Low-level RF architecture for EMMA

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Outline

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Low-Level RF Definition

- A typical conventional accelerator uses high-power RF system to accelerate the particles.
- The high-power (or high-level) RF system includes:
  - Power sources: klystron, IOT, TWT, solid-state amplifier, etc.;
  - Accelerating cavities;
  - Power distribution: waveguides, splitters, circulators.
- Some system is necessary to generate the drive signal for the high-level RF - that is Low-Level RF system.
- In the simplest case it could be just an oscillator with amplitude and phase controls.
- In modern LLRF, closed-loop control is typically employed.

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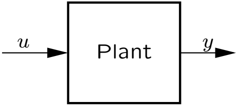
1. Introduction
   - Low-Level RF Definition
   - Closed-loop Feedback
   - EMMA LLRF Tasks
2. System Architecture
   - Overall Topology
   - Building Blocks
   - Feedback Controller
   - Cavity Frequency Detection
3. Simulation Results
   - What is Included and What is Left Out
   - Simulation Output

Closed-loop Feedback: Structure and Example



- Start with a physical system (a plant).

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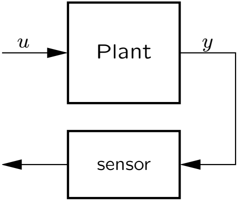

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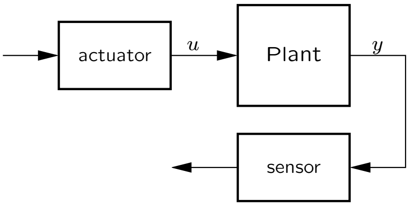

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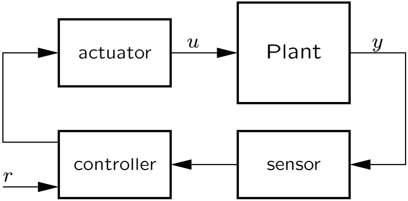

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- Measure some property of a plant with a sensor.
- Plant behavior (state) can be affected by an actuator.
- Feedback loop is completed by a controller.

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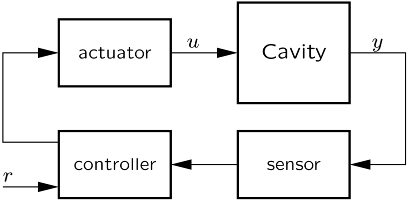

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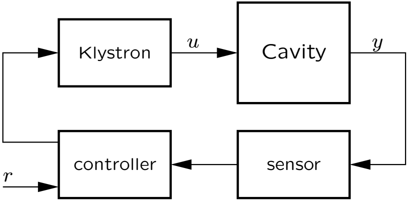

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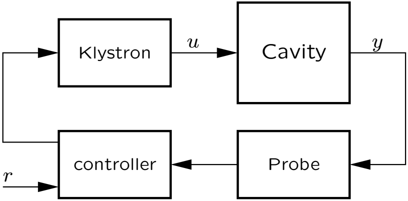

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  - Sensor - cavity probe.

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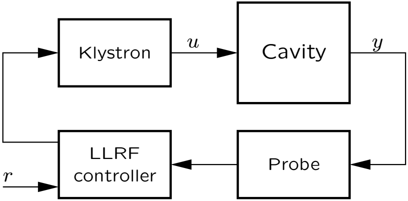

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  - Controller - LLRF module.

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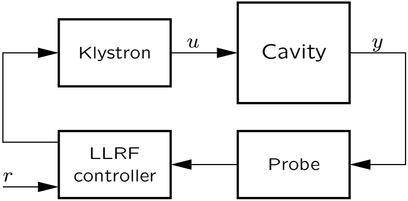

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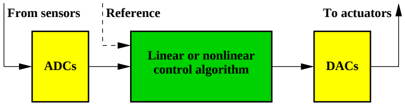
  - Our plant is an RF cavity.
  - Actuator - klystron.
  - Sensor - cavity probe.
  - Controller - LLRF module.
- Loop signals
  - Output y - cavity field;
  - Input u - klystron power;
  - Reference r - amplitude and phase.

Typical LLRF Feedback Controller



- Digital signal processing
- Cavity probe signals downconverted to intermediate frequency (IF);
- Outputs at IF as well;
- FPGA-based real-time processing.

