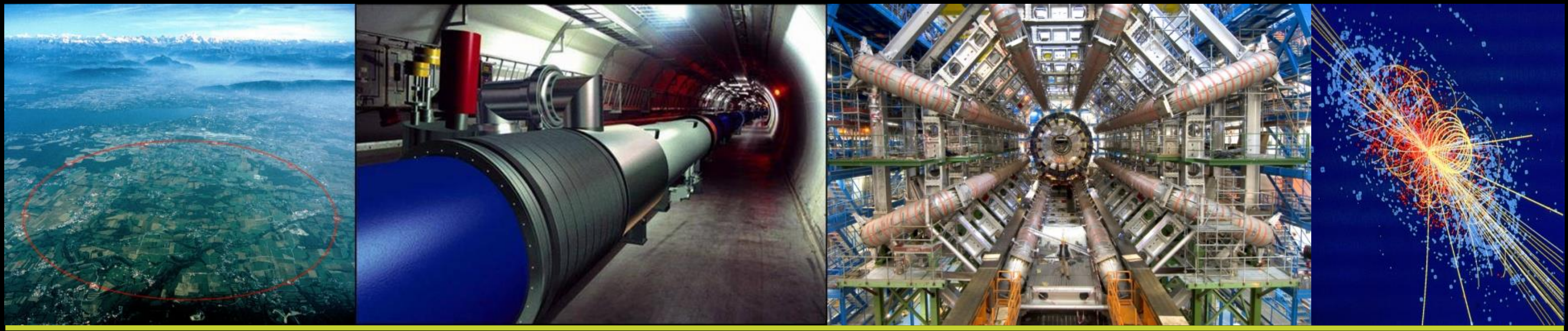


Beam Instrumentation and Diagnostics (Lecture 2)

CAS 2019

Slangerup, Denmark

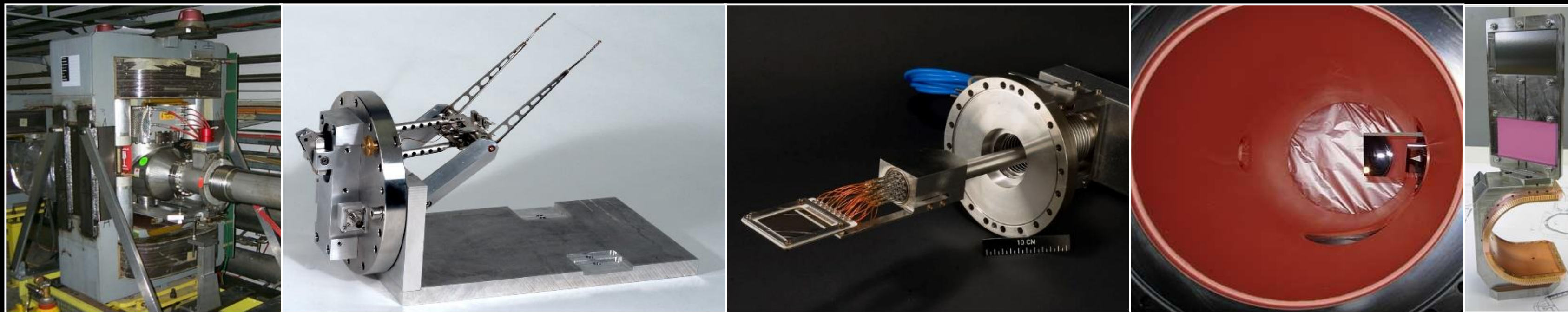
9th – 21st June, 2019

Dr. Rhodri Jones

Head of the CERN Beam Instrumentation Group

Introduction

- Yesterday was dedicated to
  - Beam position measurement
  - Beam intensity measurement
  - Beam loss monitoring
- Today we'll continue with a look at
  - Beam profile monitoring & diagnostics
  - Tune, Coupling & Chromaticity measurement & feedback
  - Making Accelerators work using beam instrumentation

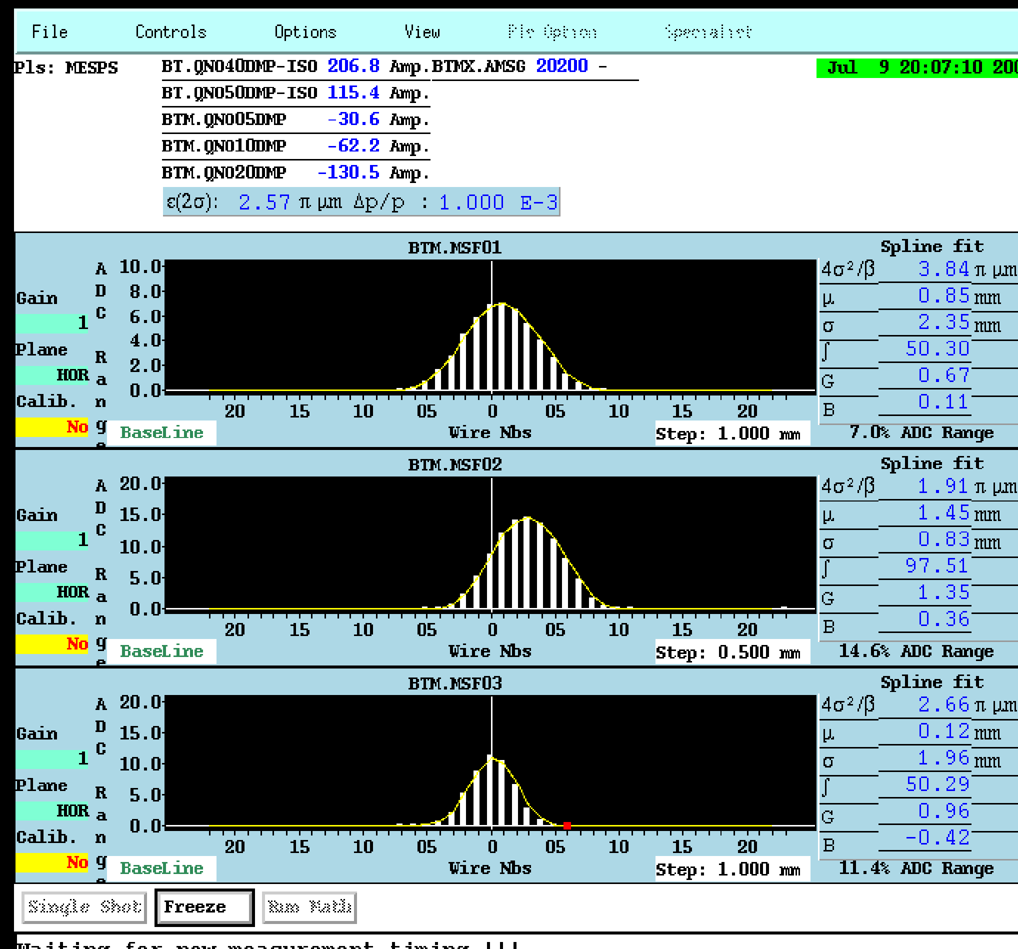


Beam Profile Monitors

(Longitudinal measurements covered next week by T. Lefevre)

