A DIGITAL LOW LEVEL RF CONTROL SYSTEM FOR THE S-DALINAC*

U. Bonnes, C. Burandt, R. Eichhorn, M. Konrad†, N. Pietralla, TU Darmstadt, Darmstadt, Germany

Abstract

The superconducting cavities of the S-DALINAC have a high loaded quality factor and are very susceptible to microphonics. To stabilize the amplitude and phase of the cavities' fields an analog control system has been used for 20 years [1]. To improve the stability and the availability of the low level RF control system it is currently replaced with a digital one. The 3 GHz signals coming from the cavities are converted down to the base band using hardware I/Q demodulators. The base band signals are digitized by ADCs and fed into an FPGA which executes the code implementing the control algorithm. The computed control signal is I/Q modulated before it is send to the cavity again. The superconducting cavities are operated with a self-excited loop algorithm whereas a generator driven algorithm is used for the low Q room temperature bunching cavities. Additionally, a 6 GHz RF board allows the operation of a new $2f$ buncher. Parameters can be adjusted via an EPICS IOC running on a standard PC. All signals from the FPGA can be monitored in real-time by the operator.

INTRODUCTION

The S-DALINAC is an 130 MeV recirculating electron linac that is operated in cw mode. It uses superconducting niobium cavities at 2 K with a loaded Q of $3 \cdot 10^7$ for acceleration. Because of their 20 cell design and the high operating frequency of 3 GHz they are very susceptible for microphonics. In addition, superconducting 2 and 5 cell capture cavities, one of them providing a lower β, are used in the injector.

Furthermore, room temperature chopper and buncher cavities are operated. Currently, a new polarized electron injector is assembled in the accelerator hall [2]. Its bunching system consists of a chopper cavity and a 3 GHz as well as a 6 GHz harmonic buncher. This means that the RF control system has to deal with different Q_Ls from some 5000 to $3 \cdot 10^7$ as well as with different operating frequencies.

HARDWARE

The RF control system converts the RF signals down to the base band. This allows to split the hardware into two parts: A frequency dependent RF board containing the I/Q (de)modulator and a frequency independent FPGA board processing the signals. A separate power detector improves the accuracy of the magnitude measurement.

The current revision of the FPGA board evolved from prototypes described in [3] and [4]. It contains redesigned analog anti-aliasing filters with a cut-off frequency of 100 kHz to filter out the $19/20\,\pi$ mode of our cavities which is only 700 kHz away from the π mode used for acceleration.

In addition to the existing 3 GHz RF board a new one for 6 GHz has been successfully tested with the new $2f$ buncher cavity.

CONTROL ALGORITHMS

For the high Q superconducting cavities a Self-Excited Loop (SEL) algorithm is used whereas for the copper cavities the much simpler Generator Driven Resonator (GDR) algorithm is sufficient.

The advantage of the SEL is that it immediately excites the cavity although the cavity's eigenfrequency might be detuned by many band widths, away from the master oscillator. Furthermore the controller can recover from a breakdown even in the presence of (static) Lorentz force detuning that might prevent a GDR from restarting oscillation.

Generator Driven Resonator

Fig. 1 shows a block diagram of the GDR algorithm as it is used for our copper cavities. The I and Q input signals are transformed into polar coordinates and back to Cartesian coordinates in the FPGA by the CORDIC algorithm [5].

After conversion to polar coordinates the phase controller consists only of an integral controller. The integral part is necessary to eliminate steady-state offsets. Since there are no fast disturbances but only slow drifts mainly caused by thermal fluctuations no proportional controller is needed for these cavities.

The magnitude controller follows a similar design but one has to avoid negative magnitude values fed into the output CORDIC which would cause ambiguities.

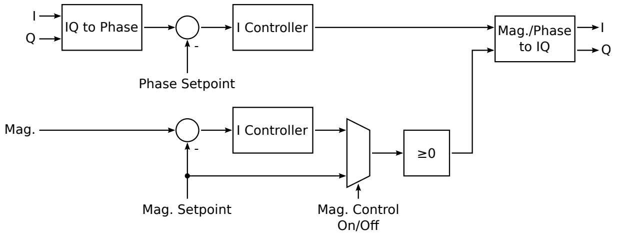

Figure 1: Block diagram of the GDR algorithm.

