FIRST ENERGY RECOVERY OPERATION AT THE S-DALINAC: RF CONTROL STABILITY MEASUREMENTS*

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Abstract

Energy recovery linacs (ERL) are used to overcome the rf power limits of rf amplifiers to further increase beam current at particle accelerators. Since the last major upgrade of the electron accelerator S-DALINAC it can be operated in ERL mode. To demonstrate the capability of a stable operation of the current rf control system during ERL operation, measurements regarding the rf control stability and the demand of rf power were done. This contribution is discussing this measurements and possible improvements for future energy recovery beamtimes.

INTRODUCTION

The recirculating superconducting linear accelerator S-DALINAC is one of the main research instruments at the institute for nuclear physics at the TU Darmstadt (see Fig. 1) [1]. Many improvements were implemented at the S-DALINAC since the first recirculated beam in 1991. One of the major enhancements is the upgrade from a twice to a thrice recirculating scheme in 2015/2016 [2]. With this upgrade the S-DALINAC can provide a beam with the same design energy of up to 130 MeV in cw operation at reduced accelerating gradients by using the main accelerator an additional time. Furthermore an rf phaseshift of the beam of up to 360° can be done due to a path length variation of the arcs in the new second recirculation. A phase shift of 180° changes the operation mode of the S-DALINAC between a conventional accelerating and an ERL mode. ERL operation was not possible when the rf control system for the superconducting structures was set up in 2010 [3]. Therefore it is not optimized for this task. The rf control system had to be tested during ERL operation in order to also demonstrate its capability of this mode.
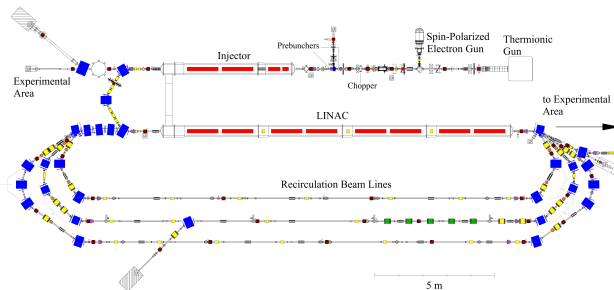

Figure 1: Current layout of the S-DALINAC.

Table 1: Design Specifications for the 20-cell Superconducting Cavities

Parameter	Design value
Material	Niobium, RRR = 280
R/Q	$1995.2\,\Omega/m$
Resonance f_0	$2.997\,GHz$
Unloaded Q_0	3×10^9
Loaded Q_L	variable (typical 3×10^7)
Accelerating E_{acc}	$5\,MV/m$

RF-CONTROL SYSTEM

The current low-level rf (LLRF) control system had to be tested to show its capability in terms of sufficient stability during the new ERL operation. In the following the current setup for LLRF control is briefly described. A design parameter overview of the used superconducting 20-cell structures is given in Table 1.

Hardware

The rf signal proccessing is done analog and digitally by an in-house developed board [3]. The rf signal is analog IQ-demodulated to baseband and for higher precision the amplitude of the rf signal is measured separately by an amplitude detector. Afterwards the analog signals are digitized by 18-bit ADCs with a 1 MS/s sampling rate. The further processing and control is done on an Xilinx Spartan-6 FPGA where a custom digital signal processor is implemented. This digital signal processor executes the control algorithm described in the next section. All data produced during signal processing on the FPGA can be streamed by an USB-2.0 interface at full ADC rate in 8 channels simultaneously. After the digital signal processor the signal is converted back by a DAC and is IQ-modulated to radiofrequency and sent to the cavity.

