Beam Diagnostics Lecture 3

Measuring Complex Accelerator Parameters

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Contents of lecture 3

- Some examples of measurements done with the instruments explained during the last 2 lectures
  - 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

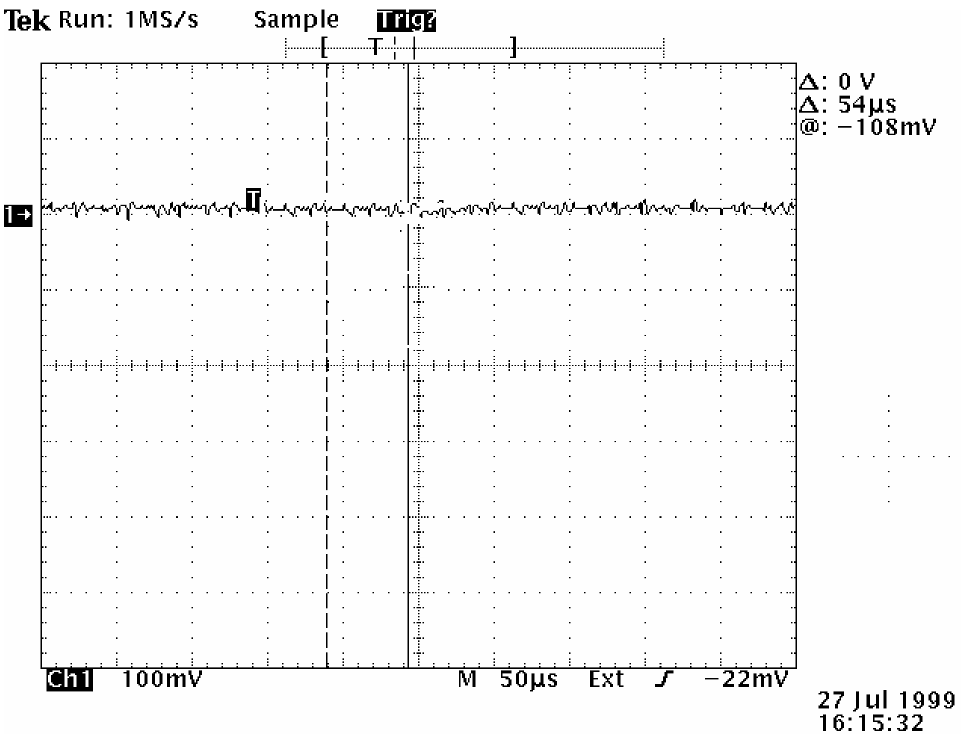
- Accelerate protons to 24 GeV and eject them onto a target
- Produce antiprotons at 2 GeV
- Collect the antiprotons and cool them
- Decelerate them and cool them
- Output energy: 100 MeV

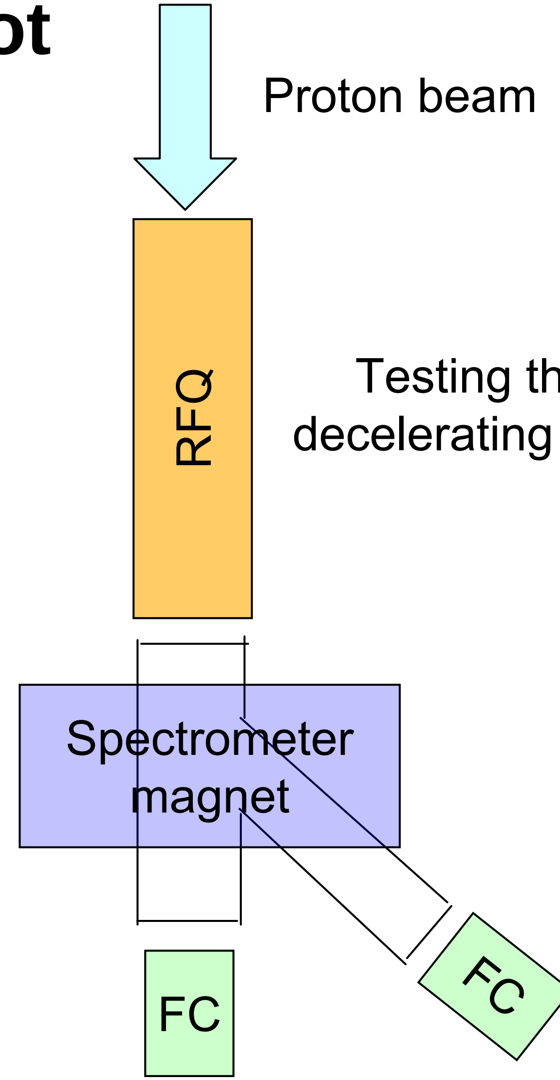
In order to get even lower energies:

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

=> Build a decelerating RFQ

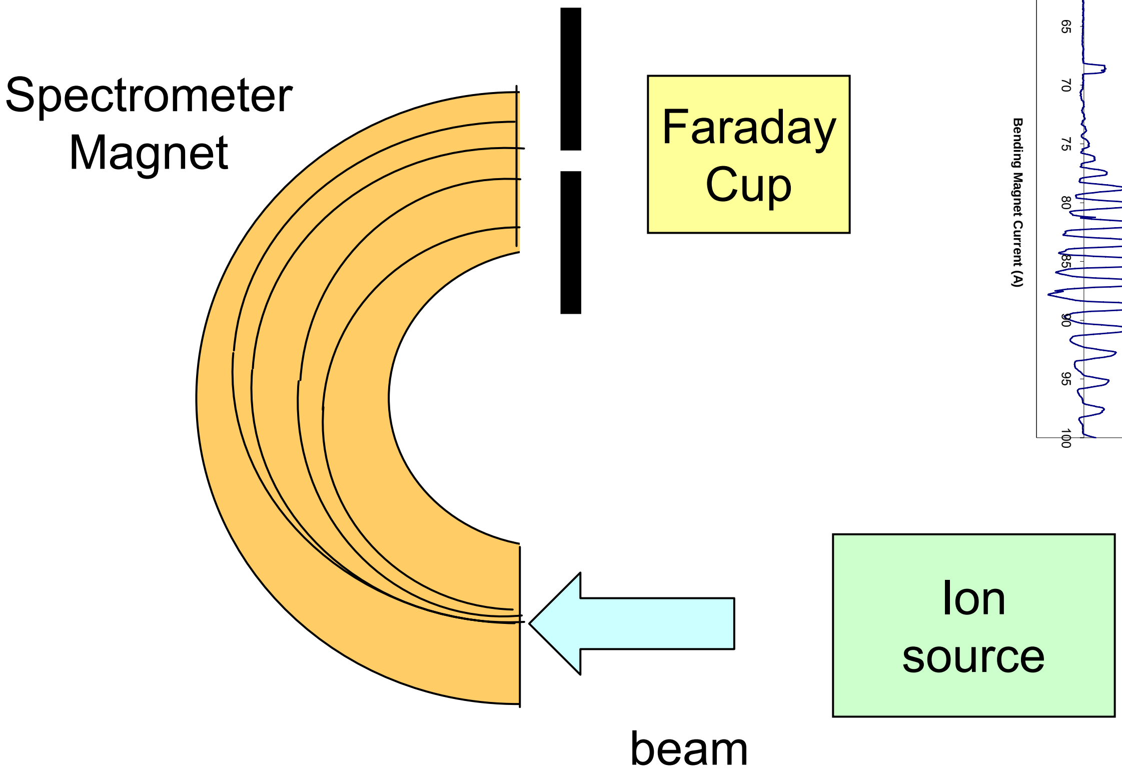
Waiting for Godot

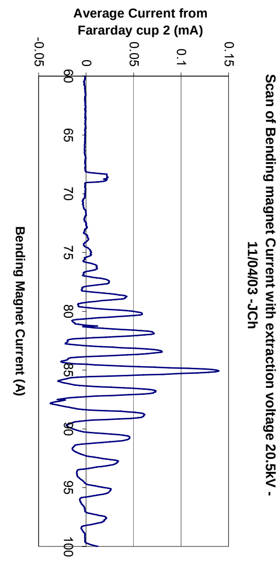




Testing the decelerating RFQ

Setup for charge state measurement





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

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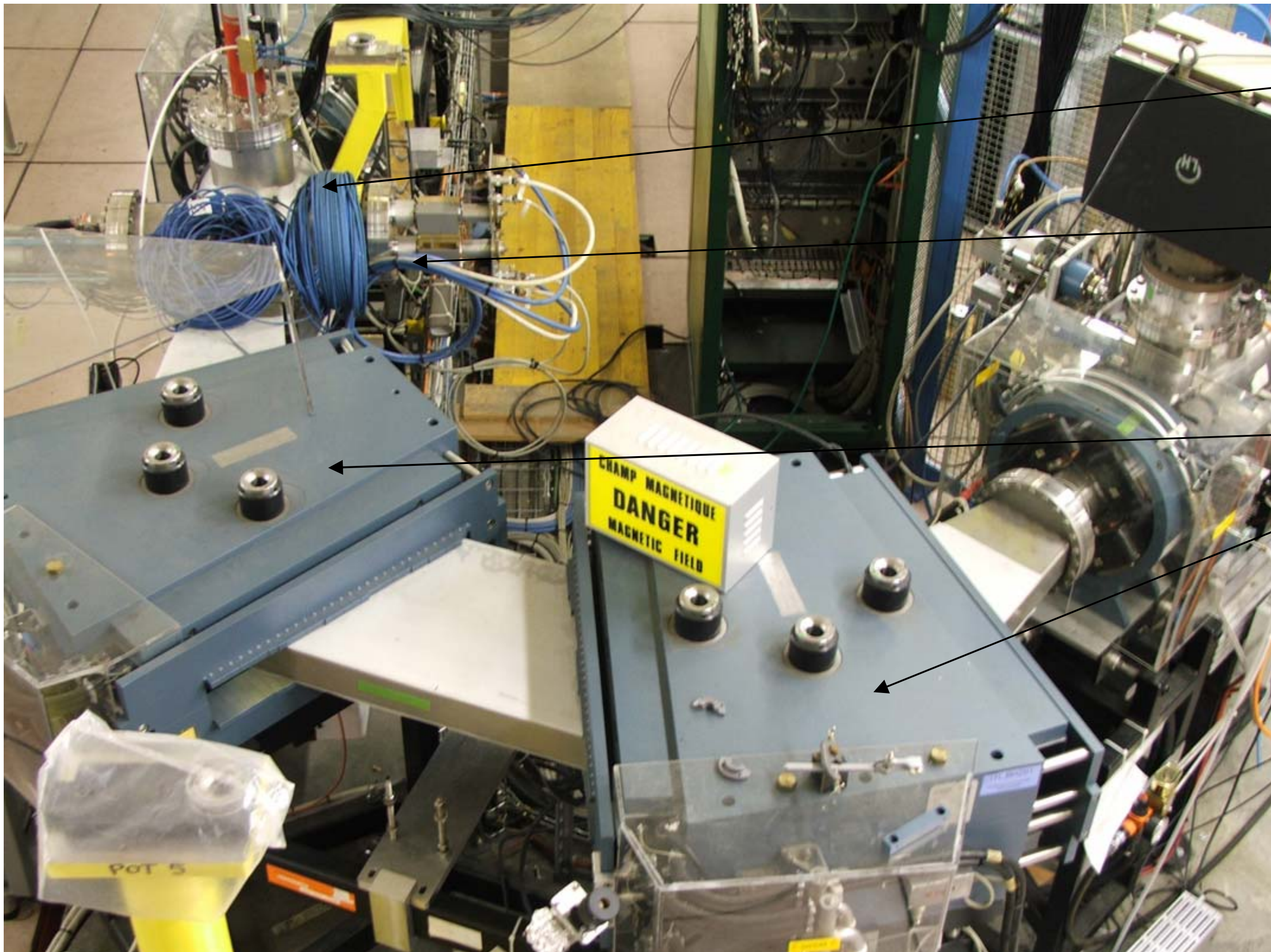
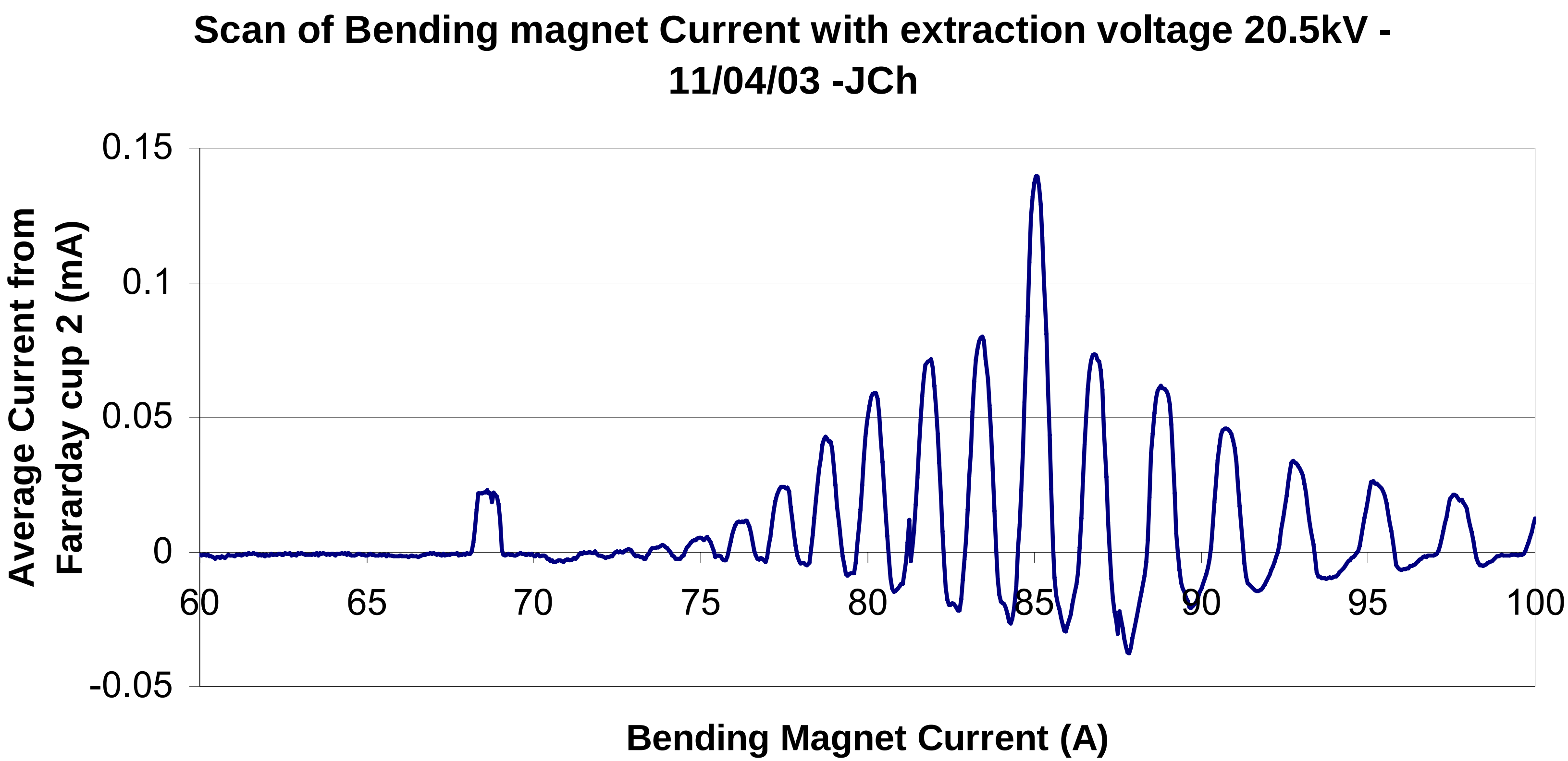
Measuring charge state distribution

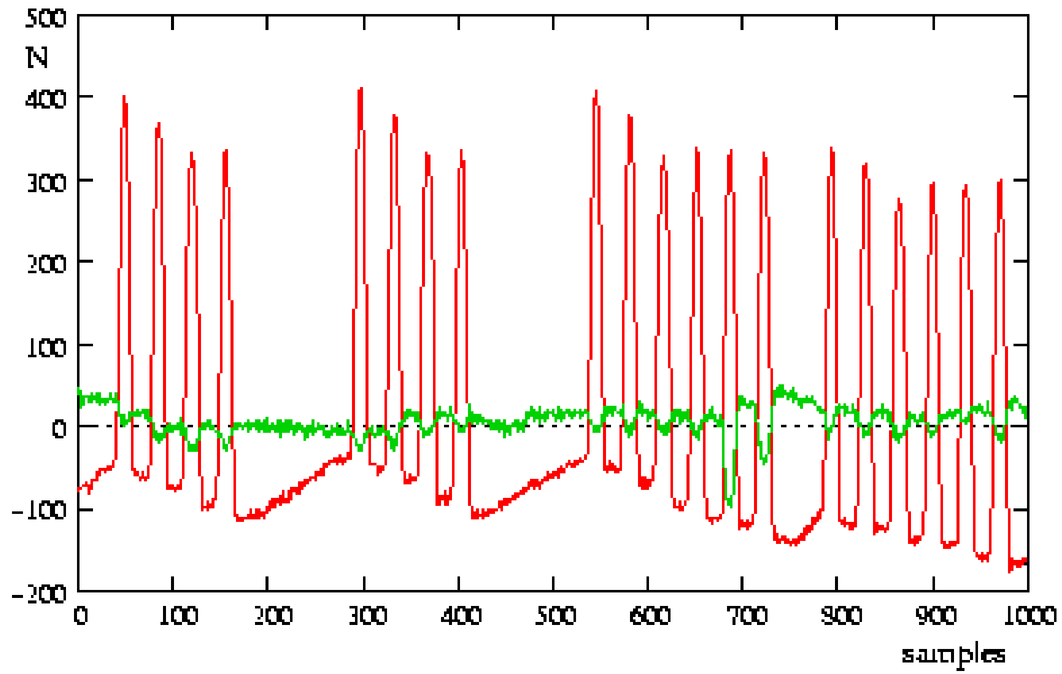


Charge state distribution measured with a Faraday Cup on a heavy ion source



Trajectory measurements in circular machines

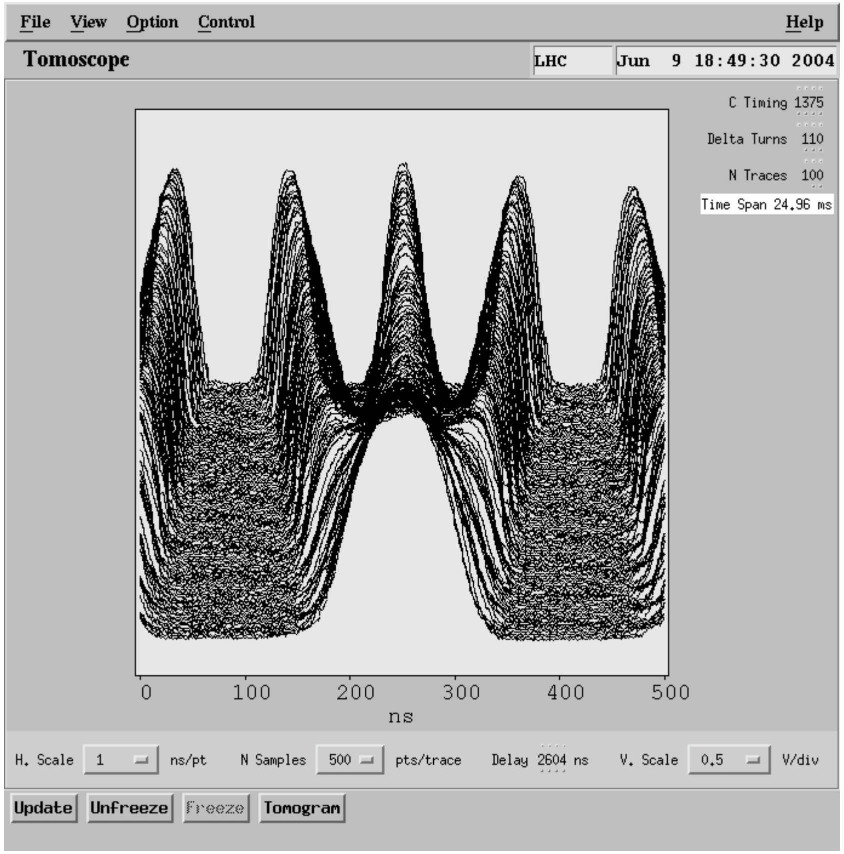
Needs integration gate
Can be rather tricky
Distance between bunches changes with acceleration
Number of bunches may change



Raw data from pick-ups
double batch injection

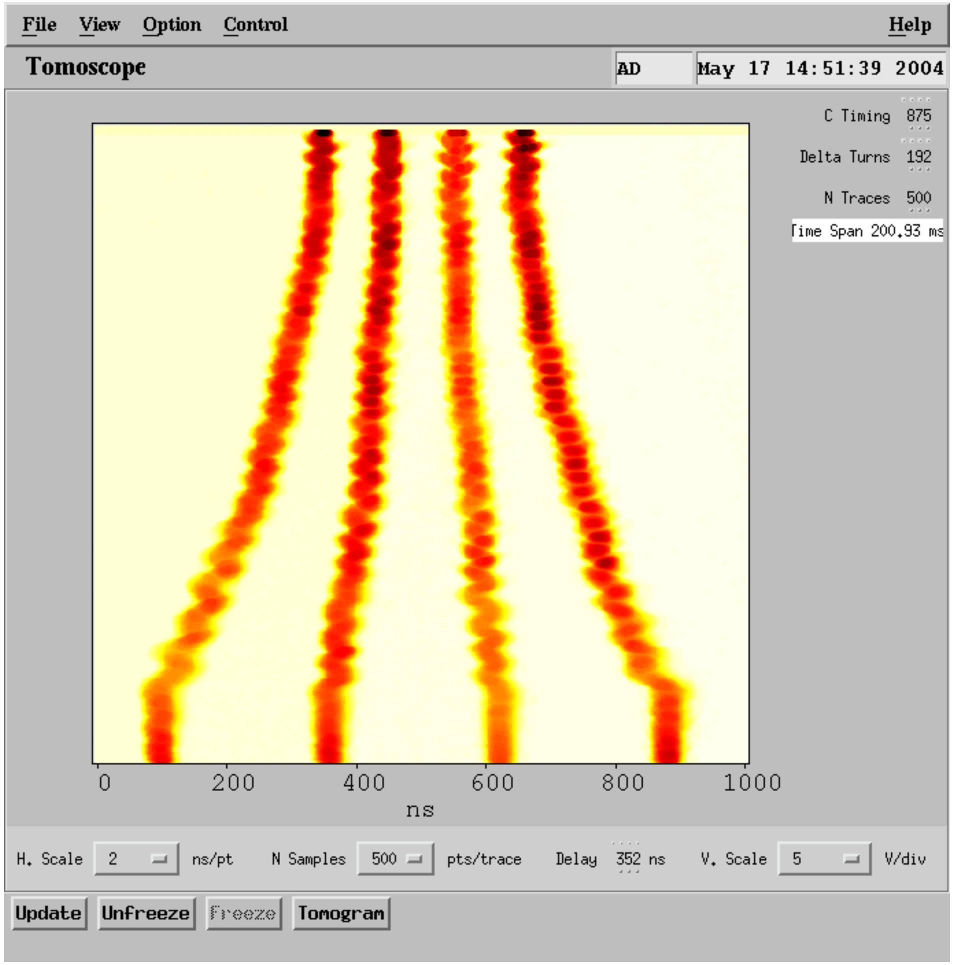
Changing bunch frequency

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



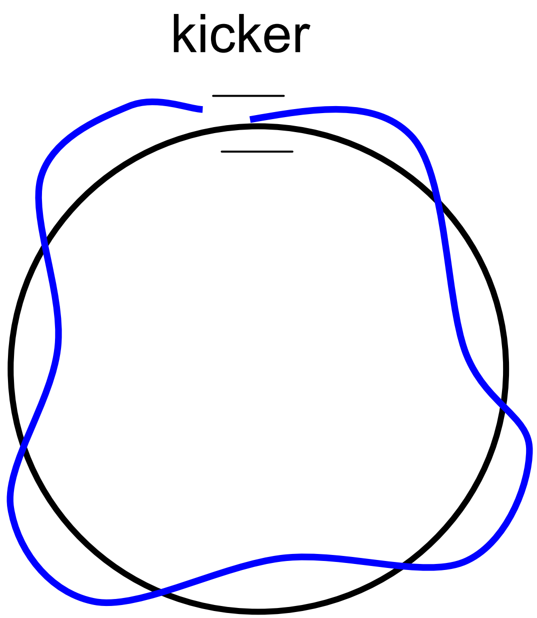
For all these cases the gate generator must be synchronized

