LINEAR CHARGED-PARTICLE ACCELERATORS

https://doi.org/10.46813/2022-141-055

CONCEPTUAL PROJECT OF THE NSC KIPT NUCLEAR PHYSICS COMPLEX FOR BASIC AND APPLIED RESEARCH IN THE FIELD OF NUCLEAR PHYSICS, HIGH ENERGY PHYSICS AND INTERACTION OF RADIATION WITH SUBSTANCE

M.F. Shul'ga, G.D. Kovalenko, I.S. Guk, P.I. Gladkikh, F.A. Peev
National Science Center “Kharkov Institute of Physics and Technology”, Kharkiv, Ukraine
E-mail: guk@kipt.kharkov.ua

The main ideas for creating a project for an accelerator complex with an energy of up to 550 MeV with a continuous electron beam for work in high energy physics and nuclear physics are presented. Schematic solutions for injectors, high-frequency system of the complex and magnetic elements are chosen. The choice of the magneto-optical scheme of the recirculator is substantiated. The dynamics of the beam in the facility and the parameters of the extracted beam are studied.

PACS: 29.20.-c

INTRODUCTION

The emergence of new accelerator technologies often leads to a significant revision of directions and methods in scientific research in the field of nuclear physics. Published in 2022, the European Strategy for Particle Physics - Accelerator R&D Roadmap [1] sets out a roadmap for research and development of European accelerators for the next five to ten years. These studies are based on the latest results on the creation of fundamentally new linear electron accelerators with energy recovery [1, 2]. The technique of energy recovery in superconducting cavities of a linear accelerator promises to increase the luminosity for physics applications by one or several orders of magnitude at an energy consumption comparable to classical solutions. The current state of these developments was discussed at the 63th ICFA Advanced Beam Dynamics Workshop on Energy Recovery Linacs ERL2019, Berlin, Germany [3]. It is assumed that the development of these technologies may affect the implementation of large accelerator projects in the next ten years [1, 2, 4].

The appearance of these installations was due to the creation of several types of superconducting accelerating structures, among which we should note the 802 MHz 5-cell structure, similar to those working in CEBAF, and the TESLA-type 9 cell modules 1.3 GHz cavities section developed for the TESLA collider, on the basis of which Three installations are being implemented: PERLE at Orsay, MESA at Mainz, and CBETA at Cornell-BNL [1, 5–9]. The module with two sections, developed in Rossendorf [10], became the basis for a number of installations [1–3], demonstrating the possibility of creating accelerators operating in continuous-wave (CW) operation. Two such modules have been working steadily in the Forschungszentrum Rossendorf Zentralabteilung Strahlungsquelle ELBE for 20 years [10, 11].

The creation of an accelerator based on superconducting technologies makes it possible to obtain a new quality in research on electron beams. So in work [12], some physical possibilities are considered that can be realized even on a low-energy installation. The low beam energy (and therefore low momentum transfer) combined with the highest beam intensity allows for highly competitive measurements at the low energy frontier of the Standard Model.

The greatly increased brightness is also of decisive importance for the discovery of new areas of low energy physics, such as nuclear photonics or spectroscopy of exotic nuclei [2].

High-intensity beams can be used in several industrial and scientific applications, such as free electron lasers, photon backscattering, neutron source, medical isotope production, and others [1].

1. MOTIVES FOR CREATING A NEW ELECTRON ACCELERATOR PROJECT AT NSC KIPT

Until 1993, the Kharkov Institute of Physics and Technology was the largest scientific center in the USSR and Ukraine, where research was carried out in nuclear physics using beams of γ-quanta, electrons, protons and other charged particles. The Institute possessed a number of unique accelerator facilities: the largest in Europe linear accelerators LU-2000 and LU-300, storage ring H-100. A large team of highly qualified specialists in nuclear physics and accelerator physics was formed at the Institute.

After 1993, large accelerators were stopped, experimental work, which is the basis of nuclear physics research, practically ceased, researchers were forced to transfer their research to other facilities outside Ukraine. The absence of "live" work in the first place led to the outflow of young specialists from this area of scientific activity and the aging of personnel.

