ESTIMATION OF THE BEAM POWER GAIN FOR DEEP-SUBCRITICAL URANIUM ASSEMBLY QUINTA UNDER RELATIVISTIC PROTON, DEUTERON AND CARBON NUCLEI IRRADIATION

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The experimental study of the beam power gain for deep-subcritical uranium target assembly Quinta (mass of natural uranium 512 kg) under relativistic protons, deuterons and carbon nuclei irradiation is presented. The Quinta assembly was irradiated with 0.66 GeV protons, 1, 2, 4, and 8 GeV deuterons and 24, 48 GeV carbon nuclei from the Phasotron and Nuclotron accelerators at the Joint Institute for Nuclear Research (JINR), Dubna. The beam power gain values obtained for the target assembly Quinta were extrapolated for a quasi-infinite uranium target using the results of the R.G. Vasilkov et al. [1]. The obtained results can be used in the ADS reactor design.

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INTRODUCTION

Within the framework of the international project "Energy and Transmutation of RAW" a series of experiments aimed at the new ADS concept [2] verification was carried out in 2011-2015 at the Nuclotron and Phasotron accelerators (JINR, Dubna). This system is intended for long-lived radioactive waste transmutation with simultaneous energy production. The basic physical idea of this approach is to use natural (depleted) uranium or thorium to create an ADS with a deep subcritical quasi-infinite (with negligible neutron leakage) multiplying target irradiated with protons, deuterons, or light nuclei with energy in the range 1…5 AGeV and possibly higher. In accordance with the experimental and theoretical results [1, 3 - 5] obtained over the last decades, such scheme can provide extremely hard neutron spectrum within the subcritical active core and ensure an effective burning of core material as well as spent nuclear fuel added to the initial core.

The experiments ("Energy and Transmutation of RAW") were carried out with a target assembly (TA) Quinta which containing 512 kg of natural uranium surrounded by a lead blanket. The TA Quinta was irradiated with 0.66 GeV protons, and deuterons and carbon nuclei with energy in the range 1…4 AGeV.

In papers [6 - 12] the energy spectra of the secondary neutrons inside and on the surface of the TA Quinta were studied. Comparison of model calculations with experiments has shown that the simulation satisfactorily describes the experimental data for neutrons with energies below 25 MeV. At the same time, for neutrons with $E_n > 25$ MeV there was a significant discrepancy between the experiment and simulations. Simulations with various standard codes did not reproduce the experimental fact of substantial hardening of the neutron spectrum with deuteron beam energy increasing from 1 to 8 GeV.

Data on the transmutation of some long-lived minor actinides from the composition of radioactive waste in the hard neutron spectrum of the TA Quinta were obtained in [13]. Nuclear reactions with ^{232}Th, ^{127}I and ^{129}I were investigated in papers [14, 15]. It should be noted that for thorium, as for ^{238}U, the reaction product yields associated with the high-energy part of the neutron spectrum are not reproduced by simulation.

In paper [18], the spatial distributions of ^{59}Co*(n, xnyp)* reaction rates in a wide range of threshold energies from 0 to 70 MeV were investigated. The simulations underestimate the production of isotopes with high threshold energy.

In experiments [7, 16, 17] spatial distributions of the ^{239}Pu production rates and ^{238}U fission were studied, and the ^{238}U fission total number and ^{239}Pu production in the volume of the uranium target were estimated. The ^{238}U total number of fission and ^{239}Pu production, normalized per 1 deuteron and per unit of its energy, turned out to be constant within the experimental errors for the energy range of the primary deuteron beam from 1 to 8 GeV, whereas simulations predict their decrease with energy increasing.

In this study the experimental values of beam power gain (or energy gain) *G* for TA Quinta irradiated by proton, deuteron and carbon beams are presented. The beam power gain in the multiplying target is one of the all-important ADS characteristics, indicating its ability to produce energy. *G* values were determined using the experimental values of the total number of fissions in the volume of uranium target. This values for the Quinta target are extrapolated for a quasi-infinite uranium assembly using results obtained by R.G. Vasilkov et al. [1], in which the uranium target (effective mass ~ 7 tons) was irradiated with 660 MeV protons.

