Beam Diagnostics Lecture 2

Measuring Complex Accelerator Parameters

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CERN AB-BI

Contents of lecture 2

- Some examples of measurements done with the instruments explained during the last lecture
  - Spectroscopy
  - Trajectory and Orbit measurements
  - Tune measurements
    - Traditional method
    - BBQ method
  - Transverse and longitudinal emittance measurements
  - Longitudinal phase space tomography

Faraday Cup application
Testing the decelerating RFQ

Antiproton decelerator

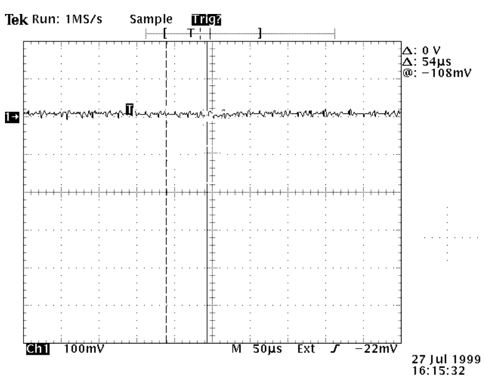
- Accelerate protons to 24 GeV and eject them onto a target
- Produce antiprotons at 2 GeV
- Collect the antiprotons and cool them
- Decelerate them and cool them
- Output energy: 100 MeV

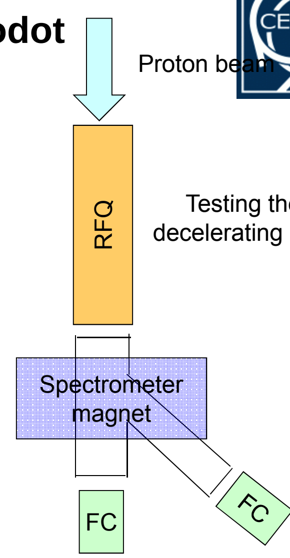
In order to get even lower energies:

- Pass them through a moderator
  - High losses
  - Large energy distribution

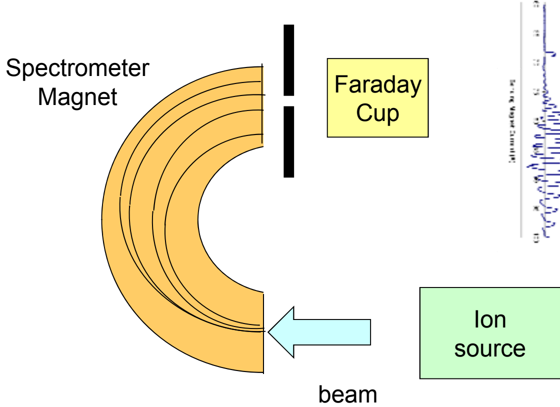
=> Build a decelerating RFQ

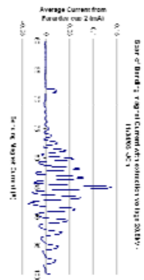
Waiting for Godot





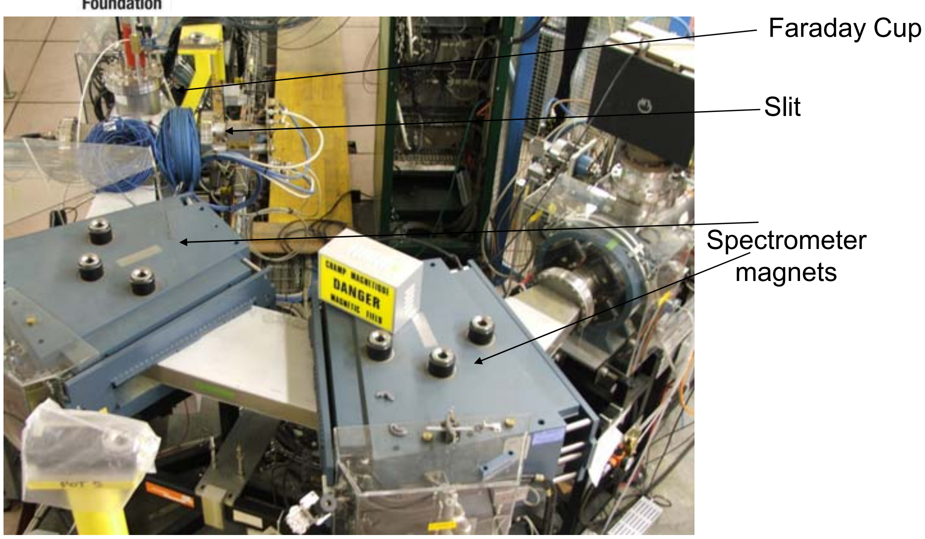
Setup for charge state measurement



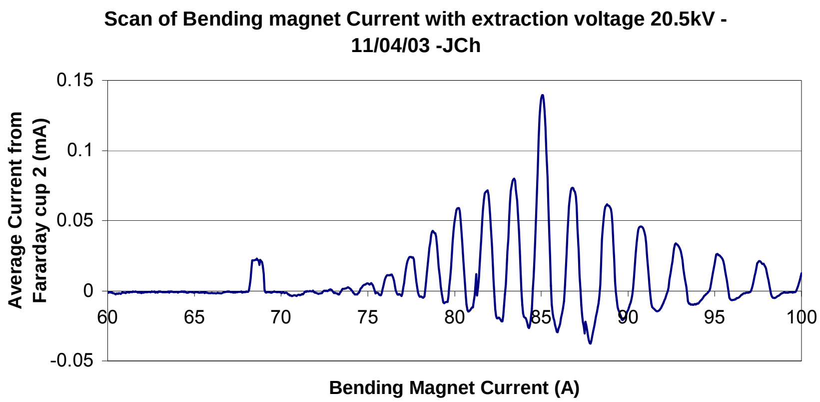


The spectrometer magnet is swept and the current passing the slit is measured

Measuring charge state distribution



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



Trajectory and Orbit measurements

Definitions:

Trajectory: The mean positions of the beam during 1 turn

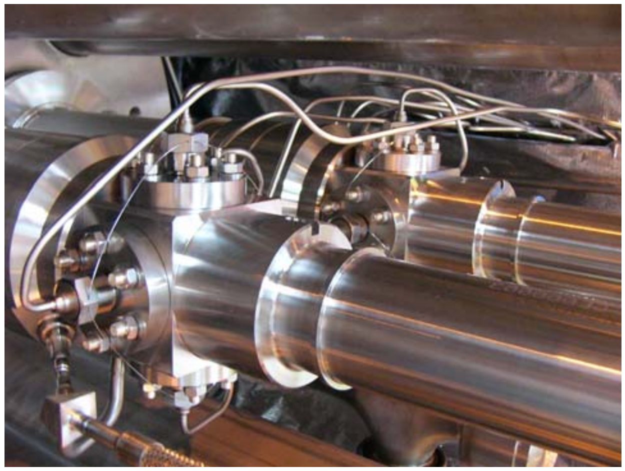
Orbit: The mean positions over many turns for each of the BPMs

The trajectories must be controlled at injection, ejection, transition

Closed orbits may change during acceleration or RF “gymnastics”

National Research Foundation

LHC Button BPMs



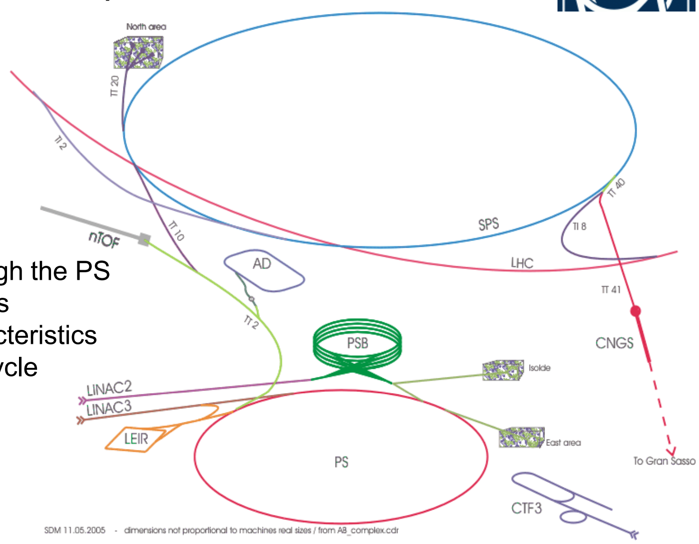
National Research Foundation

Trajectory Measurement at LHC injection

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

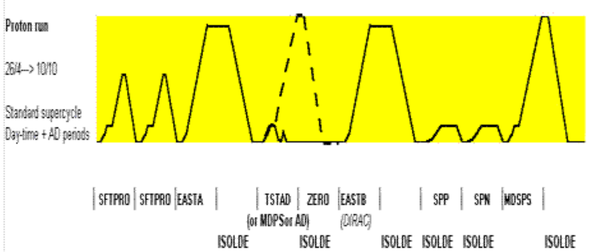
The PUs

The PS, a universal machine



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

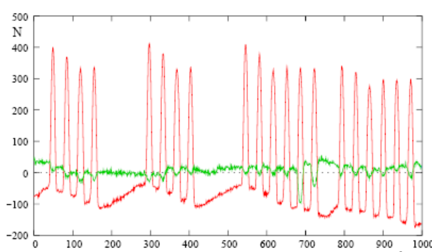
The super cycle



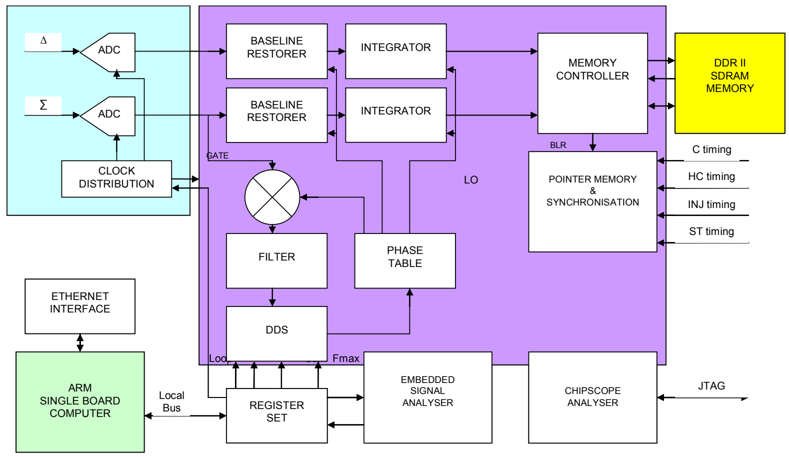
Position Measurements

Red: The sum signal
Green: The difference signal

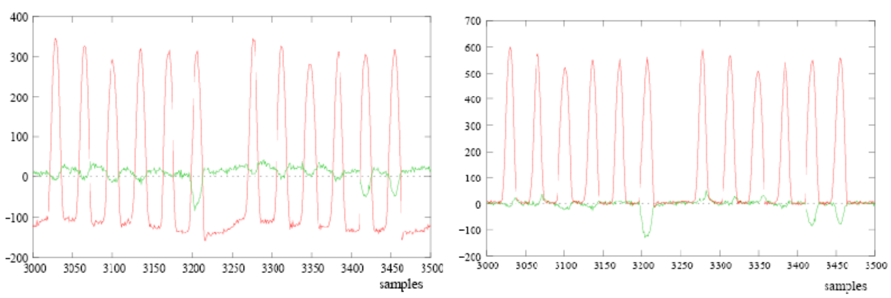
Procedure:
Produce integration gates and Baseline signals
Baseline correct both signals
Integrate sum and difference signals and store results in memory
Take external timing events into account e.g. harmonic number change, γ-transition etc.



