A new trajectory measurement system for the CERN PS

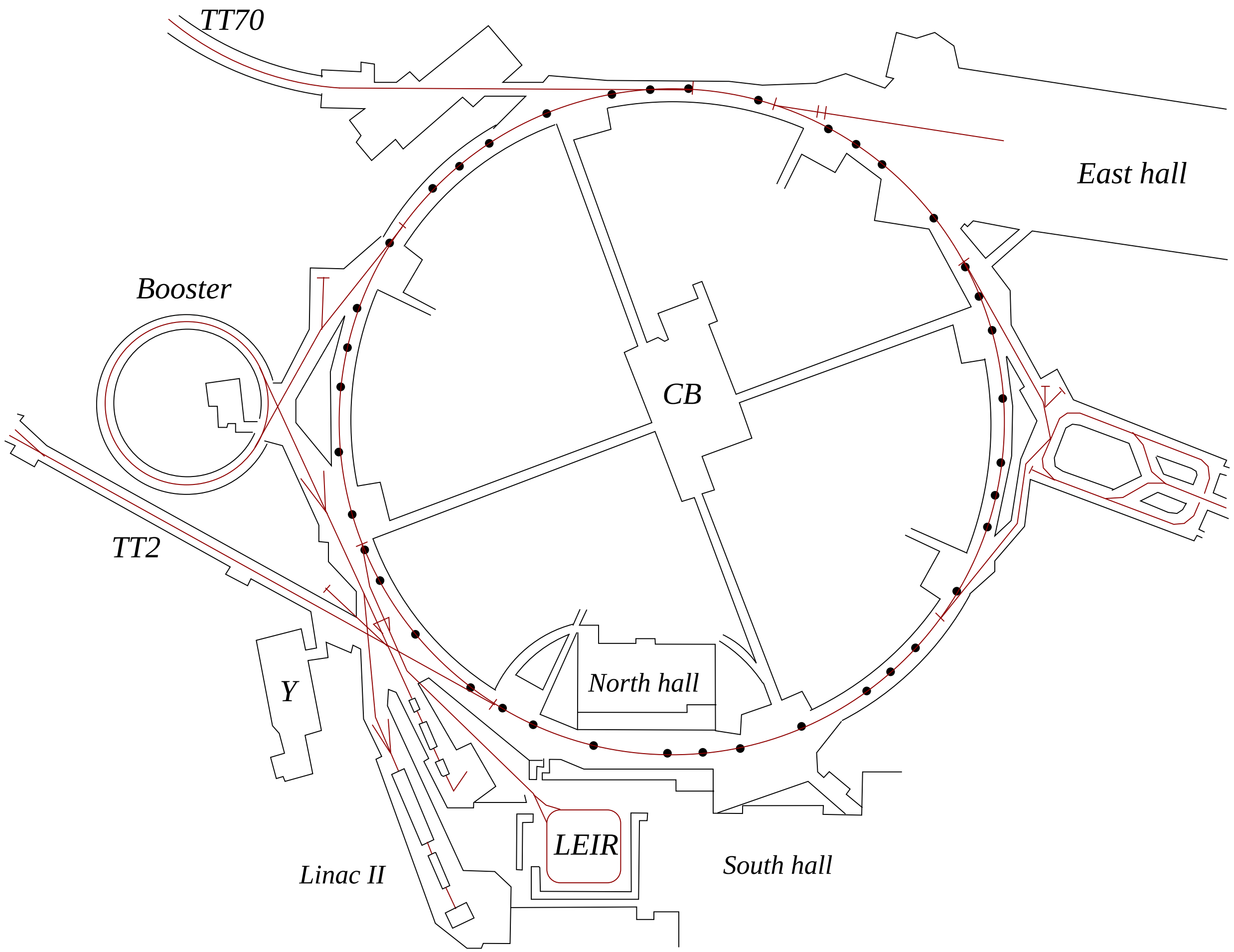
References

- These transparencies: http://cern.ch/jeroen/slides/DIPAC05slides.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
- R. Garoby, S. Hancock, A. Ozturk, J-C. Perrier, J-L. Vallet, “PS machine development report: Preparation of the nominal production beam for the AD”, PS/RF/Note 99-01 (MD)
- R. Garoby, S. Hancock, J-L. Vallet, “Demonstration of bunch triple splitting in the CERN PS”, CERN/PS 2000-038 (RF)

The CERN PS complex

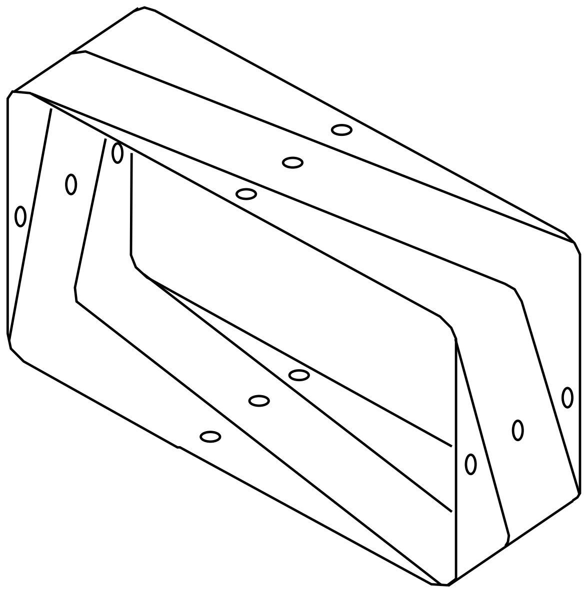
- Radius: 100 m
- Energy: 26 GeV
- RF harmonic: 8 to 420
- Bunches: 1 to 420
- Charge/bunch:

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

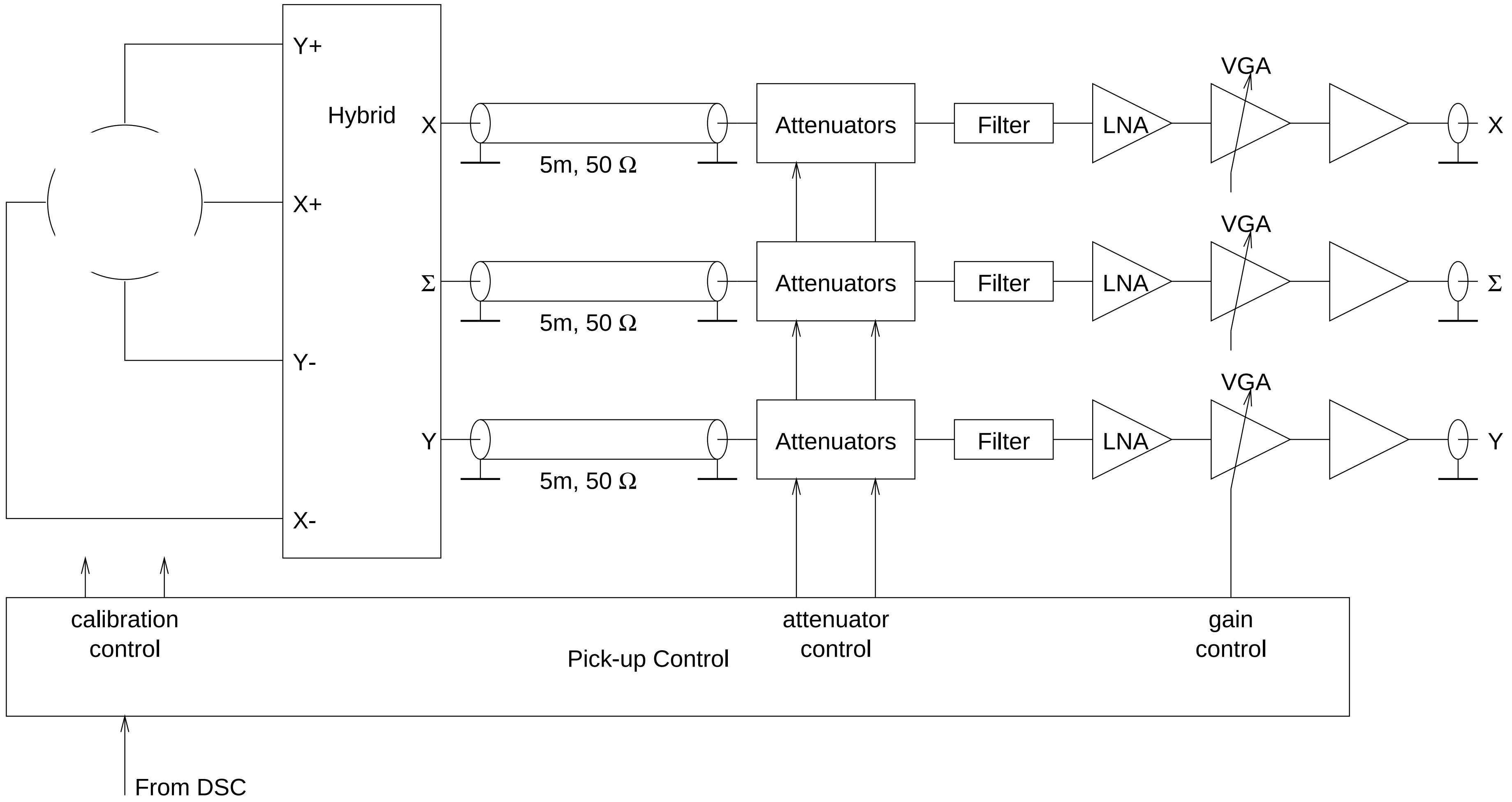


Pick-Up electrodes

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



Analogue signal processing



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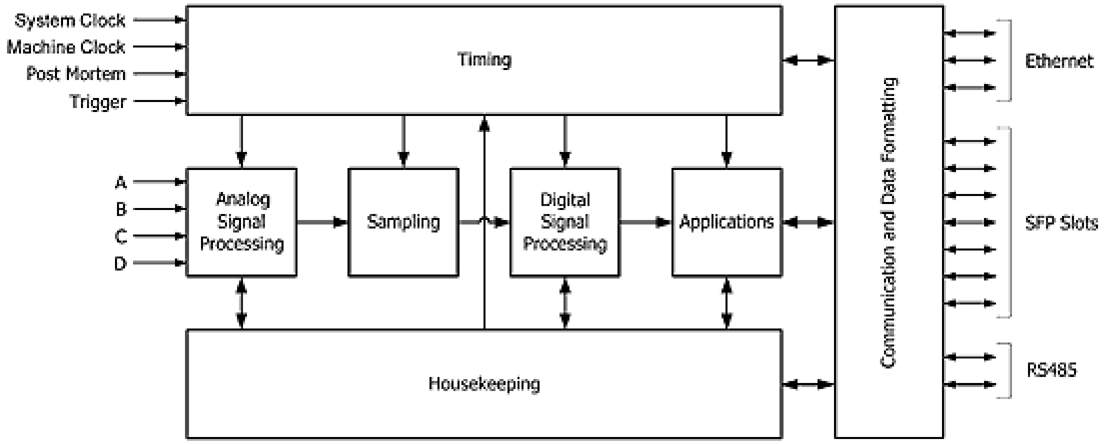
Acquisition

Digitizing hardware: Libera

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



Ref: Libera, Instrumentation Technologies d.o.o., Srebrnicev trg 4 a, SI-5250 Solkan, Slovenia

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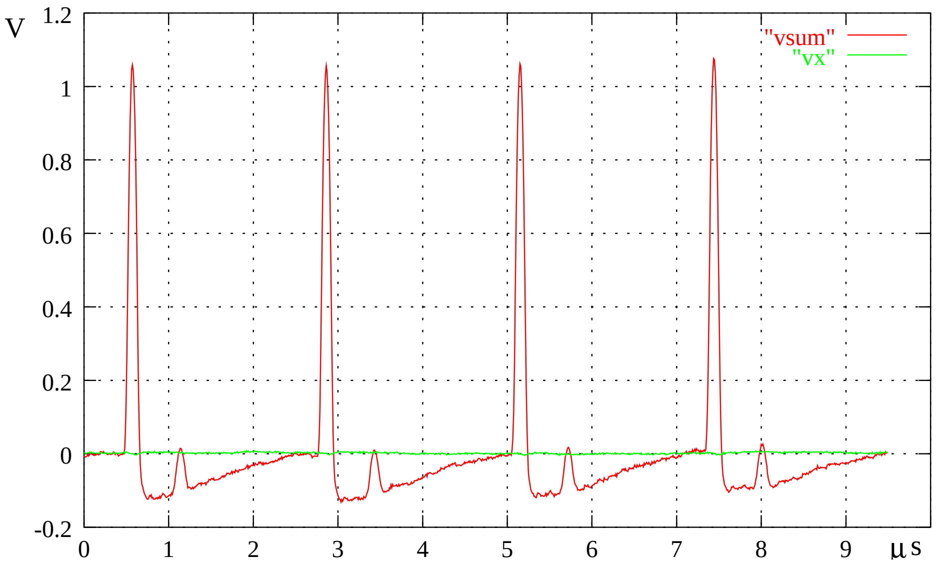
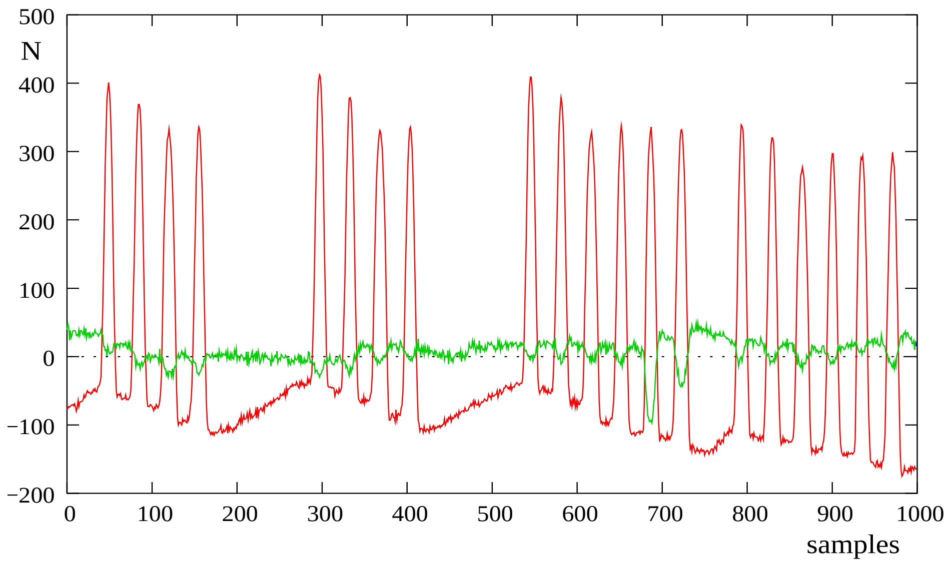
Sample signals