Batch compression

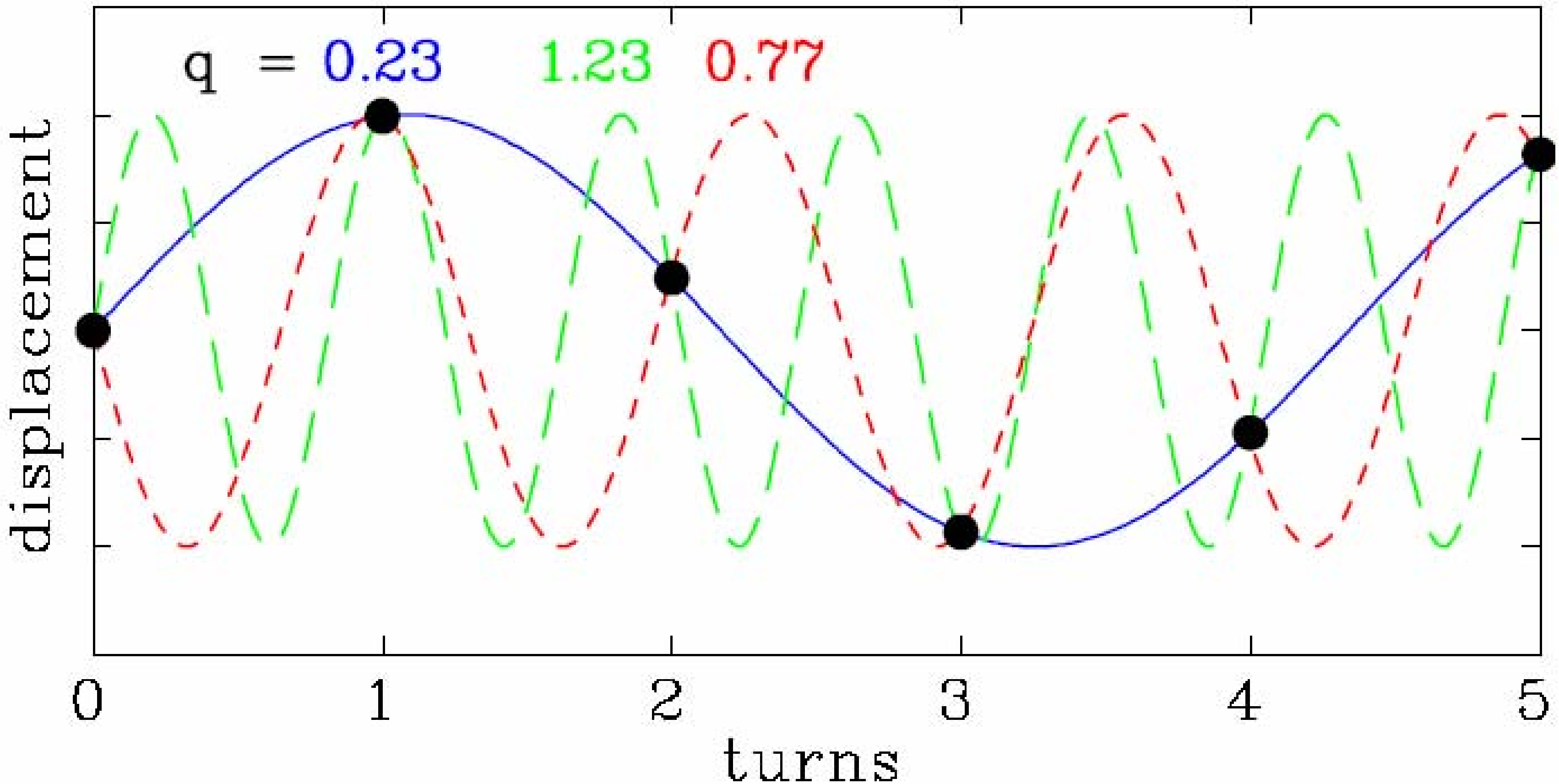


Tune measurements

- 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

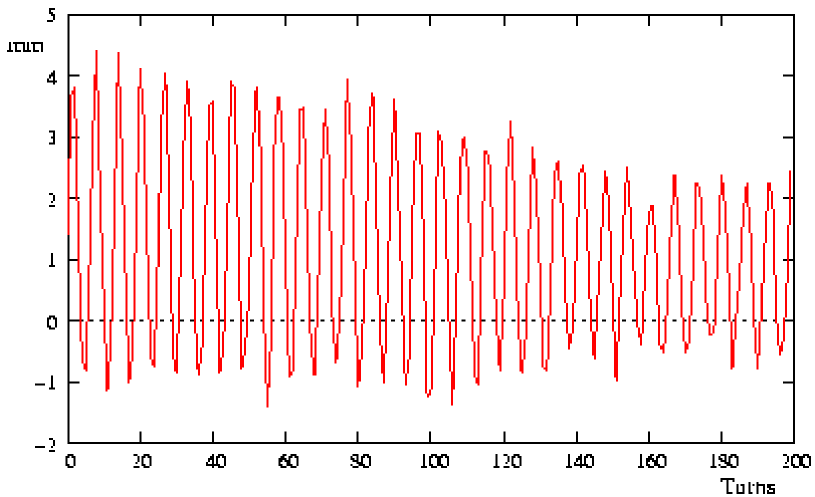


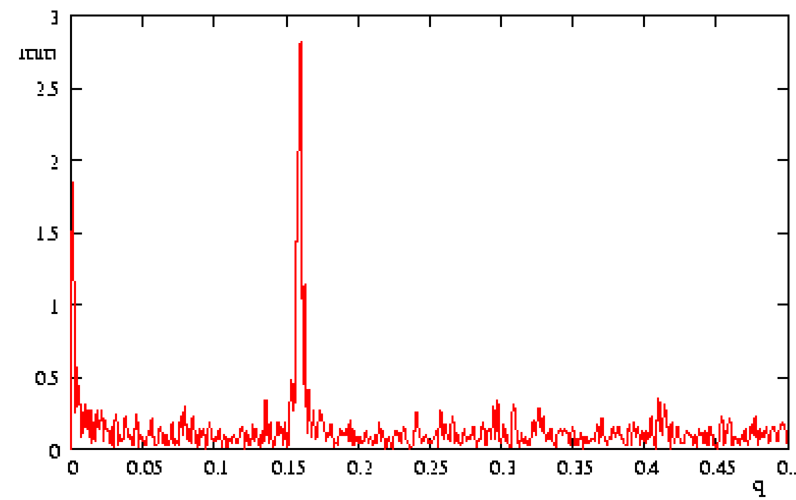
Tune measurements with a single PU



Kicker + 1 pick-up

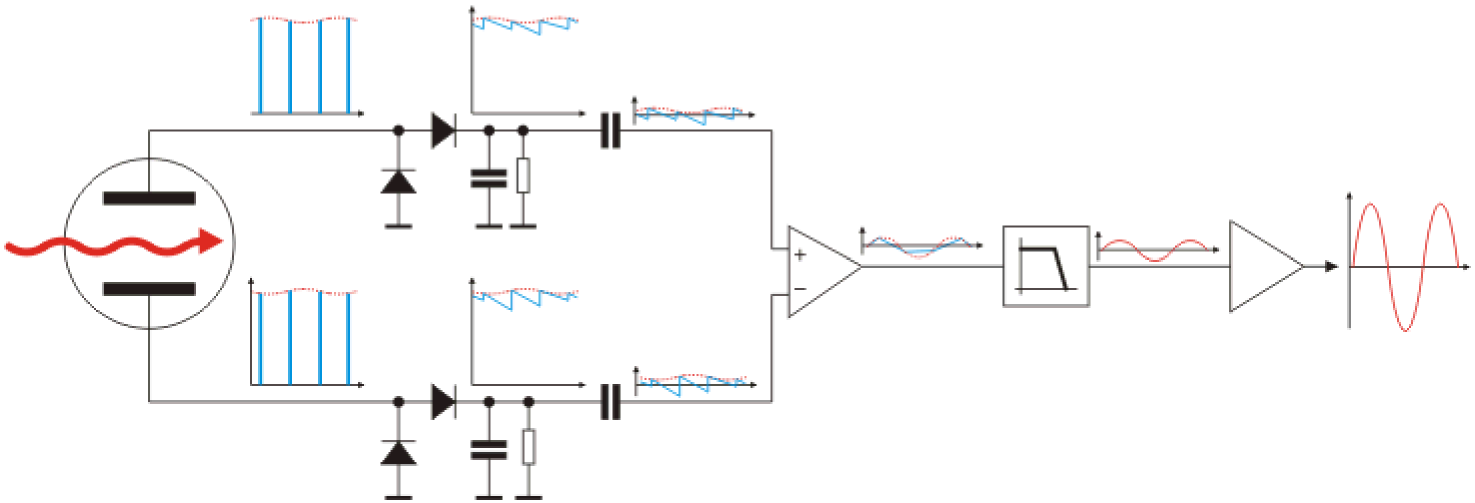
- Measures only non-integral part of Q
- Measure a beam position at each revolution





Fourier transform of pick-up signal

Direct Diode Detection Base Band Q measurement



Diode Detectors convert spikes to saw-tooth waveform

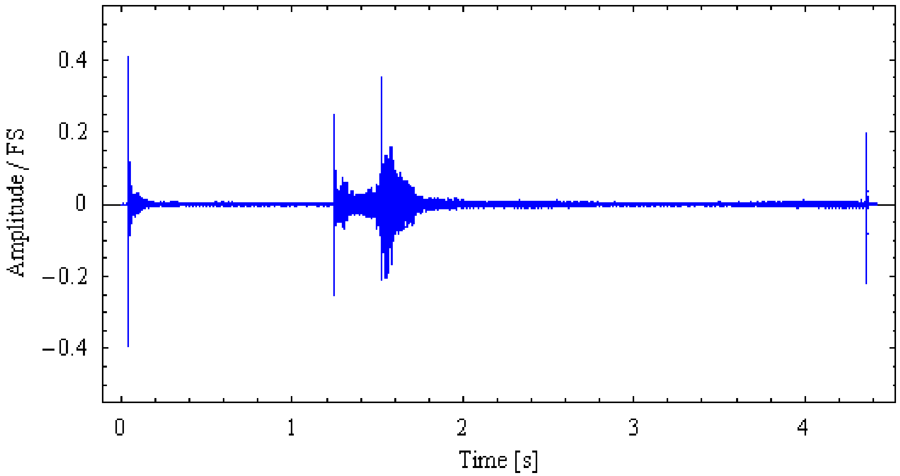
Signal is connected to differential amplifier to cut out DC level

