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FIRST ERL OPERATION OF S-DALINAC AND COMMISSIONING OF A PATH LENGTH ADJUSTMENT SYSTEM*

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Abstract

The S-DALINAC is a thrice-recirculating electron accelerator, capable of being operated in energy-recovery linac (ERL) mode. The change between conventional, accelerating operation and ERL mode is done by changing the distance traveled by the bunches in the second recirculation beam line. This distance is increased or decreased by moving dedicated magnets on a rail system. These so called path-length adjustment systems exist in all recirculation beam lines but only the stroke in the second recirculation beam line enables a phase shift of up to 360° of the RF phase. After having proven the functionality of the new systems the once-recirculating ERL operation was demonstrated successfully in August 2017. This contribution will introduce the path-length adjustment systems and present the commissioning of them. Results of the operation of the first ERL in Germany will be discussed.

INTRODUCTION

The superconducting electron accelerator S-DALINAC is in full operation since 1991 [1] at Technische Universität Darmstadt. In 2015/2016 a third recirculation beam line was installed [2]. This beam line enables to use the main accelerator a fourth time. Thus a decrease of the accelerating gradients is possible while keeping the final energy of the beam constant. The versatility of the newly installed beam line enables to change the operation mode between conventional accelerating operation and operation in energy-recovery linac (ERL) mode [3].

S-DALINAC

The S-DALINAC, floorplan see Fig. 1, houses two electron sources: a thermionic gun with a pre-acceleration of 250 keV and a spin-polarized source with a pre-acceleration of up to 125 keV. The beam is prepared for RF acceleration with 3 GHz in the normal conducting chopper-prebuncher-section. The superconducting (sc) injector accelerator increases the energy of the beam up to 10 MeV, in recirculating operation a maximum of 7.6 MeV is needed here. For recirculating operation the beam is bent into the main accelerator and further accelerated by up to 30.4 MeV per passage. In total a beam energy of up to 130 MeV with currents of up to 20 μA are possible.

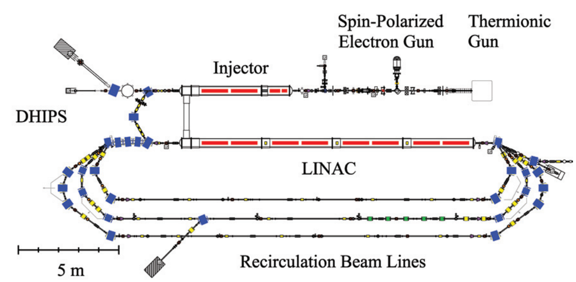

Figure 1: Floorplan of the S-DALINAC.

Energy-Recovery Linac Mode

The newly installed beam line is placed in-between the two existing beam lines. A path-length adjustment system is installed which allows to change the beam's orbit by a full RF wavelength of 10 cm and thus shift the phase of the re-injected beam by up to 360°. This versatility enables to change the operation mode of the S-DALINAC between conventional accelerating operation and ERL mode. The beam can either be accelerated once or twice before a phase shift of 180° is done in the middle recirculation beam line. Thus the lattice of the S-DALINAC allows a once or twice-recirculating ERL operation. The once-recirculating ERL mode was shown successfully in August 2017 and is presented more in detail in [4]. For the twice-recirculating ERL mode beam dynamics simulations are currently in the making.

PATH-LENGTH ADJUSTMENT SYSTEM

A crucial aspect for recirculating a beam is the exact point in time when each bunch re-enters the accelerating section. This time, respectively phase of the RF, has to be a multiple of a full period and thus for an operation frequency of 3 GHz a multiple of 10 cm. Deviations from the perfect phase will result in a decrease of beam quality.

Layout

Small changes of the distance traveled by the bunches can be made at the S-DALINAC to adjust for the perfect phase. These so called path-length adjustment systems do exist in each recirculation beam line. Figure 2 shows all four systems:

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F0PL01 in the first arc of the first recirculation beam line, S0PL01 and S2PL01 in the first respectively second arc of the second recirculation beam line and T2PL01 in the third recirculation beam line.

