Introduction to
Beam Diagnostics

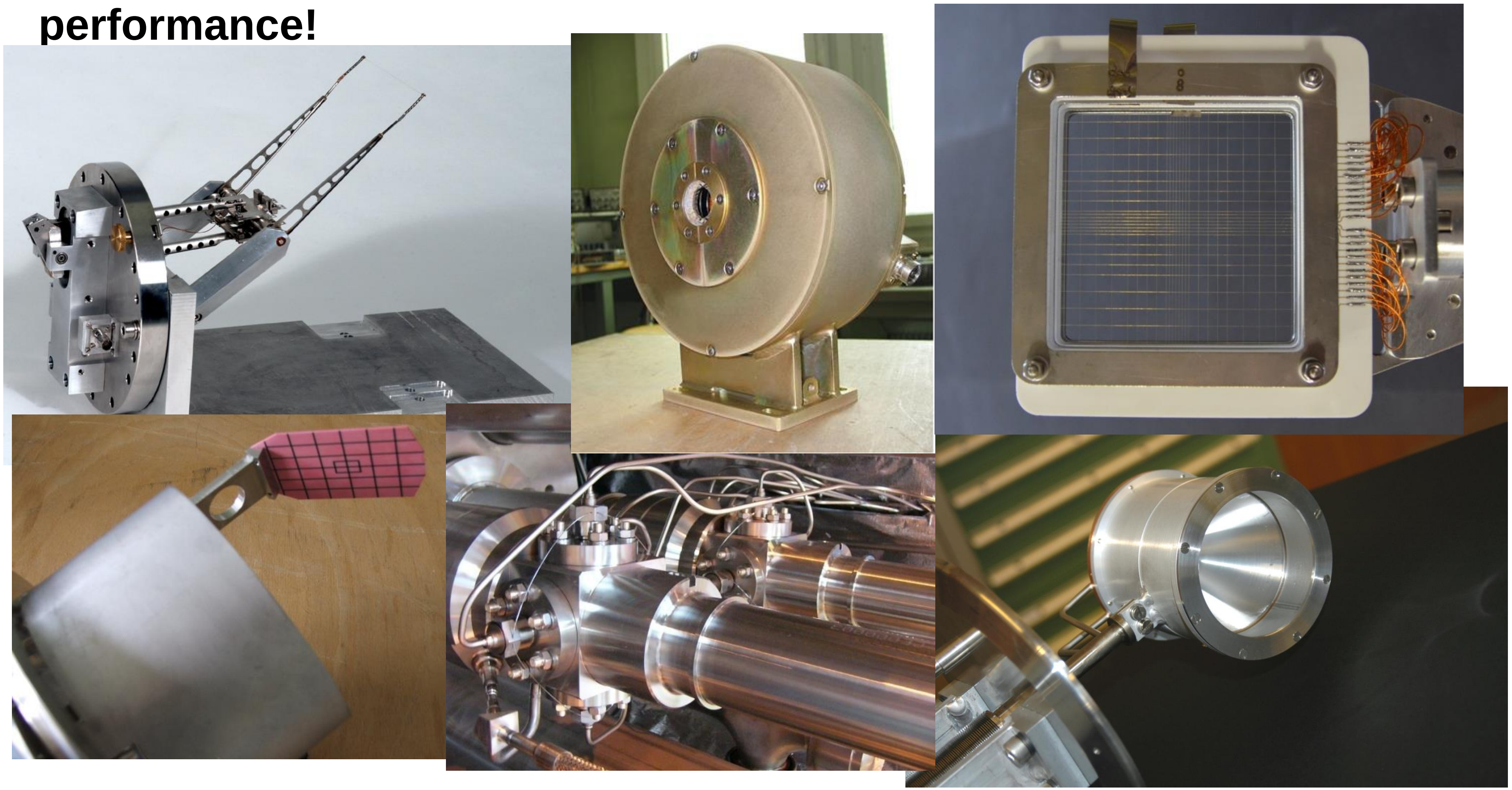
Ulrich Raich
CERN BE - BI
(Beam Instrumentation)

A few depicted examples

- Introduction
- *Beam presence*: Scintillating screens (LHC)
- *Intensity* measurement, Faraday Cup and Transformer (Linac-4)
- *Transverse Profile* measurement, wire scanner & wire grids (PSB & PS)
- *Emittance* measurement
  - Slit and Grid (Linac-4, 3 MeV line)
  - Emittance measurement line (Linac-2)
  - Longitudinal Emittance measurement (Linac-2)
- *Trajectory* measurement (LHC and PS) using Beam Position Monitors (BPMs)
- *Longitudinal phase space*: Tomoscope (PS) using a wall current monitor
- *Tune* measurement (SPS) using BPMs
- *Losses*: Beam Loss Monitors (BLMs) (LHC)

Introduction

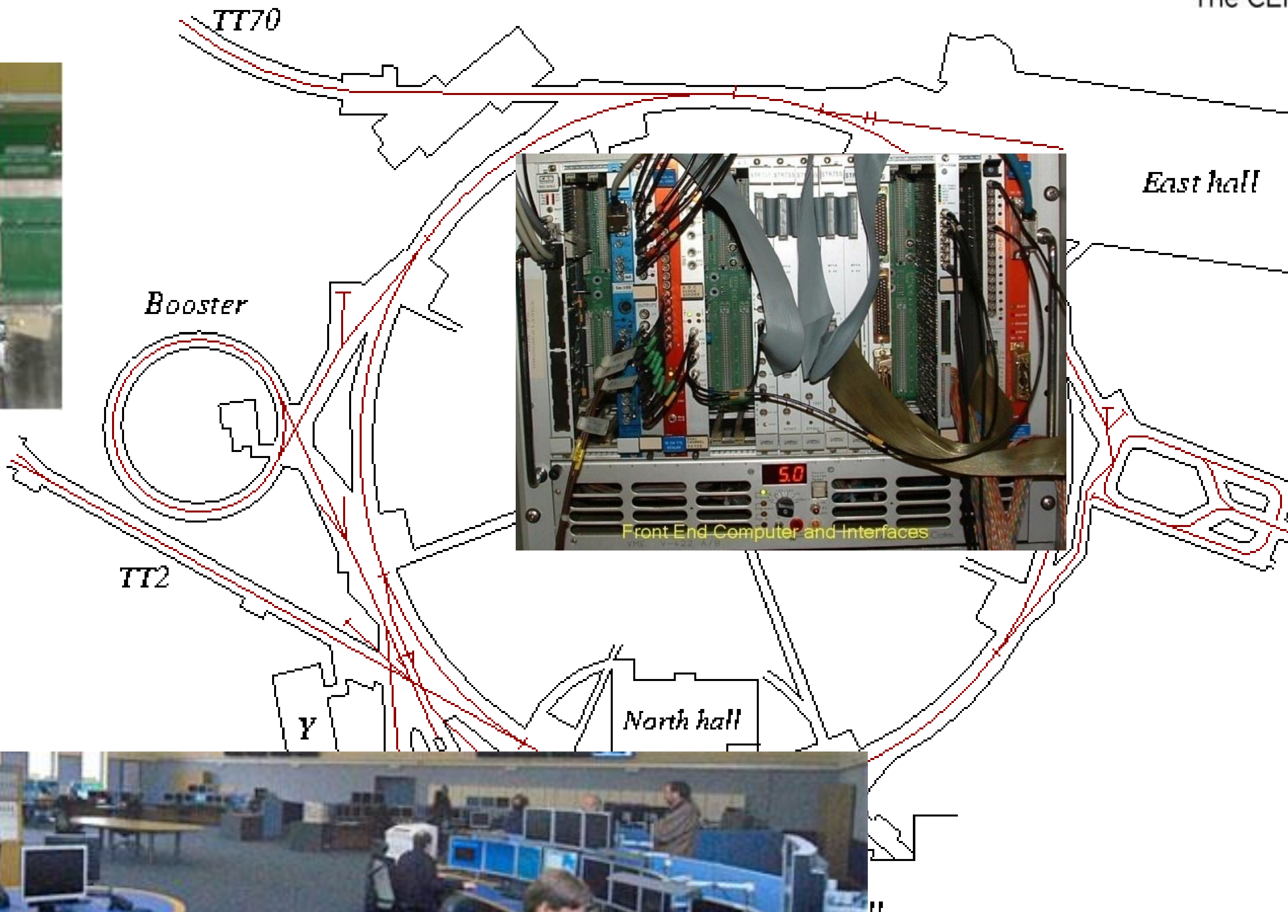
An accelerator can never be better than the instruments measuring its performance!

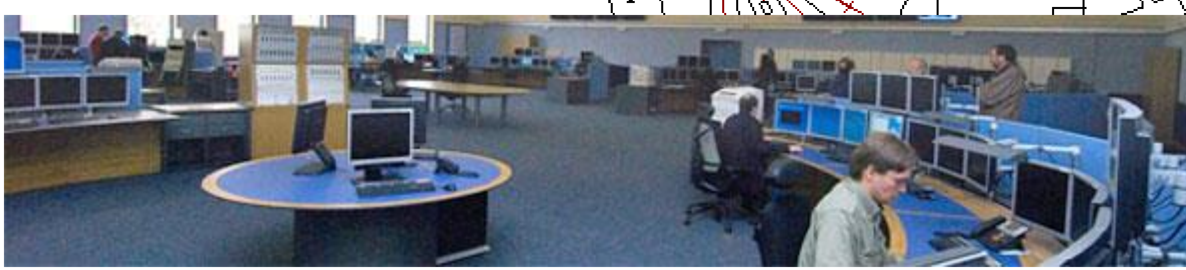


Diagnostic devices and quantity measured

Instrument	Physical Effect	Measured Quantity	Effect on beam
Faraday Cup	Charge collection	Intensity	Destructive
Current Transformer	Magnetic field	Intensity	Non destructive
Wall current monitor	Image Current	Intensity Longitudinal beam shape	Non destructive
Pick-up	Electric/magnetic field	Position, Tune	Non destructive
Secondary emission monitor	Secondary electron emission	Transverse size/shape, emittance	Disturbing, can be destructive at low energies
Wire Scanner	Secondary particle creation	Transverse size/shape	Slightly disturbing
Scintillator screen	Atomic excitation with light emission	Transverse size/shape (position)	Destructive
Residual Gas monitor	Ionization	Transverse size/shape	Non destructive

A beam parameter measurement





Beam Presence Scintillating Screens

Method already applied in cosmic ray experiments

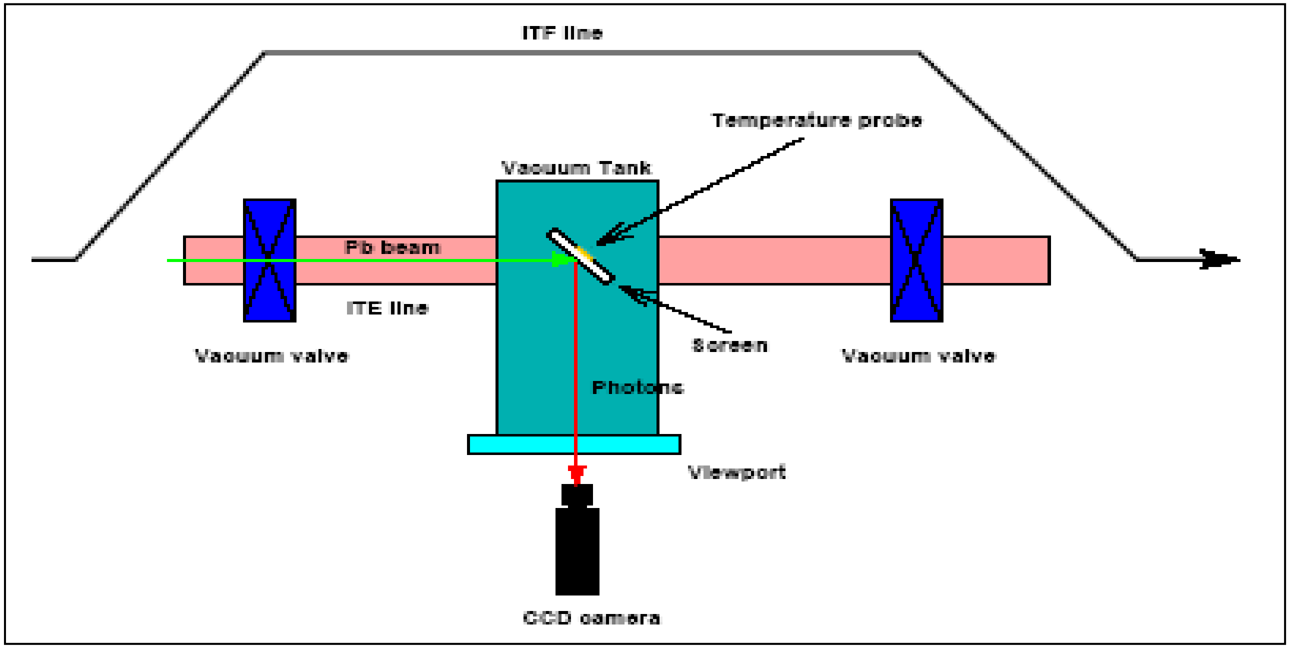
- Very simple
- Very convincing

Needed:

- Scintillating Material
- TV camera
- In/out mechanism

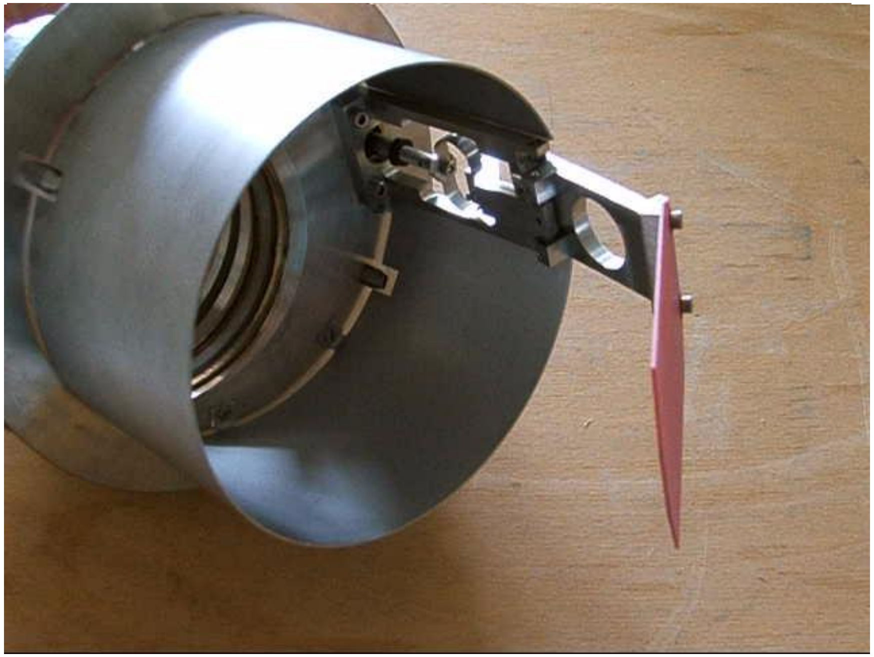
Problems:

- Radiation resistance of TV camera
- Heating of screen (absorption of beam energy)
- Evacuation of electric charges

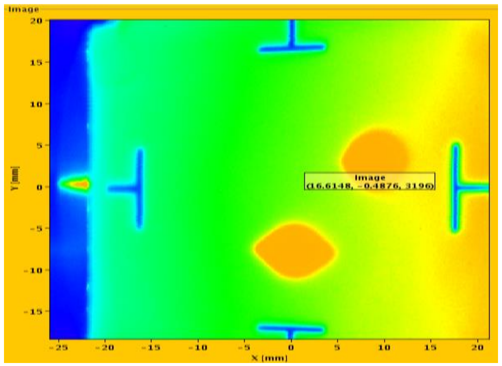


Screen mechanism

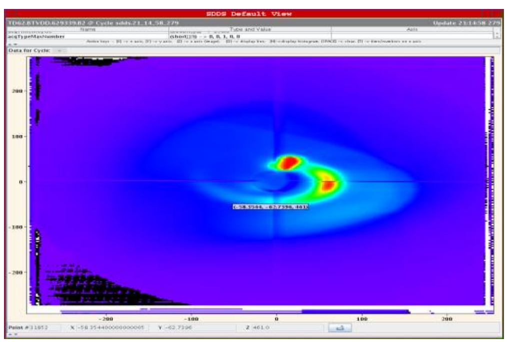
- Screen with graticule



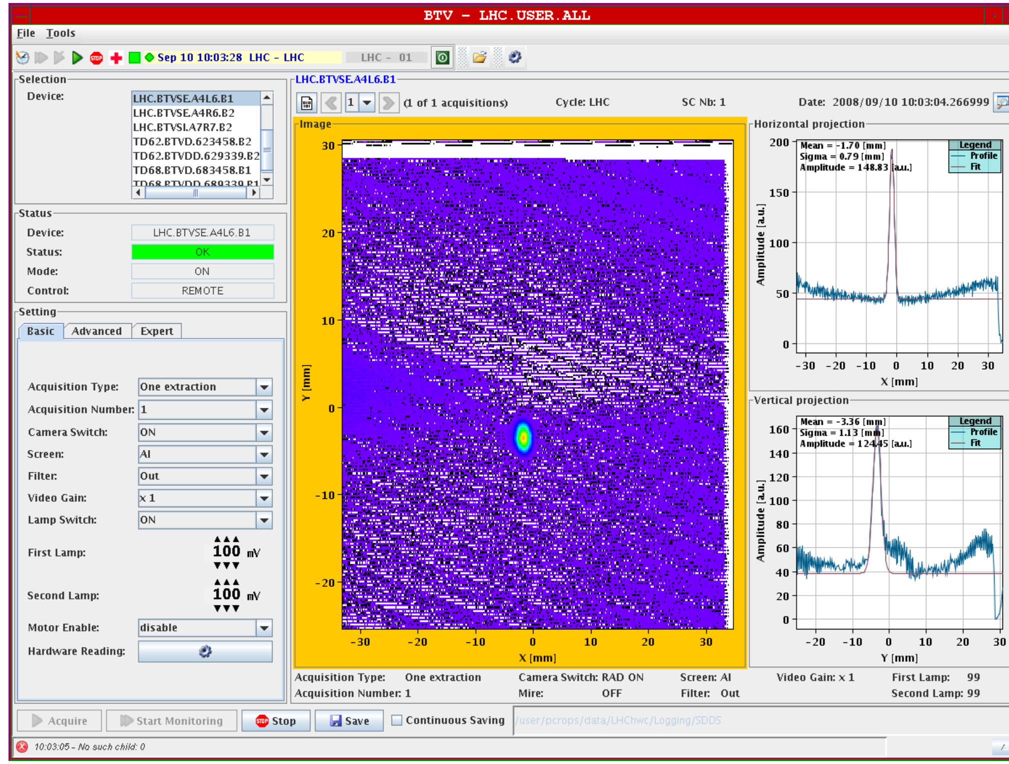
Results from TV Frame grabber



First full turn as seen by the BTV 10/9/2008



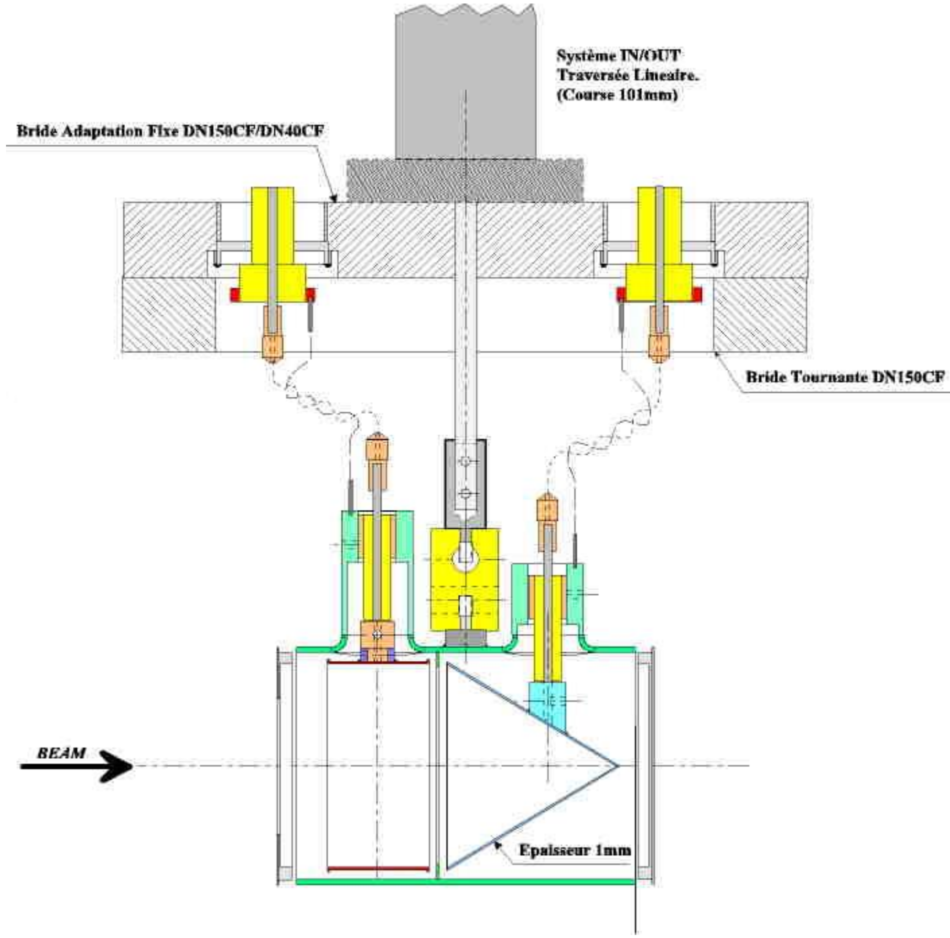
Un-captured beam sweeps through he dump line



