Development of an ERL RF Control System

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Outline

- Overview & Requirements of MESA
- Control System Basics
- Considerations for the Control System
- Summary & Outlook
OVERVIEW & REQUIREMENTS OF MESA
Mainz Energy-Recovering Superconducting Accelerator

- Lattice (preliminary):

[T. Stengler et al.: Status of the Cryomodules and Cryogenic System for the Mainz Energy-Recovering Superconducting Accelerator MESA.]
Mainz Energy-Recovering Superconducting Accelerator

- Lattice (preliminary):
  - External beam mode:
    - 3-turn LINAC, no energy recovery
    - 155 MeV, 0.15 mA polarized beam
    - Beam dump after fixed target
  - Energy-recovery mode:
    - 2-turn LINAC, 2-turn decelerator
    - 105 MeV, 1...10 mA beam
    - Internal gas target

To be constructed
@ Johannes Gutenberg-Universität Mainz

[T. Stengler et al.: Status of the Cryomodules and Cryogenic System for the Mainz Energy-Recovering Superconducting Accelerator MESA.]
MESA as a Multi-Turn ERL

180° phase shift (path length variation)

4 interleaved (!) beams

Internal gas target
SC RF Cavities – Power Demands

- “10 mA beam” means 40 mA DC in each cryomodule – but RF currents shall cancel each other

- RF power demand with beam loading:

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

- RF power demand without beam loading (perfect energy recovery):

\[
P_{RF} = \frac{V_{acc}^2}{4 \frac{R}{Q} Q_L} \frac{1 + \beta}{\beta} \left[ 1 + \left( Q_L \frac{2\delta \omega}{\omega_0} \right)^2 \right]
\]

\[\Rightarrow \text{depends only on cavity detuning } \delta \omega \text{ (due to microphonics, ...)}\]

CONTROL SYSTEM BASICS
Control System Basics

- Basic feedback control loop:

  ![Diagram of a control system with the following components:
  - Input
  - Error
  - Controller (with feedback from Sensor)
  - Plant
  - Disturbance
  - Output
  - Measurement]

  - **the plant:**
    - superconducting radio frequency (1.3 GHz) cavity with power source, including amplifier, transmission lines, coupler
  - **(different) sensors** for measurement of:
    - amplitude & phase (or I & Q), forward & reflected power, tuning, beam position, ...
  - **the controller:**
    - ideally fixes “error” to 0, counteract disturbances, feedback & feedforward, stability & dynamical behaviour, ...
The “Plant”: a SC RF Cavity & its Power Source

- Two 9-cell cavities per cryomodule
- Model represents just a single resonance
- Nevertheless very useful due to narrow bandwidth!
Theoretical Model of a SC RF Cavity

- Parallel LRC circuit with
  - Shunt impedance $R_p$ (including generator influence)
  - incoming RF power transformed to
    “generator current” $\tilde{i}_{gen}$
- Cavity voltage $U_{cav}(t)$ fulfills

$$\ddot{U}(t) + \frac{1}{R_p C} \dot{U}(t) + \frac{1}{LC} U(t) = \frac{1}{C} \frac{d}{dt} \left( \tilde{i}_{gen}(t) + i_{beam}(t) \right)$$

- In “accelerator terms” this reads

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

model parameters

model input
CONSIDERATIONS FOR THE CONTROL SYSTEM
Some Basic Requirements

- **Accuracy & Constancy** of amplitude & phase (within given tolerances)
- **Flexibility** to support different operation modes ("ERL" and "normal") with different beam energies & currents
- **Advanced Control Algorithms** feasible
- **Modularity & Scalability** for future improvements
- **Diagnostics** options available

⇒ **Digital control system** preferable
Generator-Driven Resonator & Self-Excited Loop

○ Generator-Driven Resonator:

Master Oscillator

Phase Controller

Amplitude Controller

Power Amplifier

Cavity

Accelerating Voltage

Amplitude Setpoint

Phase Setpoint

Amplitude Detector

Phase Detector

Amplitude Setpoint

Phase Setpoint
Generator-Driven Resonator & Self-Excited Loop

- Self-Excited Loop:

Master Oscillator

Phase Controller → Amplitude Controller → Power Amplifier → Cavity → Accelerating Voltage

Amplitude Setpoint

Amplitude Detector → Phase Detector

Phase Setpoint

Phase Shifter
Generator-Driven Resonator & Self-Excited Loop

- **Generator-Driven System:**
  - detuning (e.g. Lorentz force) has to be compensated
  - “planned” start up (can be fast)

- **Self-Excited Loop:**
  - starts oscillating from thermal noise regardless of detuning
  - can also excite unwanted modes
  - “random” start up (may be slow)
Further Options for the Control System

- additional: fast **piezo tuners** for cavity resonance control
- **(Adaptive) Feedforward** against *predictable* disturbances

Some options for the controller:

- classical PID  
  - Kalman filter  ("estimating" the system’s state from a series of measurements)
  - state observer  (model parallel to real system to reconstruct its internal states)
- robust control  (independency of system parameter variation / uncertainty)
  - $H_\infty$ control  (controller optimized by modelled system parameter uncertainty)
- ...

A priori not determinable – choose only after topology is set and system identification took place!
SUMMARY & OUTLOOK
Summary & Outlook

- **MESA**, a multi-turn energy recovery LINAC, will be constructed at Johannes Gutenberg-Universität Mainz (1st beam: 2020).

- R&D of a generic digital RF control system has started.
  - 1. step: modelling & understanding the systems behaviour
  - afterwards: choosing an appropriate control system topology

- Further analytical and numerical investigations to derive the greatest benefit from a digital control system will follow.
  - sophisticated controllers & signal processing possible
THANK YOU FOR YOUR ATTENTION!
References


Appendix A: Modelling a SC RF Cavity

Modelled:
- simple model, representing the RF amplitude and phase
- First-pass beam / transient and continuous behaviour & power demands
- Cavity’s reactions to beam-loading ((interleaved) bunch train)

Neglected:
- Field distribution inside the cavity
- Phase-space motion of particles / bunches
- Wakefields, HOMs, ...

Low-Level RF control point of view