Dubna **E**lectron-**R**are **I**sotope **C**ollider f**A**cility DERICA:

Step by step towards understanding of nuclear shapes and origins of nuclei in the Universe

Executive Summary:

Within this long-range program, JINR looks at another Nuclear Physics program, heavily promoted in the world of nuclear physics in the last 3 decades. Beams of rare isotopes far off the line of stability would be complementing the study of super heavy elements pursued in FLNR, and would guarantee JINR staying at the forefront of nuclear physics and providing state of the art research in nuclear physics for the member-states of JINR and the international nuclear physics community.
The aim of the Rare Isotope Beam (RIB) studies is to provide full knowledge of the nuclear chart from nuclear-stable isotopes to the limits of nuclear structure existence. The information obtained from Rare Isotope studies is indispensable to resolve fundamental problems of nuclear physics (structure, reactions, origins of the nuclear forces) and nuclear astrophysics (nucleo-synthesis, properties of the neutron matter).
Encouraged by leading international scientists of the NUSTAR community, JINR has decided to develop and to build a powerful RIB facility DERICA (**D**ubna **E**lectron – **R**are **I**sotope **C**ollider f**A**cility) covering a broad range of modern nuclear physics aspects (new isotope synthesis and production, its masses, lifetimes and decay modes, nuclear reactions and spectroscopy). The **DERICA concept** combines in-flight production of RIBs by projectile fragmentation technique (primary beams up to uranium with energy ~100 AMeV), stopping RIBs by gas catcher, reacceleration by LINAC-synchrotron combination, and usage of reaccelerated RIBs for reaction studies. The emphasis of the project is *storage ring physics* with ultimate aim of *electron-RIB scattering studies in the collider experiments*.

Elastic and inelastic electron scattering provides a powerful tool for examining nuclear structure. The most reliable evidence how nuclei actually look like originates from electron scattering. However, up to now, the electrons scattering is restricted to stable isotopes. The aim of the DERICA project is to extend this powerful method, which already gave enormous amount of information about the structure of stable nuclei, to the study of nuclei beyond the valley of stability. **DERICA** will be a unique and unprecedented tool for nuclear spectroscopy of rare isotopes, i.e., nuclei far from stability. For achieving that goal, the front-end of the accelerator complex needs to produce beams of highest intensities. A strong R&D project has been started few years ago to push the limit of beam intensities to much higher values.

Empowered by the SHE Factory of FLNP and later by DERICA, JINR DUBNA will be a world wide unique facility complementing those top nuclear physics facilities at FAIR/GSI in Germany, RIKEN in Japan, FRIB in the USA and GANIL/SPIRAL 2 in France.

Introduction:

Although studied for about 100 years, Nuclear Physics and Nuclear Astrophysics are today vibrant and have still many unanswered fundamental questions, some are listed below:

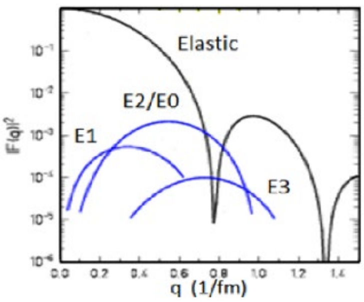
Questions in Nuclear Physics and Nuclear Astrophysics

- Where are the limits of existence of nuclear systems
- Origin of the heavy elements?
- How is shell structure changing far away from stability
- Halos, Open Quantum Systems, Few Body Correlations
- Skins, new collective modes, nuclear matter, neutron stars
- Phases and symmetries of the nuclear many body system
- How is synthesis of the elements – how do heavier than iron nuclei come into being?
- Could there be a unified theory (ab-initio, density functional, shell model) Underlying QCD structure → complex nucleon-nucleon force
- Study of exotic short-lived nuclei far off stability valley (proton/ neutron skins or halos, new magic numbers...)
- Physics of stellar explosions (core-collapse, thermonuclear supernovae, nucleo-synthesis.

Within this long-range program, JINR intends to open up another Nuclear Physics program, complementing the research on Super Heavy Elements. Heavily promoted in the world of nuclear physics in the last 3 decades. **Rare Isotope beam (RIB) facilities** have been and are being built worldwide as the key tools for studying nuclear properties up to the limit of stability.

