Beam Diagnostics

Measuring Complex Accelerator Parameters

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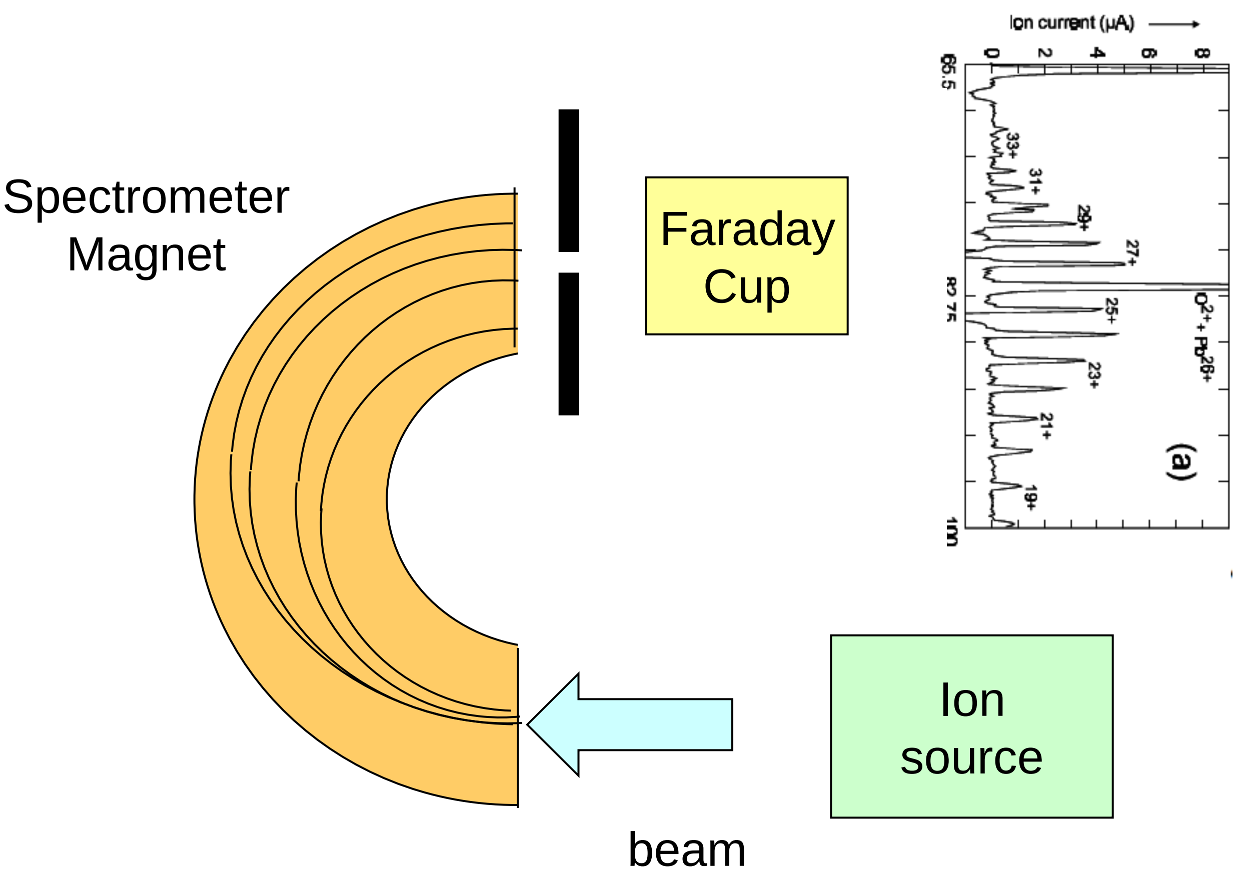
Contents

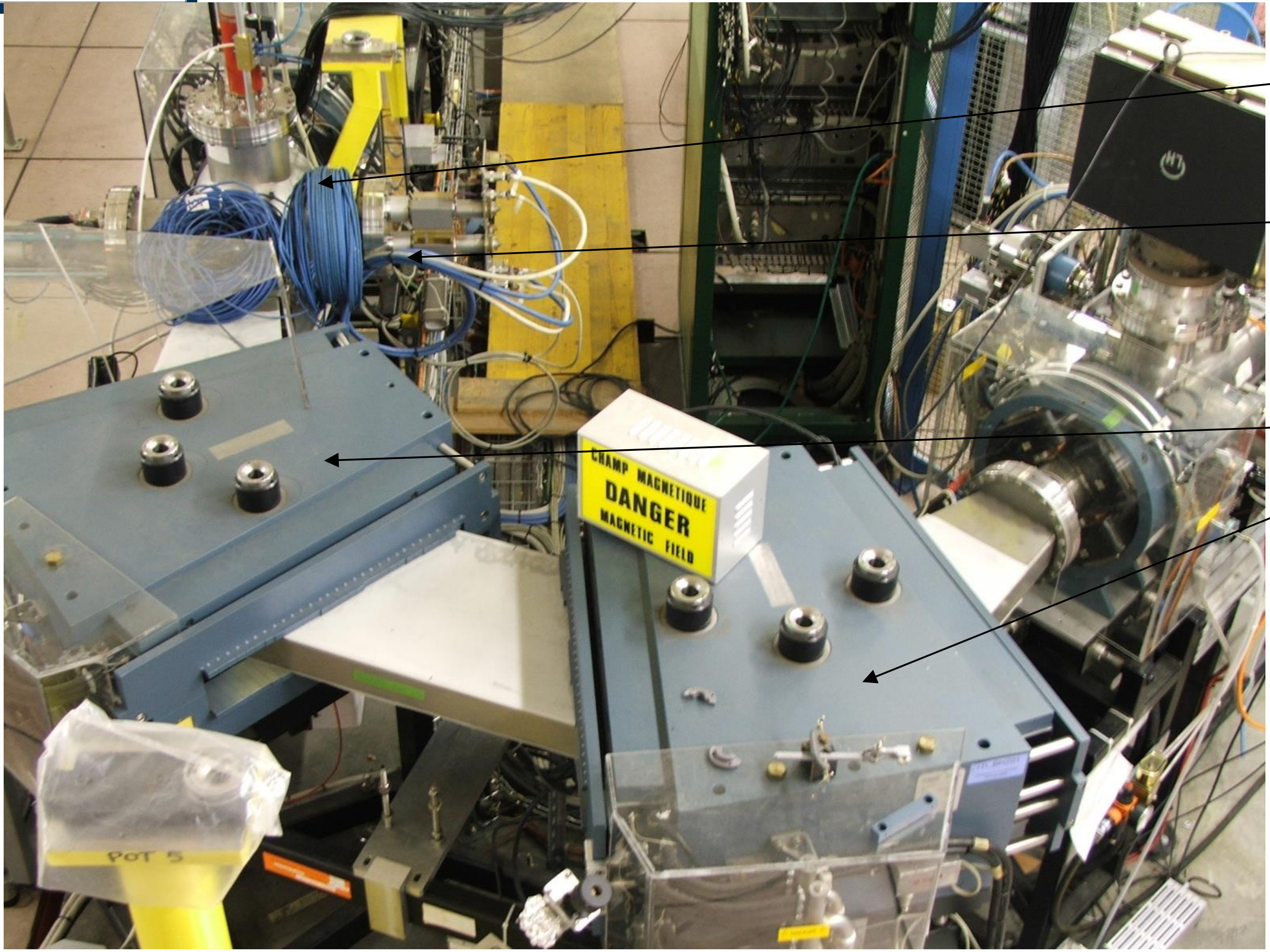
- Some examples of measurements done with the instruments explained during the lecture on beam instrumentation
  - Spectroscopy
  - Trajectory and Orbit measurements
  - Tune measurements
    - Traditional method
    - BBQ method
  - Multi-turn extraction
  - Transverse and longitudinal emittance measurements
  - Longitudinal phase space tomography

Setup for charge state measurement



- The spectrometer magnet is swept and the current passing the slit is measured

Measuring charge state distribution

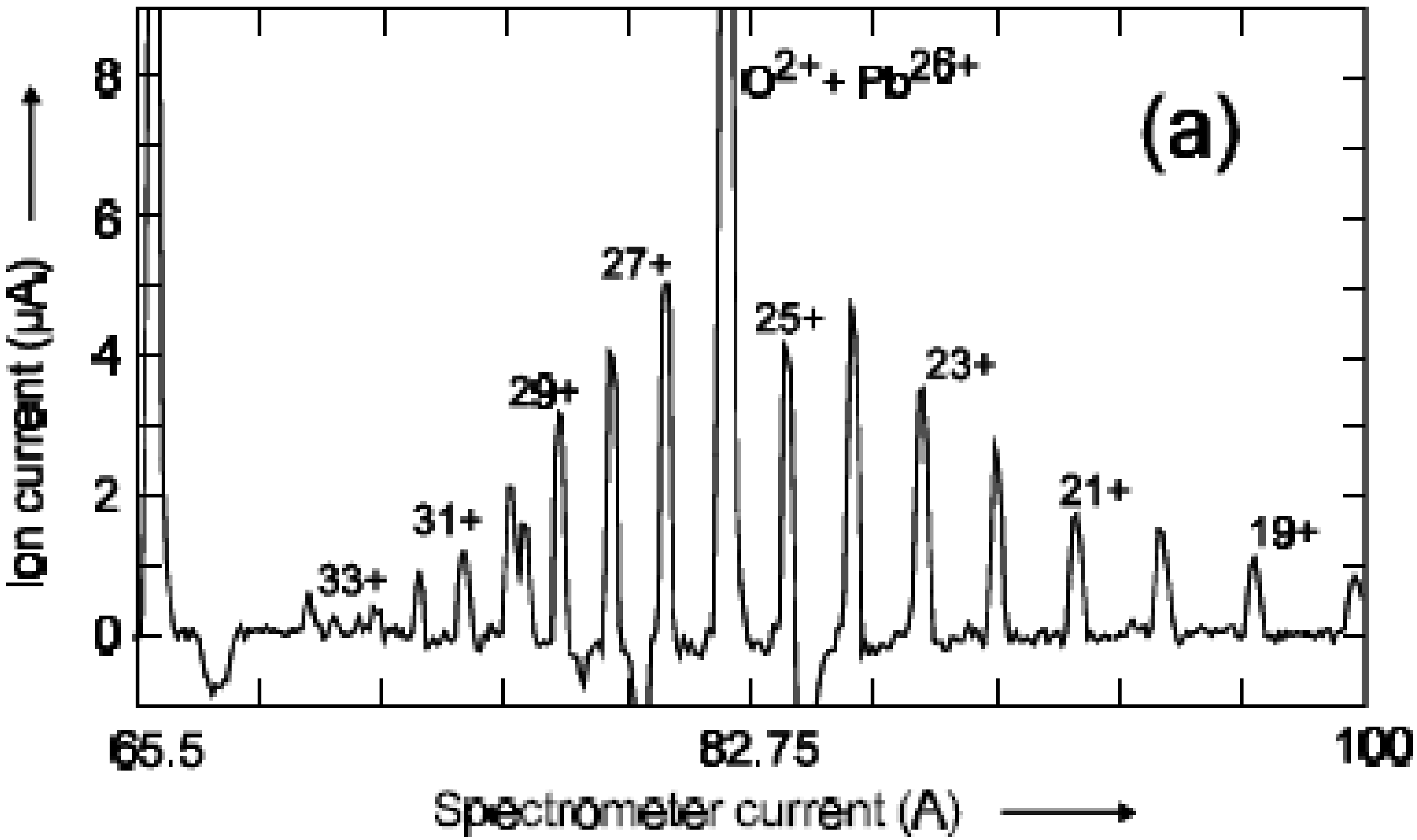


Faraday Cup

Slit

Spectrometer magnets

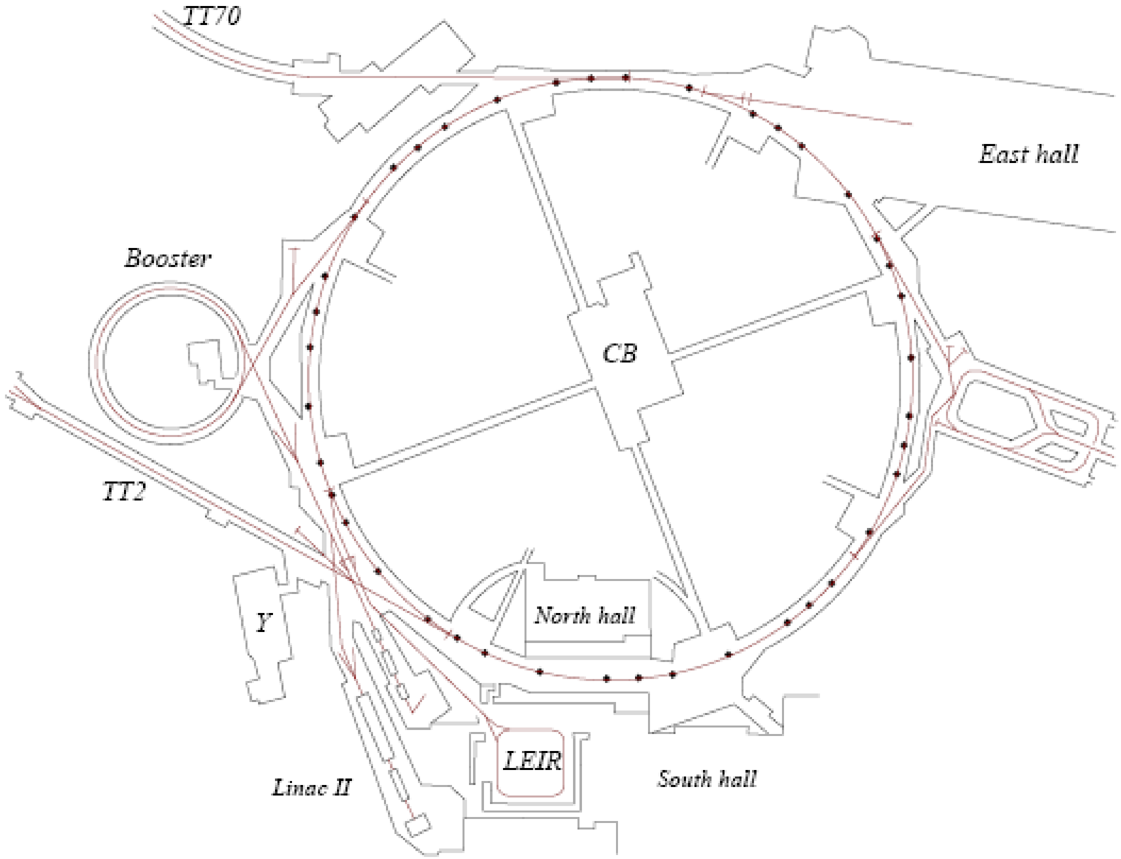
Charge state distribution measured with a Faraday Cup on a heavy ion source



