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ERL OPERATION OF S-DALINAC*

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Abstract

The S-DALINAC is a thrice-recirculating superconducting electron accelerator which can be either used in conventional accelerating operation or, since a major upgrade was installed in 2015/2016, as an energy recovery linac (ERL) alternatively. A once- or twice-recirculating ERL operation is possible due to the layout of the accelerator. During the commissioning phase the once-recirculating ERL operation was demonstrated in August 2017. Measurement data and an analytical model for the radio-frequency power behaviour due to changes in the beam loading are presented.

INTRODUCTION

The material discussed in this oral presentation is based upon the content of a scientific article which we have submitted on 4th of October 2019 to *Physical Review Accelerators and Beams*. Our present contribution to these conference proceedings, hence, contains descriptions of our work in the way which we were able to formulate them best.

S-DALINAC

The S-DALINAC is in operation since 1991 at TU Darmstadt [1]. A floorplan is shown in Fig. 1.

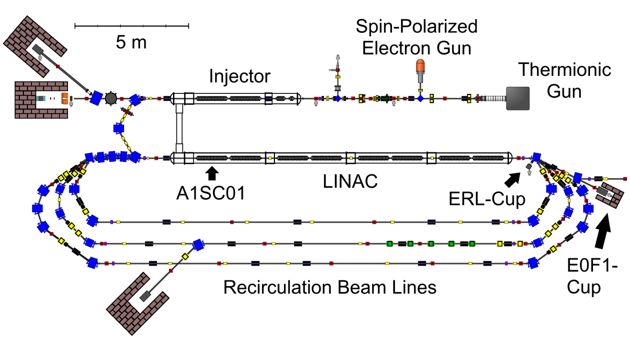


Figure 1: Floorplan of the S-DALINAC. The first main accelerator cavity A1SC01 and the two beam dumps being relevant for the measurement explained in section ”Once-Recirculating ERL Operation” are indicated.

The beam is either produced in a thermionic gun with a pre-acceleration of 250 keV or in a spin-polarized electron gun with a pre-acceleration of up to 125 keV. The beam is prepared for further acceleration with 3 GHz in the normal-conducting chopper-prebuncher section. The superconducting (sc) injector linac is able to accelerate the beam up to 10 MeV (7.6 MeV for recirculating operation). The beam is bent into the main accelerator, providing an energy gain of 30.4 MeV. The maximum design energy is 130 MeV at currents of 20 µA.

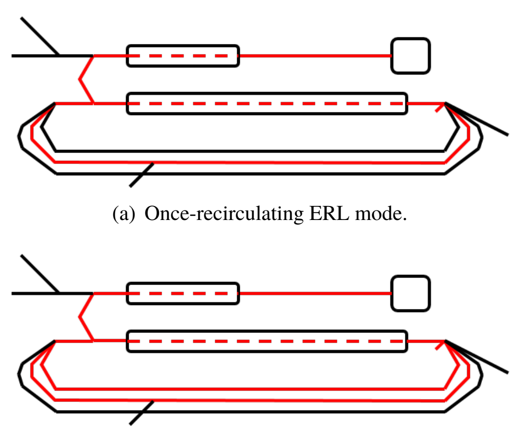
A New Recirculation Beam Line

In 2015/2016 a third recirculation beam line was installed, enabling higher end-energies and energy-recovery linac (ERL) operation due to a path-length adjustment system in the new beam line with a stroke of up to 360° [2, 3]. The beam line elements have been aligned with a laser tracker [4], achieving a global 1D positioning precision in the order of 200 µm.

Operational Modes and Commissioning

The lattice of the S-DALINAC allows different operation schemes:

- Injector operation
- Single pass mode (one passage through the main linac)
- Once-recirculating mode (two passages through the main linac)
- Thrice-recirculating mode (four passages through the main linac)
- Once-recirculating ERL mode (one accelerating and one decelerating passage through the main linac, see Fig. 2(a))
- Twice-recirculating ERL mode (two accelerating and two decelerating passages through the main linac, see Fig. 2(b)), not demonstrated yet



(a) Once-recirculating ERL mode.

