Introduction to Beam Instrumentation and Diagnostics Lecture II

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(based on previous lectures by Rhodri Jones)

Outline

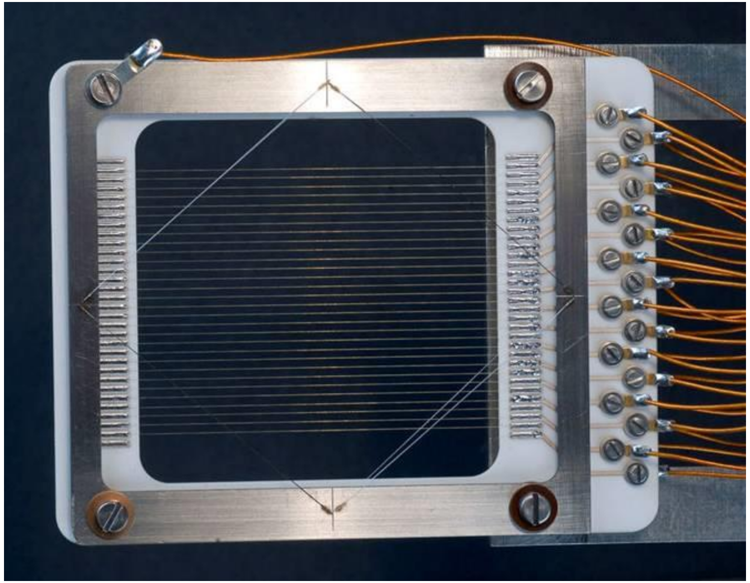
- Lecture I - yesterday
  - Introduction
  - Beam position monitoring
  - Beam intensity monitoring
  - Beam loss monitoring
- Lecture II - today
  - Transverse beam profile monitoring
  - Tune measurements
  - Coupling measurements
  - Chromaticity measurements
  - Diagnosing accelerator issues

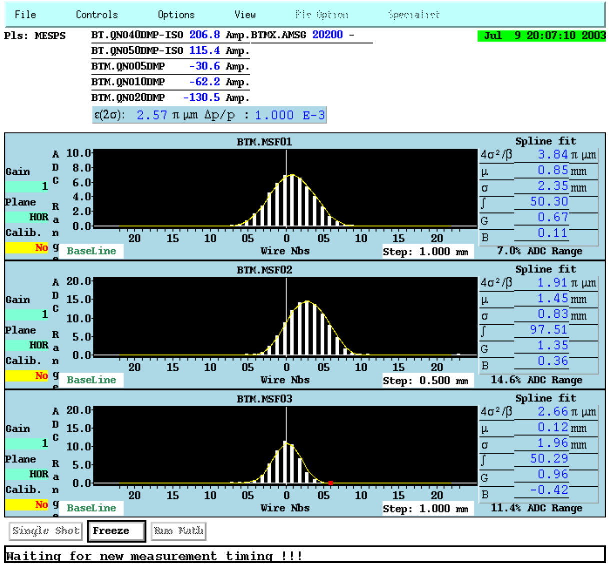
Transverse beam profile monitoring

Beam profile monitoring using wires

Secondary Emission Monitors (SEM, HARP)

- Secondary electrons emitted from beam-wire interaction – electric current in the wire
- Current in each wire read-out independently – beam profile reconstruction
- Wires can overheat – not ideal for circular machines

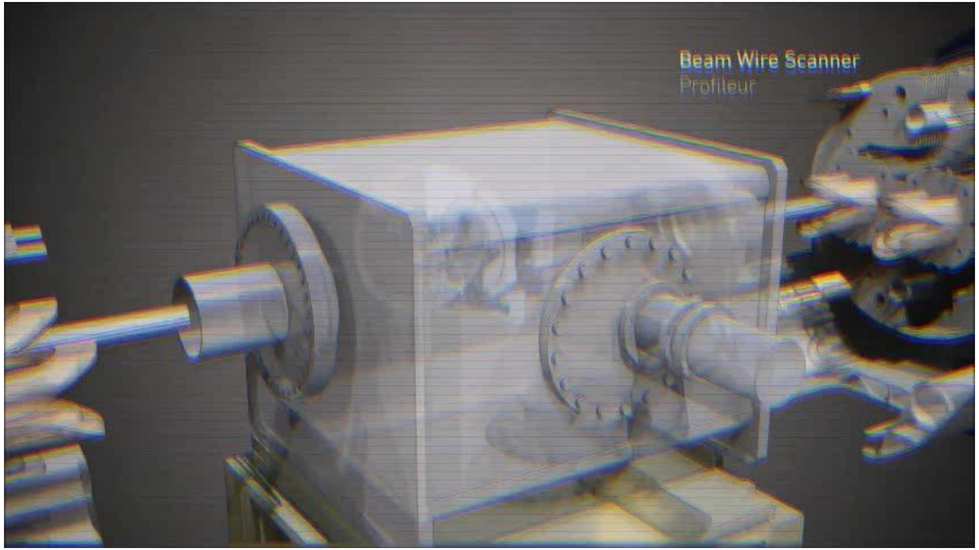




Beam profile monitoring using wires

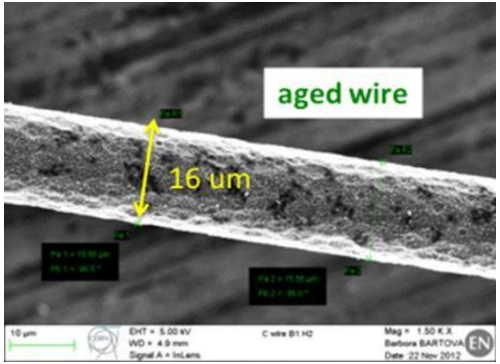
Wire scanners

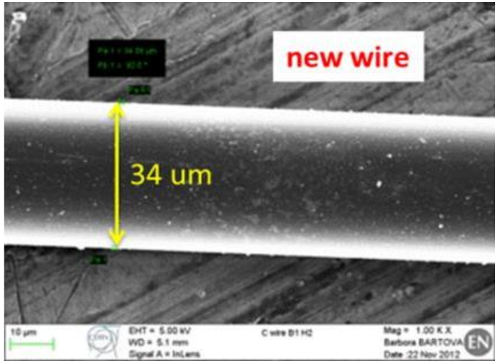
- Single thin wire swept across the beam – corelate beam-wire interactions with the wire position
- Low-energy beams: current in the wire due to secondary emission
- High-energy beams: secondary shower measured outside of the vacuum (e.g. with scintillator)
- Absolute measurements – can be used for cross-calibration of other instruments



Wire scanner limitations

- Wires can (and do!) get damaged
  - Mechanical failures – due to errors in motor controls
  - Melting / sublimation – energy deposition in the wire, large energy density for small beams
- Thermal behaviour of the wire depends on the heat capacity (increases with temperature!) and cooling (negligible during a ~ 1 ms scan time)
- Wire material: good mechanical properties, high heat capacity, high melting / sublimation point (e.g. 3915 K for carbon)

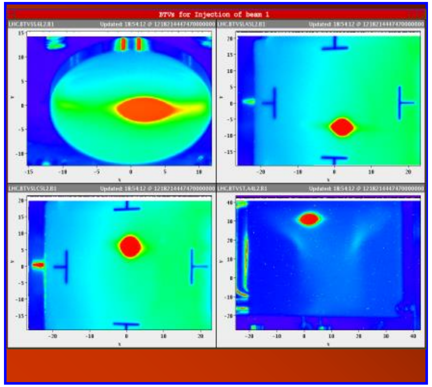


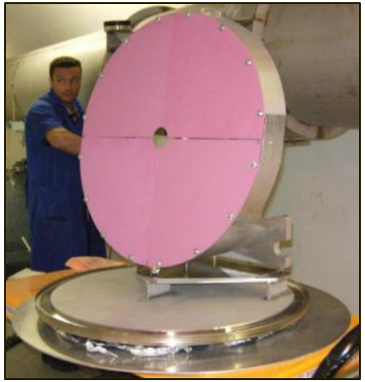


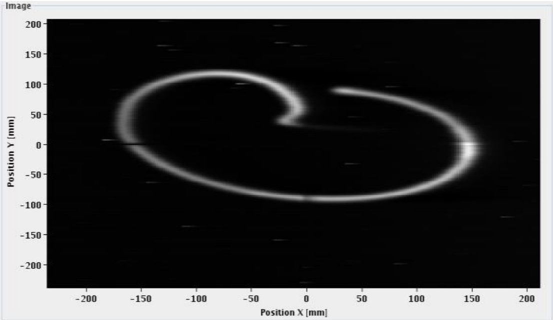
Beam profile monitoring using screens

Luminescence / scintillating screens

- Light emission upon beam-screen interaction
- Straight-forward instrument for beam size and position monitoring
  - 2D information with CCD cameras
- Thick screens are destructive to the beam but work with low intensities



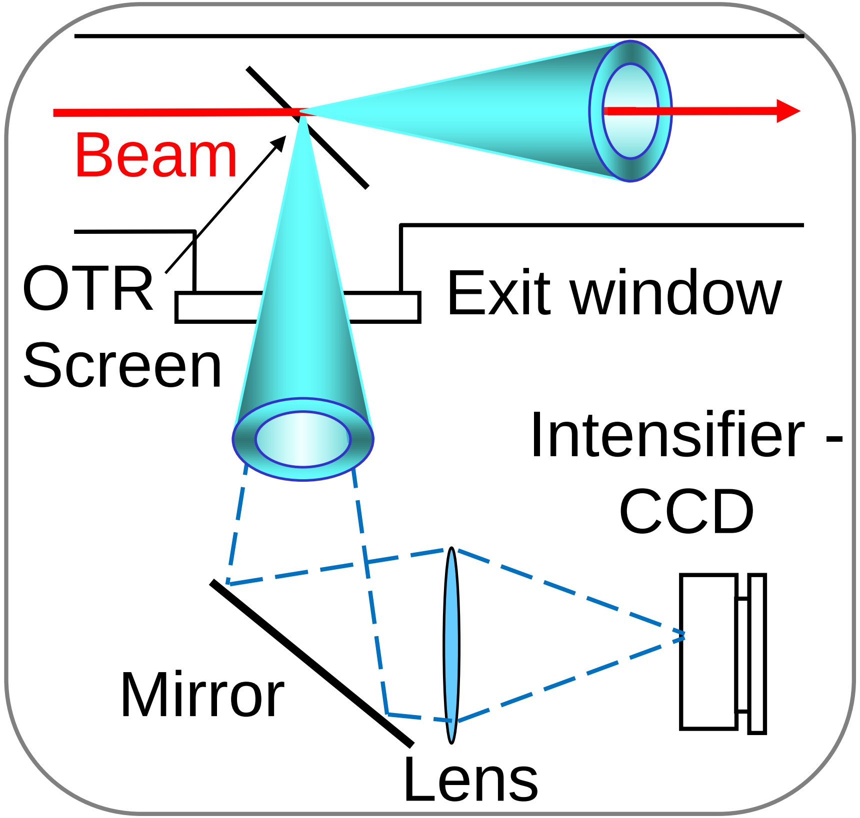




Beam profile monitoring using screens

Optical Transition Radiation (OTR) screens

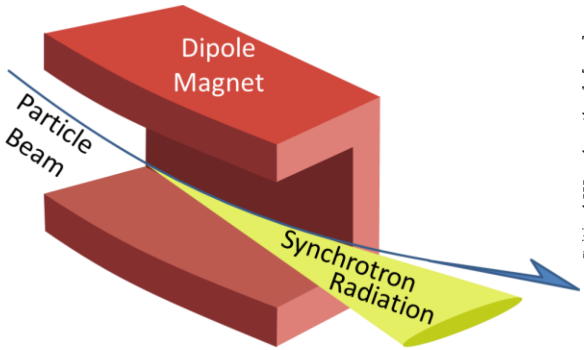
- Radiation emitted when a charged particle goes through an interface with different dielectric constants
- Surface phenomenon – very thin (10 um) screens possible
  - Multiple screen in single-pass lines
  - Measurement over hundreds of turns in rings
- Less destructive than scintillation but requires higher energy / intensity beams
- Extremely high resolution possible

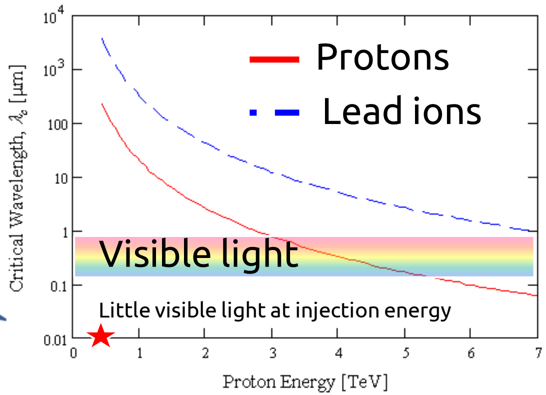


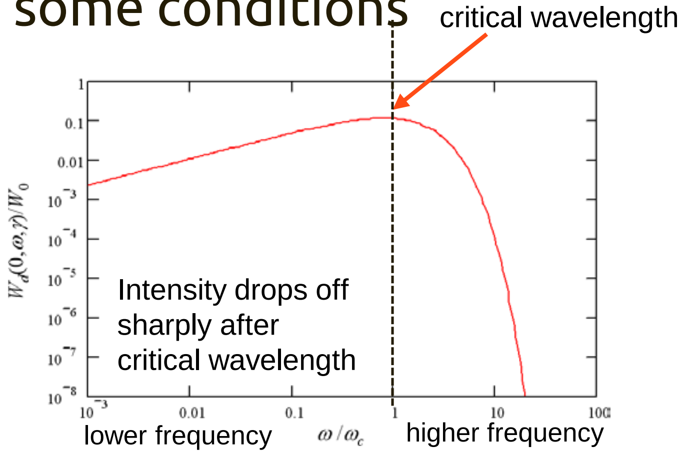
Beam profile monitoring using synchrotron light

Synchrotron light monitors

- Light emission when the trajectory of a charged beam is bent (e.g. by a dipole, undulator, wiggler)
- Scientifically exploited in light sources
- Powerful diagnostic tool – non-invasive measurements
- Measurements in the visible range possible in some conditions

