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ION BEAM DYNAMICS IN LINAC-100 FACILITY AT JINR

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Abstract

Heavy-ion linear accelerator LINAC-100 is a superconducting driver-accelerator proposed as one of the prospective projects at JINR. Its goal is to accelerate primary stable isotope CW high-intensity beams to energies up to 100 MeV/u. This linac is discussed as the first stage of a new rare isotope facility DERICA, being under development at JINR since 2017 [1-3]. LINAC-100 is supposed to work with a wide range of beams with A/Z 3.5÷7, Uranium U34+ being the heaviest. Its concept has undergone many changes, mostly considering stripping cells, to increase accelerator efficiency. During the latest investigations of various stripping cells [4, 5], Uranium beam stripping at the energy 10 MeV/u and utilizing three adjacent charge states 59-61+ resulted in 60% output beam intensity preservation (of ambitious 30 pμA cw initial Uranium beam current). In this paper three charge state Uranium beam dynamics in the current version of SC LINAC-100 section is presented.

INTRODUCTION

DERICA (Dubna Electron-Radioactive Ion Collider fAcility) is a new ambitious rare isotope facility based at JINR [1-3]. The scientific goals set up for DERICA require a complex of linear and circular accelerators for experiments with primary and secondary beams at different energies (Fig. 1). The first one in the chain is a partly superconducting driver-accelerator LINAC-100 for primary cw stable ion beams acceleration up to 100 MeV/u. The beam then either goes to the applied studies experimental hall EH-1 or goes to RIB production Dubna Fragment Separator (DFS). Secondary RIB's are then stopped in a gas cell, accumulated in an ion trap and transferred to ion source/charge breeder producing the highest charge state possible for further effective acceleration in re-accelerator LINAC-30, the set of rings LERing, FRR and high-energy storage ring CR where the final ion-electron collisions are studied.

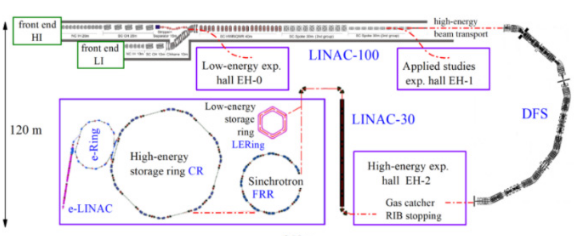

Figure 1: DERICA concept layout.

LINAC-100

Driver-accelerator LINAC-100 is supposed to accelerate primary stable high intensity cw ion beams up to 100 MeV/u. Although this driver is proposed to accelerate a wide range of stable ions with various *A/Z* (up to 7.2), all the simulations are made for Uranium beam of an ambitious 30 pμA cw current from the source. Light ion beams are planned to be accelerated to the energies of 100-150 MeV/u with the current up to 200 pμA. To obtain the announced Uranium beam current two charge states are selected from the ECR ion source – U^{33+} and U^{34+}. This two charge-state Uranium beam is then accelerated in one of the front-ends to 0.44 MeV/u, then follows the intermediate energy section where the beam is accelerated to 10 MeV/u and then stripped in the stripper section. After the stripping three charge states are selected for the further acceleration in the same bunch - U^{59+}, U^{60+} and U^{61+} continue acceleration up to the final energy of 100 MeV/u.

RFQ Section

As a front-end linac a room temperature 81.25 MHz 4-vane RFQ section is proposed as one of the options.

Table 1: RFQ Section and Output Beam Parameters

Parameter	Value	
f, MHz	81.25	
Length, m	6	
Inter-vane voltage, kV	70	
Modulation	1-2.125	
Aperture, mm	3.4	
Emax on the vane surface, Kp	1.6	
Ion charge state	34+	33+
Transverse emittance, mm mrad	200	200
Injection energy, keV/u	12	12
Output energy, MeV/u	0.44	0.44
Beam current, mA	1	1
A/Z	7	7.21
Transmission coefficient, %	>99.7	>99.8
Capture coefficient, %	>99.7	>99.4

Two charge state U^{33+}-U^{34+} beam dynamics was simulated in a 6-meter structure with inter-vane voltage limited by

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70 kV (kept constant along the structure) using BEAMDULAC-RFQ code [6, 7].

Two charge state beam was accelerated to 0.44 MeV/u with effective longitudinal emittance of 2.9 π-keV/u-ns and acceptance to emittance ratio about 4.4 (Fig. 2, Table 1).

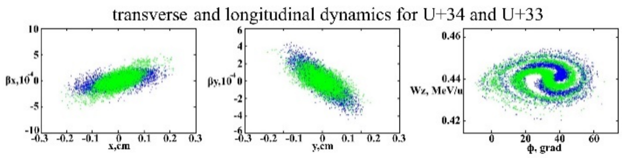

Figure 2: 33-34+ Uranium beam phase portraits at the end of the RFQ section: blue for U^{33+}, green for U^{34+}.