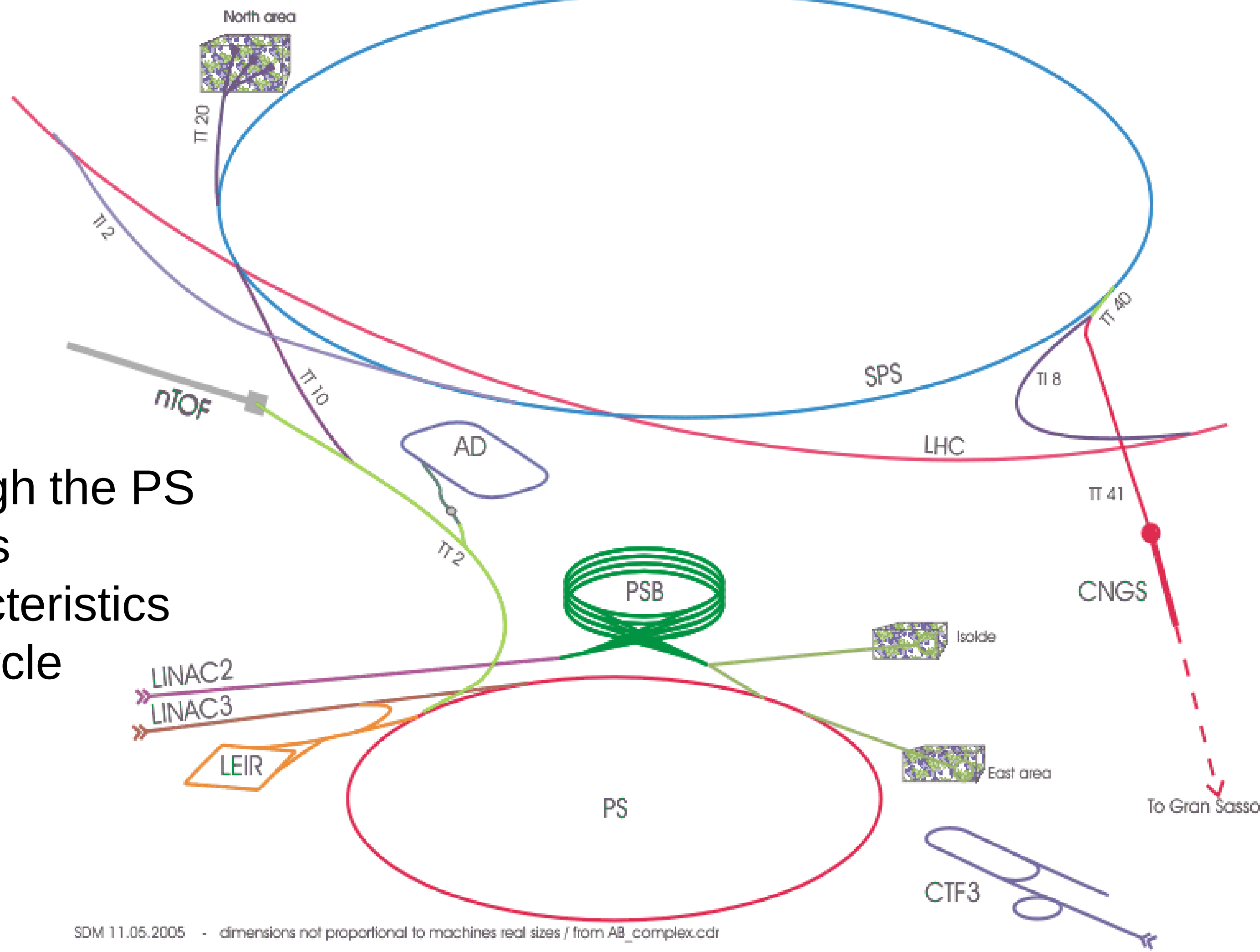
Trajectory Measurement at LHC

Knowing the optics one can deduce the orbit correction from the measurement

Trajectory in the CERN PS: The PUs

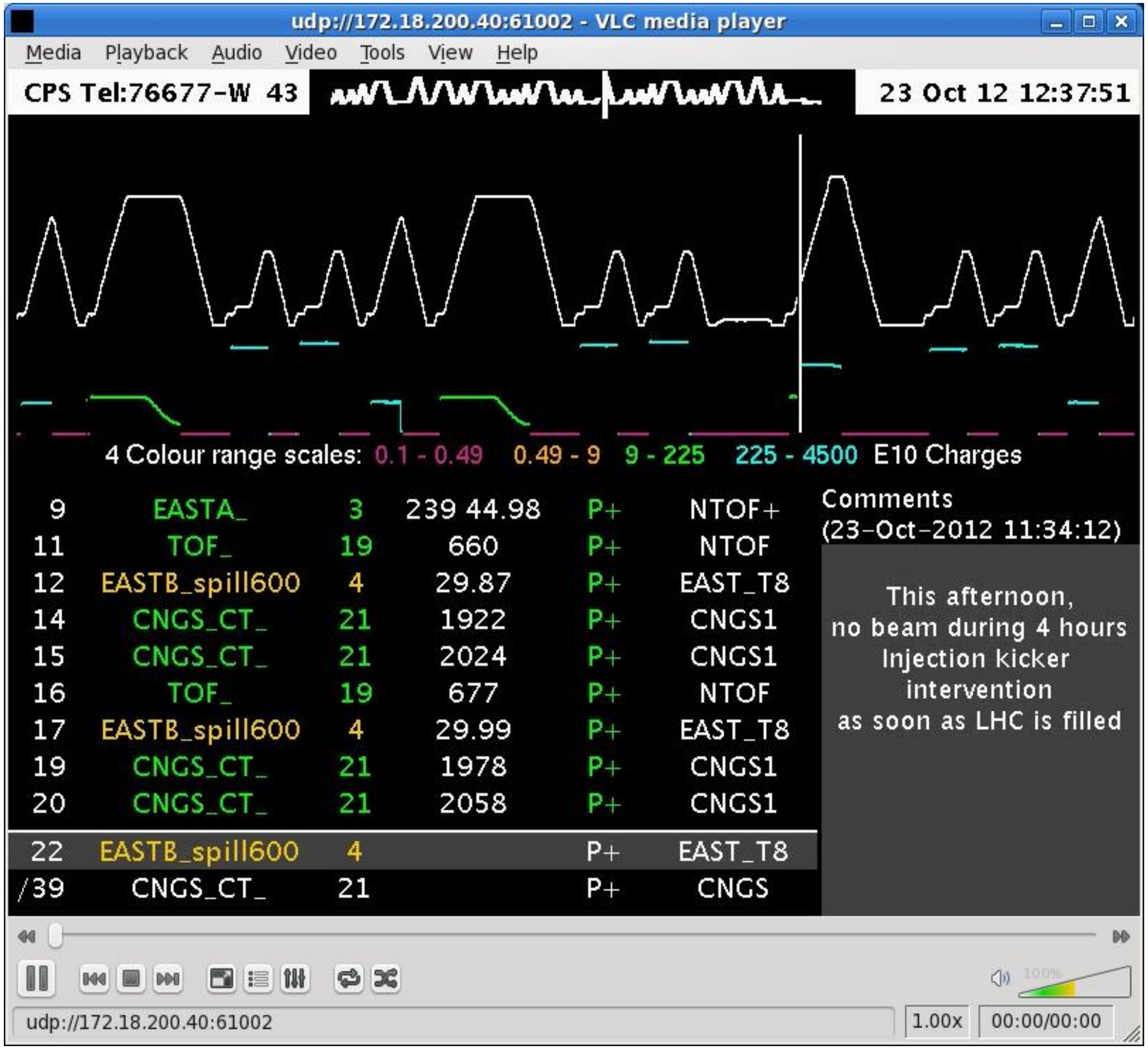


The PS, a universal machine



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

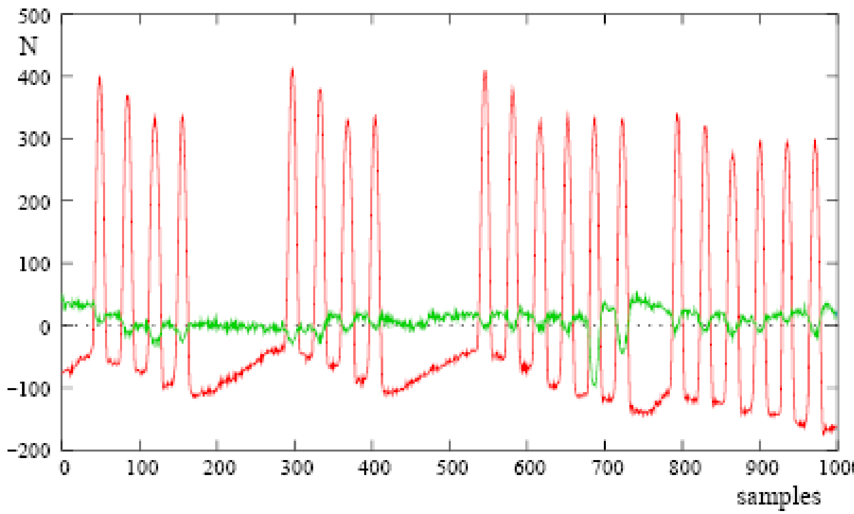
The super cycle



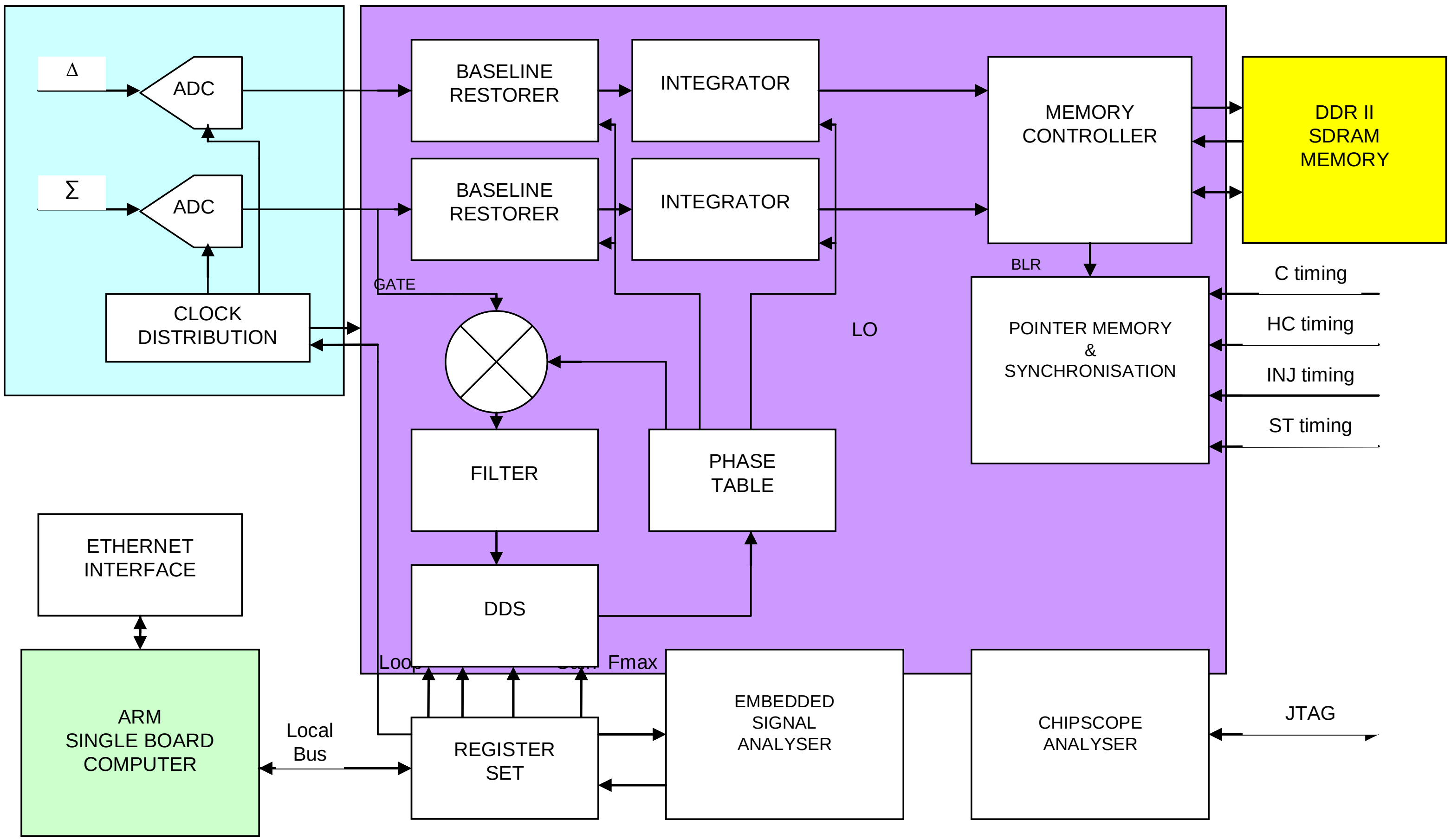
Position Measurements

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.

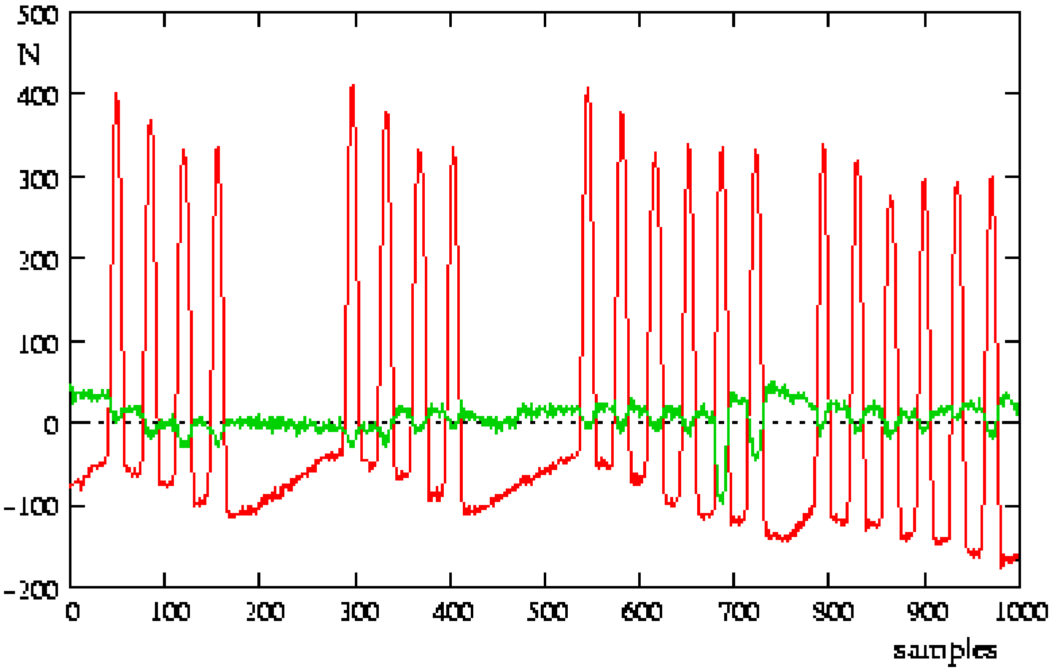


Trajectory readout electronics



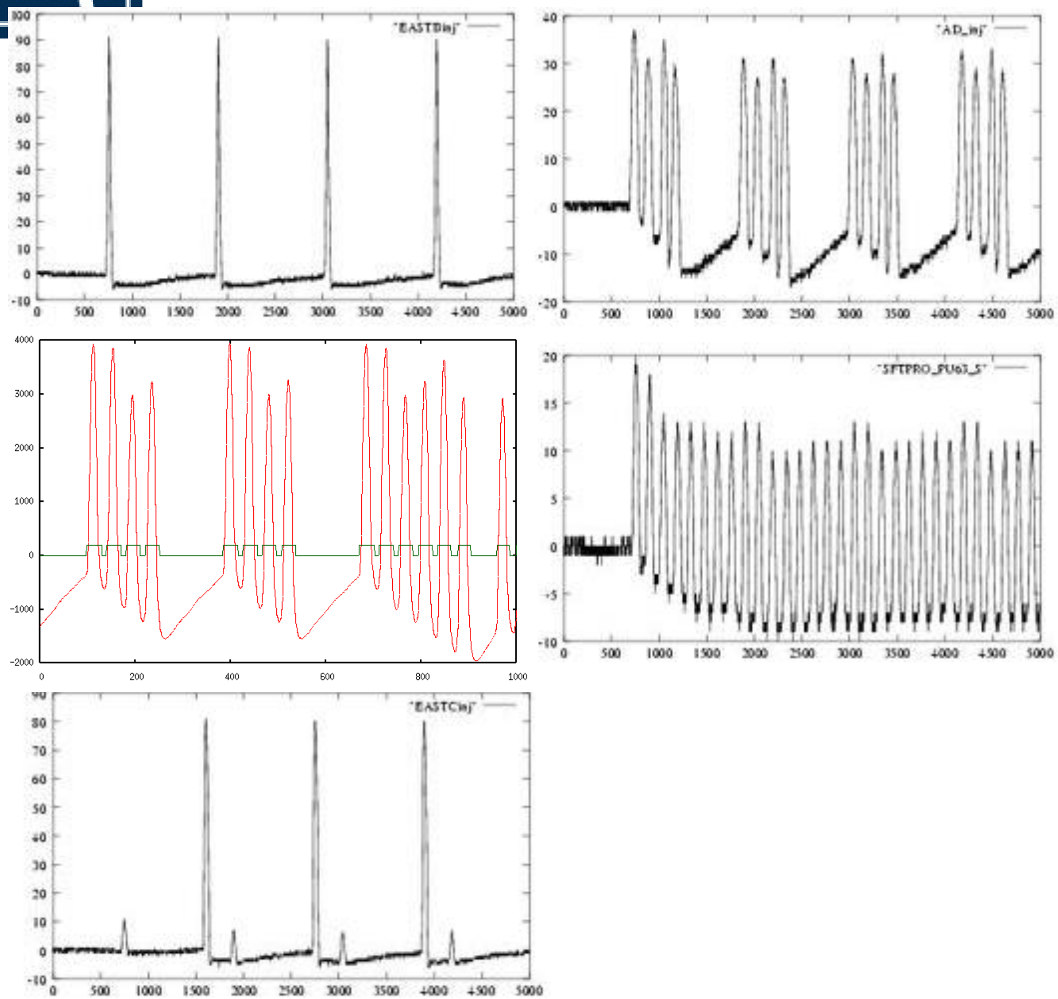
Trajectory measurements in circular machines

Needs integration gate
Can be rather tricky
Distance between bunches
changes with acceleration
Number of bunches
may change

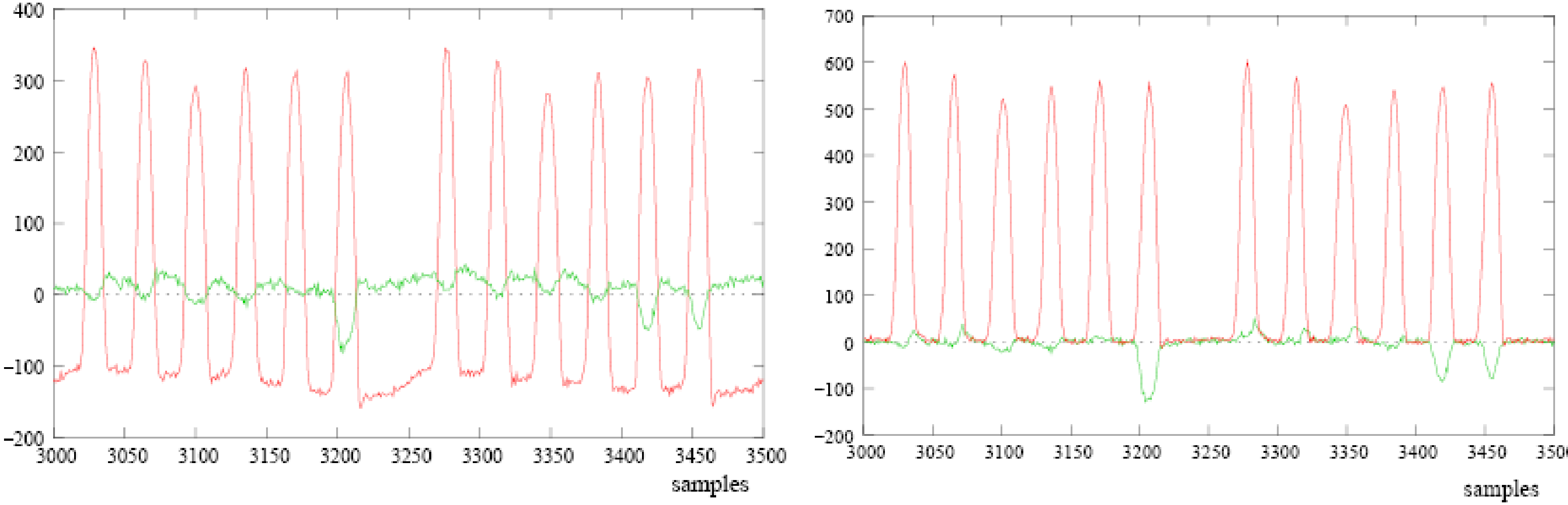


Raw data from pick-ups
double batch injection

Beams in the PS

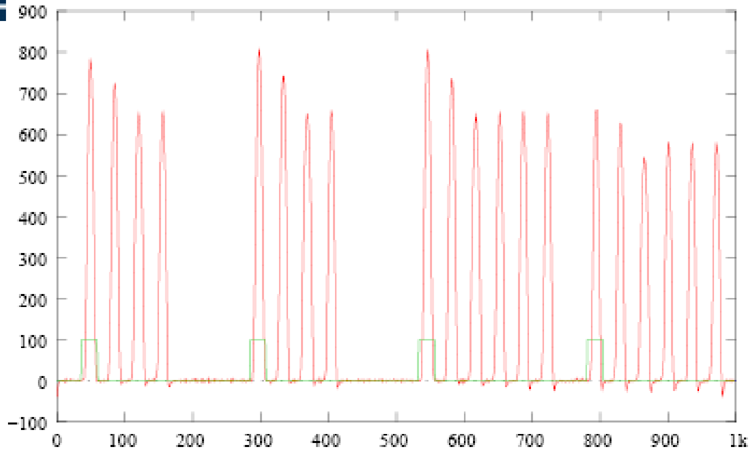


Baseline restoration

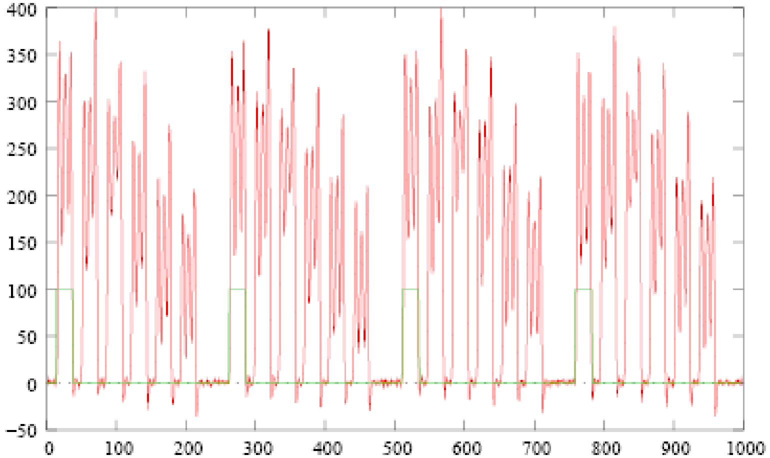


Low pass filter the signal to get an estimate of the base line
Add this to the original signal

