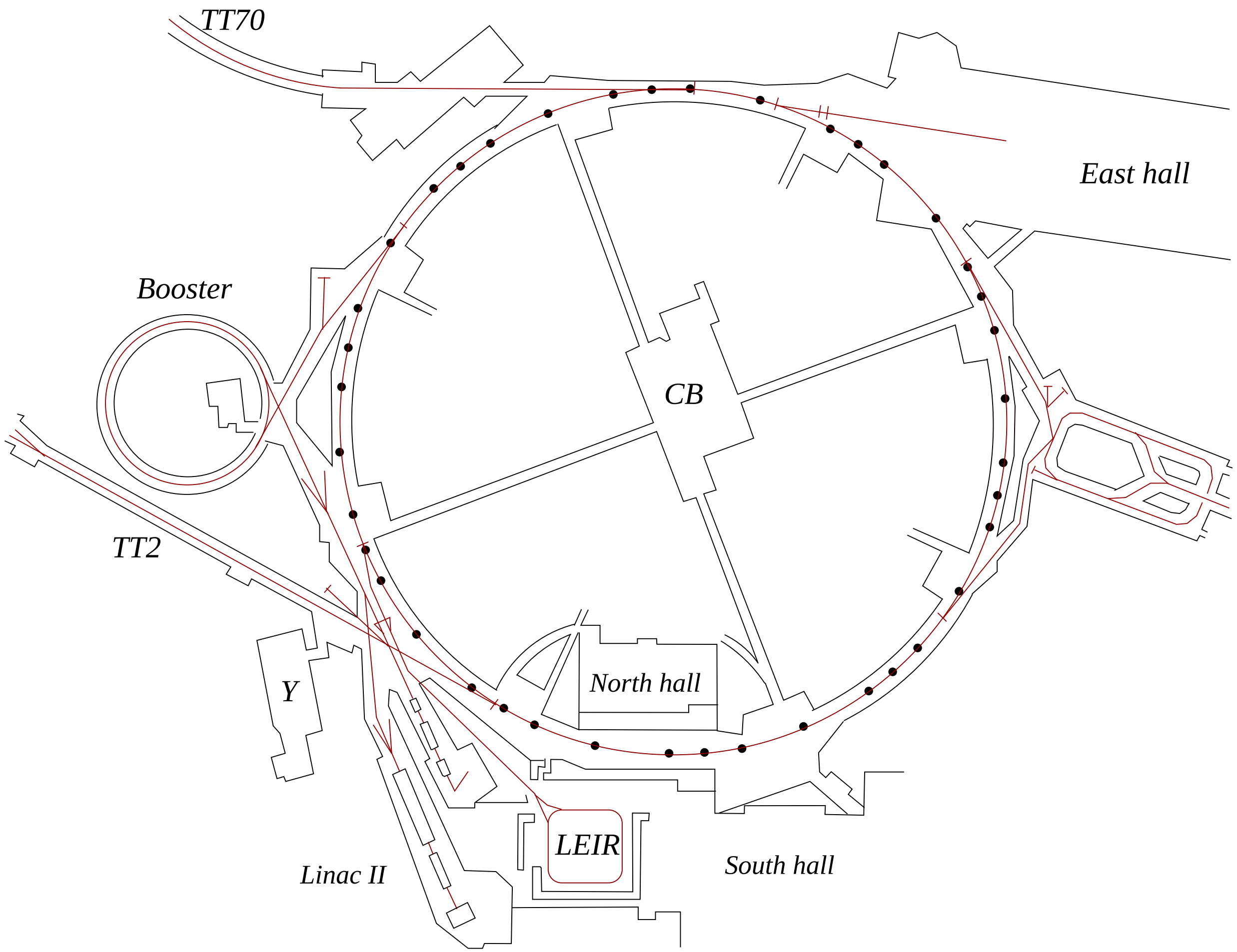
Measuring particle beam trajectories

The CERN PS complex

- Radius: 100 m
- Energy: 26 GeV
- RF harmonic: 8 to 420
- Bunches: 1 to 420
- Charge/bunch:

  $1 \cdot 10^9$ to $8 \cdot 10^{12}$ Q_0
- Pick-Ups: 40
- PU type : Electrostatic



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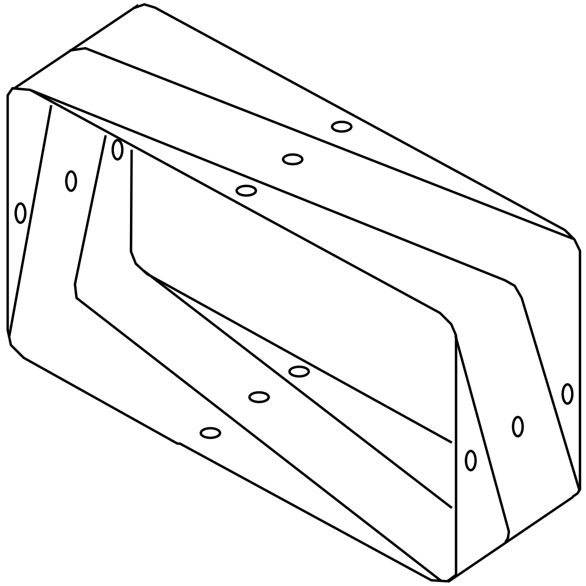
Pick-Up electrodes

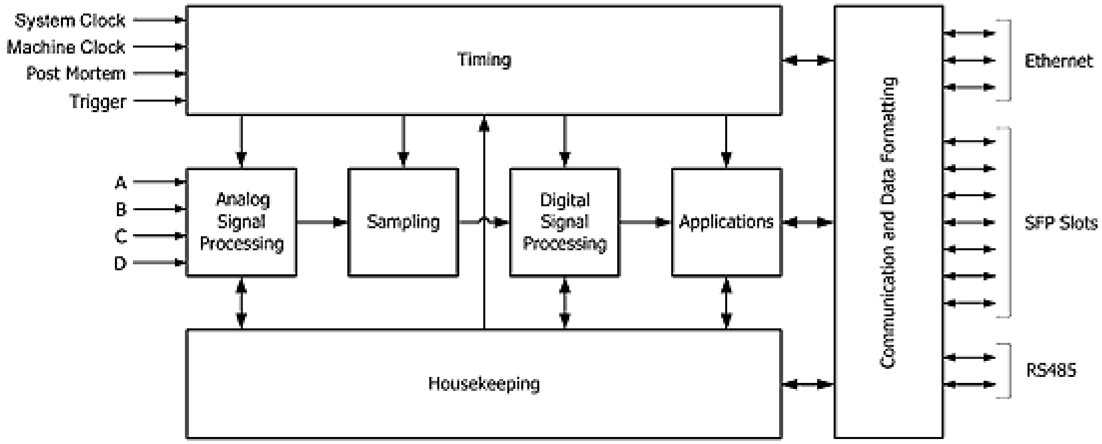
- Length: 62 mm
- Aperture: 166x80 mm
- Capacitance: 100pF
- R_t: 0.52Ω
- S_x: 174 mm
- S_y: 82 mm



