ELEMENTARY PARTICLES AND FIELDS

Experiment

DERICA Project and Strategies of the Development of Low-Energy Nuclear Physics

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Abstract—Possible strategies of the development of low-energy nuclear physics in Russian Federation on the basis of the DERICA (Dubna Electron–Rare Isotope Collider Facility) project is examined. DERICA is a multiuser multipurpose facility for the production and study of radioactive isotopes (RI). In the research program of DERICA, emphasis is placed on studying RI in collector rings, but a stage-by-stage implementation of the program of DERICA would make it possible to address a wide range of fundamental problems at each stage of its development at the cutting-edge level. The ambitious goal of creating an *electron–radioactive ion* collider for studying basic properties of RI in electron–ion scattering is proposed for the final stage of development of DERICA.

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1. LOW-ENERGY NUCLEAR PHYSICS

Historically, low-energy nuclear physics has been of paramount importance for the development of a number of fields of science and technologies in Russia. In many aspects, nuclear power engineering, reactor physics, nuclear part of the defence industry, neutron physics, and nuclear astrophysics relied on data and expert evaluation from fundamental low-energy nuclear physics. This concerns especially the possibility of performing pioneering and interdisciplinary investigations in these realms rather than conventional, well-elaborated, applications of nuclear

physics. Unfortunately, fundamental low-energy nuclear physics has recently become almost nonexistent in Russian Federation. World-class experimental investigations in the realms of fundamental nuclear physics are being conducted in Russia along specific narrow lines and predominantly only at Joint Institute for Nuclear Research (JINR, Dubna).

There were grave reasons behind this deplorable situation. In the late 1980s and the early 1990s, the paradigm of low-energy nuclear physics changed worldwide. Investigations of stable nuclei rapidly gave way to studies with beams of predominantly radioactive isotopes (RI). On one hand, the subject matter of studies with stable nuclei had been exhausted to a considerable extent by that time; on the other hand, technologies in dealing with (RI) beams had been developed to the running-order stage. In-flight (fragmentation of a fast beam of stable nuclei and in-flight separation of fragments) and ISOL (Isotope Separation On-Line—collection of fragments originating from induced uranium fission) are basic methods for the production of RI beams. (i) Highly efficient generation of RI beams according to the in-flight technology requires relatively high-energy (50- to 1500-MeV per nucleon—most frequently, the higher, the better, but there is an optimum value for each problem) heavy-ion accelerators. Instead of a single accelerator, one rather needs here a cascade of accelerators that would involve an intermediate stripping of heavy ions for raising the charge state. (ii) An efficient generation of RI beams by means of the ISOL technology requires both a highly intense driver

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(for electrons, protons, and neutrons) and the postacceleration of the emerging rare isotopes for studying a broader range of problems. Thus, a transition from single accelerators of the “dawn of nuclear era” to cascades of accelerators characteristic of facilities for high-energy physics occurred. Within this period, the development of research projects in Russia was frozen completely. Therefore, this transition did not take place in this country.

The situation currently prevailing worldwide is characterized by a vigorous construction of new-generation RI factories. New entrants appeared in addition to the ambitious programs of the upgrade of facilities that led this field for a long time, such as RIKEN $\rightarrow$ RIBF (Japan—operated since 2007), GANIL $\rightarrow$ SPIRAL2 (France—to be commissioned in 2020), GSI $\rightarrow$ FAIR (Germany—major construction work is under way), and NSCL $\rightarrow$ FRIB (USA—equipment assembly began). These new entrants include HIAF (China) and RAON (Republic of Korea), which are very large-scale RI research centers created in a greenfield. HIAF and RAON approach the equipment-assembly stage. Basic budgets of all of these projects range between about \$1 and \$3 billions.

The equipment for low-energy nuclear physics in Russian Federation is catastrophically outdated. Its renewal is being performed by means of individual institutions and along individual lines. In the past decade, all resources available at Laboratory of Nuclear Reactions at JINR were mounted on upgrading the research infrastructure. The new fragment separator ACCULINNA-2 was commissioned in 2018 [1]. In 2019, it was able to produce the first world-class results. A superheavy-element factory based on the new accelerator DC-280 began operating in 2019 [3], and the preparation of the first experiments started there. The construction of the ISOL-type IRINA facility for RI studies at the PIK reactor started at Petersburg Nuclear Physics Institute (PNPI, National Research Center Kurchatov Institute). The total budget of these projects (about \$120 millions) is quite sizable on a national scale but is very modest on an international scale. These projects are of niche nature—that is, they are able to produce world-class results in narrow specific fields of modern low-energy nuclear physics. After the mass commissioning of new-generation RI factories in the period spanning 2023 and 2027, the scientific potential of these facilities would hardly be contestable at the world level. In order to revert the situation after three decades of inadequate funding in Russian science, vision, consolidation of efforts, and generous funding at a substantially higher level are required for creating nuclear physics center (centers) of really first class.