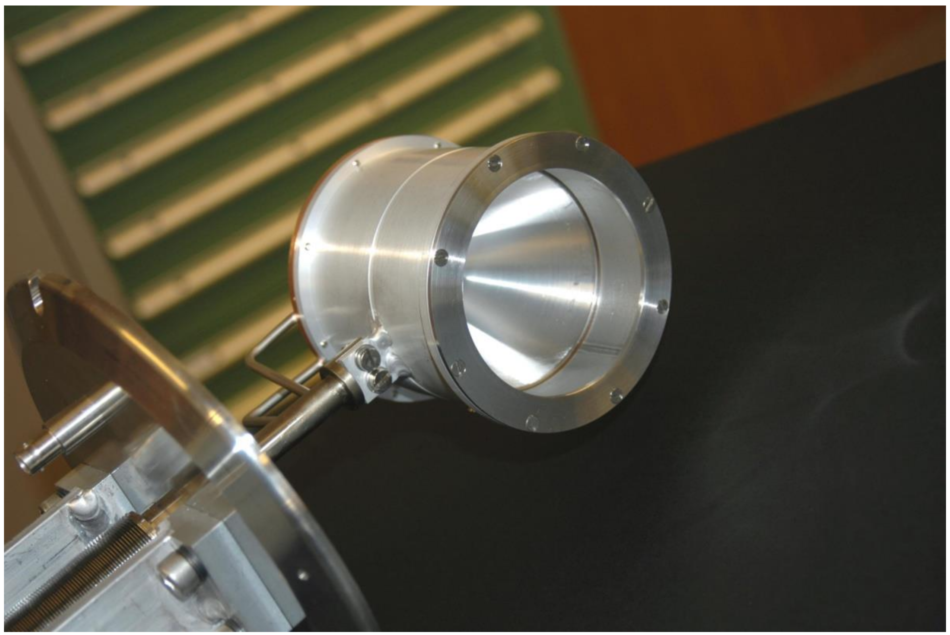
- For further evaluation the video signal is digitized, read-out and treated by program

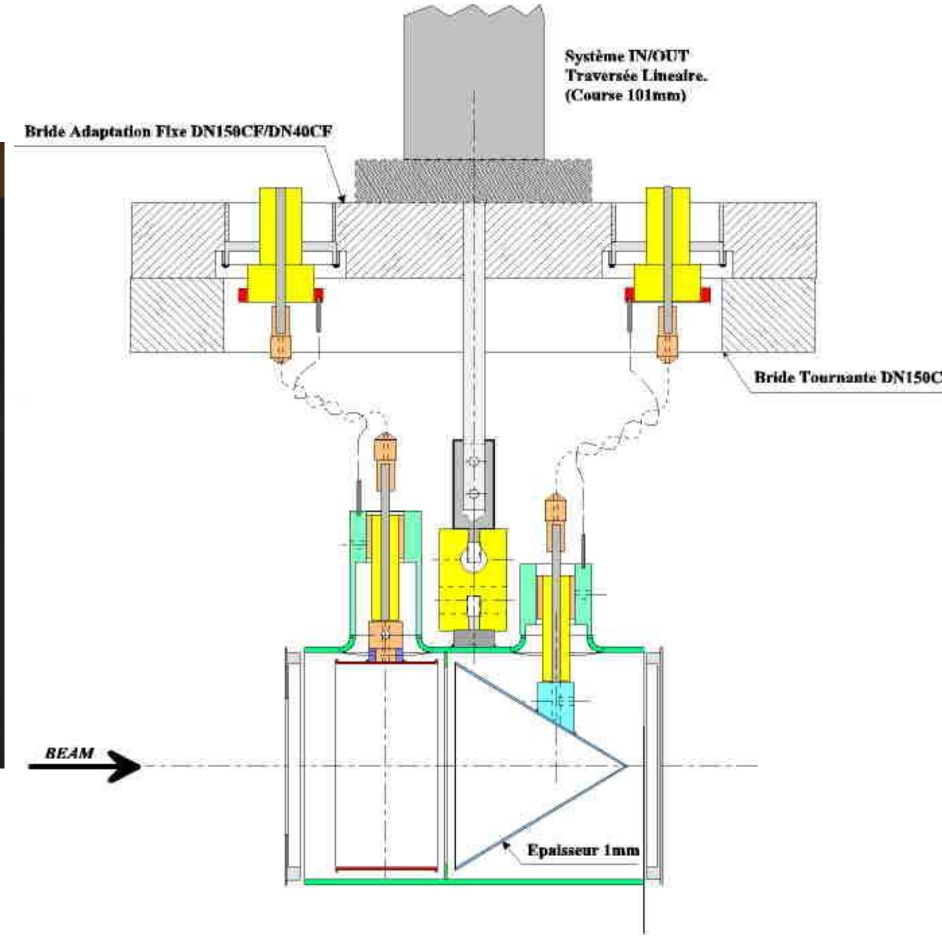
Beam Intensity
Layout of a Faraday Cup

- Electrode: 1 mm stainless steel
- Only low energy particles can be measured
- Very low intensities (down to 1 pA) can be measured
- Creation of secondary electrons of low energy (below 20 eV)
- Repelling electrode with some 100 V polarisation voltage pushes secondary electrons back onto the electrode



Faraday Cup



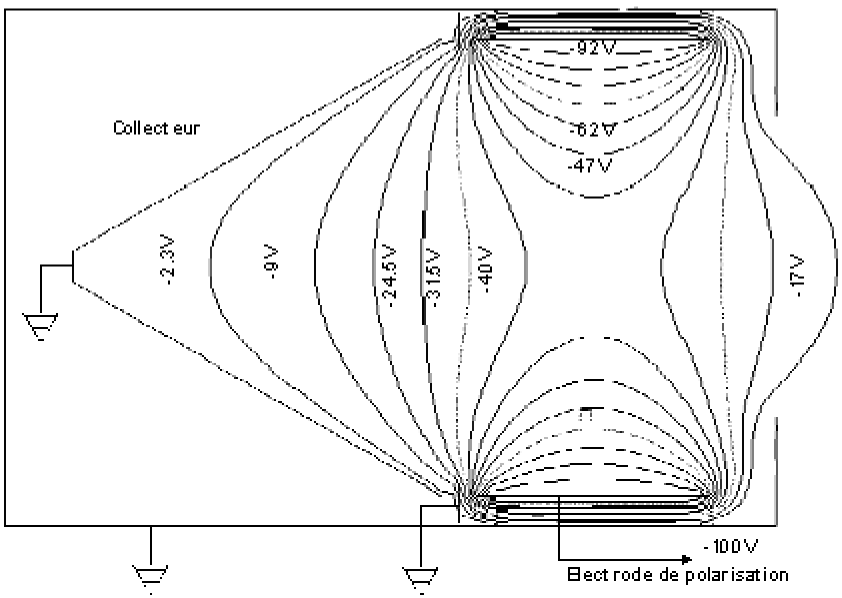


Système IN/OUT
Traversée Lineaire.
(Course 101mm)
Bride Adaptation Fixe DN150CF/DN40CF
Bride Tournante DN150CF
BEAM
Epaisseur 1mm

Electro-static Field in Faraday Cup

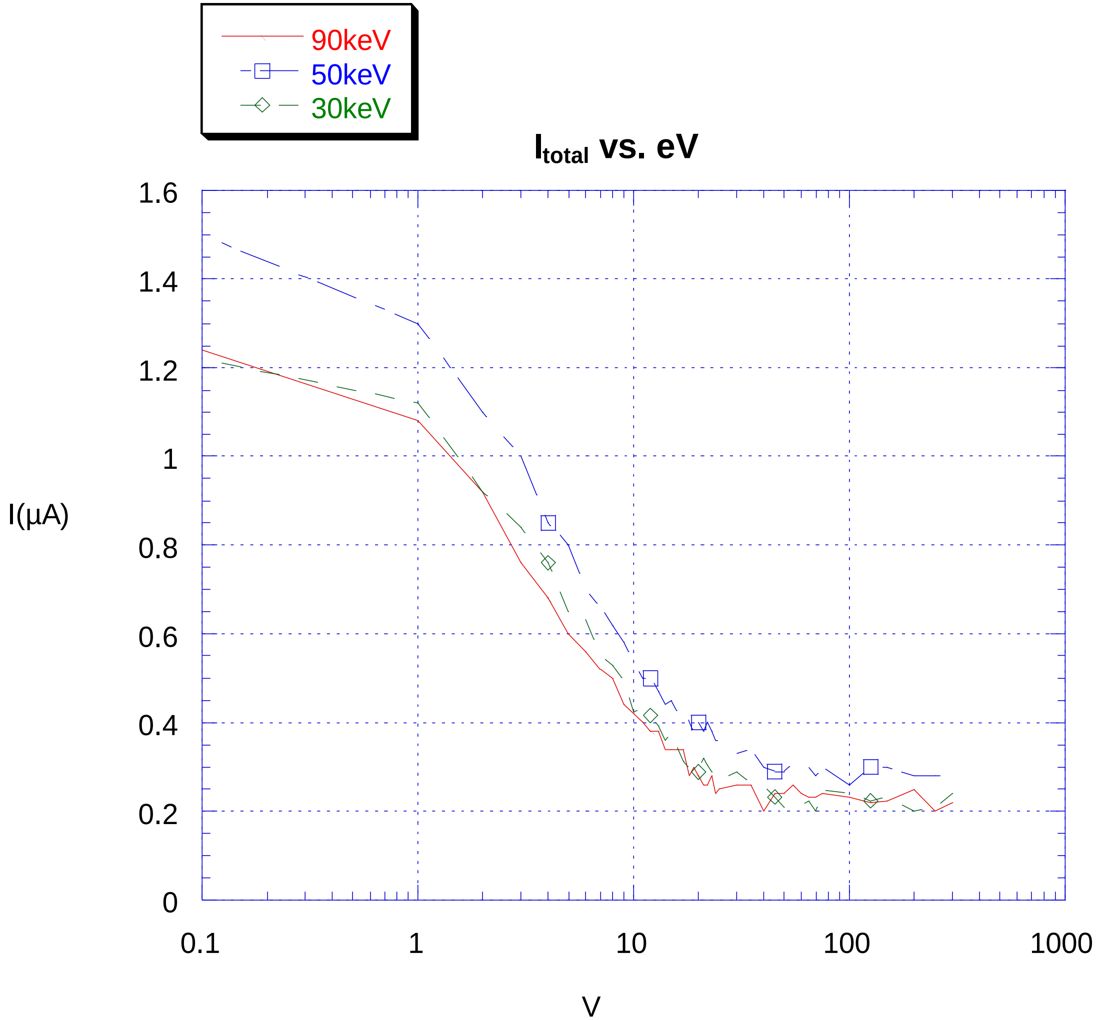
In order to keep secondary electrons with the cup a repelling voltage is applied to the polarization electrode

Since the electrons have energies of less than 20 eV some 100V repelling voltage is sufficient



Energy of secondary emission electrons

- With increasing repelling voltage the electrons do not escape the Faraday Cup any more and the current measured stays stable.
- At 40V and above no decrease in the Cup current is observed any more



Intensity
Principle of a fast current transformer

- 500MHz Bandwidth
- Low droop (< 0.2%/μs)

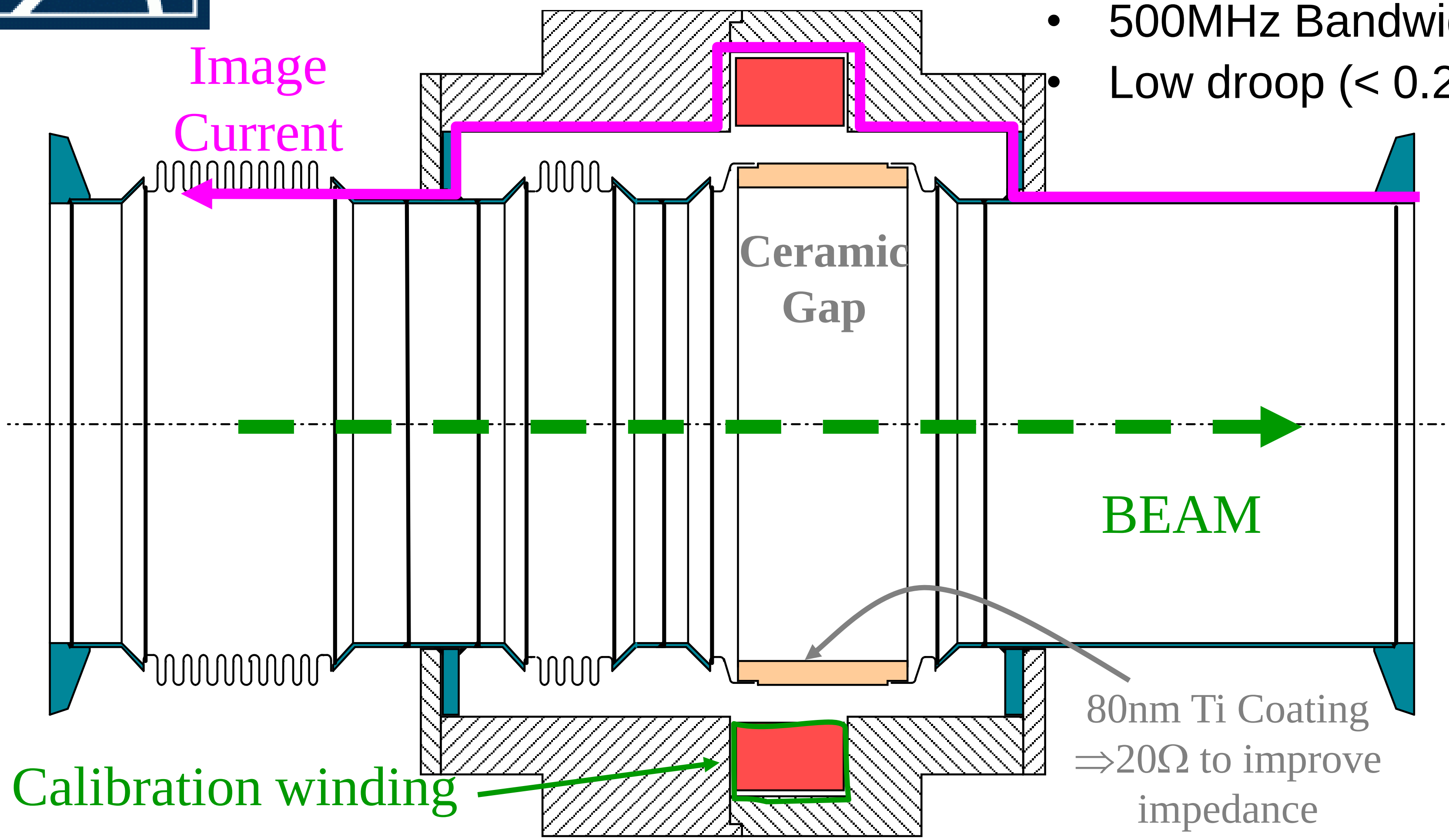
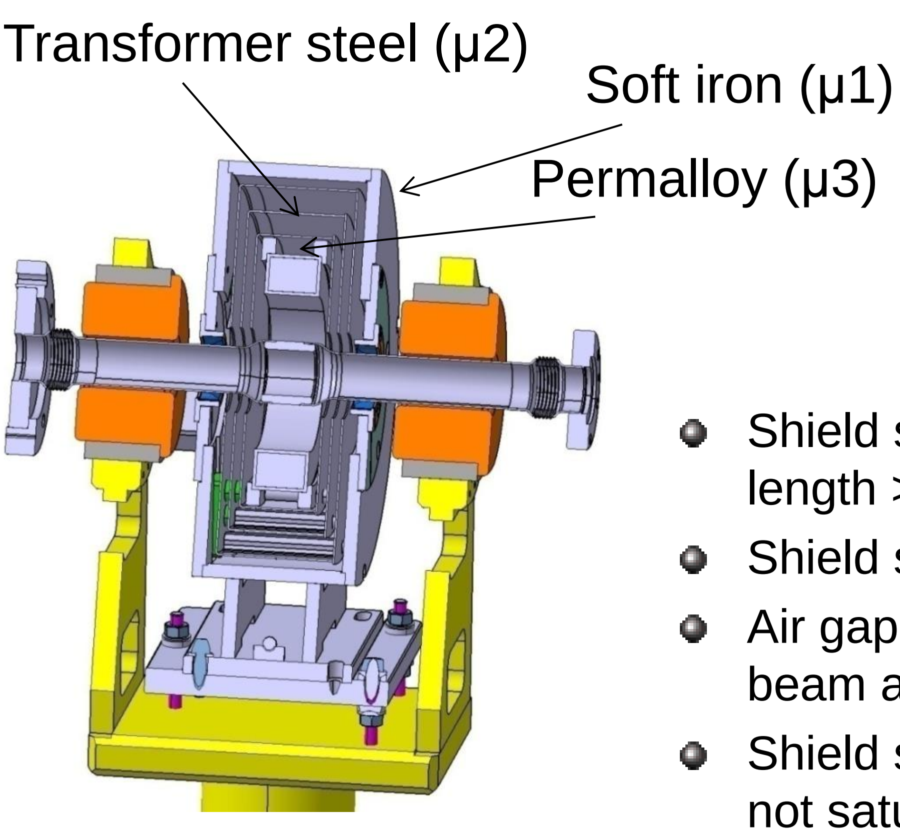
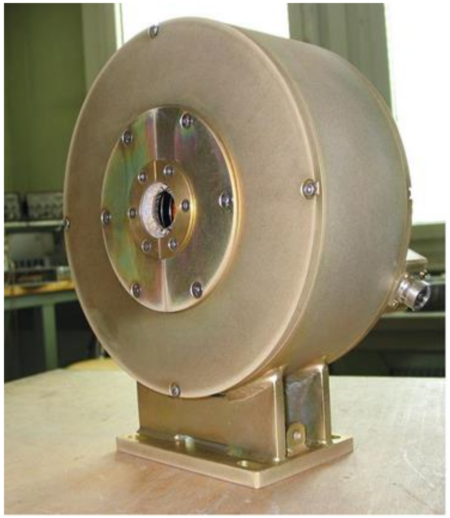


Diagram by H. Jakob

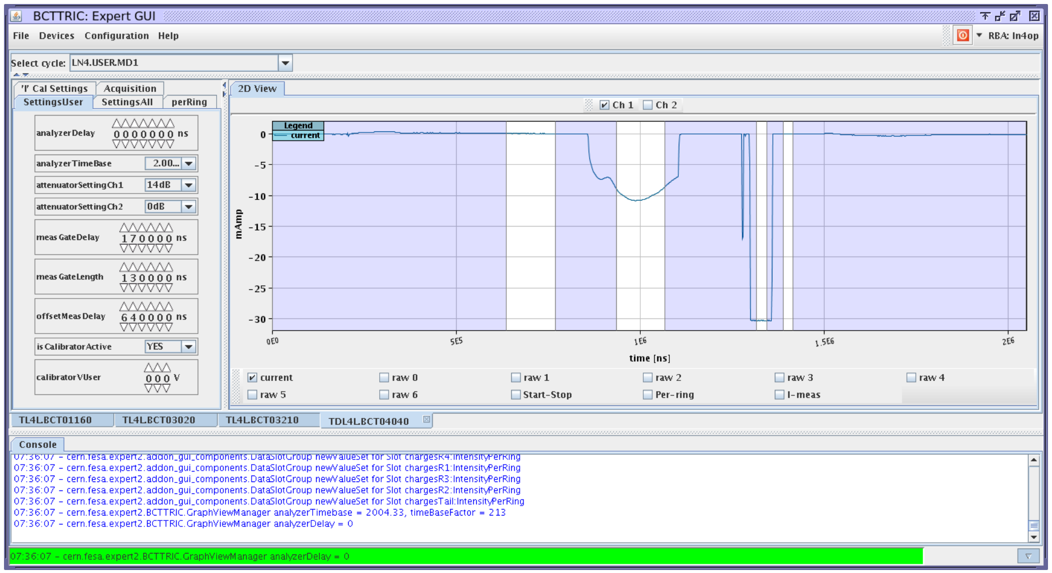
Magnetic shielding





- Shield should extend along the vacuum chamber length > diameter of opening
- Shield should be symmetrical to the beam axis
- Air gaps must be avoided especially along the beam axis
- Shield should have highest μ possible but should not saturate

