Iterative Learning Control

(or Adaptive Feed Forward)

Iterative Learning Control
(Adaptive Feed Forward)

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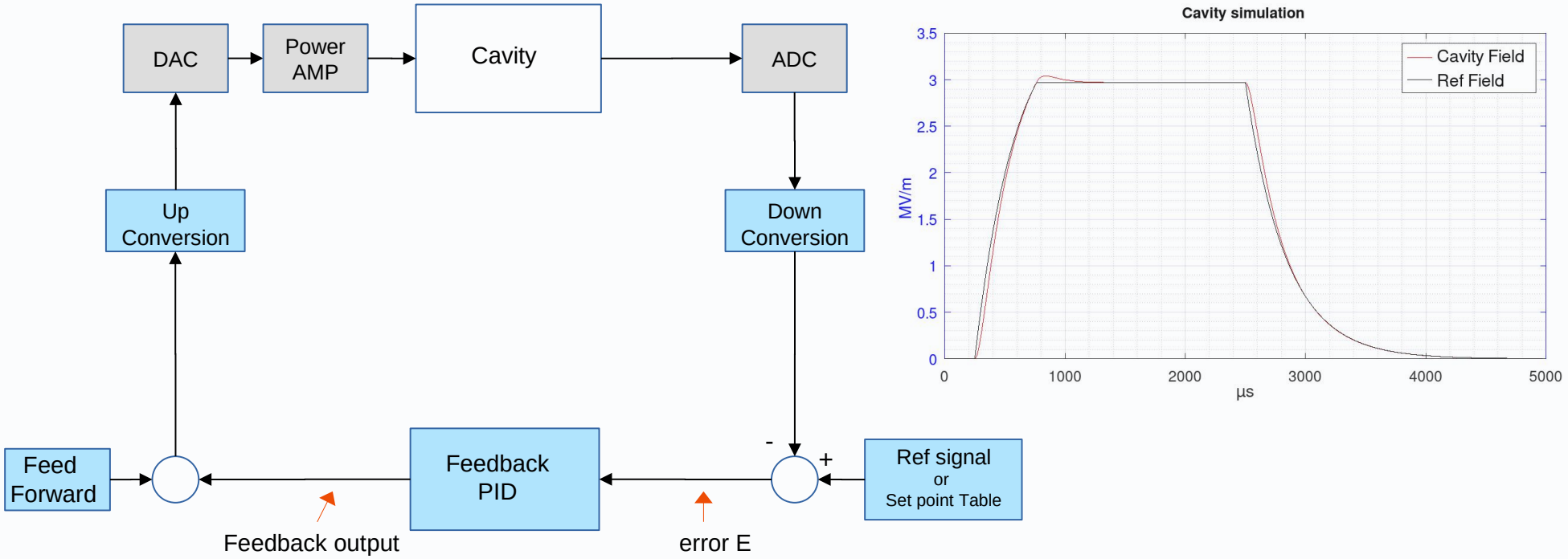
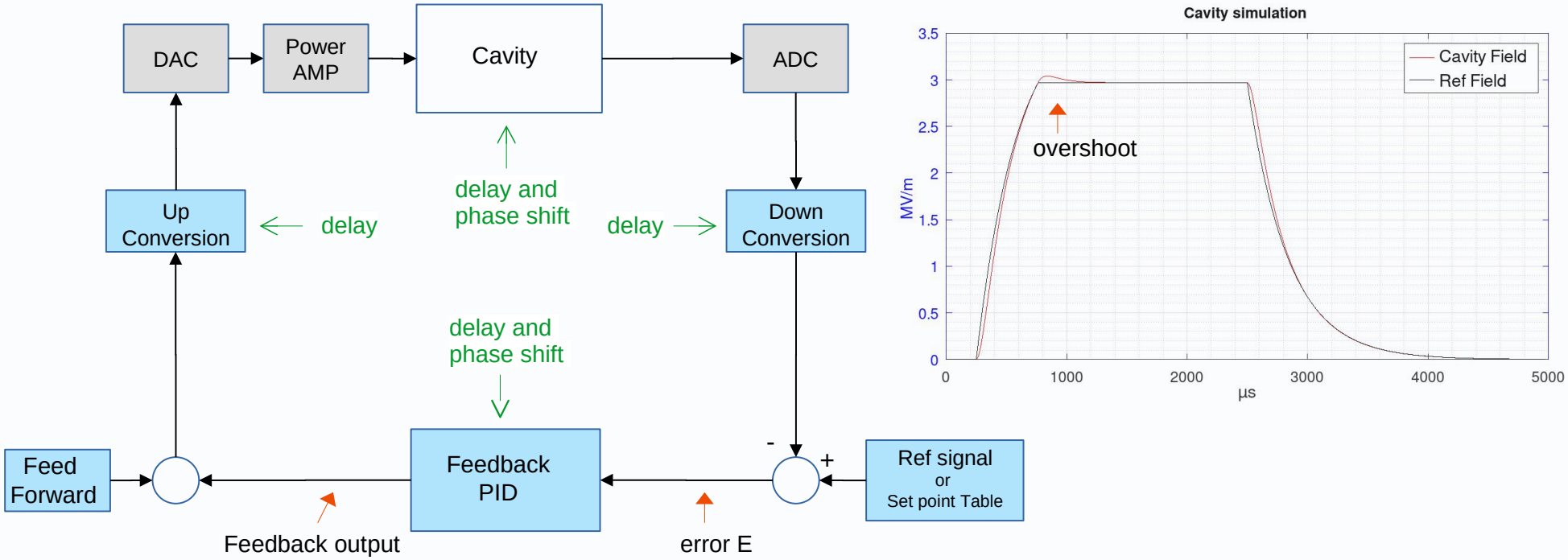
2) Basic Idea
3) First method – Time reversed signal
4) Second method – Inverse Cavity
5) Some Theory
6) Results - Compare different Methods

Iterative Learning Control
Introduction



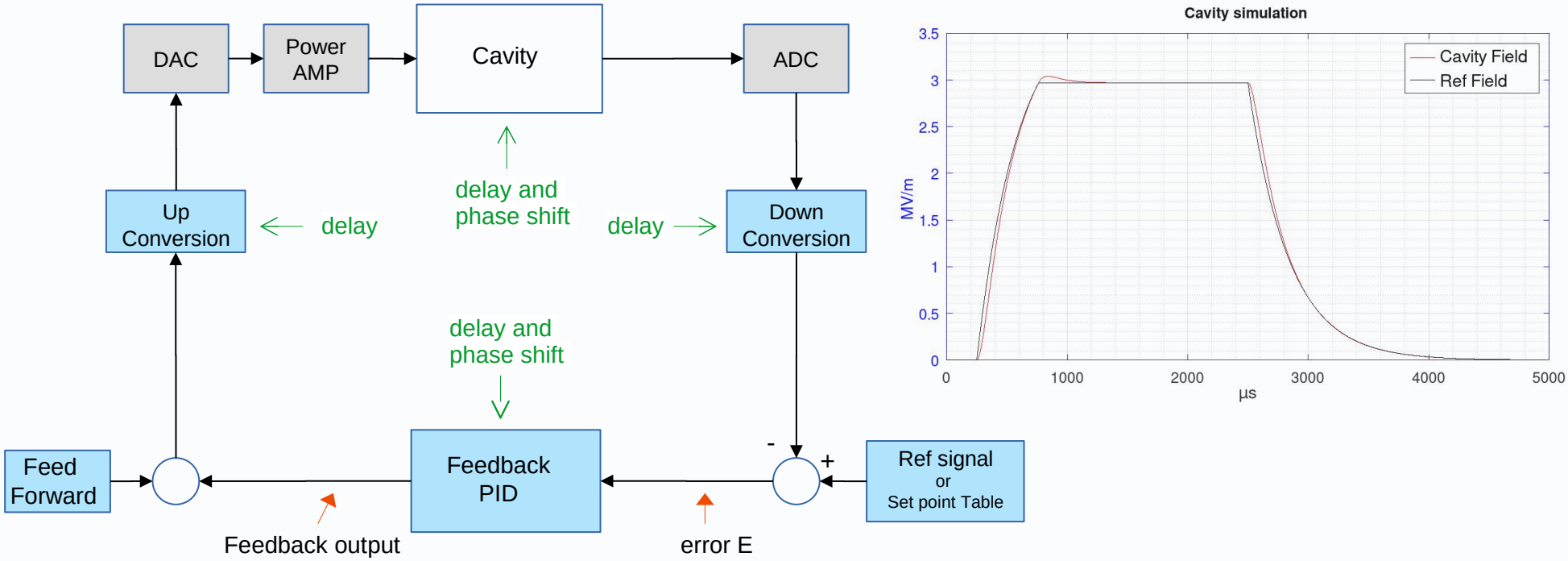
Iterative Learning Control
Introduction



The Problem:

The feedback output signal is delayed and/or phase shifted.
Also the error signal E is delayed and/or phase shifted

Iterative Learning Control
Introduction



Introduction: What is Iterative Learning Control ?