2. DERICA PROJECT

The DERICA project was proposed within the strategic plan of the development of JINR for the period spanning the years 2022 and 2030 and farther. Hopefully, this project would be able to revitalize studies in the realms of low-energy nuclear physics in Russia and propel them to the level reached by the leaders in this field [4, 5]. The project is based on a superconductor heavy-ion linear accelerator (linac) operating in a quasicontinuous-wave mode and producing beams that have record properties. Emphasis is placed on studying short-lived RI in collector rings (CR). The possibility of exploring the interactions of electrons with RI in a collider experiment with the aim of determining fundamental nuclear-matter properties, including the electromagnetic form factors of exotic nuclei, is a unique feature of the project. Below, we would like to highlight the key points of the project.

2.1. Ambitious Ultimate-Goal Program and Coverage

The ambitious ultimate-goal program of the project involves the construction of an accelerator implementing collisions between electrons and RI ions (electron–RI collider). The commissioning of this collider is expected at the last stage of the project, but a number of unique world-class scientific tasks are assumed to be performed at early stages of the implementation of the project. For example, secondary radioactive beams of energy in range between 20 and 70 MeV per nucleon will have record intensities over broad intervals of mass (A) and charge (Z) numbers. Postaccelerated RI beams of extremely high quality (purity, degree of monoenergeticity, emittance, etc.) will become available for energies extending up to about 500 MeV per nucleon. The use of a target in the form of a flow of free neutrons (or in the form of cold neutrons in a trap) for studying reactions with these neutrons in CRs is yet another possibility of great interest. These and some other technical possibilities of the proposed project will make it possible to study efficiently the most intricate fundamental issues of modern low-energy nuclear physics, such as boundaries of nuclear stability and boundaries of the existence of a nuclear structure in the nuclide map; the origin and mechanisms of strong interaction, including the interaction in highly asymmetric nuclear matter; the existence and properties of exotic forms of radioactivity ($2p$, $2n$, $4n$, etc.); the modification of the shell structure in nuclei lying far from the nuclear stability valley; and the behavior of highly charged ions under conditions close to astrophysical conditions.

Fig. 1. Preliminary general view of the facilities involved in the DERICA project. LINAC-100, which is a high-current superconductor driver operating in a continuous-wave mode, pushes the energy of a beam of stable ions to values in the range between 100 and 160 MeV per nucleon (see Subsection 3.1). Radioactive isotopes (RI) are produced on a production fragmentation target (FT); the primary beam and unneeded fragments are absorbed in the radiation-loaded zone of the preseparator of the DERICA Fragment Separator (DFS). The required RI are selected by the main separator of DFS (see Subsection 3.4) and are used in the experimental hall for high energies to study reactions at intermediate energies (50 to 100 MeV per nucleon) or are stopped in a gas. Radioactive isotopes stopped in the gas are ionized, are accelerated by LINAC-30 (a pulsed normally conducting accelerator) up to an energy of about 30 MeV per nucleon, and are transported to a collector-ring (CR) complex (see Subsection 3.5)—in particular, for a further acceleration by means of a synchrotron (FRR) to about 500 MeV per nucleon and investigation in the CR/e-Ring collider.

2.2. General Concept

The layout of the facilities involved in the DERICA project is shown in Fig. 1. A superconductor linac used as a driver of a beam of stable ions (LINAC-100) and rated to extreme intensities (see Subsection 3.1) will become the main facility of the DERICA project. It should operate in a quasicontinuous mode and provide, at the outlet, an energy of up to 100 MeV per nucleon (from here the accelerator's name derives) for heavy ions (Xe, Bi, and U) with an intensity of about 20 pμA and an energy of up to 160 MeV per nucleon for light ions (B, Ne, and Ca) with an intensity of about 300 pμA. A stage-by-stage construction of LINAC-100 is assumed, so that a beam from it can be used for experiments at lower energies upon the completion of every next stage. Radioactive ions selected by the DERICA Fragment Separator (DFS—see Subsection 3.4) are stopped in a gas cell, are accumulated in an ion trap, and are transferred to an ion source that forms the maximally high charge state for a further efficient acceleration. The postacceleration of the RI beam in the DERICA project is accomplished by means of a pulsed normally conducting linac, LINAC-30, up to an energy of about 30 MeV per nucleon, whereupon the beam is transported to a CR set (see Subsection 3.5). Higher energies are required for number of tasks. For example, an ion energy of 300 to 500 MeV per nucleon is needed for the performance of the electron–RI collider to be highly efficient. The ion acceleration energy is

further increased from about 30 to about 500 MeV per nucleon in a booster synchrotron at a maximally high rate of magnetic-field ramping in FRR (Fast Ramping Ring, whose working cycle is shorter than 0.1 s). Depending on the postacceleration scheme, the time that lapses before the injection into the experimental ring of CR will be 0.1 to 0.5 s.

Thus, the DERICA project combines structural features and feasibilities of RI complexes based on the in-flight technology with those based on the ISOL technology. In relation to the approaches proposed earlier, the DERICA concept provides a substantial gain in the time that lapses before the start of measurements, and this may be critical for studying short-lived RI.