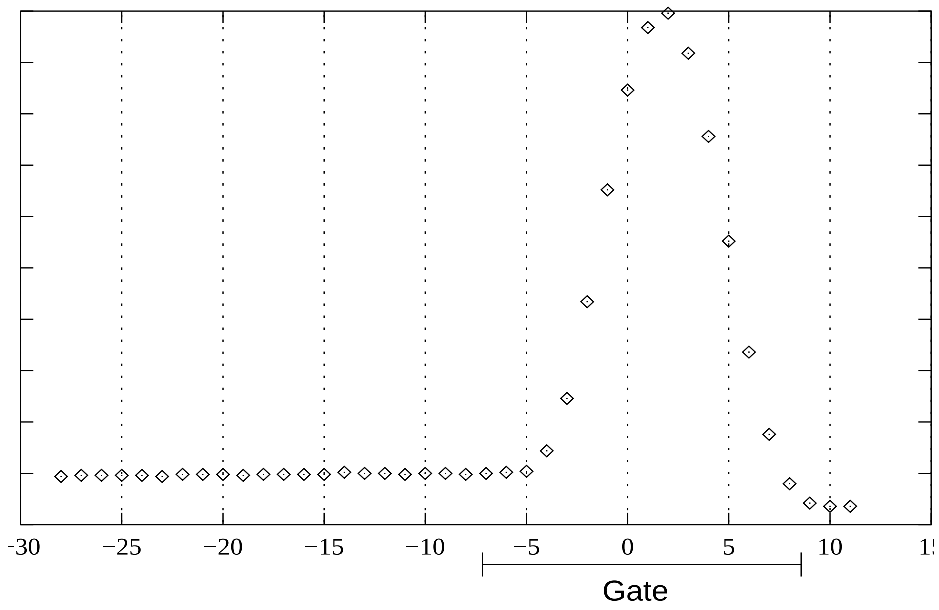


EASTC, $3.6 \cdot 10^{12} p^{+}/b + 3 \cdot 10^{11} p^{+}/b$



LHC, at 2^{nd} injection

Integration algorithm



- Base line correction is needed to remove sensitivity to gate length
- Integration is simple addition of baseline-corrected samples

(This leaves a lot of room for refinements)

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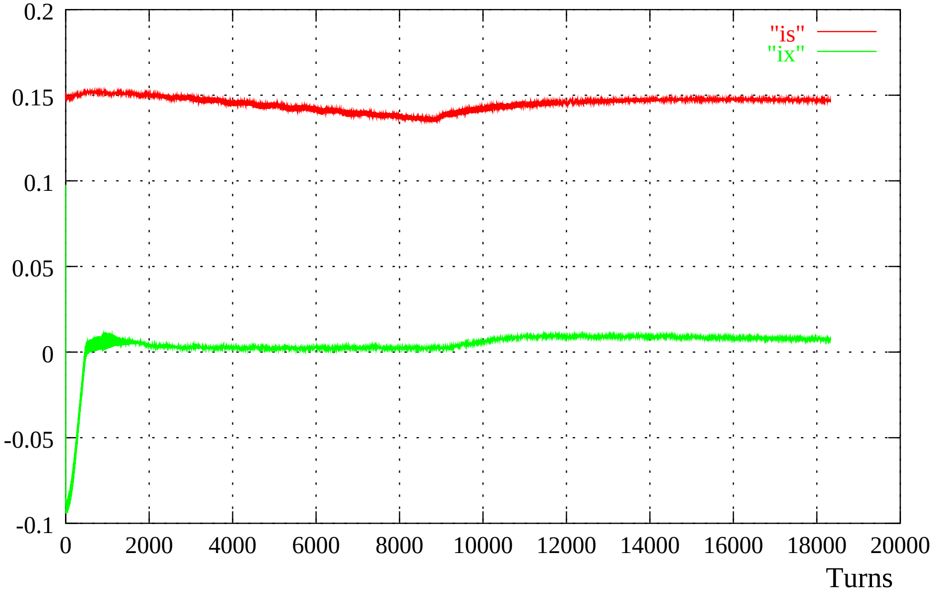
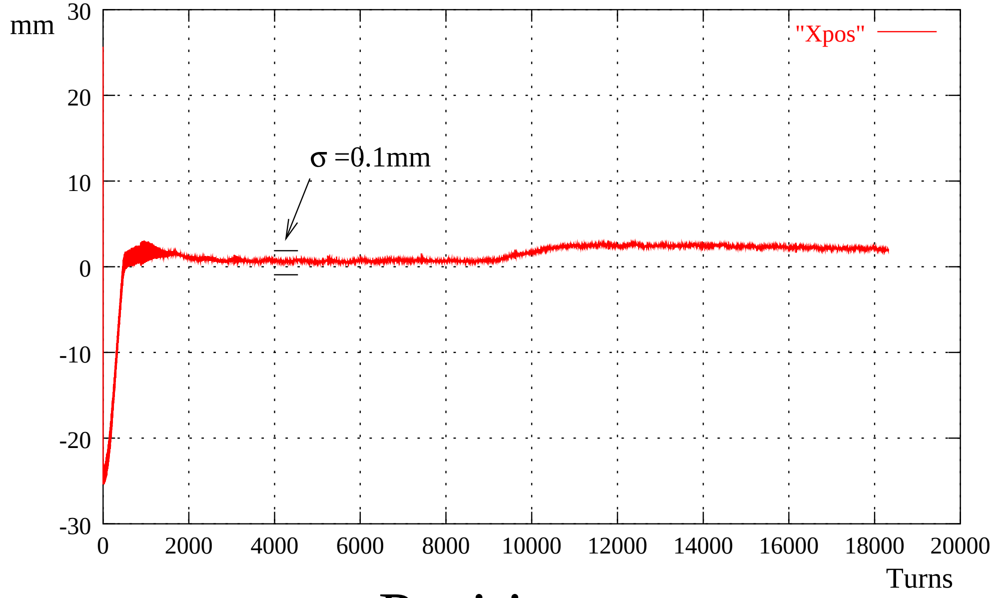
Finding the position



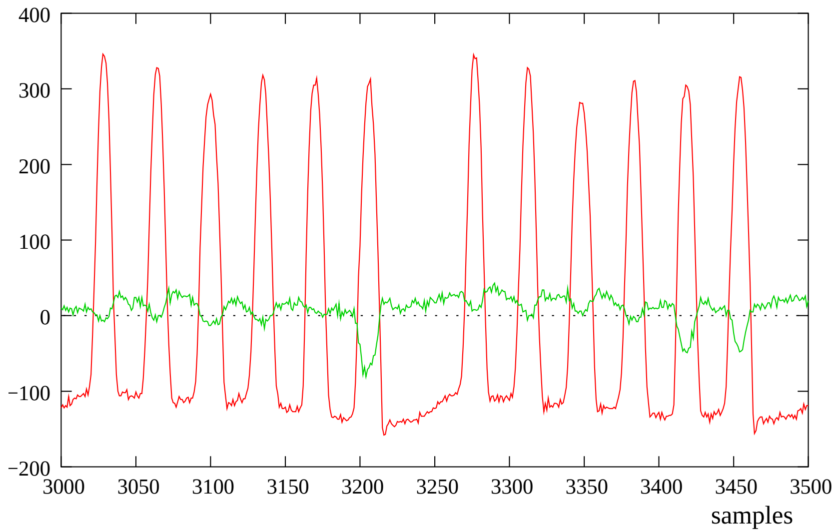
Integrals



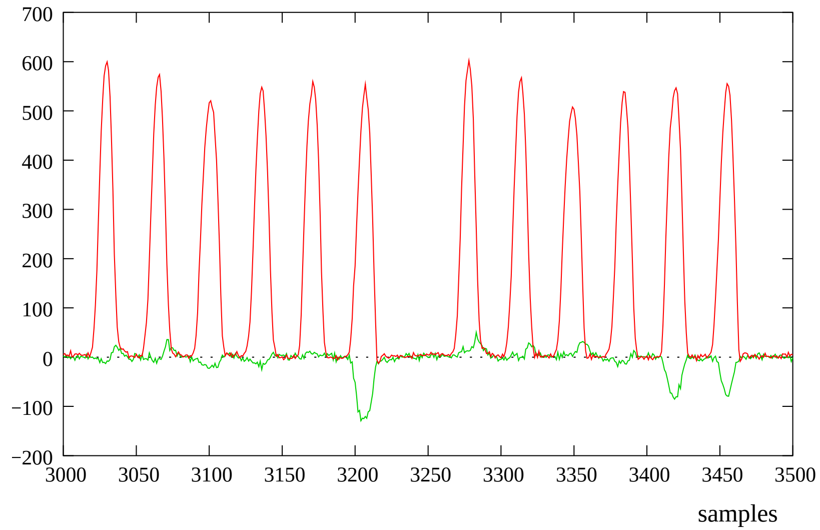
Positions

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

Principle of base line restitution



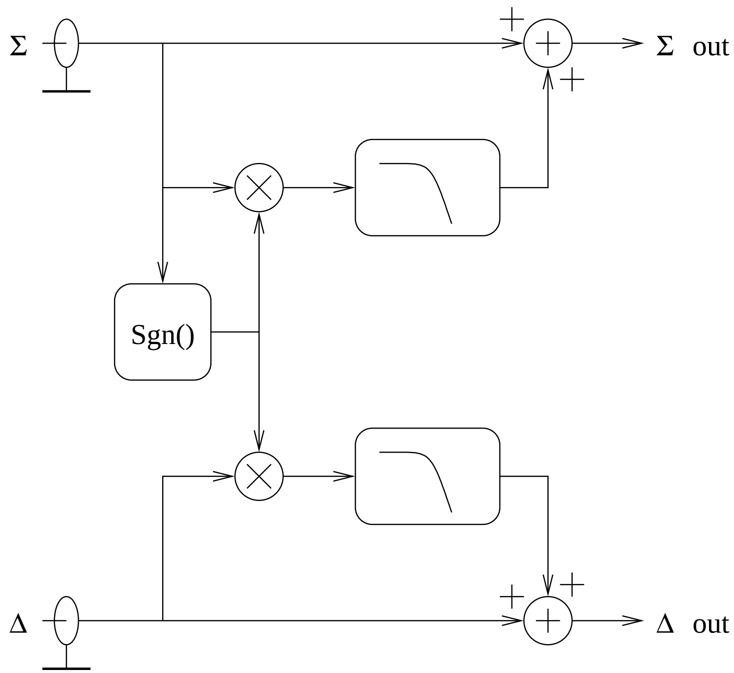
LHC beam without BLR



LHC beam with BLR

- 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

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

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

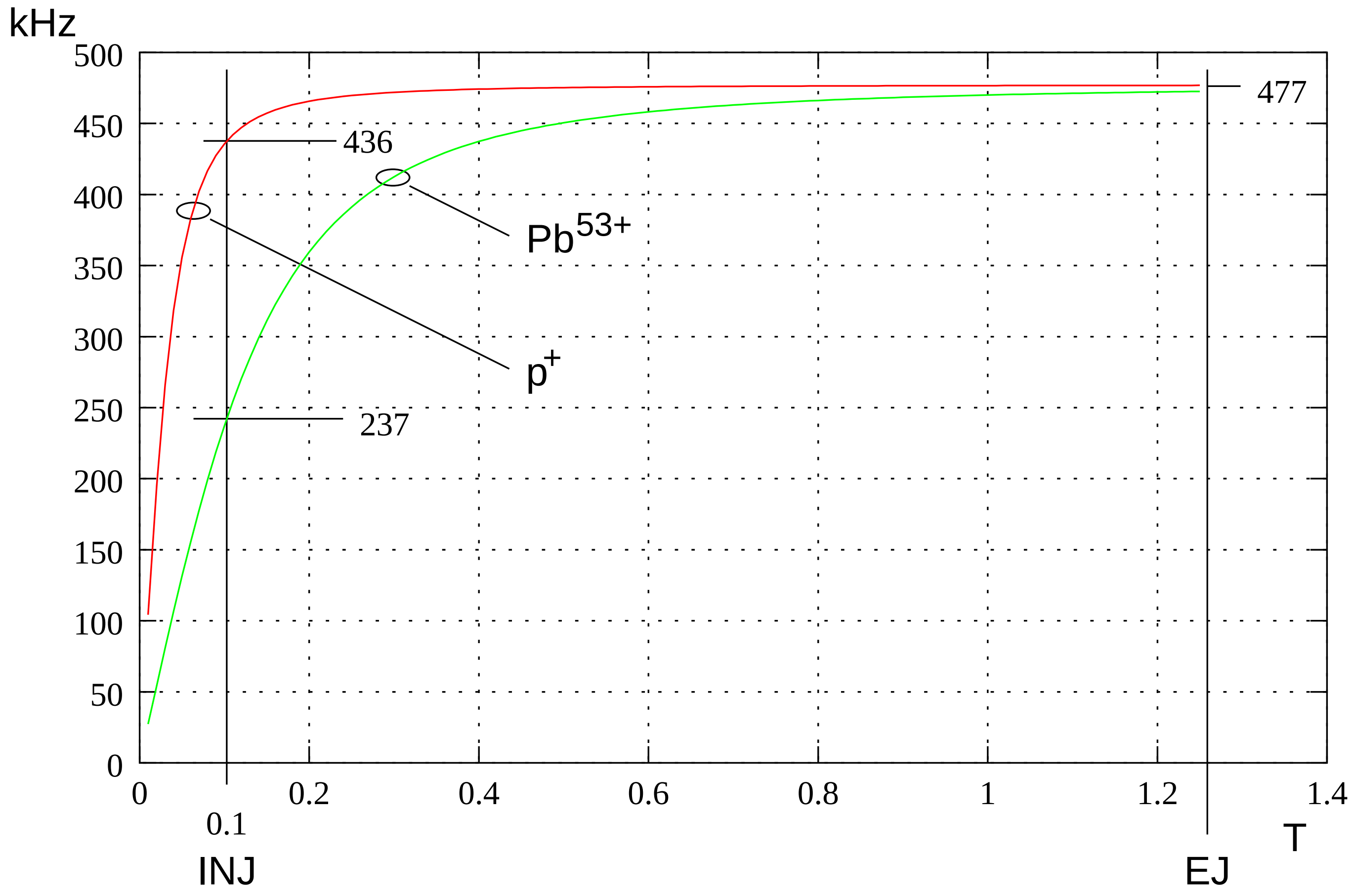
$$B_{\Delta,n}=aB_{\Delta,n-1}+(1-a)\,sgn(\Sigma)\,\Delta_{raw}$$