Quote ”The main idea in iterative learning control is to utilize the situation that the system to be controlled will carry out the same operation several times. It will then be possible to gradually improve the performance of the control system by using the results from one operation when choosing the input for the next operation”

Quote ”Errors are repeated when trajectories are repeated

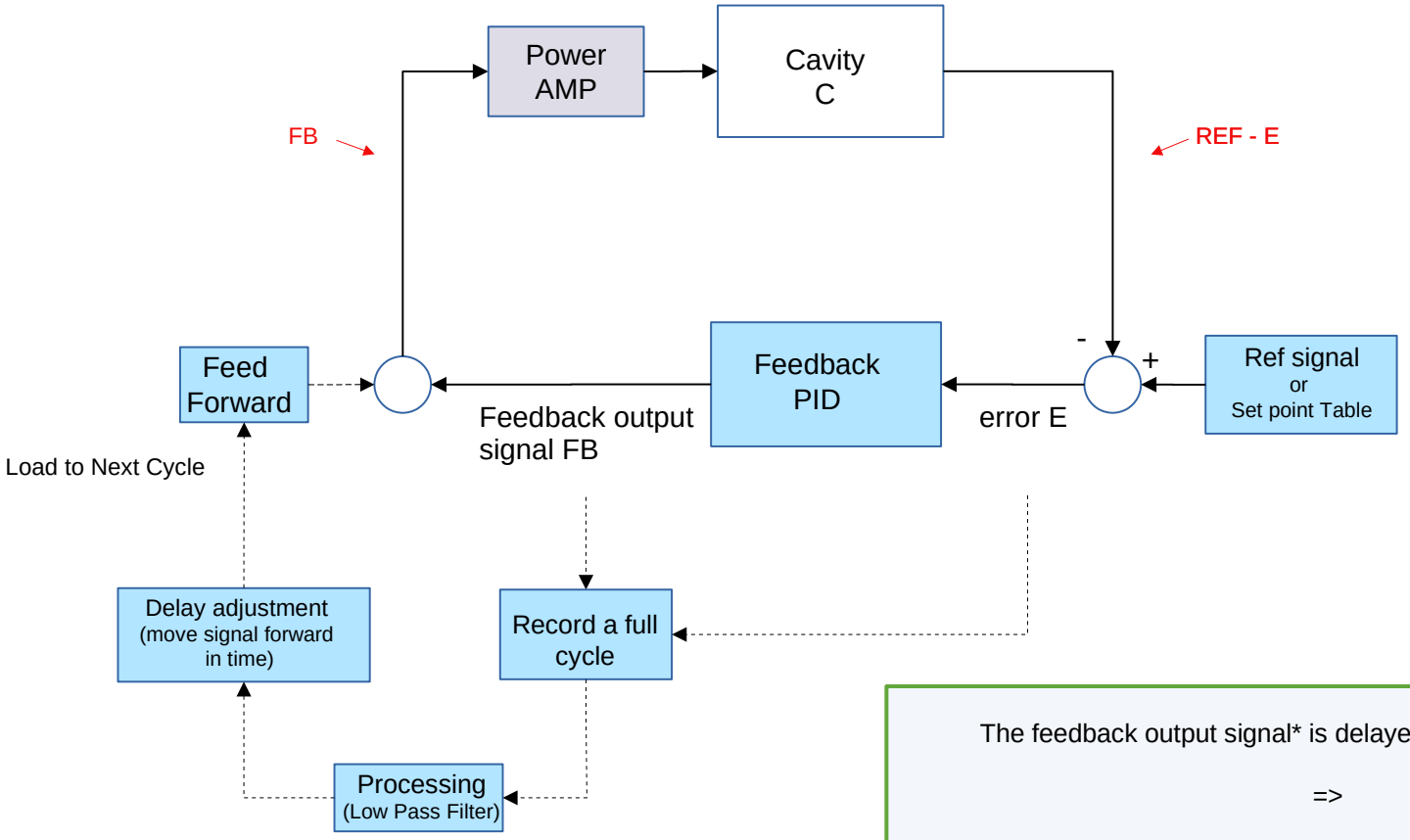
Each time the system is operated it will see the same overshoot, rise time, settling time and steady state error.

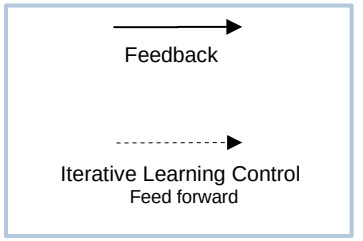
Iterative learning control attempts to improve the transient response by adjusting the input to the plant (cavity) during future system operation based on the errors observed during past operation”

ILC will be used at ESS in Lund

ILC has been implemented in the Freia LLRF system for test purposes

Iterative Learning Control
Basic Idea





The feedback output signal* is delayed and/or phase shifted.

=>

Record the feedback output signal in one cycle. Move the recorded signal forward in time to compensate for the time delay. Compensate also for the phase shift if possible

=>

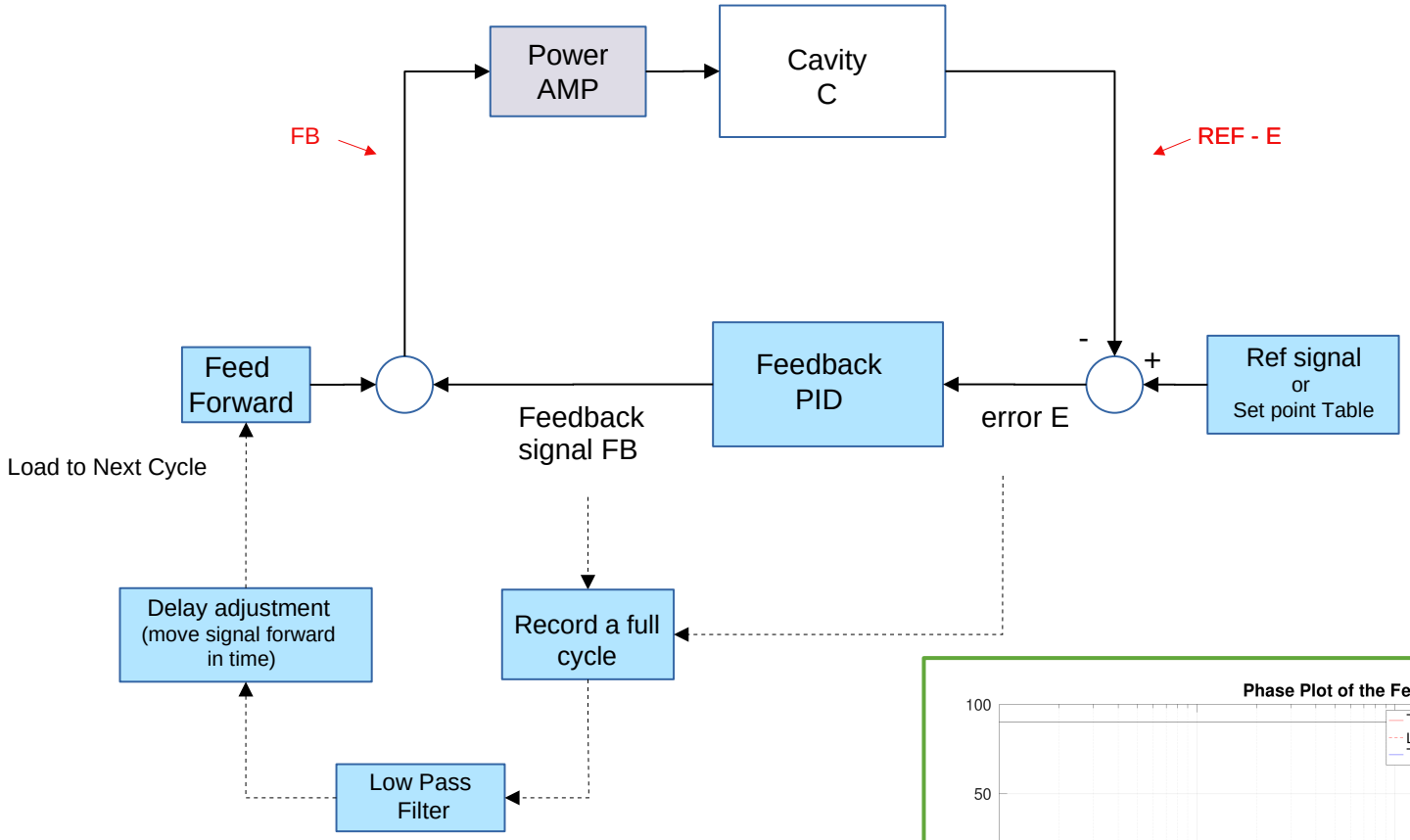
Store in the Feed forward buffer and Apply in the next cycle