The ultimate aim of the RIB studies is to provide full coverage of the nuclear chart for nuclear-stable isotopes and to promote our knowledge to the limits of nuclear structure existence. The information obtained in the RIB studies is indispensable to resolve fundamental problems of nuclear physics (mass, radius, structure, life time, reactions, origins of the nuclear forces) and nuclear astrophysics (nucleo-synthesis, properties of the neutron matter).

Elastic and inelastic electron scattering provides a powerful tool for examining nuclear structure. The most reliable evidence how nuclei actually look like originates from electron scattering. However, up to now, the electrons scattering is restricted to stable isotopes.



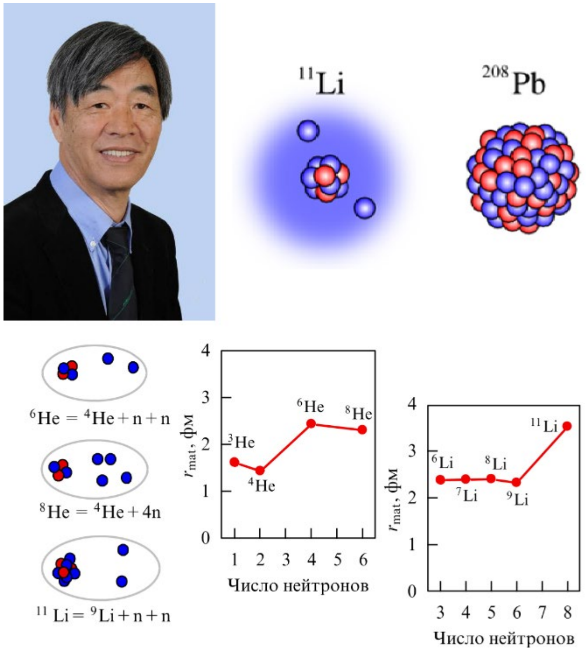
$$\left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{PWBA}} = \frac{\sigma_M}{1+(2E/M_A)\sin^2(\theta/2)}|F_{\mathrm{ch}}(q)|^2$$

$$F_{\mathrm{ch}}(q) = 4\pi \int_0^\infty dr\, r^2 j_0(qr)\rho_{\mathrm{ch}}(r)$$

$$F_{\mathrm{ch}}(q)/Z = 1 - \frac{q^2}{6}\langle r_{\mathrm{ch}}^2\rangle + \cdots$$

Masses and the radial quantities are the most important characteristics of the nuclei. In 1961 Robert Hofstadter got the Nobel price "for his pioneering studies of electron scattering in atomic nuclei and for his consequent discoveries concerning the structure of nucleons..." The major idea of the approach is simple and elegant: electron interacts with nuclear matter relatively weakly (only electromagnetic interaction) and thus can easily penetrate in the nuclear interior. The electromagnetic probe is the best studied theoretically and thus it allows straightforward interpretation of the experimental data. Moreover, this is not radius, which is measured, but electromagnetic form-factors. They contain detailed information both about charge density distribution and about nuclear excitations (so-called inelastic form-factors).

When Isao Tanihata measured the nuclear radii in the lightest isotopic chains in 1988 at the BEVALAC in Berkeley– this was a kind of shock. It appeared that near borderlines of nuclear stability – just where a turnover happens from "ordinary" isotopes to "exotic" ones – the mean radius of the nucleus grows abruptly. Such a behaviour was in a sharp contrast with the routine idea about nuclide as a droplet of "nuclear liquid" with the radius which is well approximated by a "liquid" expression $r = r_0\ A^{1/3}$. Theoreticians, however, have already had an explanation at hand: such nuclides are analogous to planetary systems with dense "core" (central sun) and 1-4 nucleons (planets), orbiting at large distances from the core. For example, in the "classical" halo nucleus ^{11}Li size of such "valence orbitals" is comparable to size of much heavier lead nuclei containing 208 nucleons. This was the emergence of the concept of halo-nuclei.



In his experiment Tanihata used very "simple instrument" – the nuclear absorption. How to apply the precision approach of Hofstadter electron scattering to exotic nuclei? Two problems are essential here. (1) It is difficult to make target of exotic nuclei (their lifetimes are typically too short for that). (2) What was the source of the major advantage of electron scattering – low interaction cross-sections with nucleons, here becomes an important obstacle – exotic nuclei by definition are simply not available in considerable quantities. Solution to both these problems is the use of the electron-ion collider. The exotic nuclei are kept on the orbit in the storage ring, forming the target for electron scattering, and every exotic ion is returned in the collision point about 500000 times per second. This once produced, each exotic ion is multiply "reused" in collider.

