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BEAM DYNAMICS SIMULATIONS FOR THE TWOFOLD ERL MODE AT THE S-DALINAC*

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Abstract

The recirculating superconducting electron accelerator S-DALINAC at TU Darmstadt is capable to run as a onefold or twofold Energy Recovery Linac (ERL) with a maximum kinetic energy of approximately 34 or 68 MeV in ERL mode, respectively. The onefold ERL mode has already been demonstrated, the twofold ERL mode not yet. In conjunction with the first test phase of the twofold ERL mode, simulations have been performed to study the beam dynamics. Acceptance studies for individual beamline sections were carried out and the influence of phase slippage on the energy recovery efficiency during the entire acceleration/deceleration process was examined. The latter is crucial, since the maximum kinetic energy for the twofold ERL mode at injection is less than 8 MeV ($\beta < 0.9982$) while multi-cell cavities are used in the main accelerator that are designed for $\beta = 1$.

INTRODUCTION

The S-DALINAC at TU Darmstadt is a superconducting electron accelerator with a maximum energy gain of 130 MeV in conventional acceleration (CA) mode [1]. This energy gain is achieved by recirculating the beam three times in order to pass the main linac four times. The second of these recirculation beamlines houses a path length adjustment system (PLAS) that offers the possibility to change the phase of the beam relative to the accelerating cavities by up to 360° [2]. In this way, the S-DALINAC can be used as an Energy Recovery Linac (ERL) which requires a phase shift of roughly 180° [3]. By realizing such a phase shift, the electrons arrive at the cavities of the main linac at a time when a decelerating electric field is present. The electrons will then lose a part of their kinetic energy, which will be stored in the electromagnetic field in the cavities and can then be used to accelerate subsequent electrons. Due to the energy recovery, the acceleration process in the main linac exhibits a high power efficiency. In 2017, the onefold ERL mode was realized at the S-DALINAC [3,4]. In this case, the electron beam was accelerated once, recirculated and decelerated. The next step is to realize the twofold ERL mode, i.e. accelerating the electrons, recirculating, accelerating again, recirculating, decelerating, recirculating and decelerating a second time. Figure 1 shows the floor plan of the S-DALINAC and schemes for the onefold and twofold ERL mode. The maximum energy gain in the onefold or twofold ERL mode is 34 MeV or 68 MeV, respectively,

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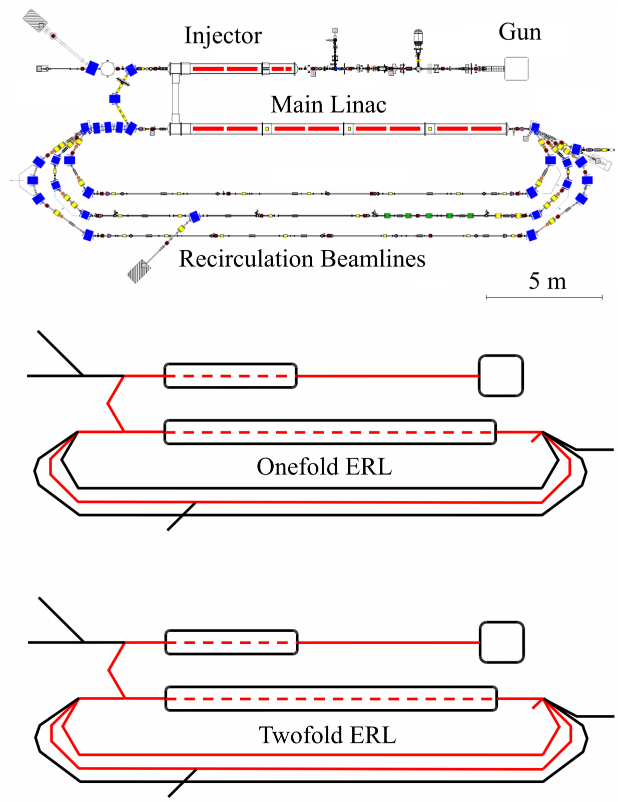

Figure 1: Floor plan of the S-DALINAC and schemes for the onefold and twofold ERL mode.

instead of 130 MeV as in the CA mode. Linked with the first test phase of the twofold ERL mode, beam dynamics simulations have been performed using the *elegant* tracking code [5]. An acceptance study of the recirculation beamlines provides the shape of the maximum phase space which can be guided through the individual beamlines. Furthermore, the negative impact of phase slippage on the ERL efficiency was investigated, if one optimizes on the first linac transit using an on-crest acceleration.

ACCEPTANCE STUDY OF THE FIRST RECIRCULATION BEAMLINE

In order to guide the beam without beam losses through the entire accelerator, it is important to know the acceptance of the beamlines. While an acceptance study of the entire accelerator is significantly influenced by the settings of all individual beam guiding devices, acceptance studies of several individual sections, which are examined independently, provide the necessary acceptance information to guide the

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Table 1: Target momenta and corresponding speed ratios at crucial locations during the acceleration/deceleration process at the first test phase of the twofold ERL mode.

	momentum p in MeV/c	**speed ratio** $\beta = v/c$
injection/extraction	3.85	0.991...
after 1st/3rd linac pass	19.25	0.9996...
after 2nd linac pass	34.65	0.9998...

beam step-by-step. The acceptance of an individual section is of high interest, if the beam could already be guided through all upstream-located sections.

