Digital Signal processing in Beam Diagnostics

Lecture 1

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(Beam Instrumentation)

THE CERN ACCELERATOR SCHOOL

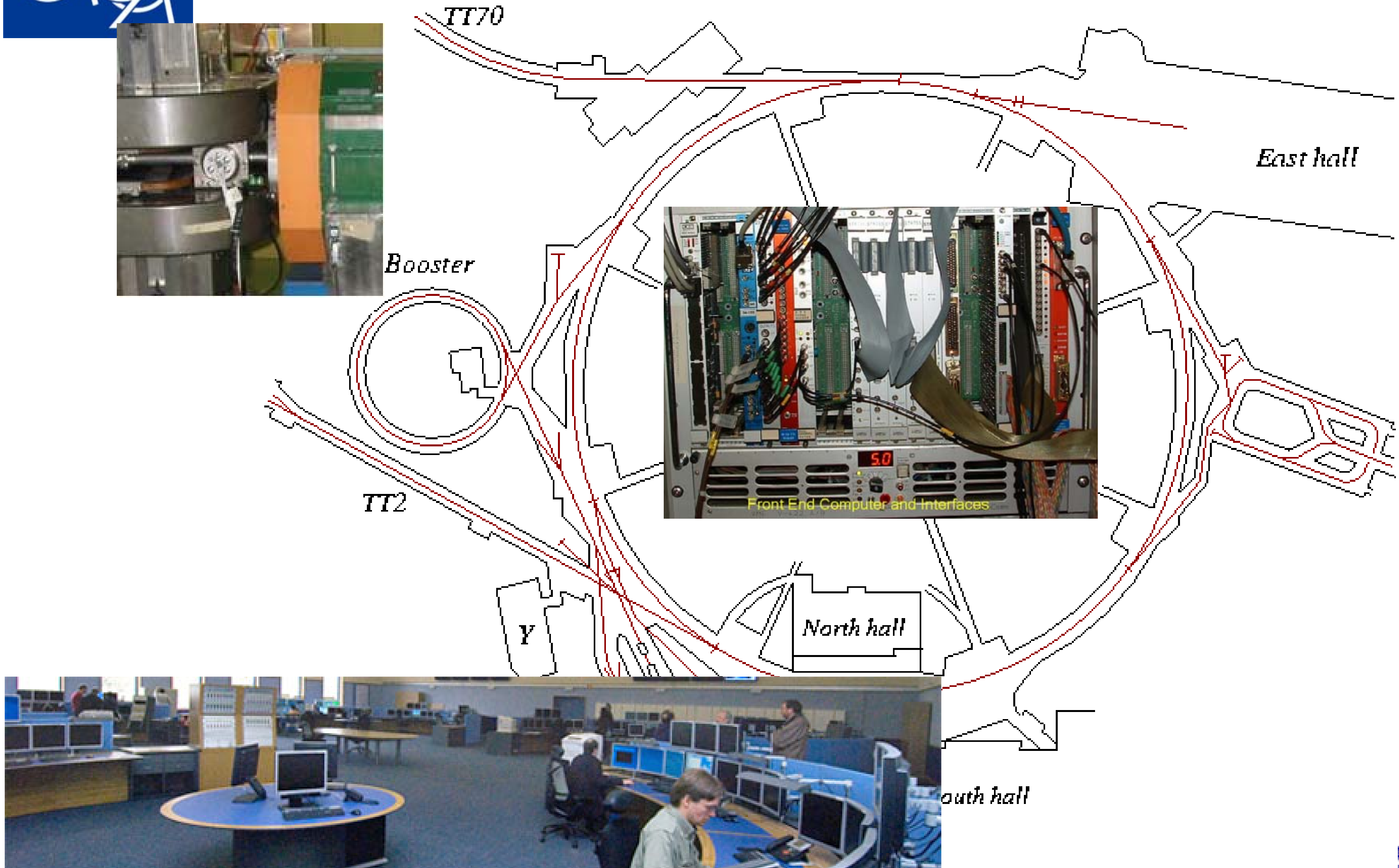
Overview

- Introduction
  - Layout of a measurement instrument
  - Types of measurements to be made on the accelerator
- The Tune
  - What is the Q value and why is it important
  - The electronics layout
  - Treatment of the BPM signal with a DSP
  - Further improvements
- Measurements of trajectories and orbits
  - The sensors
  - Different beam types
  - Synchronization
  - Baseline correction
  - RF gymnastics

Elements of a beam diagnostic system

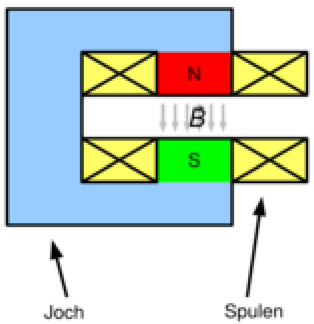
- The sensor
- Front end electronics (in the tunnel)
- Long cable from the tunnel to the equipment area
- Converter for sensor signals to digital values
- Data acquisition and control
- Transformation of the acquires values into humanly understandable machine parameter values
- Transfer to the control room
- Display in form of tables of graphs

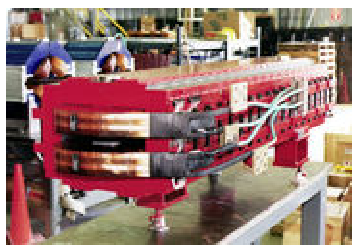
A beam parameter measurement

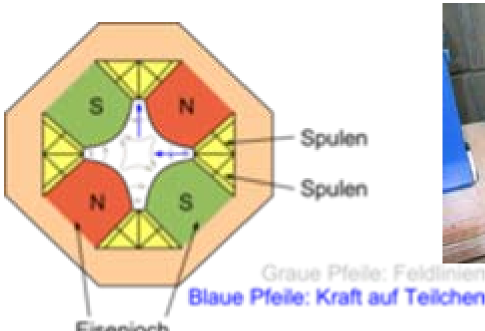


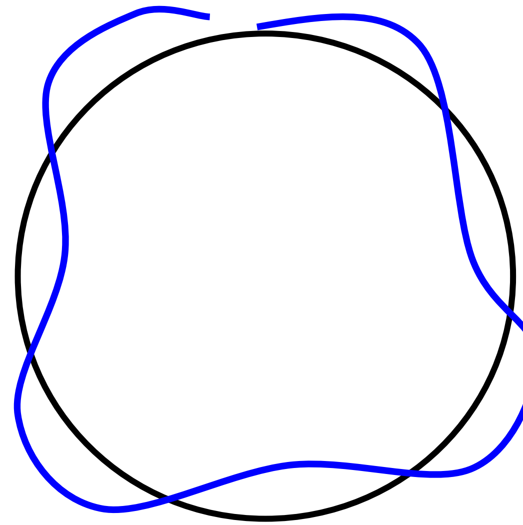
An accelerator and betatron oscillations

- An accelating cavity
- Bending magnets
- Focusing magnets



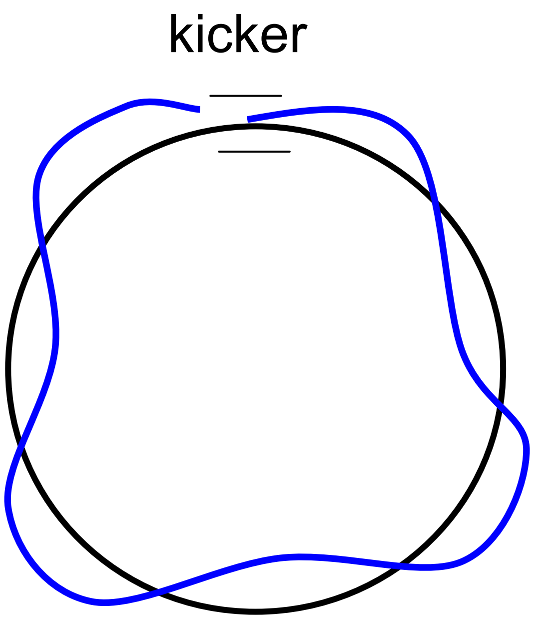






Tune measurements

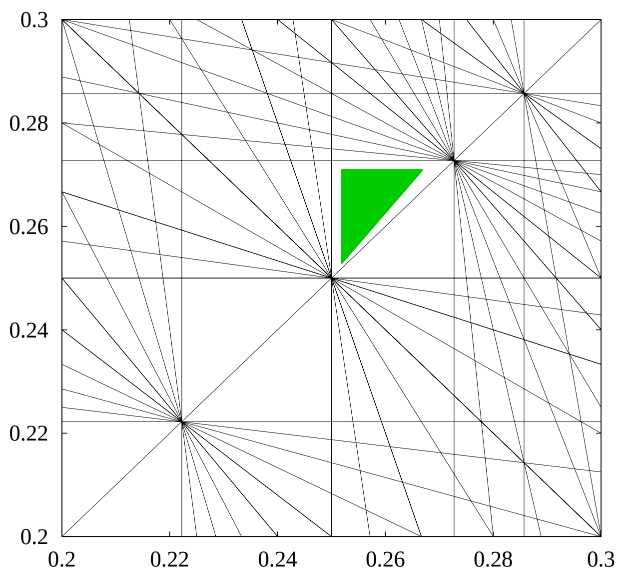
- When the beam is displaced (e.g. at injection or with a deliberate kick, it starts to oscillate around its nominal orbit (betatron oscillations)
- Measure the trajectory
- Fit a sine curve to it
- Follow it during one revolution

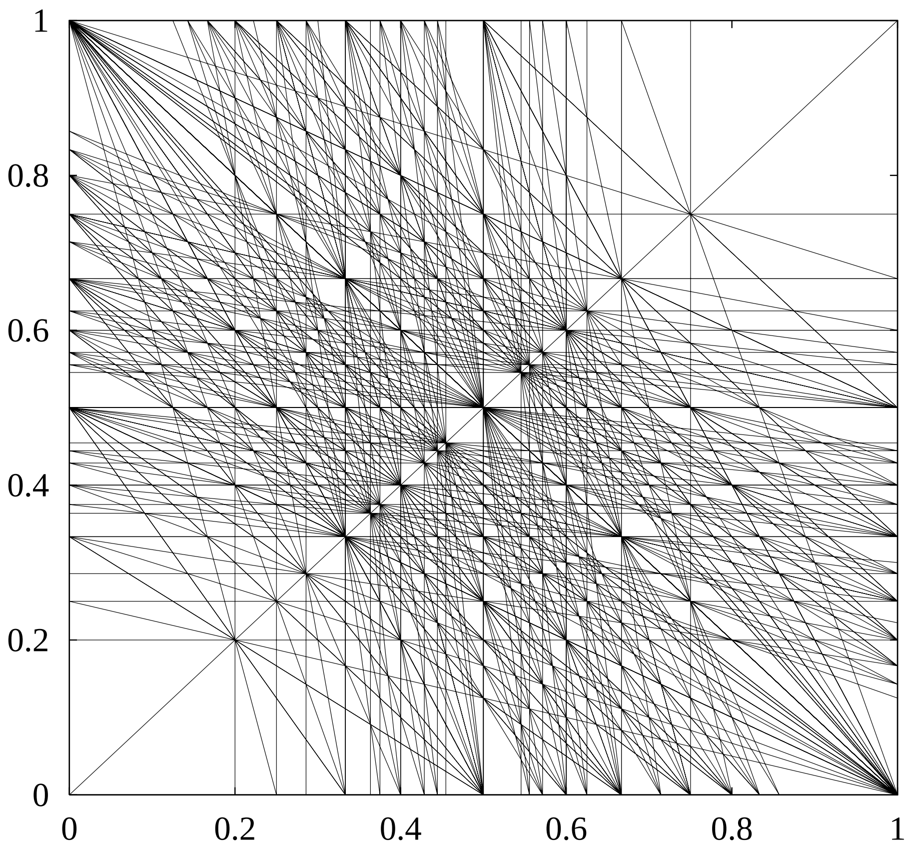


Why do we need to know the tune?

