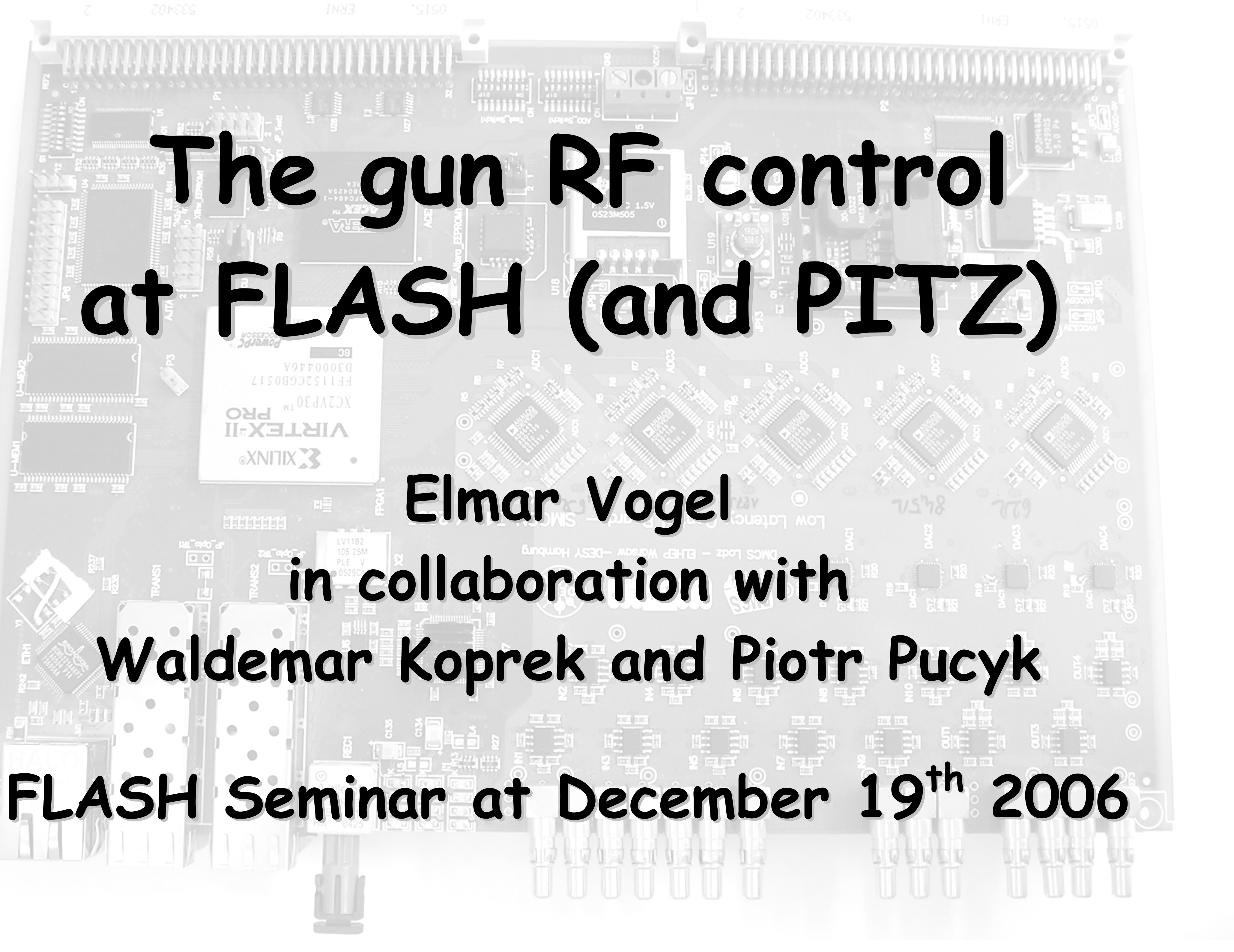


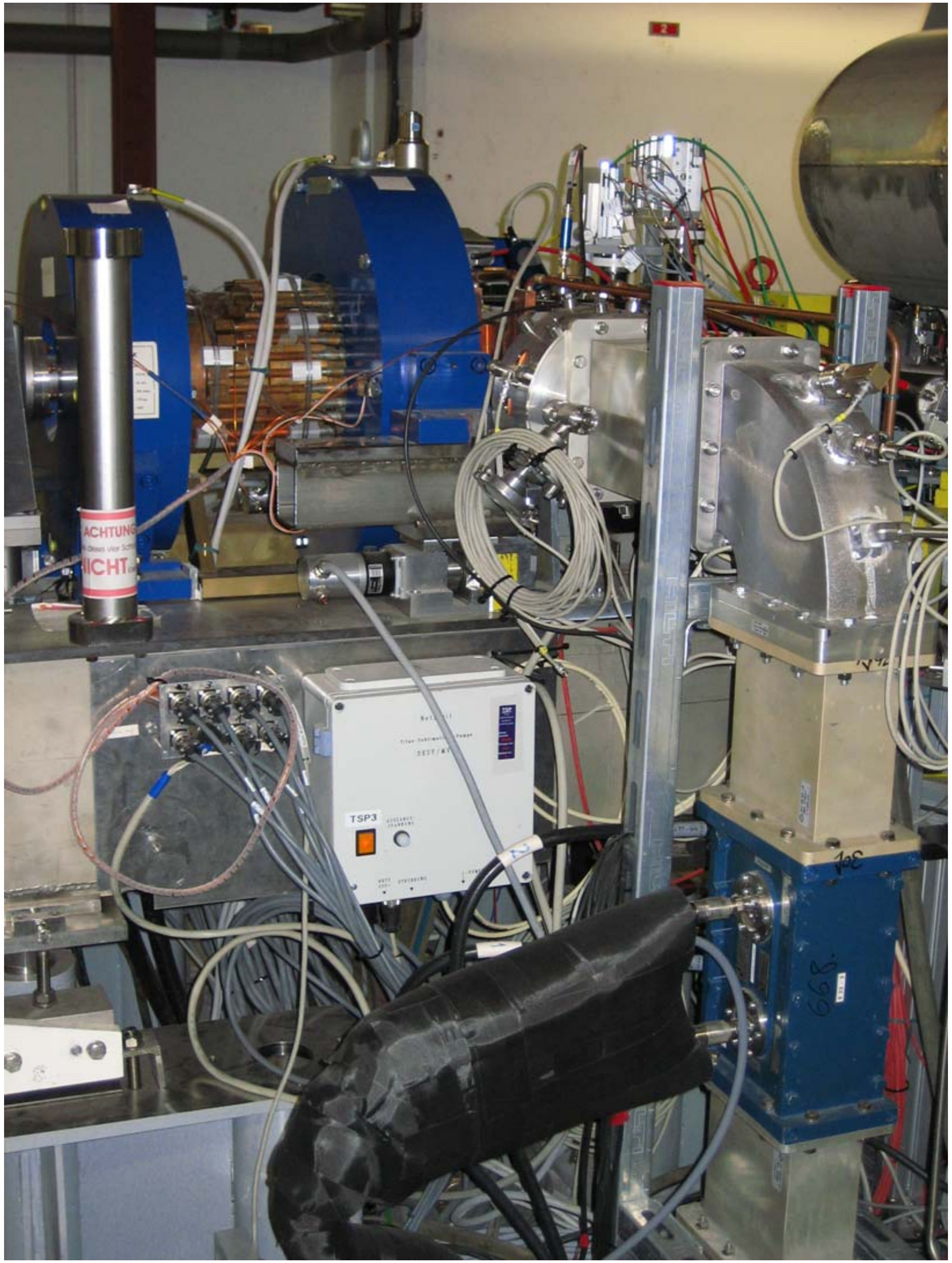
The gun RF control at FLASH (and PITZ)

Elmar Vogel
in collaboration with
Waldemar Koprek and Piotr Pucyk

FLASH Seminar at December 19th 2006

FLASH rf gun

- beam generated within the (1.3 GHz) RF gun by a laser
- filling time: typical 55 µs
- flat top time: up to 800 µs
- pulse repetition: up to 5 Hz
- high RF field: 40 MV/m
- FEL operation is sensitive to RF gun phase (0.5 deg)
- via the temperature the frequency is controlled (0.1 deg Celsius corresponds to 2.1 deg in RF phase)



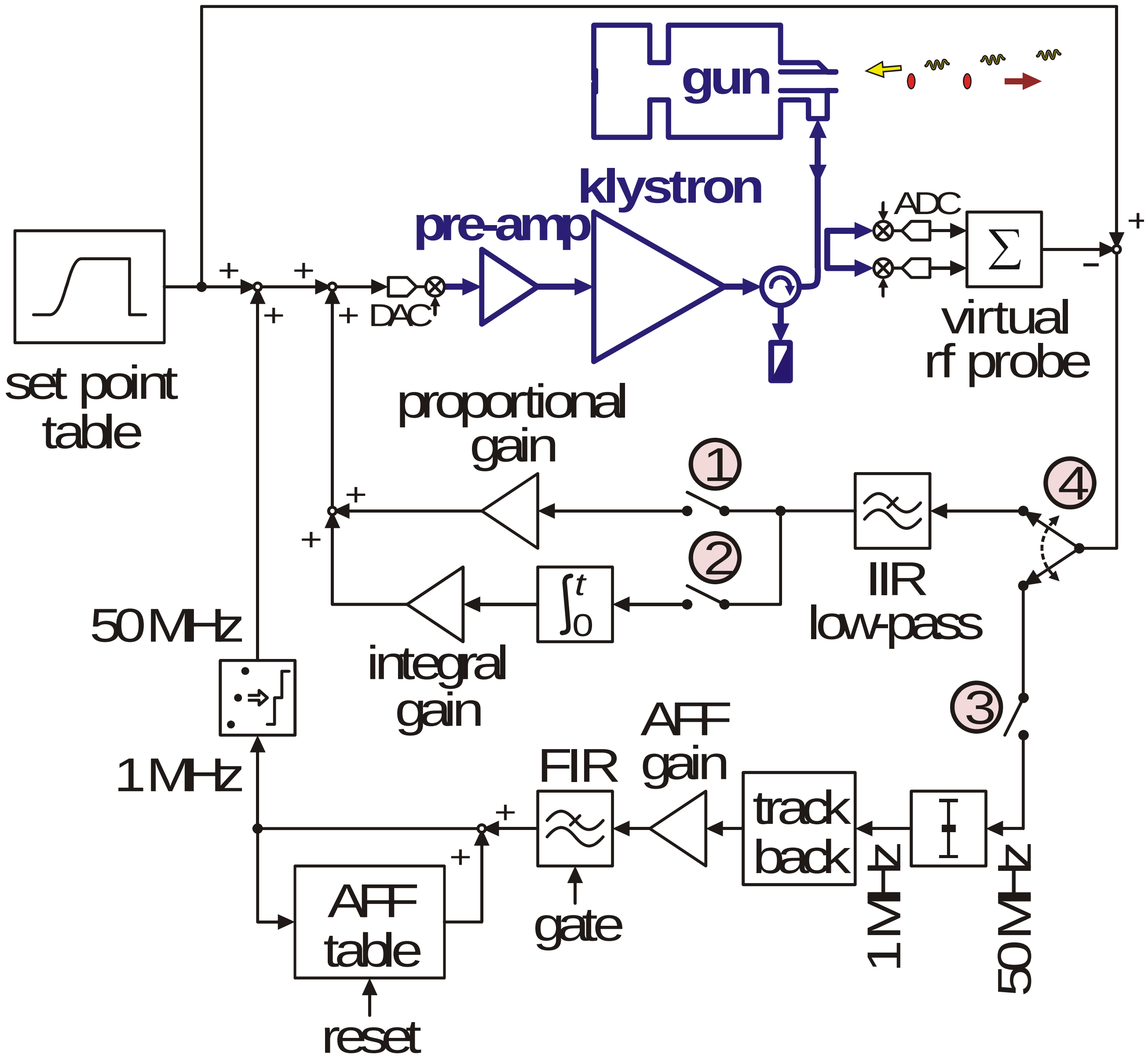
Rf gun control by SimCon 3.1 and some new algorithms

Implications of missing probe:

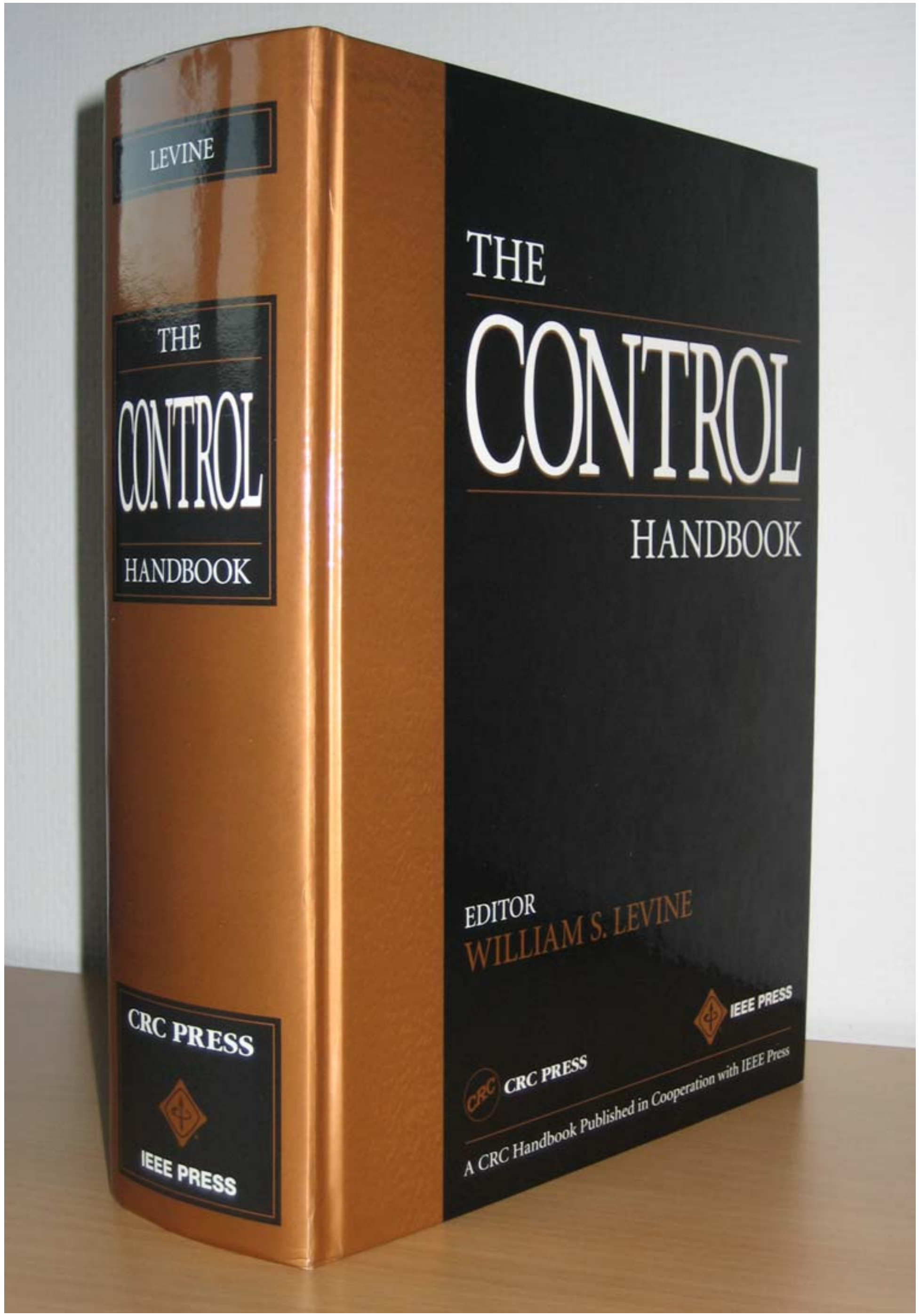
- calculation of probe form forward and reflected rf
- calibration is an issue

