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# SLOW-CONTROL LOOP TO STABILIZE THE RF POWER OF THE FLUTE ELECTRON GUN

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*Abstract*

The linear accelerator FLUTE (Far Infrared Linac and Test Experiment) at KIT serves as a test facility for accelerator research and for the generation of ultra-intense coherent THz radiation.

To achieve stable THz photon energy and optimal beam trajectory, the energy of the electrons emitted from the RF photo-injector must be stable. The accelerating voltage of the RF cavity has been shown to be a significant influencing factor. Here, we report on the development of a slow closed-loop feedback system to stabilize the RF power and thus the accelerating voltage in the RF photo-injector cavity. With this closed-loop feedback system the relative standard deviation of the RF power in the cavity can be improved by 8.5 %.

## INTRODUCTION

At FLUTE, the electron bunches are created and pre-accelerated to 7 MeV in the low-energy section, before being accelerated to 41 MeV by a traveling wave LINAC structure [1–3] (see Fig. 1).

The electron gun of the injector is of the RF photo injector type (see [4]) that uses a copper cathode where electrons are released when struck by UV laser pulses and a 2.5 cell standing wave RF cavity driven by a 2.9979 GHz low-level RF (LLRF) system, which currently does not correct for long-time drifts. Both for guidance along the beam pipe and scientific experiments, the electron energy is a key figure of the accelerator. To ensure proper operation it has to be kept constant over long periods of time (up to hours).

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As the RF-induced *E*-field in the RF cavity has major influence on the electron energy, it has to be kept stable to achieve stable electron emission. Simulations showed the relative standard deviation of the RF power has to be less than 0.01 %. When measured with a pick-up inside one of the cavity cells for every pulse of the LLRF, apart from variations from one shot to another there are also slower disturbances of varying period and an even slower drift, see Fig. 2. Some sources of these slow variations have been identified in the past to be due to the power grid, the influence of which has already been mitigated in [5]. Other disturbances mainly originate from drifts of temperature or other parameters. These effects are hard to predict and to model.

Because of that, the slow-control approach described here needs no model or a-priori knowledge about the disturbances.

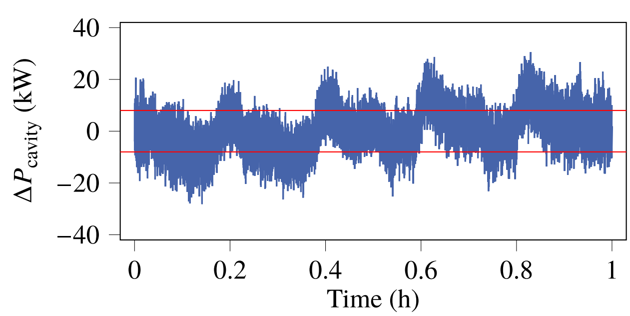


Figure 2: Deviation of the RF power as measured in the cavity from the target power $P_{\text{cavity}} = 9.5$ MW; required maximum standard deviation in red.

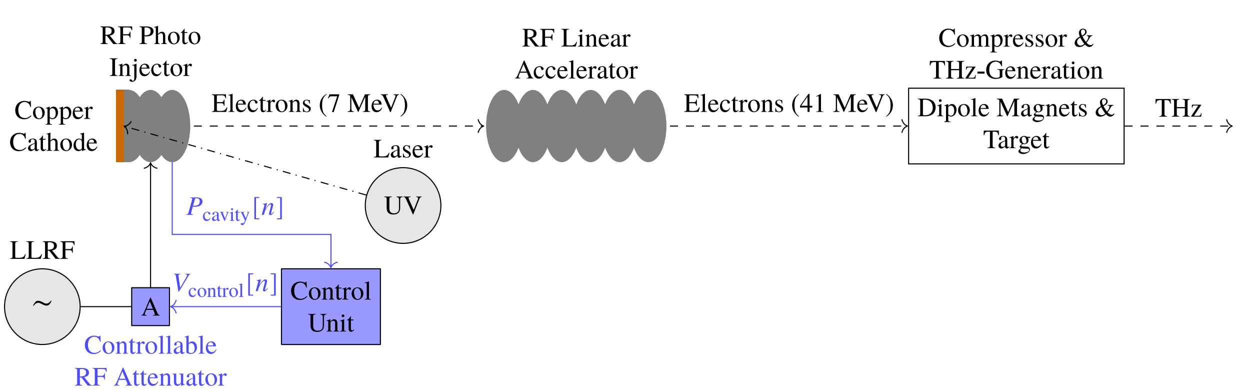


Figure 1: Simplified FLUTE architecture; components of the control system proposed here highlighted in blue (adapted from [1]).

