Development of an ERL RF Control System

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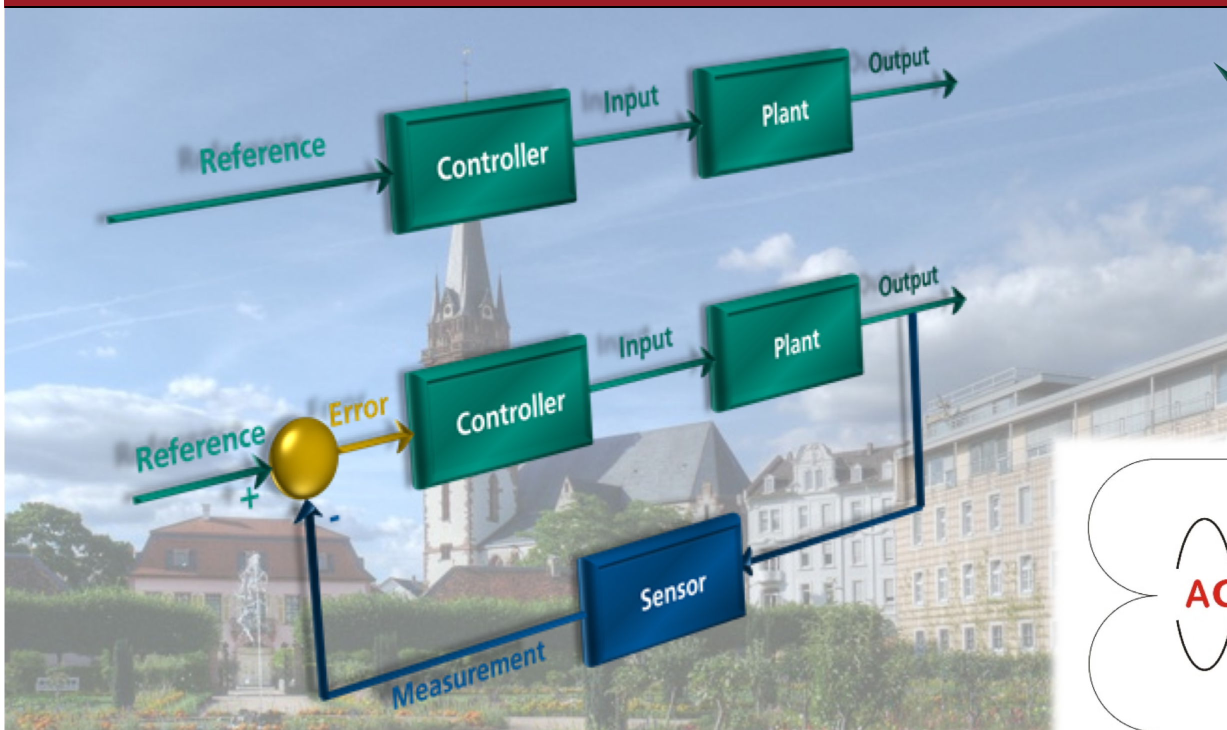


Project recently started

Work supported by DFG: GRK2128 "AccelencE"