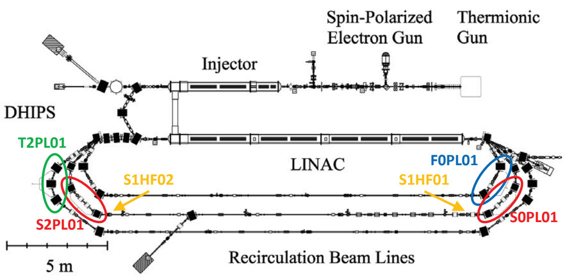

Figure 2: All path-length adjustment systems are shown (blue: first recirculation, red: second recirculation, green: third recirculation). Additionally both RF monitors of the second recirculation beam line are depicted (yellow).

All path-length adjustment systems are based on the same principle: a defined part of the beam line is shifted in parallel. Adjacent beam line sections are compressed or stretched by the usage of dedicated bellows. This motion is driven by stepper motors. The magnets are mounted on a specific linear rail system. Figure 3 presents a side view of the system S0PL01.

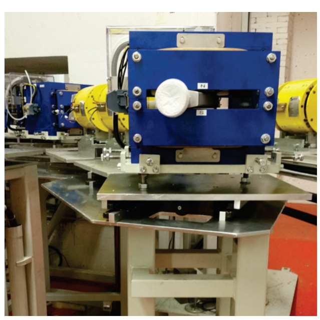

Figure 3: A side view of the S0PL01 path-length adjustment mechanism. The system consists of magnets, each mounted on a table sitting on a ball bearing slide driven by stepper motors.

Alignment

All magnets of the path-length adjustment systems have been positioned properly during the alignment of the modified lattice of the S-DALINAC. This was done with a laser tracker system [5,6]. In addition to the alignment the precise strokes of all four path-length adjustment systems have been measured. Table 1 summarizes the results. Both old systems (F0PL01, T2PL01) are capable to change the beam phase by roughly 1/3 of the RF wavelength. The new systems allow to shift the beam path-length by a total of up to a full RF wavelength

Table 1: Stroke of all four path-length adjustment systems measured with a laser tracker system. The uncertainties are in the order of ± 0.13 mm [2].

System	Stroke in mm
F0PL01	33.76
S0PL01	50.21
S2PL01	50.57
T2PL01	30.62

Commissioning with Beam

Both path-length adjustment systems installed in the new recirculation beam line have been commissioned [7]. For this measurement the phase of the beam was observed with two RF monitors (S1HF01, S1HF02, see Fig. 2) while changing the phase setpoint of the path-length adjustment system upstream (S0PL01) 36 times with a step size corresponding to 5° per step. The results are presented in Fig. 4. The expected linear behavior is observed. The abrupt change of the phase of S1HF01 arises from the conversion of IQ-demodulation data to phase angles limited to an arbitrary range of −180° to +180°.

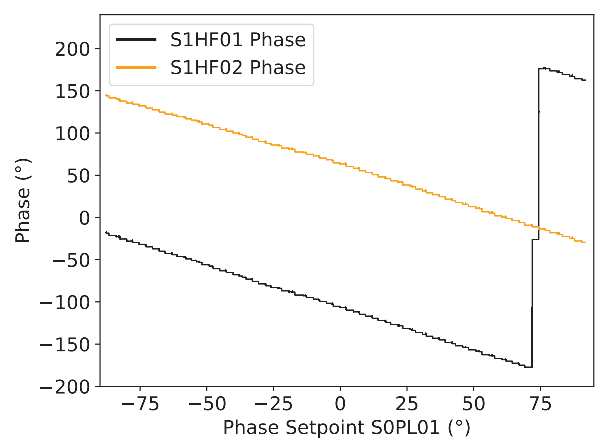

Figure 4: Beam phase measured in both RF monitors versus the change in setpoint of S0PL01.

A closer look to the data, see Table 2, reveals a little difference between the expected change in the phase of the beam due to the change in the setpoint of S0PL01 and the resulting change in the phase of the beam. These effects cannot be explained with beam dynamics effects. As soon as these effects are big enough to have a significant influence on the phase of the beam, the resulting beam is not fitting into the acceptance of the lattice anymore. We have observed some issues with our RF monitor system which are most likely responsible for these differences. Nevertheless we do see the linear behavior expected combined with the stroke needed for ERL operation. We will further investigate these issues on the beam phase measurement.

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Table 2: Comparison of change in beam phase setpoint by adjusting S0PL01 and reaction of beam phase measured with two RF monitors (S1HF01, S1HF02) after 36 steps in total and as a mean value of the single steps.

