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ERL MODE OF S-DALINAC: DESIGN AND STATUS*

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Abstract

Recently, the S-DALINAC was extended by an additional recirculation beam line to a thrice-recirculating linear accelerator. This upgrade enables an increase of the maximum achievable energy close to its design value of 130 MeV as well as an operation as an ERL. The new beam line features a path-length adjustment system which is capable of changing the phase of the beam by a full RF phase and, thus, allowing to shift the timing of the electron bunches to the decelerating phase. The project comprises different aspects concerning the design (magnets, beam dynamics, lattice, etc.) and the construction work including the alignment done at the accelerator. This contribution presents a rough overview on the design, installation and status.

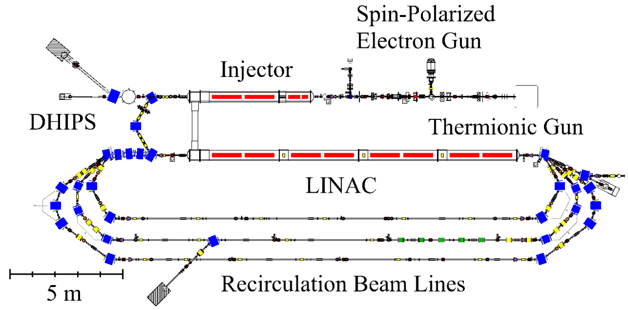

Figure 1: Floor plan of the S-DALINAC with three recirculations in the final set-up.

INTRODUCTION

The S-DALINAC is a superconducting electron accelerator of TU Darmstadt. It was operated from its first commissioning as a recirculating LINAC in 1991 [1] until autumn of 2015 in a twice-recirculating set-up. The decision was made to add an additional recirculation beam line to increase the final beam energy and to enable an ERL operation. In 2015/2016 this major upgrade of the S-DALINAC was performed. The new beam line was installed in between the two existing recirculation beam lines. An upgrade of the final beam energy was necessary as in the past the final design energy of 130 MeV could not be reached due to a lower quality factor of the superconducting (sc) cavities [2] than originally anticipated and, thus, a higher dissipated power to the helium bath. Adding a main LINAC passage by installing an additional recirculation beam line allows the operation of the sc cavities on a decreased gradient while keeping the overall design beam energy constant. In this operation the dissipated power to the helium bath is adapted to the cooling power of the cryo plant. Figure 1 shows the floor plan of the thrice-recirculating S-DALINAC. In case of a thrice-recirculating operation an energy gain of up to 7.6 MeV for the injector LINAC and up to 30.4 MeV for the main LINAC are used. A maximum beam current of 20 μA can be accelerated in the recirculating operation.

ERL MODE

The upgrade of the S-DALINAC features an Energy-Recovery LINAC (ERL) mode in its new beam line. The path-length adjustment system of this newly installed section is capable of an adjustment range of 360° of the RF phase. Thus also a phase shift of 180° is possible so that the beam re-enters the main LINAC on the decelerating phase. Figure 2 shows the area of the first arcs with one out of two path-length adjustment systems of the new beam line, the separation dipole magnet as well as the dump for the decelerated beam. The beam, coming from the main accelerator, can directly be guided into the second recirculation. In this beam line the phase shift of 180° is conducted so that the beam is dumped at injection energy after being decelerated in the main LINAC (once-recirculating ERL mode, see Fig. 3). Alternatively, the beam can be deflected into the first recirculation followed by an additional acceleration in the main LINAC. During the passage through the second recirculation beam line the necessary phase shift is performed so that the beam then passes a second time through the first recirculation. After a second deceleration the beam is finally dumped at injection energy (twice-recirculating ERL mode, see Fig. 4). The purpose of the ERL mode of S-DALINAC is to serve as a test bed for principle investigations concerning the RF controlling [3] or the beam dynamics (e.g. the effect of (transversal) beam break-up (BBU) [4]).

DESIGN OF A THIRD RECIRCULATION INCLUDING ERL MODE

Figure 5 shows a view into the accelerator hall after the installation of the new beam line was finished. Long time in advance, before this installation could start, a complex design and detailed planning of this modification was done [5, 6]. Not only the design aspects considered in the following sections have been taken into account but also the design of other magnetic elements or more general aspects like the vacuum system.