2.3. Stage-by-Stage Implementation of the Project

The project is partitioned into relatively short scientifically motivated stages. The first stages of the project will be able to furnish scientific results in about three to five years after the beginning of the construction. A next facility opening new scientific possibilities will be commissioned every three to five years. The stage-by-stage deployment of the project will make it possible to reduce many technological risks associated with the project. In particular, this will relief the acuteness (but, of course, will not remove completely) of the problem of recruiting highly qualified personnel.

2.4. Possibilities of Applied and Interdisciplinary Investigations

The DERICA accelerator complex is a source of beams of any $Z = 5$ to 92 stable ions with extremely intensities (1 to 5 emA) and energies of up to 160 MeV per nucleon. Stable and radioactive beams of lower intensity will be available up to energies of about 500 MeV per nucleon. Owing to this, the DERICA accelerator complex is appropriate for addressing a large number of applied problems from various fields, including plasma physics and high energy-density physics, spectroscopy of isomeric nuclei, neutron physics, materials science and radiation strength of materials, radiation testing of microelectronics components, radiation biology, and nuclear and radiation medicine. It should be noted that, owing to a rather high intensity of primary ion beams, many of these problems may be solved in the “background mode” (by employing a small part of the total current) without intervening in the solution of the main scientific problems.

2.5. Paradigm of User's Center

DERICA is planned within the modern user's center paradigm (so-called user's facility), where the beam time at any setup is presented at the disposal of external users according to a standard procedure. Thus, the complex should become a basic center for fundamental and applied low-energy nuclear physics in Russia and JINR participant countries. Groups from various research institutions will gain (i) access to sophisticated and expensive setups of common use and (ii) the possibility of developing and exploiting their own equipment without the obligation to support the whole infrastructure of the generation of high-intensity beams of rare isotopes.

2.6. “Window of Possibilities”

DERICA is a project of moderate cost (estimated at about \$400 millions). In modern nuclear and particle physics, a typical cost of world-class projects presently starts from values that are five to ten times higher. The possibility of creating a nuclear physics research center that is able to conduct topical and promising world-class investigations within a relatively modest budget is due to special features of the present instant. By way of example, we indicate that, because of the difficulties in the implementation of the FAIR project, part of its research program can be carried out within the DERICA project. The physics of RI is being vigorously developed in many countries, and this “window of possibilities” is not expected to be long.

3. STATUS OF THE DERICA PROJECT

At the present time, work on research and technological development, creation of prototypes of critical components of DERICA, and technological and economic substantiation of the whole DERICA project is being performed at JINR. This program is implemented in cooperation with leading Russian research centers—first of all, Institute for Theoretical and Experimental Physics (ITEP, National Research Center Kurchatov Institute, Moscow), National Research Nuclear University MEPhI (Moscow), Budker Institute of Nuclear Physics (BINP, Siberian Branch, Russian Academy of Sciences), and Russian Federal Nuclear Center—Zababakhin All-Russia Research Institute of Technical Physics [RFNC-ITP (VNIITP), Snezhinsk]. The critical components of the project include units and facilities that are crucial for the implementability of the DERICA research program as a whole and/or which require a lot of time for their development. The research program of the program was published in [4]. For the current status of the DERICA program, the interested reader is referred to the website quoted in [5]. The presumed general view of the DERICA project is shown in Fig. 1. The results of work on research and technological development that were obtained in 2019 and 2020 for the LINAC-100 driver, DFS, and CR complex are outlined in this section below.

3.1. General Comments on LINAC-100

The LINAC-100 driver of the beam of stable ions will be the basic facility for the DERICA project. The success of the whole project depends crucially on the ability to reach its rated parameters. The accelerator should operate in a continuous-wave (cw) mode and provide, at the outlet, an energy of up to 100 MeV per nucleon for heavy ions (Xe, Bi, and U) with an intensity of about 20 pμA and an energy of up to 160 MeV per nucleon for light ions (B, Ne, and Ca) with an intensity of about 300 pμA. In particular, a stage-by-stage construction of LINAC-100 is assumed. This will provide the possibility of employing the beam of this accelerator for experiments at lower energies upon the completion of its specific stages (see “experimental hall for low energies” in Fig. 1). Research and development work that would rely on cutting-edge technologies is necessary for reaching the declared ambitious parameters of heavy-ion beams at the outlet of LINAC-100. In the past decade, considerable advances in the development of heavy-ion linear accelerators have been made at IMP (Institute of Modern Physics, Lanzhou, China), GANIL (Grand Accélérateur National d'Ions Lourds, Caen, France), and FRIB (Facility for Rare Isotope Beams, East Lansing, USA) [6–12]. With

Fig. 2. General scheme of the LINAC-100: (ECR) ion source based on the electron-cyclotron resonance; (LEBT) low-energy beam-transportation channel, in which six-dimensional matching of beam parameters occurs before the inlet to the first accelerating section; (RFQ) shaper accelerator featuring a spatially uniform quadrupole focusing; (NC IH) normally conducting accelerating H-mode resonators; (SC CH) superconducting accelerating H-mode resonators—for example, CH (crossbar H-mode) resonators; (Stripper + Separator) stripper for enhancing the beam A/Z ratio and a magnetic system for separating ions of given charge-to-mass number ratio; (SC HWR/QWR) superconducting half-wave and quarter-wave coaxial accelerating resonators; (SC Spoke) superconducting Spoke cavities—two groups; and (HEBT) high-energy beam-transportation channel. This place is reserved and its length is determined by the preassigned possibility for the upgrade of LINAC-100 in energy (presumably up to 200 MeV per nucleon).

allowance for this experience and by means state-of-the-art technologies of particle acceleration, LINAC-100 should surpass its analogs existing in the world by a factor of three to thirty.