Unfortunately, now the work of linear accelerators LU-2000 and LU-300 for the program on nuclear physics and high energy physics cannot be resumed, since the existing material and technical base of research is hopelessly outdated both morally and physically. These accelerators, like the U-240 cyclotron at INR in Kyiv and other facilities in Ukraine, were designed and built more than fifty years ago, many consumables and devices for these facilities are no longer produced by industry.

The objective needs for nuclear physics research in Ukraine gave rise to the need to develop a national research program and create installations for conducting these studies. According to the decision of the Scientific Council of the IHENP NSC KIPT in 2003, the task was set to select promising directions in the creation of the basic accelerator facility of the NSC KIPT in nuclear physics and high energy physics. This work was carried out jointly with the Technical University of Eindhoven (Kingdom of the Netherlands) on the basis of an agreement on the joint creation at the NSC KIPT of an accelerator that meets the requirements of a modern physical experiment [13, 14]. The project was based on the principles given in the Introduction to this work.

Unfortunately, the project was not implemented due to lack of funding.

In the first half of 2022, as a result of hostilities, the installations located at the institute received significant damage and their restoration does not make sense.

In this regard, it became necessary to create a new state program for the development of nuclear physics research and a facility for its implementation [15].

When choosing the parameters of the accelerator, the main characteristics of the existing and currently developed installations were considered [1–3, 5, 6, 9, 13–15].

2. MAIN PROJECT PARAMETERS

When choosing the main parameters of the accelerator project, both technological and economic requirements were considered.

The limiting energy of 500 MeV was chosen from the condition of conducting physical experiments in the largest possible range of studies recognized as relevant in the near future [1, 2, 15].

TESLA accelerating structures are produced on an industrial scale by RI Research Instruments GmbH [16]. All projects of accelerators with accelerating sections TESLA-type 9 cell modules include an energy gain of 25 MeV in continuous-wave (CW) operation [1–3, 7].

Since the cost of accelerating structures is about half the cost of a linear accelerator [14], the cost of the project can be significantly reduced by using a beam recirculation system. The magnetic system with triple passage of the accelerating structures is quite simple and provides a significant reduction in the cost of the installation.

Several types of injectors have been developed and debugged, which make it possible to obtain an average current value of more than 1 mA or a charge in a bunch of more than 300 pC [11, 17–21]. The maximum electron energy is 9.5 MeV [11].

In the injection path, an accelerating module will be used, which gives an increase in energy after the 25 MeV injector. This is necessary to create a source of positrons.

The accelerating structure of the recirculator will consist of 7 modules. The maximum beam energy at the recirculator output is 559.5 MeV.

3. MAGNETIC STRUCTURE OF THE RECIRCULATOR

The magneto-optical structure of the recirculator is shown in Fig. 1. The studies carried out made it possible to optimize the parameters of the structure in order to obtain beam extraction channels with specified parameters at the output. When studying the beam motion in the selected magneto-optical system, in order to obtain results that are closest to those actually implemented in the future setup, we used the values of the effective length of dipole magnets, the quadrupole and sextupole components of the field of dipole magnets, obtained from experimentally measured field distributions in magnets , as well as models for describing fields in dipoles and quadrupoles, widely used in the literature, which showed good agreement with the experimentally measured characteristics of these magnetic elements [14].