Algorithms:

- P(I) control with recursive 20 kHz low-pass (IIR) for stability at 'high' gain (>5)
- Adaptive feed forward (AFF) from rf pulse to rf pulse



first some theory …

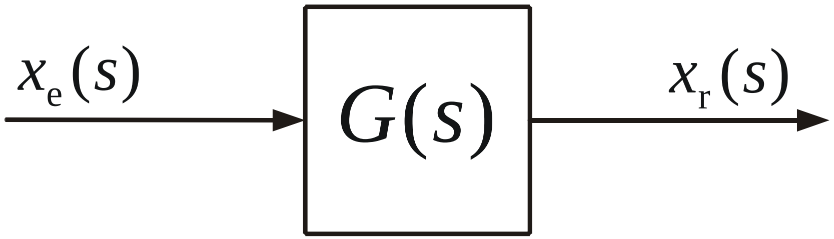


Envelope of RF cavity field: low pass (PT_1-element)

Amplitude/phase and IQ respectively obey a first order differential equation. Laplace transform results in the transfer function:

$$\tau \frac{d}{dt} x_r(t) + x_r(t) = x_e(t) \quad \Rightarrow \quad \int_0^\infty dl\, e^{-st} \ldots \quad \Rightarrow \quad G(s) = \frac{x_r(s)}{x_e(s)} = \frac{1}{1+\tau s}$$

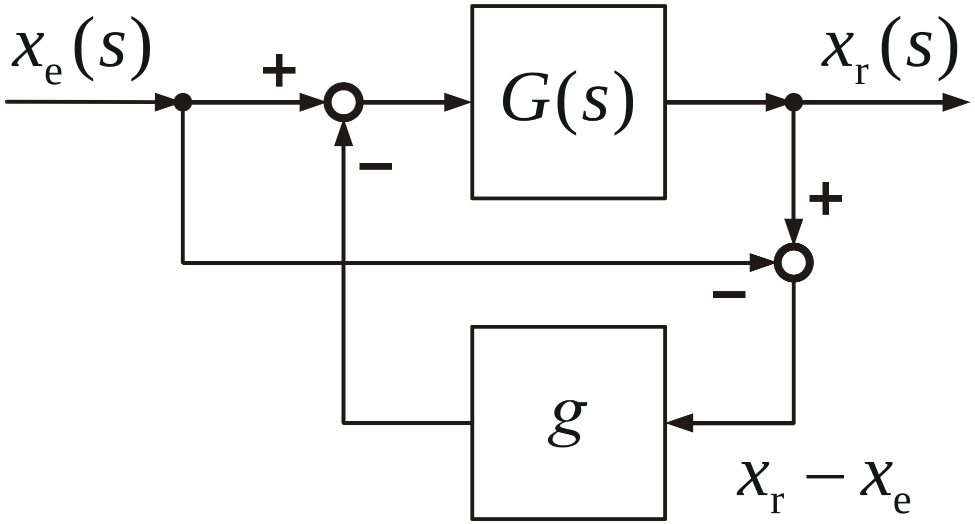
Block diagram, representing the transfer function:



Question: How to force the output signal to follow closer/faster the input signal?

Proportional control

Feeding back the error signal $x_\mathrm{r} - x_\mathrm{e}$



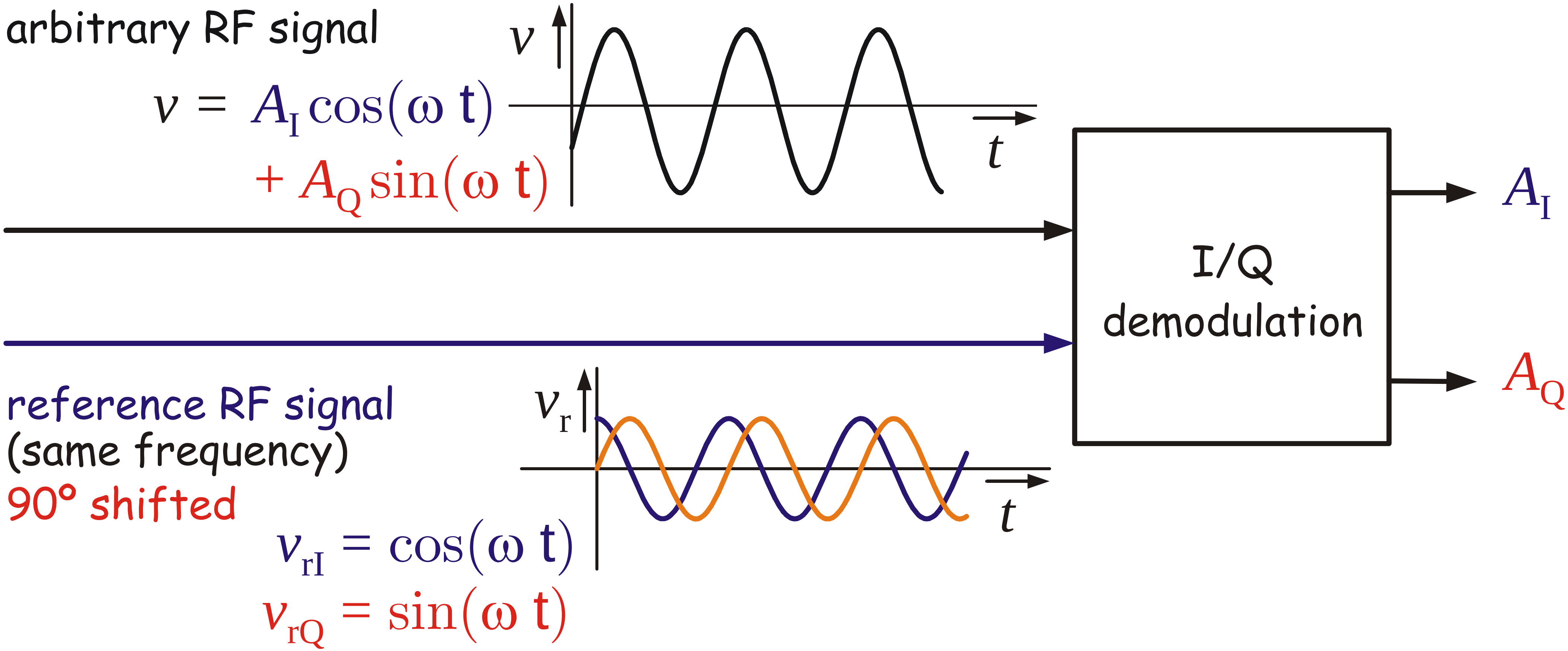
increases the bandwidth

$$\tau \frac{d}{dt} x_r(t) + x_r(t) = \left(x_e(t) - g\left(x_r(t) - x_e(t)\right)\right) \quad \Leftrightarrow \quad \frac{\tau}{1+g} \frac{d}{dt} x_r(t) + x_r(t) = x_e(t)$$

- response signal $x_r(t)$ follows quicker the stimulation signal $x_e(t)$
- errors are suppressed by the factor $1+g$.

'IQ' instead of amplitude and phase

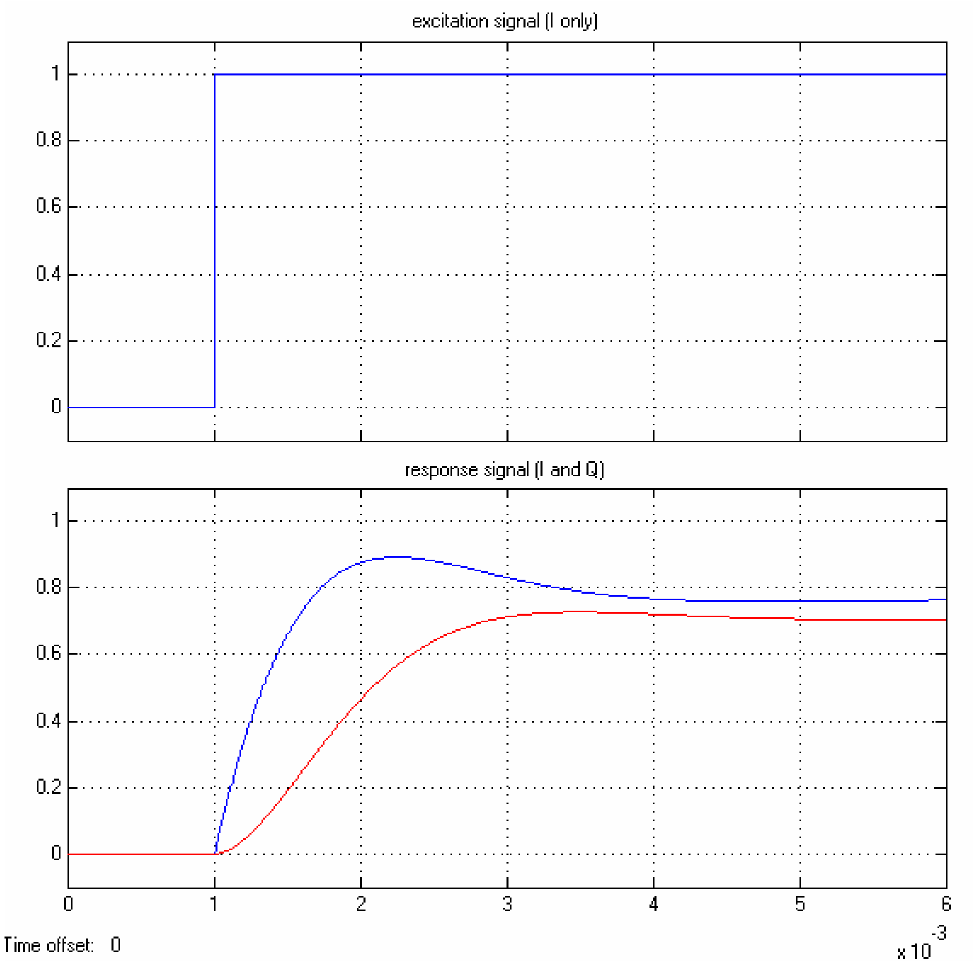
- quadrature (IQ) detection rather than dealing with amplitude and phase
- phase calibration by rotation matrices
- no manual phase adjustment needed!



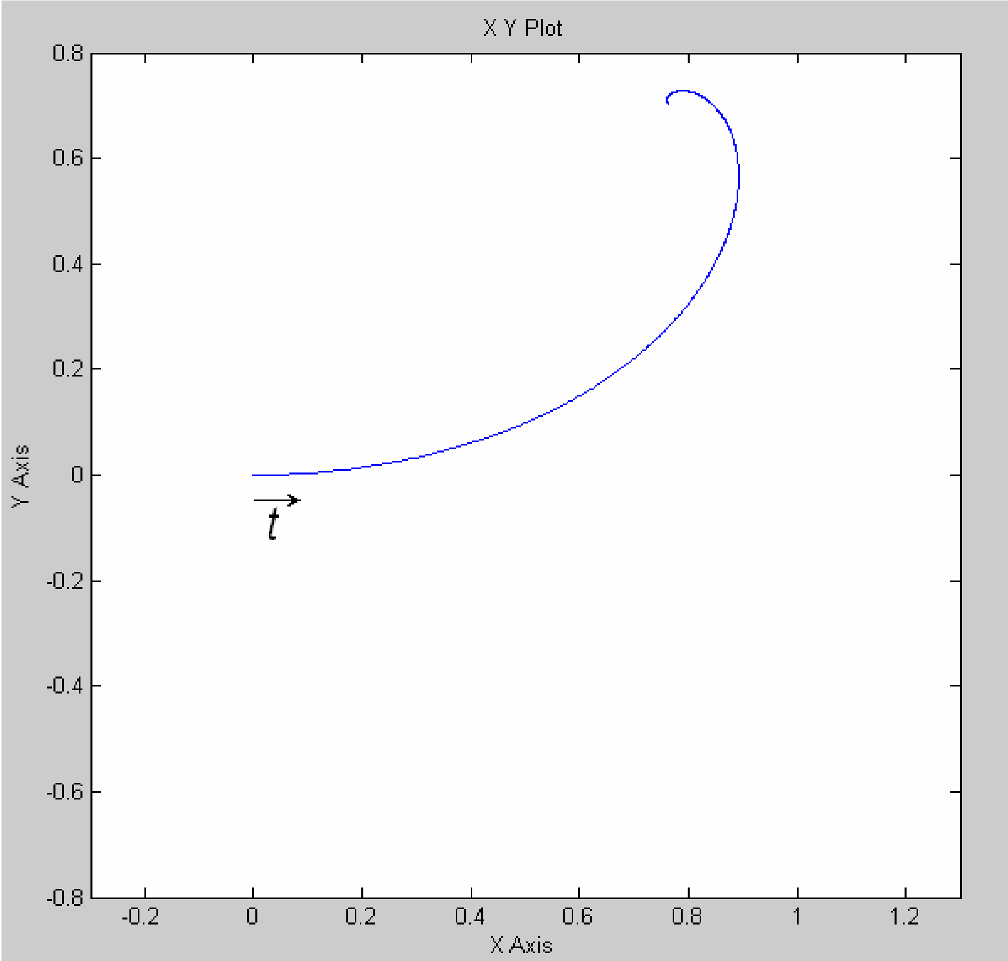
(IQ) loop phase determination

- non zero loop phase leads to an unwanted mixture of I and Q
- applying a step function (I only) and recording the response (example for $\Delta f = 200\,\text{Hz}$)