- Transverse resonances are created for certain tune values

Tune Diagram

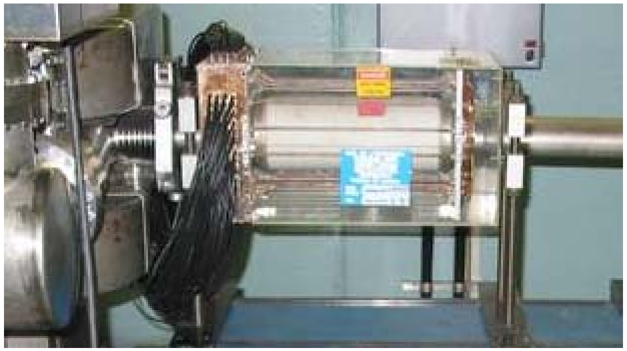


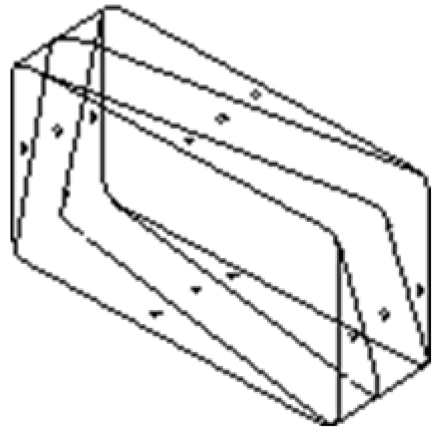


$$l \cdot Q_x + m \cdot Q_y = r$$

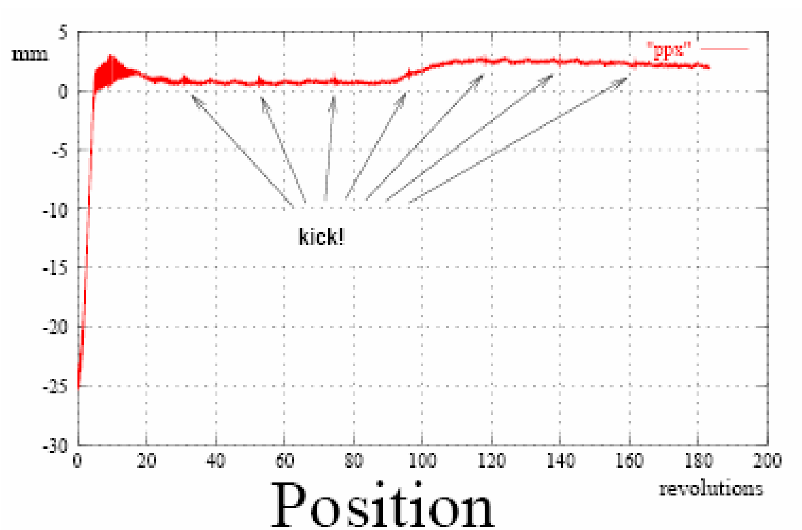
The Sensors

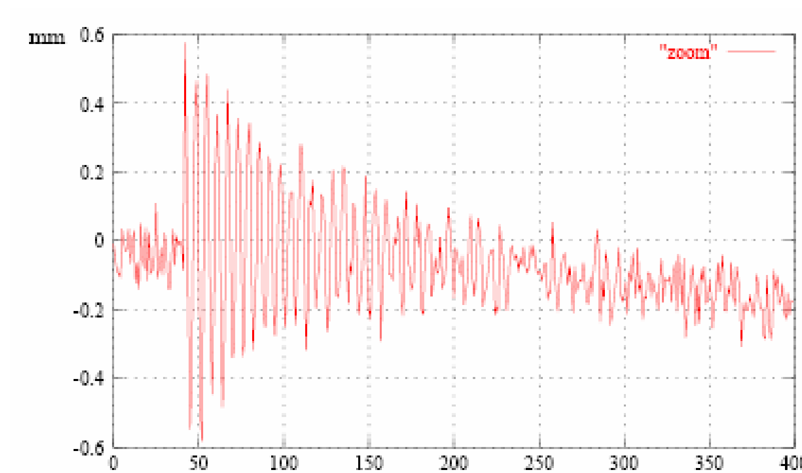
Shoebox pick-up
with linear cut



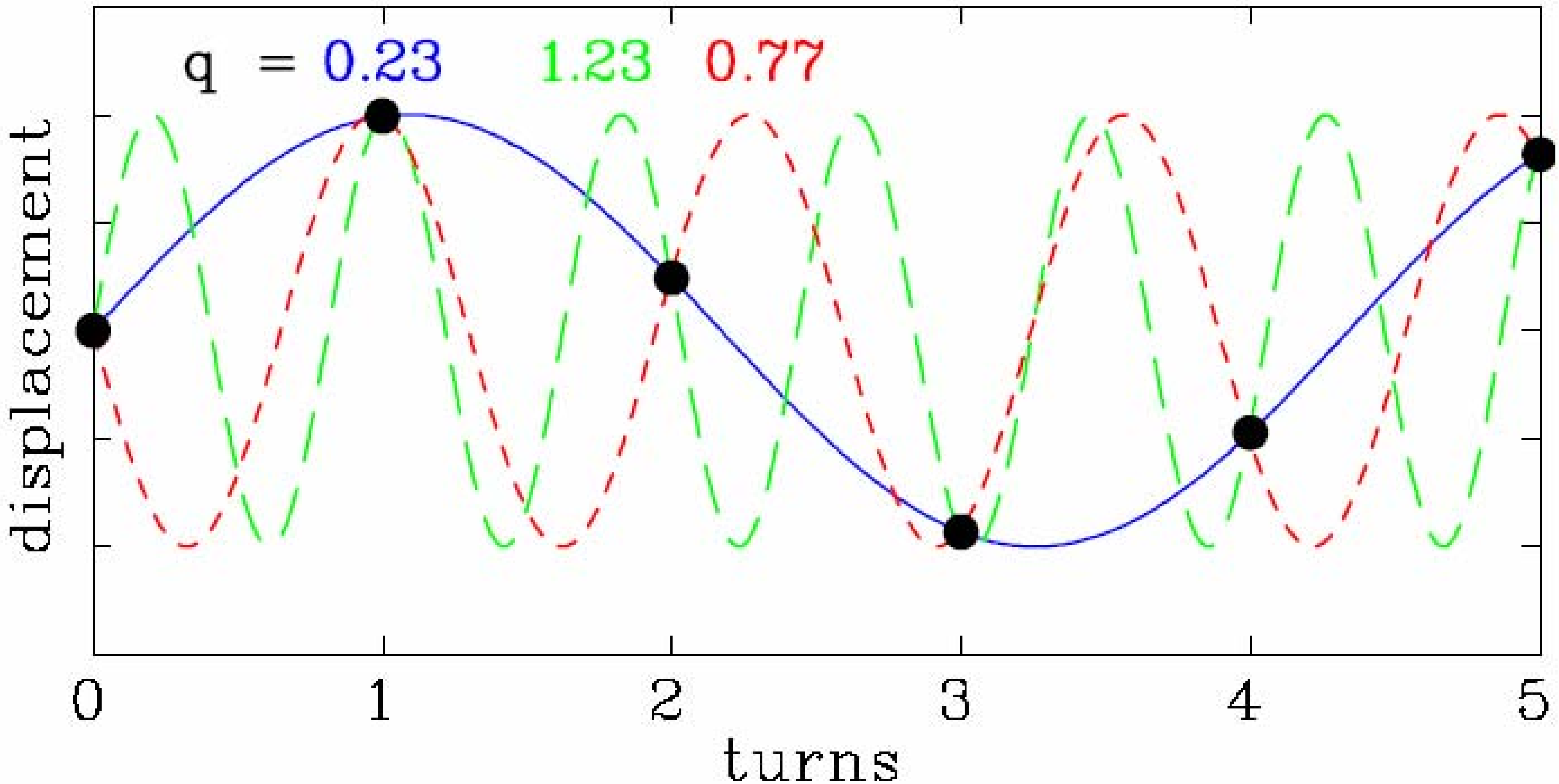


The kicker





Tune measurements with a single PU



Calculating the tune

- Kick the beam in short intervals (min. 5ms)
- The signal contains (slow) closed orbit variations due to acceleration which must be filtered out (BOSS = Beam Orbit Signal Suppressor)
- Signal contains the mode-frequencies:
- The integer part is constant

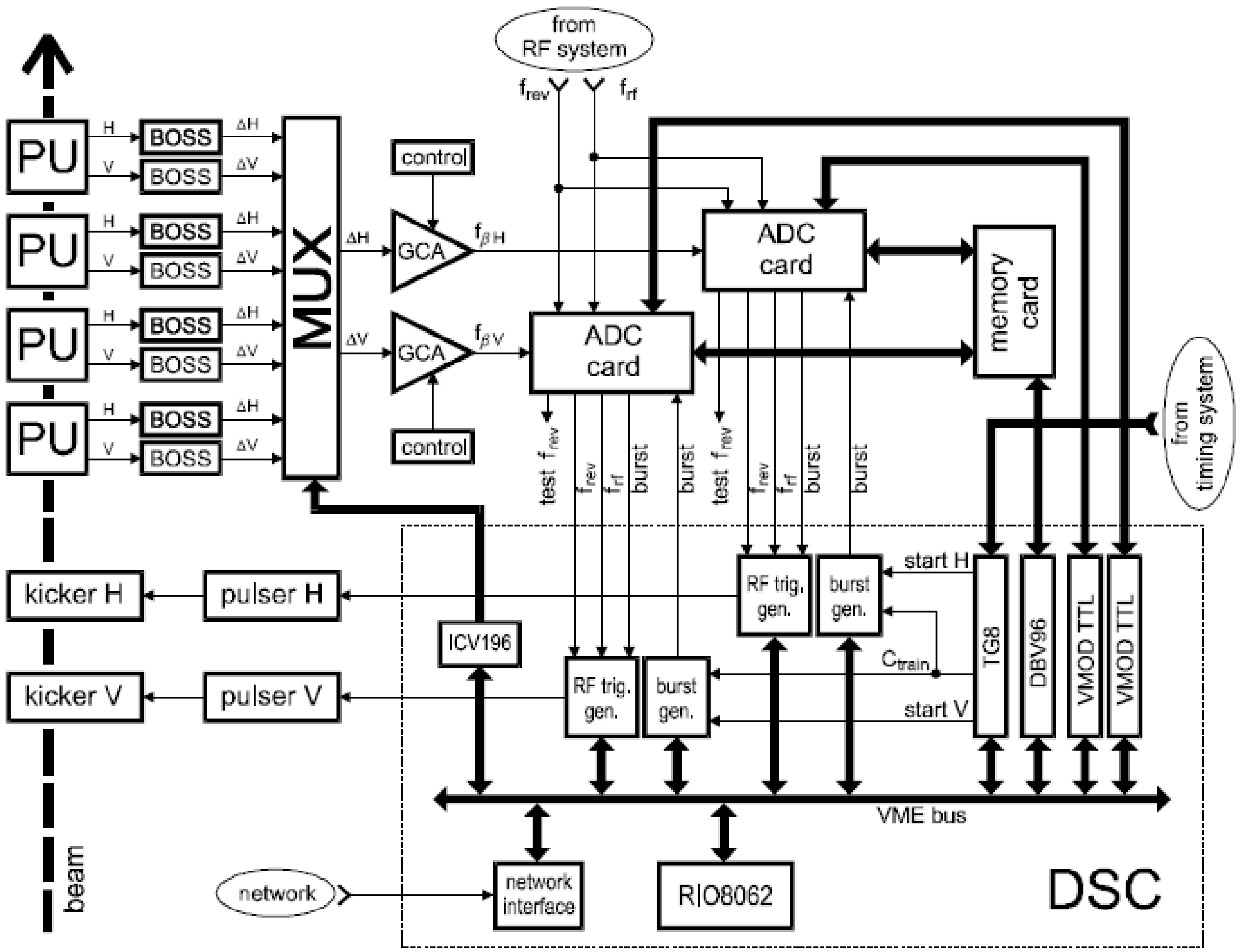
$$f_\beta = (m \pm Q)\, f_{rev}$$

- F_{rev} changes during acceleration =>
  digitize the signal with F_{rev} and perform FFT analysis

$$q = k_s \frac{n_\beta}{N}$$

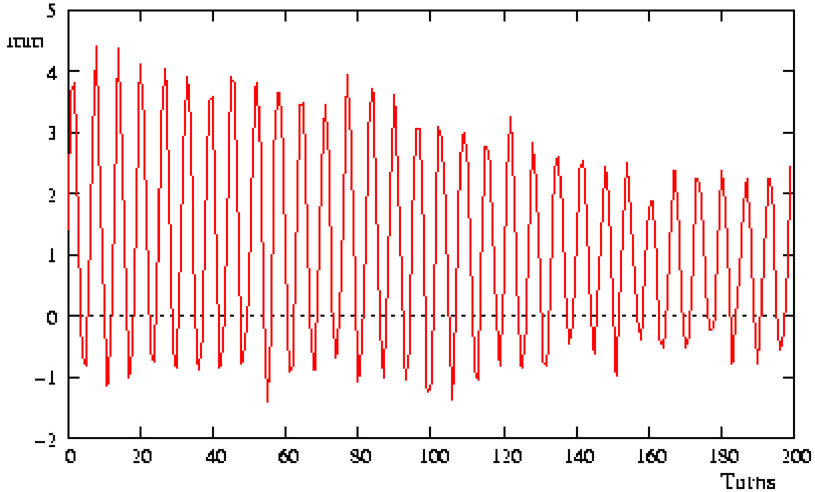
- DFT assumes that data constitutes a cycle in a periodic system
  Use windowing to avoid discontinuities when periodically extending the signal
- Peak find routine
- Interpolation to increase precision of Q value
- Digital treatment must be finished within 5 ms

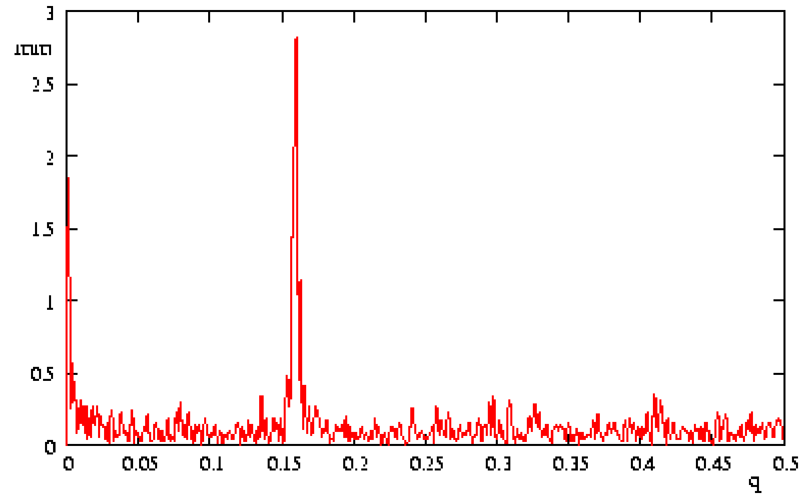
The Acquisition Electronics



Kicker + 1 pick-up

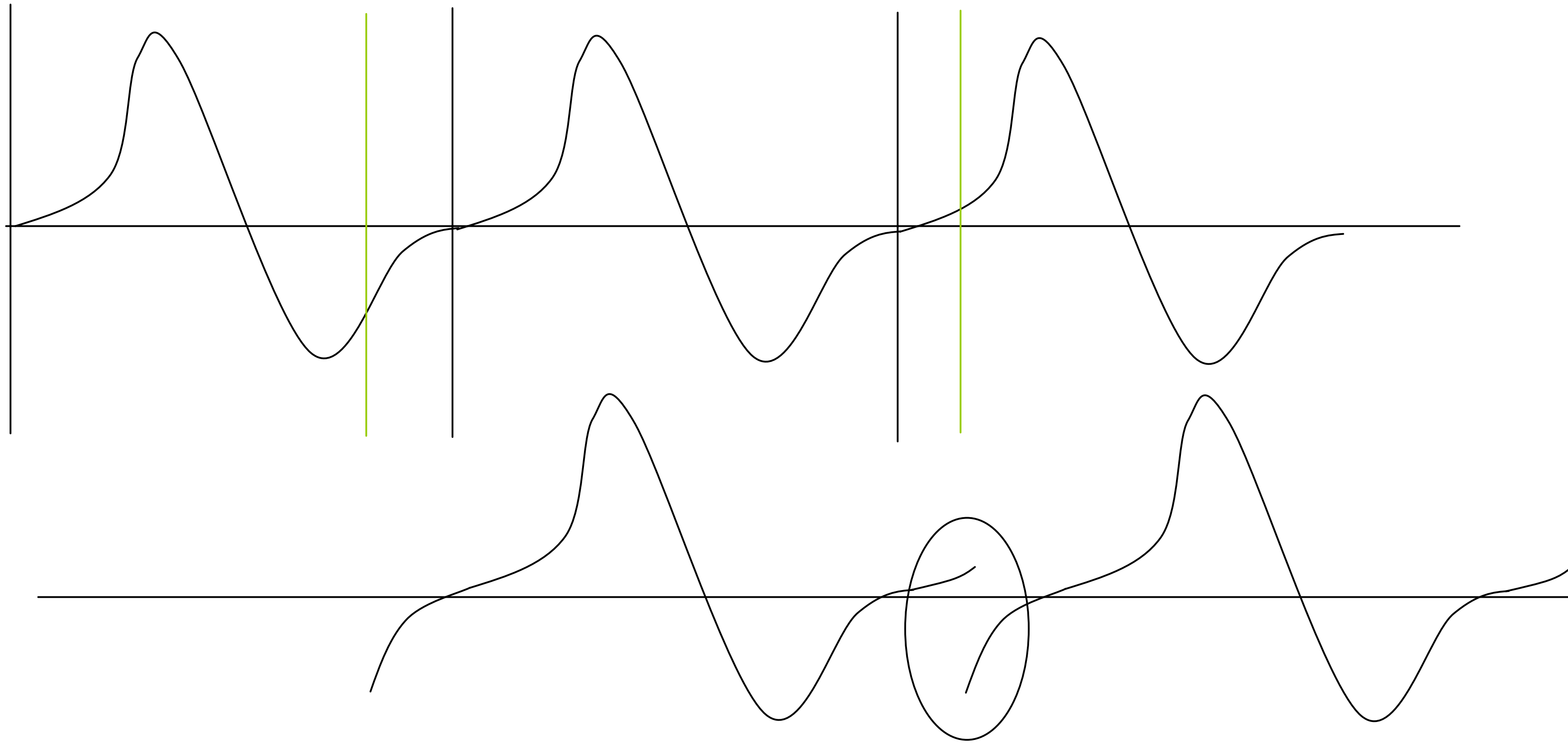
- Measures only non-integral part of Q
- Measure a beam position at each revolution