In order to create a heavy-ion accelerator of high intensity and to reach the declared ion-beam parameters at LINAC-100, it is necessary to solve a number of fundamental problems. The most important of them are the following:

(i) The generation and shaping of ion beams characterized by a maximally high charge state and an intensity not lower than $20 \text{ p}\mu\text{A}$ and by the minimum possible emittance of the beam (the requirement for the emittance is crucial, since, at high rated currents and energies, acceleration should occur nearly without losses);

(ii) Development of the accelerator-complex *front end*, which includes a structure featuring a spatially uniform quadrupole focusing more commonly known as Radio Frequency Quadrupole (RFQ) focusing; resonators involving drift tubes—drift-tube linac (DTL); and channels of six-dimensional matching of the ion beam between them, as well as of the ion beam generated by the ion source with RFQ;

(iii) Development of technologies for manufacturing normally conducting RFQ and DTL resonators and for tuning and maintaining the stability of their parameters during operation in the cw mode;

(iv) Development of systems for ion-beam acceleration on the basis of superconductor resonators and technologies for their production;

(v) Development of high-frequency generators in which preference is given to solid-state amplifiers and which are intended for operation in the cw mode;

(vi) Development of systems for diagnostics of high-intensity cw beams over a broad energy range.

At the present time, the projects of driver accelerators for RI production, as well as accelerators for nuclear power engineering or neutron sources based on spallation reactions and known as Spallation Neutron Sources (SNS), are developed and constructed according to nearly identical schemes all over the world: RFQ linac and the module part of the accelerator mostly based on superconductor elements. It should be perceived, however, that some issues do not have generally accepted solutions. Therefore, it is necessary to find solutions adapted directly to the DERICA project.

Heavy ions (HI) of specific mass in the range of $A/Z \sim 6-8$ with an intensity of several tens of $\text{p}\mu\text{A}$ units and light ions (LI) of specific mass ratio $A/Z \sim 3$ to 4 with an intensity of several hundred $\text{p}\mu\text{A}$ units can be obtained on the basis of the electro-cyclotron resonance (ECR sources). The accelerator front end includes an ECR source (or several sources), a channel of the six-dimensional matching of the beam at low energies, an RFQ accelerating section, and several short (normally conducting and/or superconducting) IH (interdigital H-mode) resonators.

The basic version of a general scheme of LINAC-100 is shown in Fig. 2. Ions in the wide range of $A/Z \sim 3-8$ should be accelerated for the tasks of the DERICA project. The creation of RFQ for this range is possible, but its size will be very large. Therefore, two approaches are possible.

(i) Use can be made of a universal front end optimized to heavy ions with $A/Z \sim 7$, in which case light ions are accelerated in it at a moderately low charge values (for example, $2+$ for boron ions and $6+$ for calcium ions). An individual ion source will then be required for light ions in the front end.

(ii) As an alternative, one can consider the inclusion of two front ends in the composition of the accelerator: one for relatively light ions from boron to calcium (LI) and the other for heavy ions (HI) up to uranium (Fig. 2 shows precisely this version of the LINAC-100 scheme).

In order to decrease the accelerator length and cost, stripper that make it possible to enhance the charge of accelerated ions and to reduce thereby the value of the total accelerating voltage are used in the majority of the projects of accelerators employed as ion-beam drivers. The energies at which stripper are placed are substantially different in different projects: from 1.4 MeV per nucleon at UNILAC (GSI, Darmstadt, Germany) to 25 MeV per nucleon at FRIB (MSU, East Lansing, USA). It is assumed that, at LINAC-100, the stripper will be installed at an ion-beam energy of about 10 MeV per nucleon.

The choice of energy for the transition to superconducting resonators for accelerating the beam from 0.3 or 0.5 MeV per nucleon (at the outlet of the RFQ section) to 10 MeV per nucleon is one of the difficult issues in designing LINAC-100. At the present time, it is vigorously studied, the experience gained worldwide being taken into account. We emphasize that the choice of energy for the transition to superconducting resonators should depend not only on the results obtained by simulating beam dynamics and by optimizing the electrodynamic characteristics of resonators but also on the relative cost and energy consumption of normally conducting and superconducting versions for this accelerator segment, as well as on the level of development of technologies for the production of superconducting resonators in Russian Federation and other countries.

At the present time, only superconducting resonators are used at energies above 10 MeV per nucleon. Since single-type and single-size superconducting accelerating resonators cannot be used at energies between 10 or 100 and 160 MeV per nucleon, this section is partitioned into several groups (specifically three ones), each being formed by identical resonators.