Trajectory readout electronics

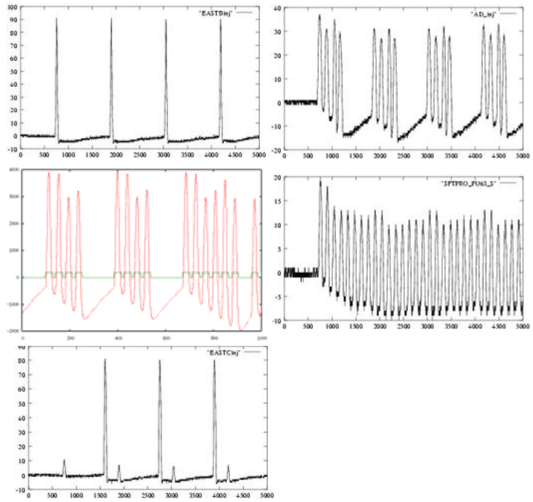


Baseline restoration

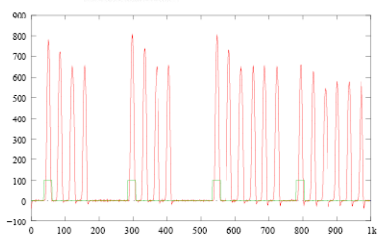


Low pass filter the signal to get an estimate of the base line
Add this to the original signal

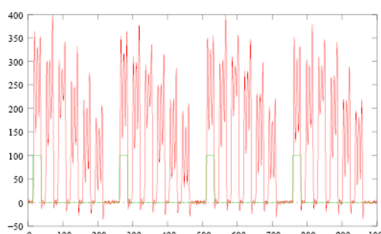
Beams in the PS



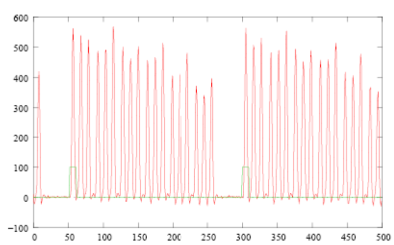
RF Gymnastics



Example of generated gate around 2nd injection

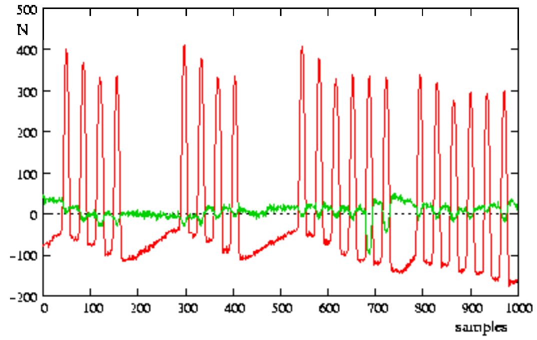


Idem, during bunch splitting



Trajectory measurements in circular machines

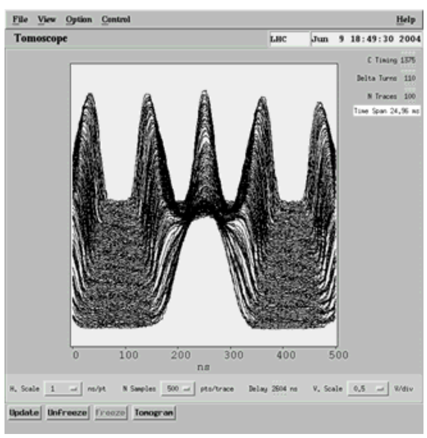
Needs integration gate
Can be rather tricky
Distance between bunches changes with acceleration
Number of bunches may change



Raw data from pick-ups
double batch injection

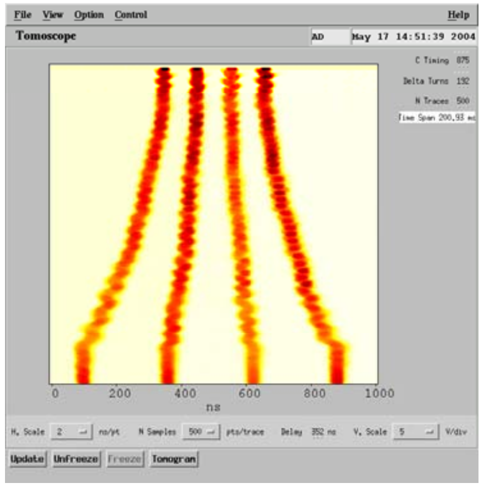
Changing bunch frequency

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



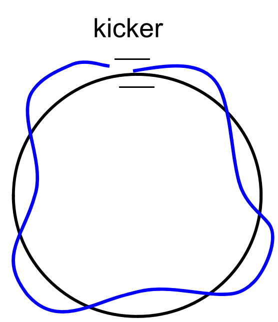
For all these cases the gate generator must be synchronized