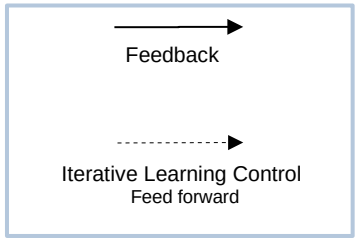
=>

Repeat (Iterate) cycle by cycle to make the error smaller and smaller

* Possible to use the error signal E instead or use both signals

Iterative Learning Control
First Method



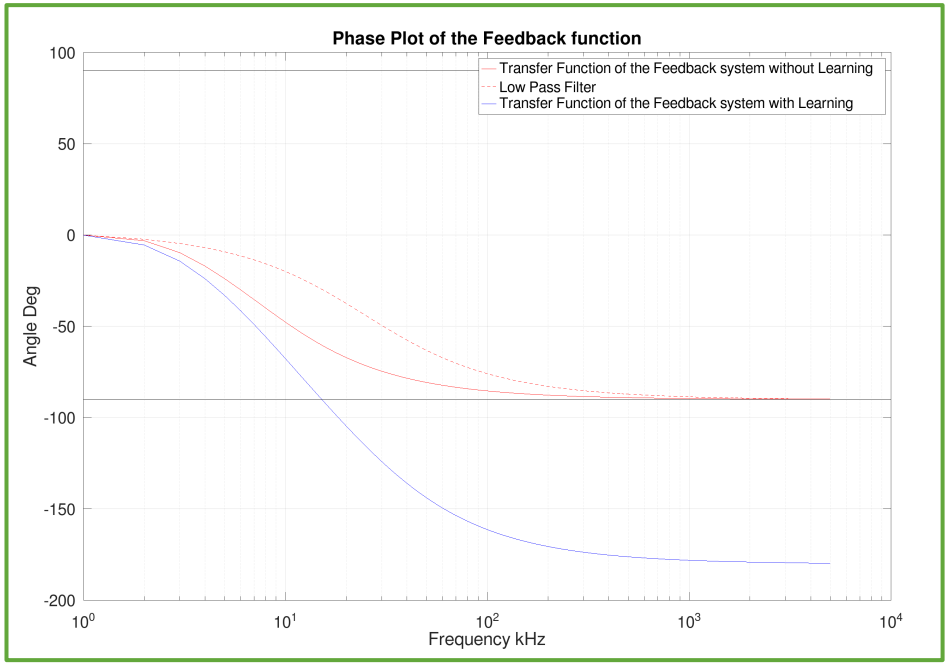


Try to use a Low Pass Filter => Problem

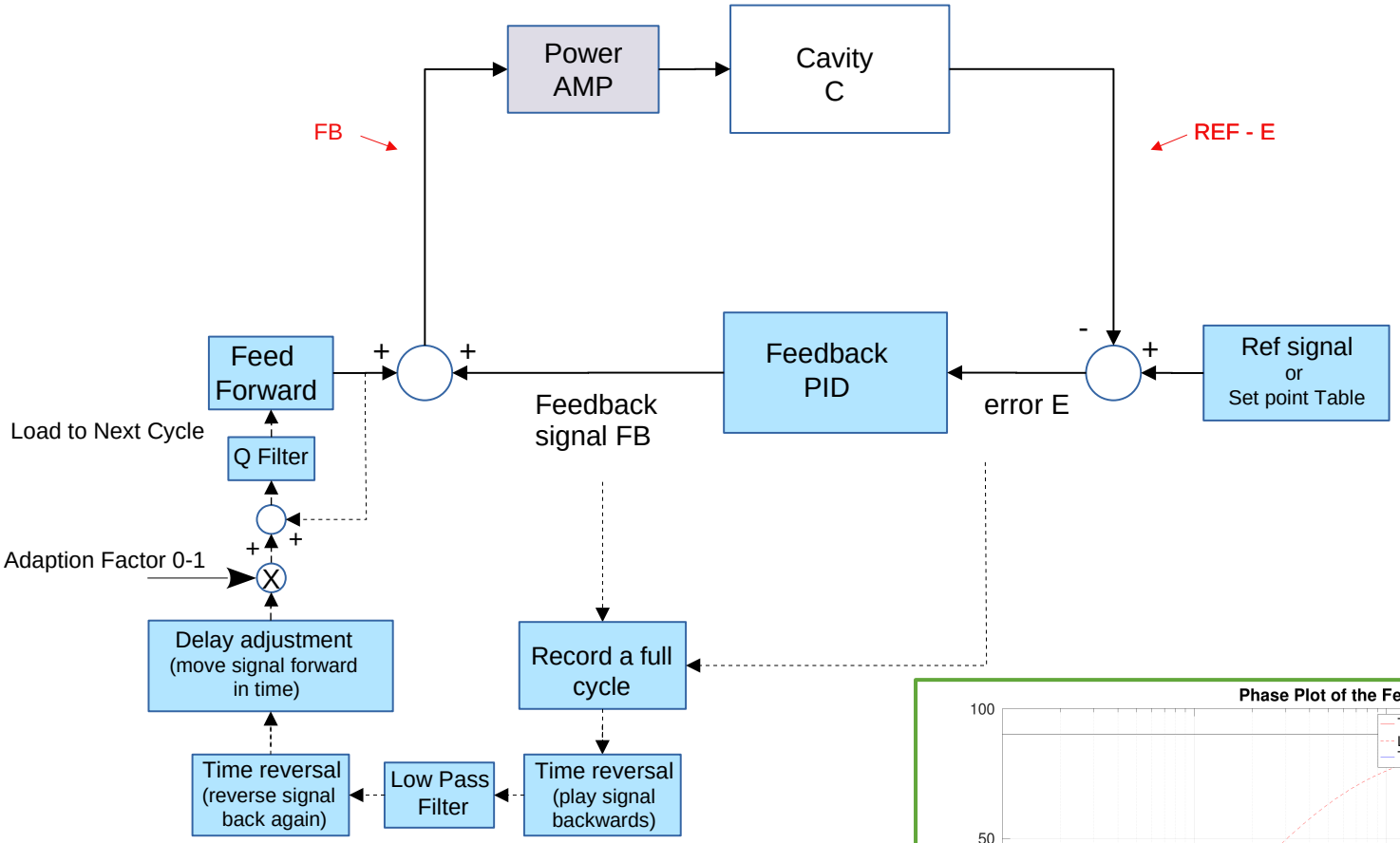
The result of the feedback system is that the phase of the signal is shifted in the negative direction. Sending the same signal through a LP filter will shift the phase even more in the negative direction

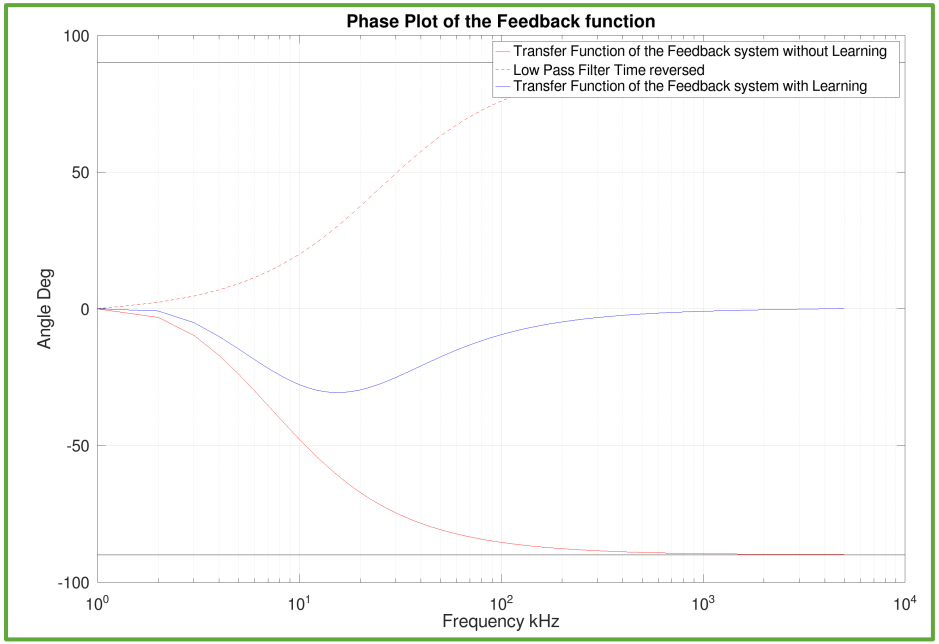
=>

Instability



Iterative Learning Control
First Method





Solution:

Time reverse the recorded signal before it is sent to the LP filter
And reverse the signal back to normal time again after the filter