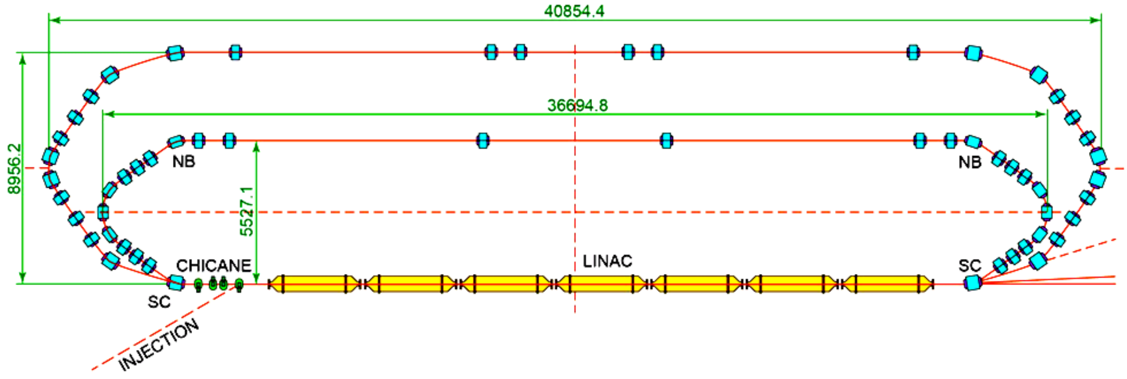

Fig. 1. General view of the structure of the recirculator

The beam is injected into the recirculator using a loop (chicane) of four magnets located in a rectilinear gap in front of the accelerating structures (LINAC). The accelerator has seven modules [7], which allow to obtain an increase in the electron energy of 175 MeV at the output. This beam can be brought into the experimental rooms for research with a maximum energy of 175 MeV plus the injection energy with the SC magnet turned off. When the distributing magnet (spreader) SC is switched on, the beam is directed along the first recirculation ring to the input of the accelerator. After receiving an energy increase of 175 MeV, upon reaching an energy of 360 MeV, the beam begins to move along the second recirculation ring. The maximum beam energy after the third pass of the accelerator will be 535 MeV. Beams with energies of 360 and 535 MeV are brought into the experimental halls with the help of a trajectory combiner-separator magnet SC.

The amplitude functions of the recirculator focusing are shown in Fig. 2.

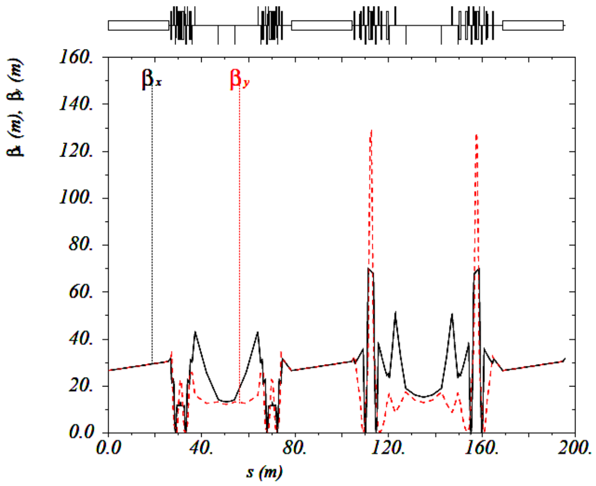

Fig. 2. Amplitude focusing functions

4. BEAM PARAMETERS AT ACCELERATOR OUTPUT CHANNELS

On Figs. 3–5 show the cross sections of the beams at the initial sections of the beam output of the main transport channels to the experimental halls.