For the first time this idea was considered in the USSR. The "K4-K10" complex was a project of massive upgrade of FLNR JINR. This development was to bring FLNR to a short-list of the world-leading facilities in the field of exotic nuclei. However, it was year 1990 and these plans were not implemented. The "fallen banner" was taken up by Isao Tanihata – the pioneer of the exotic nuclei radii research: however, the basic idea of the electron-RIB ion collider MUSES (2003) at RIKEN was inherited from the Russian colleagues. Politically the MUSES project "lost" to projects, which could be realized in shorter times and thus were expected to deliver "scientific dividend" faster. The idea of the electron-RIB collider was reanimated in the project of ELISE facility at FAIR (2007). However, the FAIR facility is strongly delayed now. Thus the future constructions of all second-stage facilities of FAIR (including ELISE) became questionable.

At JINR, beams of rare isotopes far off the line of stability would be complementing the study of super heavy elements pursued in FLNR, and allow JINR staying at the forefront of nuclear physics and providing state of the art research in nuclear physics for the member-states of JINR and the international nuclear physics community.

Encouraged by leading international scientists of the NUSTAR community, JINR has proposed to develop and to build a powerful RIB facility DERICA (**D**ubna **E**lectron – **R**are **I**sotope **C**ollider f**A**cility) covering broad range of modern nuclear physics aspects (new isotope synthesis and production, its masses, lifetimes and decay modes, nuclear reactions and spectroscopy).

DERICA concept

DERICA concept is based on a combination of the most advanced technologies in nuclear physics experiments: it combines in-flight production of RIBs by projectile fragmentation technique (primary beams up to uranium with energy ~100 AMeV) with ISOL technique by stopping RIBs in gas catcher and charge breeding, followed by reacceleration in LINAC-synchrotron ring combination. Sophisticated usage of reaccelerated RIBs for reaction studies and for storage ring experiments (experimental areas of CR ring) is foreseen. The ultimate challenging goal of DERICA is operation of the e-RIB collider. This collider mode demands very high luminosity of the collider, which requests highest intensities of secondary ion beams generated in the fragment separator DFS. That instrument should be specifically adapted to preparation of separated RIB for stopping in the gas cell. Request for high intensity of the derived RIBs is evidently translated into the request for high intensity of the primary heavy-ion beam. Therefore, a heavy-ion superconducting cw-LINAC-100 with record intensities is planned (e.g. from 3 emA of Ca to 1 emA of U, ~1 MW power in the primary beam). The beam intensity of any linear accelerators is limited by the intensity which is produced by the ion source, by the low velocity transport system before injection occurs into the linac. The DERICA concept foresees the development and construction of world record breaking so-called “front end” consisting of a highly efficient ion source and large acceptance RFQ (see Figure 1) for the first acceleration path. The whole DERICA facility depends on the requested “record” front end, which is planned to demonstrate its performance in the preparatory stage 2019-2022. Based on successfully achieved record parameters of the heavy ion front end, the feasibility of the whole DERICA accelerator scheme has to be designed and demonstrated in the preparatory phase 2020-2022.

The ultimate aim of the DERICA project is to extend this powerful method of electron scattering on nuclei, which already gave enormous amount of information about the structure of stable nuclei, to the study of nuclei beyond the valley of stability via its electron-RIB collider. Thus, **DERICA** will be a unique and unprecedented tool for nuclear spectroscopy of rare isotopes, i.e., nuclei far from stability. For achieving that goal, the front-end of the accelerator complex needs to produce beams of highest intensities. A strong R&D project has been started few years ago to push the limit of beam intensities to much higher values.