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

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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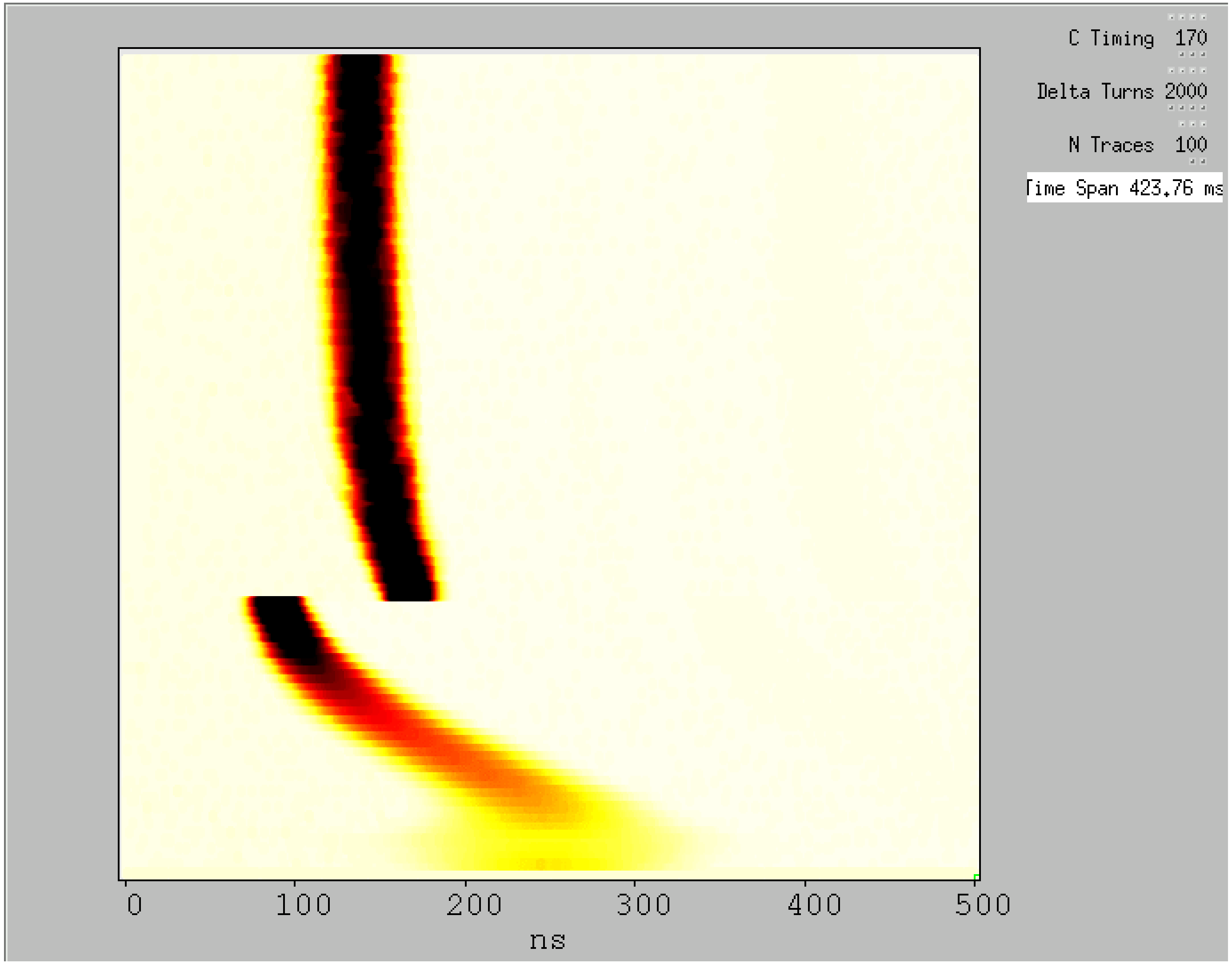
Phase of RF slides w.r.t. beam



The phase relation between beam and RF shifts with changing F_{rev} due to cable delays.

This is an EASTC beam over the first 425ms after injection.

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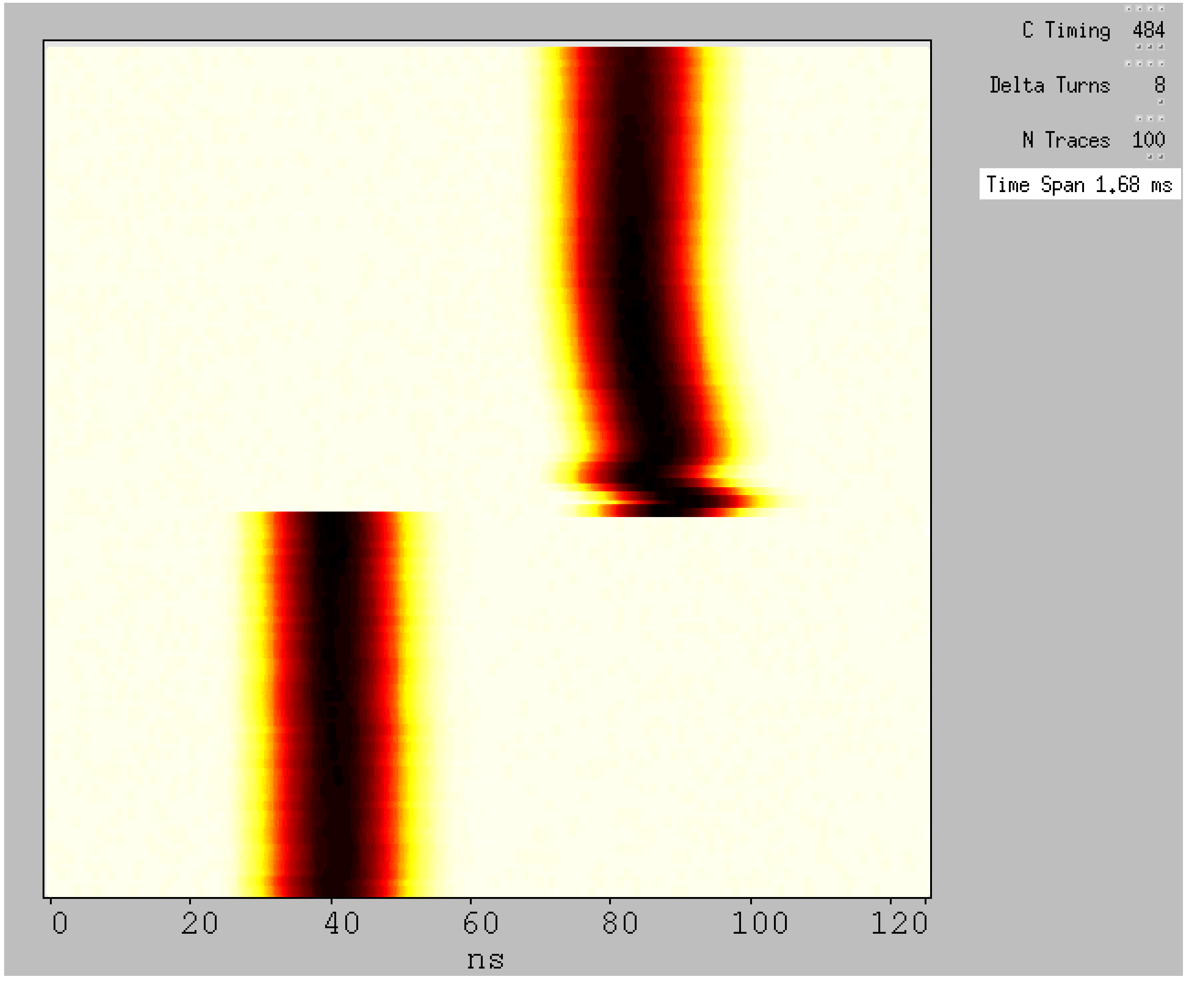
γ-transition

In the PS, a p^+ beam goes through transition at a kinetic energy of 4.8 GeV (γ_{tr}=6.08). The phase of the cavity RF is changed abruptly to maintain longitudinal stability.

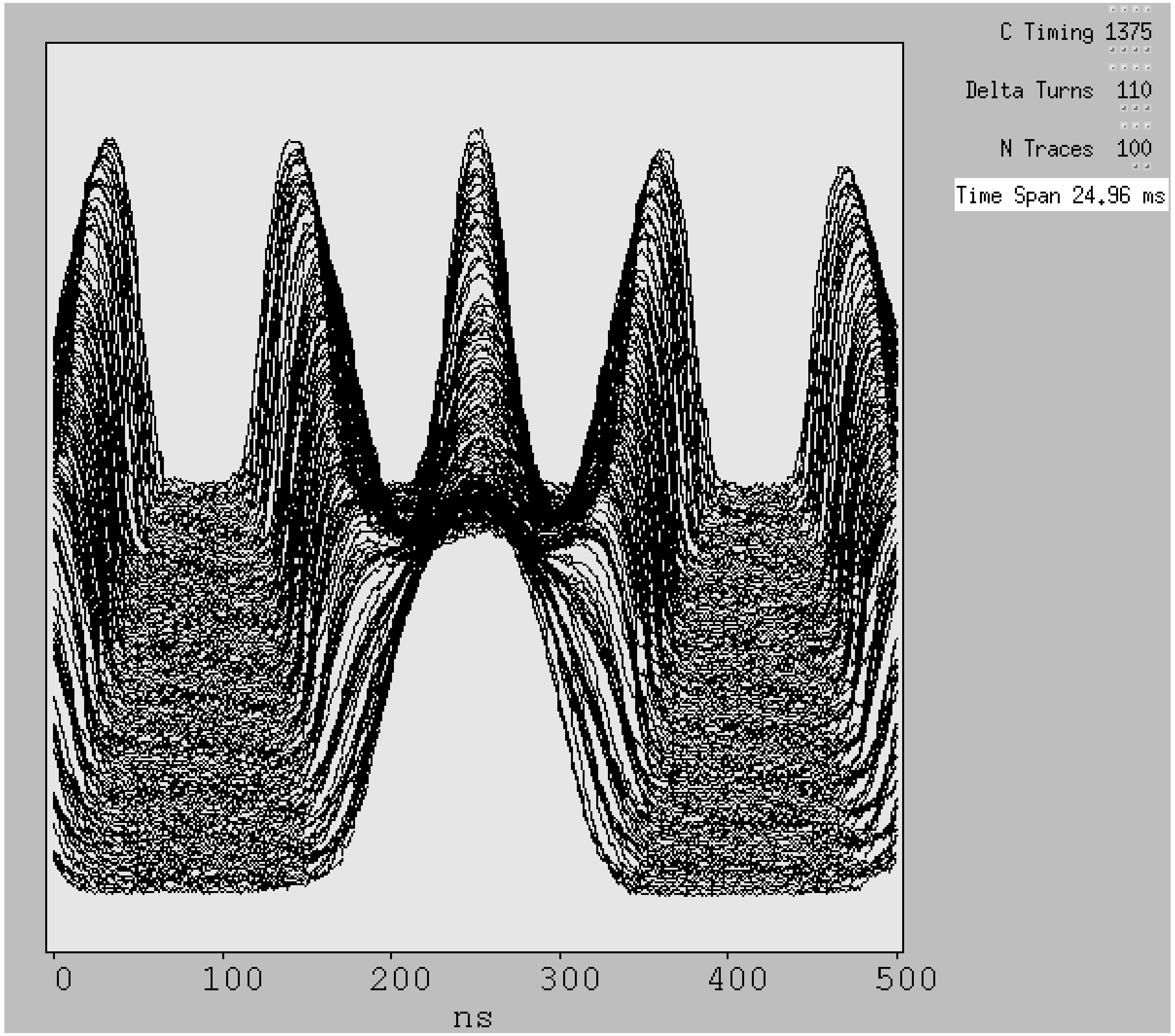
This picture has been taken on an SFTPRO cycle. The phase change due to γ-transition is about 120°.