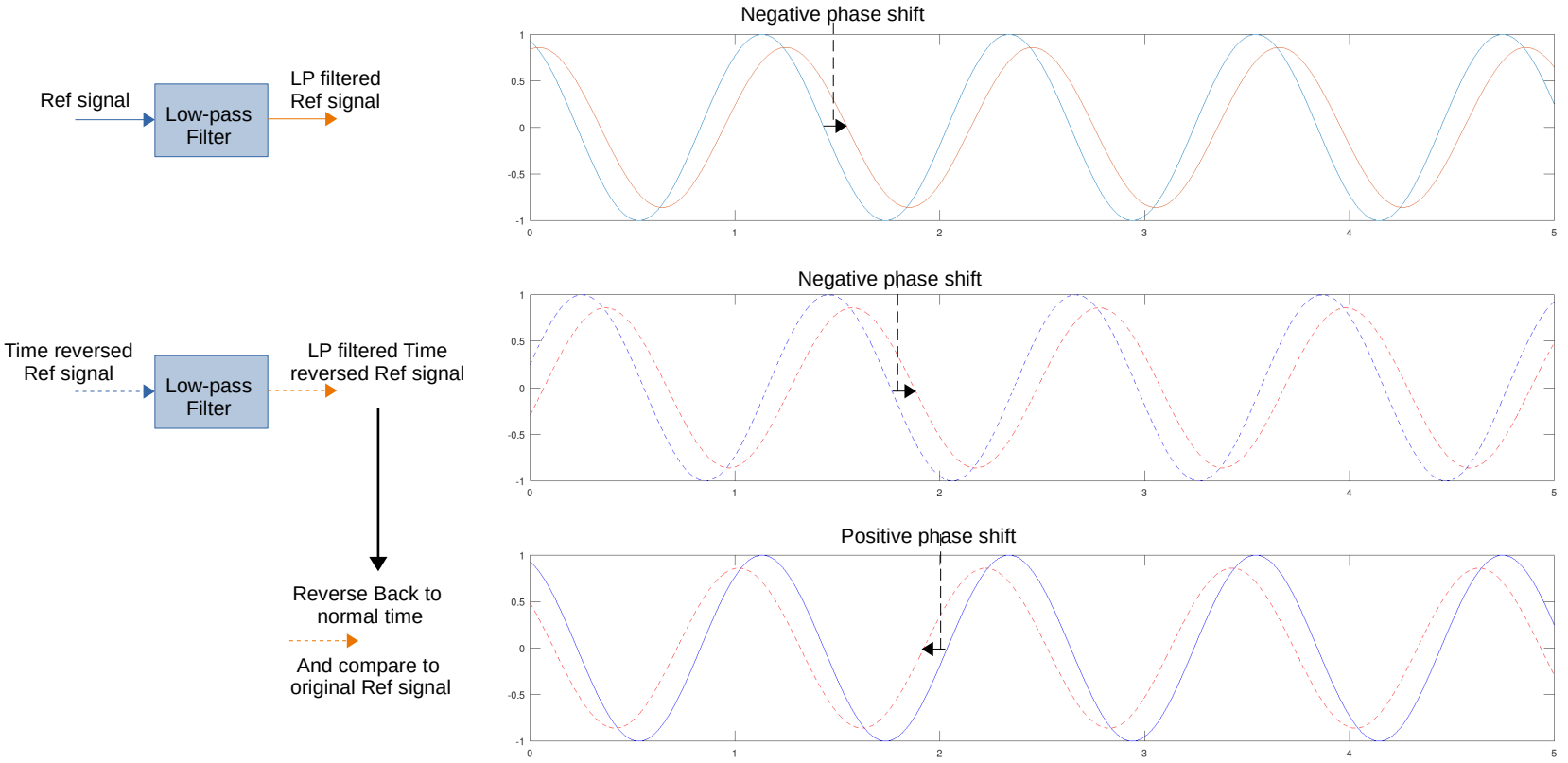
=>

The phase of the signal will be shifted in the positive direction

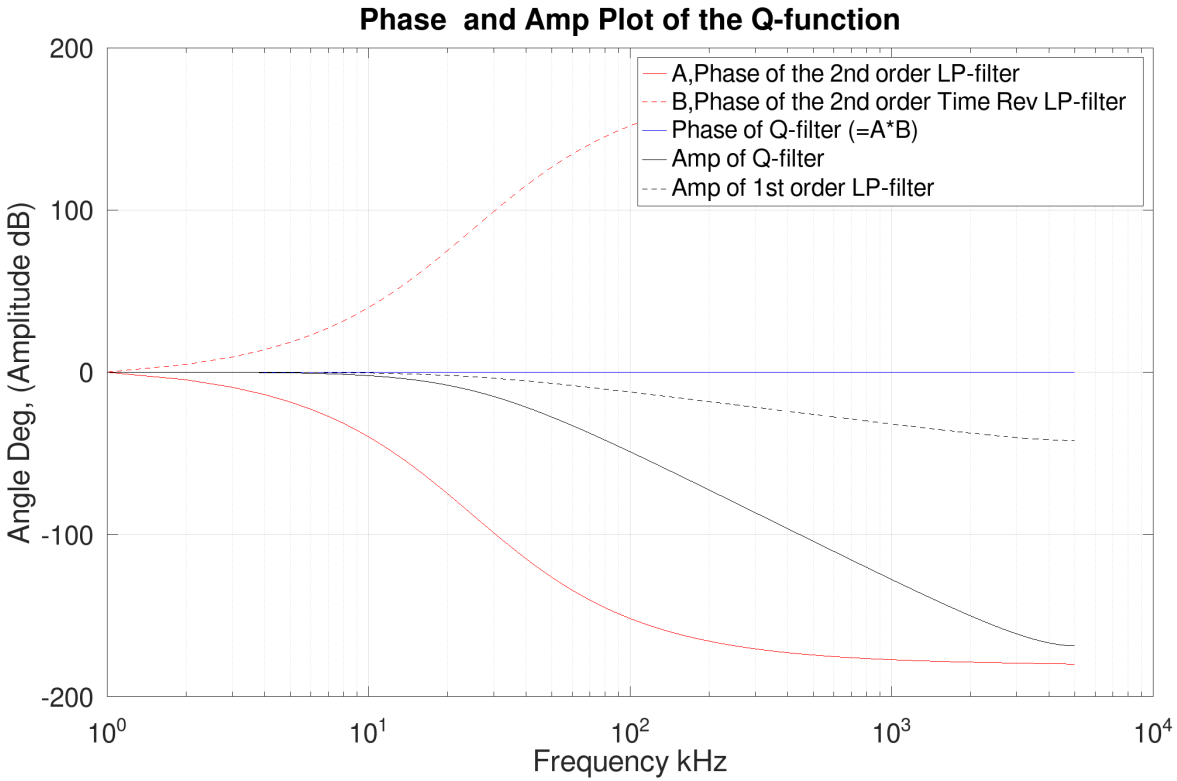
=>

Improved stability

Iterative Learning Control
First Method

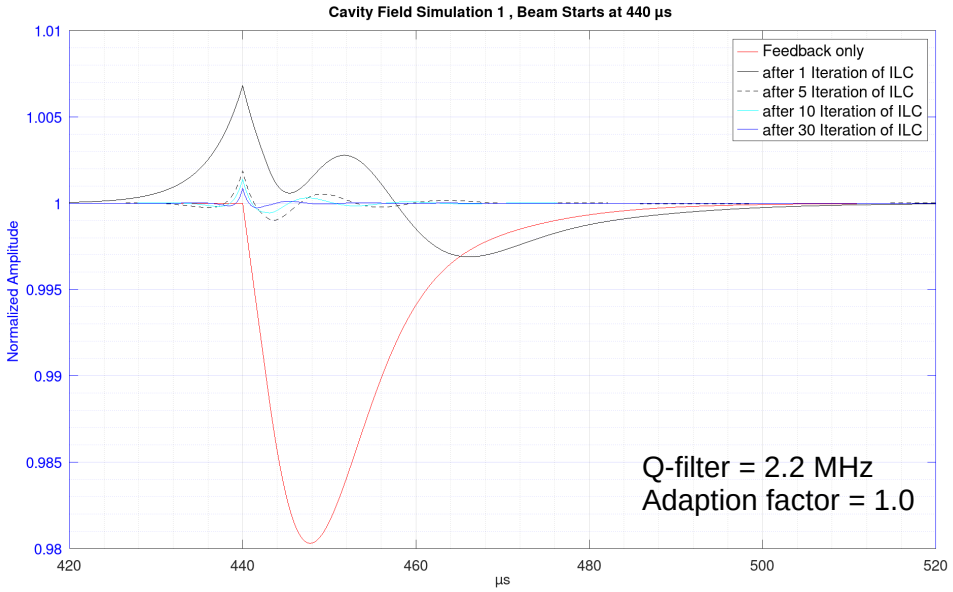


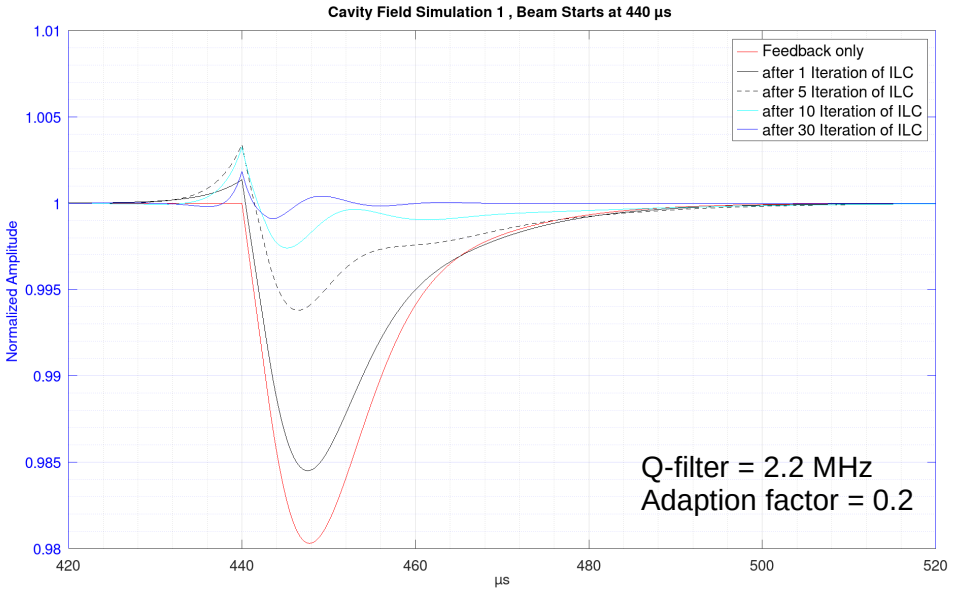
Iterative Learning Control
First Method



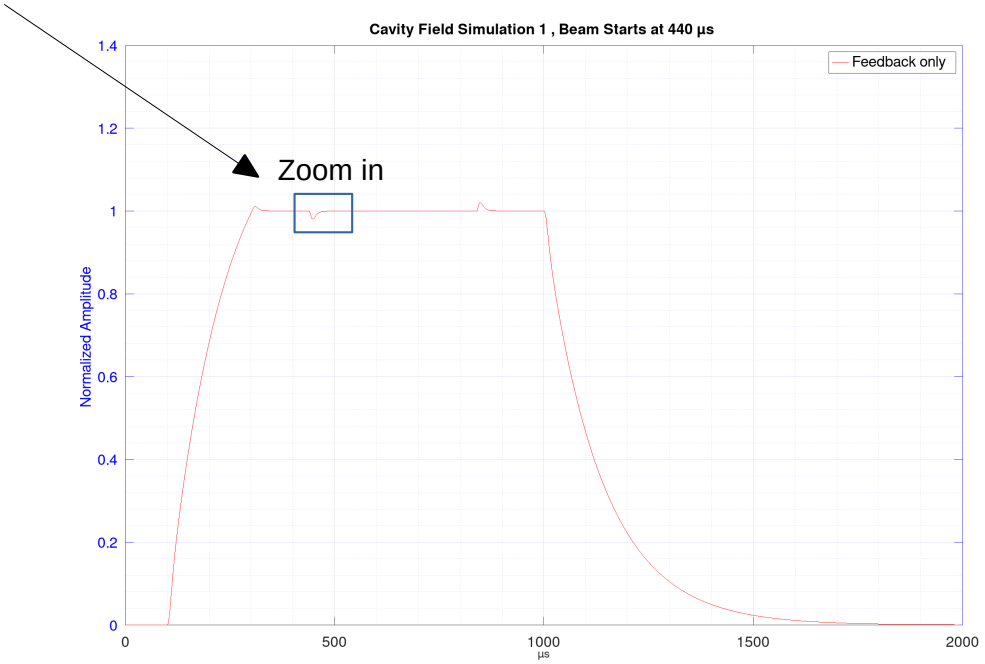
The Q-Filter

Iterative Learning Control
First Method Result

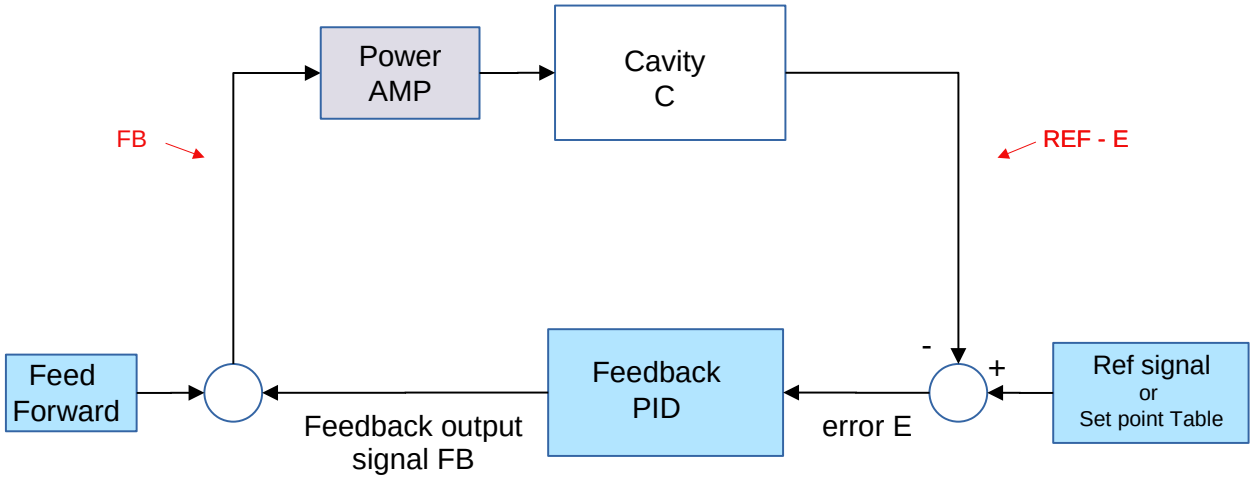




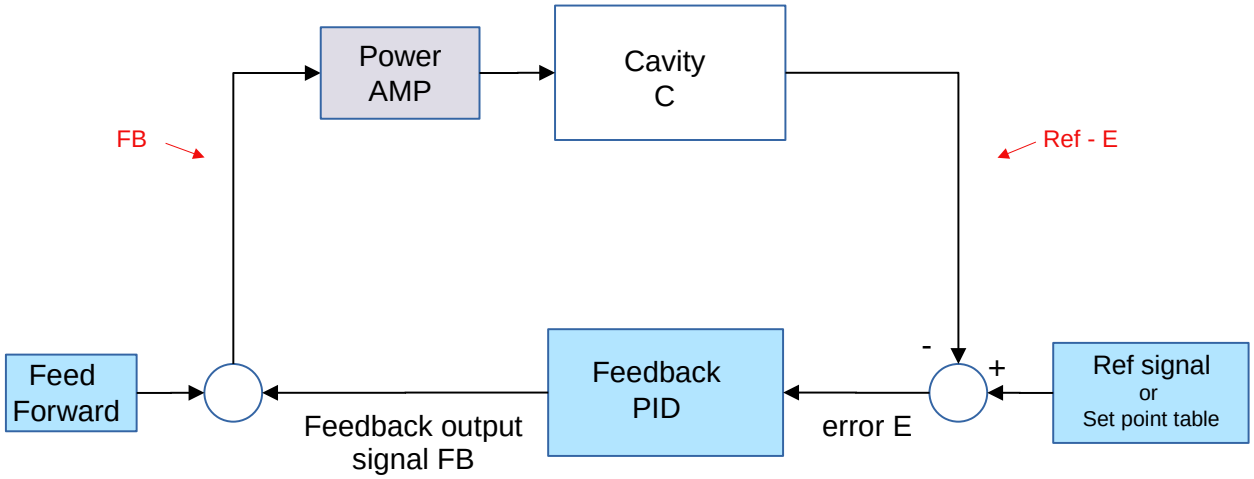
Field error from Beam arrival



Iterative Learning Control
Second method



Iterative Learning Control