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† konrad@ikp.tu-darmstadt.de

A multiplexer allows to switch between the following modes of operation:

1. Constant output magnitude: In this mode only the phase controller is active and output magnitude can be adjusted by the operator directly.
2. Magnitude control switched on: In this mode the operator sets the desired magnitude and phase values.
3. SSB sine modulation: This mode is used to generate a single side band signal of 1 kHz for calibration of the modulator.

Self-Excited Loop

Fig. 2 shows a block diagram of the SEL algorithm. Like in the GDR algorithm the I and Q signals are transformed into polar coordinates using the CORDIC algorithm. Polar coordinates allow different controllers and parameters for magnitude and phase which is not possible if the controller operates in I/Q coordinates.

Instead of an actuator that simply shifts the phase a microphonics compensator [6] is used. This block adds an orthogonal correction vector to the input vector. If the length of this correction vector is proportional to the phase error the microphonics compensator has the inverse transfer function of the resonator. Thus phase and magnitude errors which always occur correlated if they are caused by detuning of the cavity are corrected in a single step.

The microphonics compensator is used as an actuator for a proportional controller. An integral controller driving the tuner eliminates the steady-state offset by keeping the resonator on the reference frequency. The time constant of the tuner controller has to be at least $1\,\mathrm{s}$ to avoid excitation of mechanical eigenmodes of the cavity.

The following modes of operation are possible:

1. Constant output magnitude: The control system acts as a limiter. The phase is passed through unmodified. This mode is used to test if the SEL oscillates freely (no self-locking).
2. Microphonics compensation: The microphonics compensator is switched on while the output magnitude is otherwise kept constant.
3. Microphonics compensation and tuner control: Like 2 but the cavity is tuned to the reference frequency automatically.
4. Microphonics compensation, magnitude and tuner control: Like 3 but with magnitude controller activated. This mode is used for accelerator operation.
5. SSB sine modulation: This mode is used to generate a single side band signal of 1 kHz for calibration of the modulator.

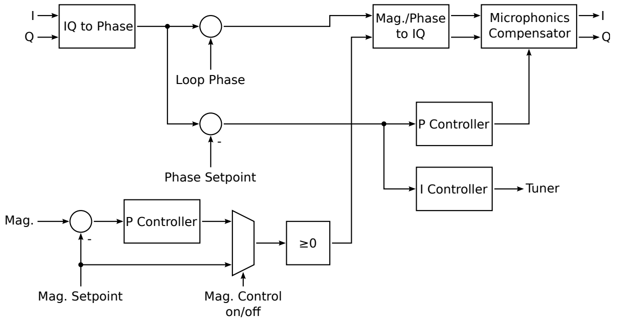


Figure 2: Block diagram of the SEL algorithm.

CONTROL SYSTEM

The FPGA board is connected to a standard PC server via CAN bus for slow control. All parameters of the RF control system can be changed by the operator via a graphical user interface implemented with Control System Studio which communicates with an EPICS IOC running on the server. The power supplies used for the magnetostrictive fine tuners and the motor tuners are controlled via CAN bus directly by the FPGA board. The server is only used for monitoring.

A USB 2.0 interface allows streaming of diagnostic data to the server. This enables the operator to monitor all signals from inside the FPGA including all intermediary results of the signal processing. Up to 8 channels can be transmitted to the PC at once with the ADC's full sampling rate of 1 MS/s.

The server distributes the signals to several clients via network. In addition to a simple data acquisition program client software used along with the server includes a software oscilloscope and a software spectrum analyzer.

TESTS AND MEASUREMENTS

Generator Driven Resonator

The GDR algorithm has been tested with different copper cavities. Typical values achieved with the new 3 GHz chopper cavity are a phase error of $0.076\,^\circ\,\mathrm{rms}$ and a relative error in magnitude of $1.37 \cdot 10^{-4}\,\mathrm{rms}$. These errors meet the specification. Further analysis in the frequency domain showed that most of the error is caused by a single frequency of 25 kHz which is the clock rate of the ADCs. leaving some playground for future improvements.