Filter eliminates most of the revolution frequency content

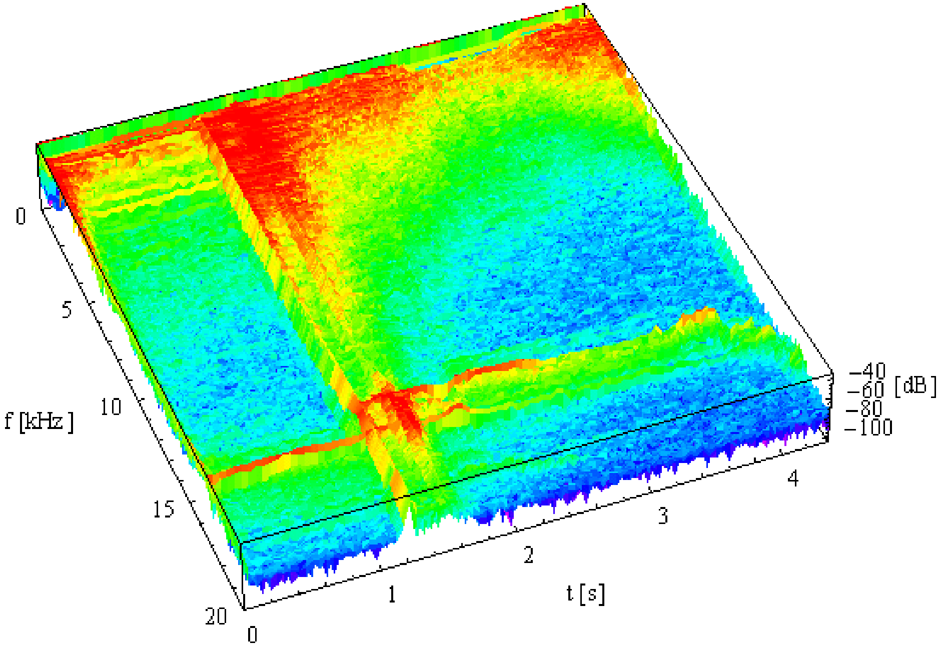
Output amplifier brings the signal level to amplitudes suitable for long distance transmission

BBQ Results from CERN SPS

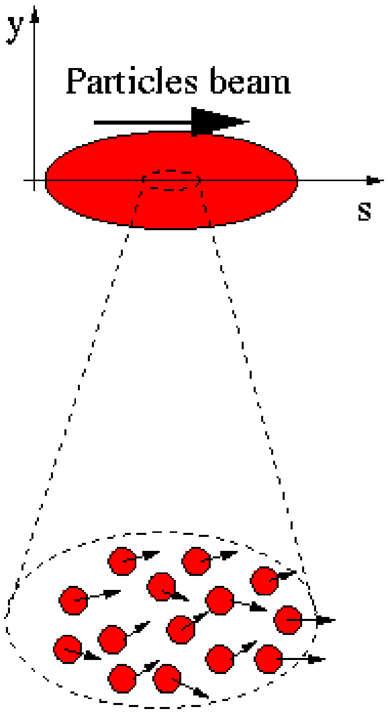
Results from Sampling



After Fourier Transform



Emittance measurements

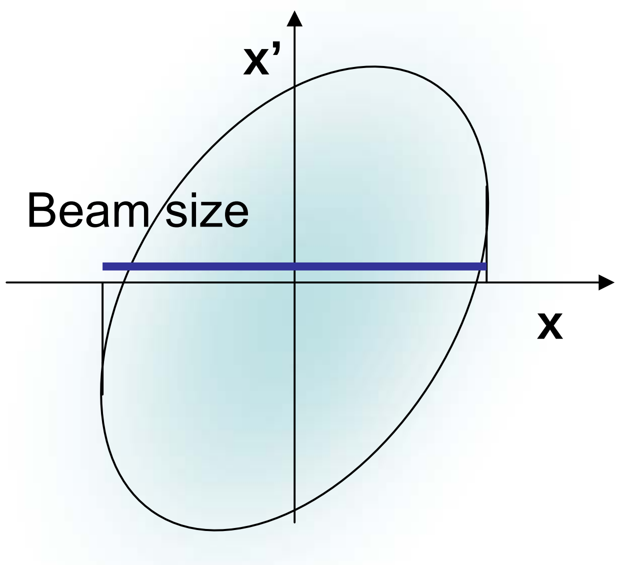


A beam is made of many many particles, each one of these particles is moving with a given velocity. Most of the velocity vector of a single particle is parallel to the direction of the beam as a whole (s). There is however a smaller component of the particles velocity which is perpendicular to it (x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

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

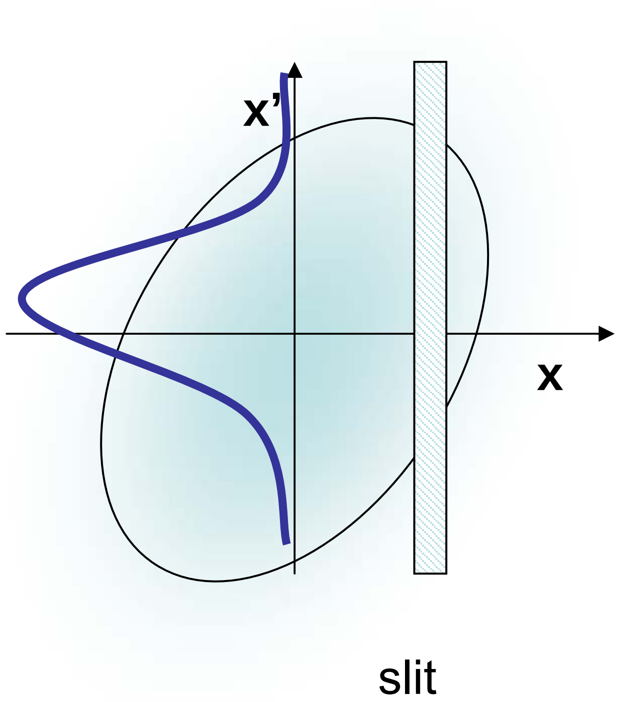
Emittance measurements

- 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



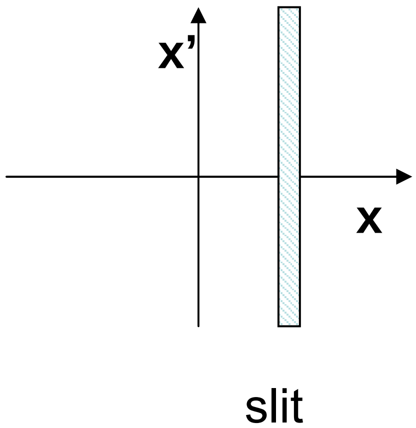
The slit method

- 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

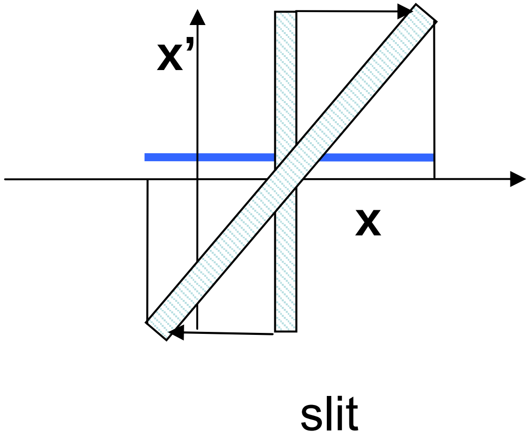


Transforming angular distribution to profile

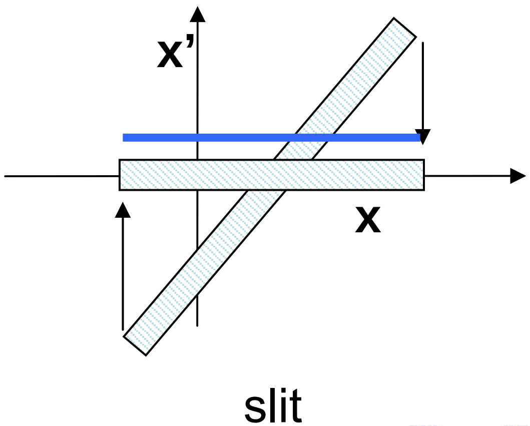
- When moving through a drift space the angles don't change (horizontal move in phase space)
- When moving through a quadrupole the position does not change but the angle does (vertical move in phase space)