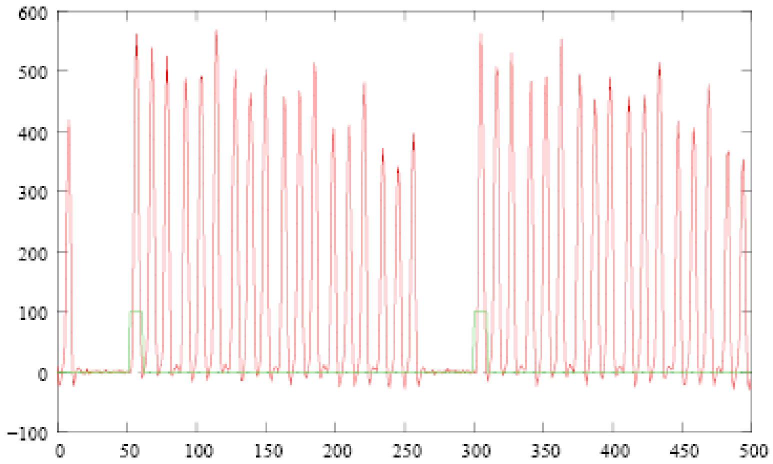
RF Gymnastics



Example of generated gate around 2nd injection

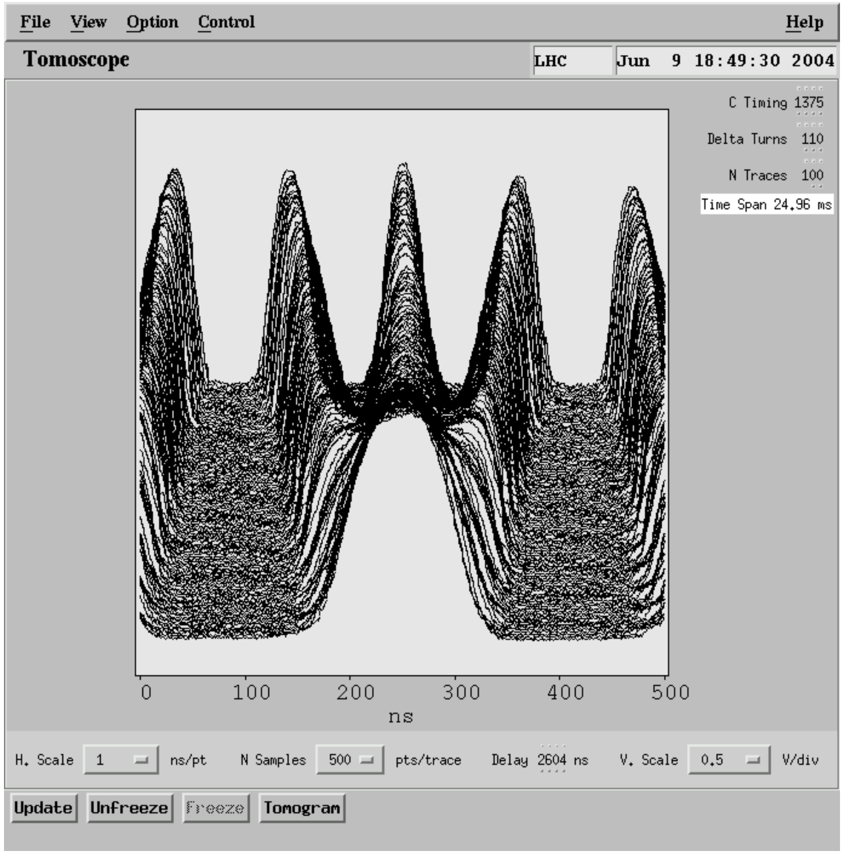


Idem, during bunch splitting



Changing bunch frequency

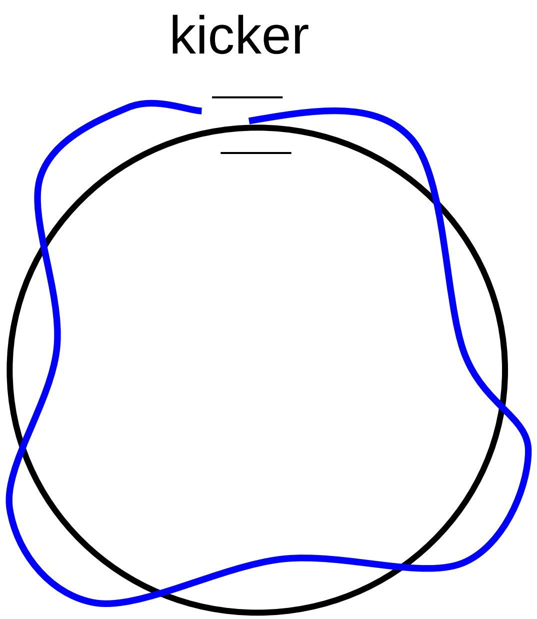
- Bunch splitting or recombination
- One RF frequency is gradually decreased while the other one is increased
- Batch compression



For all these cases the gate generator must be synchronized

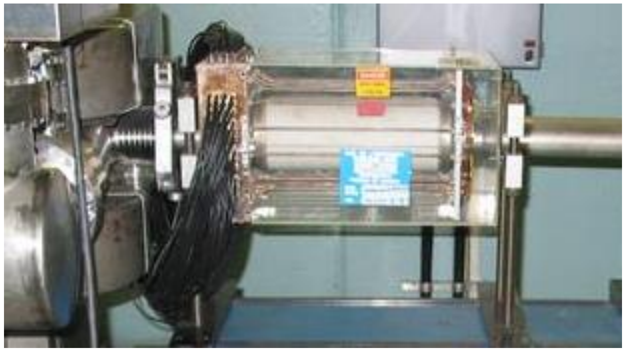
Tune measurements

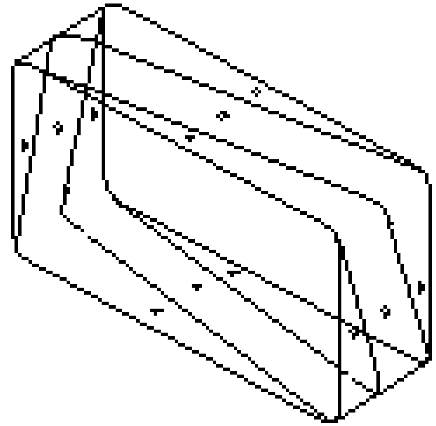
- When the beam is displaced (e.g. at injection or with a deliberate kick, it starts to oscillate around its nominal orbit (betatron oscillations)
- Measure the trajectory
- Fit a sine curve to it
- Follow it during one revolution



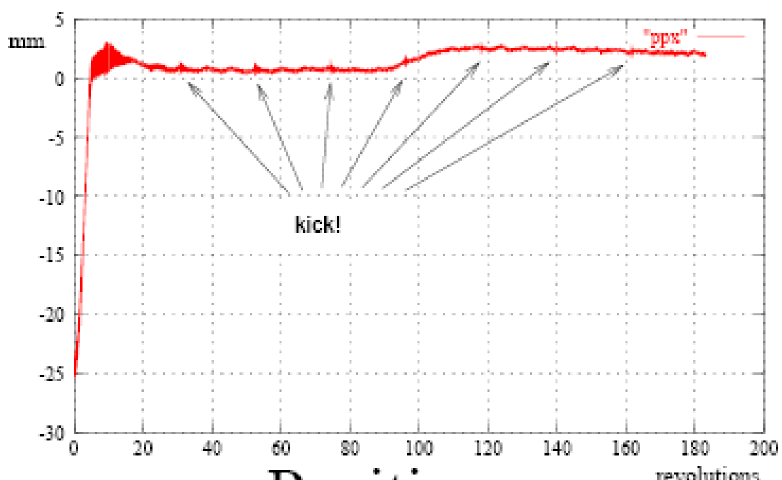
The Sensors

Shoebox pick-up
with linear cut

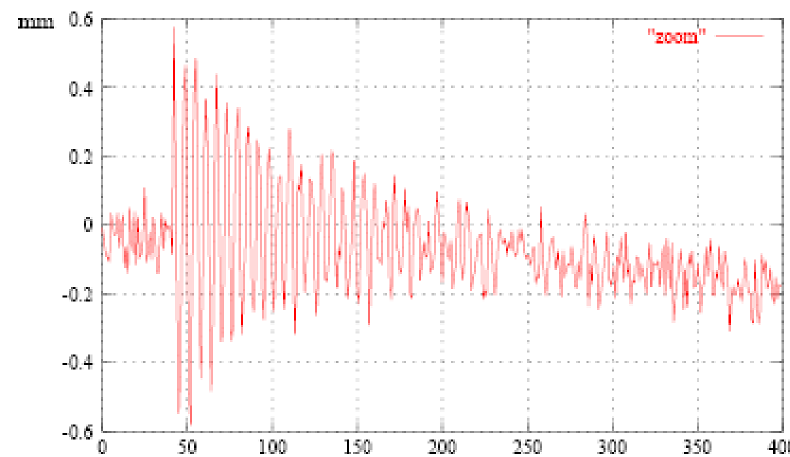




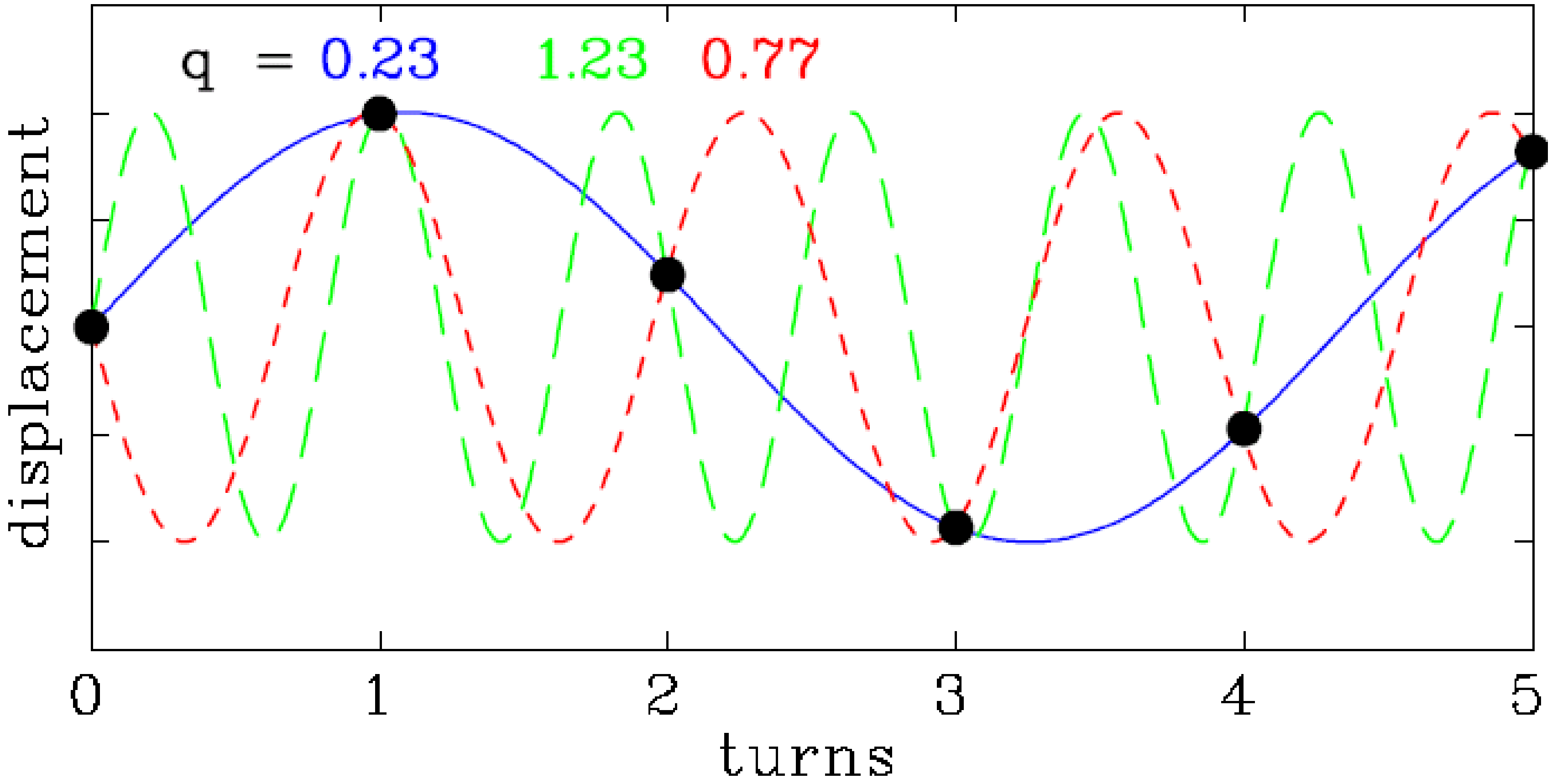
The kicker



Position



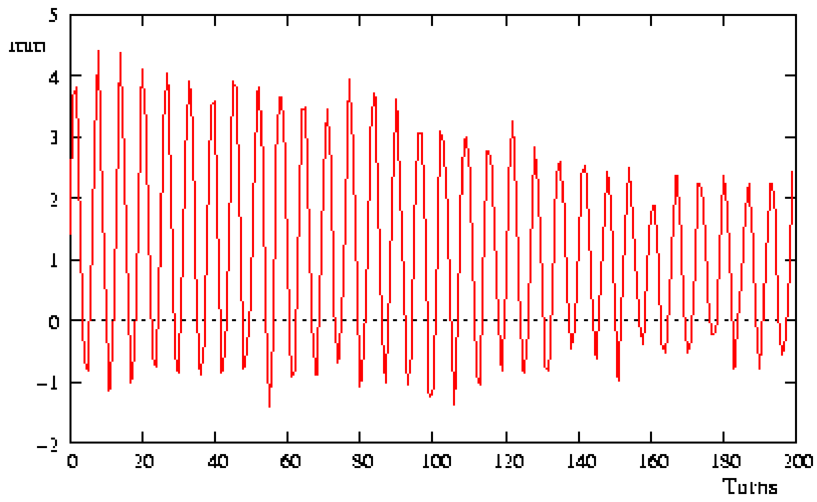
Tune measurements with a single PU

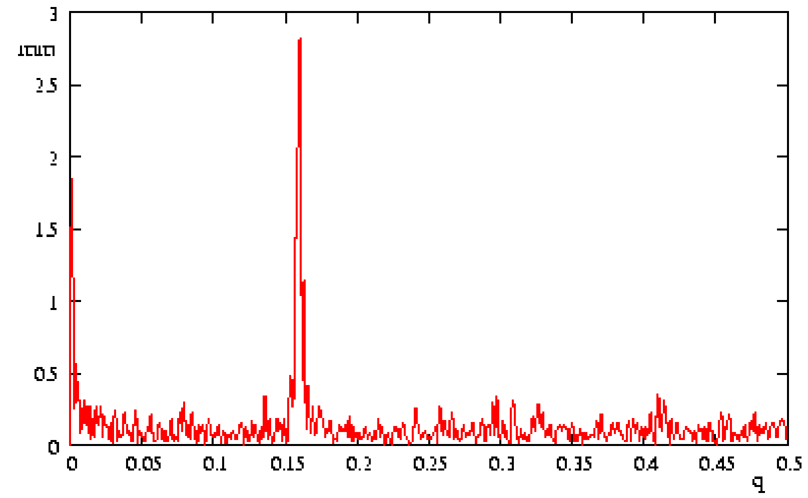


Design by P. Forck

Kicker + 1 pick-up

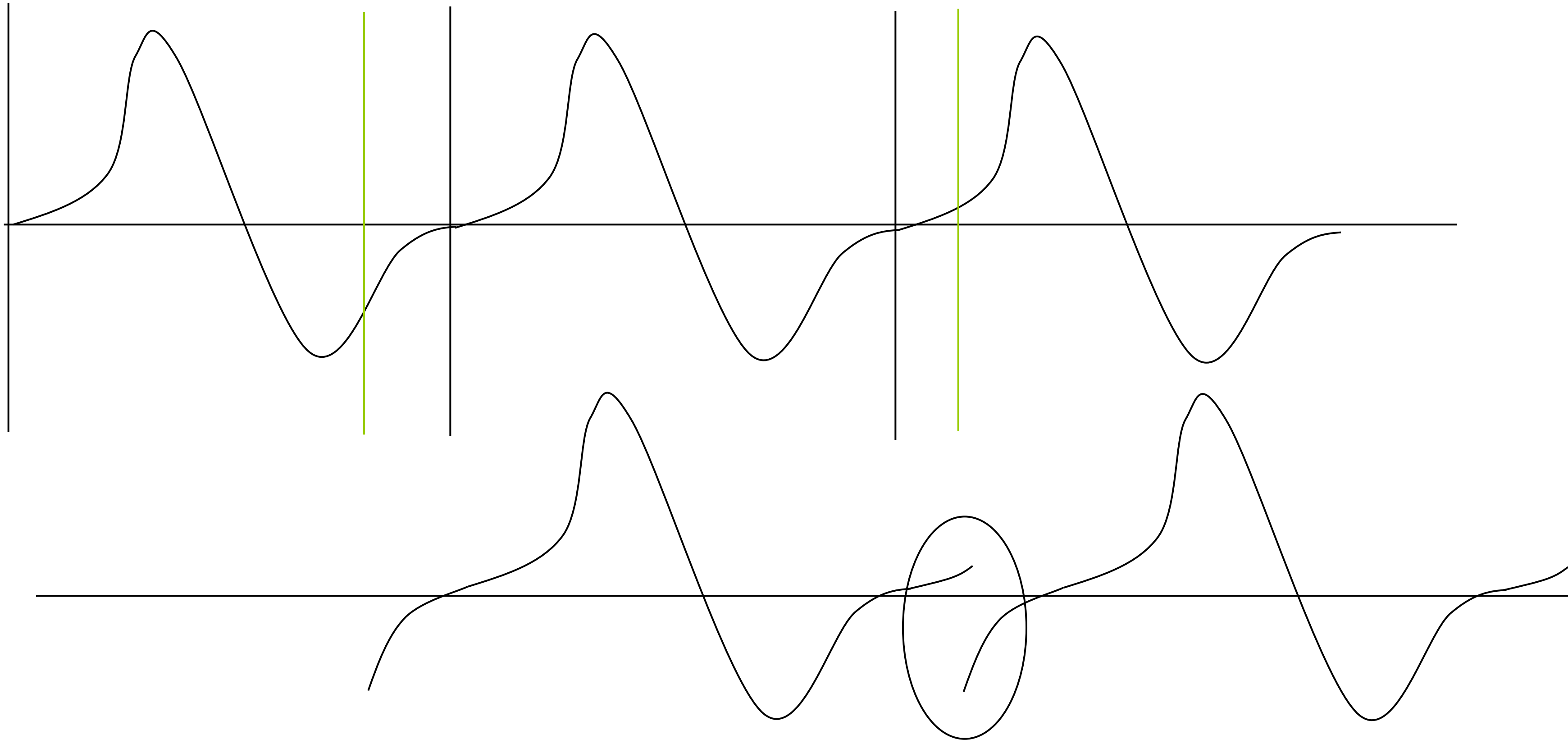
- Measures only non-integral part of Q
- Measure a beam position at each revolution





Fourier transform of pick-up signal

Periodic extension of the signal and Windowing



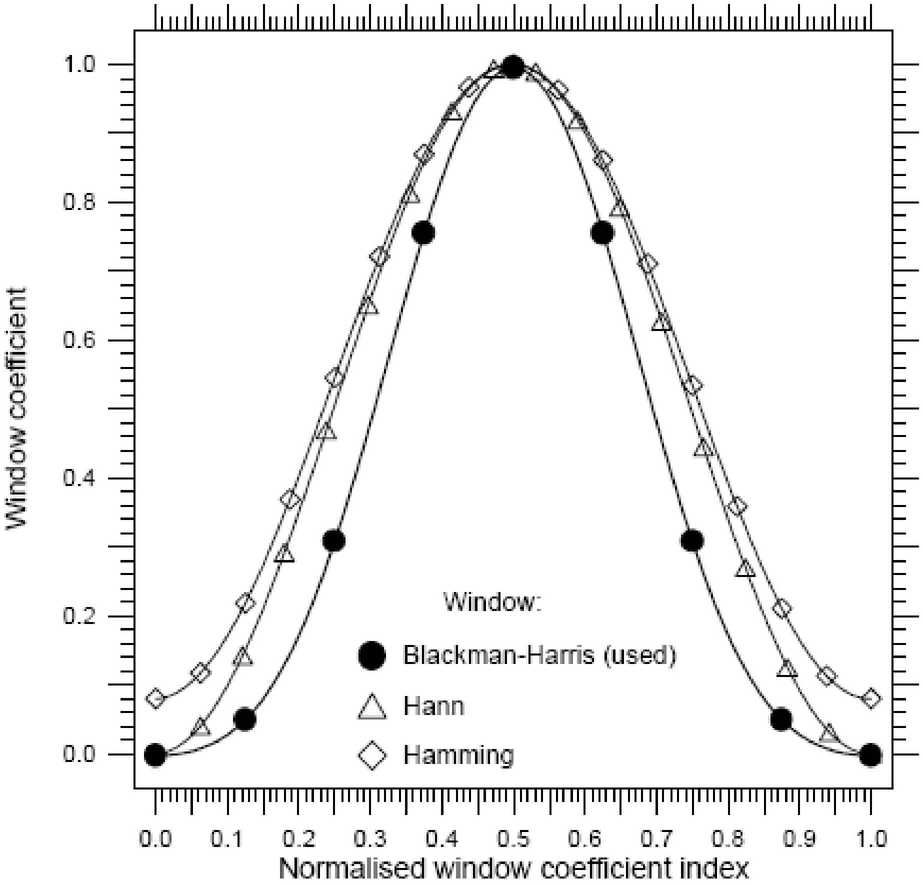
Windowing

The Discrete Fourier assumes one cycle of a repetitive signal.