(b) Twice-recirculating ERL mode.

Figure 2: The S-DALINAC lattice is capable of a once- or twice-recirculating ERL operation. The 180° phase shift is done in the second recirculation beam line.

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The commissioning of the modes started at the end of 2016 with an injector and the first single pass setting. In 2017 the focus was set to the once-recirculating modes (conventional and ERL). Both have been achieved in 2017, the ERL operation is presented in a later section. A major refurbishment of the cryo-plant was done in 2018. During the remaining year the thrice-recirculating mode was operated for the first time. The twice-recirculating ERL mode is in preparation.

ERL Efficiencies

The efficiency of an ERL is an important quantity, judging on the success of the operation. There are several ways to define an efficiency, either based on the beam or the radio-frequency (RF) powers. One of them is the *beam-recovery efficiency* defined by

$$\mathcal{E}_{\mathrm{b}} = \frac{E_{\mathrm{b,max}} I_{\mathrm{b,dump}} - P_{\mathrm{b,dump}}}{P_{\mathrm{b,max}}} \quad (1)$$

where $E_{\mathrm{b,max}}$ ($I_{\mathrm{b,dump}}$) are the beam energy (beam intensity) at maximum energy (at the beam dump) and where $P_{\mathrm{b,max}} = E_{\mathrm{b,max}} I_{\mathrm{b,max}}$ ($P_{\mathrm{b,dump}} = E_{\mathrm{b,dump}} I_{\mathrm{b,dump}}$) is the beam power at top energy (at the beam dump). The beam-recovery efficiency can only be finite if the beam energy at the dump is lower than maximum and if a finite transmission to the dump is achieved. The ideal beam-recovery efficiency of 100 % is obtained by a complete deceleration of the entire beam current available at maximum energy, *i.e.*, $I_{\mathrm{b,dump}} = I_{\mathrm{b,max}}$ and $E_{\mathrm{b,dump}} = 0$. In general, decelerating to zero energy is not possible, so the efficiency of an ERL is limited by the injector energy, usually chosen at a few MeV level to reach close to ultra-relativistic electron motion before the main linac. For optimum transmission the beam-recovery efficiency is then limited to

$$\mathcal{E}_{\mathrm{b,max}} = 1 - \frac{E_{\mathrm{b,dump}}}{E_{\mathrm{b,max}}}. \quad (2)$$

The beam-recovery efficiency, however, does not allow to judge directly the technological gain provided by the deceleration process due to the reduction of external RF power required for the machine operation. For that purpose, the *RF-recovery effect*

$$\mathcal{E}_{\mathrm{RF}} = \frac{P_{\mathrm{RF,acc.}} - P_{\mathrm{RF,ERL}}}{P_{\mathrm{RF,acc.}}} \quad (3)$$

is more useful, where the RF beam loading is compared in situations when the beam is either blocked externally at its maximum energy ($P_{\mathrm{RF,acc.}}$) or when its energy is recovered by out-of-phase recirculation to the RF cavities ($P_{\mathrm{RF,ERL}}$) at the same absolute amplitude of the RF field. The optimum RF-recovery effect is obtained when the beam loading in ERL mode vanishes completely.

ONCE-RECIRCULATING ERL OPERATION

An ERL machine time took place during the commissioning phase of the upgraded S-DALINAC (see subsection "Operational Modes and Commissioning") in August 2017 [5]. The goals of this ERL run have been to achieve once-recirculating ERL operation and to study the low-level radio-frequency system and its performance during ERL operation [6]. A summary of all main parameters of the ERL measurement is listed in Table 1. The energy gain of the injector was small, thus phase slippage effects in the 20-cell accelerating structures are strongly present. For this reason the change in phase in comparison to conventional acceleration resulted in 186° (setpoint of path length adjustment system) for an optimized operation.

Table 1: Main Parameters of the Once-Recirculating ERL Operation.