RF gymnastics

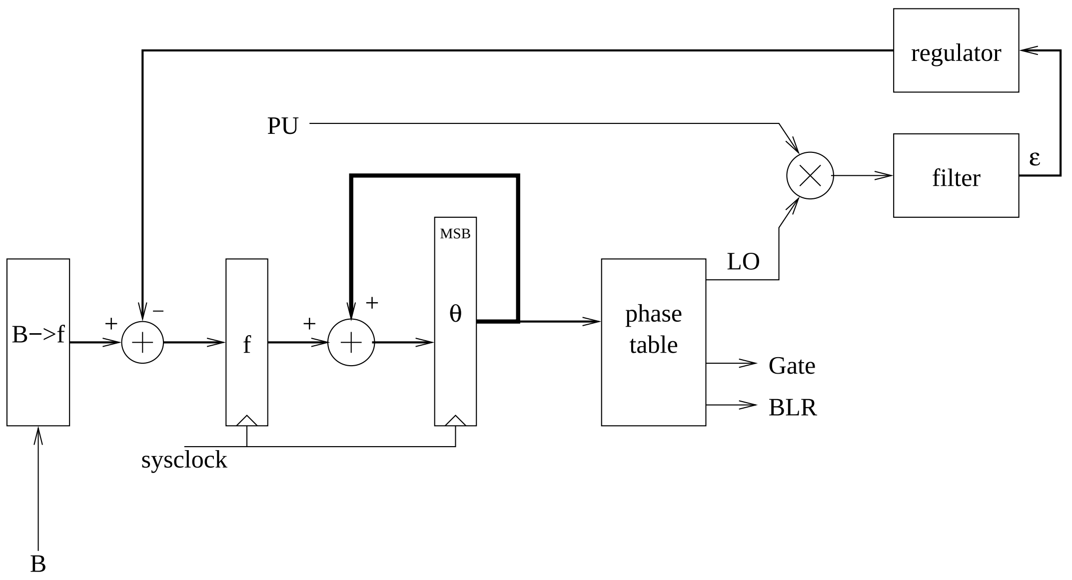
During LHC cycles, each bunch is split into three equal bunchlets in about 25ms.

This is done on the injection plateau at 1.4GeV, by gradually increasing the RF at h=21, while at the same time reducing the RF at h=7.



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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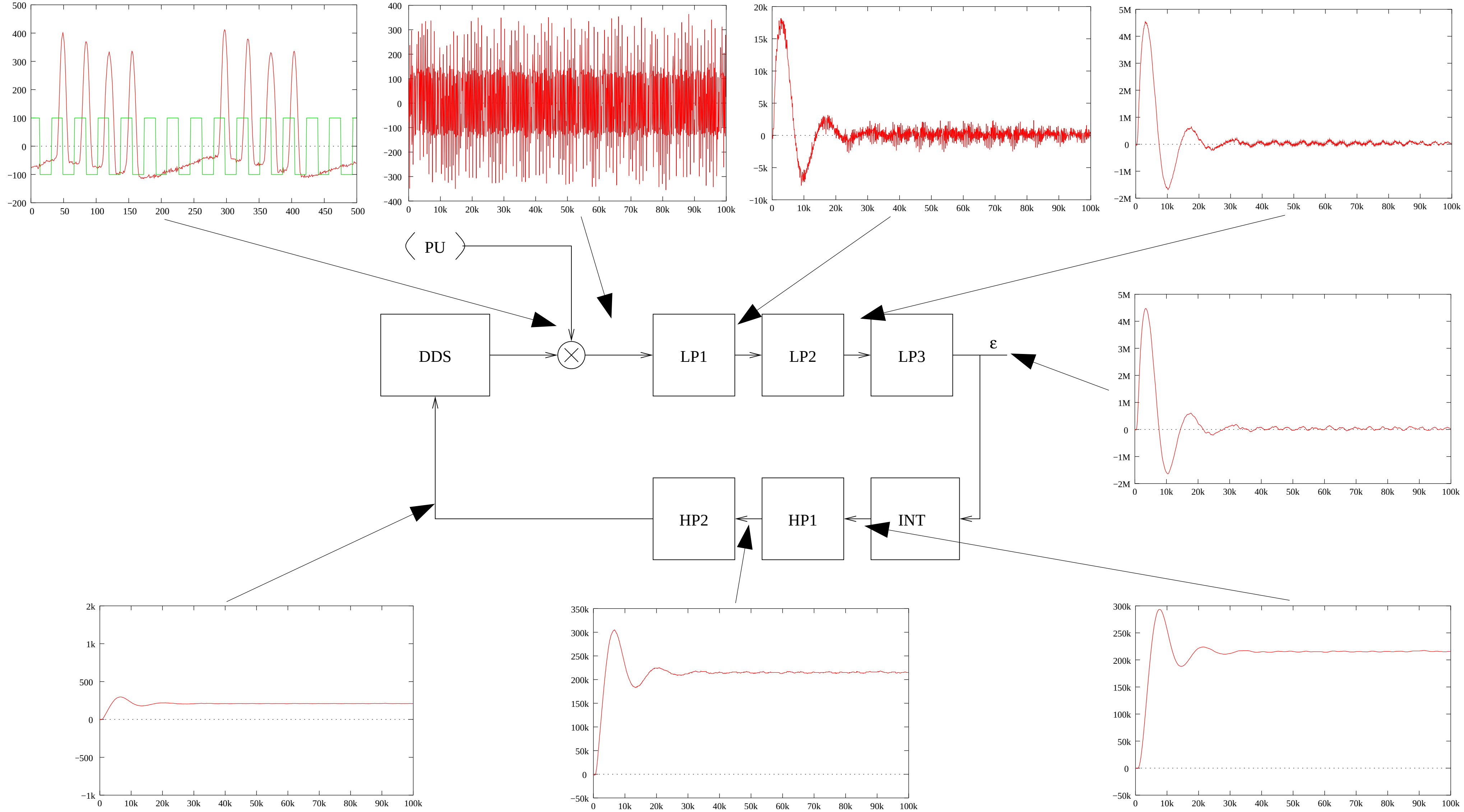
Intermediate signals



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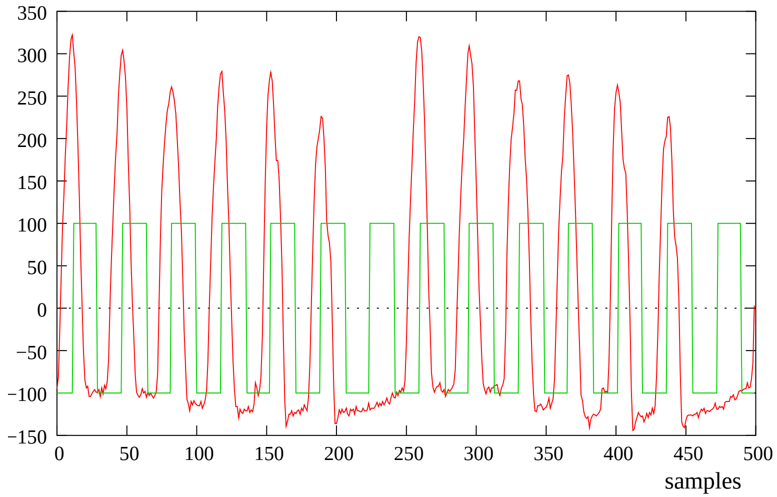
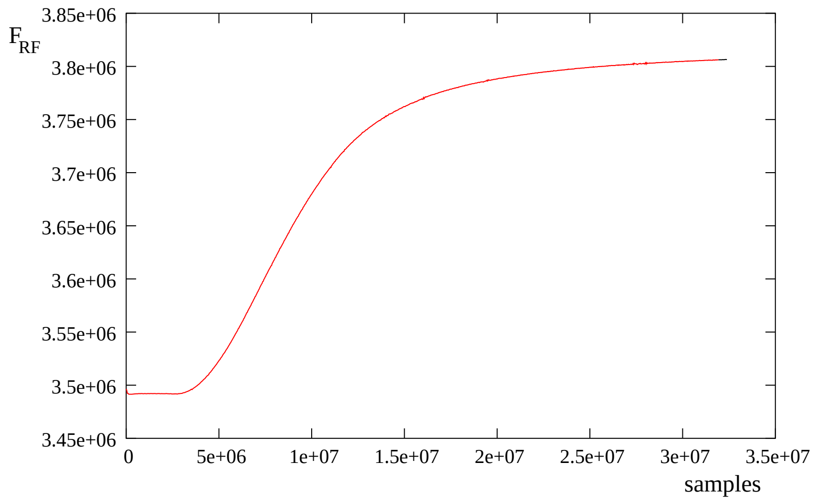
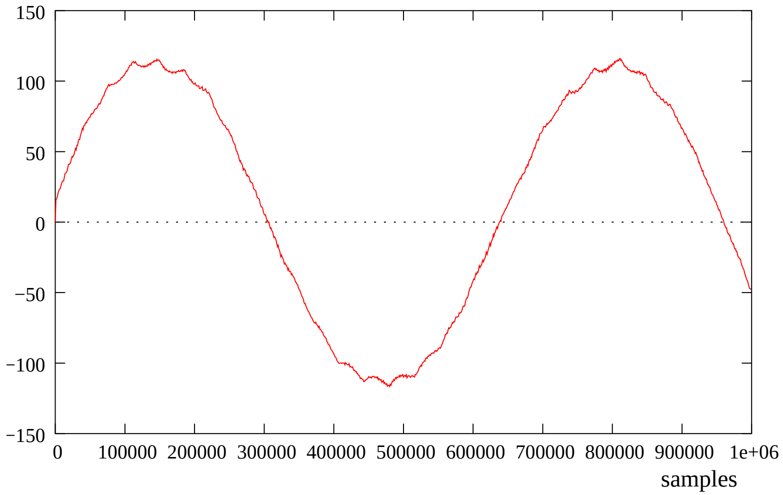
Creating a reference frequency



PU signal and reconstructed RF at h=7



Evolution of RF frequency during acceleration



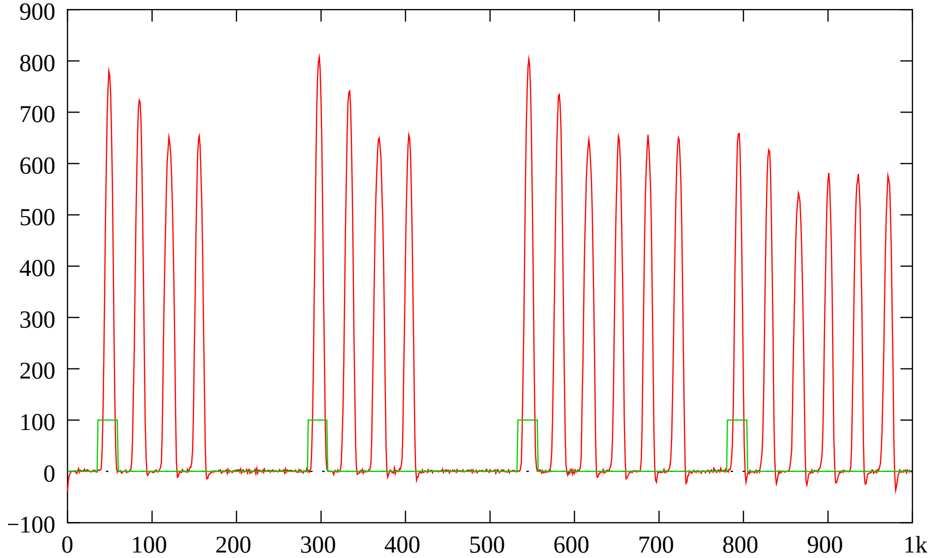
Phase error (ε) vs. PU and RF phase difference

There is a trade off between settling time and accuracy:

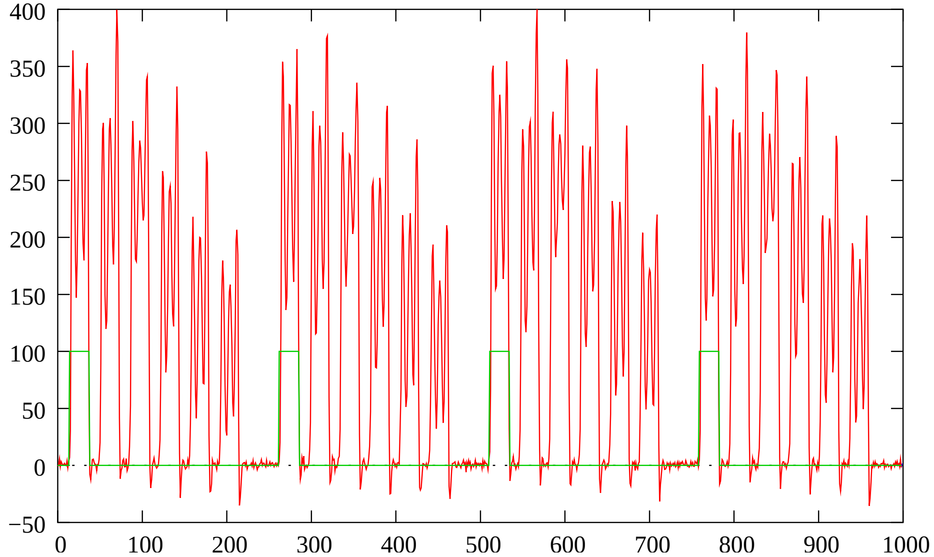
- Too slow and it won't follow acceleration
- Too fast and the reconstructed RF will be noisy

