LLRF for ESS – Modelling and Control

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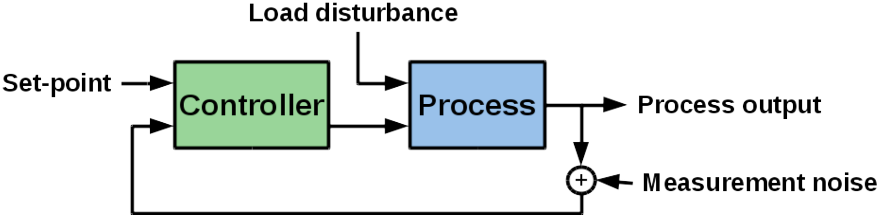
What is Control?

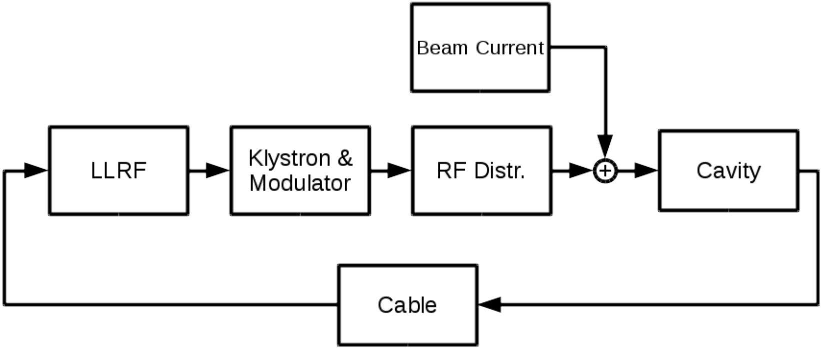
Accelerator Controls: Providing computer environment that allows remote access to accelerator hardware // . . . [3]

EPICS

Automatic Control: Modelling and controller design for dynamic systems to obtain desired performance.



What this talk will be about



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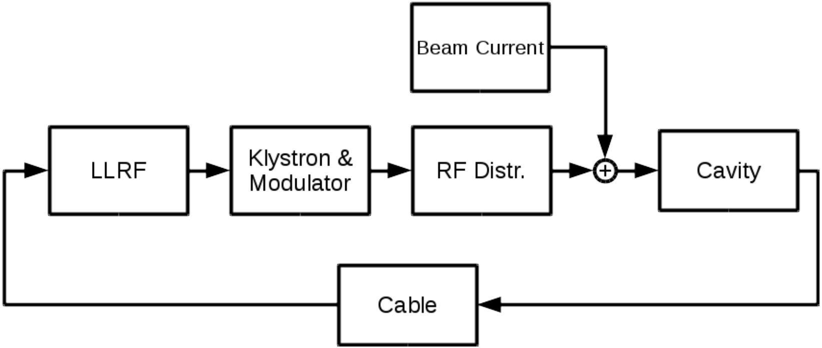
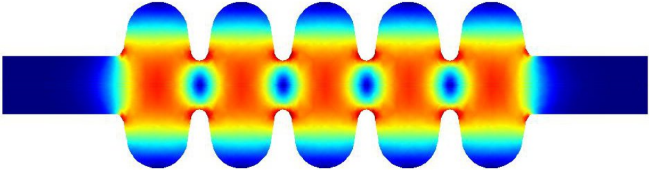


Overview

- RF System Modelling
- Analysis from a control perspective
  - Prediction of achievable cavity field stability
  - What factors limit/affect achievable performance

Cavity Model [2]



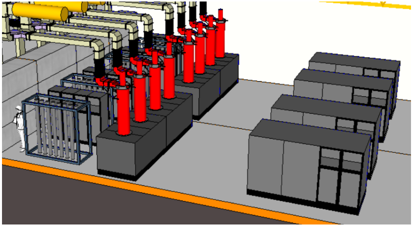
$$\frac{d}{dt}\begin{bmatrix} V_{\text{Re}} \\ V_{\text{Im}} \end{bmatrix} = \begin{bmatrix} -\omega_{1/2} & -\Delta\omega \\ \Delta\omega & -\omega_{1/2} \end{bmatrix} \begin{bmatrix} V_{\text{Re}} \\ V_{\text{Im}} \end{bmatrix} + \begin{bmatrix} R_L\omega_{1/2} & 0 \\ 0 & R_L\omega_{1/2} \end{bmatrix} \begin{bmatrix} I_{\text{Re}} \\ I_{\text{Im}} \end{bmatrix}$$