1. BEAM POWER GAIN

The beam power gain *G* can be determined by the following expression:

$$G = (E_p + n_f \cdot E_f)/E_p, \quad (1)$$

where E_p is the accelerated particle energy (GeV); n_f is the uranium fission numbers in the uranium assembly per one accelerated particle; E_f is the fission energy (0.197 GeV).

The beam power gain determined in this way approximately corresponds to the total heat release in the target assembly normalized per primary ion beam power. In this case, we assume that only a small fraction of the primary ion energy is out of the extended uranium target with γ-quanta, π^0 mesons and neutrons leakage. On the other hand, we take into account only the basic heat release due to the uranium fission, without taking into account other possible exothermic reactions on the secondary particles.

The minimum beam power gain value G_{min} required for the energy reproduction (grid power required to run the accelerator) is determined by the value of the electric to beam power conversion efficiency (the wall-plug efficiency) η_{acc} and the thermal to electric power conversion efficiency η_{el}:

$$G_{\min} \cdot P_{beam} \geq \frac{P_{beam}}{\eta_{acc} \cdot \eta_{el}} \Rightarrow G_{\min} = \left(\eta_{acc} \cdot \eta_{el}\right)^{-1}, \quad (2)$$

where P_{beam} is the power of primary ion beam.

The thermal to electric power conversion efficiency η_{el} can reach value ~ 45% (η_{el} =41% for sodium-cooled fast reactors BN-600, η_{el} = 42% for lead-cooled fast reactor "Brest").

The coefficient η_{acc} is different for different types of accelerators. In the class of high power accelerators for ADS applications, the highest value η_{acc} = 19.5% was achieved for the PSI cyclotron (The Proton Accelerator Facility of the Paul Scherrer Institute) with beam power of 1.4 MW, energy of 0.59 GeV and beam current of 2.4 mA [19 - 21].

With the beam power increasing, the coefficient η_{acc} increases. Thus, if the beam current increases to 5 mA at the PSI cyclotron, then the expected value of η_{acc} will be about 25% [19, 21]. It is also shown that the parameter optimization of the high-power accelerators for ADS makes it possible to reach η_{acc} ~ 40% [19, 22].

Thus, for sufficiently powerful beams (P_{beam} > 3 MW), the beam power gain G_{min} required for the energy reproducing must be at least about 9 (at η_{acc} = 0.25, η_{el} = 0.45). For more powerful beams (P_{beam} > 10…20 MW), it is possible to ensure energy reproduction even at G_{min} ≈ 6…7.5 (η_{acc} = 0.3…0.4).

It should be noted that it is necessary to distinguish the starting beam power gain and the corresponding equilibrium beam power gain, which is steady in the reactor core when ^{239}Pu equilibrium concentration is reached after a certain run-time of the ADS [3]. In this paper the dependence of the starting beam power gain from the energy and the type of bombarding particles for TA Quinta (512 kg ^{nat}U) is experimentally investigated.

2. EXPERIMENTAL PROCEDURE

The uranium target of the TA Quinta consists of 5 hexagonal sections (114 mm in length, 350 mm in height) filled with metallic natural uranium cylindrical rods. The total mass of uranium in 5 sections of the target is ≈ 512 kg. Quinta is a deep subcritical assembly with k_{eff} ≈ 0.22. The uranium fill factor is about 0.6. The uranium target is placed inside 10 cm thick lead blanket. Figure shows the TA Quinta at the irradiation position in focus of the Nuclotron accelerator.

Before, between and behind of the uranium target sections in 17 mm gaps, detector plates are mounted. On these plates the various types of activation and track detectors are placed. For more detailed description of TA Quinta and detectors location, see [16, 17].

TA Quinta at the irradiation position in the F3 focus of the Nuclotron accelerator

The total number of particles to hit the target was determined via ^{27}Al(a, x)^{24}Na and ^{nat}Cu(a, x)^{24}Na reaction induced in 30 μm thick aluminum and copper activation monitors. Aluminum beam monitors were placed at a distance of more than 2 m from the TA Quinta at the forward end of the gas-filled ionization chamber to avoid the contribution of ^{27}Al(n, α)^{24}Na reaction to the ^{24}Na production caused by backscattered neutrons. Detailed information of the beam monitoring is published in [23]. The beam shape and beam positioning on the target were determined using the track detector technique [24].

