CONSTRUCTION AND STATUS OF THE THRICE RECIRCULATING S-DALINAC*

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Abstract

The S-DALINAC was extended from a twice to a thrice recirculating linear accelerator to increase the maximum achievable energy close to its design value of 130 MeV by adding a third recirculation and thus enabling a fourth main accelerator passage. The new beam line also allows to operate the S-DALINAC as an ERL. A 180° phase shift in comparison to the RF-phase is possible due to a special path length adjustment system. During its operation, designated dipole magnets are moved on rails to increase or decrease the distance travelled by the beam. Both existing recirculations hold similar systems but are only capable to change the phase of up to a fraction of the RF-phase. The new system allows a 360° phase shift in total. The major pillars of this project have been the design (magnets, beam dynamics, lattice, etc.) [1], the planning of the whole project and the construction work done at the accelerator. These steps will be concluded by a commissioning. This contribution presents some insights into the construction time as well as an overview on the alignment procedure with the resulting precisions.

INTRODUCTION

The superconducting electron accelerator S-DALINAC was operated from its first commissioning as a recirculating LINAC in 1991 [2] until autumn of 2015 in a twice-recirculating set-up. In 2015/2016 a major upgrade of the S-DALINAC was performed: A third recirculation has been added between the existing beam lines. 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 [3] and thus a higher dissipated power to the helium bath. Adding an additional recirculation and thus a main LINAC passage allows to decrease the design gradient of the sc cavities while keeping the overall design beam energy constant. This change in operation is more convenient to the cooling power of the cryo plant. The actual floorplan of the thrice recirculating S-DALINAC is shown in Fig. 1. 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.

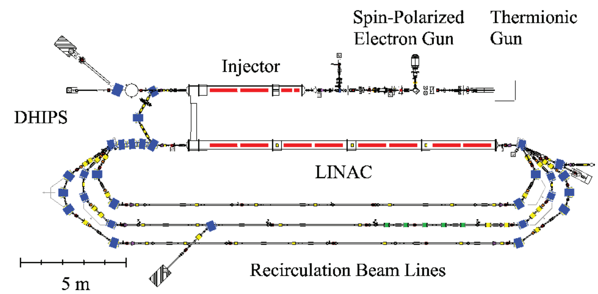

Figure 1: Floorplan of the S-DALINAC with three recirculations in the final set-up.

Energy Recovery LINAC Mode

Each recirculation of the S-DALINAC has the possibility to tune the distance the electron bunches travel from leaving the main accelerator until re-entering. These path length adjustment systems are capable to change the distance traveled by the beam up to a fraction of the RF wavelength of 10 cm only (existing recirculations) or up to a full RF wavelength (new recirculation beam line). Therefore with the new installed system a phase shift of up to 360° in the new, second recirculation is possible, allowing to switch the S-DALINAC operation mode between a conventional recirculating LINAC and an energy recovery LINAC (ERL) (180° phase shift).

PLANNING AND CONSTRUCTION

One major pillar of integrating an additional recirculation beam line was the planning and realization of the construction work. In addition to the preparation steps for the installation a detailed project plan was prepared. It defined the order of all tasks as well as their interconnecting dependencies. The resources needed (time and personnel) to fulfil all tasks have been part of this planning, too. In total, there have been 170 sub-tasks with 180 dependencies.

The installation phase had to be well prepared before it could start to allow an optimized procedure. The first step was a nearly complete disassembly of the existing beam line in the accelerator hall and the first part of the extraction beam line. Figure 2 shows a picture taken during this time. Afterwards the installation of the modified S-DALINAC could start. The dipole magnets have been positioned to define the orbit of the recirculating lattices. All other magnetic elements, beam diagnostic devices and work on the vacuum system finalized the construction phase of the lattice. In parallel the infrastructure (cooling water installation, com-

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pressed air piping, electrical cabling and connections) have been renewed completely. Figure 3 shows how the accelerator hall looked like close to the end of the whole installation phase.