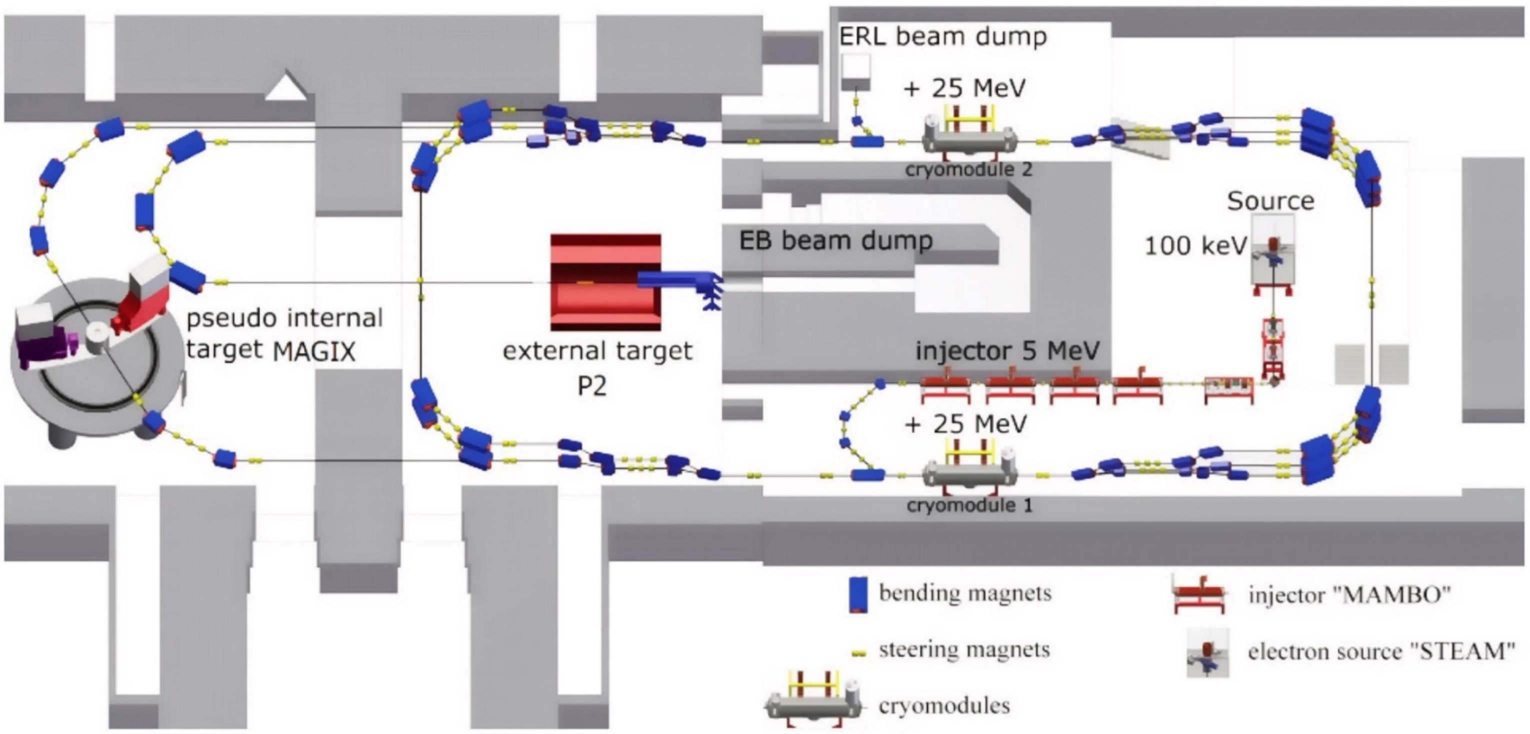
Outline

- Overview & Requirements of MESA
- Control System Basics
- Considerations for the Control System
- Summary & Outlook

OVERVIEW & REQUIREMENTS OF MESA

Mainz Energy-Recovering Superconducting Accelerator

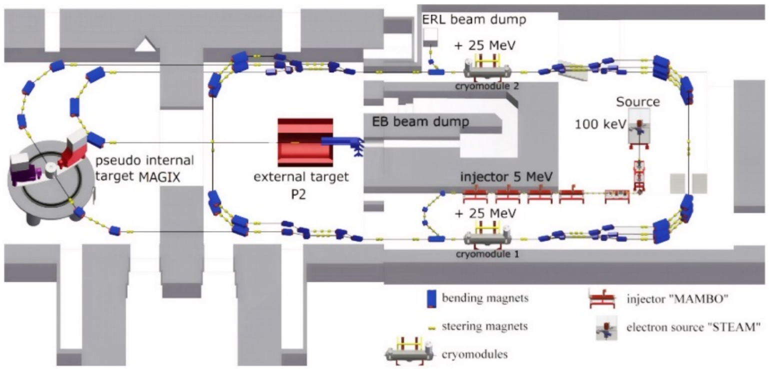
- Lattice (preliminary):



[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):