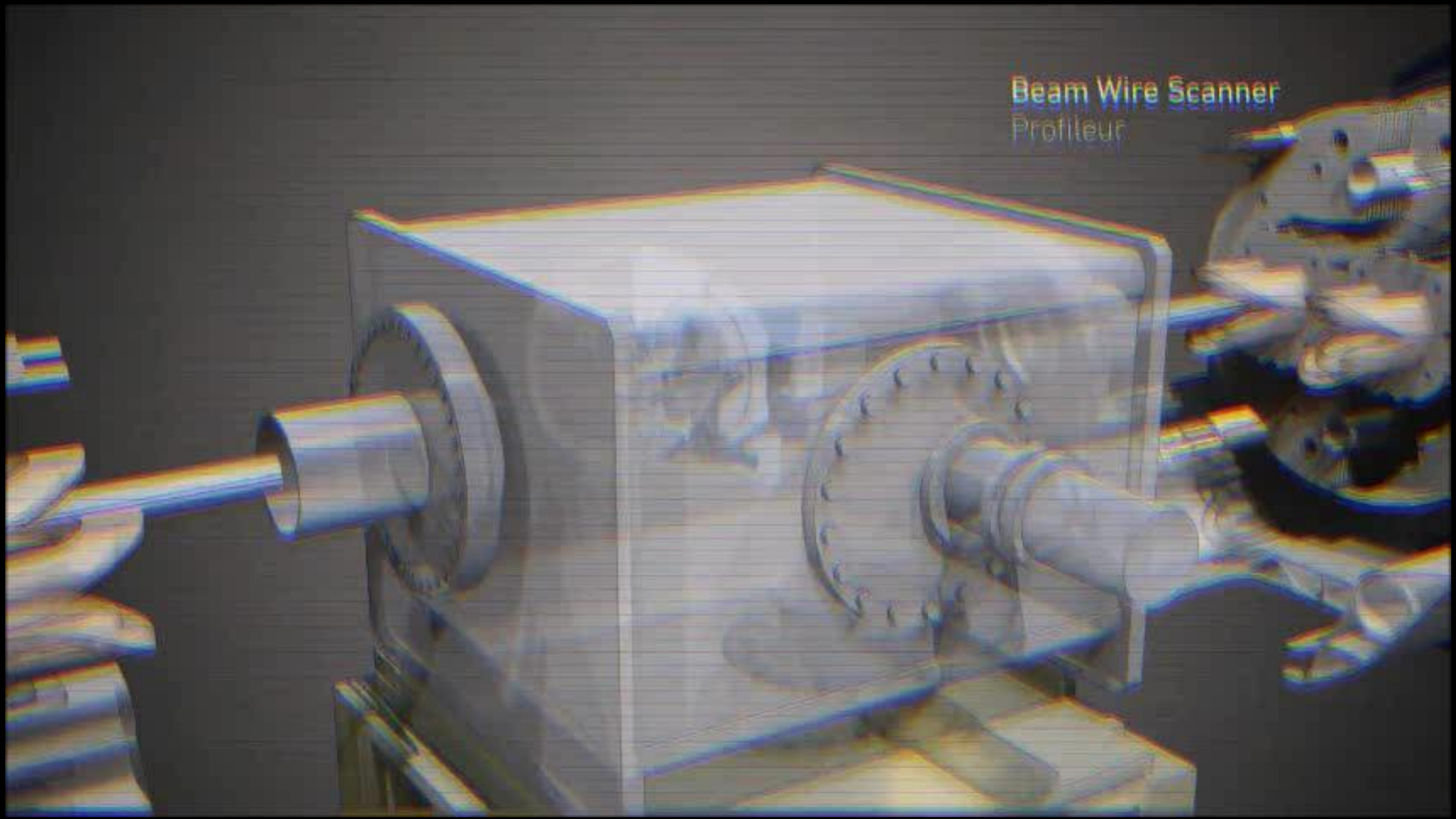
Profile Monitoring using Wires

- Secondary Emission Monitors (SEM or HARP)
  - Beam profile from secondary electrons emitted from wire grid on beam impact
  - Require many electronic channels for readout



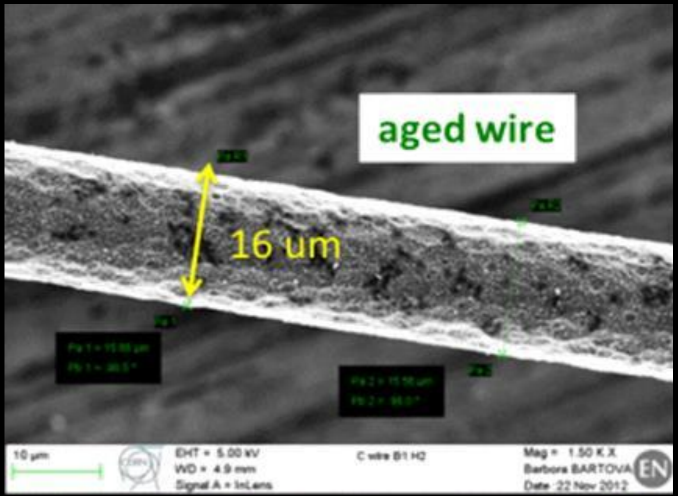
Profile Monitoring using Wires

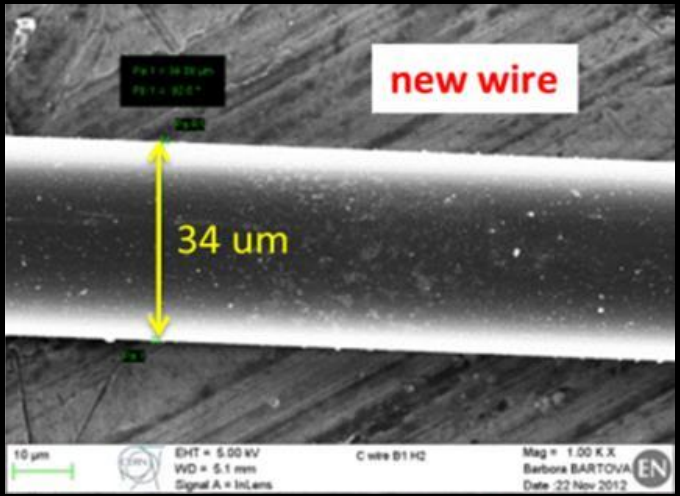
- Wire-scanners
  - Move thin wire across beam
  - Low energy : correlate wire position with secondary emission
  - High energy : correlate wire position with secondary shower



Limitation of Wire-Scanners

- Wire Breakage – why?
  - Brittle or Plastic failure (error in motor control)
  - Melting/Sublimation (main intensity limit)
    - Due to energy deposition in wire by particle beam
- Temperature evolution depends on
  - Heat capacity, which increases with temperature!
  - Cooling (radiative, conductive, thermionic, sublimation)
    - Negligible during measurements (Typical scan 1 ms & cooling time constant ~10-15 ms)
- Wire Choice
  - Good mechanical properties, high heat capacity, high melting/sublimation point
  - E.g. Carbon which sublimates at 3915K

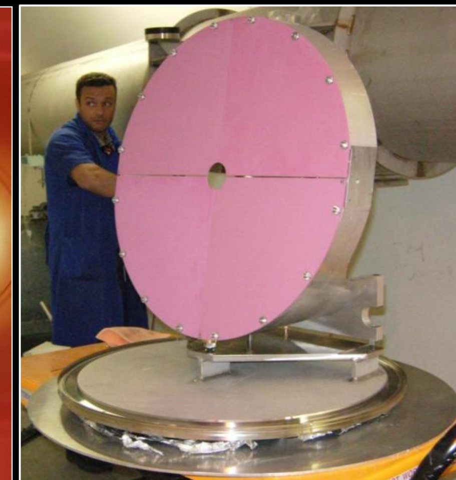


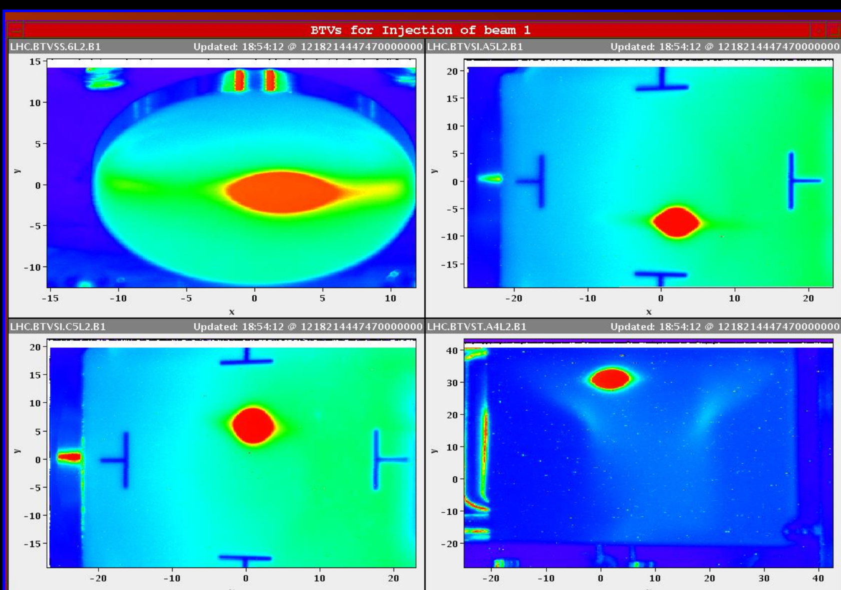


Profile Monitoring using Screens

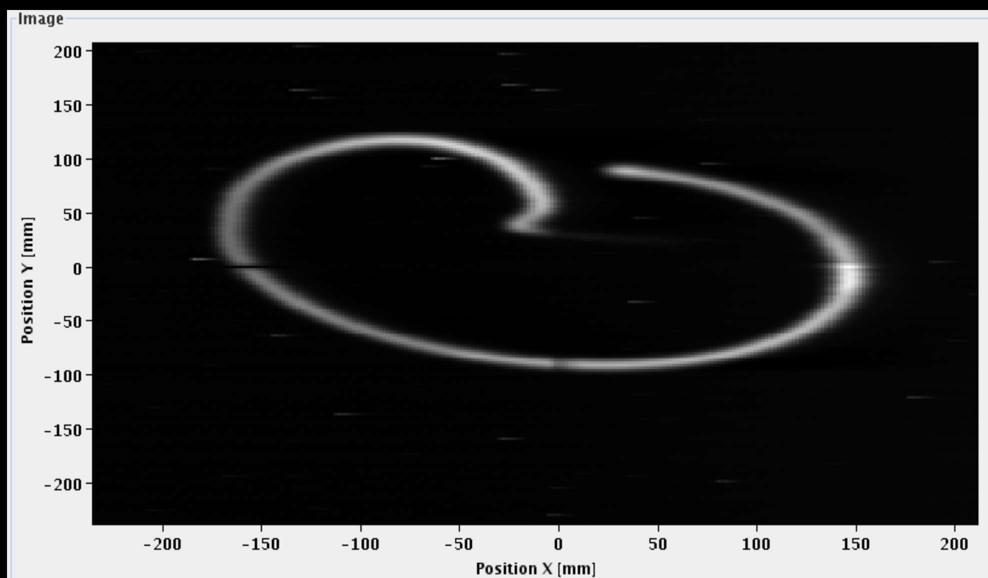
- Early Diagnostics
  - Luminescence / Scintillating Screens
    - Destructive (thick) but work with low intensities
- Advantages
  - Allows use of CCD camera
    - gives 2D information