Batch compression

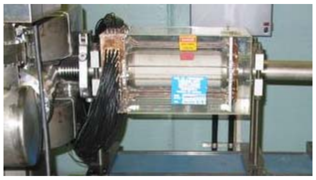


Tune measurements

- 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

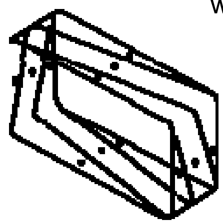


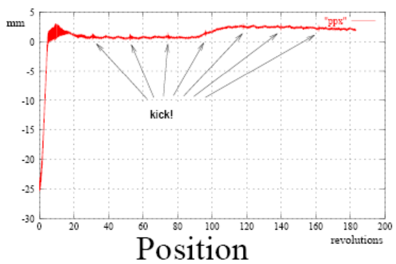
The Sensors

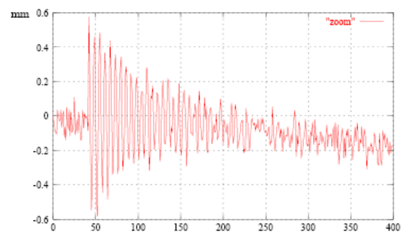


The kicker

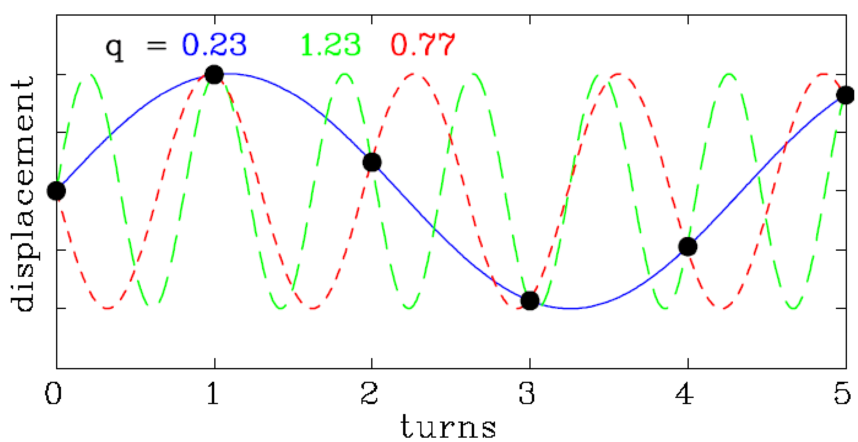
Shoebox pick-up with linear cut







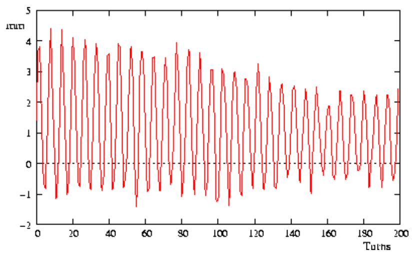
Tune measurements with a single PU

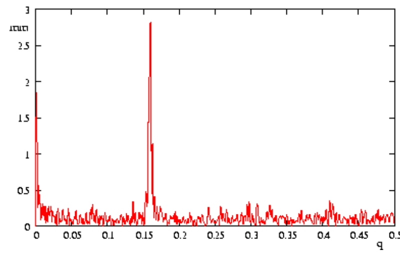


Design by P. Forck

Kicker + 1 pick-up

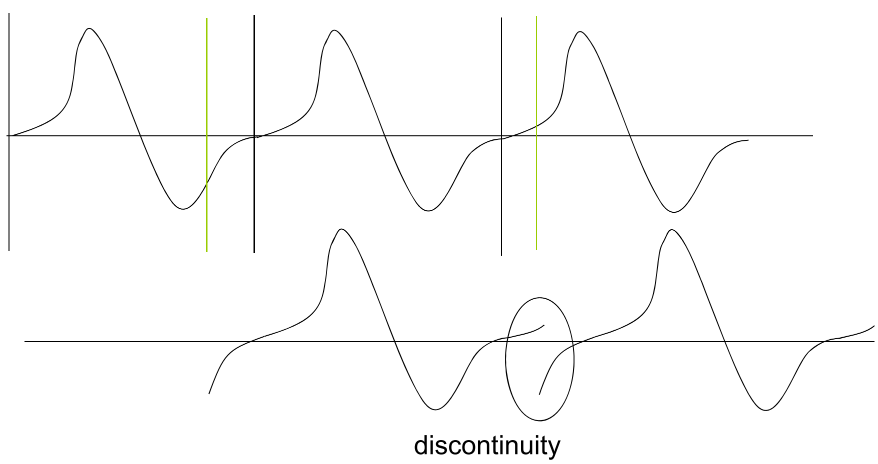
- Measures only non-integral part of Q
- Measure a beam position at each revolution





Fourier transform of pick-up signal

Periodic extension of the signal and Windowing



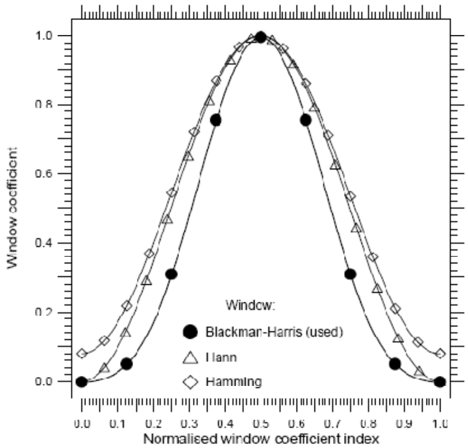
Windowing

The Discrete Fourier assumes one cycle of a repetitive signal.

Blackman-Harris Window is used

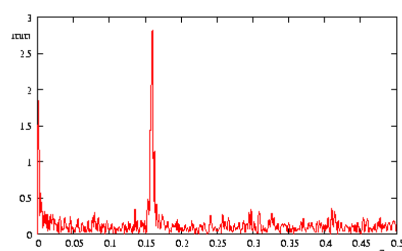
Each sample is multiplied with a coefficient

Coefficients are pre-calculated and stored in a table



Peak search algorithm

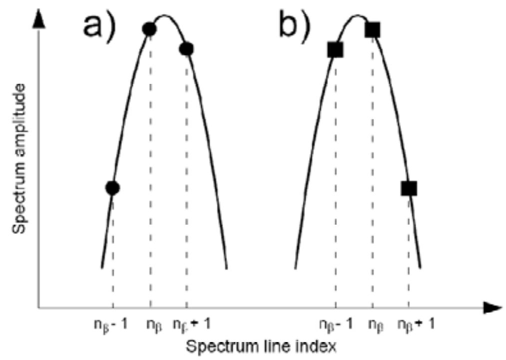
- Power value is bigger than its predecessor
- Power value is bigger than its successor
- Power value is biggest in the whole spectrum
- The power value is at least 3 times bigger than the arithmetic mean of all power bins.



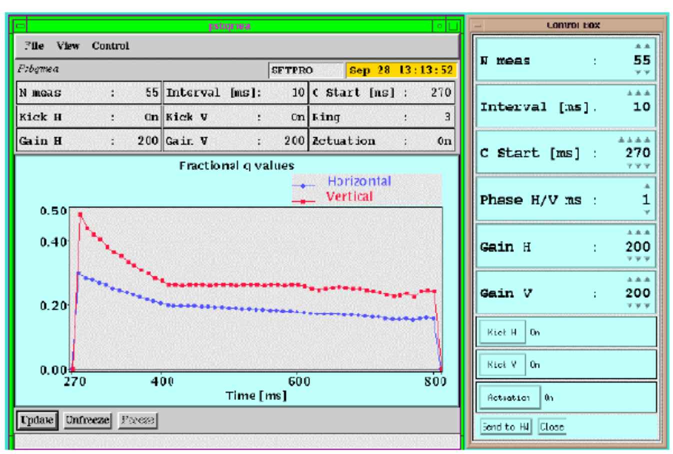
Q interpolation

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

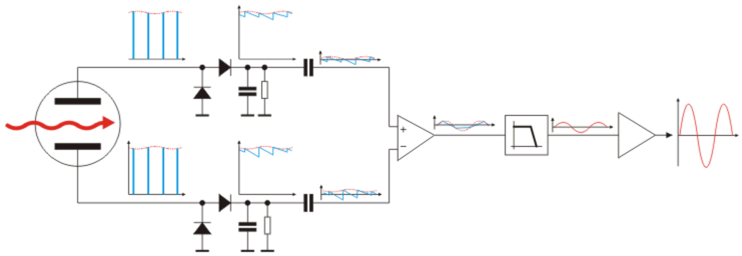
$$V(n_\beta - 1) = a(n_\beta - 1)^2 + b(n_\beta - 1) + c$$
$$V(n_\beta) = an_\beta^{\ 2} + bn_\beta + c$$
$$V(n_\beta + 1) = a(n_\beta + 1)^2 + b(n_\beta + 1) + c$$