Intermediate Energies Section

The question on what kind of structure should be used for the acceleration after the RFQ to several MeV/u is still open for LINAC-100. Although for Uranium beam acceleration from 3.5 to 10 MeV/u several types of cavities are being considered: SC or normal conducting Cross-bar H-type and Interdigital H-type cavities (CH- and IH-cavities) and 2-gap QWR/HWR. The estimations on the number of cavities for the section, composed of 6-gap SC IH-cavities with maximum gradient of 7.5 MV/m, available from the IH tests at GSI [8] resulted in three groups of identical 162.5 MHz cavities with β_g 0.097 – 0.1155 – 0.1333 with 13 cavities in total. Using 4-5 gap cavities one will get five groups of identical CH (IH) cavities with a total amount of 15. Although, in case of transition to normal conductivity the amount of CH cavities increases significantly and 2-gap short SC QWR/HWR cavities appear to be more effective.

Stripper Section

A lot of investigation was done to find the optimal energy for beam stripping and the type of stripping cell. LINAC-100 layouts with one and two low *Z* gas strippers and even liquid lithium [9] strippers on various energies were considered to reduce the equivalent accelerating voltages for Uranium beam acceleration up to 100 MeV/u thus reducing the number of SC cavities and total accelerator cost [4]. Liquid lithium strippers are a modern and promising technology with first successful and encouraging results observed for FRIB facility at the Michigan State University on March 2021.The latter analysis on stripper efficiency and the desire to ease the stripper sections maintenance resulted in choosing the layout with one H_2- or N_2 gas stripper placed at 10 MeV/u right before the SC section starts. For the ~100 mbar gas pressure inside the stripper cell one can obtain a rather narrow charge state distribution with the mean charge state of 60+. Stripping efficiency for the mean charge is about 22%, and around 20% for both two neighboring charge states – 59+ and 61+ [5]. Thus, taking and attempt to separate and further accelerate not one, but three charge state beam would allow one to save about 60% of the initial beam intensity. It should be noted that the successful acceleration of the three-charge-state Xenon beam was demonstrated this year at FRIB [10].

Superconducting Section

LINAC-100 superconducting section in its current version consists of three groups of identical cavities for the Uranium beam acceleration from 10 to 100 MeV/u [11]. In this kind of structures, composed of the short independently phased cavities, particle and equivalent wave synchronism is violated on the entire accelerator length. Difference between the cavity geometrical velocity and the instant particle velocity results in rather large phase slipping. This can lead to reduction of acceleration rate and motion instabilities. This reduction in accelerator rate is given by transit time factor $T(z)$, depending on the instant velocities difference and implicitly on the quasy-synchronous phase value. Considering the T factor, the energy gain, for example, per one cavity, can be found by the simplified Eq. (1):

$$\Delta W = \frac{Ze}{A} L_c E_0 T(z) \cos\varphi . \qquad (1)$$

where L_c is the cavity length, and E_0 is the average electric field strength on the axis. Limiting the transit time factor by a certain value one can save both the longitudinal and transverse beam dynamics stability due to the balancing the amount of time the particles are spending in the defocusing or debunching phases while saving the reasonable acceleration rate.

For Uranium beam acceleration in SC part of LINAC-100 from the 10 MeV/u after stripper section to the final 100 MeV/u it was divided into three groups of identical cavities with the maximum T = 0.86 at the group`s ends (Fig. 3) with focusing solenoids between the cavities. First group consists of 52 2-gap QWR/HWR cavities with the operating frequency of 162.5 MHz and β_g = 0.207, accelerating Uranuim beam to 36 MeV/u. It needs to be said that the accelerating field distribution for the simulation in this group corresponds to the HWR near-axis field distribution since no dipole electric field component, causing transverse beam defocusing, was yet taken into account. Maximum accelerating gradient is considered 6 MV/m [12].

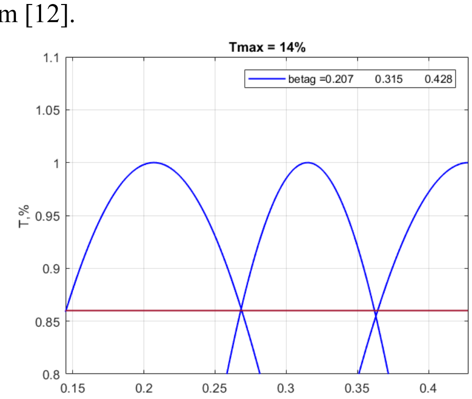

Figure 3: Transit time factor for LINAC-100 groups.

The second group is supposed to consist of 4-5 gap short Spoke or CH/IH 162.5 MHz cavities with βg = 0.315 with maximum accelerating gradient of about 14 MV/m. The beam is accelerated to 68 MeV/u in 18 cavities with the operating gradient of 7.43 MeV/u. The third group consists

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of 24 also Spoke or CH/IH 4-5 gap cavities operating at 352 MHz and having βg = 0.428. The beam is ejected at 100 MeV/u in the peak point of T curve (T = 1) for the third group being the most longitudinally bunched. Other LINAC-100 parameters can be found in Table 2.