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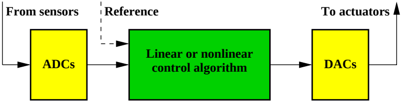

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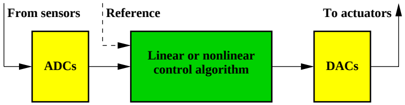

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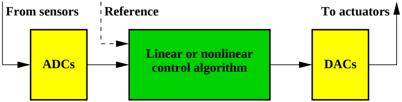

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EMMA LLRF Tasks

- Tasks, common to all accelerators:
  - Cavity field control;
  - Cavity tuning:
    - Resonant frequency measurement;
    - Tuner control;
  - Synchronization;
  - Built-in diagnostics;
  - Automated system configuration.
- EMMA-specific tasks:
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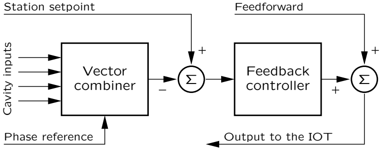
Overall Topology



- Cavity signals are lined up and added together
  - Single cavity with N_c times the shunt impedance.
- Reference channel - phase tracking.
- Feed-forward input:
  - Used for reducing feedback turn-on transients;
  - Framework for adaptive feed-forward.

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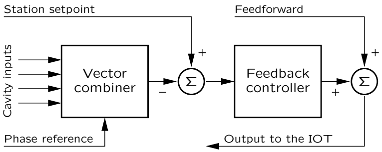

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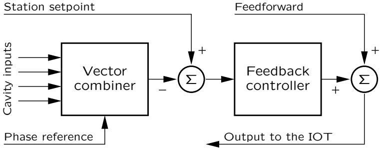

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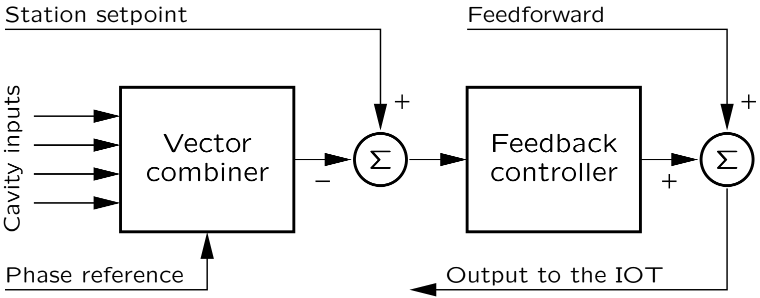
System Elements



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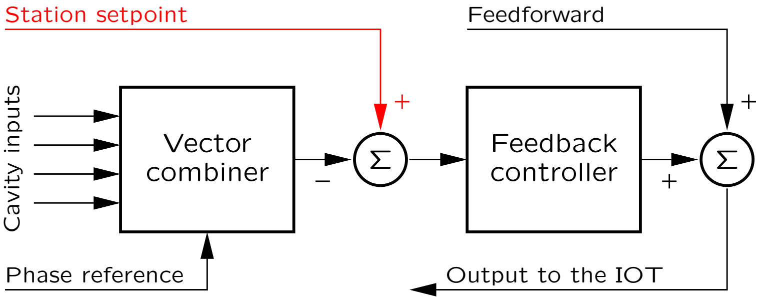
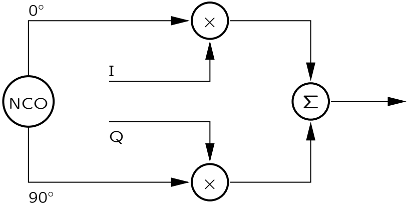


Reference Generator



- Numerically-controller oscillator at IF.
- NCO phase must be phase-referenced to some source:
  - Start NCO at the same phase every pulse;
  - Use the same NCO to downconvert master oscillator reference.

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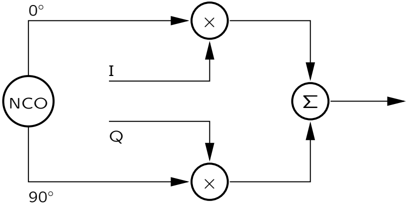

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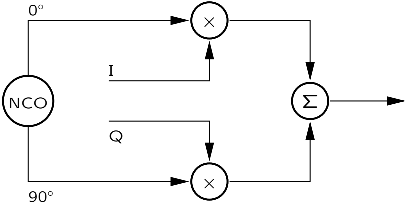

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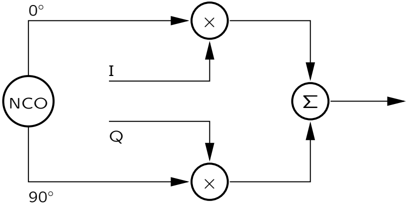