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)	186°
RF recovery effect $\mathcal{E}_{\mathrm{RF}}$	(90.1 ± 0.3) %
Beam-recovery efficiency $\mathcal{E}_{\mathrm{b,max}}$	88.9 %

During the ERL machine time, data on RF power measurements of the first main accelerating cavity A1SC01, and on the beam current at the two corresponding beam dumps (ERL mode: ERL-Cup, conventional mode: E0F1-Cup), were taken. The data was acquired for four different settings that refer to the following color code:

1. No beam in the main accelerator. (red)
2. Single pass: one beam is accelerated in the main accelerator. (grey)
3. Once-recirculating mode: two beams are accelerated in the main accelerator. (blue)
4. ERL mode: one beam is accelerated, another beam is decelerated in the main accelerator. (green)

Figure 3 gives an overview on the complete measurement. This data was taken shortly after an access to the accelerator hall was needed for maintenance work at the path length adjustment system. The measured powers (raw data) are increasing over time, being an effect during the first hours of RF operation. The increase occurs due to thermal heating of the input coupler caused by RF losses at the coupler during the operation and a corresponding change of the coupling resulting in an additional change of the length of the self-excited loop over time. This change can in common beam operation be corrected by the operators using a loop phase shifter, when the coupler temperatures have reached equilibrium. In the presented experiments this correction hasn't

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been applied as temperatures were still drifting. Therefore, we need to take the drifts into account for the analysis. For this reason a drift-correction was done for all powers, resulting in $\Delta\widetilde{P}_i$ (i: forward and reverse power).

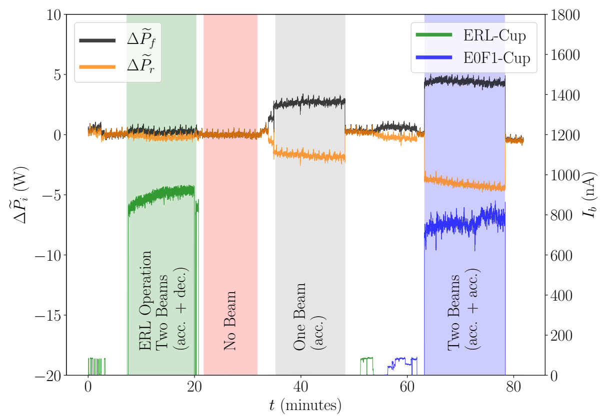

Figure 3: During four different settings (ERL: green, no beam: red, single pass: grey, twice accelerating: blue) the changes in forward (black curve) and reverse (orange curve) RF power of the first main accelerating cavity (A1SC01, see Fig. 1) have been monitored. The beam current on the corresponding faraday cups (ERL-Cup: green, E0F1-Cup: blue, see Fig. 1) was measured [5].

The forward (black curve) and reverse power (orange curve) of the first main accelerating cavity (A1SC01) have been measured and normalized to the time without beam but with electromagnetic field in the cavity (red band in Fig. 3). During the single pass setting (grey shading in Fig. 3) both powers changed with respect to the situation without beam due to the beam loading: the forward power increased while the reversed power dropped to a lower level. The absolute changes amount to about 2 W in both cases. If a second beam for acceleration is put into the cavity, the beam loading further increases (once-recirculating mode, blue shading in Fig. 3). Both, the forward power and the reverse power, change again by about the same amount as observed before. In case of the ERL operation (green shading, Fig. 3), the effective beam loading of the cavity A1SC01 was found to almost fully cancel out. The power levels were equivalent to a beam-free linac while still the beam was transported to the ERL beam dump (green curve) after having intermediately been transported through the recirculation arcs with an energy of 22.5 MeV. This is a clear evidence for operation of the S-DALINAC in ERL mode.

The current measurement is a further evidence that the beam was transported to the ERL beam dump (green curve) in the ERL mode phase (green shading) as well as to the extraction beam dump (blue curve) during the once-recirculating mode (blue shading).

More details on the evaluation of the measurement can be found in [5].