Fourier transform of pick-up signal

Periodic extension of the signal and Windowing



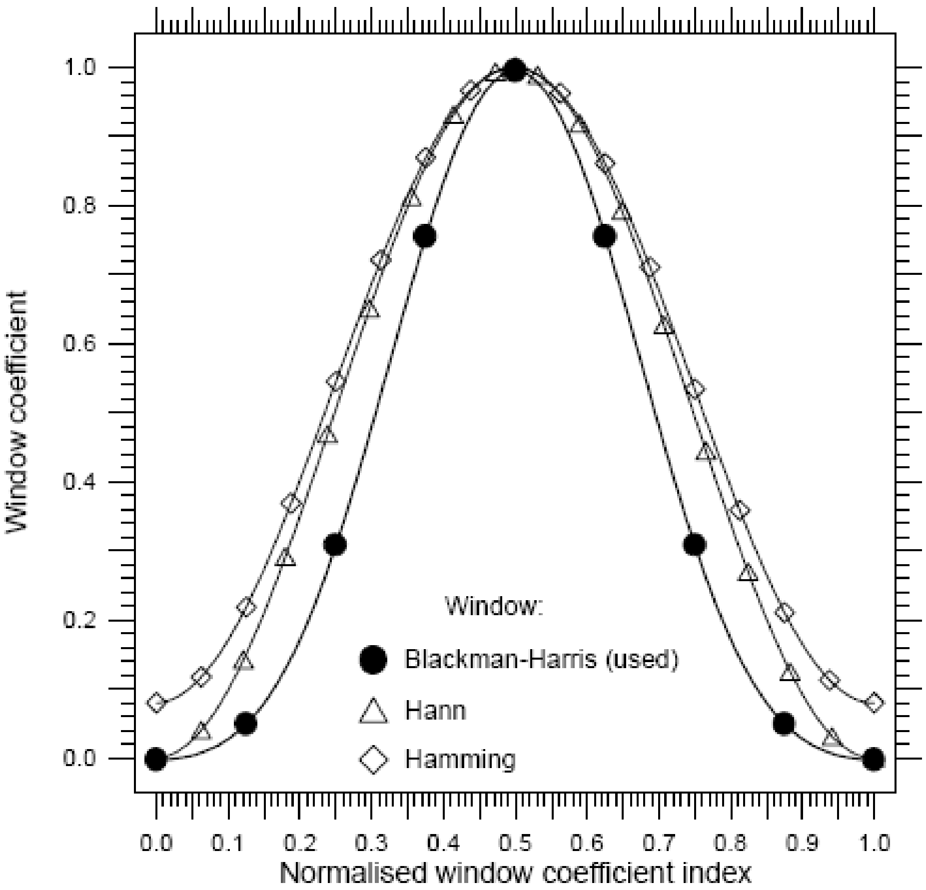
Windowing

The Discrete Fourier assumes one cycle of a repetitive signal.

Blackman-Harris Window is used

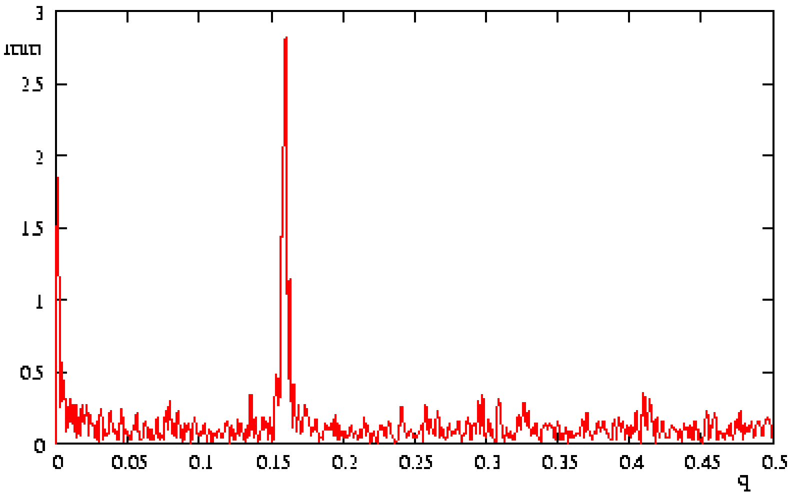
Each sample is multiplied with a coefficient

Coefficients are pre-calculated and stored in a table



Peak search algorithm

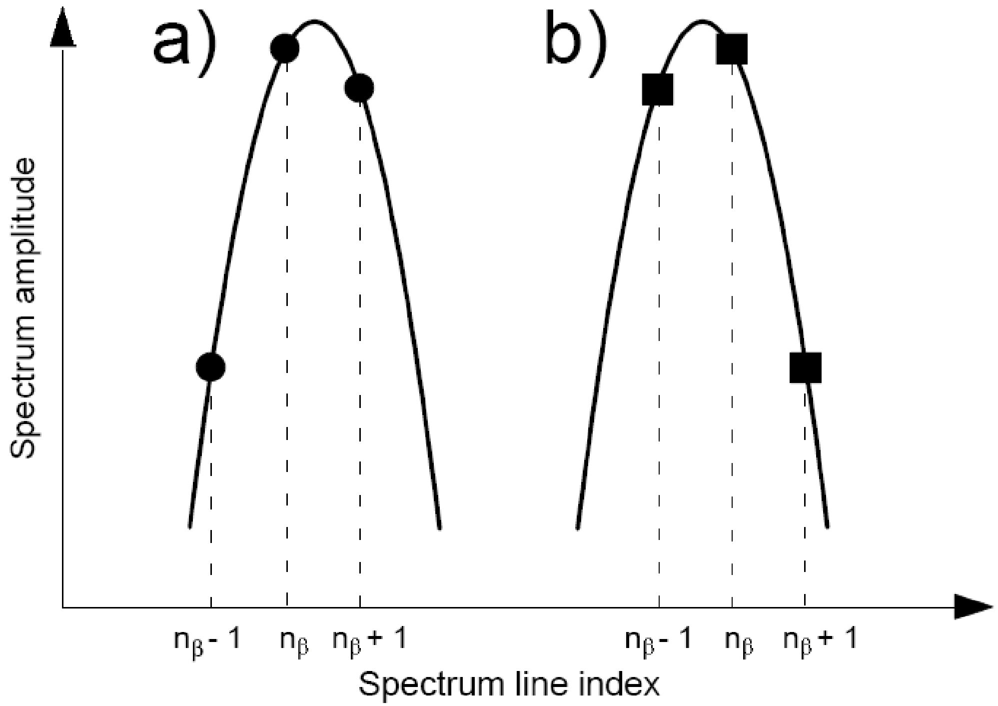
- Power value is bigger than its predecessor
- Power value is bigger than its successor
- Power value is biggest in the whole spectrum
- The power value is at least 3 times bigger than the arithmetic mean of all power bins.



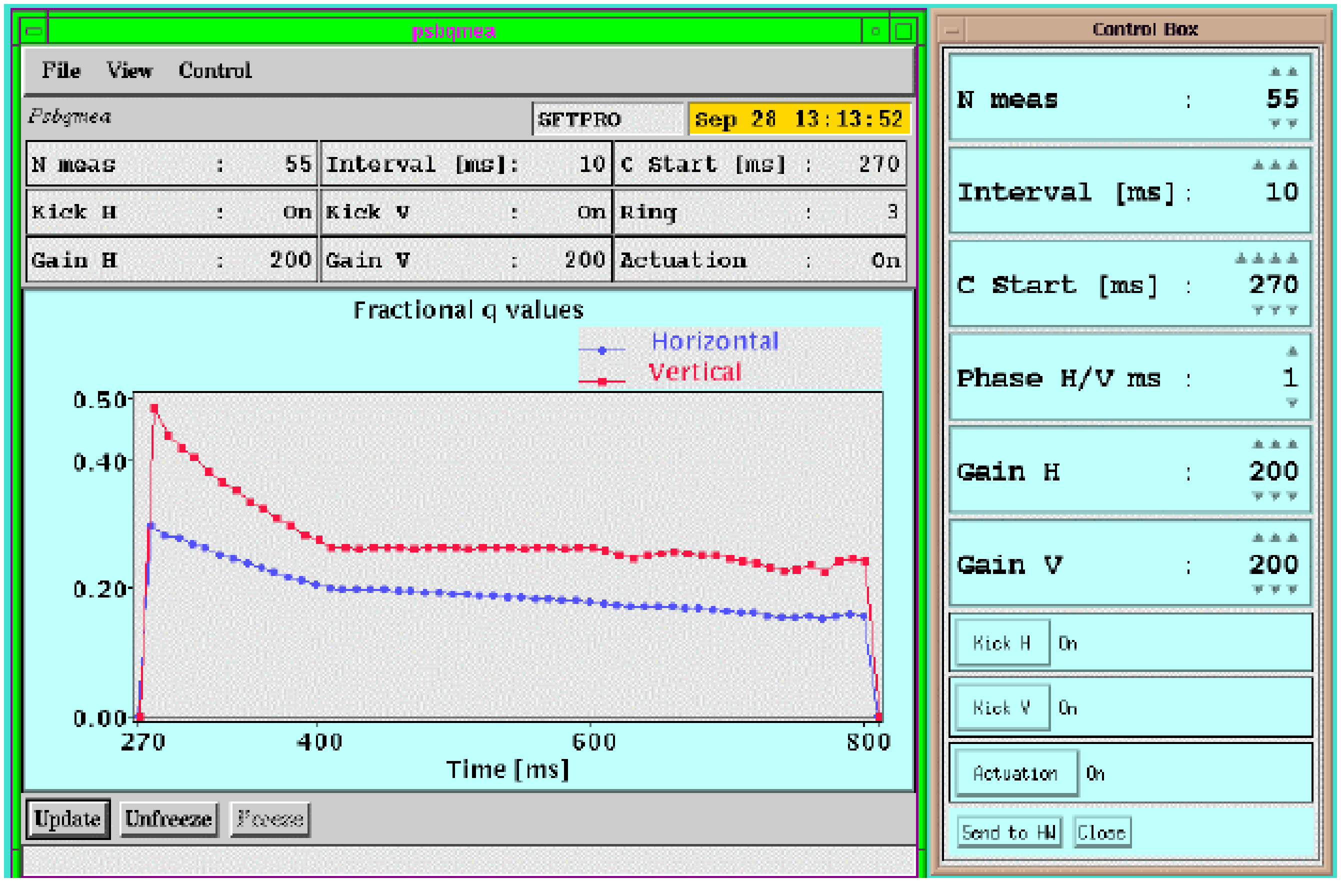
Q interpolation

Betatron signal is not a pure Harmonic but includes rev. freq Harmonics, noise …
The windowing process is not Perfect
Coherent betatron signal is Damped in the time domain

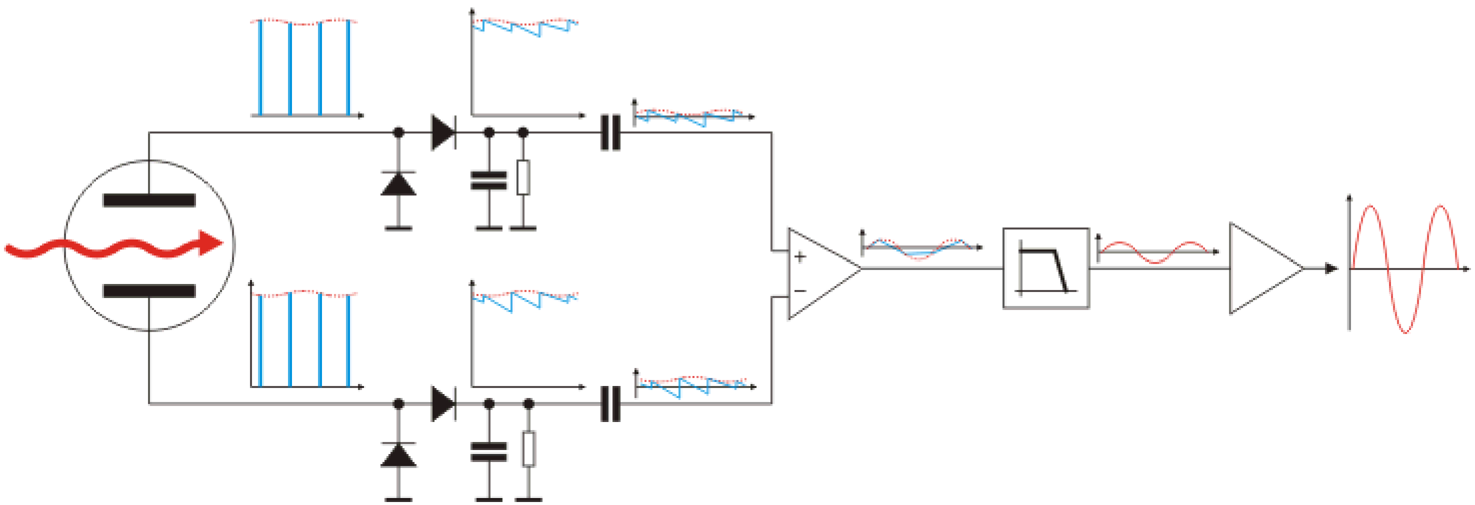
$$V(n_\beta - 1) = a(n_\beta - 1)^2 + b(n_\beta - 1) + c$$
$$V(n_\beta) = a n_\beta^{\ 2} + b n_\beta + c$$
$$V(n_\beta + 1) = a(n_\beta + 1)^2 + b(n_\beta + 1) + c$$



