DEVELOPMENT OF AN ERL RF CONTROL SYSTEM*

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Abstract

The Mainz Energy-recovering Superconducting Accelerator (MESA), currently under construction at Johannes Gutenberg-Universität Mainz, requires a newly designed digital low-level radio frequency (LLRF) system. Challenging requirements have to be fulfilled to ensure high beam quality and beam parameter stability. First, the layout with two recirculations and the requirements will be shown from an LLRF point of view. Afterwards, different options for the control system are presented. This includes the generator-driven system, the self-excited loop and classical PID controller as well as more sophisticated solutions.

OVERVIEW AND REQUIREMENTS OF MESA

At Johannes Gutenberg-Universität Mainz a new accelerator will be built: The Mainz Energy-recovering Superconducting Accelerator (MESA). This accelerator will not only feature high current beams, feasible by means of energy recovery, but will also be operated as conventional multi-turn linac with a polarized electron beam. A part of the building is yet to be constructed and civil works will begin in 2018. The accelerator itself is scheduled to be constructed in 2020, but some parts can already be tested in existing halls [1].

Figure 1 shows a (preliminary) lattice [2]. The source called STEAM [1] ("Small Thermalized Electron-source At Mainz") will deliver a beam of polarized electrons which are pre-accelerated up to 5 MeV in the injector MAMBO ("Milli Ampere Booster") before they enter the main linac. MESA uses a double-sided layout with two cryomodules, providing an energy gain of up to 25 MeV each. After passing the cryomodules the beam is guided through the arcs for multi-turn operation. Separator magnets split the beams of different energies and recombine them before entering the cryomodules again or before experimental use.

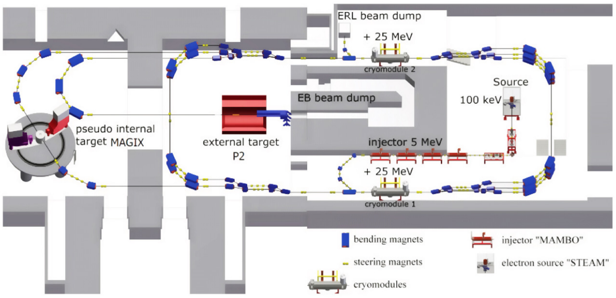

Figure 1: MESA lattice as of 2016.

Two experimental sides are foreseen: If MESA works as a 3-turn linac without energy recovery, the beam will be used in the so-called "external target P2" for high precision measurements of the Electro-Weak mixing angle [1]. In this mode, a 0.15 mA polarized electron beam will be accelerated to 155 MeV. Since there will be no energy recovery after P2 the beam will be dumped at high energy. This makes heavier shielding for radiation protection necessary.

The other operation mode will be the energy-recovery mode. In this mode, the beam will interact with the pseudo internal target called MAGIX which is a windowless gas target [1]. There will only be two passes, since this experiment only needs lower energies—but ideally, the available energies range from quite as low as 25 MeV up to a maximum of 105 MeV. The use of energy recovery makes higher currents feasible. In the first stage, a current of 1 mA is planned which shall be upgraded to 10 mA in the second stage. Currently, discussions are ongoing whether this mode will also make use of polarized electrons [1]. There are many possible experiments in MAGIX' portfolio, from nuclear physics to the search for dark matter [1].

All the experiments will require high accuracy and stability of the accelerating RF field while a wide variety of parameters (e. g. beam current and energy) has to be dealt with. The RF control system will have to handle this on demand.

Multi-Turn ERL Layout

In this paper, the focus is set to the energy-recovery mode. The path a beam takes is sketched in Fig. 2, starting from the injector through the main linac to the internal experiment and back on the decelerating phase ending in the beam dump. The beam re-enters the cavities 180° out of phase

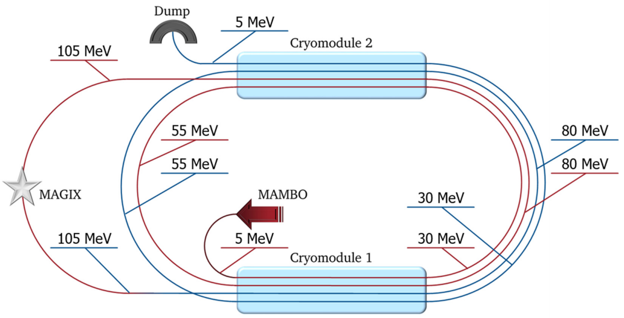

Figure 2: Sketch of the way a beam travels through MESA in the energy-recovery mode. Red: accelerating phase. Blue: decelerating phase. Note that the spatial separation is meant to clarify the different ways—in reality, the bunches are interleaved and those with the same energy share also the same beampipes in the arcs.