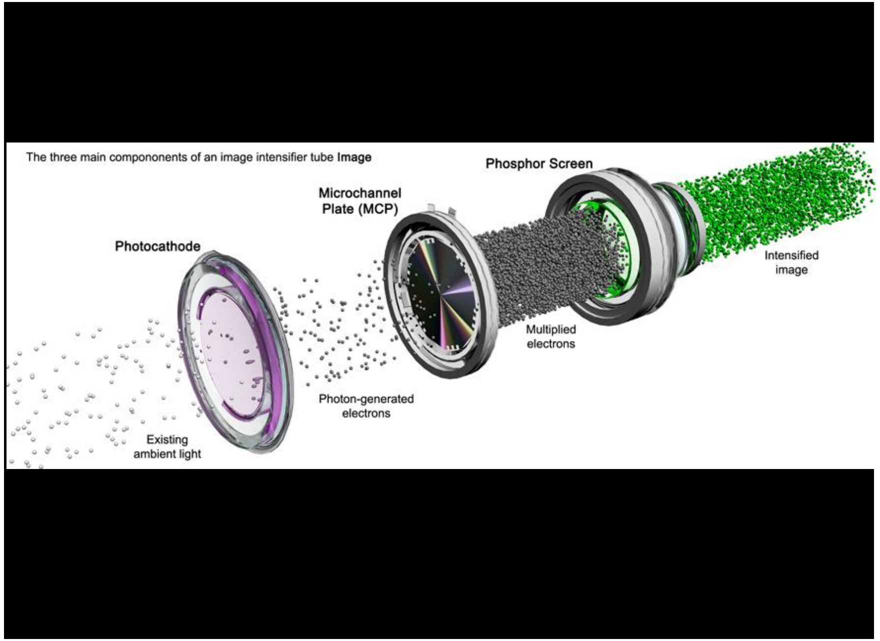






Beam profile monitoring using synchrotron light

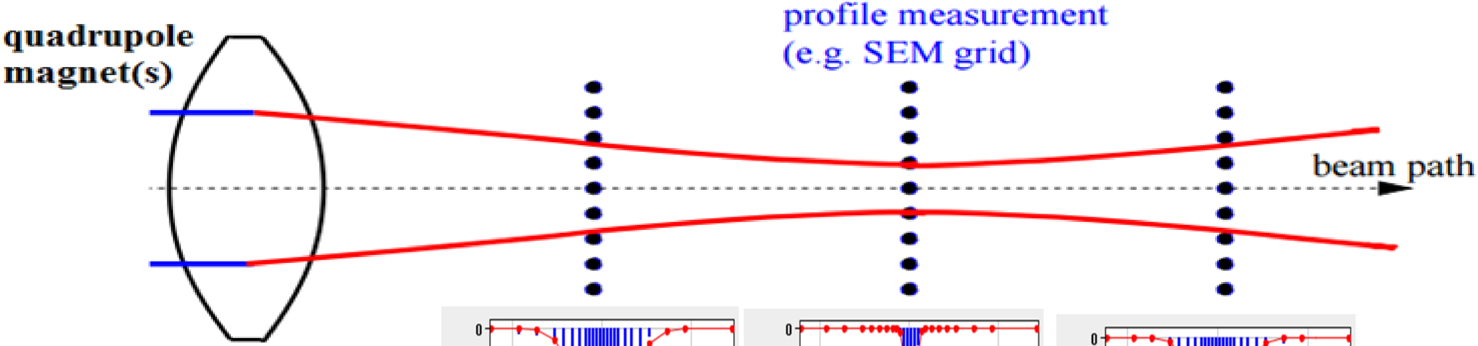
- Imaging possible with different camera types
  - Standard CCD cameras – average beam size measurements
  - Gated intensified cameras – bunch-by-bunch measurements
  - X-ray pin hole cameras – for small, high-energy electron beams
  - Streak cameras – for short bunch diagnostics



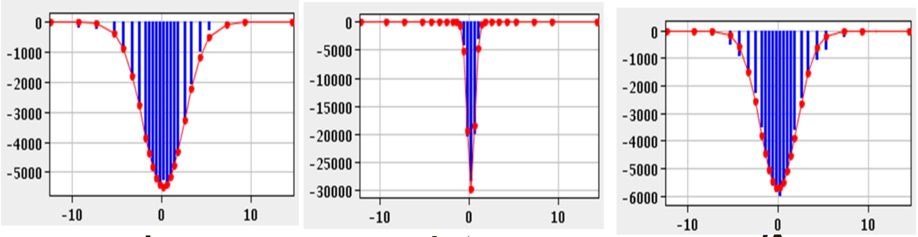
PHOTONIS

Optics measurements - 3 monitor method

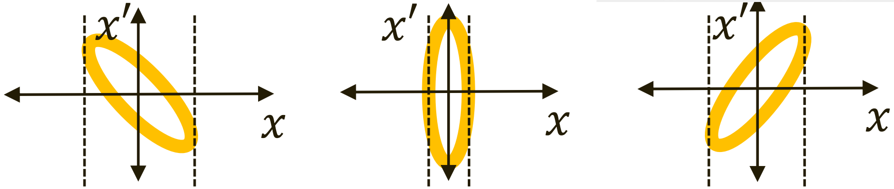
- Reconstruction of optics functions and initial emittance using transport matrix



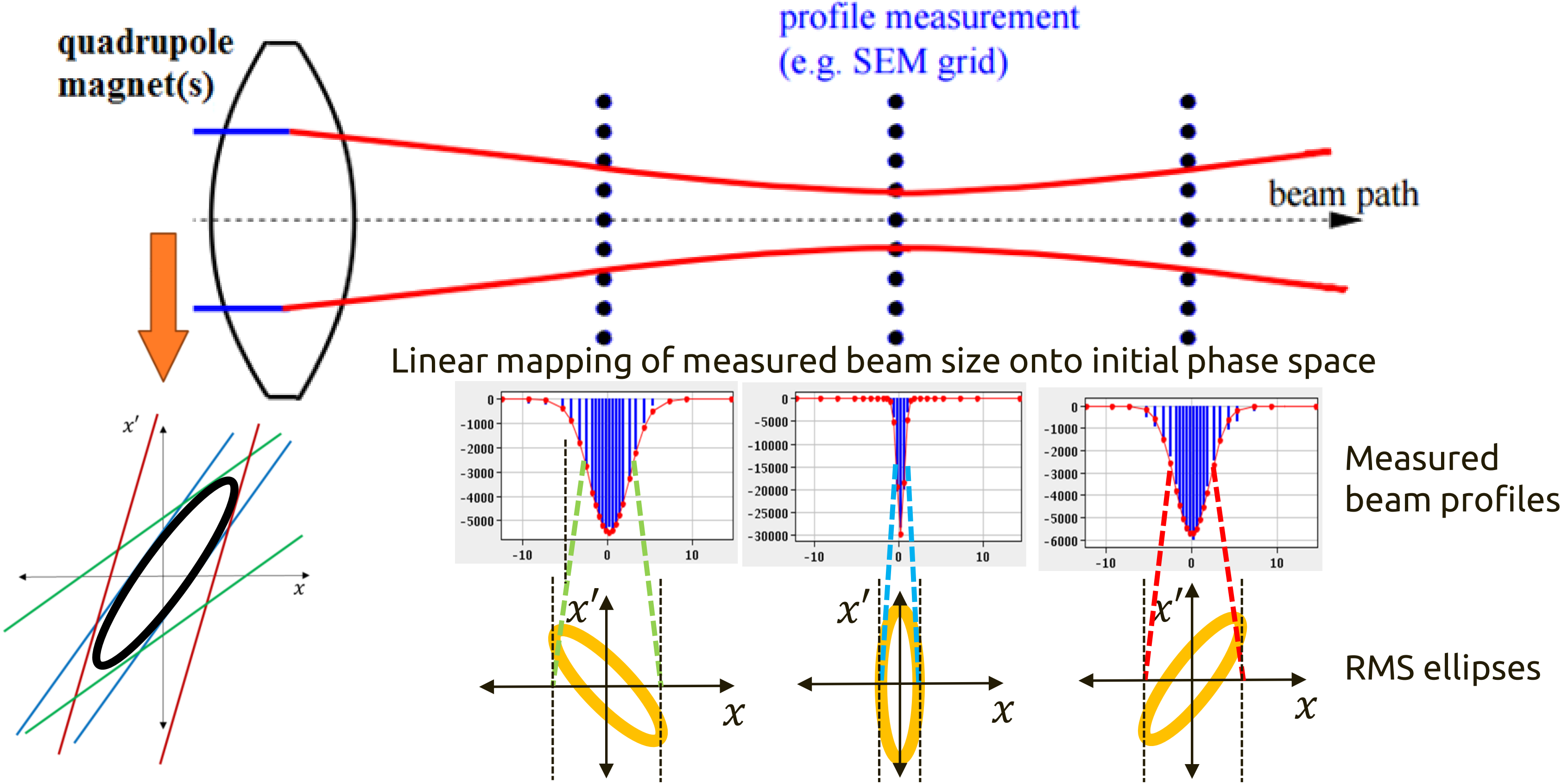
Measured beam profiles



RMS phase-space ellipses

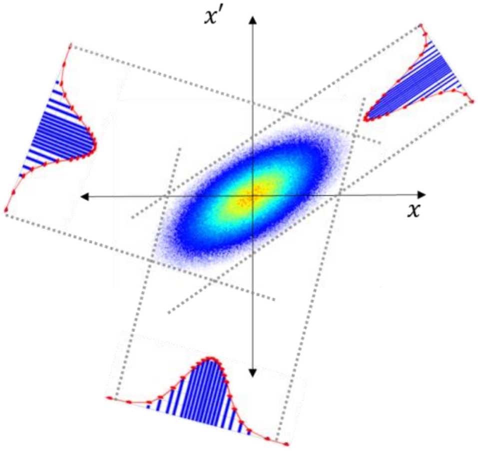


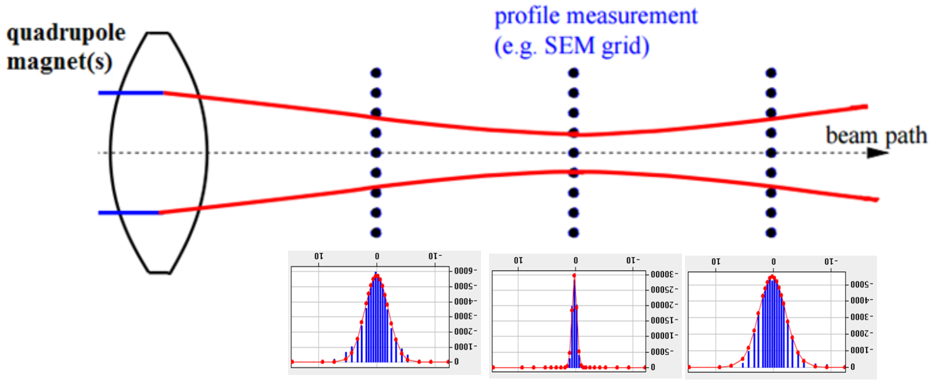
Optics measurements - 3 monitor method



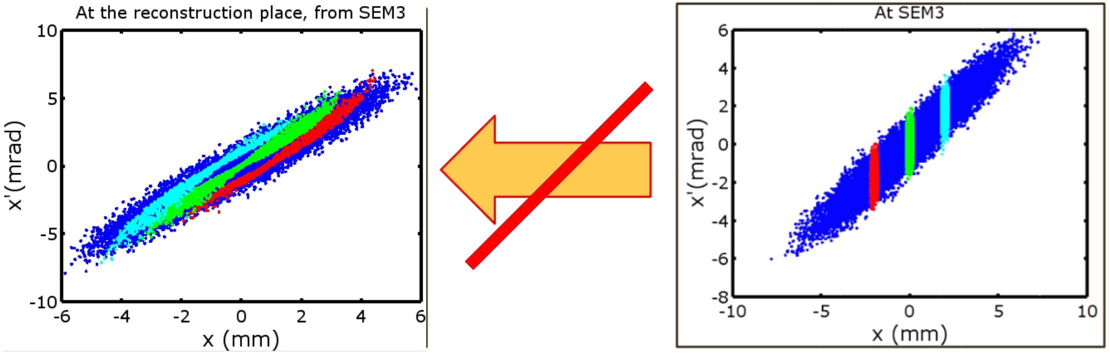
Optics measurements - 3 monitor method

- Tomography – deriving the distribution of particle density in 2D from 1D beam profile measurements



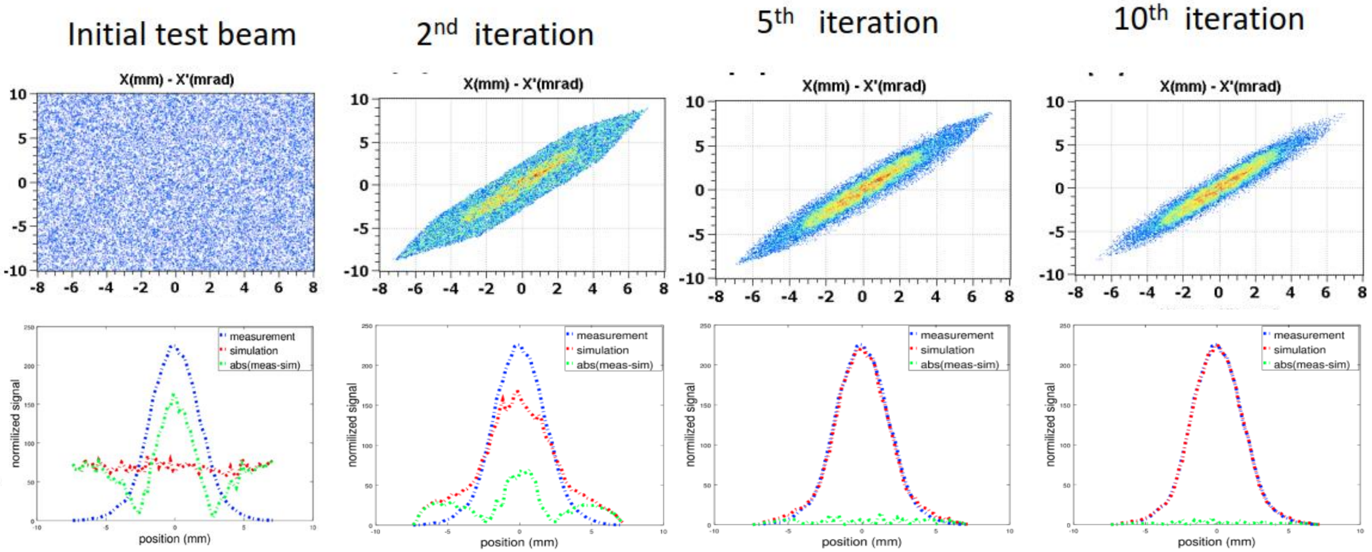


Best results for low-current and/or high-energy beams – no non-linear effects (e.g. space charge)