3.2. Prototype of LINAC-100 Front End

The beam intensity reachable at a linac is restricted first of all by the efficiency of its front end. The design of a front-end prototype in the form of a test bench was initiated in order to solve this problem. This test bench includes a high-voltage platform (~ 200 kV) with an ECR source mounted on it, the channel of six-dimensional matching of the beam generated by the ECR source with RFQ, and initial sections of RFQ (see Fig. 3).

Presently, ECR sources are nearly a unique solution in the field of generation of high-intensity continuous beams of highly charged ions. By means of the best ECR sources employing a superconductor-based magnetic system and operating at a frequency of 28 GHz that were constructed at IMP (Lanzhou, China) and Lawrence Berkeley National Laboratory (LBNL, Berkeley, USA) [13, 14], the intensities required for the DERICA project were reached for uranium ions of charge $34+$. Physicists of Laboratory of Nuclear Reactions at JINR have gained rich experience in developing ECR sources, and work on constructing a source of this generation started in cooperation with ITEP, Efremov Research Institute of Electrophysical Apparatus (NIIEFA) and Institute of Applied Physics (IAP, Russian Academy of Sciences, Nizhny Novgorod) are involved in this work. Work on developing an ion-beam shaper system intended for minimizing the beam emittance at an intensity required for the DERICA project started simultaneously. This work is supported by experts from GSI, Laboratori Nazionali di Legnaro—Istituto Nazionale di Fisica Nucleare (LNL–INFN, Legnaro, Italy), and IMP (Lanzhou, China). In constructing the aforementioned high-voltage platform, use is made of the experience gained in creating the platforms for the DC-280 cyclotron [15], linacs at LNL–INFN [16], and the IPR Indian project [17].

The development of cw-RFQ is based on concerted efforts of ITEP and VNIITP, their successful experience in designing a linac for the NICA project [13] being used. At the present time, the technology for the construction of cw-RFQ is at the stage of assimilation by leading accelerator laboratories worldwide. There are examples of functioning cw-RFQ, but they operate with low-intensity beams [14]. Specialists from ITEP have considered several versions of formation of the accelerator channel for a U^{34+} ion beam of intensity 1 emA and emittance 1π mm mrad. The possibility of obtaining a beam that would have these record features has not yet been confirmed experimentally. In designing the front end of HI for LINAC-100, the ratio of the channel acceptance to the beam emittance was therefore set to six. On the basis of the results of a simulation, it was shown that, in employing a harmonic buncher at the inlet of RFQ for the purpose of six-dimensional matching, a 100% capture of ions into the acceleration mode can be attained (see Fig. 3). Concurrently, a minimum growth of the transverse and, what is the most important, of the longitudinal emittance of the beam is ensured. A normally conducting channel version providing a 100% acceleration of beam ions from the outlet of RFQ (operating at a frequency of 40.625 MHz) to an energy of 10 MeV per nucleon and including two types of DTL (operating at frequencies

Fig. 3. Presumed configuration of the test bench for the front end of LINAC-100 and results obtained by simulating beam dynamics in RFQ (40.625 MHz) under conditions of six-dimensional matching of the beam.

of 81.25 and 162.5 MHz) based on narrow-gap resonators was developed. The construction of a normally conducting channel is motivated by the minimization of risks in this case and by the fact that, upon reaching the respective energy, fulfillment of the experimental research program along some lines, including fission barriers of complex nuclei, multinucleon-transfer reactions, and applied investigations, can be launched [4].

Work with a beam on tuning the channel of six-dimensional matching and on testing several (two to four) RFQ sections with the aid of a 14-GHz ECR source based on permanent magnets (a low charge but a high current—for example, about 3 emA for $^{14}\text{N}^{2+}$) is planned at the initial stage. It is assumed that the high-frequency power for the resonators will be obtained from power amplifiers. In Russian Federation, such amplifiers are produced by two centers: TRIADA-TV and Research Institute of Technical Physics and Automation (NIITFA). Dedicated sensors designed by JINR, ITEP, and Institute for Nuclear Research (INR, Russian Academy of Sciences,

Moscow) are intended for equipping the test bench with state-of-the-art systems for the diagnostics of beam parameters. When the units of the facility are constructed, the front end will be created on the basis of a 28-GHz ECR source and RFQ extended to the total energy (approximately 12 sections of RFQ), while the test bench in question will be used as that for new accelerator technologies.

3.3. Superconducting Part of LINAC-100

A relative efficiency of normally conducting and superconducting (SC) accelerating structures is determined by the difference in physical effects that restrict the limiting field strength in the resonators used. For normally conducting accelerating structures, the field strength is restricted by a high-frequency breakdown, while, for SC structures, it is restricted by the quench effect arising as the limiting magnetic field grows at the resonator surface. In some individual cases, the highest possible field in SC resonators may be 2.0 to 3.5 times higher than

Fig. 4. Superconducting (a) half-wave and (b) quarter-wave accelerating resonators developed by the collaboration of JINR, MEPhI, Physical-Technical Institute (PTI, National Academy of Sciences of Belarus, Minsk), and Institute for Nuclear Problems (INP, Belarusian State University, Minsk).

its counterpart in normally conducting resonators. In the past decade, classical E-type resonators supplemented with drift tubes (Alvarez's accelerators) have been abandoned in favor of more compact and more energy-efficient accelerators based on H-type resonators. For example, the viability of multigap SC CH resonators was demonstrated at GSI for intermediate energies (starting from 1.4 MeV per nucleon) [18]. However, they become more efficient at energies above 3 or 3.5 MeV per nucleon.

