a 3.2 mm edge space is spared on the target. And the beam losses are about 0.5%.

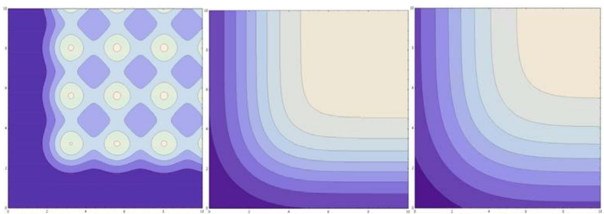

Fig. 8. Beam density contour with different beam pulse position gap on the target

METHOD WITH NONLINEAR OPTICS

The method of distribution function correction of particle density in a charged particle beam is based on changing of transversal velocity of charged particles with nonlinear magnetic field depending on transversal coordinates of a particle. Peripheral particle is much more affected by nonlinear magnetic field, while particles from the central part of the beam distribution practically have no effect of the field. As a result, peripheral particles from tails of beam distribution are shifted to the central part of beam distribution [6 - 8].

As it was shown in [8], in order to produce uniform distribution of the beam density in X and Y directions simultaneously it is necessary to use nonlinear objective with two quadrupole magnets for beam focusing and defocusing in X and Y directions, octupole magnets for redistribution of the particle density and set of quadrupole magnets to form the required beam sizes.

Fig. 9 shows the layout of the magnetic elements in non-linear objective for the transversal beam density redistribution and beam envelopes in the objective.

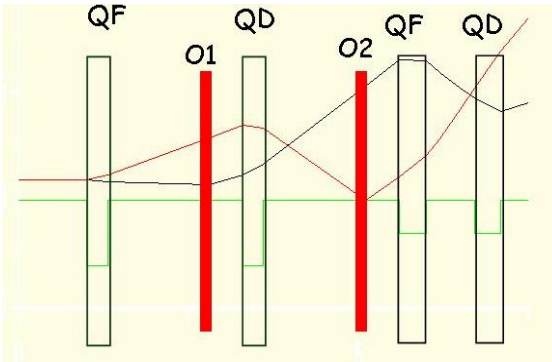

Fig. 9. Layout of the magnetic elements in a nonlinear objective for the transversal beam density redistribution and beam envelops in the objective

Calculations with DeCA code [9] showed that nonlinear objective of quadrupole and octupole combination with following parameters:

D1 : DS L=1.0;
Q1 : QL L=0.300 K1=3.58753;
D2 : DS L=1.5;
O1 : OL K3L=58000;
D3 : DS L=0.5;
Q2 : QL L=0.300 K1=-3.23126;
D4 : DS L=1.5;
O2 : OL K3L=38000;
D5 : DS L=0.5,

where D1-5 are straight parts of length L, OL1-2 are octupole lenses of K3L force and Q1-Q2 are quadrupole lenses of force K1 and length L, provides practically uniform particle distribution in both transversal directions.

Fig. 10 shows the initial particle distribution in the electron beam and particle distribution after nonlinear objective. Fig. 11 shows transversal beam distribution after nonlinear objective. It is clear from the pictures redistributed particle density and formed practically uniform beam distribution in both transversal directions X-Y.

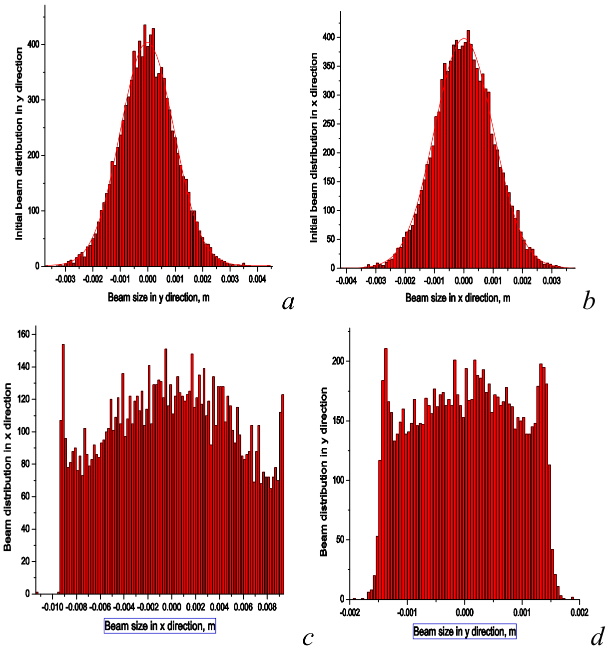

Fig. 10. Initial electron beam density distribution (a, b); electron beam density distribution after nonlinear objective (c, d)

