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LOW LEVEL RF ERL EXPERIENCE AT THE S-DALINAC*

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Abstract

In 2011 the present digital low-level RF (LLRF) control system was set into operation. The first successful one-turn ERL operation was set up in August 2017. The RF control performance was investigated during this new possible operation mode in comparison to other modes that were conventional already before at the S-DALINAC.
The efficiency of the ERL operation can be determined by measurement of the beam loading in the cavities. This could only be done for the first main accelerator cavity. Therefor, an alternative way to determine the ERL efficiency from the already done RF control stability measurements was done to have a good estimate for this measurement. To quantify the ERL efficiency via beam loading measurement an RF power measurement system was developed which is able to measure the RF powers and hence the beam loading for all cavities simultaneously.

RF STABILITY

Introduction

The recirculating superconducting Darmstadt linear accelerator S-DALINAC [1] is one of the main research instruments at the institute for nuclear physics at the TU Darmstadt. It is operating in cw mode at beam currents of up to 20 µA with energies of up to 130 MeV using a thrice recirculating scheme. The current in-house digital LLRF control system of the S-DALINAC was developed in 2011 [2]. Since 2017 the S-DALINAC can be used as an energy recovery linac (ERL). The ERL mode is adjusted by shifting the phase of the beam by 180° in the second recirculation beam line. A first succesful ERL operation was conducted in August 2017 with an injector energy of 2.5 MeV [3, 4]. To state if the current digital LLRF control system is sufficient for a stable ERL operation, it have to be tested in this operation mode and the results have to be compared with stabilities in other modes that are conventional at the S-DALINAC.

Measurement

The investigation of the stability of the current RF control system was done by measuring the residual amplitude and phase errors of all cavities in four different operation modes at a beam current of about 1 µA during an about two hours measurement run. Figure 1 shows an overview of the different operation modes. For RF stability investigation the amplitude error and phase error data of the RF signal was measured in the time domain using the RF control electronics [2, 5]. The data was then Fourier-transformed to the

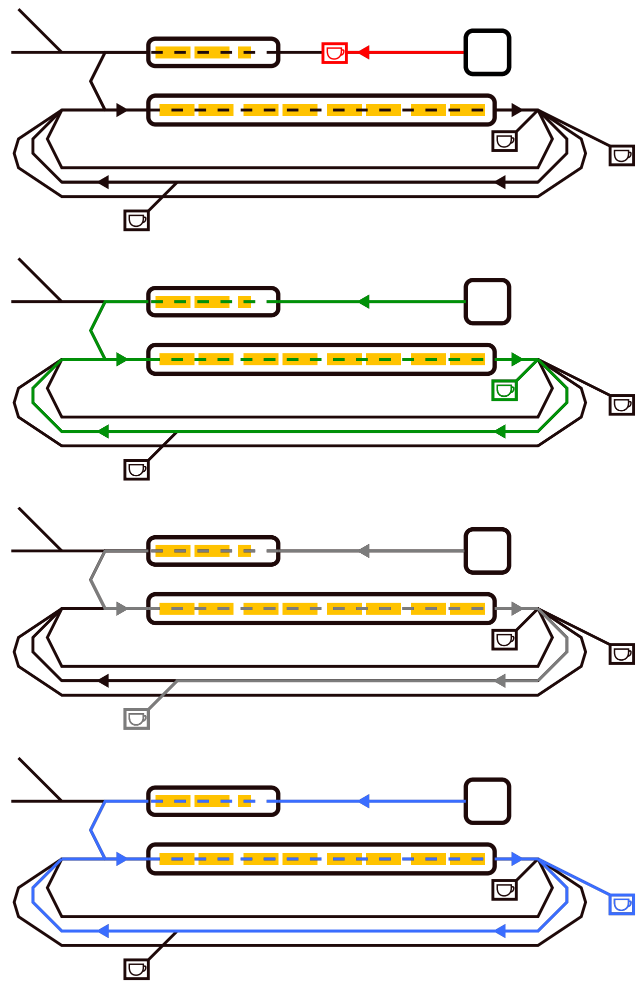

Figure 1: Schematic overview of the four different operation modes of the S-DALINAC during the ERL run. Top: Operation without beam. The beam was stopped at a Faraday cup in front of the injector (beam path indicated in red). Second: Once recirculated ERL operation. The beam was accelerated once in the main accelerator, decelerated in a second pass and dumped in a dedicated cup (green). Third: Once accelerated beam operation. After the first pass through the main accelerator the beam was dumped in a cup in the second recirculation beam line (grey). Fourth: Twice accelerated (once recirculated) beam operation. The beam was accelerated two times in the main accelerator (blue).