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

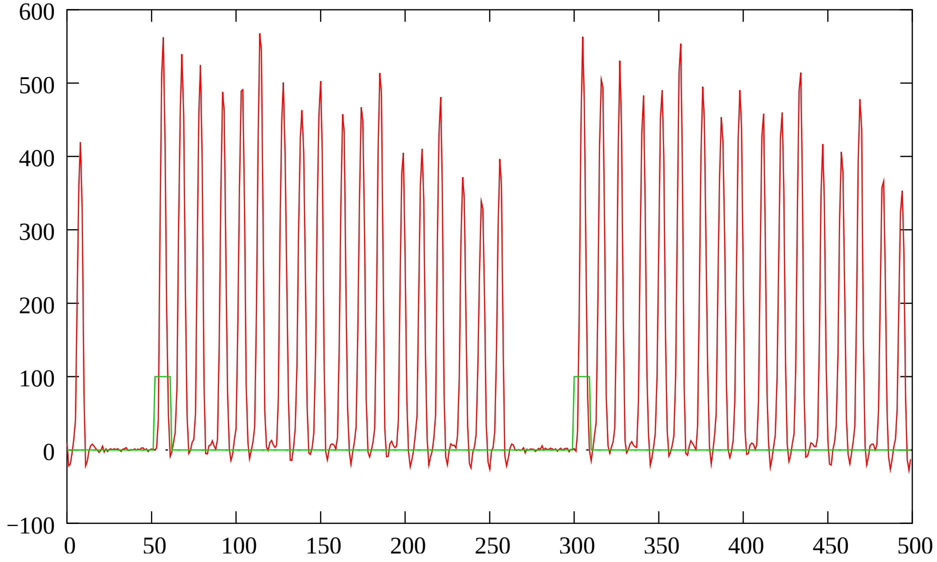
The generated Gate timing signal



Example of generated gate around 2nd injection



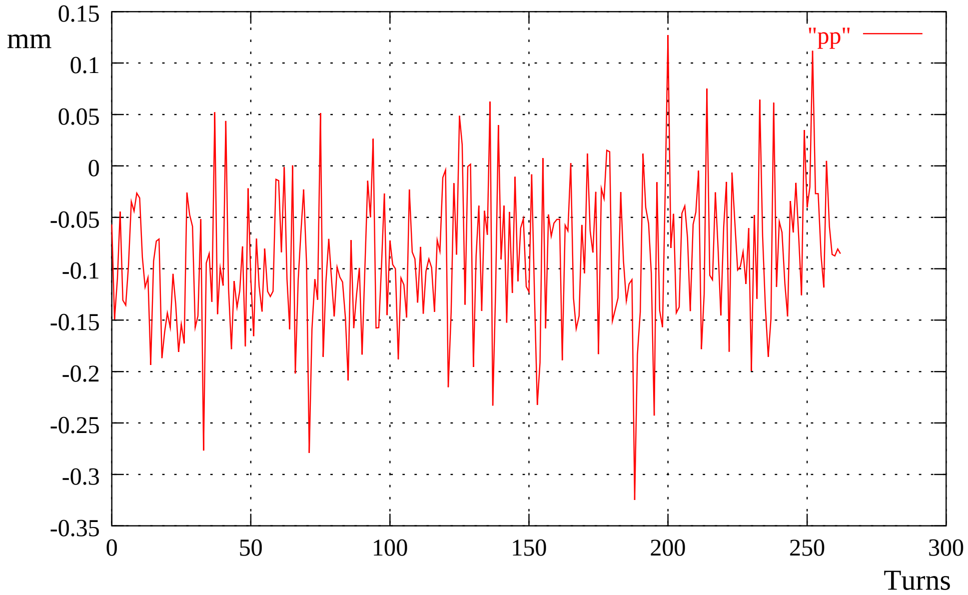
Idem, during bunch splitting

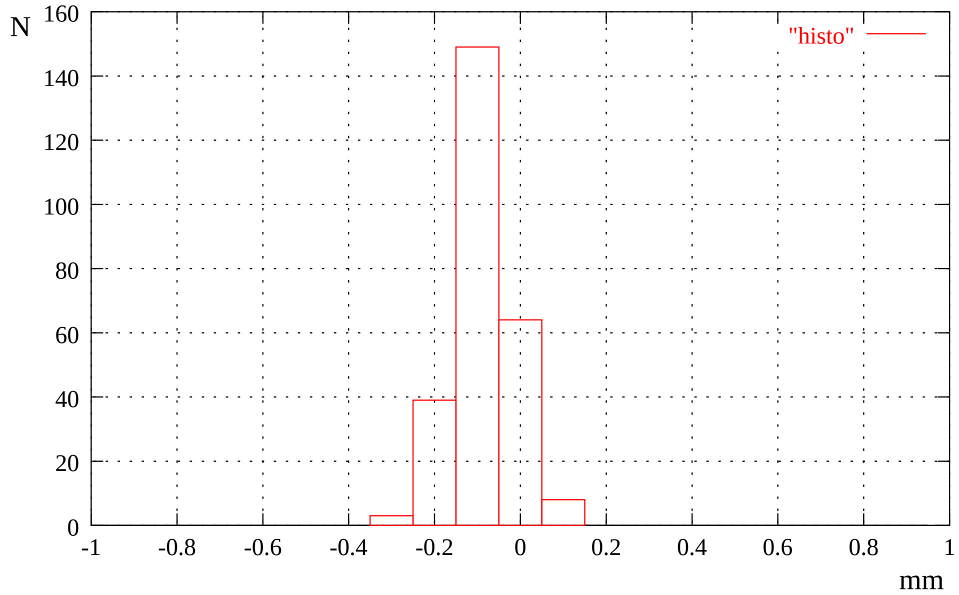


And after the harmonic change

- Gate is initially centred on the bunch
- After splitting, it remains centred on the central bunchlet, spanning almost three of them at once
- An external timing signal prompts it to readjust

On 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

Conclusions

- A prototype Libera* has been used to acquire PU signals at the CERN PS. (Sampling rate 108.37MS/s, 16Ms on two channels)
- Data processing has been done off-line, so far.
- A workable synchronisation algorithm has been designed.
- Measuring trajectories all bunches every turn with 0.1mm resolution is possible.
- Resolution is limited by analogue signal noise and sampling speed, not by ADC number of bits.

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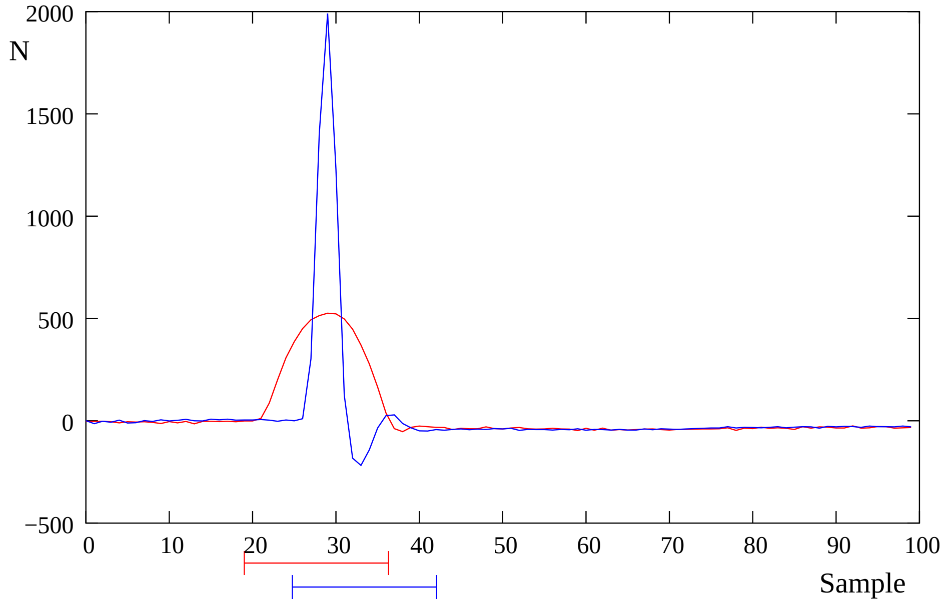
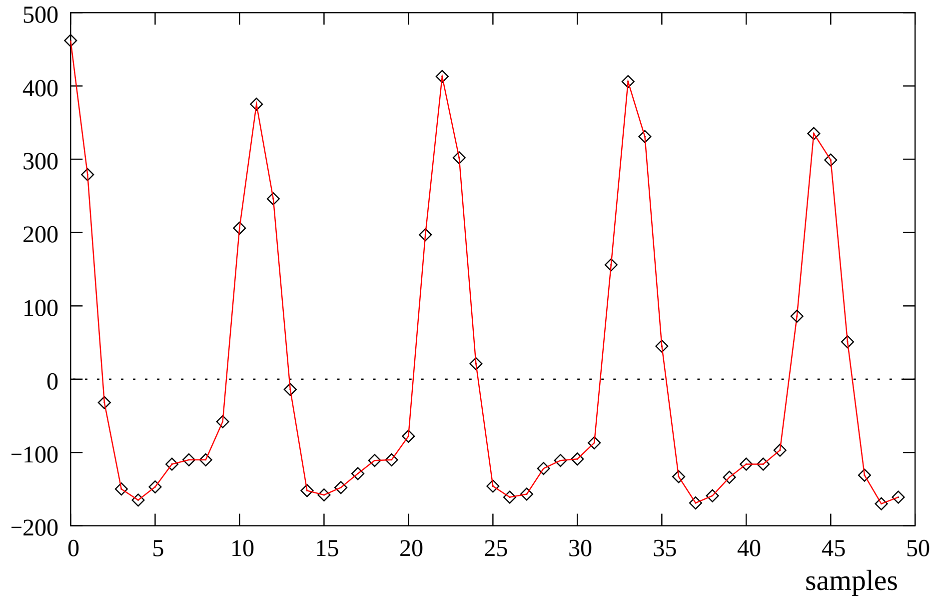
Evolution of bunch length during acceleration