excitation & response in time domain



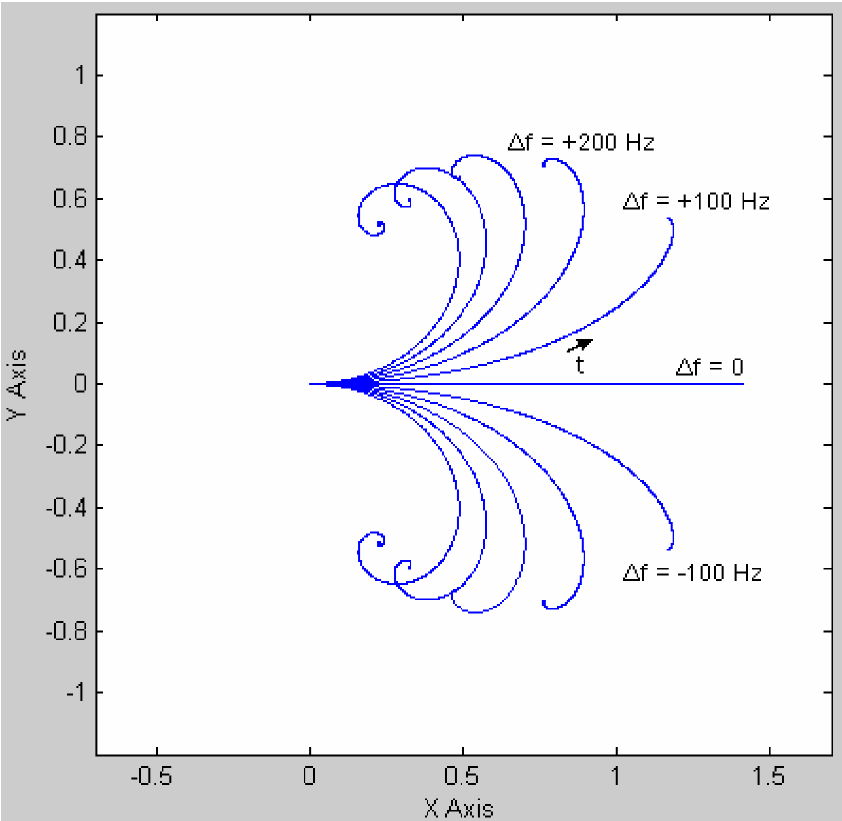
response plotted in IQ plane



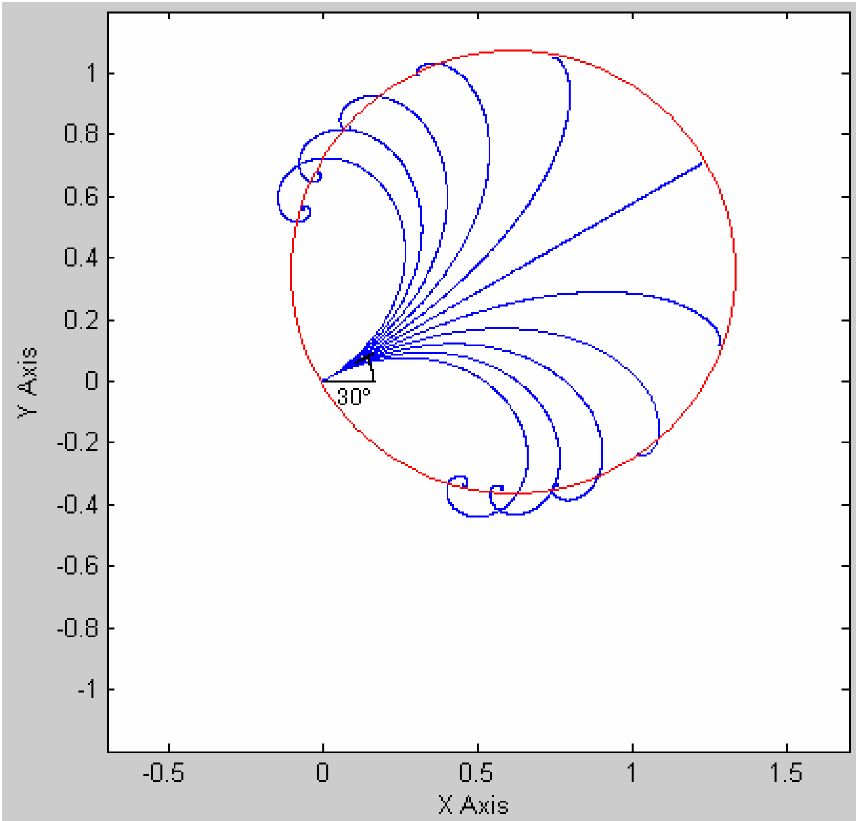
Spiral like cavity response

- the initial angle gives the loop phase
- final IQ values for different tuning describe a circle
- Alexander Brandts loop phase calibration methods are based on 'circle fitting'

cavity response for loop phase zero



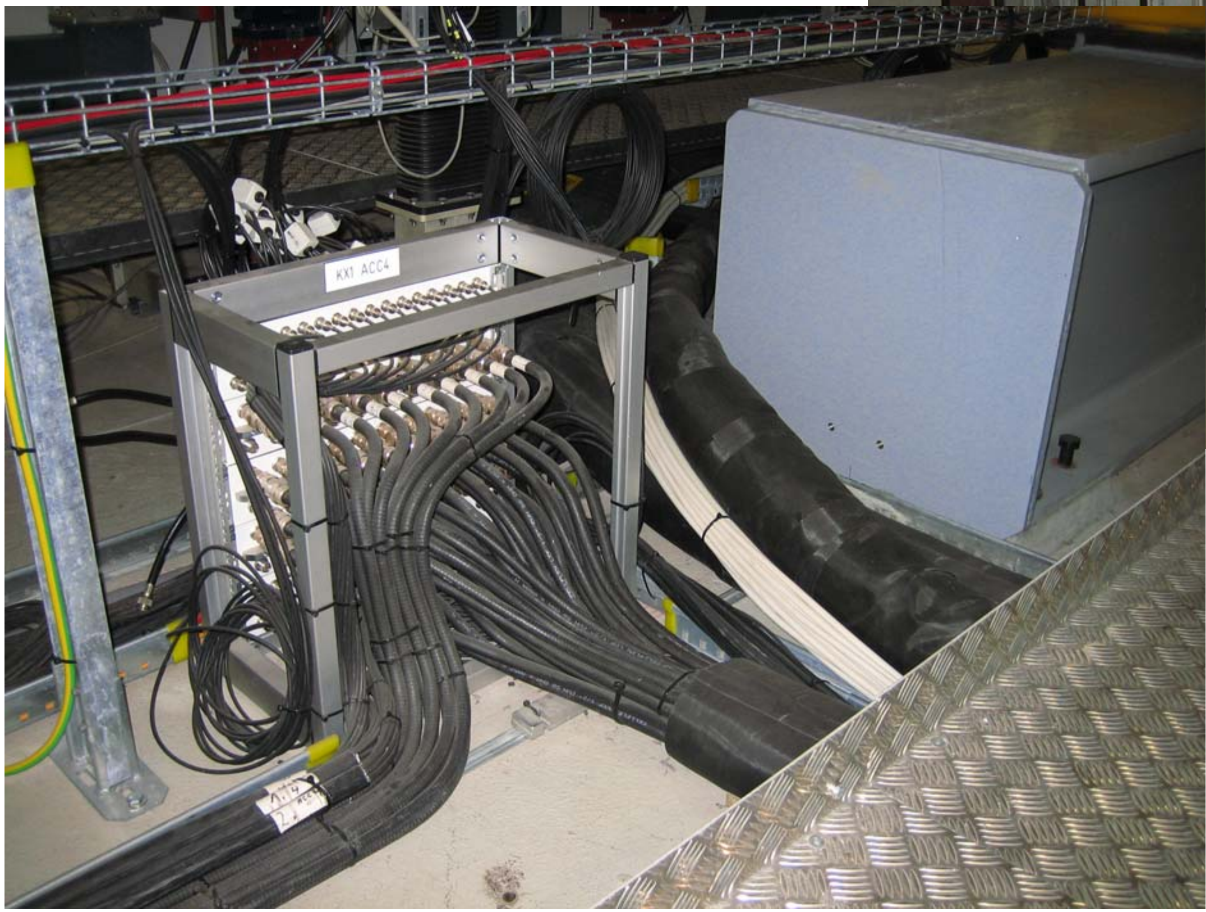
cavity response for loop phase 30°



Plots for the sc 1.3 GHz TESLA cavities, the RF gun behaves similar!

Propagation time of signals (latency)

Signals require time to propagate through cables, …



… LLRF and high power RF.

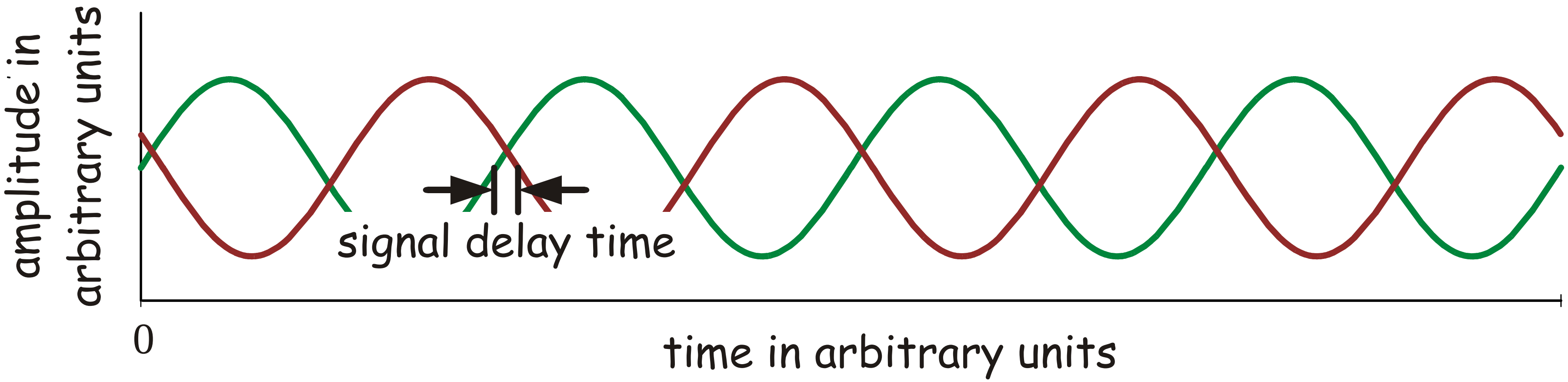
Numbers for the FLASH RF gun:

- 0.7 µs by cables klystron etc.
- 0.15 µs by FPGA (ADC to DAC)
- 0.35 µs by algorithm

Latency restricts proportional gain and loop stability

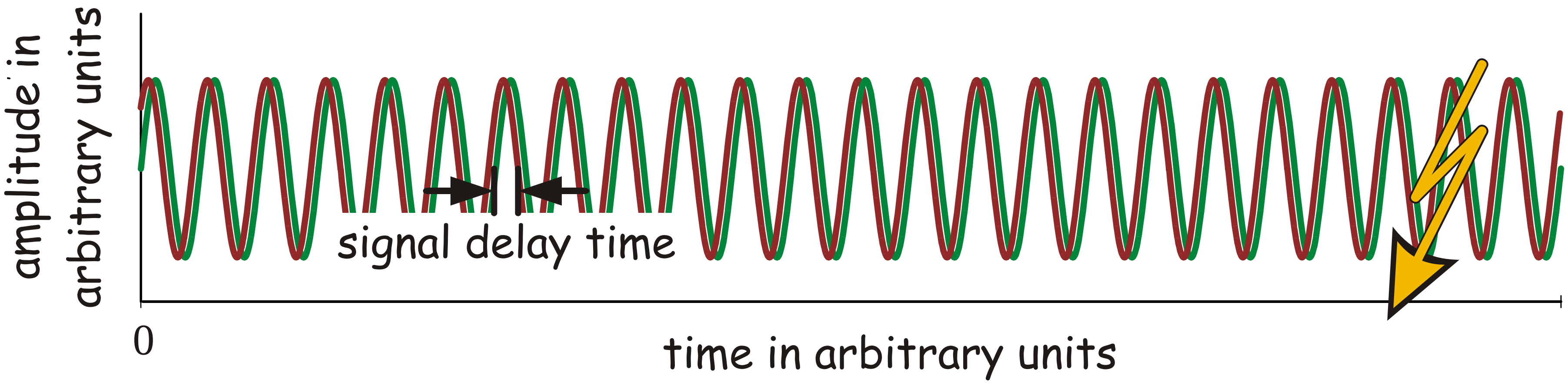
A time delay leads to an unwanted positive feedback for higher frequencies