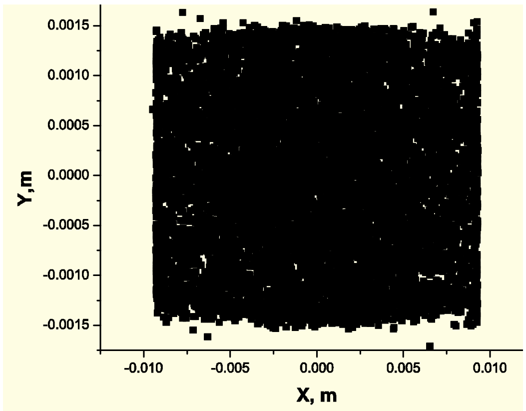

Fig. 11. The transversal electron beam distribution after nonlinear objective

This method was successfully used at design of preliminary version of the neutron facility layout [10].

Initially it was assumed that electron beam at the entrance of the transportation channel has Gaussian beam density distribution functions in both horizontal and vertical directions with the same RMS sizes (1 mm and 1 mrad). In Fig. 12,a,b profiles of electron beam at the target formed with nonlinear objective are shown. In Fig. 13 the phase map of the beam at the target in the X-Y plane is depicted. One can see from the Fig. 3 that use of octupole magnets allows to realize pseudo-uniform distribution of particle density at the target. The shape of beam profile can be corrected with slight changing of octupole strengths. The final distribution width can be edited with changing of quadrupole magnets strength.

Further simulations carried out with PARMILA code simulation data for beam distribution in the accelerator showed that because more dense presence of the particle in the center and tails of the distribution octupole magnets have strong effect on tail particles, that can lead to particle losses on the walls of the channel vacuum chamber. At the same time, particles from the center of the distribution are under weak effect of the nonlinear magnetic field and, therefore, the shape of the central part of the beam distribution is changed very slightly. With such beam distribution the particle losses due to nonlinear magnetic field are ~ 2.5%.

The simulation of the reference orbit displacement due to misalignments of the transportation channel alignment was carried out with DeCA code. The following values of the alignment errors were taking into account: in directions X, Y, Z – 200 µm, rotation angles in planes XY, YZ, ZX – 200 mrad. In Fig. 14 the results of simulation of one random realization of the element alignments with RMS value of errors, that were mentioned above, are shown. In calculations the initial Gaussian distribution of the beam density was used.

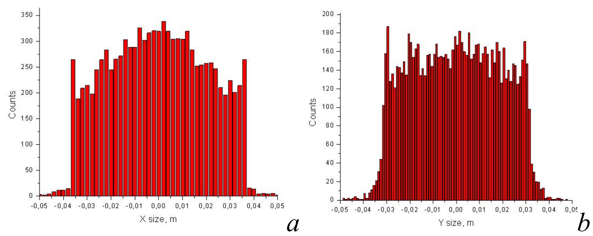

Fig. 12. Are final distributions of beam particles at the target (a, b)

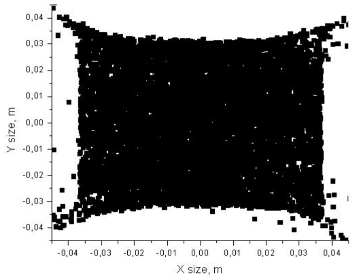

Fig. 13. Distribution of the transversal coordinates of electrons at the target

Magnetic element alignment errors with switched off octupoles lead to the shift of the Gaussian distribution center at the target with value of about ~ 0.02 mm in both transversal directions. When the octupoles were switched on, with strengths optimized for error-free case for uniform distribution production (see Figs. 12, 13), beam distributions at the target become axially-unshifted but their shapes are triangular (see Fig. 14). It can be explained by influence of sextupole magnetic field component, that effects beam particle traveling through an octupole with the shifted center. As it was shown in [3], effects of such type can be compensated with sextupole field, that can be combined to the octupole.