Second method



We now have that an Input signal FB sent to the cavity gives an Output equal to Ref - E, that is:

FB => Ref – E (1)

What signal do we need to add to the input signal FB in the next cycle in order to make the error E disappear, in the next cycle. In theory (if the cavity is linear) we have after adding a signal A:

FB + A => Ref – E + C*A (2)

Where C is the cavity response function.

So in order to make the error E disappear:

$- E + C*A = 0$

Or

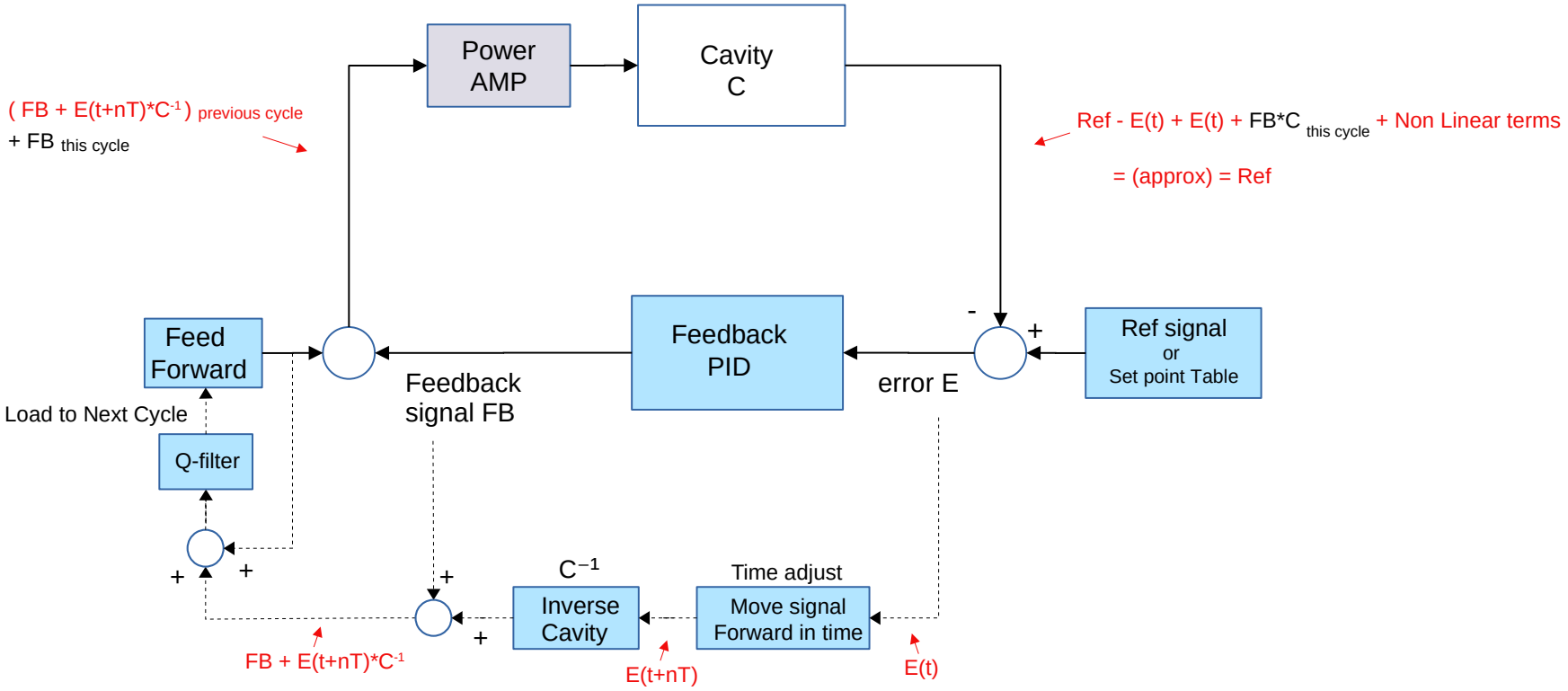
$C*A = E \Rightarrow A = C^{-1}*E$ (3)

This means that we need to store

$FB + C^{-1}*E$

in the feed forward buffer for the next cycle.