Analytical Model

The drop in reverse power, when increasing the number of beams accelerated in the cavities, can be explained with the beam being an additional external load which couples to the electric acceleration field. In absence of the amplitude control of the RF control system the forward power would stay constant. In this case the power transferred to the beam would only be measurable in the reverse power. The presence of the amplitude control causes an increase in forward power to keep the accelerating field constant despite of the beam loading. With higher beam coupling the reflection coefficient r decreases resulting in a drop of the reverse power level. It is given by the input coupling β_1, output coupling β_2 and beam coupling β_b. P_0 is the dissipated power in the cavity, P_f and P_r are the forward respectively reverse powers:

$$r = \frac{\beta_1 - (1+\beta_2+\beta_\mathrm{b})}{\beta_1 + (1+\beta_2+\beta_\mathrm{b})} = \sqrt{\frac{P_\mathrm{r}}{P_\mathrm{f}}}. \tag{4}$$

Both effects mentioned above cause the steps in the corresponding powers. In the following, an analytical model to the power data will be applied to show the expected behaviour of the reverse power. An expression for the forward power P_f is given by

$$P_\mathrm{f}(t) = P_0 \frac{[\beta_1(t) + (1+\beta_2(t)+\beta_\mathrm{b})]^2}{4\beta_1(t)}, \tag{5}$$

The reverse power P_r can be expressed as:

$$P_\mathrm{r}(t) = P_0 \frac{[\beta_1(t) - (1+\beta_2(t)+\beta_\mathrm{b})]^2}{4\beta_1(t)}. \tag{6}$$

The different coefficients have been obtained by fits to the data in the different situations: first with no beam loading, second with fits to the data on the forward power in presence of beam (ERL, single linac pass, double linac pass). Figure 4 shows the achieved curves. More details on the analytical model can be found in [5].

SUMMARY AND OUTLOOK

The S-DALINAC was extended by a third recirculation beam line, allowing a phase shift of up to 360°. During the commissioning process of all machine operation modes the once-recirculating ERL operation was achieved in August 2017. An RF recovery effect of (90.1 ± 0.3) % in the first main accelerating structure was reached. An analytical model was found, that predicts the behaviour of the reverse power for measured and fitted forward power.

The twice-recirculating ERL operation is in preparation. Investigations on the effect of phase slippage are ongoing [7]. A crucial aspect for a twice-recirculating ERL operation is the diagnostics, as two beams of the same energy are travelling through the same beam line. Different possibilities to measure both beams are under investigations [8]. The twice-recirculating ERL operation will be worked on during an upcoming beam time.

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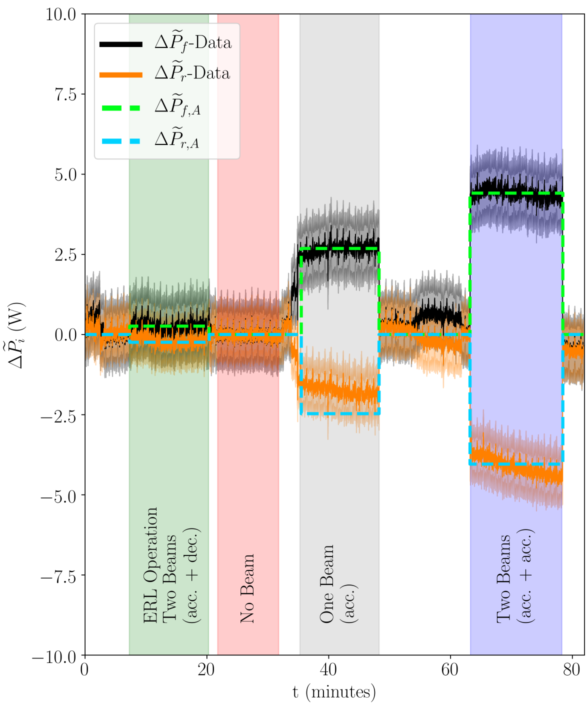

Figure 4: Curves of the forward (black) and reverse (orange) power data including uncertainties marked as areas. The dashed lines show the curves extracted from the analytical model via curve fitting. The analytical curves show the theoretical behaviour of forward (green) and reverse power (blue) in absence and presence of the beam (steps) [5].

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