Spatial distributions of ^{238}U(n, f) reaction rate were determined via activation of the natural uranium foils (29 pieces) located inside the uranium target on the detector plates.

After the end of irradiation, the uranium foils were taken out from the target to measure γ-spectra using HPGe detectors. Detection efficiency curves of HPGe detectors for various measurement positions were constructed using the following standard gamma sources: ^{54}Mn, ^{57}Co, ^{60}Co, ^{88}Y, ^{109}Cd, ^{113}Sn, ^{133}Ba, ^{137}Cs, ^{139}Ce, ^{152}Eu, ^{228}Th, and ^{241}Am.

The fission number in the foils was determined by measuring the intensity of γ-lines at 743.36 keV (93% yield per decay), 364.49 keV (81.5%), 529.9 keV (87%), and 293.3 keV (42.8%), which accompany the β-decay of fission products ^{97}Zr, ^{131}I, ^{133}I, and ^{143}Ce, respectively. The γ-lines listed above are the most intense for these isotopes and, in addition, are isolated in the measured γ-spectra. The cumulative yields of these fission products do not greatly change (< 30%) in a wide range of neutron energies from fission spectrum to 60 MeV [25 - 30]. Table 1 shows the values of the cumulative yields of fission fragments, which were used to determine the number of fissions in uranium foils. These values were obtained by averaging the cumulative yields of ^{238}U fission by the fission neutrons and 14 MeV neutrons.

The experimental fission rates obtained via production rates of isotopes ^{97}Zr, ^{131}I, ^{133}I, and ^{143}Ce were averaged with weights corresponding to their statistical uncertainties.

Table 1

Cumulative yields of some fragments in neutron induced fission of ^{238}U [25]

Neutron energy	Cumulative yields, %			
	^{97}Zr	^{131}I	^{133}I	^{143}Ce
Fission spectrum	5.56	3.29	6.76	4.62
14 MeV	5.28	3.99	6.00	3.91
Average	5.42	3.64	6.38	4.27

3. RESULTS AND DISCUSSION

In the series of experiments the uranium fission number spatial distributions inside the Quinta target were obtained for various primary beams: 0.66 GeV protons, 1, 2, 4, and 8 GeV deuterons, and 24 and 48 GeV carbon nuclei. The total fission number in the uranium target was determined by numerical integration of the measured uranium fission rate spatial distributions in the approximation of a cylindrical target with diameter D = 286 mm (the vertical size of the uranium target sections). The determination of the integral fission values was carried out taking into account the radial volumes for each point, the effective density of uranium in each section (the mass of the uranium section divided by the geometric volume of the section) and the beam position on the target (recalculation of the foil distances from the beam axis).

The total numbers of fission obtained for the TA Quinta are shown in Table 2 per one accelerated particle, and per beam power. Errors in this values obtained for deuteron beams are given in the table without taking into account the systematic error (10%) in the reference cross-section of the Al(d, x)^{24}Na reaction used for determining the total intensity of the deuteron beams.

Table 2

Total numbers of fission per 1 particle, and per beam power

Beam, GeV	N_f /particle	N_f/particle/GeV
p(0.66)	4.1 ± 0.3	6.2 ± 0.5
D(1)	8.9 ± 0.6	8.9 ± 0.6
D(2)	19 ± 1	9.7 ± 0.6
D(4)	37 ± 2	9.2 ± 0.5
D(8)	71 ± 4	8.9 ± 0.5
^{12}C(24)	160±20	6.7±0.9
^{12}C(48)	340±40	7.1±0.8

It should be noted that total number of the fission reaction (per beam power) in the volume of the uranium target Quinta for deuteron beams with energies from 1 to 8 GeV is independent of the beam energy within the limits of statistical errors (up to 7%). The total number of fission for deuterons is in 1.4 to 1.5 times greater than for protons with energy of 660 MeV at the same beam power. In the case of ^{12}C nuclei the total number of fission is noticeably lower than in case of deuteron irradiation. Perhaps this is due to underestimate the monitor reaction cross sections used for determining the total intensity of ^{12}C beams.