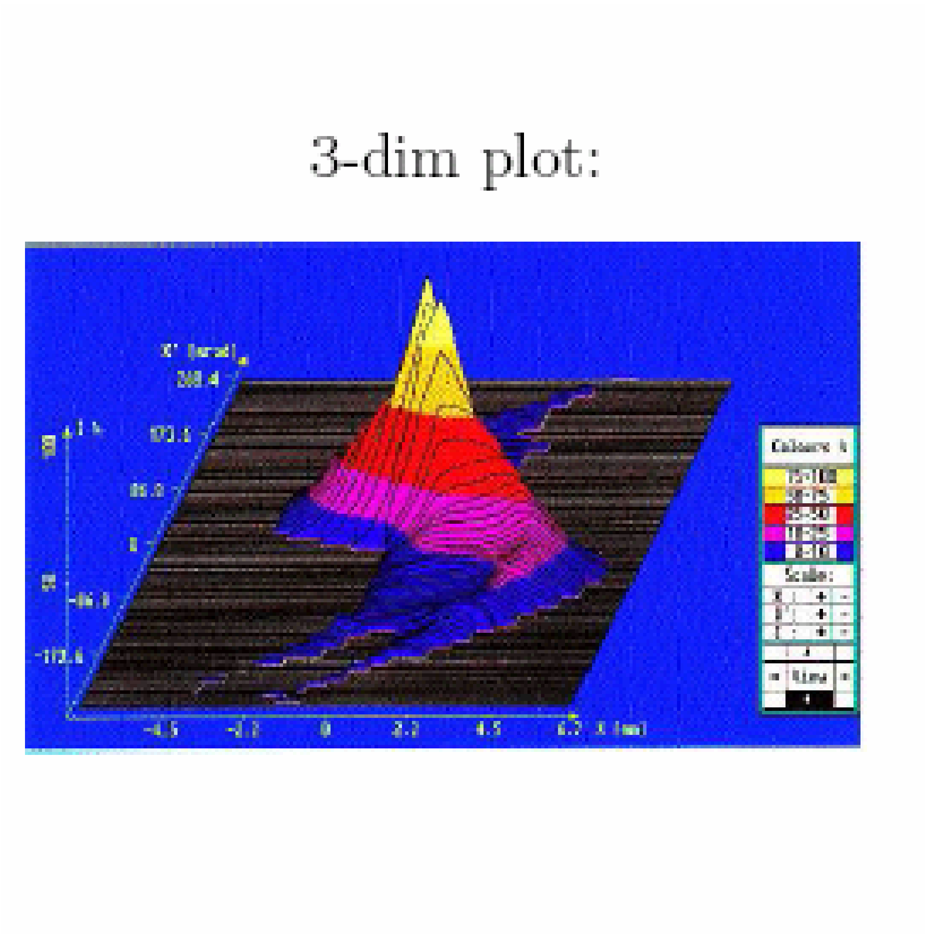
Influence of a drift space

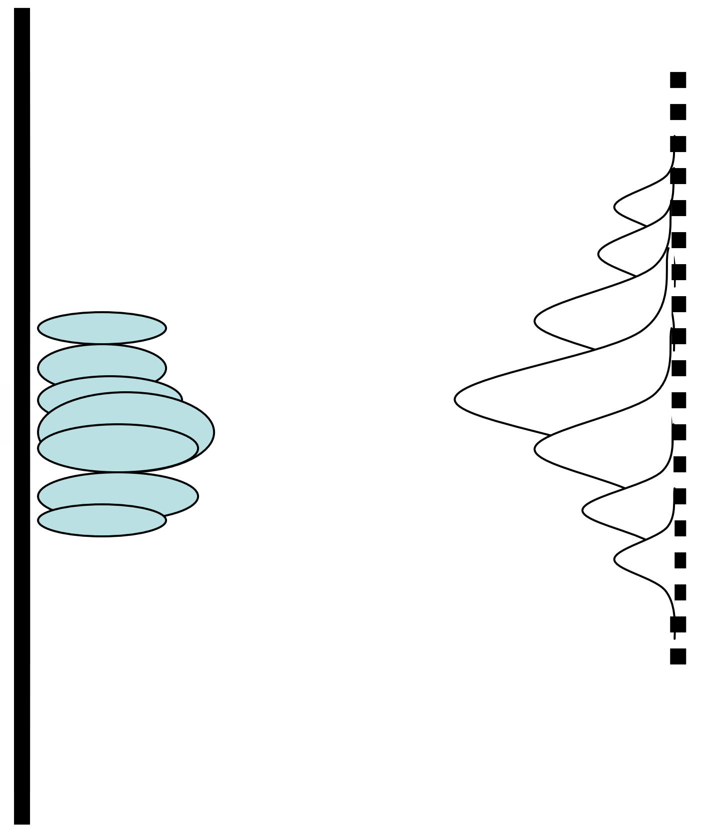


Influence of a quadrupole



The Slit Method

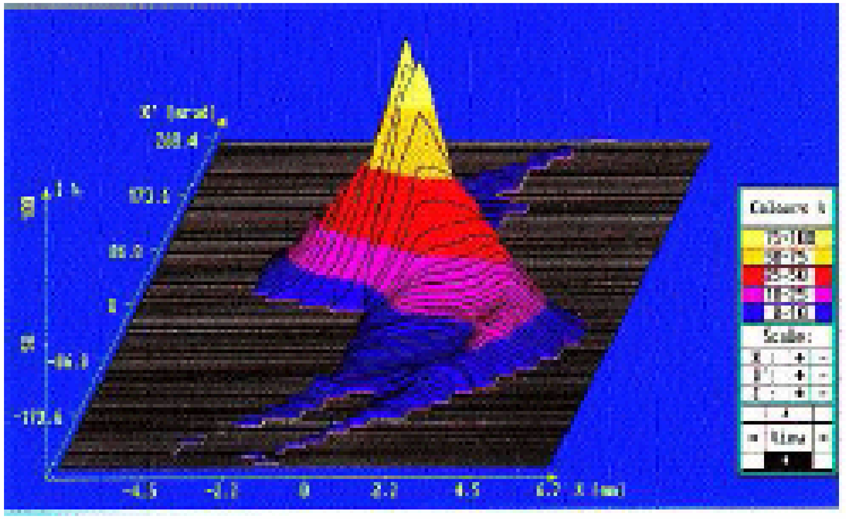


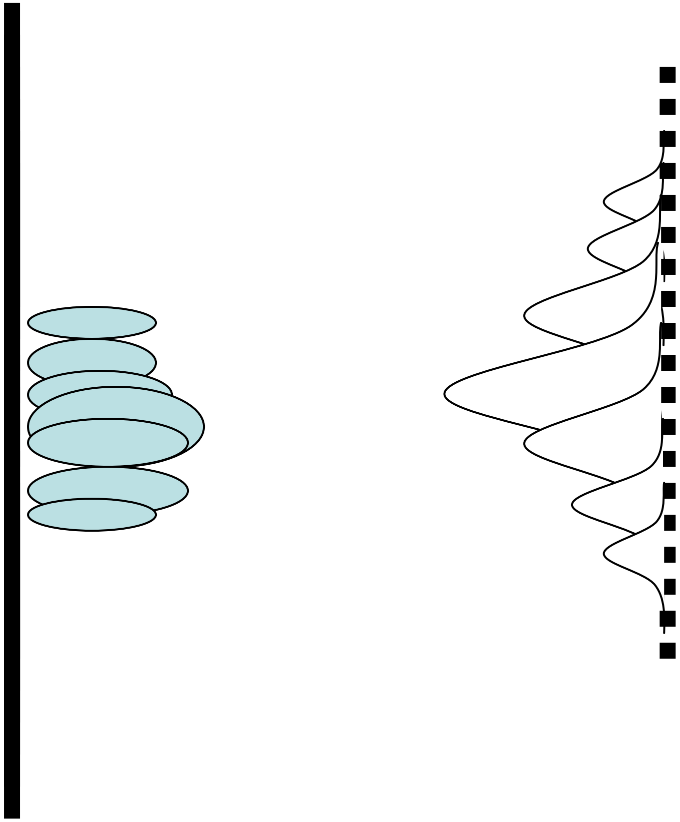


3d plot from P. Forck

The Slit Method

3-dim plot:





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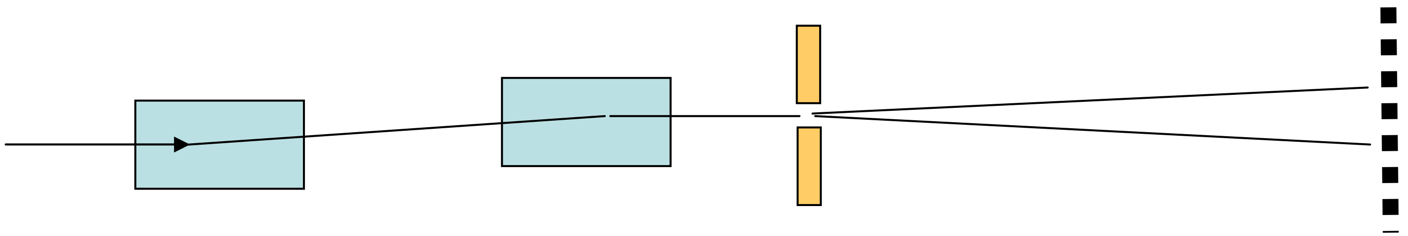
Moving slit emittance measurement