Of crucial interest is the first recirculation beamline (FRB) since two beams will be guided through this beamline at the same time: the once accelerated and the once decelerated beam. Furthermore, this beamline has sections with narrow beampipe diameters where nonzero transverse dispersions exist. In order to investigate the acceptance of this beamline, electrons with deviations from the design particle have been tracked through the beamline. For the acceptance studies for every individual beamline, the tracking has been performed for deviations in the following quantities: transverse positions x and y, transverse divergences x' and y', momentum p and longitudinal position l relative to the design particle. For the FRB, a deviation of l is not relevant since it houses only beam guiding devices which are independent of the longitudinal position relative to the design particle. Of interest is not only the shape of the phase space with all the particles which can be guided through the section, but also the resulting quantities at the end of the section, depending on the initial deviations. Figure 2 shows two cross sections of the acceptance phase space of the FRB. The resulting divergence x' at the end of the FRB can be determined from the contour plot. In particular, the results show that small absolute values for the divergence at the end of the beamline result if the particle is within the acceptance, which is consistent to the possibility of subsequent beam guiding.

IMPACT OF PHASE SLIPPAGE

Relating to the ERL operation, it is of particular interest in which way the electron beam suffers from phase slippage, especially if the acceleration process is optimized on the first main linac transit using the on-crest acceleration, which is sufficient for the CA mode. Phase slippage is an issue because the electrons fly with low momenta (see Table 1) which leads to speeds which differ significantly from speed of light and since up to eight 20-cell cavities are used in the main accelerator that are designed for $\beta = 1$. Therefore, 6D beam dynamics simulations were performed in order to verify if a beam guiding is still possible in this case.

Figure 3 shows the resulting momenta due to the acceleration/deceleration process in the case that the main linac is optimized on the first transit using on-crest acceleration. As visualized in this figure, an asymmetric setting of energy

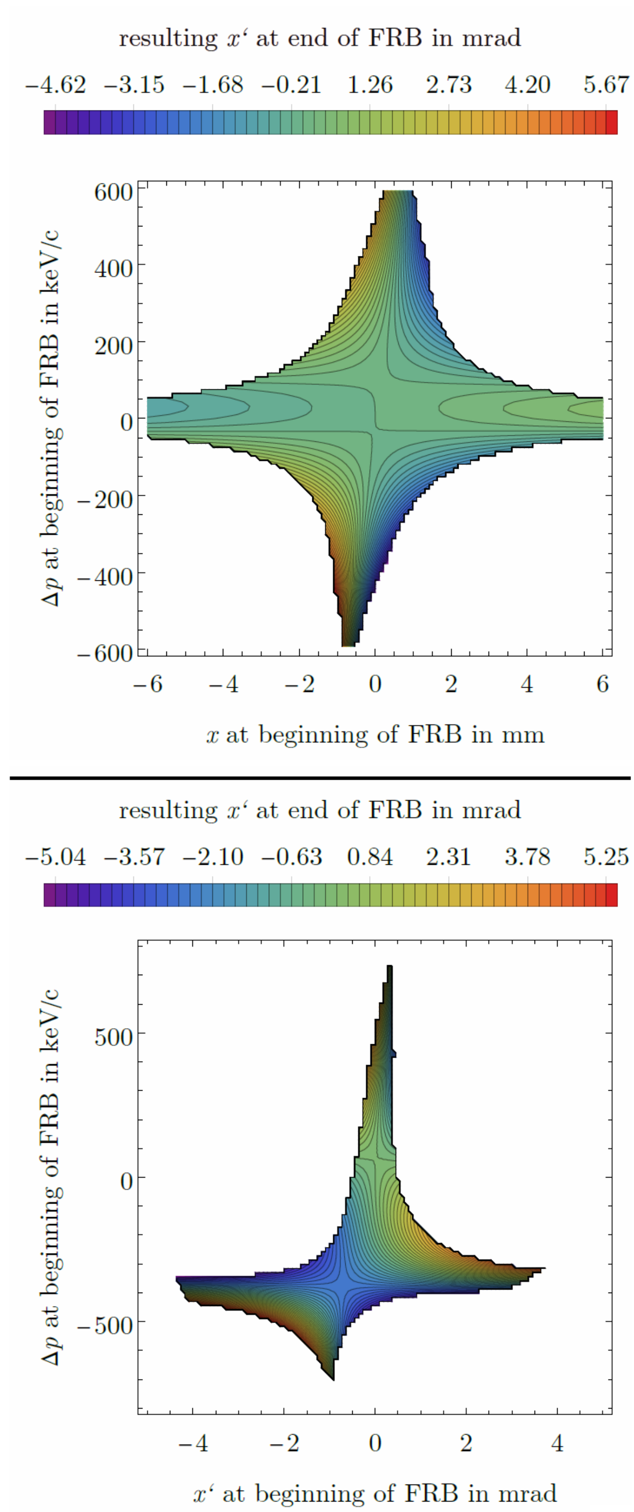

Figure 2: Two cross sections of the acceptance phase space of the first recirculation beamline (FRB). The variables are deviations at the beginning of the FRB, the values of the contour plot represent the resulting divergence x' at the end of the FRB.