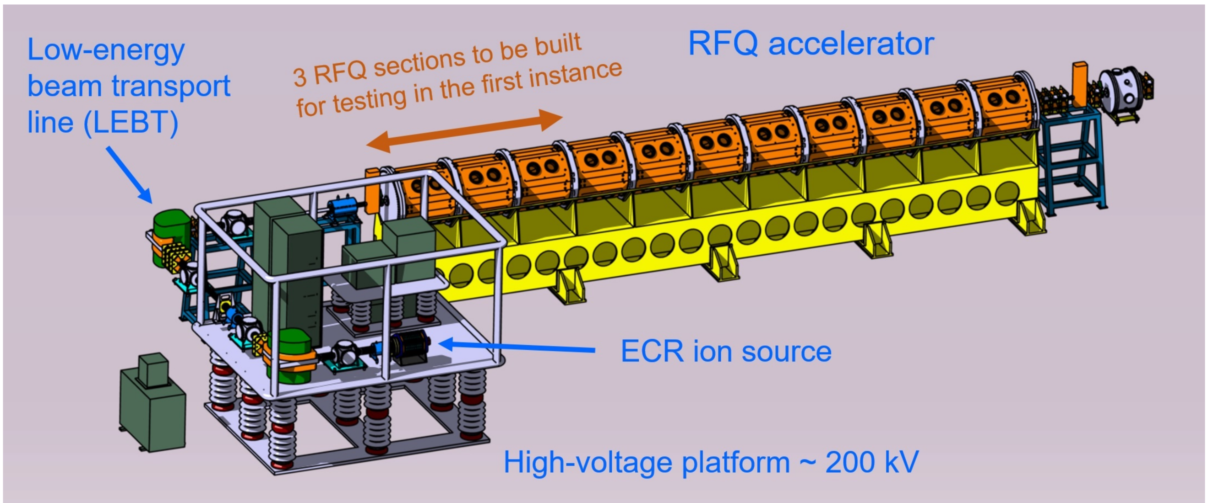


Figure 1. Schematic view of the prototype front end of the prospective heavy-ion cw-LINAC.

After having drafted the design of **DERICA** in a worldwide collaboration, the JINR (Dubna) and BINP (Novosibirsk) submitted in April 2018 a joint proposal for the construction of an accelerator and storage ring radioactive ion beam facility DERICA to the Russian Ministry of education and science within the call for proposals of “megascience”-class facilities to be constructed in Russian Federation. In September 2018 the proposal has successfully passed assessment in the Russian Academy of sciences and now it is in a short list of the recommended projects. April 2019 the DERICA project has got extraordinarily financing from JINR Directorate to “kickstart” the most long-term R&Ds. 25 June 2019 the JINR PAC has approved the new project «Construction of a prototype of the initial section of the high-current heavy-ion linear accelerator for the production of intense radioactive ion beams for basic research». Expected construction time is over a period of about 16 years and the facility cost are estimated to be in the range of 500 M$. After completion, the facility should employ a staff of about 200 technicians, engineers and scientists.