- 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

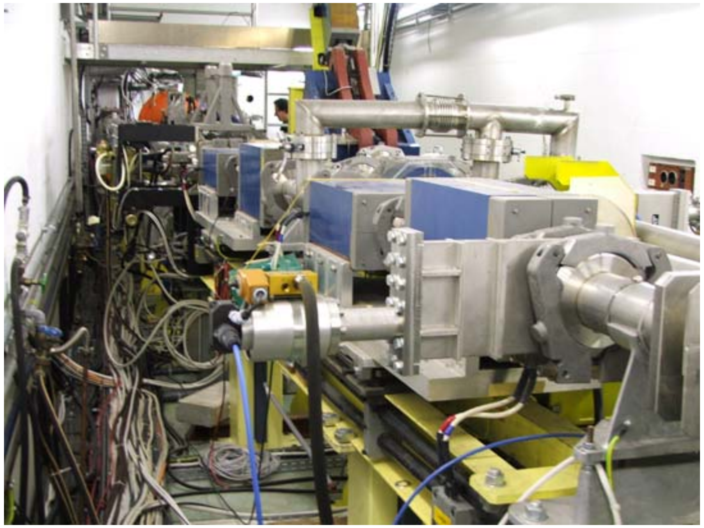
Every 100 ns
a new profile

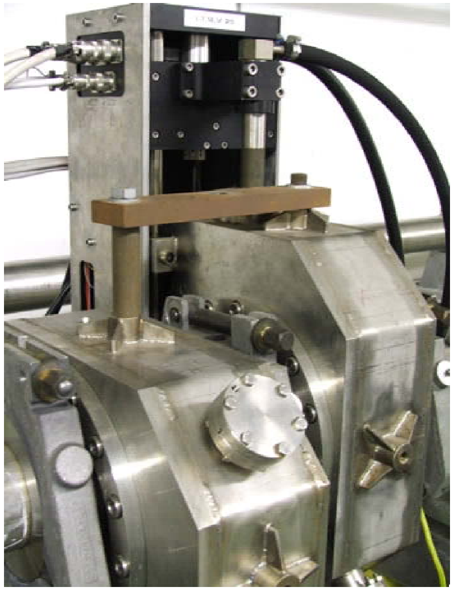


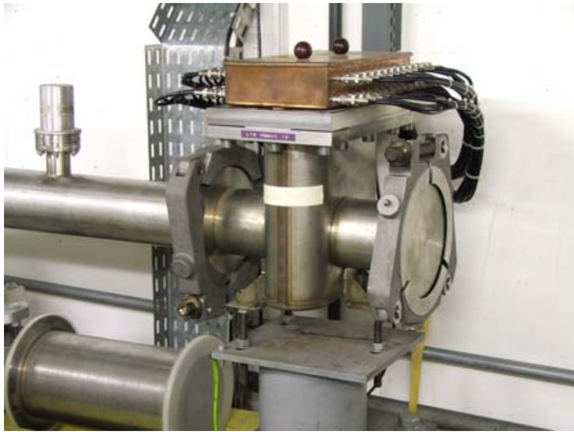
Kickers

slit

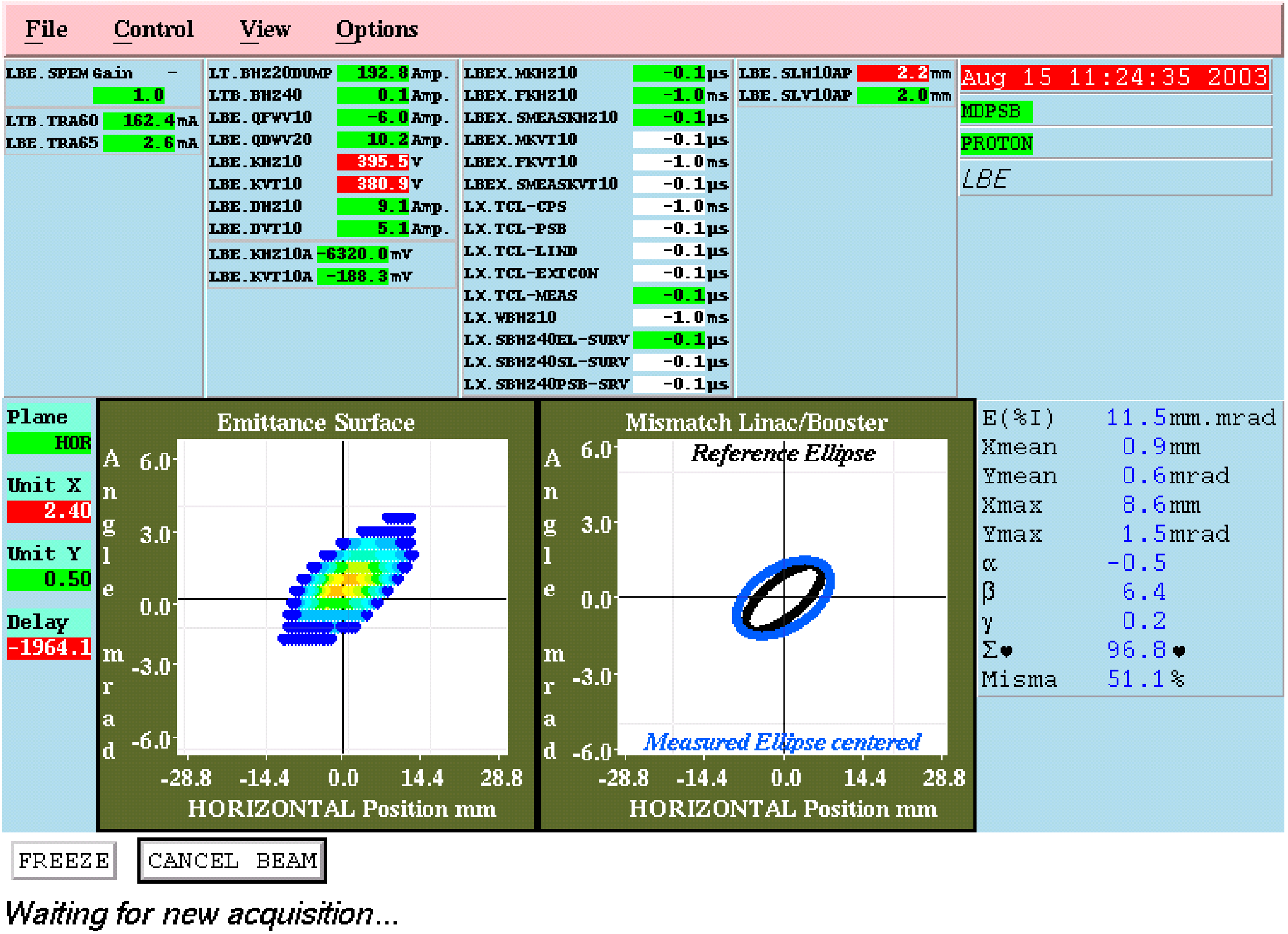
SEMgrid







Result of single pulse emittance measurement

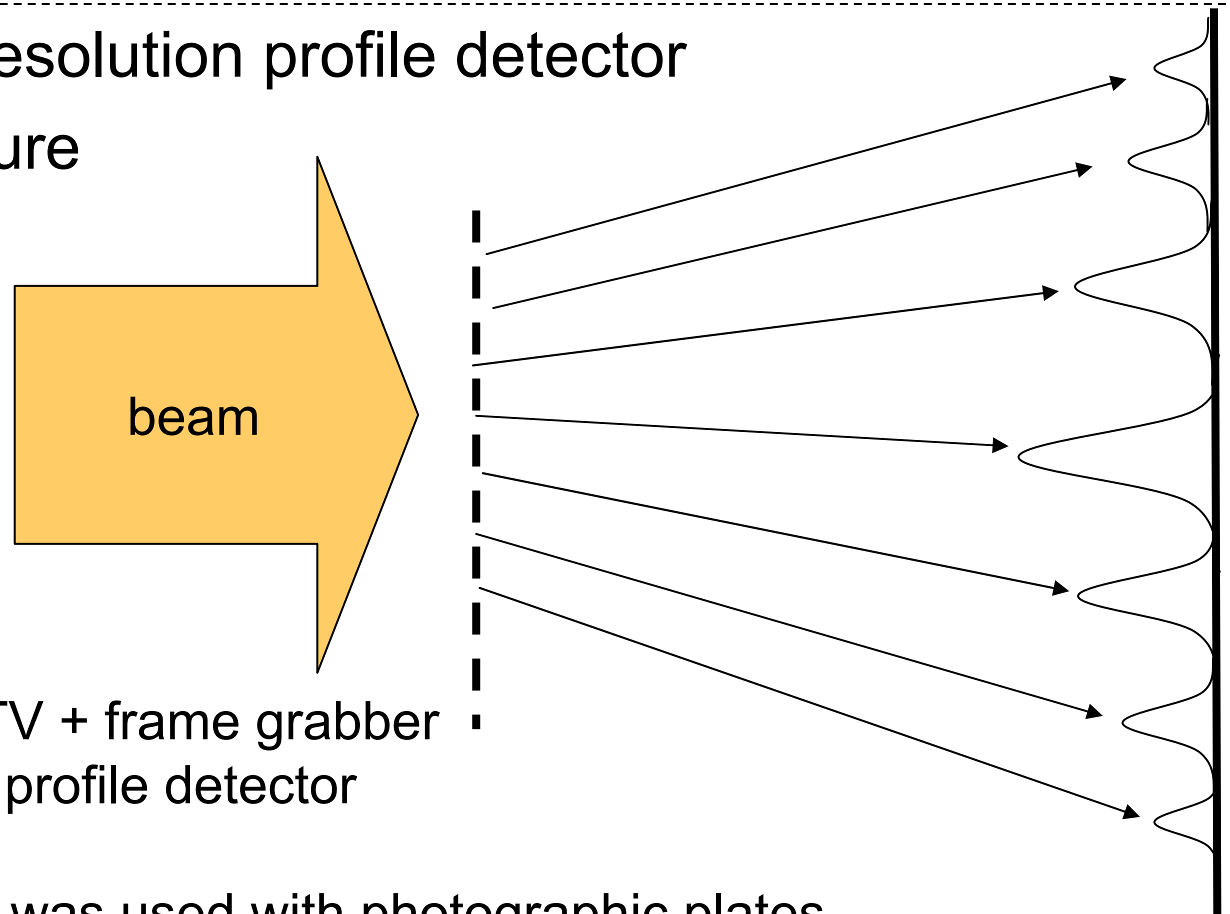


Single Shot Emittance Measurement

- 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

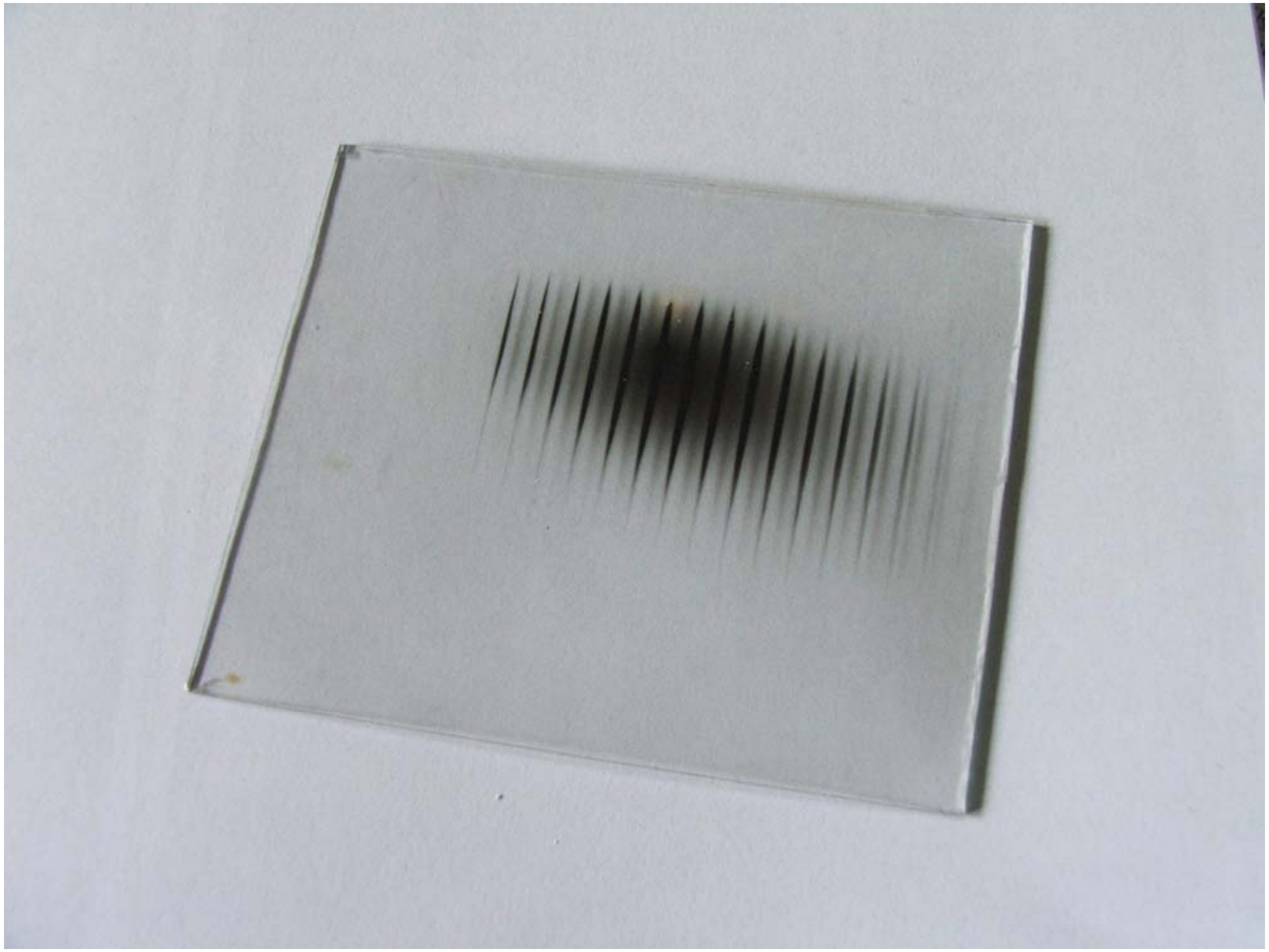
- Needs high resolution profile detector
- Must make sure that profiles dont overlap



Scintillator + TV + frame grabber
often used as profile detector

Very old idea, was used with photographic plates

The method is not new !