Q-Measurement Results



Direct Diode Detection Base Band Q measurement

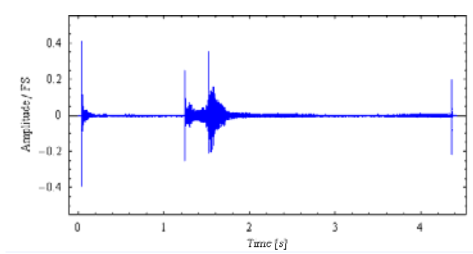


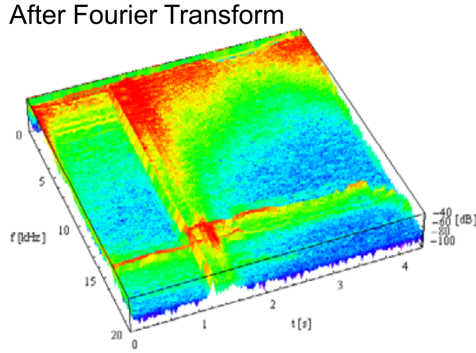
- Diode Detectors convert spikes to saw-tooth waveform
- Signal is connected to differential amplifier to cut out DC level
- Filter eliminates most of the revolution frequency content
- Output amplifier brings the signal level to amplitudes suitable for long distance transmission

BBQ Results from CERN SPS

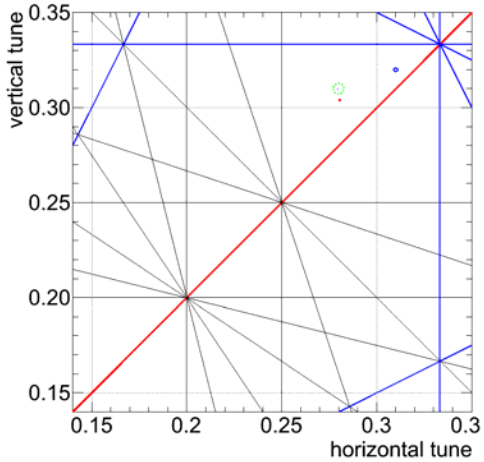
Results from Sampling

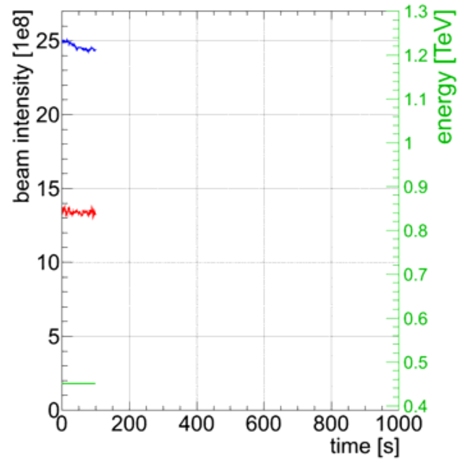
After Fourier Transform



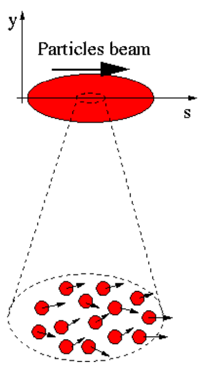


Tune feedback at the LHC





Emittance measurements



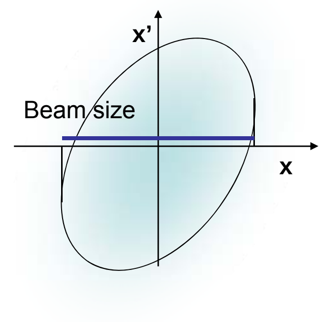
A beam is made of many many particles, each one of these particles is moving with a given velocity. Most of the velocity vector of a single particle is parallel to the direction of the beam as a whole (s). There is however a smaller component of the particles velocity which is perpendicular to it (x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