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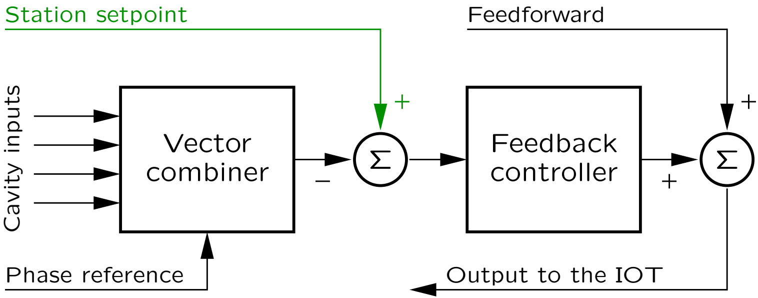

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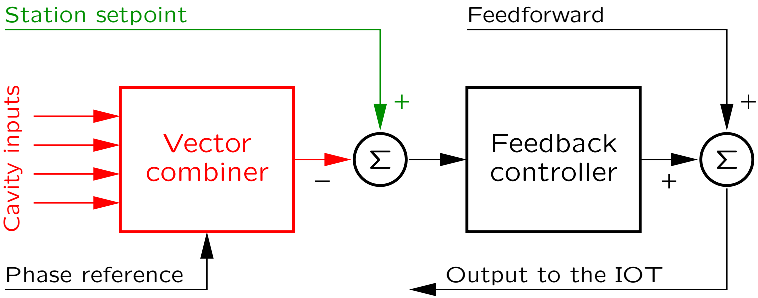
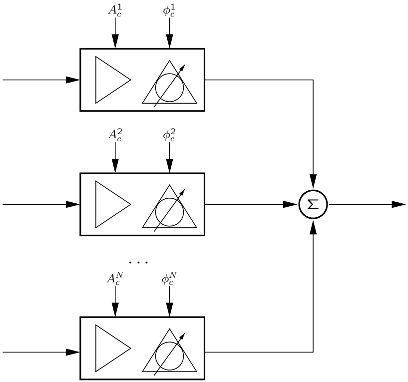


Vector Combiner



- Uses multiple gain/phase blocks.
- Per cavity amplitude and phase adjustments.
- Common-mode phase adjustment:
  - Track reference phase;
  - Adjust feedback loop phase shift.

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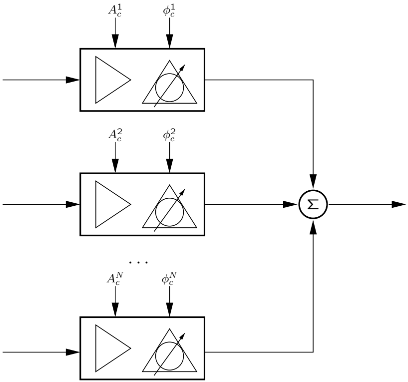

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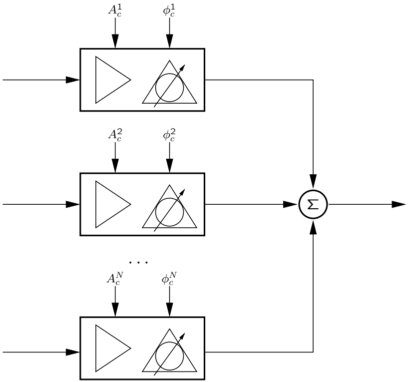

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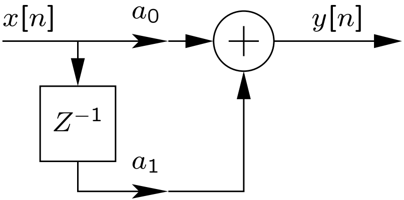
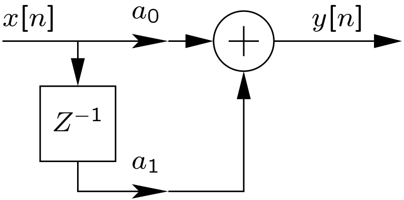


- Two-tap FIR filter.
- θ is the IF phase advance per sampling period.