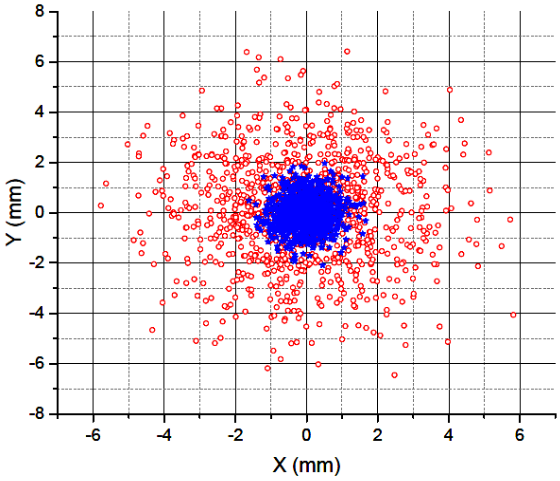

Fig. 3. Beam after the first pass of the accelerator – 185 MeV

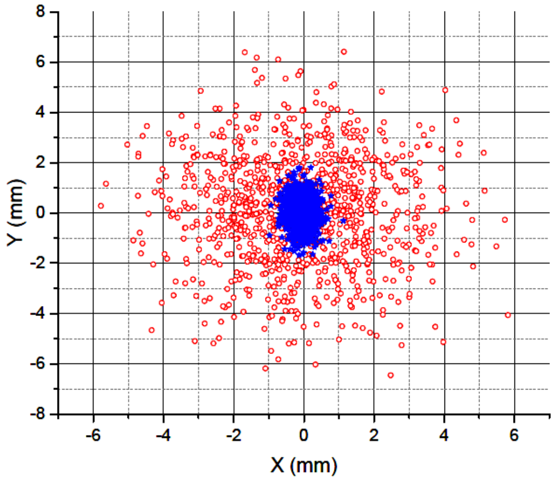

Fig. 4. Energy – 350 MeV

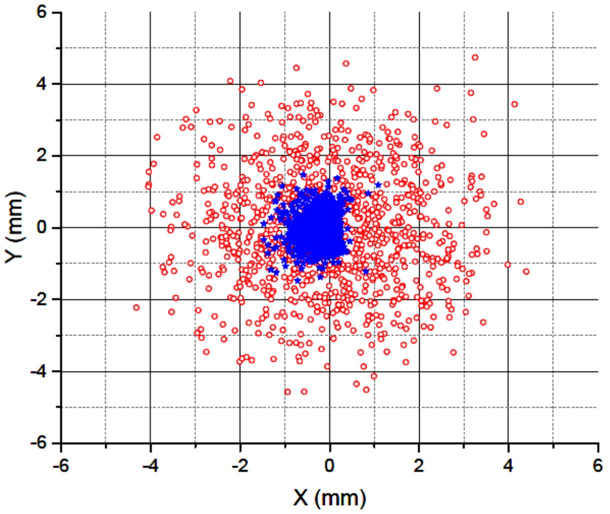

Fig. 5. Energy – 535 MeV

The red color in the figures indicates the injector beam at the entrance to the CHICANE, the blue color indicates the beam at the entrance to the channel.

The vertical beam divergence can be estimated from the image of the beam on the Py-Y phase plane (Fig. 6).

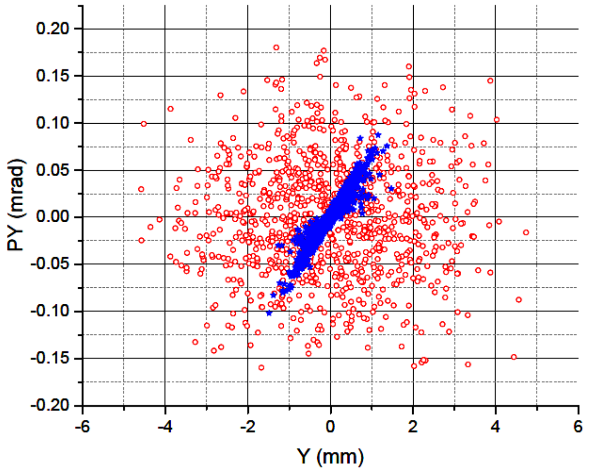

Fig. 6. Energy – 535 MeV

5. ELEMENT BASE AND LOCATION OF THE COMPLEX

As an accelerating structure, a module containing two TESLA structures, modified for use in the MESA project [7], was chosen. The general view and main dimensions of the module are shown in Fig. 7.

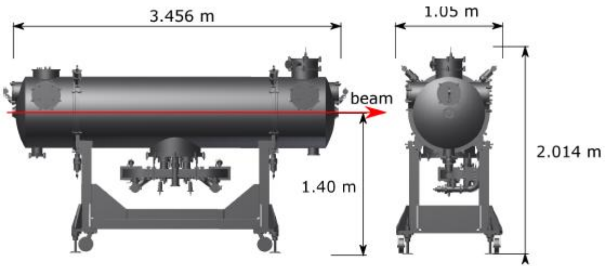

Fig. 7. Design of the cryomodule based on the ELBE cryomodule [7]

RF power sources at the ELBE are 20 kW Solid State Amplifier Blocks [22, 23]. The use of these blocks made it possible to change the energy consumption by almost two times compared to the use of klystrons.

