CHALLENGES OF A STABLE ERL OPERATION CONCERNING THE DIGITAL RF CONTROL SYSTEM OF THE S-DALINAC*

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Abstract

The recent upgrade of the S-DALINAC makes it possible to use the S-DALINAC as an ERL. The RF control system is an important part for a stable ERL operation. The current digital Low-Level RF control system is not optimized for this task.

This contribution describes the current RF control system and challenges for an upcoming ERL operation. Considerations of microphonics compensation are made. Requirements for the minimum RF power of the RF amplifiers counting in microphonic detuning and beam loading are presented.

INTRODUCTION

The S-DALINAC is a superconducting electron linear accelerator with a triple recirculating scheme at the institute for nuclear physics at TU Darmstadt (see Fig. 1) [1]. It serves as a large scale research device to investigate nuclear structure physics and is operated since 1991. The design values of the beam are a total energy of 130 MeV at a maximum current of 20 µA. The accelerator is operated in continuous wave mode at a frequency of 3 GHz. As electron sources there are a thermionic and a spin polarized photo source available. The accelerator consists of a copper based chopping and prebunching system, an up to 10 MeV superconducting injector and an up to 30 MeV superconducting main linac.

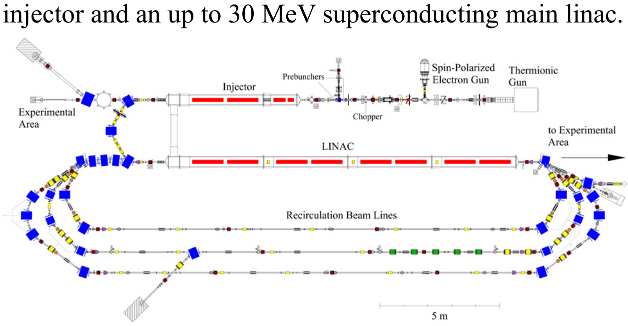

Figure 1: Floorplan of the triple recirculating S-DALINAC.

The injector consists of a 2-cell, a 5-cell and two 20-cell and the main linac of eight 20-cell niobium cavities. They are located in a liquid helium bath at a temperature of 2 K to maintain the superconducting state of the cavities. The specifications of the 20-cell cavities are listed in Table 1 and a photograph is shown in Fig. 2.

Optimizations of these structures in regard to *Higher Order Mode* (HOM) suppression have never been done and in addition to that most HOMs are expected to be located in the middle of the 20-cell structures.

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Table 1: 20-cell Cavity Specifications

Parameter	Design value
Material	Niobium, RRR = 280
f_0	2997.1 MHz
E_{peak}	5 MV/m
Q_0	3×10^9
Q_L	variable (3×10^7 typically)
R/Q	1995.2 Ω/m

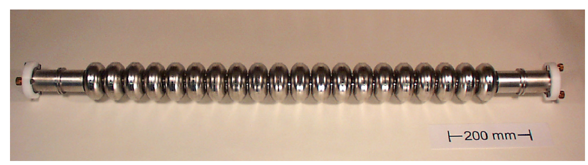

Figure 2: 20-cell niobium cavity.

The cavities are designed to maintain an electric field of 5 MV/m. Waveguides and coaxial input couplers are used for transfering the power into the cavities. The power is fed by cutoff coupling. The coupling of the input coupler can be changed by adjusting the penetration depth of the antenna (see Fig. 3).

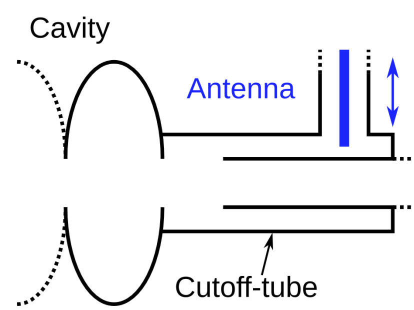

Figure 3: Cutoff coupling scheme with variable coupling.

The three recirculation beam lines can be used to let the electron beam pass the main linac up to four times. After the installation of a third recirculation in 2016 the S-DALINAC can be operated as an *Energy Recovery Linac* (ERL) [2] which makes it an appealing object for accelerator science.

ENERGY RECOVERY LINAC

The new recirculation beamline provides a 0°–360° phaseshift of the beam through adjustment of the pathlength by maneuverable bending magnets in the recirculation arcs. Therefore it is possible to use the S-DALINAC for an ERL operation in a once recirculating

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scheme. Calculations for a twice recirulating ERL scheme are under investigation.

For the one time recirculating ERL mode only the new second recirculation beamline is used. After leaving the injector the beam is accelerated in the main accelerator and subsequently led to the recirculation where the phase of the electron bunches is shifted by 180° relative to the accelerating RF. The beam is then decelerated to injection energy during the second passage through the main accelerator and dumped in a dedicated ERL cup.

One option during ERL operation at the S-DALINAC is to study *Beam Break Up* (BBU) [3] which is caused by HOM excitation in the cavities. At the S-DALINAC BBU occurs already at currents in the order of few µA. The risk of damaging parts of the accelerator during BBU study is negligible due to the low currents and therefore the S-DALINAC is a good research instrument to investigate BBU. The goal is to study and improve methods that increase the BBU threshold current during ERL operation.