Control Algorithm

At the S-DALINAC two different control algorithms are used, both controlling the amplitude and phase of the rf signal. The bunching of the continuous beam after the thermionic electron source is done by normal conducting copper cavities with cylindrical geometry. For control of this low Q factor cavities with a resonance bandwidth in the MHz range a generator-driven resonator algorithm is used. The reference master oscillator is used to directly inject the
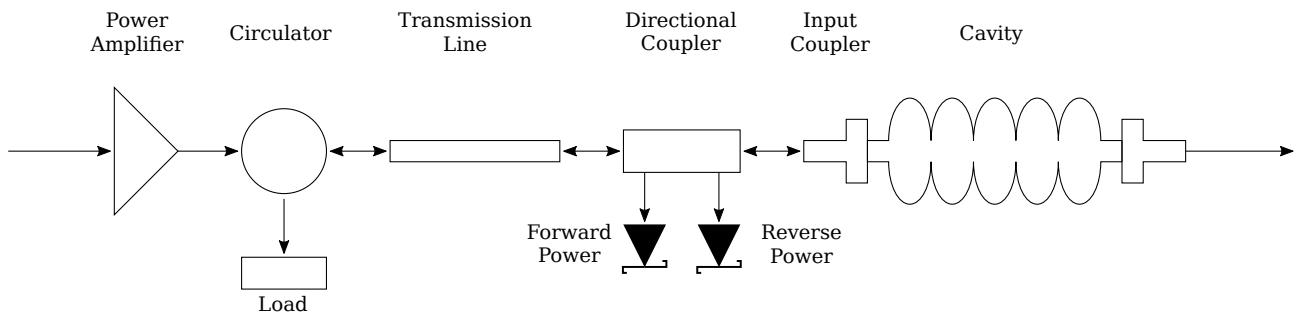
Figure 2: Schematic view of the setup that was used during the ERL operation [4]. By coaxial directional couplers a 40 dB attenuated forward and reverse rf signal was extracted and measured by Schottky diodes. The DC voltage signal after the Schottky diodes was further processed via electronics of the S-DALINAC control system.

signal which is controlled via an electric integral controller to maintain the correct phase and ampltidue setpoints.

The control of the narrow band high Q superconducting cavities used in the injector and main accelerator is done by an algorithm based on a self-excited loop which is phase-locked when phase control is active. To compensate eigenfrequency shifts in the superconducting cavities caused by microphonics, magnetostatic and piezoelectric fine tuner elements are used. The algorithm is using proportional and integral controllers for both amplitude and phase of the signal.

ENERGY RECOVERY LINAC OPERATION

In August 2017 a first once recirculating ERL operation was achieved with a beam current of 1 μA [5]. For comparison of the rf control system stability during ERL operation and commonly used operation modes four different modes were used. During this beamtime several measurements were done regarding rf forward and reverse power and rf control stability. This section covers the rf power measurement at the first main accelerator cavity A1SC01 and rf control stability measurements with A1SC01 as an example.

ERL Introduction

A charged particle beam is accelerated in a rf electric field where the energy gain per cavity pass is given by

$$\Delta W \propto E_0 \cos(\varphi), \tag{1}$$

where E_0 is the amplitude of the electric field and φ is the phase of the particle beam relative to the amplitude. To keep the electric field constant and compensate this energy taken out by the beam from the electric rf field more power has to be sent to the accelerating cavities. This amount of additional power needed is called beam loading. If the particle beam is sent again through the accelerating structure at a 180° shifted phase, the energy gain becomes negative and the beam stores the energy back in the electric field of the cavities. In this case the effective beam loading left is vanishing.

High beam current particle accelerators have a very high beam loading. The beam current itself is limited by the available amount of rf power. One of the ideas using ERL operation is to push the beam current limits because of the very small effective beam loading left.

Power Measurement

The efficiency of an energy recovery operation is a figure of merit for ERLs. It is given by the ratio of the beam loading for a single main accelerator pass to the beam loading during ERL operation. The beam loading can be measured via forward and reverse rf power. The beam loading is in principle given by the difference of both powers. Due to losses in the rf transfer line both powers have an offset without beam loading. This offset is calibrated by measuring both powers without beam where the difference of forward and reverse power is the offset. Considering this offset the beam loading can be measured when beam is on.

During the ERL beamtime the forward and reverse rf power of the first main accelerator cavity A1SC01 was measured. The rest of the cavities could not be measured because no complete power measurement system was existing. For the power measurement 40 dB coaxial directional couplers in the rf transfer line in combination with Schottky diodes (model 423B from Hewlett Packard) were used. The scheme for the setup is shown in Fig. 2. The diodes are transforming the AC signal to a DC signal with a exponential dependence in regard to power. A calibration of the diodes was done beforehand to calculate the power in Watts. The measured forward and reverse powers can be seen in Fig. 3.

RF-Control Stability

The sufficiency of the current LLRF control system had to be demonstrated during ERL operation. Therefore the performance of the control system in conventional operation modes in comparison to ERL operation had to be tested. For better comparability four different operation modes including ERL were used during one run.