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## ARCHITECTURE

The electron gun is driven by the LLRF, a power amplifier and a klystron. To be able to control the RF power to the gun –and not interfere with the LLRF system– a voltage controllable RF attenuator is inserted in the low power signal path between the LLRF and the power amplifier. Around the operating point of 10 V, the used Mini-Circuits ZX73-2500-S+ voltage controlled attenuator [6] has a sensitivity of $-0.151\,\mathrm{dB\,V^{-1}}$ to the control voltage, which allows the control voltage to be set with a remote controlled signal generator. The sensitivity to the power supply stability was measured to be $0.004\,\mathrm{dB\,V^{-1}}$, i.e. it is negligible for common lab bench power supplies. An E-field pick-up in one of the cavity cells, that is calibrated to yield a RF power measurement, is used as sensor. The measured power is available via the EPICS [7] system (see [8]). The control unit then uses the RF power value and the voltage controlled attenuator to construct a feedback loop, see Fig. 1.

## CONTROLLER DESIGN

To determine the controller parameters of the control unit, the response of the plant to a controller output has to be known. This relation is described by the plant transfer function $p[n]$, which summarizes the result of a unit impulse from the controller output to the controlled quantity (here the RF cavity power) [9]. For the measurement at FLUTE, step functions are used as the driving signal instead of impulses, as they are easier to generate and the responses easier to measure. As the length of the significant part of the response is not known beforehand, a pseudo random binary sequence, i.e. a series of step functions with different lengths is used. To get the analytical representation of the plant, numerical optimization is used to fit a time-discrete rational model to the measured data. By allowing more degrees of freedom (DoF), the model accuracy is improved, however too many DoF can lead to over-fitting. Finally a model with 3 DoF is used, see Fig. 3.

The cavity power measurement suffers from noise due to shot-to-shot variations. To mitigate their contribution to the controller input, a digital low-pass filter $h[n]$ of the order $N$ is used. In general higher order low-pass filters reject out-of-band frequency components better, but introduce a significant group delay to their output signal [10].

For the controller itself a common time discrete PID architecture is selected. Its output $u[n]$ is the sum of the responses proportional to the input signal itself $e[n]$, the integral of the signal over time $e_i[n]$ and the derivative over time $e_d[n]$, each weighted by a coefficient $k_{\{p,i,d\}}$:

$$u[n] = k_p\, e[n] + k_i\, e_i[n] + k_d\, e_d[n] \tag{1}$$

The coefficients $k_{\{p,i,d\}}$ have to be tuned for the system to have a high disturbance rejection but also to be stable [11]. There are different ways to do so. One traditional way is the Ziegler-Nichols method [12], which is used here for quick preliminary tests. The final coefficient determination is done by numerical optimization with the two design parameters response time $RT$ and filter order $N$. The results for different $RT$ and $N$ is shown in Fig. 4. There, the controller $g_1[n]$ for $RT = 5\,\mathrm{s}$ and $N = 10$ shows fast decay of the simulated disturbance step and only minor ringing, which indicates stability.

By calculating the cross-covariance between the cavity power and some readily available diagnostic signals, a strong inverse correlation between the cavity power and the gun temperature is found. As this relation is deterministic and linear around the operating temperature of the gun, a feed-forward path is added to the control system. This way the feed-back loop is only responsible for disturbances not caused by the gun temperature drift and can be operated less aggressively. The final control system architecture is shown in Fig. 5.

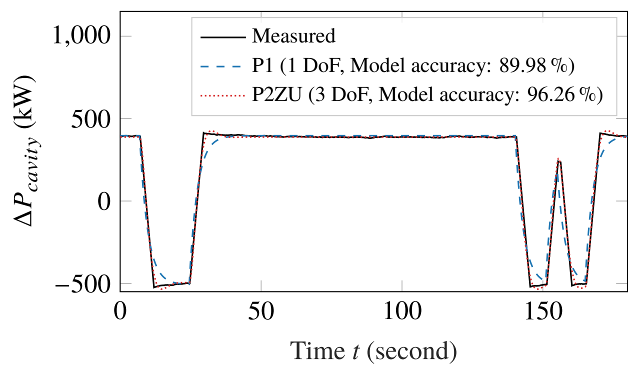


Figure 3: System identification to get the plant transfer function.

