

DESIGN OF LINAC-100 AND LINAC-30 FOR NEW RARE ISOTOPE FACILITY PROJECT DERICA AT JINR

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Abstract

DERICA (Dubna Electron-Radioactive Ion Collider fAcility) is the new ambitious project under development at JINR [1]. DERICA is proposed as the next step in RIB facilities development. It is planned that in the DERICA project the RIBs produced by the DERICA Fragment Separator (DFS), will be stopped in a gas cell, accumulated in the ion trap and then be transferred to the ion source/charge breeder, creating the highest possible charge state for the further effective acceleration (system {gas cell - ion trap - ion source/charge breeder}). From the accelerator point of view DERICA will include the driver LINAC-100 (energy up to 100 MeV/u) with the operating mode close to CW, the fragment separator, the re-accelerator LINAC-30 (energy up to 30 MeV/u), the fast ramping ring (energy < 300 AMeV), the collector ring and the electron storage ring with an injector. DERICA general concept and first results of LINAC-100 and LINAC-30 general layout are presented in this paper.

INTRODUCTION

Dubna Electron-Radioactive Ion Collider fAcility (DERICA) is the new ambitious RIB facility project which was started in 2017. Scientists from a number of research institutes and universities from Russia and other countries took part in DERICA concept [1] preparation: JINR, NRC Kurchatov Institute, Budker INP, NRNU MEPhI, Lomonosov MSU, GSI, HIM and other.

The main aim of the DERICA project is the development and construction of RIB “factory” based on the ion trap for secondary ions. Finally it is planned to have a facility provided the direct radioactive isotopes (RI) studies in ion-electron collisions.

The DERICA complex will include a number of accelerators and other components. The first high-intensity quasi-CW driver linac called LINAC-100 will be used for generation of 50-100 MeV/u heavy ion beams which will be used for secondary RI production. Generated radioactive isotopes will be accumulated in an ion trap and after ionization they will be injected to a re-accelerator LINAC-30. This linac will produce pulses of ion beams in two energy bands (5-10 and 20-30 MeV/u) with smoothly varying energy. First time re-accelerated in LINAC-30 beams are planning to use in experiments with the stationary target. The possibility of LINAC-30 construction before LINAC-100 and its commissioning and operation with ACCULINNA -2 RIB facility are also under discussion (ACCULINNA -2 is the new fragment separator at U-400M cyclotron). The third stage of

DERICA project will include the construction of a fast ramping synchrotron for further secondary radioactive ion beam acceleration up to 300 AMeV/u. A collector ring and an electron storage ring will be constructed during the last stage of DERICA project. After that the main aim of the project will be achieved - direct study of radioactive ions in ion-electron collision will be possible.

DERICA RESEARCH AIMS AND GENERAL CONCEPT

Structure, properties and transformations of atomic nuclei are the main subjects of fundamental researches in low-energy nuclear physics. The comprehensive understanding of structure of atomic nuclei is necessary for description of astrophysical processes, including nucleosynthesis, and for investigations of various cross-disciplinary problems where the nuclear structure plays a key role. Significant progress in this direction has already been achieved, but the aim is still far away. More than three thousand radioactive isotopes (RI) were synthesized before now. According to theoretical estimates from 2000 to 3000 more isotopes are still waiting for its discovery (Fig. 1). Furthermore it is no answer yet even the most fundamental question of nuclear physics: where is the location of borderline of nuclear stability in the major part of the nuclear chart. The dripline is only known for the lightest nuclei (with number of protons $Z < 32$ or number of neutrons $N < 20$), but even here our knowledge almost does not extend beyond it and, thus, the limits of existence of nuclear structure is an open question.

The radioactive isotopes are characterized by an excess of neutrons or protons compared to the nuclear stable nuclides and often have unusual properties. Essential modification of structure of nuclei far from the “stability valley” has already been observed experimentally: discovery of new type of nuclear structure - neutron or proton halo, changes in the shell structure of nuclei caused by disappearance of old and emergence of new magic numbers. Though many of radioactive isotopes are very short-lived, they play a crucial role in the nuclear reactions taking place during the explosive nucleosynthesis. During the supernovae explosions and collisions of neutron stars these processes saturate the interstellar space with elements heavier than lithium. Finally, such processes define the chemical composition of planetary systems and, respectively, the world surrounding us. Another question, important for understanding of the star evolution processes, concerns the properties of neutron matter, which defines the life cycle of the neutron stars. Usual nuclear

matter is almost symmetric and consists of almost equal number of protons and neutrons (the typical ratio N/Z is in the range $1 < N/Z < 1.6$), therefore studies of stable nuclei do not answer this question. Studies of heavy exotic nuclear systems with considerable excess of neutrons ($N/Z > 1.6$) can be a basis for experimental investigation of extremely asymmetric neutron nuclear matter.