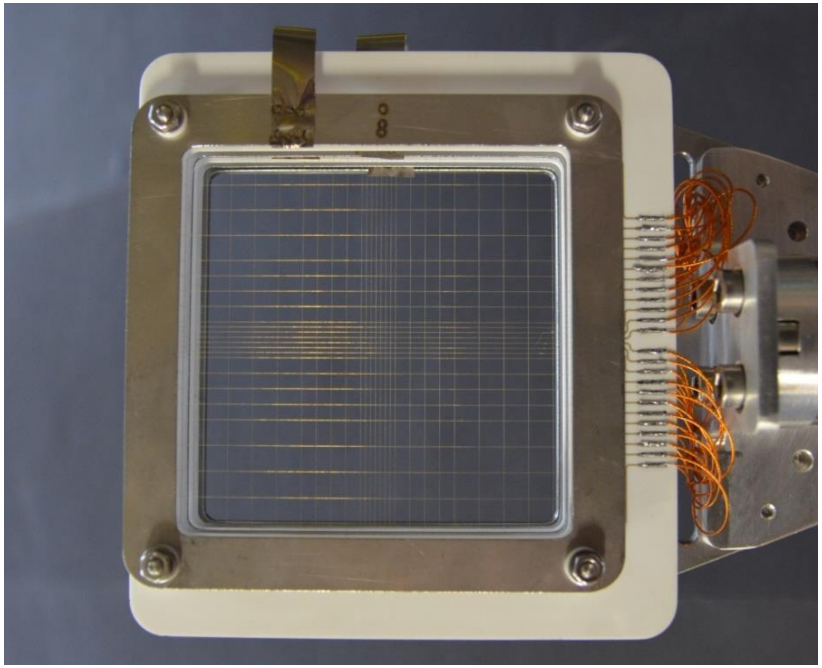
Calibration of AC current transformers



- The transformer is calibrated with a very precise current source
- The calibration signal is injected into a separate calibration winding
- A calibration procedure executed before the running period
- A calibration pulse after the beam pulse measured with the beam signal

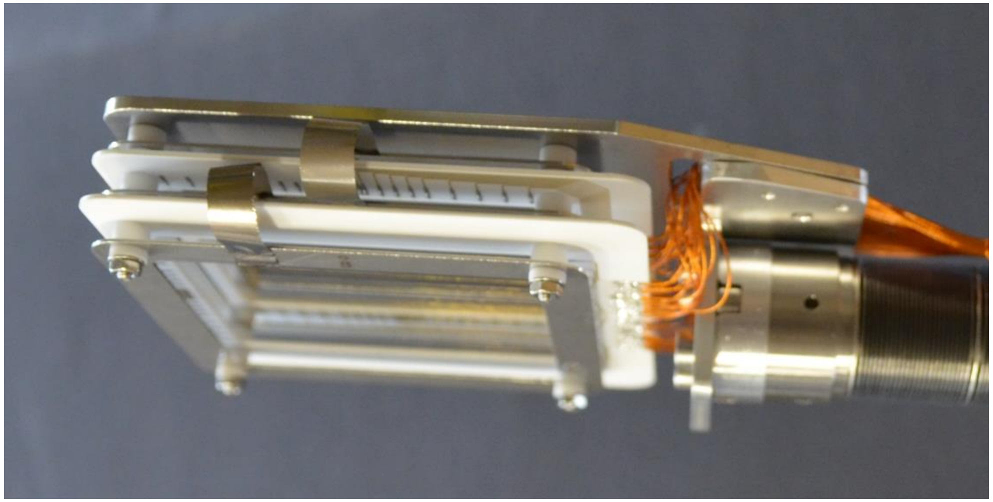
Profile measurements

- Secondary emission grids (SEMgrids)



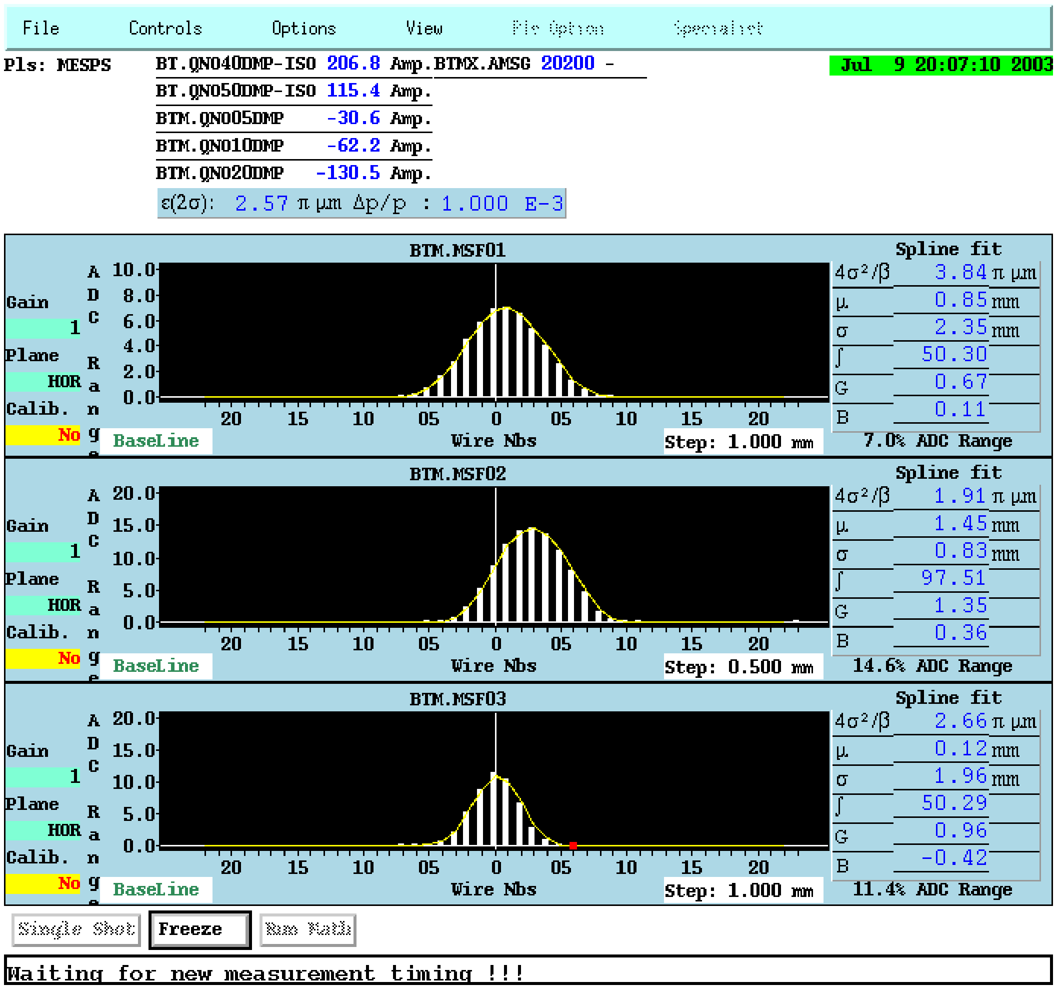
When the beam passes secondary electrons are ejected from the wires

The current flowing back onto the wires is measured



The ejected electrons are taken away by polarization voltage

Profiles from SEMgrids



Projection of charge density projected to x or y axis is Measured

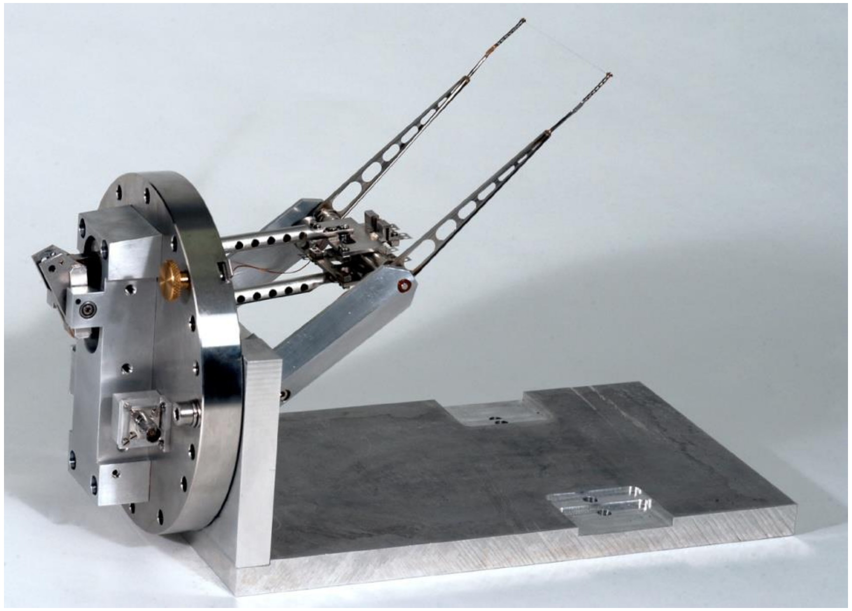
One amplifier/ADC per wire
Large dynamic range

Resolution is given by wire distance

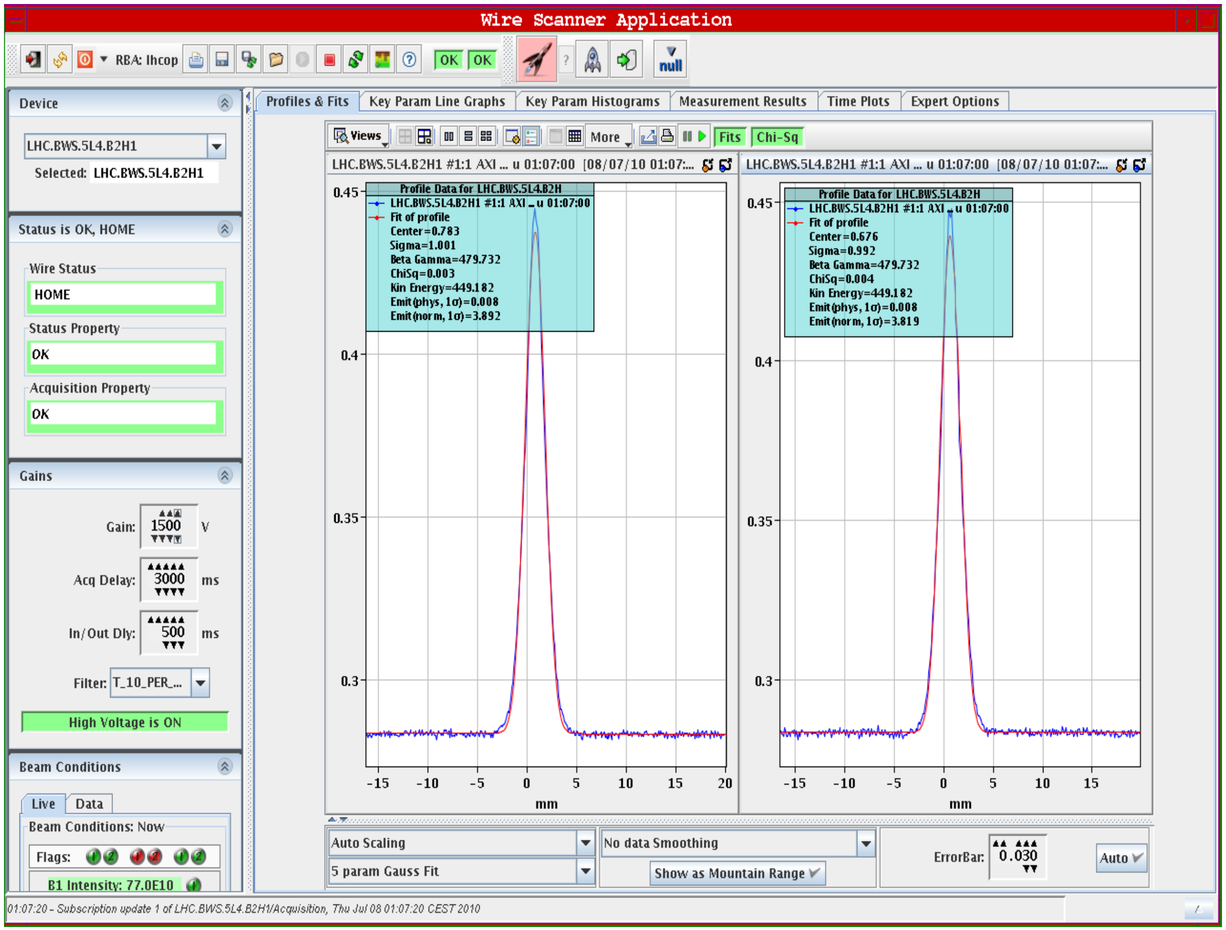
Used only in transfer lines

Wire Scanners

A thin wire is quickly moved across the beam
Secondary particle shower is detected outside the vacuum chamber on a scintillator/photo-multiplier assembly
Position and photo-multiplier signal are recorded simultaneously



Wire scanner profile



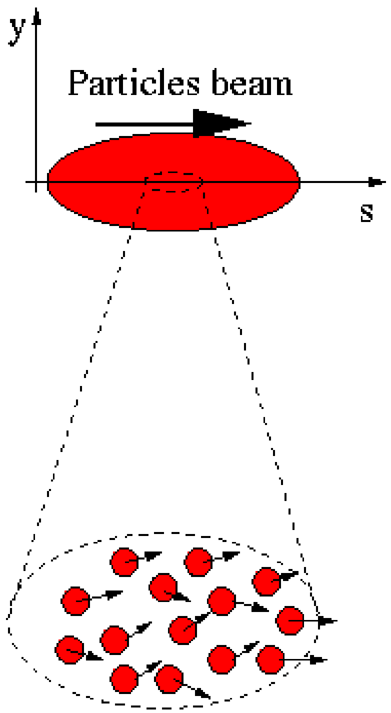
High speed needed because of heating.

Adiabatic damping

Current increase due to speed increase

Speeds of up to 20m/s => 200g acceleration

Emittance measurements



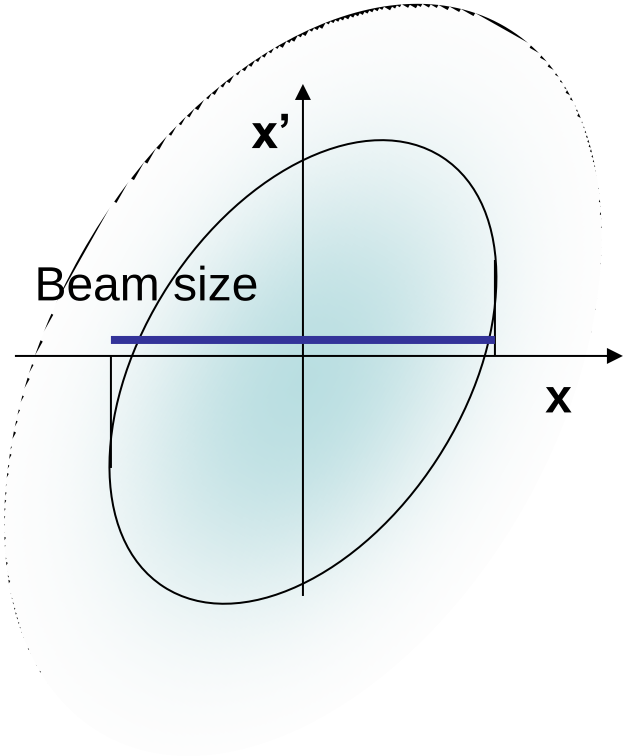
Design by E. Bravin

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).

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

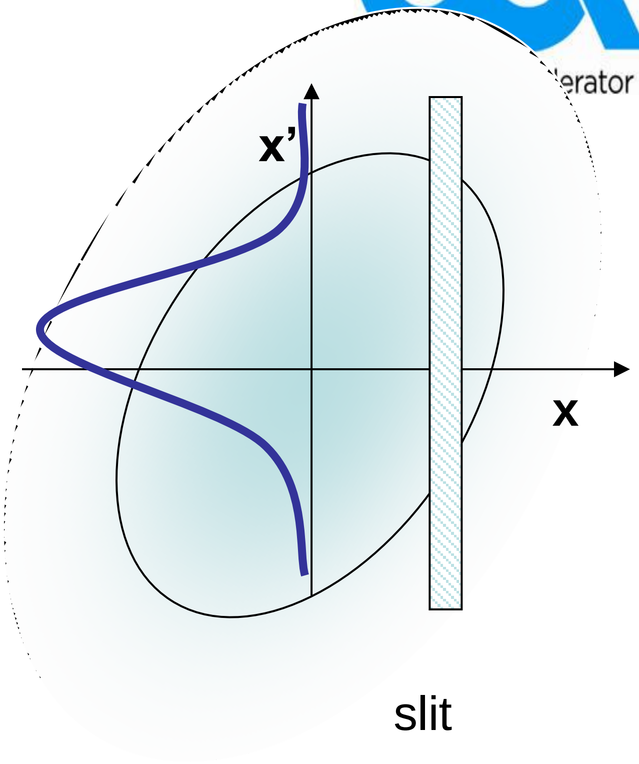
Emittance measurements

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



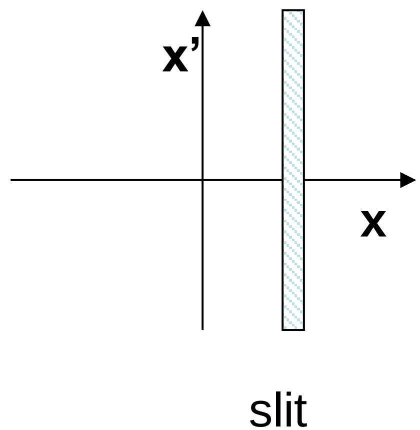
The slit and grid method

- 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

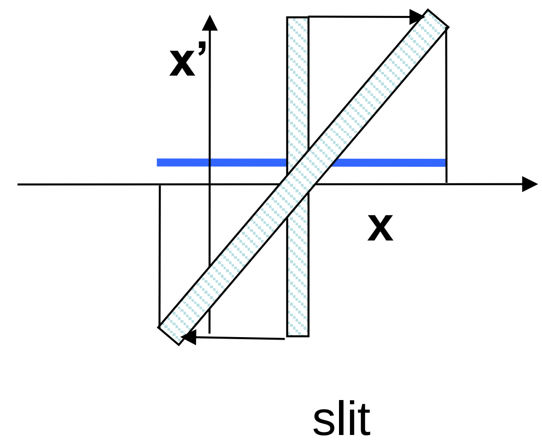


Transforming angular distribution to profile

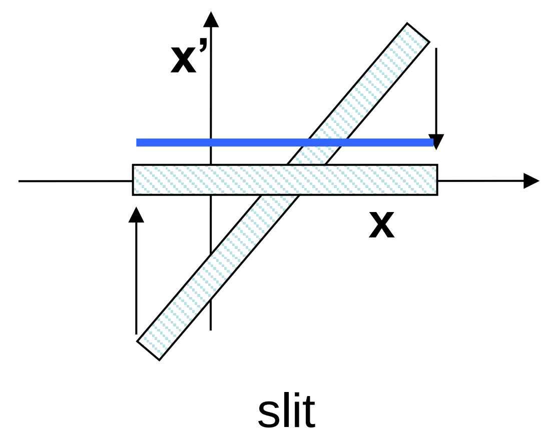
- When moving through a drift space the angles don’t change (horizontal move in phase space)
- When moving through a quadrupole the position does not change but the angle does (vertical move in phase space)