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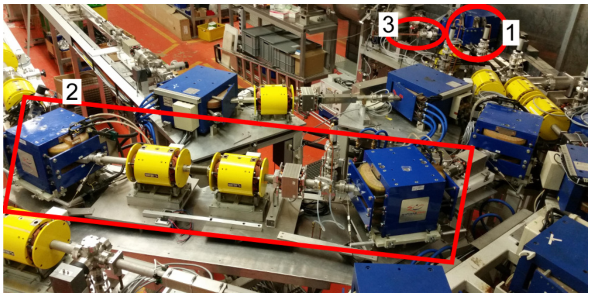

Figure 2: This photograph shows the first arc section of the S-DALINAC. The beams are bend by the separation dipole (1). One of two path-length adjustment systems of the new beam line is shown (2). They are capable to shift the phase of the beam by 180° for an ERL operation. The decelerated beam is then stopped at injection energy in the ERL beam dump (3).

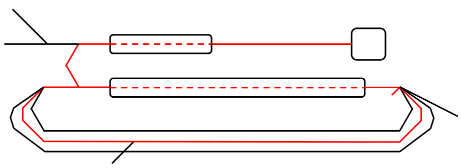

Figure 3: Scheme for once-recirculation ERL operation.

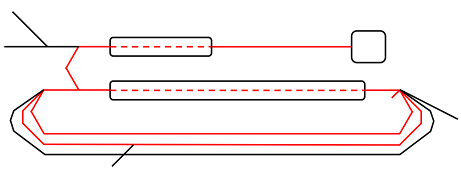

Figure 4: Scheme for twice-recirculation ERL operation.

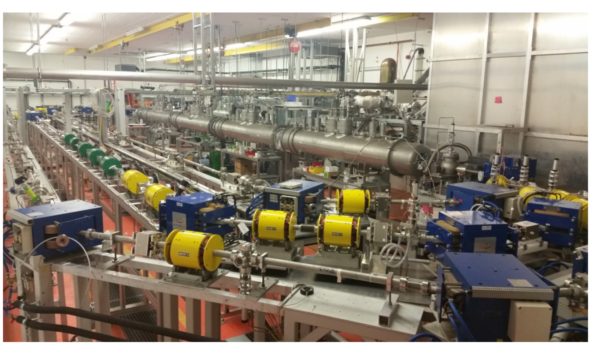

Figure 5: View into the accelerator hall with its three recirculations.

Separation Dipole Magnet

The separation dipole magnet as well as its mirrored version (recombination dipole magnet) are the most complex dipole magnets used at the S-DALINAC. Beams of up to five different energies are bent into their corresponding beam line. The new version of this magnet had to fit to the existing beam line sections on very limited space and demanding conditions. There has been a long list of requirements on this magnet concerning a variety of aspects. The most important in the context of its design will be mentioned. The properties of the magnetic field are defined in the so called good field region (GFR). The GFR is described by a circle with a radius of 5 mm which follows each orbit of every beam. The deflecting properties of the magnet have to be fulfilled to guarantee a perfect bending of all beams. For an optimal result of the beam dynamics simulations as well as of the beam operations, the homogeneity of the magnetic field (transversal, longitudinal) and the multipole components (without dipole part) have to stay below/are equal to $1 \cdot 10^{-3}$. In addition, a fixed energy gain ratio of injector to main LINAC of one to four has to be considered for the different beams. This ratio is a basis for the layout of the whole machine and had to be taken into account for the upgrade. Due to the change in energies and addition of a new beam line, all beam lines except for one had to be modified in position to fit new needs. During the demanding design the mirror plates of the dipole magnet have been the key elements for a best possible result. The magnetic field of 0.65 T is reached for the maximum electron energy. Figure 6 shows a photograph of the final magnet.

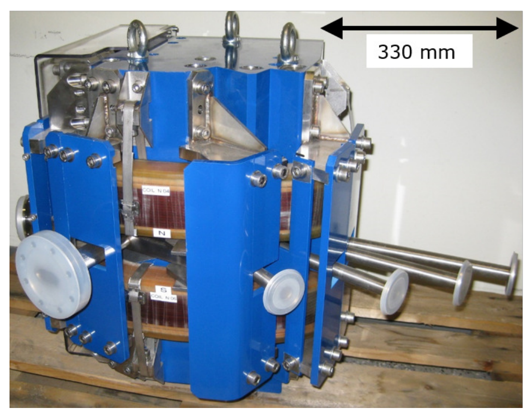

Figure 6: The new separation dipole magnet before its installation into the beam line. The four flanges for the three recirculation beam lines and the high-energy extraction beam line are visible to the right. The flange to the left leads to the ERL beam dump.

Beam Dynamics

One major pillar of the whole design was the simulation of the beam dynamics in different lattice sections for different operation schemes of the S-DALINAC. In this paper some exemplary simulations will be shown.