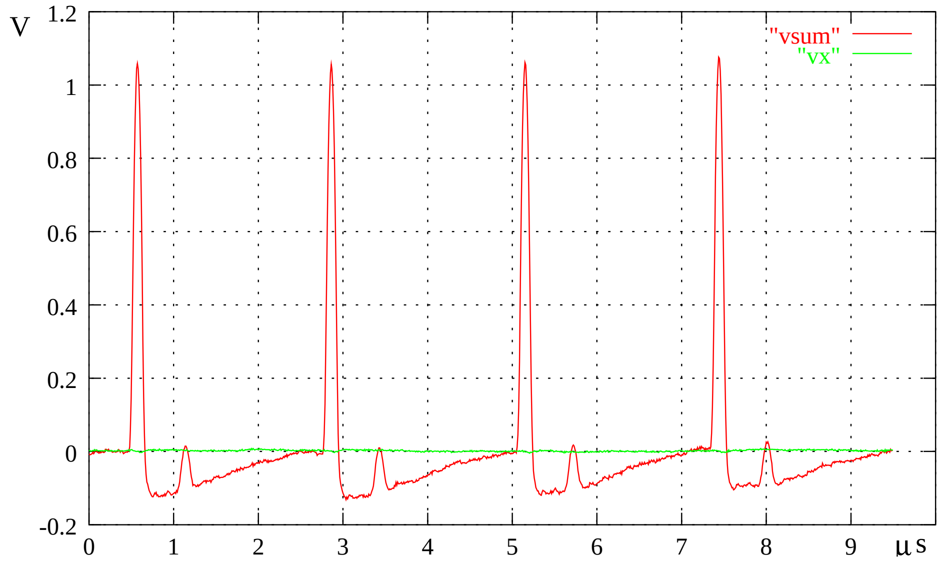
Acquisition

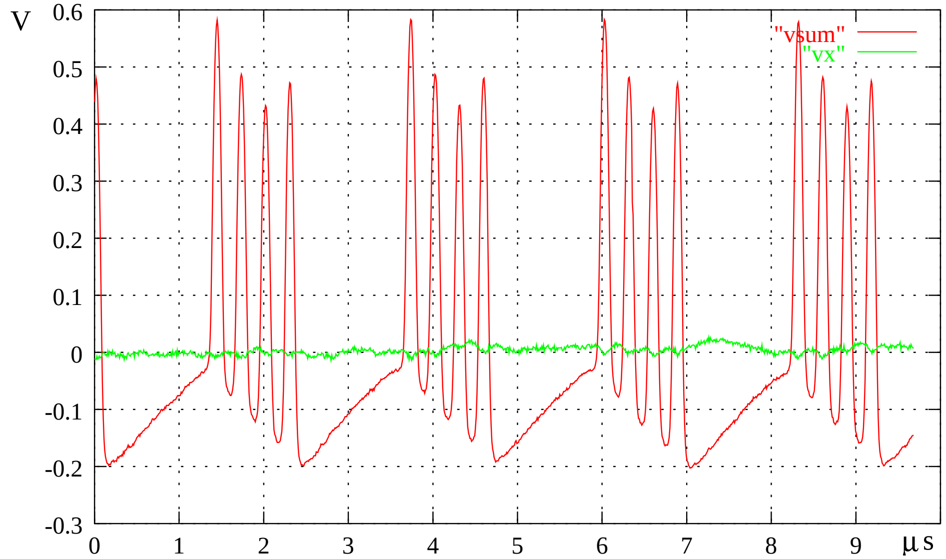
Digitizing hardware: Libera

- Four 125MSPS, 12 bit ADCs
- Large SDRAM
- Xilinx Virtex II FPGA



Sample signals



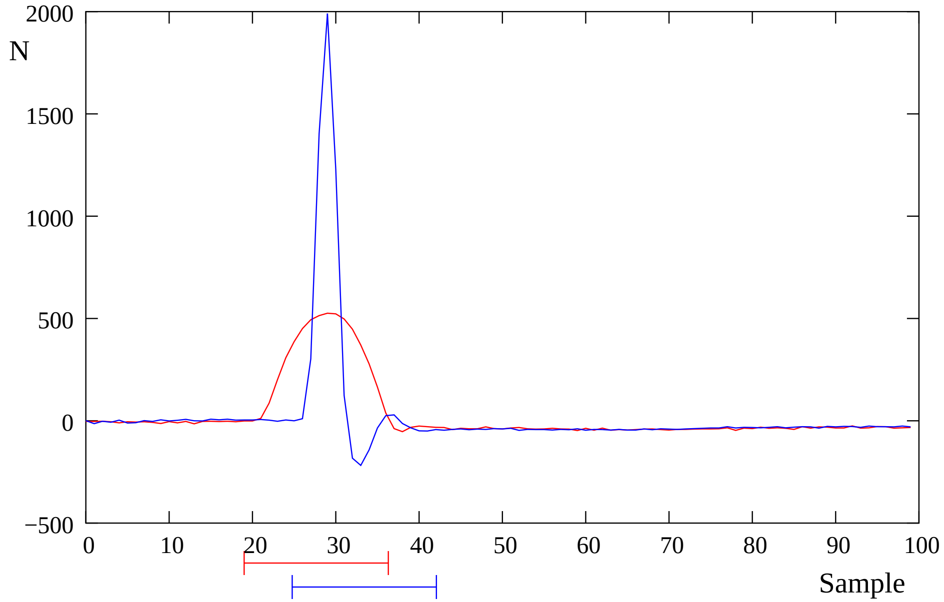


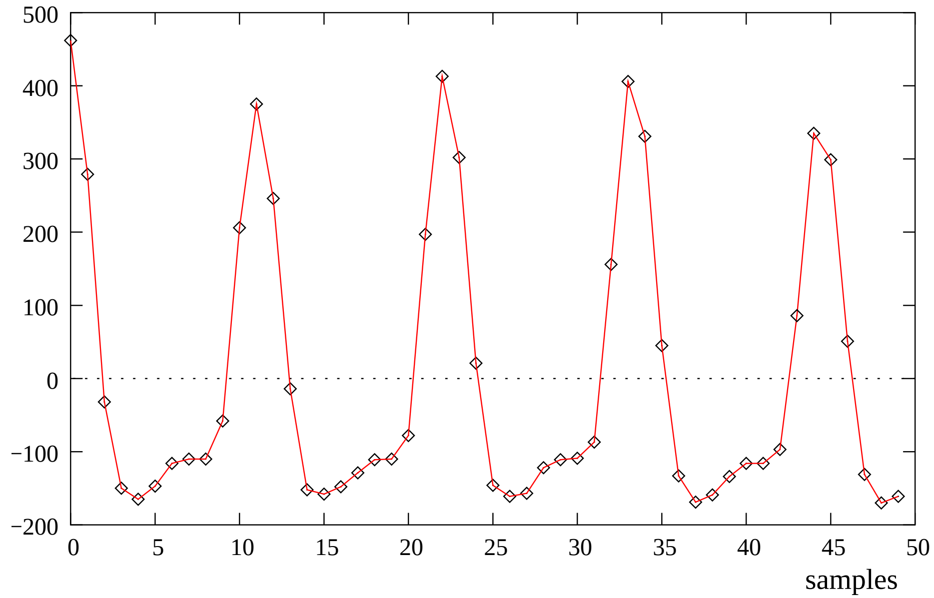
EASTC, 3.6·1012p+/b + 3·1011p+/b

AD, 3.7·1012p+/b

Measuring particle beam trajectories

Evolution of bunch length during acceleration





Bunch length near injection: 120ns
Bunch length near transition: 30ns

