Digital Signal processing in Beam Diagnostics

Lecture 2

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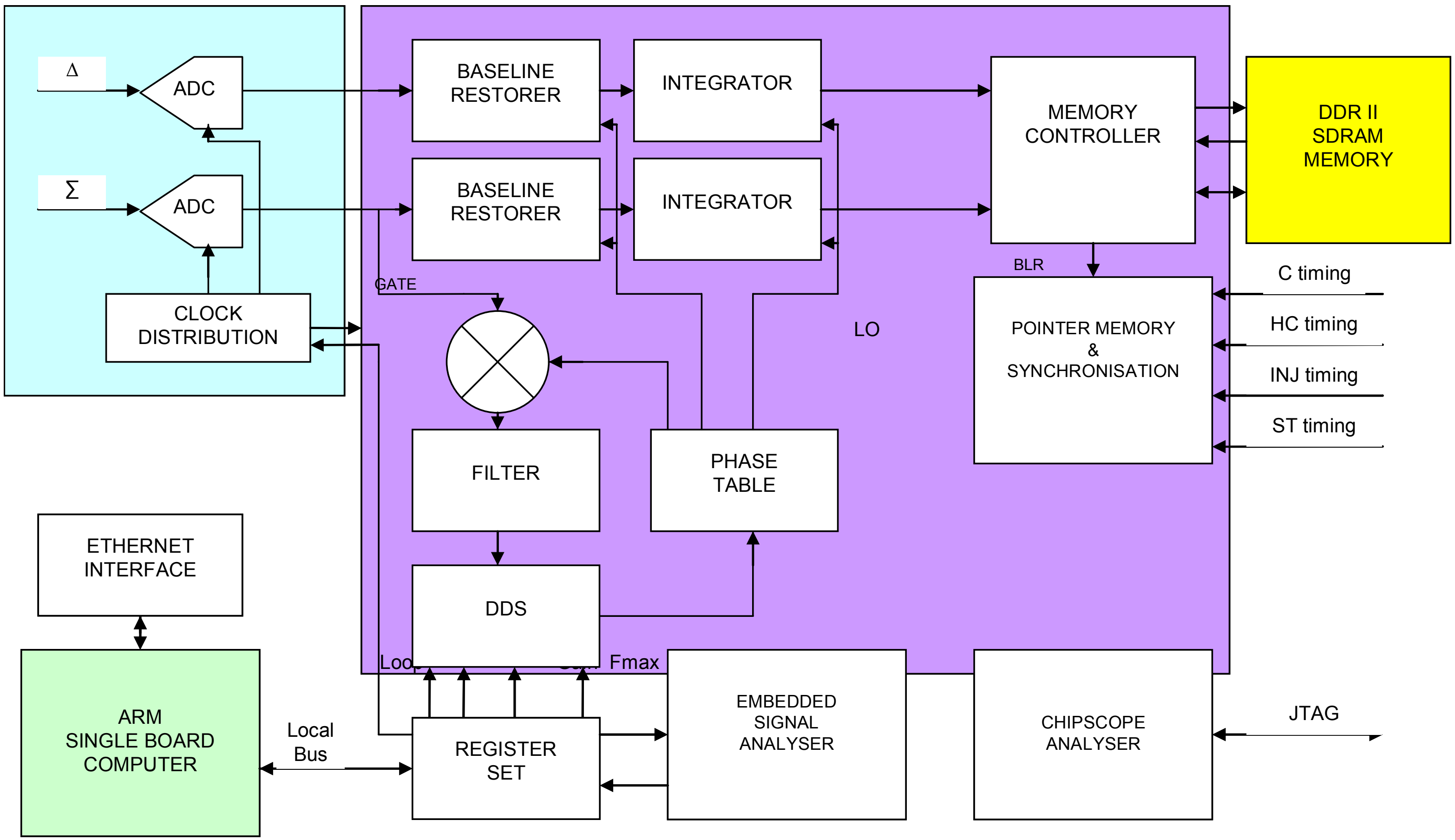
THE CERN ACCELERATOR SCHOOL

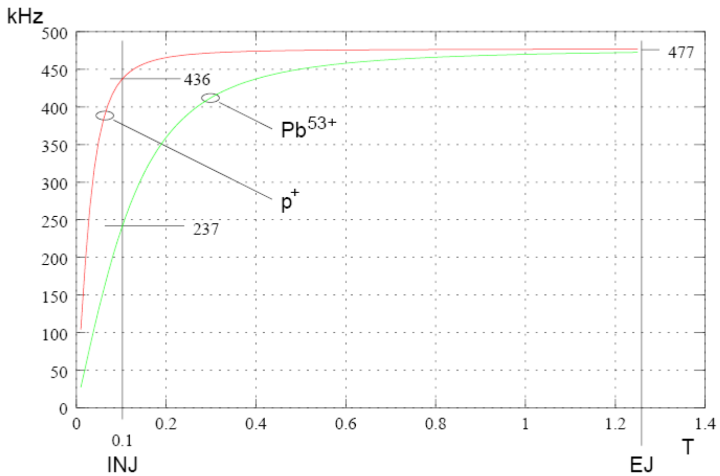
Overview Lecture 2

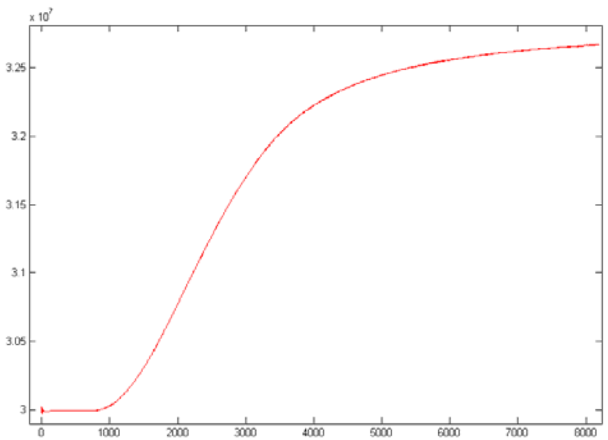
- Left-over from yesterday:
  Trajectory measurements
  Synchronisation to BPM signals for position calculations
- Beam loss measurements
  - Why do we need a machine protection system?
  - Beams losses and protection thesholds
  - System requirements
  - Beam loss monitors
  - BLM system electronics
  - a Data Acquisition Board
  - Data treatment
- Phase space tomography
  - Longitudinal phase space
  - Computed tomography in medicine
  - Longitudinal phase space reconstruction through tomography
  - The sensor
  - Some pretty pictures

Trajectory readout electronics



Following the accelerating frequency





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

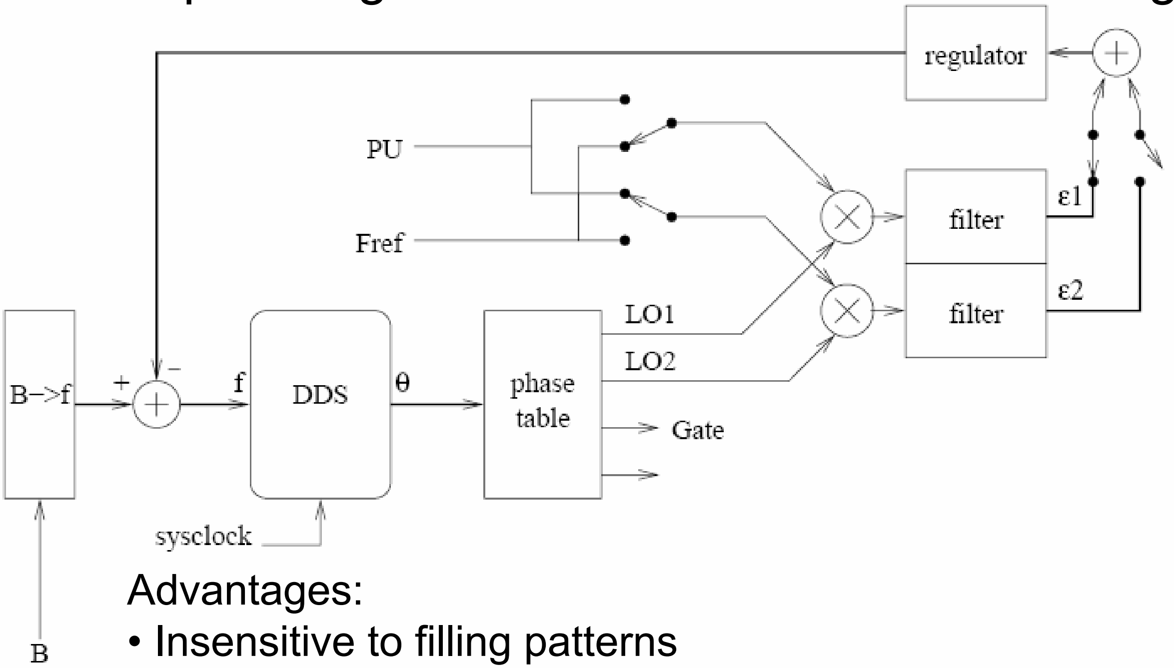
c	speed of light
Q_0	elementary charge
mp	proton mass
R_m	magnetic bending radius
R_0	machine mean orbit radius
h	harmonic number
B	magnetic field

Revolution frequency calculated from the measured gate frequency

Synchronisation

Creating a frequency reference:

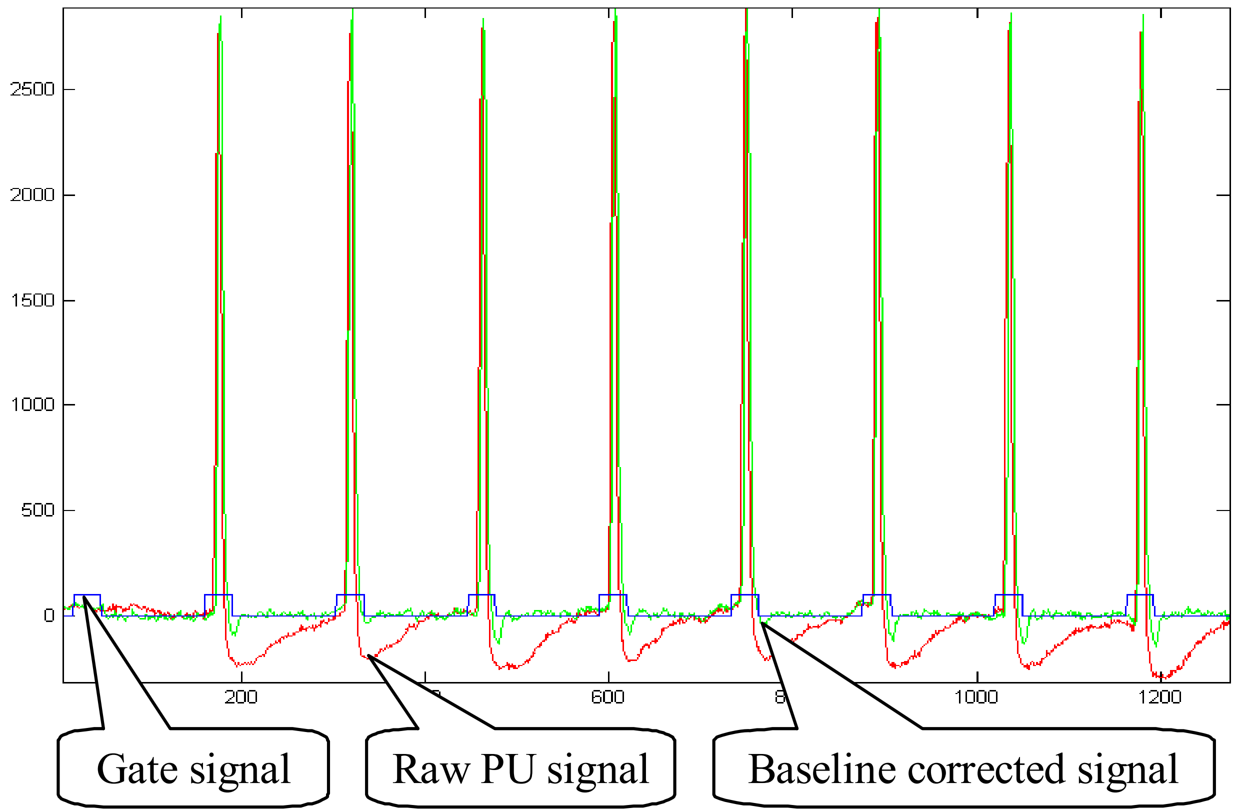
- Numerical PLL
- DDS at F_{rev}
- Lookup table generates local oscillator and integration gate



Advantages:

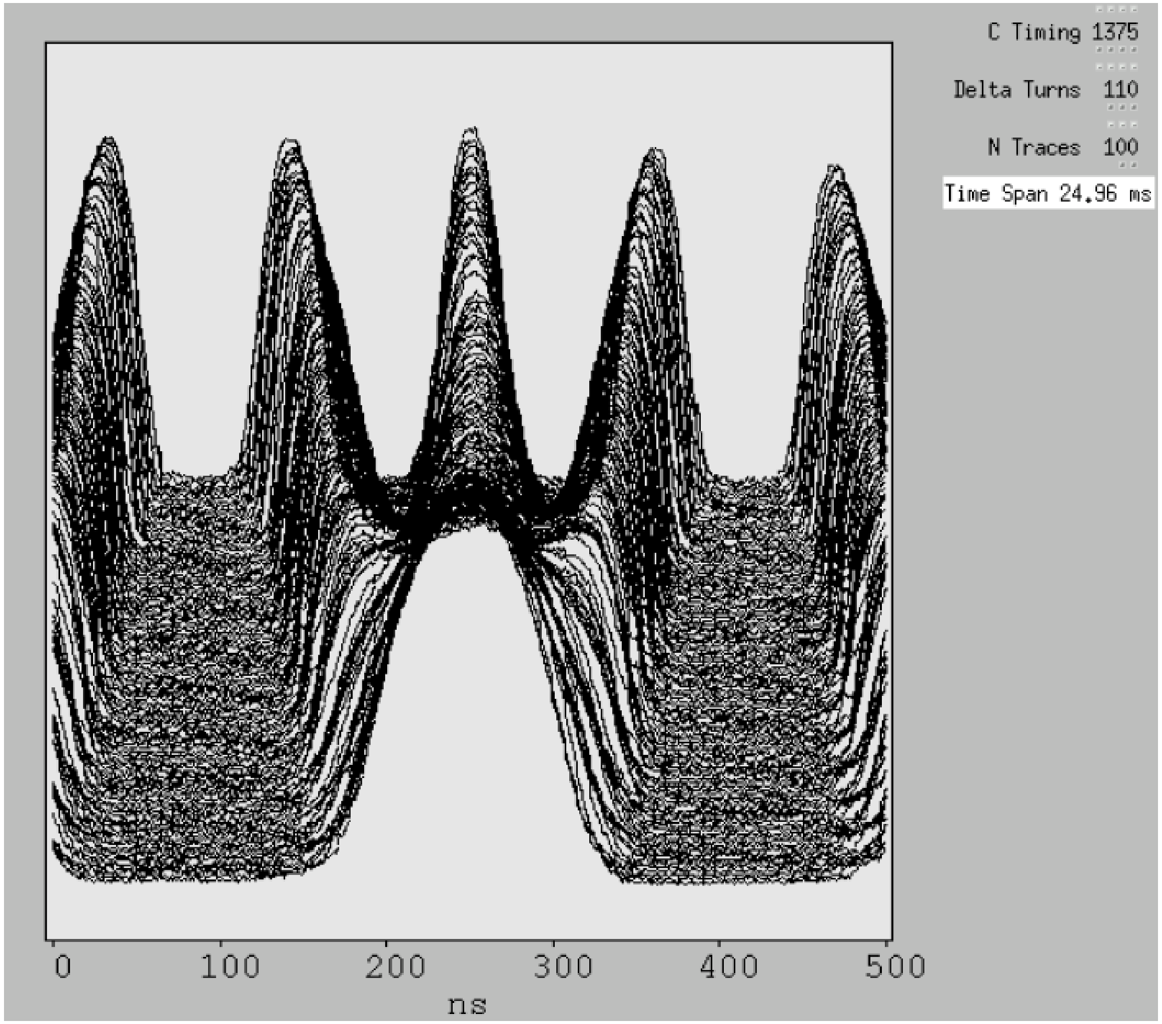
- Insensitive to filling patterns
- Independent of signal polarity
- Can be made to deal cleanly with RF gymnastics