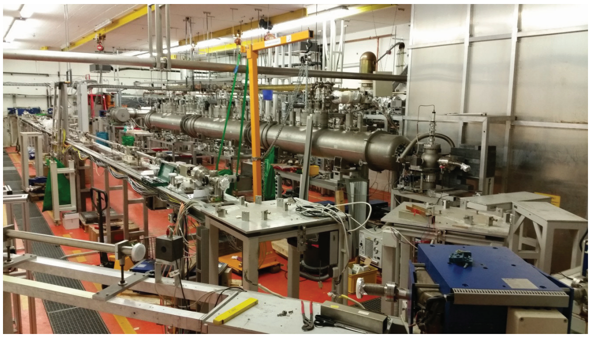

Figure 2: Main parts of the old beam line have been disassembled before the installation of the thrice recirculating S-DALINAC could start.

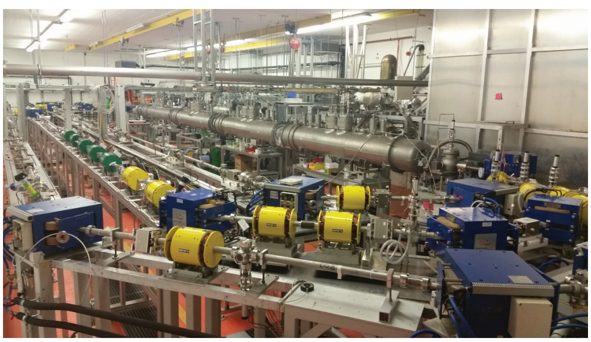

Figure 3: A view in the accelerator hall with all three recirculation beam lines.

ALIGNMENT OF THE LATTICE

The alignment of the lattice is a crucial topic. A reliable operation is only possible if the accuracy is sufficient. As a first step during the construction phase all dipole magnets have been placed on their coarse positions within the adjustment range of their corresponding support frames. This step allowed the installation of the beam line in between the dipole magnets. After a first alignment of the dipole magnet positions the remaining elements have been pre-aligned by the usage of in-house instrumentation (e.g. line laser). The final alignment was conducted at the end of the construction phase. The instrumentation used, the procedure as well as the accuracy achieved will be presented in this section.

Requirements

Beam dynamics simulations define the alignment accuracy of all lattice elements. To define these accuracies a Gaussian-based modulation of different alignment tolerances like rotations or offsets have been simulated several times with a random seed number for every single simulation. These random seed numbers generated randomly chosen deviations within the Gaussian-distribution. These simulations have been conducted using *elegant* [4]. The resulting deviations on the beam have not been corrected to generate a worst-case estimation. They have shown that, without any corrections, a maximum offset of 0.5 mm for a single axis or a maximum rotation of 0.1° around a single axis are tolerable. For this calculation the lattice of the first recirculation was chosen. In this section, the beam with the lowest energy in comparison to the other recirculations is transported and thus the most sensitive to misalignments. Figure 4 shows as an example the one-sigma envelope in x-direction following the first recirculation. Each separate simulation is represented by a curve in a different color. With the alignment tolerances stated above the size of the beam will grow by a factor of up to ten until the end of the recirculation in comparison to an optimized setting of the lattice.

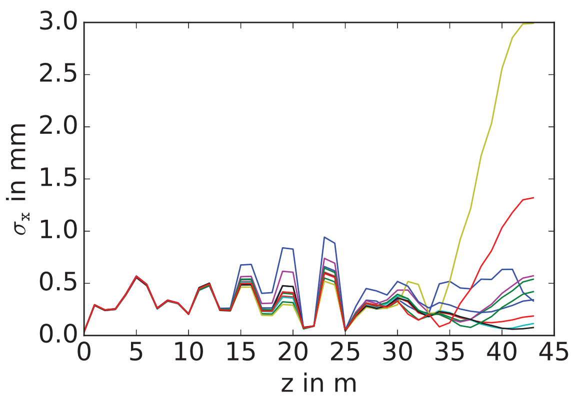

Figure 4: The one-sigma envelope in x-direction following the first recirculation for ten different misalignment settings is shown. An increase of the x-dimension of a factor of up to ten is possible until the end of the recirculation in comparison to an optimized lattice.