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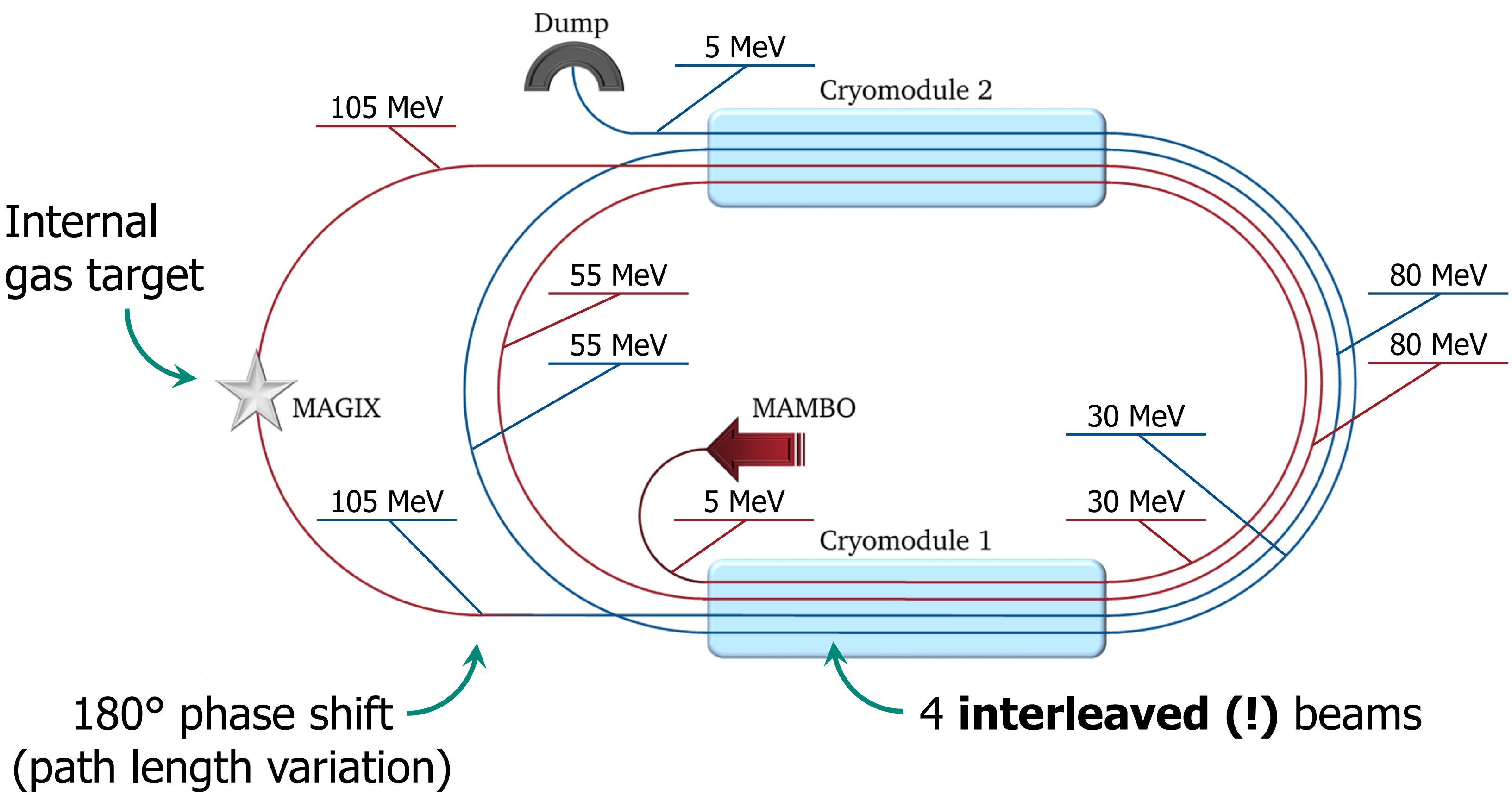
To be constructed
@ Johannes Gutenberg-Universität Mainz

- General RF operation mode: CW

- 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

MESA as a Multi-Turn ERL



SC RF Cavities – Power Demands

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- "10 mA beam" means 40 mA DC in each cryomodule – but RF currents shall cancel each other
- RF power demand with beam loading:

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

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

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

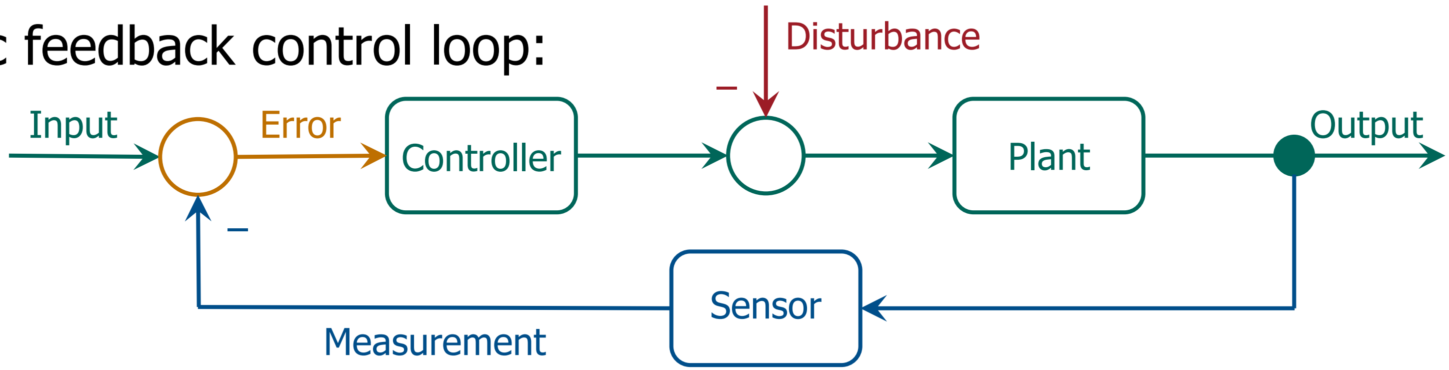
$\Rightarrow$ depends only on cavity detuning $\delta\omega$ (due to microphonics, …)

[Formulas based on K. Aulenbacher, J. Diefenbach, F. Fichtner, S. Friederich, R. Heine, C. Matejcek, F. Schlander, and D. Simon. *Elementary Design Report for the Mainz Energy Recovering Superconducting Accelerator MESA*.]

CONTROL SYSTEM BASICS

Control System Basics

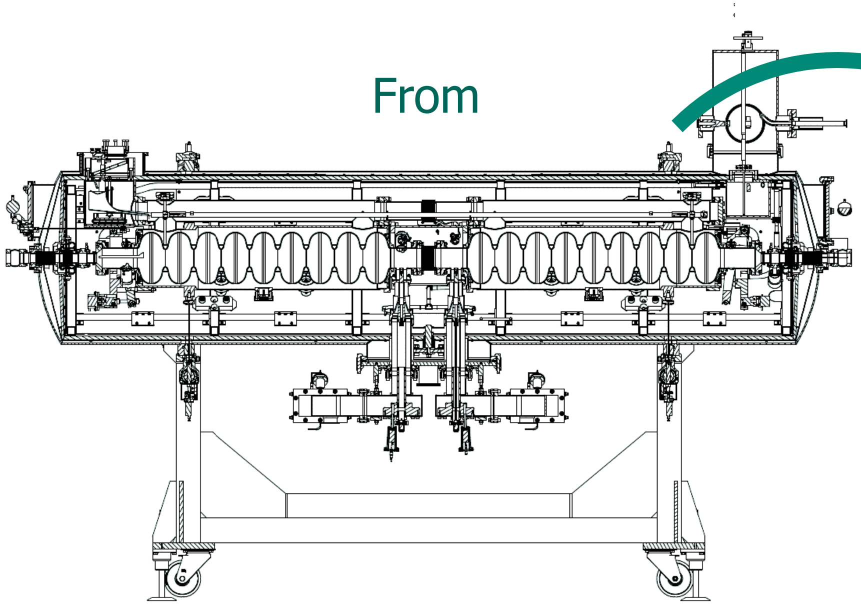
- Basic feedback control loop:



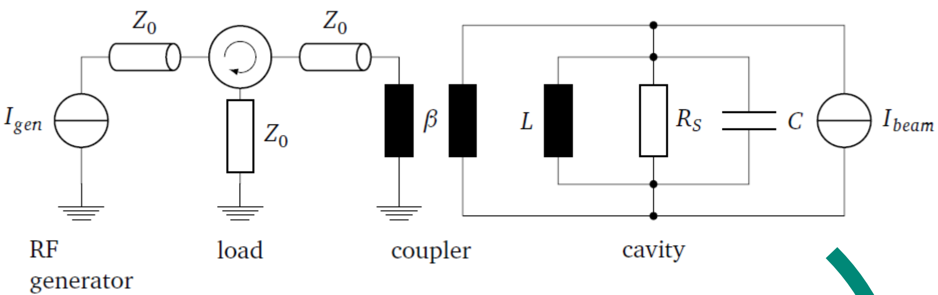
- the plant:
  - superconducting radio frequency (1.3 GHz) cavity with power source, including amplifier, transmission lines, coupler
- (different) sensors for measurement of:
  - amplitude & phase (or I & Q), forward & reflected power, tuning, beam position, …
- the controller:
  - ideally fixes "error" to 0, counteract disturbances, feedback & feedforward, stability & dynamical behaviour, …

The "Plant": a SC RF Cavity & its Power Source

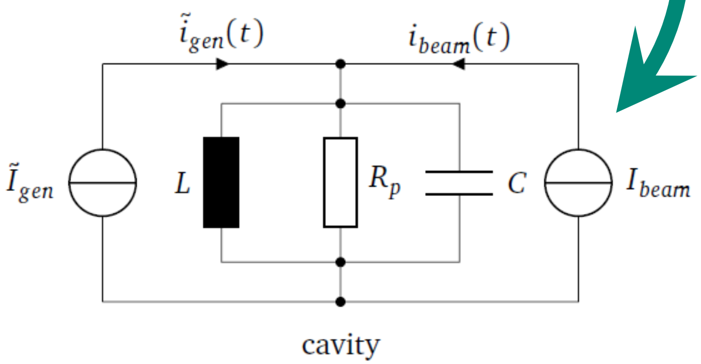
From



to



and simplifying to



- 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

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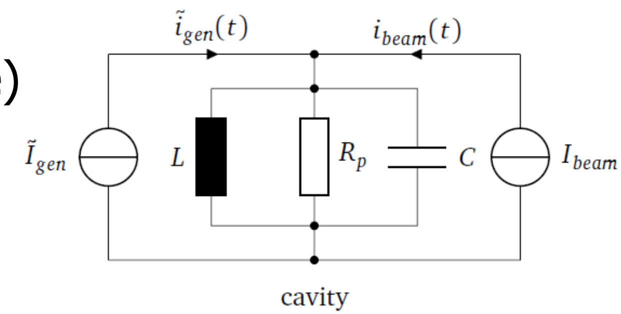
- Parallel LRC circuit with
  - Shunt impedance R_p (including generator influence)
  - incoming RF power transformed to "generator current" $\tilde{i}_{gen}$