For all primary beams the beam power gain values *G* for TA Quinta were determined using the expression (1). The results are shown in Table 3. The beam power gain values are in range from 2 to 3 for all beams. The small values of *G* are explained by the insufficient dimensions of the uranium target used in the experiments, which leads to a large neutron leakage. In particular, simulations performed using the MCNPX 2.7 code show that almost 80% of all the generated neutrons leave the Quinta target without further interaction in uranium [13]. The large neutron leakage is also confirmed by the results published in [7, 16].

Using the results of the R.G. Vasilkov et al. [1], the beam power gain values for the Quinta assembly were extrapolated for a quasi-infinite uranium assembly in which all the generated neutrons are completely utilized.

In paper [1], for a large natural uranium target with a mass of about 3.5 tons (due to asymmetric beam input, the effective mass was about 7 tons), the fission total number of 18.5 ± 1.7 per 1 proton with an energy of 0.66 GeV was obtained. The corresponding beam power gain value is 6.5. This is without considering the fissions in the central part of the target (3-4 fissions) and a small neutron leakage of 10…12%.

Taking into account 3 fissions in the central part and neutron leakage of 11%, for a quasi-infinite natural uranium target for the fission number per one proton (0.66 GeV), we obtain:

$$N(\,fission, R=\infty)\approx 18.5\cdot 1.11+3\approx 23.5$$

and corresponding beam power gain G_∞ value is about 8.

Comparison of our experiments performed with proton beams and deuteron beams shows that for a deuteron beam with 2 GeV energy, the total number of fission per beam power is 1.5 times larger than for 0.66 GeV protons (4.6 times larger per particle), i.e., in a quasi-infinite uranium target for the deuteron beam power gain with 2 GeV energy, we can expect the value

$$G_\infty(D\,2\,GeV)\equiv(23.5\cdot 4.6\cdot 0.197+2)/2\approx 11.6\,.$$

Values of G_∞ for the other beams estimated in a similar way are shown in Table 3.

Table 3

Beam power gains for TA Quinta and corresponding estimations for quasi-infinite uranium target

Beam (Energy, GeV)	G Quinta	G_∞
p(0.66)	2.2	-
d(1)	2.7	11
d(2)	2.9	11.6
d(4)	2.9	11.4
d(8)	2.8	11
^{12}C(24)	2.3	8.5
^{12}C(48)	2.4	9
p(0.66) [1]	-	8

The estimated G_∞ values satisfy the minimum requirements ($G_{min} > 7$) for energy reproduction (grid power required to run the accelerator). At the same time, simulations for quasi-infinite targets give significantly lower beam power gain values. For example, simulation with the MARS15 code (120 cm diameter uranium target with 110 cm length) gives the maximum beam power gain value ~ 5.5 for protons with an energy of 2…4 GeV [31]. Simulation with the MCNPX 2.7e code [32] for the quasi-infinite depleted uranium target with a mass of ~ 22 tons, irradiated by protons and deuterons of 1, 6, 12 GeV, gives beam power gain about 4.

If the beam power gain estimates based on experimental data are correct, a deep subcritical reactor with a quasi-infinite natural uranium target can, for example, be used for minor actinide transmutation with return of the spent energy back to the electrical mains. Indeed, in the fast neutron spectrum (> 1 MeV) the fission cross sections are equal to 1…2 barns for all minor actinides and exceed the corresponding fission cross sections of 238-uranium. For the fissile ^{239}Pu and ^{241}Pu isotopes the effective cross section over the neutron spectrum produced in the natural uranium target will be an order of magnitude larger. The minor actinide fission energy is also ~ 0.2 GeV, i.e., the spent nuclear fuel (minor actinides) placed in the natural uranium target will not reduce the energy release in such target.

SUMMARY

In this study the starting beam power gain dependence from the energy and the type of bombarding particles for uranium target assembly Quinta (512 kg ^{nat}U) was experimentally investigated.

It is shown that for such natural uranium target and for deuteron beams with 1…8 GeV energy range the beam power gain is independent of the deuteron energy within the limits of statistical errors (up to 7%).