Zoom in on LHC-type bunches at h=21

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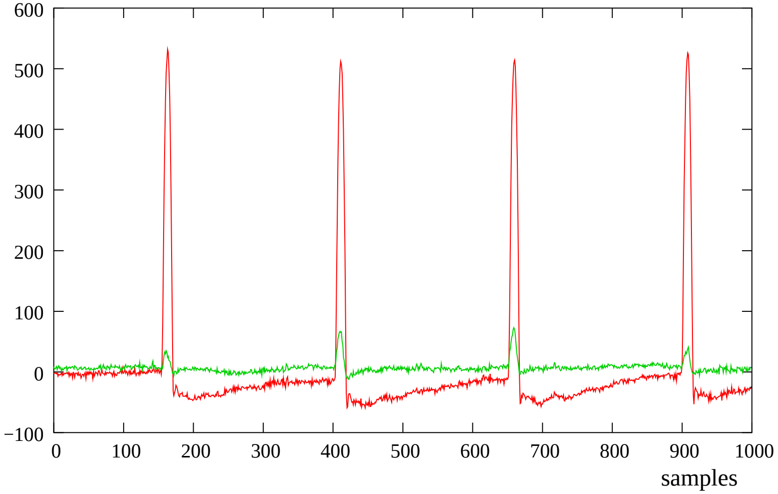
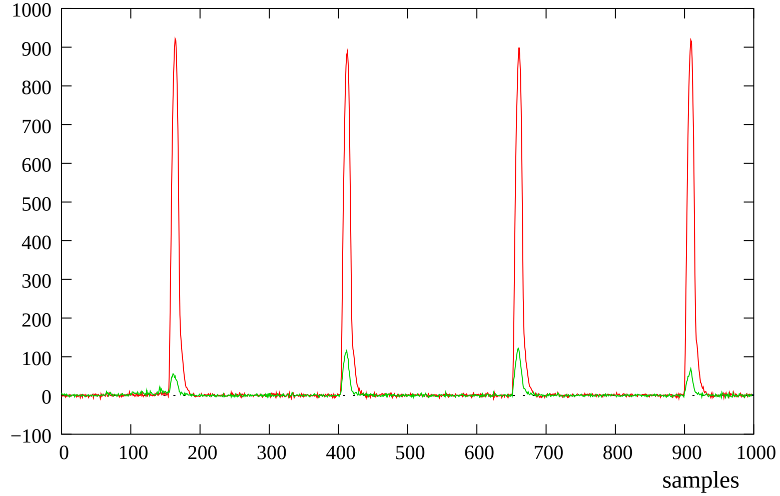
Measuring particle beam trajectories

Principle of base line restitution



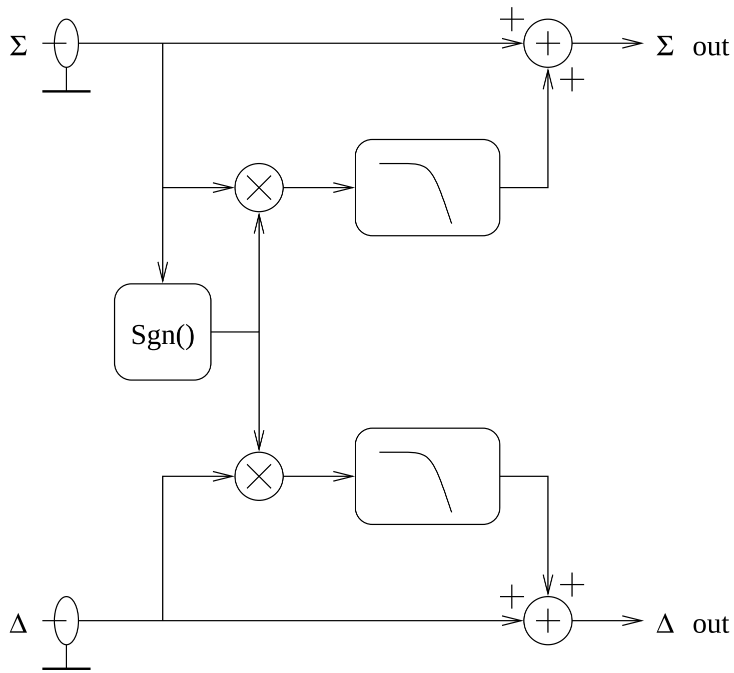
Raw signal



With base line restored

- Fullwave rectify and low-pass filter Σ to get an estimate of the baseline
- Then add that to the original Σ
- Similar for Δ, but still use Σ to get the sign of the correction