Pepperpot

Uses small holes instead of slits

Measures horizontal and vertical emittance in a single shot

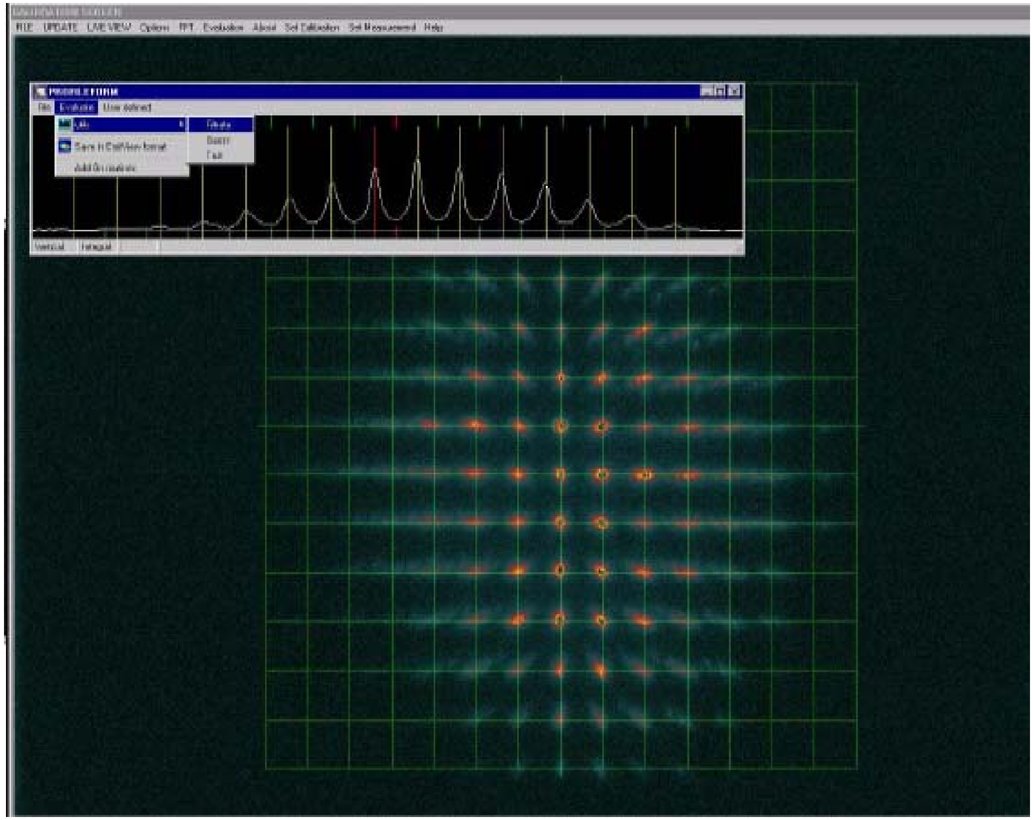
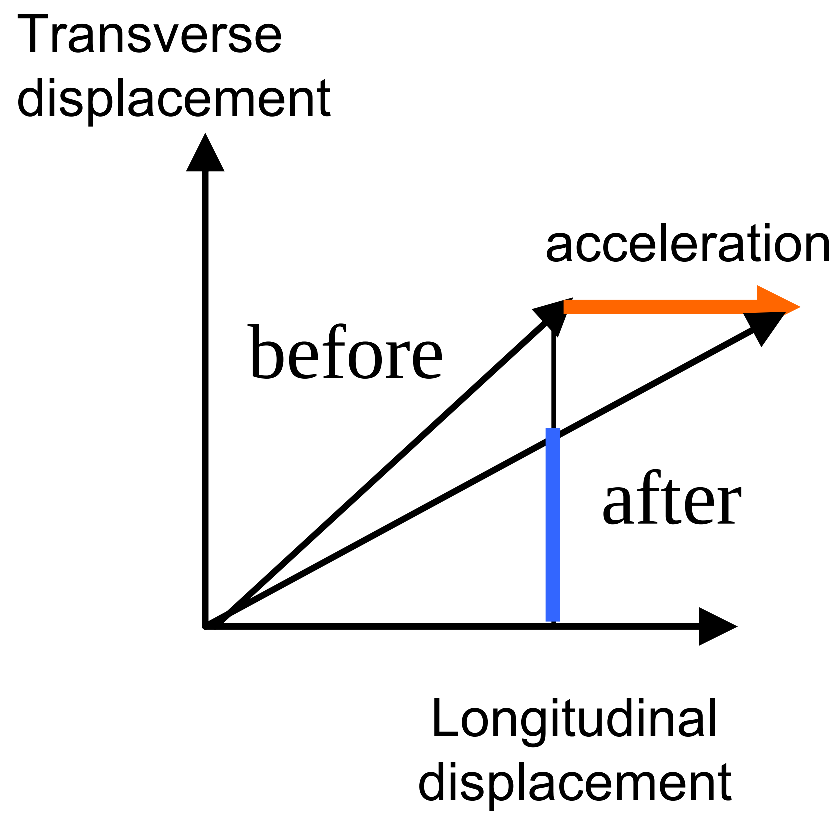


Photo P. Forck

Adiabatic damping

- Change of emittance with acceleration

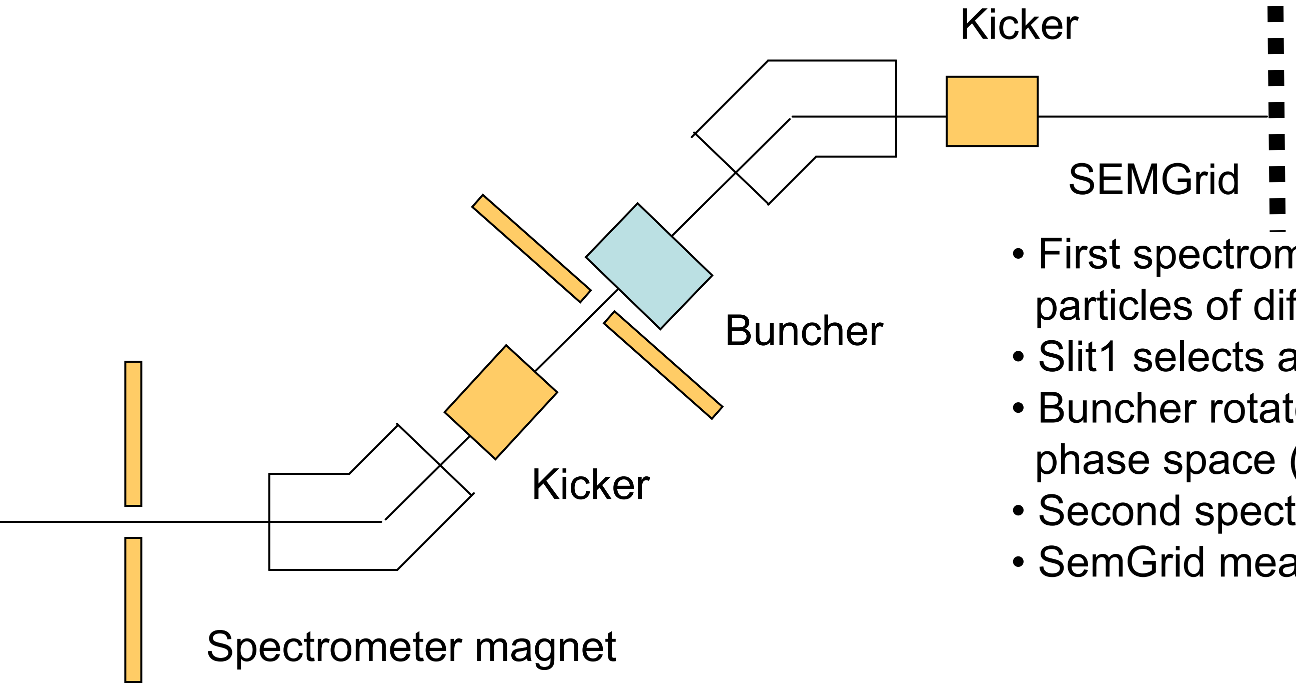


$$\varepsilon_{norm} = \varepsilon_{physical} \beta\gamma$$

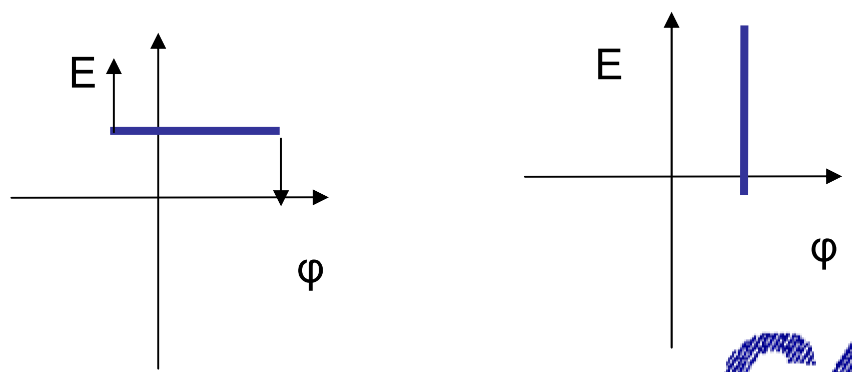
β: speed
γ: Lorentz factor

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

Longitudinal Emittance



- First spectrometer magnet spreads out particles of different energy
- Slit1 selects a slice of energies
- Buncher rotates this slice by 90˚ in phase space (transforms phase to energy)
- Second spectrometer spreads out energies
- SemGrid measures phase profile



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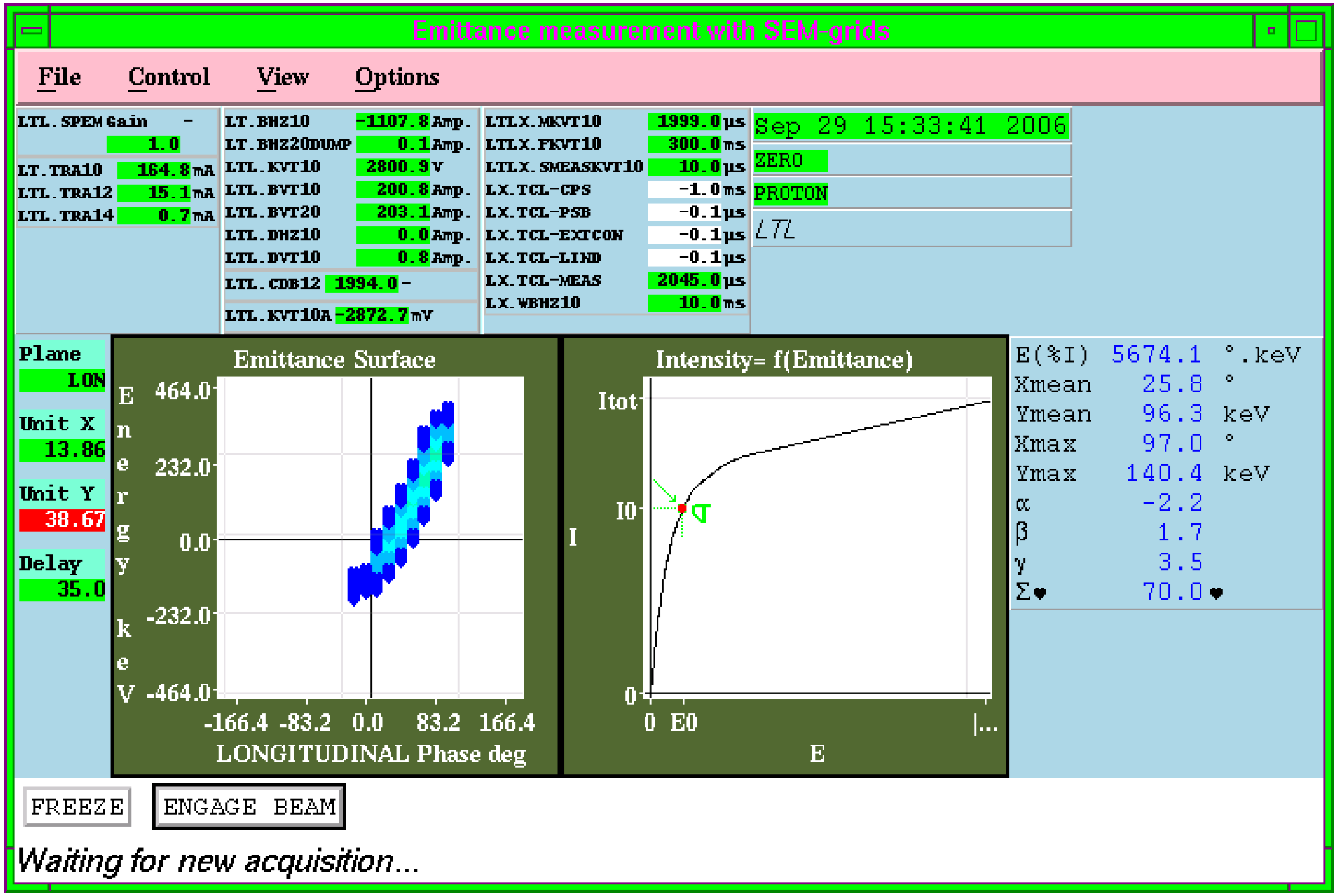
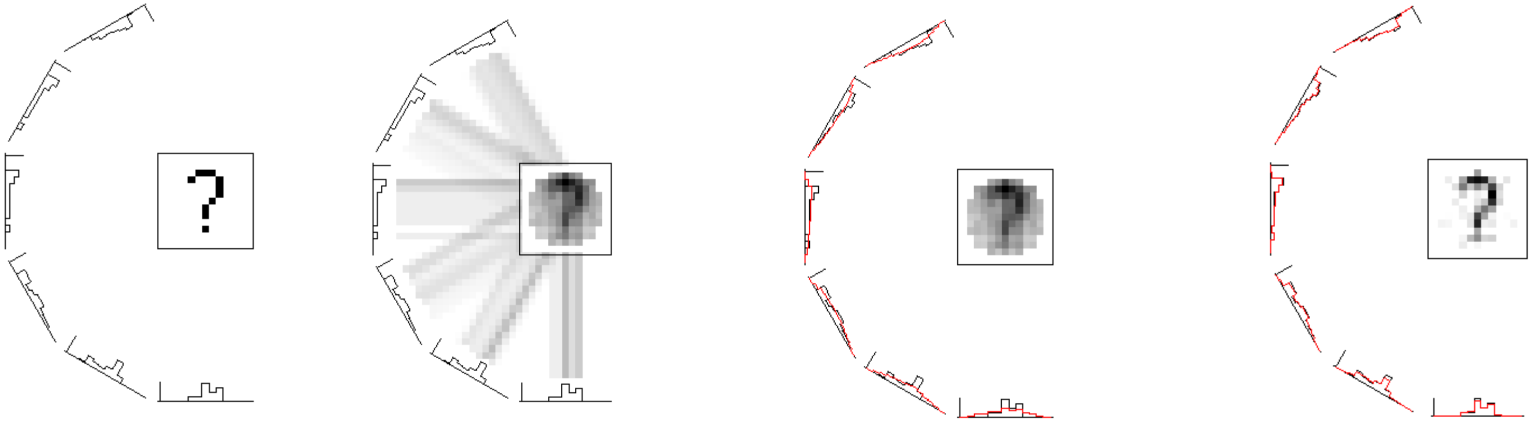
Results from the Longitudinal Profile Measurement