Instrumentation and Method

The requirements on the alignment accuracy can only be met by the usage of a lasertracker system and the corresponding knowledge of geodesists. For the alignment, a lasertracker AT401 from Leica was used (see Fig. 5). As a first step 18 drift nests have been installed to define a global coordinate system in the accelerator hall and extraction beam line area. The twice recirculating S-DALINAC was measured to have exact knowledge on the machine before the modification started [5, 6]. This data set served as an initial information on the old lattice and to test the whole measurement procedures. Afterwards the coordinates of all magnets have been determined in the global coordinate system to serve as an input data set for the final alignment. It was conducted by adjusting the single lattice elements one by one following the beam line. In the end the final positions of all magnets have been determined to serve as an optimized input for the beam dynamics simulations. The alignment was done with respect to the demanded accuracies of a maximum

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offset of 0.5 mm for a single axis or a maximum rotation of 0.1° around a single axis.

Figure 5: The lasertracker AT401 from Leica is shown during its operation for the alignment at the S-DALINAC.

Resulting Precision

During 20 measurment days, the final alignment of approx. 100 magnets as well as the commissioning of all path length adjustment systems have been finalized. The final precision reached was determined stepwise. As a first element the accuracy reached with the lasertracker for the different measurement types including for example its positioning accuracy have been determined. They are different measurement types due to the usage of different equipment to enable all diverse measurements needed. These values have been calculated as a 3D uncertainty. Afterwards the deviations to the target positions have been determined for all three axes (1D-values) for every single element type (dipole magnet, two different types of quadrupole magnets and sextupole magnet). Based on the data taken this way the mean value and the standard deviation have been calculated and added to the uncertainties determined in the first step as a "realistic-worst-case-precision" (1D and 3D mixed). The different magnet types have different adjustment possibilities. Due to these differences, it was for example much more easy to align a dipole magnet than to adjust a sextupole magnet. For the magnet types aligned the priorities to match the target positions have been weighted depending on the axis considered. For example is a match to the target position along the beam axis (z) for a quadrupole or sextupole magnet not that important as a match in both transversal axes due to a resulting and unwanted deflection of the beam in the case of a misalignment. These z-positions have been met quite precisely in the end. The knowledge on the final position along all axes is indeed very important to adjust the beam dynamics simulations. The slight differences in the z-positions can be compensated by a variation of the magnetic strengths (quadrupole and sextupole magnet). Table 1 shows the final precision achieved.

The rotation around the different axes was adjusted using a special tilt sensor. Table 2 gives an overview on the resulting precisions for the rotations around the horizontal (x) and longitudinal (z) axis. The tilt around the vertical (y) axis was not corrected separately due to the amount of fiducials along the beam direction for every magnet type. With the positioning of all of them a possible tilt around the y-axis was corrected automatically.

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

CONCLUSION AND OUTLOOK

The modification from a twice recirculating to a thrice recirculating set-up was a complex and demanding task which is completed. One of the last and crucial working packages was the alignment of approx. 100 magnets in the accelerator hall in position and tilt. The resulting precisions have been well in the requested margins. These efforts enable us to adjust the lattice settings as predetermined by the beam dynamics simulations.

At the moment, the commissioning of the renewed S-DALINAC is proceeding. In a first phase the once recirculating ERL-operation will be investigated followed by a thrice recirculating conventional operation to prepare additionally the commissioning of the newly installed high-energy-scraper-system [7] as well as first electron-scattering experiments after this shut-down time.

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