For LINAC-100, beam dynamics in CH resonators was simulated for the range of energies between 3 and 10 MeV per nucleon. The results obtained by studying beam dynamics in LINAC-100 revealed that it will be necessary to use either 15 six-gap SC CH resonators (90 accelerating gaps) or 44 analogous normally conducting resonators (264 gaps). At the same time, serious difficulties should be overcome in constructing SC CH resonators. Moreover, they are very expensive.

At a beam energy not higher than 10 MeV per nucleon, a stripper will be installed. This will permit increasing the charge of uranium ions from U^{34+} до U^{60+} and reducing thereby the required number of resonators; as a result, the accelerator cost will become substantially lower. At the present time, the stripper type (gaseous one versus that based on liquid lithium) is being discussed, since different approaches are used at different heavy-ion accelerators. In the UNILAC accelerator (GSI), a gaseous stripper has been successfully used for many years, while, in the

FRIB project, it is planned to use liquid lithium. It should be noted that, for uranium ions, the efficiency of stripping for one ultimate charge value is 20% to 25%. In order to enhance the intensity of the beam after stripping, one can examine the possibility of jointly accelerating, in the SC section, ions that have three neighboring charge values. Theoretically, this will permit retaining more than 60% of the primary-beam intensity. However, this method has not been tested experimentally so far for continuous beams (in the driver of the FRIB accelerator complex, it is planned to accelerate, after the stripper, ions that have two neighboring charge values).

The stripper is followed by the main SC part of the accelerator. It is intended for accelerating the beam in the energy range from 10 to 100 MeV per nucleon. On the basis of the results obtained by simulating beam dynamics [19], it was proposed to divide this acceleration part into three segments where use is made of resonators belonging to different types. The first segment should be formed by coaxial two-gap half-wave resonators (up to an energy of about 35 MeV per nucleon); at higher energies, it is proposed to employ two types of Spoke cavities. A numerical simulation of beam dynamics reveals that the total number of resonators required in the energy range from 10 to 100 MeV per nucleon is 92 and that the total length of the superconducting part will be about 100 m (without technological gaps necessary for arranging there beam-parameter diagnostics blocks and bending magnets intended for directing the beam to experimental channels).

The absence of technologies in Russia that are necessary for mass production of SC resonators is a key problem encountered in developing the SC segment of LINAC-100. In recent years, a collaboration formed by JINR, MEPhI, and a number of Belarusian research centers—primarily Physical-Technical Institute (PTI, National Academy of Sciences of Belarus, Minsk), and Institute for Nuclear Problems (INP, Belarusian State University, Minsk)—began work on mastering such technologies [20, 21]. The development of an SC half-wave coaxial resonator has been completed, and its copper prototype has been manufactured and has been found to have parameters fully in accord with rated values. It is expected that the first SC resonator from niobium will have been produced to the end of 2020. Figure 4 shows the developed models of half-wave and quarter-wave resonators, whose production and testing are currently under way.

3.4. DERICA Fragment Separator (DFS)

At intensities of about 20 to 300 μA (about 10^{14} to 10^{15} ions per second), there should be about 10^3

to 10^9 secondary ions per second at the DFS outlet (their specific number being dependent on the task at hand). Up to one megawatt of thermal energy may be released at the production target and in the zone of primary-beam stopping. This may be accompanied by the generation of up to 5×10^{14} neutrons per second (so that applied investigations with neutrons may be planned on this basis). Technical requirements on the future fragment separator for the DERICA project are indeed extreme.

The fragment separator is manufactured according to the two-cascade scheme that includes a preseparator and a main separator (see Fig. 5), the cascade dispersions being summed. This two-cascade scheme was used in the BigRIPS cascade separator (RIKEN, Japan) [22]. It is a standard scheme for promising RI factories. The structure of the preseparator is determined to a considerable extent by the need for ensuring the absorption of a high-intensity primary beam (see, for example, SuperFRS@FAIR [23] or ARIS@FRIB [24]). The task of creating a highly efficient setup by employing only normally conducting magnetic elements was addressed in order to simplify the exploitation of DFS under extreme radiation conditions. The list of these elements includes six dipole magnets and forty-eight quadrupole, twenty-six sextupole, and twelve octupole lenses. An S-shaped scheme of magnetic elements that provides the total rotation angle of 174° and which involves an additional 6° deflecting magnet positioned upstream of the target and intended for preventing the backflow of ballistic particles from the production target to the accelerator was proposed on the basis of the experience gained worldwide in designing RI factories. All multipole elements, with the exception of the first two quadrupoles, have an aperture 35 cm in diameter. The height of the interpole gap in the dipole magnets is 10 cm.

The separator is rated to magnetic rigidities of the fragments under study not higher than 7 Tm. The angular acceptance of the separator is ± 50 mrad in the dispersion plane and ± 30 mrad in the direction orthogonal to it. The momentum acceptance is $\Delta P/P = \pm 3\%$ (FWHM). The ion-optical scheme of the separator ensures a complete compensation of second-order spatial aberrations of the image and a compensation of the most important third-order aberrations.