Principle of base line restitution



Block diagram of base line restorer

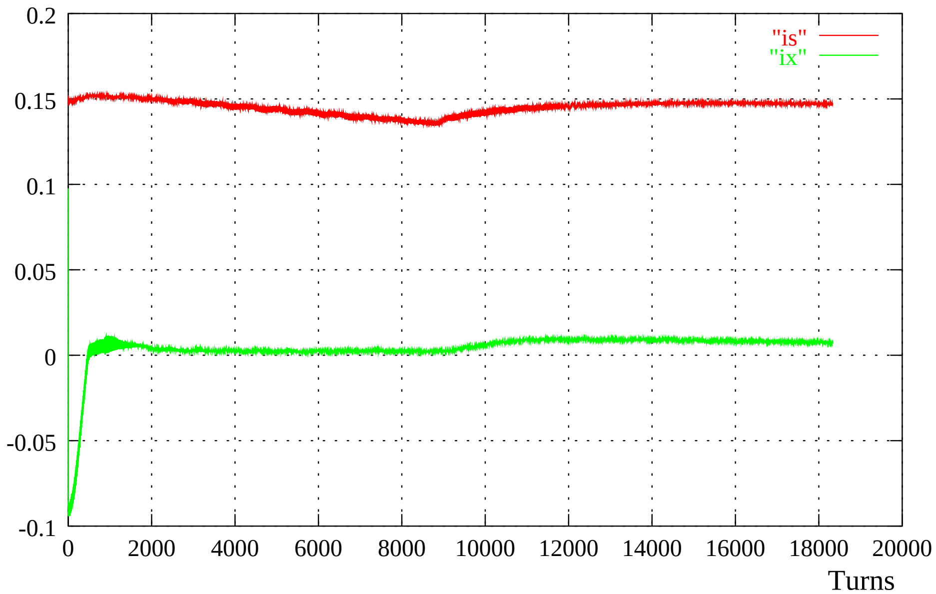
$$B_{\Sigma,n} = aB_{\Sigma,n-1} + (1-a)|\Sigma_n|$$

$$\Sigma_n = \Sigma_{raw} + B_{\Sigma,n}$$

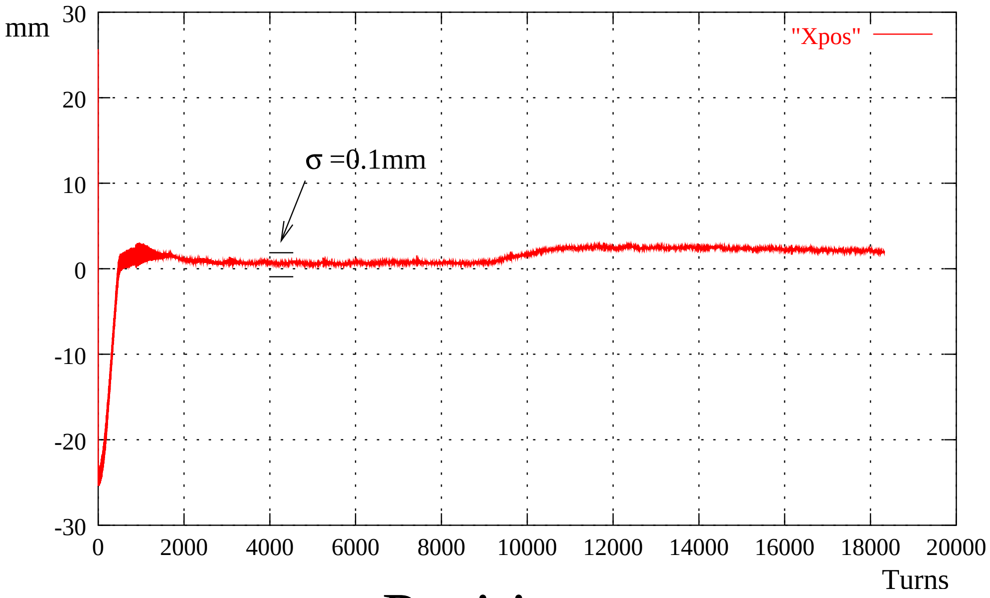
$$B_{\Delta,n} = aB_{\Delta,n-1} + (1-a)\,sgn(\Sigma)\,\Delta_{raw}$$