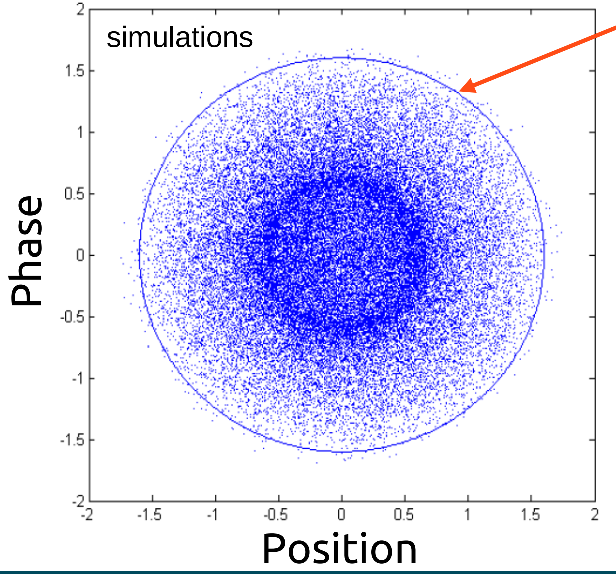
Hybrid phase space tomography – CERN Linac4

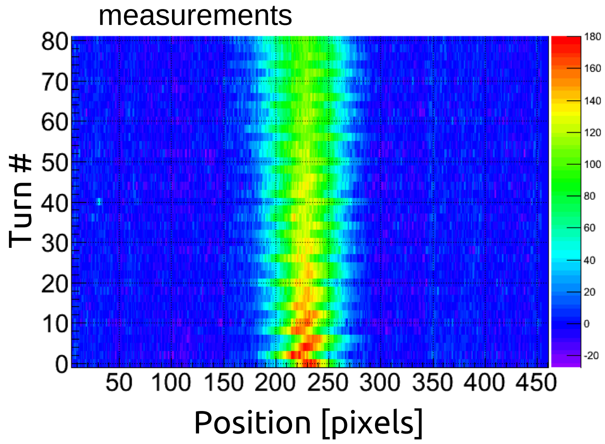
- Random phase space at the reconstruction position
- Transport it to the measurement position (track particles)
- Compare the simulation output to the measurement
- Deduce a better distribution at the reconstruction position
- Repeat iteratively

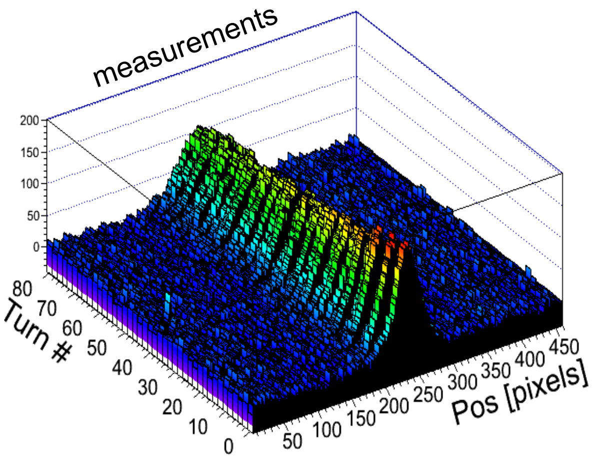


Injection matching with OTR screens

- Injection off-axis due to machine-machine mismatch
- Filamentation – beam moves around the phase space (oscillation) and fills the entire phase space ellipse
- Emittance growth – beam quality degradation



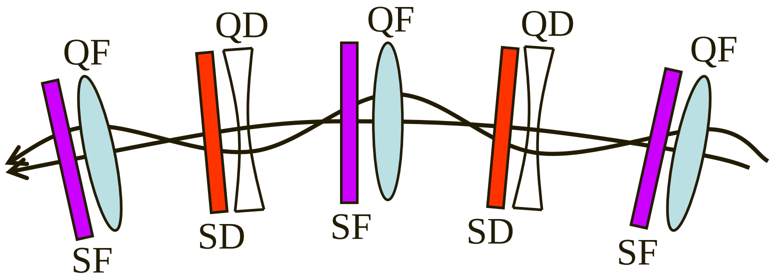


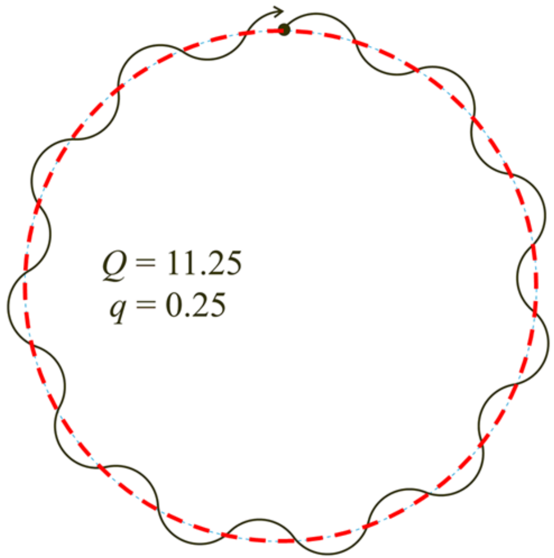


Tune measurements

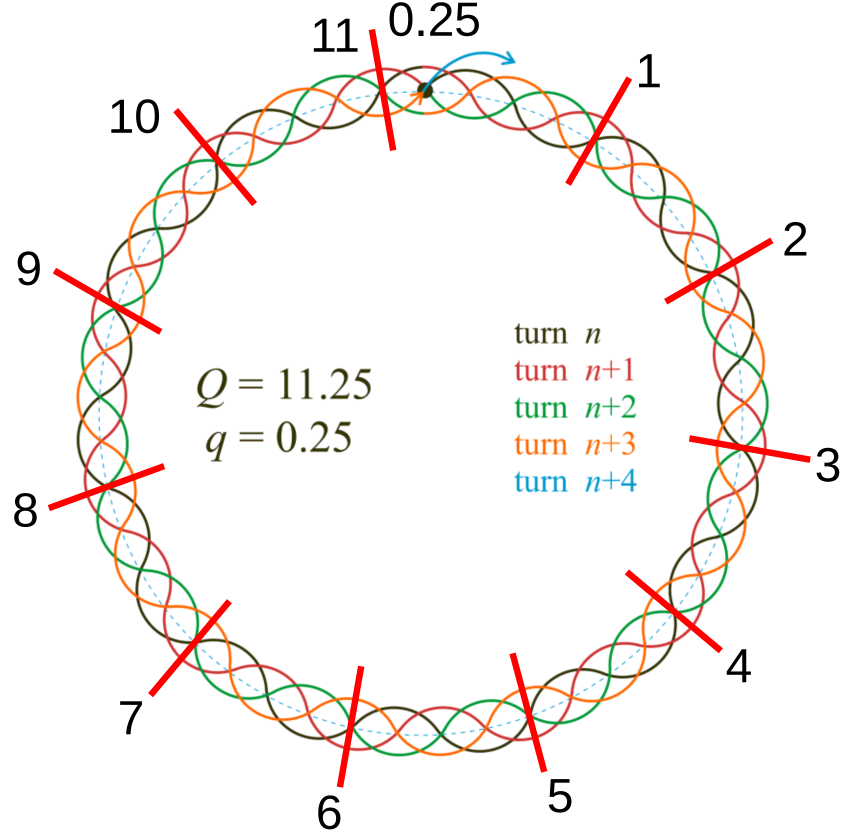
Accelerator tune

- Characteristic frequency of the magnetic lattice – betatron oscillation of off-axis beam particles
  - Set by the strength of quadrupoles
- For each transverse plane (H and V):
  - Q – full betatron tune
  - q – fractional tune (operating point)
- Real life is more complex
  - Oscillations in both planes are coupled
  - Betatron oscillations are non-linear at large amplitudes



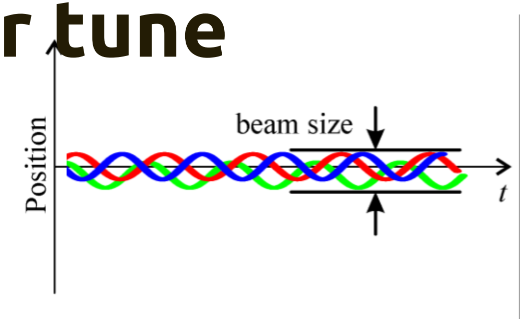


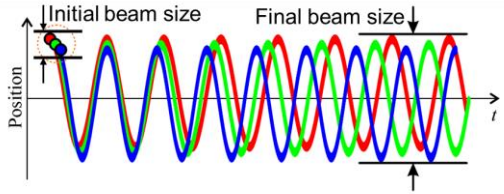
Betatron motion and accelerator tune

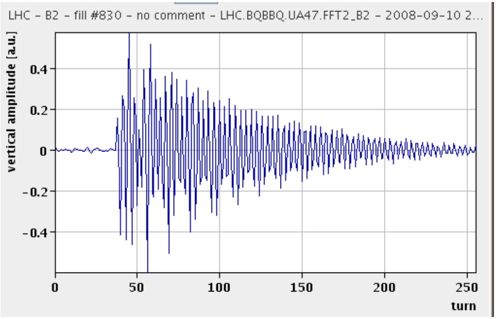


Betatron motion and accelerator tune

- Beam size is defined by the incoherent betatron motion of all particles
- Momentum spread of beam particles leads to a spread of focusing strenght by the quadrupoles and to a spread in the frequency of the betatron oscillations (chromaticity)
- Coherent oscillations eventually de-cohere
  - Hadrons do not forget and once hit they keep oscillating – there is no damping mechanism
  - Any excitation must be kept as low as possible



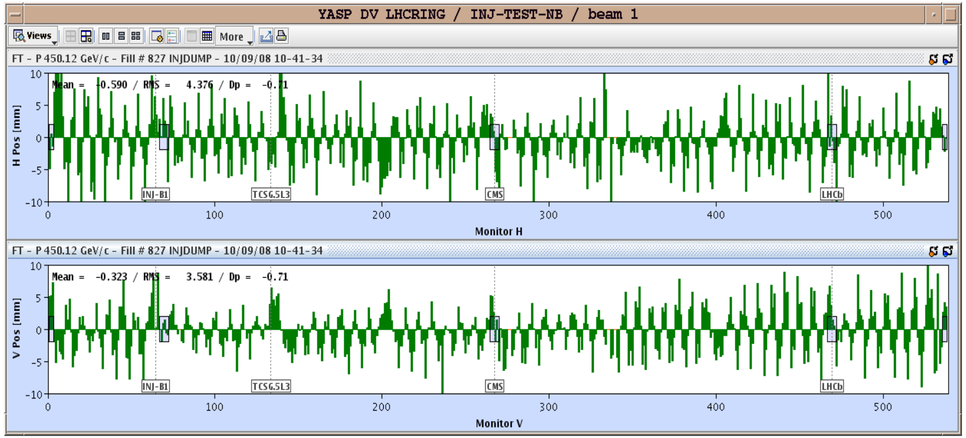


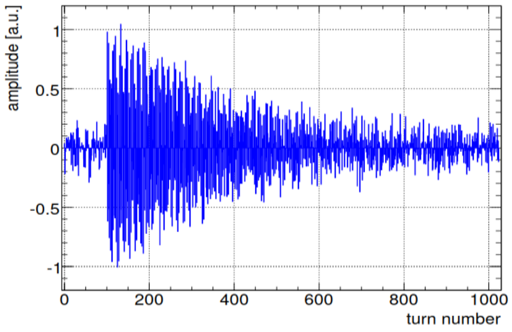


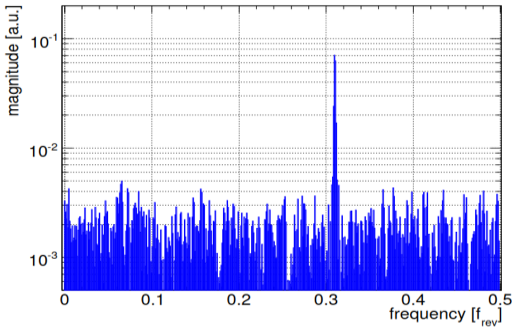
Tune measurements

- **Integer tune**
  - Seen in beam orbit measurements of all BPMs
- **Fractional tune (q)**
  - Seen in turn-by-turn measurements of a single BPM if a beam is kicked
  - Resonant frequency (q) identification in the frequency domain through Fast Fourier Transform (FFT)