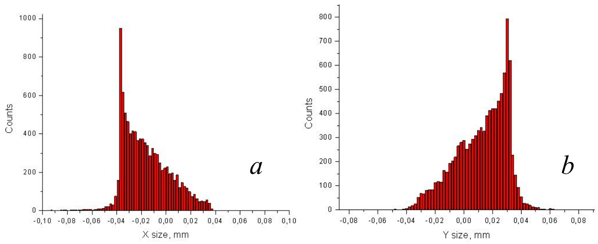

Fig. 14. Distribution, of beam particles at the target taking into account errors of element alignments: in horizontal plane(a); in vertical plane (b)

The same calculations were made for the new layout transportation channel [11]. Two octupole magnets were set between Q6-Q7 and Q7-Q8 respectively (see Fig. 2) and were used to change electron beam distribution function. The final electron beam distribution at the target surface is shown in Fig. 15. The beam losses at walls of vacuum chamber due to nonuniformity of the beam distribution are of about 1.5…2%. The main disadvantage of the method is big beam sizes in bending magnets. With use of the method one should have about 100 mm gap in bending magnets of the transportation channel that leads to the big magnet sizes and unreasonable power consumption.

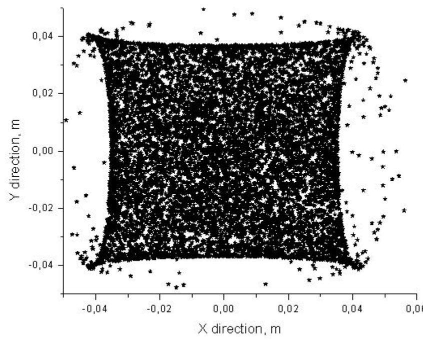

Fig. 15. Distribution of the transversal coordinates of electrons at the target

COMBINED METHOD

It seems that combination of two methods described above gives the best opportunity to form homogeneous electron beam density distribution. Preliminary calculations show that it is possible to improve the value of particle losses in the transportation channel forming rectangular shape of the beam at target with 5.26×5.26 mm and use scanning system described above. In case of need to improve energy losses and beam uniformity the presented transportation channel lattice allows modifications.

4. ELECTRON BEAM DISTRIBUTION AT THE TARGET DURING THE FACILITY ADJUSTMENT AND START UP

After analysis of the methods of the uniform beam distribution at the target of NSC KIPT subcritical facility "Neutron source" it was decided to use fast scanning method during the facility adjustment, start up and pilot operation. During further operation it allows to use combined method if it is necessary. To realize fast scanning method two scanning magnets were manufactured and installed at the transportation channel (Fig. 16). The maximum magnet coil current is about ±150 A that allows to deflect electron beam with angle ±35 mA.

At the first stage of NSC KIPT subcritical facility adjustment the dependence of neutron flux value on the electron beam position at the target was measured.

As it was determined during preliminary accelerator beam parameter adjustment with target dummy and lame screen monitors at the end of beam transportation channel, with chosen set of the electromagnetic elements parameters and electron beam energy of 100 MeV, the electron beam sizes at the target should be of about 3×3 mm and put at the target center. Because absence of beam diagnostic equipment in the end of accelerator transportation channel it is possible to confirm real beam position with neutron flux measurements only. To move electron beam at the target surface, one can observe the picture of neutron flux distribution change and find the edges of the target.

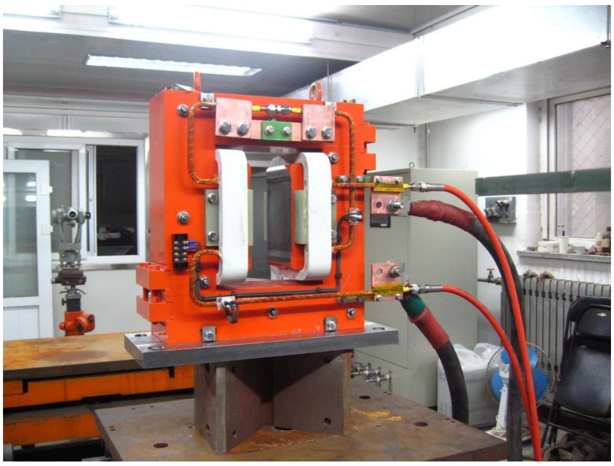

Fig. 16. Transportation channel scanning magnet

The measurements were done with 10^{-3} sensitivity sensors (sensors 1 (channel B), 3 (channel A), and 5 (channel C) in Fig. 17). Sensor 1 is the nearest to the accelerator. As it was determined during previous accelerator adjustment the excitation coil current of B2 dipole magnet equal to 510 A corresponds to the central electron beam position at the target. Changing B2 excitation current we can move the electron beam in longitudinal direction. The shifting distance can be calculated in accordance with B2 geometry and distance till the target surface. The measurements were done during 5000 electron beam pulses with beam repetition rate of 20 Hz and pulse beam current of about 35 mA. Simultaneously the electron beam charge was registered.