$$\Delta_n = \Delta_{raw} + B_{\Delta,n}$$

Finding the position



Integrals

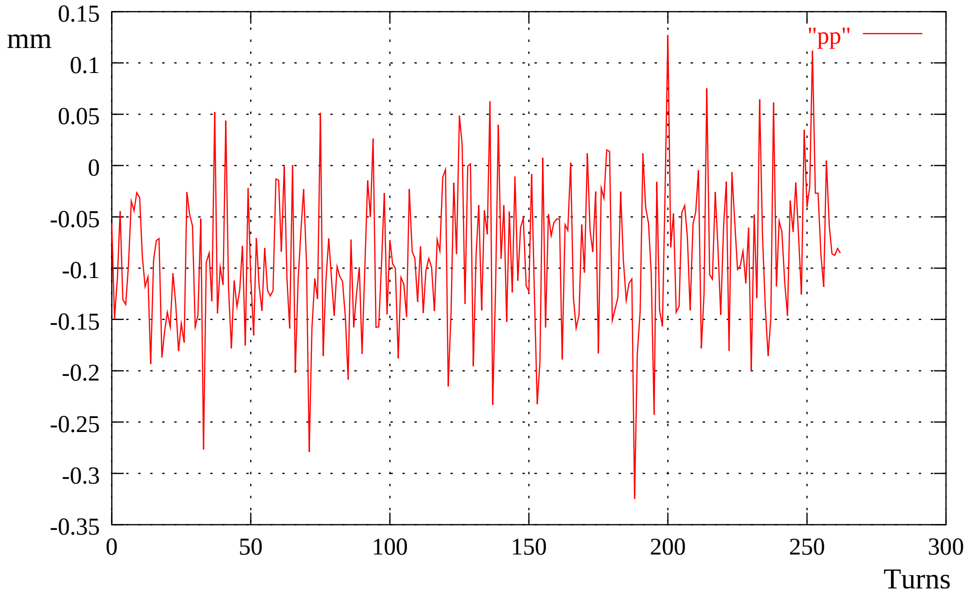


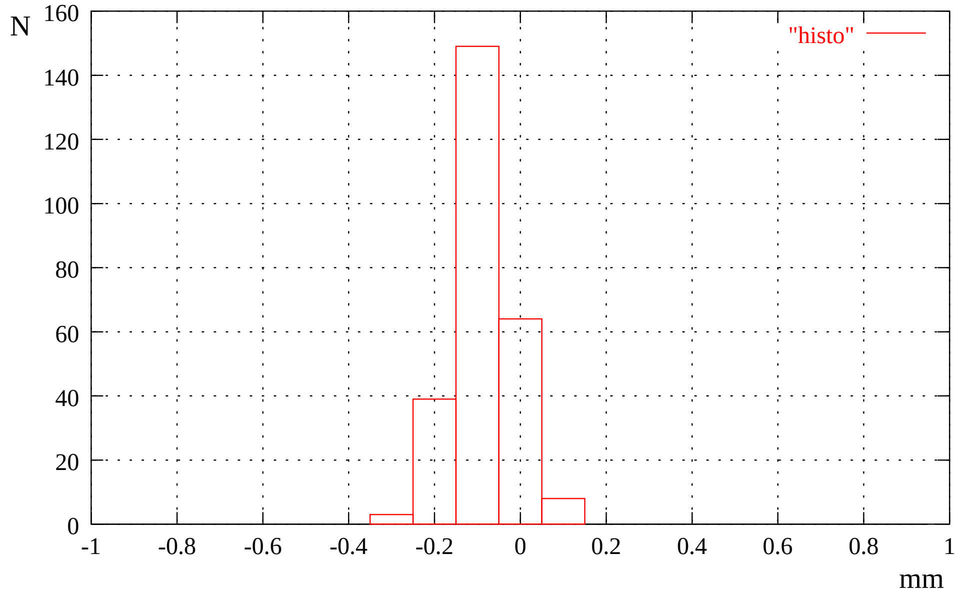
Positions

$$x = S_x \frac{\Delta_x}{\Sigma}$$

Measuring particle beam trajectories

Resolution





$$\sigma_{X/\Sigma} = S_x \frac{\overline{X}}{\overline{\Sigma}} \sqrt{\frac{\sigma_X^2}{\overline{X}^2} + \frac{\sigma_\Sigma^2}{\overline{\Sigma}^2}}$$

μ : -0.09mm

σ : 0.07mm

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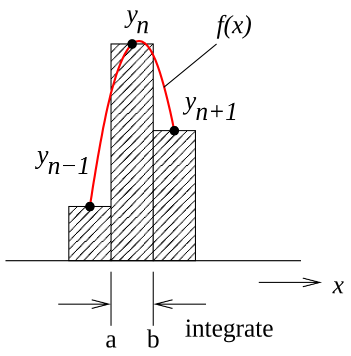
Interpolation between sampling points

- Fit a parabola through each successive sample triplet
- Sum the definite integrals



$$\int_a^b f(x)dx = A_n = \frac{k_1 y_{n-1} + k_2 y_n + k_1 y_{n+1}}{2k_1 + k_2}$$

(For example, with a=-0.5 and b=+0.5, this gives k_1=1 and k_2=22)

This doesn't yield any improvement!

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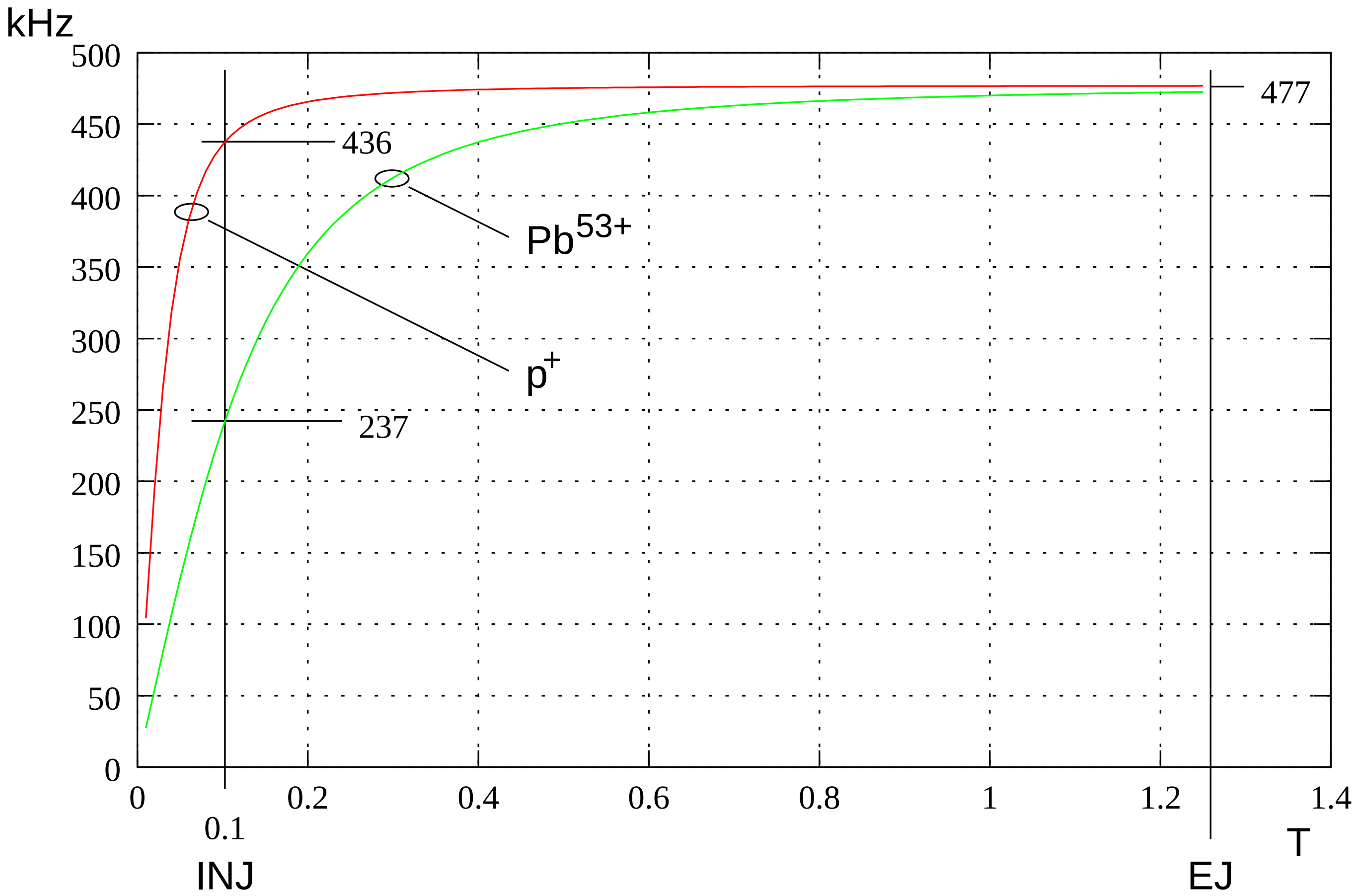
Revolution Frequency vs. B field

$$f = \frac{R_m Q h B}{2\pi R_0 m \sqrt{1 + \left(\frac{R_m Q B}{m c}\right)^2}}$$

R_m = 70.0789 m
R_0 =100 m
Q = [C]
m = [kg]
B = [T]