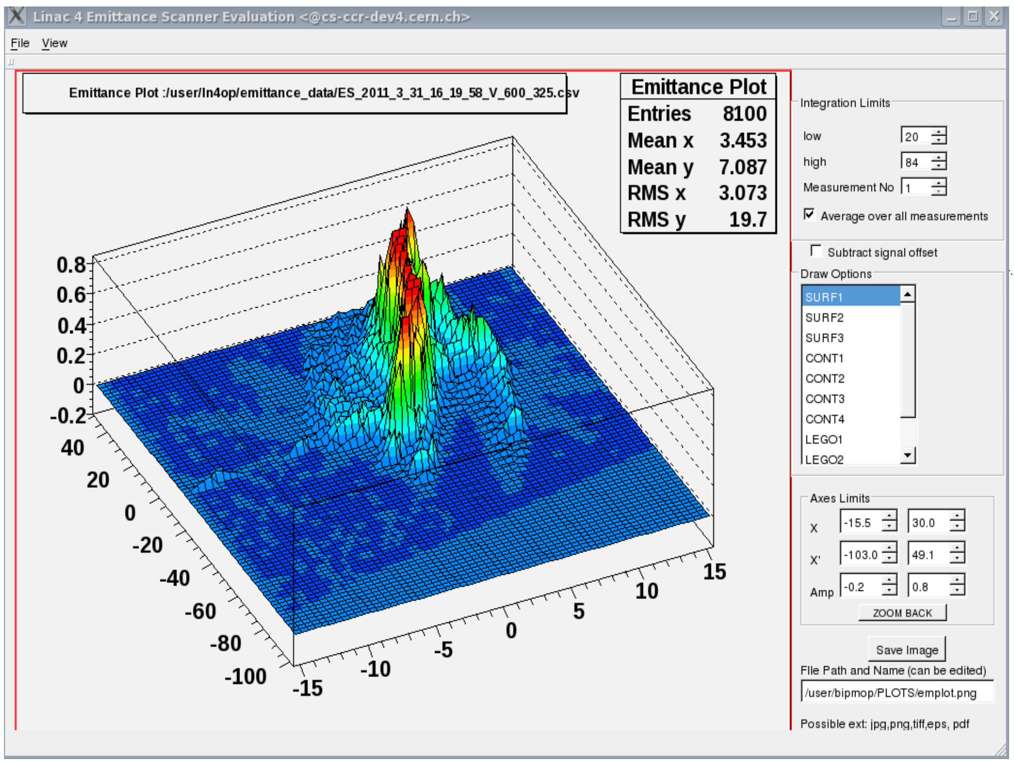
Influence of a drift space

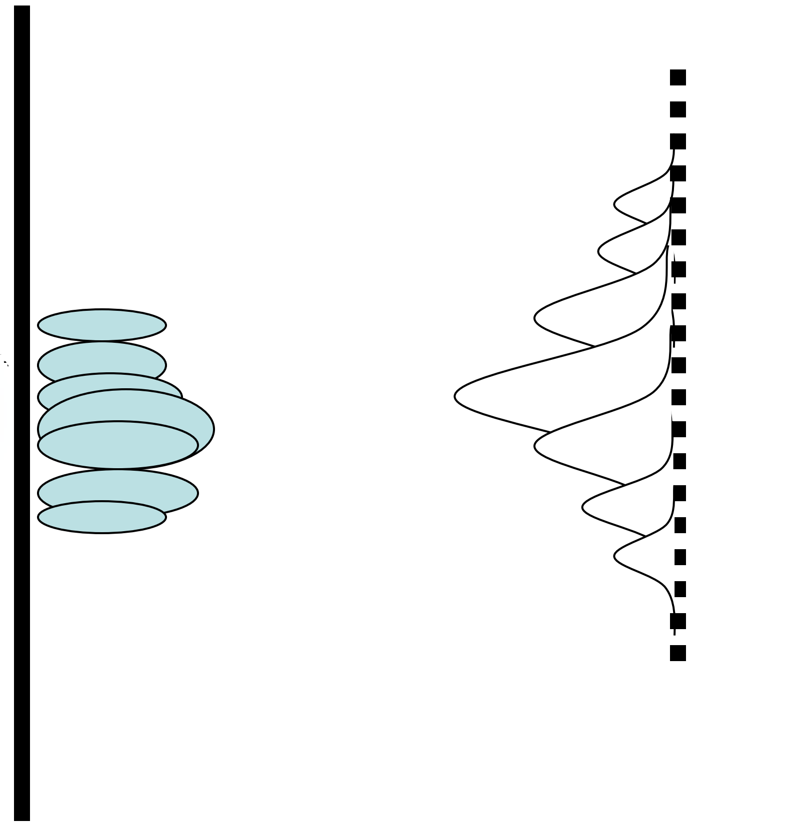


Influence of a quadrupole

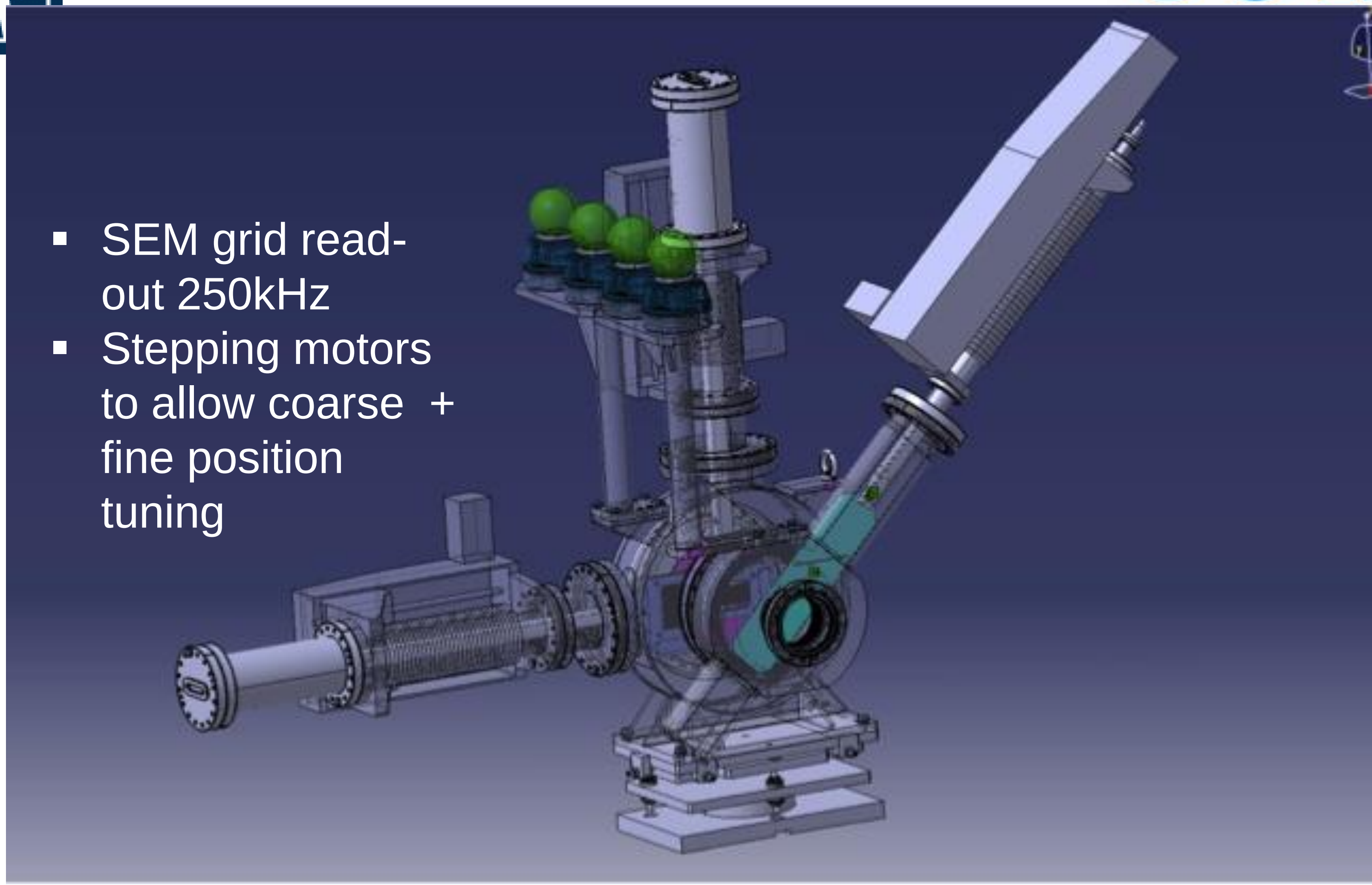


The Slit Method



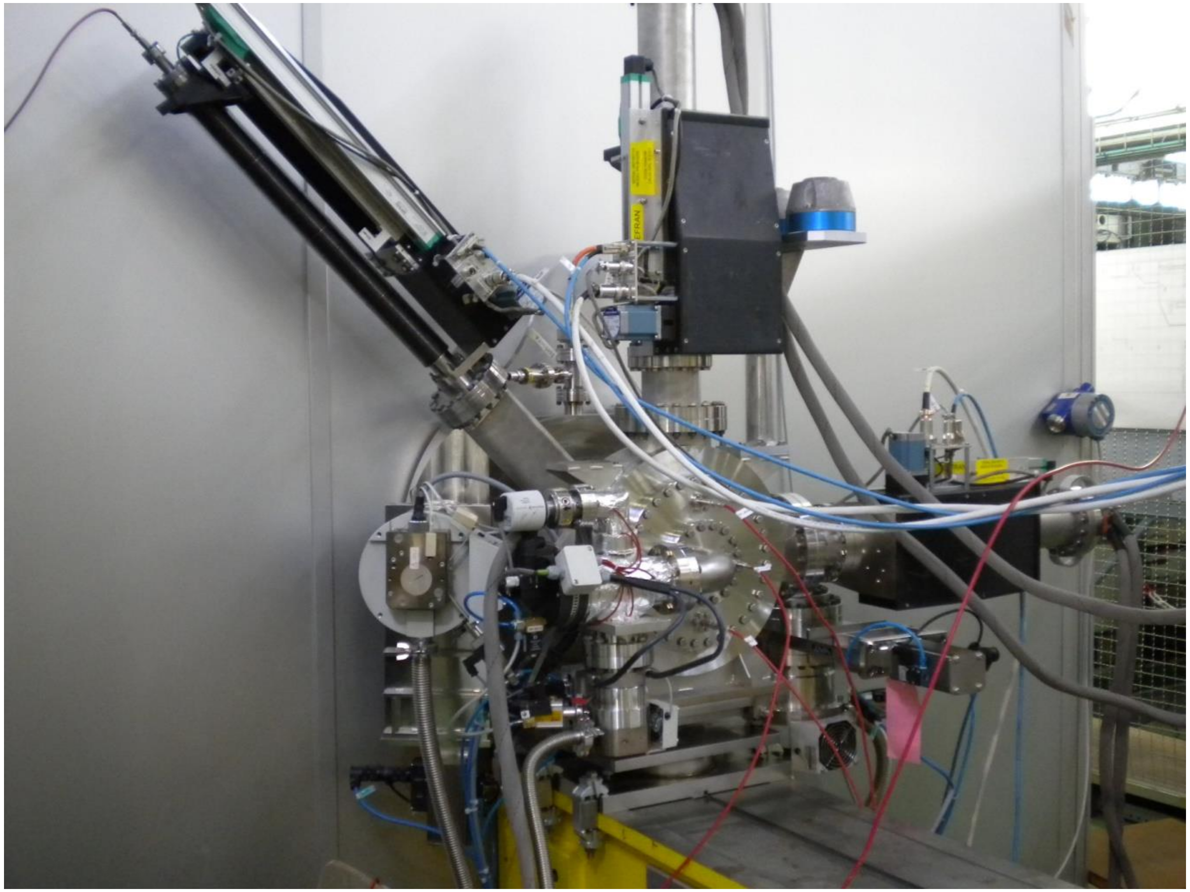


Emittance Meter



- SEM grid read-out 250kHz
- Stepping motors to allow coarse + fine position tuning

Transverse Emittance Measurement



Slit and grid phase space scanner

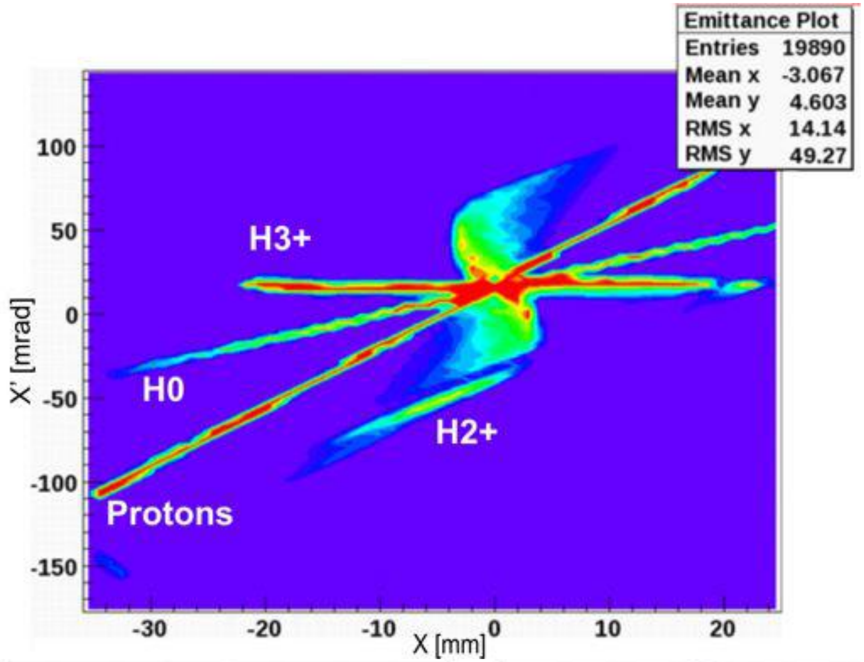
L-shaped 0.1mm slit moves under 45 degrees

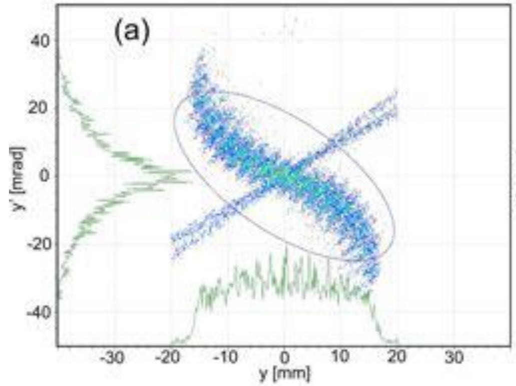
Slit and grids move independently
Positioning precision: 50 µm
Movement PLC controlled

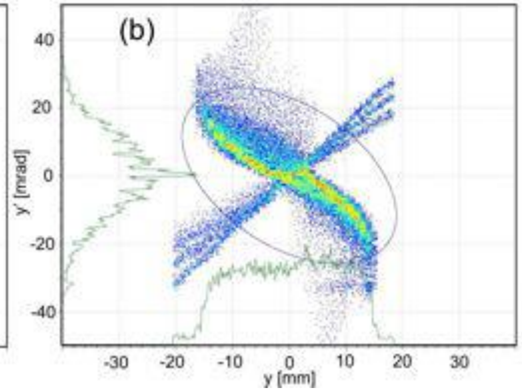
Slit and grids mounted in 2 independent vacuum boxes which can be separated

Horizontal and vertical SEMGrid
- wire distance .75 mm
- 30 signal wires
- readout with home built 36 channel 250 kHz ADC
- time resolved profiles