LOW-LEVEL RF

Electron scattering experiments require a high precision in terms of energy resolution. At the S-DALINAC a relative energy spread in the order of $\Delta E/E \approx 1\times10^{-4}$ has been demonstrated. To achieve this the amplitude and phase of the superconducting cavities have to be controlled and stabilized. A corresponding digital *Low-Level RF* (LLRF) system has been developed in-house [4]. It consists of a controller board containing an FPGA and a separate RF module (see Fig. 4). For phase and amplitude control fast electric actuators and for control of the eigenfrequency of the cavities slow magnetostatic and piezoelectric tuners are used.

Figure 4: FPGA board containing the RF module and the baseband signal processing components.

The RF module transforms the RF signal to the baseband via analog quadrature amplitude (de)modulation. In addition the amplitude of the signal is measured with a dedicated detector for higher accuracy. After the demodulation the signal is digitized by an 18 bit ADC with a sampling rate of 1 MS/s. The control algorithm itself is realized on the FPGA. The algorithm for the superconducting cavities is based on the principle of a self-exited loop. After the signal modification in the FPGA the signal is converted back to analog by a DAC. Subsequently it is modulated and sent to the amplifiers.

For slow control a mirco-controller with CAN bus interface provides access to FPGA registers. Through an additional USB interface the data of 8 channels can be streamed simultaneously out at the full sampling rate.

CONSIDERATIONS FOR AN ERL OPERATION

Some important factors need to be considered for an optimized ERL operation. High energy and high current ERLs require a good suppression of HOMs and minimization of microphonics. Beam loading has to be taken into account in addition [5]. The phaseshifted accelerated and decelerated beams contribute to beam loading in an ERL. The beam loading of both beams should cancel out if the phaseshift amounts to 180° due to the superposition. A varying phaseshift around these 180° leads to a varying beam loading.

It is possible that the beam spectrum frequency matches with a HOM and a resonant excitation occurs. The power stored in this HOM is $P_{HOM}=2Q_L(R/Q)I_b^2$ with I_b being the beam current. This power can be very large for high currents depending on the quality factor of this HOM. This leads to higher forward power of the power generator and higher beam instability up to BBU. No HOM couplers are used at the S-DALINAC and they cannot be integrated subsequently due to the design of the cryostats. But the S-DALINAC is operated at low currents and therefore the stored power in the HOMs is low.

Microphonics is caused by external vibrations and fluctuations. It results in deformation of an RF cavity and therefore in a time-dependent detuning of it. Sources for this are liquid helium pressure fluctuations or vibrations of the turbomolecular pumps at the cryostats. Spectra of the microphonics at the S-DALINAC are displayed in Fig. 5.

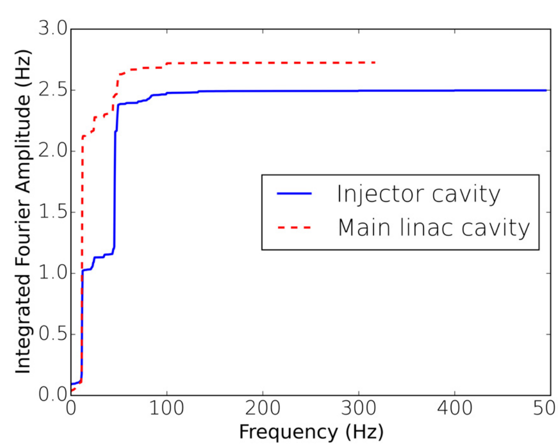

Figure 5: Integrated microphonics spectra of an injector and a main linac cavity at the S-DALINAC. Data from [6].

The predominant contribution to microphonics occurs below 500 Hz. The typical rms detuning is at about

(2.5 – 2.75) Hz. The microphonics peak detuning is often estimated as 6σ of the rms microphonics detuning [7]. This leads to a peak detuning of about 16.5 Hz for the S-DALINAC.

The RF power which is required to maintain an accelerating voltage V_a in the cavity considering only the detuning by microphonics is given by [8]

$$P_g = \frac{V_a^2}{4 \cdot R/Q \cdot Q_0} \frac{(\beta+1)^2}{\beta} \left\{ 1 + \frac{Q_0^2}{(\beta+1)^2} \left(2 \cdot \frac{\Delta\omega}{\omega_c} + \frac{I_b \cdot R/Q}{V_a} \cdot \Delta\phi \right)^2 \right\}. \quad (1)$$

In Eq. (1) $\Delta\omega = \omega_c - \omega$ stands for the cavity peak detuning by microphonics, β for the coupling factor and I_b for the beam current. $\Delta\phi$ describes an additional phase-variation of the accelerated and decelerated beams differing normally by 180° in phase. Beam loading is taken into account by this phase-variation. If $\Delta\phi=0$ the beam loading effects of the accelerated beam and the decelerated beam cancel. In Fig. 6 the required RF power is illustrated for the S-DALINAC at a beam current of 20 µA. It can be seen that the varying beam loading is neglectible at the S-DALINAC due to the low beam currents.