negative feedback for low frequencies



feedback is stable

positice feedback for high frequencies

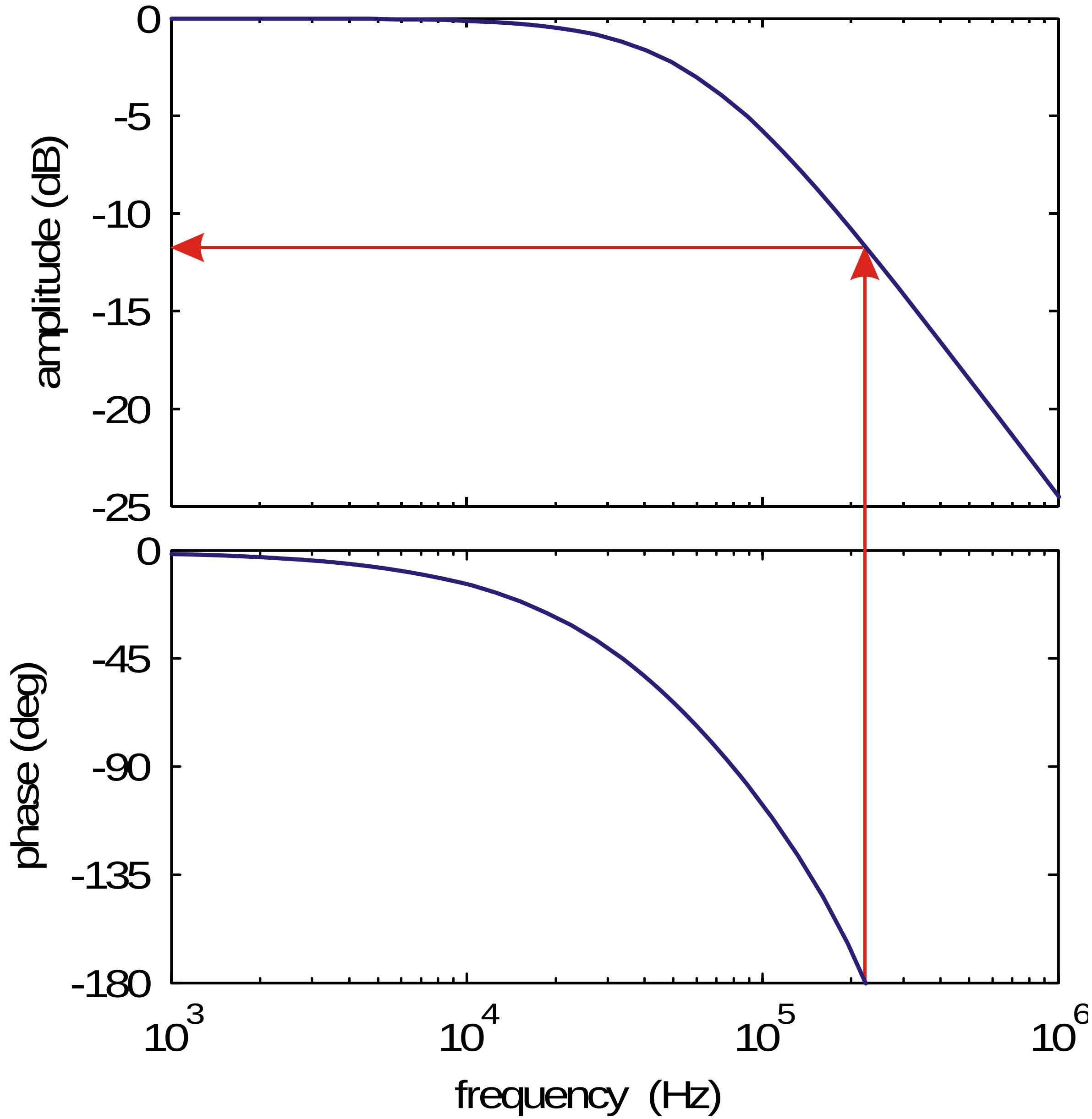


feedback is unstable

Inspection of open loop transfer function bode plot

- loop is unstable if the phase shift is larger than 180 deg and the signal amplified
- by drawing Bode plots we can check whether this is the case
- we can operate the gun with a gain of about 3 (4 minus margin)

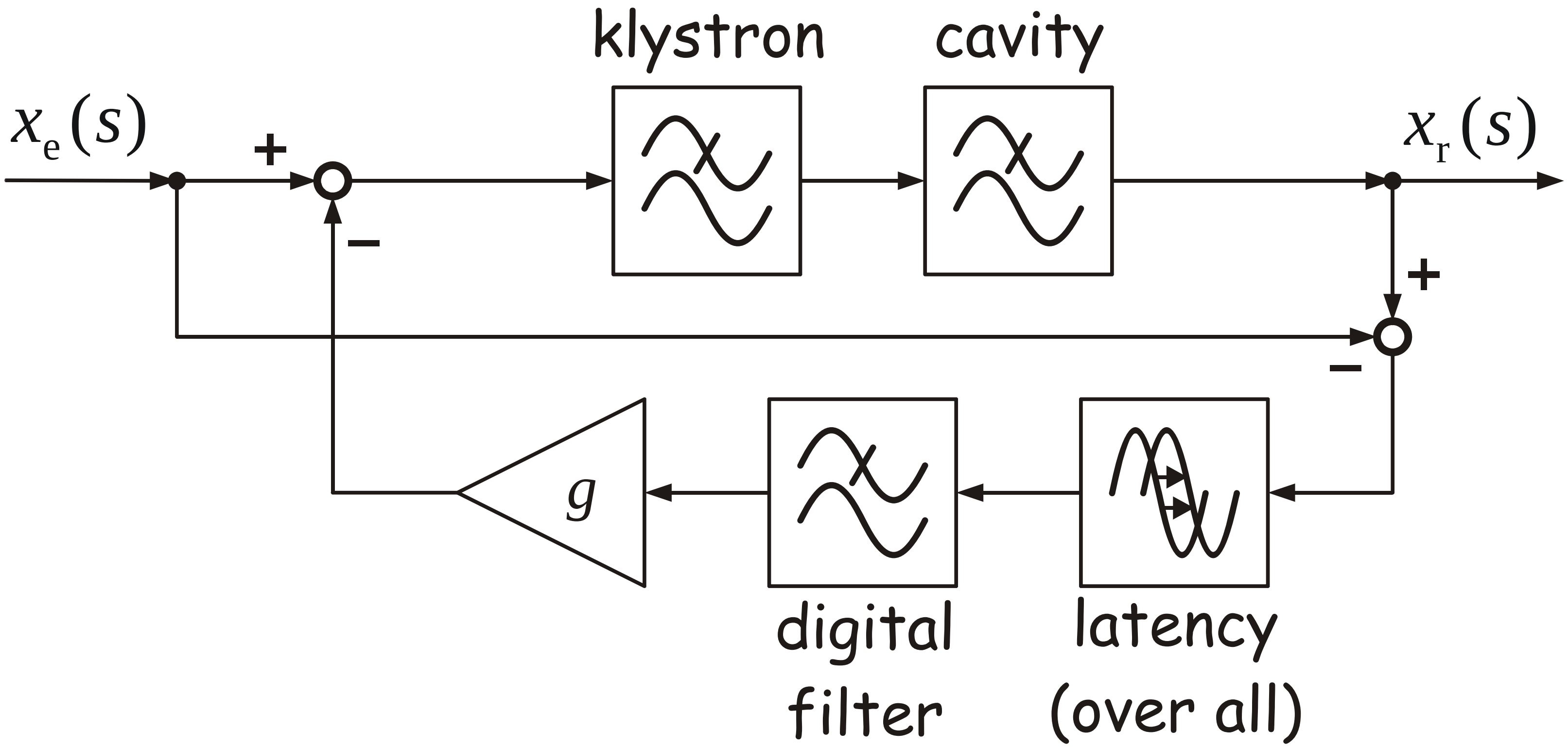
(Gun bandwidth: 60 kHz)



Suppression of high frequencies

Suppression of high frequencies by

- the cavity bandwidth
- the restricted bandwidth of high power RF (e.g. klystron)
- and digital low pass filters in the LLRF.

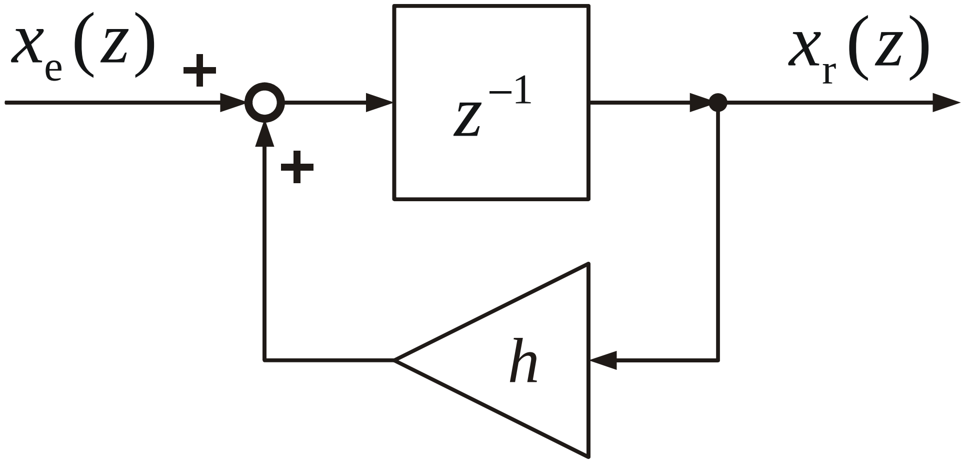


Recursive or Infinite Impulse Response (IIR) filter

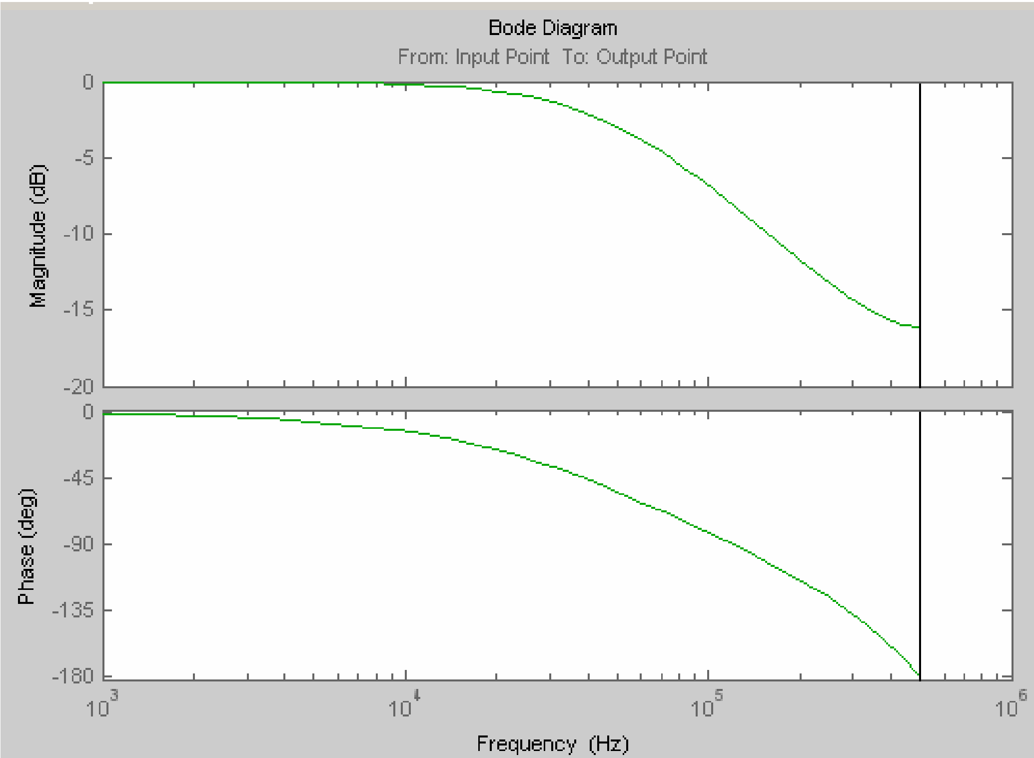
- IIRs are usually digital copies of analog filters
- impulse response of an analog low pass is an exponential decay
- to model this we reduce the output of a one step delay by

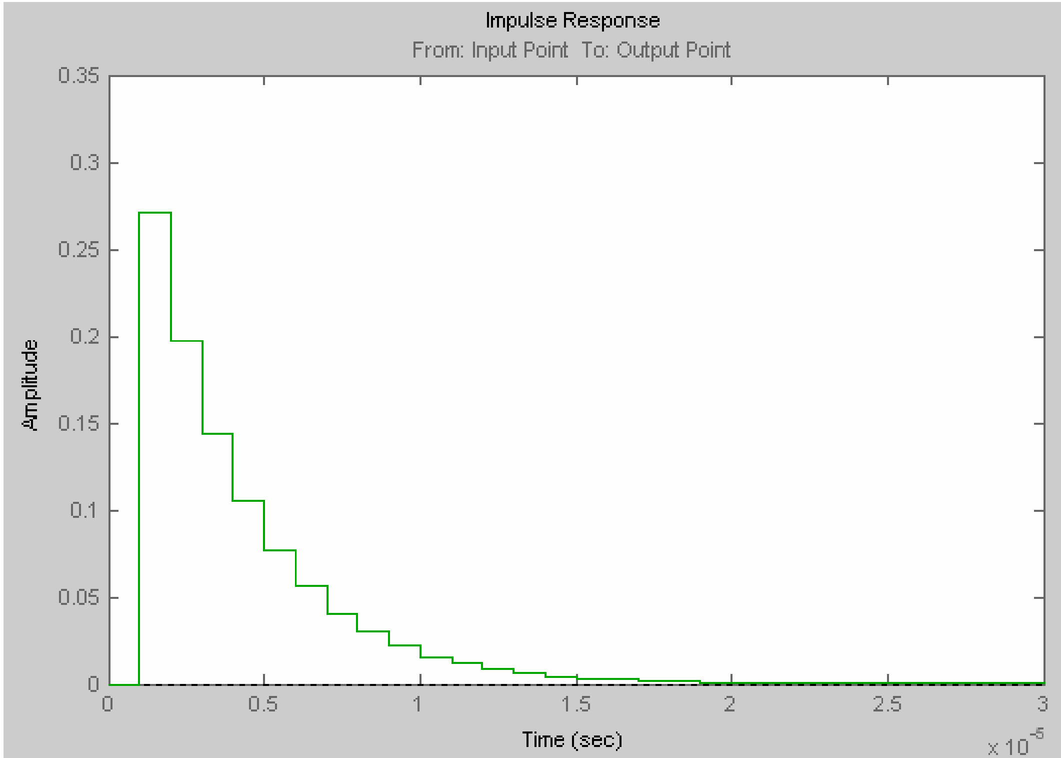
$$h \approx 1 - \frac{2\,\pi\; f_{3\text{dB}}}{f_{\text{samp}}}$$