LHC: ~ 550 BPMs per beam; Integer tunes: H: 59, V: 64

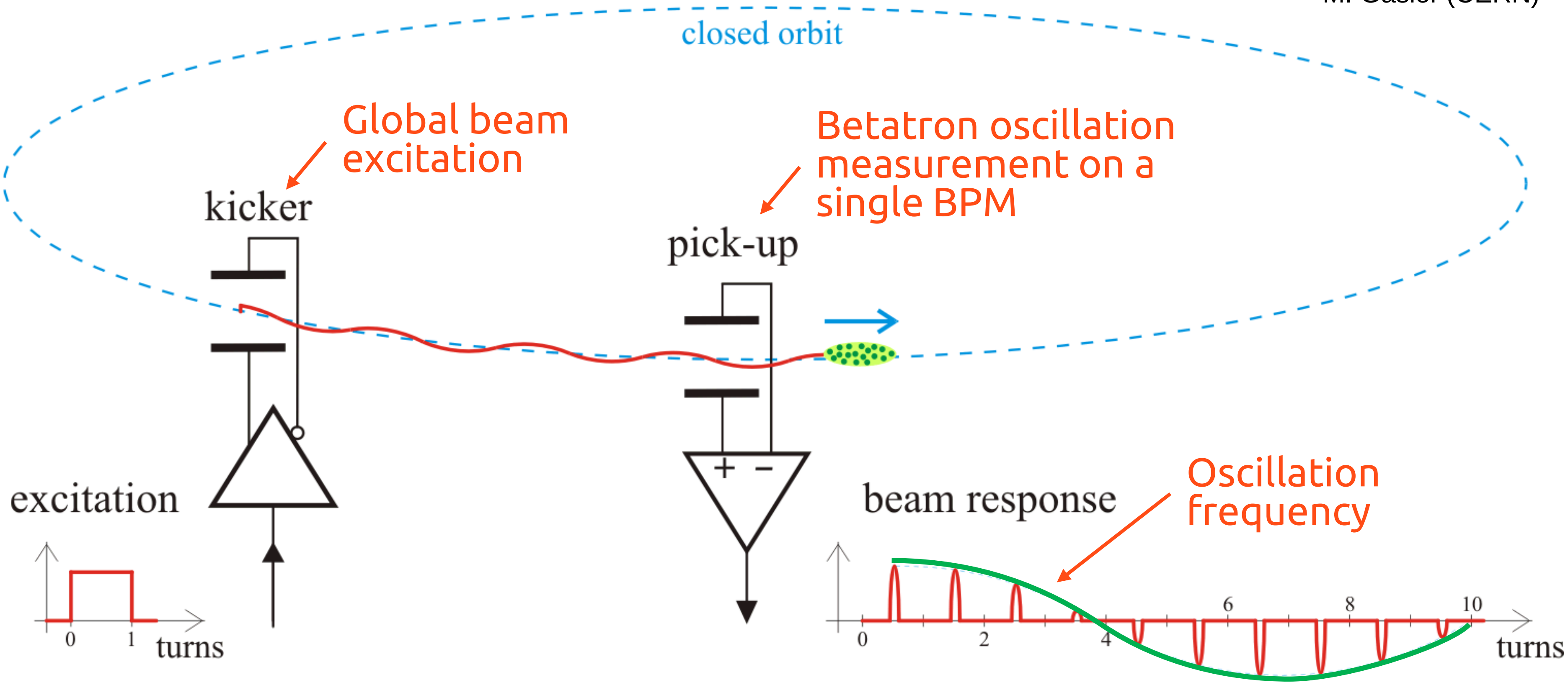






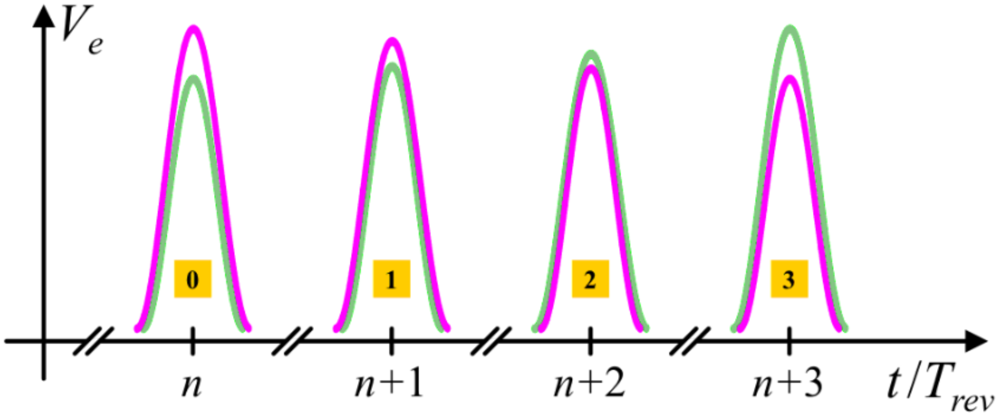
Tune measurements

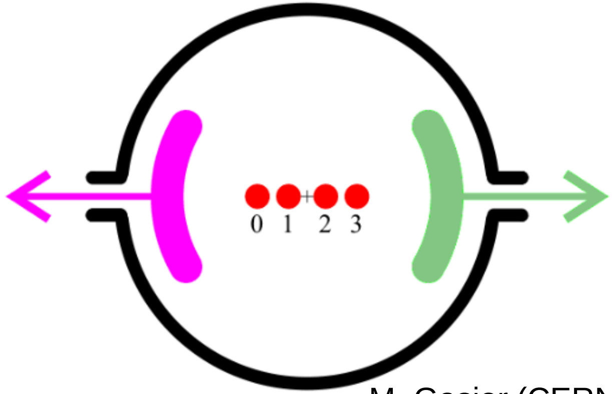
M. Gasior (CERN)



Tune measurements

- Pre-requisite: turn-by-turn position measurements from a BPM
- BPM electrode signal is proportional to the beam/bunch intensity and weakly modulated by the beam position (1-10% per mm of beam displacement)
  - Such signals are difficult to simulate in laboratory environment

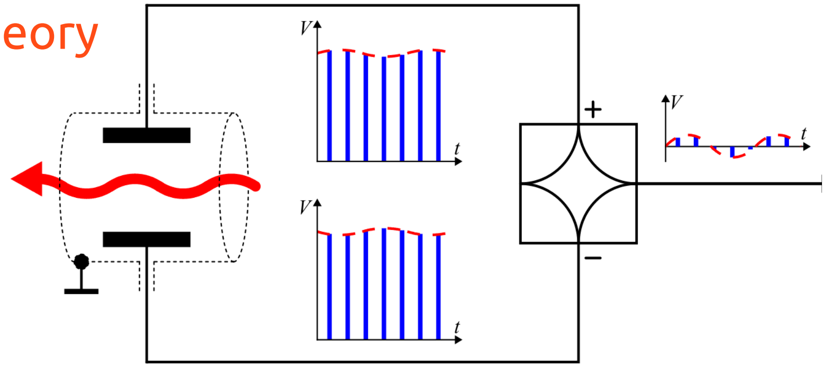




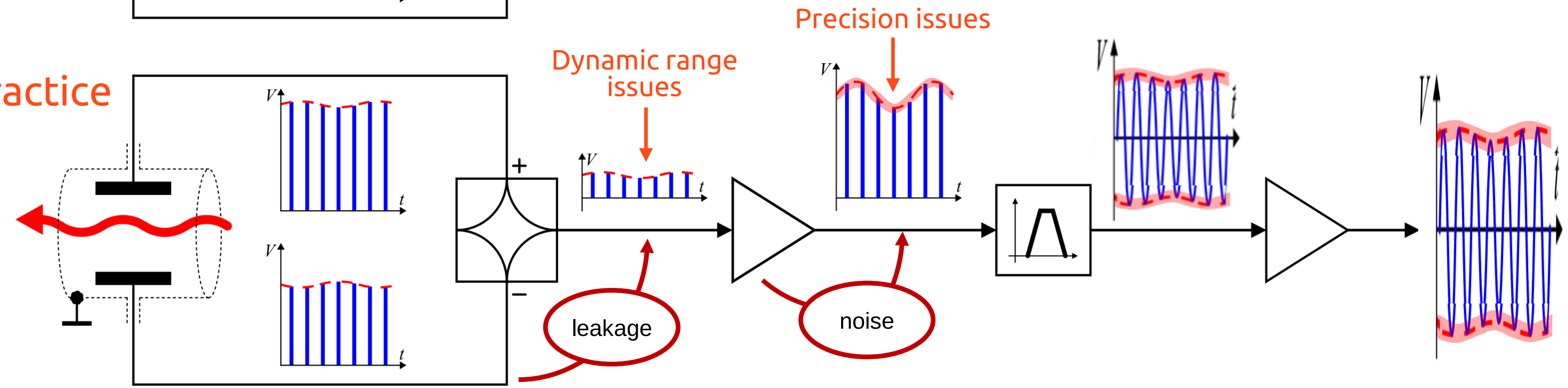
M. Gasior (CERN)

Tune measurements

Theory

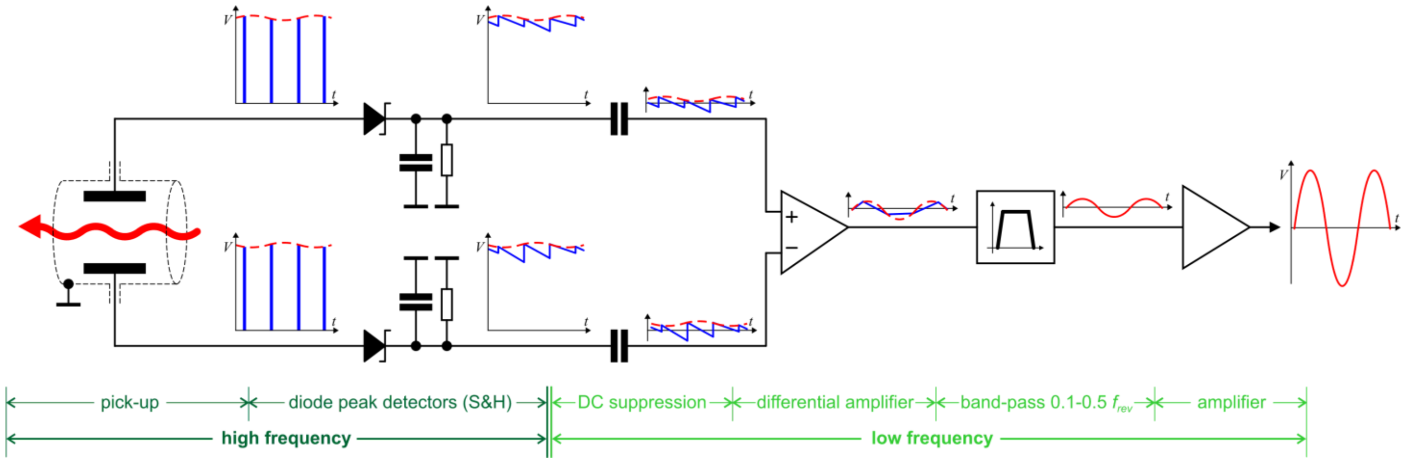


Practice

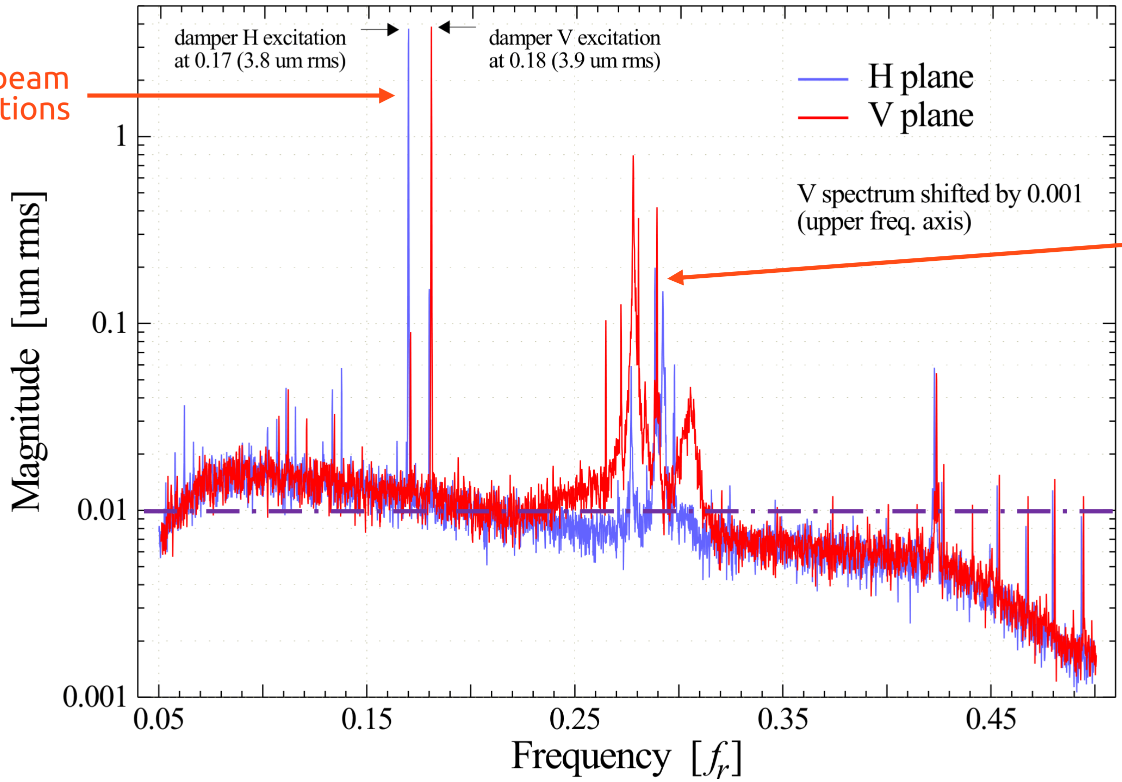


BaseBand Tune (BBQ) system based on Direct Diode Detection

- Single RF Schottky diode – peak voltage handling up to 50 V
  - Several diodes in series possible (e.g. 6 for the LHC)
- Downmixing of the betatron modulation to below the revolution frequency
  - Signal processing with relatively inexpensive high-performance audio ADCs
- Similar to an AM radio receiver but with extremely low noise, very slow discharge, and with brutal filtering of the carrier (revolution) frequency and the out-of-band signals



