References

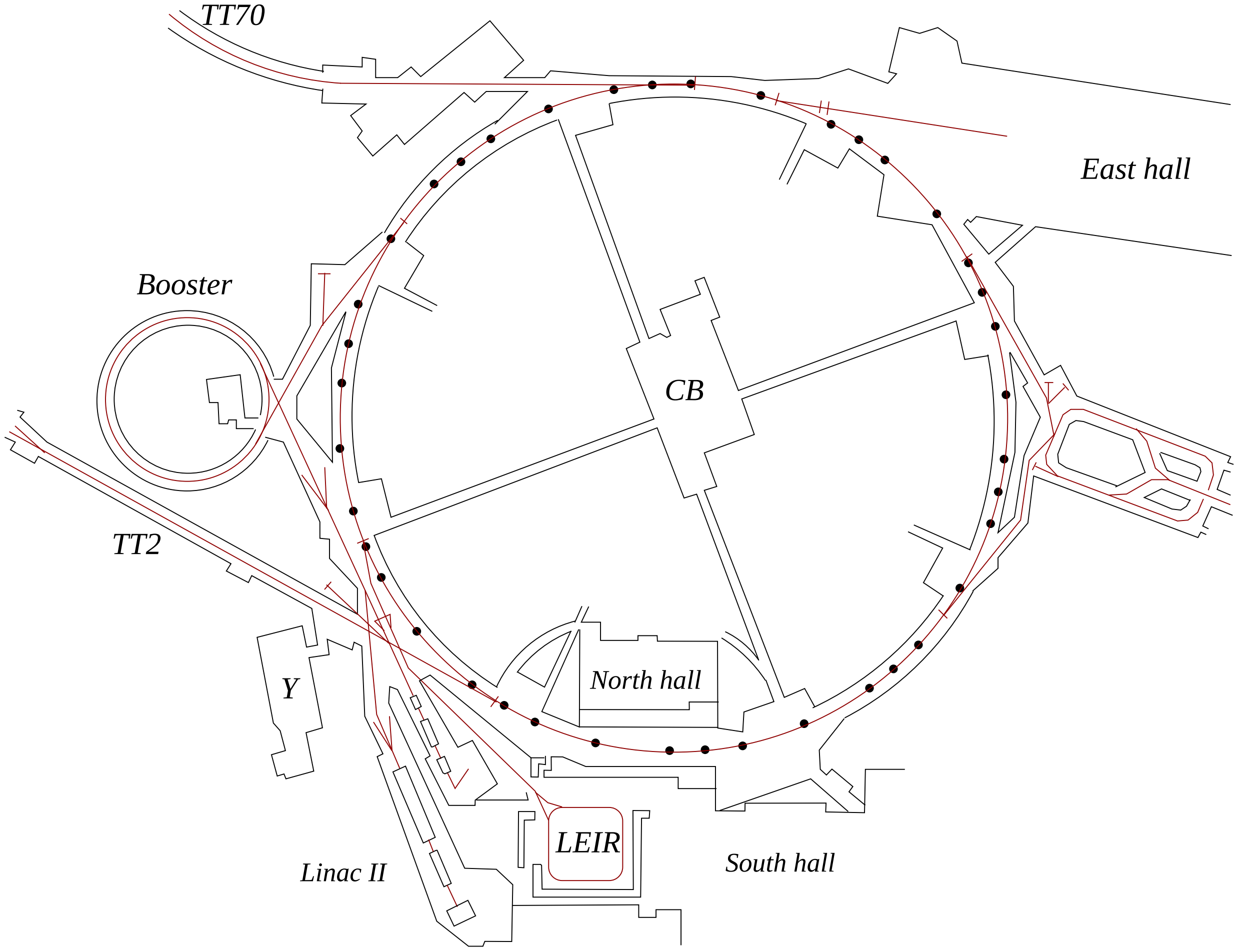
- These transparencies: http://cern.ch/jeroen/slides/DIPAC05slides.pdf
- J.M. Belleman, "Using a Libera signal processor for acquiring position data from the PS orbit pick-ups", CERN AB-Note-2004-059 BDI, http://documents.cern.ch//archive/electronic/cern/others/ab/ab-note-2004-059.pdf
- R. Garoby, S. 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)

A new trajectory measurement system for the CERN PS

The CERN PS complex

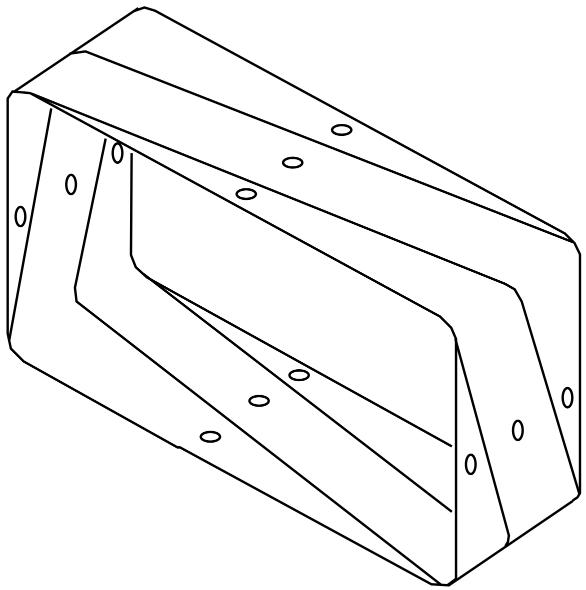
- Radius: 100 m
- Energy: 26 GeV
- RF harmonic: 7 to 420
- Bunches: 1 to 420
- Charge/bunch:

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



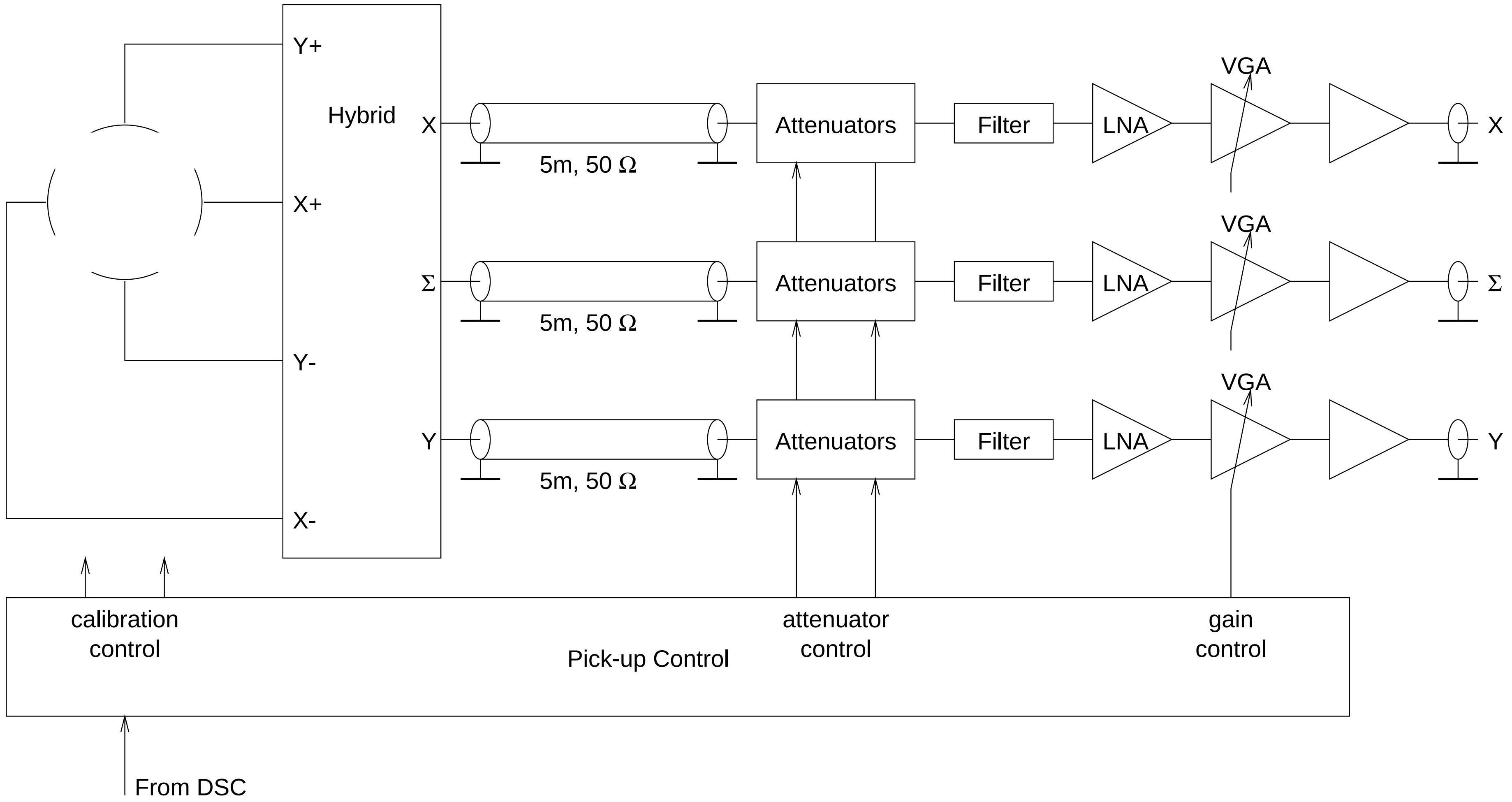
Pick-Up electrodes

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



A new trajectory measurement system for the CERN PS

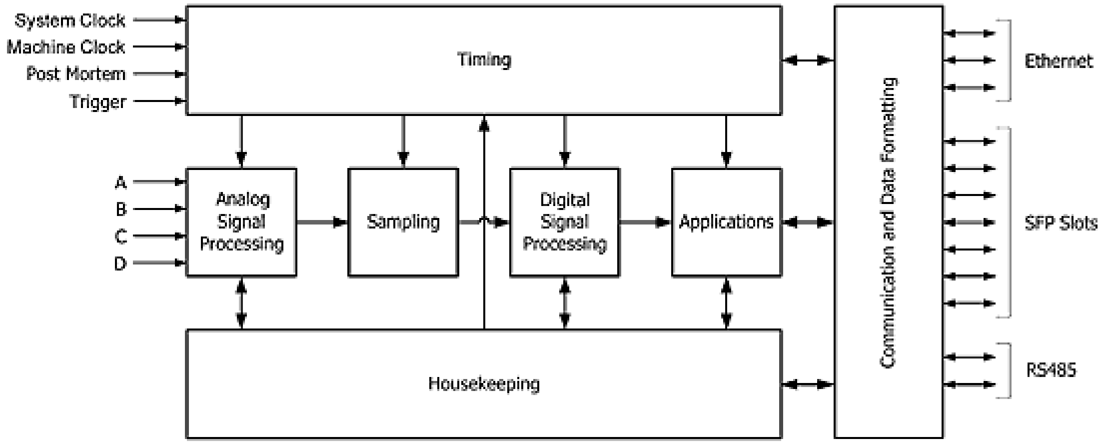
Analogue signal processing



Acquisition

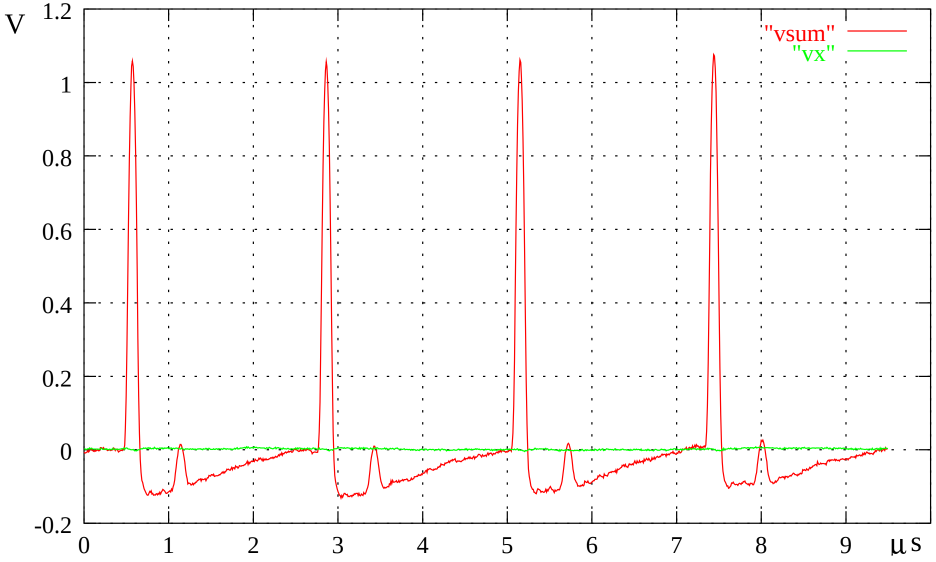
Digitizing hardware: Libera

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

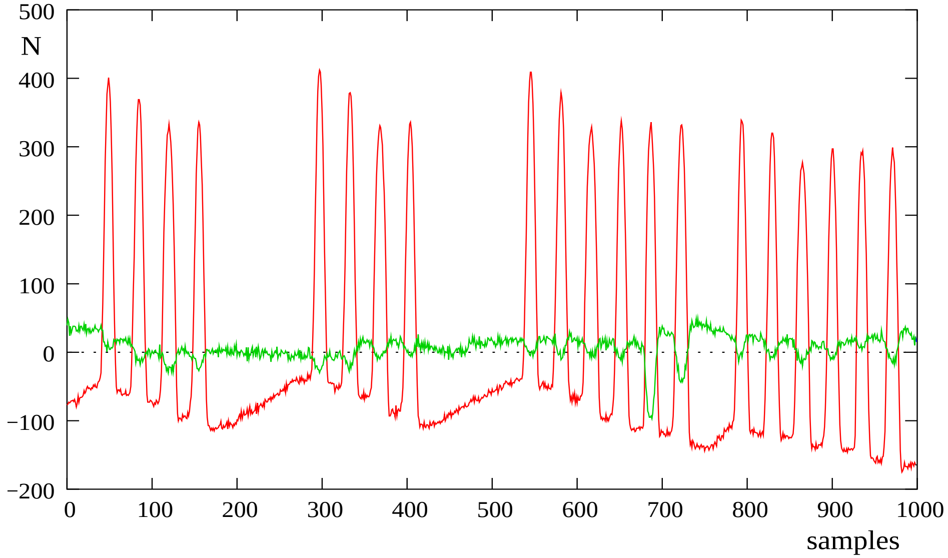


Ref: Libera, Instrumentation Technologies d.o.o., Srebrnicev trg 4 a, SI-5250 Solkan, Slovenia