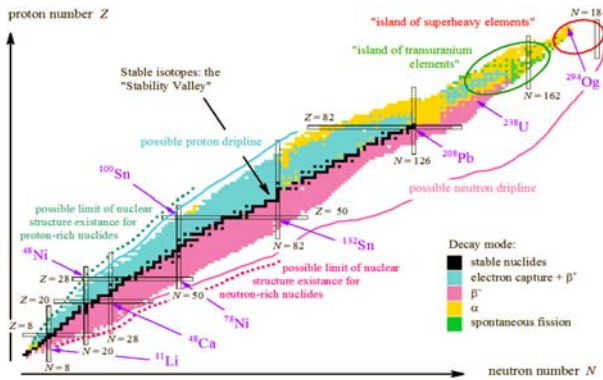


Figure 1: Global structures in the nuclear chart [2]. Vertical and horizontal bands indicate the “magic” numbers corresponding to number of protons Z and number of neutrons N .

Search for solution of these fundamental problems requires studies of unstable isotopes synthesized in laboratory conditions. For this reason, construction of radioactive ion beam (RIB) “factories” nowadays is the highway to the low-energy nuclear physics development. The world-largest such project FAIR (Darmstadt, Germany) is being developed at present [3]. FLNR JINR is one of places where the RIB studies are currently carried out. ACCULINNA and ACCULINNA-2 facilities driven by the U-400M cyclotron are under operation now [4]. The idea of RI-electron collider experiments appeared quite long time ago, reached a stage of well-developed projects and for more than two decades it repeatedly attracts attention of researchers. K4-K10 [5] was the project of FLNR JINR upgrade and transformation into the advanced RI factory. It has been completely accepted in 1990, but has not been implemented for the known non-scientific reasons. The complex included two rings, K4 (storage ring/accelerator with $B_{\max} \rho = 4$ Tm) and the experimental ring K10 (with $B_{\max} \rho = 10$ Tm).

Some ideas of the K4-K10 project were realized or proposed before present in a number of facilities. MUSES project [6] (two rings - storage/cooler and the experimental ring) was an important part of the RI factory development in RIKEN (Japan). It was also cancelled for non-scientific reasons in favor of more easily implementable projects. Now attempts to attack this problem in RIKEN continue within the SCRIT project (Self-Confining Radio-Isotope Ion Target - electron scattering on RI “fixed target” consisting of ions stored in the electromagnetic Penning trap) [7]. The project ELISE [8] is a part of the program of FAIR facility but it is “frozen” at least until 2030. Several ideas of the K4-K10 were realized in the storage complex IMP (Lanzhou, China). How-

ever, because of the low-intensity driver accelerator, the luminosity achieved there is far from sufficient value for the collider studies of electron-ion collisions. The project of a storage ring TSR@ISOLDE [9] at CERN was indefinitely postponed in order to better concentrate efforts on the researches in the fields of physics of ultrahigh energy (LHC, etc.) and antimatter (AD, ELENA, and etc.).

Thus the development and construction of new facility DERICA aimed at studies of the radioactive nuclei properties in the electron-RI collisions in the storage rings looks very actual.