Iterative Learning Control
Second method



Feedback output signal FB to Cavity => Ref + error E

FB*C => Ref + E

Store (FB + E(t+nT)*C⁻¹) in feedforward buffer to next cycle

First cycle;

$FB_{First}*C \Rightarrow Ref + E$ (FeedForward buffer empty)

Second Cycle;

$(FB_{First} + E*C^{-1}) * C + FB_{Second}*C =$

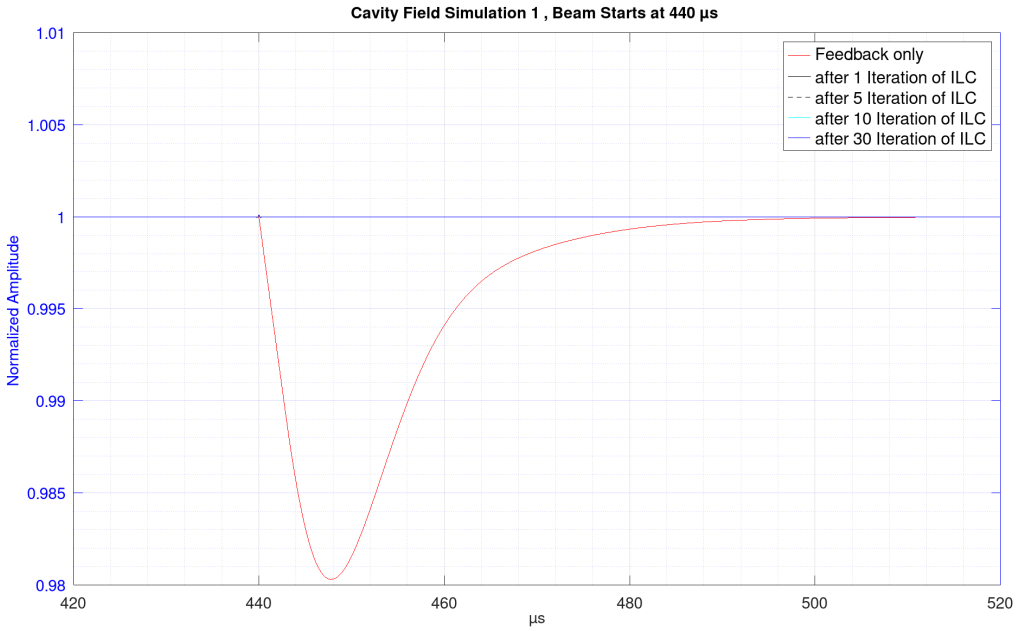
$FB_{First}*C + E*C^{-1}*C + FB_{Second}*C + NLT =$

Where NLT are nonlinear terms since the cavity is nonlinear

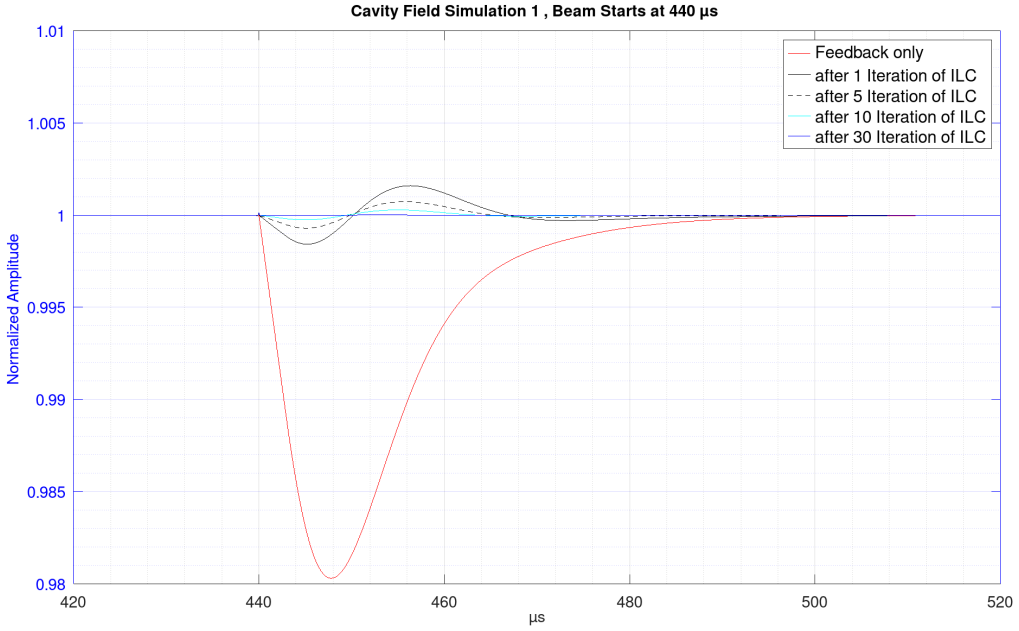
$Ref + E - E + FB_{Second}*C + NLT = Ref + FB_{Second}*C + NLT =$

= (approx) = Ref

Iterative Learning Control
Second method



Q-filter = 2.2 MHz
Adaption factor = 1.0
Error Parameter estimation +/- 0 %



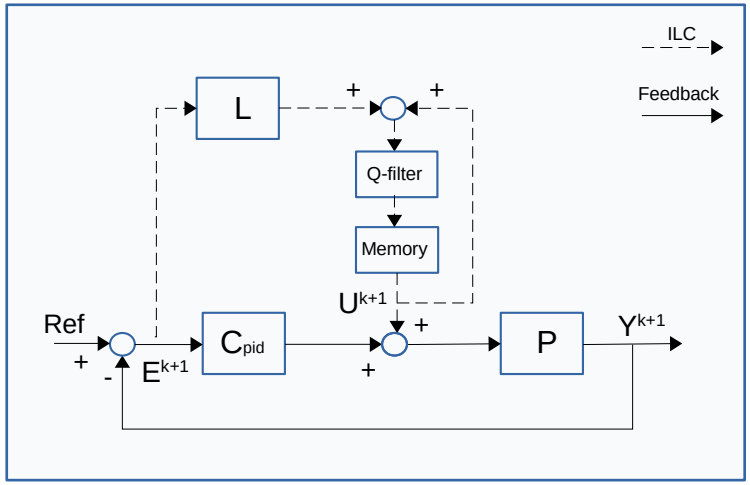
Q-filter = 2.2 MHz
Adaption factor = 1.0
Error Parameter estimation +/- 12 %

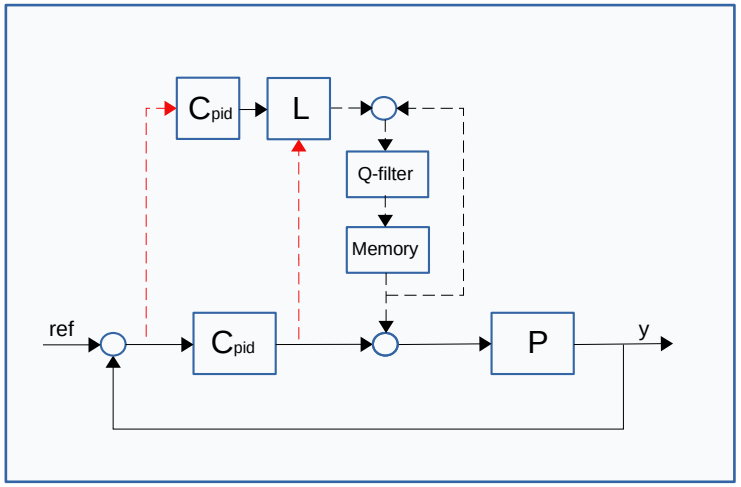
Iterative Learning Control
Theory

In Frequency Domain:

L(jω) = Learning function C(jω) = Feedback_PID P(jω) = Plant (Cavity) Memory = Feedforward Buffer

$E^k(j\omega)$ = Error in iteration k $U^k(j\omega)$ = Learning in iteration k $Y^k(j\omega)$ = Output in iteration k





ILC with feedback. Equations:

$E^{k+1} = Ref - Y^{k+1}$ (1)

$U^{k+1} = U^k + L * E^k$ (2)

$Y^{k+1} = P * U^{k+1} + P * C * E^{k+1}$ (3)

Using the above equations it is possible to derive the equation:

$E^{k+1} = [1 - L*P / (1 + C*P)] * E^k$ (4)