Self-Excited Loop

The SEL algorithm was tested with a cavity mounted in the cryo-module of the S-DALINAC. Fig. 3 shows the phase error during SEL operation while all controllers are switched off (operation mode 1). The signal is a superposition of several sinusoidal-like oscillations of different frequencies. The total magnitude of the phase fluctuations is $4.4\,^\circ\,\mathrm{rms}$. The integrated phase spectrum (see Fig. 4(a)) shows that almost all measured microphonics occur at frequencies below 100 Hz. Fig. 4(b) shows the same spectrum for a cavity with the RF control system activated (operation

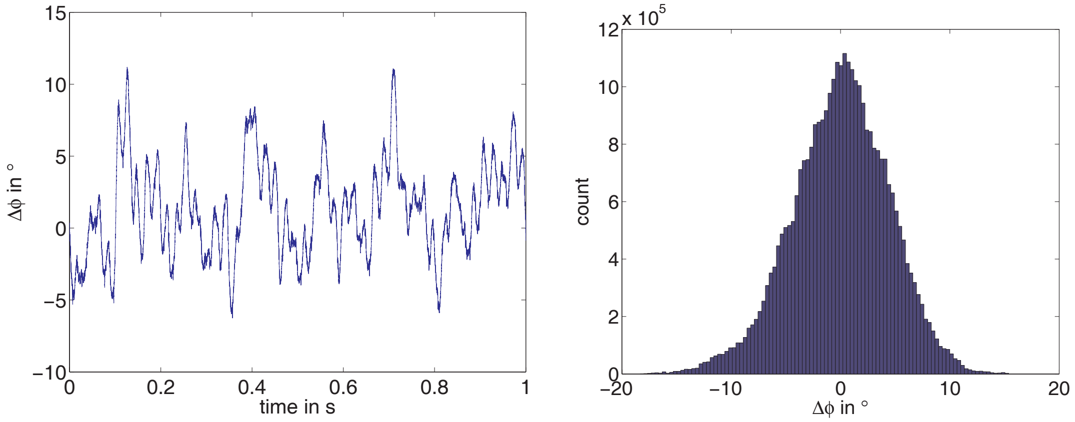
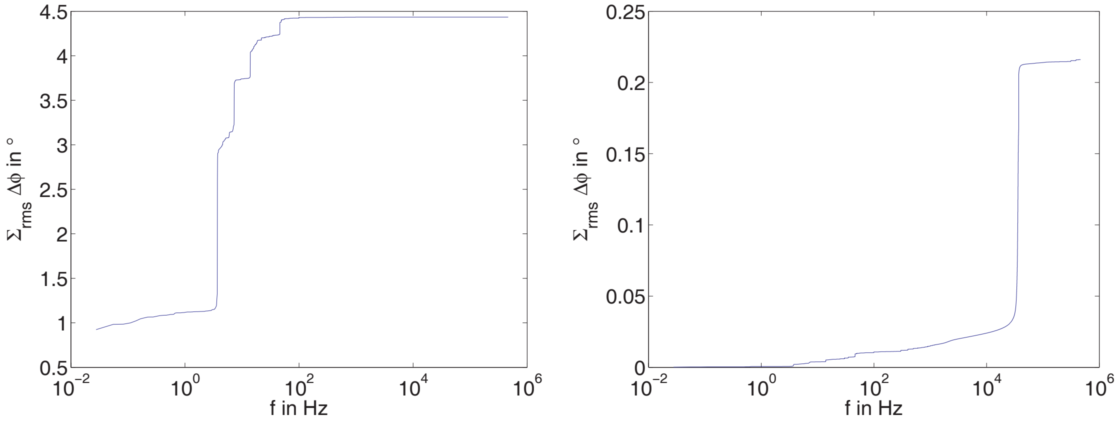


Figure 3: Phase error of a freely oscillating superconducting cavity in SEL mode. Sinusoidal-like structures of several frequencies are superposed resulting in a nearly Gaussian distribution of the phase error.



(a) Phase controller deactivated.

(b) Phase controller activated.

Figure 4: Integrated amplitude spectra of phase error of the SEL.

mode 3). The total phase error is now reduced to $0.22\,^\circ\,\mathrm{rms}$ which is better than our target specification of $0.7\,^\circ\,\mathrm{rms}$. On the contrary the total amplitude error of $6.6 \cdot 10^{-4}\,\mathrm{rms}$ is 8 times higher than the specification of $8 \cdot 10^{-5}\,\mathrm{rms}$. These are only first results measured recently. Investigation and improvements still go on. The amplitude error might be reduced by applying magnitude control to the compensated SEL by switching to operation mode 4.

SUMMARY

Hardware, control algorithms and control system integration have made good progress. First tests with the GDR and SEL algorithms are promising but the high magnitude error needs further investigation. The handling by the operator has been improved significantly by the extended diagnostic features. By now the new system is much more reliable than the existing analog system. That is why it is planned to put the new system into operation by the end of this year.

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