Coefficients

$$\begin{bmatrix} 1 & \cos\theta \\ 0 & \sin\theta \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \end{bmatrix} = G \begin{bmatrix} \cos\phi \\ \sin\phi \end{bmatrix}$$

Gain/phase Block



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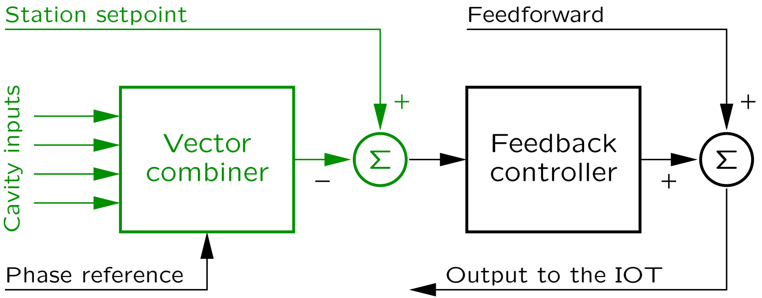

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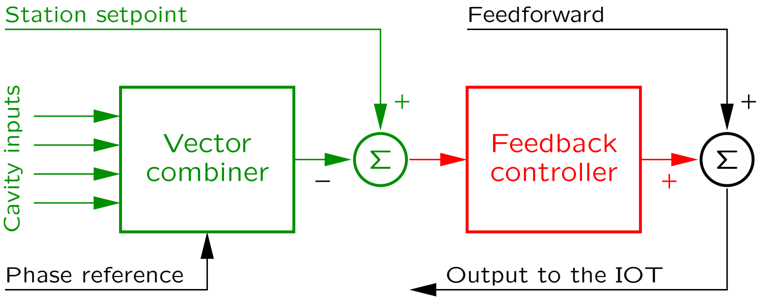
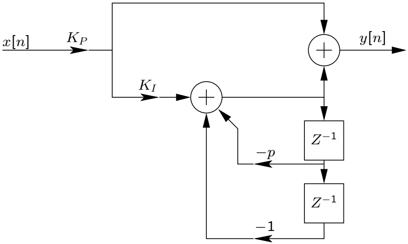


Feedback Controller



- Proportional/integrator (PI) response.
- Processing at IF - AC integrator.
- Critically stable pole at IF.
- Coefficient p depends on IF as $2\cos\theta$.

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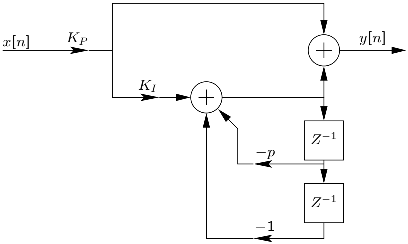

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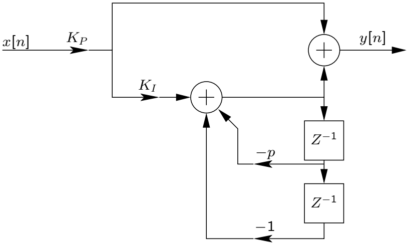

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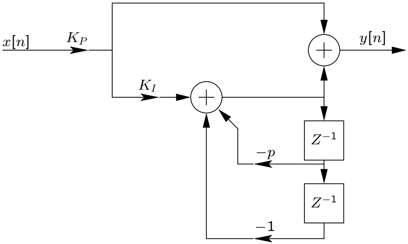

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Cavity Frequency Detection

- In a pulsed machine it is possible to measure cavity frequency and Q on a pulse-by-pulse basis.
- After power source drive is turned off, cavity field shows natural decay.
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What is Included and What is Left Out

- Included:
  - Tuneable LLRF controller;
  - ADC quantization and noise;
  - IOT frequency response;
  - IOT saturation;
  - IOT gain modulation by power supply;
  - Cavity frequency estimation.
- Not implemented:
  - Beam loading;
  - IOT phase shift modulation by power supply;
  - Signal path filters;
  - Automatic vector sum setup.

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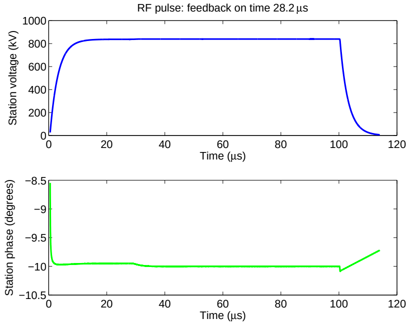
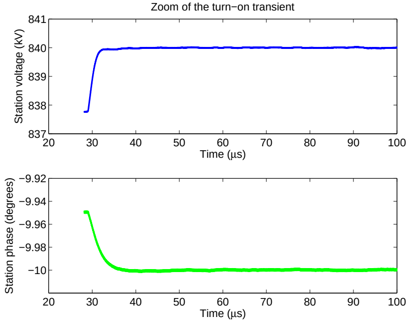
No Frequency Offset, No Errors



- Simulate for 100 μs to save time.
- Station setpoint 840 kV, -10 degrees.
- Feedback turn-on is well controlled, settling by 40 μs.
- Residual errors 0.004 % amplitude, 0.002° phase.