Q-Measurement Results



Improvements



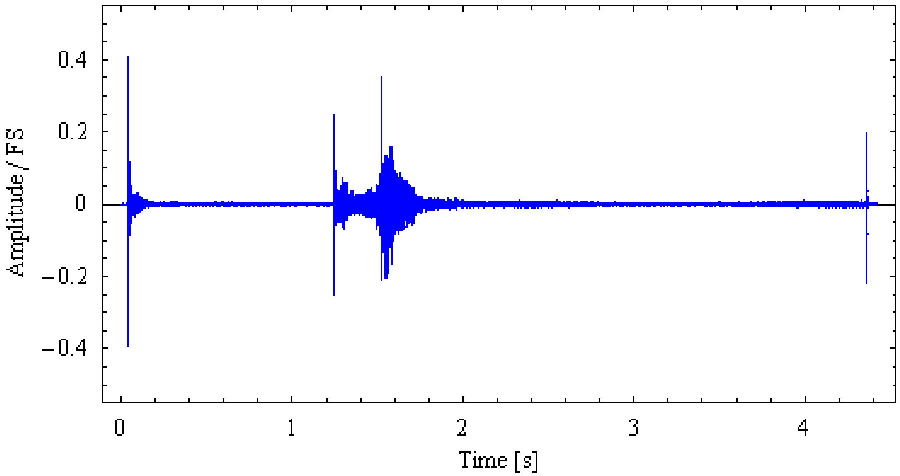
Restrict the power spectrum to smaller bandwidth
Do Fourier Transform on many more sampled values
(use algorithm in FPGA to get the necessary speed)
Measure coupling between planes

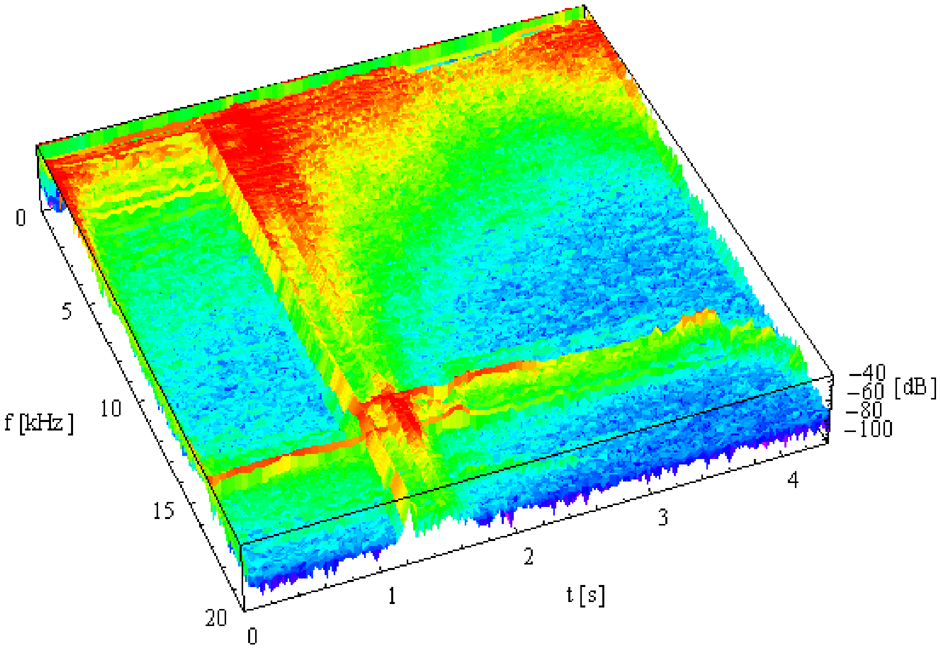
Results of Q measurements from the CERN SPS

Measurements without excitation

Waterfall model of Fourier spectra

Raw data





Trajectory and Orbit measurements

Definitions:

Trajectory: The mean positions of the beam during 1 turn

Orbit: The mean positions over many turns for each of the BPMs

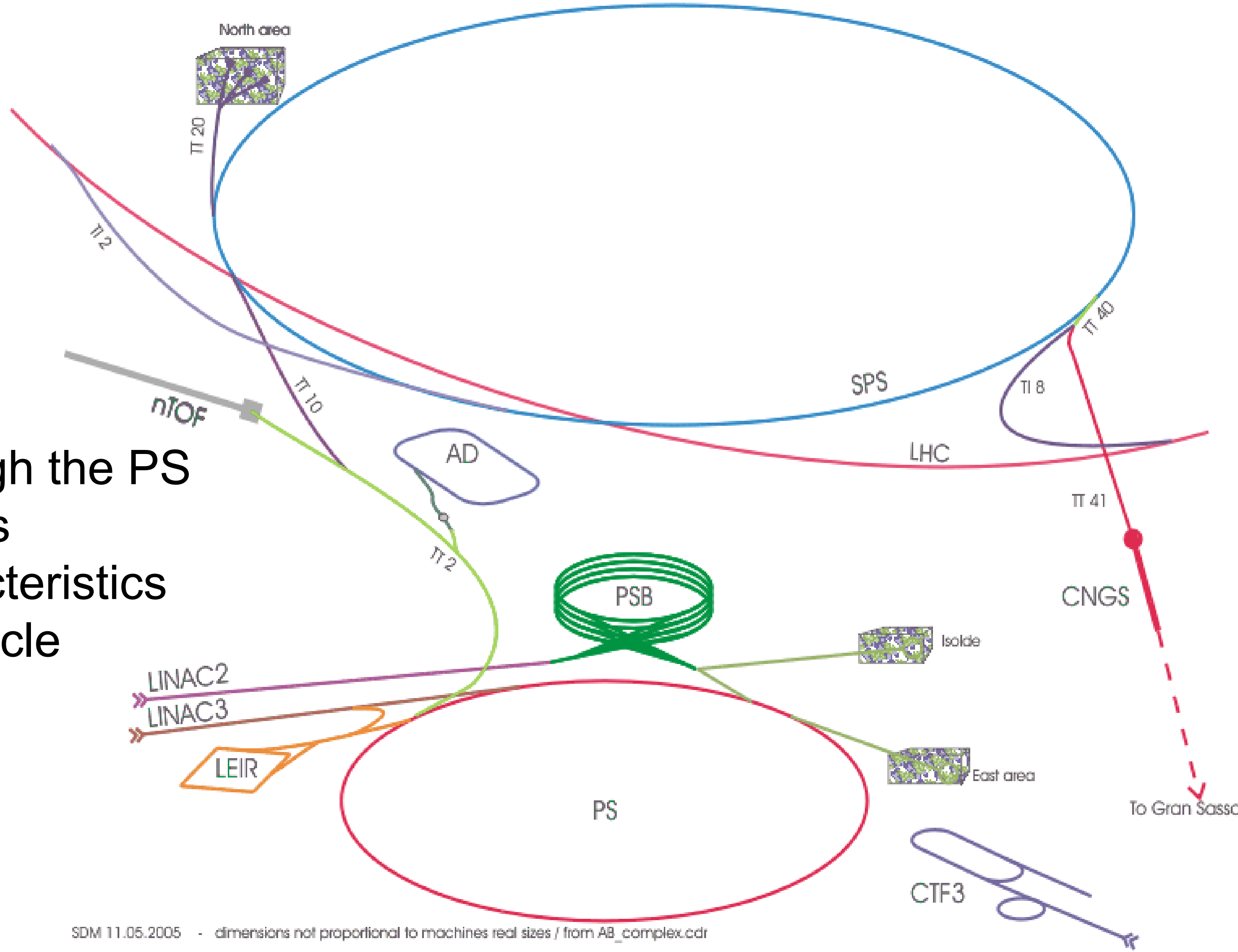
The trajectories must be controlled at injection, ejection, transition

Closed orbits may change during acceleration or RF "gymnastics"

The PUs

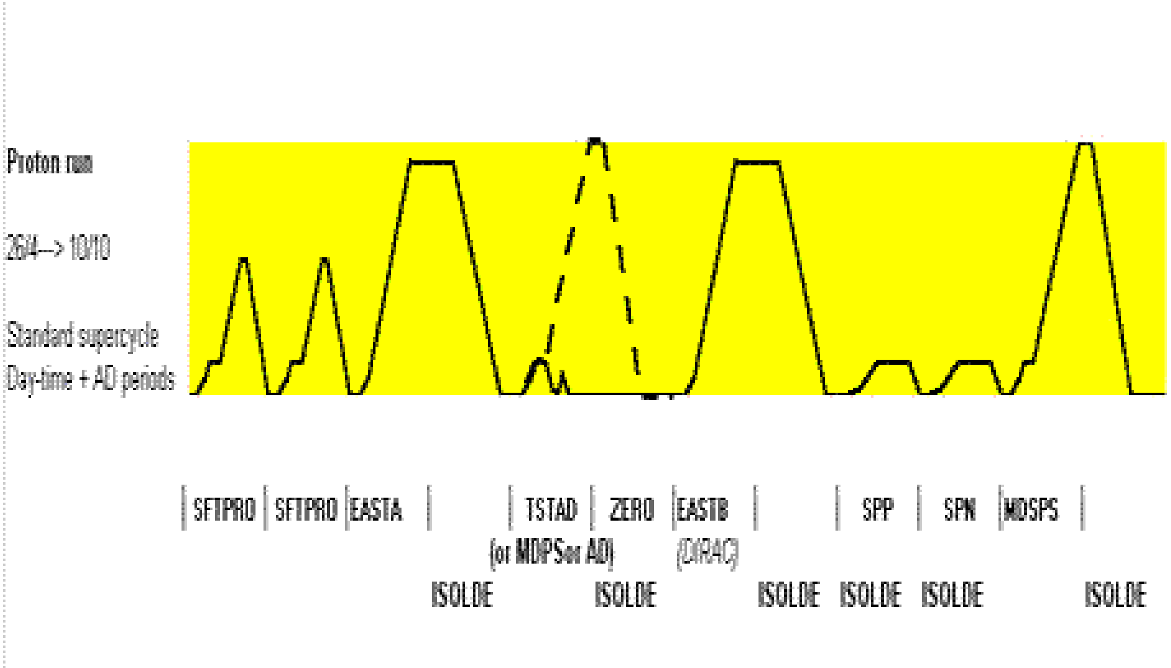

TT70
East hall
Booster
CB
TT2
Y
North hall
LEIR
Linac II
South hall

The PS, a universal machine

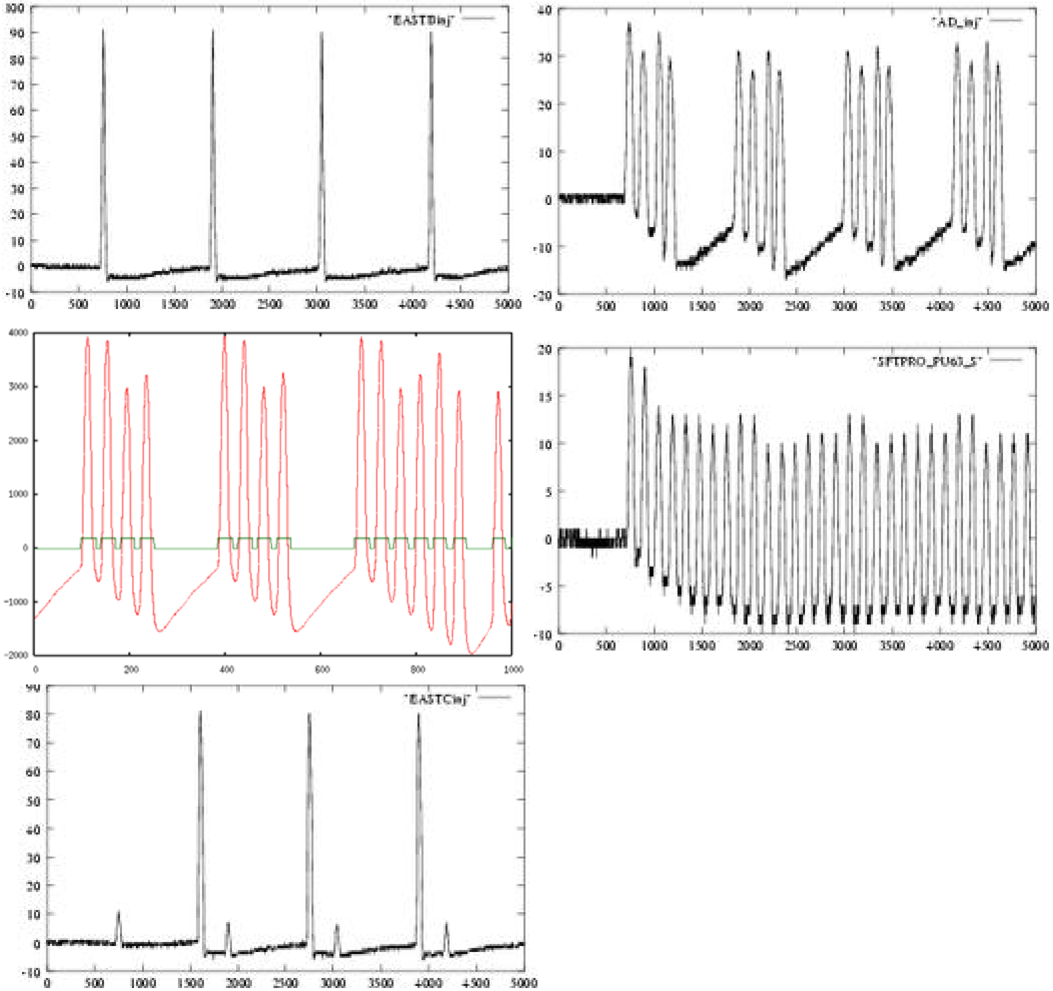


All beams pass through the PS
Different particle types
Different beam characteristics
Concept of a super cycle