Dipole magnets providing a rotation angle of 35° and having an inclined outlet boundary for performing an intermediate spatial focusing of beam fragments at the location of the primary-beam quencher (see Fig. 5) are used in the preseparator. The first-order resolution of the preseparator is $P/\Delta P = 1500$ at the primary-beam diameter of 1 mm at the target. The

momentum dispersion in the degrader plane (median plane of the preseparator) is 2 m.

The main separator employs four dipole magnets, each providing a rotation angle of 26° , and is usable in two modes shown in the inset in Fig. 5. In mode (I), the first two dipole magnets operate according to the dispersion-addition scheme; the achromatic degrader lies in the middle of the separator; and the last two dipole magnets compensate for the dispersion of the first two, ensuring an achromatic transportation of the beam. In this mode, the first-order resolution of the main separator is $P/\Delta P = 3000$, while the momentum dispersion in the degrader plane is 5 m. In mode (II), the achromatic degrader is positioned in the image plane between the first and second dipole magnets combined in such a way that the dispersion of the first magnet is compensated by the second one. The achromatic image is then formed in the median plane of the main separator, where a spatial separation of fragments is performed. In this mode, the resolution of the main separator is $P/\Delta P = 1500$, while the momentum dispersion in the degrader plane is 5.4 m. The remaining second half of the main separator is used as a transporting system for the time-of-flight identification of fragments. In mode (II), the momentum acceptance of the main separator decreases somewhat, becoming $\Delta P/P = \pm 2.5\%$ (FWHM).

3.5. Complex of Collector Rings

At the present time, the creation of a complex formed by three collector rings is proposed within the DERICA project (see Fig. 1). An FRR (Fast Ramping Ring) booster is intended for capturing and subsequently accelerating a beam of rare ions coming from LINAC-30. A Collector Ring (CR) is optimized for performing various experiments with the accumulated RI beam. Investigation into the internal structure of exotic nuclei by means of the scattering of a high-quality electron beam colliding with them is one of the most important experimental goals of the whole project. Such electron beams are created in a dedicated Electron Ring that has one common collision point with CR. The question of the need for a fourth ring intended for experiments with ions in the region of low energies, Low-Energy Ring (LERing) is being additionally considered.

Injection to the FRR booster is performed in the multirevolution mode at an energy of 30 MeV per nucleon. The apertures of magnetic elements of the ring may be relatively small, since the incoming beam was preliminarily cooled according to the scheme of the whole project. The maximum energy to which radioactive ions are accelerated is 500 MeV per nucleon. Thus, the beam energy changes by a factor

Fig. 5. General view of the fragment separator for DERICA project (DFS) and ion trajectories in the linear approximation within the main separator in two modes: (I) that which corresponds to the maximum resolution and (II) that which corresponds to half of the maximum resolution and which employs the second half of the main separator for time-of-life measurements.

Fig. 6. Optical functions for one period of the structure for the (a) FRR booster and (b) collector ring (CR).

of 17, but the magnetic-field strength changes by a factor less than five, from 2.1 T to 9.8 T. This facilitates an ambitious task of creating an accumulating

booster with a working cycle of 0.1 s. The ring length proposed at the present stage of development is 105 m, which, at the bending radius of 6.1 m, yields

Fig. 7. (a) Scheme for organizing the gap of intersection with a standard electron spectrometer (“butterfly”). (b) Scheme of the longitudinal profile of an alternative electron spectrometer featuring toroidal superconducting coils.

a change from 0.35 to 1.6 T in the field of the bending magnets. These parameters can be reached without employing superconducting elements in creating the magnetic structure of the ring. Sectorial bending magnets are grouped by two ones. They provide a rotation angle of 15° . Ring optics employs a doublet scheme of quadrupole lenses, providing versatility in choosing a betatron working point and a large acceptance, which is necessary for a multirevolution injection [25]. A twelvefold symmetry makes it possible to suppress the majority of betatron resonances. The optical functions for one period of the ring are shown in Fig. 6a. The gradients of the magnetic field in the quadrupole lenses are moderate, up to 5 T/m. After injection, the beam is grouped by means of a high-frequency system, is accelerated to the energy required for a specific experiment, and is re-injected into CR according to a one-revolution scheme. The use of additional high-frequency structures for combining bunches before ejection is possible.