For target assembly Quinta the beam power gain values are 2.7…2.9 for 1…8 GeV deuteron beams, 2.2…2.4 for 0.66 GeV proton, and 24, 48 GeV for carbon beams.

Comparing our experimental data obtained using proton and deuteron beams with the results of the experimental work [1] it follows that the beam power gain for deuteron beams with 1…8 GeV energy can reach value about 11 for a quasi-infinite uranium target.

In terms of further research, first of all, it is necessary to conduct experiments using the quasi-infinite uranium target “Buran” [31] built in JINR, Dubna (21 tons of depleted uranium with a replaceable central zone of the target), and with 660 MeV proton beam to confirm the results of Ref. [1].

REFERENCES

1. R.G. Vasil’kov, V.I. Gol’danskii, B.A. Pimenov, Yu.N. Pokotilovskii, L.V. Chistyakov. Neutron multiplication in uranium bombarded with 300…660 MeV protons // *Atomic Energy*. 1978, v. 44 (4), p. 377-384.
https://doi.org/10.1007/BF01124414
2. А.А. Балдин, Е.М. Белов, М.В. Галанин и др. Ядерные релятивистские технологии (ЯРТ) для производства энергии и утилизации отработанного ядерного топлива (ОЯТ). Результаты первых экспериментов по физическому обоснованию ЯРТ // *Physics of Particles and Nuclei Letters*. 2011, v. 8, p. 1007-1023.
3. В.С. Барашенков, А.Н. Соснин, С.Ю. Шмаков. *Временная зависимость характеристик электроядерной системы («эффект разгонки»)*: Препринт ОИЯИ. 1992, Р2-92-125, Дубна.
4. V.I. Yurevich, R.M. Yakovlev, V.G. Lyapin. The study of neutron emission in the interaction of nuclei ^{1}H, ^{2}H, ^{4}He, ^{12}C, with energy of 1…2 AGeV with lead nuclei // *Nuclear Physics*. 2006, v. 69, № 9, p. 1531-1543.
5. V.I. Yurevich, R.M. Yakovlev, R.G. Vassilkov, et al. Production and multiplication of neutrons in lead targets induced by protons above 1 GeV // *Nucl. Instr and Meth. in Phys. Research.* 2006, v. A 562, p. 747-749.
6. W. Furman, A. Baldin, A. Rogov, et al. Time-dependent spectra of neutrons emitted by interaction of 1 and 4 GeV deuterons with massive natural uranium and lead targets // *Journal of Korean Physical Society*. 2011, v. 59(2), p. 2006-2009.
7. M. Artiushenko, A. Baldin, A. Berlev, V. Chilap, O. Dalkhajav, V. Sotnikov, S. Tyutyunnikov, V. Voronko, A. Zhadan. Comparison of neutron-physical characteristics of uranium target of assembly "Quinta" irradiated by relativistic deuterons and ^{12}C nuclei // *Problems of Atomic Science and Technology. Series “Nuclear Physics Investigations”*. 2016, №3(103), p. 74-79.
8. M. Suchopar, V. Wagner, J. Vrzalova, et al. MonteCarlo simulation of natural uranium setups irradiated with relativistic deuterons by means of MCNPX code // *Proceedings of Science* (*Baldin ISHEPP*. *XXI 091*). 2012, September 10-15, Dubna.
9. N.L. Asquith, S.R. Hashemi-Nezhad, S. Tyutyunnikov, et al. Activation of ^{197}Au and ^{209}Bi in a fast spectrum sub-critical assembly composed of 500 kg natural uranium irradiated with 1 and 4 GeV deuterons // *Annals of Nuclear Energy.* 2014, v. 63, p. 742-750.
10. J. Adam, A.A. Baldin, V. Chilap, et al. *Measurement of the High-Energy Neutron Flux on the Surface of the Natural Uranium Target Assembly QUINTA Irradiated by Deuterons of 4 and 8 GeV Energy*: Preprint JINR. 2014, E3-2014-92, Dubna.
11. J. Adam, A.A. Baldin, V.V. Chilap, W.I. Furman, et al. Measurement of high energy neutron flux on surface of natural uranium target assembly QUINTA irradiated by deuterons of 4 and 8 GeV // *Physics Procedia*. 2015, v. 80, p. 94-97.
12. L. Zavorka, J. Adam, M. Artyushenko, et al. Validation of Monte-Carlo simulation of neutron production in a spallation target // *Annals of Nuclear Energy*. 2015, v. 80, p. 178-187.
13. L. Zavorka, J. Adam, A. Baldin, et al. Neutron-induced transmutation in ^{237}Np, ^{238}Pu and ^{239}Pu at the massive natural uranium spallation target // *Nucl. Instr. and Meth. in Phys. Res*. 2015, B 349, p. 31-38.
14. J. Khushvaktov, J. Adam, A.A. Baldin, et al. Interactions of secondary particles with thorium samples in the setup QUINTA irradiated with 6 GeV deuterons // *Nuclear Instruments and Methods in Physics Research.* 2016, v. B 381, p. 84-89.
15. J. Adam, V.V. Chilap, V.I. Furman, et al. Study of secondary neutron interactions with ^{232}Th, ^{129}I, and ^{127}I nuclei with the uranium assembly “QUINTA” at 2, 4, and 8 GeV deuteron beams of the JINR Nuclotron accelerator // *Applied Radiation and Isotopes*. 2016, v. 107, p. 225-233.
16. I. Adam, M.Yu. Artiushenko, A.A. Baldin, et al. *The Study of Spatial Distributions of Neutron Capture and Fission Reactions in Massive Uranium Target Irradiated by Deuterons with Energies of 1…8 GeV (“Quinta” Setup)*: Preprint JINR. 2012, P1-2012-147, Dubna.