The DERICA project purpose is to construct a unique accelerator and storage ring facility for the pioneering low-energy nuclear physics studies. These include production of still unknown RI, their mass measurements, studies of RI decay modes, fission barriers of heavy nuclei, studies of the nuclear reaction dynamics, and also determination of structure details of exotic nuclei, i.e. measurements of charge and matter radii with a high accuracy. There are some basic qualitative features of the DERICA project to be emphasized. In the K4-K10, MUSES, and ELISE projects the “hot” beam of RI, produced by fragment-separator, is injected into the storage ring and cooled there until it reaches the required quality for the experiments or for the injection into the next experimental ring. In DERICA project, the RIBs is planned to produce by the fragment separator DFS (DERICA Fragment Separator) also but following ions will be stopped in a gas cell, accumulated in an ion trap and then will be transferred to the ion source/charge breeder, creating the highest possible charge state for the further effective acceleration (system {gas cell - ion trap - ion source/charge breeder}). This scheme differs from conventional ISOL technology which is used in SPIRAL-2, ISAC-II and in a number of other operating RIB facilities. It is planning in DERICA project that RI will be re-accelerated by the LINAC-30 accelerator up to the energy of ~ 30 AMeV. For some tasks the higher energies are required. In particular, the effective operation of the electron-RI collider requires energies of the ions about 100 - 300 AMeV. For these purpose, further acceleration from ~ 30 to ~ 300 AMeV will be performed by the booster synchrotron FRR (Fast Ramping Ring) with high ramping rate of the magnetic field. The cycle duration {gas cell - ion trap - ion source/charge breeder} should be 0.1 - 0.3 sec. Depending on the scheme of the post-acceleration (only LINAC-30 or LINAC-30 + FRR) the time before injection into the experimental ring of CR is 0.1 - 1.0 sec. Compared to the earlier suggested approaches, the DERICA concept allows significant improvement of the time preceding the measurements start. This can be crucial for studies of short-lived RI (with $T_{1/2} < 1 - 5$ sec).

DERICA GENERAL LAYOUT, STAGES AND POSSIBLE SITE

The general layout of the DERICA complex is shown in Fig. 2. As one can see, finally DERICA will consist of a number of heavy-ion sources, quasi-CW driver LINAC-

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100, fragment separator DFS, gas cell (ion trap), re-accelerator LINAC-30 with a number of experimental channels, fast ramping ring FRR, collector ion ring CR and electron storage ring ER with injector. Last two rings will be used for direct study of radioactive ion structure in collisions with electrons.

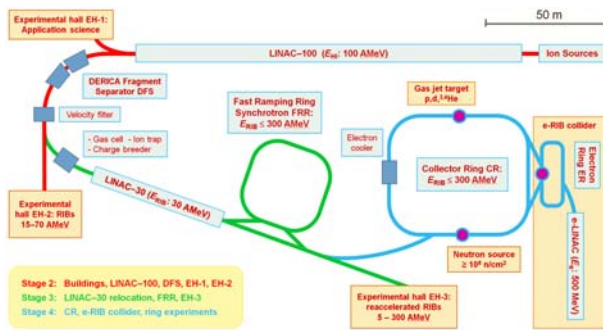


Figure 2: Concept of the DERICA project, stages 2 - 4. Different stages of the project are indicated by colours of beamlines. In the first stage the experiments can be conducted in experimental halls 1 (applied research using stable beams 25 - 100 AMeV) and 2 (direct reaction studies with RIBs at intermediate energies 20 - 70 AMeV). In the second stage high-quality post-accelerated RIBs in a broad energy range (5 - 300 AMeV) become available in experimental hall 2. In the third stage three experimental halls at the CR are added.

A staged implementation of the DERICA project was proposed to have the new experimental and applied researches in each stage (Fig. 2). For the total duration of the project construction 12 - 17 years, the first new experiments would appear already over 5 - 7 years. The stages can be divided like follows:

Stage 0: the scientific agenda is fully formulated, the technical concept is formed, required R&Ds are carried out.

Stage 1: equipment of the {gas cell - ion trap - ion source/charge breeder} system; experiments with stopped RI in the electromagnetic traps; construction and commissioning of the system of RI re-acceleration based on the LINAC-30; high-quality post-accelerated RIBs with energies 5 - 10 and 20 - 30 AMeV become available.

Stage 2: LINAC-100 construction and commissioning; applied studies with high-intensity stable-ion beams; DFS construction and commissioning, reaction studies with RIBs at intermediate energies 20 - 70 AMeV.

Stage 3: gas cell will be constructed; the equipment of the system {gas cell - ion trap - ion source/charge breeder} is relocated from the ACCULINNA-2 to DFS; after its commissioning experiments with RI in electromagnetic traps will become available; LINAC-30 is relocated from the ACCULINNA-2 to the DFS; high-quality post-accelerated RIBs with variably energy of 5 - 30 AMeV become available; intensities of the RIBs at this stage would exceed those available at the Stage 1 by orders; FRR construction and commissioning; high-quality post-accelerated RI beams with energy in the range of 5 - 300 AMeV become available.

Stage 4: CR and ER construction and commissioning; experiments can be performed at three independent experimental locations of the CR ring: (1) a collider experiment on the electron scattering, (2) reactions on the gas jet target [10] and (3) reactions on neutrons from the D+T reaction in the “merged beams” kinematics.