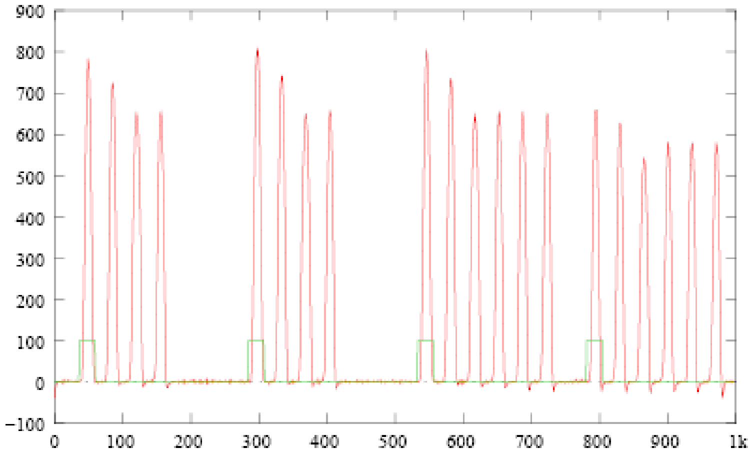
The super cycle



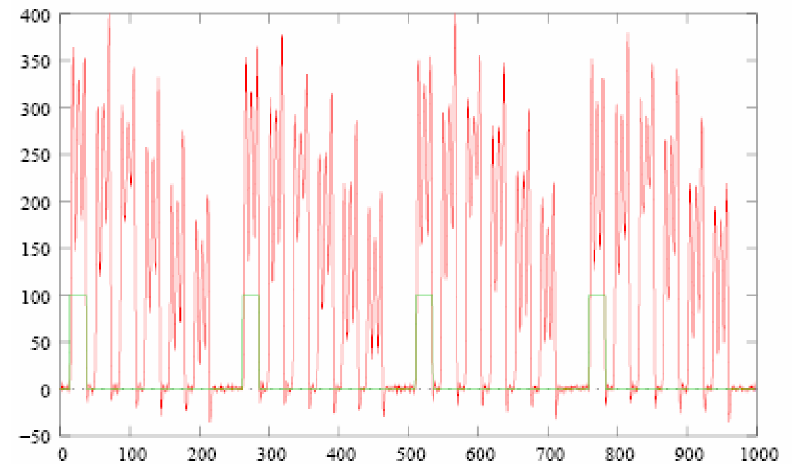
Beams in the PS



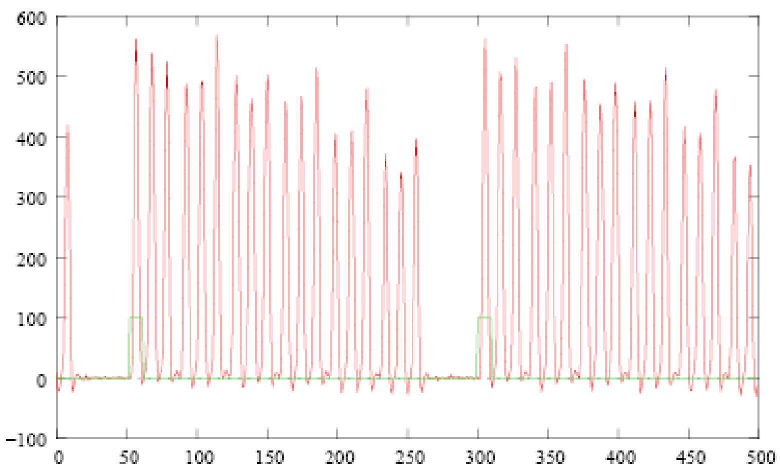
RF Gymnastics



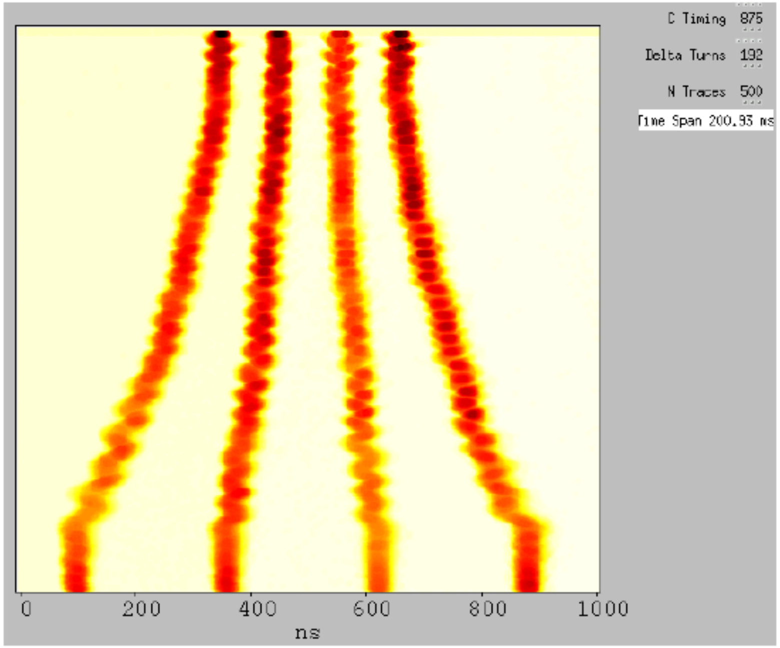
Example of generated gate around 2^{nd} injection

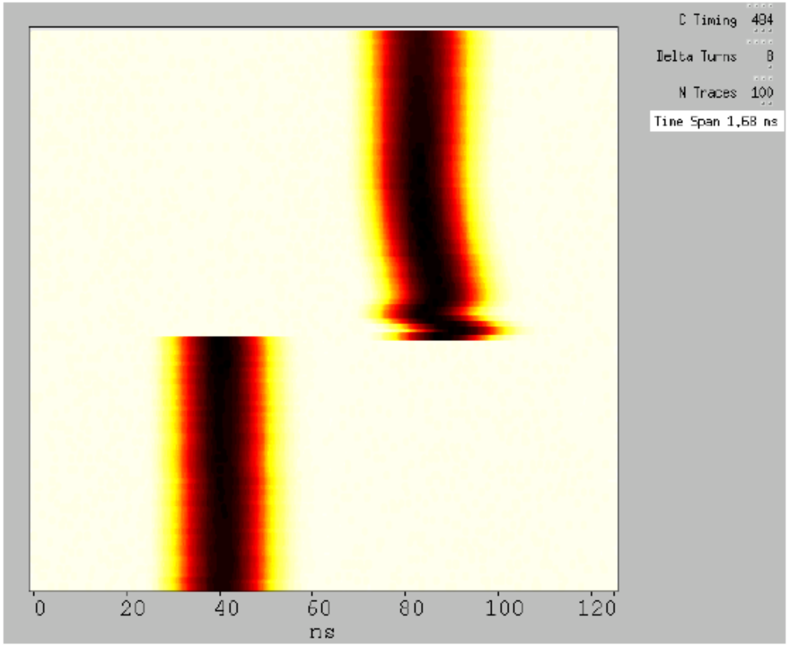


Idem, during bunch splitting



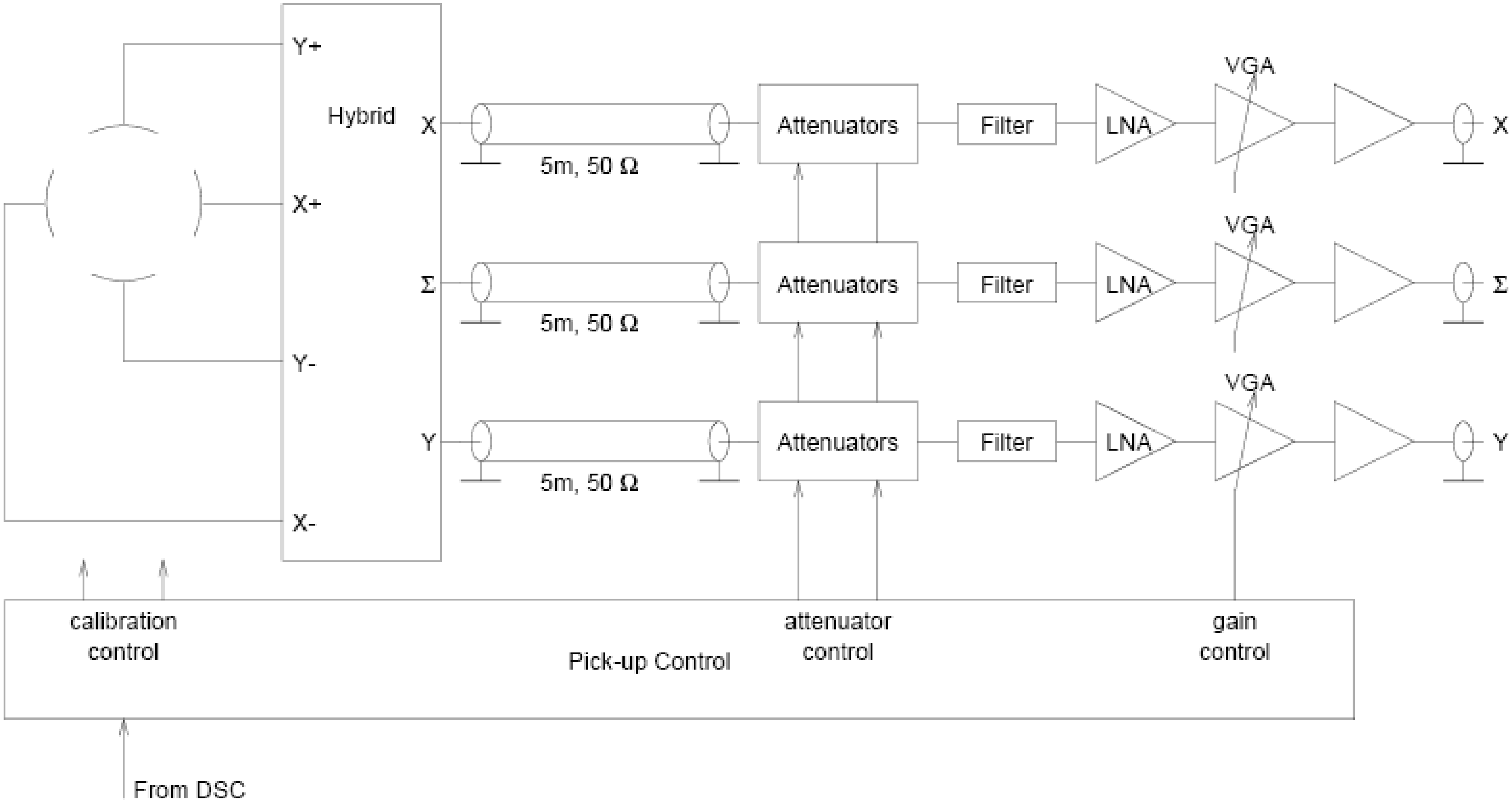
More RF changes



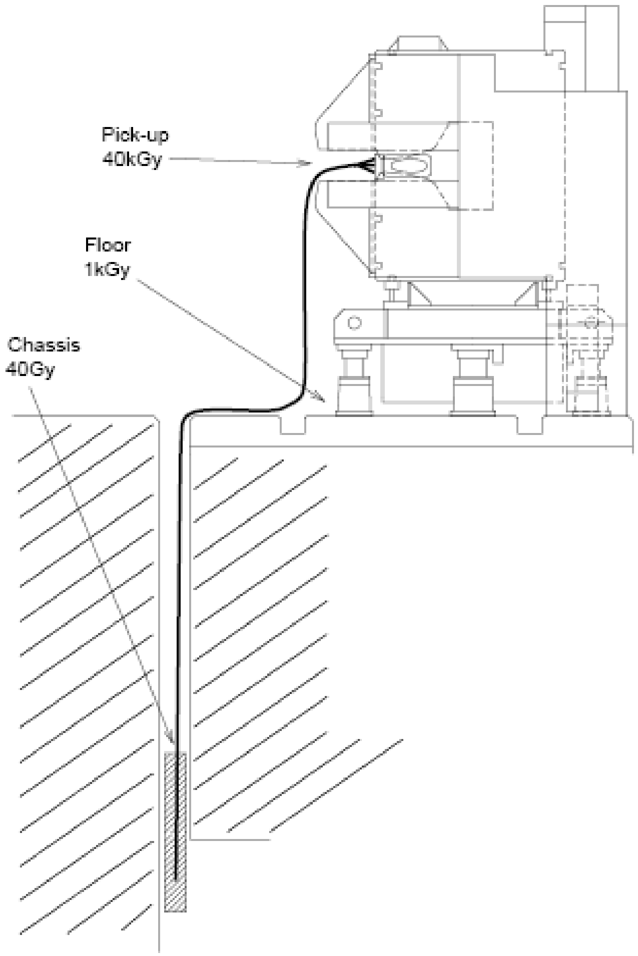


The AD beam is first equally distributed along the PS ring but then squeezed together By changing the harmonic in steps 8,10,12,… 20