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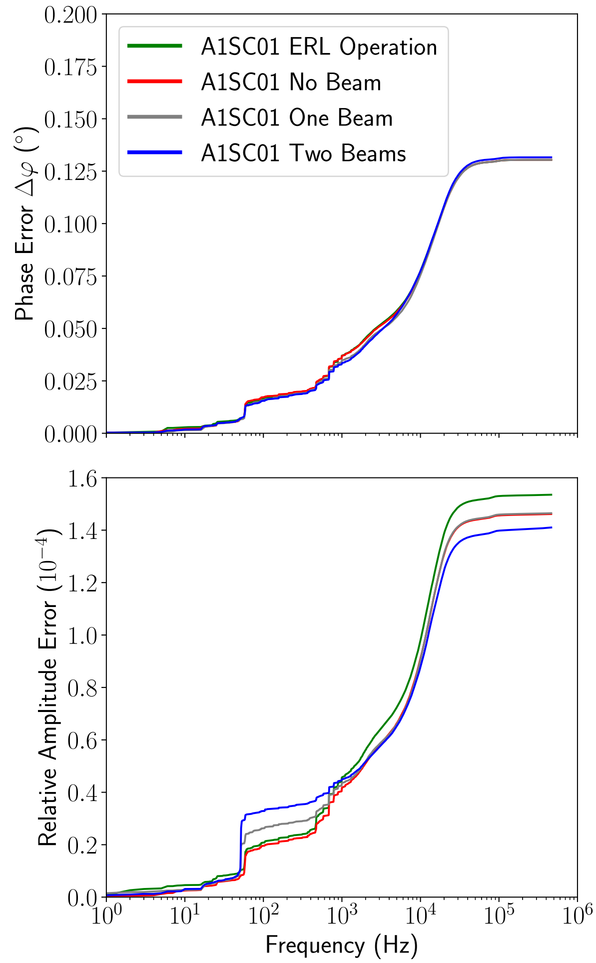

Figure 2: Integrated Fourier spectra of the phase error (top) and the relative amplitude errors (bottom) at the four different operation modes. The contribution of the frequency-dependent disturbances to the total residual errors are visible by the height of the increases [5].

frequency domain. The extracted Fourier spectrum contains information about the frequency-dependent disturbances of the whole RF control loop including cavity, amplifiers and transfer line. Via integration of the Fourier spectrum the contribution of the perturbations to the total residual errors of the system are determined by the step heights at the different frequencies. The higher the step height the higher the contribution of the disturbances at a given frequency. The integrated Fourier data for the four different operation modes is shown in Fig. 2 for the first main accelerator cavity A1SC01.

The integrated Fourier spectra of the phase error do not show significant differences between the four different operation modes. For the integrated Fourier spectra of the relative amplitude error, the final values as well as step sizes in the region of 1 Hz to 1 kHz differ for the four modes.

The RF control stability of ERL operation, hence lowest beam loading (except no beam operation), and once-recirculated operation, i.e. highest beam loading, are compared in Table 1. The estimated relative uncertainty of the measurement is about 5 %.

Table 1: RF stability comparison the total residual errors at ERL operation and at once-recirculated operation with two accelerated beams in the main accelerator. These two modes differ in beam loading in the cavities. The data of all eight main linac cavities is shown with an estimated uncertainty of 5 %.

Cavity	Relative Amp. Error (10^{-4})		Phase Error (°)	
	ERL	Two Beams	ERL	Two Beams
A1SC01	1.5	1.4	0.13	0.13
A1SC02	4.4	4.3	0.43	0.41
A1SC03	1.9	4.0	0.13	0.14
A1SC04	3.4	3.7	0.11	0.11
A1SC05	2.4	2.1	0.17	0.17
A1SC06	1.1	1.2	0.14	0.14
A1SC07	0.9	0.9	0.13	0.13
A1SC08	1.7	1.3	0.12	0.12

In comparison with the specified absolute phase stability of 0.7° and relative amplitude stability of 8×10^{-5}, the phase errors are better than specified and the relative amplitude errors do not fullfill the specifications. For the ERL run, the control parameters of the LLRF system have been optimized to minimize the phase error resulting in a slight increase of the relative amplitude error at the same time.