And if we assume that the feedback, with the transfer function of

$G_0 = [CP / (1 + CP)]$

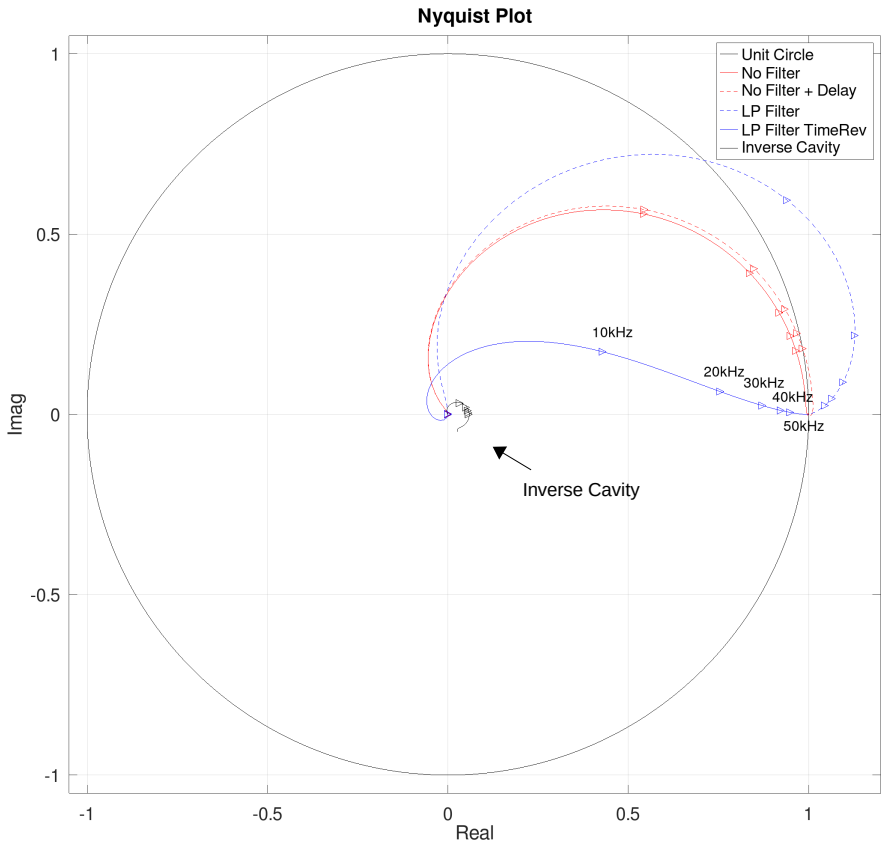
is stable, then the learning converges if:

$|| 1 - LP / (1 + CP) || < 1$ For all ω.

ILC with feedback and with L after Cpid

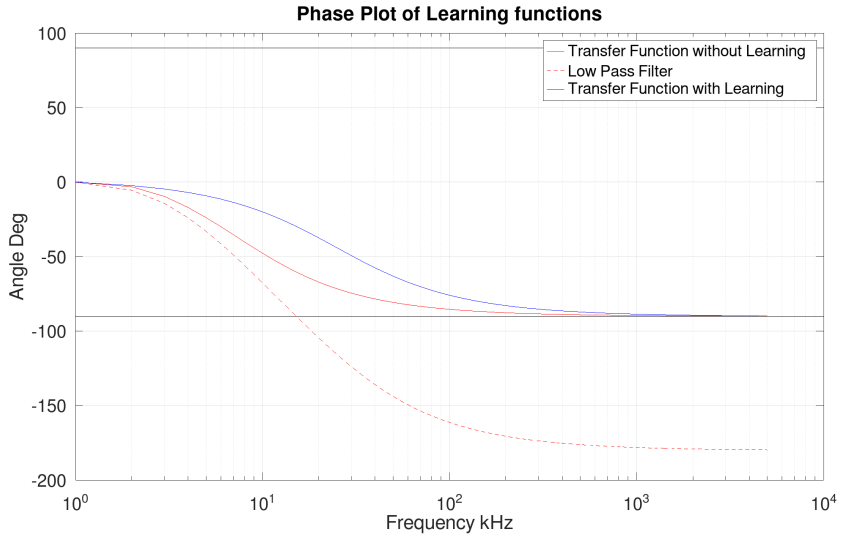
Learning converges if: $|| 1 - LCP / (1 + CP) || < 1$