Fig. 18 shows the results of neutron counts registration in dependence on B2 coil excitation current. As one can see:

- value of neutron flux increases with approaching to the sensor and vice versa, decreasing with moving off the sensors 3 and 5;
- value of neutron flux at sensor 1 is practically the same because with beam movement along accelerator axis the distance to the sensor 1 keeps practically the same;
- the current of 510 A corresponds to the center beam position at the target because of equal results for sensor 1and 5;
- the sensitivity of sensor 3 is about 10% lower than sensitivity of sensors 1 and 5;
- the edges of the target are bounded with 501 A (decreasing of the neutron flux at sensors 1 and 5) and 517 A (decreasing of the neutron flux at sensors 1 and 3).

Fig. 19 shows the sum of sensor counts in depends on electron beam distance from the target center. One can see that neutron flux value is within ± 1% when electron beam is at the target surface. When the beam reaches the edge of the target (± 32 mm) the total flux is dropped down.

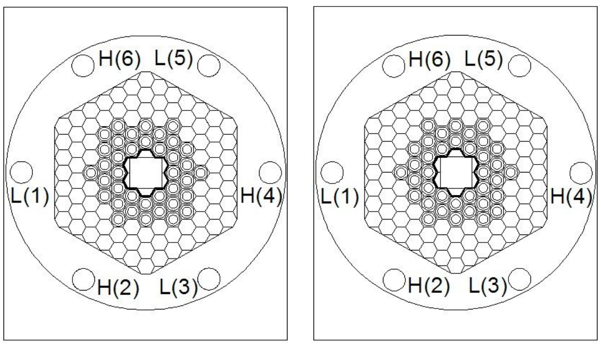

Fig. 17. Layout of the neutron sensor installation in the SCA core

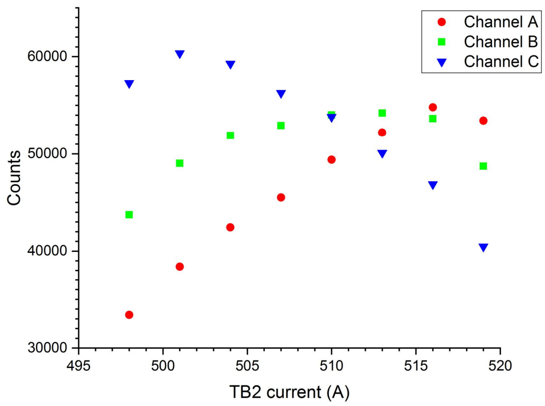

Fig. 18. The results of neutron counts registration in dependence on B2 coil excitation current

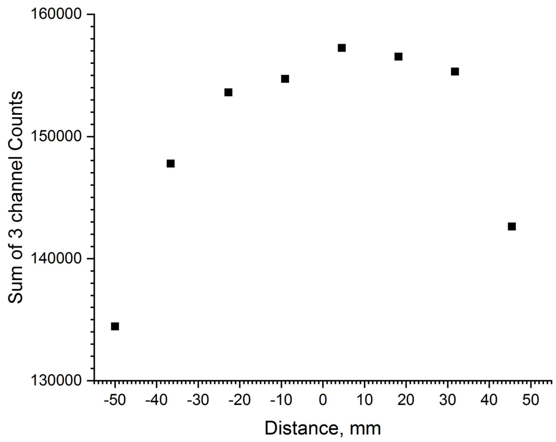

Fig. 19. The results of neutron counts registration in dependence on B2 coil excitation current

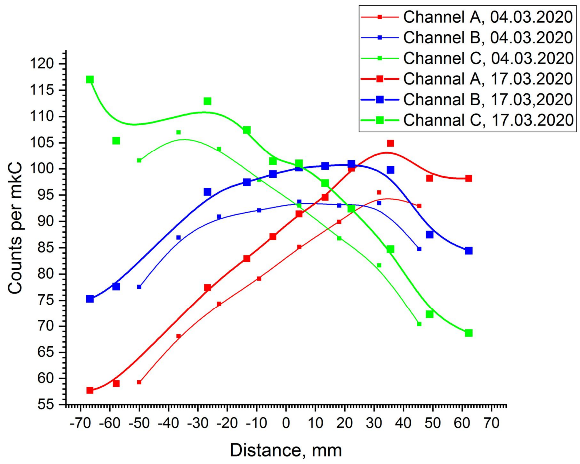

Fig. 20. The results of neutron counts registration in dependence on beam position shift along the target normalized to registered beam charge (results of two shifts)