Sample signals

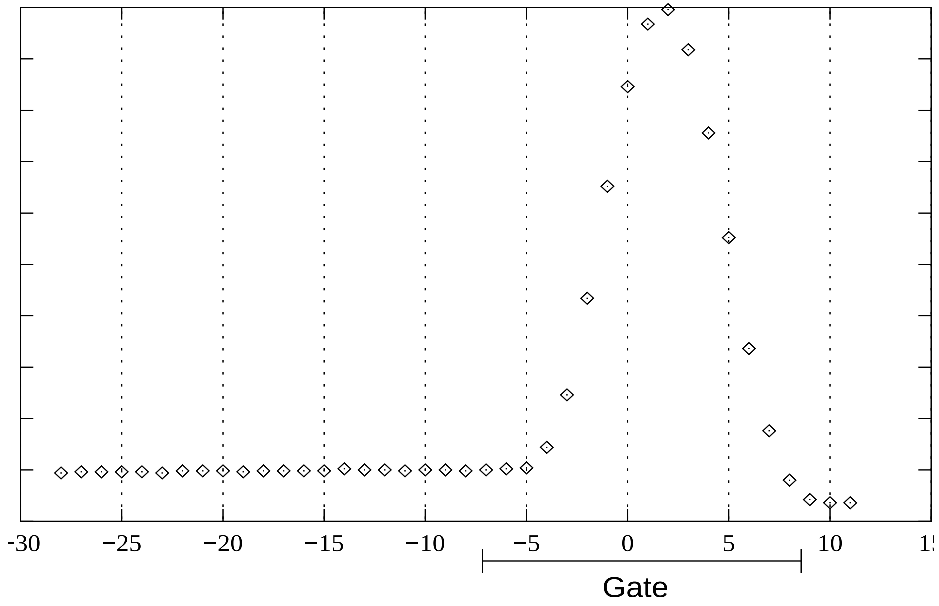


EASTC, $3.6\cdot10^{12}p^{+}/b + 3\cdot10^{11}p^{+}/b$



LHC, at 2nd injection

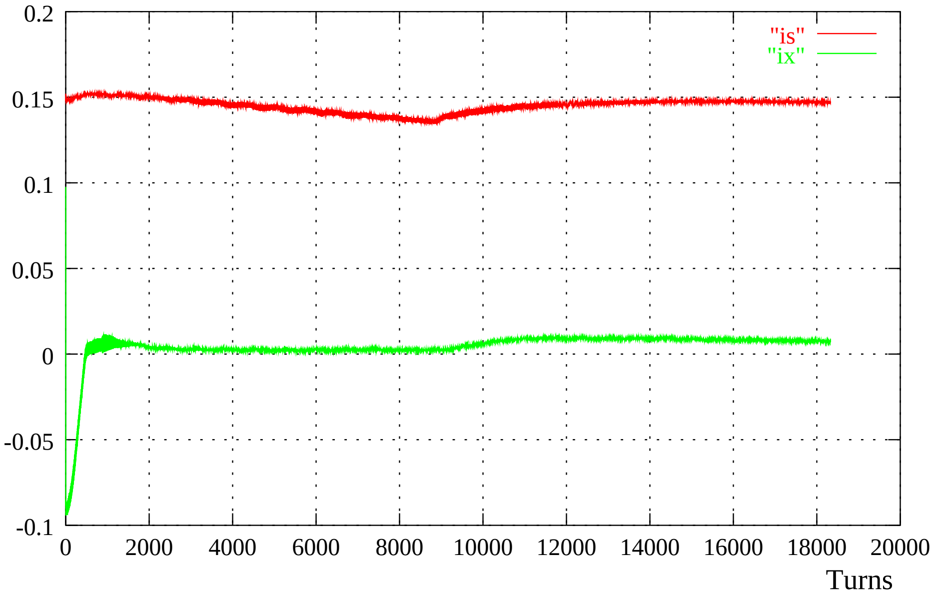
Integration algorithm



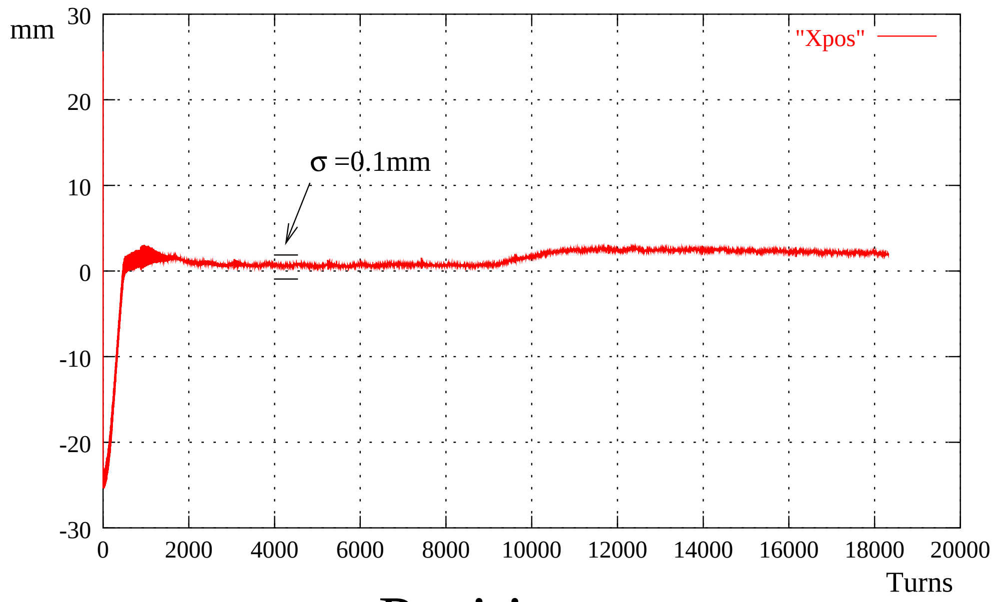
- Base line correction is needed to remove sensitivity to gate length
- Integration is simple addition of baseline-corrected samples

(This leaves a lot of room for refinements)