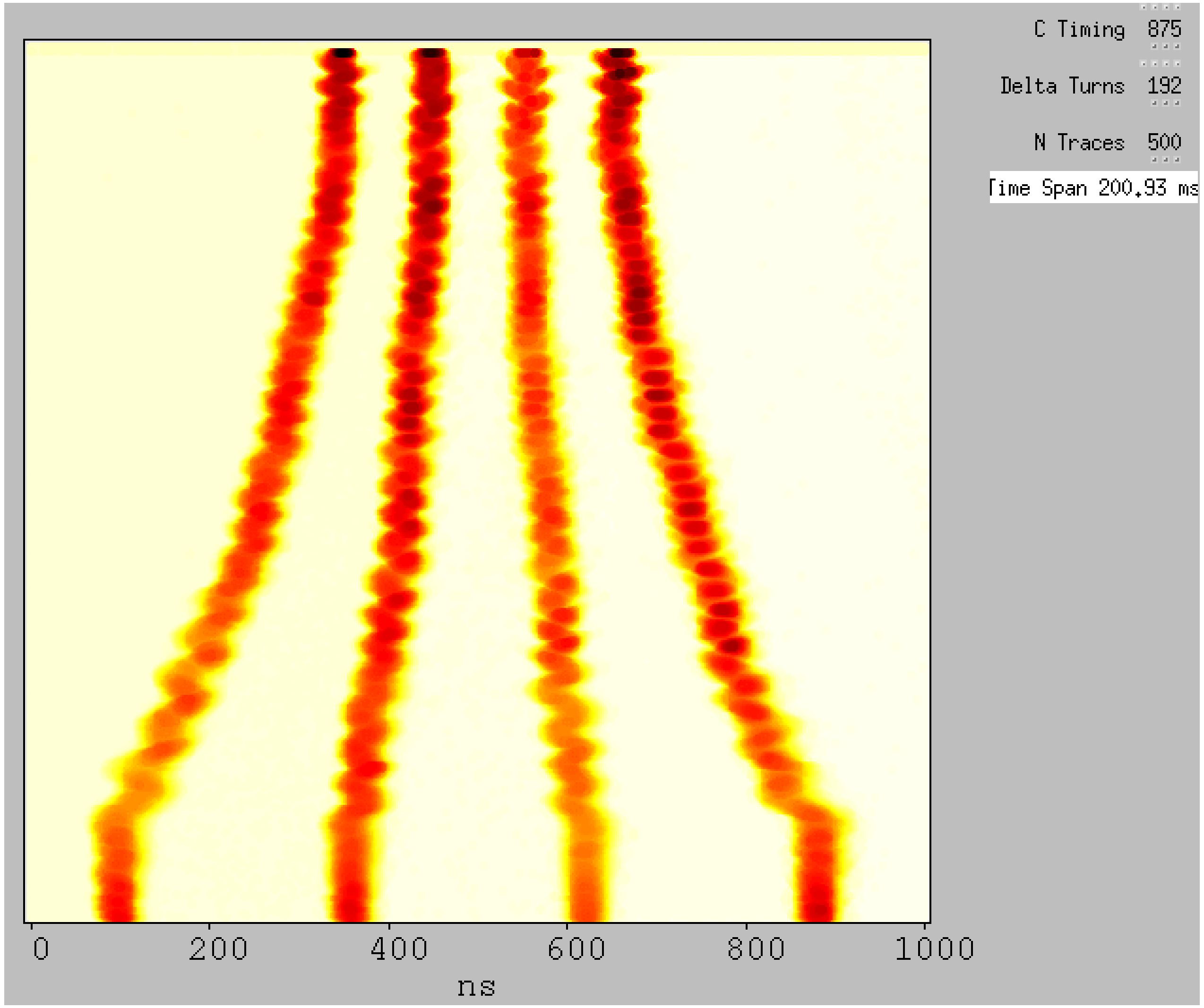


Bunch length near injection: 120ns
Bunch length near transition: 30ns

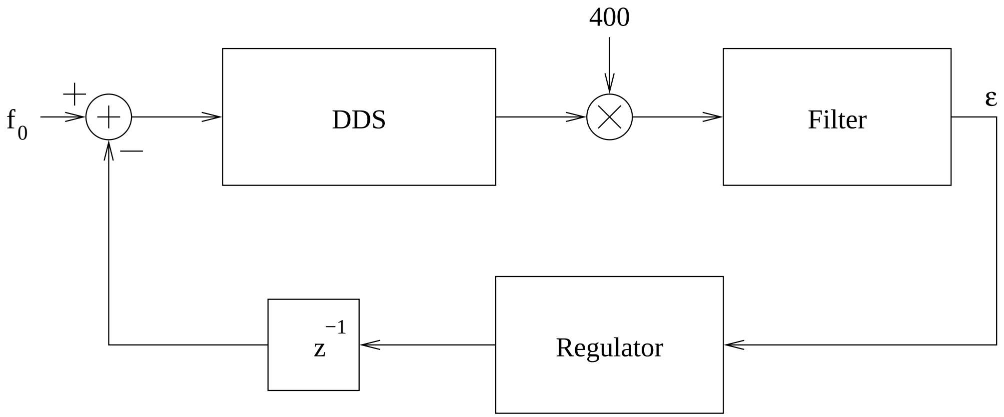
Zoom in on LHC-type bunches at h=21

Beam compression on AD

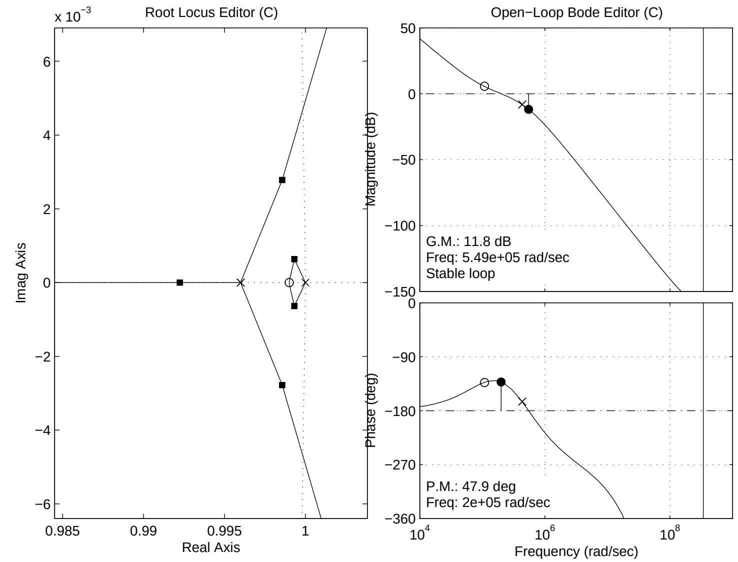
On AD cycles, the four injected bunches, which are initially equally distributed around the ring, are squeezed together using a sequence of harmonic changes, 8, 10, 12 ... 20.



PLL response analysis



Simplified block diagram



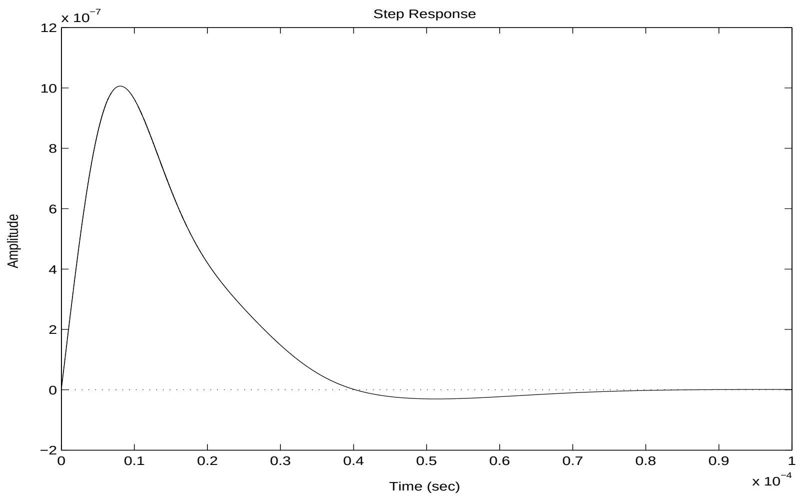
Root locus and Bode plots

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

Mixer $$H_m=400$$

Low-pass filter $$H_F=\frac{1}{256}\left\{\frac{z^{-1}}{1-0.996\,z^{-1}}\right\}^3$$

Regulator $$H_R=K_R\cdot z^{-3}\cdot\frac{(1-0.999\,z^{-1})^2}{(1-z^{-1})}$$



Step (in ε) response

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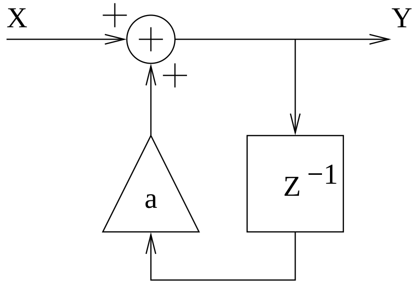
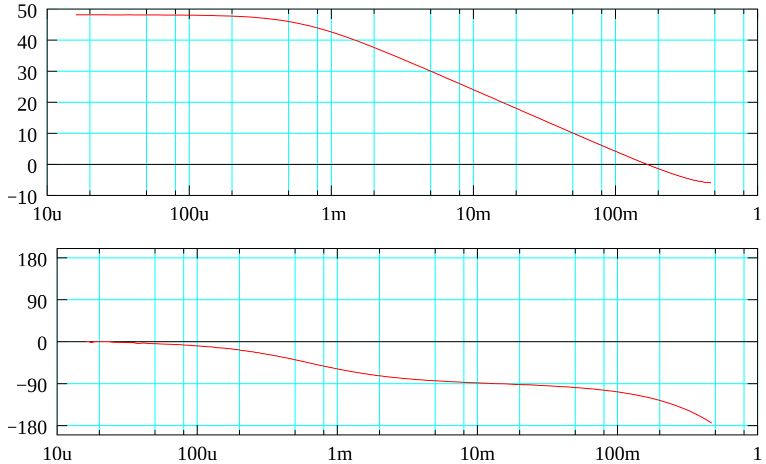
Low pass filter stage

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

$$y_n=0.996\,y_{n-1}+x_n$$

y = x + y - (y>>8);



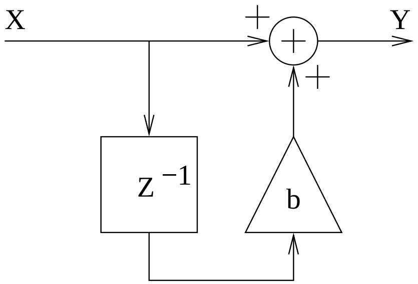


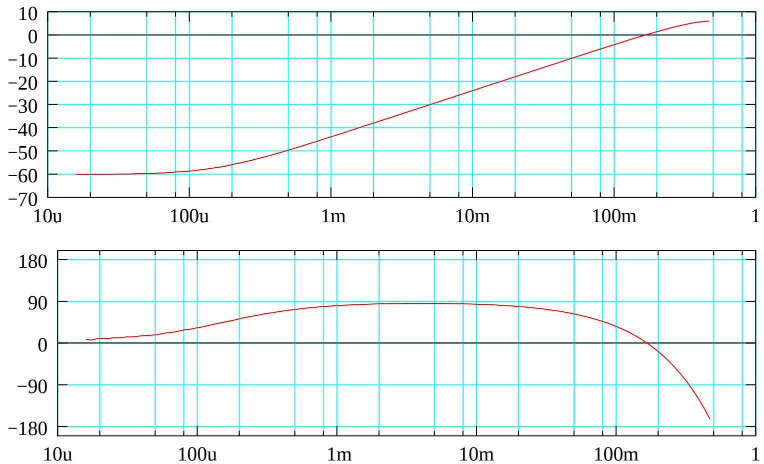
High pass filter stage

$$\frac{y}{x}=z^{-1}\left(1-0.999\,z^{-1}\right)$$

$$y_n=x_n-0.999\,x_{n-1}$$

y = x - ix;
ix = x - (x>>10);





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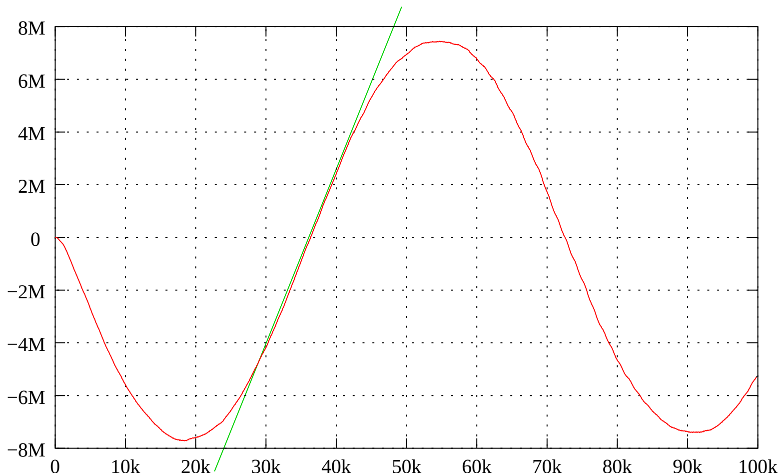
Phase noise I



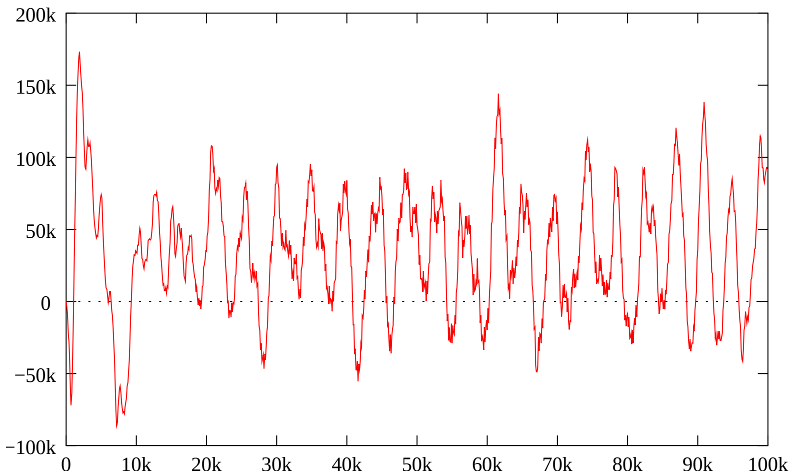
First find the phase error gain:

$$f(x) = 8M \sin\frac{2\pi x}{72k}$$

$$f'(x) = \frac{16\pi M}{72k}\cos\frac{2\pi x}{72k}$$

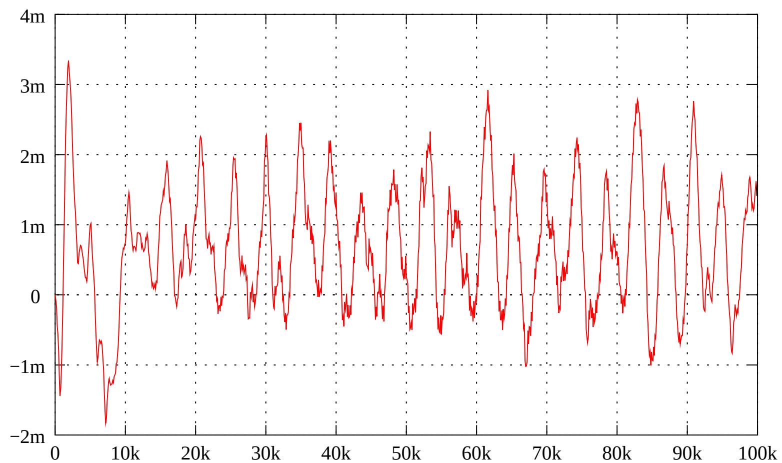
Normalised to one period of the phase error:

$$G_\epsilon = 16\pi M = 50\cdot 10^6$$



Raw phase noise

$$\frac{1}{G_\epsilon}$$



Phase noise as a fraction of an RF period

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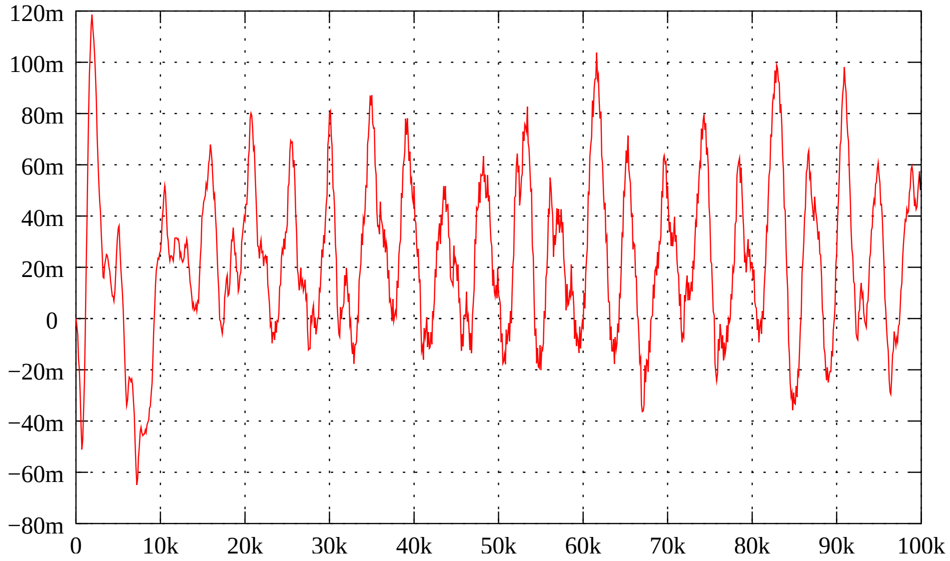
Phase noise II

There are $\frac{2^{32}}{17296830\,h}=35.5$ samples in one RF period. (For LHC, h=7)