- $\mathbf{V}$ - cavity voltage
- $\mathbf{I} = 2\mathbf{I_g} + \mathbf{I_b}$ = klystron current + beam current
- $\omega_{1/2}$ - cavity bandwidth
- $\Delta\omega$ - detuning of the cavity

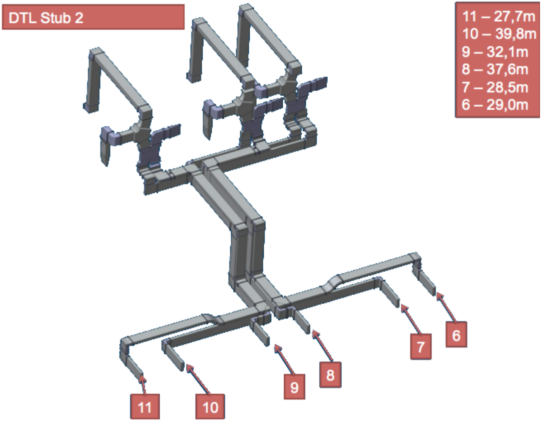
Klystron & Modulator Model

Klystron dynamics are modelled by 1st order low-pass filter with 1.9 MHz bandwidth.

Each % of modulator voltage variation induces >10° phase shift and 1.25% amplitude change in the klystron output [1].



RF Distribution & Cables



Time delays:

Klystron → Cavity (Waveguide)	40 m / 0.68c = 175 ns
Cavity Probe → LLRF (Coax.)	40 m / 0.82c = 145 ns
LLRF → Klystron (Coax.)	10 m / 0.82c = 40 ns
	360 ns

LLRF

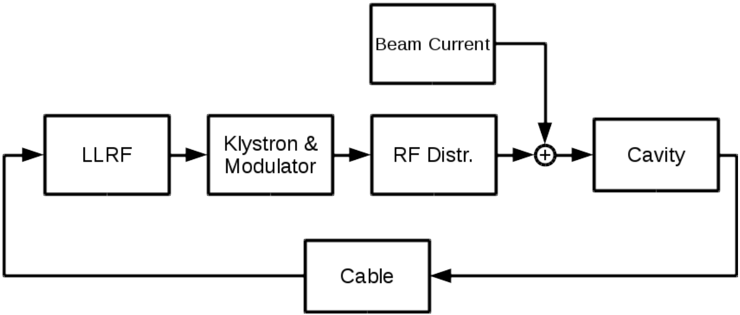
Control algorithm execute @ 100 MHz on FPGA

Analog/Digital Converter Noise: 60 dB SNR

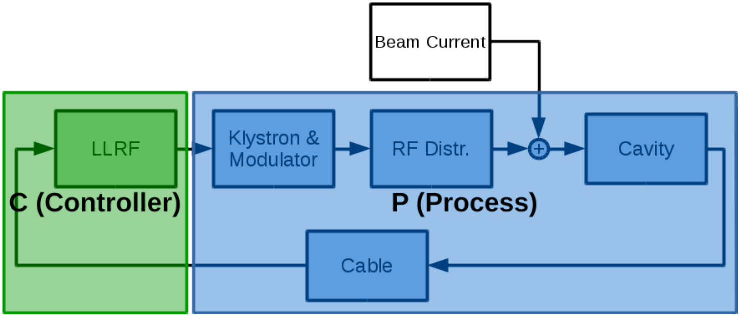
Downsampling (improves SNR 10 dB) modelled as 1st order filter with 5 MHz bandwidth

Time-delays	
ADC latency	130 ns
25 FPGA cycles	250 ns
DAC delay	90 ns
Total	490 ns