No Frequency Offset, No Errors



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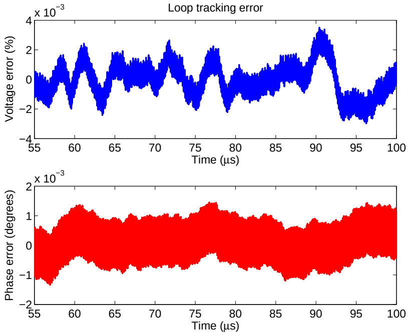

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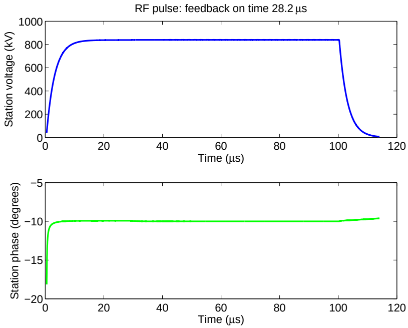
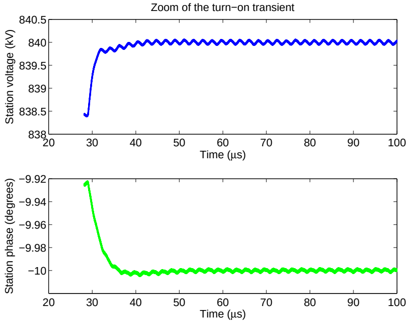
Frequency Offset -2 MHz, No Errors



- Feedback turn-on is slightly slower, settles by 50 μs.
- Residual errors 0.005 % amplitude, 0.002° phase.

Frequency Offset -2 MHz, No Errors



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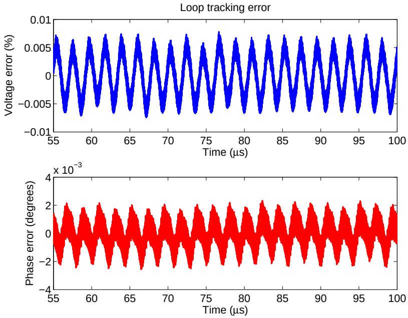

- Feedback turn-on is slightly slower, settles by 50 μs.
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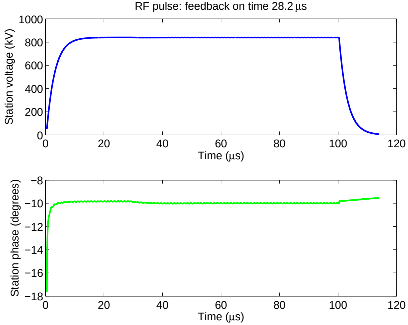
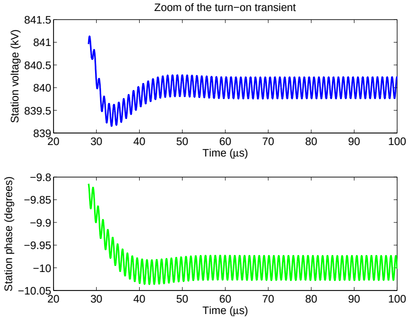
Frequency Offset -4 MHz, No Errors



- Some overshoot in feedback settling, damped by 60 μs
- Residual errors 0.03 % amplitude, 0.03° phase.
- Low-level oscillation is likely a simulation artifact, needs further investigation.
- At this offset we are outside IOT bandwidth, so loop gain and drive signal must be raised by 6 dB.

Frequency Offset -4 MHz, No Errors



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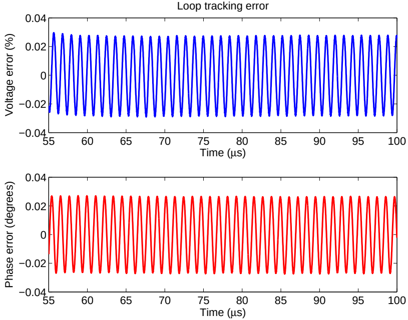