17. M.Yu. Artiushenko, V.A. Voronko, K.V. Husak, et al. Investigation of the spatial and energy distributions of neutrons in the massive uranium target irradiated by deuterons with energy of 1…8 GeV // *Problems of Atomic Science and Technology*. *Series "Nuclear Physics Investigations"*. 2013, №6(88), p. 170-174.
18. J. Adam, A.A. Baldin, M. Baznat, et al. Secondary particle distributions in an extended uranium target under irradiation by proton, deuteron, and carbon beams // *Nuclear Inst. and Methods in Physics Research*. 2017, v. A 872, p. 87-92.
19. M. Haj Tahar, F. Meot, S. Peggs. Energy Efficiency of High Power Accelerators for ADS Applications // *Proceedings of IPAC2016, Busan, Korea*. 2016, TUPOY044, p. 2001-2003.
20. J. K. Grillenberger, S.-H. Kim, M. Yoshii, M. Seidel, V.P. Yakovlev. The energy efficiency of high intensity proton driver concepts // *Proceedings of IPAC2017, Copenhagen, Denmark*. 2017, FRXCB1, p. 4842-4847.
21. M. Seidel, A.C. Mezger. Performance of the PSI High Power Proton Accelerator // *International Topical Meeting on Nuclear Research Applications and Utilization of Accelerators, Vienna.* 2009.
22. Accelerator and Spallation Target Technologies for ADS Applications // *Nuclear Energy Agency Report*. 2005, №5421, © OECD, p. 92.
23. M.Yu. Artiushenko, V.A. Voronko, Yu.T. Petrusenko, et al. Monitoring of high energy deuteron beams in the experiments with massive targets // *Problems of Atomic Science and Technology. Series «Nuclear Physics Investigations»*. 2014, №3(91), p. 186-189.
24. M.Yu. Artyushenko, V.A. Voronko, K.V. Gusak, et al. Measuring deuteron beam parameters with solid-state track detectors in experiments with the QUINTA target assembly // *Physics of Particles and Nuclei Letters*. 2013, v. 10(6), p. 544-548.
25. T.R. England, B.F. Rider. Evaluation and Compilation of Fission Product Yields // *LA-UR-94-3106, 46 ENDF-349*. 1993, p. 1-173.
26. Y. Liu, Y. Yang, J. Feng, et al. Mass Distributions of 22.0 MeV Neutron-induced Fission of ^{238}U // *Communication of Nuclear Data Progress*. 2001, v. 26, p. 2-4.
27. I.V. Ryzhov, S.G. Yavshits, G.A. Tutin, et al. Fragment-mass distributions in neutron-induced fission of ^{232}Th and ^{238}U at 33, 45, and 60 MeV // *Phys. Rev. C*. 2011, v. 3, p. 054603.
28. S. Nagy, K.F. Flynn, J.E. Ginder, et al. Mass distributions in monoenergetic-neutron-induced fission of ^{238}U // *Phys. Rev. C*. 1978, v. 17, p. 163-171.
29. K.-H. Schmidt, B. Jurado, C. Amouroux, C. Schmitt. General Description of Fission Observables // *GEF Model Code Nuclear Data Sheets*. 2016, v. 131, p. 107-221. http://www.khs-erzhausen.de/GEFY.html.
30. M. Chadwick, M. Herman, P. Oblozinsky, et al. ENDF/B-VII.1 Nuclear Data for Science and Technology: Cross Sections, Covariances, Fission Product Yields and Decay Data // *Nuclear Data Sheets*. 2011, v. 112, p. 2887-2996.
31. V.S. Pronskich, N.V. Mokhov, I. Novitski, S.I. Tyutyunnikov. Energy Production Demonstrator and Material Testing Station optimization for Megawatt proton beams // *Annals of Nuclear Energy*. 2017, v. 109, p. 692-697.
32. P. Zhivkov, W. Furman, and Ch. Stoyanov. Calculation of ADS with deep subcritical uranium active core – comparison with experiments and predictions // *Journal of Physics: Conference Series*. 2014, v. 533. 012053.