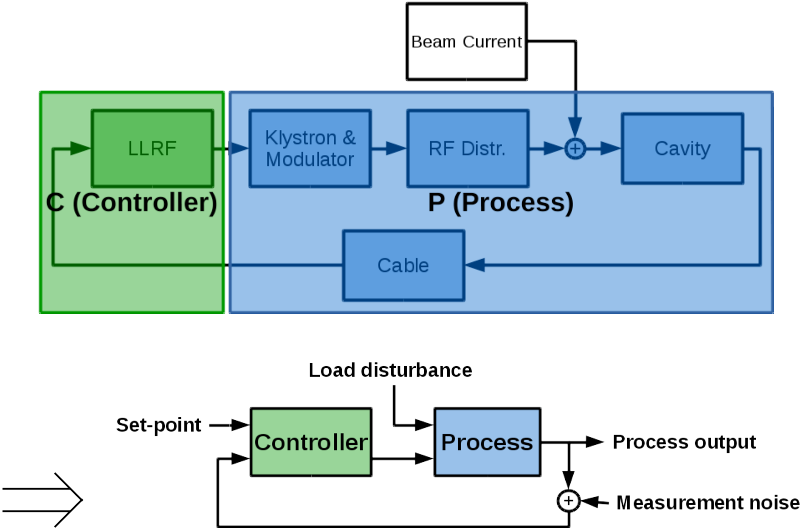
Putting things together



Putting things together



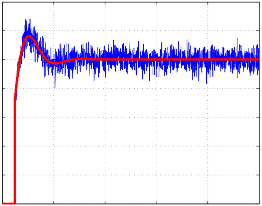
Putting things together

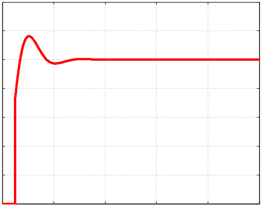


Analysis from a control perspective

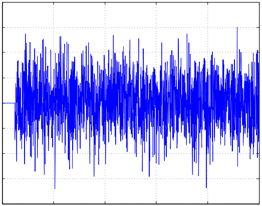
Control Methodology

Flat-top operation is considered. Disturbances are either repetitive or random.





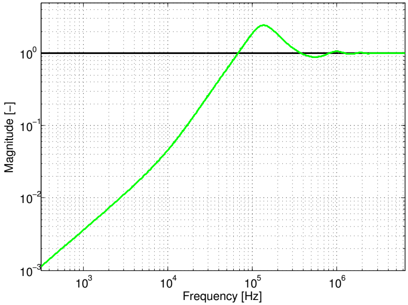
Repetitive disturbance
-> Iterative Learning Control



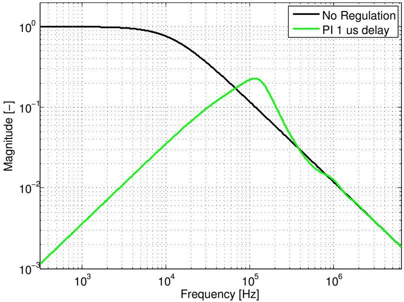
Random disturbance
-> Feedback

Disturbance Rejection using Feedback

$\frac{1}{1+PC}$ - Sensitivity Function



$\frac{P_{\text{Cav}}}{1+PC}$ - Disturbance Rejection



Disturbance Rejection using Feedback

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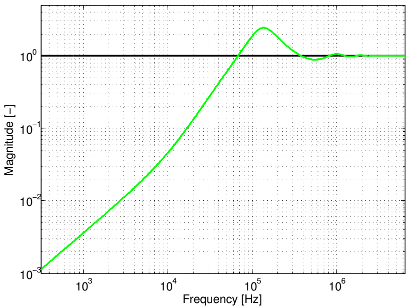
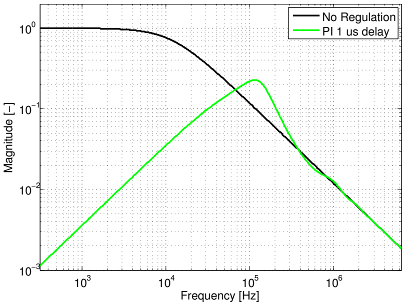




Bode's Integral Theorem,

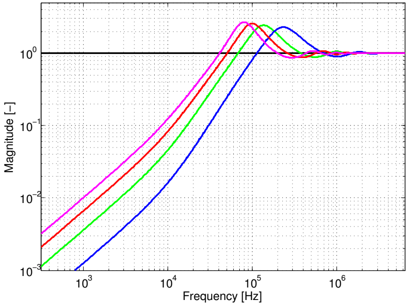
$$\int_0^\infty \ln \frac{1}{1 + P(i\omega)C(i\omega)} \mathrm{d}\omega = 0$$

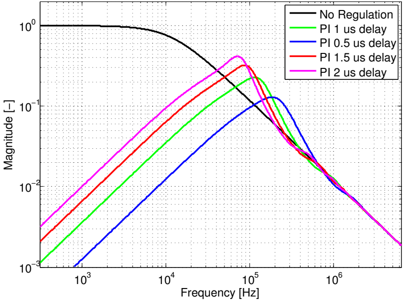
puts fundamental limitation on achievable control performance.