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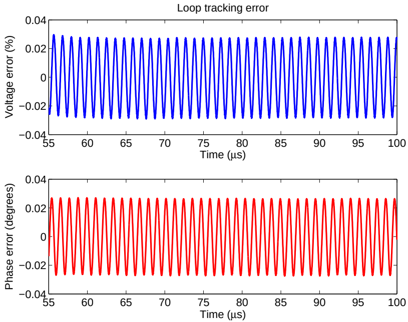

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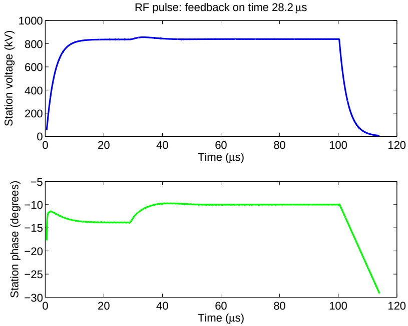
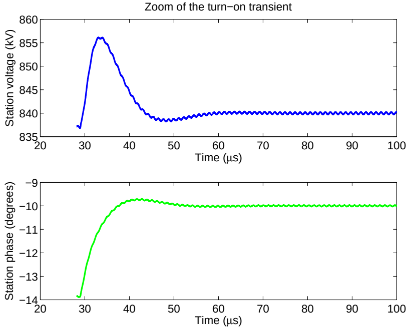
dimtel

Frequency Offset -4 MHz, 10 kHz Cavity Tuning Errors



- Cavity tuning errors cause open-loop amplitude and phase errors.
- Some overshoot in feedback response, damped by 60 μs
- Residual errors 0.03 % amplitude, 0.03° phase.
- Average tuning error of 5 kHz, much larger than realistically expected.

Frequency Offset -4 MHz, 10 kHz Cavity Tuning Errors



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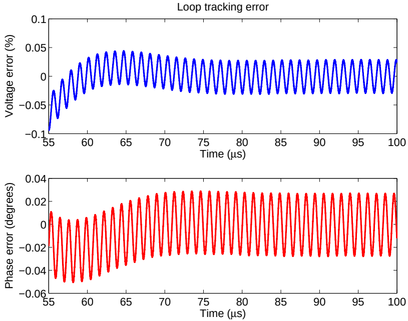

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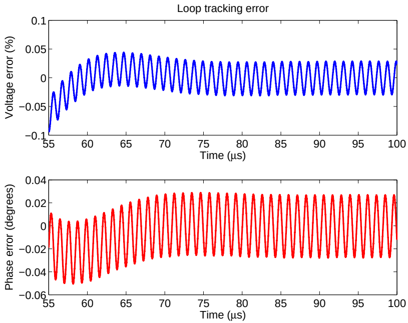

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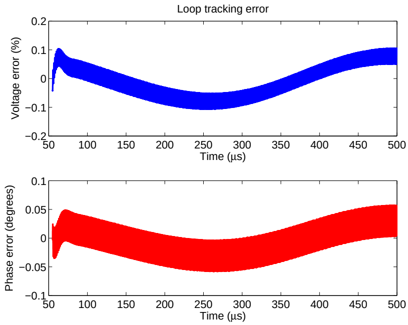
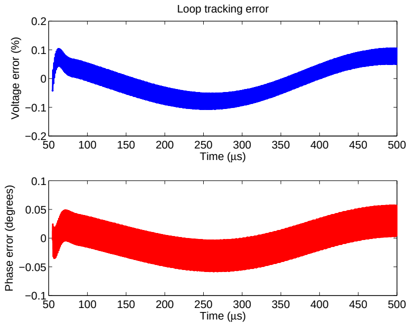
Frequency Offset -4 MHz, 10 kHz Cavity Tuning Errors, HVPS Ripple



- 1% HVPS ripple at 2 kHz.
- Longer pulse simulated to map out the response.
- Residual errors 0.1 % amplitude, 0.05° phase.

Frequency Offset -4 MHz, 10 kHz Cavity Tuning Errors, HVPS Ripple



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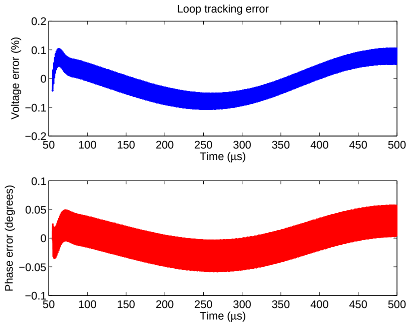

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Summary

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- Modeling results show the feasibility of this architecture.
- With the proposed approach the RF system can be expected to easily meet current performance targets (0.3%, 0.3°).
- Trigger jitter effects must be carefully considered for frequency offset operation.

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