- and add it to the next input for the delay



Response of 50 kHz IIR with 40 MHz sample frequency



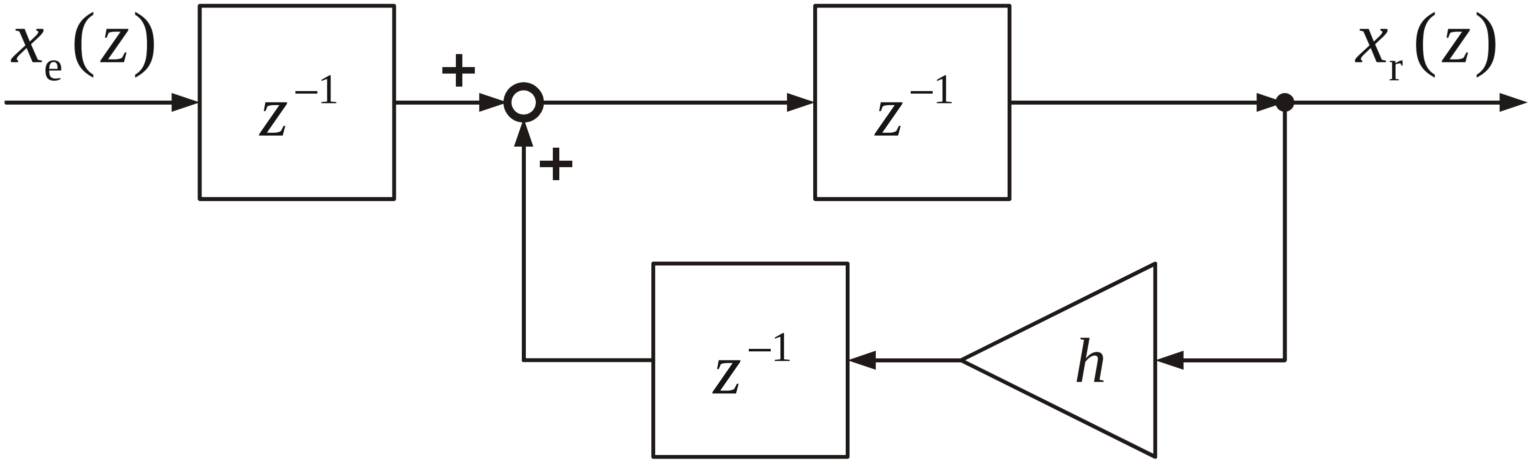


Advantage: the signal delay is only one sample step (25 ns)

Disadvantage: nonlinear phase response ⇒ different group delay ⇒ signal distortion

Concession to real life

- multiplication and sum can hardly performed together in FPGA



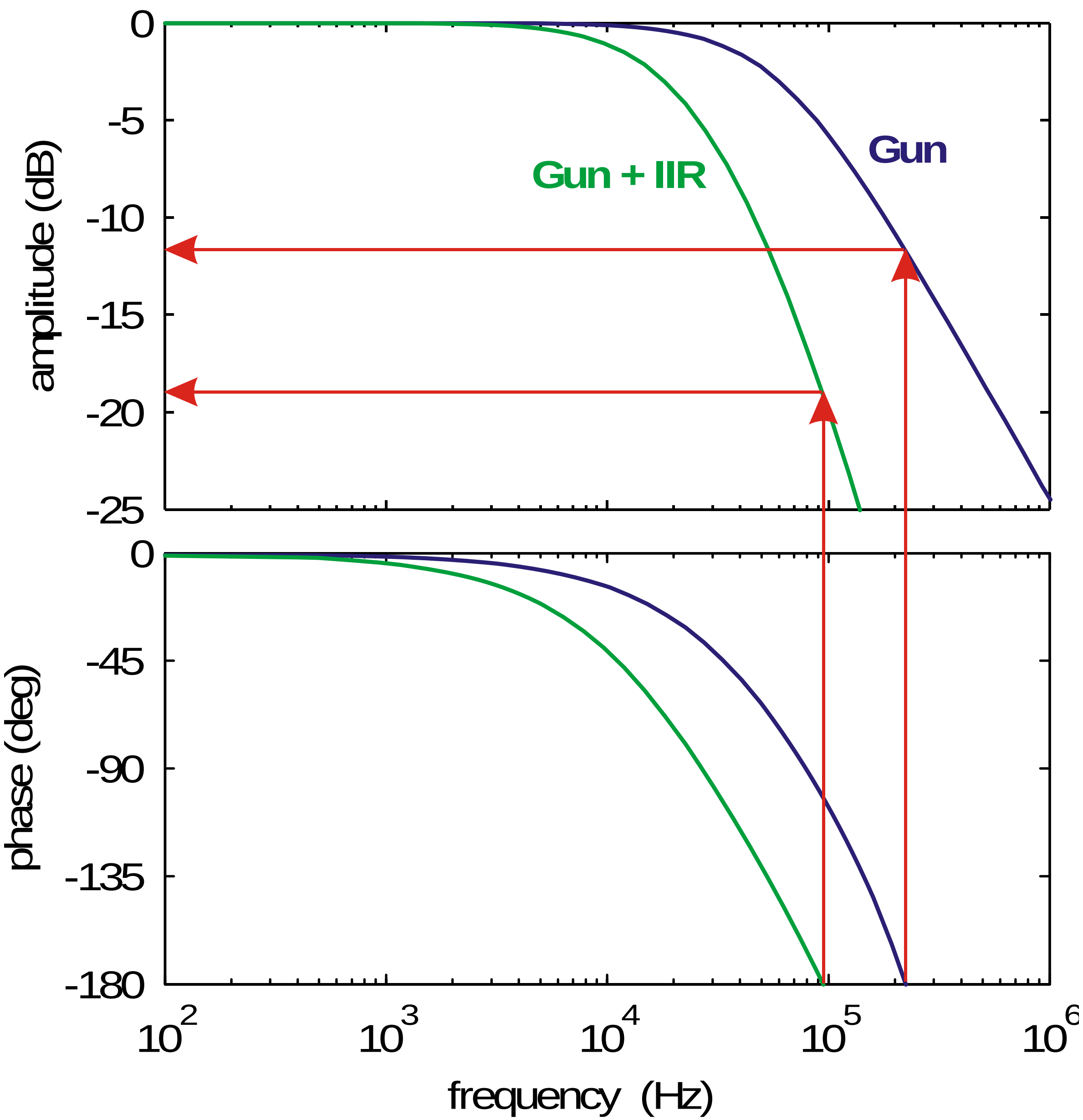
➢ additional delays double reduction value

$$h \approx 1 - \frac{4\,\pi\;f_{3dB}}{f_{samp}}$$

➢ Bode diagram and the impulse response is similar to previous version

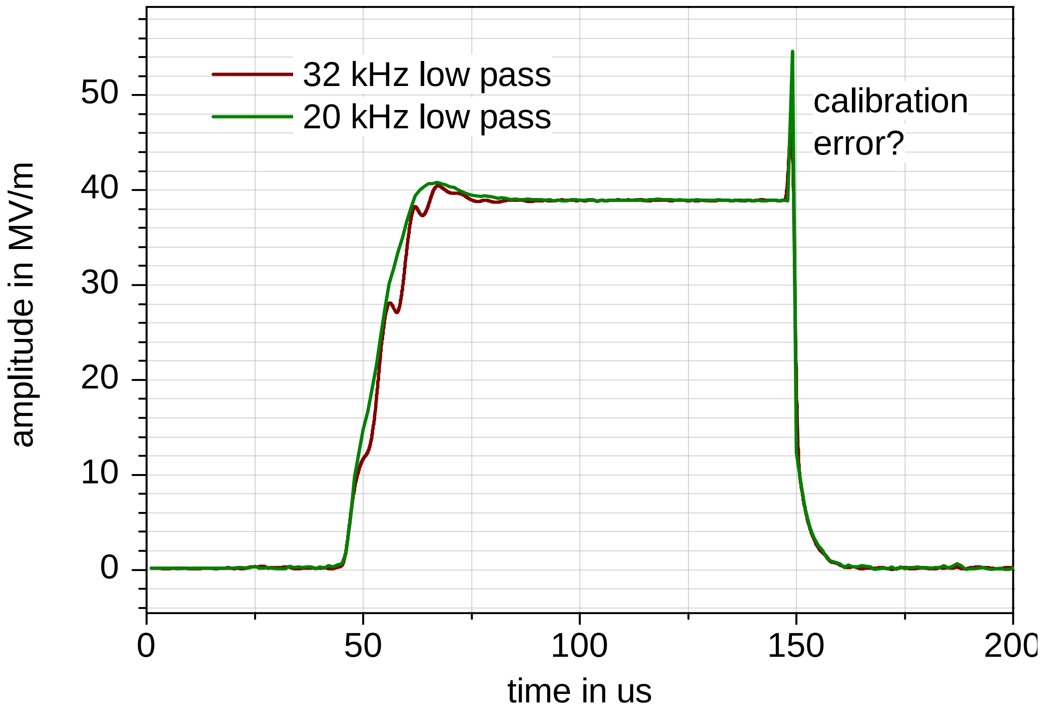
Bode plot of 'gun with 20 kHz IIR'

- with 20 kHz low pass we can operate the gun with a gain of about 6 (8 minus margin)

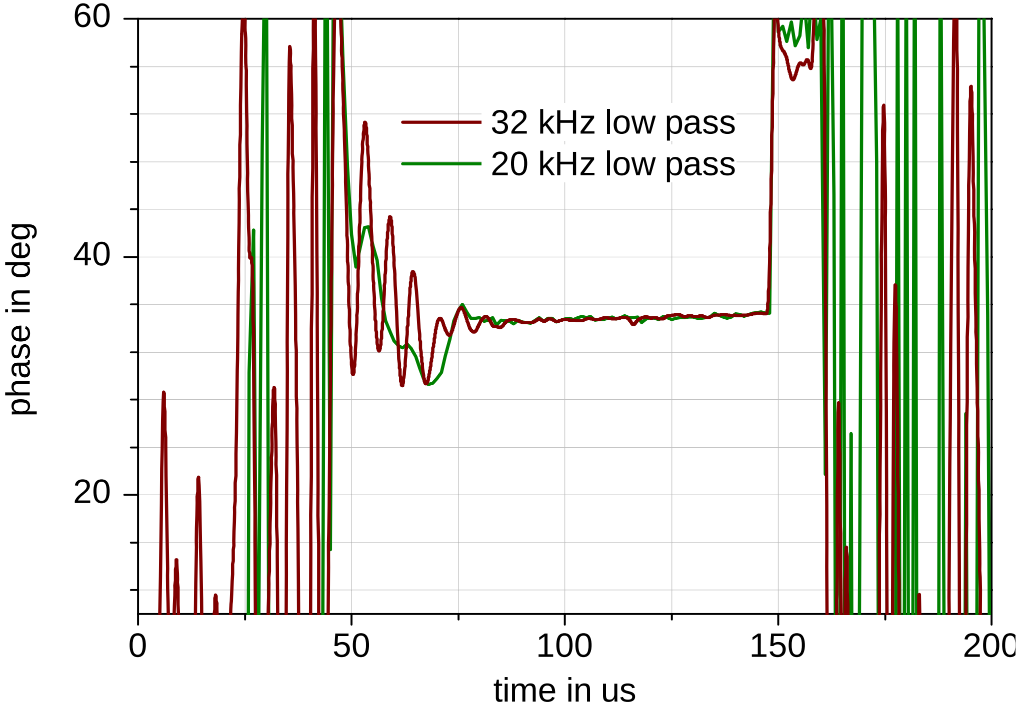


Confirmation by measurement

amplitude with proportional IQ control and gain larger 3



phase with proportional IQ control and gain larger 3



Conclusion: an edge frequency of 20 kHz shall be used in practice

Question:

How to get rid of

- systematic errors due to imperfect technical components?
- errors varying slower than the pulse repetition (drifts)?

Answer:

Using an adaptive feed forward (AFF).

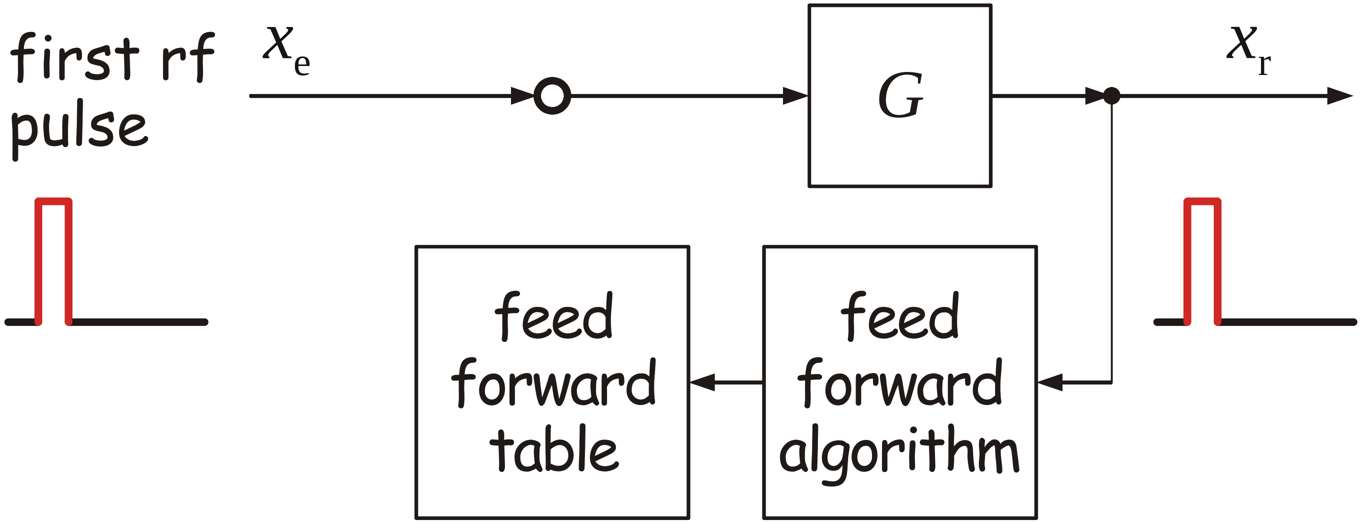
Main idea of adaptive feed forward algorithms