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gradients was used for the simulations which is identical to the one used at the first test phase of the twofold ERL mode. The asymmetric setting of energy gradients had to be used due to several temporary restrictions and have led to the reduced target values for this test phase listed in Table 1. In the case of optimizing on the first transit using on-crest acceleration, only the PLAS of the FRB can be used to optimize on the second main linac transit. Due to the low momenta (see Table 1) the electrons suffer from phase slippage and the resulting momentum after the second main linac pass differs from the target value by -185 keV/c (-0.53 %) as visualized in Fig. 3. Using the PLAS of the second recirculation beamline (SRB) in order to optimize on the first deceleration process, a relaxation of the deviation from the target momentum can be achieved and the difference is only +7 keV/c (+0.04 %). Since the beam then has to travel again through the FRB, the beam passes the last main linac transit in such a way, that the electrons with low momentum (due to the first deceleration) suffer strongly from the phase slippage and can not be completely decelerated to injection momentum; the momentum of the final beam is +947 keV/c (+24.6 %) too large. Thus, there is an insufficient efficiency of the twofold ERL mode, if the beam is tuned as described.

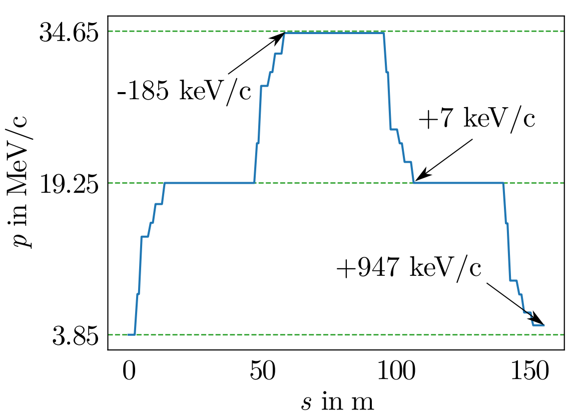

Figure 3: The acceleration/deceleration process is visualized for the case of a beam tracking with optimization on the first main linac transit, operating on-crest. The used energy gradients are identical to the ones used at the first test phase of the twofold ERL mode. Due to phase slippage, the acceleration/deceleration is not optimal for the subsequent main linac transits. The mentioned values are the deviations from the target momenta.

As visualized in Fig. 4, the beam can be guided four times through the main linac (twice accelerating, twice decelerating). That is, a twofold ERL mode is possible with an impaired efficiency, due to phase slippage caused by the low momenta (as shown in Fig. 3). Since the final momentum differs strongly from the injection momentum, which is also the necessary momentum to deposit the electrons in the intended dump, the particles will be lost in the last deflection section (see Fig. 4).

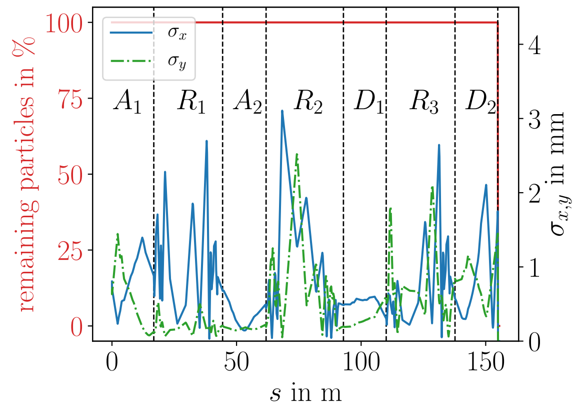

Figure 4: Beam losses and envelopes in the case of a beam tuning with optimization on the first main linac transit, operating on-crest. Highlighted sections: (A)cceleration, (R)ecirculation, (D)eceleration. Due to imperfect deceleration, the electrons can not be guided into the intended beam dump, but are lost during the last deflection due to beam rigidity.

The results expound that it is of crucial importance to optimize the entire acceleration/deceleration process in order to get a high efficiency. In particular, it shows that a suitable setting for the cavities' phases and amplitudes (resulting in off-crest acceleration/deceleration) as well as for the both PLAS have to be found.

CONCLUSION

In 2017, it was demonstrated that the S-DALINAC is capable to run in the onefold ERL mode. Currently, preparations are made to operate the S-DALINAC also in the twofold ERL mode. Acceptance studies have shown, what limits exist and what minimum requirements on the beam quality have to be fulfilled in order to guide the beam without losses through the machine in the twofold ERL mode. It was also examined whether a simplified beam tuning (optimization on first main linac transit, working on-crest) will lead to a successful twofold ERL operation. Although this mode is possible, an unsatisfactory recovery efficiency results and the electrons will not be dumped at the intended cup due to beam rigidity. Therefore, investigations on the optimization of the entire acceleration/deceleration process with the focus on high recovery efficiency and the control of phase slippage are currently performed.

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