Emittance plot Solenoid

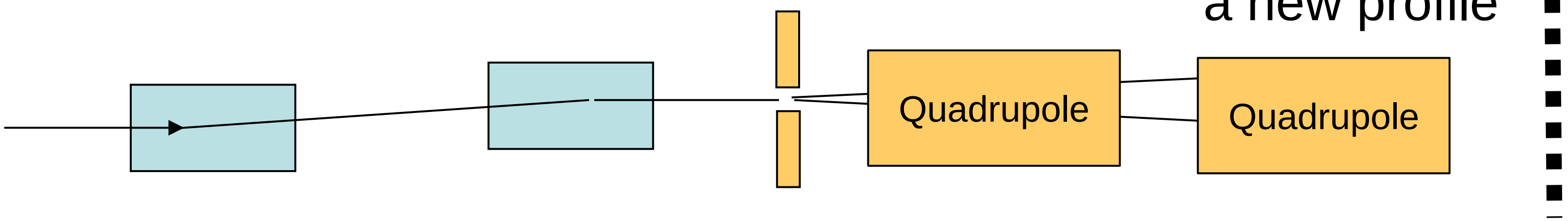






Single pulse emittance measurement

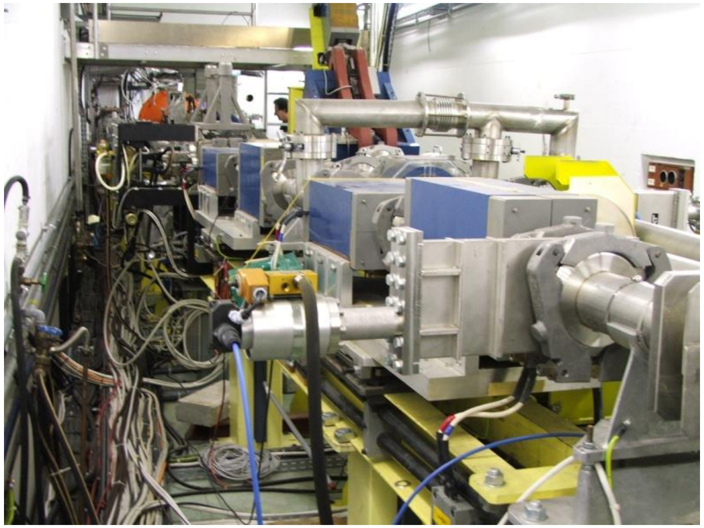
Every 100 ns
a new profile

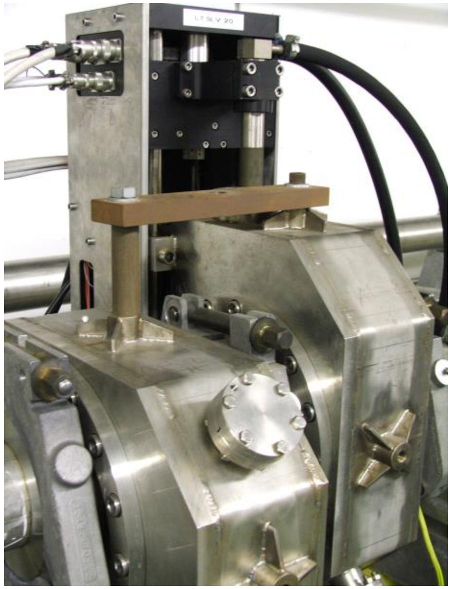


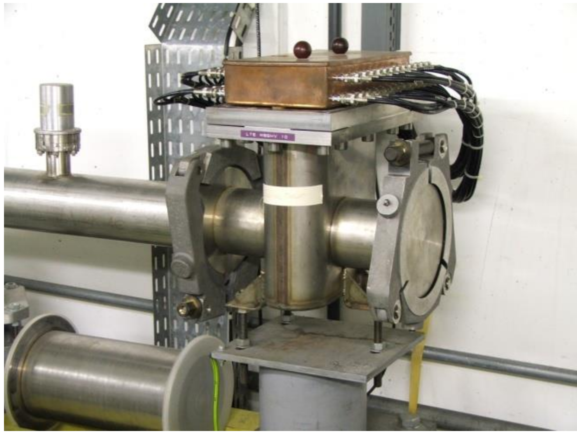
Kickers

slit

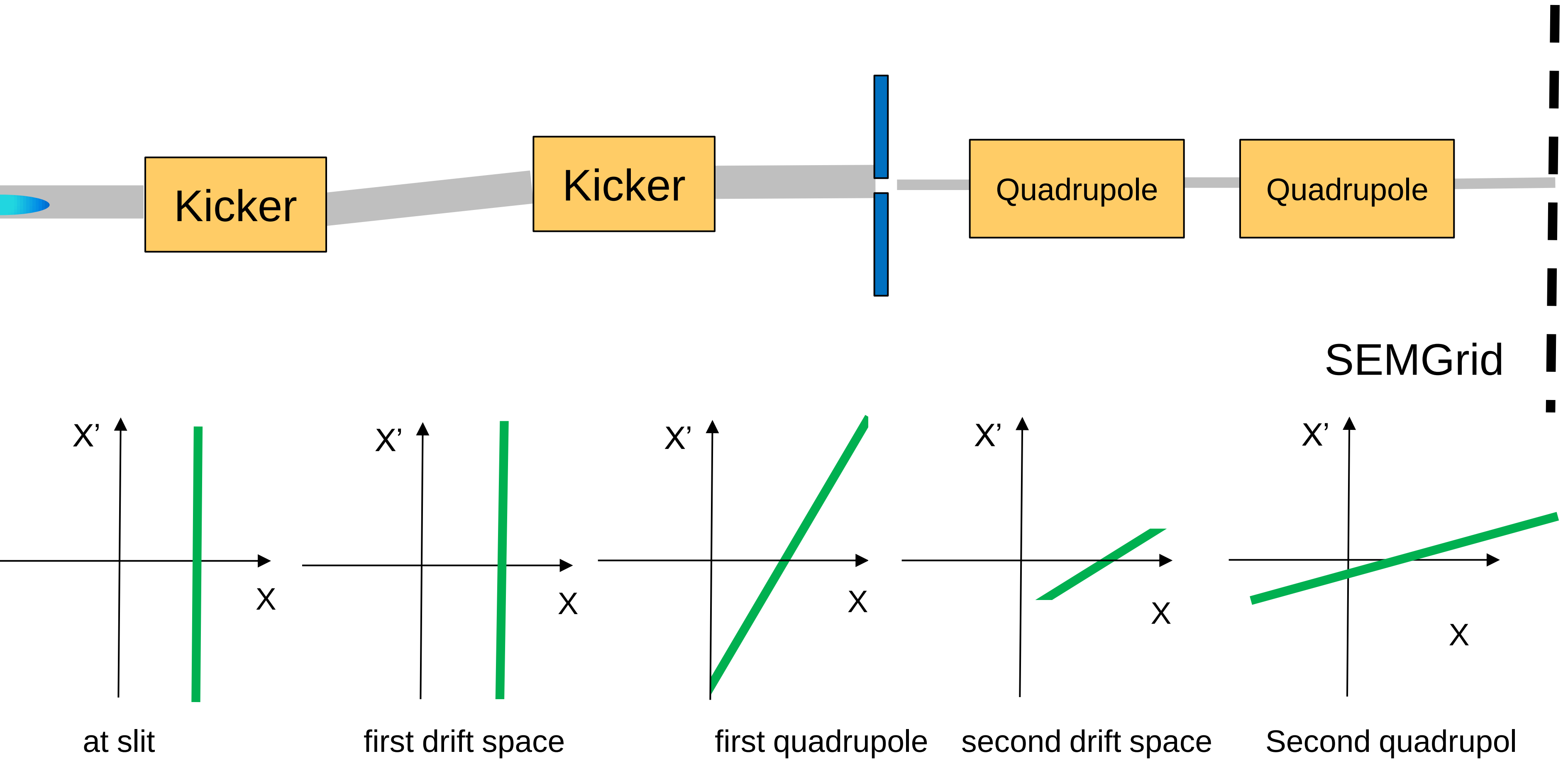
SEMgrid



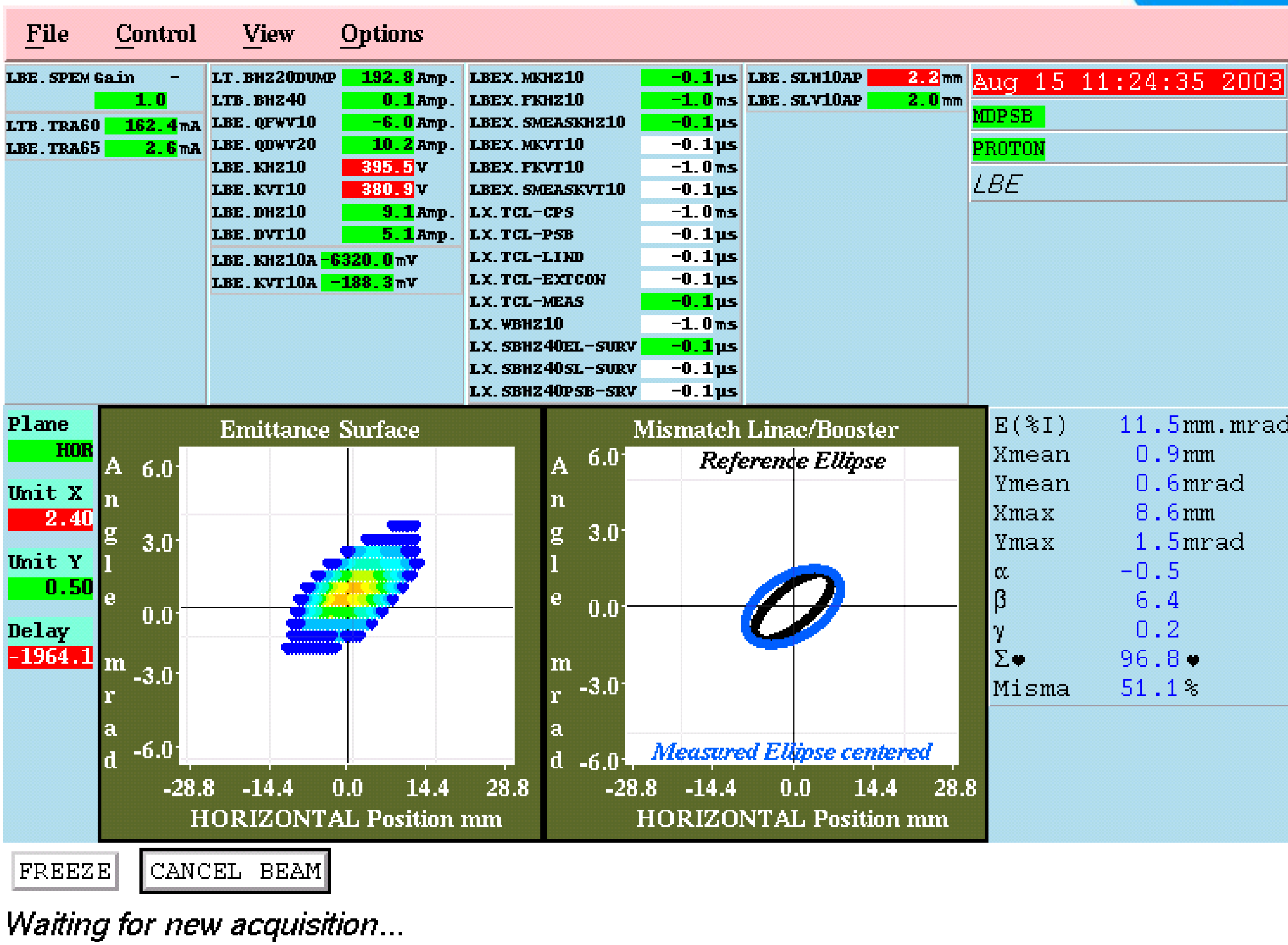




Transformation in Phase Space

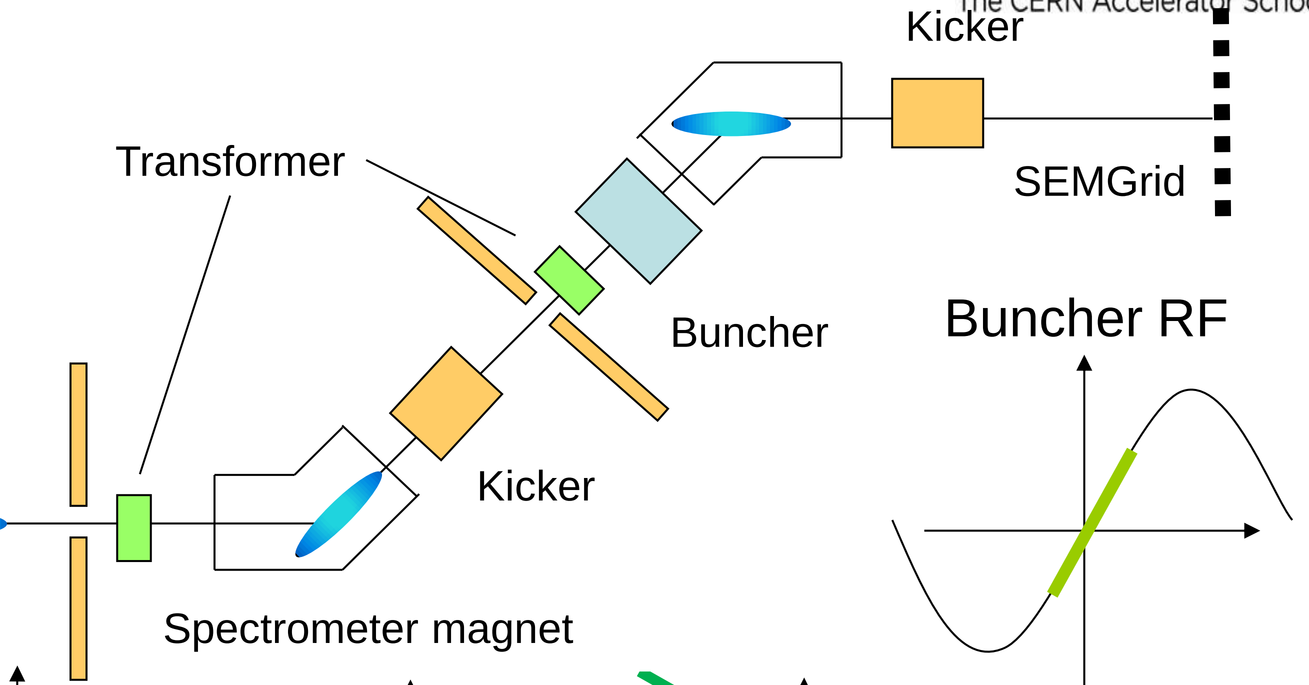


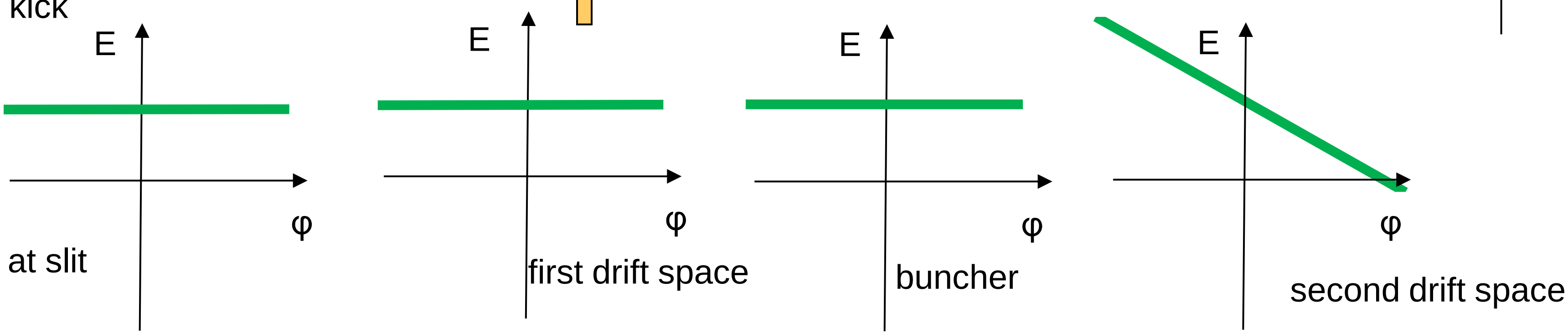
Result of single pulse emittance measurement



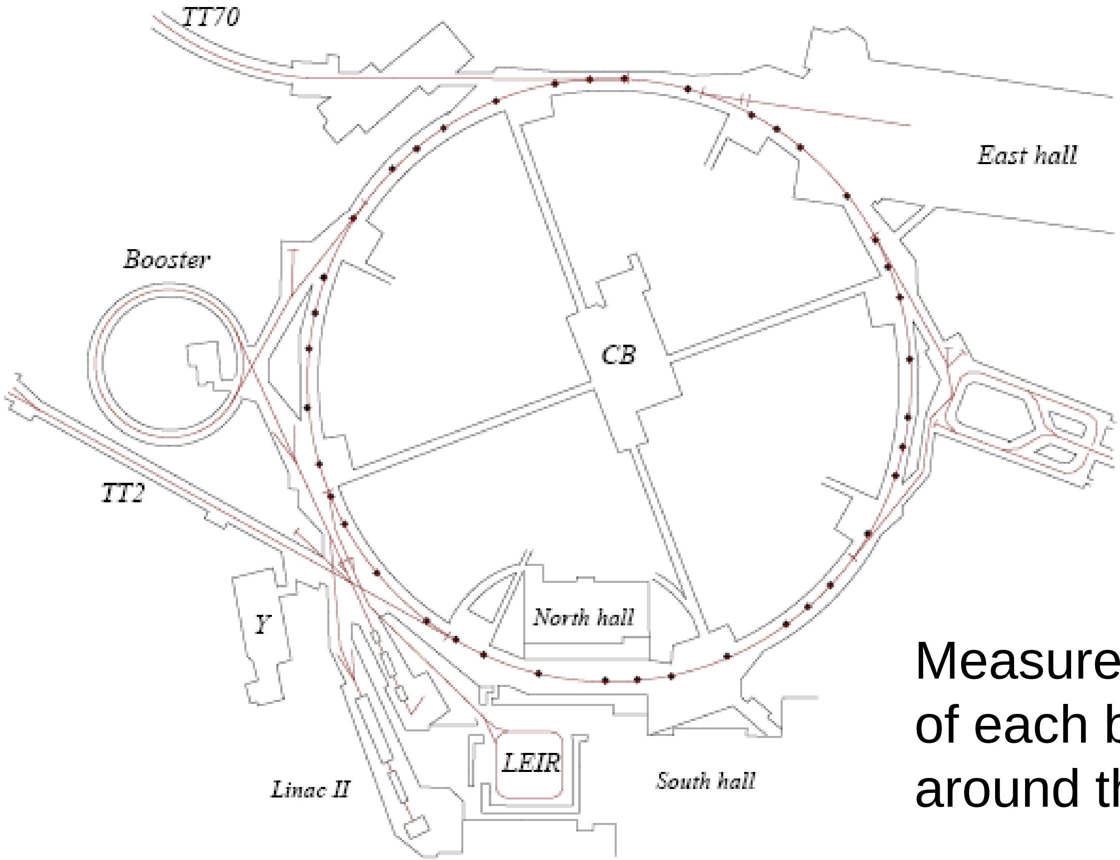
Longitudinal Emittance measurement

- 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





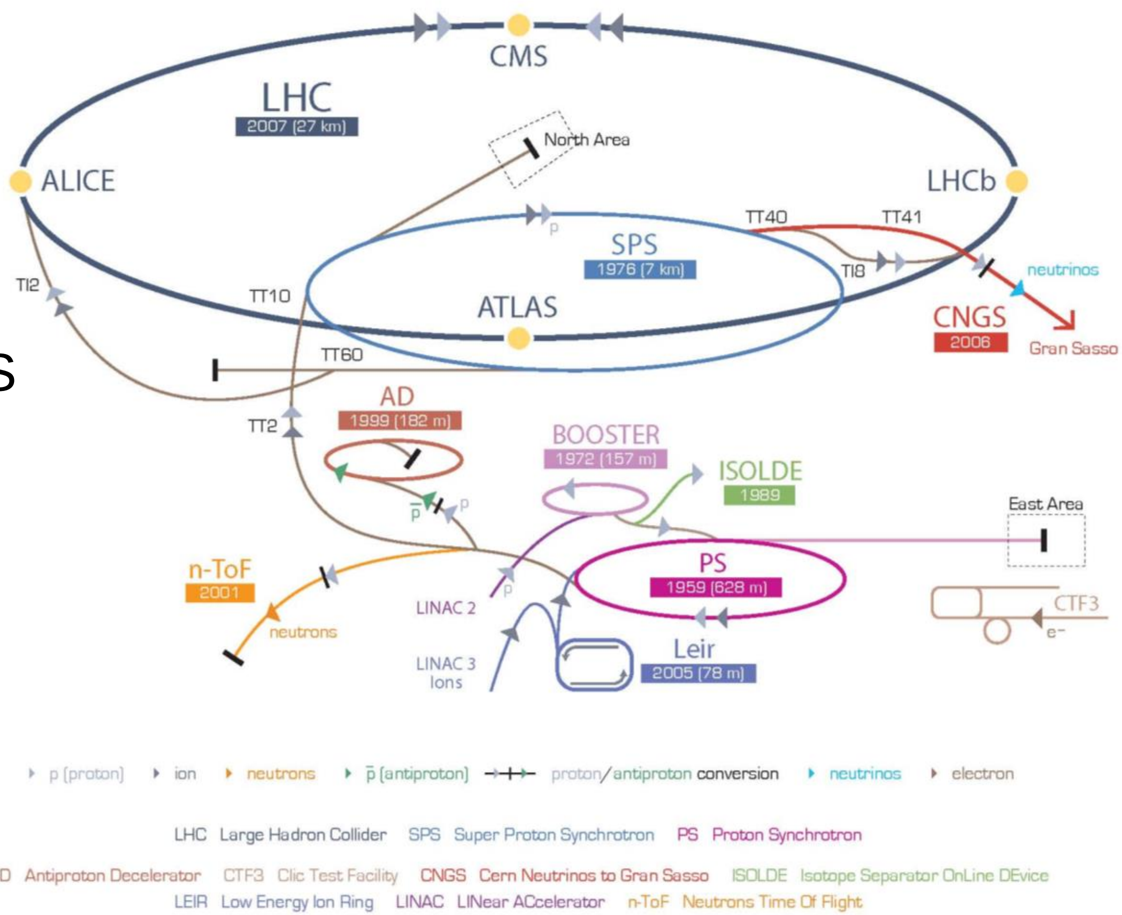
Trajectory and Orbit Measurements



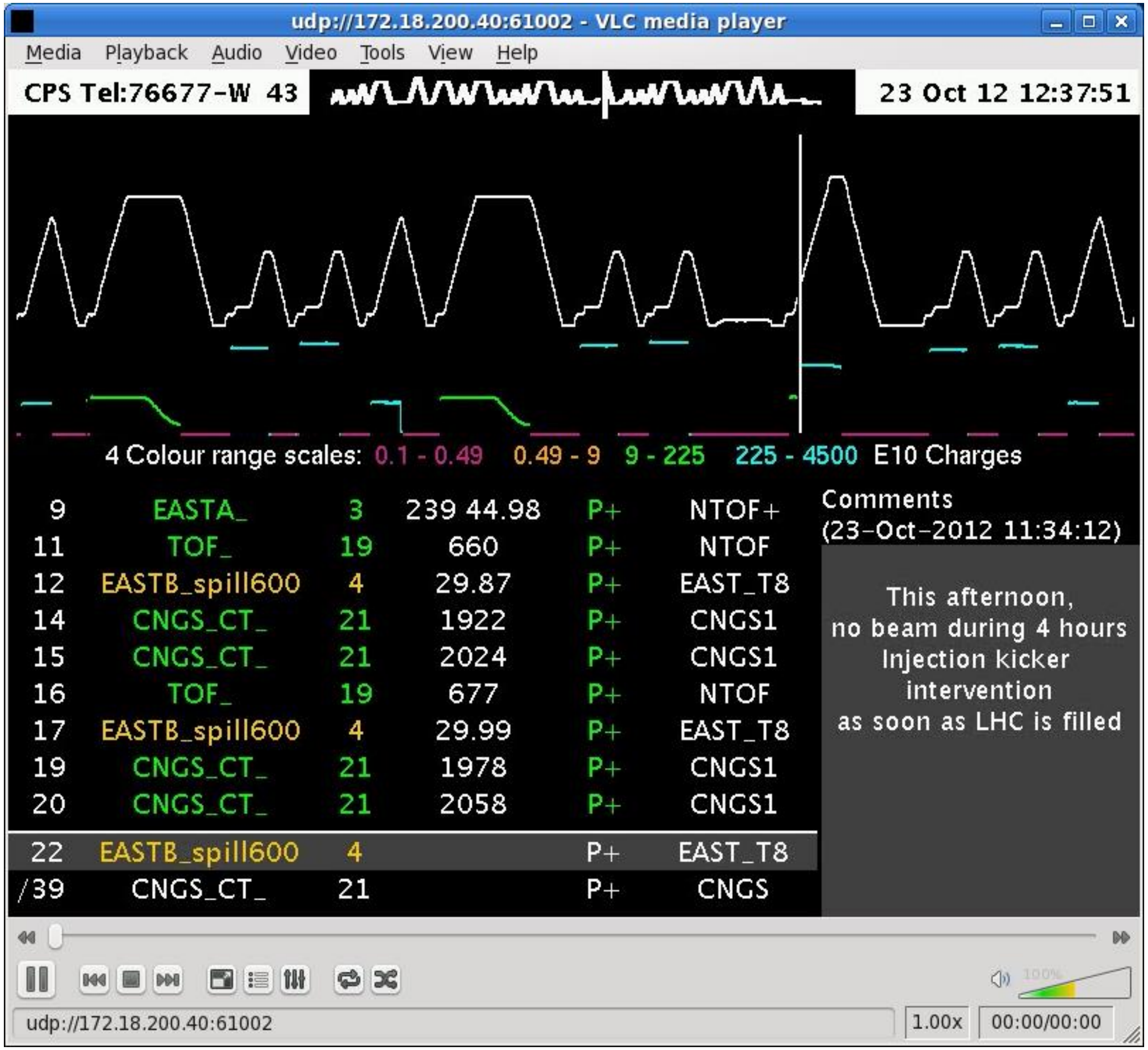
Measure the particle position of each bunch as it travels around the ring

The PS, a universal machine

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



The Supercycle

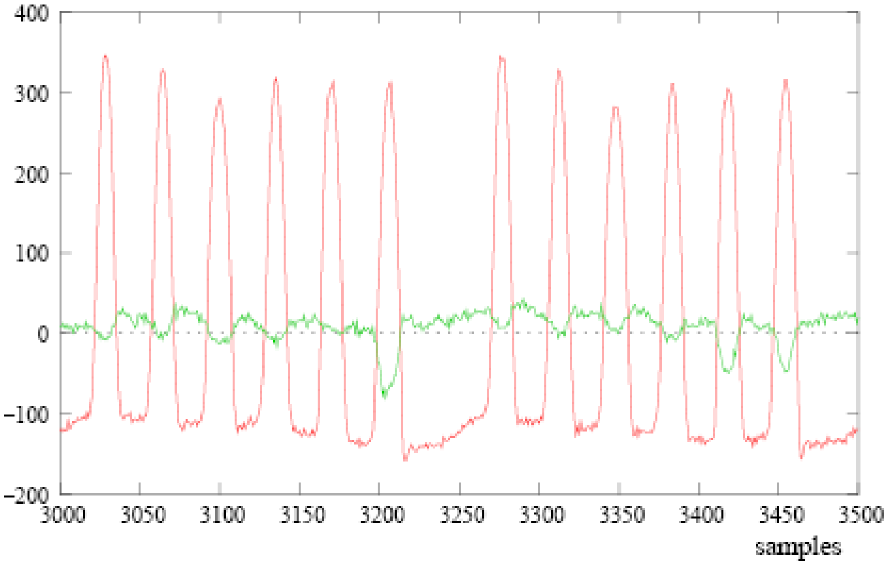


Position Measurements

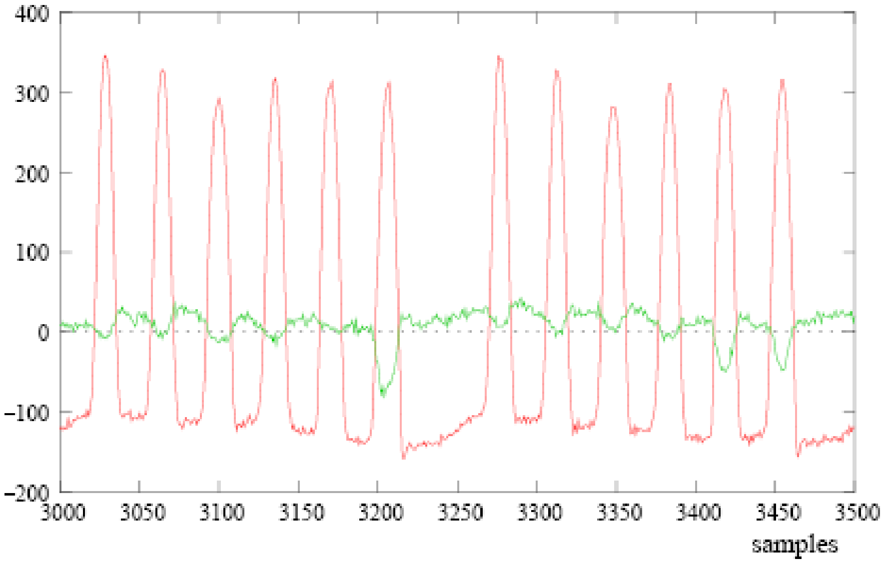
BPM signals sampled at 120 MHz

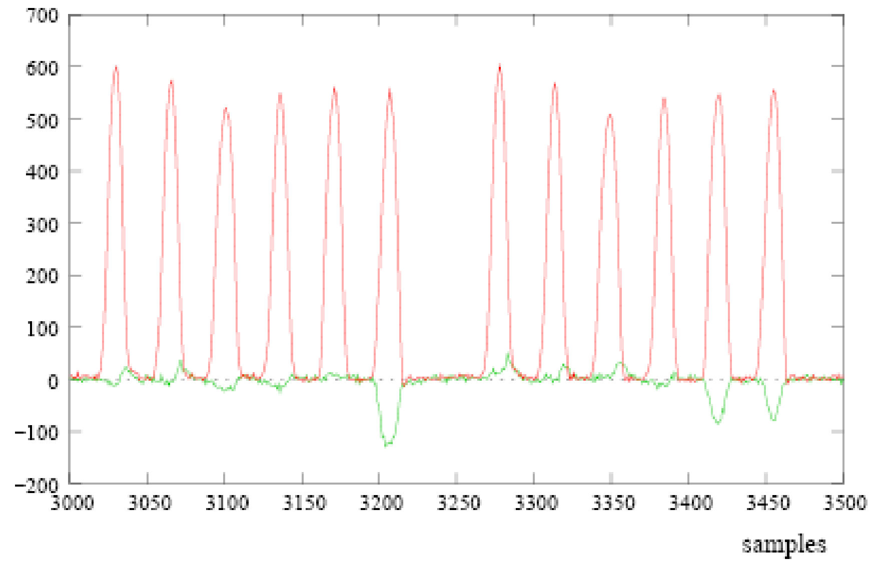
Red: The sum signal
Green: The difference signal

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.