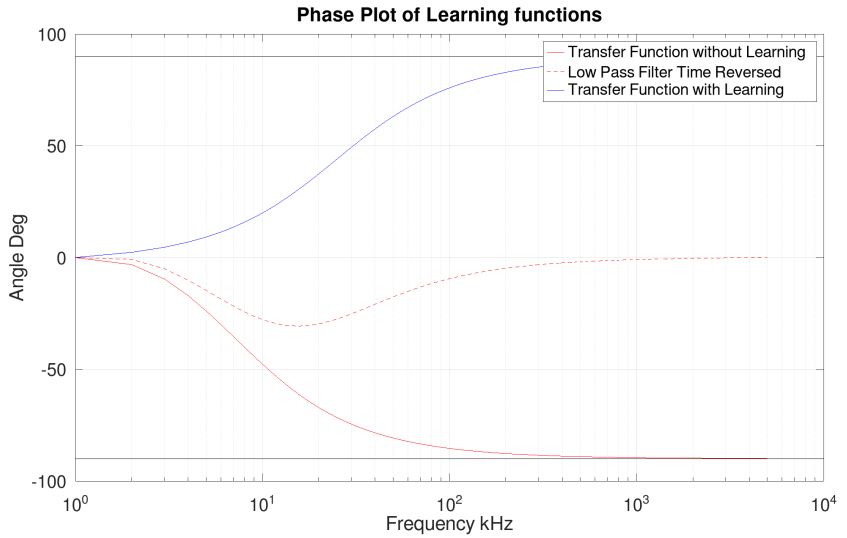
Iterative Learning Control
Theory



Plot of: || 1 – LP / (1 + CP) ||

Learning converges if: || 1 – LP / (1 + CP) || < 1

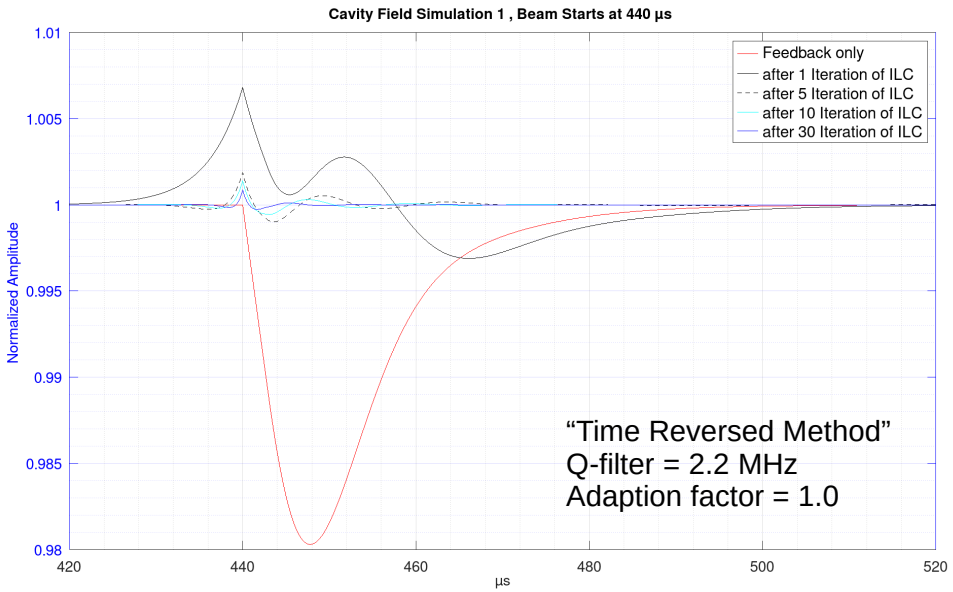


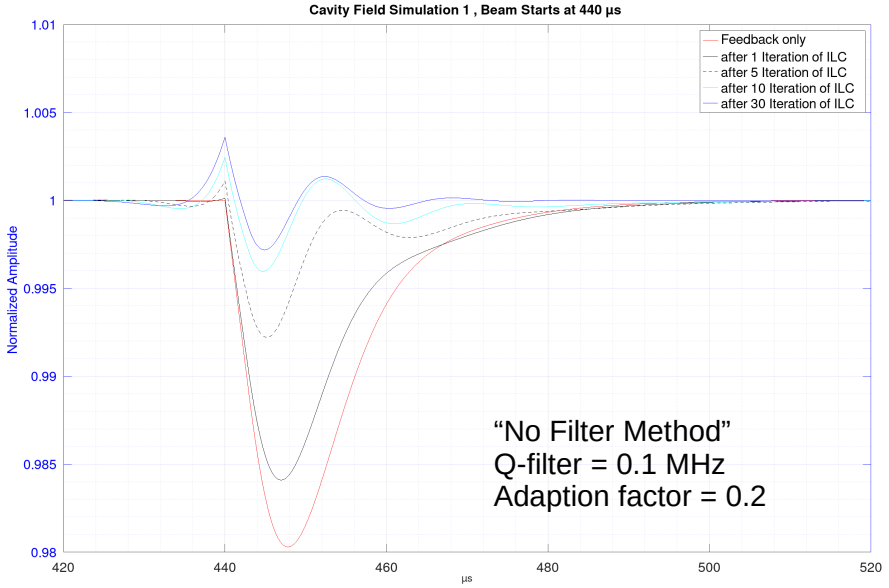


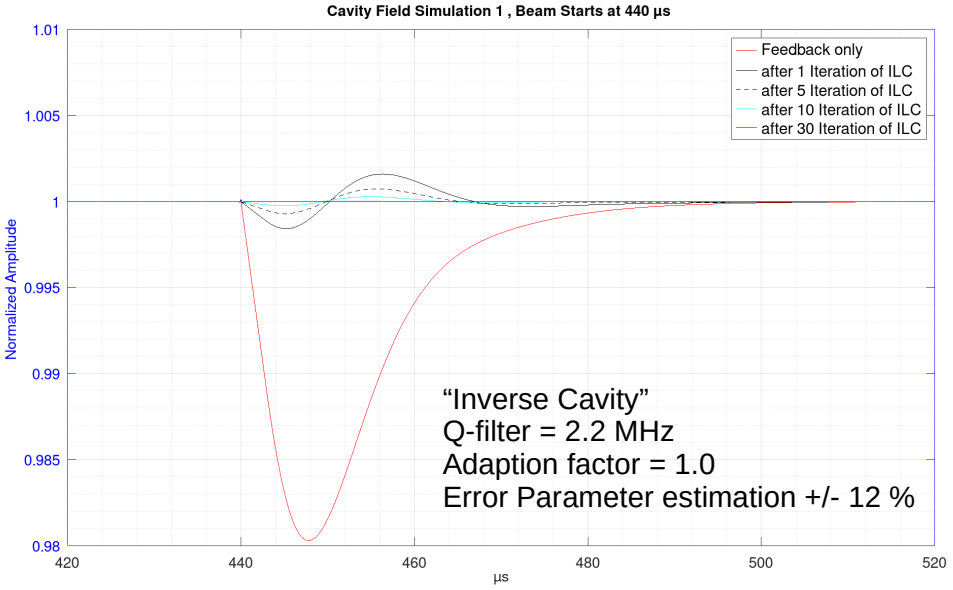
Plot of: Angle (LP / (1 + CP))

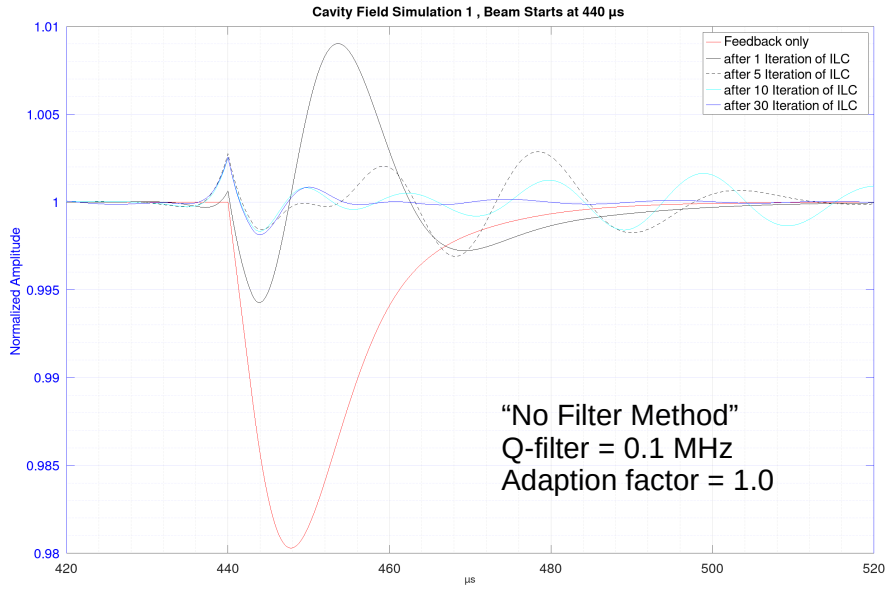
Iterative Learning Control

Results - Compare different Methods





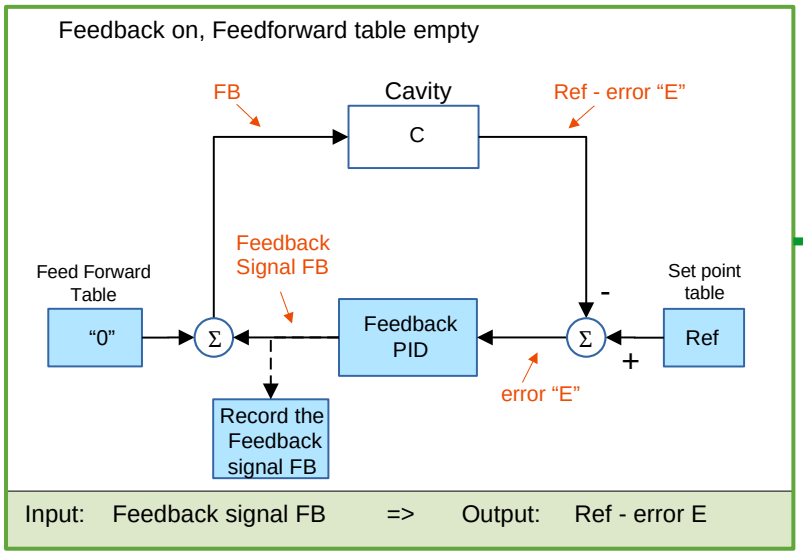




Thank You

Iterative Learning Control
Second method Alternative explaination

First Cycle

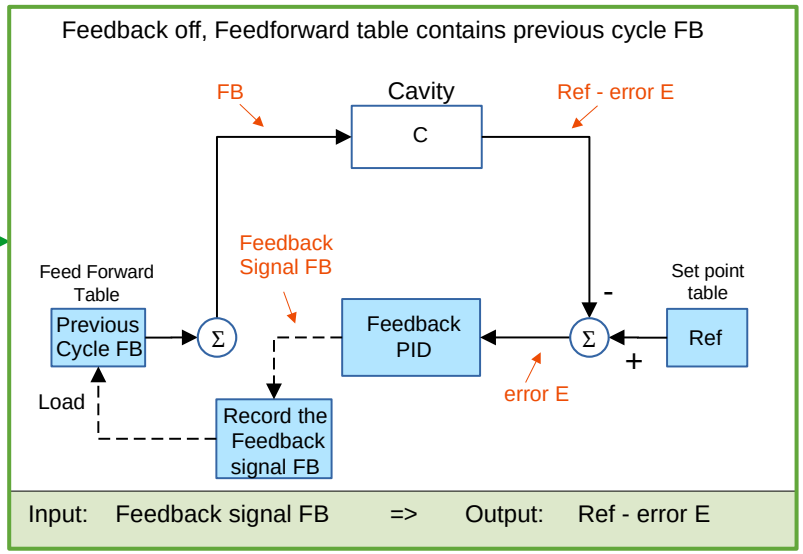


Between Cycles

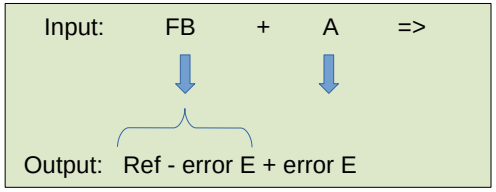
Load Recorded FB signal to Feed-forward table

Turn off Feeback

Second Cycle



Add a signal A to the input signal so that the output of A is equal to error E



Calculate A

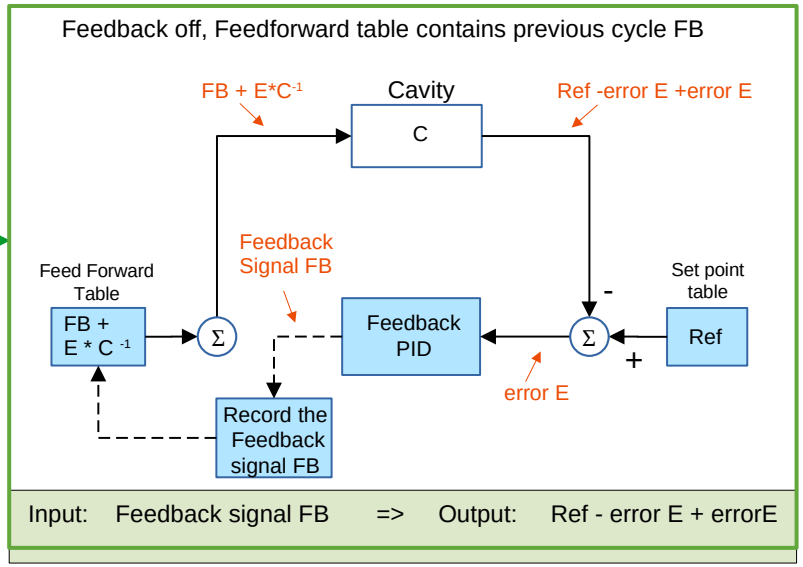
$A * C = E$

Multiply both sides with C^{-1} =>

$A * C * C^{-1} = E * C^{-1}$ =>

$A = E * C^{-1}$

Third Cycle



A is equal to the error signal E multiplied with an inverse Cavity C^{-1}