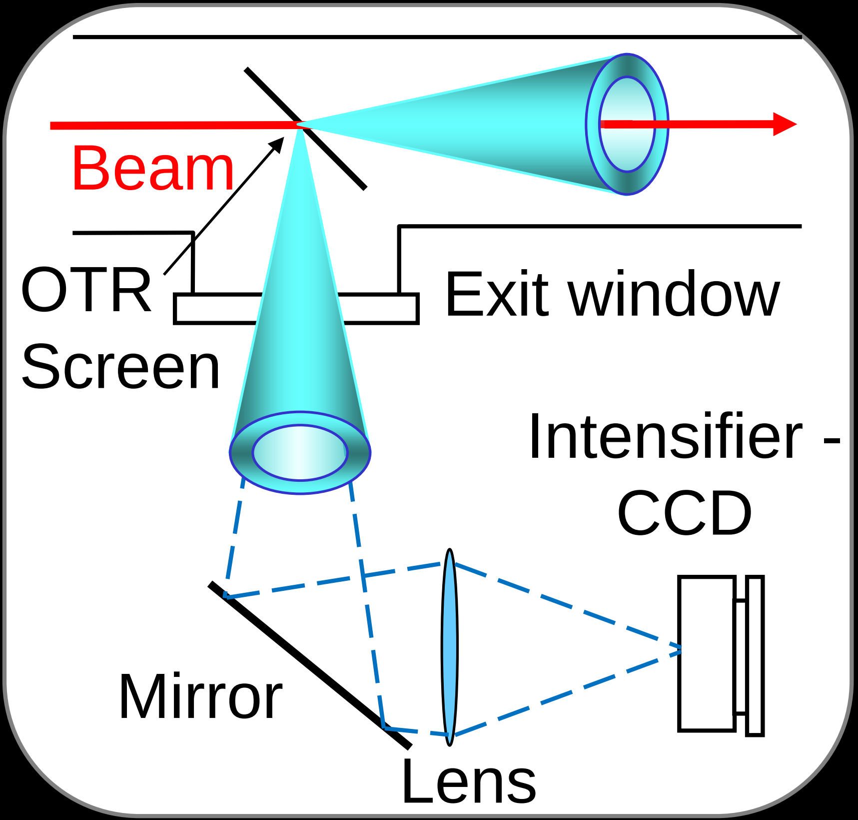


First Beam in the LHC 8/8/2008

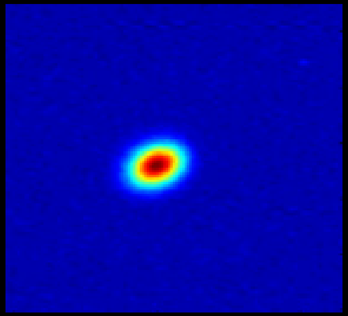


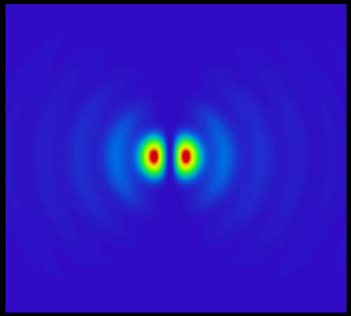
Profile Monitoring using Screens

- Optical Transition Radiation
  - Radiation emitted when a charged particle goes through an interface with different dielectric constants
  - Surface phenomenon allows use of very thin screens (~10µm)
    - Can use multiple screens with single pass in transfer lines
    - Can leave it in for hundreds of turns e.g. for injection matching

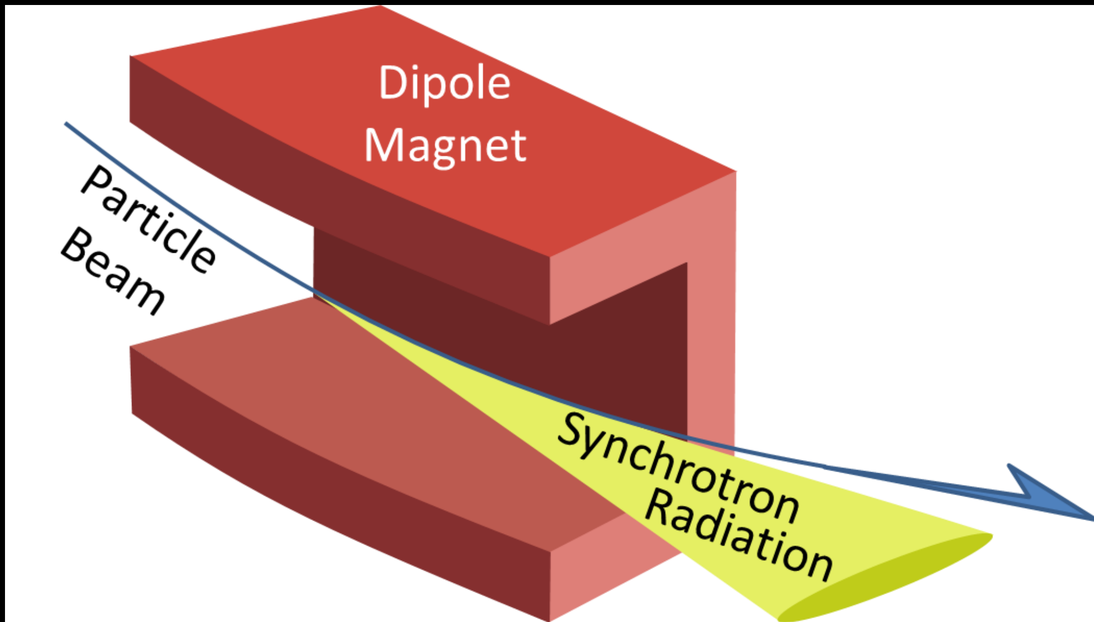


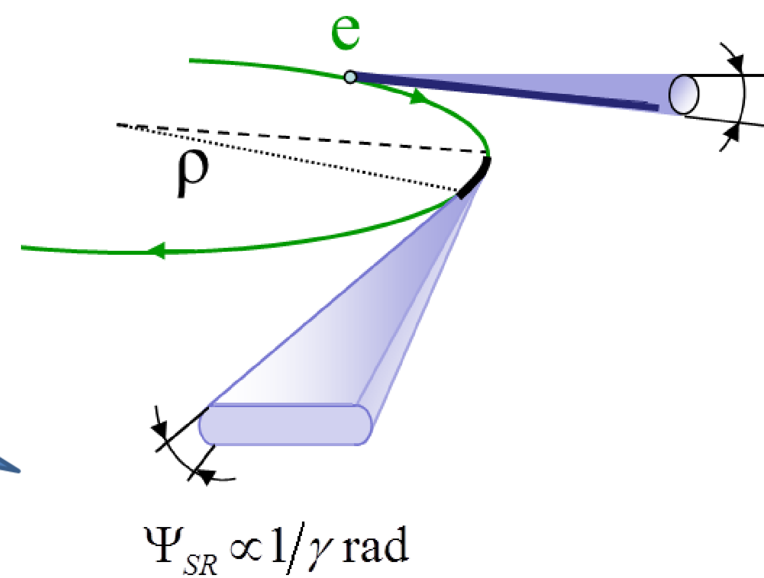
- OTR screens
  - Less destructive than scintillation but requires higher energy / intensity beam
  - Can be used for extremely high resolution measurements