Fig. 8 shows the draft designs of the dipole and quadrupole magnets developed for the injection channel and the CHICANO recirculator.

The magnets have air-cooled windings. A prototype dipole magnet was made and its parameters were measured. Passed the test for radiation resistance as part of the optical system of one of the technological accelerators [13]. Worked more than 9 thousand hours in radiation conditions, two orders of magnitude higher than the expected radiation levels at the new installation, without changing its parameters and operational properties.

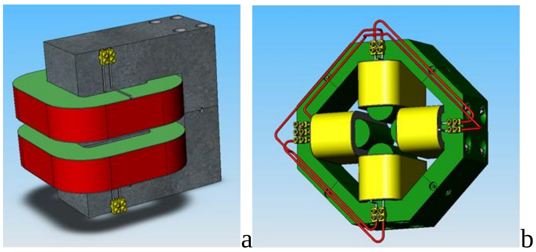

Fig. 8. Dipole magnet and quadrupole injection system

The design of the dipole magnet and the quadrupole lens of the recirculator rings are shown in Fig. 9.

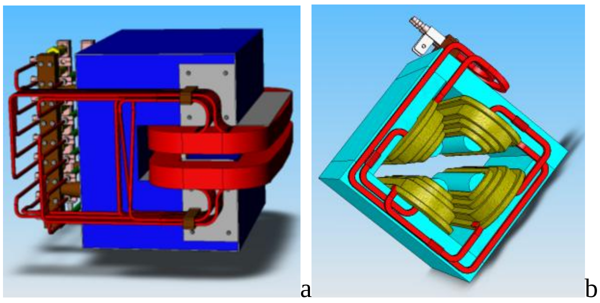

Fig. 9. Dipole magnet and recirculator quadrupole lens

Prototypes of magnets were made and their characteristics were measured [14]. They meet the requirements for use in the recirculator magnetic system.

One of the possible options for the draft design of the combiner-separator magnet is shown in Fig. 10.

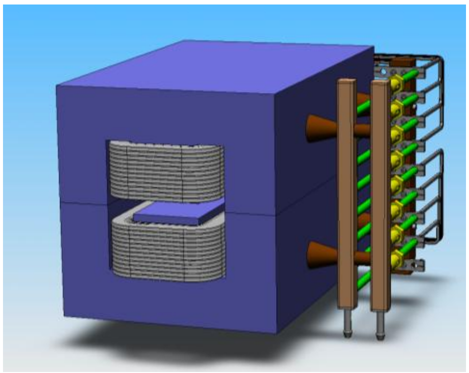

Fig. 10. Beam distribution magnet

Additional research is needed to select the final design of the magnet.

A preliminary design of the corrector was also developed [14].

The free space along the LU-2000 accelerator building can be used to accommodate the accelerator complex. The dimensions of the room for placing the equipment are set by the selected structure of the recirculator. The number and placement of experimental halls will be specified after the formation of a research program for the output channels of the recirculator. A general view of the main directions of output of the recirculator beams is shown in Fig. 11.

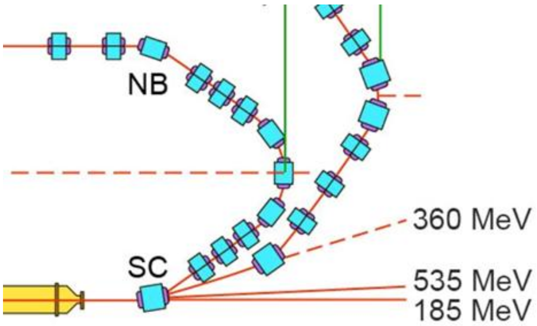

Fig. 11. Possible beam extraction channels

CONCLUSIONS

The conducted studies form the basis for further development of recirculator systems and preparation for the implementation of the project as a whole.