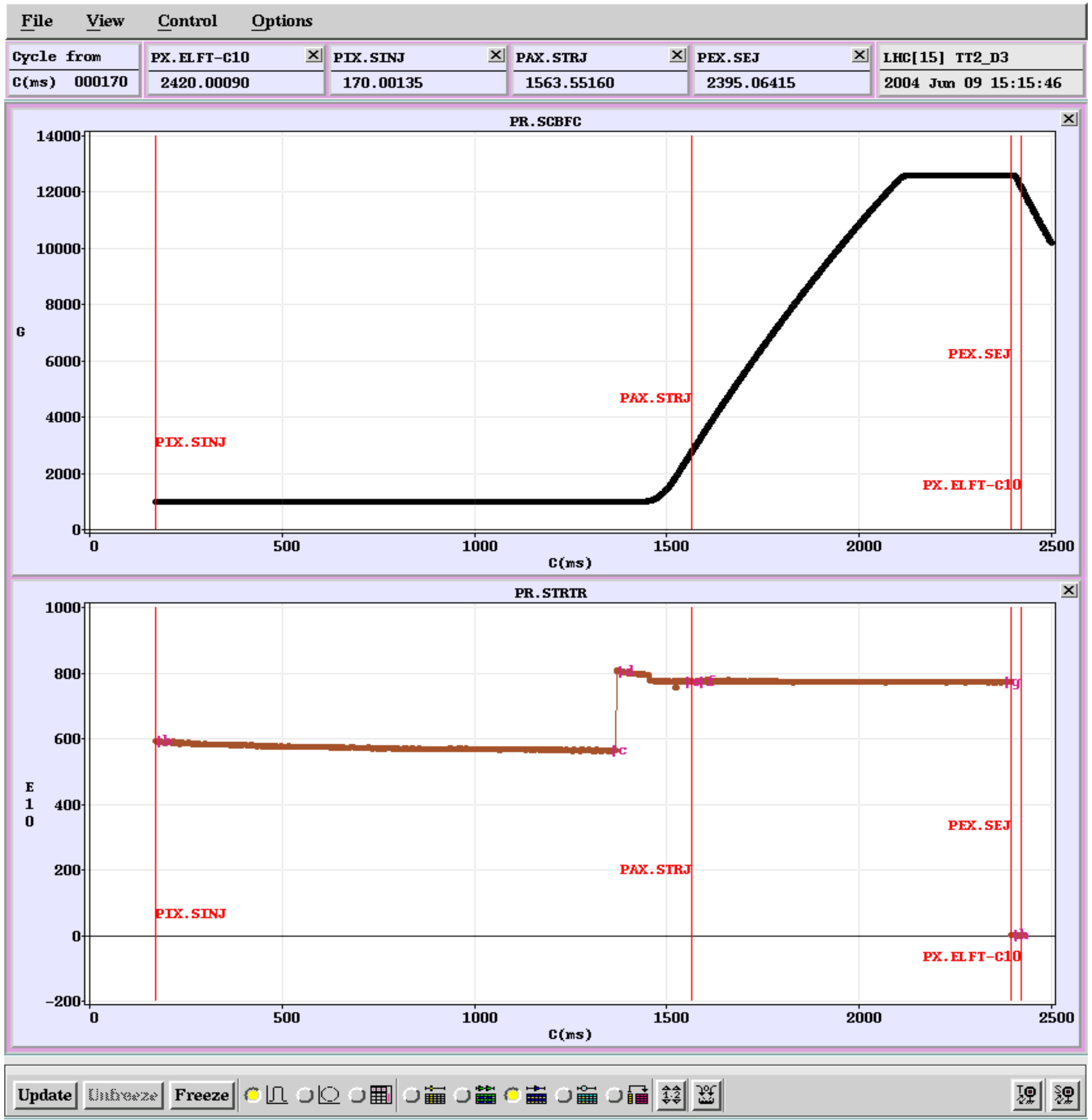


Phase noise normalised to one sample

σ=0.03 samples

Magnetic Cycles

- Peak B=1.26T
- $\frac{dB}{dt} = 2.3\text{T/s}$
- $\frac{dF}{dt} = 1.6\text{MHz/s}$
- Injection field B=0.1T
- Injection at C170
- Injection E=1.4 GeV (p^+)



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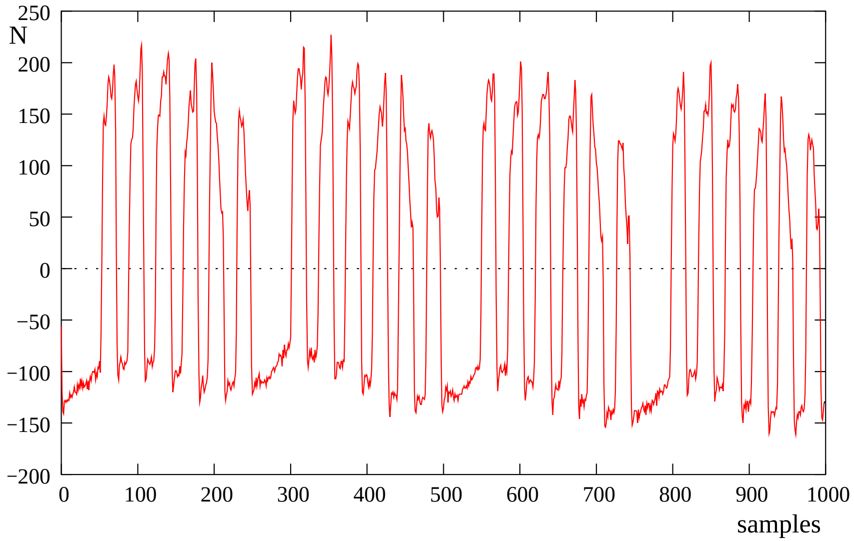
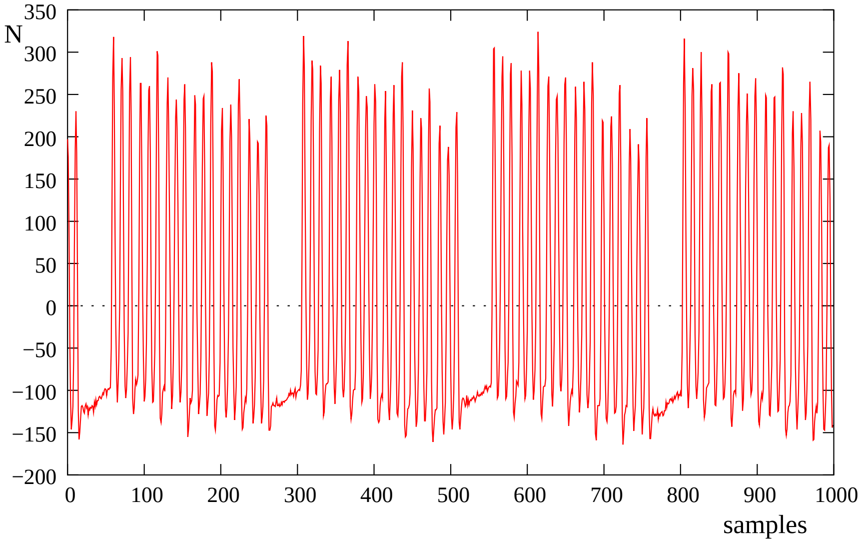
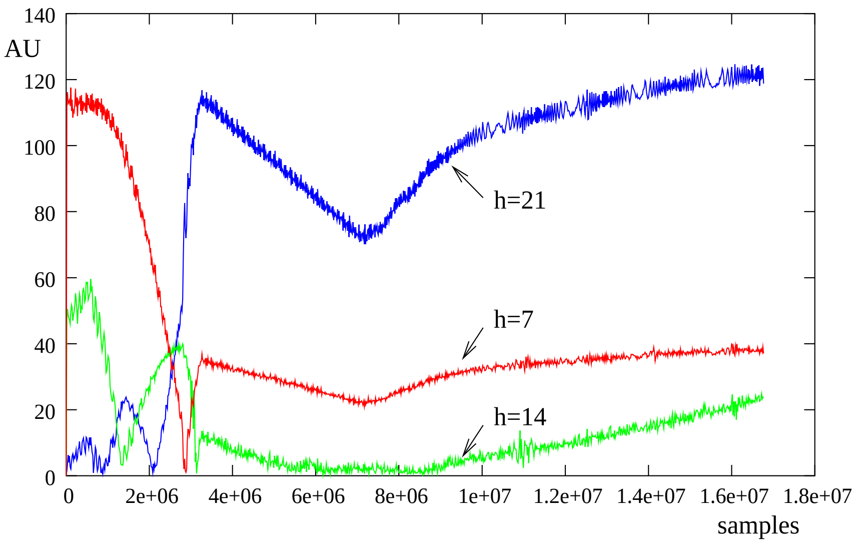
Handling harmonic changes



LHC beam at h=7



LHC beam at h=21

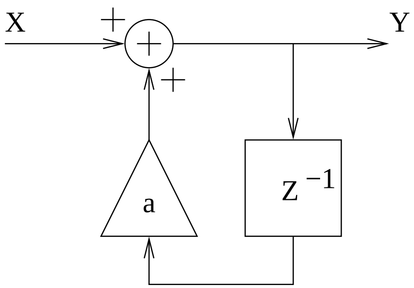


Evolution of magnitude of harmonics on LHC

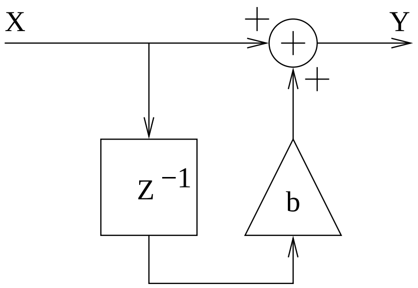
RF gymnastics in PS have special requirements:

- Choose signal from several possible sources
- Produce several LO harmonic numbers
- Produce appropriate gate timings
- Switch from one to another dynamically
- WITHOUT LOSING LOCK!

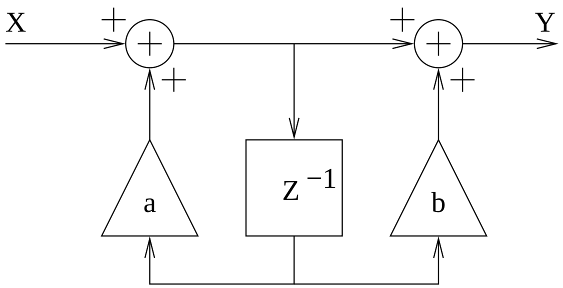
Digital filters



One pole: $\frac{y}{x}=\frac{1}{1-a z^{-1}}$

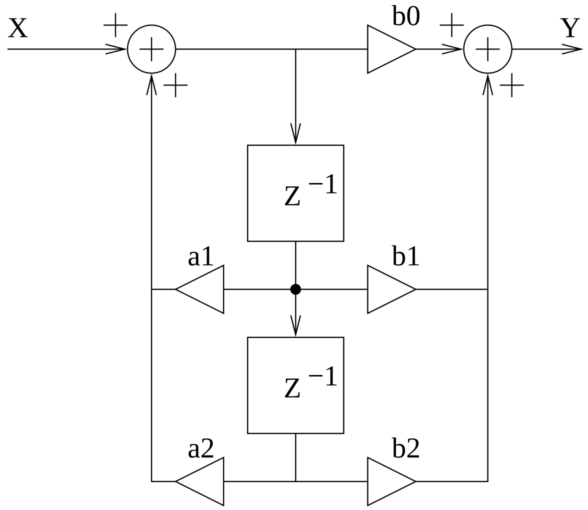


One zero: $\frac{y}{x}=1+b z^{-1}$



One pole & one zero

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



Two poles & two zeroes

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

Choosing sweet filter coefficients

Nice filter coefficients are:

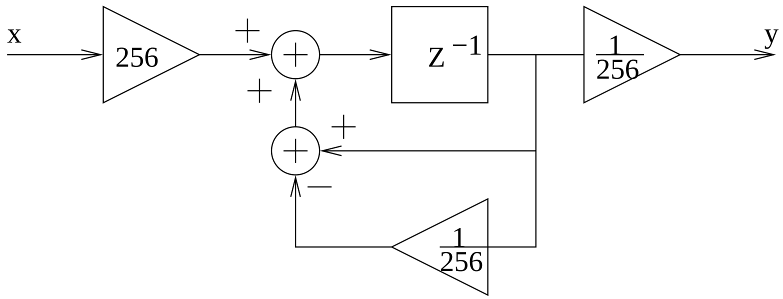
127/128=0.992...

255/256=0.996...

511/512=0.998...

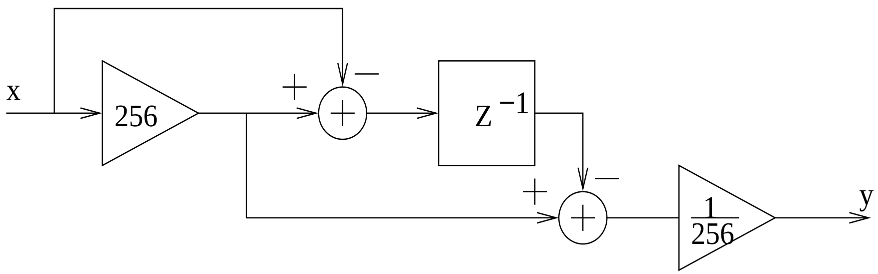
1023/1024=0.999...