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with respect to the accelerating field. This is achieved by path-length variation in the last arc with the internal target. As can be seen in Fig. 2, there will be four different beams in each cryomodule. MESA will be operated in continuous-wave (CW) mode and in the upgraded stage 2 this would result in a DC current of 40 mA in each cryomodule and thereby a very high beam loading. But since two of the four beams are on the decelerating phase their energy is given to the accelerating beams so that for perfect energy recovery the "RF currents" cancel each other. This results in a significantly reduced RF power demand, as can be seen from Eq. (1) and Eq. (2), which describe the required RF power in terms of the amplitude of the accelerating voltage V_{acc}, the (resulting) beam current I_{beam}, the beam phase relative to the crest φ_{beam}, the cavity's $\frac{R}{Q}$, the loaded quality factor Q_L, the coupling factor β_c, the detuning $\delta\omega$ and the 3 dB bandwidth $\Delta\omega_{BW}$ [3].

$$P_{RF} = \frac{V_{acc}^2}{4\frac{R}{Q}Q_L}\frac{1+\beta_c}{\beta_c}\left[\left(1+\frac{R}{Q}Q_L\frac{I_{beam}}{V_{acc}}\cos\left(\varphi_{beam}\right)\right)^2 + \left(\frac{2\delta\omega}{\Delta\omega_{BW}}+\frac{R}{Q}Q_L\frac{I_{beam}}{V_{acc}}\sin\left(\varphi_{beam}\right)\right)^2\right] \tag{1}$$

In the case of perfect energy recovery there is no beam loading [3] and Eq. (1) reduces to

$$P_{RF} = \frac{V_{acc}^2}{4\frac{R}{Q}Q_L}\frac{1+\beta_c}{\beta_c}\left[1+\left(\frac{2\delta\omega}{\Delta\omega_{BW}}\right)^2\right]. \tag{2}$$

Note that due to different conventions other authors may use the factor 8 instead of 4—here the so-called linac definition is used, while there also exists the circuit definition originating from the cavity's equivalent LRC model.

Equation (2) also reveals that the RF power demand in the energy-recovery mode strongly depends on the cavity detuning $\delta\omega$ due to microphonics. Therefore resonance control is crucial.

In the next section some control system basics are summarised and a theoretical model of the cavity is presented before the attention is drawn back to more specific issues related to the control of superconducting cavities.

CONTROL SYSTEM BASICS

In Fig. 3 the basic feedback loop is shown. A desired input signal is given to the controller to generate a steering signal for the plant. The output of the plant is then measured by a sensor and fed back to the input. The difference between the input and the actual measured output gives the "error" signal which the controller tries to reduce and ideally fix to zero. In reality there are also disturbances acting on the steering signal and the measurement is noisy as well (the latter is not shown here).

The "plant" in question are superconducting cavities with a resonance frequency of 1.3 GHz together with the power sources, couplers, transmission lines, amplifiers, and the cavity tuners.

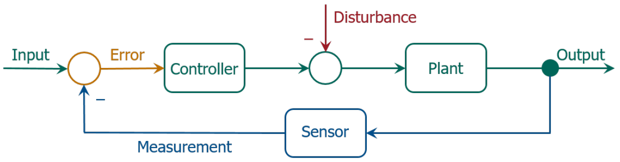

Figure 3: Basic feedback control loop.

In general there will be more than just one sensor. In the special case of an LLRF system one could measure the amplitude and phase of the RF field inside the cavities (or the so-called in-phase and quadrature components I & Q) but additionally measuring the forward and reflected power as well as the actual tuning and the beam position would be possible. Since the measurement is an important component of the feedback loop, controlling a quantity (like the amplitude) without proper measurements is (almost) impossible.

In the following section some options for the controller will be shown, but first the "plant" is discussed in more detail.

Model of SC RF Cavities

MESA will make use of two modified "ELBE-type" cryomodules [2]. Their cross section is shown in Fig. 4. As can be seen, each cryomodule will house two nine-cell cavities. For the development of an RF control system, a theoretical model of the plant is needed. Superconducting cavities are usually simplified by an equivalent LRC circuit [4, 5]. The "RF generator", which includes the amplifier, delivers the power to the cavity via waveguides. A circulator prevents the amplifier from damage by reflected power and couplers connect the transmission line to the cavity, see Fig. 5. From the cavity's point of view this model can still be simplified by substituting the coupler and all elements to the left of it by an *equivalent power source* delivering the current $\tilde{i}_{gen}(t)$ while the beam itself is also modelled as a current source delivering $i_{beam}(t)$. In this process the cavity's shunt impedance also has to be modified, since it is connected in parallel to