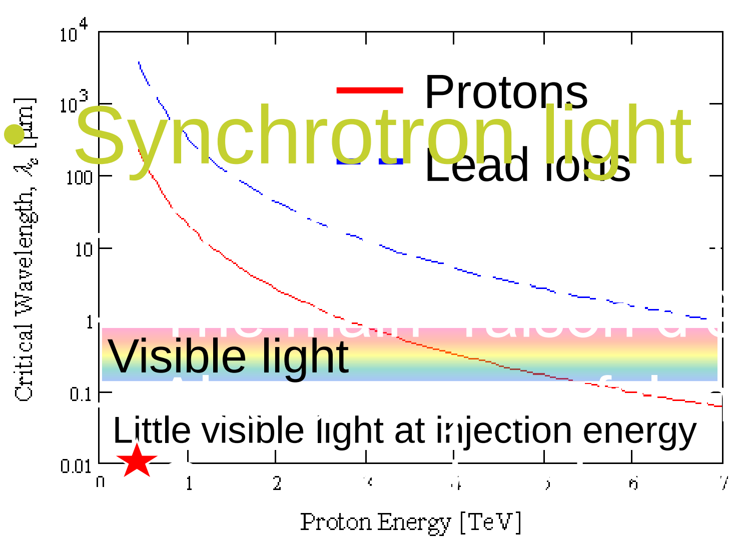


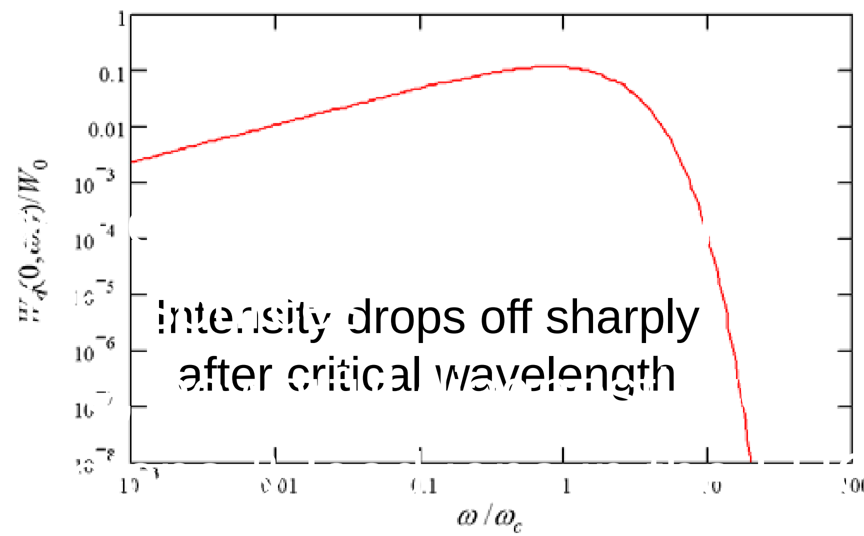
Synchrotron Light Monitors





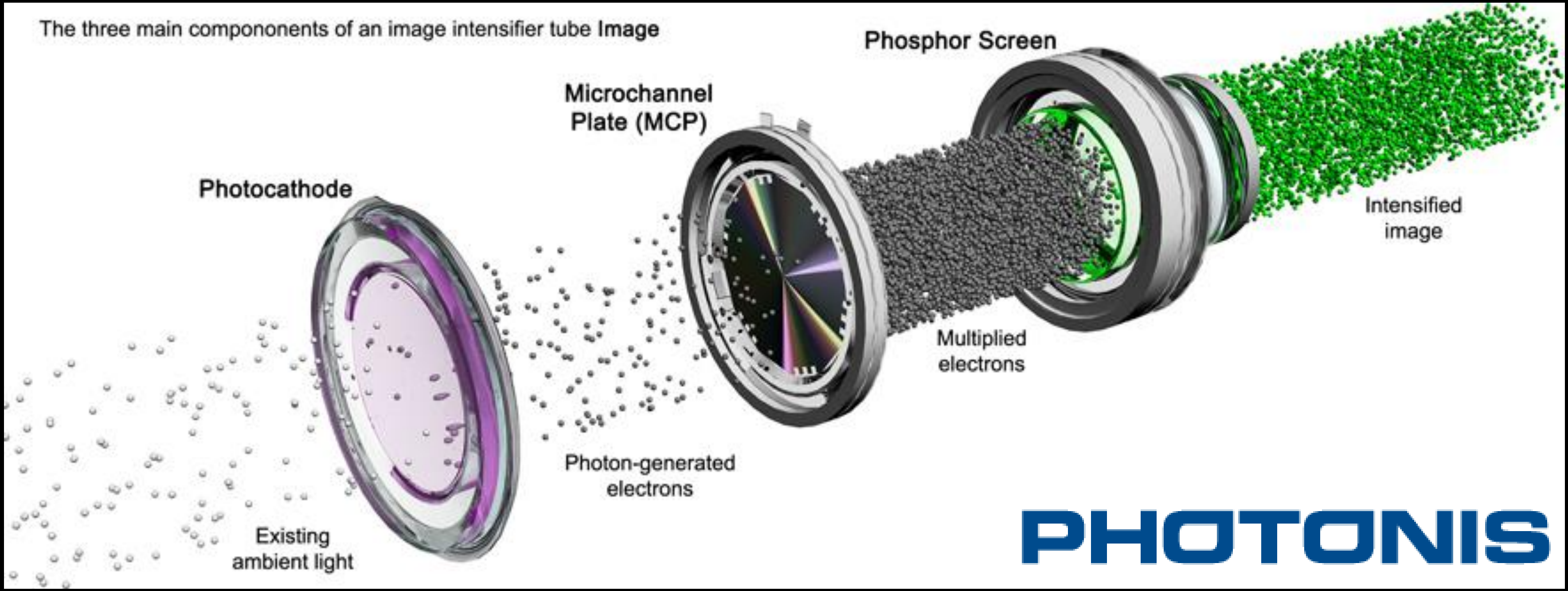
- Synchrotron light

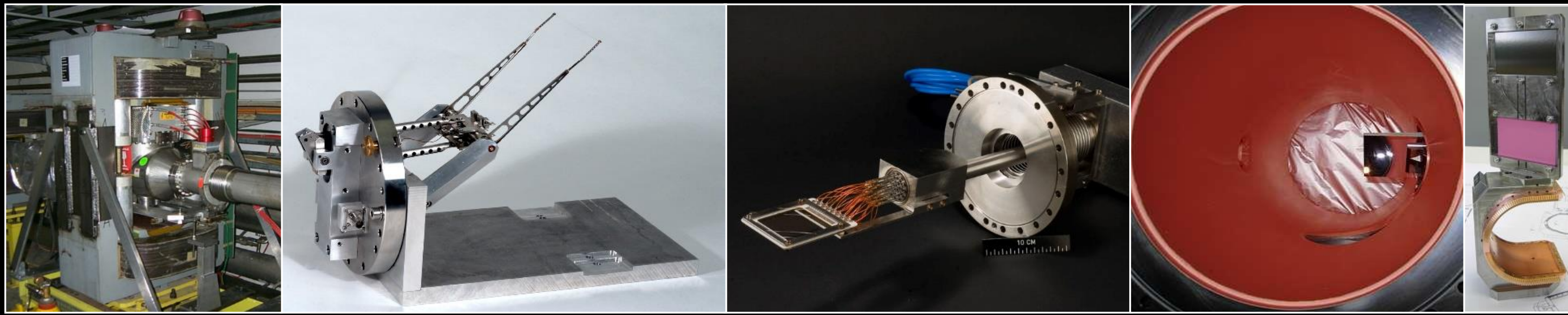




Synchrotron Light Image Acquisition

- Using various cameras
  - Standard CCD cameras for average beam size measurements
  - Gated intensified camera
    - For bunch by bunch diagnostics
  - X-ray pin hole cameras
    - For imaging small, high energy electron beams
  - Streak cameras
    - For short bunch diagnostics