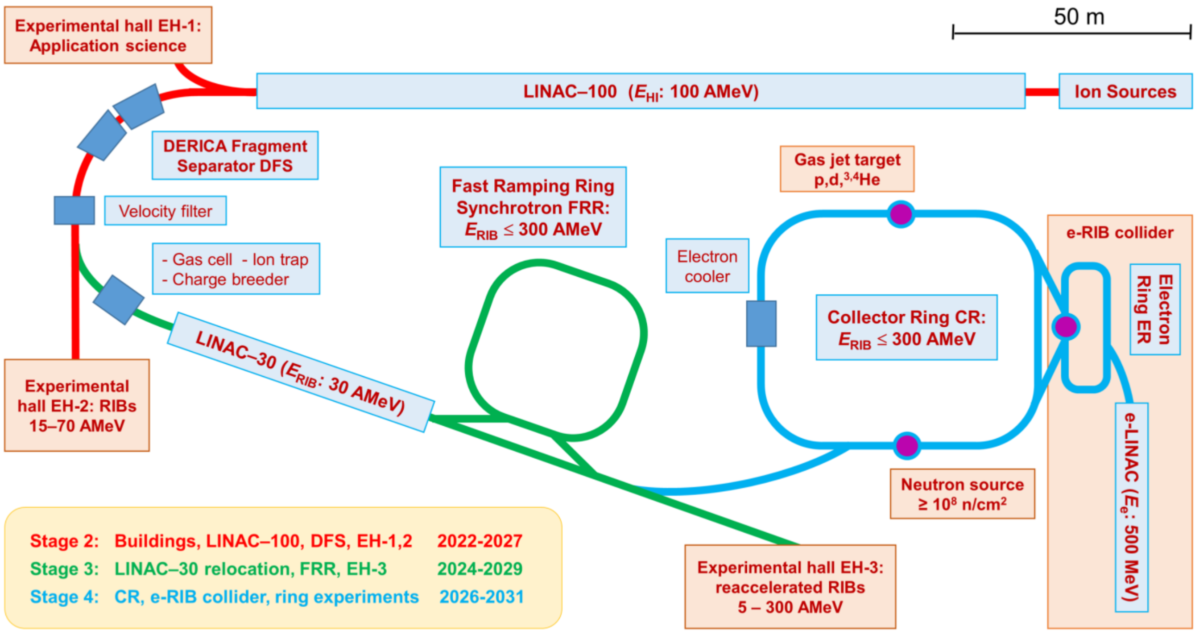


Figure 2. DERICA project, stages 2-4. Color of the beamline corresponds to the stage of the project. Stage 2: applied studies with stable beams 25-100 AMeV (in EH-1) and direct reaction studies with intermediate energy RIBs 20 – 70 AMeV (in EH-2). Stage 3: reaction studies with reaccelerated RIBs (5 – 300 AMeV) in EH-3. Stage 4: storage ring experiments in CR.

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DERICA project time line

Timeline for development of the facility in four major stages during the years 2020-2035 (see Figure 2). New scientific opportunities are arising on each stage with the interval of few years. The first scientific/application results can be expected in ~5 years after construction start from the operation of the low-energy (<7 AMeV) room temperature section of LINAC-100:

– Stage 1. Development of the prototype front end for LINAC-100: the ability to build super-high-current continuous wave acceleration to be confirmed. CDR for LINAC-100, CDR for fragment separator DFS, CDR for Ring Branch. TDR for LINAC-100 building. 2019-2022.

– Stage 2. New facility buildings are constructed; "driver" accelerator LINAC-100 (~ 100 AMeV acceleration for A/Z = 6 ions) and fragment separator DFS are installed, see Figure 3. Applied studies (experimental hall EH-1), reaction studies with stable low-energy beams (~6–7 AMeV, experimental hall EH-1), and intermediate-energy RIBs (~20–70 AMeV, experimental hall EH-2).

(i) LINAC-100(6) starting configuration begins low-energy operation (6 AMeV room temperature resonators only, experimental hall EH-1 2022-2025.

(ii) LINAC-100(50) advanced configuration for intermediate-energy operation. Fragment separator DFS starts operation in the low-intensity regime (50 AMeV, experimental hall EH-2). 2026-2028.

(iii) LINAC-100 is installed in full configuration. Fragment separator DFS is ready for operation in the full-intensity regime (100 AMeV, experimental hall EH-2). 2029-2030.

– Stage 3. System for RIB reacceleration ({gas cell - ion trap - ion source/charge breeder} and LINAC-30) are installed in experimental hall EH-2. Together with fast ramping ring synchrotron FRR the reaccelerated RIBs in the range ~5–300 AMeV are available (experimental hall EH-3). 2026-2032.

– Stage 4. Construction of storage rings. Experiments, including electron-RIB collider studies, can be conducted in three experimental areas of the Ring Branch. 2027-2035.

Expected construction time ~ 16 years and facility cost ~ 300 M$. The facility should employ about 200 staff members.

Hot topics of the modern nuclear physics expected to be tackled by DERICA

Nuclear structure. Quest for the limits of existence. Halos, Open Quantum Systems, Few Body Correlations. Changing shell structure far away from stability. Skins, new collective modes, nuclear matter, neutron stars. Phases and symmetries of the nuclear many body system. Origin of the elements – how do heavier than iron nuclei come into being? unified theory (ab-initio, density functional, shell model). Underlying QCD structure → complex nucleon-nucleon force. Study of exotic short lived nuclei far off stability valley (proton/ neutron skins or halos, new magic numbers...). Pave way for theoretical framework with predictive power for nuclei beyond experimental reach.

Astrophysics. Origin of the heavy elements? In what ratio of protons to neutrons can nuclei exist? What are the limits of nuclear existence? Physics of stellar explosions (core-collapse, thermonuclear supernovae, nucleosynthesis). Compact objects and the explosions on their surfaces (x-ray bursts).

- **International collaboration**. Modern powerful linear accelerators as RIB program drivers at Legnaro, Spiral2, FRIB, HIAF, RAON. Modern storage ring complexes at Lanzhou, FAIR, HIAF. Expertise transfer from CEA and ELISE@FAIR to DERICA.

