DEVELOPMENT OF A NEW LOW-LEVEL RF-CONTROL-SYSTEM FOR THE S-DALINAC*

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Abstract

The Superconducting DArmstadt electron LINear ACcelerator S-DALINAC has a maximum energy of 130 MeV and beam currents of up to 60 µA. To reach this energy conveniently in cw, superconducting cavities with a high Q at a frequency of 3 GHz are used. In order to achieve a minimum energy spread, the amplitude and phase of the cavities have to be controlled strictly in order to compensate the impact of microphonic perturbations. The existing analog rf control system based on a self exited loop, converts the 3 GHz signals down to the base band. This concept will also be followed by the new digital system currently under design. It is based on an FPGA in the low frequency part, giving a great flexibility in the control algorithm and providing additional diagnostics. We will report on the design concept, the status and the latest results measured with a prototype.

INTRODUCTION

The Superconducting DArmstadt electron LINear ACcelerator S-DALINAC [1] is used as a source for astro- and nuclear physical experiments since 15 years and is currently the central instrument of the SFB 634 of the Deutsche Forschungsgemeinschaft (DFG).

The layout of the S-DALINAC is shown in Fig. 1. Its rf-system consists of twelve 20 cell, one 5 cell and one 2 cell superconducting (sc) cavities, operating at 2 K at a frequency of 3 GHz. The design accelerating gradient of the cavities is 5 MV/m at a quality factor of $3 \cdot 10^9$. The final energy of 130 MeV can be reached when the beam is recirculated twice.

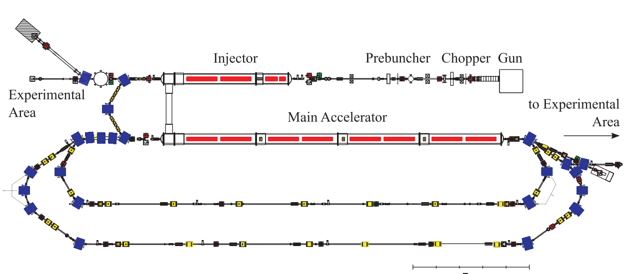

Figure 1: Floor plan of the S-DALINAC.

MOTIVATION

In principle, sc cavities are more sensitive against perturbations than normal conducting cavities, even when strongly coupled. The loaded quality factor of $3 \cdot 10^7$ typically maintained leads to a resonance width of some 100 Hz. The main perturbations are caused by microphonics, having frequencies from a few Hz up to some kHz. Another source of perturbation is pressure variation in the helium bath, which influences the cavity frequency in periods of seconds and minutes. These perturbations have to be compensated by the low-level rf control system. Ensuring an optimum energy resolution of the accelerated beam ($\pm 1 \cdot 10^{-4}$) in the experimental areas, the specifications given in Table 1 have to be met.

Table 1: Stability specifications

Relative amplitude stability	$\Delta E/E$	$\pm 8 \cdot 10^{-5}$
Phase stability	$\Delta\varphi$	$\pm 0.7°$

CONTROL LOOP

Fig. 2 shows a simplified Self Excited Loop (SEL) [2, 3]: The signal from the cavity is split to analyze the phase and the amplitude, giving correction signals for the modulators. The main signal path from the cavity goes to a phase shifter and a limiter before it is modulated with the correction signals which, after amplification, drive the cavity. With a SEL, the cavity starts to oscillate by itself from noise, even when the resonator frequency does not match to the generator frequency. Only two constraints apply: The loop phase must be a multiple of 2π and the loop gain must be greater than 1.

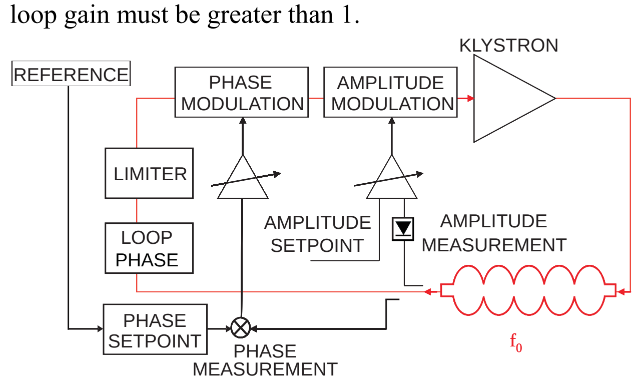

Figure 2: Self Excited Loop diagram.

The amplitude modulation can be done by a simple proportional controller. In contrast, the phase has to be controlled using a Complex Phase Modulator (CPM) [4], which works by adding a small orthogonal vector to the loop vector. This CPM has the inverse transfer function of the cavity and thus decouples the amplitude and phase characteristics of the control loop.