Disturbance Rejection using Feedback

$\frac{1}{1+PC}$ - Sensitivity Function

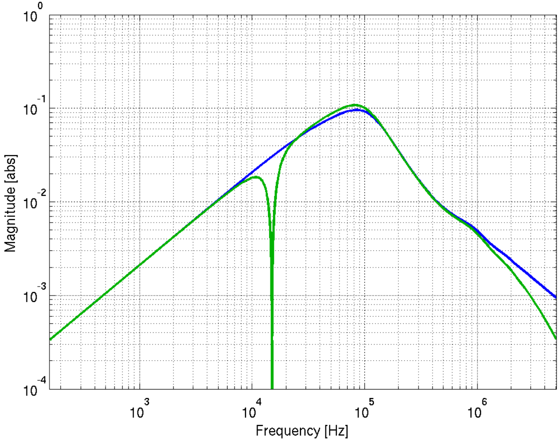
$\frac{P_{\text{Cav}}}{1+PC}$ - Disturbance Rejection





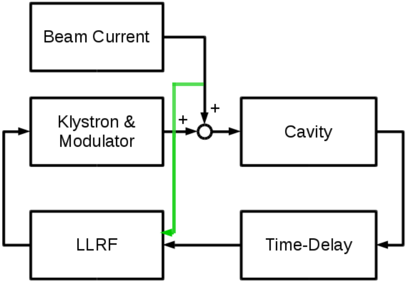
Loop delay has large impact on achievable performance!

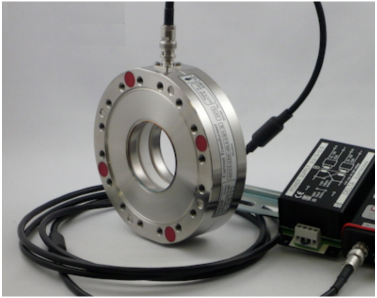
Frequency Specific Disturbance Rejection



Increased controller gain at a specific frequency gives improved narrow-band disturbance rejection. Small degradation for other frequencies.

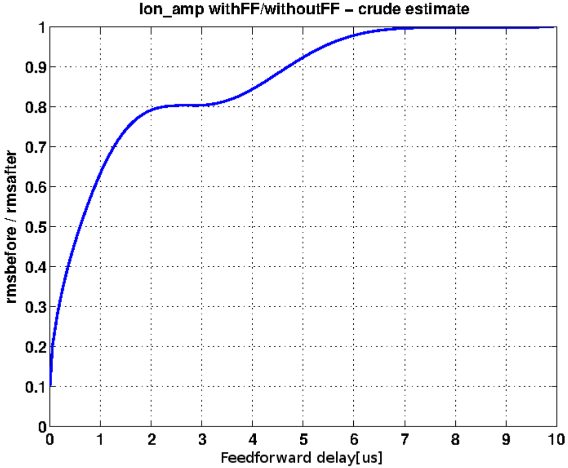
Feed-Forward of Beam Current Ripple (1/2)





Accessing the measurement signal from the Beam Current Monitors seems feasible.

Feed-Forward of Beam Current Ripple (2/2)



Potential performance gain from using feed-forward from beam current monitor.

Assumptions: BCM BW = 1 MHz, good SNR for the BCM. Ion Source BW = 0.65 MHz, Cavity BW = 12 kHz, Loop-delay 1us

Summary

- There are limitations to what can be achieved by control.
- Time delays, beam current ripple and klystron ripple are the main performance limitations.
- Good disturbance rejection for
  - Low frequencies (< 1 kHz)
  - High frequencies (> 1 MHz)
  - Narrow-band disturbances (with modified controller)
- Two methods for improved disturbance suppression were presented.

Thanks!

Thanks to the following people for providing input to the presentation

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- Prof. Anders Karlsson, Gabrielle, Renato @ EIT, Lund University
- Hooman Hassanzadegan @ ESS
- My supervisors Bo Bernhardsson, Anders J Johansson, Rolf Johansson

References

[1] R. Zeng A. Johansson K. Rathsman S. Molloy.
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2011.

[2] Thomas Schilcher.
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Joint Universities Accelerator School, 2015.