Analogue signal treatment



Radiation problems

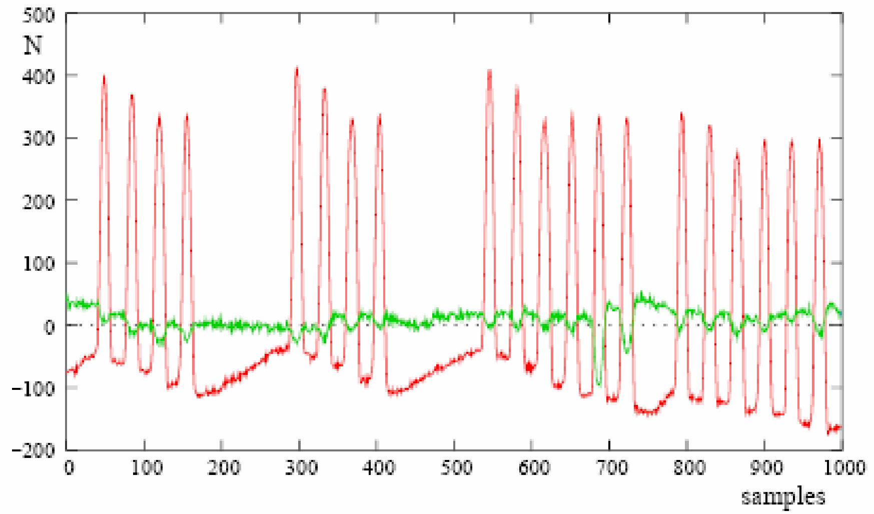


Radiation Levels:
40 kGy/y at 1.3 m
1kGy/y on the floor
40 Gy/y in the gap

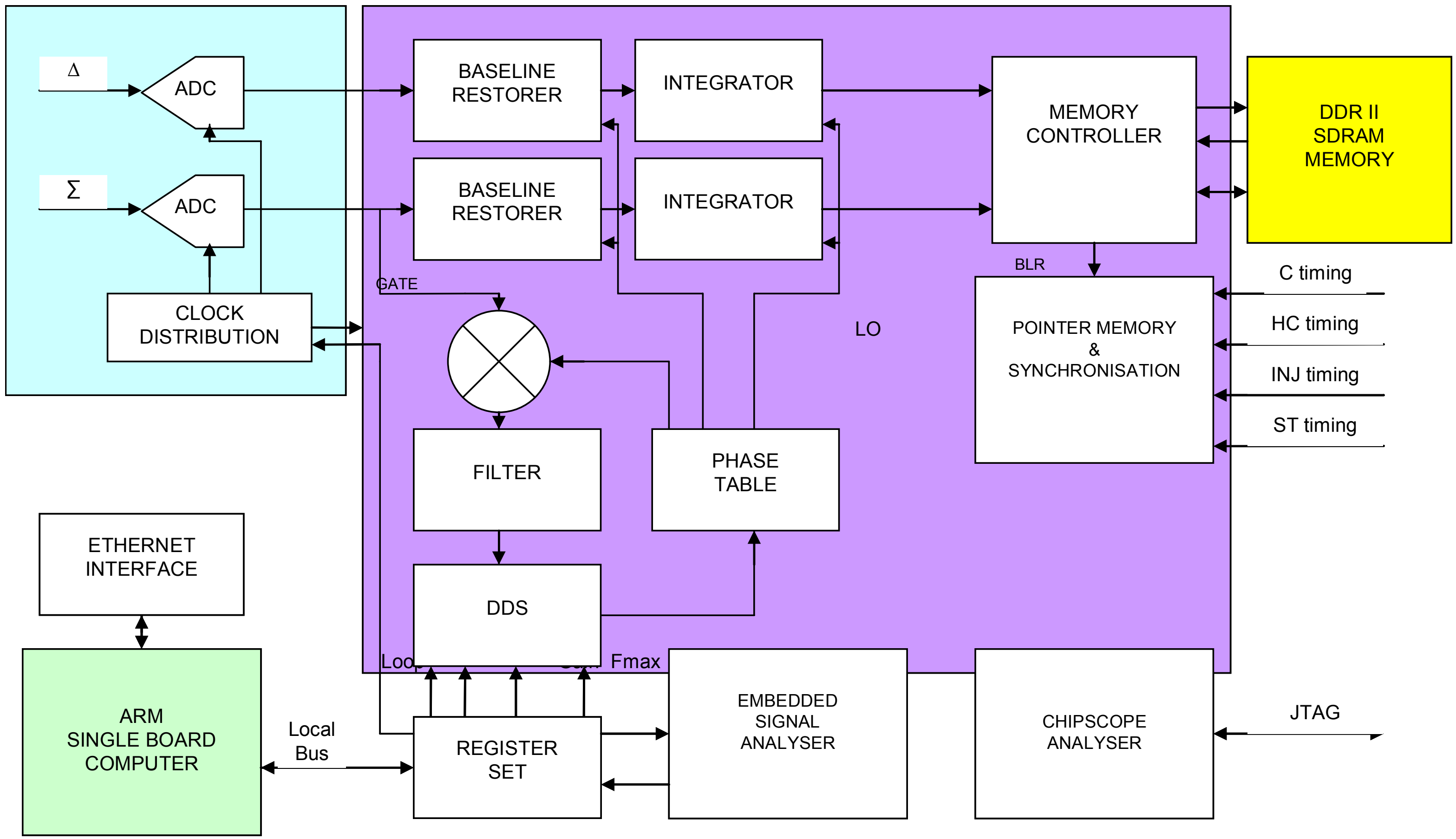
Calculating the position

Red: The sum signal
Green: The difference signal

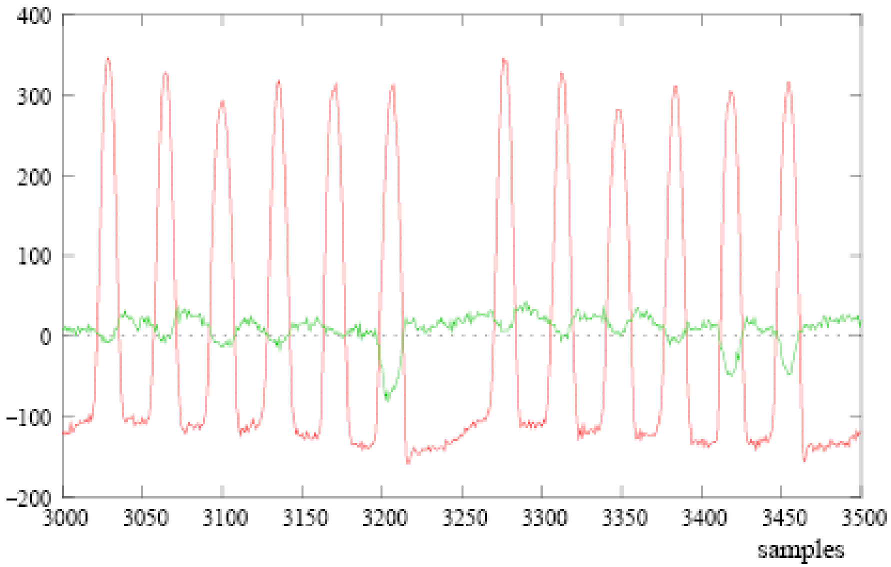
Procedure:
Produce integration gates and
Baseline signals
Baseline correct both signals
Integrate sum and difference signals
and store results in memory
Take external timing events into
account e.g. harmonic number
change, γ-transition etc.

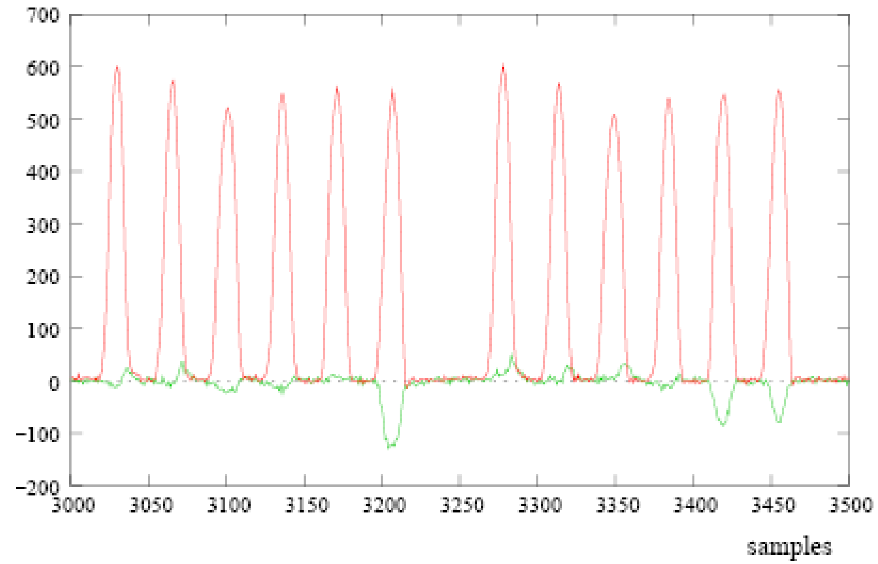


Trajectory readout electronics



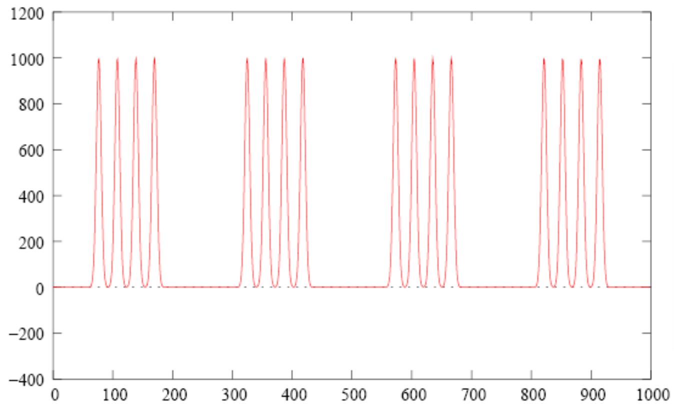
Baseline restoration



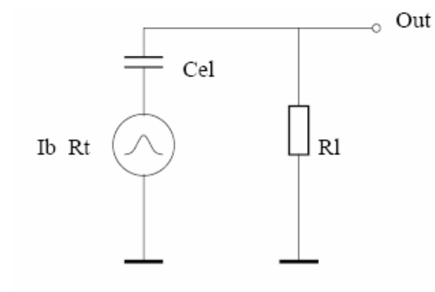


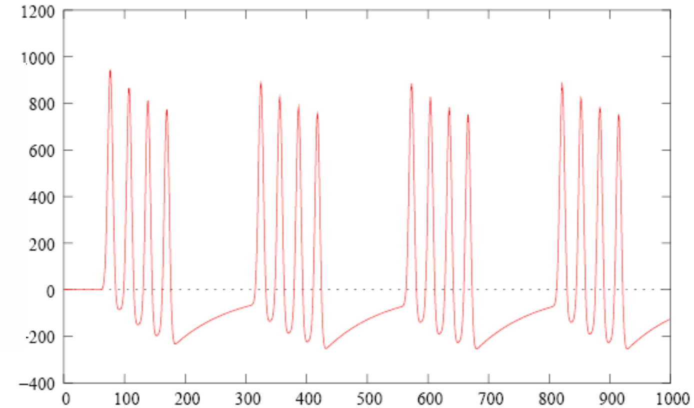
Low pass filter the signal to get an estimate of the base line
Add this to the original signal

Problems with the baseline restorer

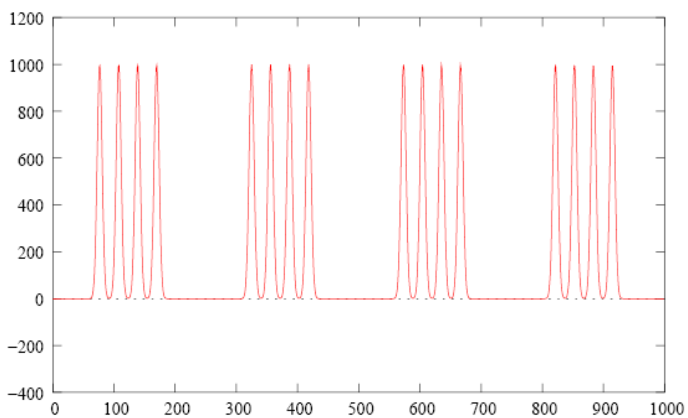


Simulated signal

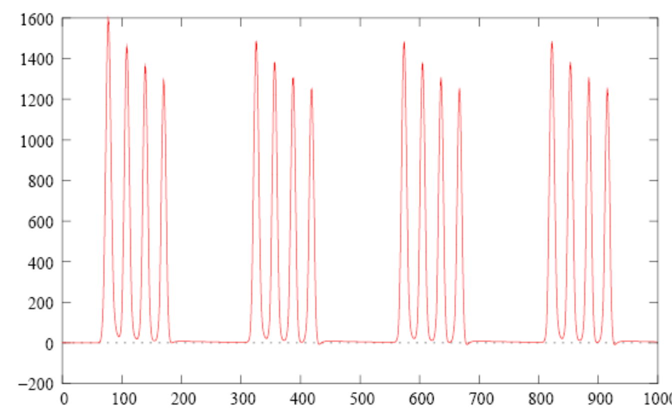




After high pass filter



Expected baseline corrected signal

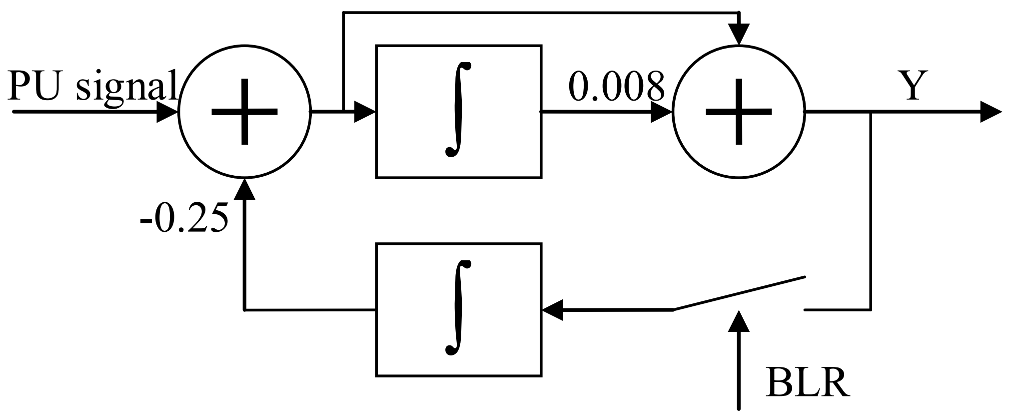


What we get!

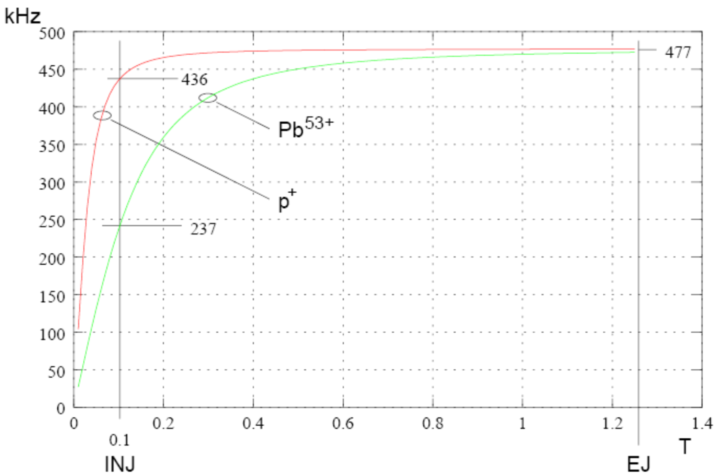
Baseline correction

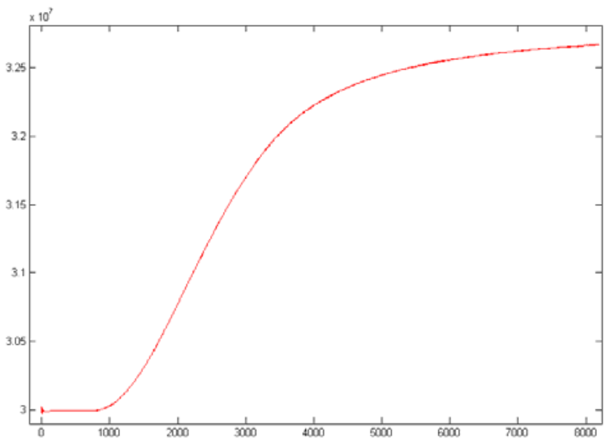
- Capacitive coupling to the beam
- DC is not passed
- The signal is differentiated

- Baseline correction through integration



Following the accelerating frequency





$$F_{rf} = \frac{R_m Q_0 h B}{2\pi R_0 m_p \sqrt{1 + \left\{ \frac{R_m Q_0 B}{m_p c} \right\}^2}}$$