The possible site for the DERICA construction is shown in Fig. 3. It can be placed at JINR FLNR at the place close to the cyclotron U-400 building. The available area near FLNR is more than sufficient for the current DERICA project and for possible future upgrades.

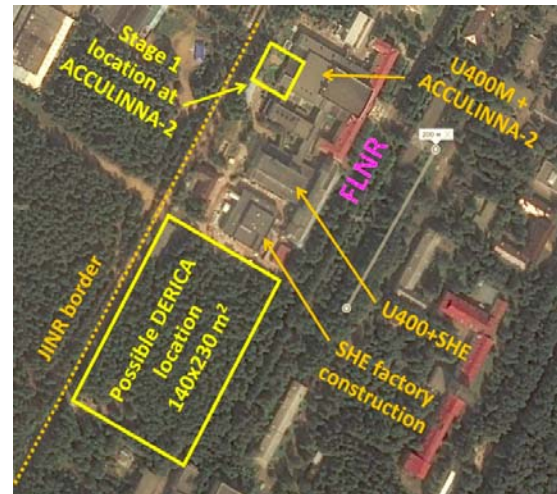


Figure 3: Possible location of the new laboratory at the JINR territory close to FLNR buildings.

LINAC-100 GENERAL LAYOUT AND FIRST BEAM DYNAMICS SIMULATION RESULTS

The general layout of the heavy-ion driver LINAC-100 is shown in Fig. 4. Such layout is similar to conventional driver linacs of many RIB complexes as SPIRAL-2 [11], FRIB [12] etc. Linac will include RFQ section, a number of normal conducting cavities for energies up to ~2-2.5 MeV/u and long medium-energy and high-energy sections which consist of SC cavities. This part of LINAC-100 will include short SC cavities with independent phase control for the high energy gain and SC solenoids or quadrupoles for focusing.

Necessary primary ions for DERICA driver are presented in Table 1. It is clear that for all ions the mass-to-charge ratio is $5.5 < A/Z < 6.0$. Note, that the beam current for a number of ions is non-zero and current will effect to the beam dynamics and accelerating cavities operation sufficiently.

The SC part of the linac is economically allowable in the case of identical cavities; otherwise the total accelerator cost dramatically increases. It means that the wave for all cavities will have the same phase velocity value. Wave and particle synchronous motion will be not observed here due to of particles reference phase slipping. The slipping value should not exceed some allowable limits. Otherwise the rate of the energy gain decreases, both

transverse and longitudinal beam stability disturbs and current transmission decreases. In this case there are a lot of cavities can be used in the accelerator. It is practical to divide them in several groups consisting of identical cavities. It should be noted that phase motion analysis problem is accentuated by the absence of synchronous particle. Analytical and numerical methods of beam dynamics study with accelerator layout optimization were developed at NRNU MEPhI [13-17]. Let us consider first results of the LINAC-100 parts general development and beam dynamics simulations.

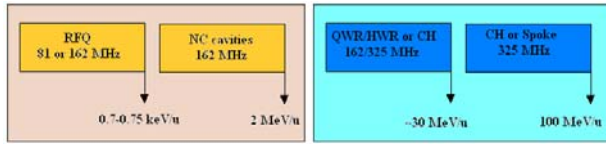


Figure 4: First version of DERICA's driver LINAC-100 general layout.

Table 1: Supposed Primary Beams in the LINAC-100 Accelerator. Most Available Charges of Bi and U Correspond to Modern Capacities of the Intensive Cryogenic ECR Sources

Ion	A/Z	I, μA
$^{11}\text{B}^{2+}$	5.5	> 10
$^{18}\text{O}^{3+}$	6.0	> 10
$^{20,22}\text{Ne}^{4+}$	5.5	> 8
$^{32,36}\text{S}^{6+}$	6.0	> 5
$^{36}\text{Ar}^{6+}$	6.0	> 5
$^{40,48}\text{Ca}^{7+}$	6.0	> 5
$^{56,64}\text{Ni}^{11+}$	5.8	> 5
$^{86}\text{Kr}^{15+}$	5.7	5
$^{132}\text{Xe}^{22+}$	6.0	5
$^{160}\text{Gd}^{27+}$	5.9	5
$^{209}\text{Bi}^{37+}$	5.65	4
$^{238}\text{U}^{40+}$	5.95	$\sim 0.8^*$

*Performance of the modern ECR sources with 28 GHz operating frequency can be as large as $\sim 1 \mu\text{A}$ for $^{238}\text{U}^{40+}$ [18-21].