The phase errors in the two operation modes are similar to each other with a maximum relative difference of about 8 % for cavity A1SC03 (see Table 1). Except A1SC03 the relative amplitude errors differ at maximum by about 20 % for A1SC08Some of the main linac cavities had some general RF issues and have shown far higher relative amplitude errors and phase errors in comparison to others. The cavity A1SC02 had a problem with one of the piezoelectric eigenfrequency tuners which was exchanged by now.

For the cavity A1SC03 the reason for much higher relative amplitude errors is not fully known. The main contribution to this errors is a beam induced disturbance at 52 Hz (see Sec. *ERL Efficiency*). There is evidence that the cavity is detuned in respect to field flatness. This cavity quenches at a relativly low RF forward power but had an unloaded quality factor $Q_0 = (1.23 \pm 0.07) \times 10^9$ which is comparable to the other cavities. This leads to the conclusion that the field in some cells is much higher than in others leading to a quench. It is assumed that the field at the end cells of the cavity was relativly small in comparison to the front cells, i.e. the impact of the beam and hence the beam induced disturbance is higher at the end cells. There the RF control signal is extracted which was then measured for the RF control stability.

Despite these RF issues it could be assumed in general that the current RF control system is sufficient for a once-

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recirculating ERL operation at the S-DALINAC. To increase RF stability generally, the RF control loop has to be tuned with a focus on decreasing the relative amplitude errors. The RF stability in a multi-turn ERL operation at the S-DALINAC has to be proven in future. The behaviour at beam loading exceeding 1 µA will be studied in upcoming measurements.

ERL Efficiency

During the ERL machine time just the RF forward and reverse powers of the first main accelerator cavity could be measured. This measurement is needed to quantify the energy recovery efficiency for all cavities. The efficiency

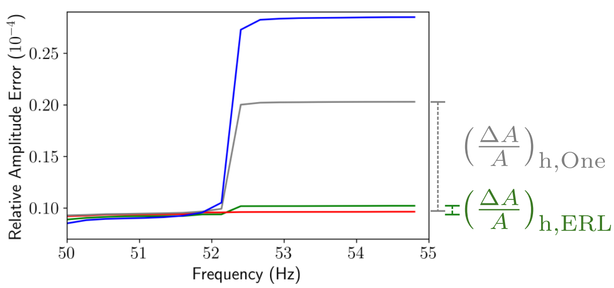

Figure 3: Extract of the relative amplitude error spectrum around the 52 Hz disturbance induced by the electron beam for the first main accelerator cavity. The step height is in first order proportional to the beam loading in the cavity. Using the step heights of ERL operation and once accelerated operation the ERL efficiency of all main accelerator cavities can be estimated.

$\mathcal{E}_{\mathrm{RF}}$ via RF beam power measurement is given by

$$\mathcal{E}_{\mathrm{RF}} = \frac{P_{\mathrm{b,Acc}} - P_{\mathrm{b,ERL}}}{P_{\mathrm{b,Acc}}} \tag{1}$$

with $P_{\mathrm{b,Acc}}$ being the beam power corresponding to the beam loading in once accelerating mode and $P_{\mathrm{b,ERL}}$ as the beam power corresponding to the effective beam loading in ERL operation. The beam loading power P_{b} in cw operation is determined via

$$P_{\mathrm{b}} = P_{\mathrm{f}} - P_{\mathrm{r}} - P_0 - P_{\mathrm{t}}. \tag{2}$$

with P_f and P_r as forward and reverse power, P_0 as the dissipated cavity power and P_t the transmitted power. At zero beam loading ($P_{\mathrm{b}} = 0\,\mathrm{W}$) $P_0 + P_{\mathrm{t}}$ can be quantified with a measurement of P_{f} and P_{r}. The beam loading can then be determined assuming the beam loading does not affect $P_0 + P_{\mathrm{t}}$.
Every cavity in the main accelerator had shown a disturbance at 52 Hz in the residual relative amplitude errors of the RF control. The step height at 52 Hz is zero and the step heights of the once accelerated operation and twice accelerated operation scaled with the beam current in the cavities which was measured in Faraday cups. Therefore, it is assumed that the disturbance step height in the spectra is proportional to the beam loading in the respective cavity. The relative effective beam loading in ERL operation can be measured indirectly with this method. Analog to the RF efficiency determination the efficiency can be estimated with the step heights $\left(\frac{\Delta A}{A}\right)_{\mathrm{h}}$ in the relative amplitude errors by

$$\mathcal{E}'_{\mathrm{RF}} = \frac{\left(\frac{\Delta A}{A}\right)_{\mathrm{h,One}} - \left(\frac{\Delta A}{A}\right)_{\mathrm{h,ERL}}}{\left(\frac{\Delta A}{A}\right)_{\mathrm{h,One}}}. \tag{3}$$

Table 2: Estimated efficiencies for all main accelerator cavities with an estimated uncertainty of about 10 %.