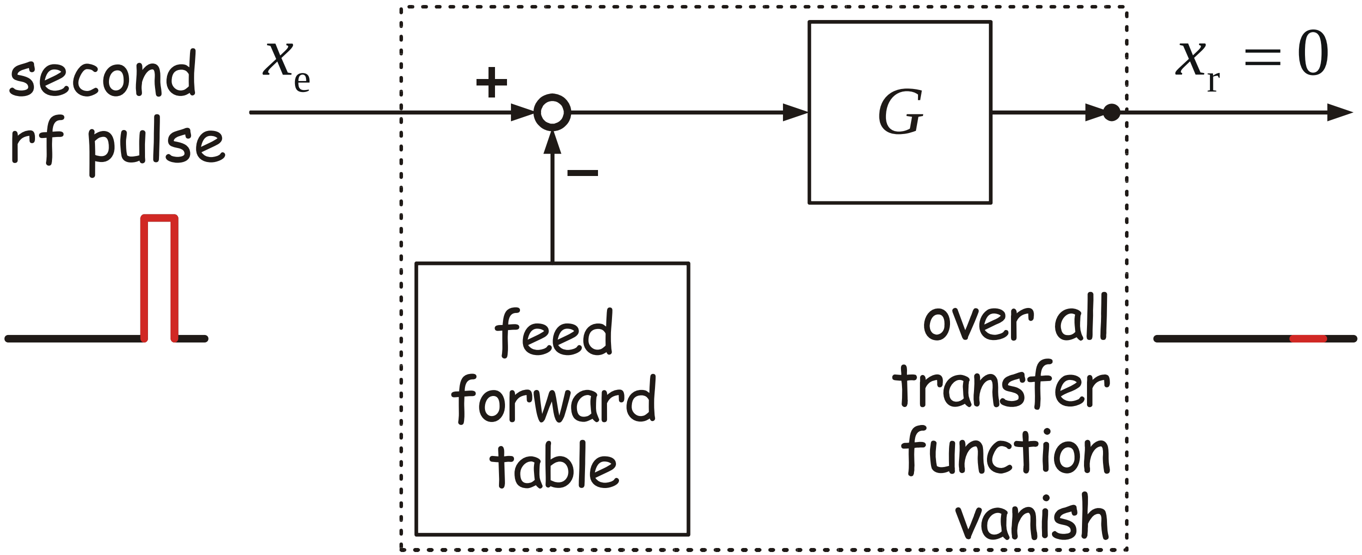
- each RF pulse shows similar errors
- transfer function of the ideal system is 'well-known'
- calculate back the input signal for the ideal system leading to the error
- subtraction from the set point signal minimizes the error

Algorithms on the market use

- inverse system model from state space formalism
- 'tracking'
- 'time reverse' filtering

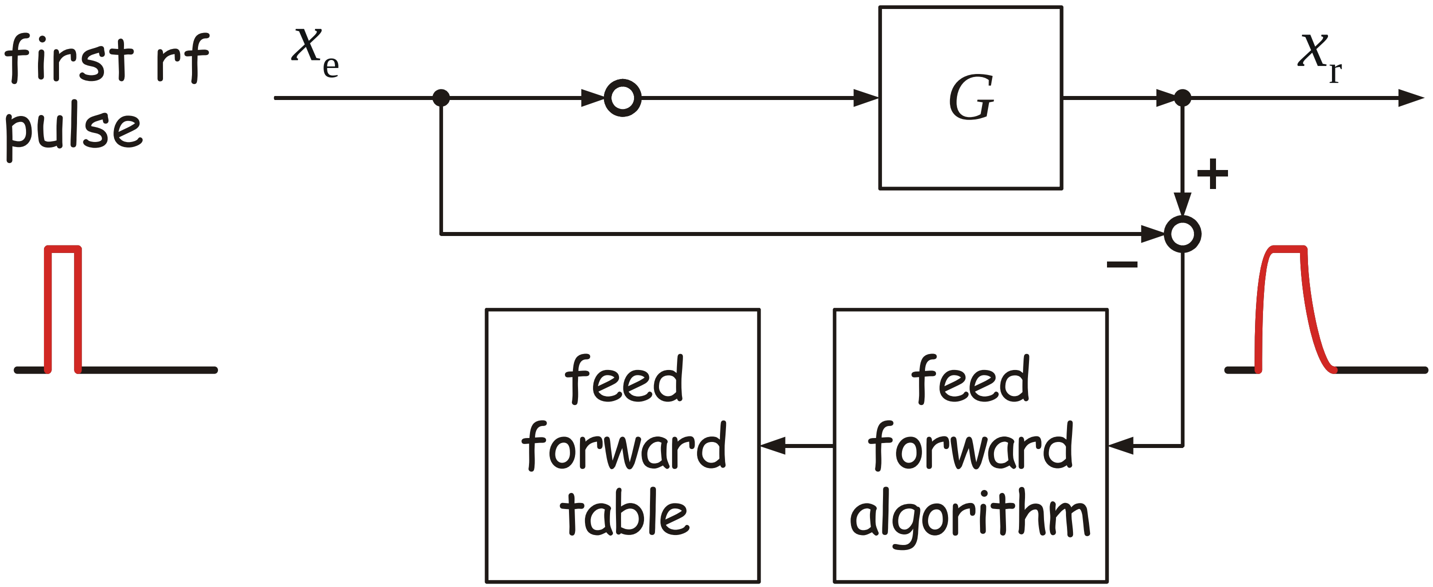
Check of system (G) inversion by AFF algorithm:

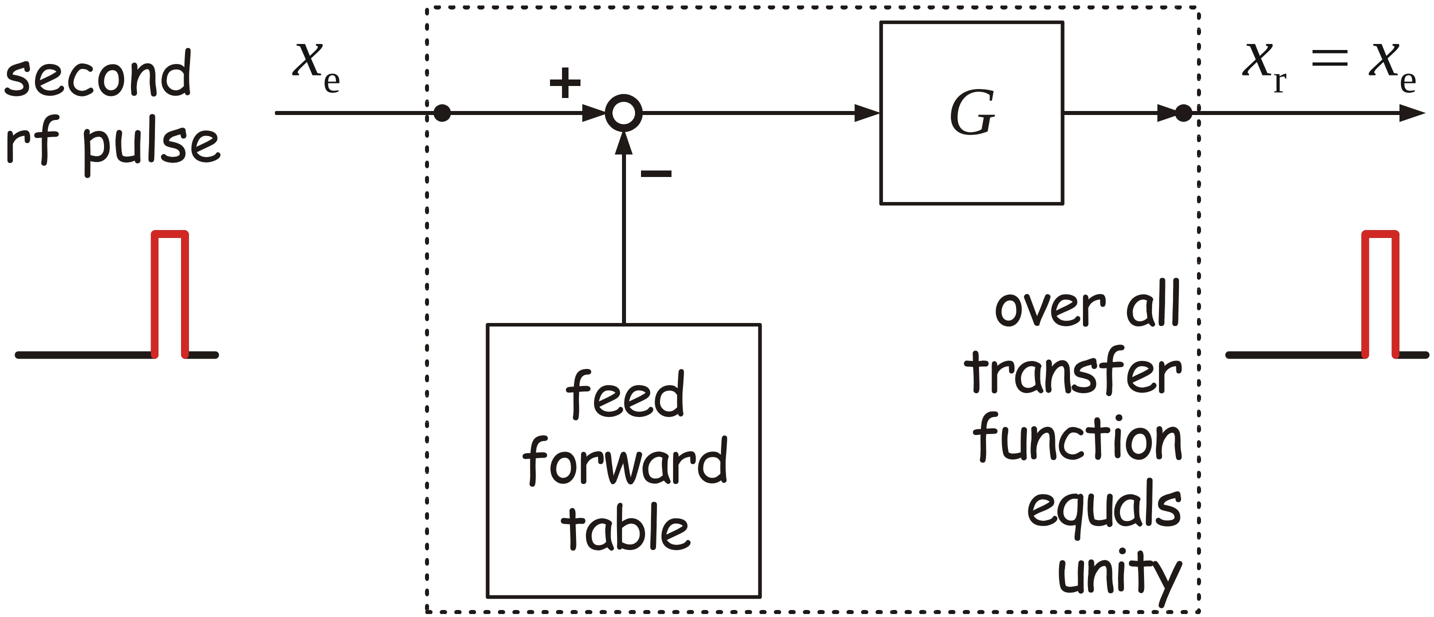




- application on ideal system (G) output cancels next output

Application of adaptive feed forward algorithm



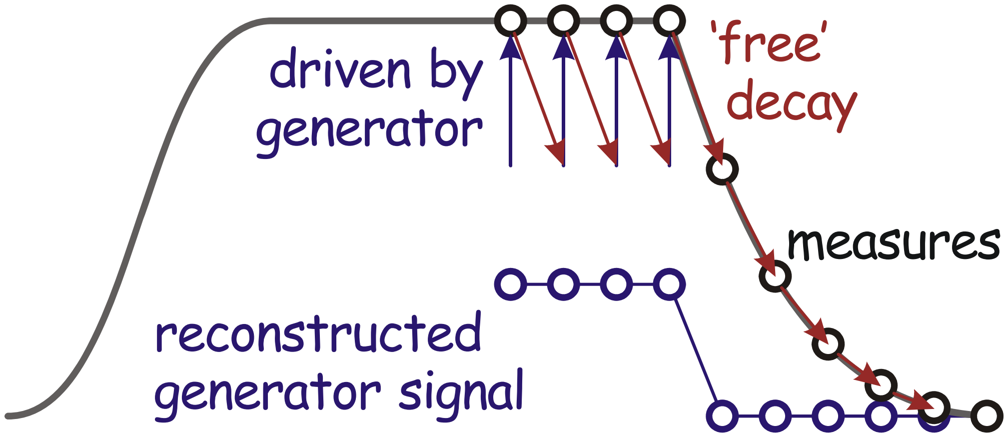


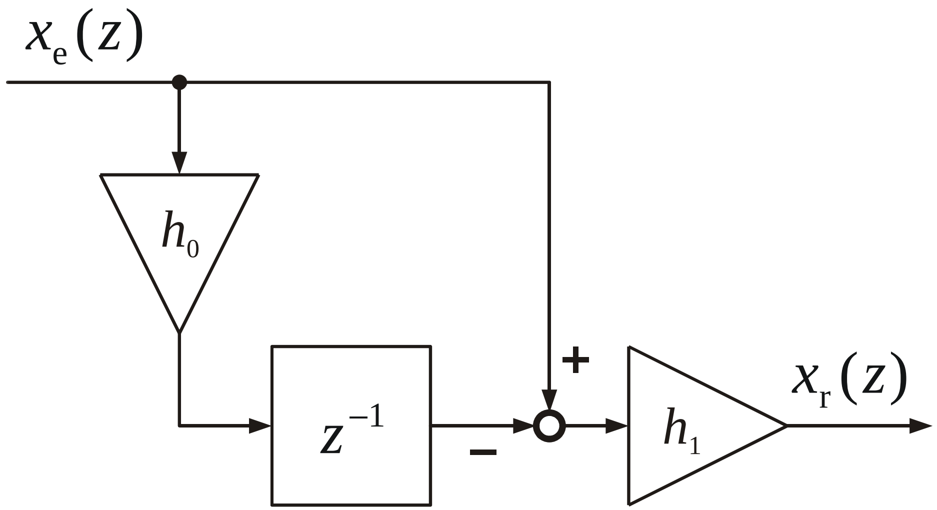
- application on ideal system (G) leads to unity transfer function for next pulse

A lean adaptive feed forward algorithm using 'tracking'

- calculate next sample
- difference is input signal driven by the generator

- ideal tuning assumed
- two subsequent I or Q samples used
- cavity time constant τ

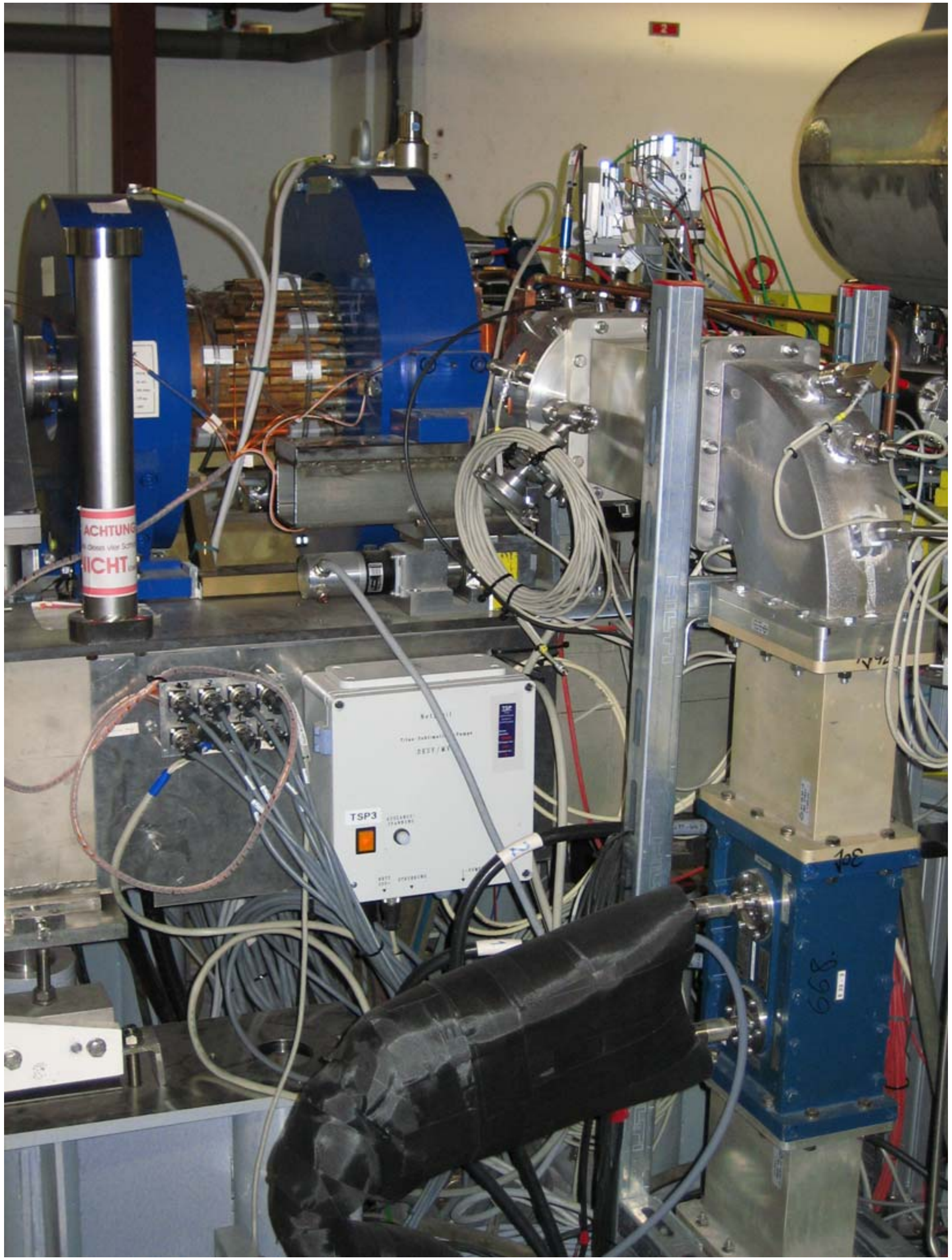




'filter' coefficients:

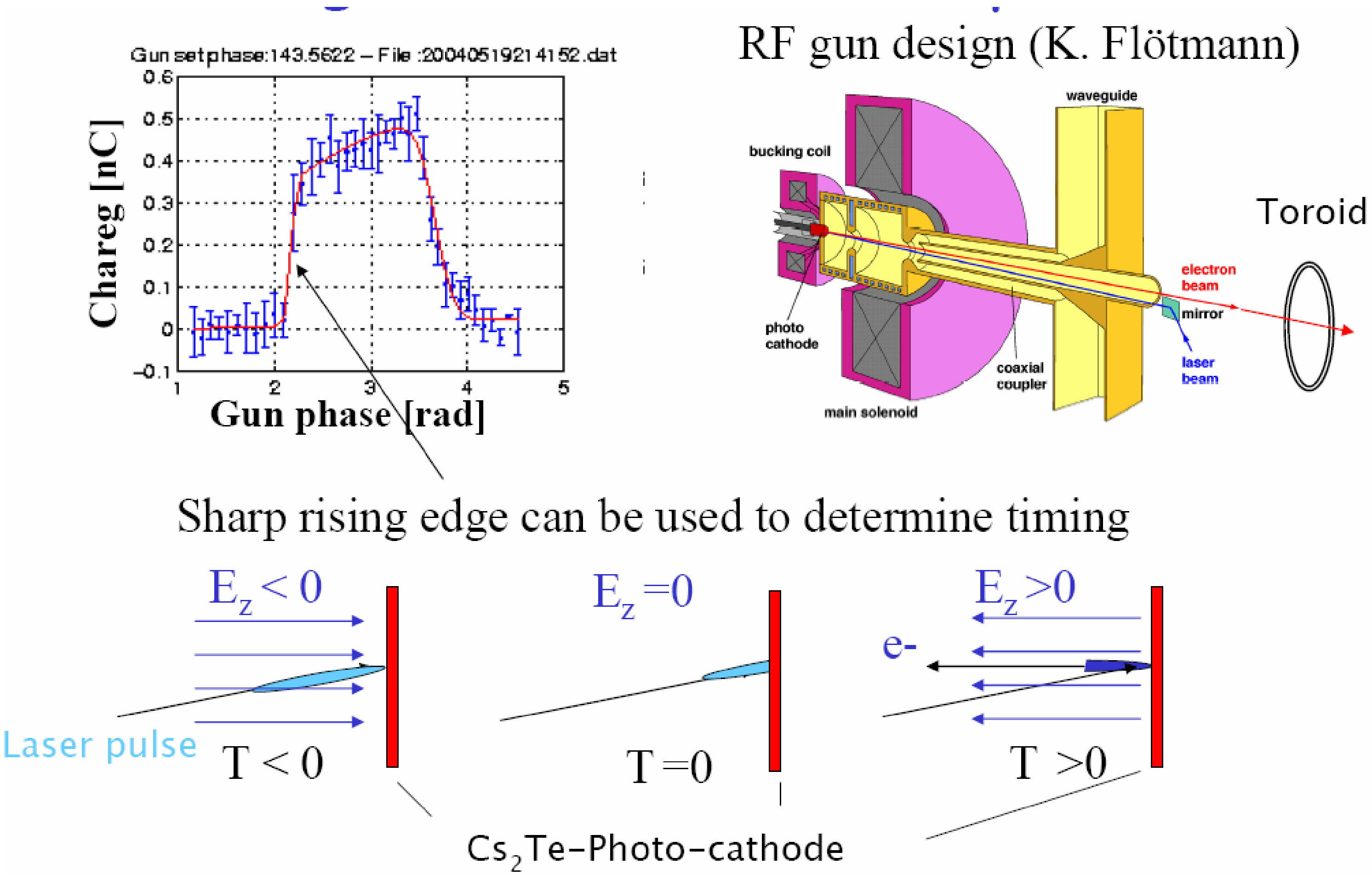
$$h_0 = 1 - \frac{1}{\tau \ f_{samp}} \quad \text{and} \quad h_1 = \tau \ f_{samp}$$

to practice…



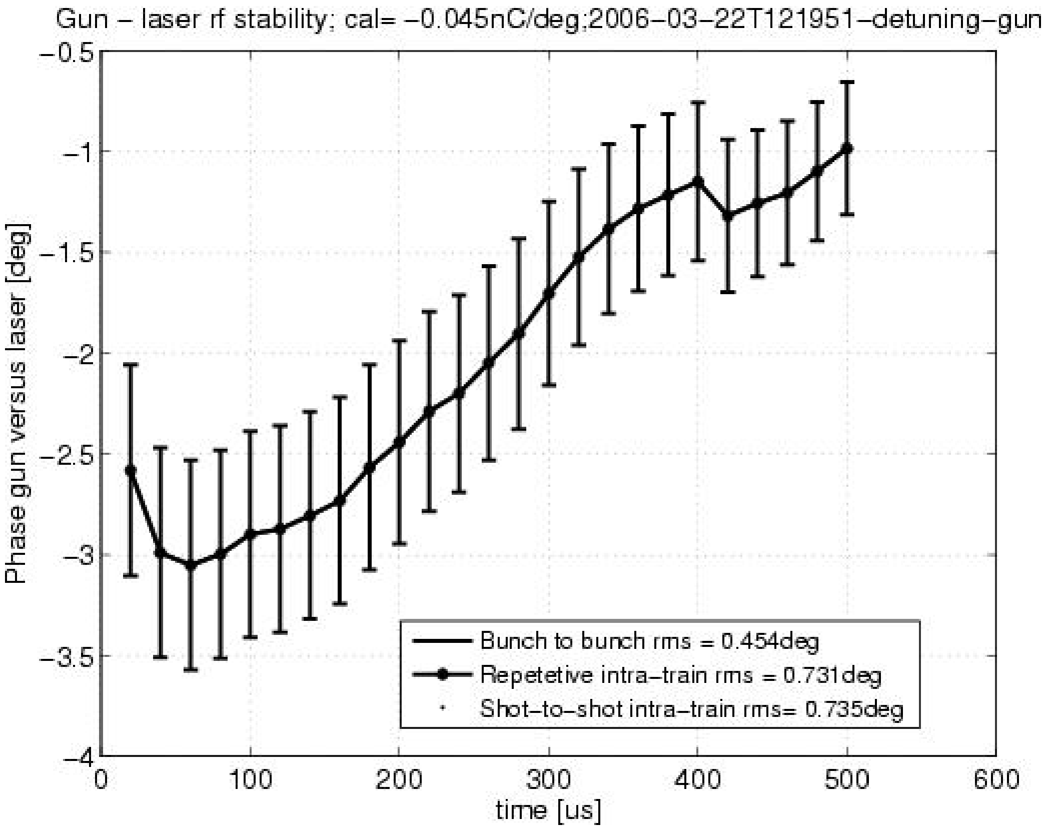
Emission phase stability measured with beam (H. Schlarb)

- indirect rf phase measurement
- bunch charge depends on rf phase at 'edge'
- measurement resolution: ± 0.1°
  ⇒ to be improved!

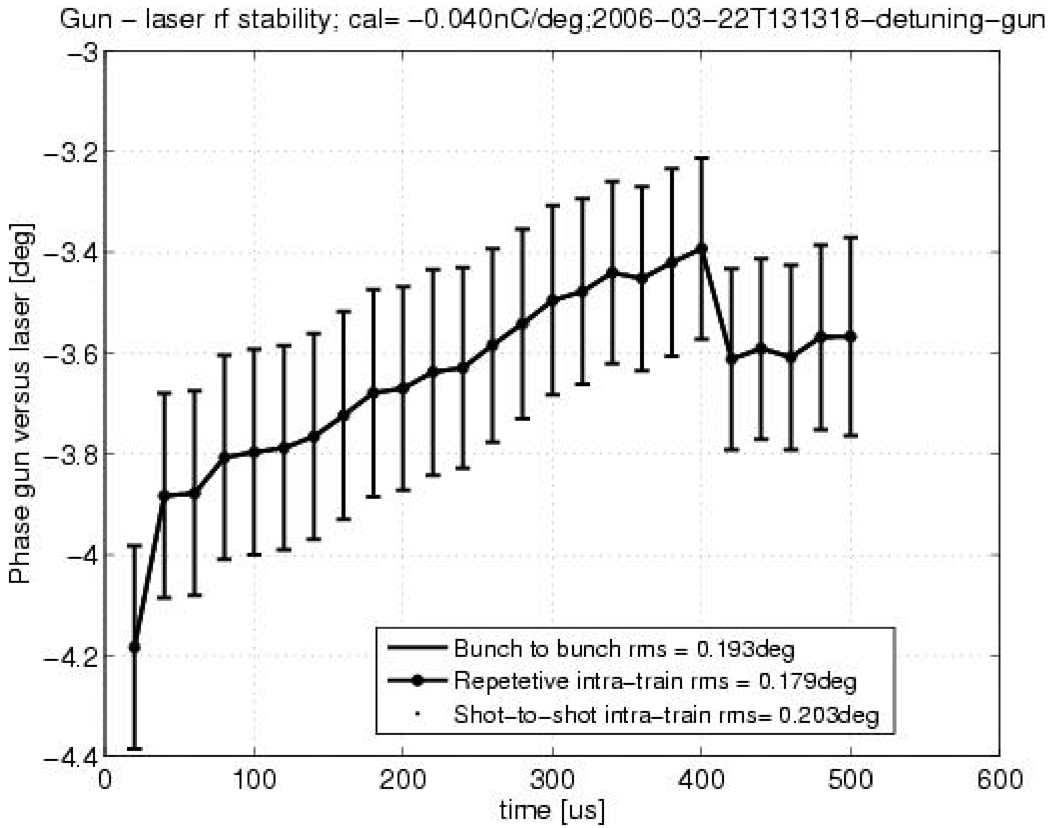


Bunch to bunch stability

RF drive only / similar to DSP



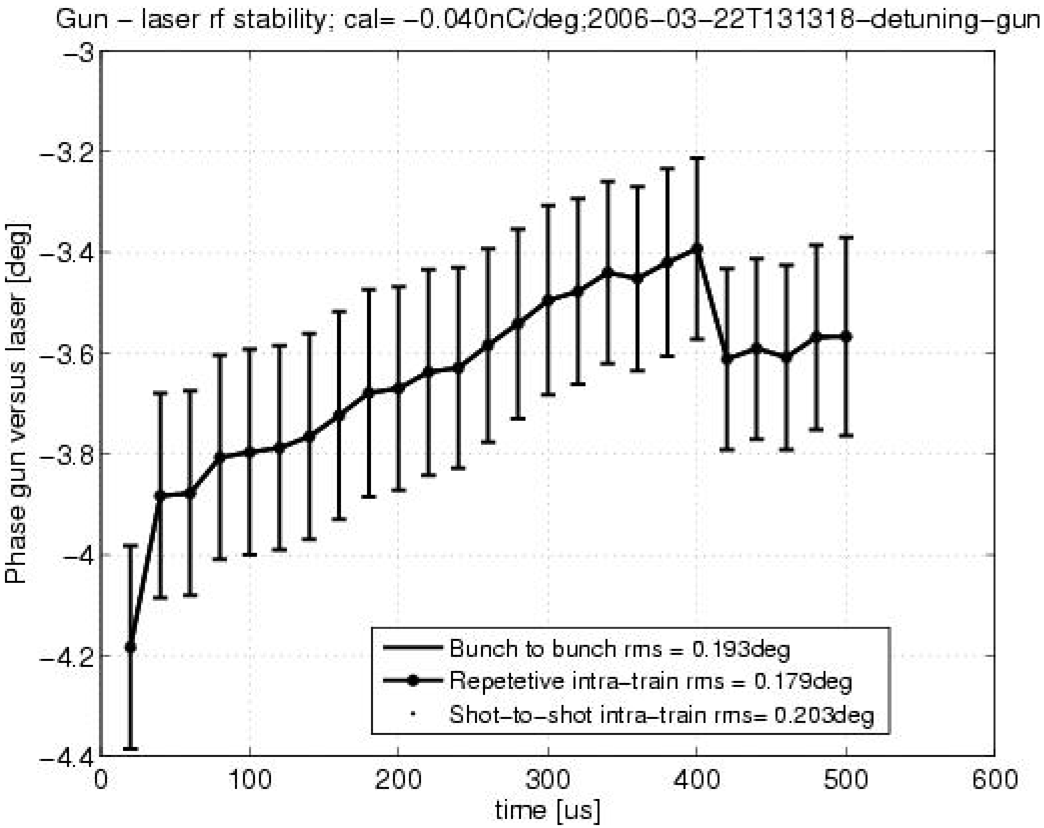
PI control



- resonance frequency change due to gun temperature change within pulse
- step caused by dark current kicker
- error suppression by about 5 (= gain)