RFQ for LINAC-100

The operating frequency of RFQ will be defined from the maximal transverse acceptance availability. As it is known, modern ECR ion sources can provide heavy ion beams with high charge state (40+ for U ions, as an example [18-21]). Such beam will have very high transverse emittance. It can achieve 100-200 mm·mrad for the heaviest ion as uranium.

Firstly we compare the acceptance of RFQ linac with operating frequencies of 81 and 162 MHz. Analytical result shows that 81 MHz RFQ is much more preferable for LINAC-100 and the lower frequencies as 54 or 40 MHz can be also discussed. Base parameters of linac both for 81 and 162 MHz are summarized in Table 2, results of the beam dynamics simulation in RFQ linac are presented in Fig. 5. It is clear that the current value of 81 MHz-RFQ acceptance is not enough for LINAC-100 and

it will be further enlarged. The 162 MHz RFQ will not discuss in future therefore.

The design of RFQ cavity will be based on the CW segmented-vane RFQ [22] developed by the joint team of MEPhI, ITEP, GSI and HIM [23-25]. The intervane voltage was limited by 1.3 of the Kilpatrick criterion value for this design.

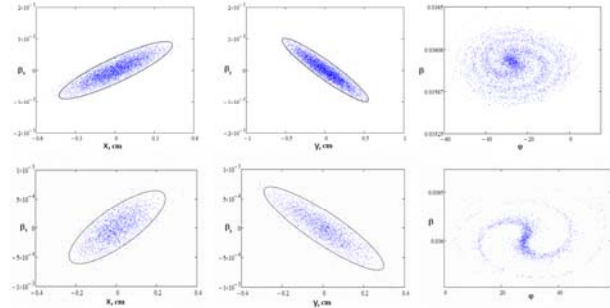


Figure 5: Beam dynamics simulation in RFQ of LINAC-100 (162.5 MHz on top, 81.25 MHz - bottom).

Table 2: Base Parameters of LINAC-100 RFQ both for 81 and 162 MHz

Parameter	Value	
Operating freq., MHz	162.5	81.25
Input energy, keV/u	16.9	16.3
Output energy, keV/u	611.9	614
Max modulation	1.4	1.9
Aperture, mm	3.2	4.4
Particle transmission, %	> 98	99.8
Synchr. phase, grad.	-90 ... -30	-90 ... -30
Voltage, kV	100	100
Initial emittance, mm·mrad	200	200
Length, cm	600	600

Normal Conducting Cavities for Intermediate Energies

The intermediate energy band (after RFQ and up to 2.0-2.5 MeV/u) has some difficulties both from the beam dynamics and the RF efficiency of the accelerating cavities. RFQ is not very effective here because of the low energy gain. But such energies is too low for short (2-gap) SC cavities: the energy gain per cavity should be decreased to 0.25-0.3 MeV per one gap. The longitudinal beam stability cannot be achieved here for higher RF potentials and the acceleration efficiency fall down here.

Let us discuss the possible types of the intermediate energy cavities for LINAC-100: RF Crossed Lenses (a method of ion focusing in linac by RF decelerating fields of crossed lenses, RFCL [26]); modified electrode form RFQ [27]; short 3-cell or 5-cell CH/IH cavities with focusing lenses between resonators.

High-Energy Superconducting Part

The beam dynamics in the superconducting part of LINAC-100 was studied by means of BEAMDULAC-SCL code developed at MEPhI especially for linacs con-

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sisting of short independently phased cavities [14-16, 28-29]. The ion beam motion stability analysis shows that with the slipping factor about 20 % (see Fig. 6) the SC part of the linac will consist of six groups of cavities which have geometrical velocities close to $\beta_g=0.07, 0.10, 0.14, 0.21, 0.30$ and 0.43 . All groups of cavities should be two- or four-gap (two QWR's or HWR's or four-gap CH/IH/Spoke). Using both transfer matrix calculation method [29] and smooth approximation [28] the preliminary SC linac parameters were defined for minimal linac length and lowest cost (Table 3). It is clear that ion injection energy of 1.5 MeV/u is too low for SC part because it will need to reduce the energy gain per cavity to 0.5 MeV. The transverse defocusing will too high in the opposite case and we should to enlarge the number of cavities in the first group that will lead to growth of the linac length and cost. The injection energy should be increased to 2.0-2.5 MeV due to. As one can see, LINAC-100 will consist of 156 four-gap cavities and it's total length will about 140 m. The number of cavity can be reduced in case of higher injection energy but the main problem is observed with high-energy part which consists of 80 cavities. The using of a charge stripper (or two of them) after 3rd group of cavities (or in the other place) can leads to the number of cavities and LINAC-100 length reduction.