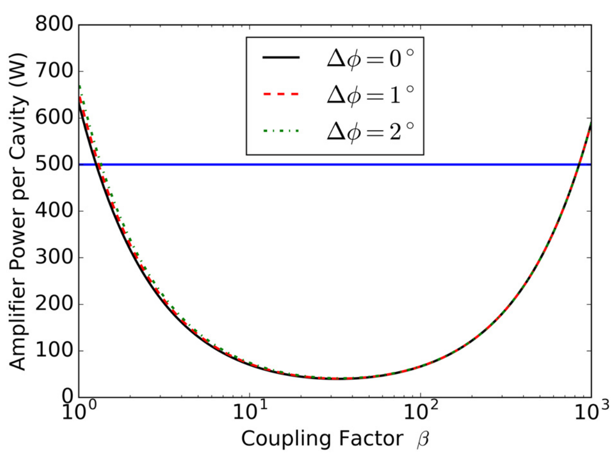

Figure 6: Calculated RF power required for an accelerating field gradient of 3.75 MV/m in a 20-cell cavity for a beam current of 20 µA. The horizontal line indicates the maximum possible output power of the RF power amplifier at the S-DALINAC.

The goal is to minimize the required forward RF power. This can be done by adjusting the coupling factor β. In the following $Q_L=Q_0/(1+\beta)$ is used. The optimum coupling factor using Eq. (1) is given by

$$\beta_{min} = \sqrt{1 + Q_0^2 \cdot \left(2 \cdot \frac{\Delta\omega}{\omega_c} + \frac{R/Q \cdot I_b}{V_a} \cdot \Delta\phi \right)^2}. \quad (2)$$

which leads to a minimum at $\beta=33.3$, $Q_L=9.0\times10^7$ and a power of 40.3 W if $\Delta\phi=1°$ is assumed. The amplifier forward power of 40.3 W is well below the maximum power of 500 W. The phaseshift of the two beams is adjusted by variation of the pathlength. For that purpose the magnets of the recirculation arcs are mounted on maneuverable tables and change the pathlength precisely. The phase is measured by RF monitors with a resolution below 0.1°. So for $\Delta\phi$ values near 0° are expected because it should be well adjustable. For the case of $\Delta\phi=0°$ the minimum is at $Q_L=9.2\times10^7$ and at a power of 39.7 W.

The current LLRF control system usually operates at about $Q_L=3\times10^7$. At higher Q_L the stability decreases. Therefore the operation at higher Q_L has to be investigated to find a good compromise between stability and manageable RF amplifier forward power for the S-DALINAC.

SUMMARY & OUTLOOK

The new possible ERL operation at the S-DALINAC brings new requirements for the RF control system which is not optimized for this task yet. Good supression of mircophonics and HOM damping are important. HOM damping is not used at the S-DALINAC due to the design of the cryostats and it cannot be integrated subsequently. Microphonic peak detuning about 16.5 Hz should lead to manageable forward power for a 20 µA beam.

The current RF control system has to be optimized to achieve a stable ERL operation at the S-DALINAC for higher Q_L. Investigations of the LLRF up to $Q_L=1\times10^8$ are pending.

REFERENCES

[1] A. Richter, *"Operational experience at the S-DALINAC"*, in *Proc. EPAC'96*, Sitges, Spain, June 1996, pp. 110-114.

[2] M. Arnold, "Construction and Status of the Thrice Recirculating S-DALINAC", presented at IPAC'17, Copenhagen, Denmark, May 2017, paper TUPAB030, this conference.

[3] T. Kürzeder *et al., "Investigations on transverse beam break up using a recirculated electron beam"*, in *Proc. ERL'15*, Stony Brook, USA, June 2015, paper TUICLH2032 , pp. 30-33.

[4] M. Konrad *et al.*, "Digital base-band rf control system for the superconducting Darmstadt electron linear accelerator", *Phys. Rev. ST Accel. Beams*, vol. 15, p. 052802, 2012.

[5] M. Liepe and J. Knobloch, "Superconducting RF for energy-recovery linacs", *Nucl. Instrum. Methods Phys. Res. Sect. A*, vol. 557, pp. 354-369, 2006.

[6] M. Konrad, "*Implementation of basic control algorithms for the digital rf control system at the S-DALINAC*", diploma thesis, Phys. Dept., Institut für Kernphysik, TU Darmstadt, Darmstadt, Germany, 2008, unpublished.

[7] M. K. Kelly *et al.*, *"Microphonics measurements in SRF cavities for RIA"*, in *Proc. PAC'03*, Portland, Oregon, USA, May 2003, paper TPAB043, pp. 1291- 1293.

[8] G. H. Hoffstaetter *et al.*, *"Cornell Energy Recovery Linac Project Definition Design Report"*, Cornell University, Ithaca, New York, USA, Rep. Cornell ERL PDDR, June 2013.

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