Fig. 20 shows the results of two operation shifts normalized to registered electron beam charge. The number of registered neutrons per mkC is about 100. The measurement results are different for the different operating shifts. The difference value is about 5…6%. It means that efficiency of the beam current registration by the FCT5 was different during shifts.

To test scanning magnets efficiency two direct current sources were connected to the scanning magnets instead scanning current source. Current sources allowed to change supply current in a range ± 45 A. Such current can not provide changing electron beam position from edge to edge of the target but allowed to estimate the efficiency of the scanning magnets. Fig. 21 shows the normalized neutron counts depending on beam displacement in vertical direction with B2 magnet and vertical scanning magnet. Fig. 22 shows the normalized neutron counts depending on current in horizontal scanning magnet excitation coils.

To complete the activity scanning magnet testing the series of neutron flux measurements with different currents of scanning magnet scanning current sources were done. The measurement results show that electron beam reaches the edges of the target with 65 A current of horizontal scanning magnet and 110 A current of vertical scanning magnet that corresponds to design calculations. So, to use excitation current of the scanning magnet coils of about 50, and 90 A for horizontal and vertical scanning magnets respectively it possible to provide uniform beam distribution at the surface of the target without beam losses.

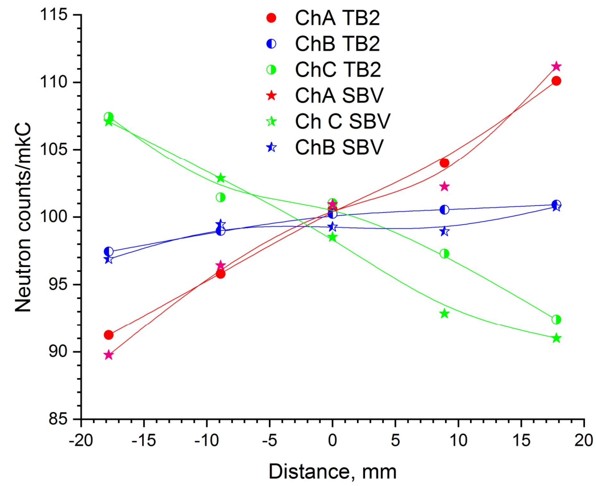

Fig. 21. Normalized neutron sensor counts in depends on electron beam displacement (● with TB2 current change; ☼ with SBV vertical scanning magnet current change)

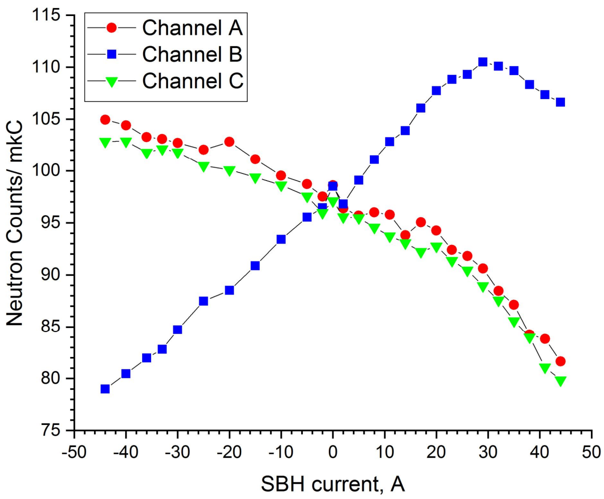

Fig. 22. Normalized neutron sensor counts in depends on horizontal scanning magnet current

The program of the physical start up of the NSC KIPT subcritical facility “Neutron Source” supposes to use electron beam repetition rate of 20 Hz. Simultaneously, the frequency of the excitation current oscillations can not be changed in the scanning magnet power supply sources. So, during the physical start up with switched on scanning magnet power supply sources and 20 Hz electron beam repetition rate 20 electron bunches will uniformly distributed along target surface (see Fig. 6).