REFERENCES

1. *European Strategy for Particle Physics – Accelerator R&D Roadmap* / Ed. N. Mounet. CERN, 2022, 260 p.
2. Chris Adolphsen et al. *The Development of Energy-Recovery Linacs* // arXiv:2207.02095v1 [physics.acc-ph] 5 Jul 2022.
3. *63th ICFA Advanced Beam Dynamics Workshop on Energy Recovery Linacs ERL2019*, Berlin, Germany, JACoW Publishing, ISBN: 978-3-95450-217-2, doi:10.18429/JACoW-ERL2019-MOCOXBS04, 202 p.
4. P. Agostini et al. The Large Hadron–Electron Collider at the HL-LHC // *J. Phys. G: Nucl. Part. Phys.* 2021, v. 48, p. 110501, doi:10.1088/1361-6471/abf3ba.
5. D. Angal-Kalinin et al. PERLE. Powerful energy recovery linac for experiments. Conceptual design report // *J. Phys. G: Nucl. Part. Phys.* 2018, v. 45, p. 065003, doi:10.1088/1361-6471/aaa171.
6. S. Alex Bogacz. PERLE – ERL Test Facility at Orsay // *Sci. Post Phys. Proc.* 2022, v. 8, p. 013.
7. T. Stengler, K. Aulenbacher, F. Hug, D. Simon, C.P. Stoll. Cryomodules for the MAINZ energy-recovering superconducting accelerator (MESA) // *63th ICFA Advanced Beam Dynamics Workshop on Energy Recovery Linacs ERL2019*, Berlin, Germany, JACoW Publishing, doi:10.18429/JACoW-ERL2019-TUCOZBS06.
8. T. Stenglery, K. Aulenbacher, R. Heine, F. Schlander, D. Simon, M. Pekeler, D. Trompetter. Modified ELBE type cryomodules for the MAINZ energy-recovering superconducting accelerator MESA // *Proceedings of SRF2015*, Whistler, BC, Canada, THPB116, p. 1413-1416.
9. *CBETA Design Report, Cornell-BNL ERL Test Accelerator* / Editor: C. Mayes, arXiv:1706.04245v1 [physics.acc-ph] 13 Jun 2017.