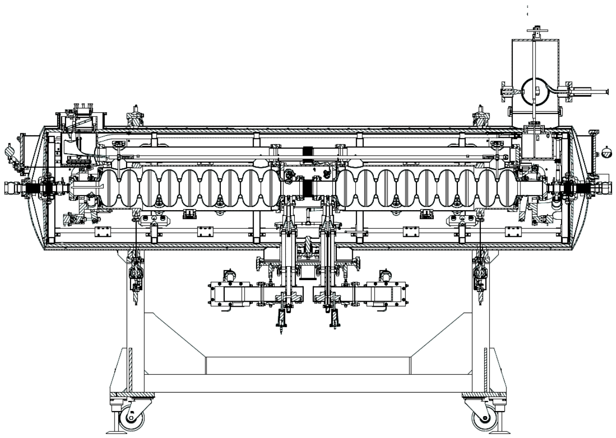

Figure 4: Modified ELBE-type cryomodule for MESA.

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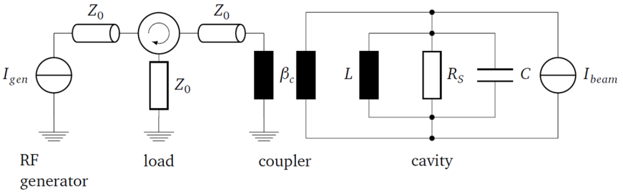

Figure 5: Simplified model of a superconducting cavity, including the power source and transmission lines.

the generator impedance (seen through the coupler). One finally ends up with the simplified circuit shown in Fig. 6. This model represents just a single resonance, but due to the narrow bandwidth of superconducting cavities, this is nevertheless useful for describing the accelerating mode [4].

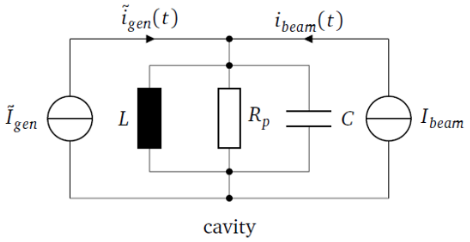

Figure 6: Simplified model of a superconducting cavity with (equivalent) current sources.

Applying Kirchhoff's current law, one can easily derive the linear differential equation describing the cavity voltage $U_{cav}(t)$. By replacing the model's parameters R_p, L and C by their corresponding "accelerator" expressions, this equation reads [4]

$$\ddot{U}(t)+\frac{\omega_0}{Q_L}\dot{U}(t)+\omega_0^2 U(t) = \omega_0 \frac{R}{Q}\frac{d}{dt}\left(\tilde{i}_{gen}(t)+i_{beam}(t)\right). \quad (3)$$

For the development of an RF control system, the model shown in Fig. 6 together with Eq. (3) is used for simulations. It is a simple but yet powerful model which can represent the RF amplitude and phase, their transient & steady state behaviour as well as the cavity's reactions to beam loading, especially with an (interleaved) bunch train. It neglects the exact field distribution inside the cavity and is not able to reproduce HOMs, wakefields or the 6D phase-space motion of particles. At the very beginning of the development of an LLRF control system this is acceptable.

CONSIDERATIONS FOR THE CONTROL SYSTEM

Based on the basics described in the previous section, one can start to collect more specific requirements for the LLRF system.

First of all, the amplitude and phase of the accelerating (and decelerating) field shall be accurate and constant (within given tolerances that still need to be specified). In addition, especially for MESA, the control system has to support the two different operation modes (energy-recovery mode and external-beam mode) with different numbers of passes, beam energies and currents as well as varying beam loading. Advanced control algorithms can enhance the stability and provide the user with additional diagnostic information. For further development and improvement the system should be modular and scalable so that one will be able to substitute some components without having to redesign the whole system. These key-points make a *digital control system* preferable (see also [6]).

Options for the Feedback Loop

For the basic design of the feedback loop, two different approaches exist: the Generator-Driven Resonator (GDR), see Fig. 7, and the Self-Excited Loop (SEL), see Fig. 8 [4].

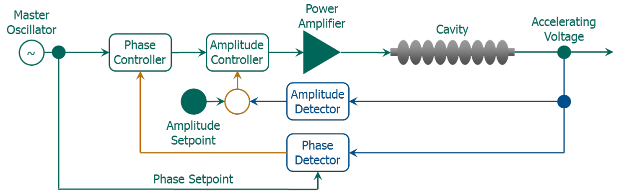

Figure 7: Example of the "Generator-Driven Resonator" feedback loop.