Because the facility physical start up is carried out with low electron beam power of about 175 W it is no necessity to use fast scanning during the start up accelerator operation and neutron flux measurements. But, in order to test the scanning system and to confirm the correctness of the neutron flux measurements the measurements of the neutron pulse response were done for several fuel assemblies loadings with excitation current of 45 and 85 A for horizontal and vertical scanning magnets correspondently. As a result, in all measurements the total number of registered neutrons were lower on about 0.5% from the number of the registered neutrons without beam scanning. Such results show the good efficiency of the facility scanning system and low level of the electron beam losses at the target.

CONCLUSIONS

Three different ways to provide uniform beam distribution at the NSC KIPT subcritical facility “Neutron Source” were considered and analyzed during the facility design. For the stage of the facility adjustment and physical start up the method of the fast beam scanning with two dipole scanning magnet was chosen, realized and tested.

The results of the beam density distribution measurements obtained during the facility adjustment and start up showed that realised lattice of transportation channel allows to deliver electron beam from linear accelerator to neutron target with beam losses of about 0.5% and electron beam density distribution uniformity of about 1% that corresponds to the design parameters.

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РАСПРЕДЕЛЕНИЕ ПЛОТНОСТИ ПУЧКА НА МИШЕНИ ПОДКРИТИЧЕСКОЙ УСТАНОВКИ «ИСТОЧНИК НЕЙТРОНОВ»

И.М. Карнаухов, А.Ю. Зелинский

Подкритическая установка «Источник нейтронов» ННЦ ХФТИ использует прямоугольную вольфрамовую или урановую мишень размером 64×64 мм в поперечном сечении. Для генерации максимального потока нейтронов, предотвращения перегрева мишени и снижения температурного стресса материала мишени при работе на полной мощности ускорителя необходимо обеспечить равномерное распределение частиц на поверхности мишени. При проектировании установки были рассмотрены три возможности перераспределения плотности электронного пучка на поверхности мишени, такие как быстрое двухмерное сканирование электромагнитами, метод формирования однородной плотности частиц линейными (дипольными и квадрупольными магнитами) и нелинейными (октупольными) фокусирующими элементами, когда окончательная прямоугольная форма пучка с однородным распределением плотности частиц формируется на мишени, и комбинированный метод, когда небольшой квадрат с однородной плотностью формируется нелинейными фокусирующими элементами и затем сканируется по поверхности мишени дипольными магнитами. Рассмотрены все три метода, принимая во внимание структуру канала транспортировки пучка подкритической установки «Источник нейтронов» ННЦ ХФТИ. На первой стадии физического пуска и опытно-промышленной эксплуатации метод быстрого сканирования был выбран для реализации и протестирован. Представлены результаты измерений распределения плотности электронов на поверхности мишени, которые были получены при подготовке и в течение физического пуска установки.

РОЗПОДІЛ ГУСТИНИ ПУЧКА НА МІШЕНІ ПІДКРИТИЧНОЇ УСТАНОВКИ «ДЖЕРЕЛО НЕЙТРОНІВ»

І.М. Карнаухов, А.Ю. Зелінський

Підкритична установка «Джерело нейтронів» ННЦ ХФТІ використовує прямокутну вольфрамову або уранову мішень розміром 64×64 мм у поперечнику. Для генерації максимального потоку, запобігання перегріву мішені та зниженню температурного стресу матеріалу мішені при роботі на повній потужності прискорювача необхідно забезпечити рівномірний розподіл частинок на поверхні мішені. При проектуванні установки було розглянуто три можливості перерозподілу густини електронного пучка на поверхні мішені, такі як швидке двомірне сканування електромагнітами, метод формування однорідної густини частинок лінійними (дипольними та квадрупольними магнітами) та нелінійними (октупольними) фокусуючими елементами, коли остаточна прямокутна форма пучка з однорідним розподілом густини частинок формується на мішені, та комбінований метод, коли маленький квадрат з однорідною щільністю формується нелінійними фокусуючими елементами, а потім сканується по поверхні мішені дипольними магнітами. Розглянуто та обговорено всі три методи, беручи до уваги структуру каналу транспортування пучка підкритичної установки «Джерело нейтронів» ННЦ ХФТІ. На першій стадії фізичного пуску та дослідно-промислової експлуатації метод швидкого сканування було вибрано до реалізації та протестовано. Представлено результати вимірювань розподілу щільності електронів на поверхні мішені, які було отримано при підготовці та протягом фізичного пуску установки.

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