So for a (real) pole:



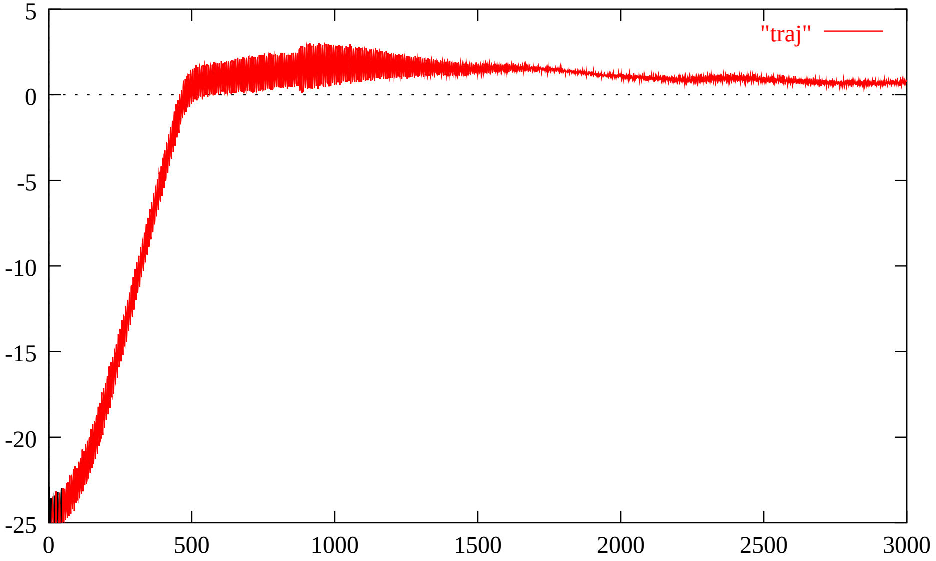
$$= \frac{y}{x} = \frac{z^{-1}}{1-0.996\,z^{-1}}$$

... and for a zero:

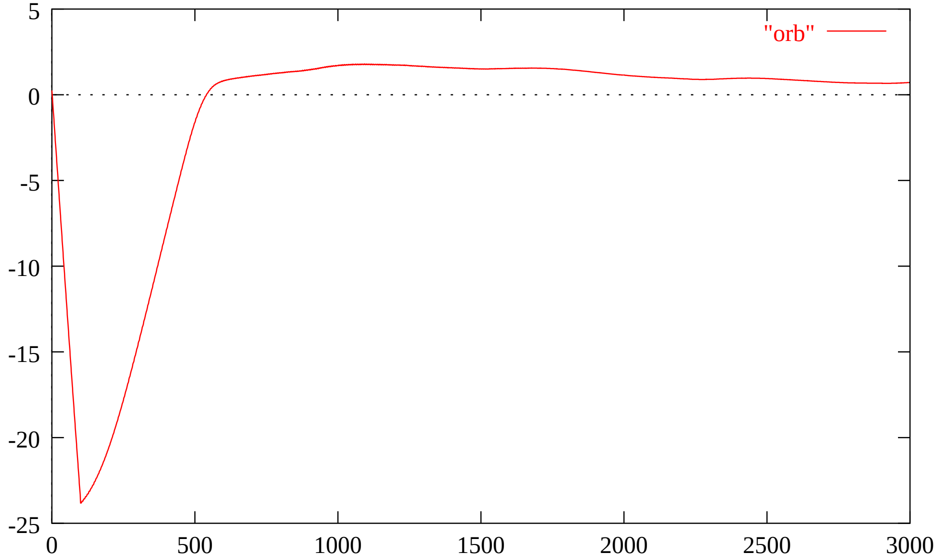


$$= \frac{y}{x} = 1-0.996\,z^{-1}$$

Orbits



Trajectory

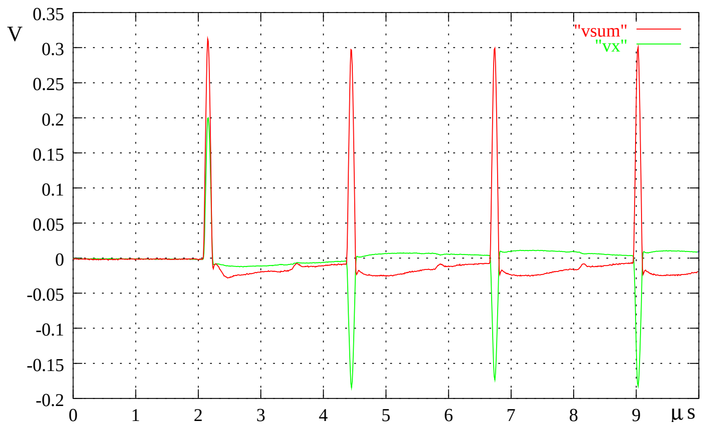


Orbit

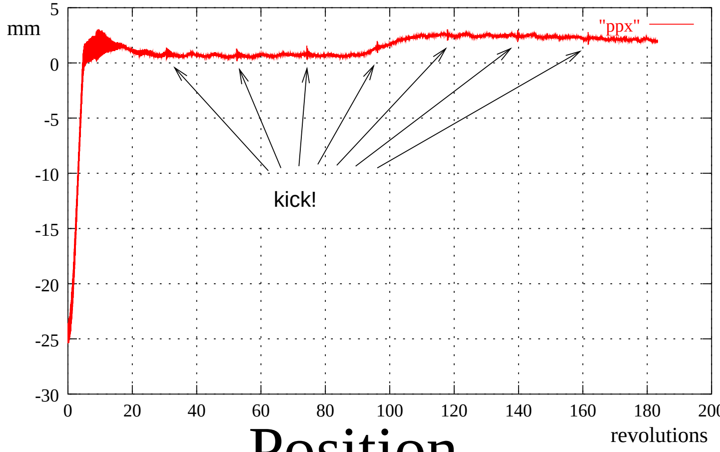
- Average N trajectories (N~100)
- Gain 10 times in resolution

A new trajectory measurement system for the CERN PS

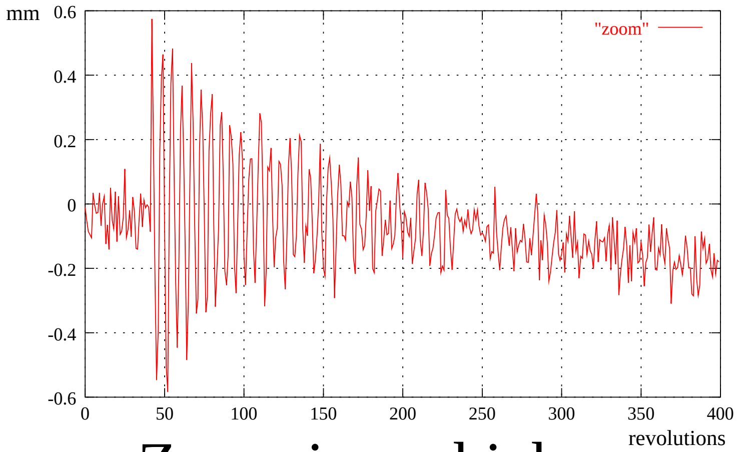
Tune measurement



Raw data

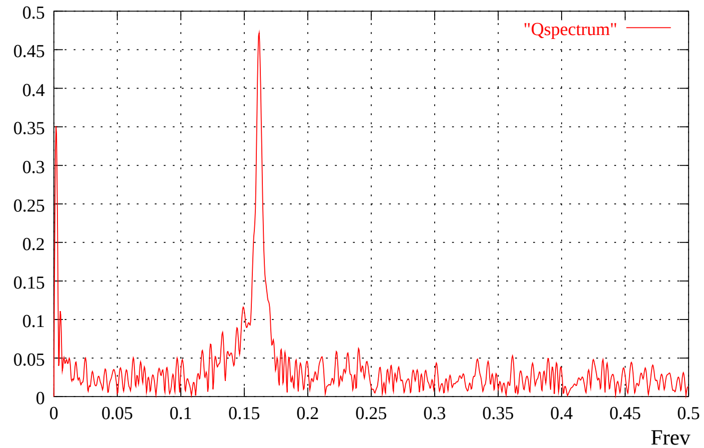


Position



Zoom in on kick

Fourier →



q=0.1615

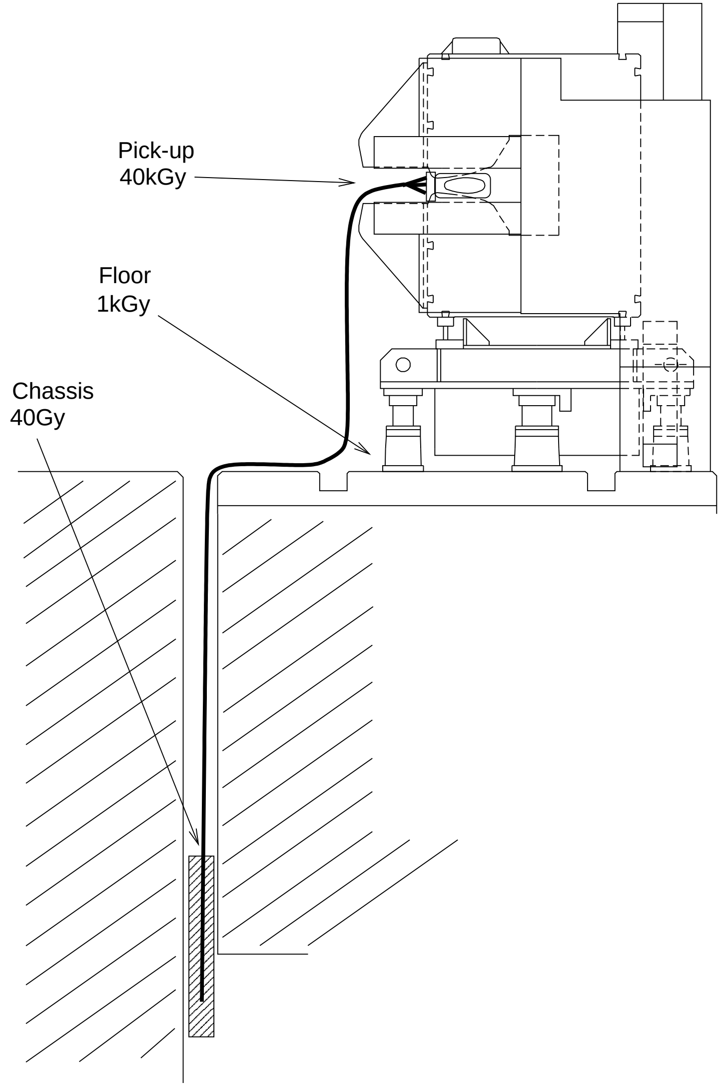
Radiation

Radiation levels

- 40kGy/y at 1.3m
- 1kGy/y on the floor
- 40Gy/y in the gap

Electronics can take 30 - 300Gy.
Careful choice of components and
careful design can extend that to a few kGy.

Cable length from PU to pre-amp : 5m
Double shielded cable



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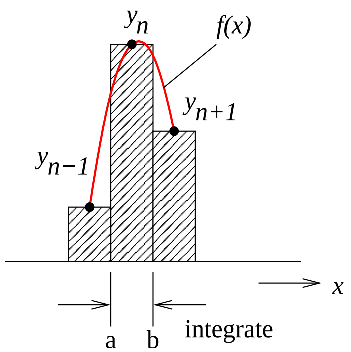
Interpolation between sampling points

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

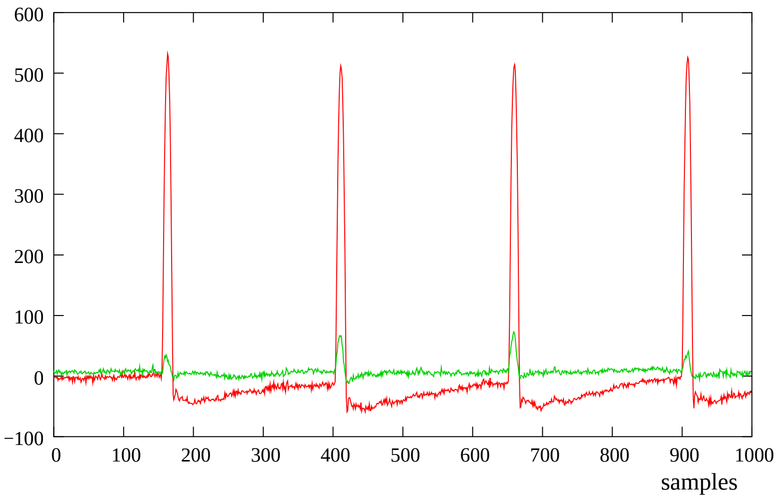


$$\int_a^b f(x)\,dx = A_n = \frac{k_1 y_{n-1} + k_2 y_n + k_1 y_{n+1}}{2k_1 + k_2}$$

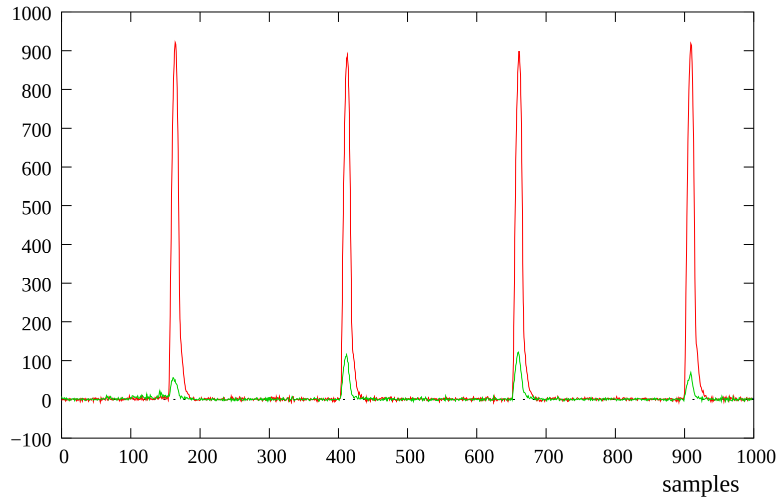
(For example, with a=-0.5 and b=+0.5, this gives k_1=1 and k_2=22)

This doesn't yield any improvement!

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