Finding the position



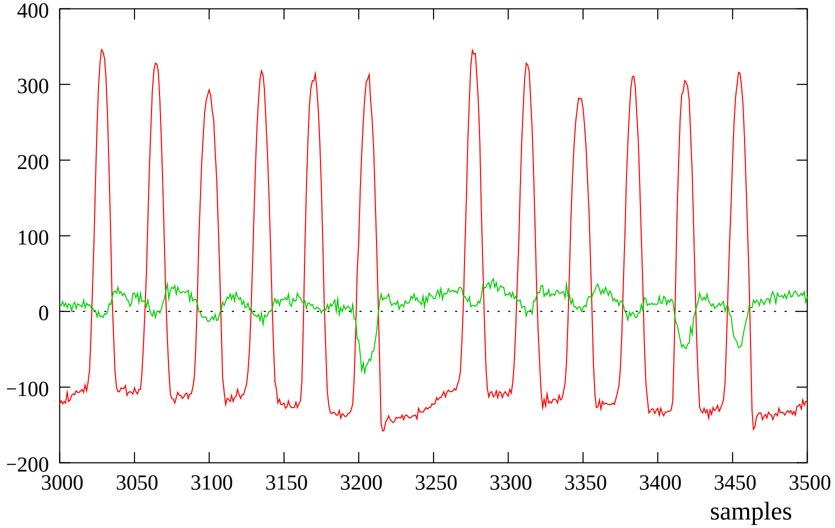
Integrals



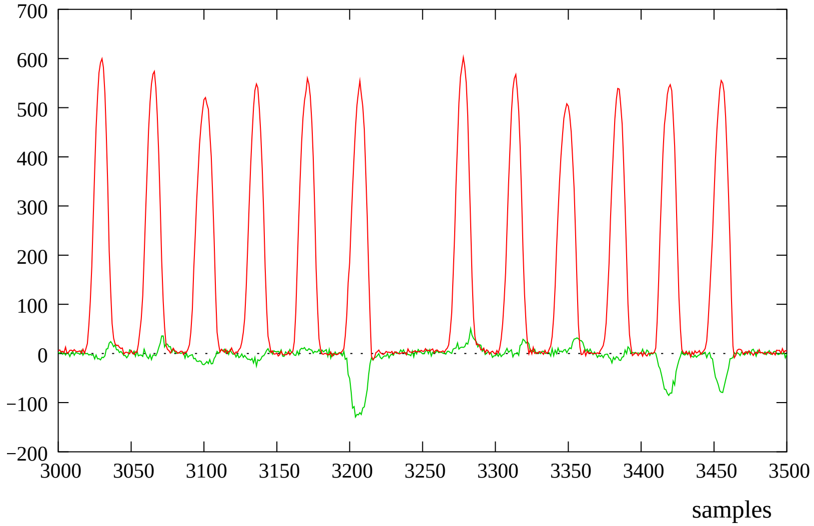
Positions

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

Principle of base line restitution



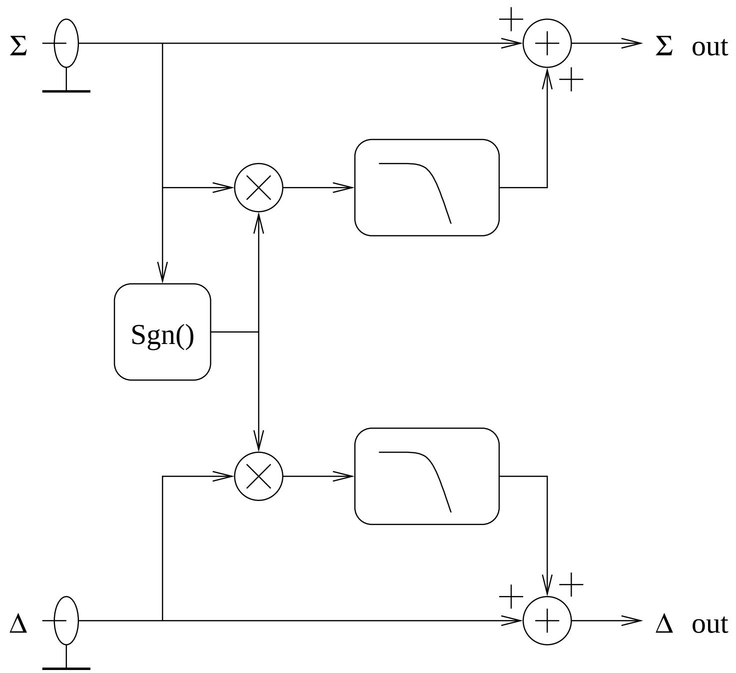
LHC beam without BLR



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

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

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

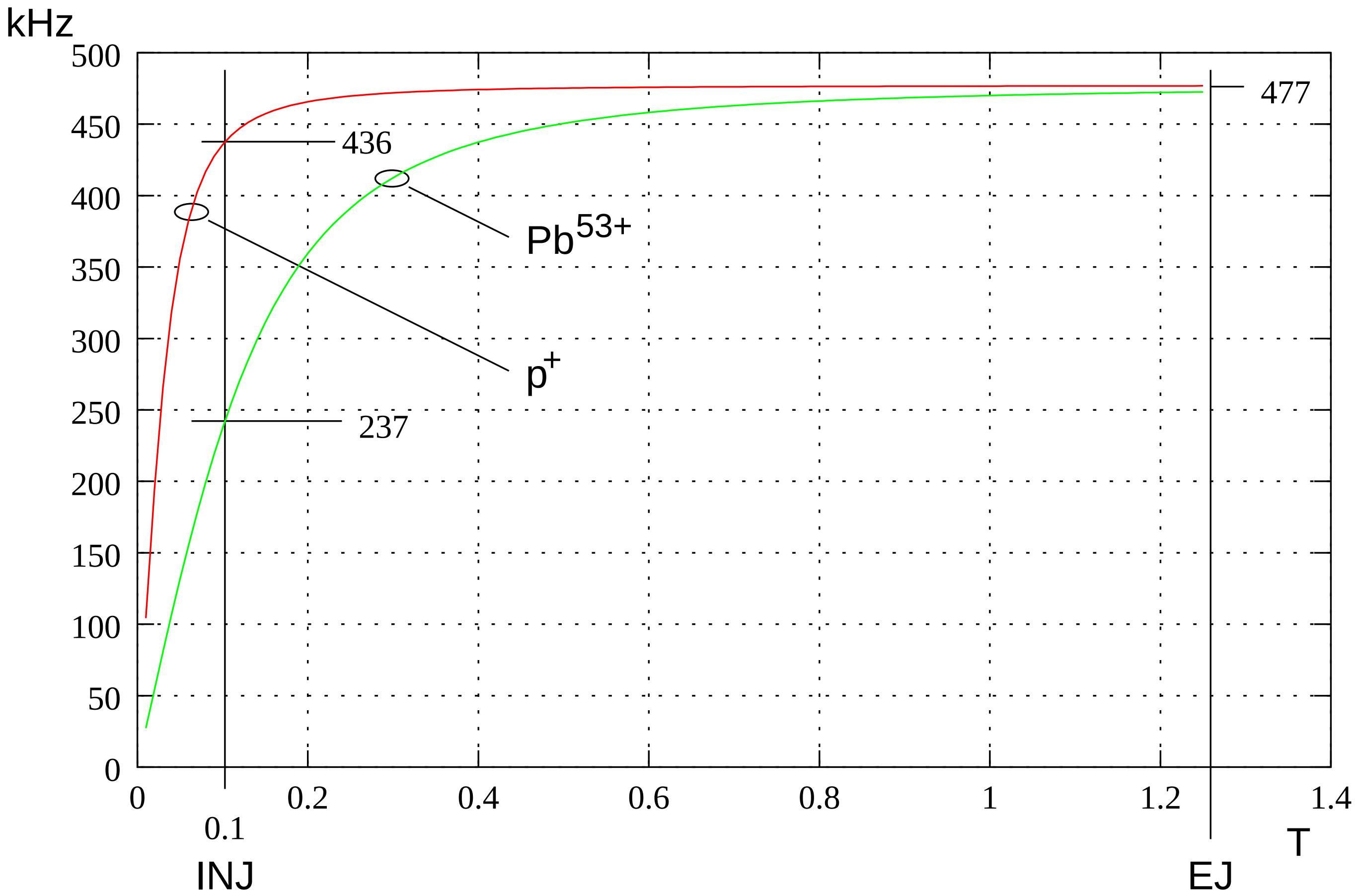
$$B_{\Delta,n}=aB_{\Delta,n-1}+(1-a)\,sgn(\Sigma)\,\Delta_{raw}$$

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

Revolution Frequency vs. B field

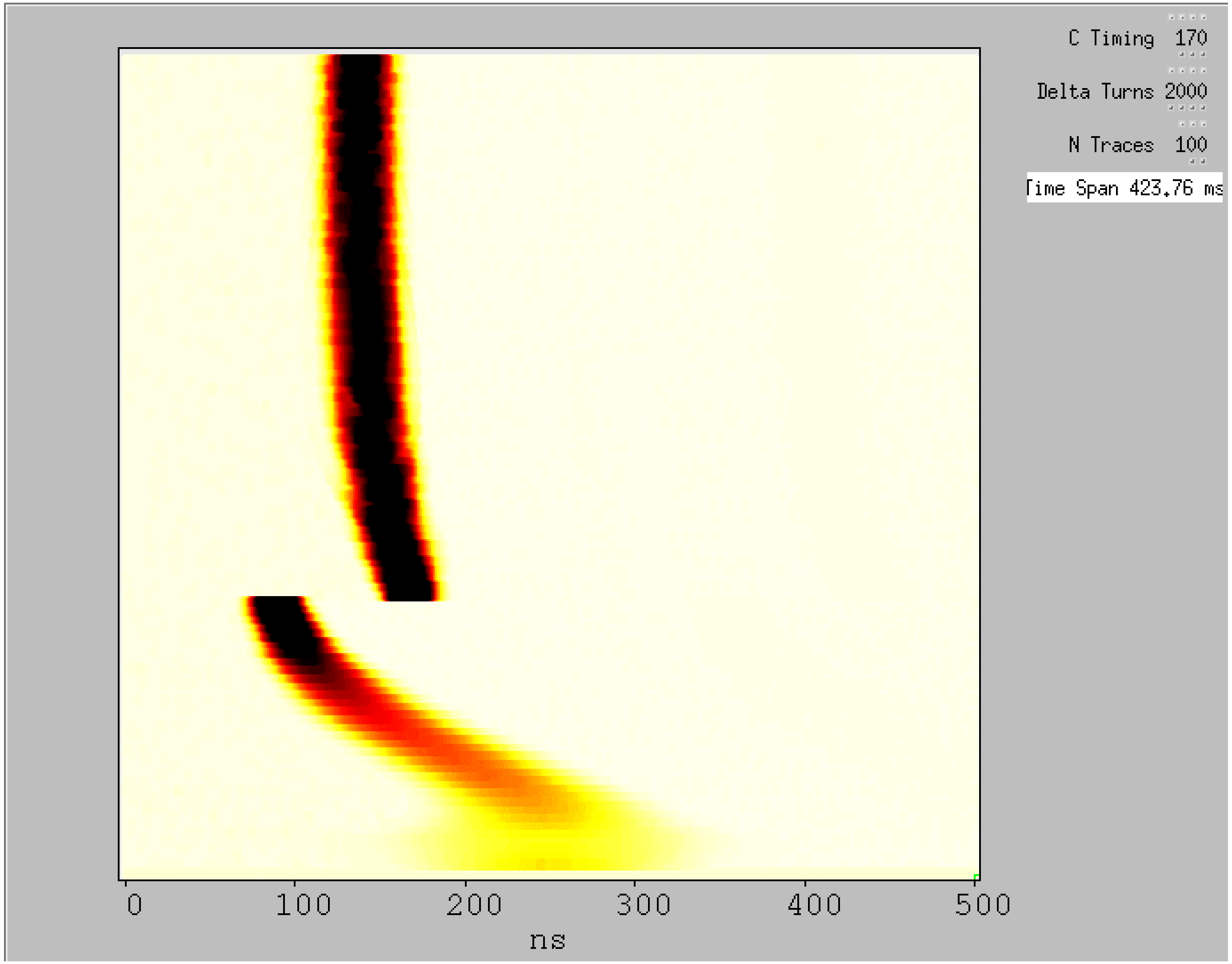
$$f = \frac{R_m Q h B}{2\pi R_0 m \sqrt{1 + \left(\frac{R_m Q B}{m c}\right)^2}}$$

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



A new trajectory measurement system for the CERN PS

Phase of RF slides w.r.t. beam



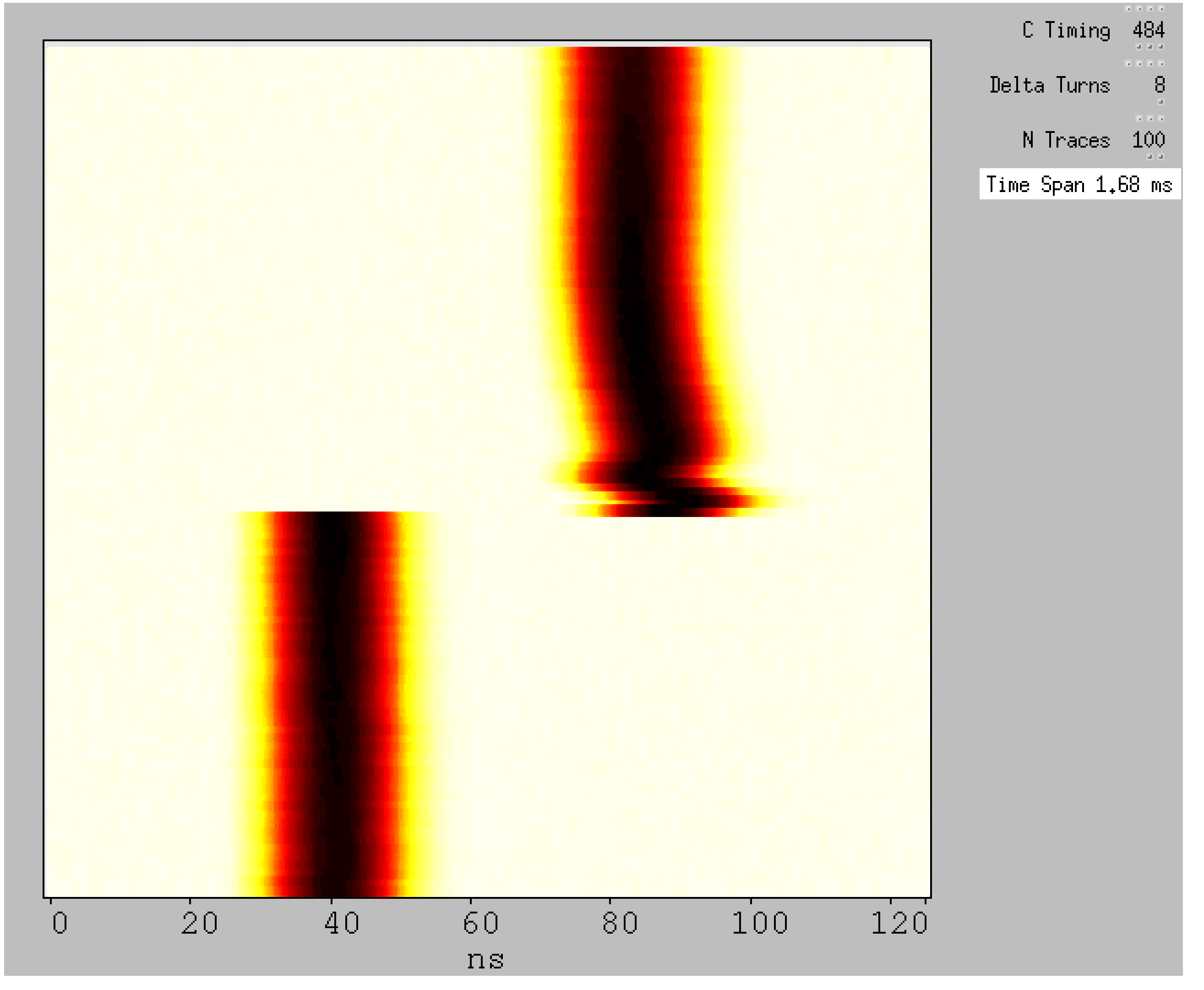
The phase relation between beam and RF shifts with changing F_{rev} due to cable delays.

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

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.

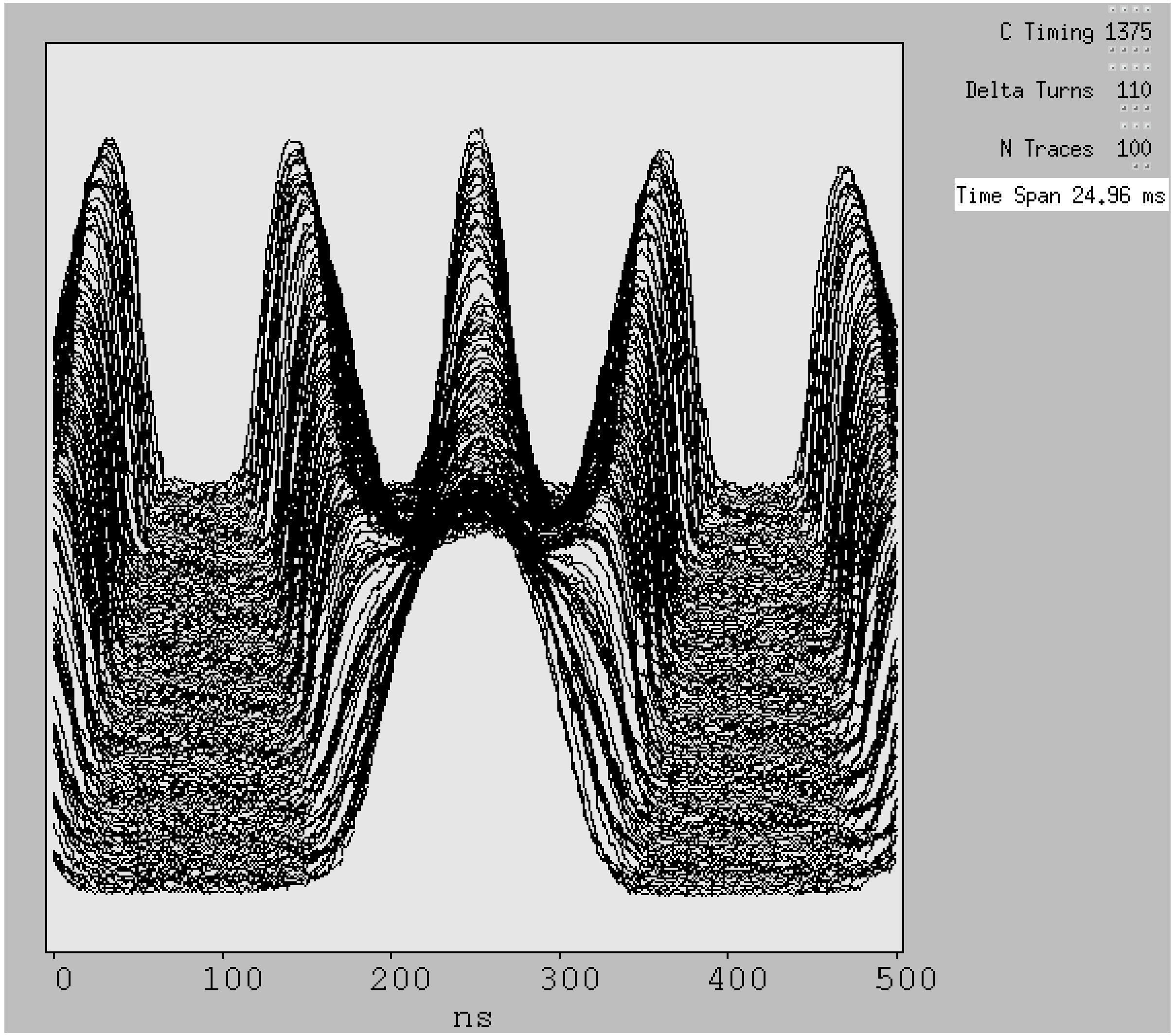
This picture has been taken on an SFTPRO cycle. The phase change due to γ-transition is about 120°.