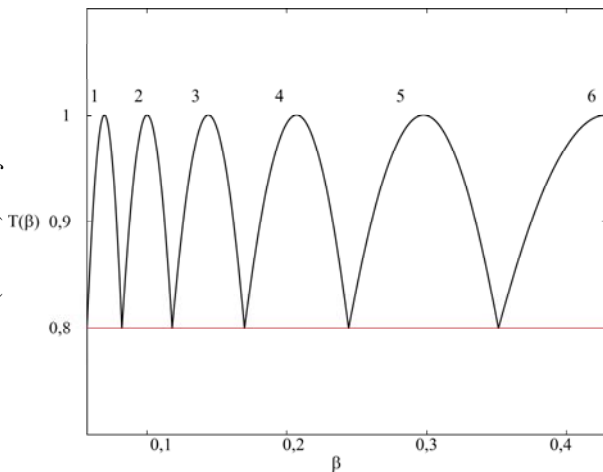


Figure 6: The slipping factor T for each cavities group.

Conventional QWR and HWR cavities can be used in the 1-3 groups. Such cavities are under design and manufacturing by the joint team of JINR, MEPHI, ITEP and PTI NANB [30-33]. CH- or Spoke cavities can be used for high-energy groups 4-6.

New effective low-energy CH-cavities were proposed, manufactured (by Research Instruments) and tested at GSI and HIM [34-38]. These cavities will be used in new GSI-CW-Linac which is under construction now. It was shown that multi-gap CH-cavities can be used for comparatively low energies (from $\beta_g \approx 0.06$) and the energy gain per cavity can be very high here - up to 7 MV/m.

LINAC-30 GENERAL LAYOUT AND BEAM DYNAMICS

Some examples of radioactive isotopes which are planning to generate are presented in Table 4. It is clear that all of them have A/Z from 1.6 to 4.0.

There are observed two ways for LINAC-30 development and construction. By the first way we can be used the same technologies and the same cavities (segmented-vane RFQ, a number of normal conducting cavities for intermediate energies and SC part) as for LINAC-100. But LINAC-30 will operate in the pulse mode contrary of LINAC-100. Normal conducting cavities can be used instead of SC one for high energies and the detail comparison of normal conducting and superconducting solutions can be performed to reduce the LINAC-30 length and cost.

Table 3: General Parameters of SC Part of LINAC-100

Group	1	2	3	4	5	6
W_{in} , MeV/u	1.5	3.16	6.59	13.78	29.24	63.8
β_{in}	0.056	0.08	0.12	0.170	0.244	0.351
β_g	0.069	0.01	0.144	0.207	0.298	0.428
W_{out} , MeV/u	3.16	6.59	13.78	29.24	63.8	100.0
β_{out}	0.082	0.12	0.170	0.244	0.351	0.428
T , %	20	20	20	20	20	20
f , MHz	162	162	162	324	324	324
φ_{inj} , deg	-30	-30	-30	-30	-27	-20
U , MV	0.52	1.5	2.7	3.0	6.0	9.5
E , kV/cm	2	4	5.1	7.83	10.9	11.93
N_{gap}	4	4	4	4	4	4
L_{cav} , m	0.257	0.37	0.532	0.383	0.551	0.796
B_{sol} , T	3.1	4.5	5.5	6	7	7.5
L_{sol} , m	0.2	0.2	0.2	0.2	0.2	0.2
L_{per} , m	0.657	0.77	0.932	0.783	0.951	1.196
N_{per}	22	16	18	36	40	24
K_T , %	100	100	100	100	100	100

Table 4: Representative secondary radioactive isotopes for LINAC-30. Mass band is defined from known location of borderline of nuclear stability, the charge state is typical for contemporary ECR ion sources.

Ion	Possible A	Charge	A/Z band
B	8 - 19	5+	1.6 - 3.8
O	13 - 24	8+	1.63 - 3.0
Ar	31 - 46	16+	1.94 - 2.88
Sn	100 - 132	38+	2.63 - 3.47

CONCLUSION

The general layout of new research complex DERICA is presented. This complex is under discussion now and it's construction can be provided at JINR. Possible research aims for DERICA are briefly presented. Start version of LINAC-100 driver is presented and first beam dynamics simulation results are briefly discussed.

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