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PRESENT RF CONTROL SYSTEM

The present rf control system was designed in the late 1980s. At that time, the commercial use of wireless communication standards was not yet developed. The high frequency circuits needed for the 3 GHz modulation were difficult to find and highly integrated circuits were not yet developed. Therefore, the I/Q-modulator and demodulator of the loops were built using unbalanced mixers and microstrip lines. The 3 GHz signals were demodulated to the base band, the low frequency signals gained from this modulation could be manipulated and controlled with analog feedback control circuits before the new signals were modulated onto the 3 GHz carrier frequency again. The amplitude and phase controller were operated as proportional controllers. The whole system led to an energy spread of the electron beam of typically $\pm 5 \cdot 10^{-4}$.

During the last years, aging of the circuits could be observed, resulting in energy drifts within several hours. Furthermore, the reliability decreased and maintaining operation of the circuits required more and more efforts. On the other hand, future experiments at the S-DALINAC put more demanding constraint on the rf-control-system, which could not be met by the old system. As a consequence, the design of a new control system was triggered, making use of modern components offering better performance.

DIGITAL CONTROL SYSTEM

Advantages

Following the main stream in rf control system design, the advantages of a digital solutions based on FPGAs or DSPs were investigated. One of the most important features of a digital solution is its great flexibility. Once the hardware is designed, it is possible to analyze every signal (with analog and digital diagnostic channels), the algorithm can be changed easily and more complex control loops can be realized.

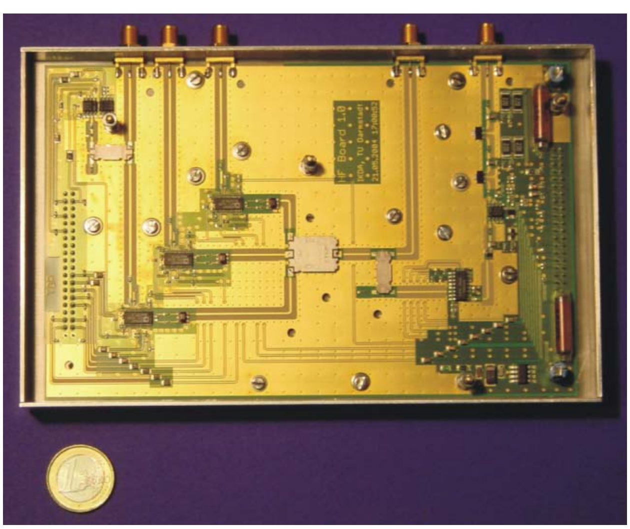

Figure 3: Picture of the new rf-boards.

Prototype Layout

Even today it is not possible to digitize and process the 3 GHz signals from the cavities directly. In contrast to the design elsewhere [5], the signals are demodulated to the baseband as in our old system. Therefore, a new rf-board was developed (shown in Fig. 3) using commercial available wifi components. The rf board delivers an amplitude signal as well as I/Q signals which somehow is redundant but was required by the design constraints.

The low-frequency signals from the rf-board are transmitted as analog signals to the FPGA-board, shown in Fig. 4, where they are digitized with a rate of 1 M samples per second.

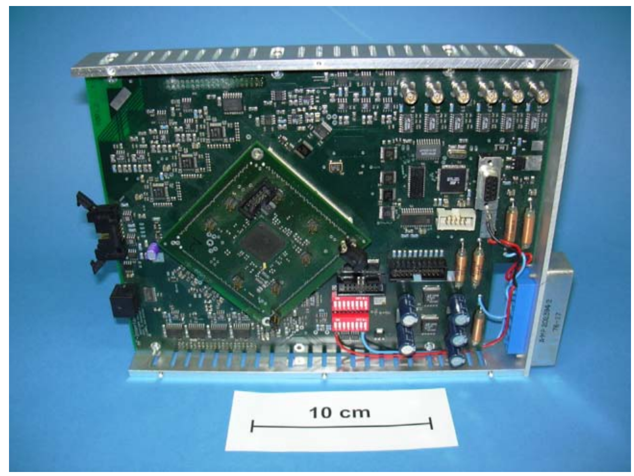

Figure 4: Picture of the FPGA-boards prototype.

First Operation

The FPGA was programmed with an algorithm analog to the existing rf control loops (show in Fig. 2) to allow a direct comparison. The rf module was carefully calibrated ensuring optimum signal levels. The parameters of the control algorithm (e.g. gains of the amplitude and phase loop, the overall loop gain, set-points and loop phase) were set consecutive via an USB interface. Some of the parameters were quite crucial and missetting led to strange behavior.

During the processing of the data inside the FPGA it was possible to read out several diagnostic signals. Especially to detect bit shifting errors and clipping effects this was of particular benefit.

Calibrating, programming the FPGA (using VERILOG) and finding adequate control parameters took several months. Finally, during an injector run of the accelerator, the control loop operated on a cavity in the main linac successfully.