Results from signal treatment

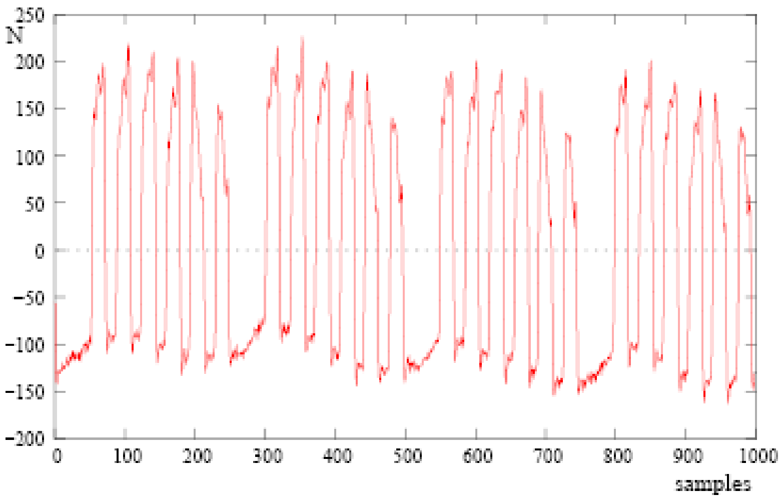


The integration gate is always aligned with the beam pulse

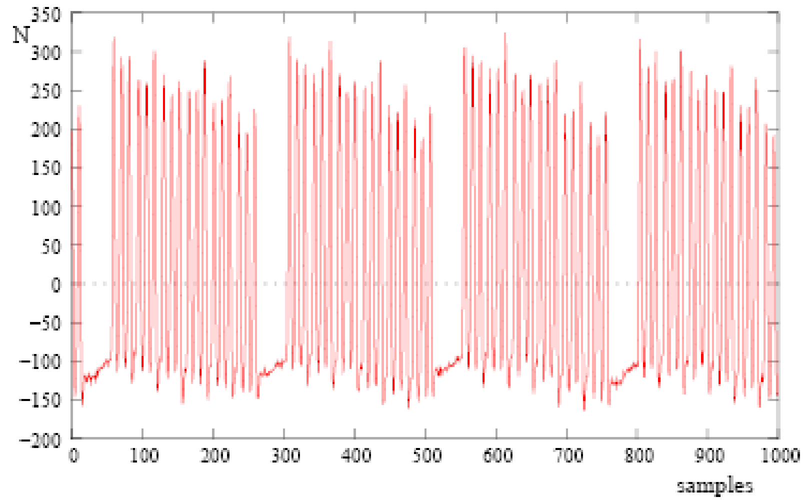
Bunch splitting



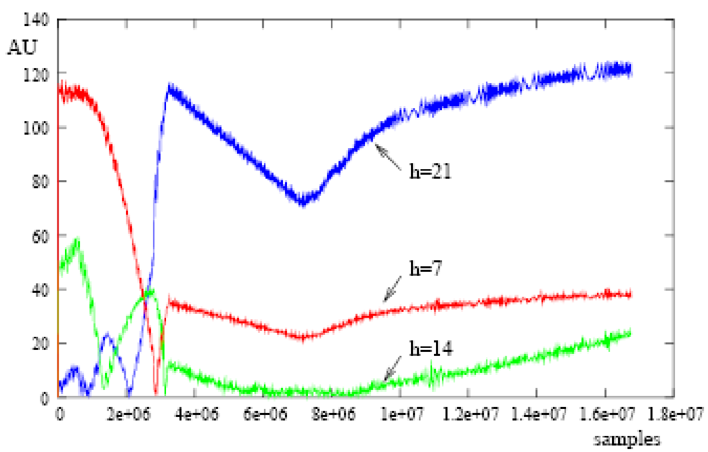
Harmonic number changes



LHC beam at h=7



LHC beam at h=21

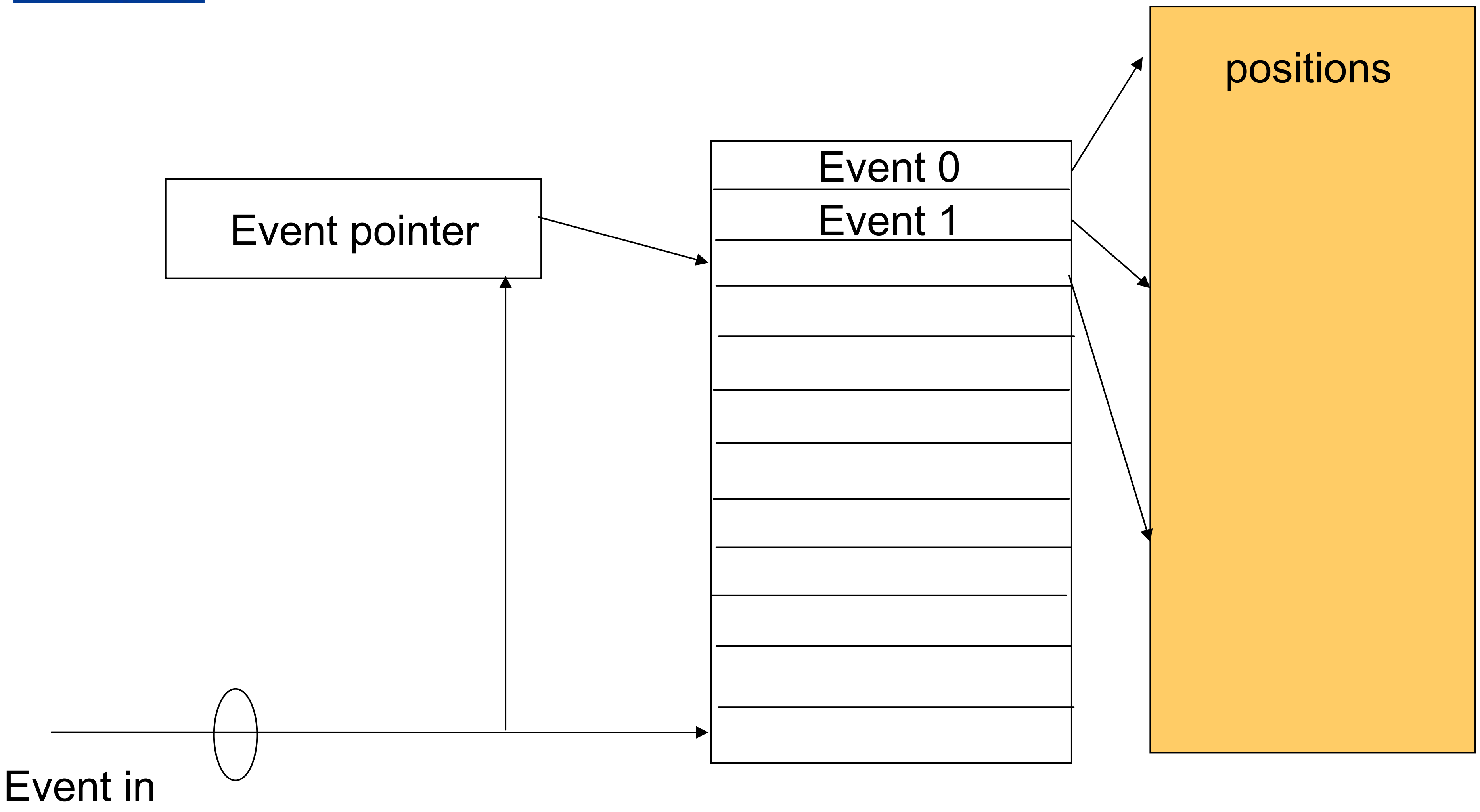


Evolution of magnitude of harmonics on LHC

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



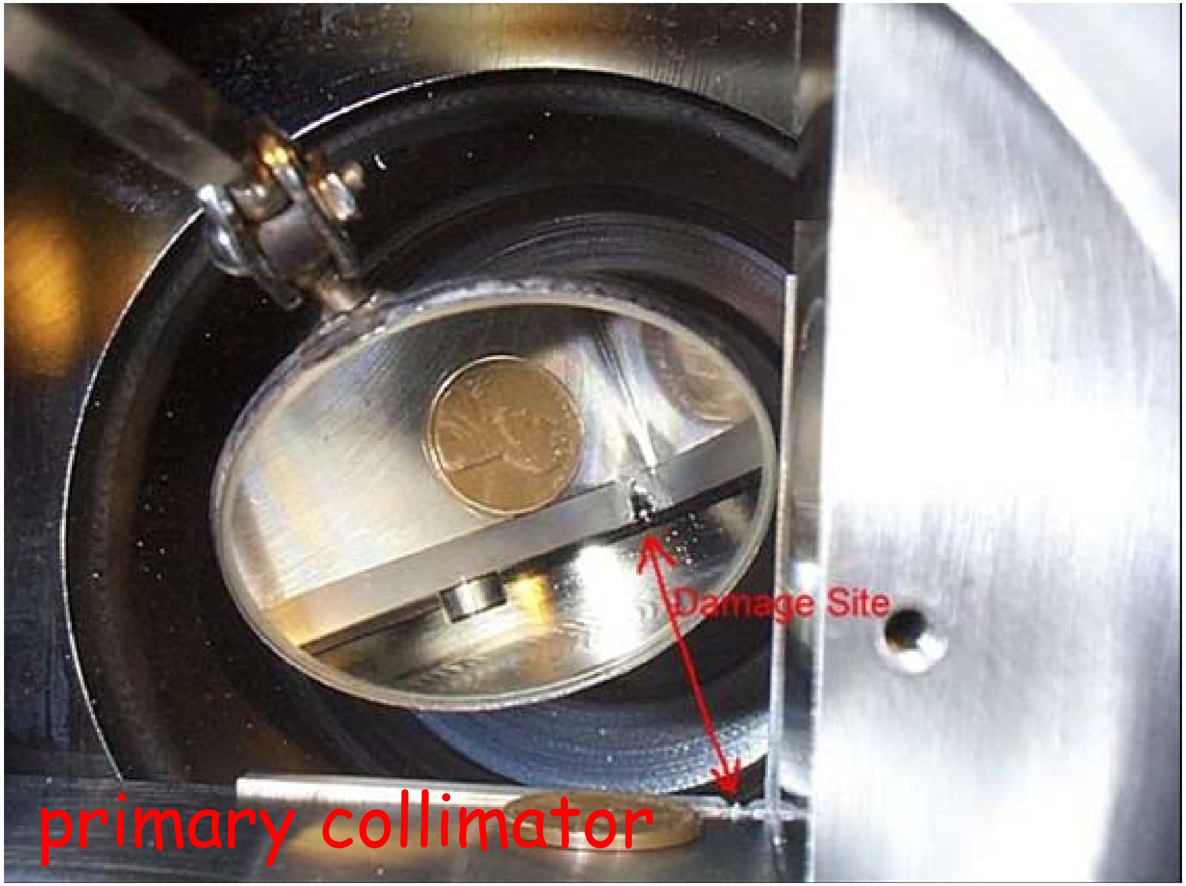
Beam power in the LHC

The Linac beam (160 mA, 200µs, 50 MeV, 1Hz) is enough to burn a hole into the vacuum chamber

What about the LHC beam: 2808 bunches of $15*10^{11}$ particles at 7 TeV?

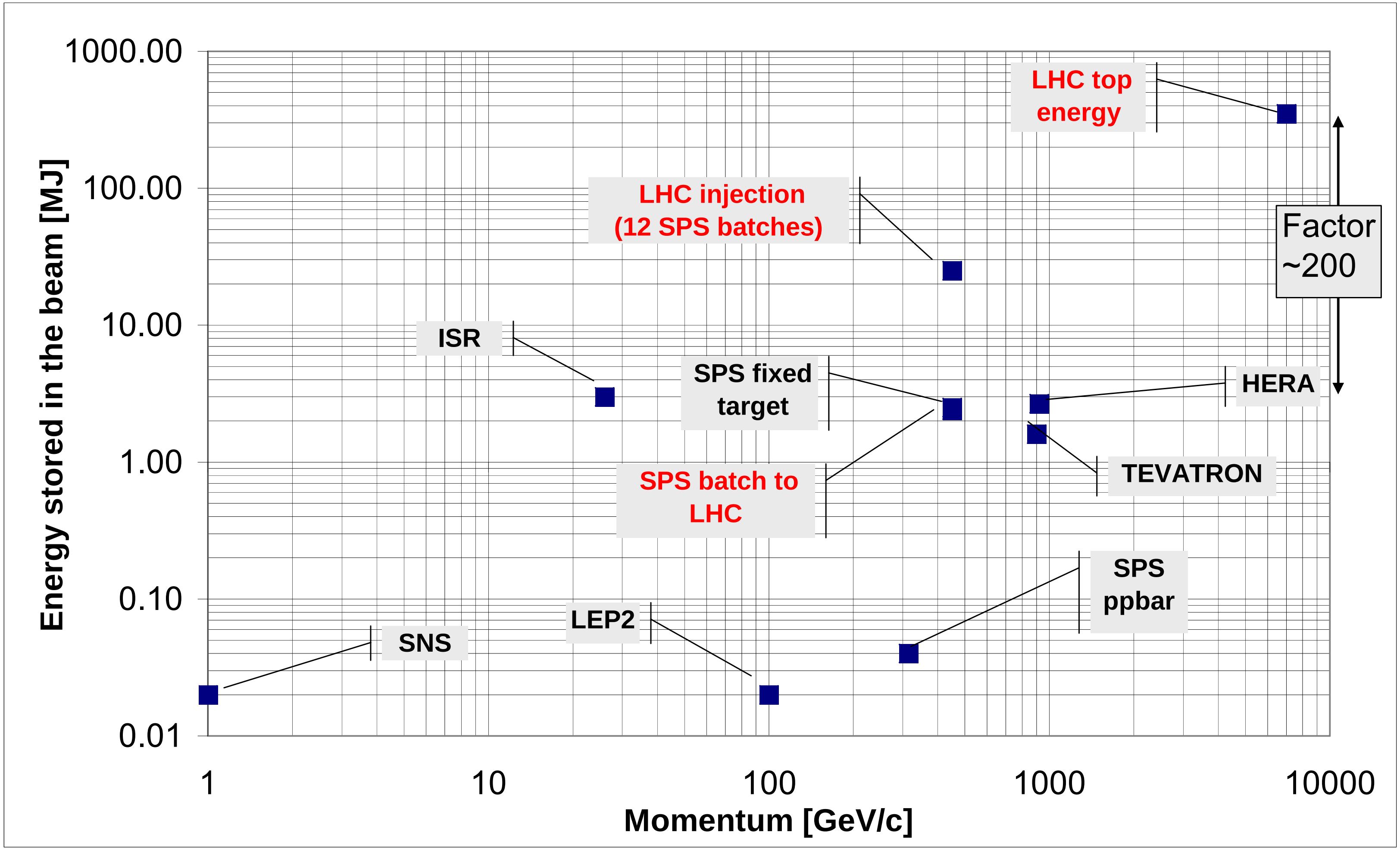
1 bunch corresponds to a 5 kg bullet at 800 km/h