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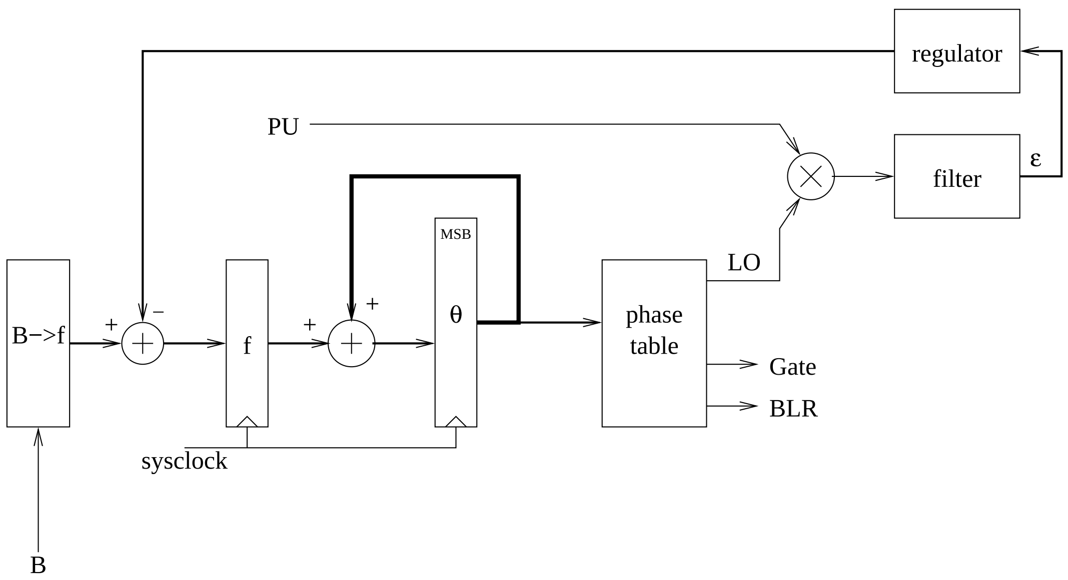
Measuring particle beam trajectories

Creating a reference frequency

- Numerical phase locked loop
- DDS running at F_{rev}
- Lookup table generates LO and Gate



- Insensitive to changes in filling patterns
- Independent of signal polarity
- Can be made to deal cleanly with RF gymnastics

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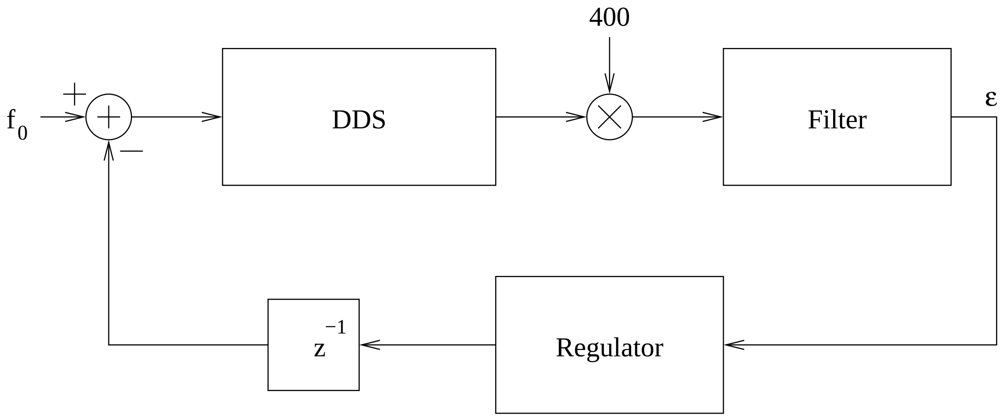
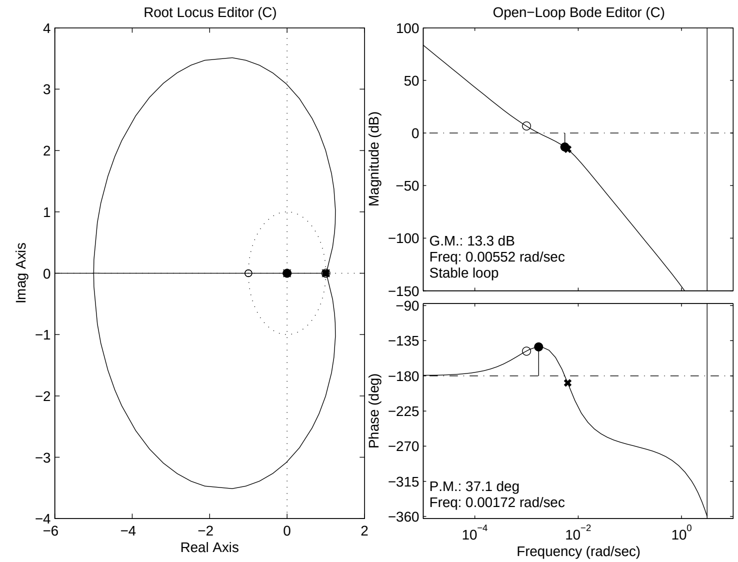
Measuring particle beam trajectories

PLL response analysis



Simplified block diagram



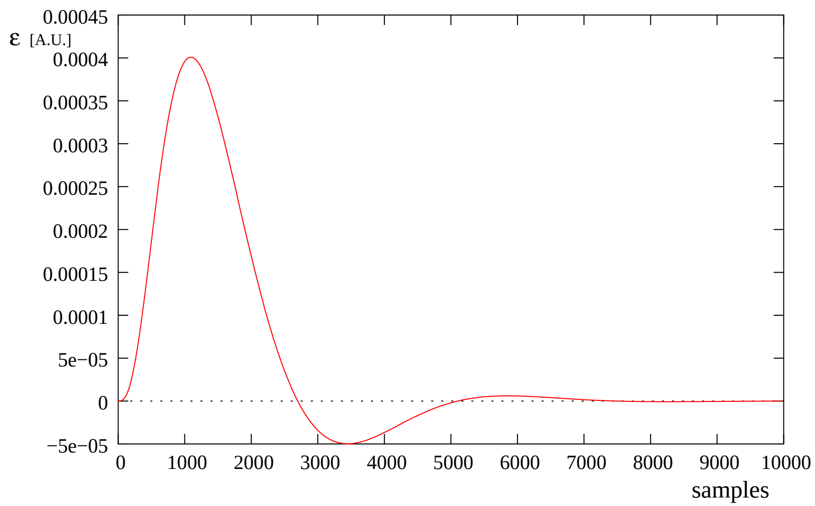
Root locus and Bode plots

DDS $$H_{dds}=\frac{h}{2^{32}}\frac{z^{-1}}{1-z^{-1}}$$

Mixer $$H_m=400$$

Low-pass filter $$H_F=9.8\cdot 10^{-6}\frac{1+2z^{-1}+z^{-2}}{1-1.9911z^{-1}+0.9911z^{-2}}$$