Blackman-Harris Window is used

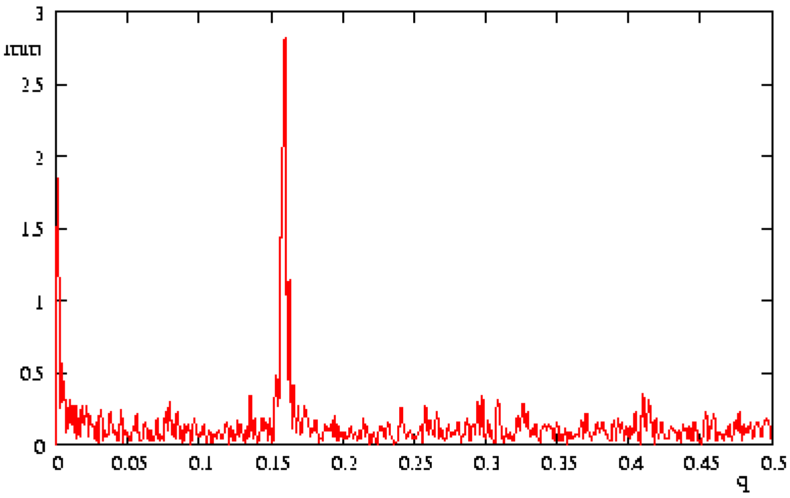
Each sample is multiplied with a coefficient

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.



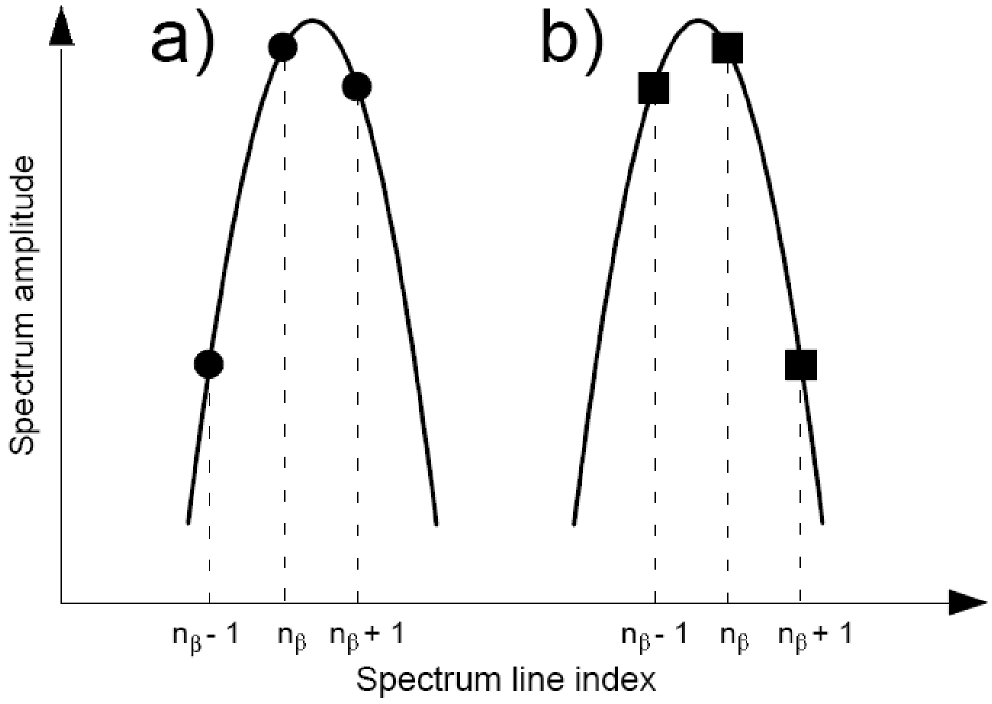
Q interpolation

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

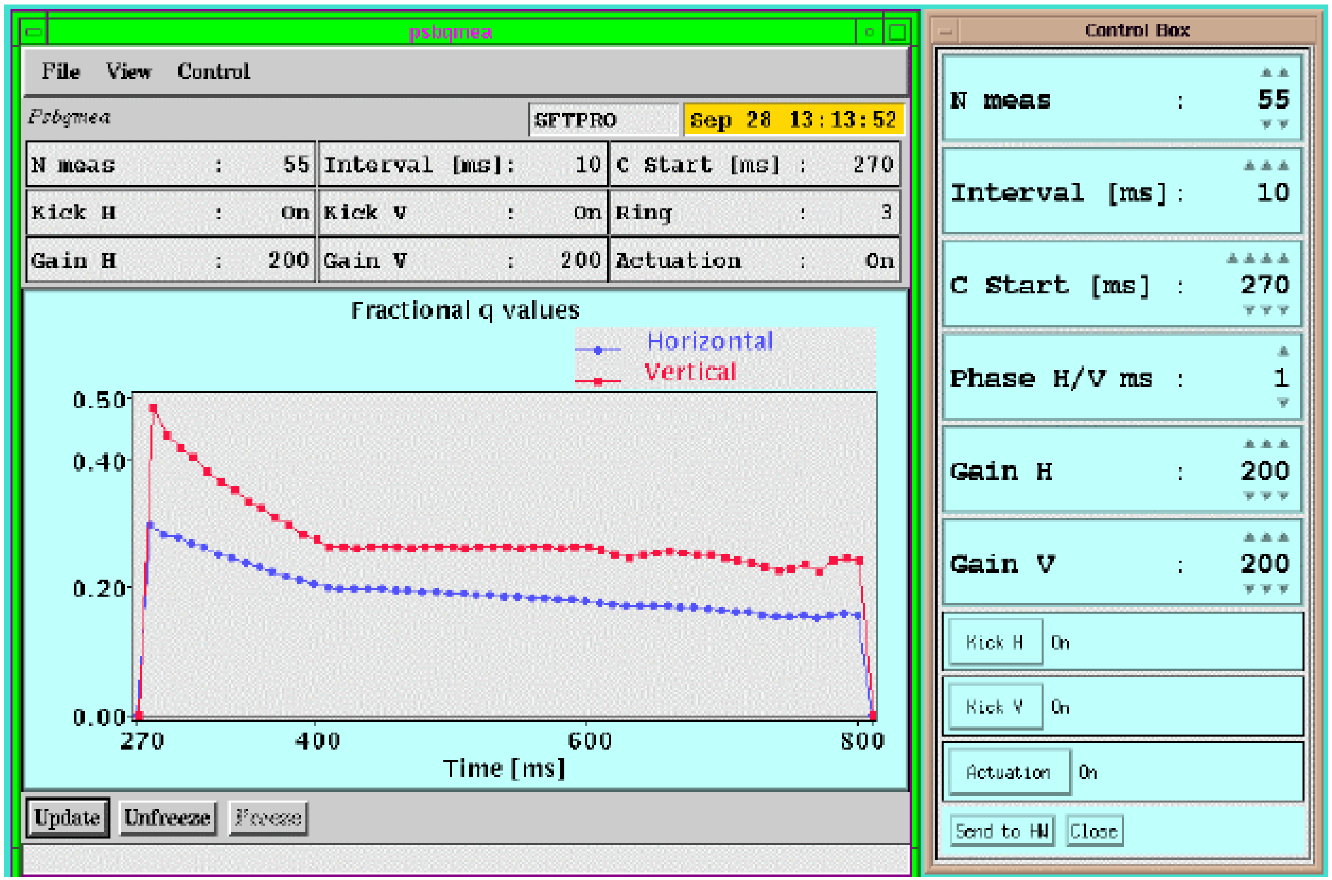
$$V(n_\beta - 1) = a(n_\beta - 1)^2 + b(n_\beta - 1) + c$$

$$V(n_\beta) = an_\beta{}^2 + bn_\beta + c$$

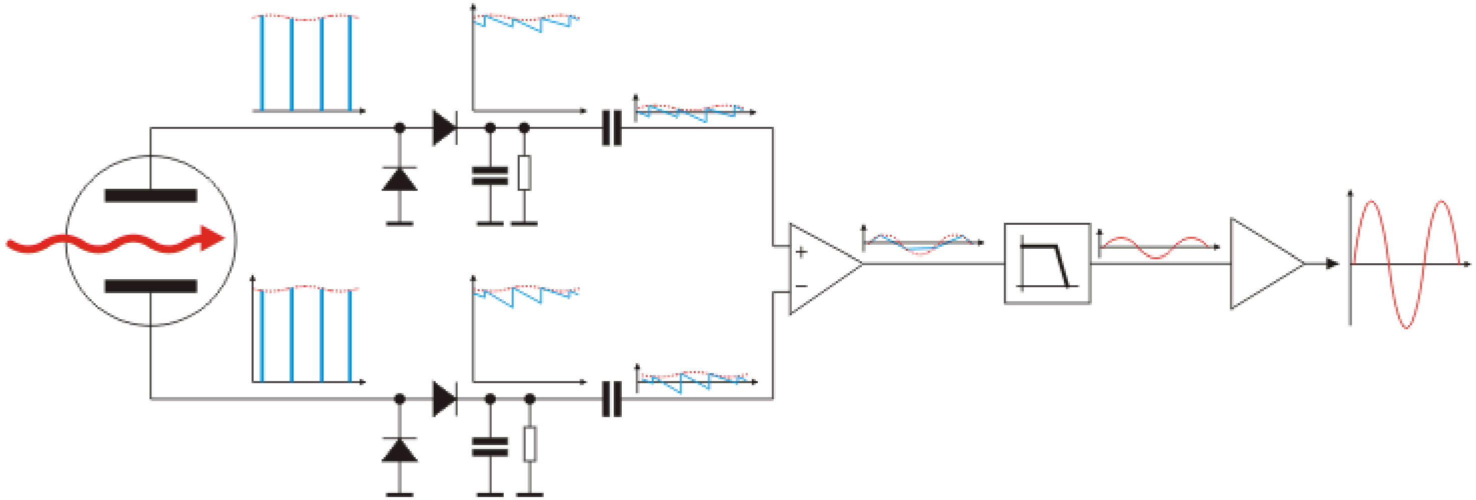
$$V(n_\beta + 1) = a(n_\beta + 1)^2 + b(n_\beta + 1) + c$$



Q-Measurement Results



Direct Diode Detection Base Band Q measurement



Diode Detectors convert spikes to saw-tooth waveform

Signal is connected to differential amplifier to cut out DC level

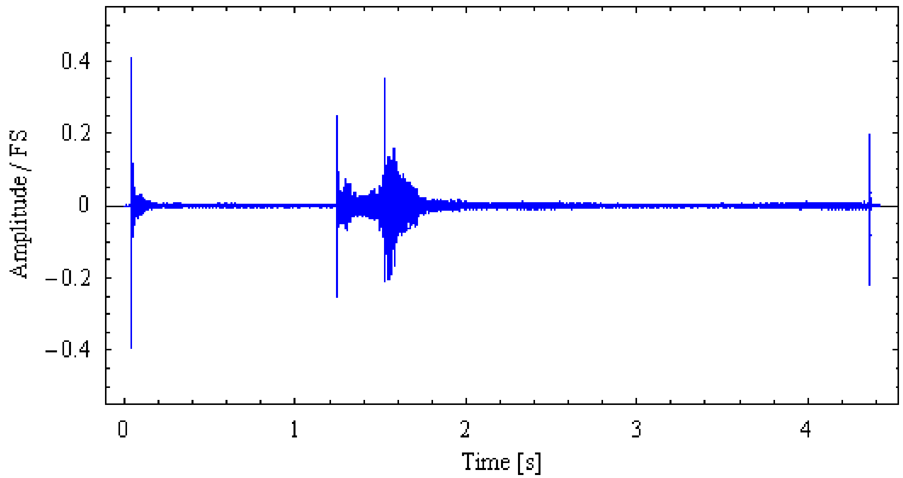
Filter eliminates most of the revolution frequency content

Output amplifier brings the signal level to amplitudes suitable for long distance transmission