Beam Dammage

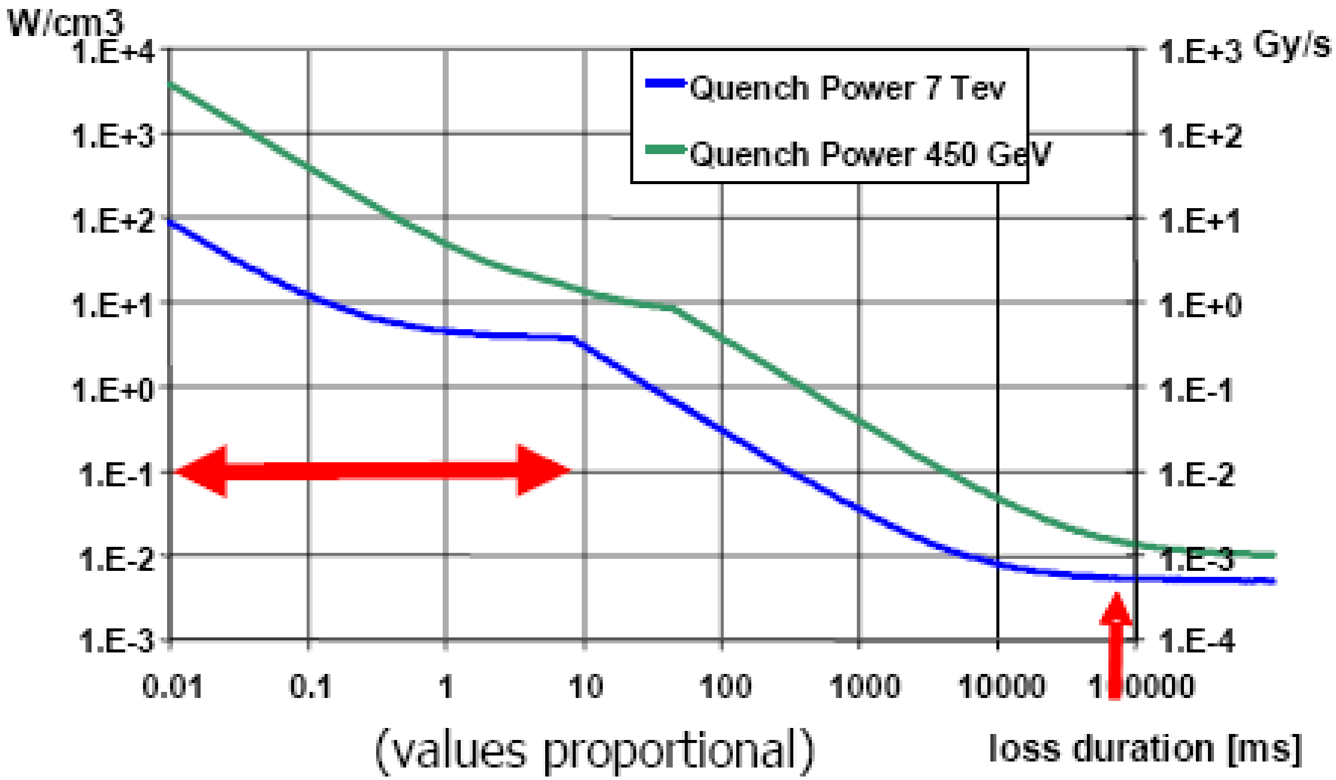


Fermi Lab'sTevatron has 200 times less beam power than LHC!

Beam power in various accelerators



Quench levels



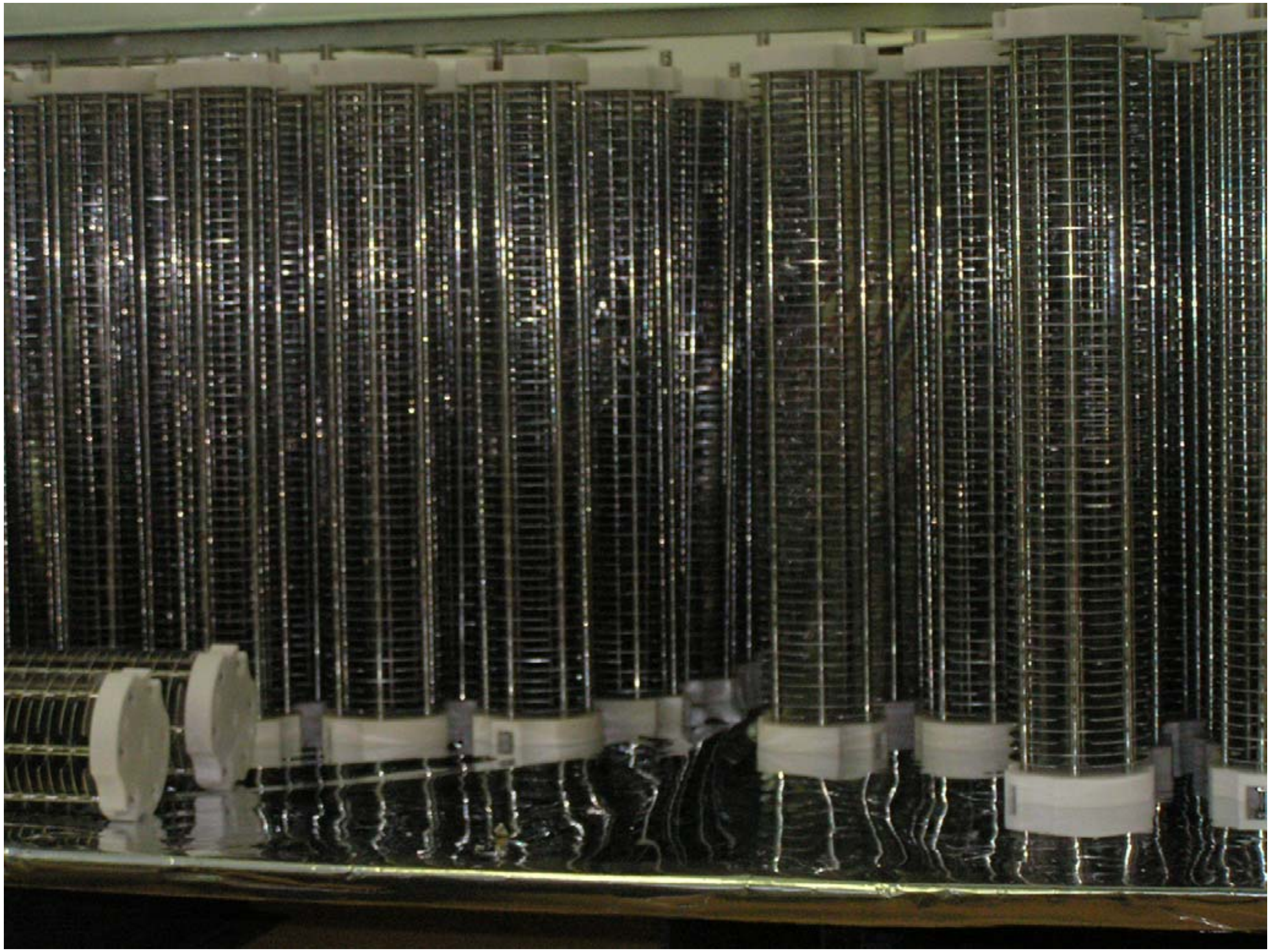
The sensor

Nitrogen filled cylinder with metallic plates

Advantages:

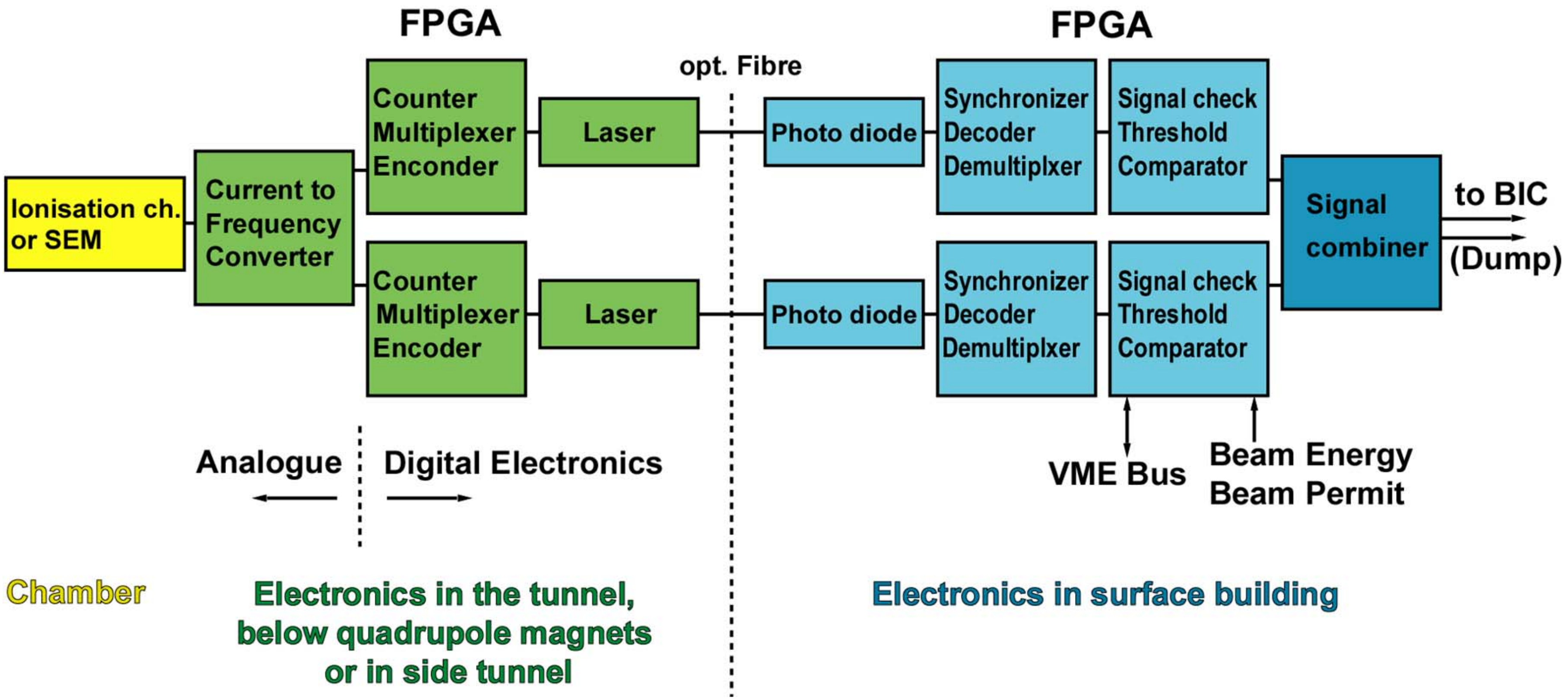
- Very good resistance to radiation (several MGy/year)
- High dynamic range (10^8)
- High reliability and availability
- Losses are measured outside the vacuum chamber
- Development of the secondary particle shower must be simulated in order to calculate the losses