Regulator $$H_R=K_R\cdot z^{-1}\cdot\frac{1-0.999z^{-1}}{(1-z^{-1})}$$



Step (in ε) response

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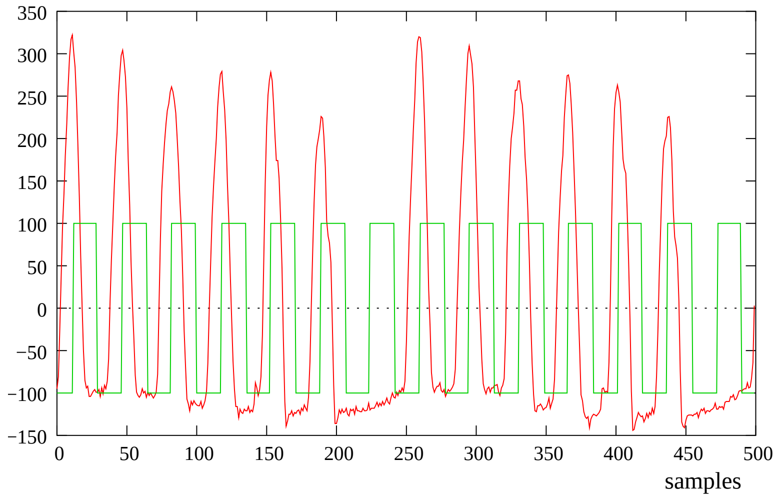
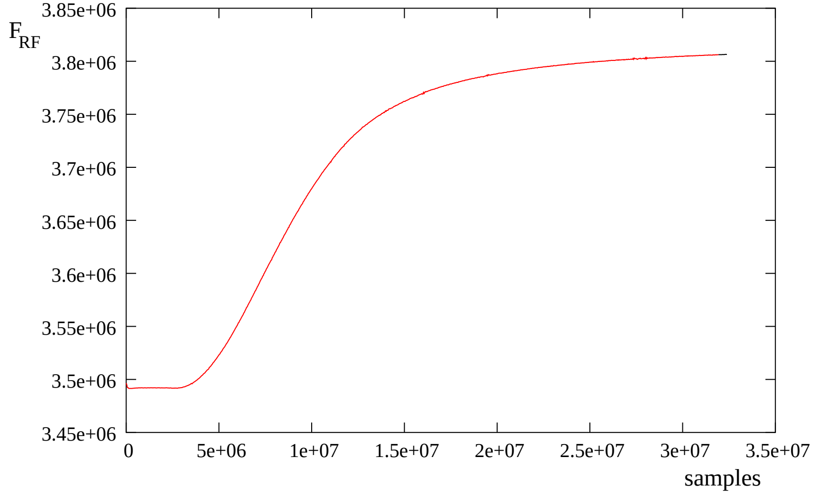
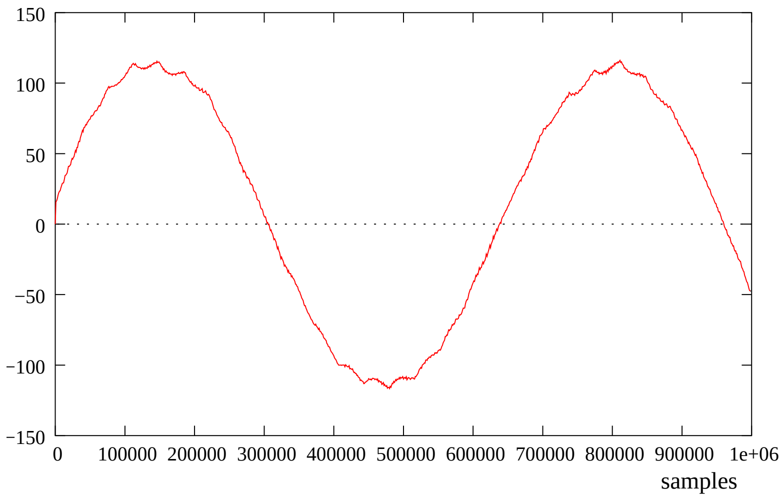
Measuring particle beam trajectories
Creating a reference frequency



PU signal and reconstructed RF at h=7



Evolution of RF frequency during acceleration



Phase error (ε) vs. PU and RF phase difference

There is a trade off between settling time and accuracy:

- Too slow and it won't follow acceleration
- Too fast and the reconstructed RF will be noisy

(Past experience indicates that 20-100μs is about right)

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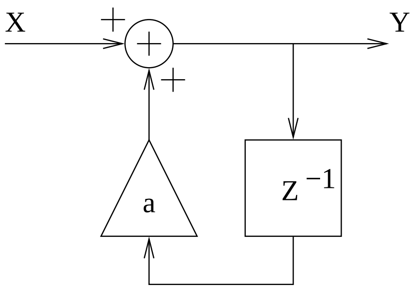
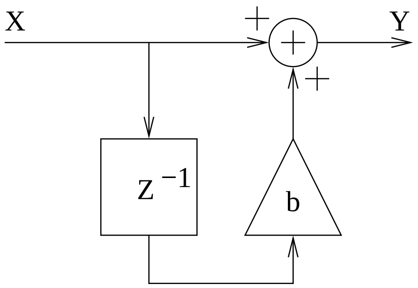
Digital filters

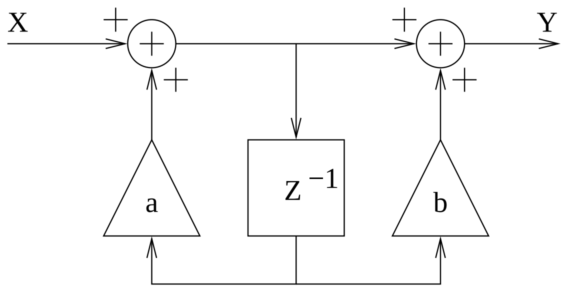


One pole:

$$\frac{y}{x}=\frac{1}{1-a\,z^{-1}}$$

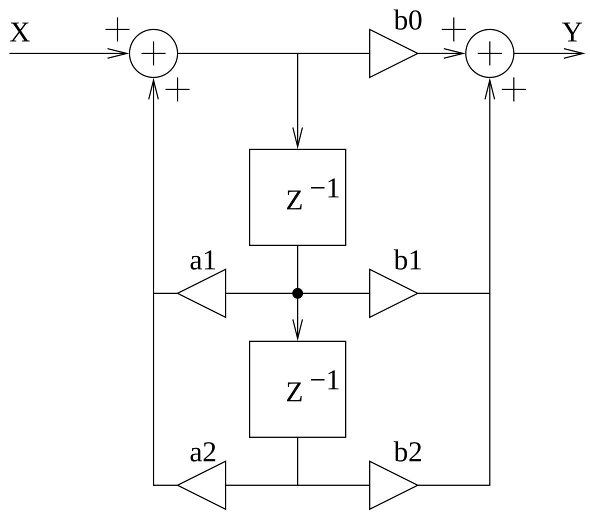


One zero: $\frac{y}{x}=1+b\,z^{-1}$



One pole & one zero

$$\frac{y}{x}=\frac{1+b\,z^{-1}}{1-a\,z^{-1}}$$



Two poles & two zeroes

$$\frac{y}{x}=\frac{b_0+b_1 z^{-1}+b_2 z^{-2}}{1-a_1 z^{-1}-a_2 z^{-2}}$$

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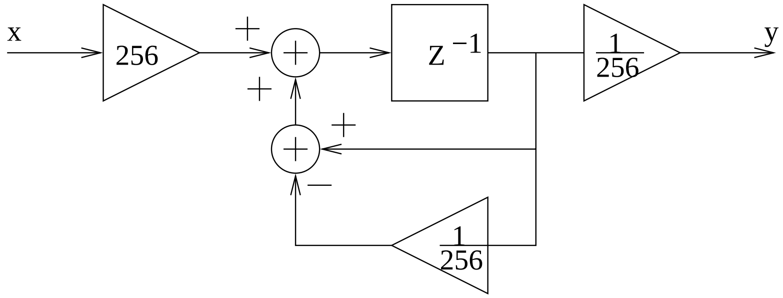
- 0.9911... is an awkward value for a filter parameter

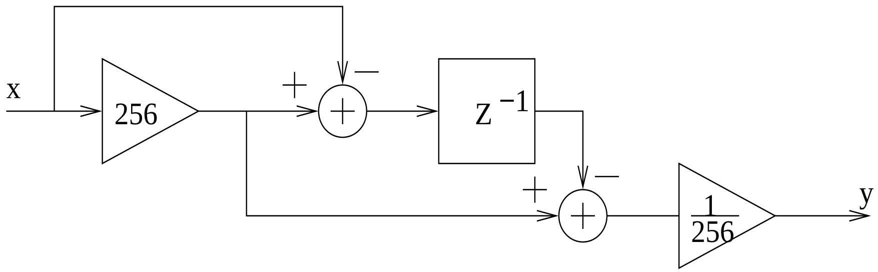
So for a (real) pole:



$$= \frac{y}{x} = \frac{z^{-1}}{1-0.996\,z^{-1}}$$

Nice values are:
127/128=0.992...
255/256=0.996...
511/512=0.998...
1023/1024=0.999...

... and for a zero:



$$= \frac{y}{x} = 1-0.996\,z^{-1}$$

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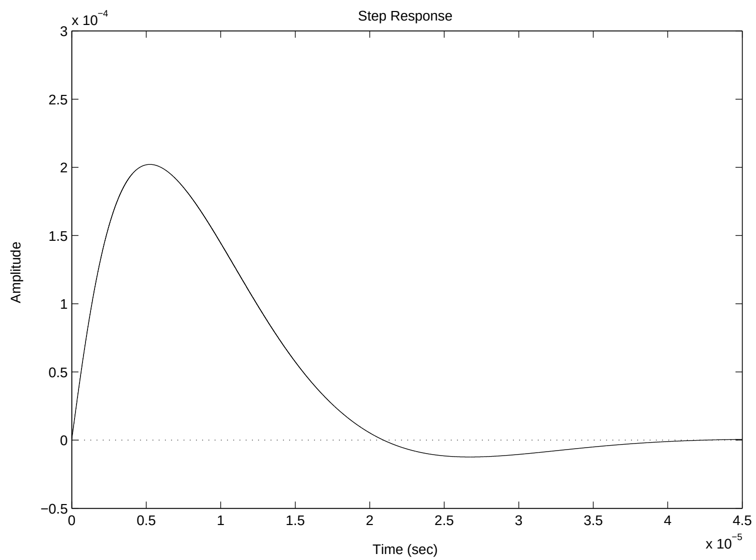
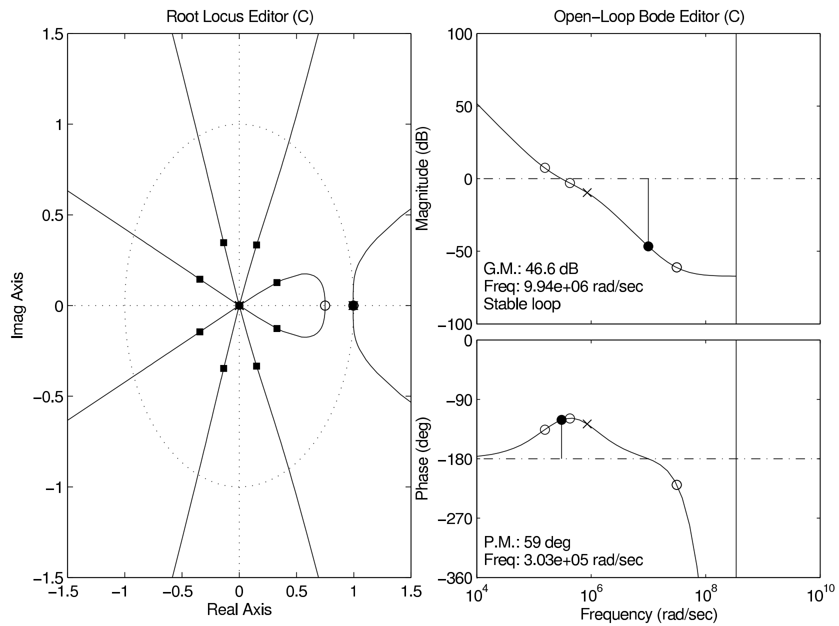
Using sweet filter values and inserting (unavoidable) pipeline delays

DDS $H_{dds}=\frac{h}{2^{32}}\frac{z^{-1}}{1-z^{-1}}$

Mixer $H_m=400$

Feedback $H_R=800\frac{(z-0.996)(z-0.999)(z-0.75)^2}{(z-1)(z-0.992)^2 z^9}$





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References:

- These transparencies:
  http://www.cern.ch/jeroen/slides/Trajectory.pdf
- E. Bravin et al, “Specification of the beam position measurement in the PS machine”, AB-Note-2004-001(ABP),
  http://documents.cern.ch//archive/electronic/cern/others/ab/ab-note-2004-001.pdf
- J.M. Belleman, "Using a Libera signal processor for acquiring position data from the PS orbit pick-ups", CERN AB-Note-2004-059 BDI,
  http://documents.cern.ch//archive/electronic/cern/others/ab/ab-note-2004-059.pdf
- The transparencies on the PU pre-amplifier electronics:
  http://cern.ch/jeroen/slides/Darmstadt2004/electronics.pdf