	Step Size	Total
S0PL01 (setpoint)	5.0°	180.0°
S1HF01 (measured)	5.1(6)°	180.9(6)°
S1HF02 (measured)	4.8(5)°	174.0(5)°

FIRST ERL OPERATION

The first successful once-recirculating ERL beam time was performed at the S-DALINAC in August 2017. In this operation scheme the beam is accelerated once by the main linac, is then bent into the second recirculation beam line where a phase shift of 180° is done. The next passage of the main linac is on the decelerating phase, so that the beam leaves the main accelerator at injection energy and is dumped directly after the exit of the main linac in a dedicated ERL beam dump. This run was the first operation of an ERL in Germany. Table 3 gives an overview on the general parameters.

Table 3: Overview of parameter settings for the once-recirculating ERL operation. The current value refers to a measurement in front of the injector linac.

Parameter	Value
Energy gain injector	2.5 MeV
Energy gain linac	20.0 MeV
Current (before injector)	1.2 µA
Total change in phase, setpoint (S0PL01 + S2PL01)	186.0°

During the measurement the S-DALINAC was operated in four slightly different phases:

- ERL mode: Two beams in the main linac of which one was accelerated and one decelerated
- No beam: No beam was traveling through the main linac, the sc cavities have been running in steady-state
- One beam: A single-pass setting was chosen with one accelerated beam in the main linac
- Two beams: A conventional, only accelerating operation was performed, so that two beams have been accelerated

Dedicated observables have been recorded in order to prove the successful ERL operation. Figure 5 shows the beam path during this operation scheme (red) as well as the position of the corresponding diagnosis elements.

Figure 6 presents the results of the ERL run with all four phases. The power consumption due to beam loading in the first main linac cavity (A1SC01) cancels in the ERL mode

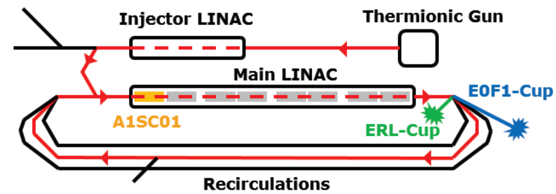

Figure 5: The beam path of the once-recirculating ERL mode is shown in red. Parameters observed during the measurement are the powers of A1SC01 as well as the beam currents for ERL mode (ERL-Cup) and normal, accelerating operation (E0F1-Cup).

almost completely out. The efficiency of the ERL operation is calculated to $92.1^{+3.7}_{-13.9}$ %. The RF power needed is almost identical to in the situation of no beam loading. A significantly bigger power than during the ERL operation is required for accelerating one or two beams. The beam currents for ERL mode and conventional, normal accelerating operation have been measured at dedicated beam dumps and are an additional evidence for both operation schemes.

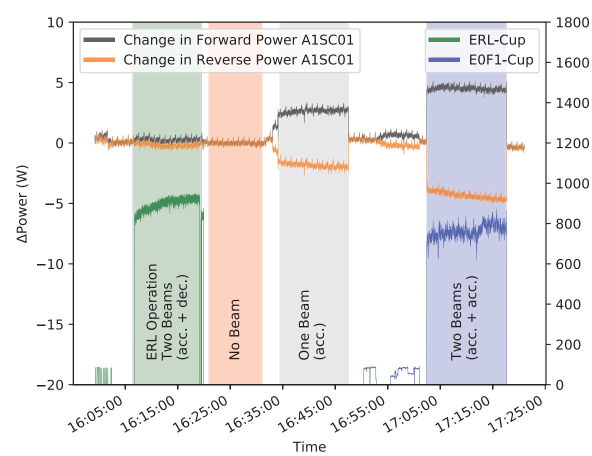

Figure 6: During all four measurements of the ERL run the forward and reverse power of A1SC01 have been monitored as well as the beam currents in the for each operation corresponding beam dump (ERL: ERL-Cup; normal, accelerating operation: E0F1-Cup).

CONCLUSION AND OUTLOOK

The path-length adjustment systems are used to shift the beam phase for the bunches re-entering the main linac. The total stroke of the systems of the newly installed recirculation beam line enables a phase shift of up to 360° and thus a change to ERL operation. In August 2017 the S-DALINAC was operated for the first time as a once-recirculating ERL. Dedicated measurements have shown the successful operation with an efficiency of $92.1^{+3.7}_{-13.9}$ %.

At the moment the little numeric issues found on the RF monitor system are being investigated further. In addition, beam dynamics simulations are performed to prepare op-

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erational tests of the S-DALINAC as a twice-recirculating ERL.

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