Performance

The performance of the new control loop was measured with a setup shown in Fig. 5. To have independent

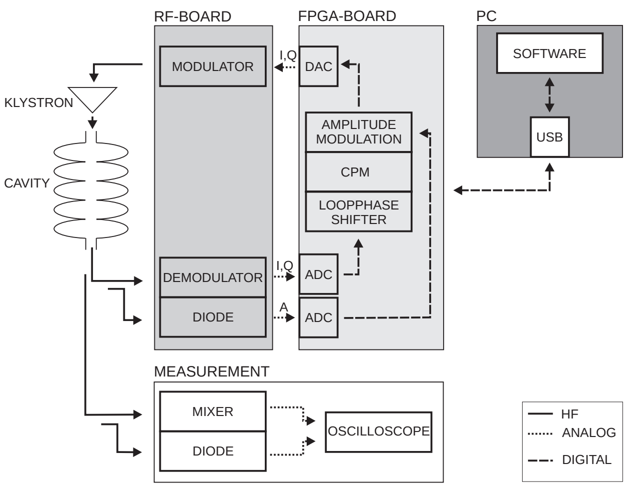

Figure 5: Measurement setup.

diagnostics, the amplitude and phase detection was done on a separate board (not using the control loop signals). The phase was measured with a mixer while a rf diode was used to detect the amplitude. These signals were digitized with a high resolution oscilloscope.

The new control loop drove a standard 20 cell cavity, the amplitude was set to 4 MV/m , the loaded quality factor was some $3 \cdot 10^7$. During the test, a beam current of 30 µA was accelerated leading to a typical operation situation. Locking phase and amplitude of the cavity was easy and convenient when compared to our old control loops.

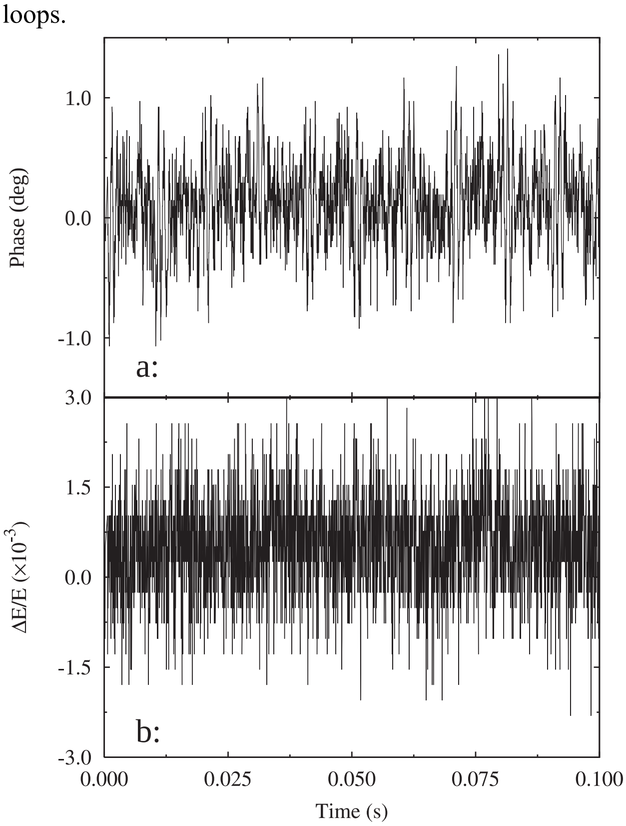

Figure 6: Phase (a) and amplitude error (b) of the digital control-system.

Fig. 6 now gives the measured control quality of the new loop: During this first test, the phase could be stabilized to about 0.5° (rms value), fulfilling the specifications. Unfortunately, the amplitude error measured is of the same order as in our analog system. Only $1.5 \cdot 10^{-3}$ was achieved being beyond the requirements.

CONCLUSIONS

So far, two conclusions can be drawn. During its first operation, the digital control loop was able to lock the phase and the amplitude of our superconducting cavity while accelerating a beam. The accuracy of the phase control was as expected; the amplitude error is roughly one order of magnitude higher than envisaged. However, the digital control loop reached the performance of the existing analog loops easily.

Nevertheless, the designated performance, esp. the required amplitude stability was not reached. There are clear measures for improvements:

- The prototype control circuit was reworked many times; some rf connections became bad. Therefore, a slightly modified board is currently set-up.
- The rf part was not fully shielded, the FPGA board was not shielded at all but both were operated close to other rf sources. Consequently, efficient shielding will be an issue.
- The algorithm used was of a simple proportional type. Having now a flexible system allows algorithm improvements being the main focus of the ongoing efforts.

Currently, new versions of both boards are under construction and will be available in autumn this year. These boards will form a scalable system which is required to operate all 15 control loops in parallel. With the necessary modifications in the control system and the user interface, the system is expected to be operational in summer 2009.

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