LHC BBQ performance

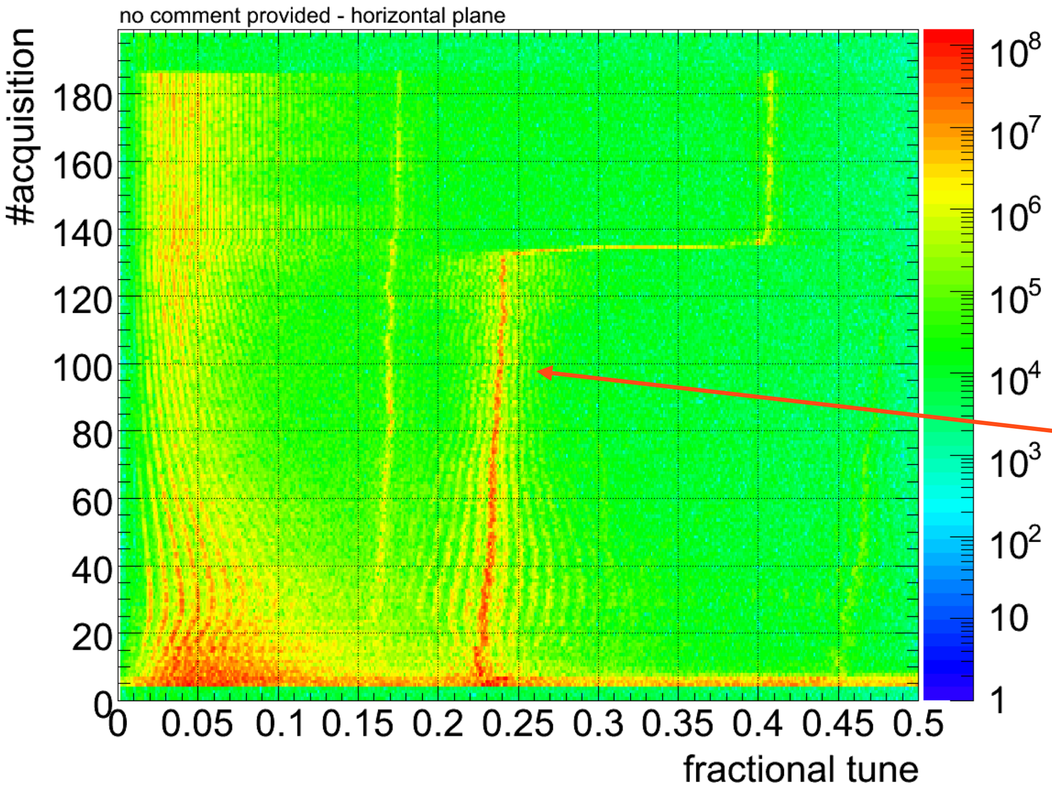


Intentional beam excitations

Residual beam oscillation with no added excitation

~ 10 nm noise floor

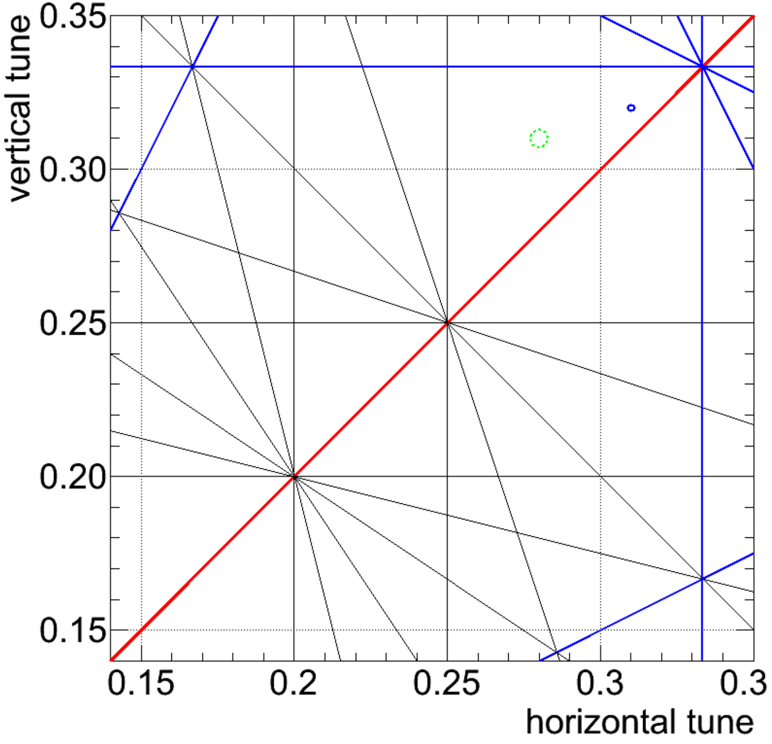
Real-time tune measurements

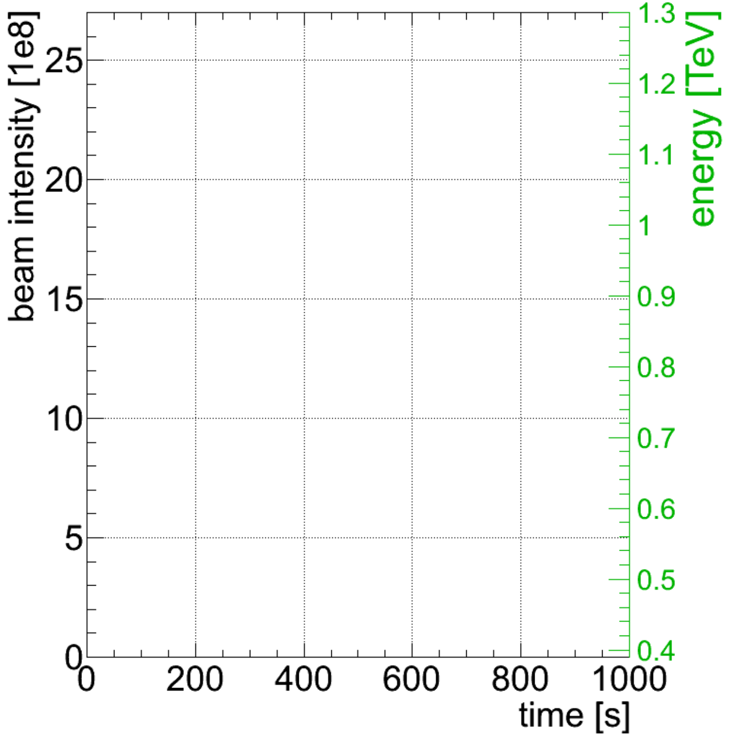


CERN SPS example:
Tune clearly visible from residual oscillations without additional excitation

LHC tune measurements during the energy ramp

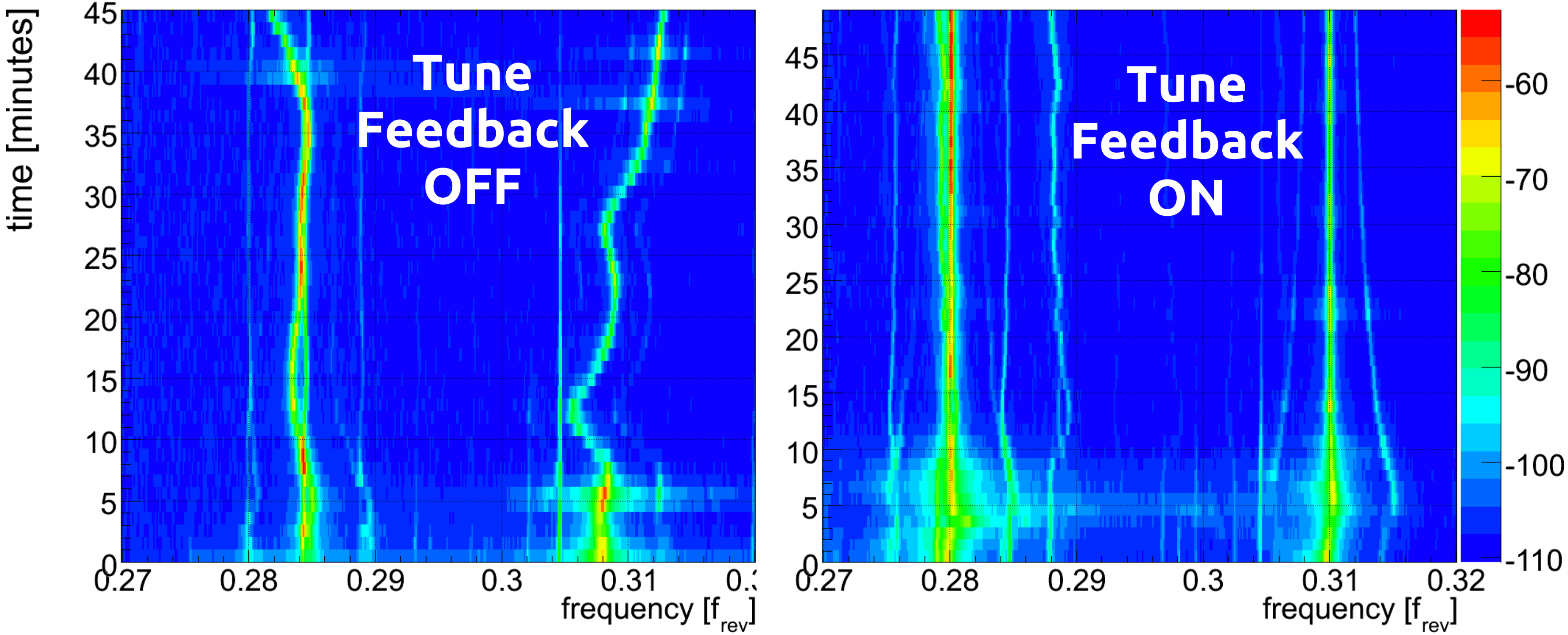
Early LHC - what happens without good tune control





LHC tune feedback

- FFT peak fit with 0.1-0.3 Hz bandwidth
- Feedback correction with trim quadrupoles



Coupling measurements

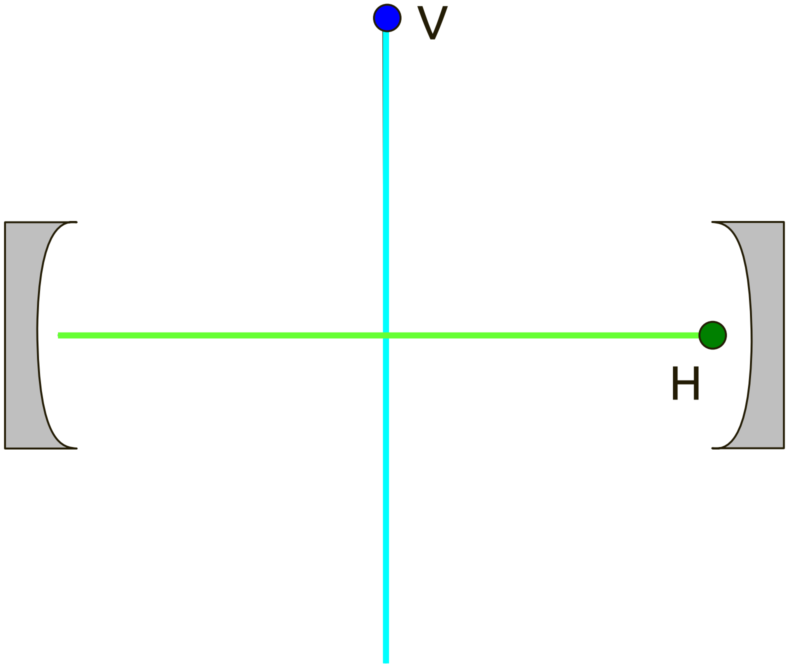
Coupling

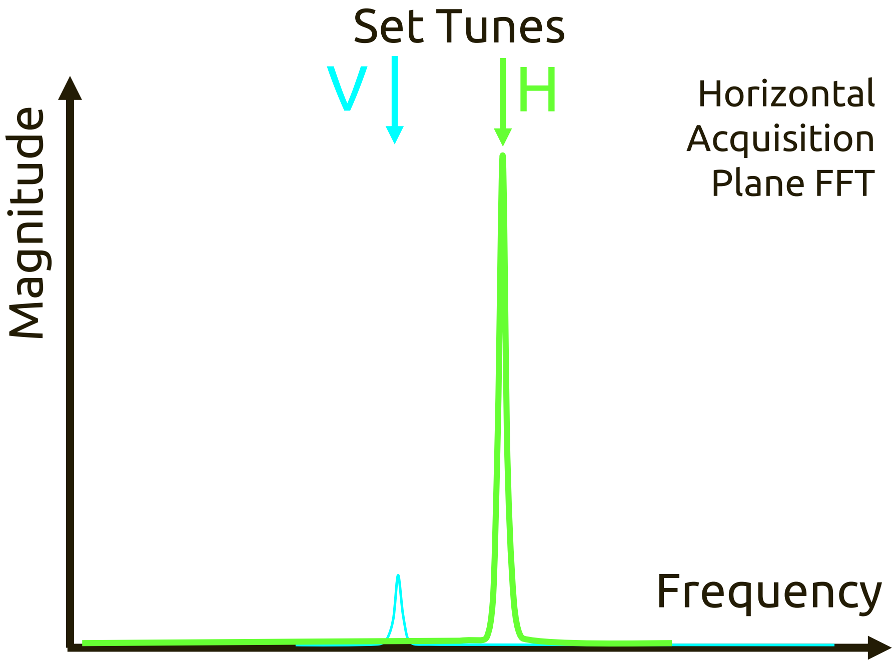
$$\overbrace{Q_{I,II}}^{\text{Measured Tunes}} = \frac{1}{2}\left(\overbrace{Q_x + Q_y}^{\text{Set Tunes}} \pm \sqrt{\left(Q_x - Q_y\right)^2 + |C^-|^2}\right)$$

- Measured tunes - the physical observables seen in FFT
  - Often called the 'normal modes' or 'eigenvalues'
- Set tunes - what the tunes would be in absence of coupling
  - Tune split $\Delta = (Q_x - Q_y)$ – difference between the set X and Y tunes
- Magnitude of the coupling coefficient $|C^-|$
  - The closest Q_I & Q_{II} can approach each other - 'closest tune approach'
  - Any closer is a 'forbidden zone' in a system of coupled oscillators

Coupling measurements

- Decoupled machine – only horizontal tune in horizontal FFT
- Gradually increase coupling – vertical mode shows up and frequencies shift