Cross-disciplinary and applied aspects of the DERICA project

– High intensity heavy-ion irradiation for volumetric modification of massive materials and development of high-performance technology for irradiating multilayer targets. Material science with intense beams of highly charged ions.

– Simulation of a heavy ion component in cosmic ray spectrum in testing of the microelectronics elements used in the space industry by irradiation of multilayer targets.

– DERICA as a neutron source. For operation with intense heavy (e.g. U) beam the target and beam dump areas for DFS are expected to generate up to 5×10^{14} neutrons per second in 4π-geometry. For DFS this is unwanted background to be suppressed. Continuous neutron flow from the beam dump and possibly for pulsed regime with extracted beam pulses are demanded in neutron scattering experiments.

Highly upgradable facility design

The preliminary LINAC-100 is layout is folded with chicane (see Figure 3). This enables possible extension of driver accelerator to LINAC-200. DFS design should be sufficiently versatile to include upgrade option to higher energies. The target and beam dump areas are to be constructed to accept the highest radiation load foreseen for the facility. Opportunity to use the target area as a neutron source and opportunity to augment the target area with ISOL method facility are to be considered and reflected in the prospective design.

DERICA status

In April 2018 the JINR (Dubna) and BINP (Novosibirsk) joint proposal for the construction of an accelerator and storage ring radioactive ion beam facility DERICA was submitted Russian Ministry of education and science within the call for proposals of “megascience”-class facilities to be constructed in Russian Federation. In September 2018 the proposal has successfully passed assessment in the Russian Academy of sciences and now it is in a short list of the recommended projects. April 2019 the DERICA project has got extraordinarily financing from JINR Directorate to “kickstart” the most long-term R&Ds. 25 June 2019 the JINR PAC has approved the new project «Construction of a prototype of the initial section of the high-current heavy-ion linear accelerator for the production of intense radioactive ion beams for basic research».

Letter-of-Intent for DERICA project is published in [L.V. Grigorenko *et al.*, Physics-Uspekhi **62** (2019) 675-690, http://derica.jinr.ru/pdf/publications/2019-Grigorenko-UFN_DERICA_en.pdf]. Status of DERICA project and the most recent information can be obtained at http://derica.jinr.ru/index.html.

Scientific challenge of the DERICA project

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$M_1 + M_2 \rightarrow M_3 + \gamma$

$M_1 + M_2 - M_3 = \Delta M$ $\quad\quad \Delta E = \Delta M c^2$

Within the DERICA project we get back to the topic of electron collider with exotic radioactive ions, but in a new technical framework. In the project layout and timeline we tried to avoid a "trap" which hampered the previous projects in this field: the approach to construction of modern RIB centers is very comprehensive (so-called "RIB factories" are developed) and, consequently, very expensive. On the other hand, it is certainly not admissible to develop "facility of one experiment" and certain compromise is needed. Development of DERICA is arranged in such a way, that well defined technical stages also allows to access scientific problems which are of interest and importance on the world's scale.

Already the very first stage of the project (LINAC-100+DFS) should provide the production of secondary RIBs of record (!) intensity for certain energy range (20-70 AMeV). Such an energy range is optimal for studies of exotic nuclei in the direct reactions – and this approach for today remain to be the most universal one.

In the next stage the technology of the post-accelerated RIBs is developed. Intensities of the post-accelerated RIBs are dropped down for about order of the magnitude. However, for high-intensity secondary beam this technology may lead to broadening of experimental opportunities. The point is that ordinary technology of utilization of "hot" RIBs from fragment separators works "event-by-event", which allows intensities not more than 10^6 particles per second. Thus for primary intensities exceeding 10^6 particles per second the usage of post-accelerated beams is a natural solution of the intensity issue.

Construction of storage rings opens the next chapter of the DERICA project. Even without collider, storage rings are extremely powerful tools. First of all this is very high resolution spectrometer for mass measurements. Storage rings can also preserve high ionization states of heavy ions imitating the situation of nuclear astrophysics – behaviour of hot substance in the Universe. Also to astrophysical "curriculum" belong the studies of radiation capture reactions. In the storage rings such reactions can be studied using the "windowless" (gas jet) targets, getting rid of the background processes. Extreme dilute character of the gas jet target is compensated in this case by the multiple "reuse" of exotic ions in the storage ring. Absolutely unique topic for research can be unification of storage ring with free neutron target. Concentration of neutrons in such a target can be provided by powerful neutron source, surrounded by layers of moderators and reflectors. Again, the dilute character of such a target is compensated by the revolution frequency of ions in the storage ring.