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



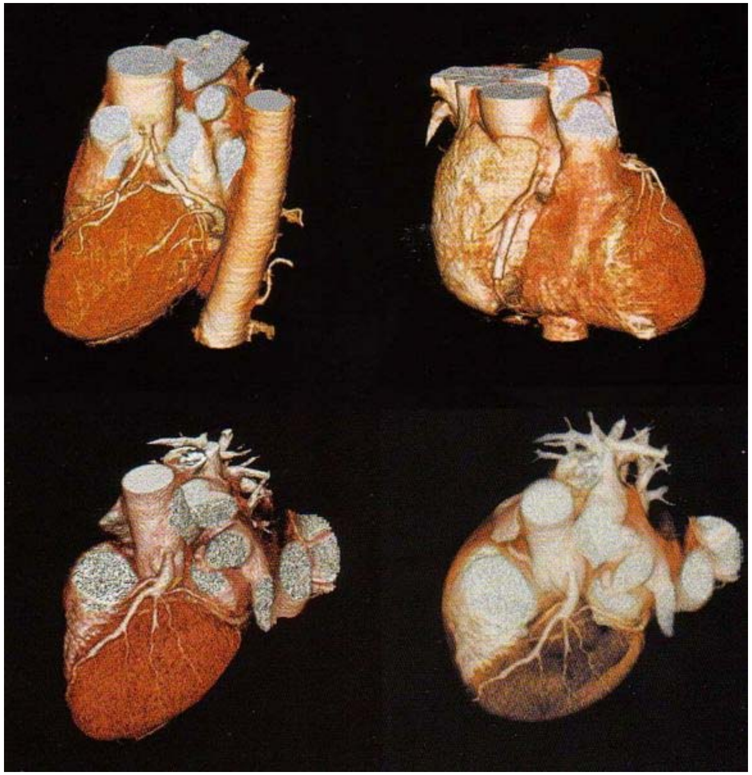
Produce many projections of the object to be reconstructed

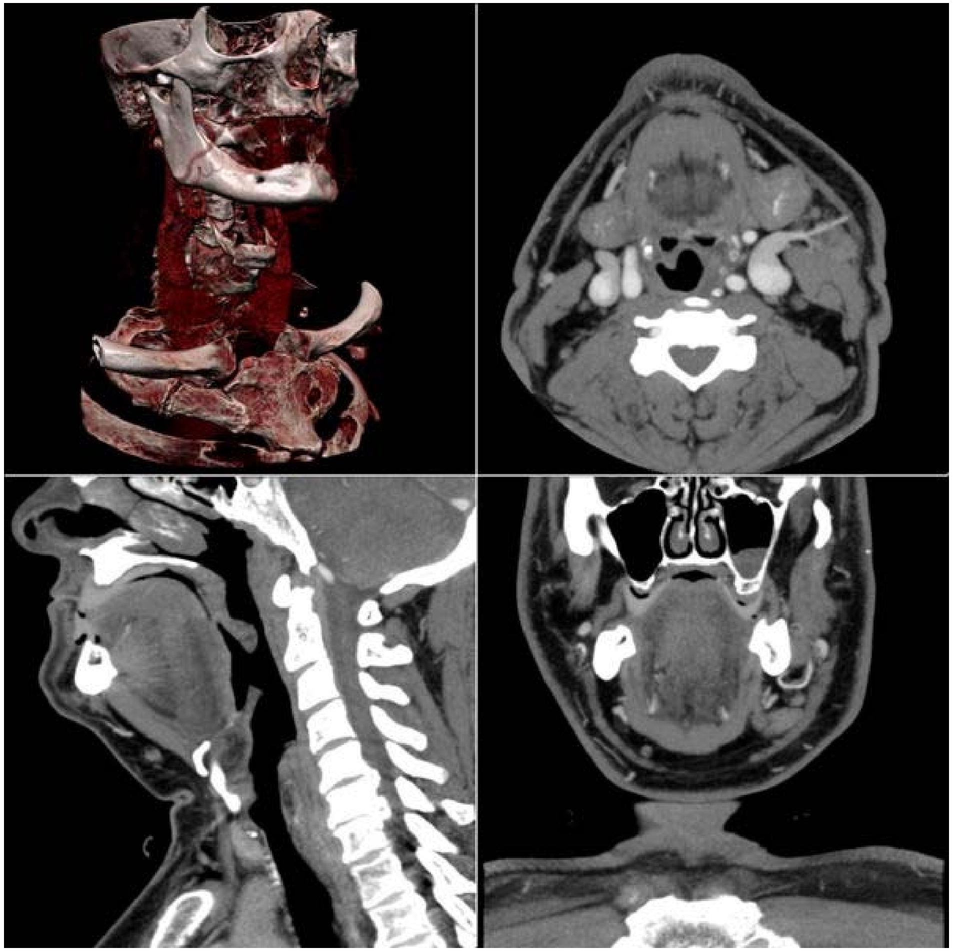
Back project and overlay the “projection rays”

Project the back-projected object and calculate the difference

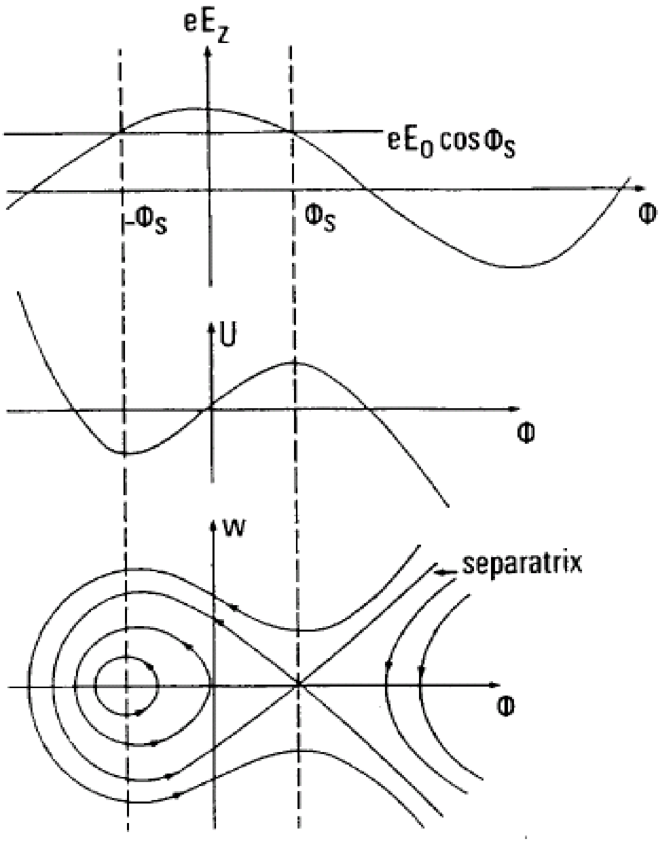
Iteratively back-project the differences to re-construct the original object

Some CT resuluts





Computed Tomography and Accelerators



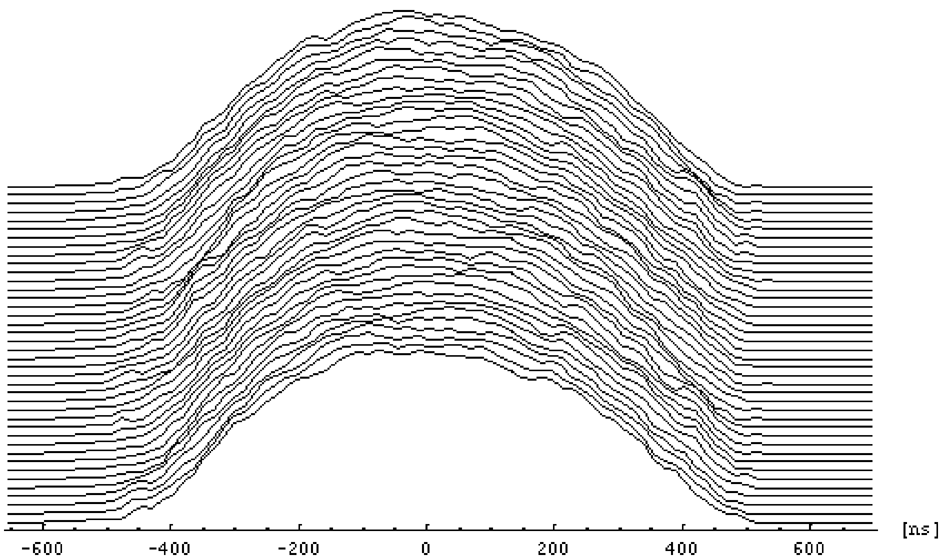
RF voltage

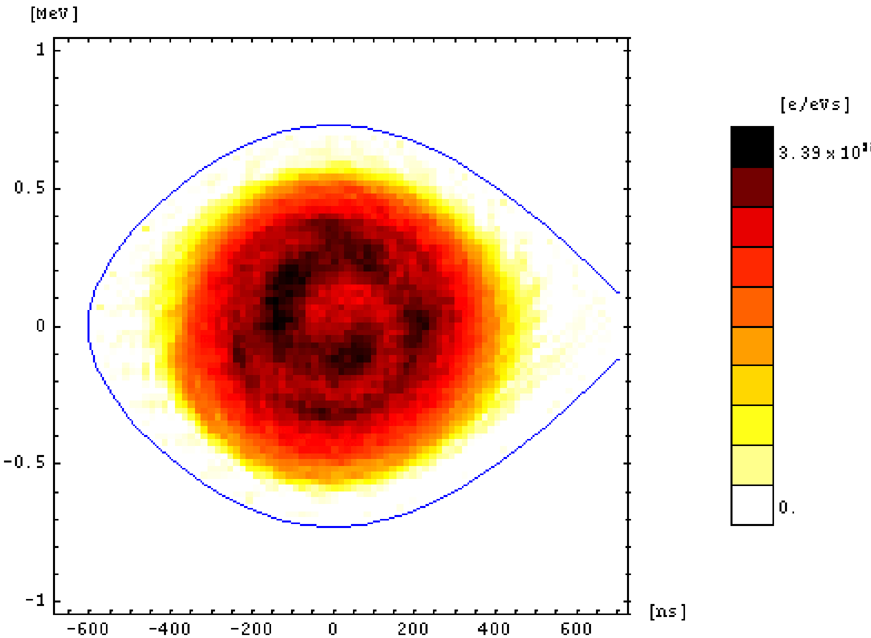
Restoring force for non-synchronous particle

Longitudinal phase space

Projection onto Φ axis corresponds to bunch profile

Reconstructed Longitudinal Phase Space





Bunch Splitting