Cavity	$\mathcal{E}'_{\mathrm{RF}}$
A1SC01	92 %
A1SC02	73 %
A1SC03	92 %
A1SC04	98 %
A1SC05	96 %
A1SC06	100 %
A1SC07	100 %
A1SC08	60 %

The corresponding steps are illustrated in Fig. 3. The estimated efficiencies $\mathcal{E}'_{\mathrm{RF}}$ for all cavities are shown in Table 2. $\mathcal{E}'_{\mathrm{RF}}$ for the first cavity A1SC01 is in accord with the measured $\mathcal{E}_{\mathrm{RF}}$ of (90.1 ± 0.3) % [3]. The explanation for the drop of efficiency for A1SC08 is the presence of phase slippage due to the low injection energy of 2.5 MeV. At this low energy the beam is not in the ultrarelativistic regime. The main accelerator cavities are designed for ultrarelativistic particles. This mismatch results in a phase slip during the transit of the particles which has to be compensated. This was done by adjusting the RF field from on-crest to off-crest acceleration in the first main accelerator cavity. All other cavities were operated on-crest. Therefor, the cavity A1SC08 were adjusted for an ultrarelativistic beam leading to a phase slip at deceleration because the particles are not ultrarelativistic anymore. The drop of efficiency for A1SC02 has to be further investigated. In all other cavities a high recovery of at least 92 % could be achieved.

NEW RF POWER MEASUREMENT SYSTEM

The test setup used during this ERL beamtime is based on Schottky-diodes mounted directly in the accelerator hall. The diodes can be damaged due to the RF and beam induced radiation. Additionally the setup was not temperature stabilized. Therefore, a new power measurement system was developed in-house and setup at the S-DALINAC which is also compatible with the EPICS-based control system [6]. Figure 4 shows a new RF power board. It contains three RF inputs each with a 65 dB wide dynamic range power detector [7]. In the power detectors the RF signals are rectified.

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The digitization and averaging of the DC-voltage is done on a microcontroller [8] comunicating via CAN-bus protocol. Ten power measurement boards are currently in usage allowing up to thirty RF powers to be measured simultaneously. For the superconducting cavities 22 RF powers are measured including forward and reverse power.

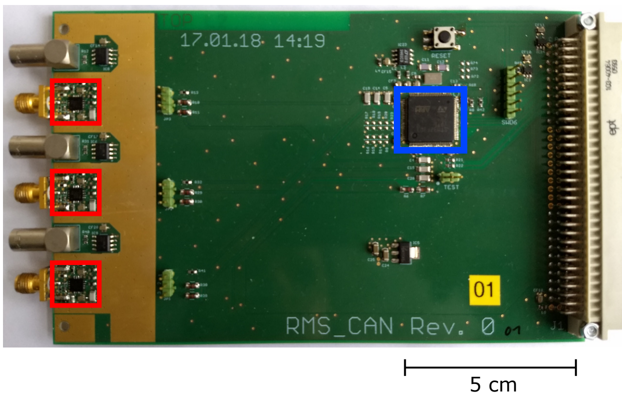

Figure 4: Photography of an in-house developed power measurement board. The power detectors are marked in red and the microcontroller is marked in blue. The board contains three RF-inputs where the RF-signal is rectified in the power detectors. The DC-voltage is digitized in the microcontroller and send to the EPICS-based control system via CAN-bus protocol.

SUMMARY AND OUTLOOK

In August 2017 the first ERL operation was achieved at the S-DALINAC. During this machine time four different operation modes where set up to measure beam loading and RF control stability in respect to relative amplitude and phase errors. The RF control system showed comparable results in all four different operation modes which differ in general in the amount of beam loading in the main accelerator.
Additionally a beam induced disturbance was found in the superconducting cavities at 52 Hz. The disturbance is assumed to be approximately proportional to the amount of beam loading. Because of that the origin of the disturbance is presumed to be a modulation with the netfrequency in the electron gun. With the beam loading proportionality the energy recovery efficiency for all main accelerator cavities can be estimated. This is favourable because the efficiency could be measured directly only in the first main accelerator cavity. The approximated value fits the measured efficiency for this case.
For the next ERL beamtimes, a new RF power measurement system was set up to directly measure energy recovery efficiencies via beam loading quantification in all cavities simultaneously. The system was already used as diagnostic tool and is ready for upcoming ERL machine times.

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