Normal Mode In the normal operation scheme of S-DALINAC, concerning the recirculation beam lines, a once- or thrice-recirculating setting is feasible. Depending on the mode, the ratio of energy gain from injector to main LINAC changes from one to four (thrice-recirculating) to one to eight (once-recirculating). Each lattice section was simulated separately with *xbeam* [7] and further simulations (e.g. start-to-end) have been conducted with *elegant* [8]. For recirculating operation modes it is possible to use an

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isochronous or a non-isochronous setting of the recirculation beam lines in combination with an on-crest and off-crest acceleration, respectively. This special technique enables an increase of the energy resolution of the electron beam [9]. The necessary scaling of the quadrupole magnets in the arc sections have been calculated. Figure 7 shows the one-sigma envelope of a non-isochronous setting of the second recirculation as an example.

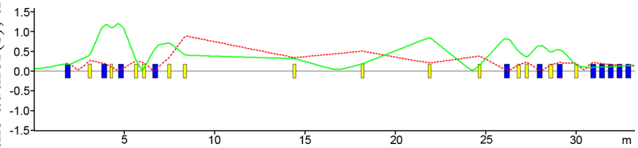

Figure 7: One-sigma envelope of the second recirculation. The dipole magnets are marked as blue boxes, the quadrupole magnets as yellow symbols. The envelope in x- (red) and y-direction (green) is shown in mm along the beam line (simulation done with *xbeam* [7]).

ERL Mode For ERL operation two schemes have to be taken into account: A once- and a twice-recirculating ERL mode (see Fig. 3 and 4). While the simulations for the twice-recirculating case are currently under investigation, first results for the once-recirculating setting have been achieved. Figure 8 shows the envelope of the once-recirculating ERL mode. The simulation, calculated with *elegant* [8], starts behind the injector LINAC. Then the beam is accelerated, guided through the second recirculation before it is decelerated and stopped in the beam dump. The size of the envelope is comparable to the results from Fig. 7. Small deviations are also caused by the change of the simulation tool.

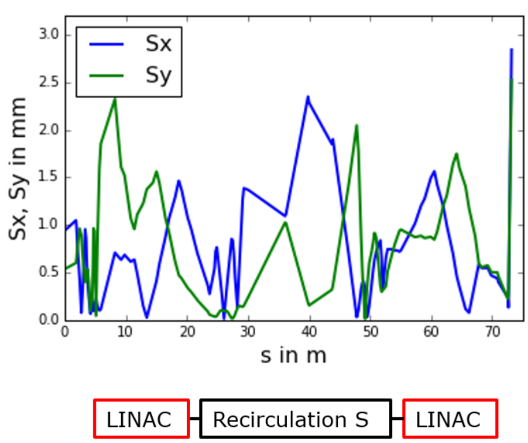

Figure 8: One-sigma envelope of the once-recirculating ERL mode is presented. The scheme shows the position along the orbit (simulation done with *elegant* [8]).

Increasing BBU Limit The cavities of S-DALINAC have not been optimized for a suppression of higher order modes (HOMs) and they do not have any HOM damping. So only several μA are sufficient for the occurrence of BBU at the S-DALINAC [4]. Several possibilities exist to increase the BBU threshold current. One theory uses the complete exchange of both transversal phase spaces [10]. This exchange is conducted by five skew quadrupole magnets which have been installed in the new recirculation beam line. Figure 9 and 10 show for a once-recirculating ERL operation the exchange of the transversal phase spaces: The main diagonal matrix elements are transformed to zero while the outer diagonal elements are unequal zero after the exchange.

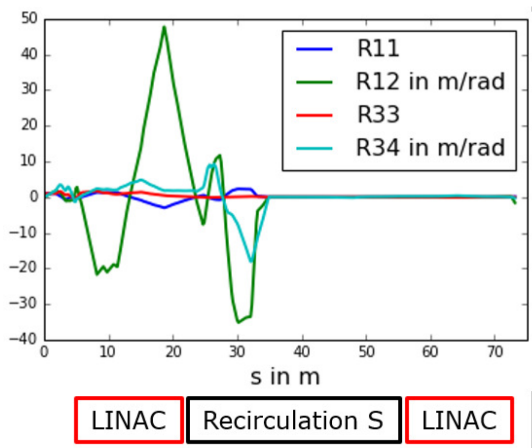

Figure 9: The exchange of the transversal phase spaces transforms the main diagonal matrix elements to zero (simulation done with *elegant* [8]).