A hexagonal shape of CR facilitates its accommodation in the experimental hall of the DERICA project and provides additional possibilities for simultaneously performing several investigations owing to a sufficient number of experimental gaps. The total length of the ring is 193 m, and the length of each of its six straight-line segments is about 10 m. One gap serves for a one-revolution injection—the collector is able to operate both in the mode of a defocused beam, in which case it is necessary to switch off the

high-frequency system after the injection, and in the multibunched mode, where the number of bunches may reach 120. A setup for electron cooling, which is necessary for maintaining a high quality of the beam during experiments (for example, an ion-beam emittance of about 50 mm mrad in the collider mode at currents of up to 1.5×10^{10} particles of $^{11}\text{Be}^{4+}$) is arranged in another technological gap. The use of stochastic cooling is not assumed at the present stage of development. The remaining four gaps in CR are used to deploy experiments—in particular, experiments that would employ a gas target, a neutron target, and colliding electron–ion beams. Ring optics was optimized in such a way as to annihilate the beam dispersion in all straight-line segments by means of achromatic arcs. Each arc consists of four sectorial bending magnets providing an angle of 15° and generating a field of up to 1.6 T (we do not exclude the use of single-type magnets with an accumulating buster in order to render the project less expensive) and seven quadrupole lenses of length 1 m and strength up to 5 T/m. The optical functions for one period of the ring are shown in Fig. 6b.

From the point of view of the accelerator infrastructure, experiments with colliding beams of electrons and rare ions are of course the most involved. Since the implementation of such experiments requires changing substantially the magnetic structure of the experimental ring and since it is impossible to accumulate beams of the above two types

within a single ring because of very different values of the relativistic parameter β , the following experimental scheme is considered: electron beams are accumulated individually in the Electron Ring having a perimeter substantially smaller than that of CR, and the collision region is moved away from the standard orbit of the ion ring by means of a dedicated bypass structure. Thus, one can group separately all additional elements required in the collider mode and minimize constraints imposed by them on other operation modes. These elements include final-focus quadrupoles used in both rings to ensure small beam radii at the collision point, bending magnets and dipole correctors for bringing beams together and apart, beam-position sensors, detectors of scattered ions, and a spectrometer for detecting electrons scattered on nuclei of rare ions. The total length of the bypass structure is about 30 m, and the distance between the collision point and the standard orbit of CR is about 1.5 m. All magnetic elements around the collision gap have conflicting parameters—on one hand, they should have a large aperture, since the beam transverse size grows fast with the distance from the collision point; on the other hand, the magnetic field should retain its high quality under conditions of its large gradients. In order to meet all of these requirements, it is proposed to use superconducting magnets for the bypass elements. A general scheme of the collision gap is shown in Fig. 7a.

The length of the Electron Ring is 56 m. This choice pursued the goal that the electron bunch collided with five bunches of rare ions. Here, the difference between the electron speed nearly equal to the speed of light and the speed of ions for which $\beta \approx 0.75$ at the maximum energy of 500 MeV per nucleon was taken into account. This scheme may lead to the enhancement of coherent collision effects but permits minimizing the cost of the facility. The electron-ring energy may vary between 200 and 500 MeV. All magnetic elements of the electron ring, with the exception of the collision-gap elements, are normally conducting.

In experiments with colliding beams of electrons and rare ions, the luminosity depends on the ion-source efficiency, electron-cooling power, collision parameters, and many other factors. Preliminary estimations reveal that the limiting accessible luminosity is $5 \times 10^{29} \text{ cm}^{-2} \text{ s}^{-1}$ for the beam of $^{11}\text{Be}^{4+}$ ions and $2 \times 10^{27} \text{ cm}^{-2} \text{ s}^{-1}$ for the beam of $^{238}\text{U}^{92+}$ ions. The estimations were performed for the ion energy of 300 MeV per nucleon. Two versions of the electron spectrometer for the collision gap are being developed at the present time. One version, which is normally conducting, inherits principles of operation proposed in designing the analogous project ELISE@FAIR [26]. In this version, the turn-off field for scattered

electrons is created by a specially profiled dipole magnet, and subsequent focusing is performed by means of a series of additional quadrupole lenses and magnets. This version is relatively simple in structure but has the disadvantage of covering a small solid angle— $\pm 30 \text{ mrad}$ in the vertical direction and 10° to 45° in the horizontal direction with respect to the orbit plane. A spectrometer where one uses toroidal coils to generate the deflecting transverse field and where detection occurs directly at the walls of the vacuum chamber (see Fig. 7b) is an alternative version. In this version, the covered solid angle of scattered electrons is nearly 4π , but the creation of a magnetic field that would have the required quality is an extremely difficult challenge. The rated relative resolution of the spectrometer is about 10^{-4} .

4. CONCLUSIONS

The DERICA project is highly significant not only for solving fundamental problems of nuclear physics but also for developing a technological basis of physics investigations. High-frequency superconductivity, high-frequency electronics and power electronics, technologies of normally conducting and superconducting linacs operating in the cw mode, high-vacuum technologies, a target complex rated to a beam power of about 1 MW, and other “extreme” technical aspects of the DERICA project will require resorting to the potential of a considerable number of Russian research and engineering organizations. In particular, the examination by experts from institutions of the Rosatom state corporation will be needed in creating a robotized target complex operating under extreme radiation conditions.

Fulfillment of the DERICA project may be launched within the JINR budget on a limited scale (an accelerator rated to a halved energy plus a fragment separator). Even in this truncated form, the proposed complex will become the basis of a promising world-class research program for JINR in the realms of radioactive-isotope physics. The full-scale DERICA project belongs to the megascience class; in fact DERICA is a strategy of the development of fundamental low-energy nuclear physics in Russian Federation for decades ahead rather than a customary project of an isolated facility.

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