Industrial production of chambers

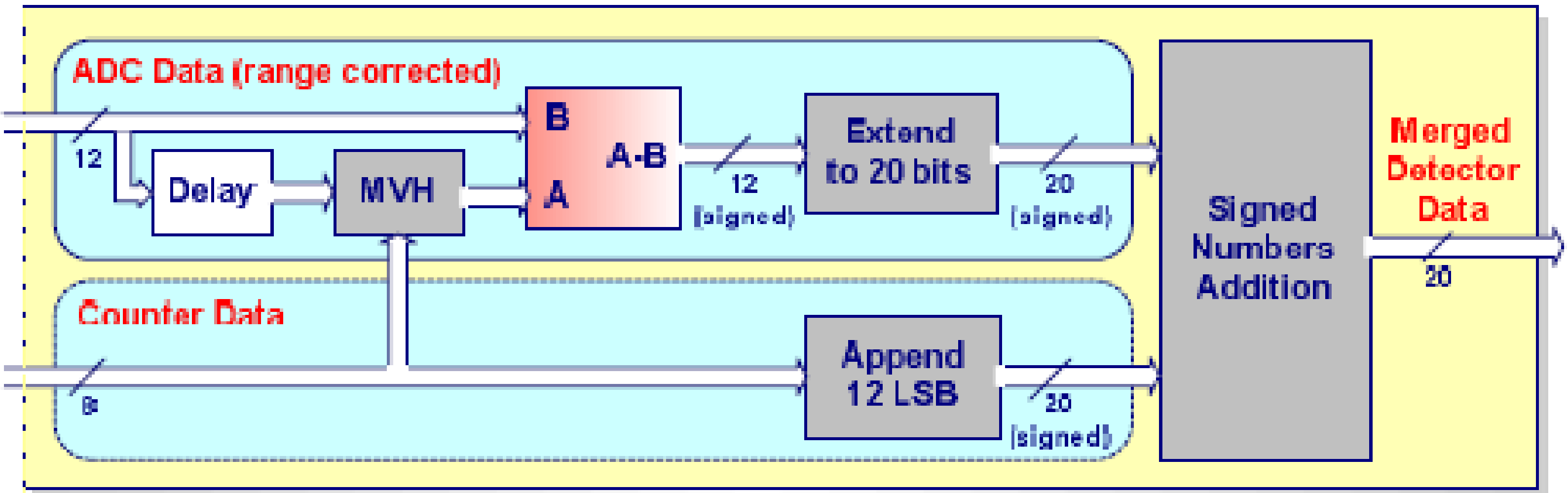


Beam loss must be measured all around the ring
=> 4000 sensors!

System layout



Data treatment in the tunnel



The BLM signal is converted to frequency (amplitude to frequency converter)
The pulses are counted (coarse value)
Between pulses: ADC does the fine grain conversion
20 bit data are send over a fiber link to the surface

Data transmission

- The data from 8 channels are multiplexed on a single transmission channel
- Radiation resistant FPGA created transmission packet + CRC
- The packets are transmitted through 2 independent optical fibers
- In addition to beam loss data, status information is sent so monitor correct functioning of the tunnel installation
- Gigabit transmission in order to minimize system latency

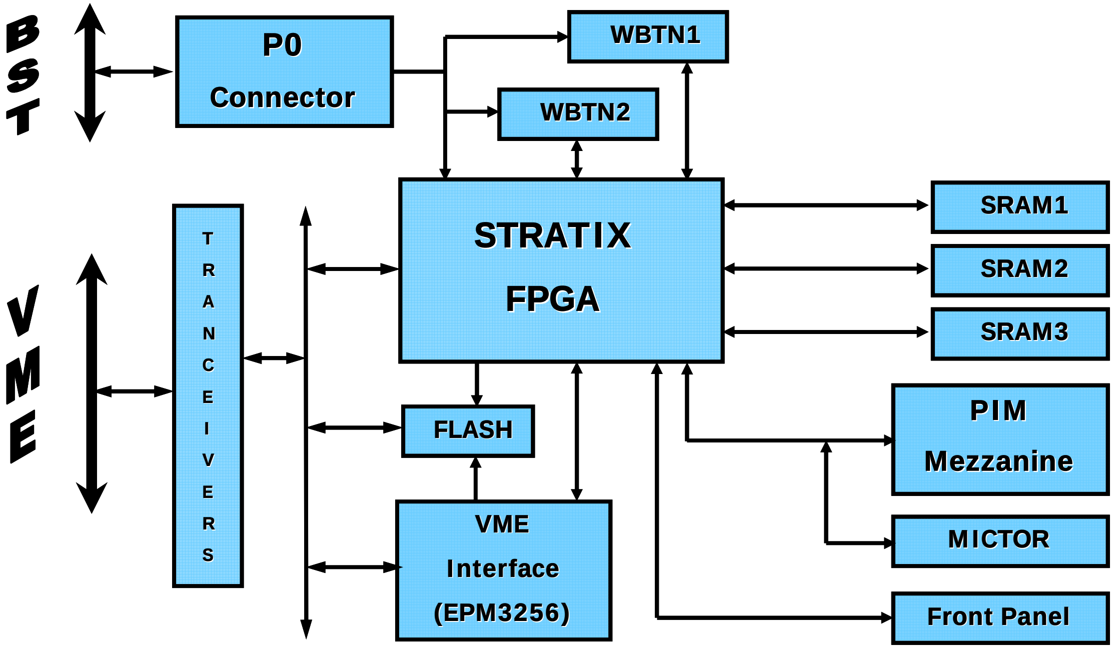
8b/10b encoding

- 8 bit values are encoded into 10 bit symbols
- Low 5 bits into 6-bit group. Upper 3 bits into 4-bit group
- Dxx.y (xx: 0-31, y: 0-7)
- DC balancing
  (as many zeros as ones)
- Enough state changes
  to recover clock
- Uses look-up tables

5B/6B code

input		RD = -1	RD = +1	input		RD = -1	RD = +1
	EDCBA	abcdei			EDCBA	abcdei	
D.00	00000	100111	011000	D.16	10000	011011	100100
D.01	00001	011101	100010	D.17	10001	100011	
D.02	00010	101101	010010	D.18	10010	010011	
D.03	00011	110001		D.19	10011	110010	
D.04	00100	110101	001010	D.20	10100	001011	
D.05	00101	101001		D.21	10101	101010	
D.06	00110	011001		D.22	10110	011010	
D.07	00111	111000	000111	D.23	10111	111010	000101
D.08	01000	111001	000110	D.24	11000	110011	001100
D.09	01001	100101		D.25	11001	100110	
D.10	01010	010101		D.26	11010	010110	
D.11	01011	110100		D.27	11011	110110	001001
D.12	01100	001101		D.28	11100	001110	
D.13	01101	101100		D.29	11101	101110	010001
D.14	01110	011100		D.30	11110	011110	100001
D.15	01111	010111	101000	D.31	11111	101011	010100
				K.28		001111	110000

The data acquisition board



Requirements for a data acquisition board

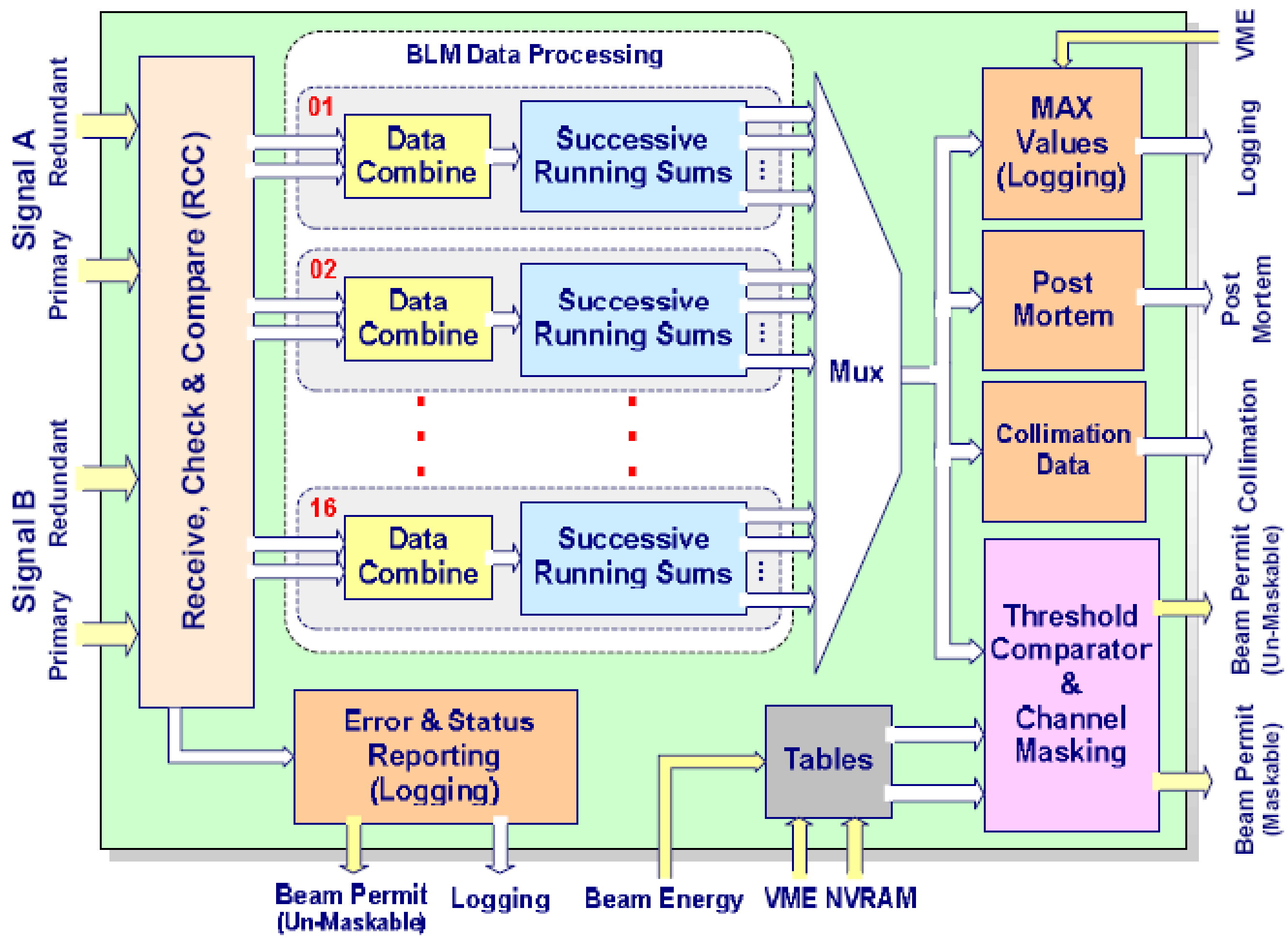
- Get access to sensor data through mezzanine card
- Get access to beam synchronous fast timing signals
- Treat the data in an FPGA and store results in fast RAM
- Initialize the FPGA at start-up
- Re-program the FPGA in situ