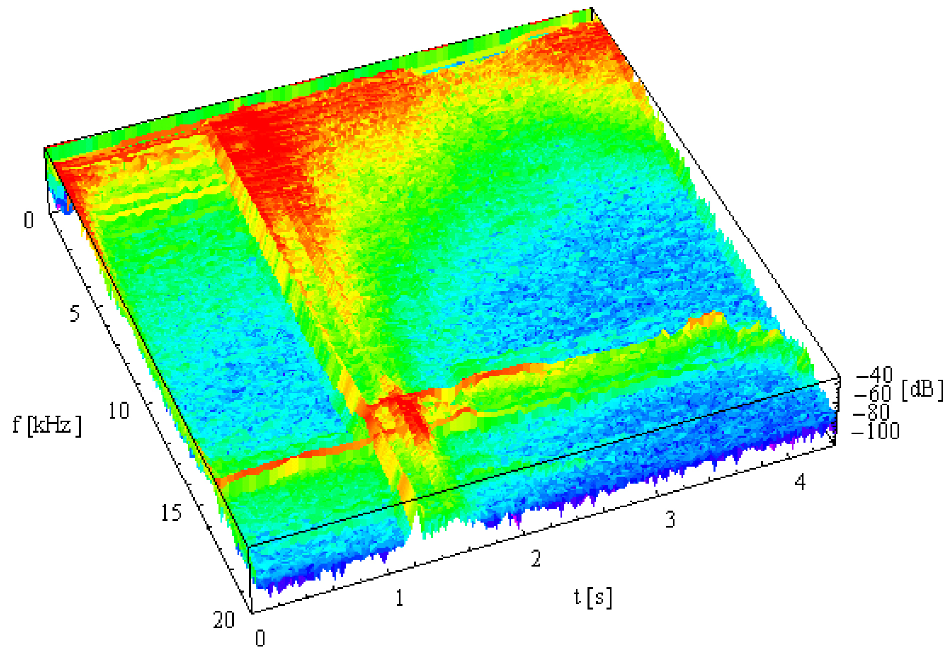
Curtesy M. Gasior

BBQ Results from CERN SPS

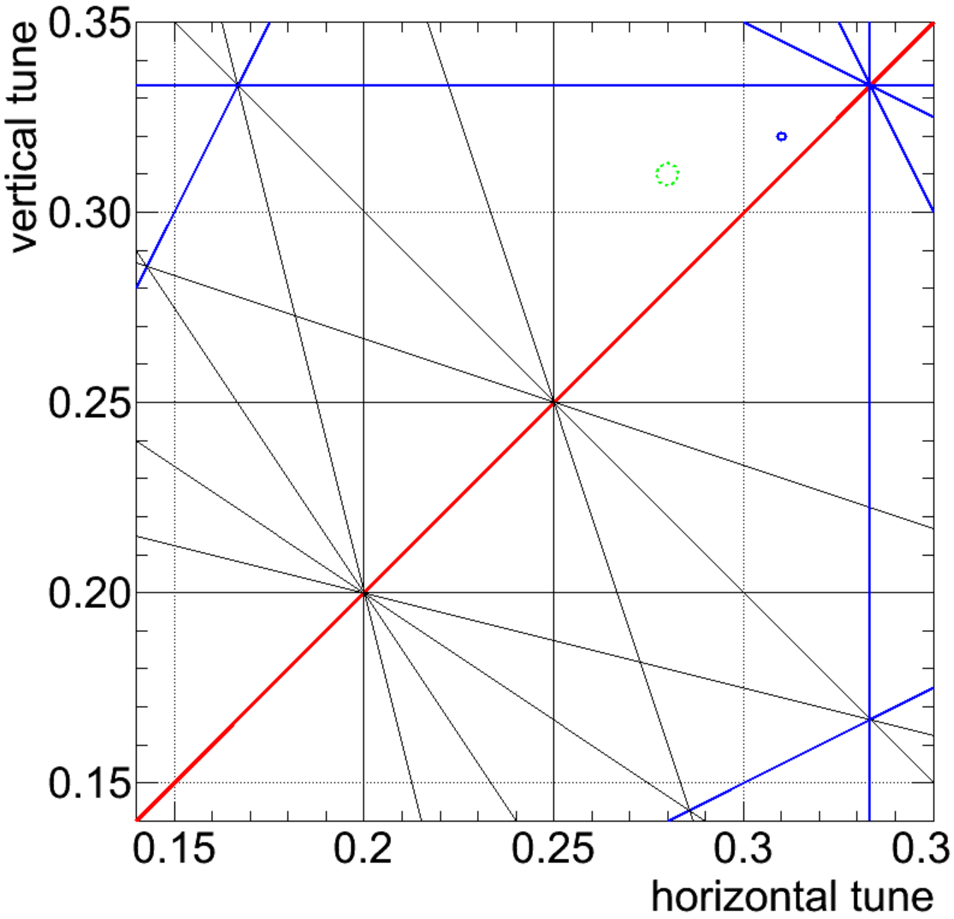
Results from Sampling

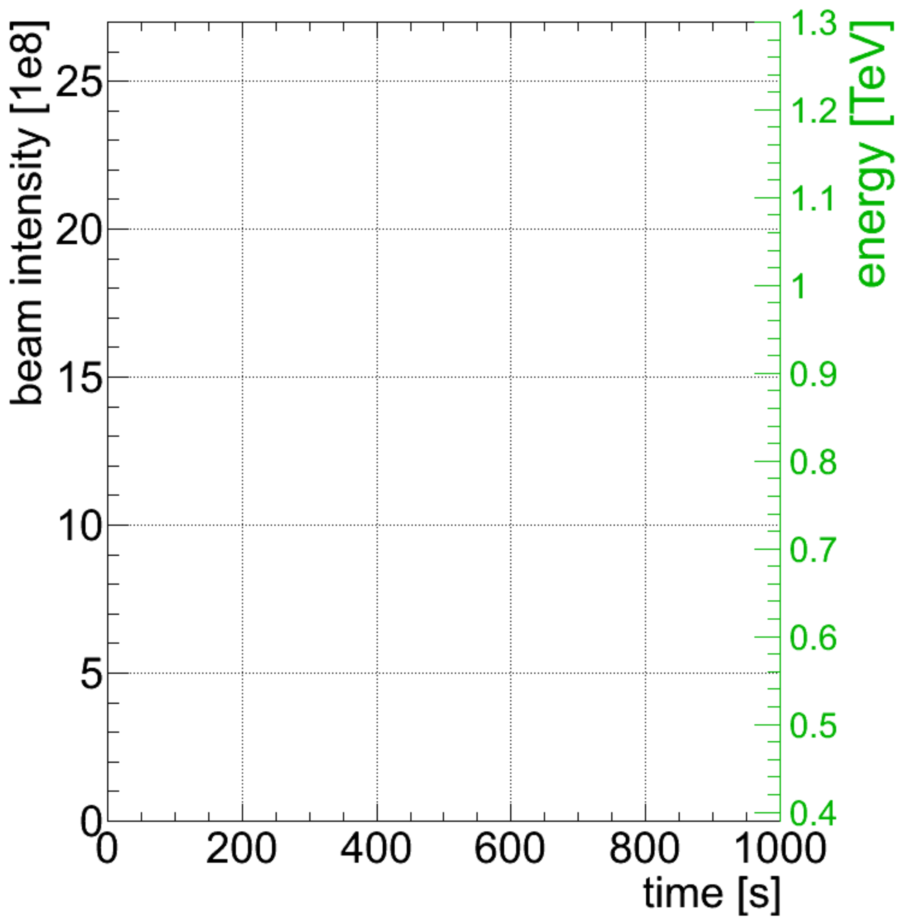


After Fourier Transform

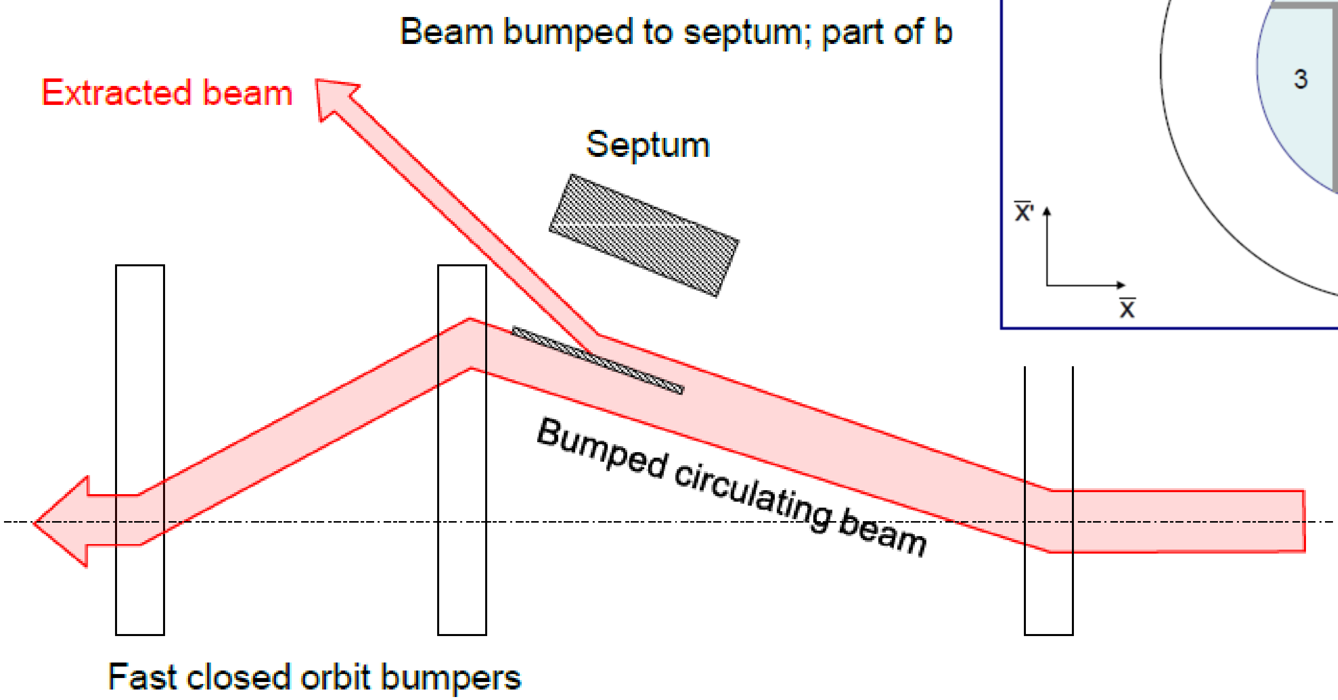


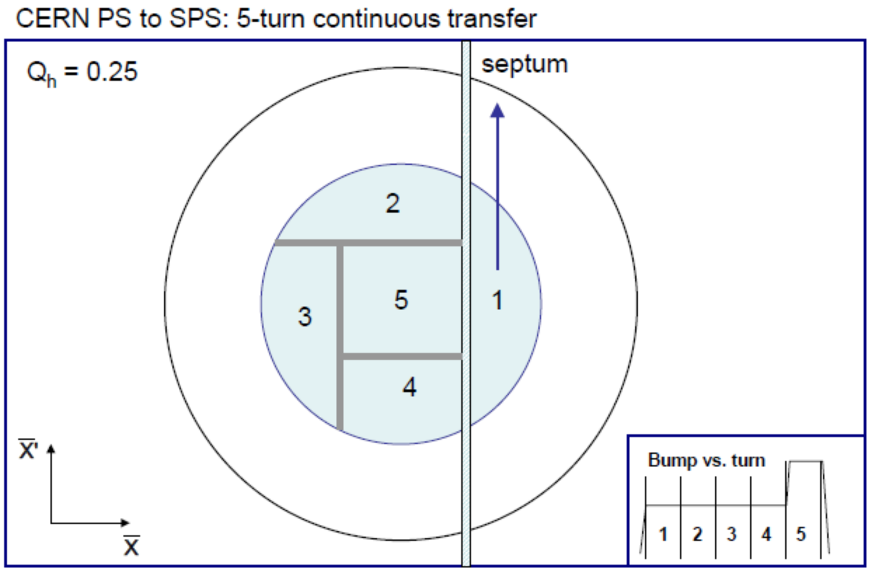
Tune feedback at the LHC





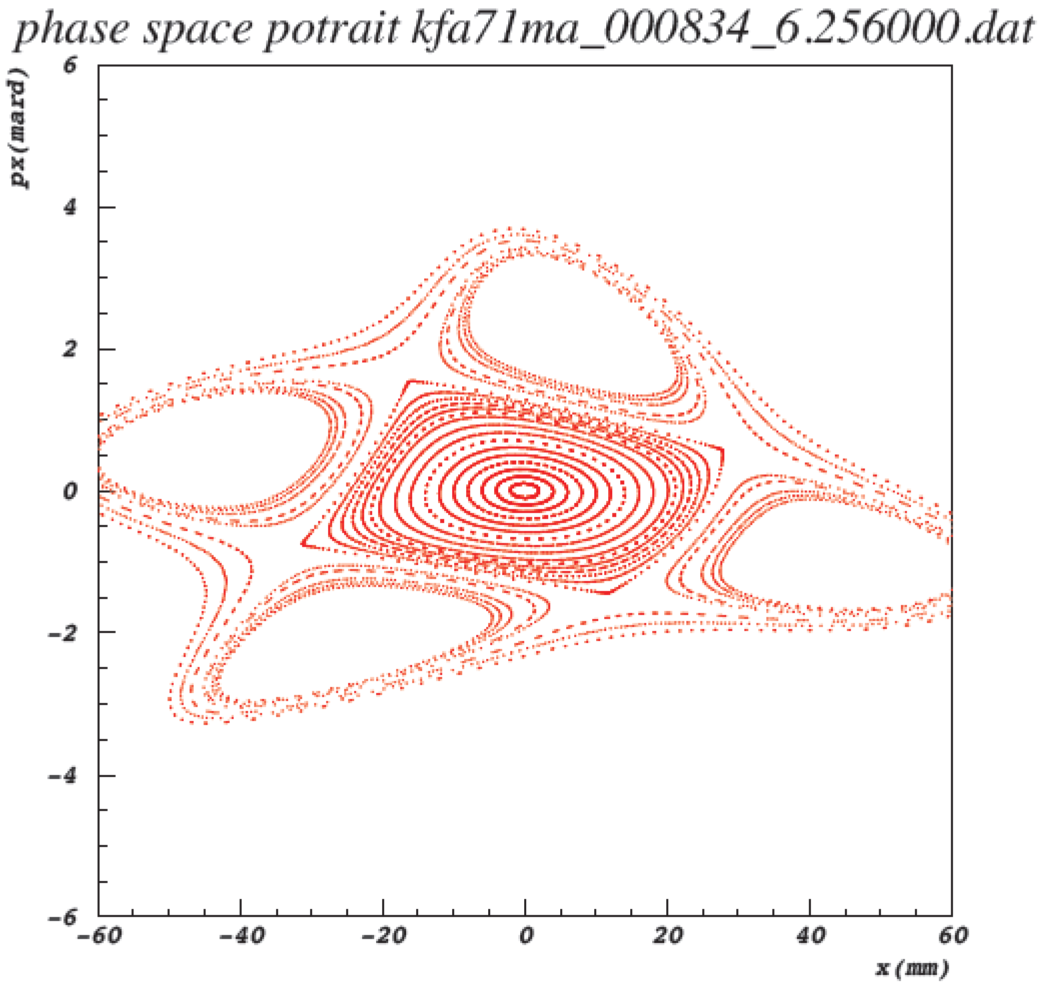
Multi-Turn Extraction





Losses on the septum blade

Islands in transverse phase space

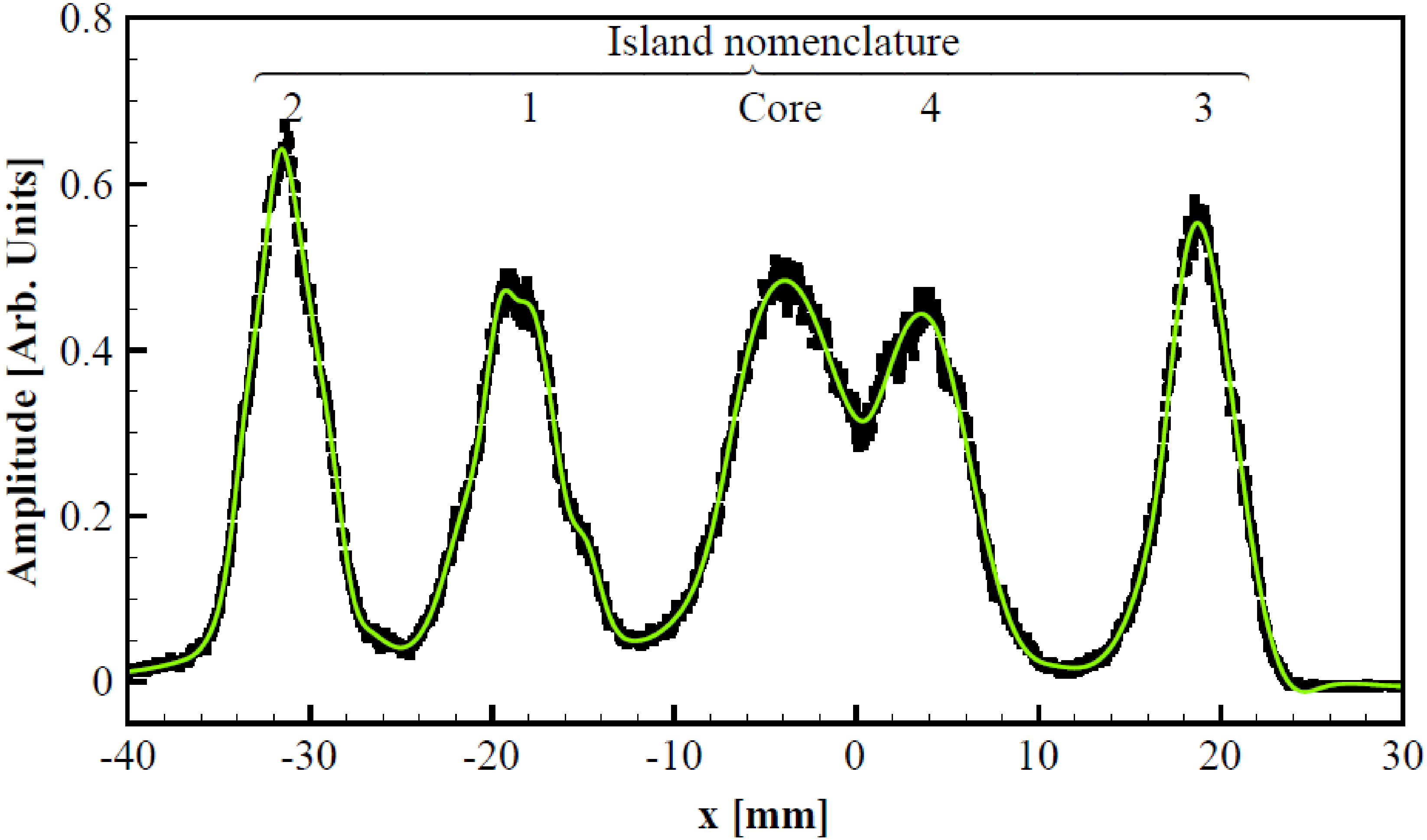


Create stable island
in phase space through
excitation with hexapoles and
octopoles and capture
the beam in them

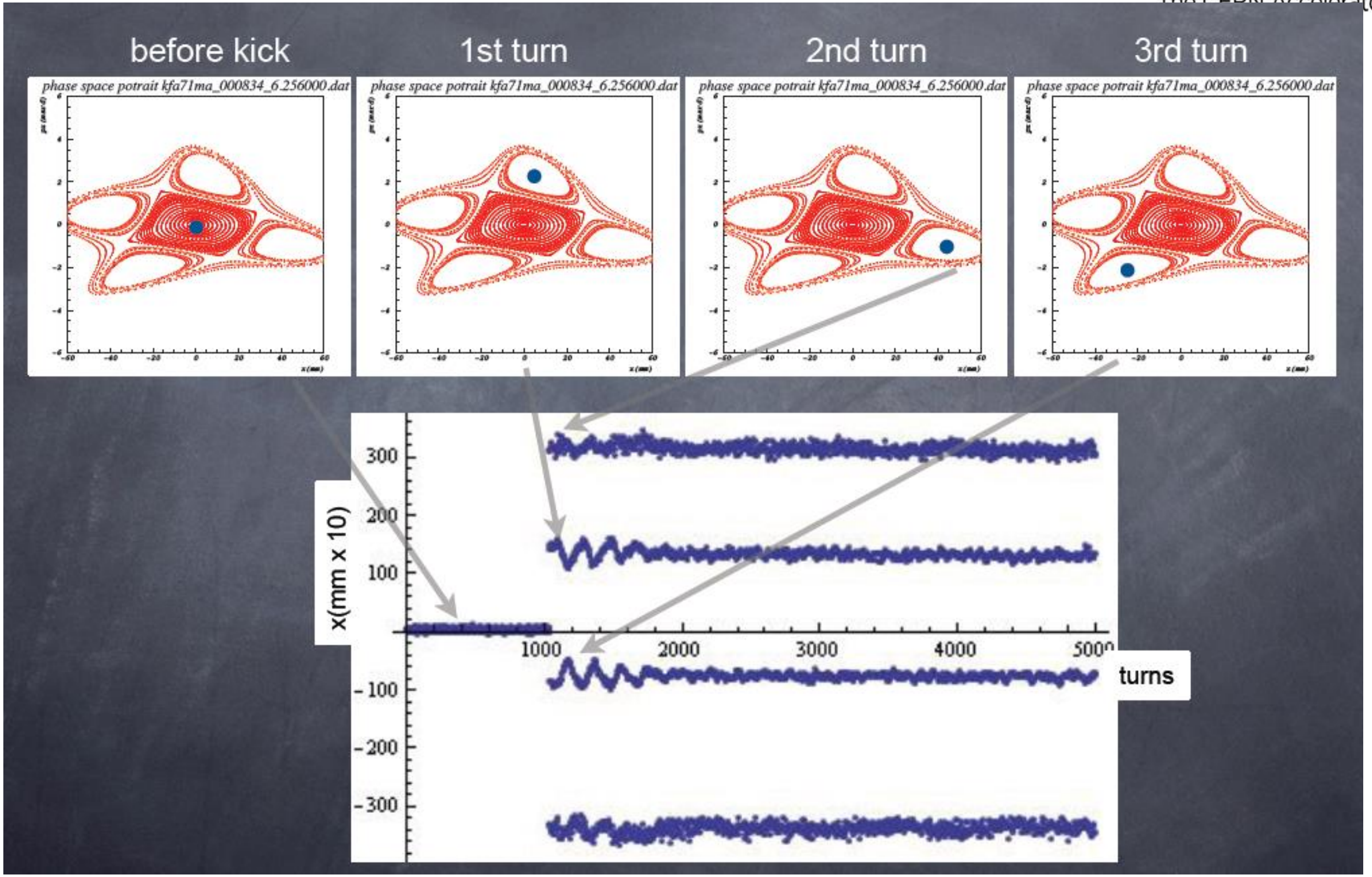
Can this be measured?