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

Design by E. Bravin

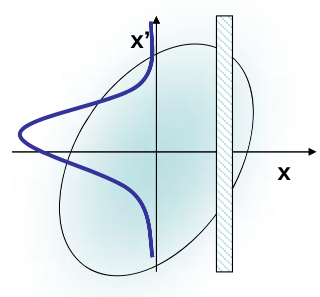
Emittance measurements

- 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



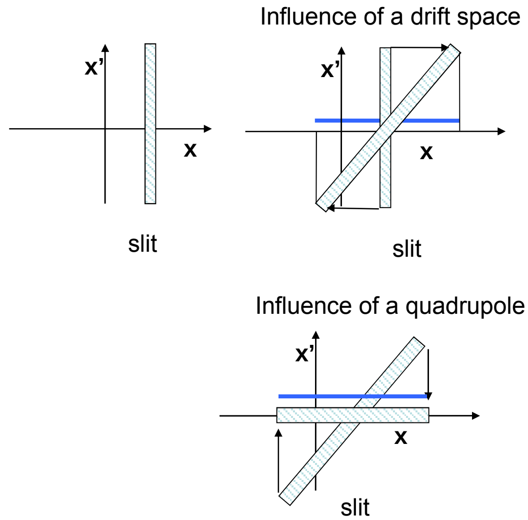
The slit method

- 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

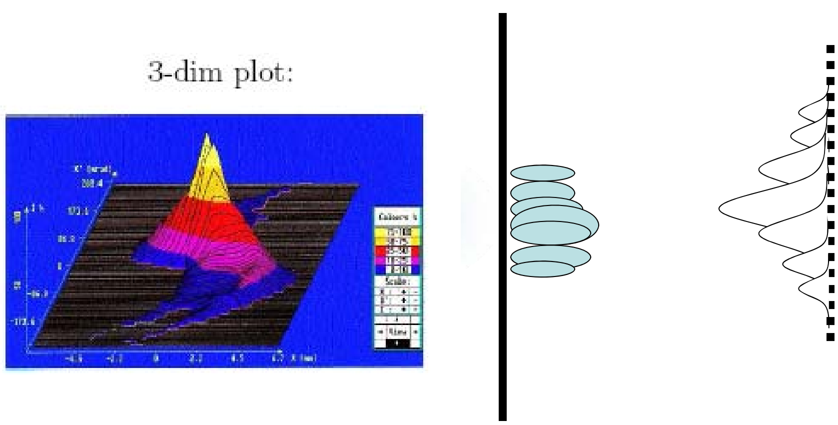


Transforming angular distribution to profile

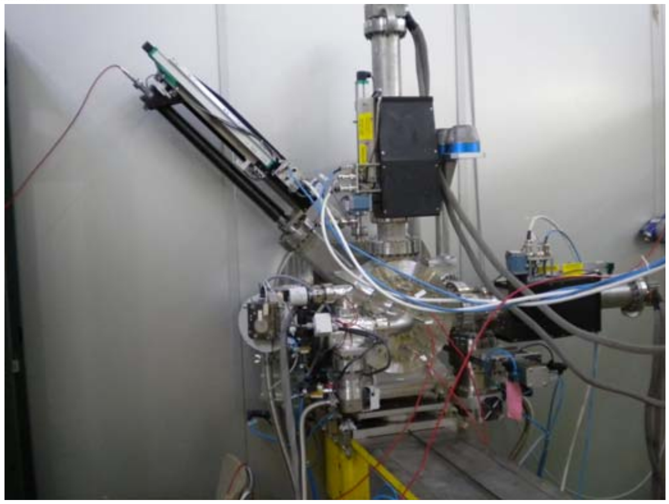
- When moving through a drift space the angles don't change (horizontal move in phase space)
- When moving through a quadrupole the position does not change but the angle does (vertical move in phase space)



The Slit Method



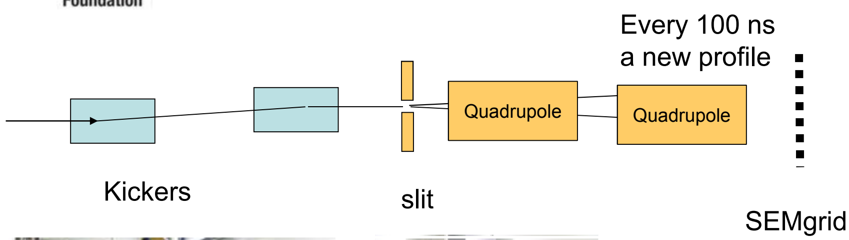
Phase Space Scanner

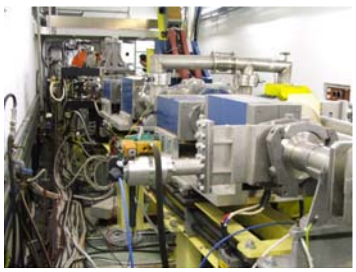


Moving slit emittance measurement

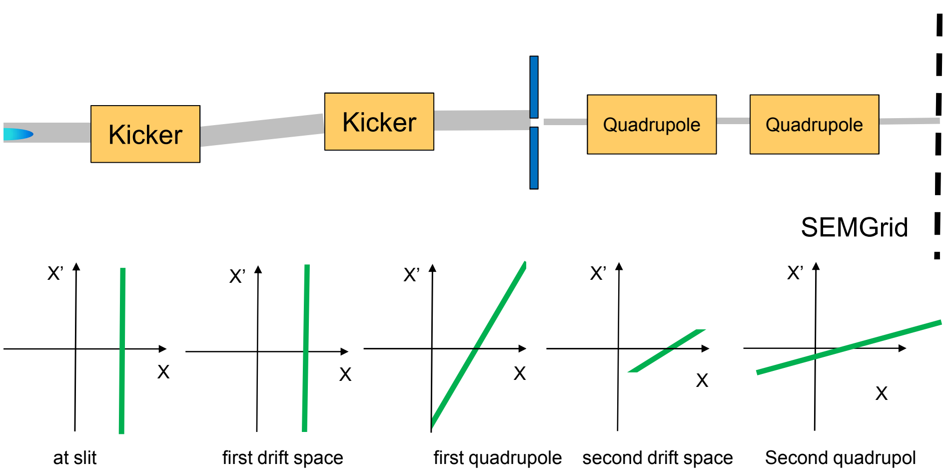
- Position resolution given by slit size and displacement
- Angle resolution depends on resolution of profile measurement device and drift distance
- High position resolution → many slit positions → slow
- Shot to shot differences result in measurement errors

Single pulse emittance measurement

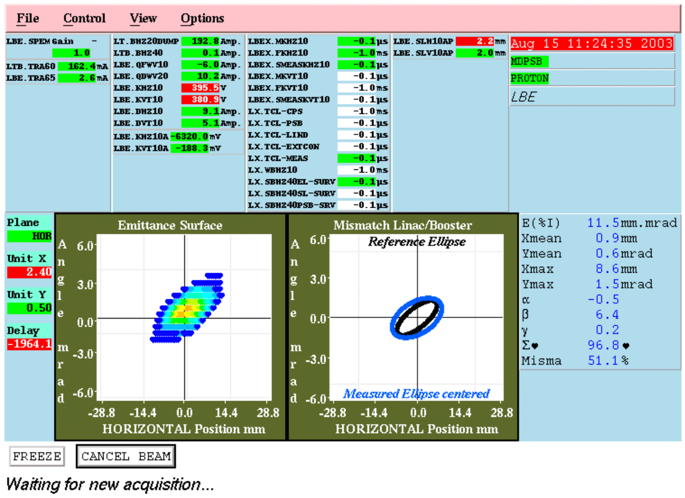




Transformation in Phase Space



Result of single pulse emittance measurement

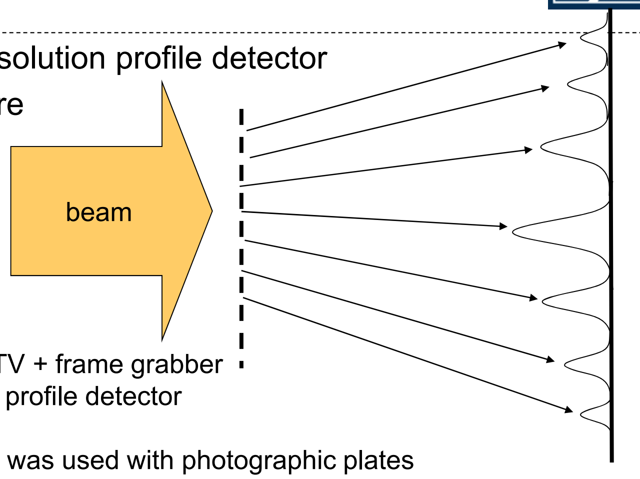


Single Shot Emittance Measurement

- 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 measurement

Multi-slit measurement

- Needs high resolution profile detector
- Must make sure that profiles dont overlap