Baseline restoration

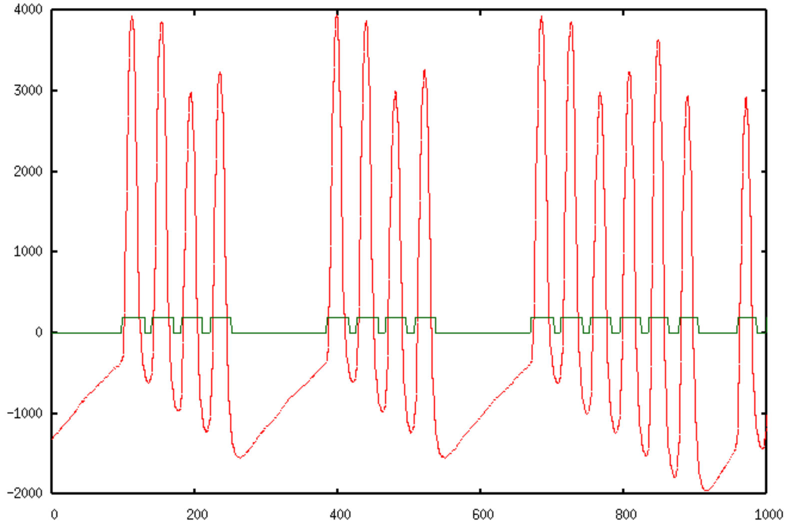


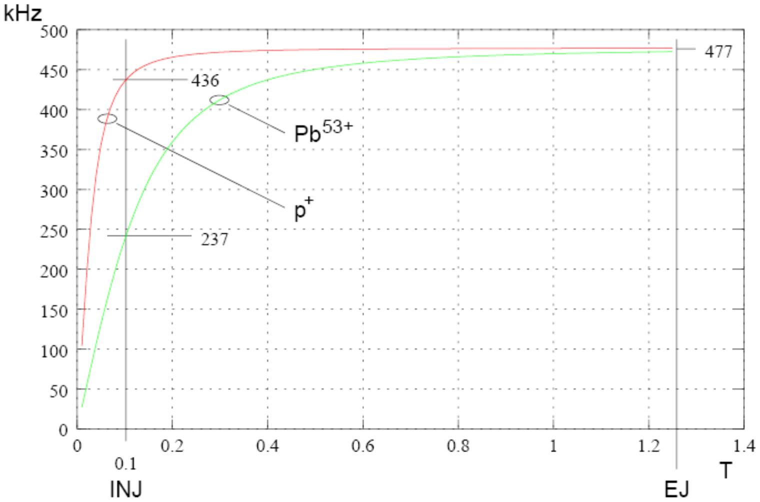


Low pass filter the signal to get an estimate of the base line
Add this to the original signal

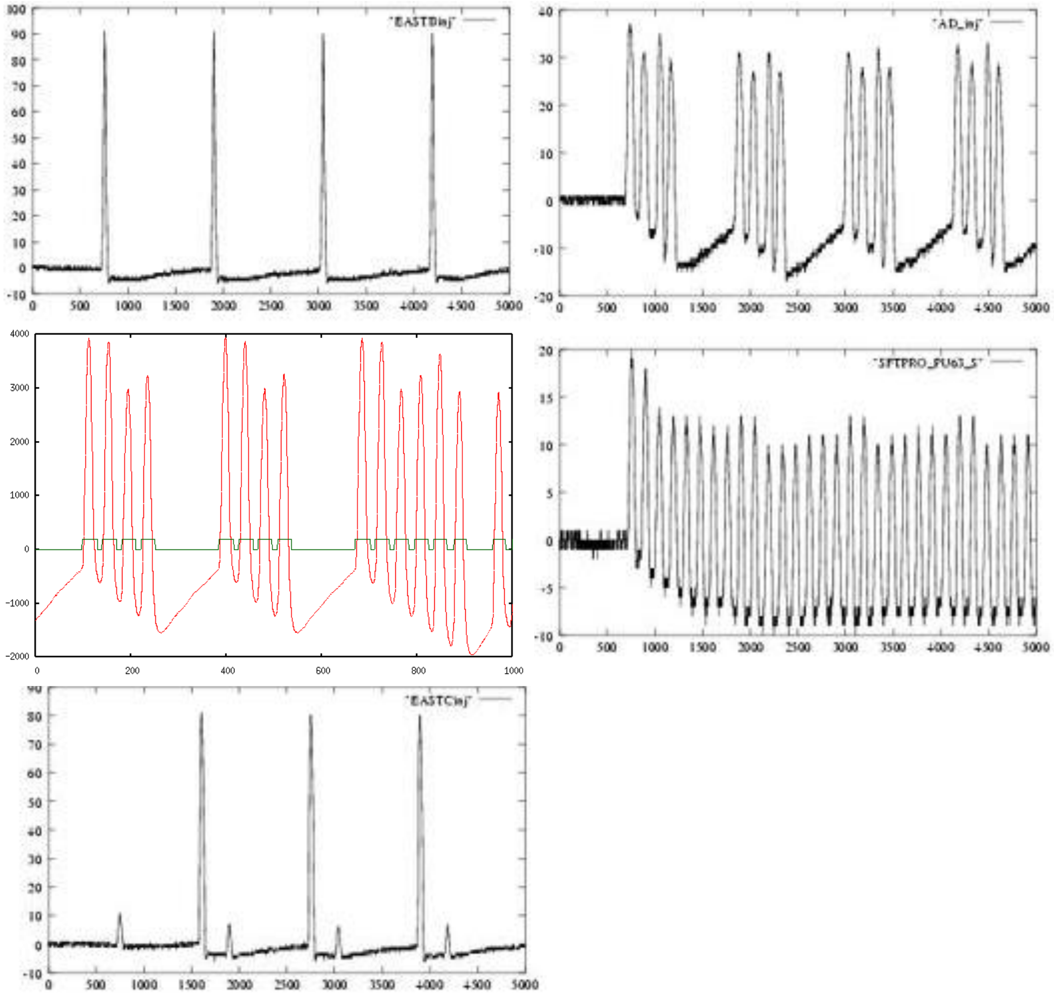
Trajectory measurements in circular machines

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





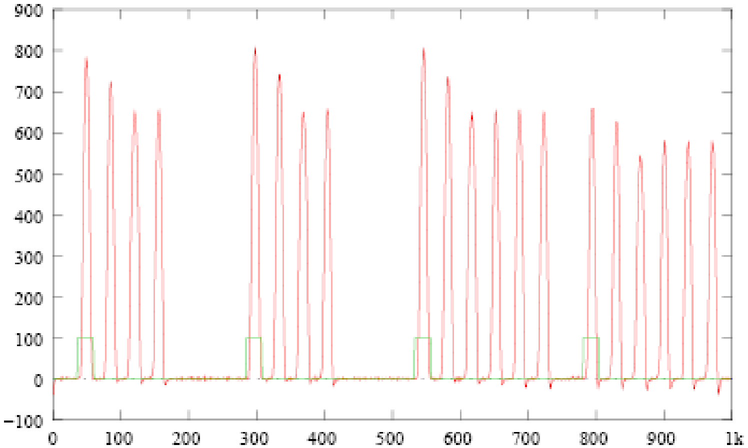
Beams in the PS



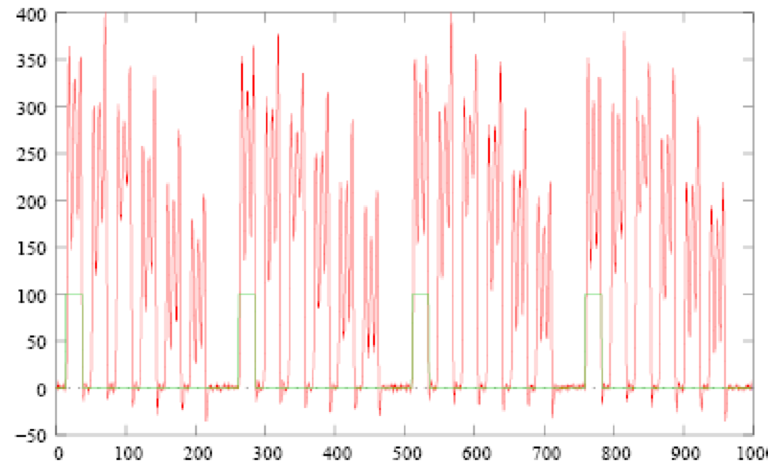
CERN

RF Gymnastics

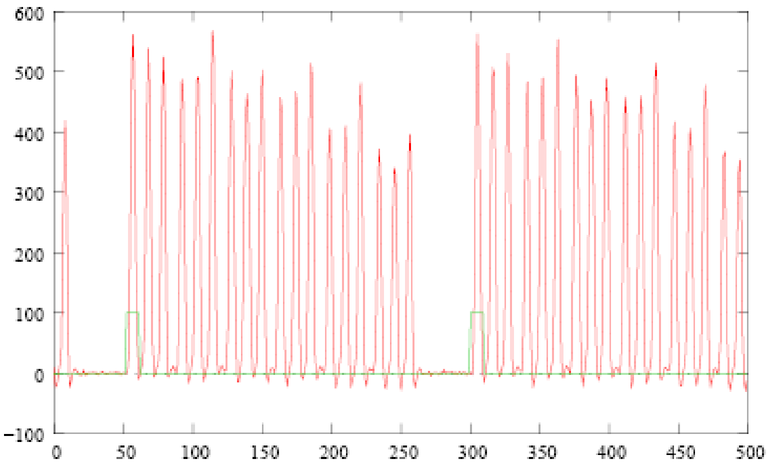
The CERN Accelerator School



Example of generated gate around 2nd injection

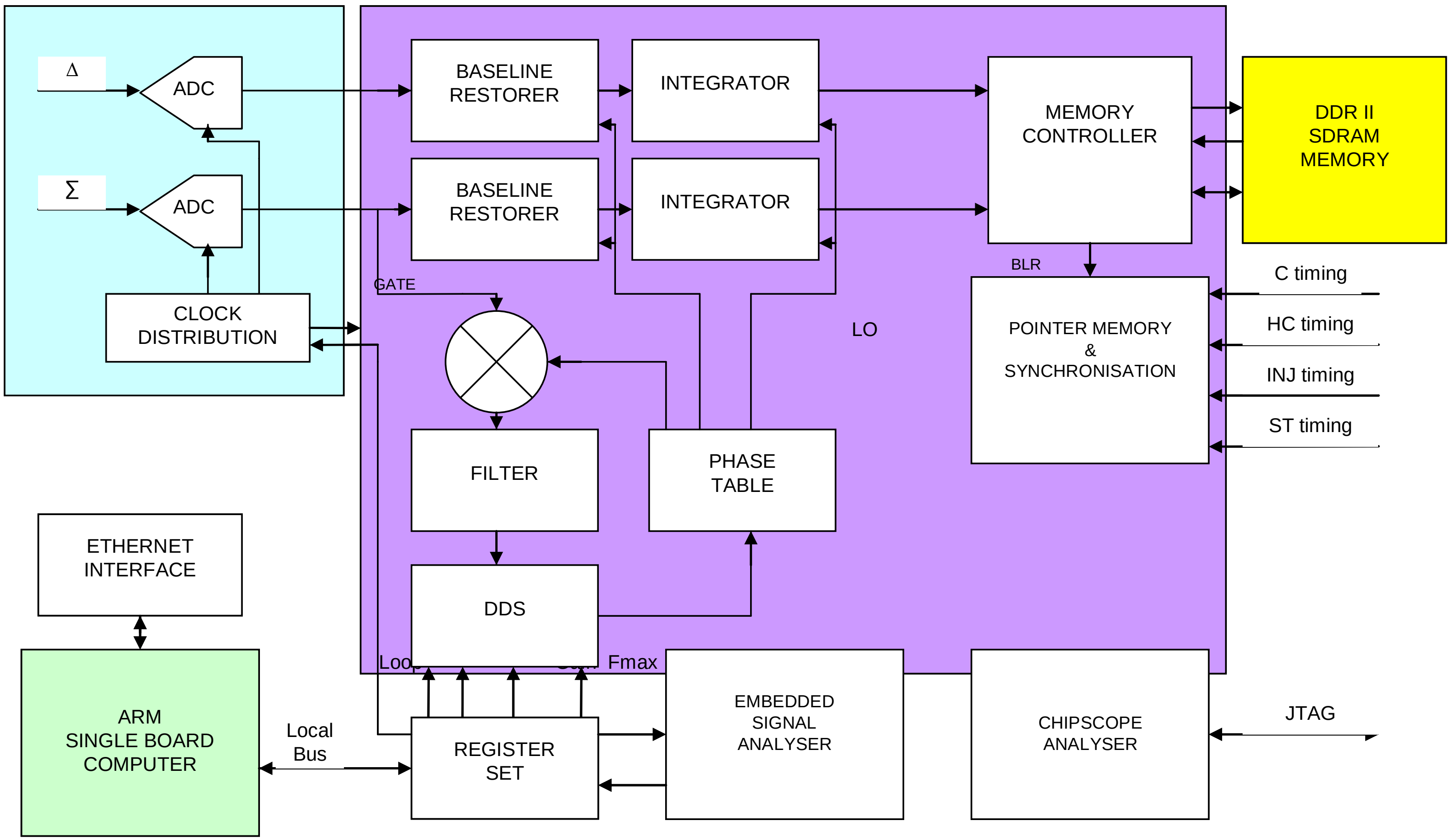


Idem, during bunch splitting



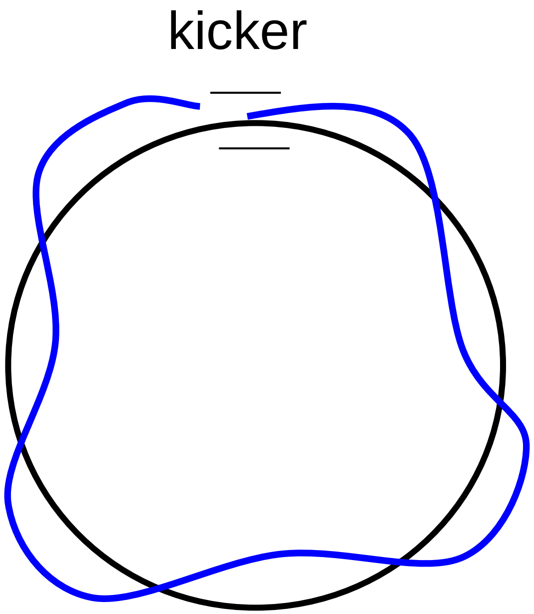
- Bunch splitting or recombination One RF frequency is gradually decreased while the other one is increased
- The gate generator must be synchronized

Trajectory readout electronics

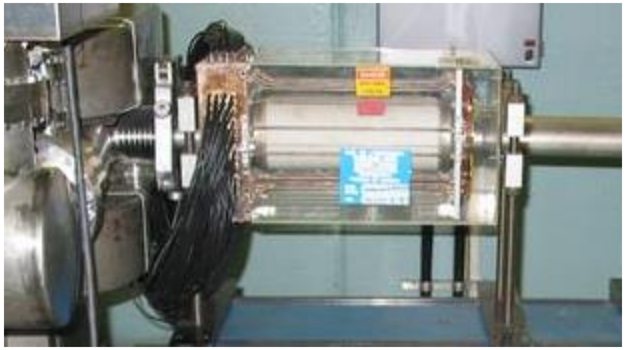


Tune measurements

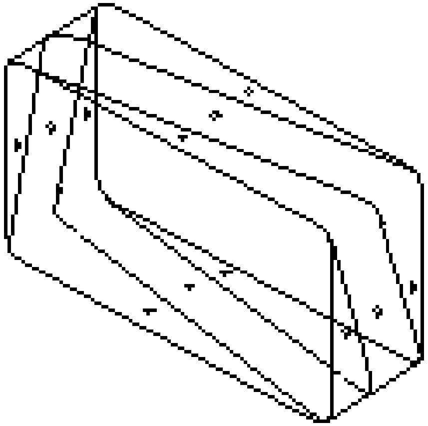
- When the beam is displaced (e.g. at injection or with a deliberate kick, it starts to oscillate around its nominal orbit (betatron oscillations)
- Measure the trajectory
- Fit a sine curve to it
- Follow it during one revolution