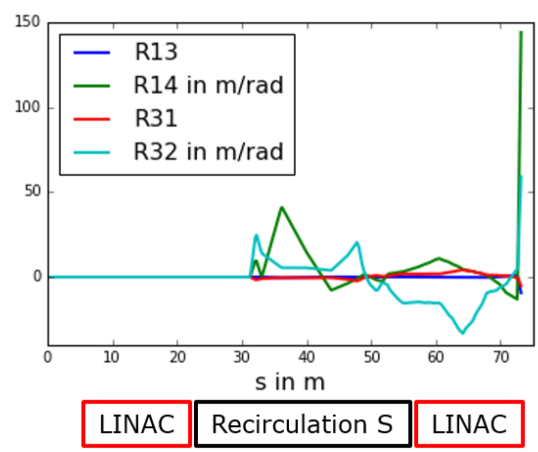

Figure 10: The exchange of the transversal phase spaces transforms the outer diagonal matrix elements to non-zero values (simulation done with *elegant* [8]).

INSTALLATION

After the preparation of all elements the installation was conducted. In the beginning of this phase a major part of all recirculation beam lines had to be disassembled (new position/lattice design of recirculation loop). Installing all beam lines very cautiously was scheduled afterwards followed by an alignment of the whole lattice.

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Alignment

Aligning all magnetic elements ensures a perfect transfer from the beam dynamics simulations to the real machine. The alignment was done with a lasertracker AT401 from Leica [11, 12]. In the beginning a coordinate system was defined to work with. There have been several phases of alignment to guarantee an optimized result. Finally the precision shown in Table 1 as well as the accuracy of the tilt around the axes (see Table 2) have been achieved.

Table 1: Resulting positioning precision for the different magnet types for the horizontal (x), vertical (y) and longitudinal (z) direction.

Magnet Type	x in mm	y in mm	z in mm
Dipole	0.27 ± 0.12	0.20 ± 0.14	0.17 ± 0.13
Quadrupole 1	0.27 ± 0.11	0.19 ± 0.12	0.23 ± 0.18
Quadrupole 2	0.32 ± 0.16	0.21 ± 0.17	0.28 ± 0.23
Sextupole	0.33 ± 0.18	0.29 ± 0.22	0.15 ± 0.11[1]

Table 2: Resulting precision in terms of tilt around the horizontal (x) and longitudinal (z) axis for the different magnet types.

Magnet Type	Tilt in ° around x and z
Dipole	0.020 ± 0.019
Quadrupole 1 and 2	0.057 ± 0.051
Sextupole	0.104 ± 0.084

Path-Length Adjustment System

Figure 11 shows the position of all path-length adjustment systems in the floor plan of the S-DALINAC. These systems are used to optimize the phase of the beam in each recirculation for the re-entry into the main LINAC. Also a change from a normal operation to an ERL operation is possible, if the stroke is big enough (more than 180° is necessary). The stroke of all systems was measured with the lasertracker and is summarized in Table 3. A full RF wavelength is equivalent to a distance of 100 mm. So only the second recirculation (sum of both systems amounts to 100.8 mm) is capable of an ERL setting.

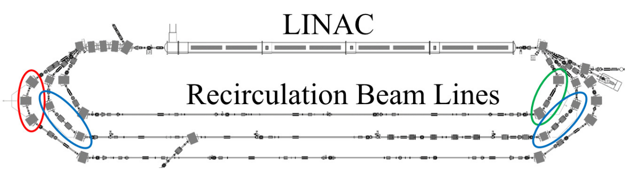

Figure 11: The path-length adjustment systems of the first (green), second (blue) and third (red) recirculation are marked in the floor plan of S-DALINAC.

Table 3: All strokes of the path-length adjustment systems have been measured with the lasertracker. The uncertainty amounts to < 0.2 mm.

System	Stroke in mm
First	33.8
Second 1	50.2
Second 2	50.6
Third	30.6

STATUS OF COMMISSIONING

The commissioning of the upgraded S-DALINAC started in December 2016. A first transport of the beam through the injector and main LINAC including the first passage of the new separation dipole magnet was achieved at the end of December before end-of-year shut-down. After some maintenance the beam was brought from the injector into the main LINAC and transported for the first time through the new recirculation beam line with a subsequent crossing of our main LINAC. The beam was than stopped at the beginning of the extraction (similar to once-recirculating ERL operation, see Fig. 3). At the moment the commissioning is continued.

CONCLUSION AND OUTLOOK

The superconducting Darmstadt linear accelerator (S-DALINAC) has been modified. The design and installation of an additional beam line including an ERL mode as well as all necessary modifications of the old layout was a complex and challenging task which is successfully completed. Some insights into the design concerning the most important dipole magnet - the separation dipole magnet - as well as some beam dynamics simulations and the final alignment have been presented. All path-length adjustment systems and the stroke, they are capable of, have been introduced. At the moment the modified S-DALINAC is under commissioning. First successes, as a transport of the beam trough the new beam line and a second passage through the main LINAC, have been achieved. The next steps will be the investigation of a once-recirculating ERL mode followed by a thrice-recirculating normal operation to prepare for first electron-scattering experiments after the current shut-down time.

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