Scintillator + TV + frame grabber often used as profile detector

Very old idea, was used with photographic plates

Pepperpot

Uses small holes instead of slits

Measures horizontal and vertical emittance in a single shot

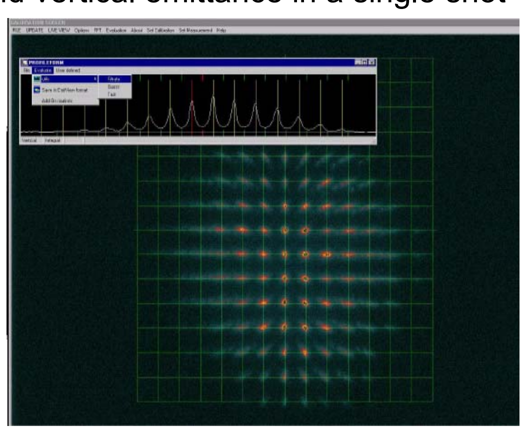
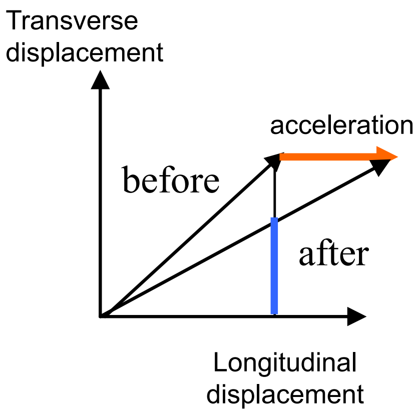


Photo P. Forck

Adiabatic damping

Change of emittance with acceleration



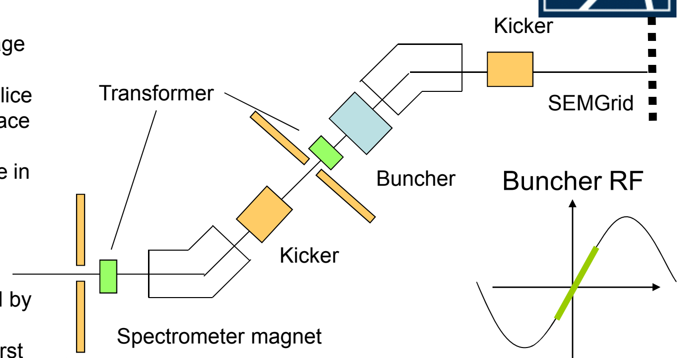
$$\varepsilon_{norm} = \varepsilon_{physical} \beta\gamma$$