RF gymnastics

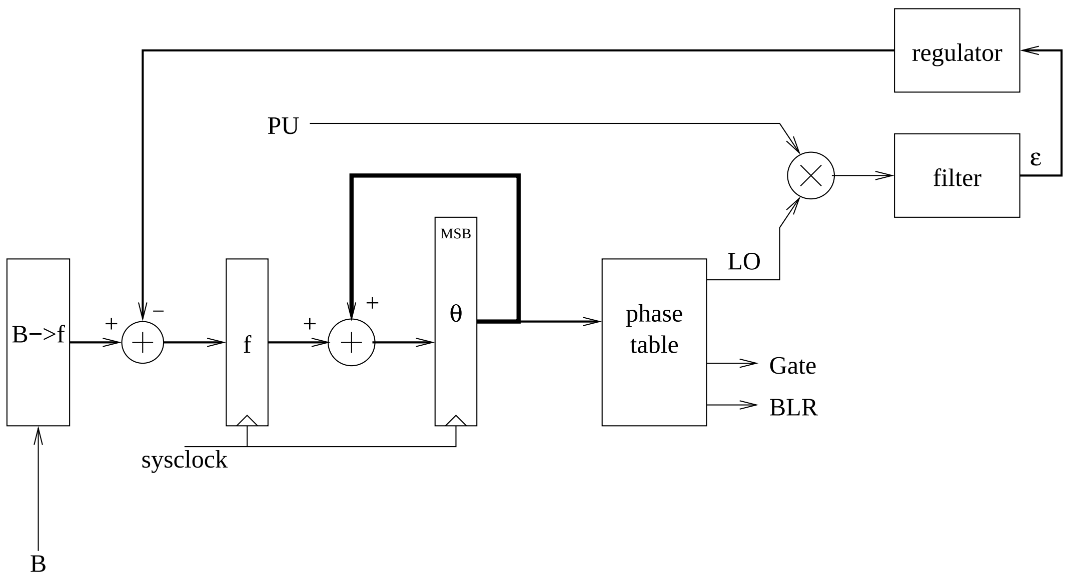
During LHC cycles, each bunch is split into three equal bunchlets in about 25ms.

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

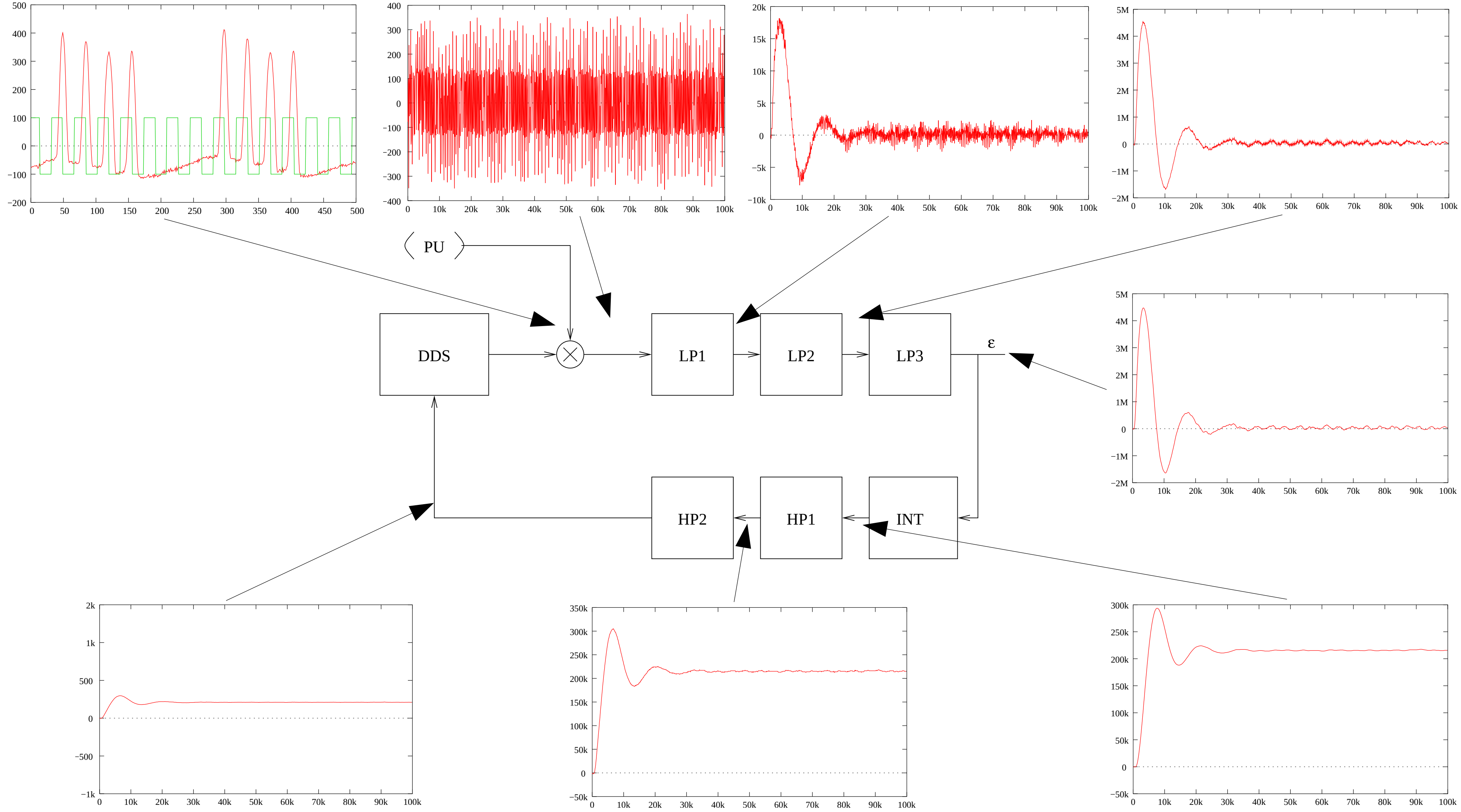
- Numerical phase locked loop
- DDS running at F_{rev}
- Lookup table generates LO and Gate



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

A new trajectory measurement system for the CERN PS

Intermediate signals



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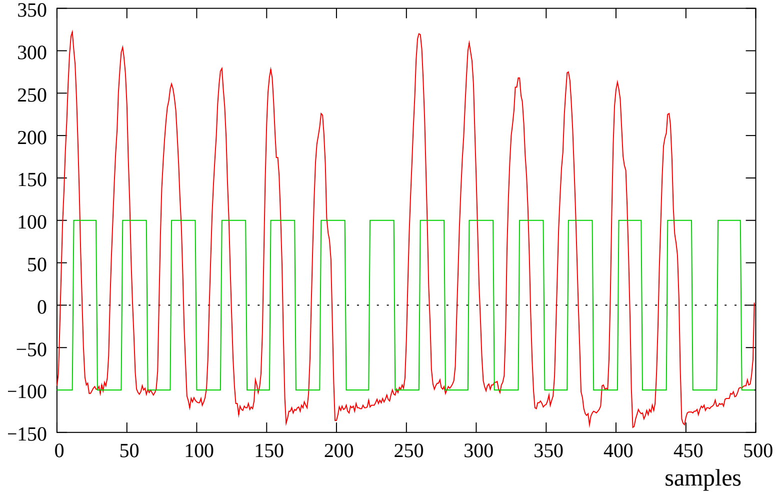
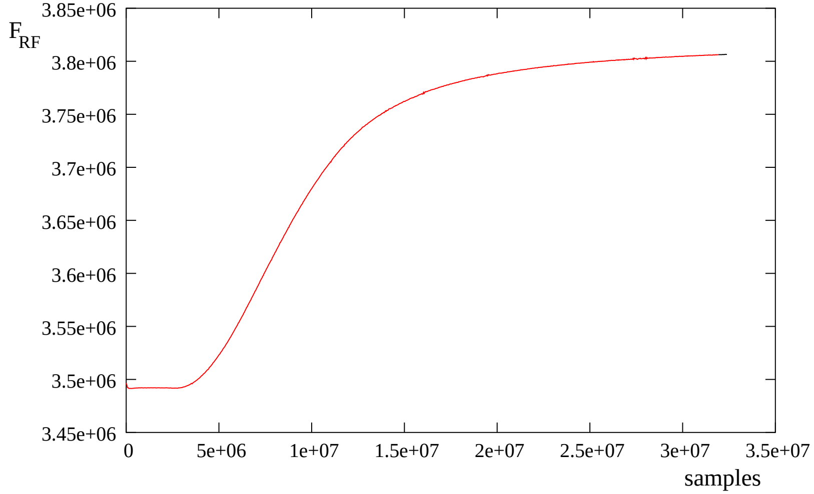
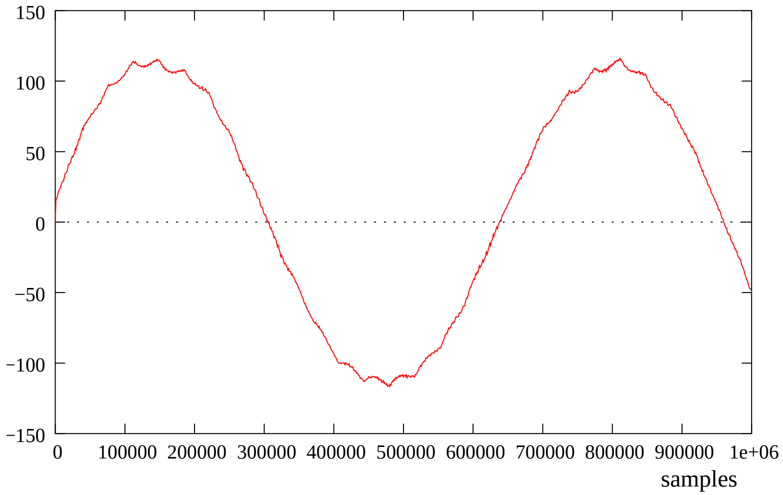
Creating a reference frequency



PU signal and reconstructed RF at h=7



Evolution of RF frequency during acceleration



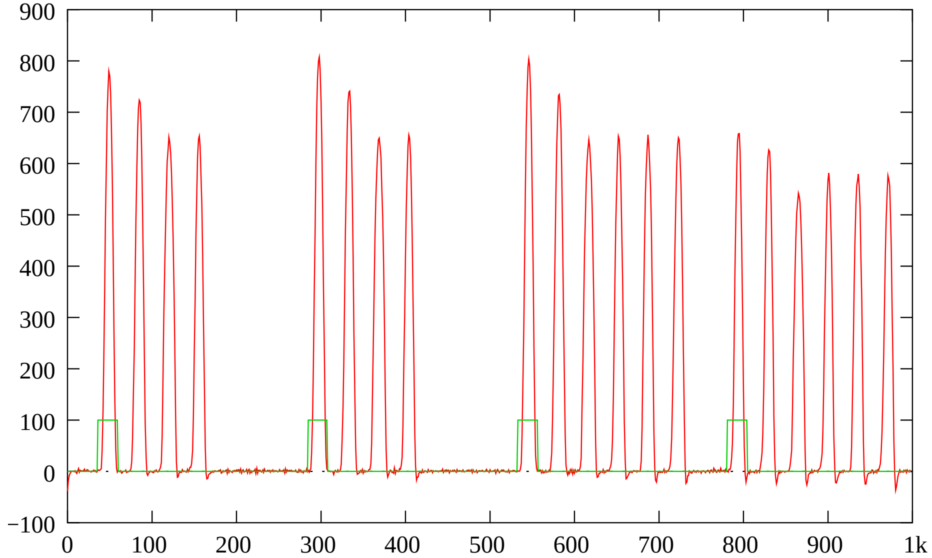
Phase error (ε) vs. PU and RF phase difference

There is a trade off between settling time and accuracy:

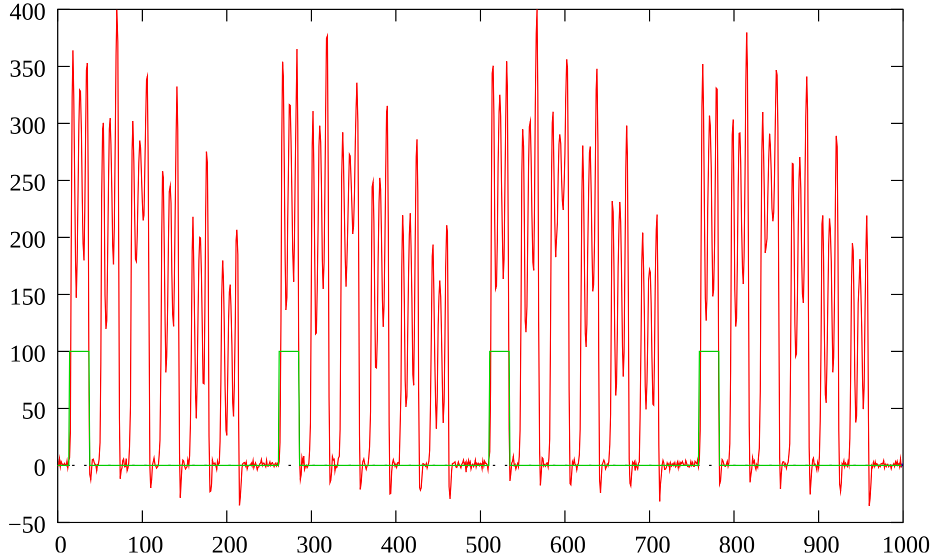
- Too slow and it won't follow acceleration
- Too fast and the reconstructed RF will be noisy