- Readout the final results through the VME bus

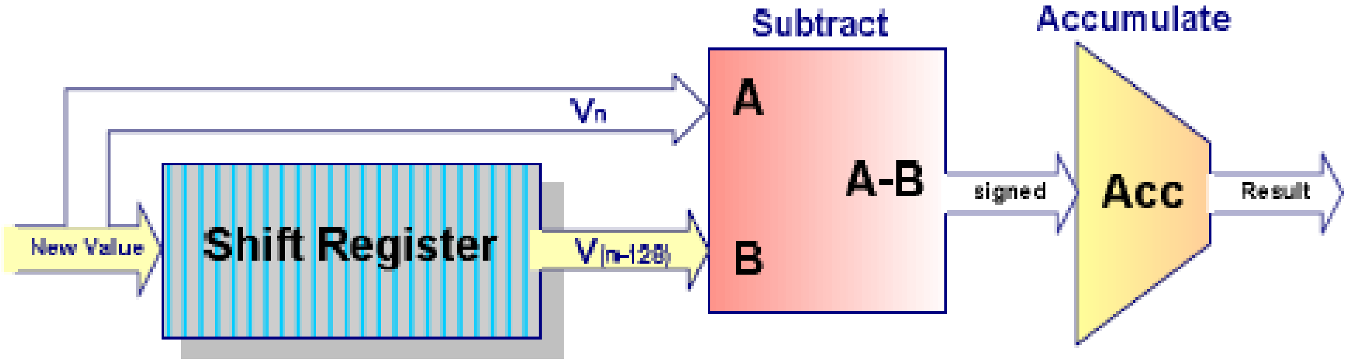
Signal treatment at the surface

- Receive the values from the electronics in the tunnel via the optical fibers
- De-multiplex the data coming from different BLMs
- Check the CRC and compare the data coming from the redundant communication channels. If the data from the two channels differ: decide which one is right
- Calculate successive sums in order to see fast big losses as well as slow small losses.
- Compare the successive sums to threshold values in order to trigger beam dumps should the losses be too high
- Give access to beam loss data for inspection in the control room together with status information
- Keep measured data in a circular buffer for post mortem analysis

BLM signal treatment at the surface



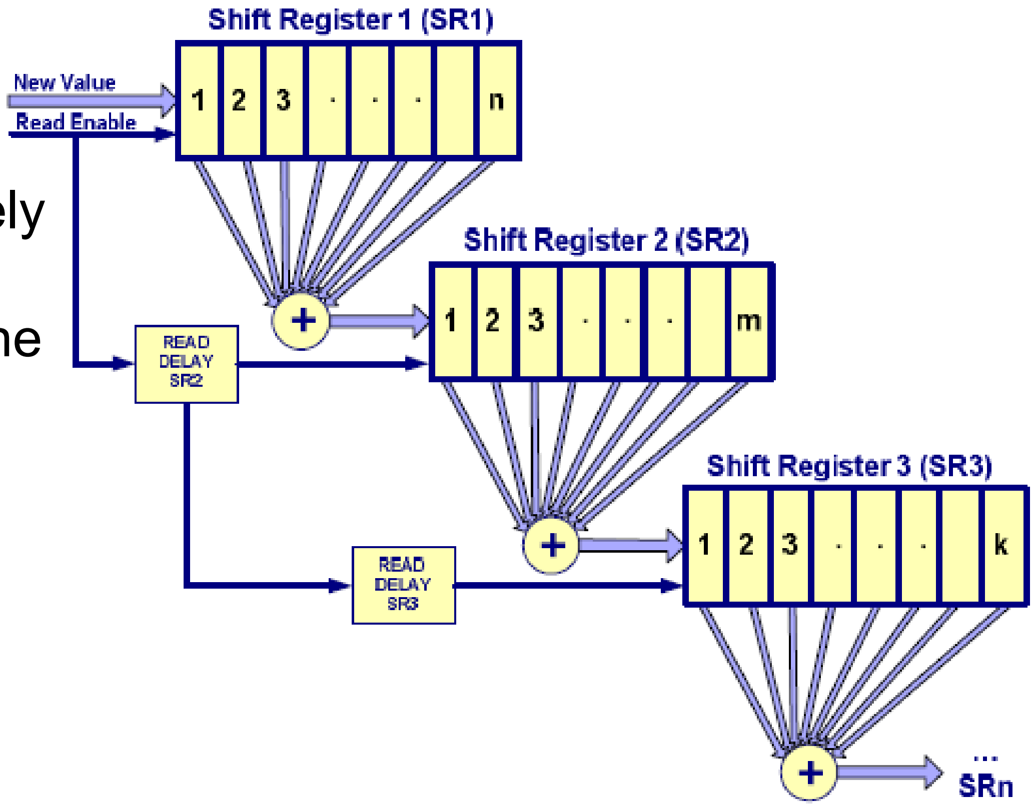
Calculating running sums



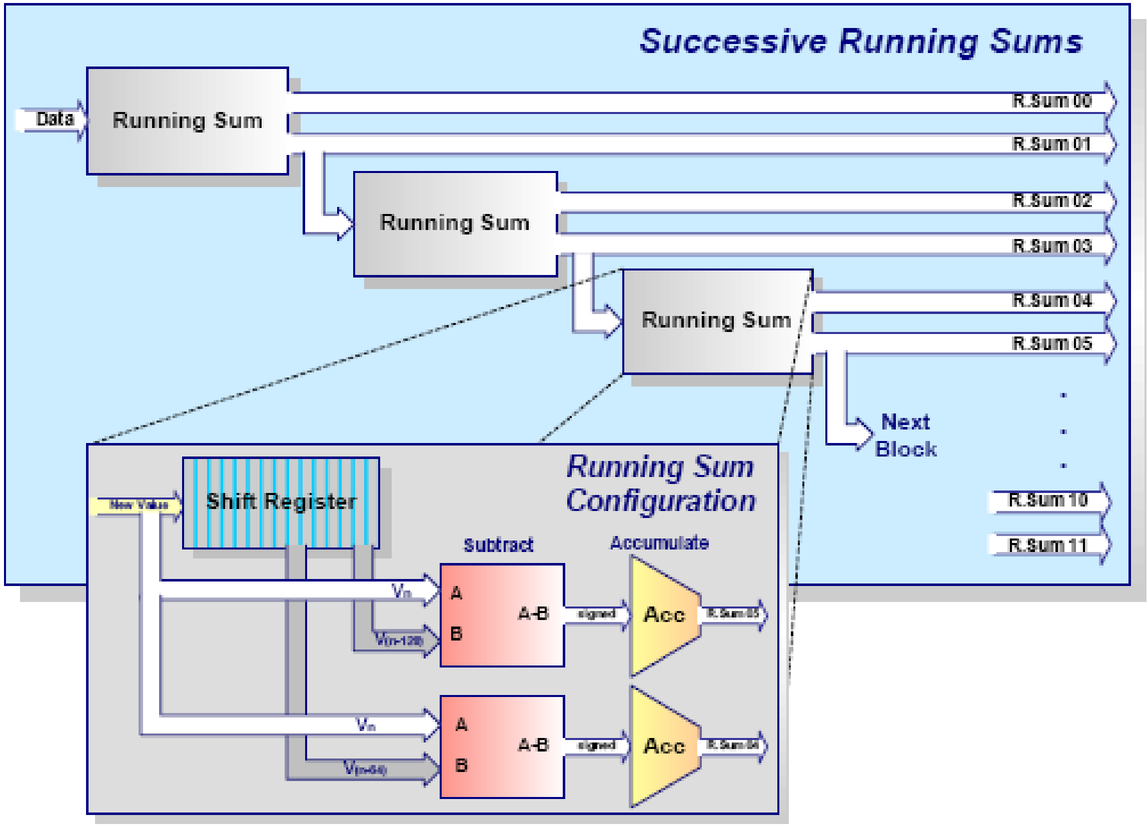
Running sum:
Subtract the oldest value, add the newest one
The number of values kept defines the integration time
or… use shift register and add the difference between first and last value

Limiting the length of the shift register

Update the following Shift register once the preceding one is completely updated.
The latency depends on the integration time



Successive running sums



Threshold comparison

- Quench depends on loss level and loss duration
- Threshold levels are calculated from the quench curve
- Each detector has his own, individual threshold table
- The abort trigger may me maskable

1 card serves 16 detector channels

There are 12 running sums

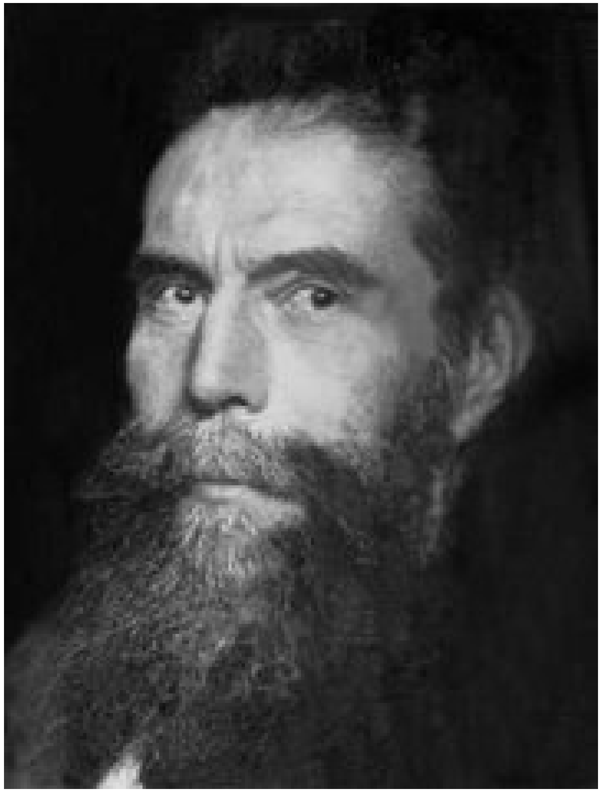
Threshold depends on beam energy (32 levels)

=> 16*12*32 = 6144 threshold values per card.

BLM display and logging

- The beam loss values go to the control room
- Online display updated at 1 Hz
- Post mortem:
  - 20000 turns of 40μs samples = last 1.75 s
  - 82ms sum values for 45 mins

Who is this?