- 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

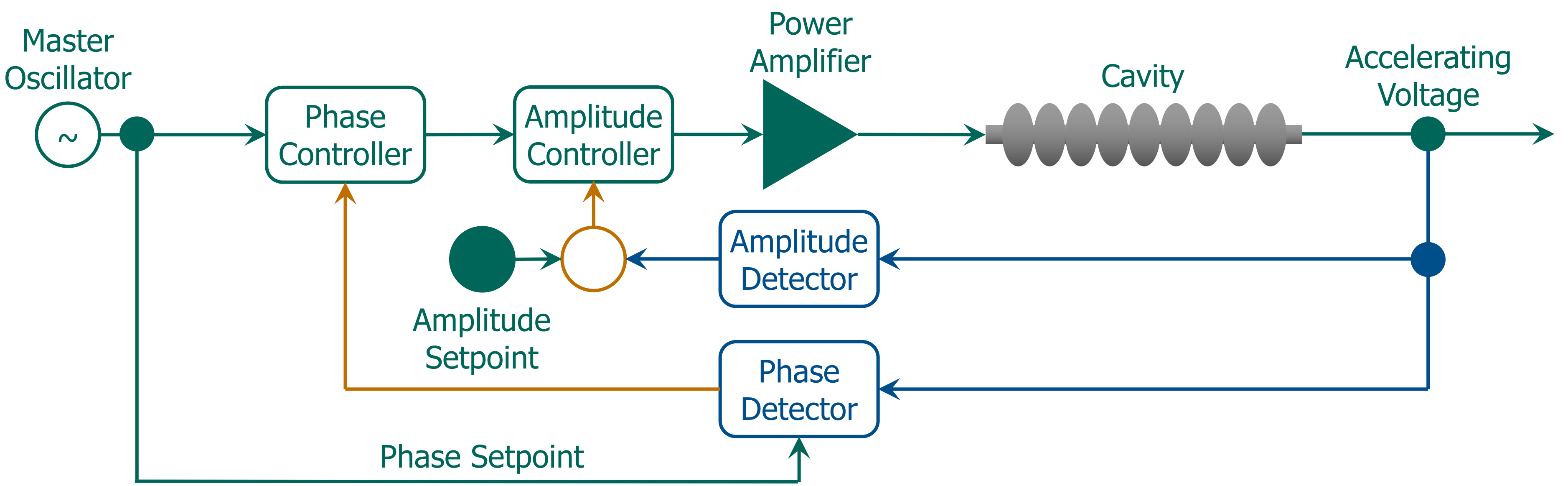
Some Basic Requirements

- **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

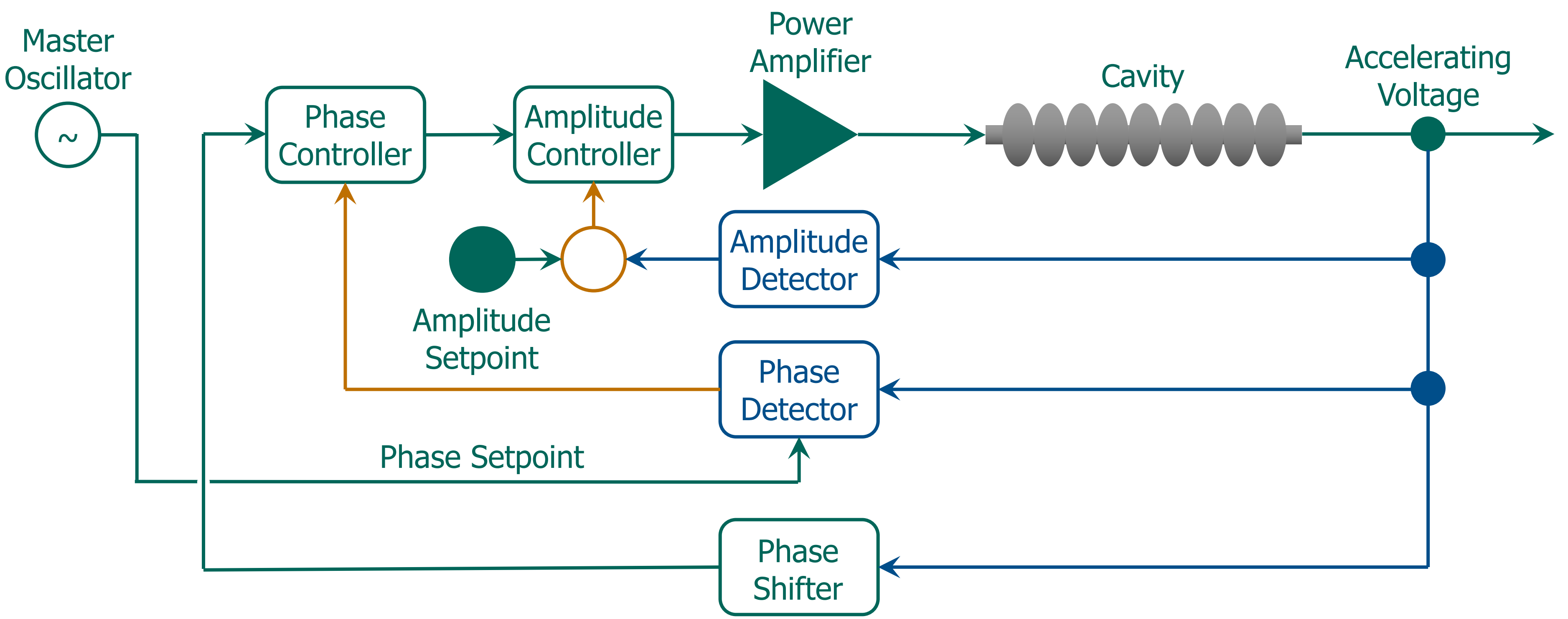
Generator-Driven Resonator & Self-Excited Loop