Figure 4 shows longitudinal and transverse phase portraits at the entrance to the first group and at the end of LINAC-100 at 100 MeV/u. One can see that even with the beam transmission coefficient equal to 100% in each of the groups and no beam losses observed in the simulation the beams still tend to "tail" due to the phase slipping to the values, were stability conditions are temporarily violated, that can potentially lead to the beam losses and walls activation. This difficulty will be further resolved by tuning the quasy-synchronous phase pattern inside the group from equal phase in every cavity (utilized now for simplicity) to individual phase in each of the cavities.

Normalized transverse beam emittances in both planes are 1.1 π-mm-mrad, Fig. 5 shows that effective three-charge state bunch size blows less than 0.2 mm at the end of the third group of cavities. Initial longitudinal emittance is taken equal 31 π-keV/u-ns to fully fill the available phase space area. Longitudinal acceptance-to-effective emittance ratio for this case evolves from 1 to ~8 excluding the bunch tails. Beam fractions with different charge states are considered initially coincided within the phase space, and no additional emittance growth and energy spread caused by the strippers is taken into account.

Table 2: LINAC-100 SC Section Group Parameters

Parameter		I	II	III
Uranium ion charge state		59-61+	59-61+	59-61+
W^{60+}_{in}, MeV/u		10.00	35.64	68.26
W^{60+}_{out}, MeV/u		35.64	68.26	100.0
β_g		0.207	0.315	0.428
f, MHz		162.5	162.5	325
L_c, m		0.382	1.166	0.787
N_{gaps}		2	4	4
E_{acc}		5.69	7.43	7.89
Input phase, deg	59+	-25.0	-23.9	-25.5
	60+	-25.0	-28.0	-27.0
	61+	-25.0	-29.0	-30.0
$\Delta W^{all}/W^{60+}$ input, % (97%)		±2.0	±2.0	±1.6
Input phase length, deg		16	20	20
$\Delta W^{all}/W^{60+}$output, % (97%)			±0.7	
Output phase length, deg			30	
B, T		3.7	4.8	5.6
L_{sol}, m			0.2	
L_{space}, m			0.1	
N_{cav}		52	18	24
Transmission coeff., %		100	100	100

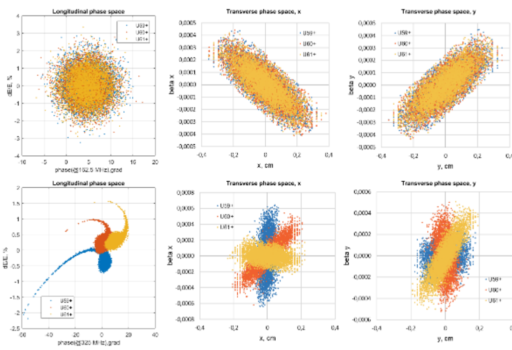

Figure 4: Input and output three-charge Uranium beam phase portraits.

Several charge state beam also undergoes a similar to auto-phasing process along the linac, where the adjacent charge state fractions oscillate around the mean charge state. Figure 6 shows the deviation of the U^{59+} and U^{61+} fractions centroids velocities of the U^{60+} velocity along the LINAC-100 SC part.

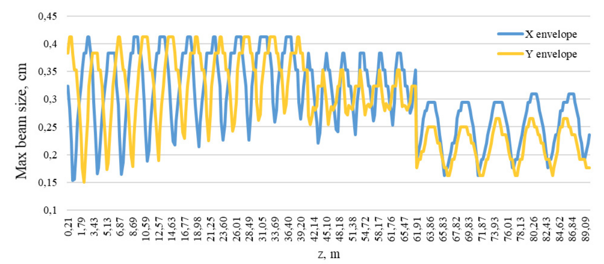

Figure 5: Three-charge state effective beam size through the SC part of LINAC-100.

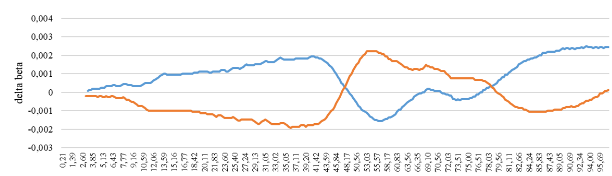

Figure 6: Averaged U^{59+} (blue) and U^{61+} (orange) centroid β deviations from the U^{60+} along the LINAC-100 SC section.

CONCLUSION

This paper contains the current results on beam dynamics investigation for the driver-accelerator LINAC-100 for new rare isotope facility DERICA at JINR. Preliminary accelerator layout for Uranium beam acceleration up to 100 MeV/u was obtained and initial two- and three-charge state beam dynamics was simulated in the chosen structure. Results of the beam dynamics simulation show that three charge states of Uranium can be successfully captured after stripping and accelerated to the final energy in the same bunch.

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