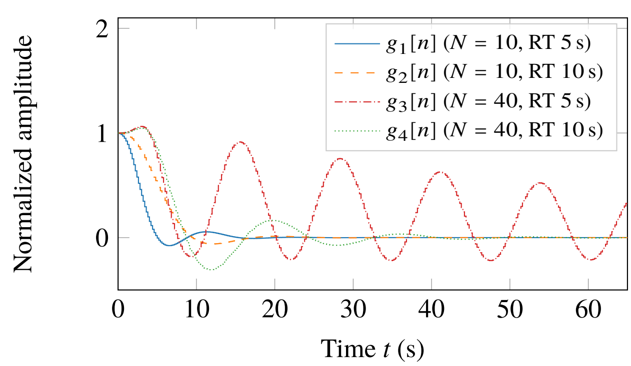


Figure 4: Simulated disturbance rejection for different filter lengths $N$ and response times $RT$.

### *Verification at FLUTE*

The effectiveness of the control system is verified at FLUTE by operating the low-energy section first with and then without the control system enabled for five hours each (see Fig. 6). To better illustrate the reduction of the slow drifts, Fig. 7 shows a periodogram of the time signal in Fig. 6 in which the spectral composition is calculated for the turn-on and turn-off segments of the controller.

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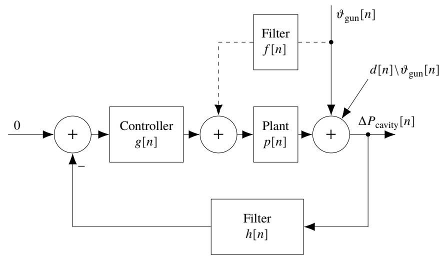


Figure 5: Control system architecture with feed-back loop and added feed-forward path.

### *Tests with Faraday Cup*

Currently, instead of injecting the electron beam into the linac section of FLUTE, a Faraday cup [13] is placed at the end of the low-energy section. It measures the emitted electron charge destructively, so it cannot be used as a diagnostic tool in normal operation. But for the commissioning stage its output reading may give a more accurate indication of electron energy stability than the RF cavity power measurement.

For that reason the current signal, measured and digitized by a charge amplifier [14] and a DAQ system, is evaluated as quantity to be controlled. The control unit was able to handle the beam charge as the input/output with minor tweaks to the $k_{\{p,i,d\}}$ coefficients. Since the electron charge and the RF cavity power show no simple correlation the decision which parameter should be kept constant with the control unit is deferred until direct electron energy measurements are performed.

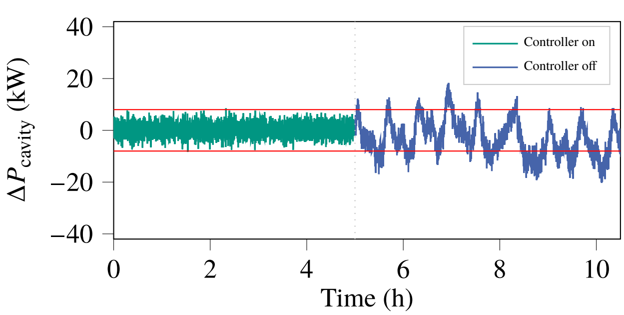


Figure 6: Deviation of the cavity power $\Delta P_{\mathrm{cavity}}$ with the control system on and off (set value $P_{\mathrm{cavity}} = 9.5\,\mathrm{MW}$, required standard deviation in red).

## SUMMARY AND OUTLOOK

The present FLUTE LLRF system is not able to correct for the type of long-term drifts and slow periodic disturbances of the RF cavity power. Therefore, in this paper we showed how a slow-control system can be designed and demonstrated its effectiveness on the cavity RF power stability. Over the time span of five hours, utilizing the new slow-control system improved the relative standard deviation by about 8.5 % and

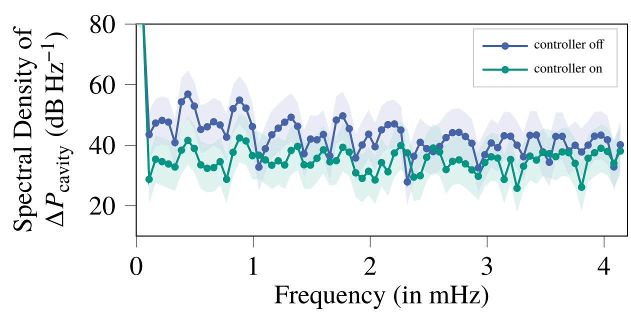


Figure 7: Periodogram of the cavity power deviations in Fig. 6.

thus is effective in compensating the long-term drifts. In the future, the system could be integrated into the LLRF and possibly take advantage of other system parameters, such as the electron charge.

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