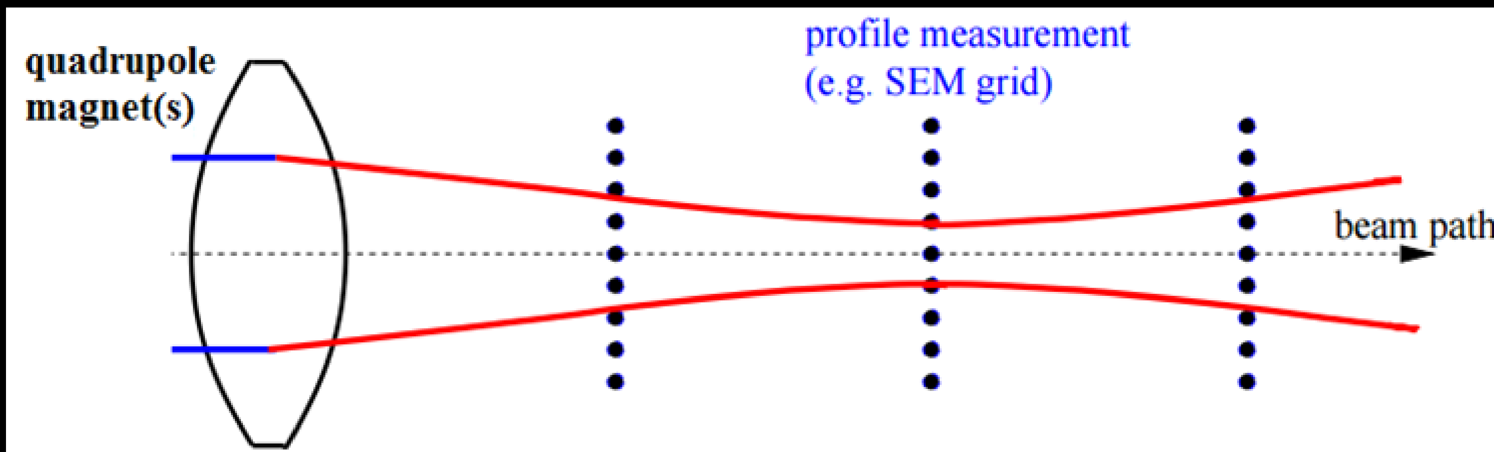


Diagnostics using Beam Profile Monitors

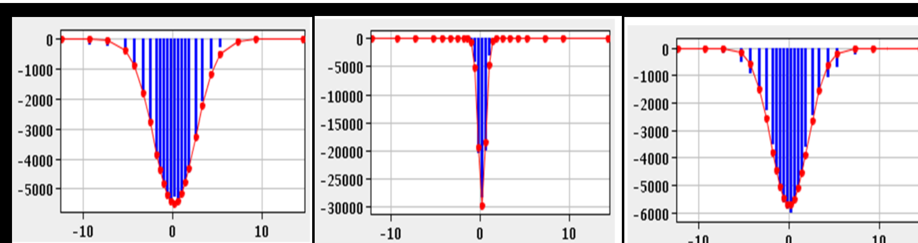
Optics Measurement in LINACs

3 Monitor Method

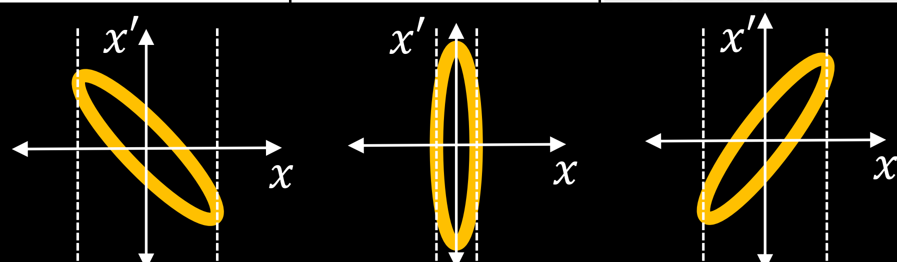
– Optics functions & initial emittance reconstructed using transport matrix