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КОЭФФИЦИЕНТЫ УСИЛЕНИЯ МОЩНОСТИ ДЛЯ ГЛУБОКО ПОДКРИТИЧНОЙ УРАНОВОЙ СБОРКИ КВИНТА ПРИ ОБЛУЧЕНИИ РЕЛЯТИВИСТСКИМИ ПРОТОНАМИ, ДЕЙТРОНАМИ И ЯДРАМИ УГЛЕРОДА

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Представлены результаты экспериментального определения коэффициентов усиления мощности первичного пучка при облучении релятивистскими протонами, дейтронами и ядрами углерода глубоко подкритичной урановой сборки КВИНТА (512 кг ^{nat}U). Сборка КВИНТА облучалась 0,66 ГэВ протонами; 1, 2, 4 и 8 ГэВ дейтронами и 24, 48 ГэВ ядрами углерода на ускорителях ФАЗОТРОН и НУКЛОТРОН Объединенного института ядерных исследований (ОИЯИ), г. Дубна. Значения коэффициентов усиления мощности для сборки КВИНТА были экстраполированы для квазибесконечной урановой мишени с использованием результатов работы [1]. Полученные результаты могут быть использованы при проектировании ADS установок.

КОЕФІЦІЄНТИ ПОСИЛЕННЯ ПОТУЖНОСТІ ДЛЯ ГЛИБОКО ПІДКРИТИЧНОЇ УРАНОВОЇ ЗБІРКИ КВІНТА ПРИ ОПРОМІНЕННІ РЕЛЯТИВІСТСЬКИМИ ПРОТОНАМИ, ДЕЙТРОНАМИ І ЯДРАМИ ВУГЛЕЦЮ

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Представлені результати експериментального визначення коефіцієнтів посилення потужності первинного пучка при опроміненні релятивістськими протонами, дейтронами і ядрами вуглецю глибоко підкритичної уранової збірки КВІНТА (512 кг ^{nat}U). Збірка КВІНТА опромінювалася 0,66 ГеВ протонами; 1, 2, 4 і 8 ГеВ дейтронами і 24, 48 ГеВ ядрами вуглецю на прискорювачах ФАЗОТРОН і НУКЛОТРОН Об'єднаного інституту ядерних досліджень (ОІЯД), м. Дубна. Значення коефіцієнтів посилення потужності для збірки КВІНТА були екстрапольовані для квазібезкінечної уранової мішені с використанням результатів роботи [1]. Отримані результати можуть бути використані при проектуванні ADS установок.