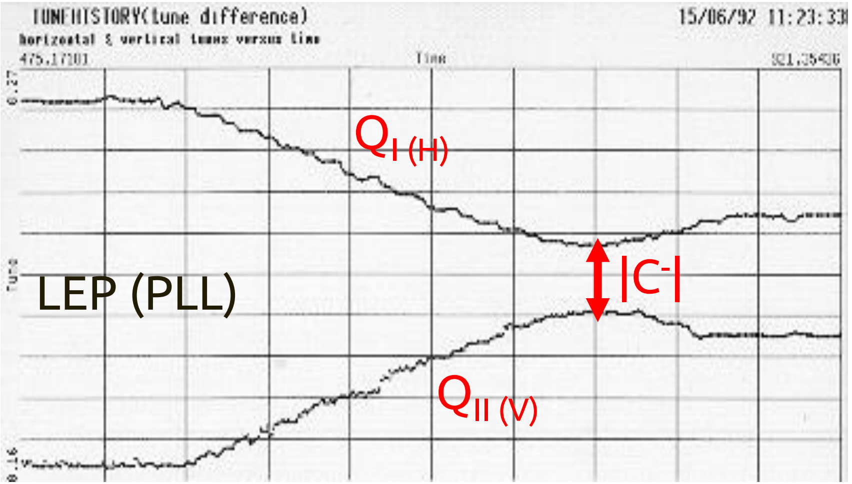
Coupling measurements

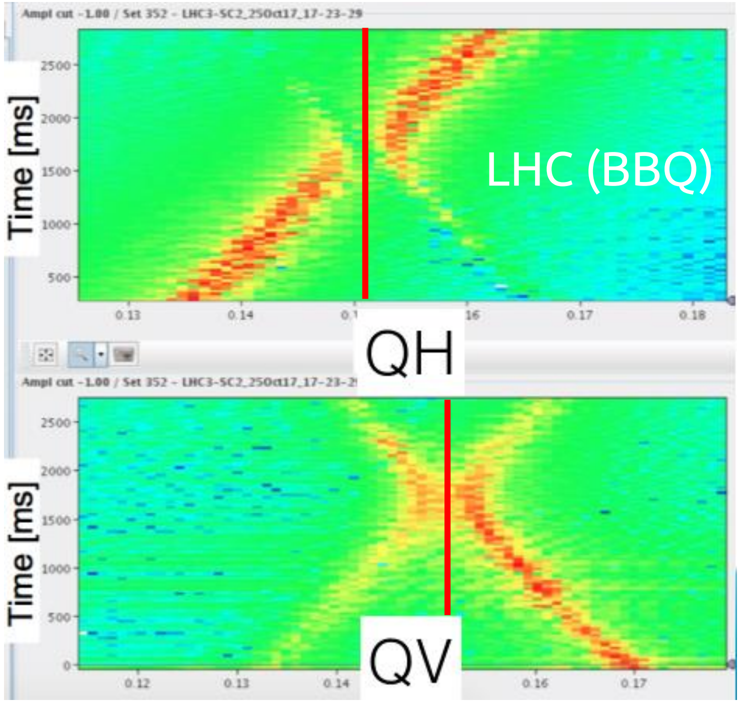
- **Orbit changes**
  - Change orbit in one plane by exciting steering correctors or by changing injection conditions and measure effect in other plane
  - Large coupling sources identified as locations where horizontal orbit change generates a vertical kick and vice versa
  - Acquire large numbers of orbits for excitation of different correctors to determine skew quadrupole component of each magnet
- **Closest tune approach**
  - Approach horizontal and vertical tunes until they cross
  - Coupling derived from how close tunes can approach
- **Kick response**
  - Kick the beam in one plane & measure in other using Tune FFT or pairs of BPMs to derive Resonance Driving Term

Closest tune approach

- Measure tunes while changing the quadrupole strength

$$\overbrace{Q_{I,II}}^{\text{Measured Tunes}} = \frac{1}{2}\left(\overbrace{Q_x + Q_y}^{\text{Set Tunes}} \pm \sqrt{(Q_x - Q_y)^2 + |C^-|^2}\right)$$





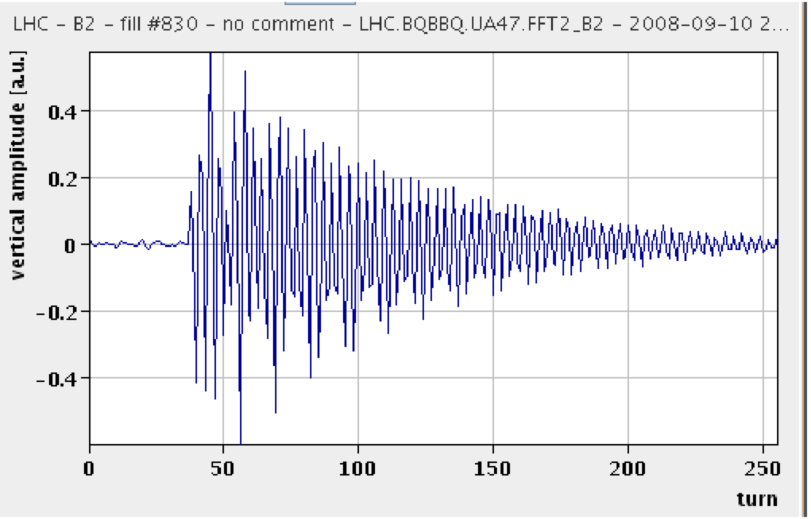
Kick response

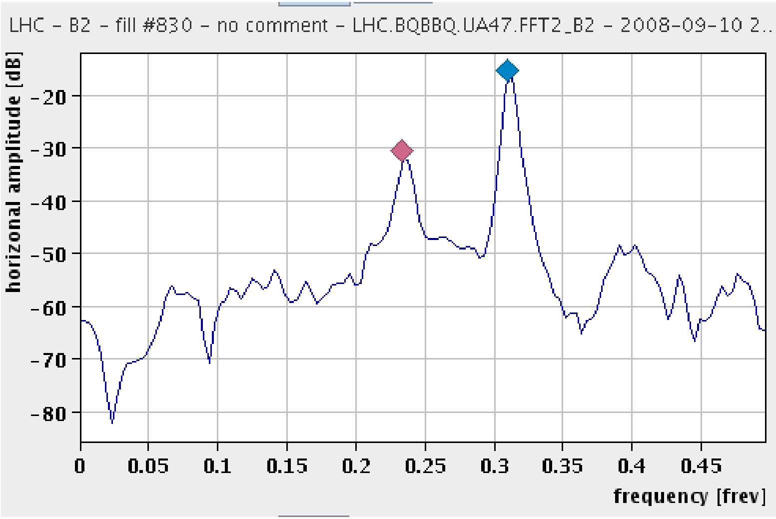
- Kick the beam in one plane and measure the tune in the other
  - Magnitude of local coupling can be derived from amplitude ratios of tune peaks

$$|C^-| \propto \frac{\sqrt{r_1 r_2}}{1 + r_1 r_2} \qquad r_1 = \frac{A_{1,y}}{A_{1,x}} \qquad r_2 = \frac{A_{2,x}}{A_{2,y}}$$

← x tune measured by y pick-up

← y tune measured by y pick-up

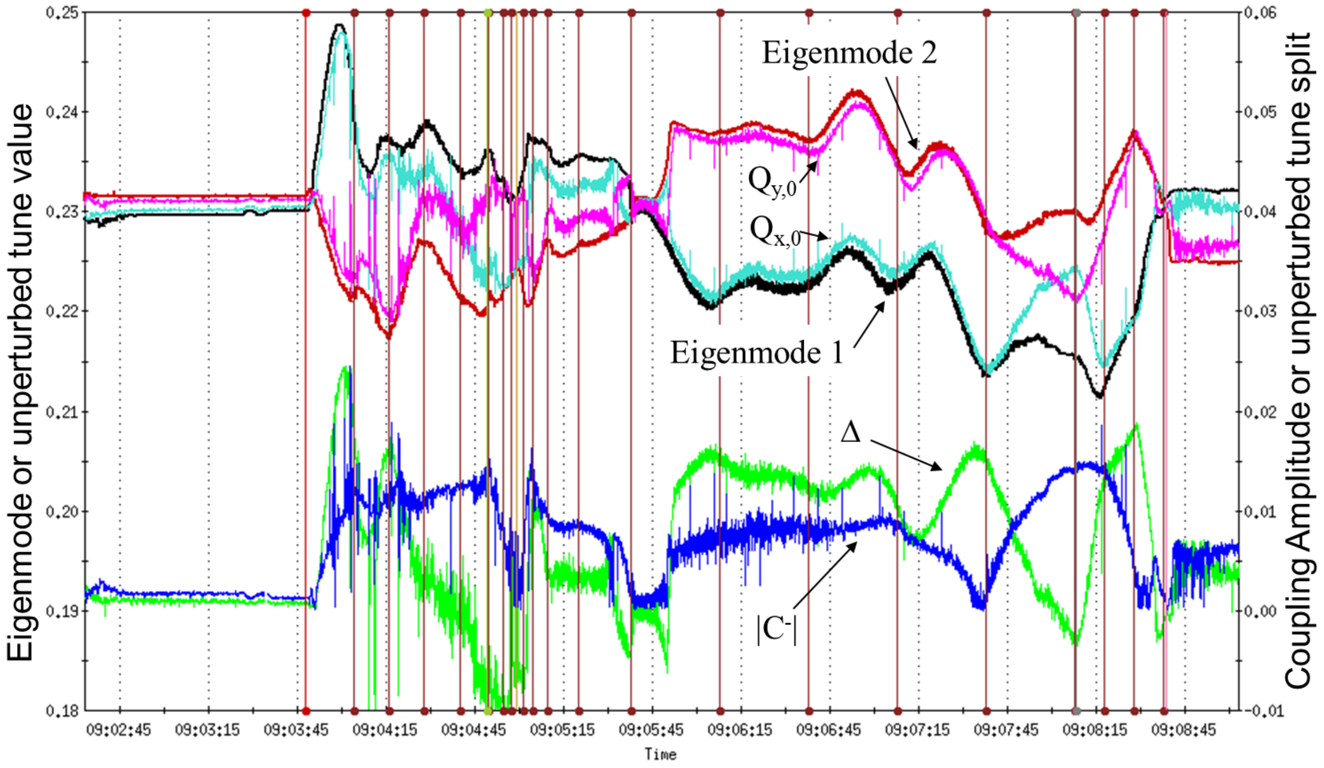




Coupling and tune feedback at RHIC (BNL)

Measurement during the acceleration cycle using 4 PLLs:

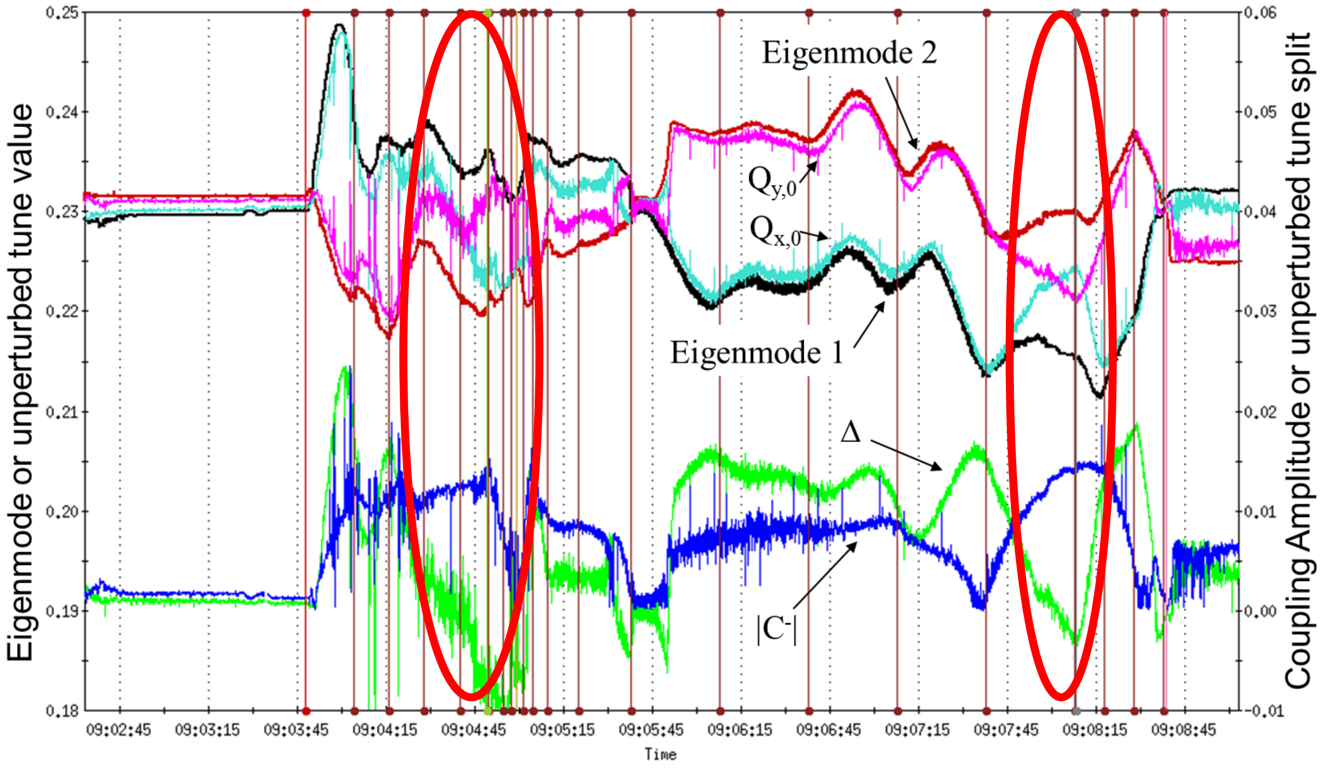
Q_H (excite in H, measure in H),
$Q_{H,V}$ (excite in H, measure in V),
Q_V (excite in V, measure in V),
$Q_{V,H}$ (excite in V, measure in H)



Coupling and tune feedback at RHIC (BNL)