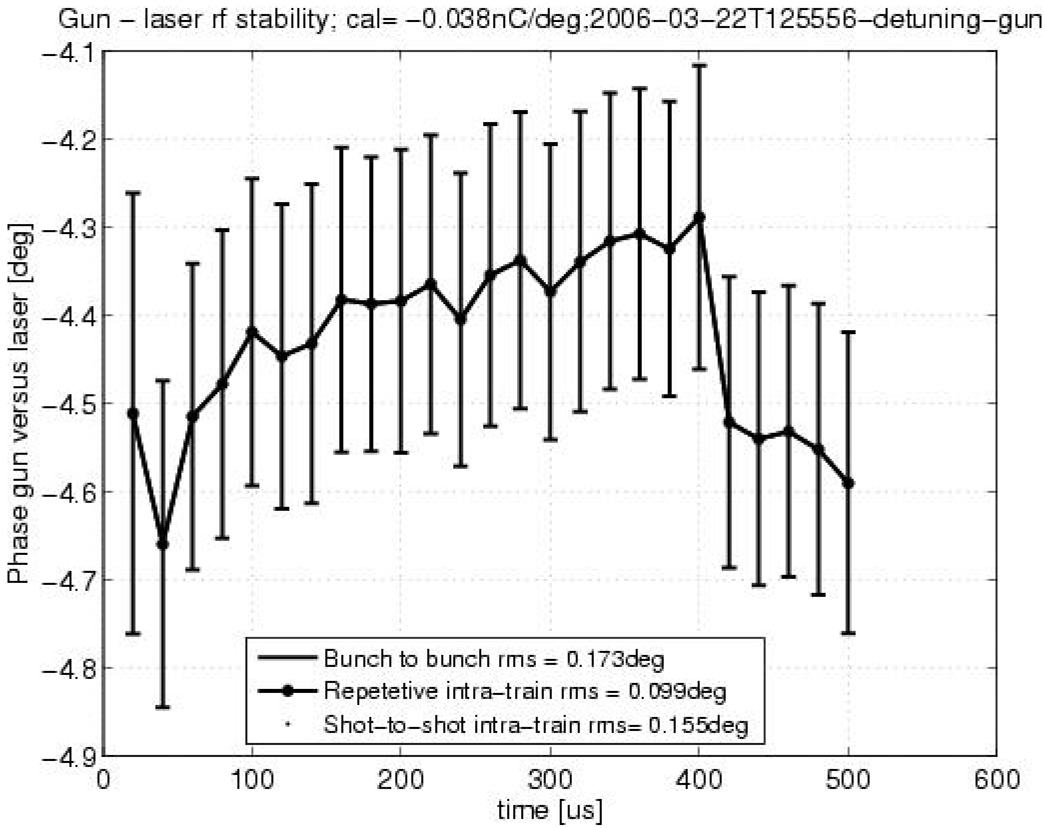
Bunch to bunch stability (continued)

PI control (repeated)



- error suppression by about 5 (= gain)

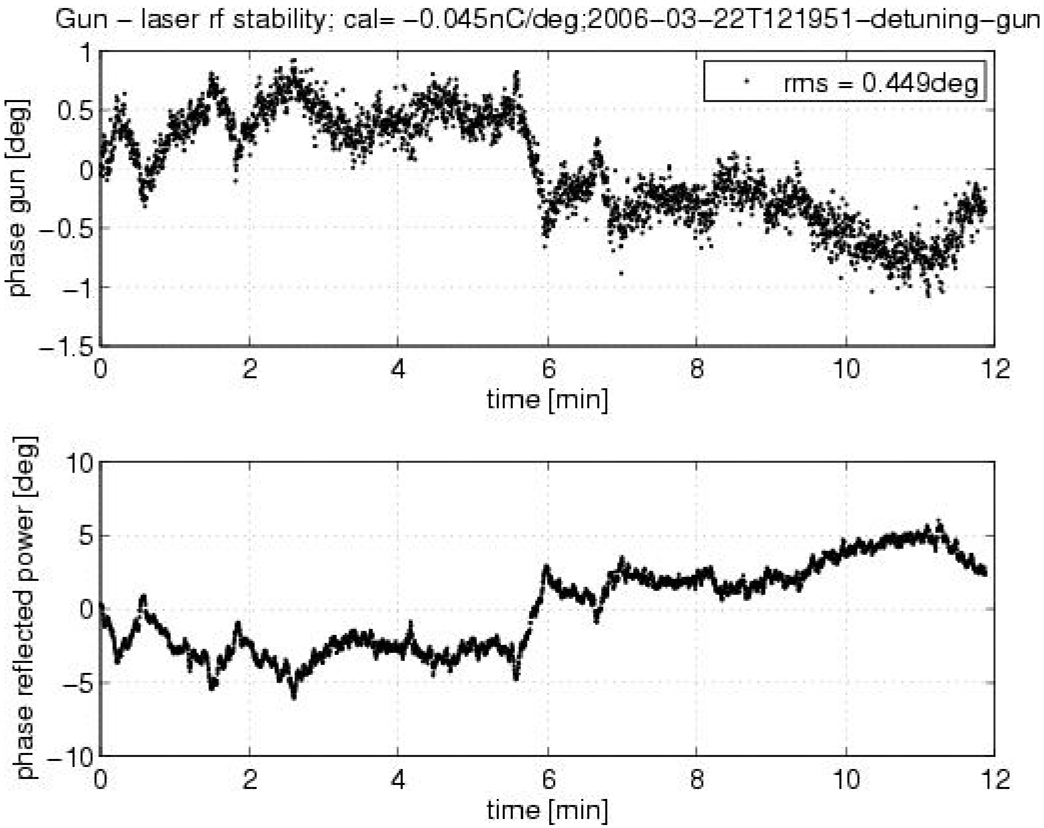
Alternating AFF and PI control



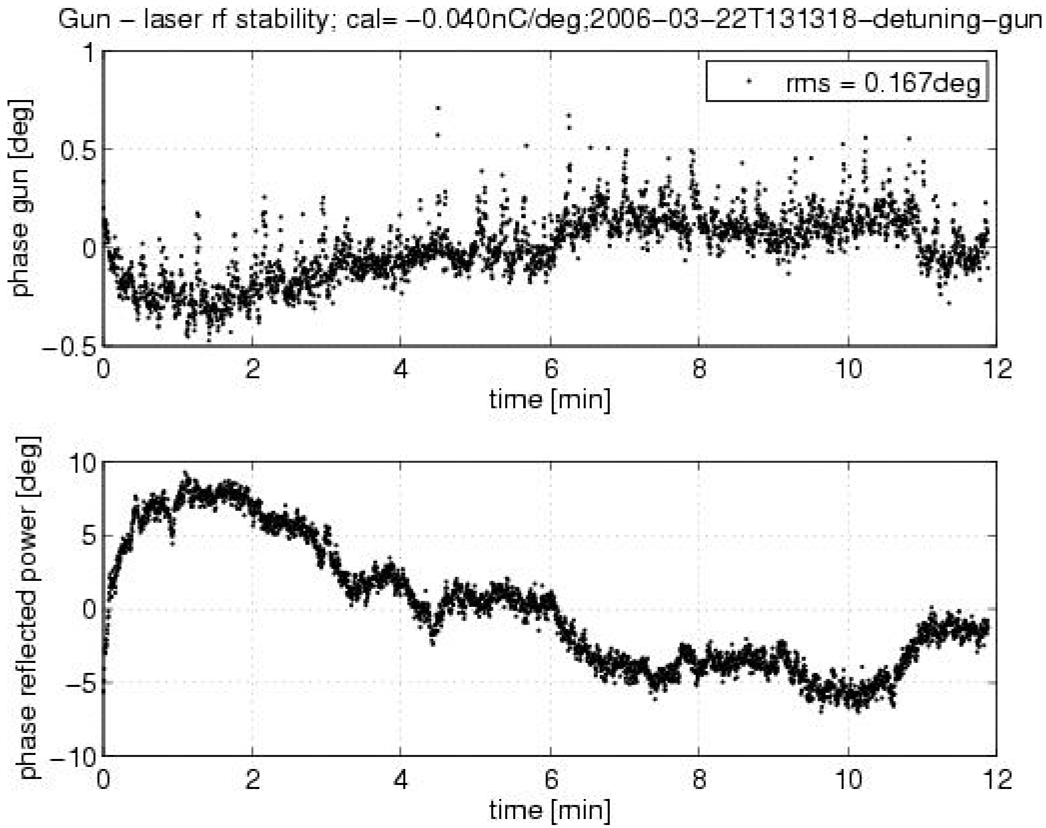
- gun temperature slope decreased by an other factor of 2

Rf pulse to rf pulse stability

RF drive only / similar to DSP



PI control

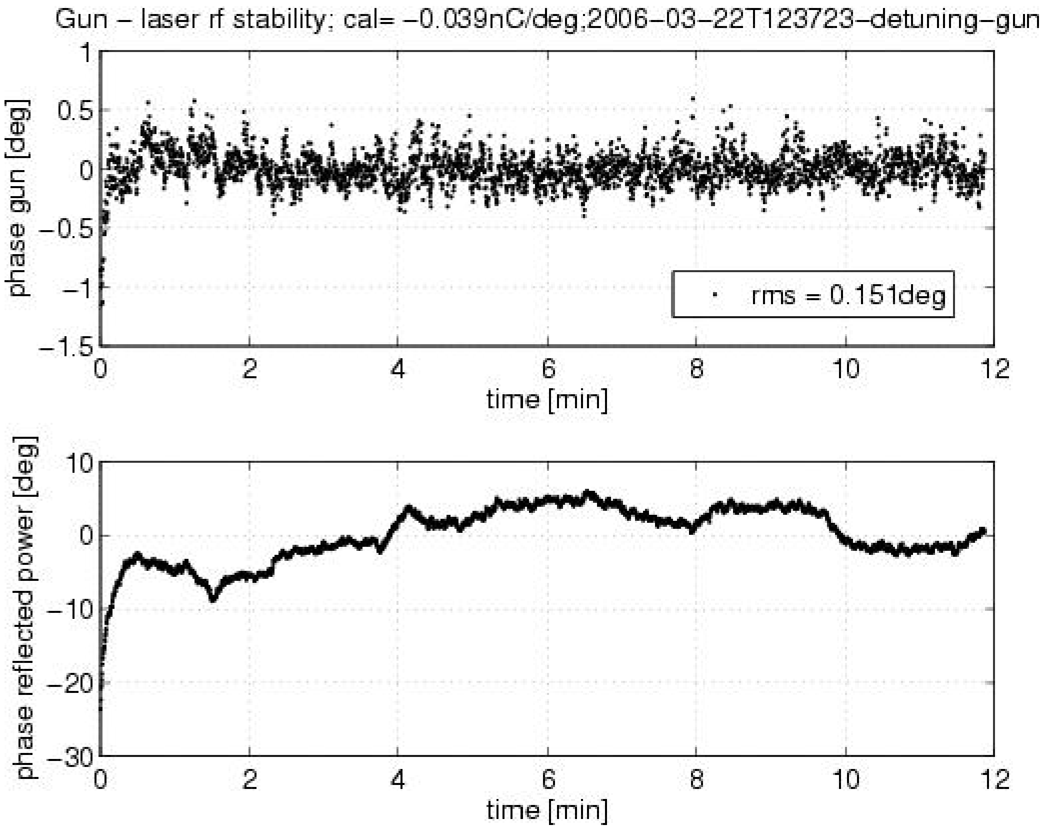


- resonance frequency changes together with the rf gun temperature
- the emission phase changes

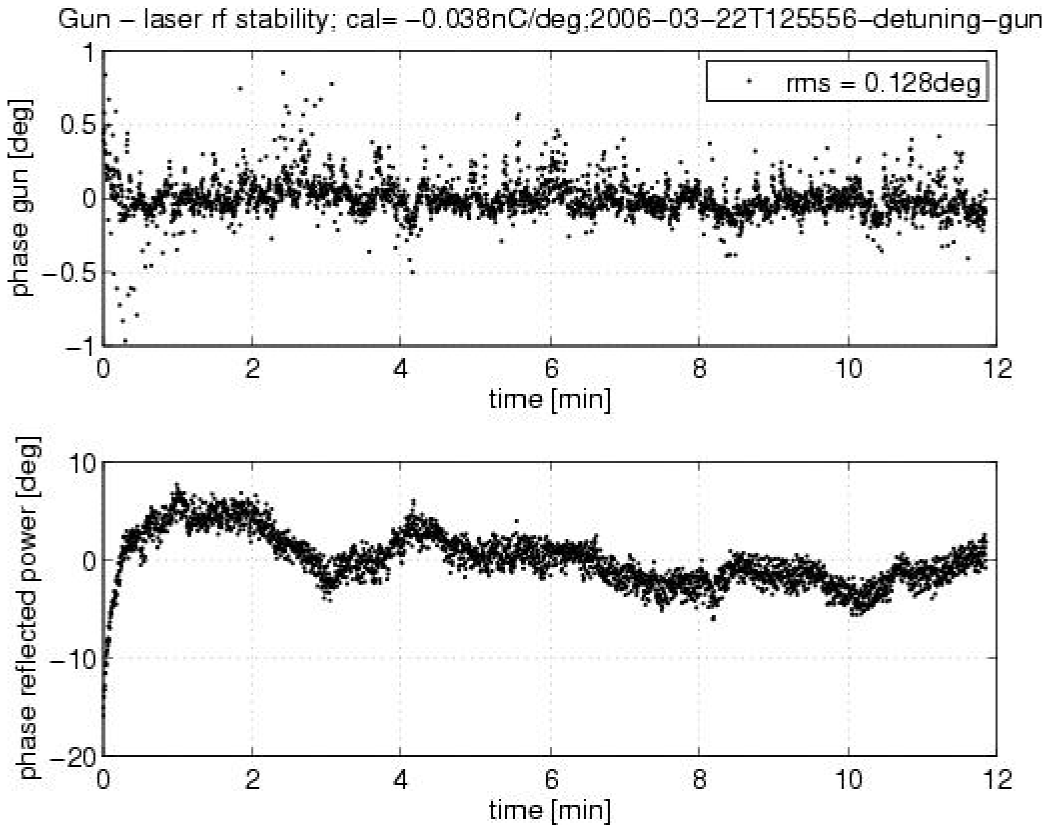
- error suppression by about 3 (< gain)

Rf pulse to rf pulse stability (continued)

AFF only



Alternating AFF and PI control



- error suppression by about 5 (= gain)
- gun temperature slope decreased by an other factor of 2

Subsequent studies since spring 2006

In August 2006:

- 'improved' toroid signals
- slope on phase measured
- first operation with 800 μs
- SASE with 600 (800) bunches

In October 2006:

- reflected power interlock due to second circulator removed

In December 2006:

- operation with 800 μs reestablished
- slope on phase due to gun laser?
- compensation of phase -> amplitude nonlinearity within forward power implemented

In January 2007:

- compensation of phase -> amplitude nonlinearity within sensor part
- hopefully 'final' measurements?

Summary: gun rf control

Rf gun control with DSP:

- insufficient processing power for virtual probe (forward - reflected)
- only forward power was regulated
- field stability > 2°
  < 0.5° required for SASE

Rf gun control with SimCon 3.1:

- sufficient processing power for virtual probe
- sufficient processing power for rf pulse to rf pulse AFF
- field stability obtained: rms ~ 0.15°
  fine for SASE at FLASH

What remains open?

Repetition of qualification measurements:

- without dark current kicker and other problems
- also for AFF & P-control