Wilhelm Conrad Röntgen

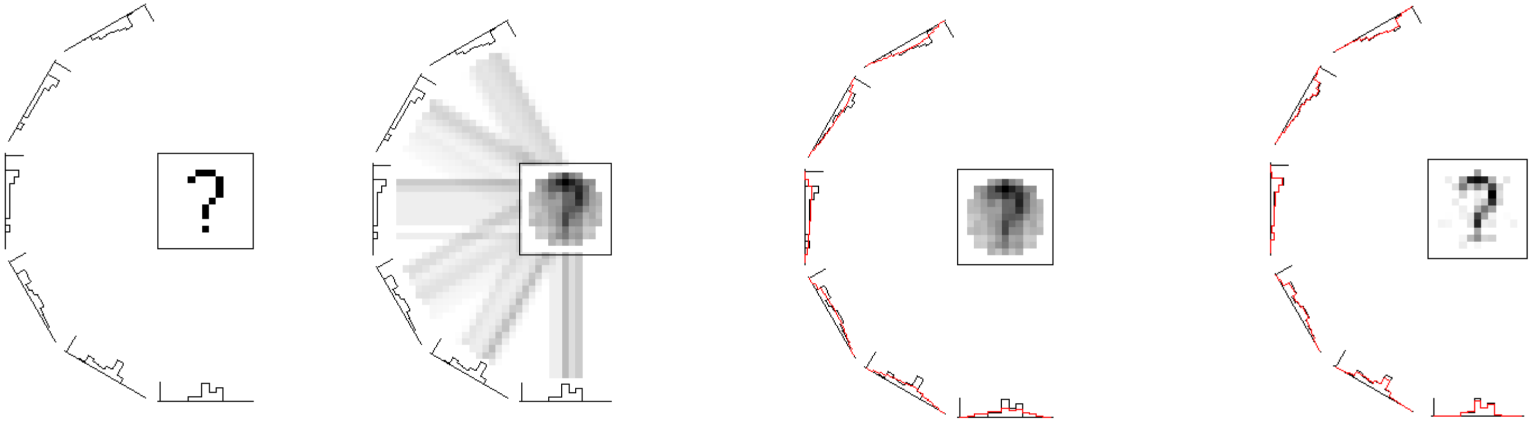
Computed Tomography (CT)

Principle of Tomography:

• Take many 2-dimensional Images at different angles

• Reconstruct a 3-dimensional picture using mathematical techniques (Algebraic Reconstruction Technique, ART)

The reconstruction



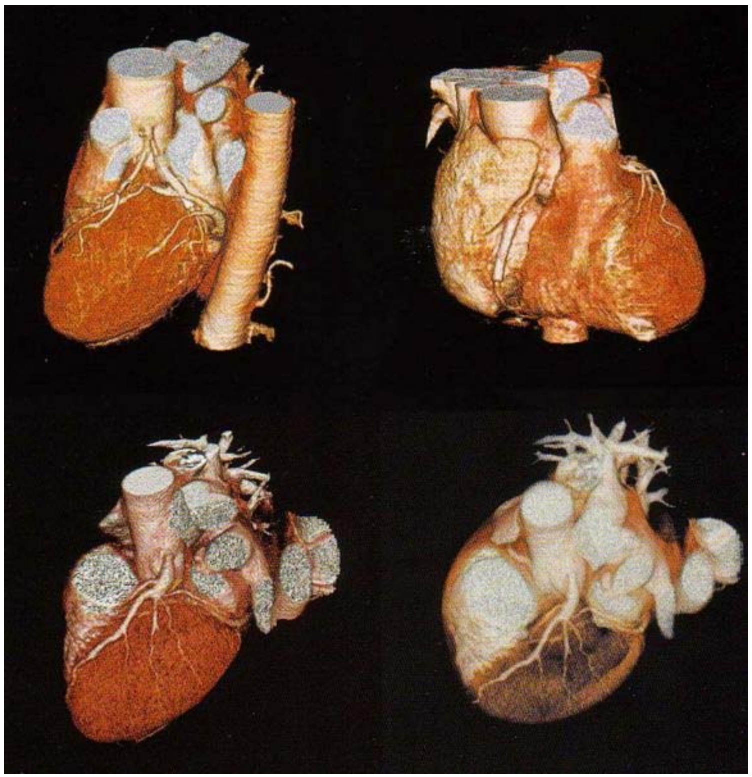
Produce many projections of the object to be reconstructed

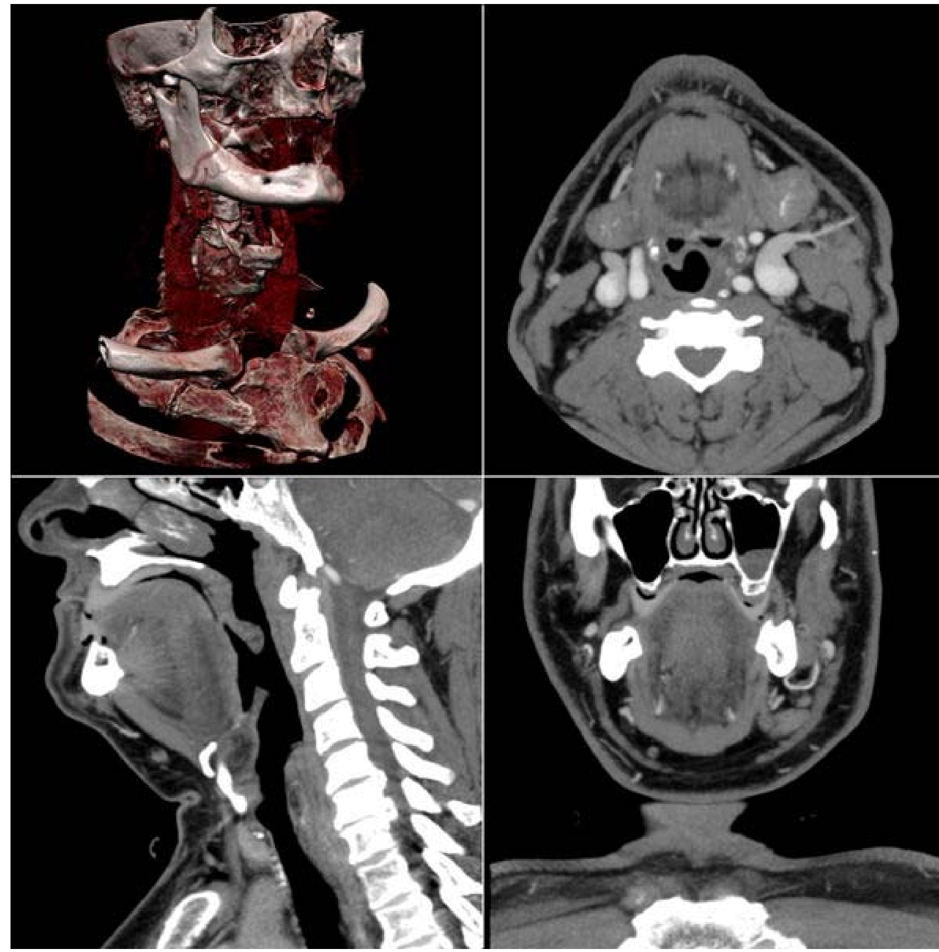
Back project and overlay the “projection rays”

Project the back-projected object and calculate the difference

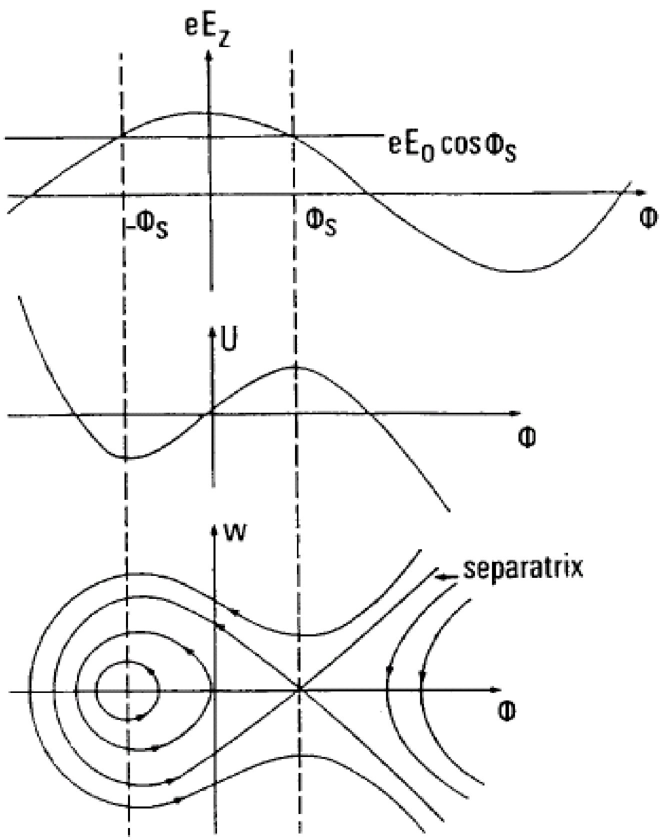
Iteratively back-project the differences to re-construct the original object