Conclusion

The e-RIB collider and all the facilities downstream – are demanding forefront technologies at the edge of technical capabilities of modern accelerators, providing record precision, selectivity, resolution for shortest lifetimes of nuclei. The development of DERICA project should become a strong driver for development in JINR member states and in Russian Federation of a number of key technologies, such as radio-frequency superconductivity, high-intensity acceleration of electrons and ions, high-vacuum technology and power RF technology. The collider expertize in Russian Federation is now concentrated in Novosibirsk and is focused on electron colliders. With the development of NICA project at Dubna the rise of the new center of expertize in ion colliders can be foreseen and DERICA project fits well in this line of development. The DERICA project in certain sense this is not an isolated initiative with the well-defined start- and end-points but a long-term vision of the low-energy nuclear physics development strategy for decades ahead.

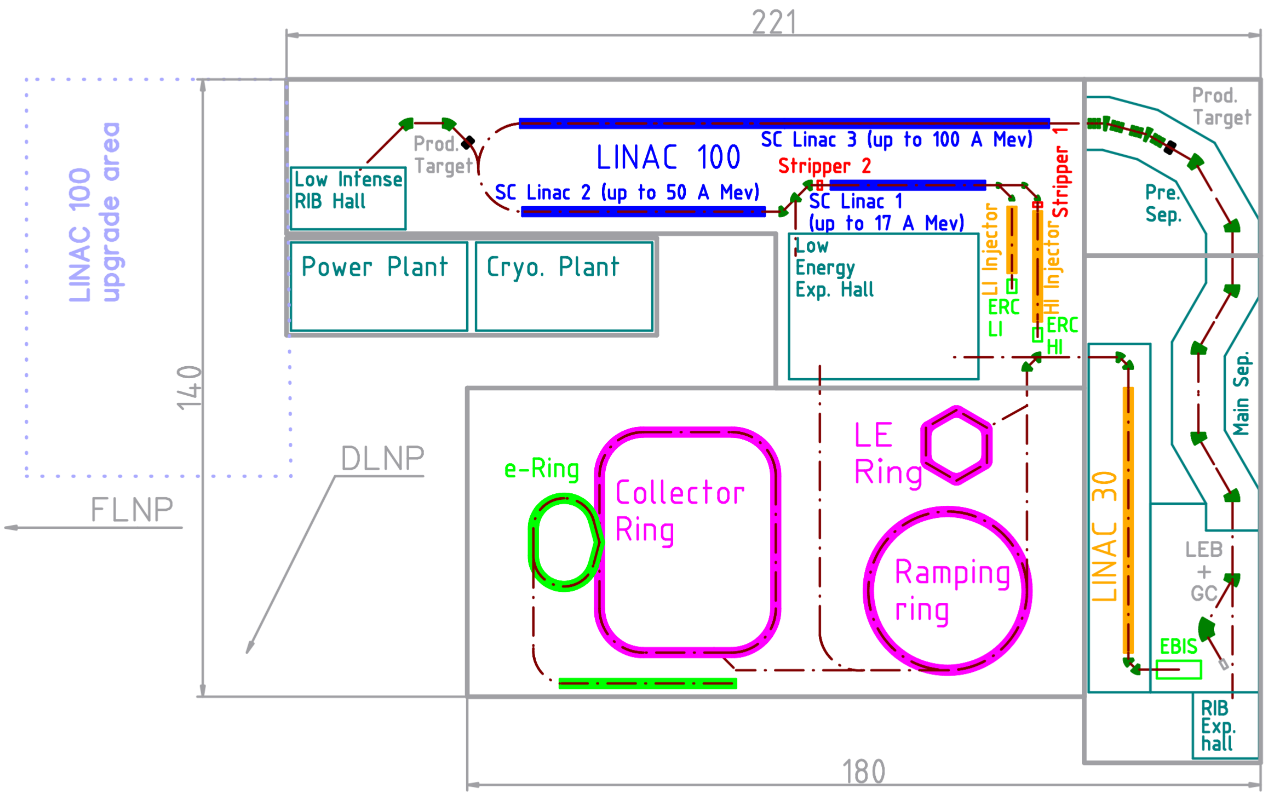

Figure 3. Preliminary schematic layout of DERICA facility.