Poor man‘s phase space
meter using 2 BPMs at
90° phase advance

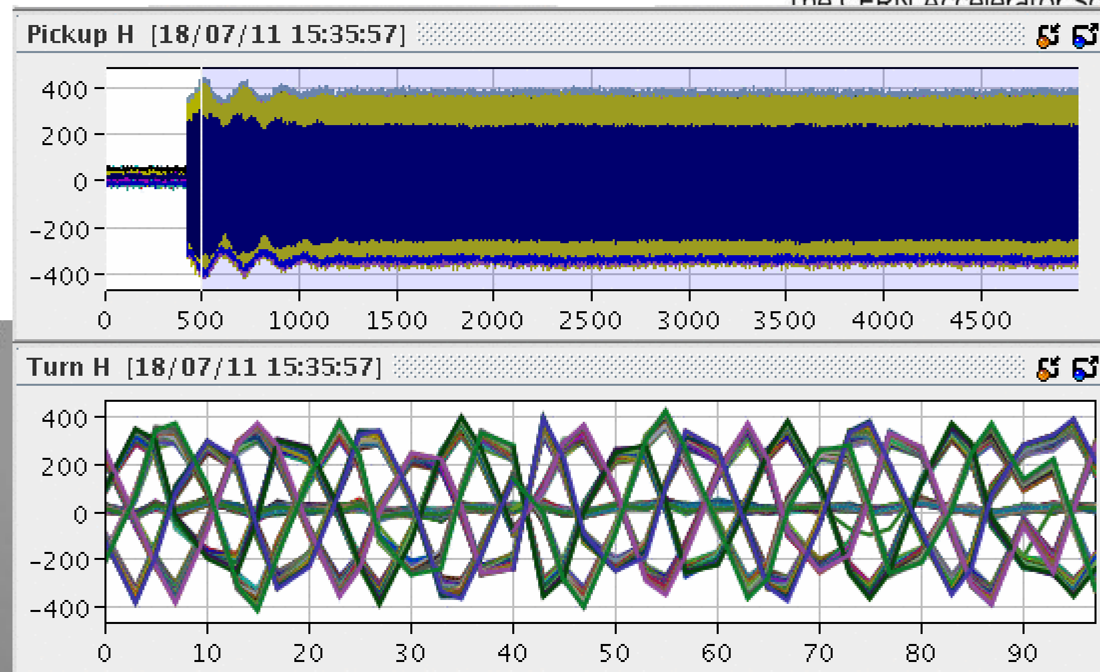
Profile of Islands

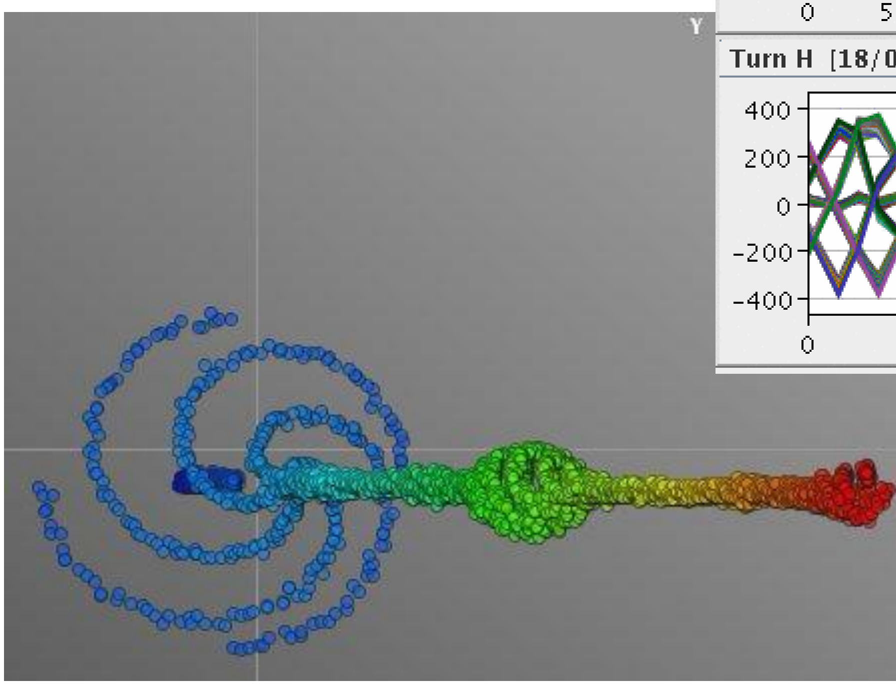


Stable Islands in Phase Space

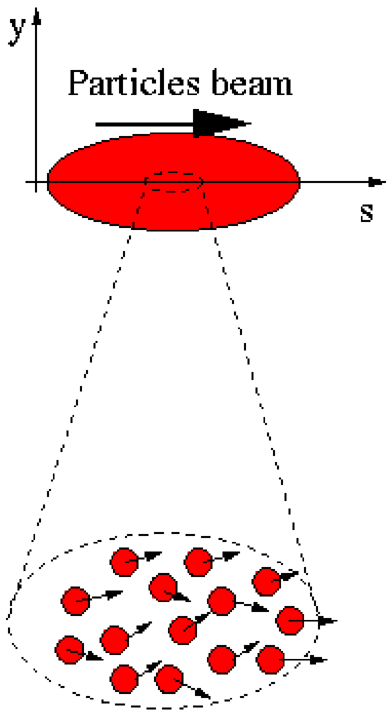


Projection in Phase Space





Emittance measurements



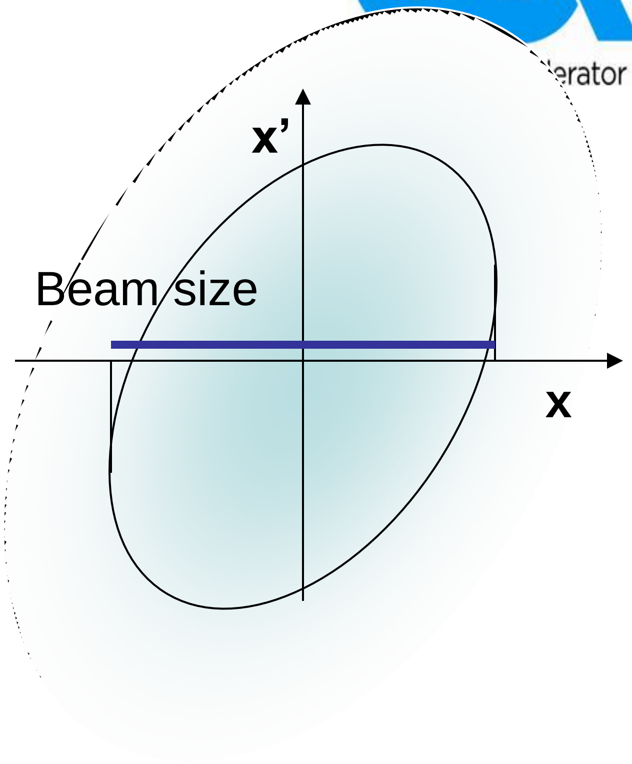
A beam is made of many many particles, each one of these particles is moving with a given velocity. Most of the velocity vector of a single particle is parallel to the direction of the beam as a whole (s). There is however a smaller component of the particles velocity which is perpendicular to it (x or y).

$$\vec{v}_{particle} = v_s \hat{u}_s + v_x \hat{u}_x + v_y \hat{u}_y$$

Design by E. Bravin

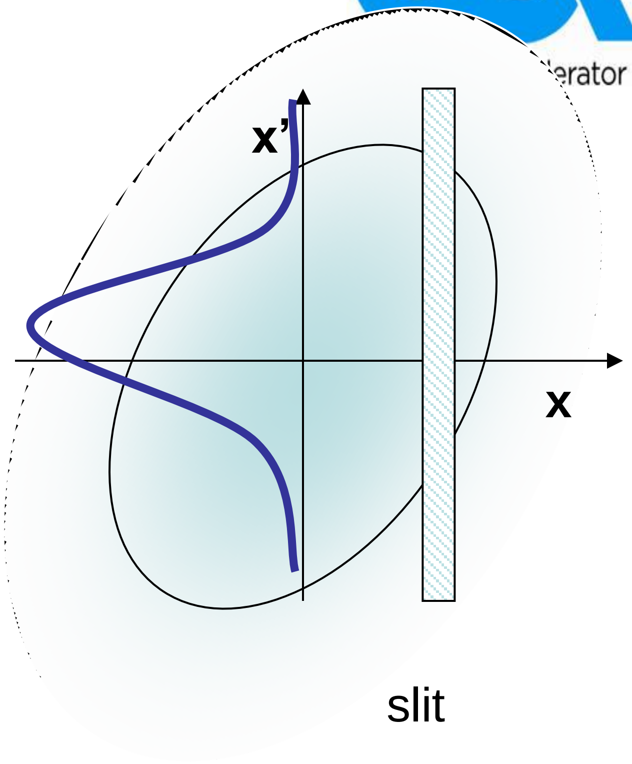
Emittance measurements

- If for each beam particle we plot its position and its transverse angle we get a particle distribution who's boundary is an usually ellipse.
- The projection onto the x axis is the beam size



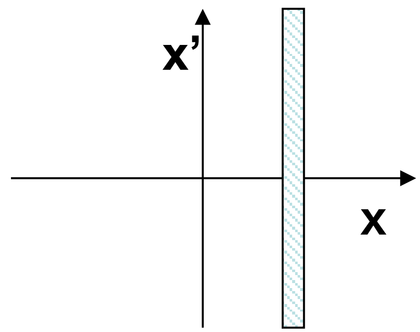
The slit method

- If we place a slit into the beam we cut out a small vertical slice of phase space
- Converting the angles into position through a drift space allows to reconstruct the angular distribution at the position defined by the slit



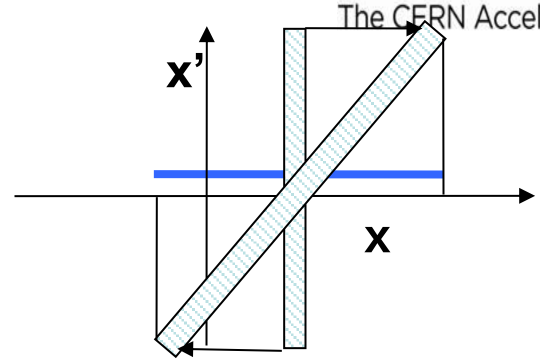
Transforming angular distribution to profile

- When moving through a drift space the angles don't change (horizontal move in phase space)
- When moving through a quadrupole the position does not change but the angle does (vertical move in phase space)