Some CT resuluts





Computed Tomography and Accelerators



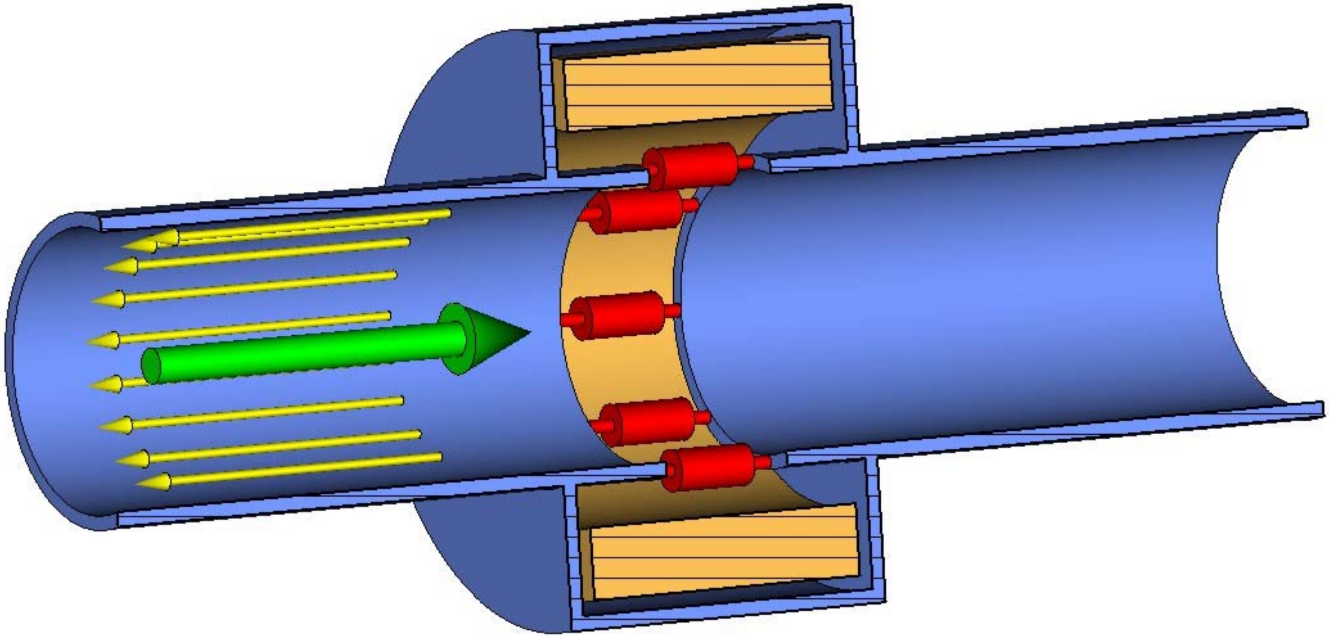
RF voltage

Restoring force for non-synchronous particle

Longitudinal phase space

Projection onto Φ axis corresponds to bunch profile

The wall current monitor



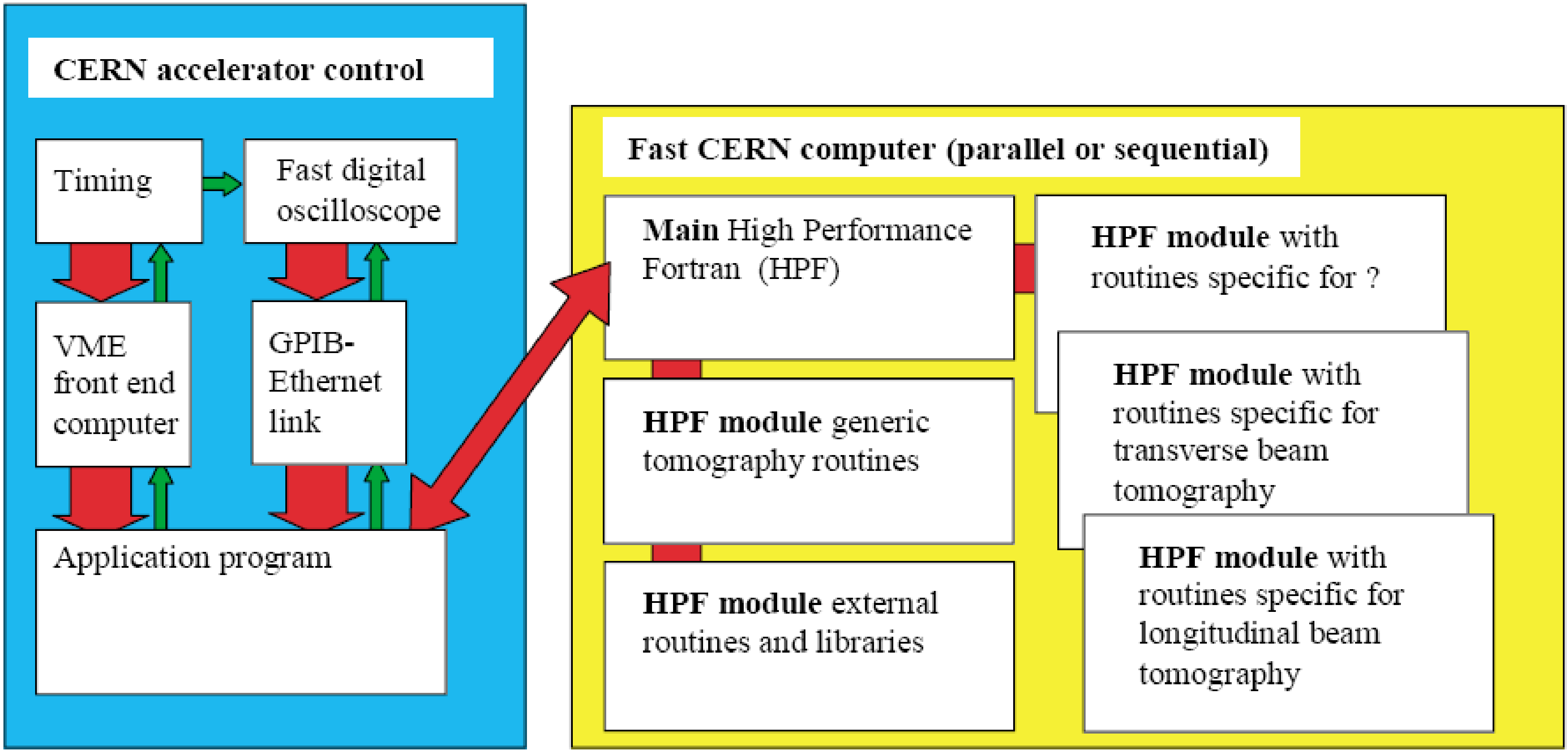
Data handling

- Typical bunch lengths in hadron machines:
  several tens to hundreds of ns
- Read the signal with a high performance oscilloscope
- Readout the traces and transfer them to the number crunching computer
- The synchrotron movement is non-linear for big excursions.
  This non-linearity must be corrected for.
  Corrections are determined through simulations

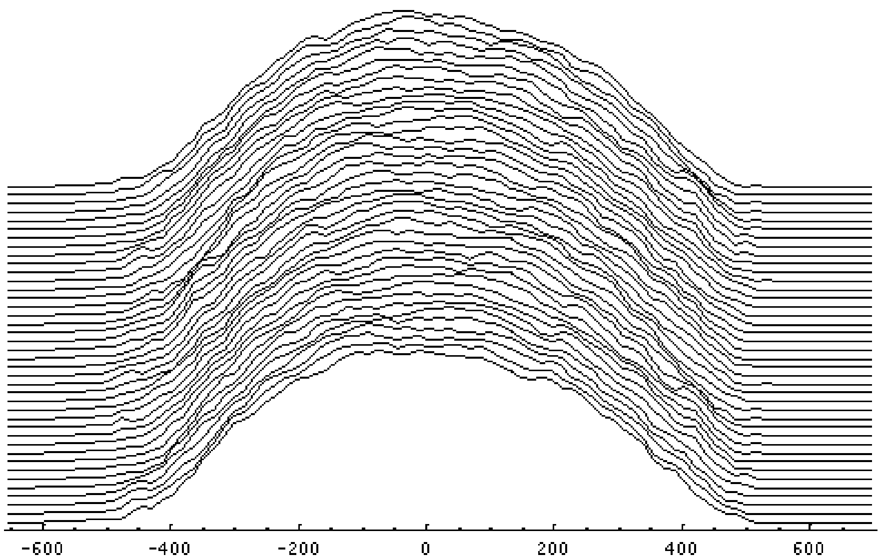
Calculation speed

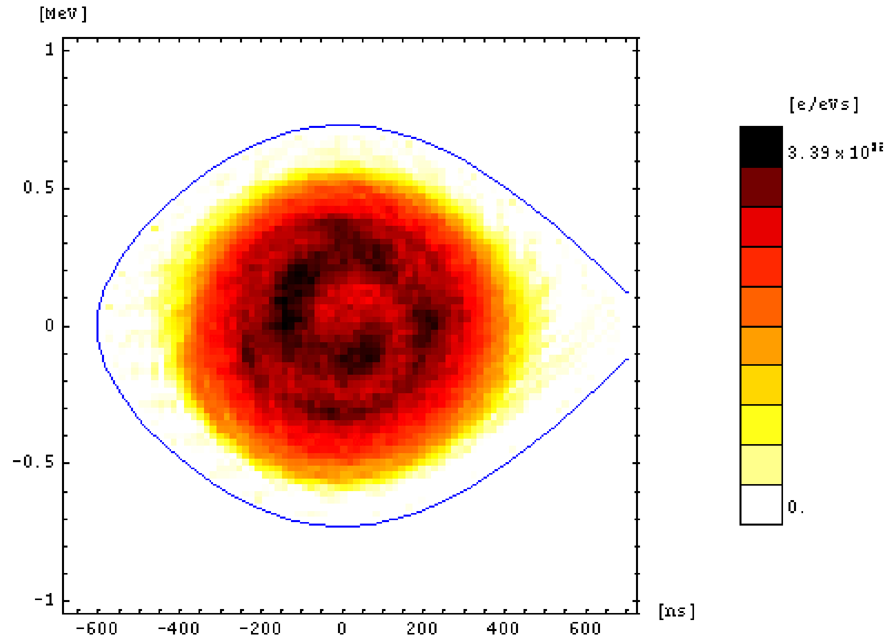
- Program is sub-divided into
  - Equipment readout
  - Graphical User Interface
  - Tomographic calculations
- First versions of tomographic reconstruction in Mathematica (proof of principle)
- Ported to High Performance Fortran (multi-processor code) goal: speed improvement by factor 100!
- Typical calculation times on dedicated dual Pentium: 15s (uses integer code + look-up tables to speed calculations)

Acquisition and controls layout

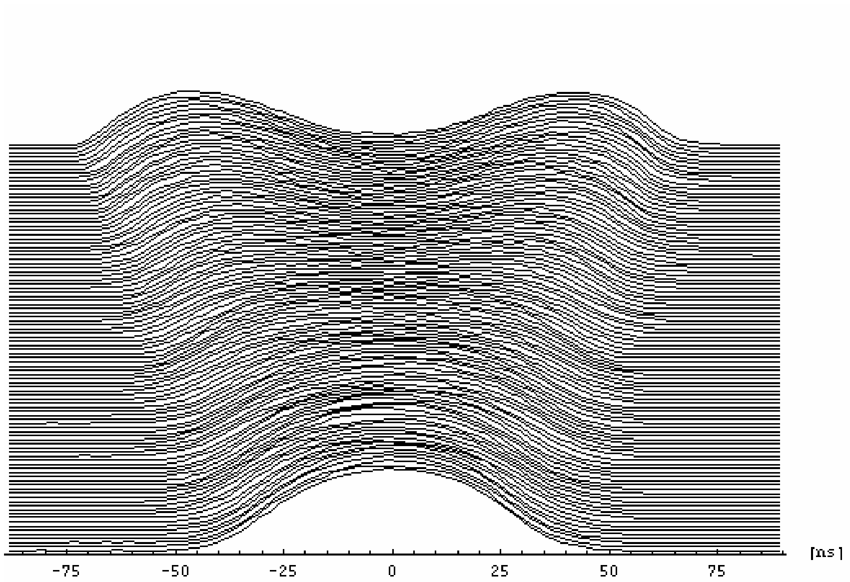


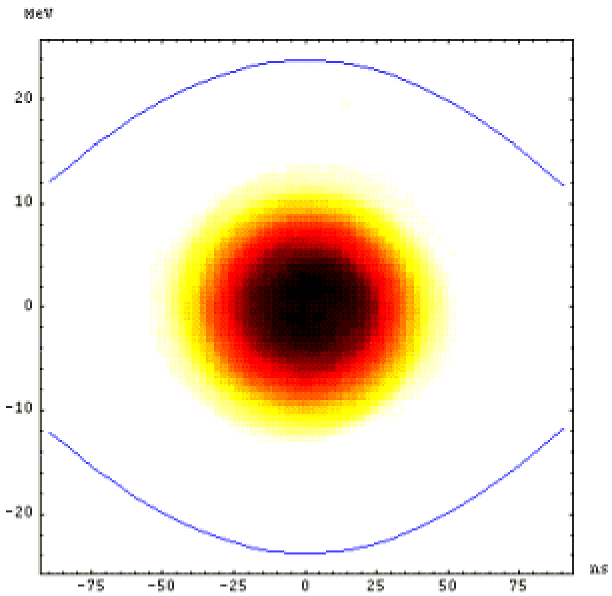
Reconstructed Longitudinal Phase Space





Bunch Splitting





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