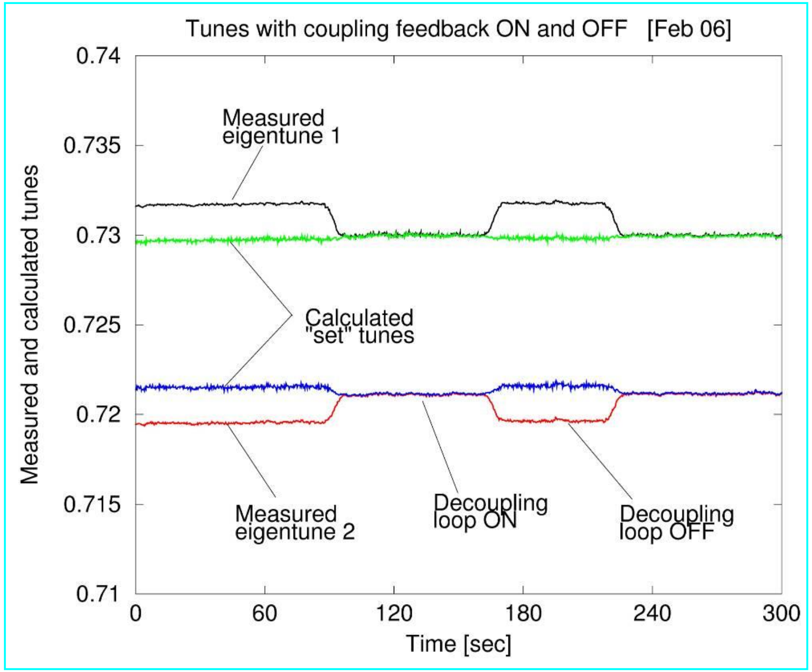
At several points the measured tune is defined by coupling – tune feedback breaks at these points

Coupling must be corrected first

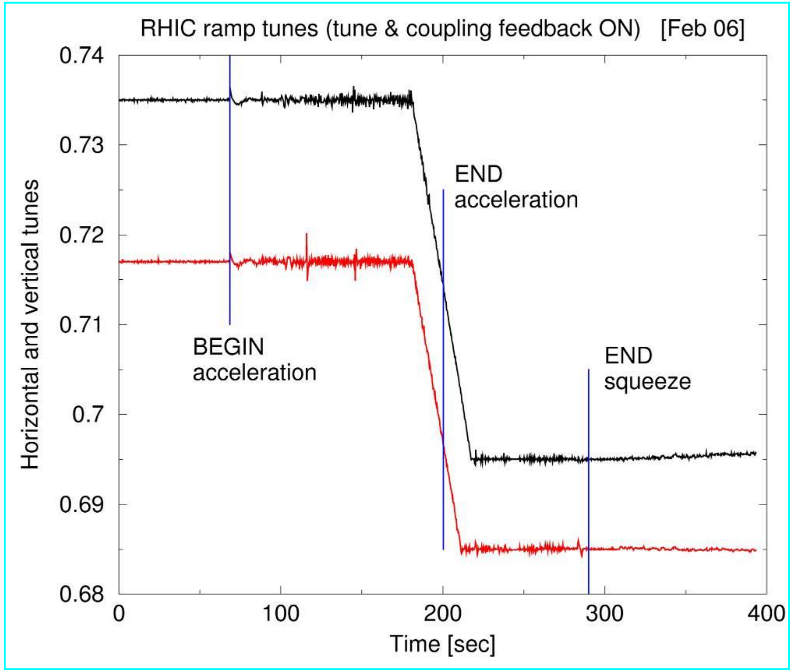


Coupling and tune feedback at RHIC (BNL)

Measure coupling and correct with skew quadrupoles to maintain a decoupled machine



Coupling and tune feedback tracks and corrects tune through the acceleration cycle



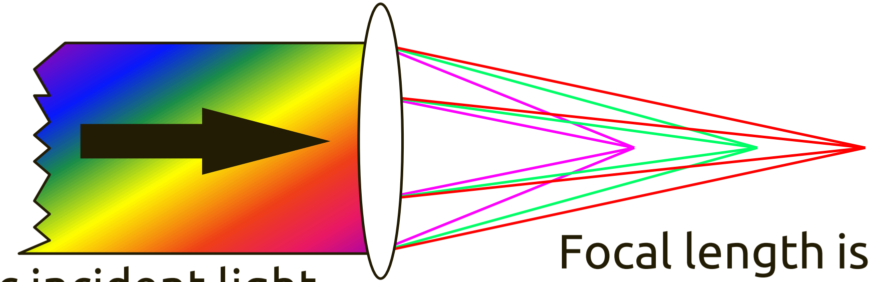
Chromaticity measurements

Chromaticity

- Spread in the machine tune due to particle energy spread
  - Controlled by sextupole magnets

Optics Analogy:

Lens
[Quadrupole]



Achromatic incident light
[Spread in particle energy]

Focal length is energy dependent

First Order

$$\Delta Q = Q' \frac{\Delta p}{p} = \left(\frac{1}{\gamma^2} - \alpha \right)^{-1} Q' \frac{\Delta f}{f}$$

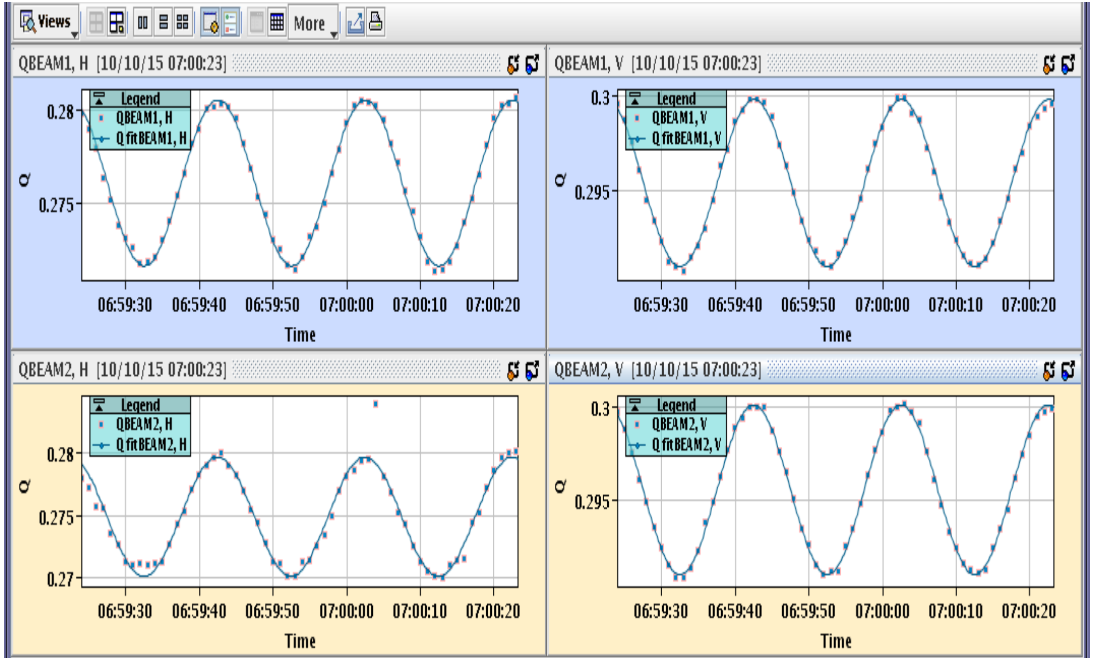
$$\xi = \frac{Q'}{Q}$$

Chromaticity measurement methods

- **Tune change for different beam momenta**
  - Standard method used on all machines
  - Can be combined with PLL tune tracking to give on-line measurement
- **Width of tune peak or damping time**
  - Model dependent, non-linear effects, not compatible with active transverse damping
- **Amplitude ratio of synchrotron sidebands**
  - Difficult in hadron machines (low synchrotron tune); influence of collective effects
- **Width ratio of Schottky sidebands**
  - Used often and ideally suited to unbunched or ion beams; very slow
- **Bunch spectrum variations during betatron oscillations**
  - Difficult to disentangle all other sources – e.g. bunch filling patterns, pick-up response
- **Head-tail phase advance (same as above, but in time domain)**
  - Good results but requires kick stimulus (emittance growth!)

Tune change for different beam momenta

- Slow RF modulation with continuous tune measurement
  - Amplitude of the tune modulation is proportional to chromaticity



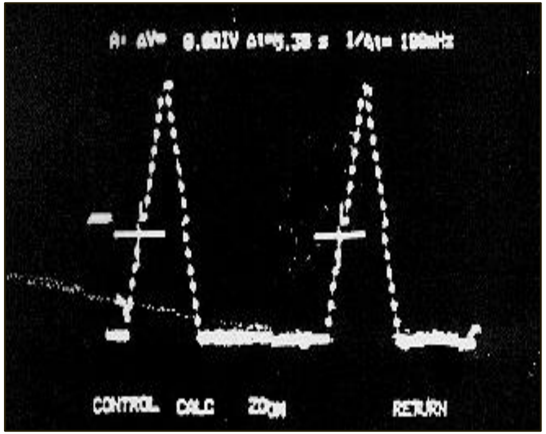
$$\Delta Q = Q'\frac{\Delta p}{p} = \left(\frac{1}{\gamma^2} - \alpha\right)^{-1} Q'\frac{\Delta f}{f}$$

Example from the LHC

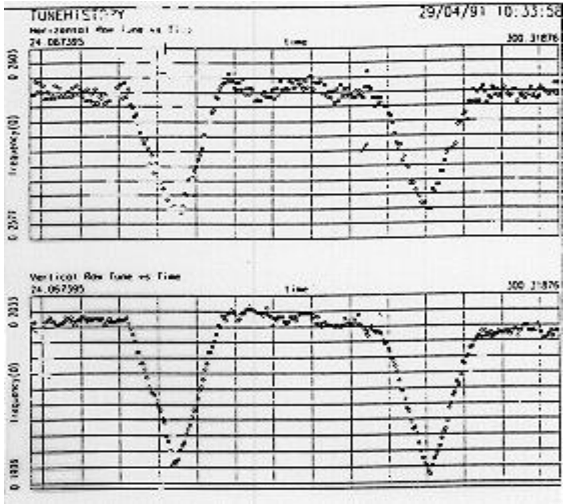
- Sinusoidal RF modulation at 0.05 Hz
- Tune continuously tracked in both planes of both beam
- Chromaticity calculated once acquisition complete

Tune change for different beam momenta

- Slow RF modulation with continuous tune measurement
  - Amplitude of the tune modulation is proportional to chromaticity



Applied Frequency Shift

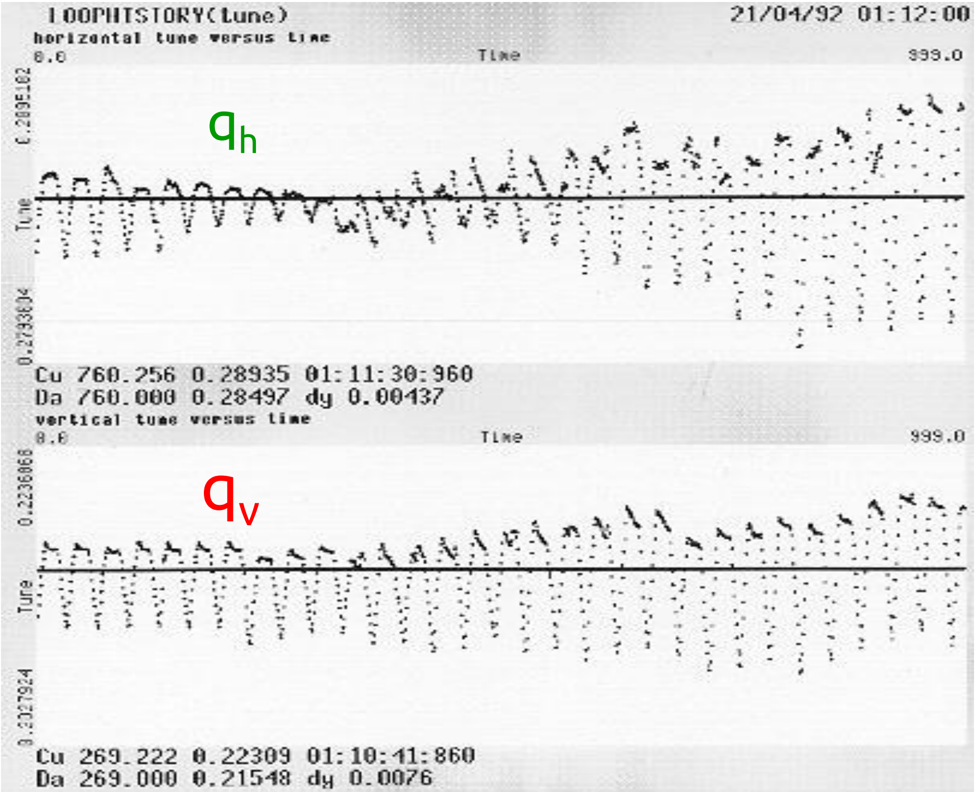


Q_h & Q_v Variation

Example from LEP (CERN)