10. J. Teichert, A. Büchner, H. Büttig, F. Gabriel, P. Michel, K. Möller, U. Lehnert, Ch. Schneider, J. Stephan, A. Winter. RF status of superconducting module development suitable for CW operation: ELBE cryostats // *Physics Nuclear Instruments and Methods in Physics Research Section A – accelerators, Spectrometers, Detectors and Associated Equipment*. 2006, v. 557, is. 1, p. 239-242, https://doi.org/10.1016/j.nima.2005.10.077.
11. Radiation Source at the ELBE Center for High-Power Radiation Sources, https://www.hzdr.de/db/Cms?pNid=145.
12. Achim Denig. Recent Results from the Mainz Microtron MAMI and an Outlook for the Future // *XVIth International Conference on Hadron Spectroscopy, AIP Conf. Proc.* 1735, 020006-1–020006-8; doi: 10.1063/1.4949374.
13. I.S. Guk, A.N. Dovbnya, S.G. Kononenko, F.A. Peev, J.I.M. Botman. Recirculator SALO. The physical foundation // *PAST.* 2015, N 6, p. 3-7.
14. I.S. Guk, A.N. Dovbnya, S.G. Kononenko, F.A. Peev, J.I.M. Botman. *Basic accelerator facility of the NSC KIPT in nuclear physics and high energy physics, physical justification.* Kharkiv: NSC KIPT, 2014, 225 c.
15. M.F. Shul'ga, G.D. Kovalenko, V.B. Ganenko, L.G. Levchuk, S.H. Karpus, I.L. Semisalov. Concept of the state targeted NSC KIPT program of experimental base development for basic and applied research in nuclear and high-energy physics and physics of radiation interaction with matter // *Problems of Atomic Science and Technology. Series “Nuclear Physics Investigations”*. 2022, N 3(139), p. 3-6; https://doi.org/10.46813/2022-139-003
16. RI Research Instruments GmbH, https://research-instruments.de/
17. J. Teichert. Superconducting rf guns: emerging technology for future accelerators // *5th International Particle Accelerator Conference IPAC2014, Dresden, Germany,* JACoW Publishing, ISBN: 978-3-95450-132-8, doi:10.18429/JACoW-IPAC2014-MOZB01.
18. R. Xiang, A. Arnold, P. Murcek, J. Teichert, J. Schaber. Metal and semiconductor photocathodes in HZDR SRF gun // *63th ICFA Advanced Beam Dynamics Workshop on Energy Recovery Linacs ERL2019,* Berlin, Germany JACoW Publishing, ISBN: 978-3-95450-217-2, doi:10.18429/JACoW-ERL2019-THCOYBS01
19. P. Murcek, A. Arnold, J. Teichert, R. Xiang, P. Lu, H. Vennekate. The srf photo injector at ELBE - design and status 2013 // *Proceedings of SRF2013,* Paris, France, p.148-150.
20. J. Teichert, A. Arnold, H. Buettig, D. Janssen, M. Justus, U. Lehnert, P. Michel, P. Murcek, A. Schamlott, Ch. Schneider, R. Schurig, F. Staufenbiel, R. Xiang, T. Kamps, J. Rudolph, M. Schenk, G. Klemz, I. Will. Initial commissioning experience with the superconducting rf photoinjector at ELBE // *Proceedings of FEL08,* Gyeongju, Korea, p. 467-472.
21. J. Teichert, A. Arnold, G. Ciovati, J.-C. Deinert, P. Evtushenko, M. Justus, M. Klopf, P. Kneisel, S. Kovalev, M. Kuntzsch, U. Lehnert, P. Lu, S. Ma, P. Murcek, P. Michel, A. Ryzhov, J. Schaber, C. Schneider, R. Schurig, R. Steinbrück, H. Vennekate, I. Will, and R. Xiang. Successful user operation of a superconducting radio-frequencyphotoelectron gun with Mg cathodes // *PHYS. REV. ACCEL. AND BEAMS* 24, 033401, 2021, DOI: 10.1103/PhysRevAccelBeams.24.033401
22. H. Büttig, A. Arnold, A. Büchner, M. Justus, M. Kuntzsch, U. Lehnert, P. Michel, R. Schurig, G. Staats, J. Teichert. RF power upgrade at the superconducting 1.3 GHz CW LINAC “ELBE” with solid state amplifiers // *NIM A.* 2013, v. 704, p. 7-13.
23. H. Büttig, A. Arnold, A. Büchner, M. Justus, M. Kuntzsch, U. Lehnert, P. Michel, R. Schurig, G. Staats, J. Teichert. Two years experience with the upgraded ELBE rf-system driven by 20 kW solid state amplifier blocks (SSPA) // *Proceedings of IPAC2014,* Dresden, Germany, WEPME003, ISBN 978-3-95450-132-8, 2257.

Article received 03.09.2022

КОНЦЕПТУАЛЬНИЙ ПРОЕКТ ЯДЕРНО-ФІЗИЧНОГО КОМПЛЕКСУ ННЦ ХФТІ ДЛЯ ПРОВЕДЕННЯ ФУНДАМЕНТАЛЬНИХ І ПРИКЛАДНИХ ДОСЛІДЖЕНЬ В ОБЛАСТІ ЯДЕРНОЇ ФІЗИКИ, ФІЗИКИ ВИСОКИХ ЕНЕРГІЙ І ВЗАЄМОДІЇ ВИПРОМІНЮВАНЬ З РЕЧОВИНОЮ

М.Ф. Шульга, Г.Д. Коваленко, І.С. Гук, П.І. Гладких, Ф.А. Пєєв

Наведено основні ідеї щодо створення проекту прискорювального комплексу з енергією до 550 МеВ з безперервним пучком електронів для робіт з фізики високих енергій та ядерної фізики. Вибрано схемні рішення для інжекторів, високочастотної системи комплексу та магнітних елементів. Обгрунтовано вибір магнітооптичної схеми рециркулятора. Досліджено динаміку пучка в установці та параметри виведеного пучка.