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

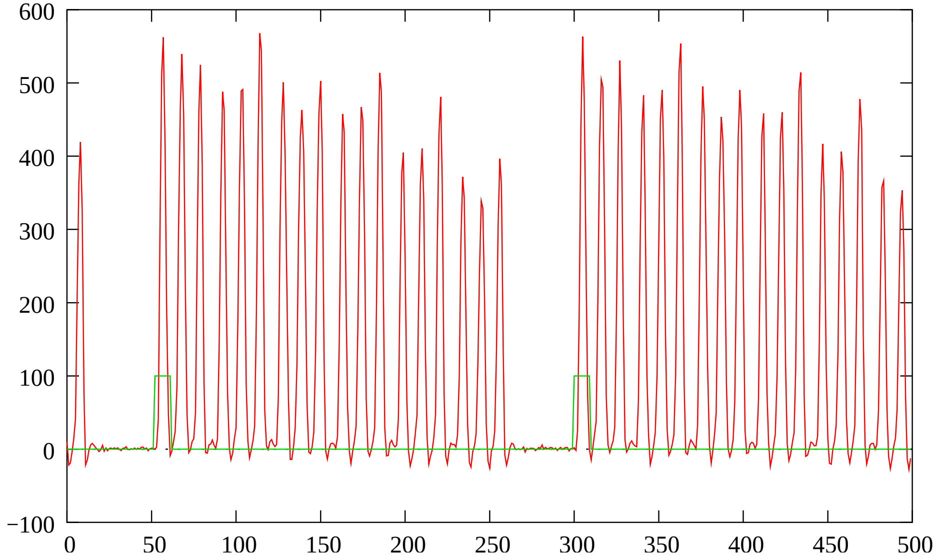
The generated Gate timing signal



Example of generated gate around 2nd injection



Idem, during bunch splitting

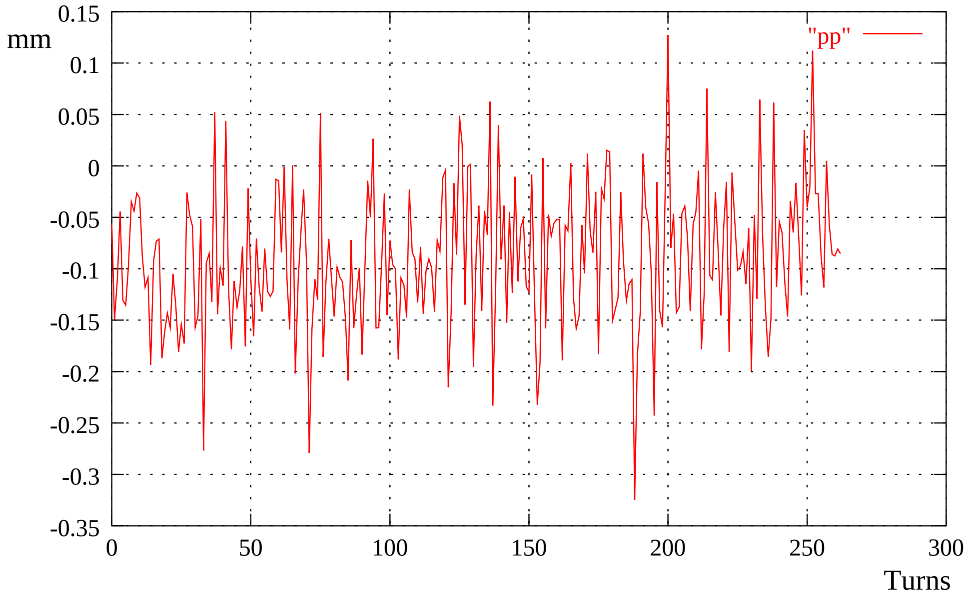


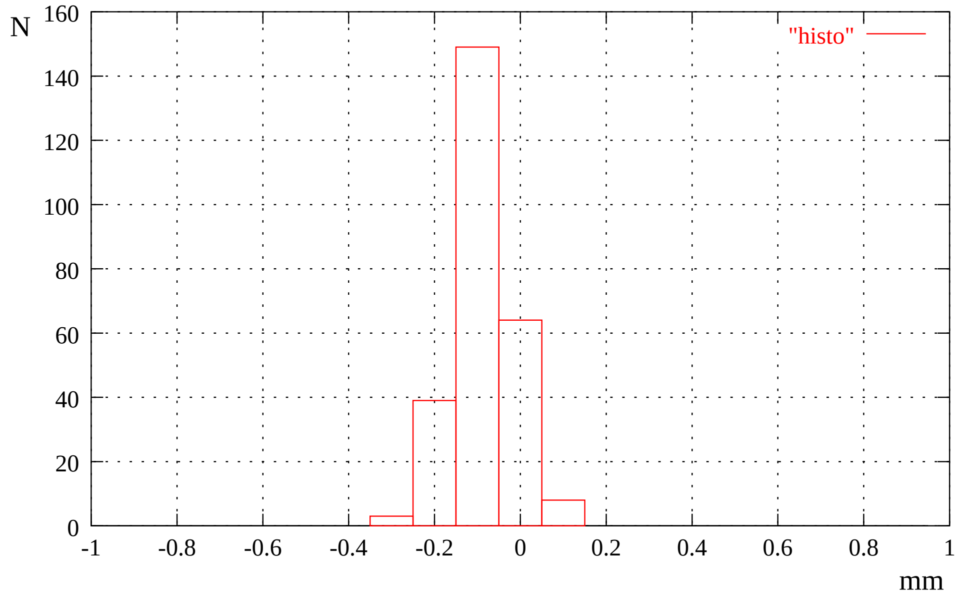
- Gate is initially centred on the bunch
- After splitting, it remains centred on the central bunchlet, spanning almost three of them at once
- An external timing signal prompts it to readjust

And after the harmonic change

A new trajectory measurement system for the CERN PS

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

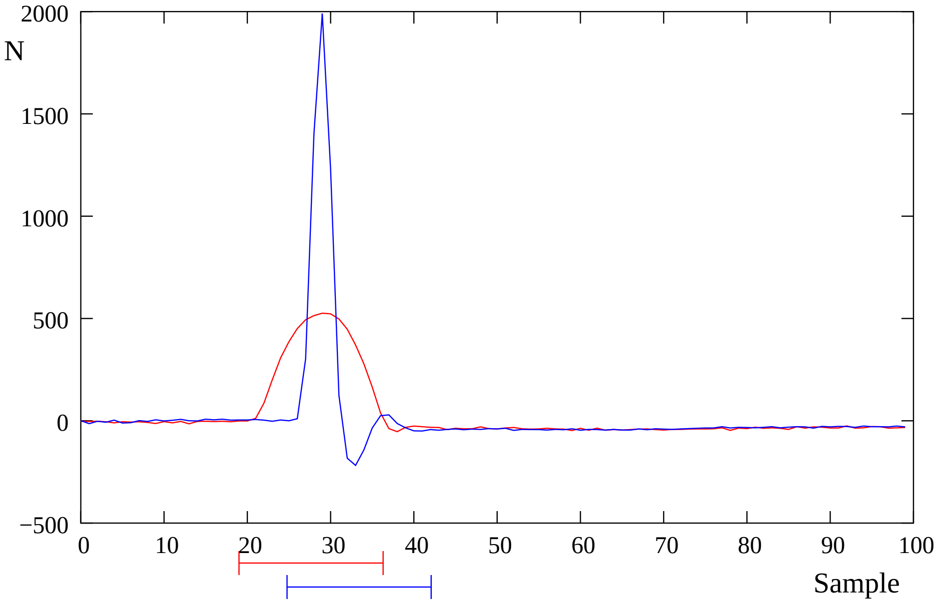
σ : 0.07mm

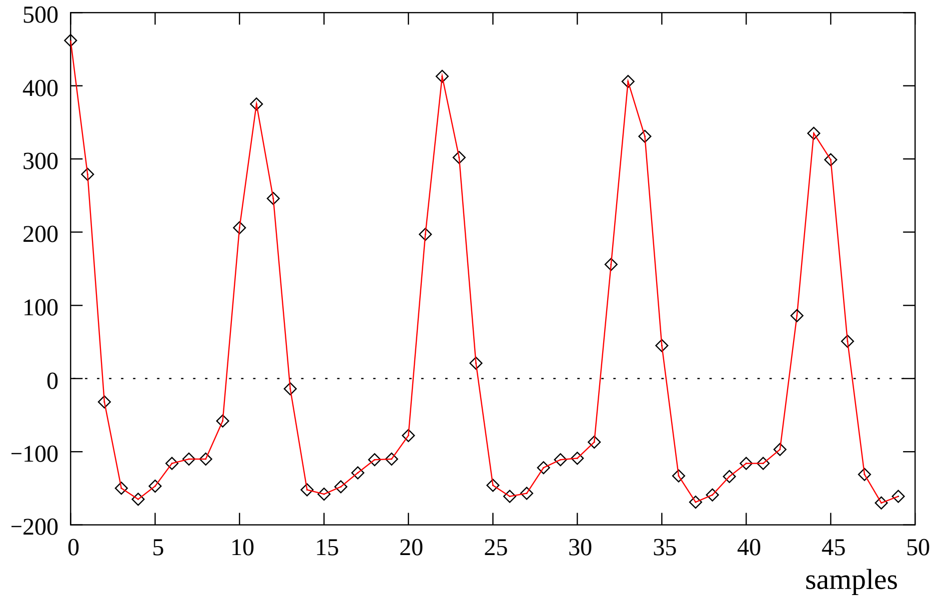
Conclusions

- 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.

* Instrumentation Technologies d.o.o., Srebrnicev trg 4 a, SI-5250 Solkan, Slovenia

Evolution of bunch length during acceleration





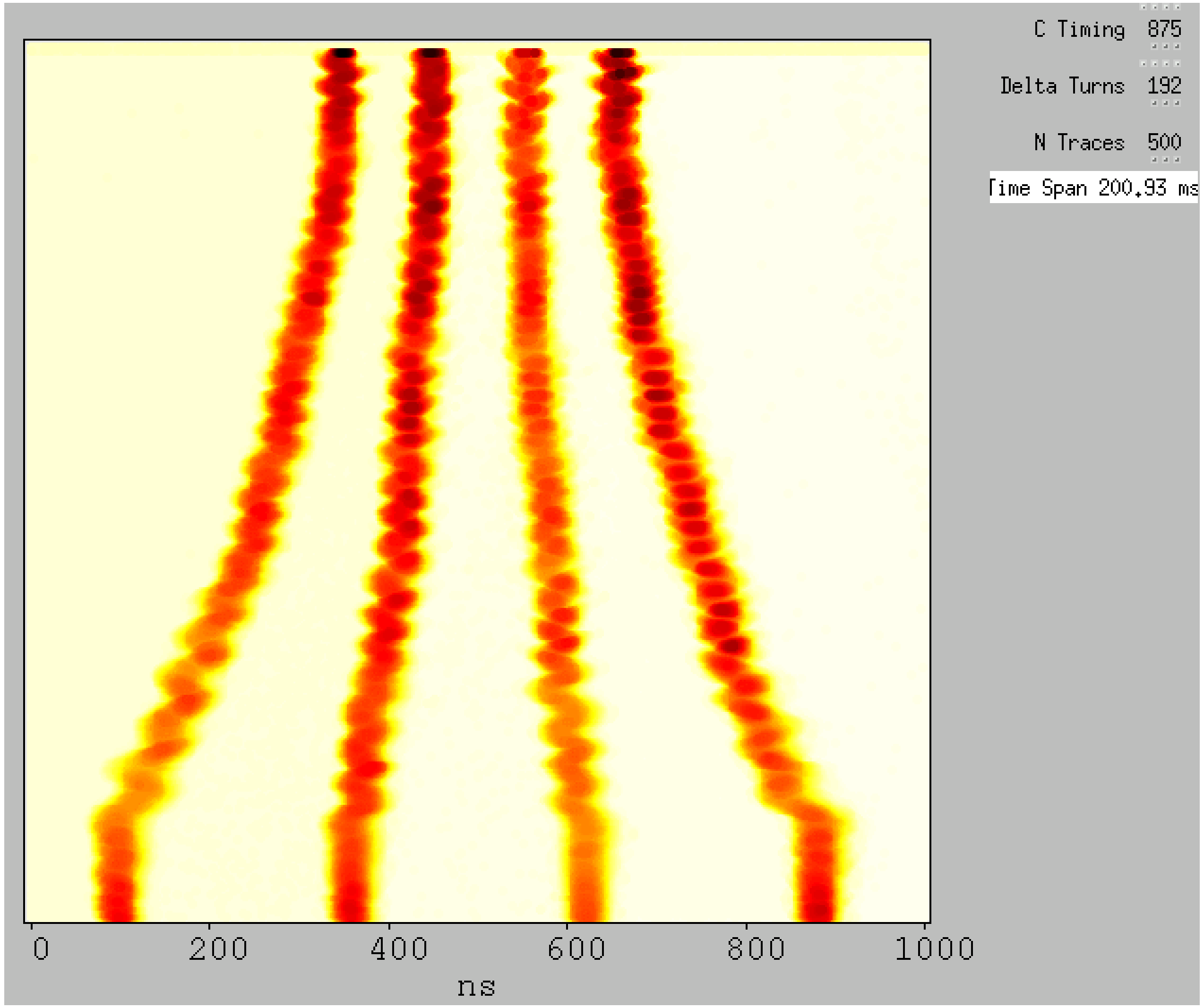
Bunch length near injection: 120ns
Bunch length near transition: 30ns

Zoom in on LHC-type bunches at h=21

A new trajectory measurement system for the CERN PS

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.