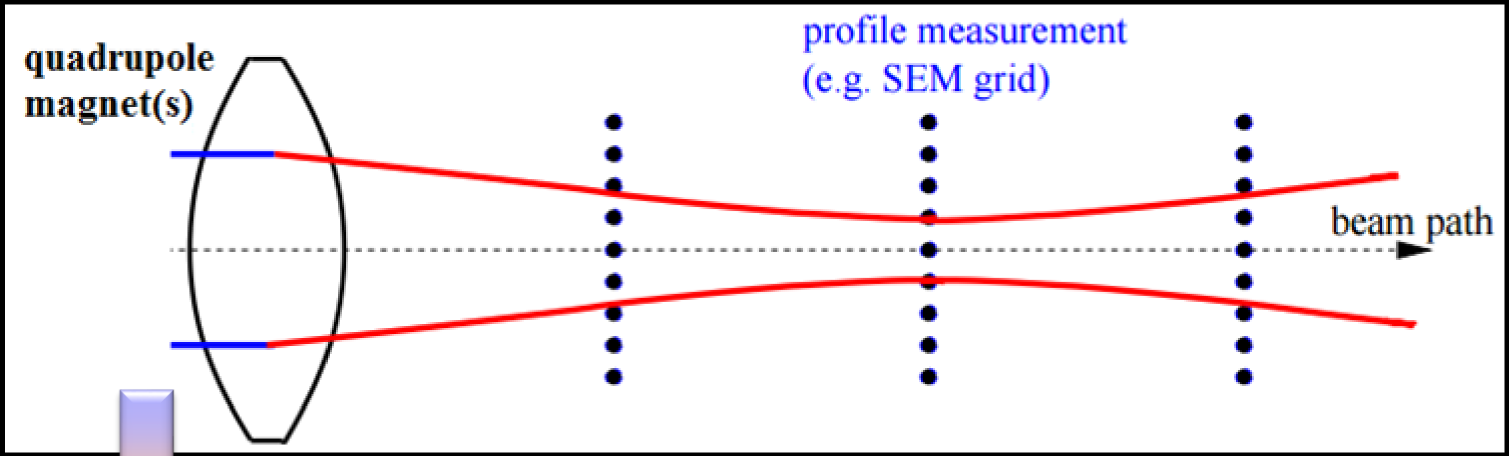
Measured Beam Profiles



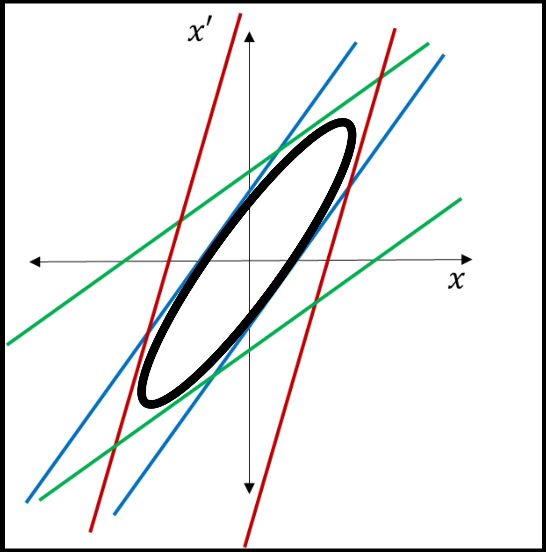
rms ellipses

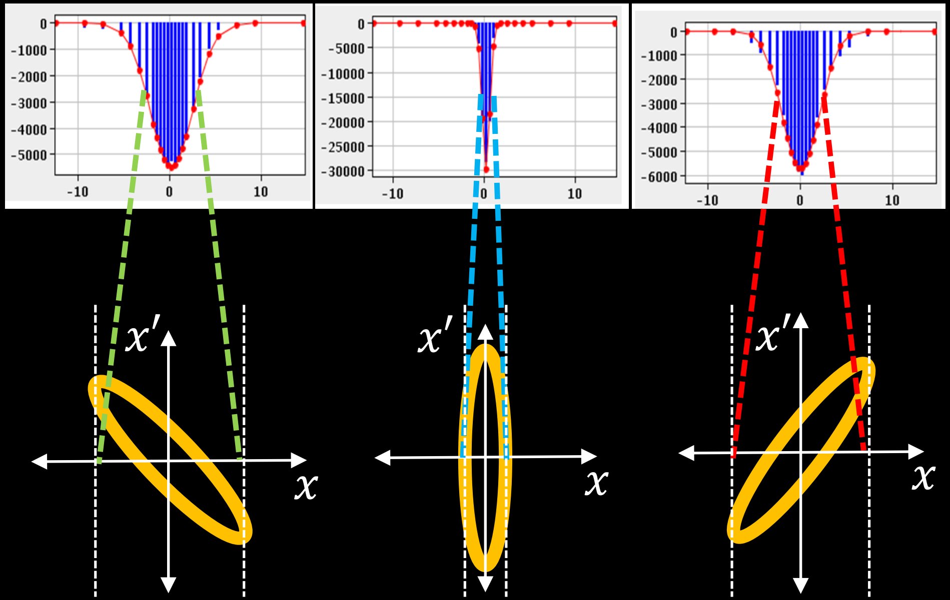


Optics Measurement in LINACs



Linear Mapping of measured beam size onto initial phase space



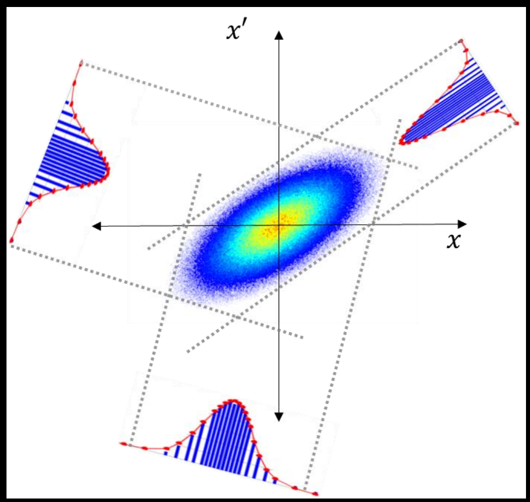


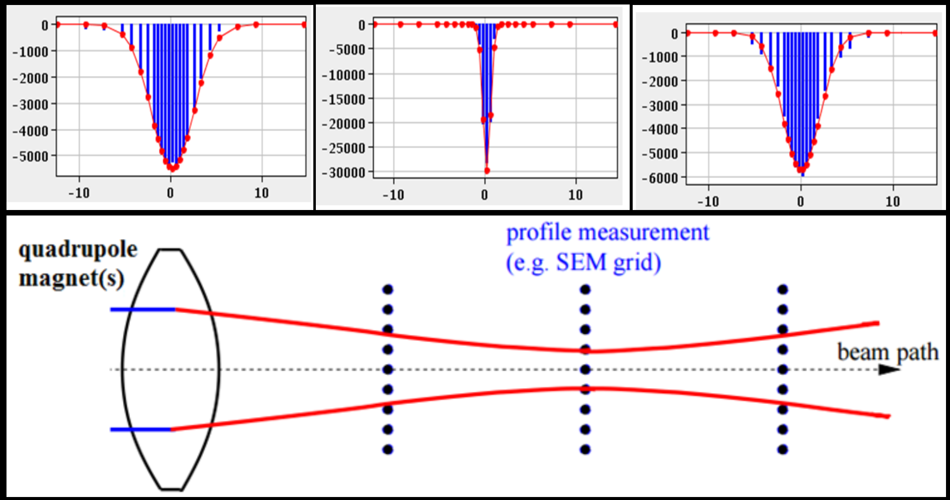
Measured Beam Profiles

rms ellipses

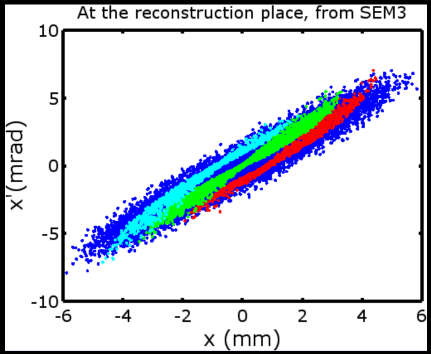
Optics Measurement in LINACs

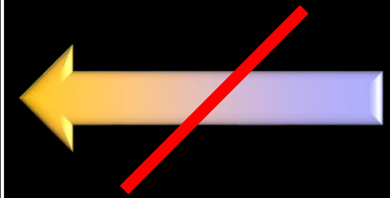
- More advanced reconstruction
  - Linearly map measured profiles onto initial phase space
  - Use tomography to reconstruct particle density distribution

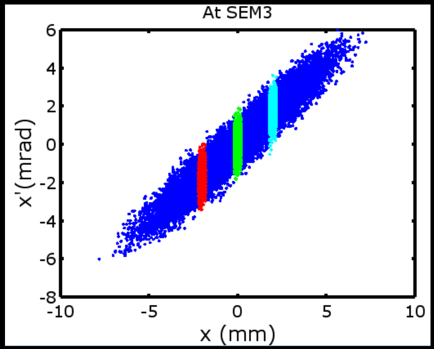




- Things get more complicated when you add space charge

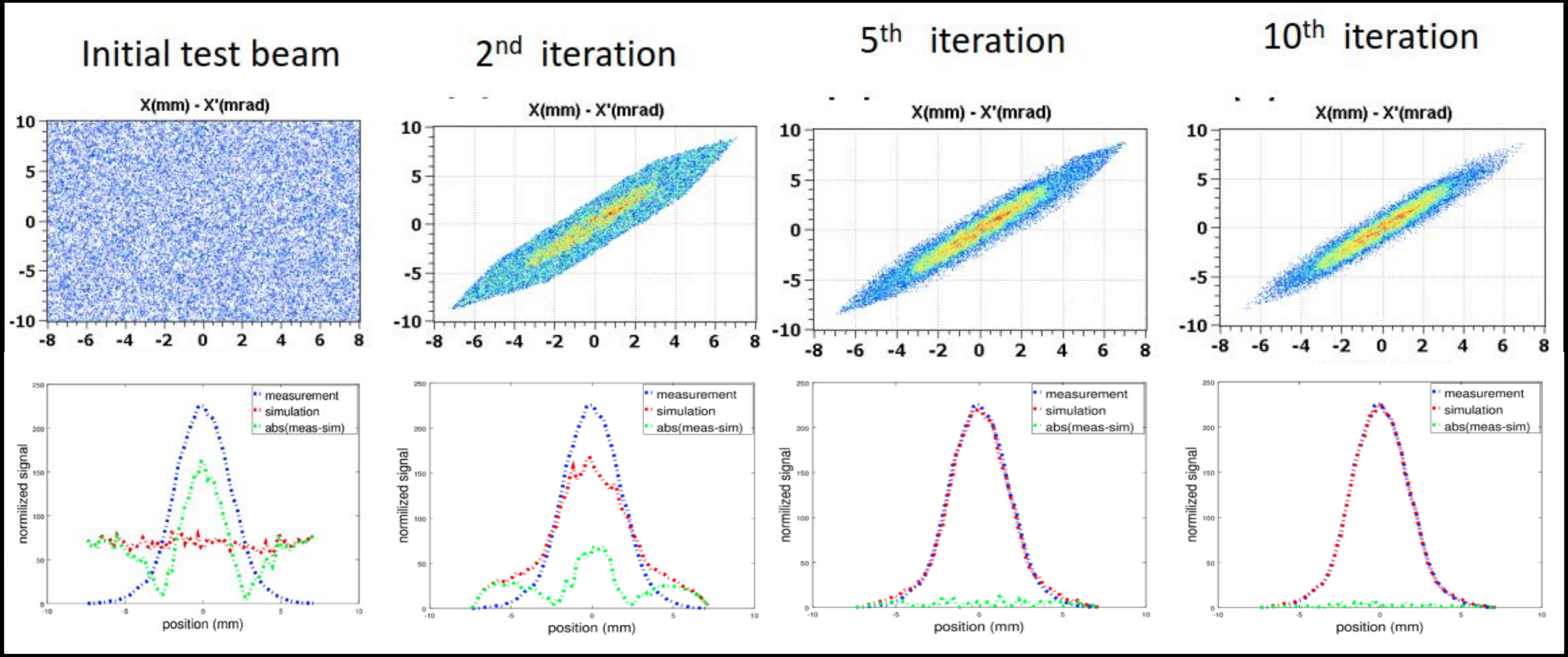






Optics Measurement in LINACs

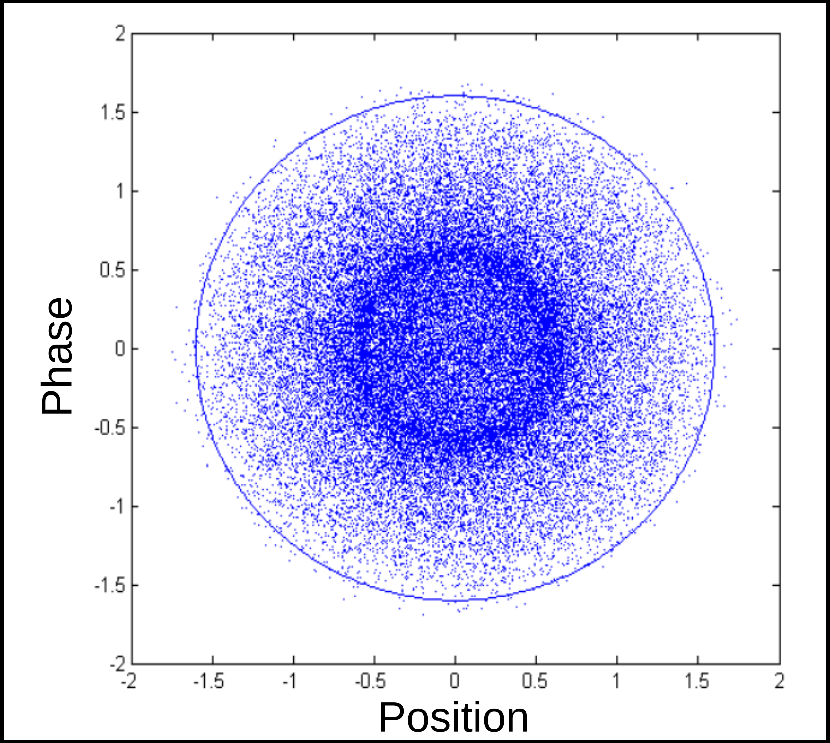
- Hybrid Phase Space Tomography in Linac4
  - Iteratively vary Twiss parameters
  - Track to the measurement locations including space-charge
  - Deduce new distribution of density in phase space from which particles fall on which wires
  - Generate new beam distribution & use for next iteration