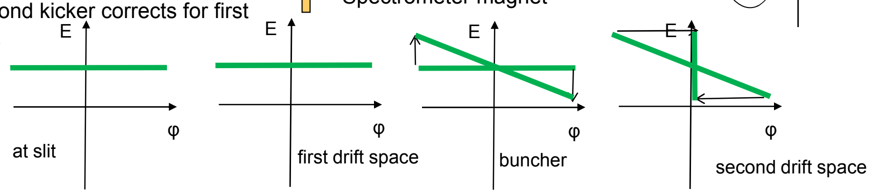
β: speed
γ: Lorentz factor

$$\gamma = \frac{1}{\sqrt{1-\beta^2}}$$

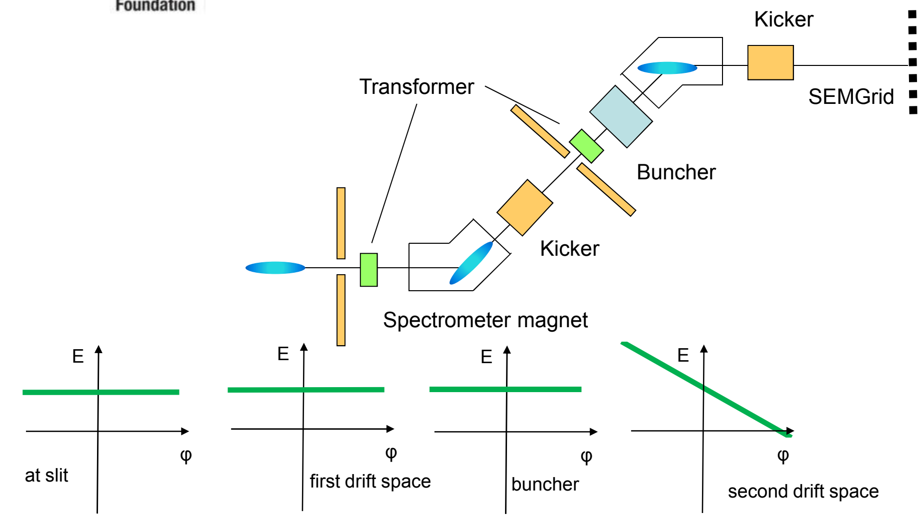
Longitudinal Phase Space Transformation

- 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

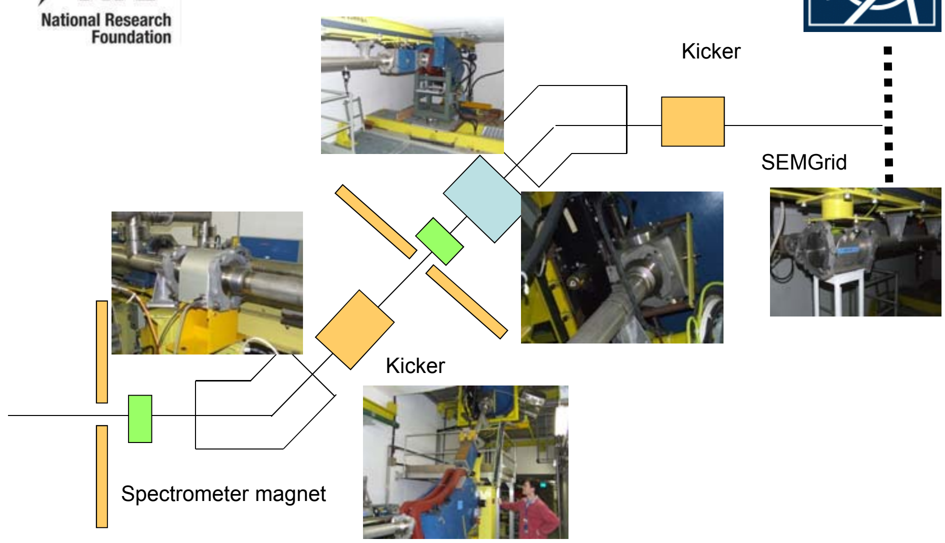




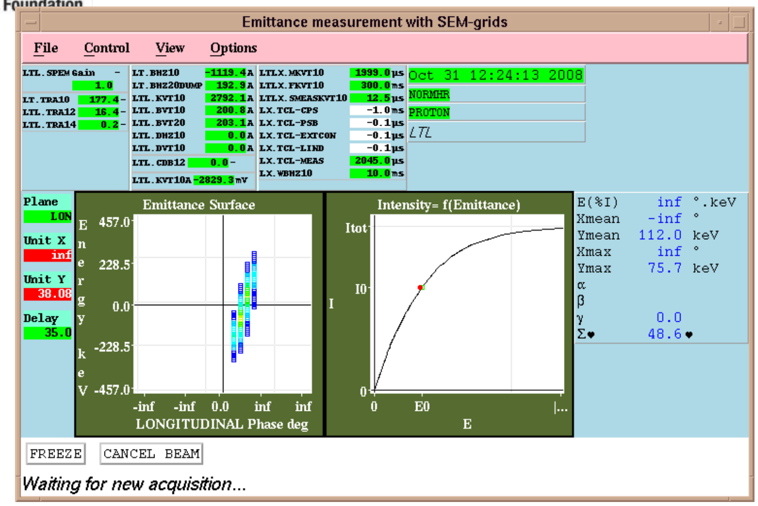
Transverse Emittance measurement



Photos of the line



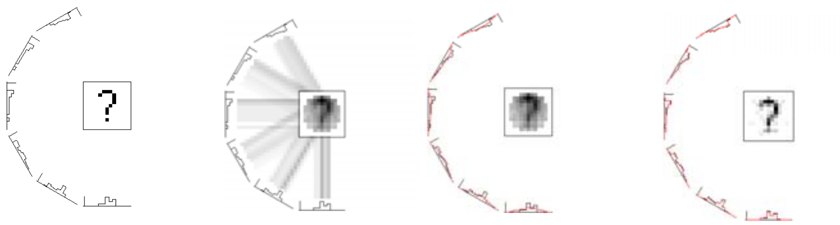
Application Program



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



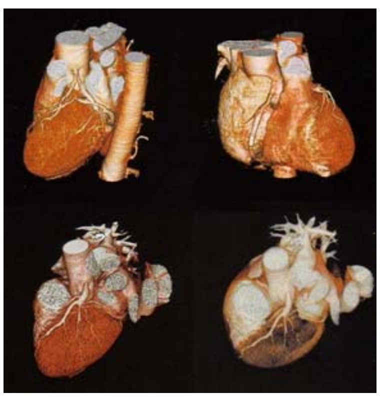
Produce many projections of the object to be reconstructed

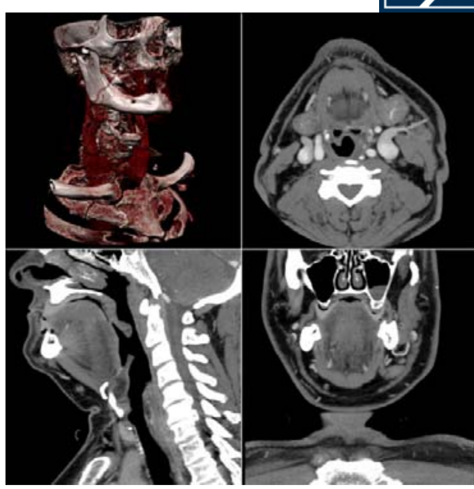
Back project and overlay the “projection rays”

Project the back-projected object and calculate the difference

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

Some CT resuluts





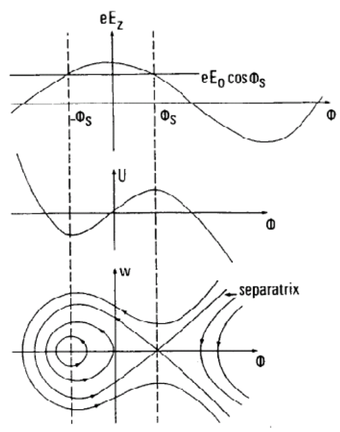
Computed Tomography and Accelerators

RF voltage

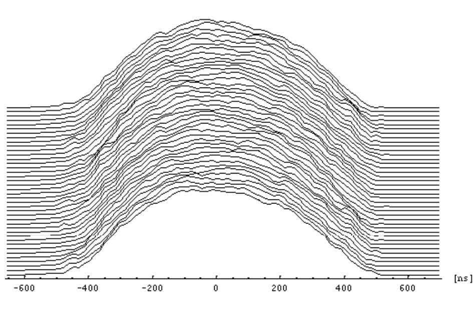
Restoring force for non-synchronous particle

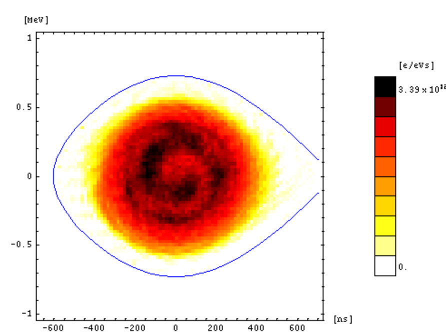
Longitudinal phase space

Projection onto Φ axis corresponds to bunch profile

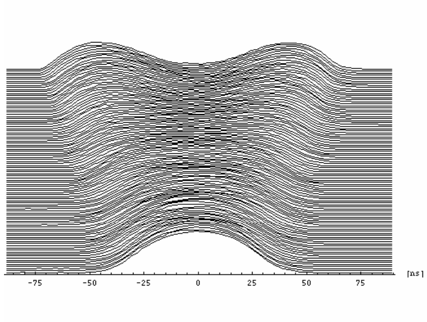


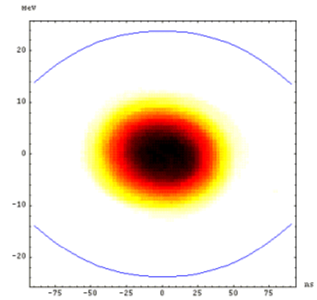
Reconstructed Longitudinal Phase Space





Bunch Splitting





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57