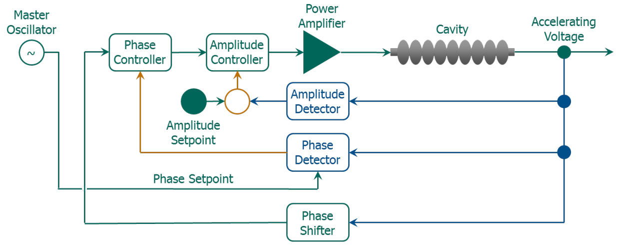

Figure 8: Example of the "Self-Excited Loop".

The GDR is a "straight-forward" approach, i. e. it resembles the basic feedback loop shown in Fig. 3. The Master Oscillator's signal is directly used to drive the amplifiers which power the cavity. In this example, amplitude and phase feedback is shown instead of I & Q. This "direct way" has the advantage that the start-up, i. e. filling the cavity with RF power, can be precisely timed and fast. Therefore one needs to carefully control the cavity's resonance frequency—the amplifiers won't be able to power the cavity if they are operating too far away from the cavity's resonance frequency. Lorentz-force detuning and its compensation are a major issue for the GDR.

In the SEL, the Master Oscillator is used as reference for the phase setpoint but the amplifier's input is the cavity's voltage signal itself. If the phase of the cavity's voltage signal is adjusted to an integer multiple of 2π, even small thermal noise will be amplified—the cavity can start oscillating without any external input or reference. The real system will include a limiter which is not shown in Fig. 8. The main advantage is that one does not have to care about Lorentz-force detuning since this effect is automatically compensated. Since the cavity starts oscillating from thermal noise it can also start in an unwanted mode. This gives some “randomness” to the start-up and may slow down this process. One can account for this by *modifying the noise* [7]: The cavity acts as a very narrow bandpass filter and if some weak narrow bandwidth random signal centered on the expected resonance frequency of the accelerating mode is used as input, the SEL will lock to this desired mode. After that, the amplifiers can be turned to full operation power. This start-up procedure can be as fast as the GDR start-up but benefits from all advantages the SEL has over the GDR [7].

Options for the Controller

As mentioned earlier, the RF power needed in the energy-recovery mode is highly affected by microphonics. In addition—and even worse for the experimentalists—the stability of the accelerating field is affected by it. Since stability is a key feature of future experiments, compensating microphonics will be very important. The modified ELBE-type cryomodules will make use of fast piezo tuners for cavity resonance control (the tuners are not shown in Fig. 7 & 8). For predictable disturbances, e. g. arriving bunches, the concept of (adaptive) feedforward can bring additional benefits and improve the overall performance of the control system [6].

For the controller there are also a couple of options. The classical PID controller is a widely-used concept, which suffers from noise in the “D” part. Therefore many LLRF control systems for superconducting cavities deploy PI control only. This reduces the speed of the control system but if it is fast enough the increased stability is considered to be better. Nevertheless, since this is a known problem, there are some solutions. One is the so-called Kalman filter which replaces the system’s state with an *estimator* from a series of measurements, thereby significantly reducing the noise. Another option is the state observer. This control scheme places a model of the actual “plant” in parallel to the real system. The model’s input is exactly the same as for the real system and by comparing the outputs of both systems (real and model) one can adjust the model to track the real system. Internal states of the real system can be read out from the model and used for feedback control (when the controller uses internal states of the system, this is commonly referred to as “state control”). Besides that there is robust control, a design that makes the controller independent of system parameter variation or uncertainty (to some extent). This can be done by “H infinity” control ($H\infty$)—the controller is optimized by modelled system parameter uncertainties.

But: All these options are a priori not determinable. The development of an LLRF control system—like any control system—starts with system identification and setting up the topology. At the current state of this project, these options are considered, but a deep understanding of the system’s dynamical behaviour is the precedent step.

SUMMARY AND OUTLOOK

MESA, a multi-turn energy recovery linac, will be constructed at Johannes Gutenberg-Universität Mainz. Civil works are scheduled to start in 2018 and the building of the accelerator itself shall start in 2020. In the meantime some components can already be tested in the existing halls.

The LLRF system design has started and R&D of a generic digital RF control system is in progress. The first step will be modelling and understanding of the system behaviour, especially in multi-turn energy-recovery mode. Afterwards, an appropriate control system topology will be chosen.

Since there is some time until the commissioning of the accelerator, further analytical and numerical investigations shall follow to optimize the digital control system and to improve the system performance applying more sophisticated controllers & signal processing techniques.

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