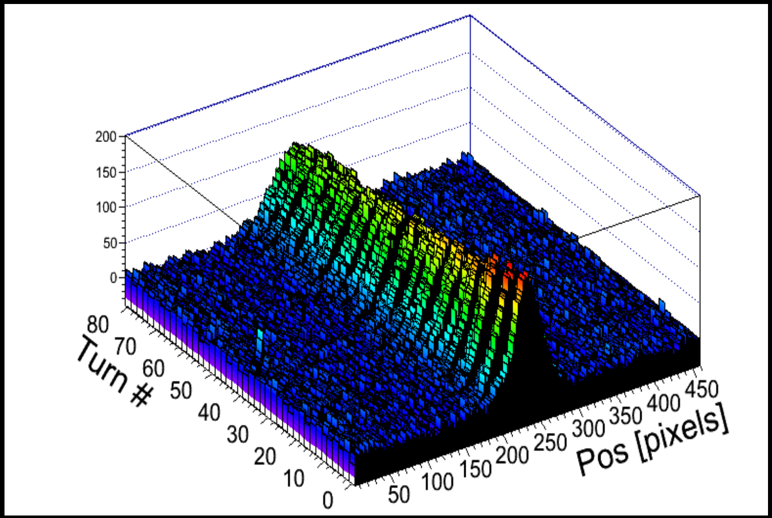


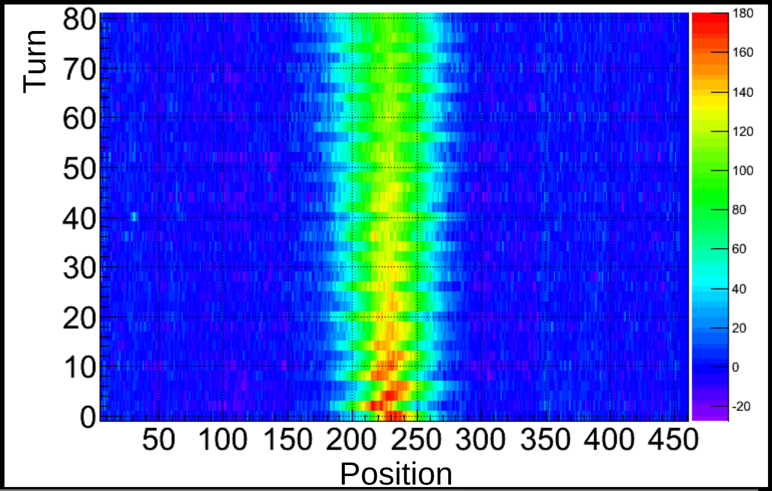
Reconstructed & Measured profiles at last SEM grid

Measurements with Screens

- Injection matching measurements with OTR
  - Machine settings mismatch
  - Leads to filamentation
  - Results in emittance growth







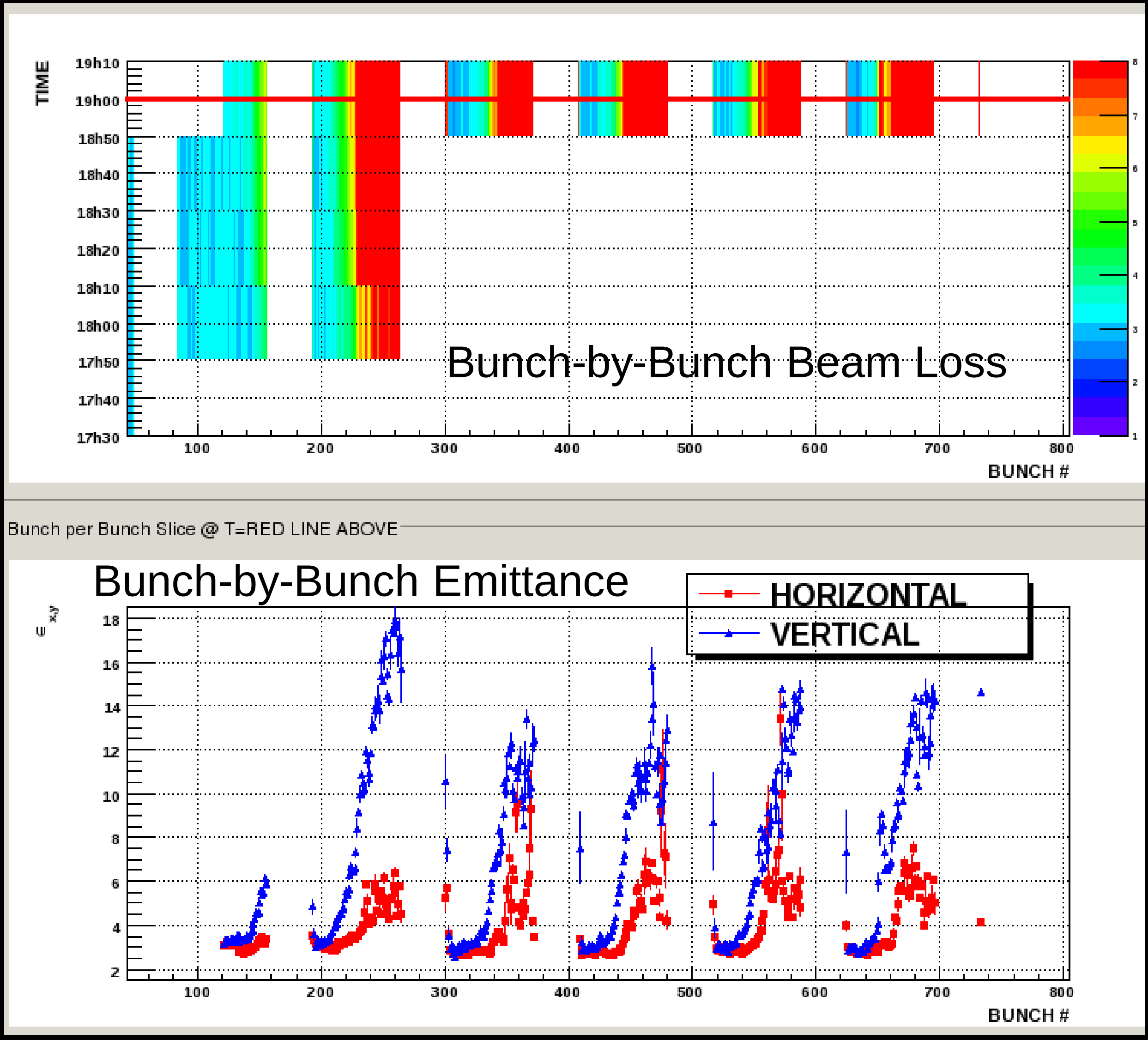
Bunch by Bunch Diagnostics

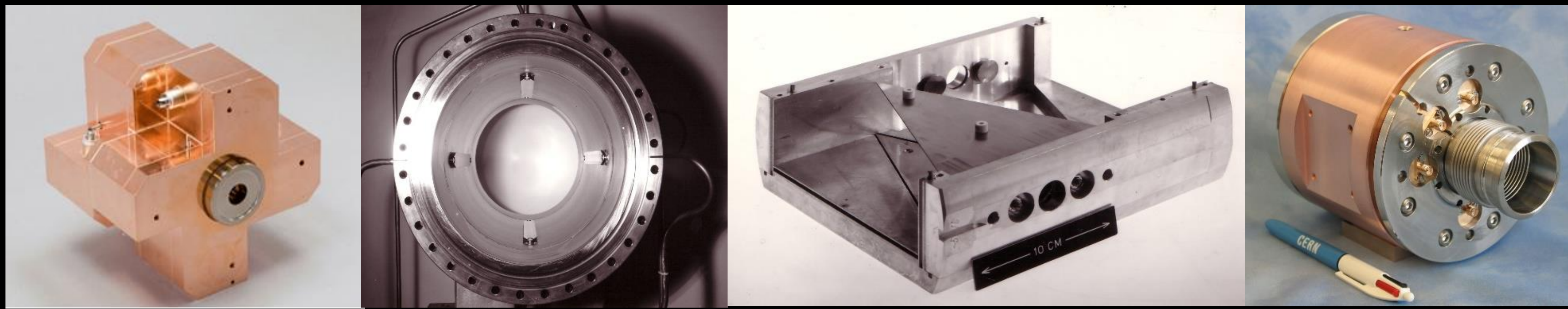
LHC Synchrotron Light Diagnostics

- Gated intensified Camera
- Allows bunch by bunch profile measurement

Electron Cloud

- Electron cloud creates instability in tail of bunch trains
- Increases the size of the bunches towards the end of each bunch train
- Leads to losses for these bunches
- Adjustments made to counter this effect
  - Chromaticity
  - Transverse feedback
  - Beam scrubbing