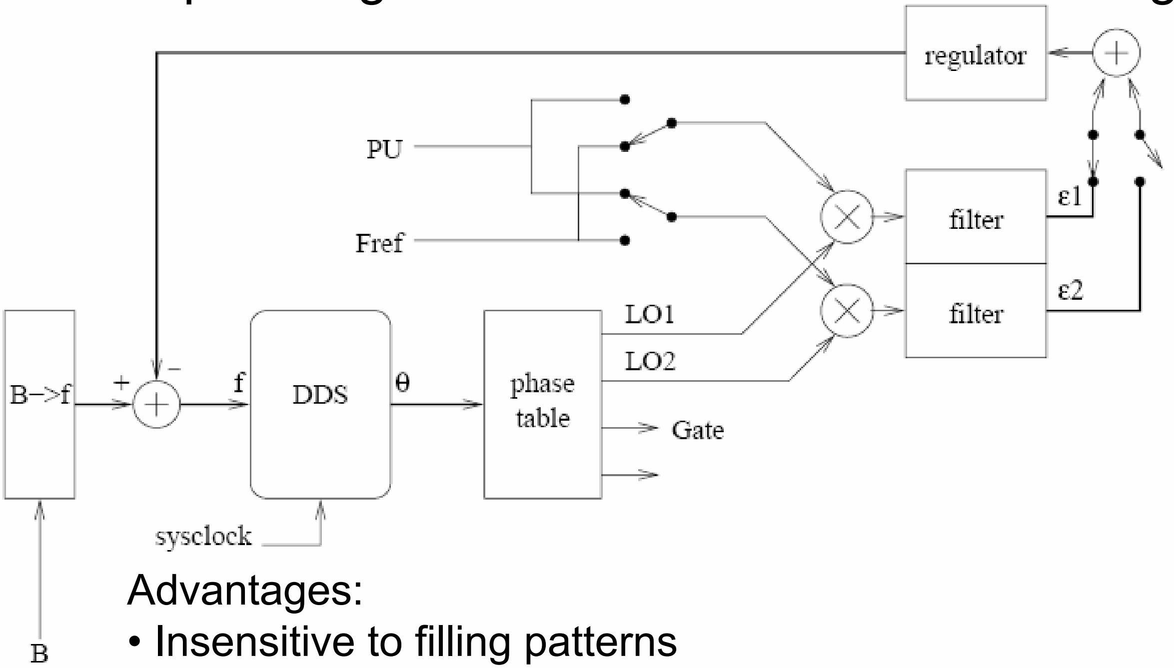
c	speed of light
Q_0	elementary charge
mp	proton mass
R_m	magnetic bending radius
R_0	machine mean orbit radius
h	harmonic number
B	magnetic field

Revolution frequency calculated from the measured gate frequency

Synchronisation

Creating a frequency reference:

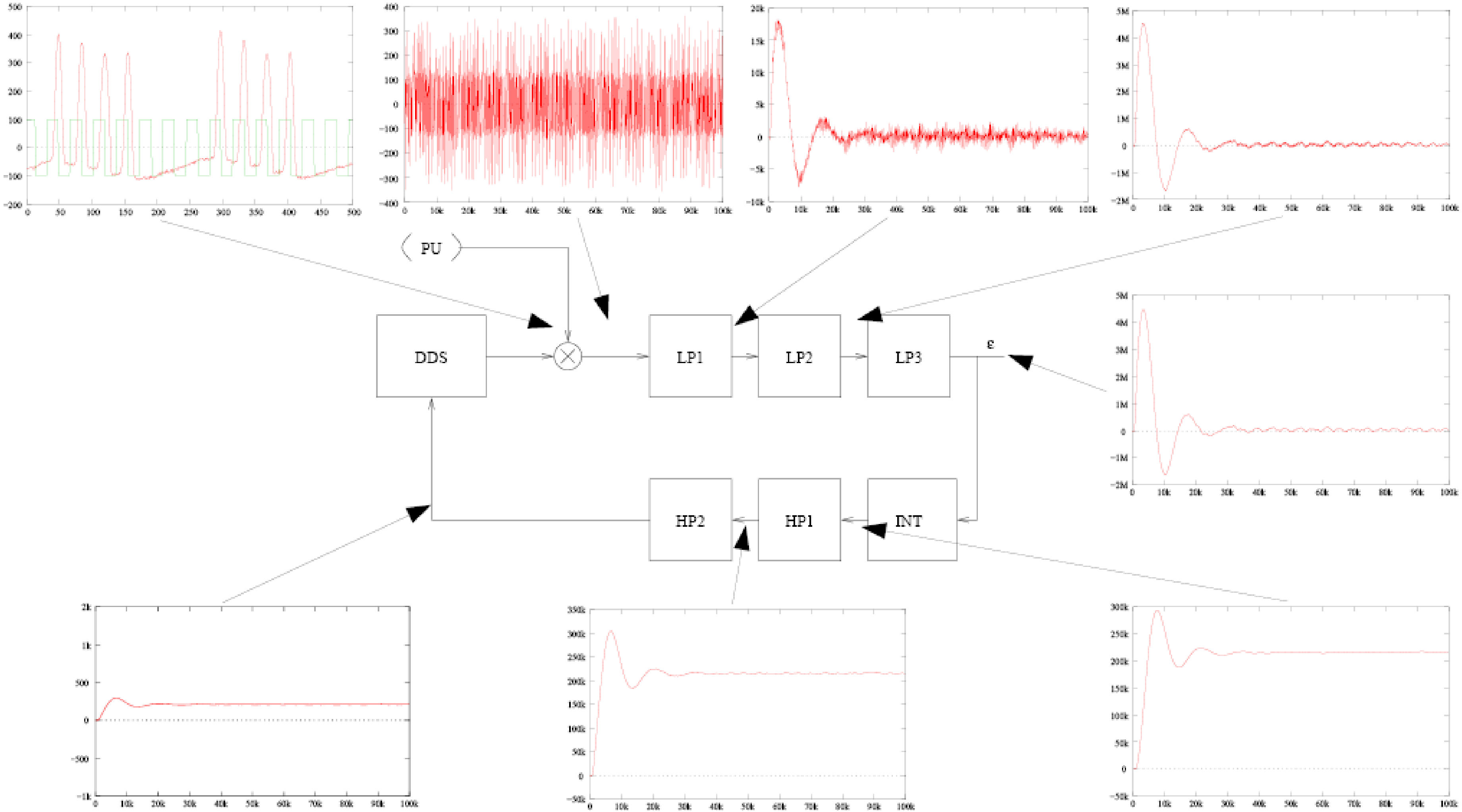
- Numerical PLL
- DDS at F_{rev}
- Lookup table generates local oscillator and integration gate



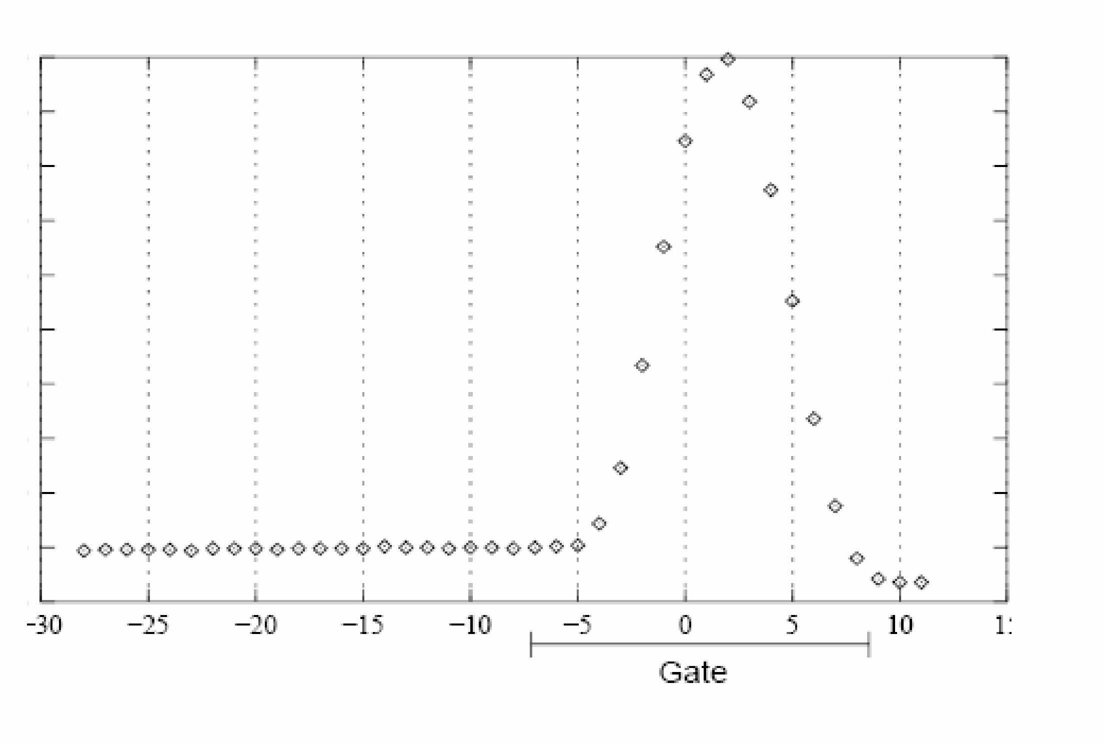
Advantages:

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

Splitting the filter

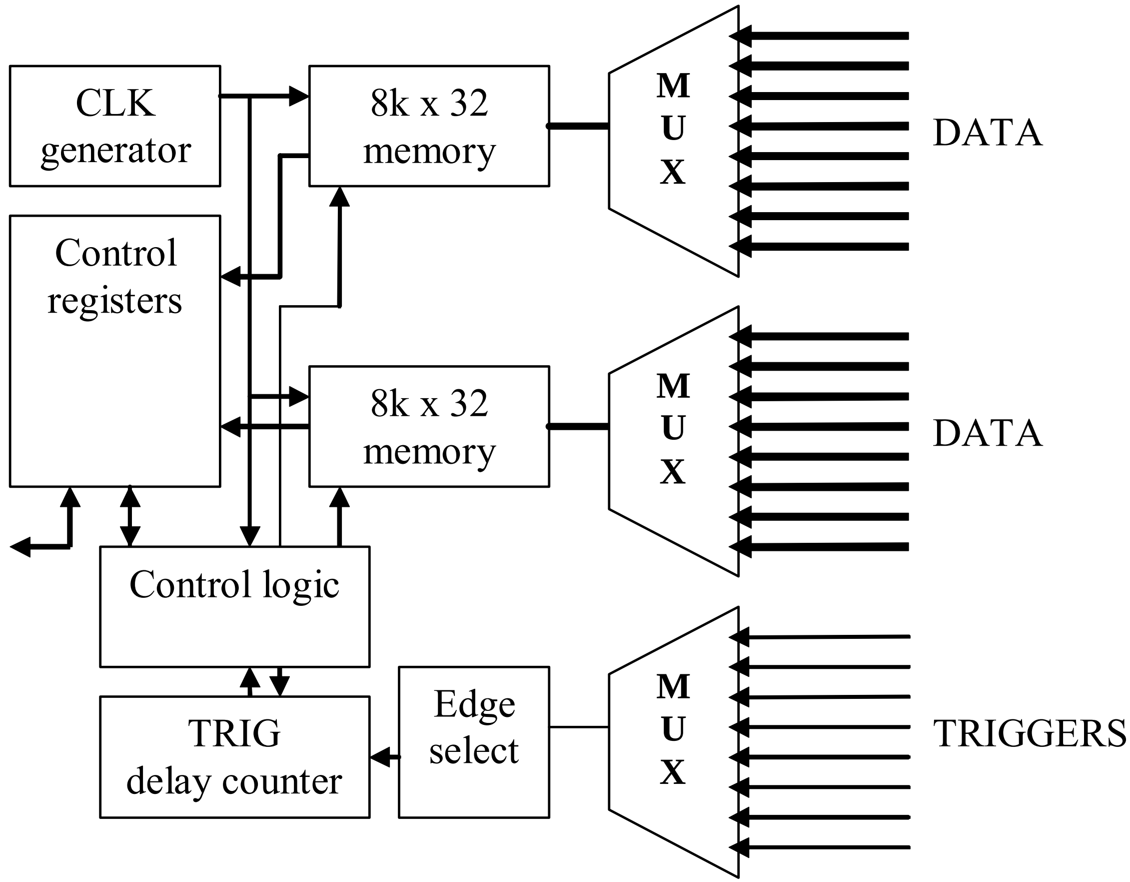


Integration

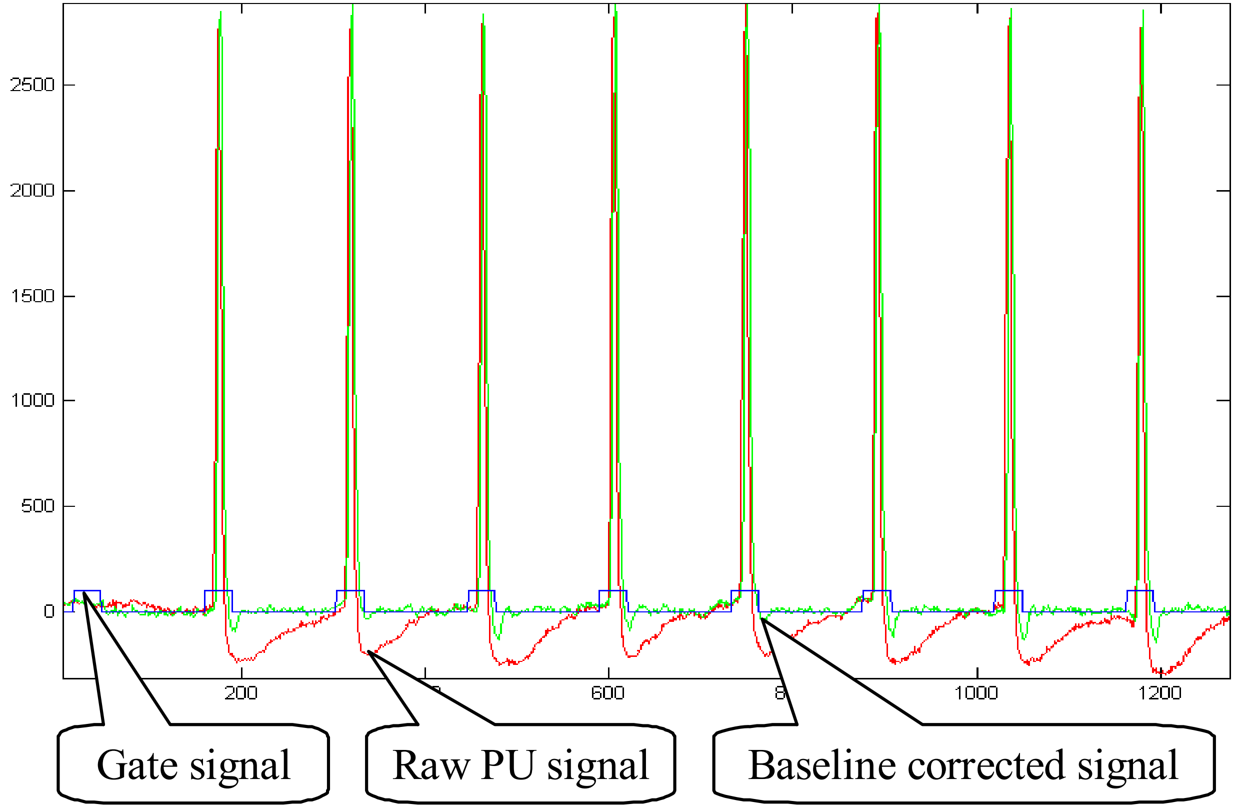


Base line correction is needed to remove sensitivity to gate length
Integration is simple addition of baseline-corrected samples