- Triangular RF modulation
- Allows sign of chromaticity to be easily determined

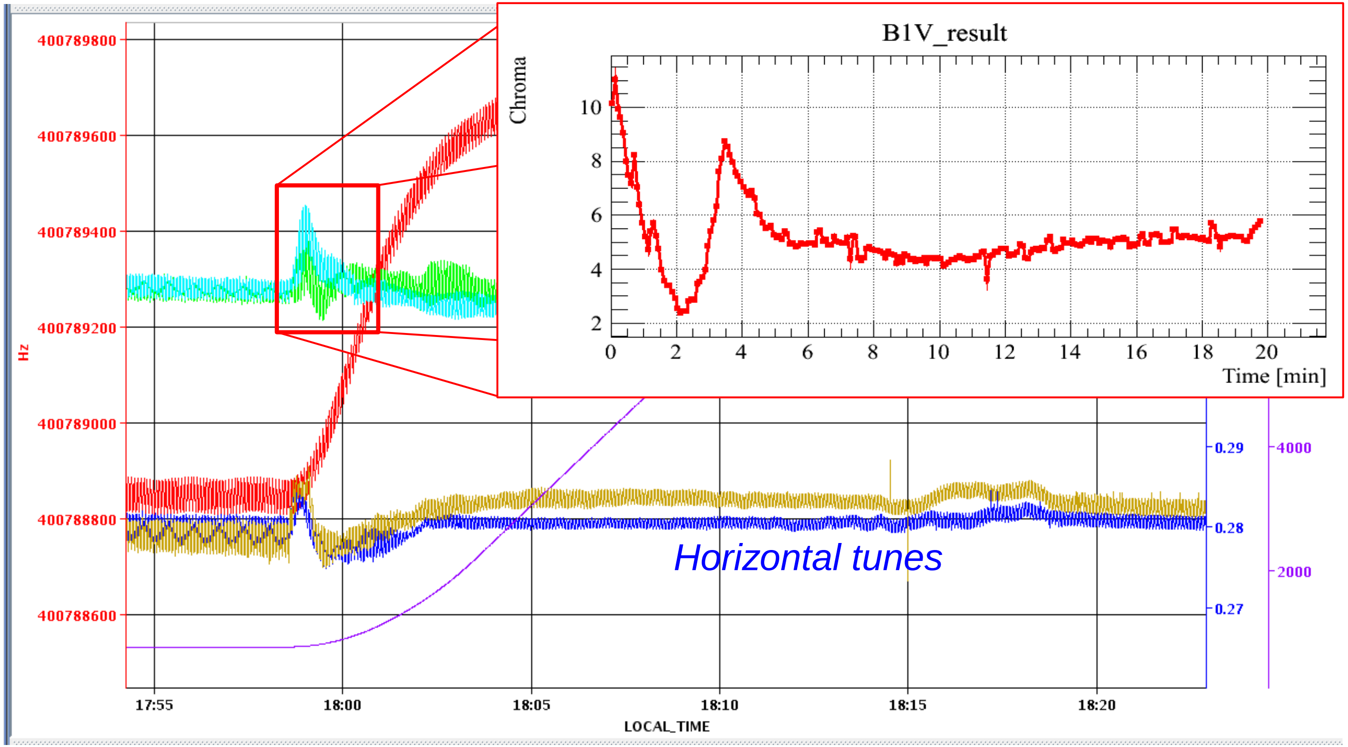
Tune change for different beam momenta



Example from LEP (CERN)

- Tune measurement during beta-squeeze

Tune change for different beam momenta



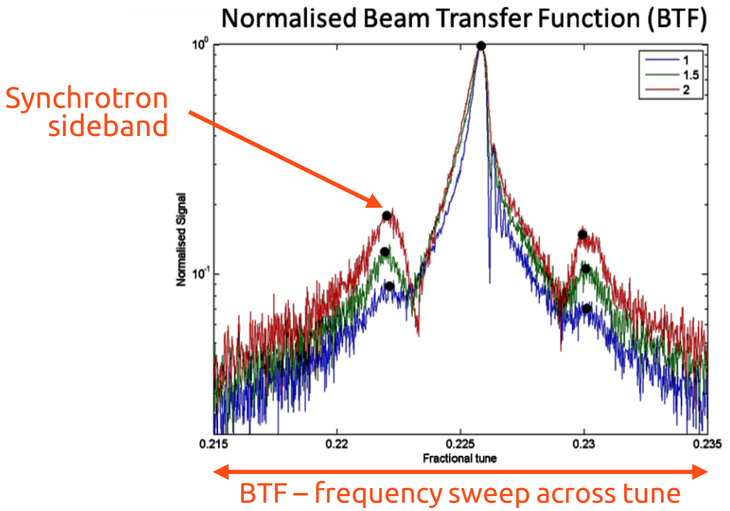
Example from LHC

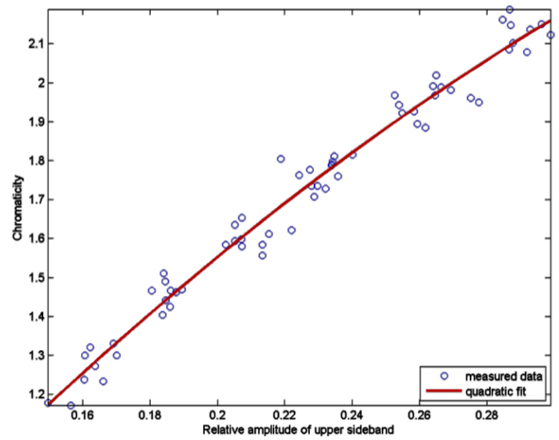
- Tune measurement during energy ramp
- RF continuously modulated
- Tune measured continuously
- Chromaticity calculated from tune modulation amplitude

$$\Delta Q = Q' \frac{\Delta p}{p} = \left(\frac{1}{\gamma^2} - \alpha \right)^{-1} Q' \frac{\Delta f}{f}$$

Amplitude ratio of synchrotron sidebands

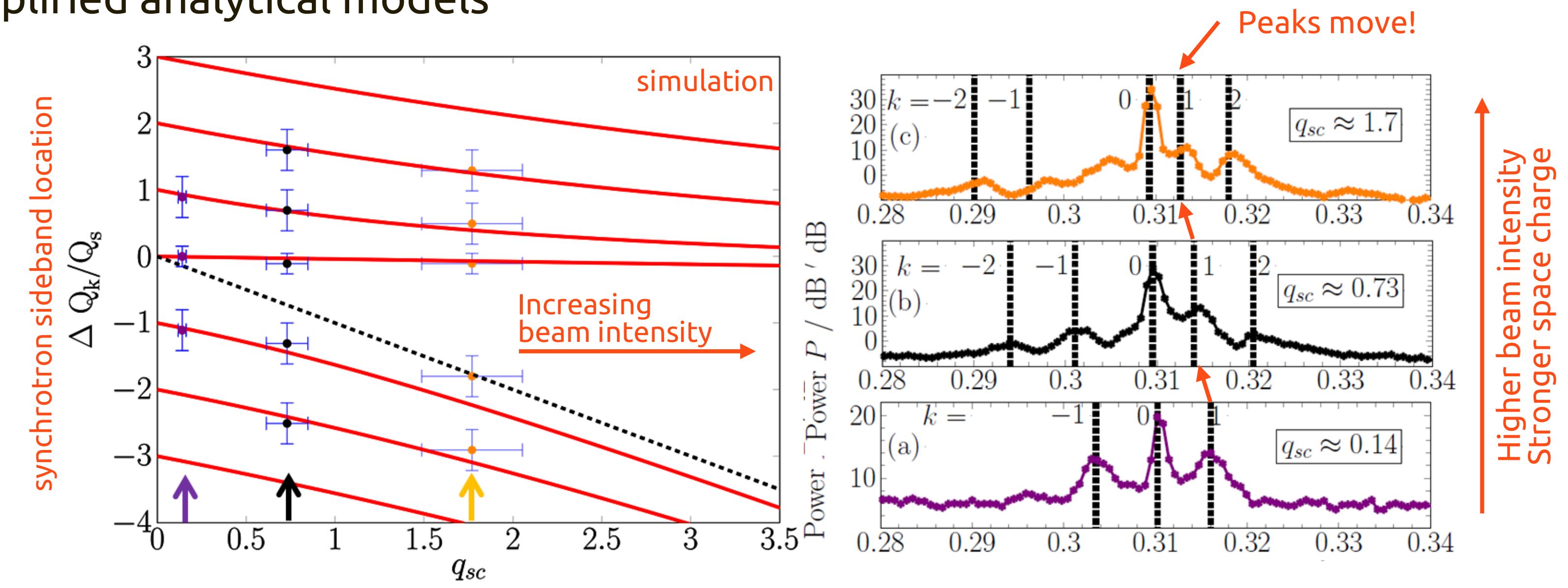
- Particle energy modulated by synchrotron motion – tune changes modulated at the synchrotron frequency due to chromaticity
- Successfully demonstrated at Diamond (UK)
- Beam Transfer Function (BTF) measurements on a single bunch using the transverse bunch-by-bunch feedback system
  - Emittance blow-up of the single affected bunch irrelevant





Amplitude ratio of synchrotron sidebands

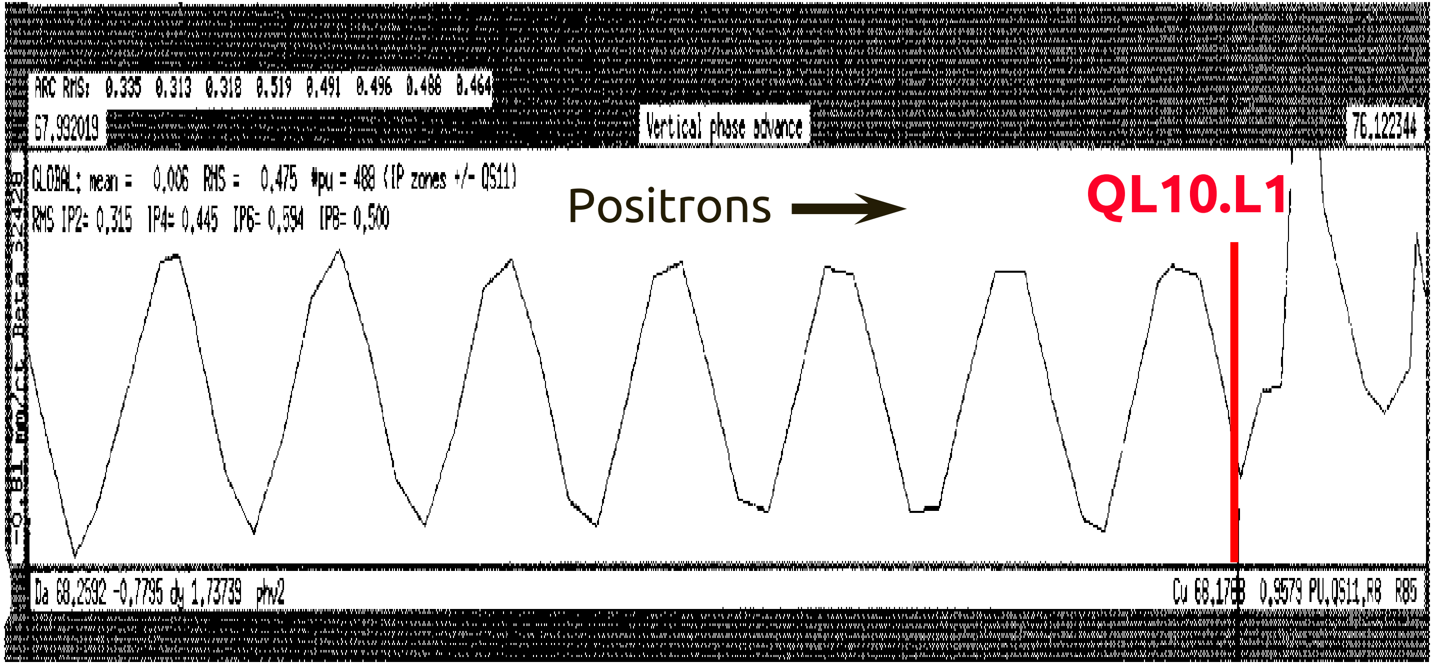
- Must be careful with high-intensity effects!
- Modification of tune spectra by space charge and impedance observed by GSI
- Relative heights and mode structure given by chromaticity – can be calculated with simplified analytical models



Diagnosing accelerator issues

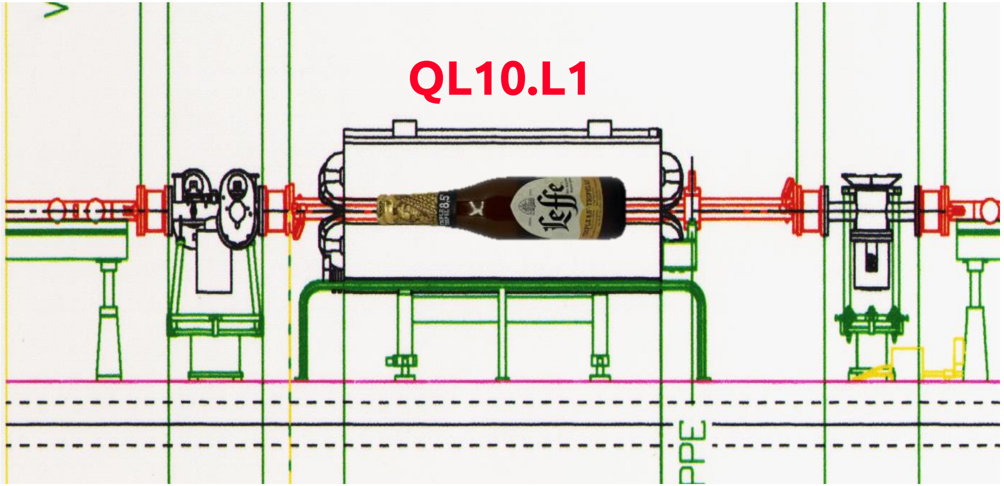
LEP (CERN) – no circulating beam

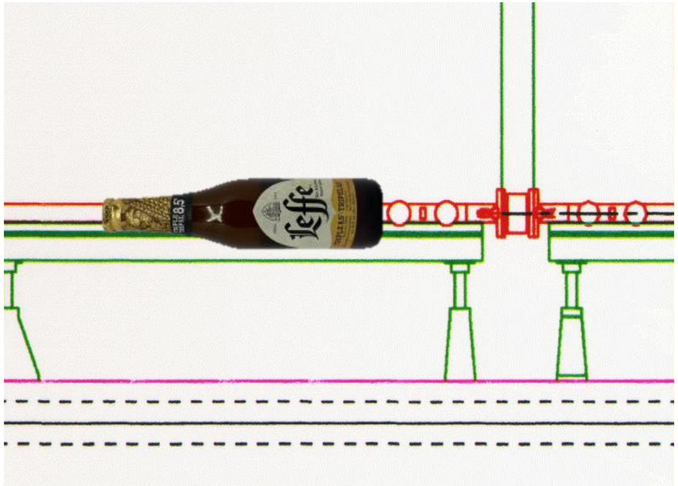
- Phase advance from BPMs show that optics is not longer correct after a specific quadrupole



LEP (CERN) – no circulating beam

- After long investigation – open the vacuum chamber of QL10.L1
- And 10 m downstream!





Double sabotage – both bottles were empty!

Summary

- We covered the most common BI systems and their diagnostics usage
  - Two more lectures on longitudinal diagnostics by L. Bobb next week
  - Much More at BI CAS in 2025!
- Take home message: BI systems can give you a good insight into the beam and its behaviour
  - Go and talk to your BI colleagues to see what is possible