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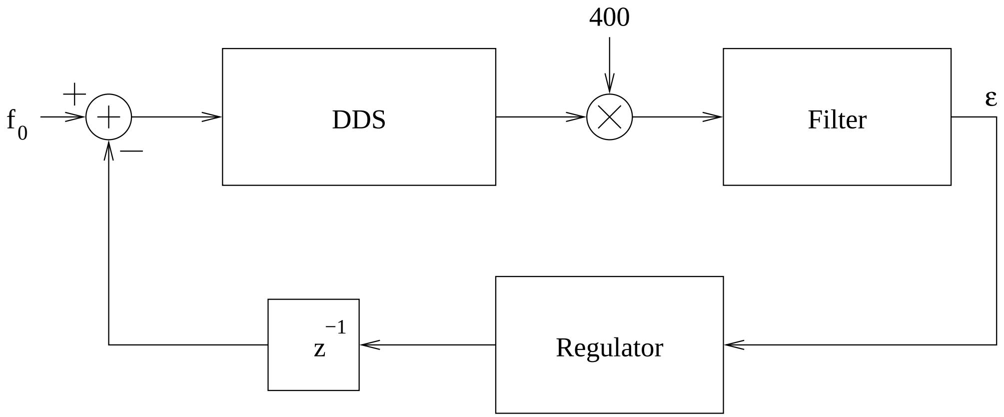
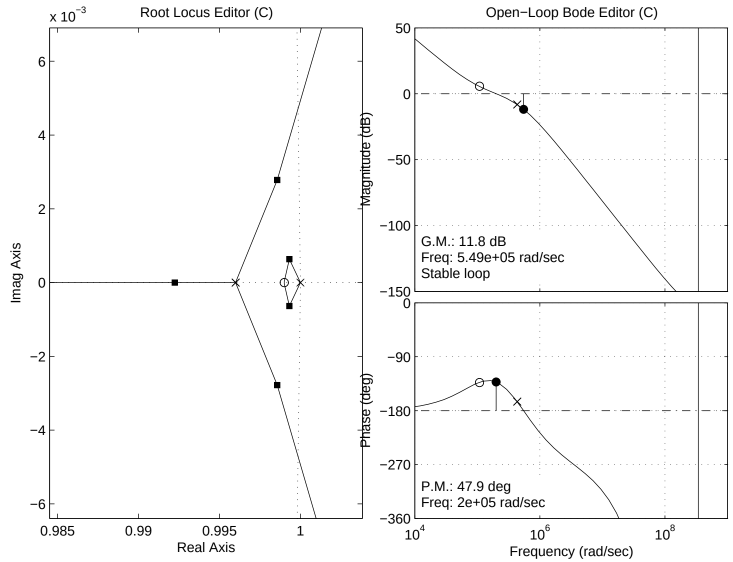
PLL response analysis



Simplified block diagram



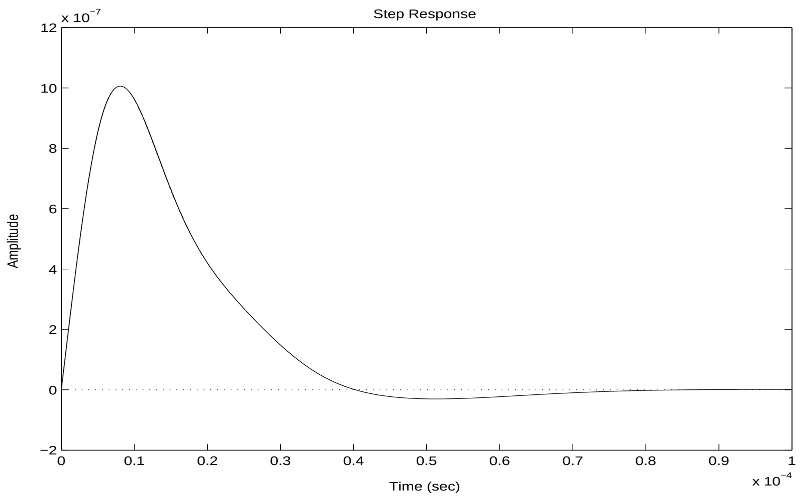
Root locus and Bode plots

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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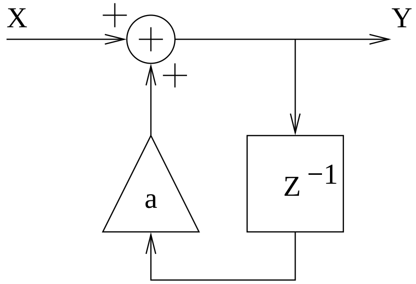
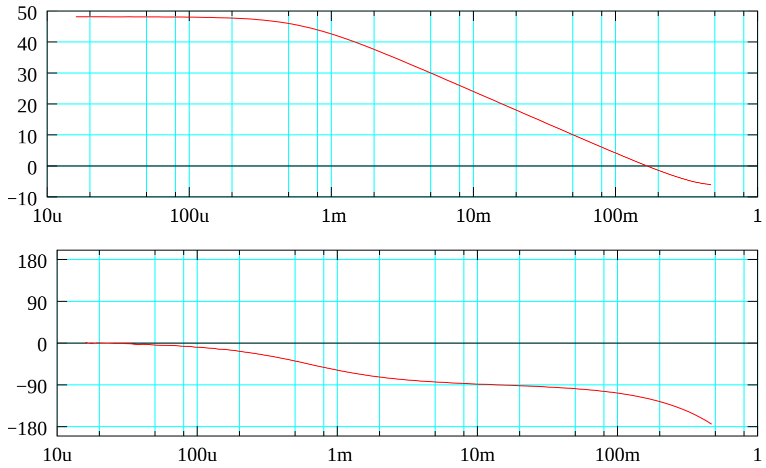
Low pass filter stage

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

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

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



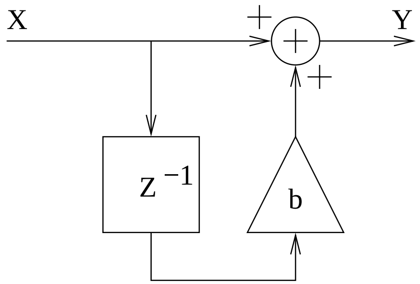


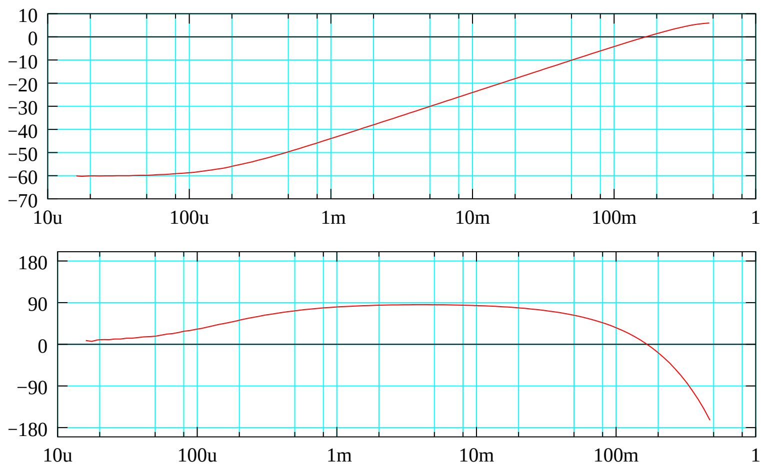
High pass filter stage

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

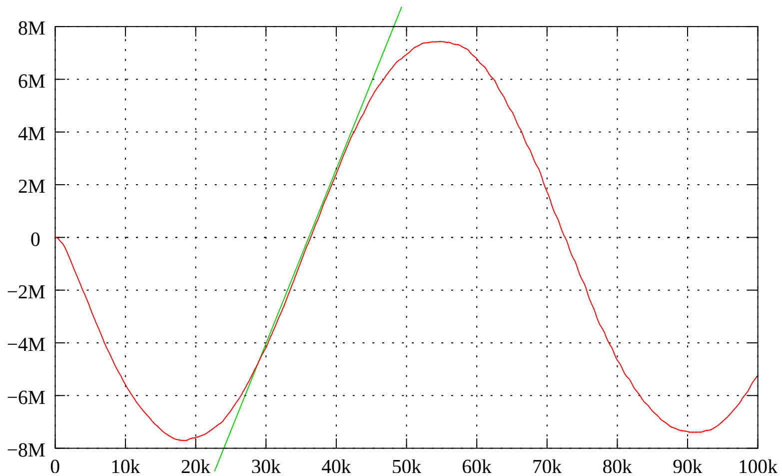
$$y_n=x_n-0.999\,x_{n-1}$$

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





Phase noise I



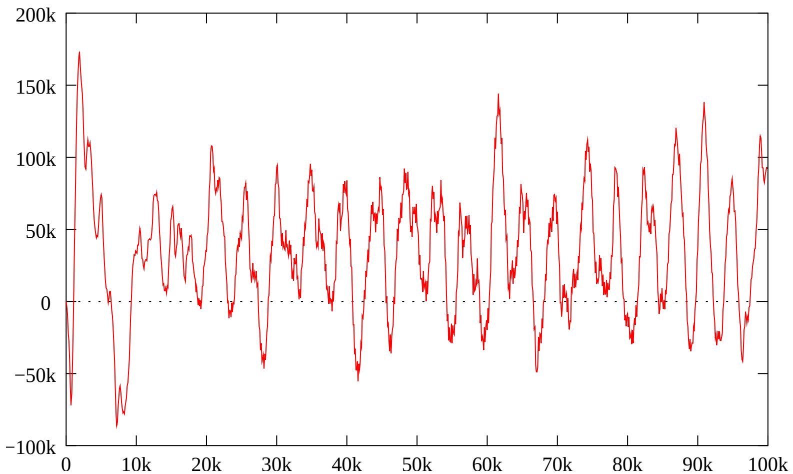
First find the phase error gain:

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

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

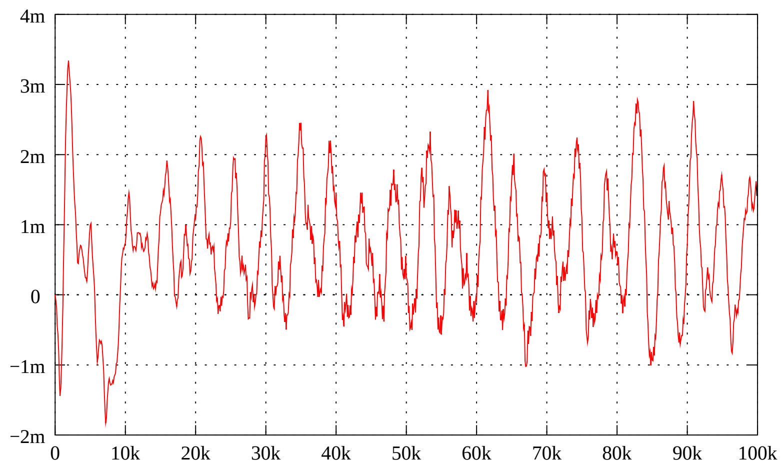
Normalised to one period of the phase error:

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



Raw phase noise

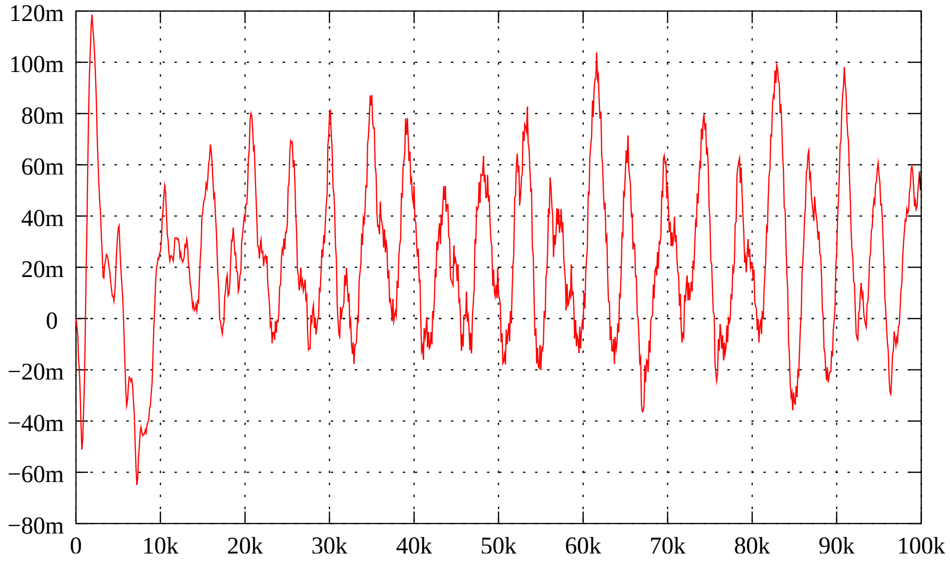
$$\frac{1}{G_\epsilon}$$



Phase noise as a fraction of an RF period

Phase noise II

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

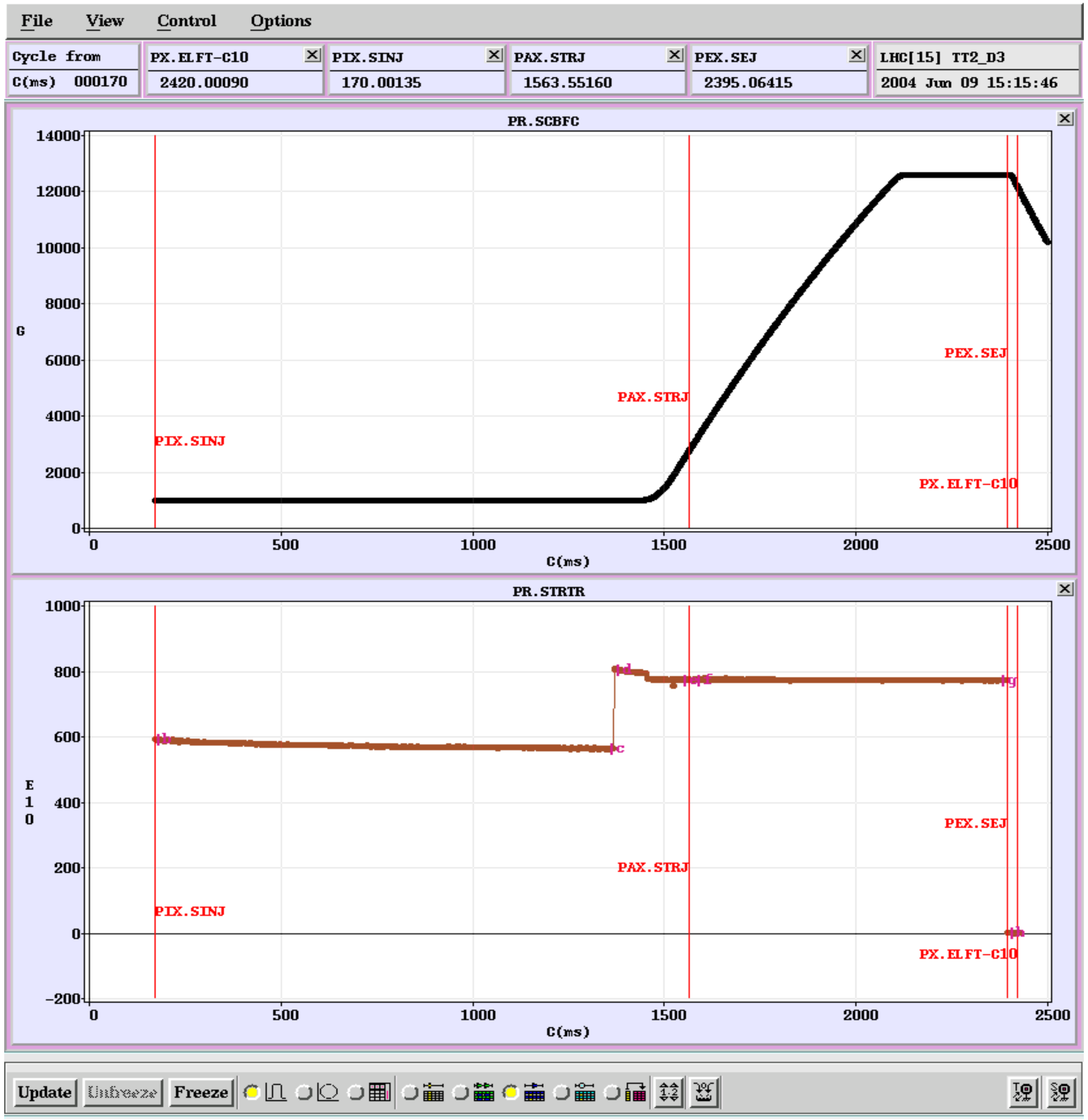


Phase noise normalised to one sample

σ=0.03 samples

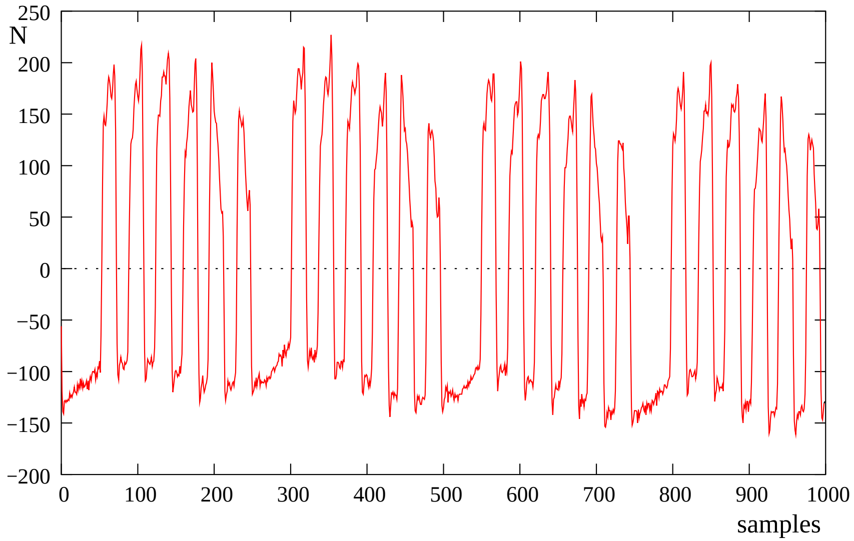
Magnetic Cycles

- 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^+)

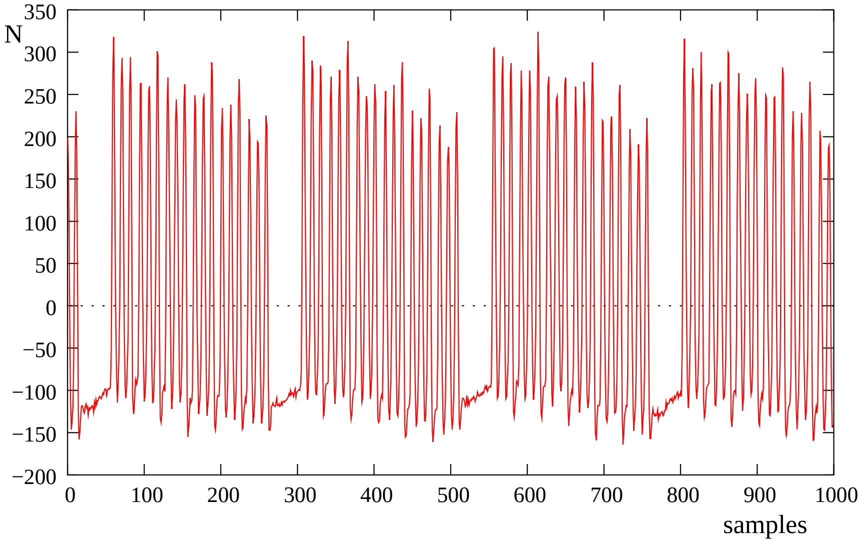


A new trajectory measurement system for the CERN PS

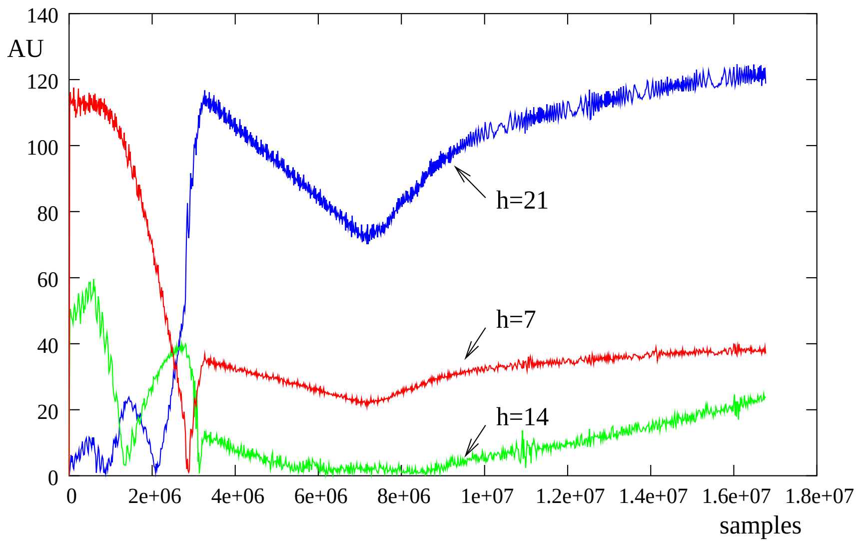
Handling harmonic changes



LHC beam at h=7



LHC beam at h=21

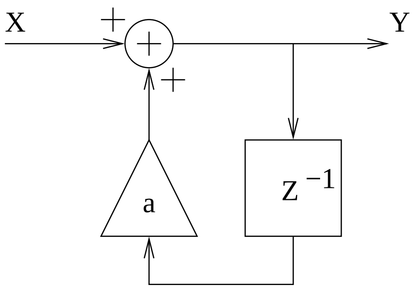


Evolution of magnitude of harmonics on LHC

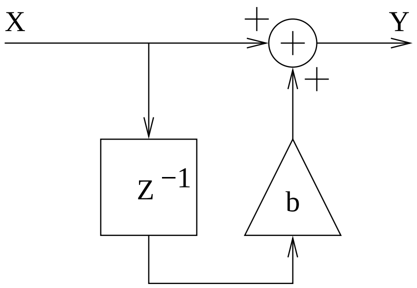
RF gymnastics in PS have special requirements:

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

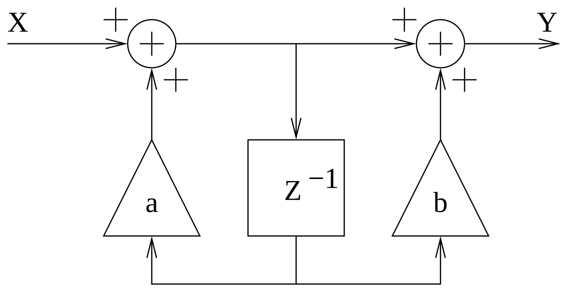
Digital filters



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

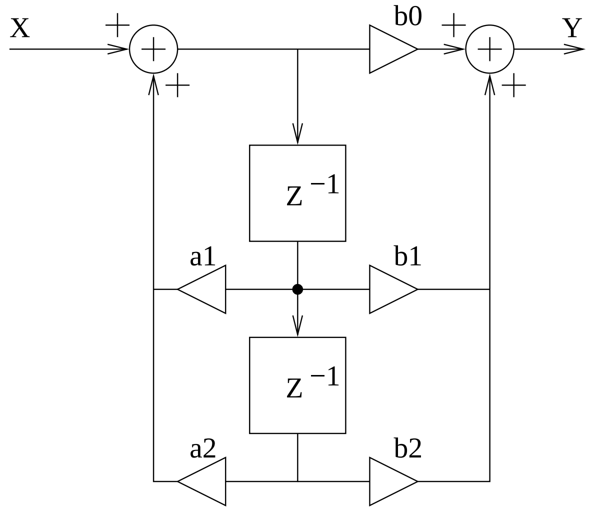


One zero: $\frac{y}{x}=1+b\,z^{-1}$



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:

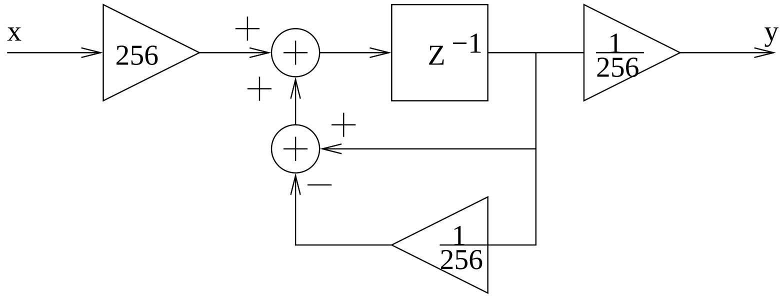
127/128=0.992...

255/256=0.996...

511/512=0.998...

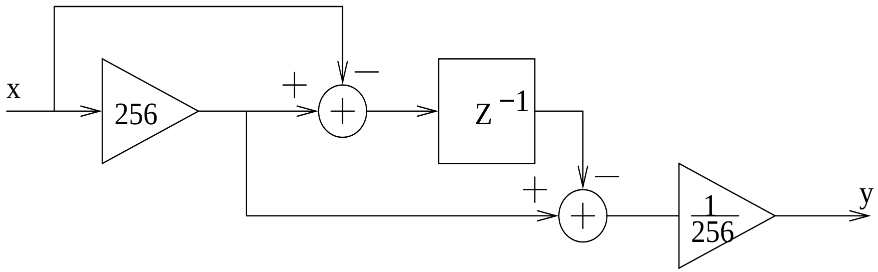
1023/1024=0.999...