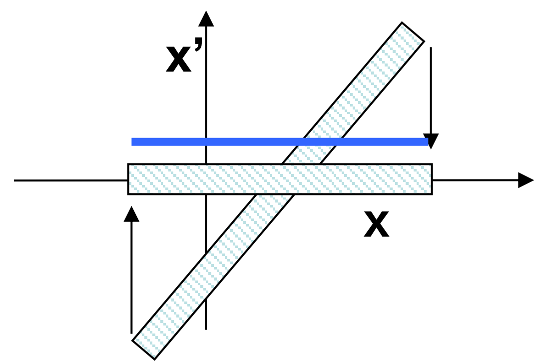
slit

Influence of a drift space



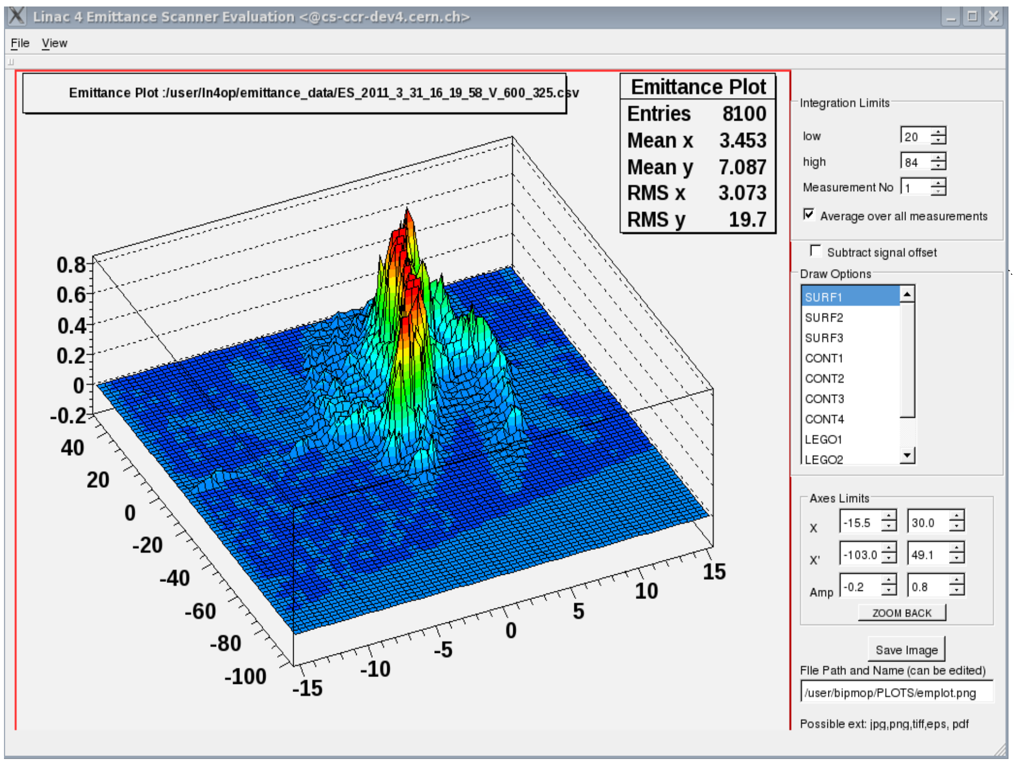
slit

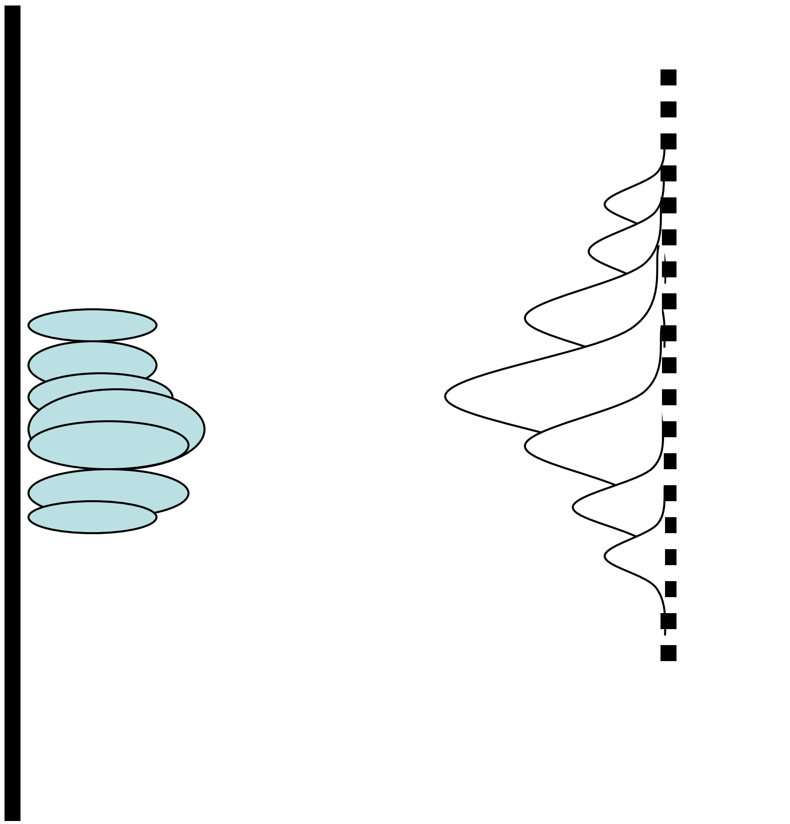
Influence of a quadrupole



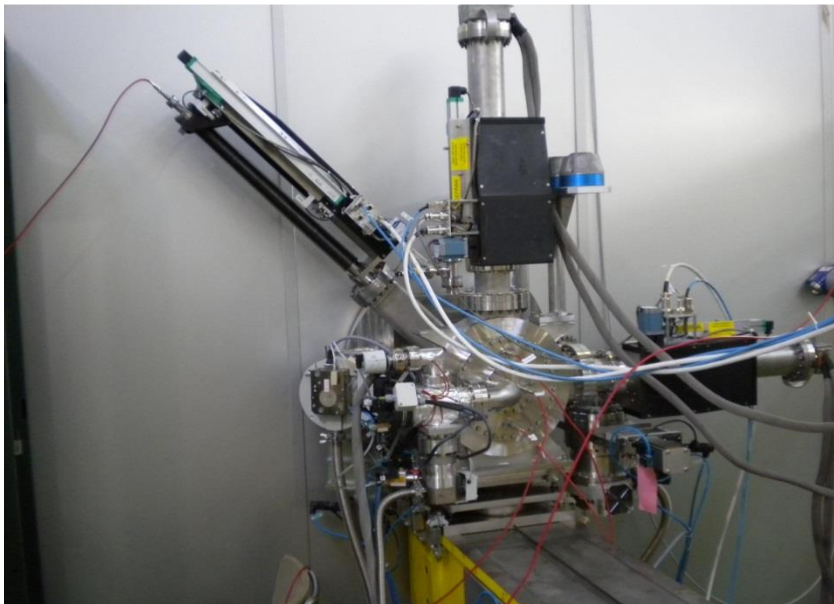
slit

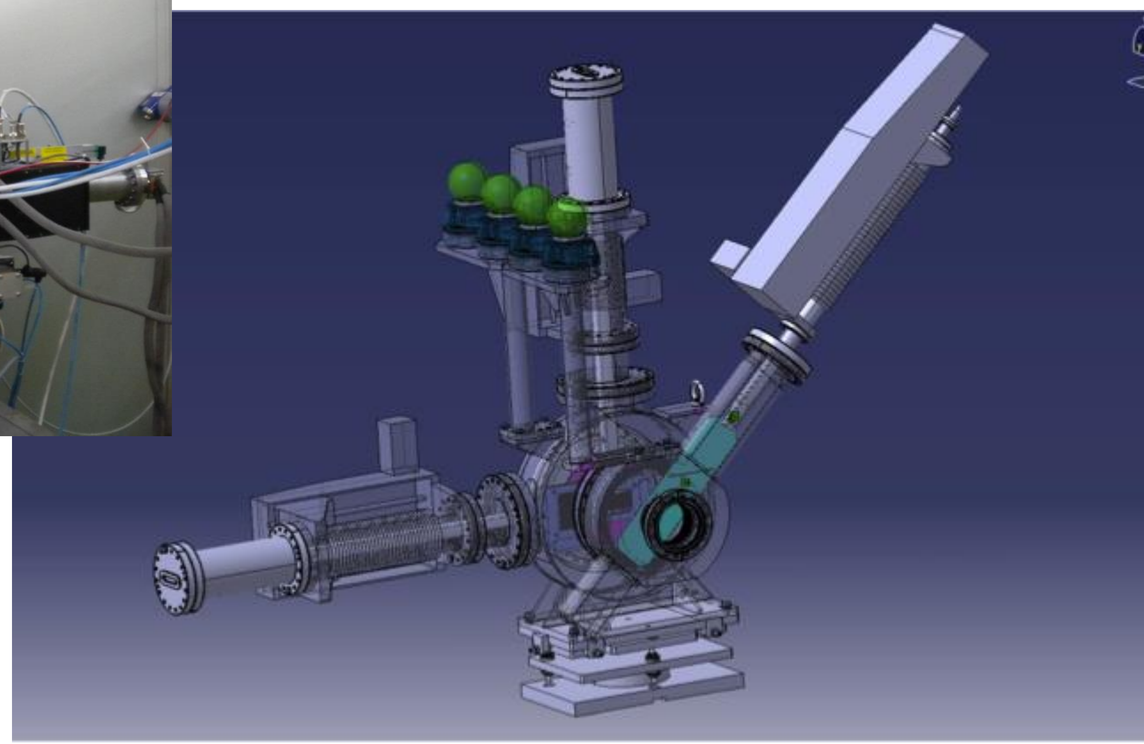
The Slit Method





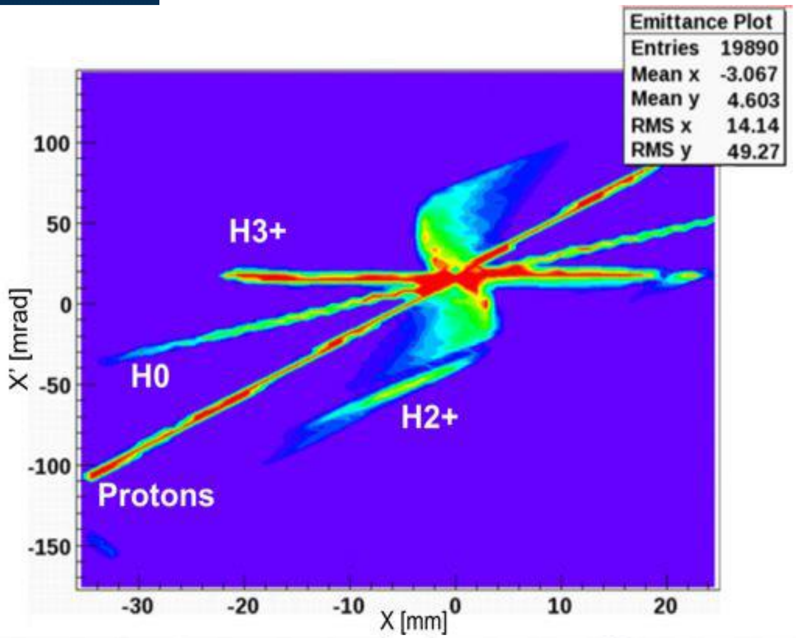
Phase Space Scanner

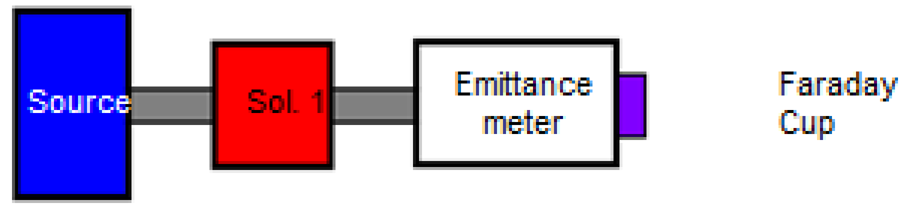


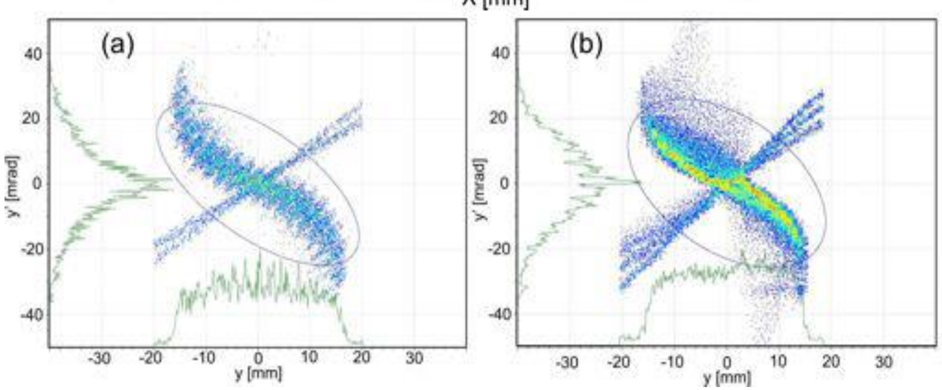


Emittance plot Solenoid

- (







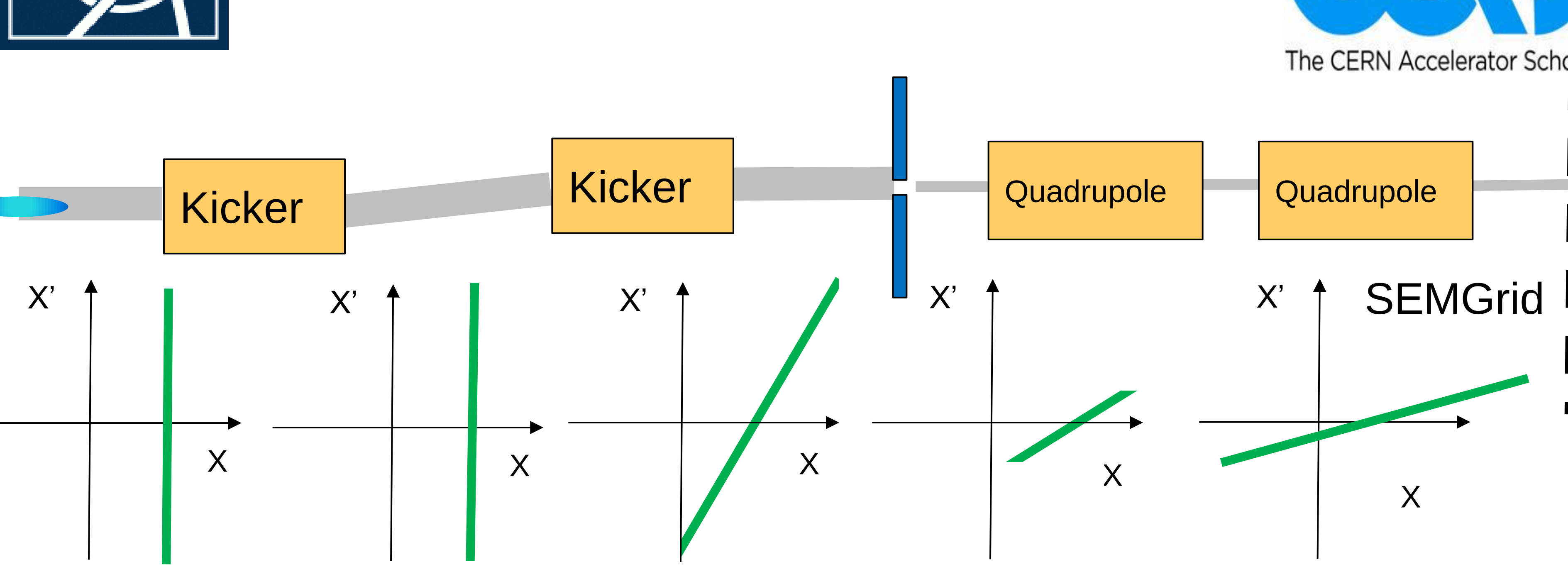
The solenoid splits
the trajectories according to
particle type.
The source produces

- protons
- H^0
- H_2^+
- H_3^+

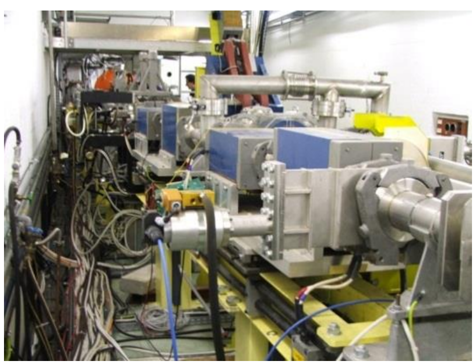
Moving slit emittance measurement

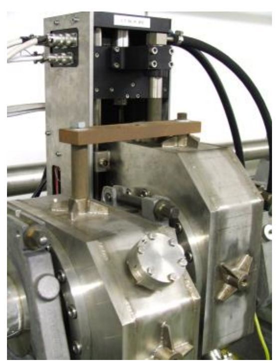
- Position resolution given by slit size and displacement
- Angle resolution depends on resolution of profile measurement device and drift distance
- High position resolution → many slit positions → slow
- Shot to shot differences result in measurement errors

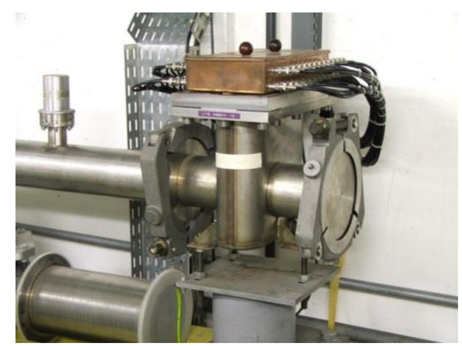
Transformation in Phase Space



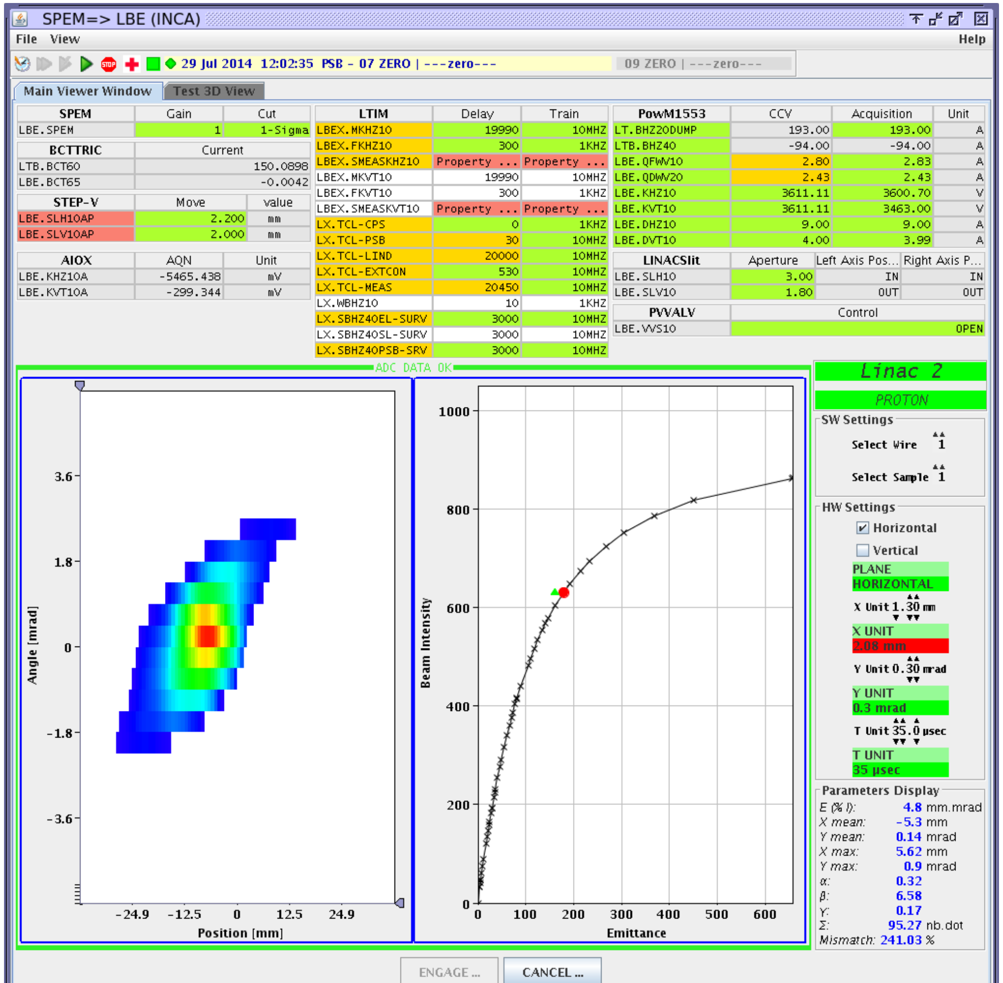
at slit | first drift space | first quadrupole | second drift space | Second quadrupol





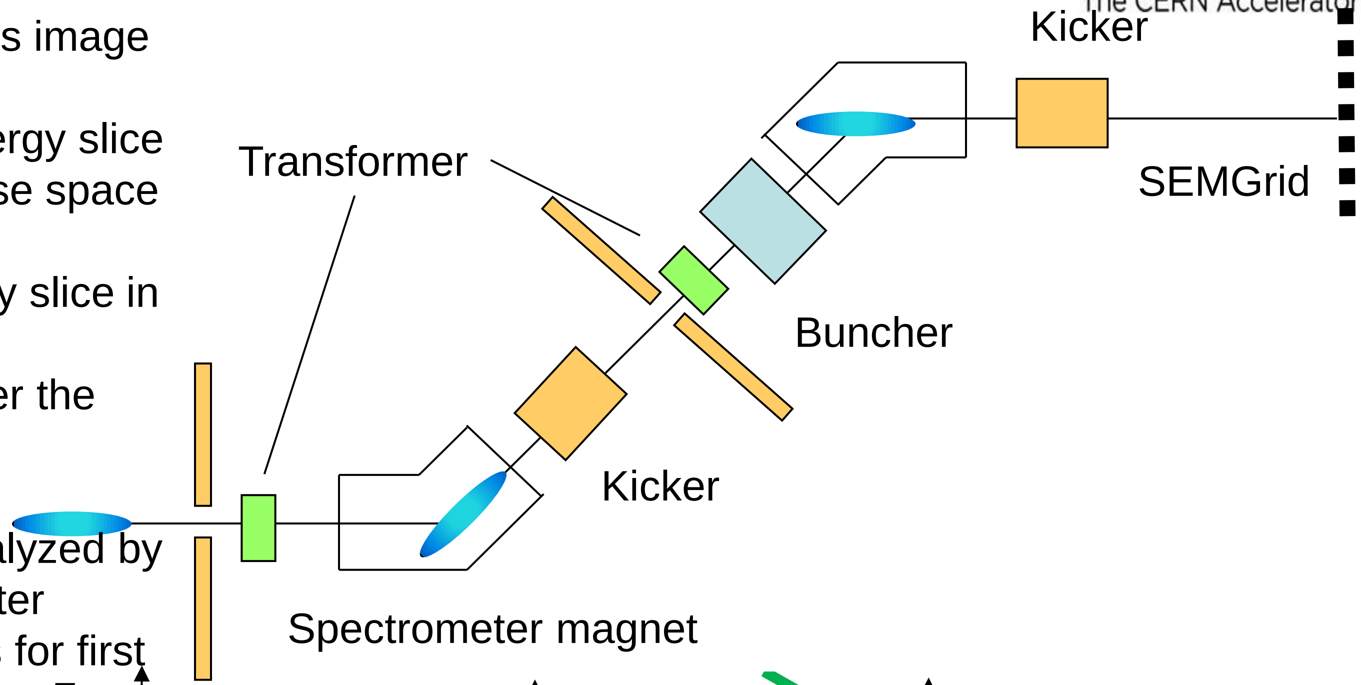


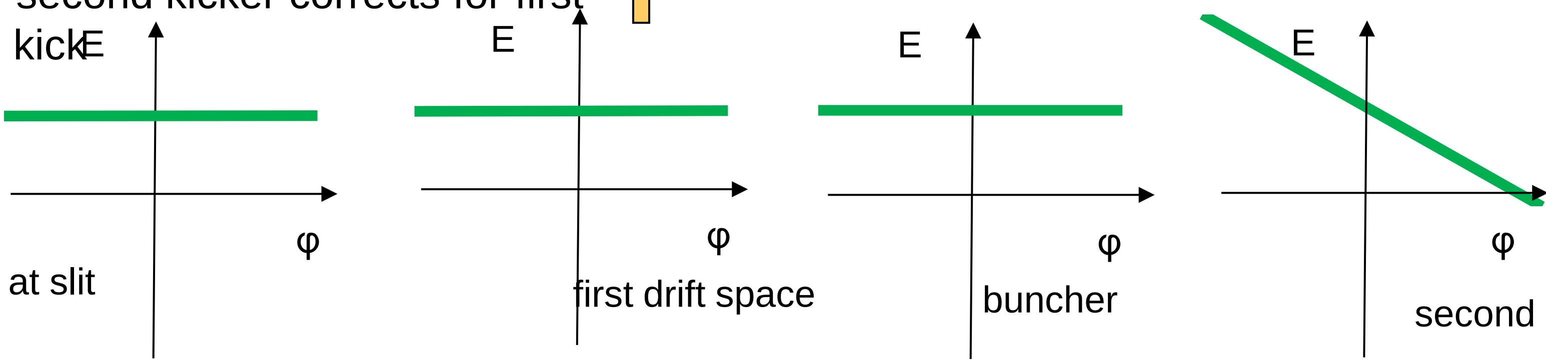
Result of single pulse emittance measurement



Transverse Emittance measurement

- Spectrometer produces image of slit on second slit
- second slit selects energy slice
- first kicker sweep phase space over all energies
- buncher rotates energy slice in phase space
- at second spectrometer the phase distribution is transformed into an energy distribution analyzed by the second spectrometer
- second kicker corrects for first kick





Single Shot Emittance Measurement

- Advantage:
  - Full scan takes 20 μs
  - Shot by shot comparison possible
- Disadvantage:
  - Very costly
  - Needs dedicated measurement line
  - Needs a fast sampling ADC + memory for each wire
- Cheaper alternative:
  - Multi-slit or pepperpot measurement

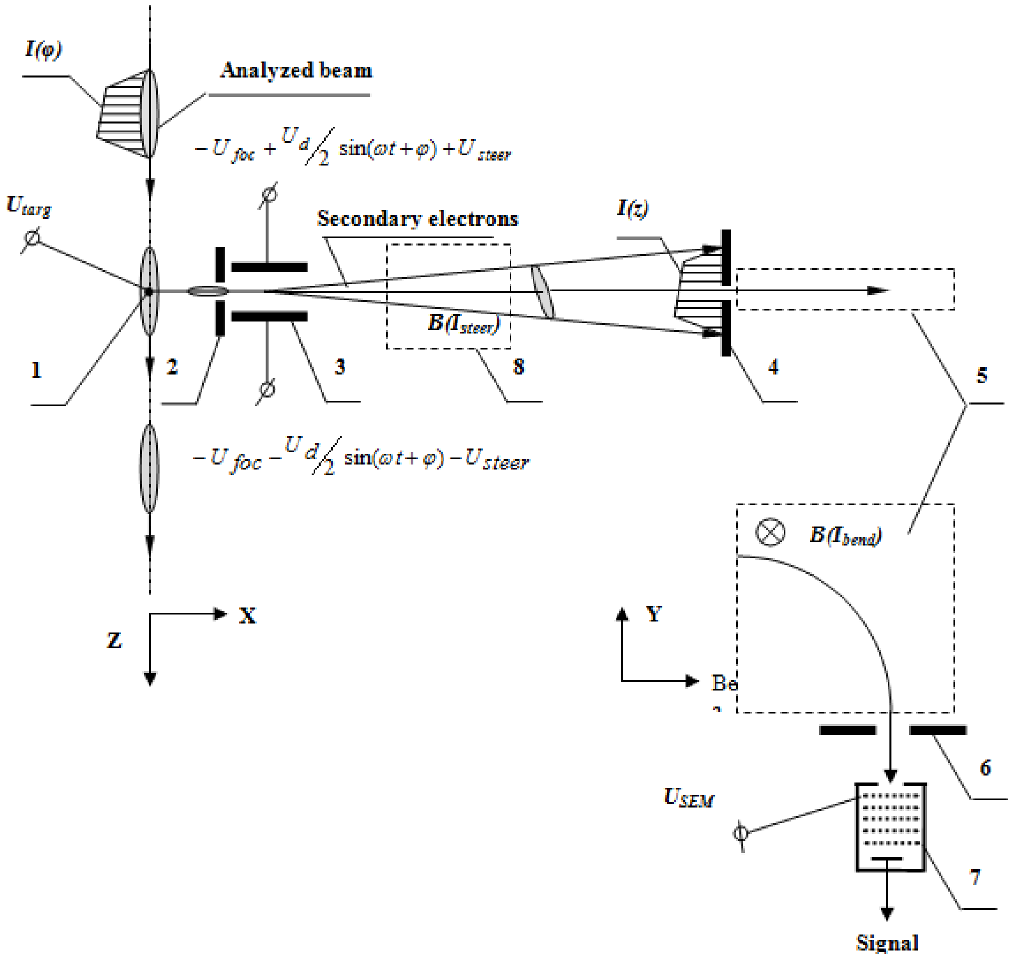
A Bunch Shape Monitor

At CERN Linac-4:

- RF frequency: 352 MHz
  - RF period: 2.85 ns
  - Bunch length ~ 20% : 570 ps

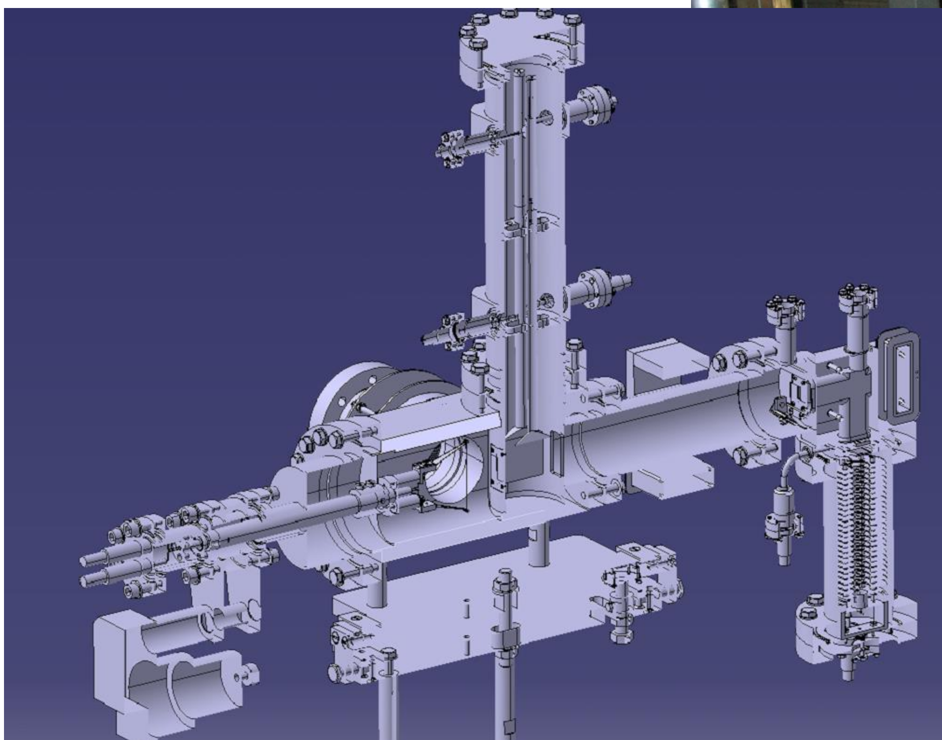
How can we measure the shape of such a short micro-pulse ?