Embedded logic state analyser

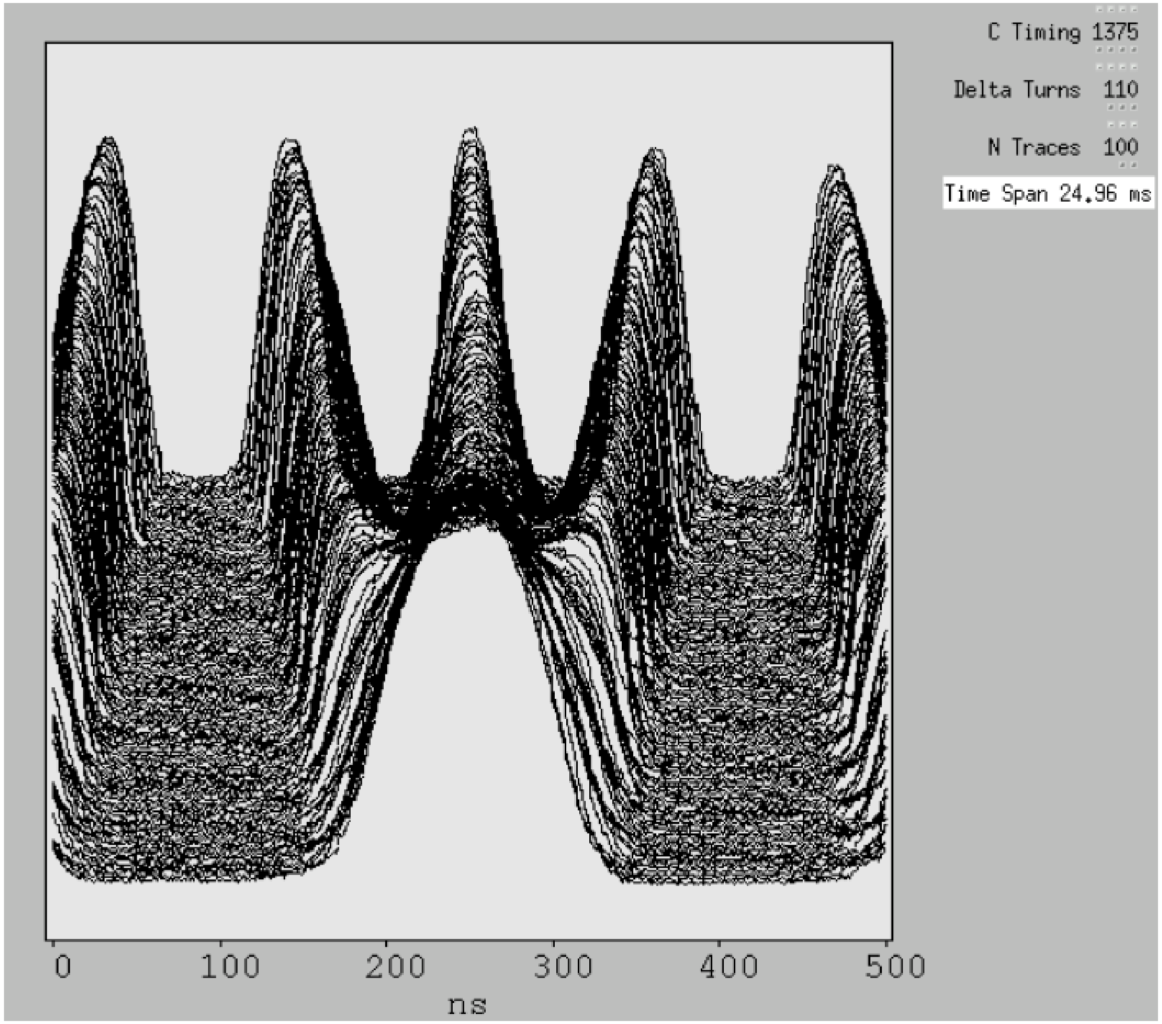


Results from signal treatment

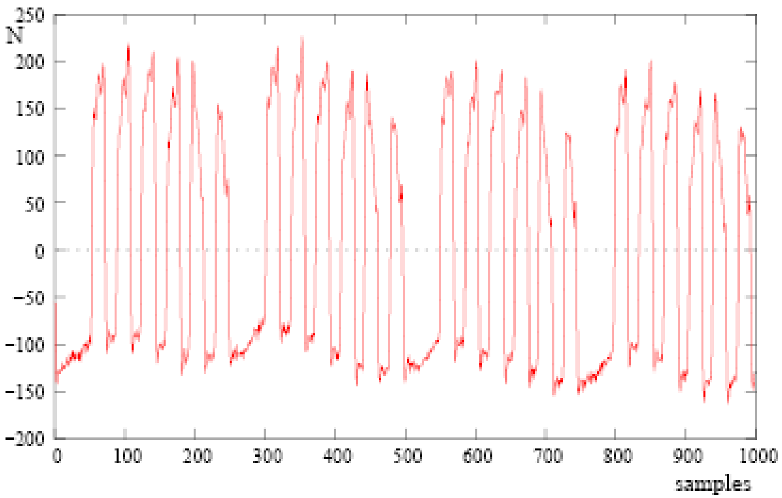


The integration gate is always aligned with the beam pulse

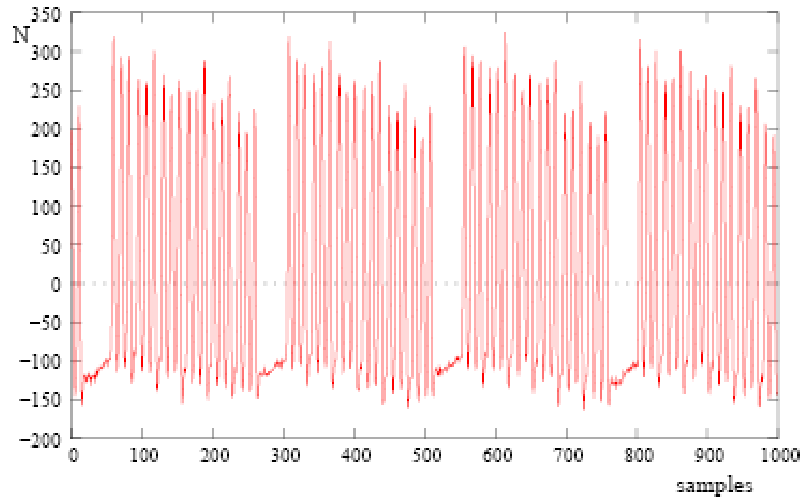
Bunch splitting



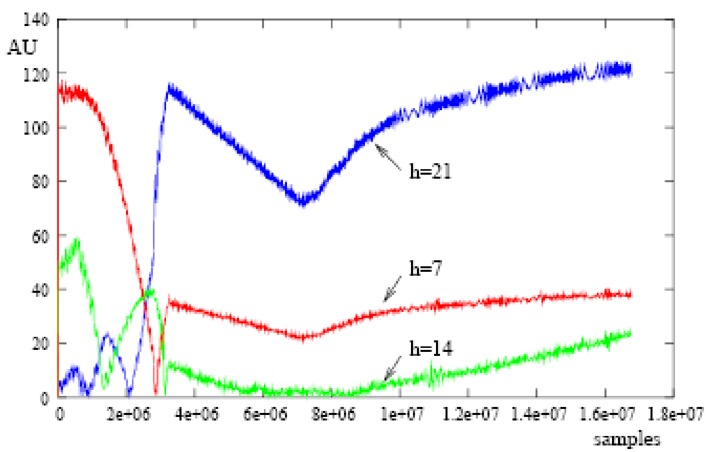
Harmonic number changes



LHC beam at h=7



LHC beam at h=21

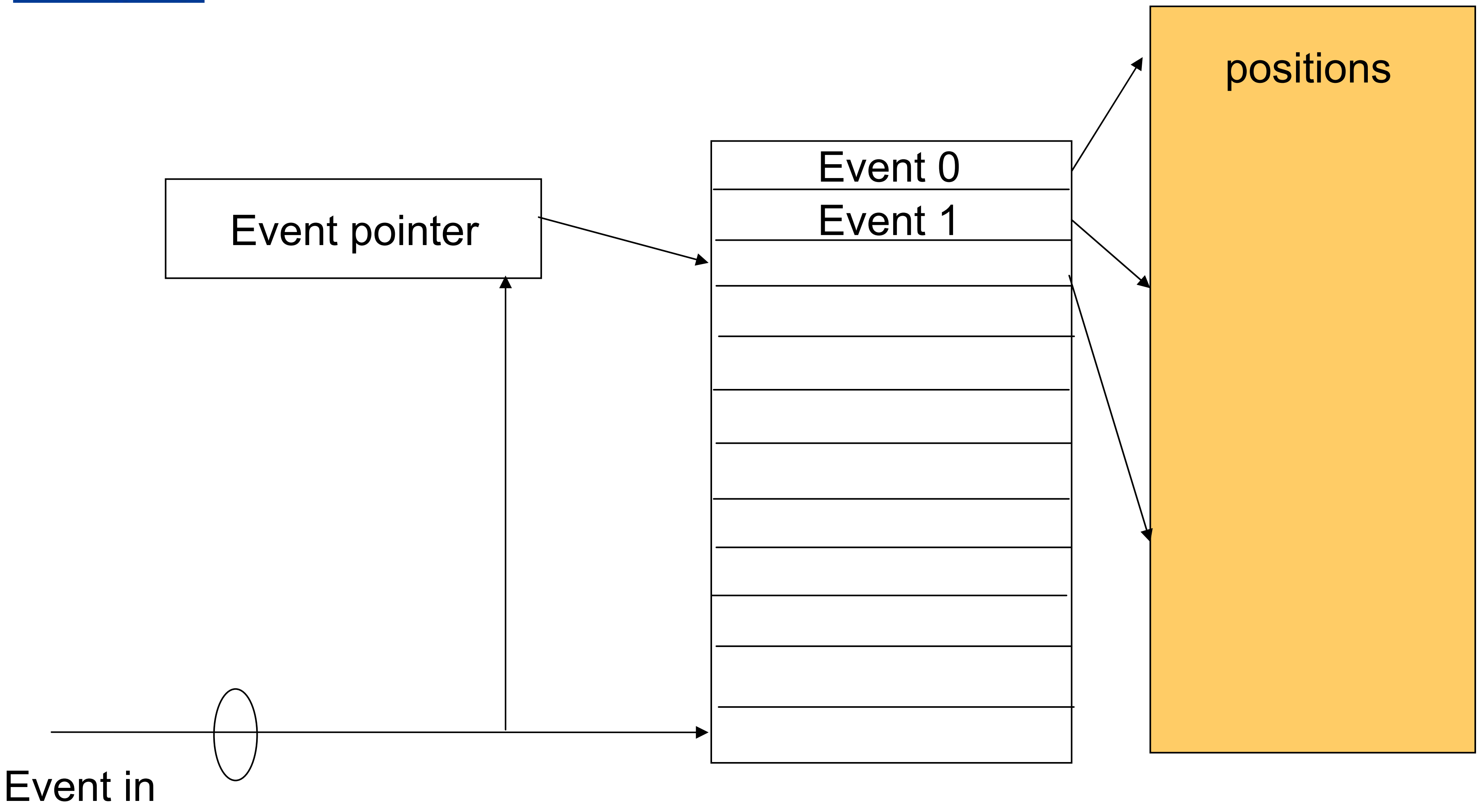


Evolution of magnitude of harmonics on LHC

RF gymnastics in PS have special requirements:

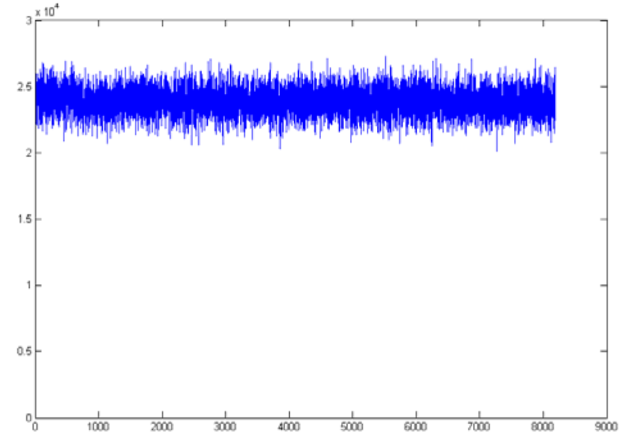
- Choose signal from several possible sources
- Produce several LO harmonic numbers
- Produce appropriate gate timings
- Switch from one to another dynamically
- WITHOUT LOSING LOCK!

External timing

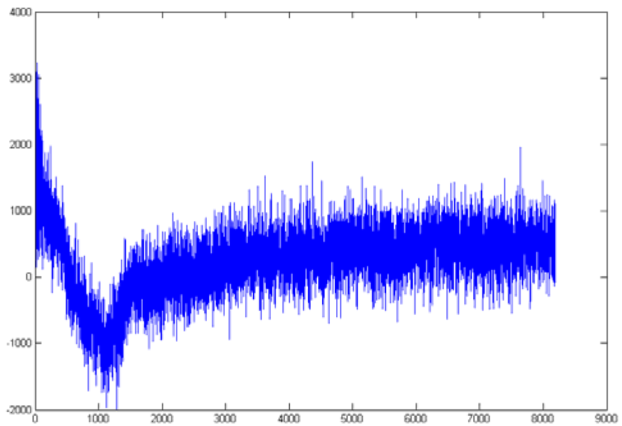


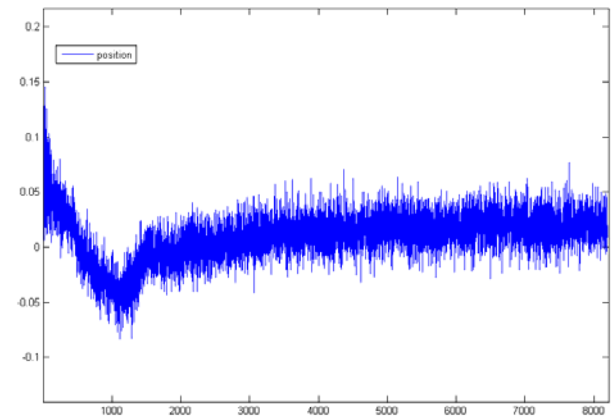
Position calculations

Sum



Difference





Relative position

Problems: Still too much noise
Could be due to
- Not good enough baseline correction
- Too low sampling frequency (60 MHz)
- gate position
- Fixed point algorithms