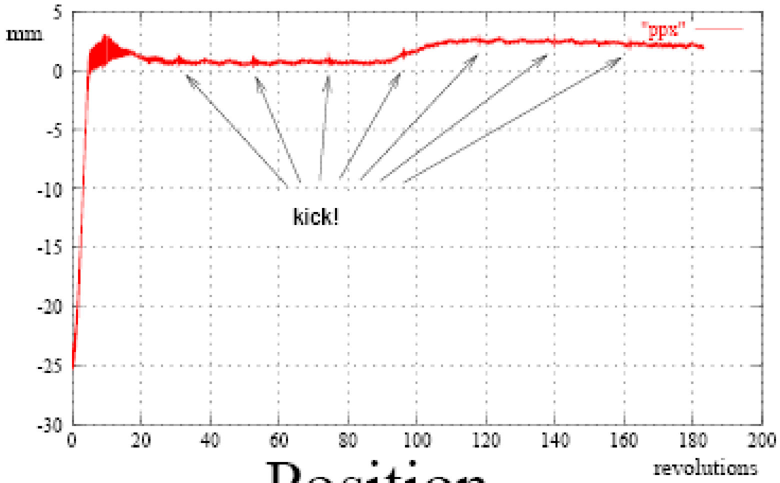
The Sensors



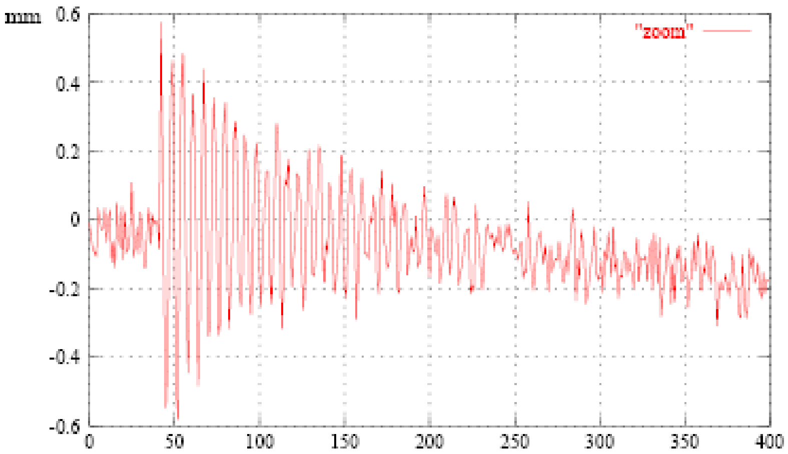
The kicker



Shoebox pick-up
with linear cut

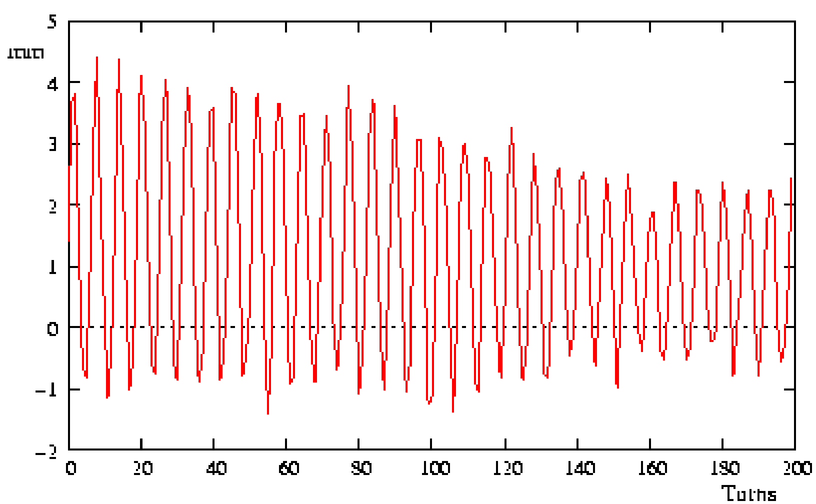


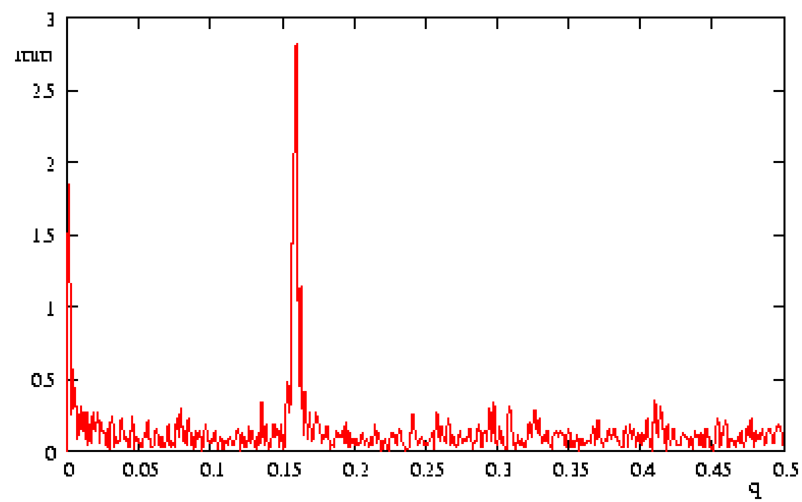
Position



Kicker + 1 pick-up

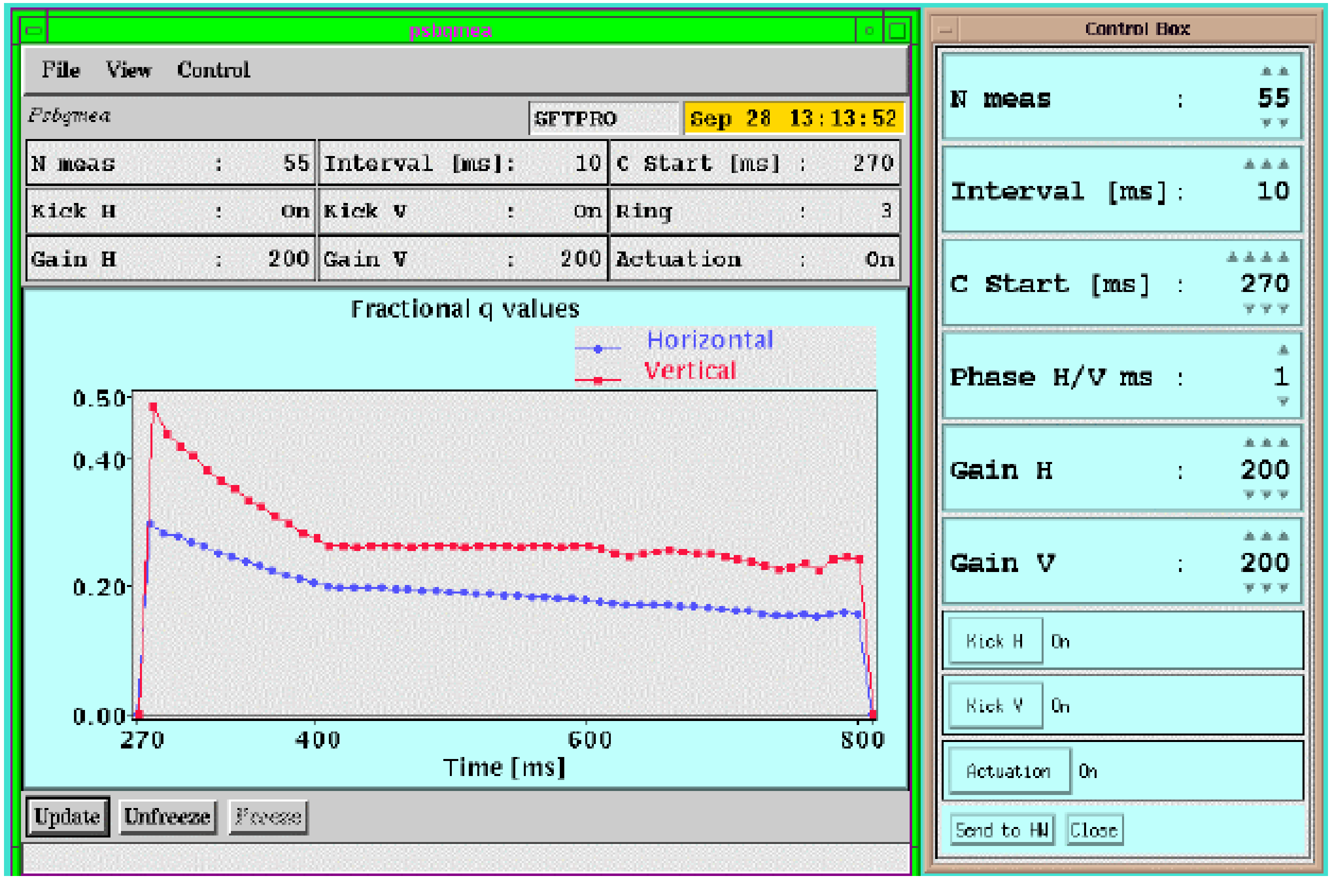
- Measures only non-integral part of Q
- Measure a beam position at each revolution
- Fourier transform BPM signal
- Search peak in Fourier Spectrum



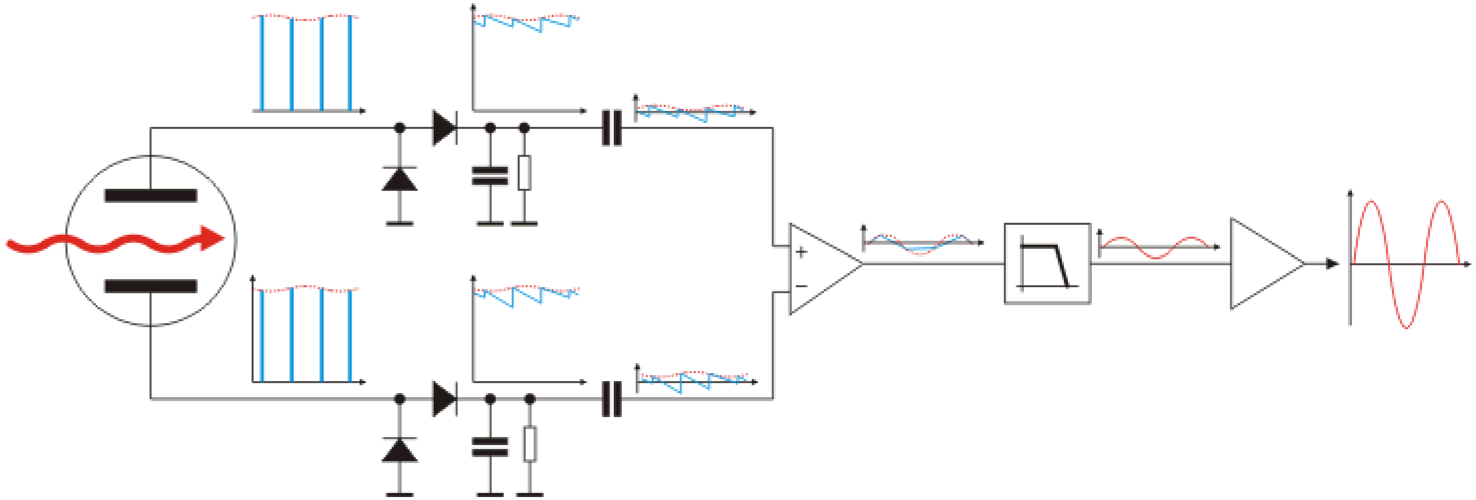


Fourier transform of pick-up signal

Q-Measurement Results



Direct Diode Detection Base Band Q measurement



Diode Detectors convert spikes to saw-tooth waveform

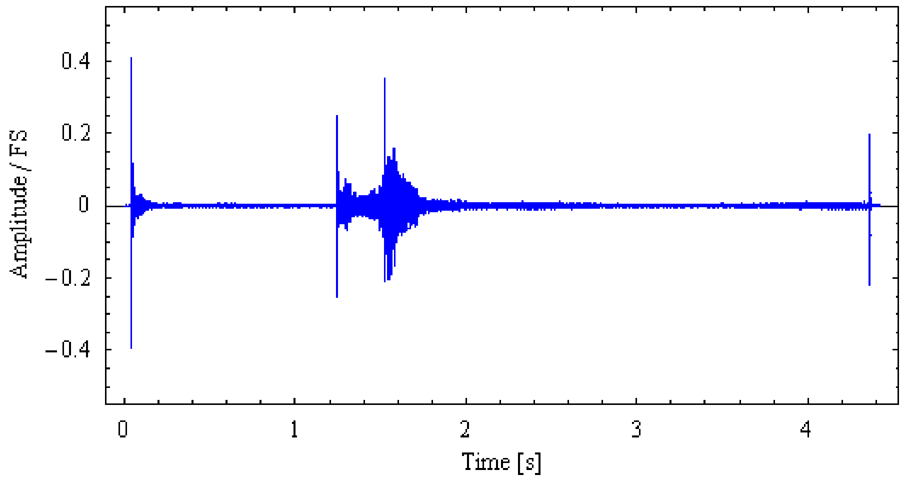
Signal is connected to differential amplifier to cut out DC level

Filter eliminates most of the revolution frequency content

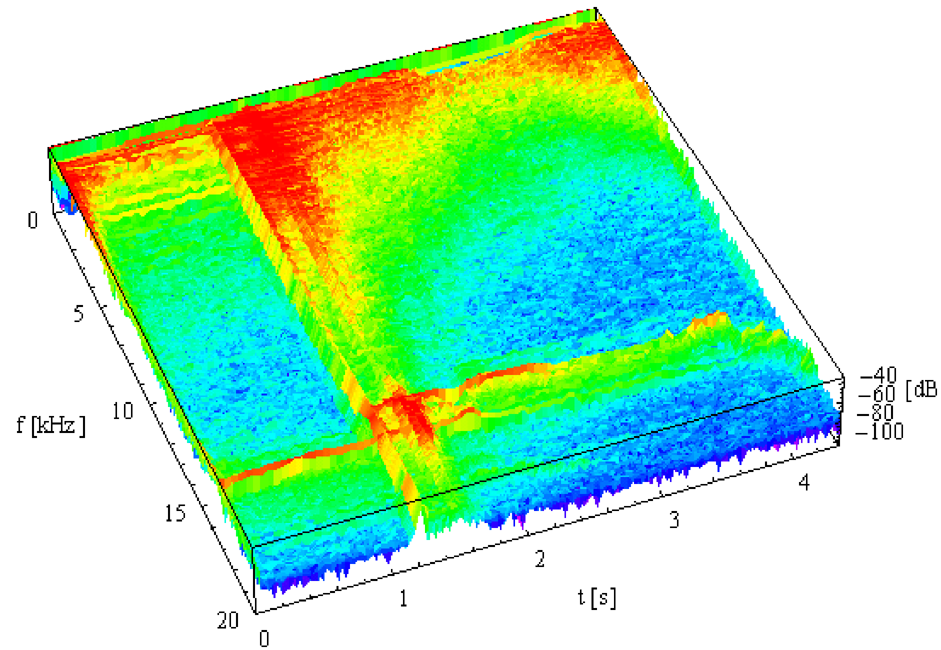
Output amplifier brings the signal level to amplitudes suitable for long distance transmission

BBQ Results from CERN SPS

Results from Sampling

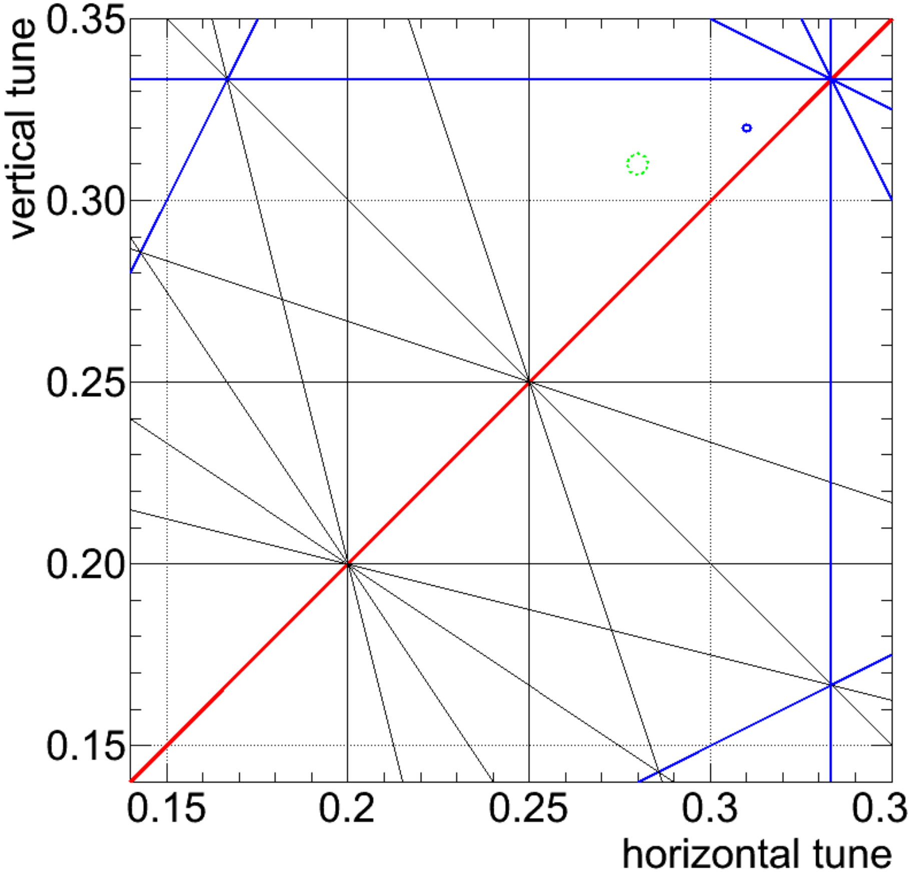


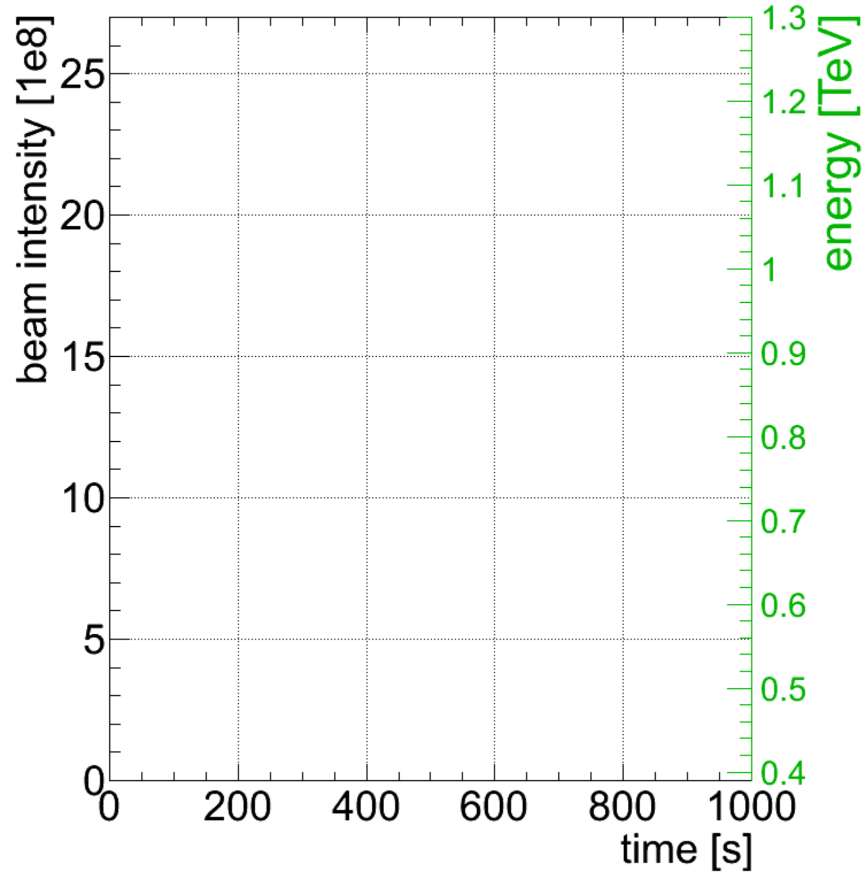
After Fourier Transform



(.wav)

Tune feedback at the LHC

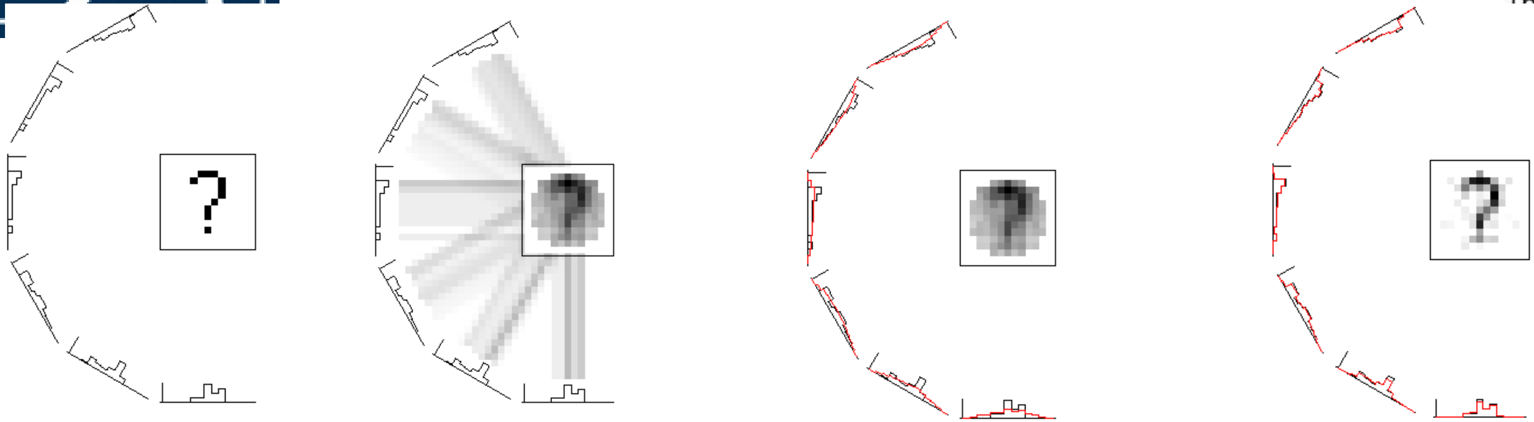




Computed Tomography (CT)

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



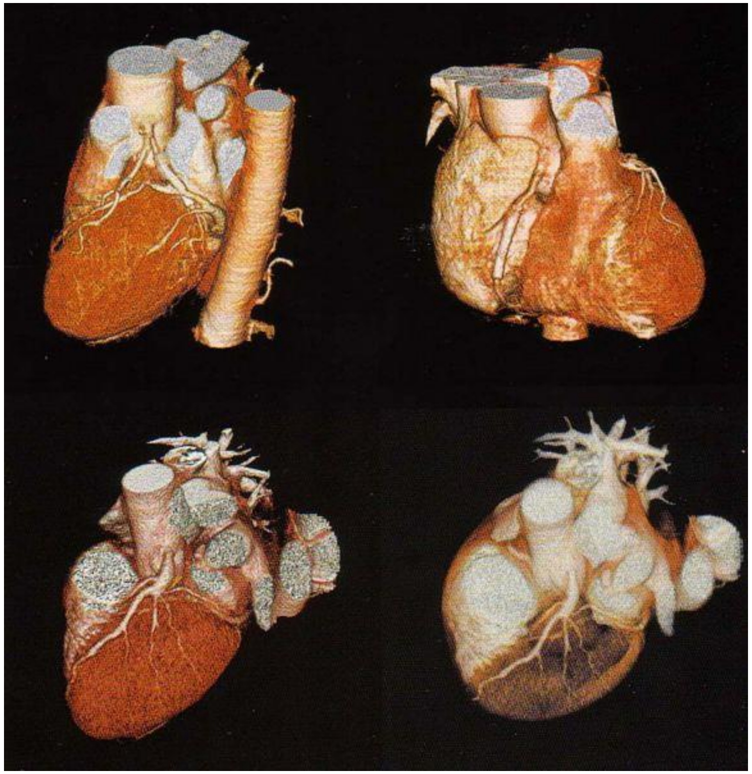
Produce many projections of the object to be reconstructed