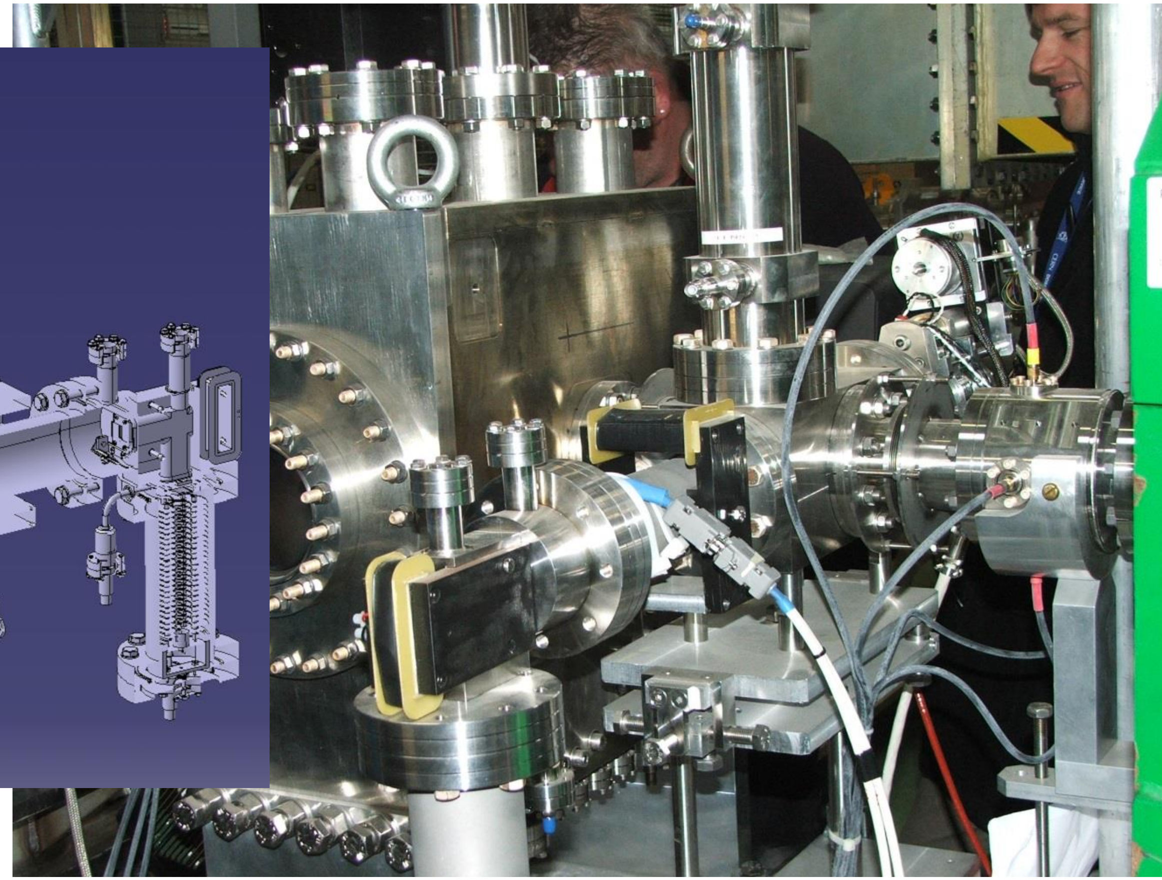
Principle of BSM



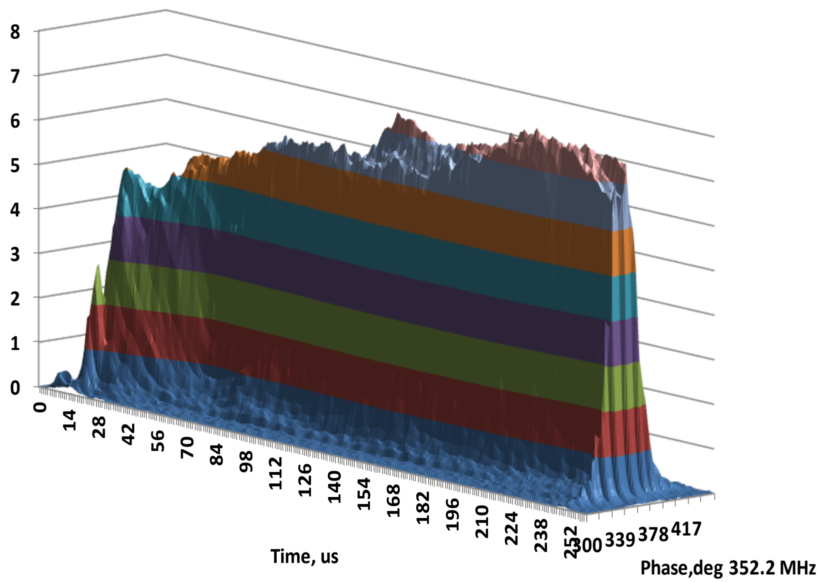
- The primary beam hits a target wire (1)
- 10 kV HV on the wire quickly accelerates the emitted secondary electrons such preserving the time structure
- Beamlet passes a slit (2)
- Secondary electrons are focused and steered (3) out a second slit (4)
- The electron beam is deflected with an
- RF signal synchronous with the accelerating frequency
- The deflecting signal can be phase shifted with 1 degree resolution 8 ps resolution
- The longitudinal distribution is transformed into a transverse one.
- In case of Linac-4 (H^- primary beam) a spectrometer separated SEM electrons from detached electron from stripping (6).
- An electron multiplier amplifies the signal (7)

BSM photos



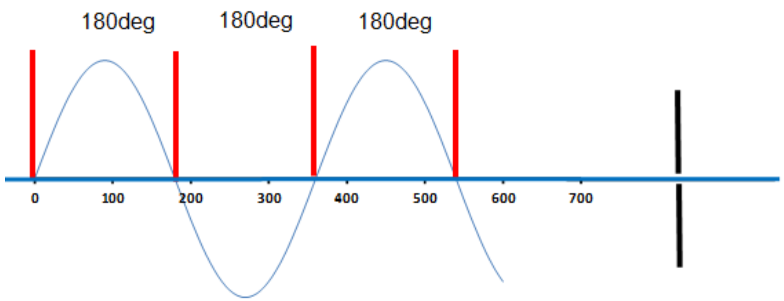


BSM results

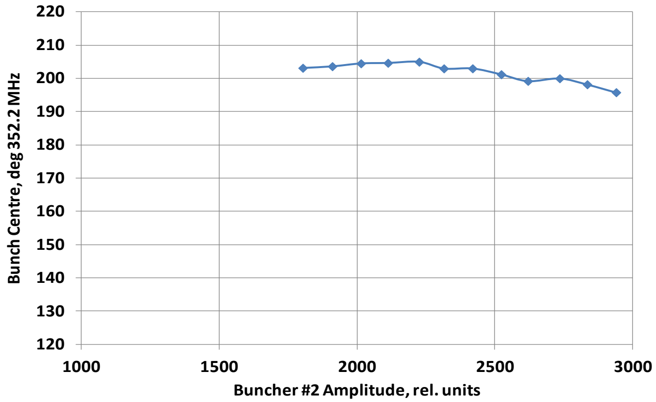


Bunch shape along the 400us
Beam pulse

Used to setup buncher phase and amplitude



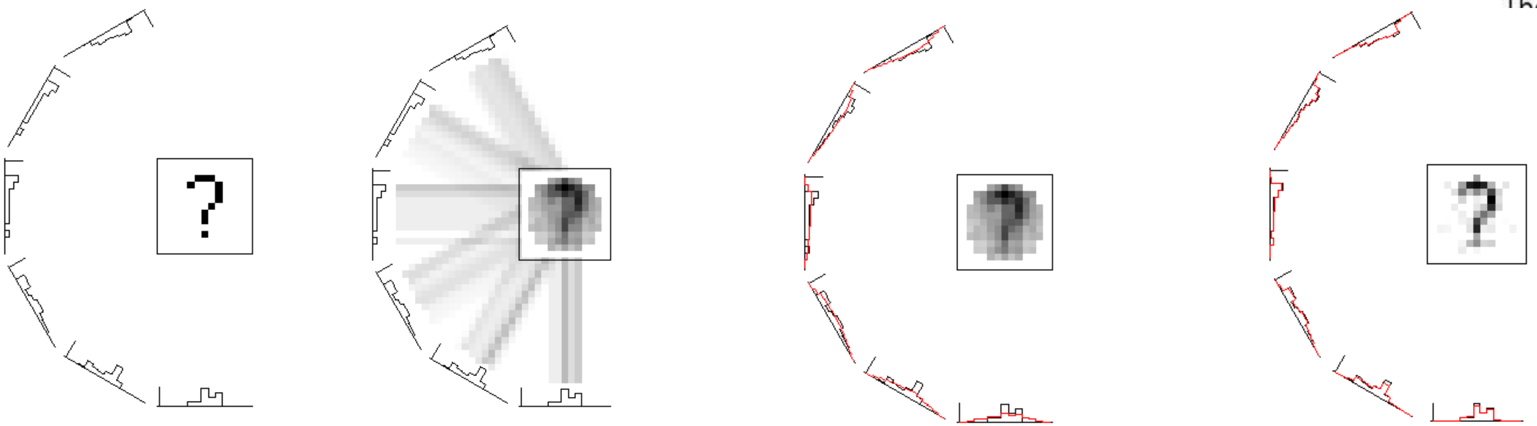
If the beam passes at the zero crossing, it
Will neither loose nor gain energy but the bunch
width will shrink



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



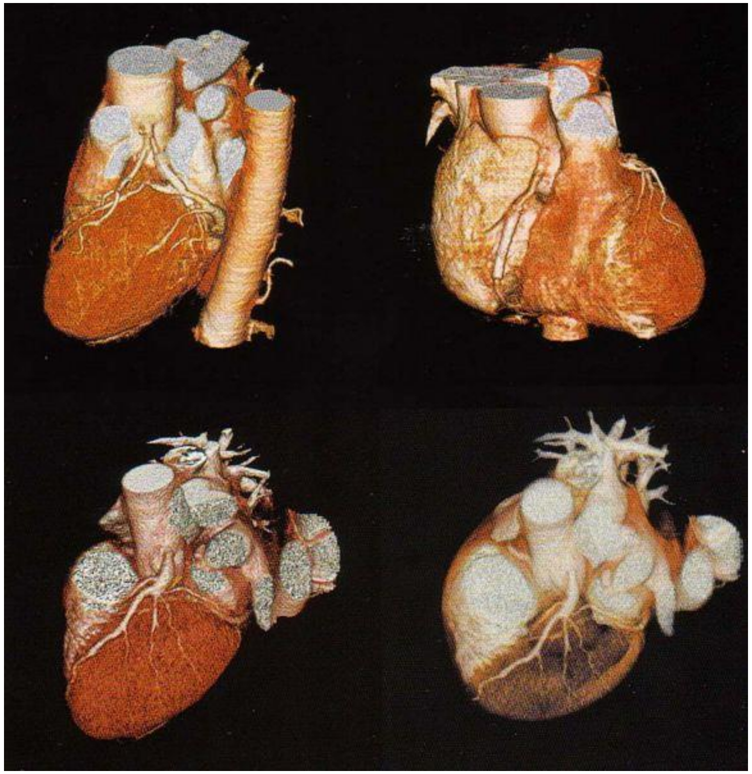
Produce many projections of the object to be reconstructed

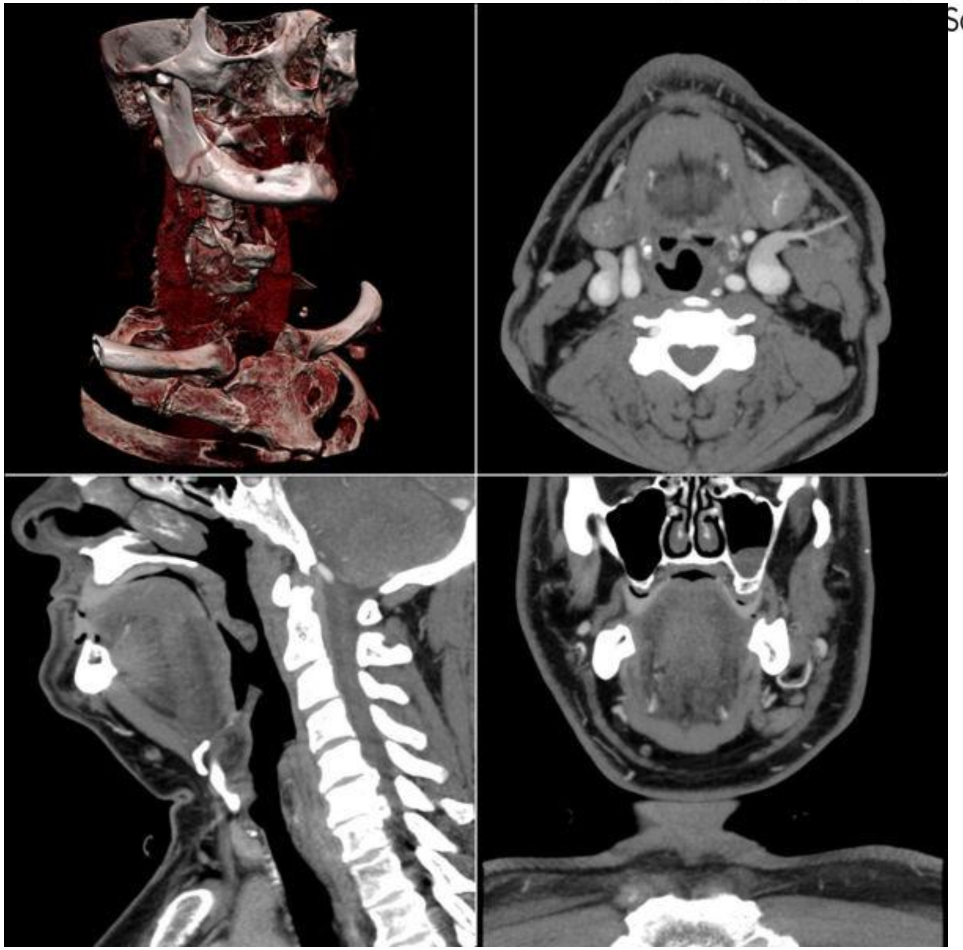
Back project and overlay the “projection rays”

Project the back-projected object and calculate the difference

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

Some CT resuluts





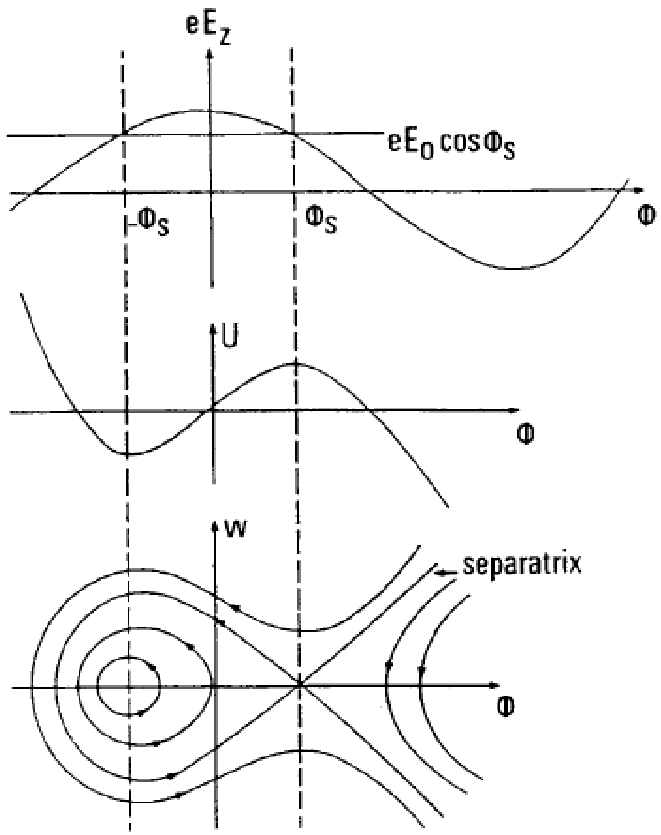
Computed Tomography and Accelerators

RF voltage

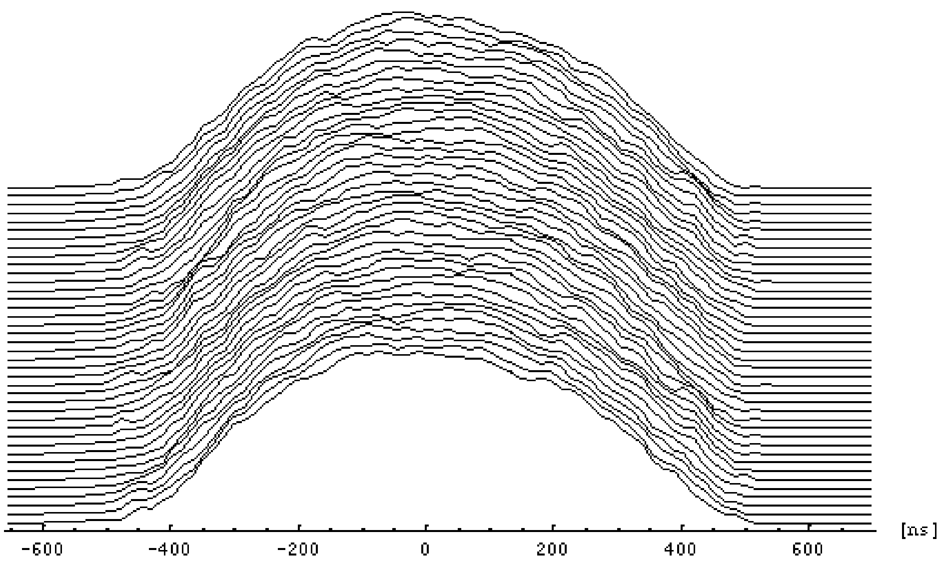
Restoring force for non-synchronous particle

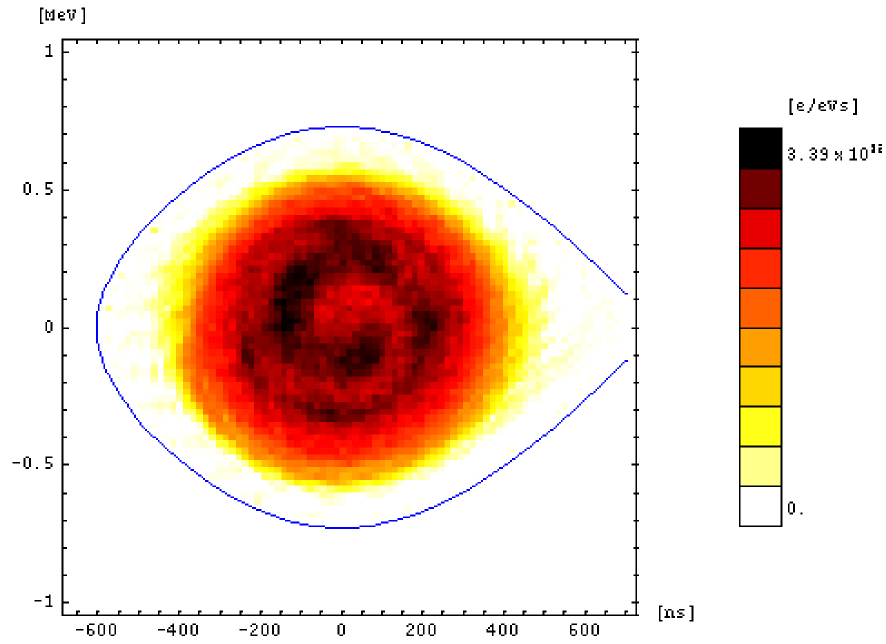
Longitudinal phase space

Projection onto Φ axis corresponds to bunch profile



Reconstructed Longitudinal Phase Space





Bunch Splitting