During every mode the performance in terms of phase and amplitude stability was measured. Therefore the time series data for phase and amplitude error was measured via datastreaming from the processed signals of the FPGA. This time series were transformed to frequency domain with Fourier transform. The frequency data was additionally
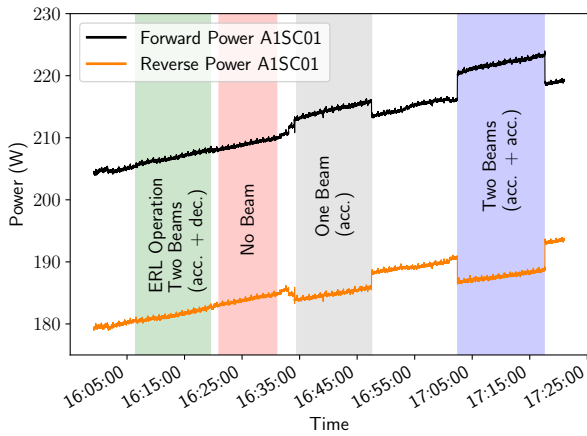
Figure 3: The measured forward and reverse powers of the first main accelerator cavity during the four different operation modes (marked with colored areas) [4]. The beam loading is calculated by the difference of forward and reverse power counting out the offset in the area without beam (red). The increase of both powers over time is dedicated to a heating of the input coupler when the system is not in equilibrium. This powers stay constant when the system is running a certain amount of time.

integrated to better resolve the impact of certain frequencies to rf control. Figure 4 shows the integrated phase and amplitude Fourier spectra of the four different operation modes for the first main accelerator cavity. It can be seen that the performance for all modes is comparable. The errors are dominated by noise. There are two bigger specific disturbance around 50 Hz. One of them is assigned to the beam itself which can be seen especially at the relative amplitude errors during the one beam and two beams mode.

RF POWER MEASUREMENT SYSTEM

During the ERL beamtime the rf power measurement was limited to one cavity because of no dedicated measurement electronics for all cavities. A new rf power measurement system is under development for upcoming beamtimes. The new system will have a wide dynamic range based on the TruPwr^{TM} detector ADL5902 from Analog Devices [6]. A permanent integration to the control system allows to measure and access all cavity powers simultaneously. The beam loading in a cavity depends on the phase of the beam in reference to the accelerating field phase when the beam current is constant according to (1). Therefore via beam loading it is possible to measure the beam phase in reference to the rf phase with the new power measurement system. This can be used to set up the rf phase to on-crest acceleration where the beam loading has its maximum. From on-crest acceleration any other phase can be adjusted. Also rf control schemes based on minimizing the rf forward power could be implemented.
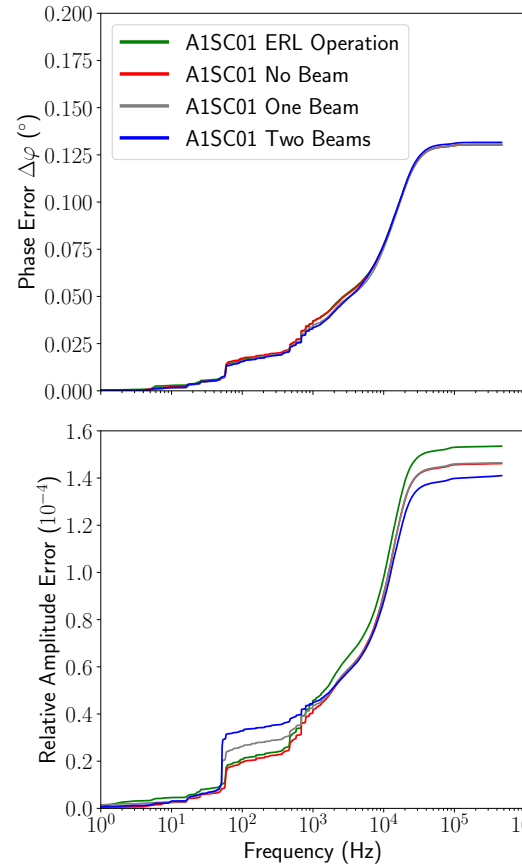

Figure 4: Integrated Fourier spectra of phase and relative amplitude errors of the rf control system during the four different operation modes for the first main accelerator cavity A1SC01 [4]. The total rms errors are corresponding to the maximum values. The similarity of the different spectra curves and maximum values shows that the stability of the rf control system is sufficient to be operated in energy recovery mode at 1 μA beam current.

SUMMARY

In August 2017 the first successful ERL beamtime was achieved. During this beamtime several measurements were done. Investigations regarding rf control stability and rf power consumption were conducted. A sufficient stability of the rf control system was demonstrated with a 1 μA beam current. The behaviour of the rf during ERL mode was comparable to an operation without beam.

An rf power measurement system to measure all cavity powers simultaneously is in development because the power measurement was limited to one cavity during ERL beamtime. Upcoming beamtimes will show the total efficiency of ERL operation.

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