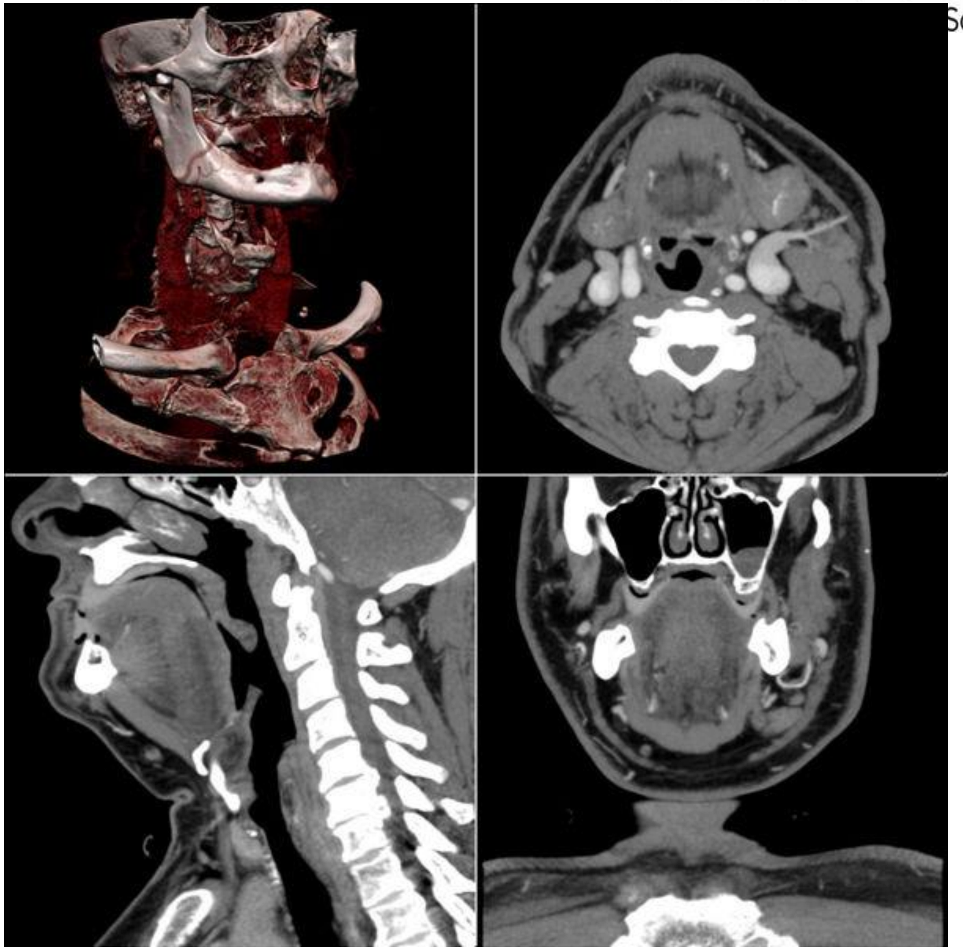
Back project and overlay the “projection rays”

Project the back-projected object and calculate the difference

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

Some CT resuluts





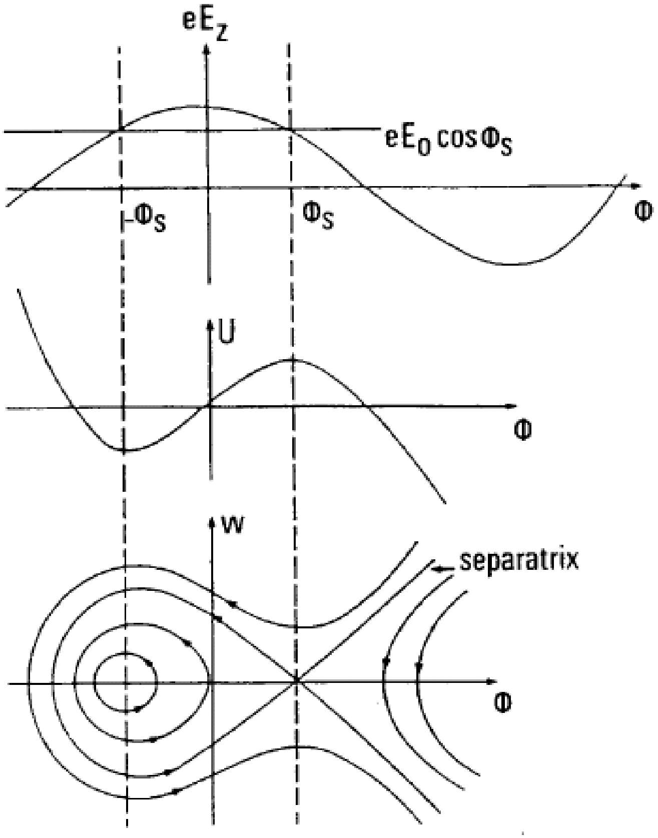
Computed Tomography and Accelerators

RF voltage

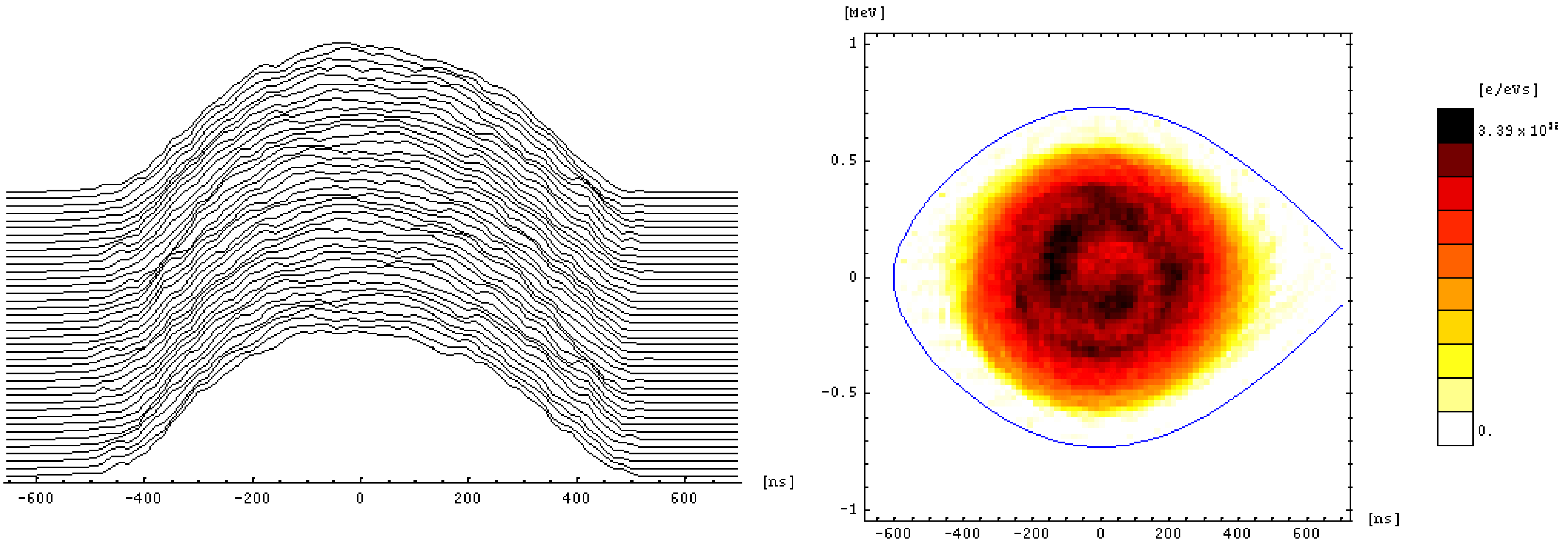
Restoring force for non-synchronous particle

Longitudinal phase space

Projection onto Φ axis corresponds to bunch profile

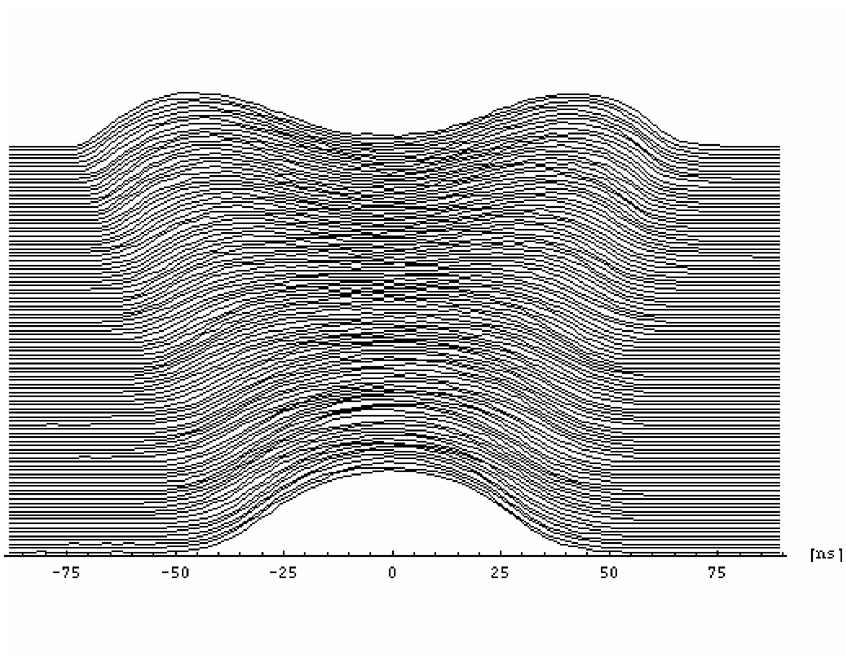


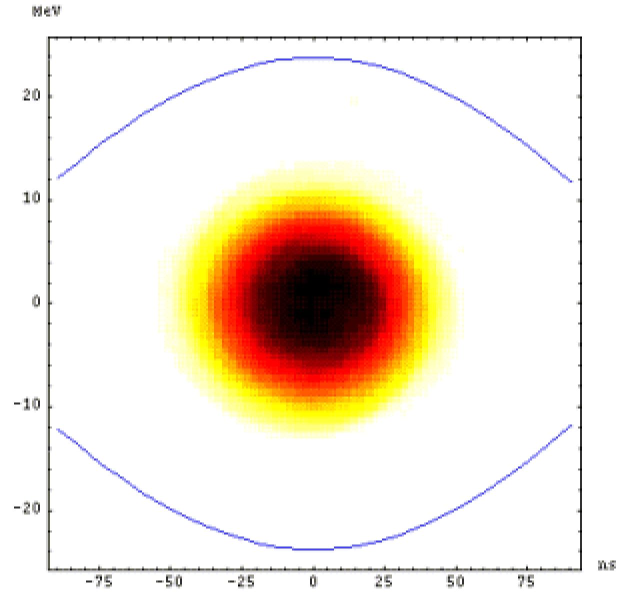
Reconstructed Longitudinal Phase Space



Courtesy S. Hancock

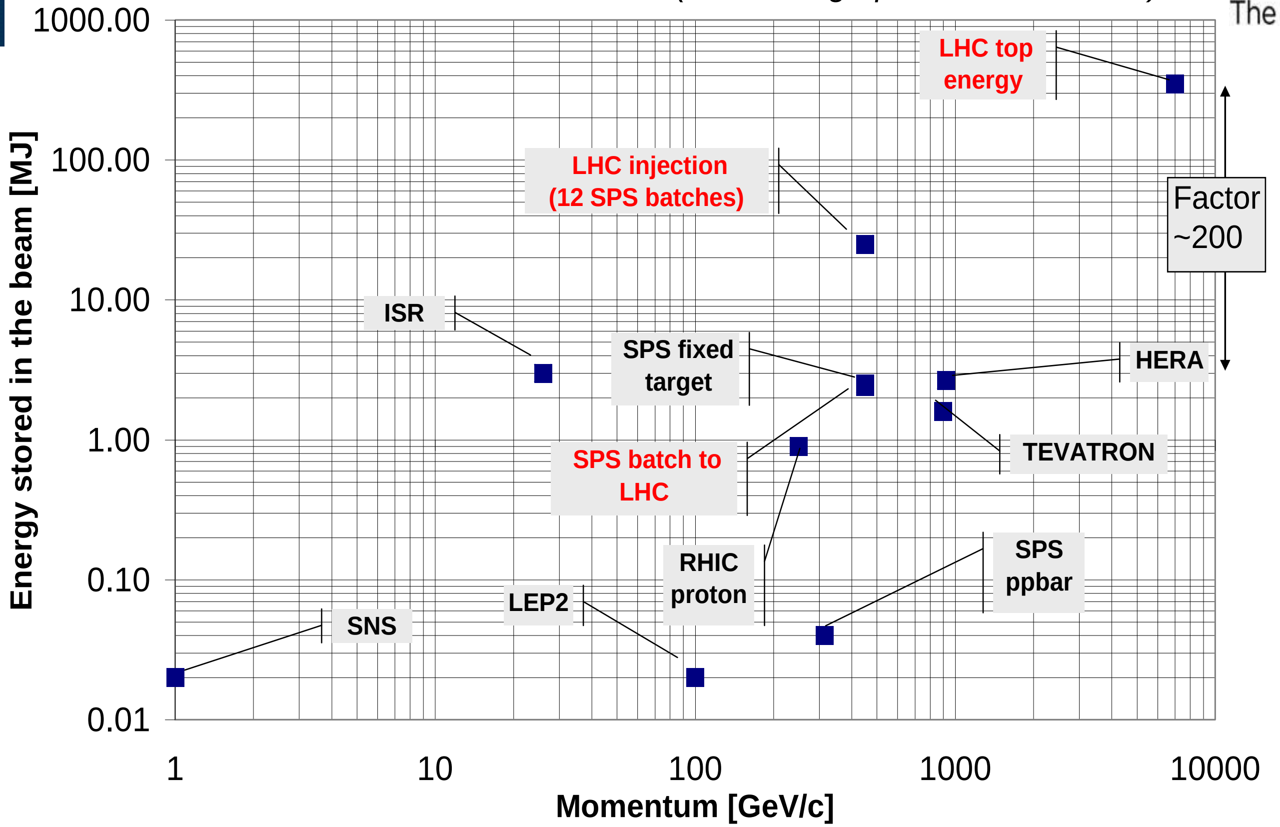
Bunch Splitting





Stored Beam Energies

(Based on graph from R. Schmidt)



Quench Levels	Units	*Tevatron*	*RHIC*	*HERA*	*LHC*
***Instant loss* (0.01 - 10 ms)**	[J/cm³]	$4.5\ 10^{-03}$	$1.8\ 10^{-02}$	$2.1\ 10^{-03}$ - $6.6\ 10^{-03}$	$8.7\ 10^{-04}$
***Steady loss* (> 100 s)**	[W/cm³]	$7.5\ 10^{-02}$	$7.5\ 10^{-02}$		$5.3\ 10^{-03}$

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 Loss Monitor Types

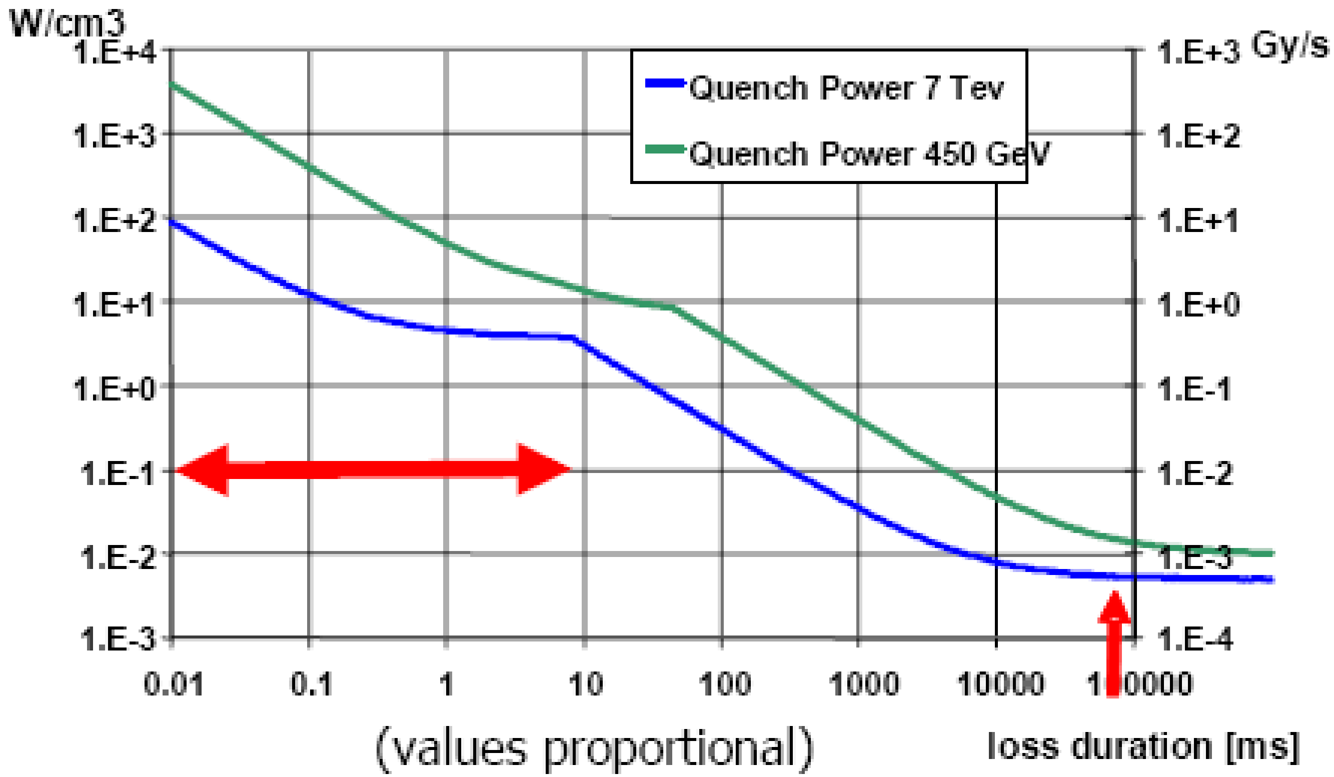
- Design criteria: Signal speed and robustness
- Dynamic range (> 10^9) limited by leakage current through insulator ceramics (lower) and saturation due to space charge (upper limit).

Secondary Emission Monitor (SEM):
- Length 10 cm
- P < 10^{-7} bar
- ~ 30000 times smaller gain

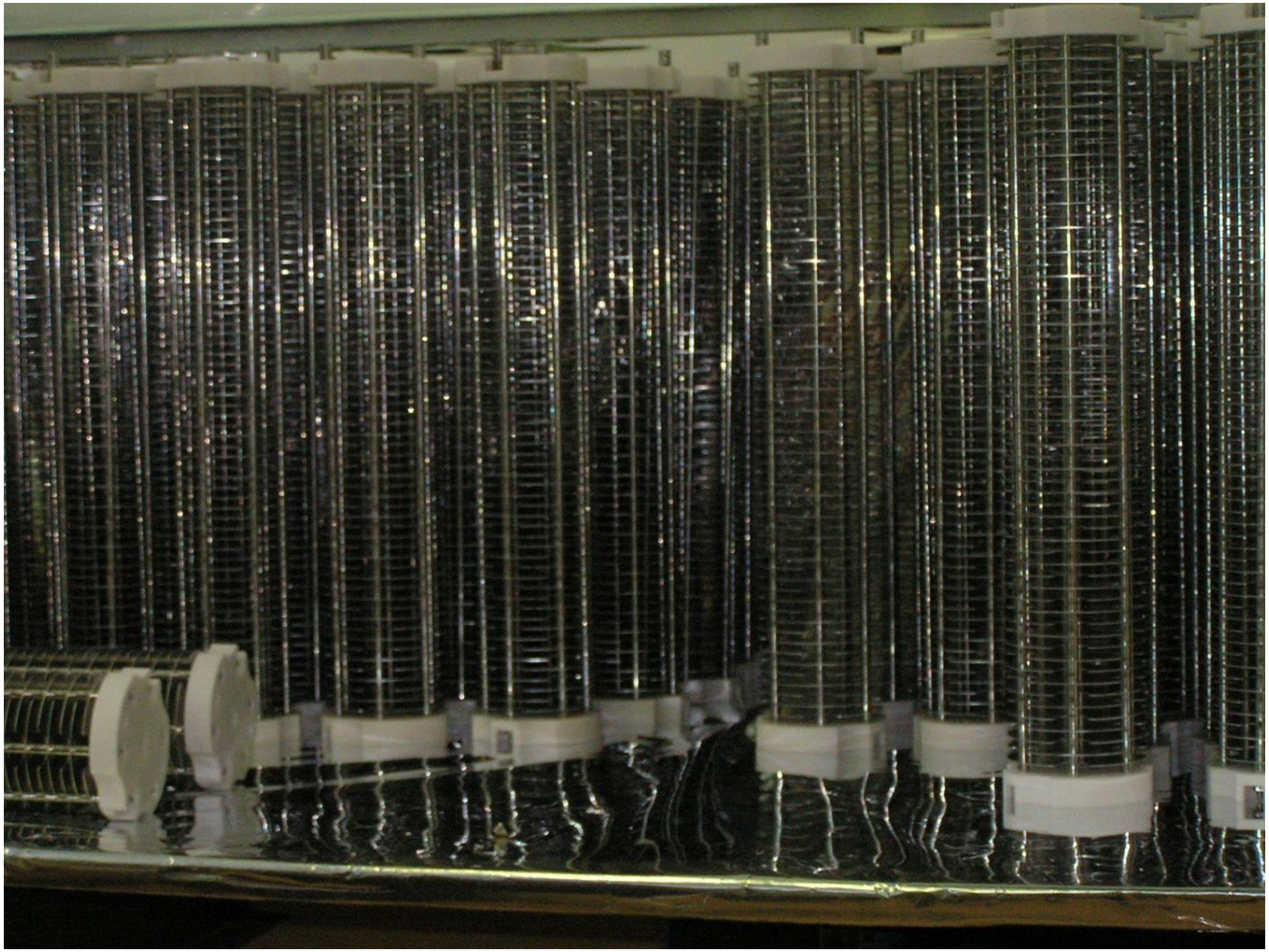
Ionization chamber:
- N_2 gas filling at 100 mbar over-pressure
- Length 50 cm
- Sensitive volume 1.5 l
- Ion collection time 85 μs

- Both monitors:
  - Parallel electrodes (Al, SEM: Ti) separated by 0.5 cm
  - Low pass filter at the HV input
  - Voltage 1.5 kV

Quench levels



Industrial production of chambers



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

Conclusions

- Beam diagnostics is a very wide field where many different competences are needed
  - Machine physics
  - Electronics
  - Computing
  - Mechanics
- The instruments are the eyes with which we observe the beam
- The beam can never be adjusted with higher precision than what can be measured