So for a (real) pole:



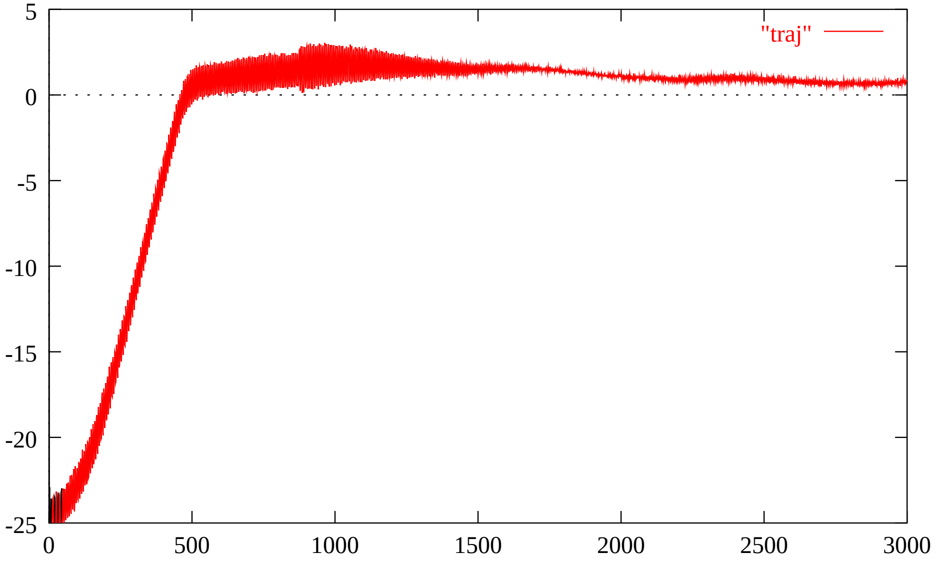
$$= \frac{y}{x} = \frac{z^{-1}}{1-0.996\,z^{-1}}$$

... and for a zero:

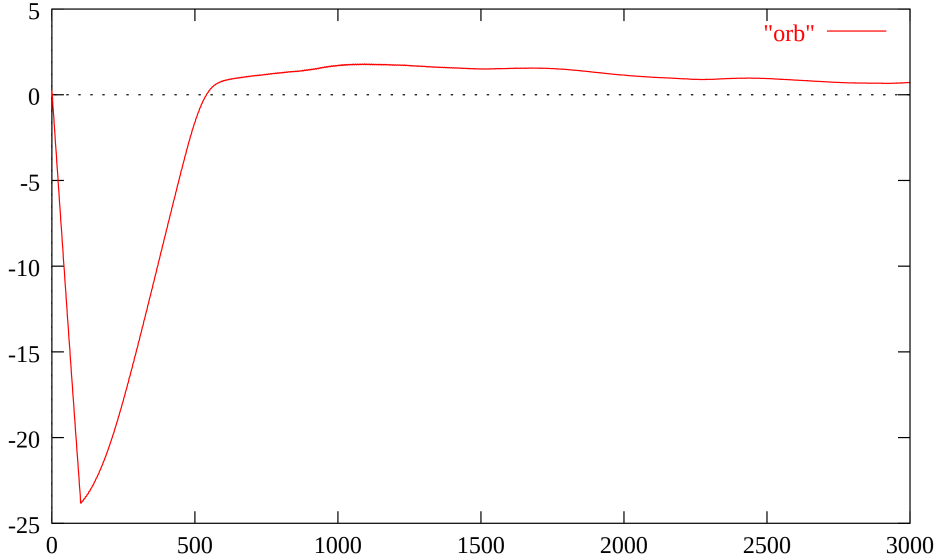


$$= \frac{y}{x} = 1-0.996\,z^{-1}$$

Orbits



Trajectory

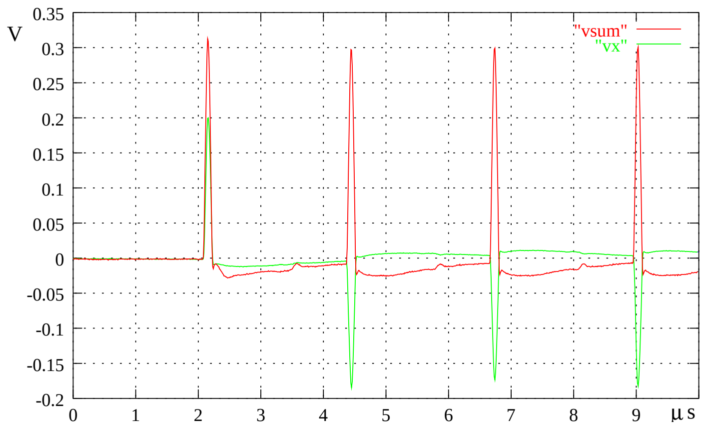


Orbit

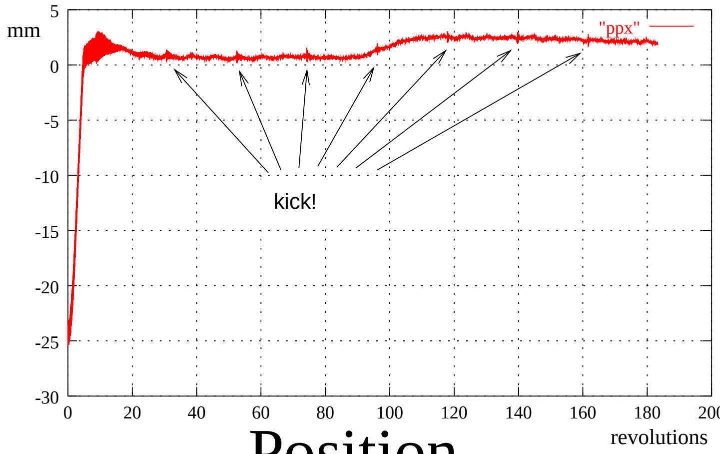
- Average N trajectories (N~100)
- Gain 10 times in resolution

A new trajectory measurement system for the CERN PS

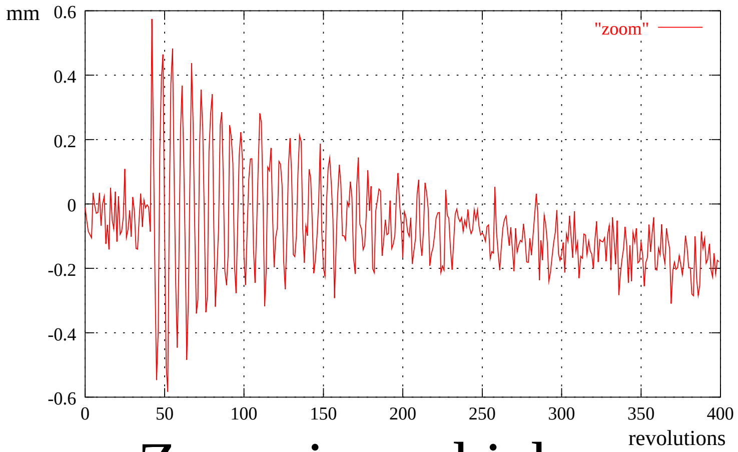
Tune measurement



Raw data

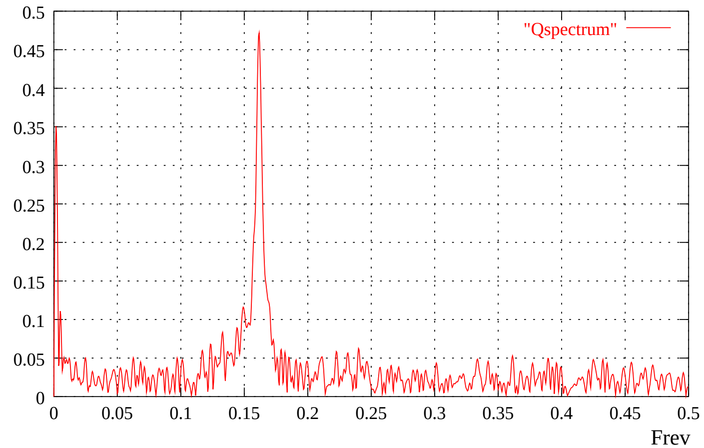


Position



Zoom in on kick

Fourier →



q=0.1615

J. Belleman - CERN

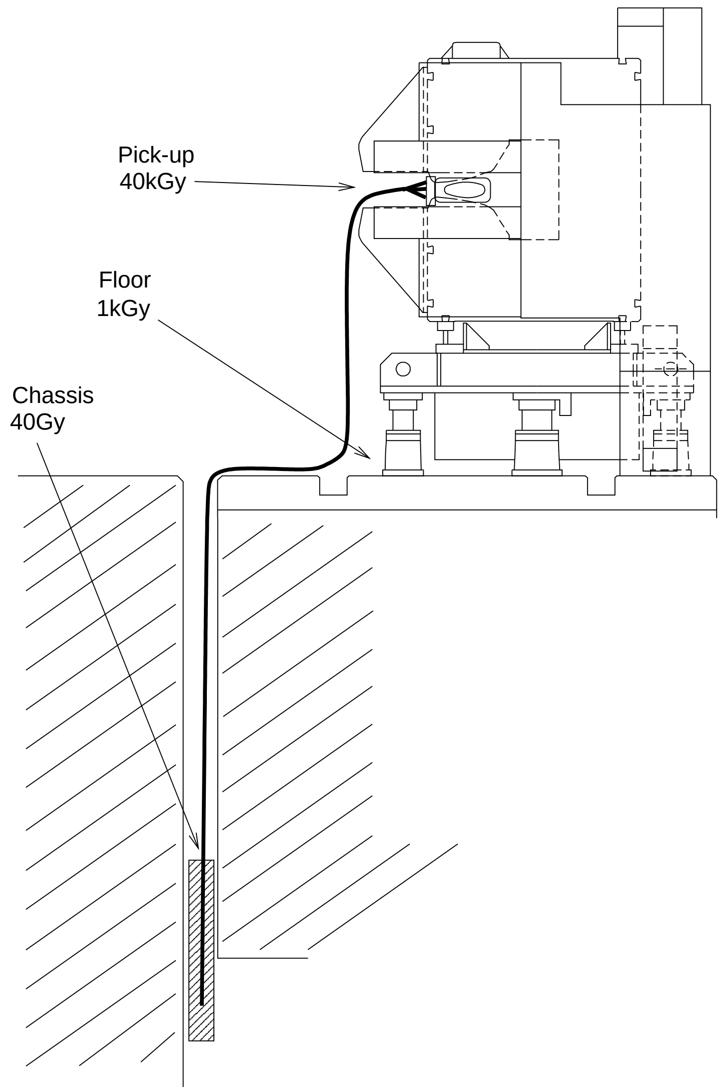
A new trajectory measurement system for the CERN PS

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.

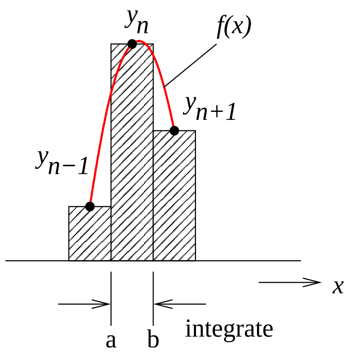
Cable length from PU to pre-amp : 5m
Double shielded cable



J. Belleman - CERN

Interpolation between sampling points

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

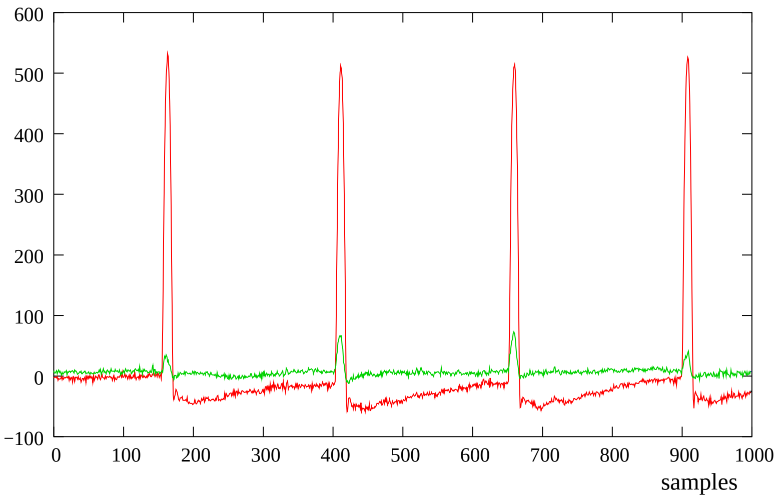


$$\int_a^b f(x)\,dx = A_n = \frac{k_1 y_{n-1} + k_2 y_n + k_1 y_{n+1}}{2k_1 + k_2}$$

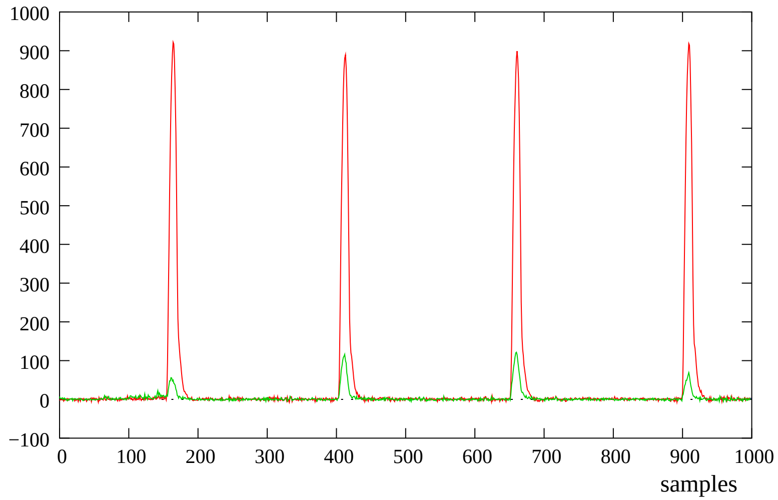
(For example, with a=-0.5 and b=+0.5, this gives k_1=1 and k_2=22)

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