- Generator-Driven Resonator:



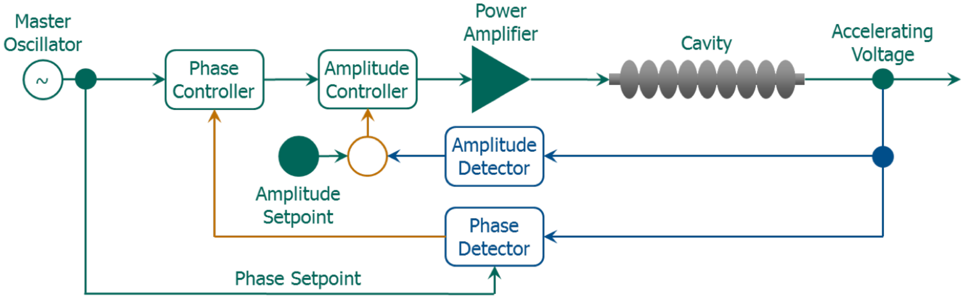
Generator-Driven Resonator & Self-Excited Loop

- Self-Excited Loop:

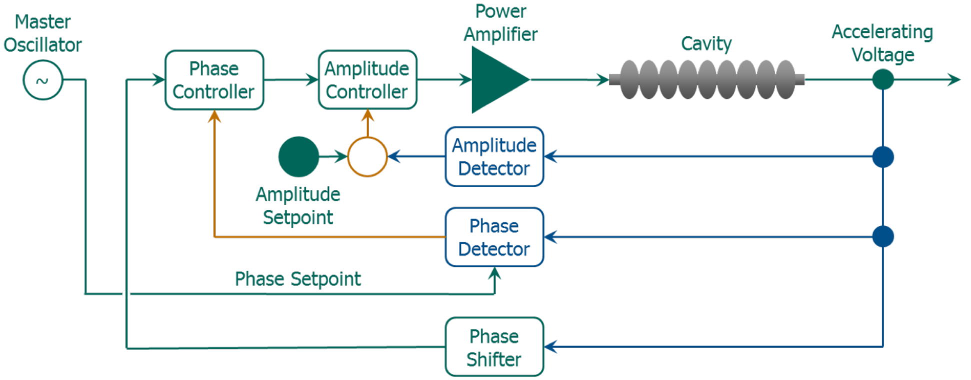


Generator-Driven Resonator & Self-Excited Loop

- 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

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

- Some options for the controller:
  - classical PID (or only PI because of noise, or replace "D" with an estimator…)
    - 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

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THANK YOU FOR YOUR ATTENTION !

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(1) N. Pietralla et al.: *GRK 2128 AccelencE - Proposal to Establish a Research Training Group (RTG) in "Accelerator Science and Technology for Energy Recovery Linacs"* , 2016.

(2) T. Stengler et al.: *Status of the Cryomodules and Cryogenic System for the Mainz Energy-Recovering Superconducting Accelerator MESA*. Proceedings of IPAC2016 (p. 2134-2137), Busan, Korea, 2016.

(3) K. Aulenbacher, J. Diefenbach, F. Fichtner, S. Friederich, R. Heine, C. Matejcek, F. Schlander, and D. Simon: *Elementary Design Report for the Mainz Energy Recovering Superconducting Accelerator MESA*. Technical report, Institut für Kernphysik, JGU Mainz, 2014.

(4) M. Konrad: *Development and commissioning of a digital rf control system for the S-DALINAC and migration of the accelerator control system to an EPICS-based system*. Ph.D. Thesis, TU-Darmstadt, 2013.

(5) S. Simrock: *Options for RF Control & State of Art Simulation and Performance*. ERL Workshop 2005 (presentation).

(6) S. Simrock, Z. Geng: *Cavity Field Control - RF Field Controller*. LLRF Lecture Part 3.3 (presentation), 4th LC School, Huairou, Beijing, China, 2009.

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