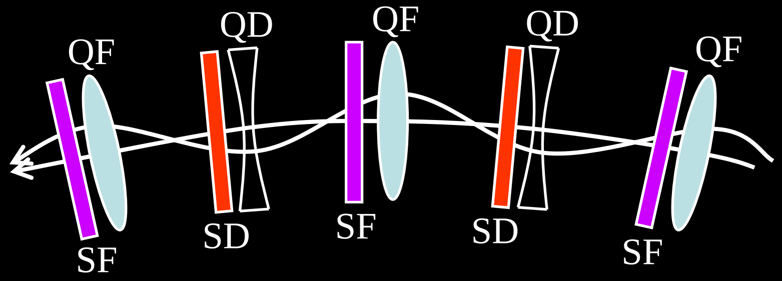




Tune Measurement

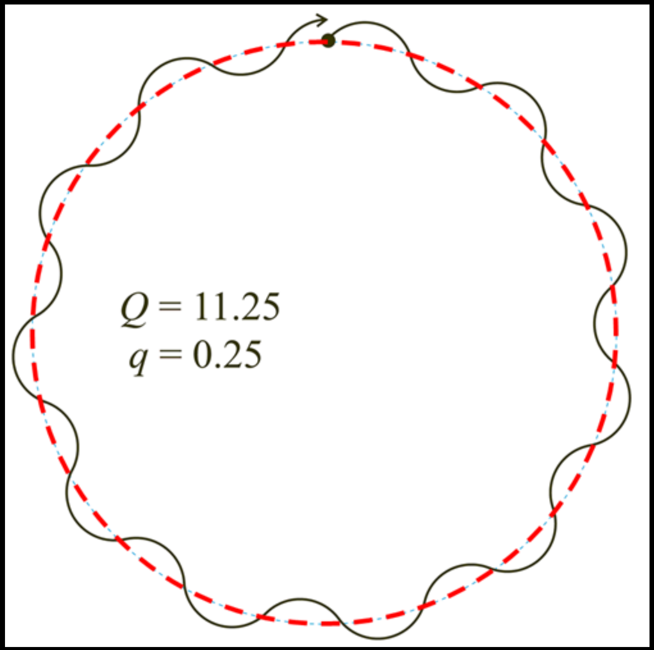
Machine Tune

- Machine Tune



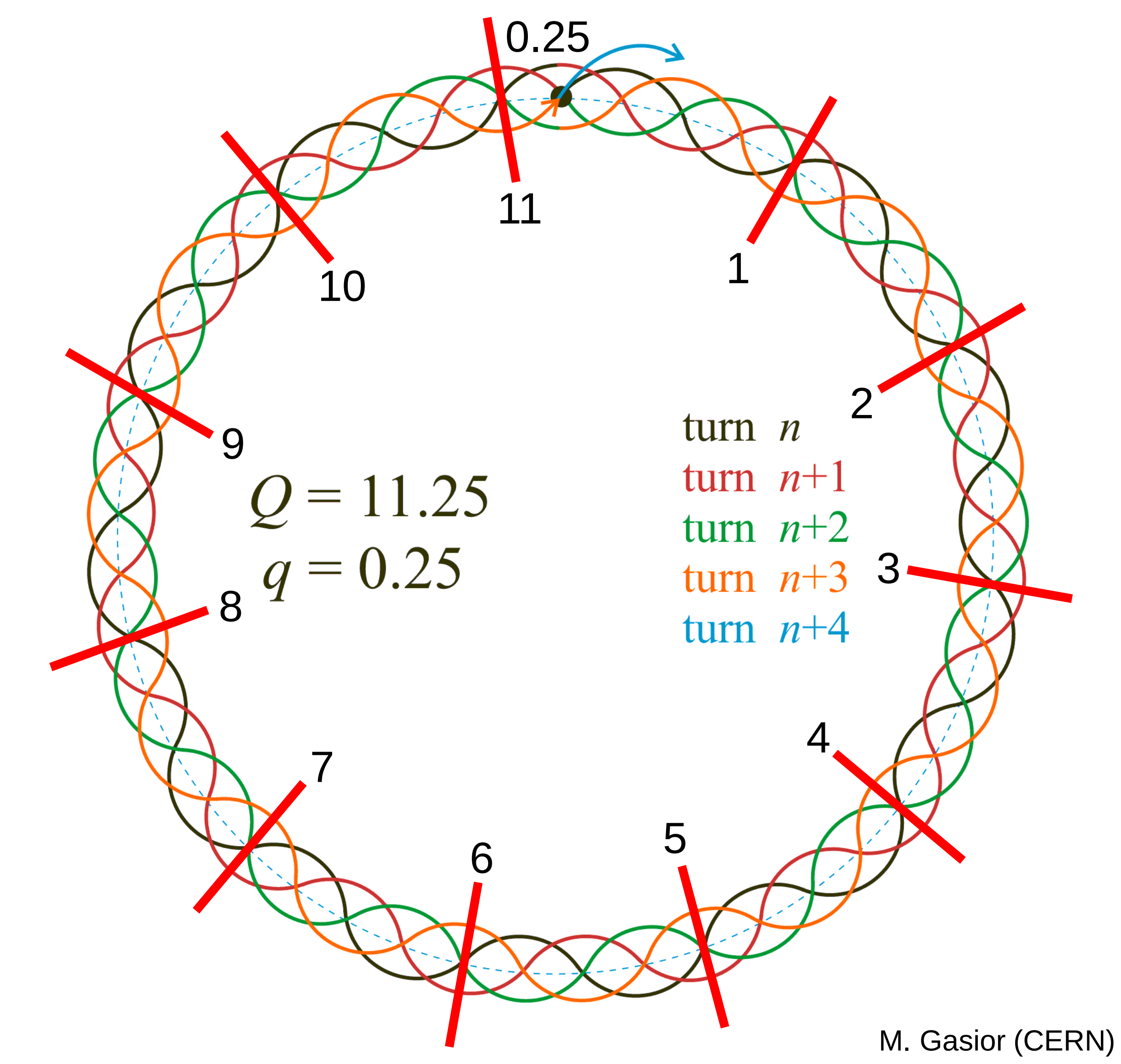
Characteristic Frequency of the Magnetic Lattice

Given by the strength of the Quadrupole magnets

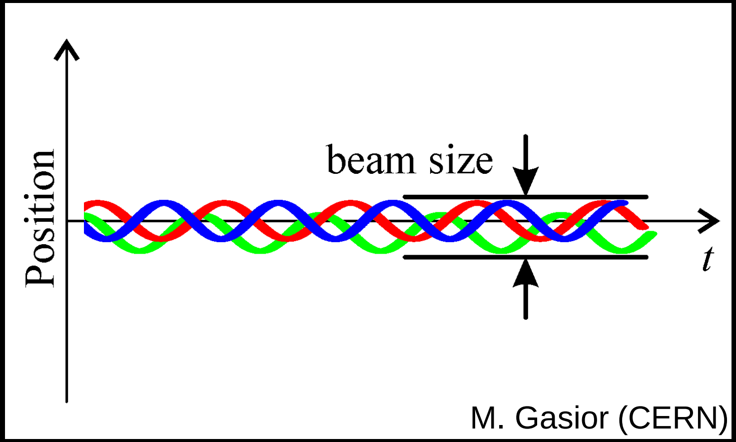


- Parameters per plane
  - Q : Full betatron tune
  - q : Fractional tune (operating point)
- Real life more complex
  - horizontal & vertical oscillations couple
  - betatron motion at large amplitudes non-linear

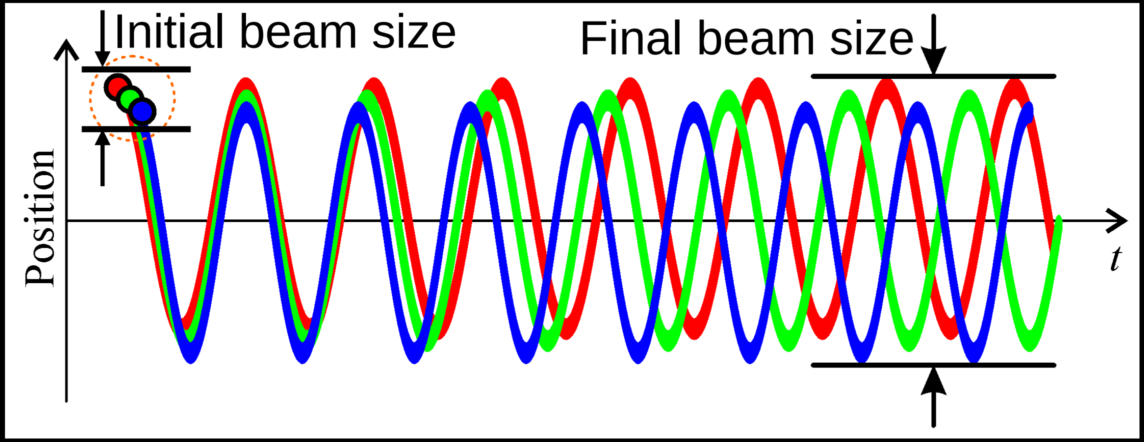
Betatron motion and the Tune

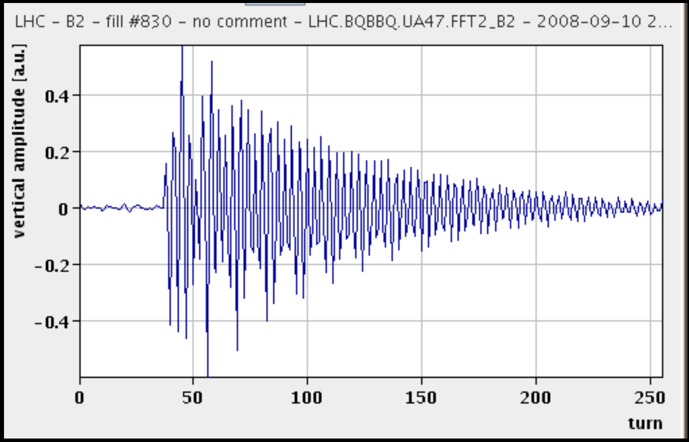


Betatron motion and the Tune

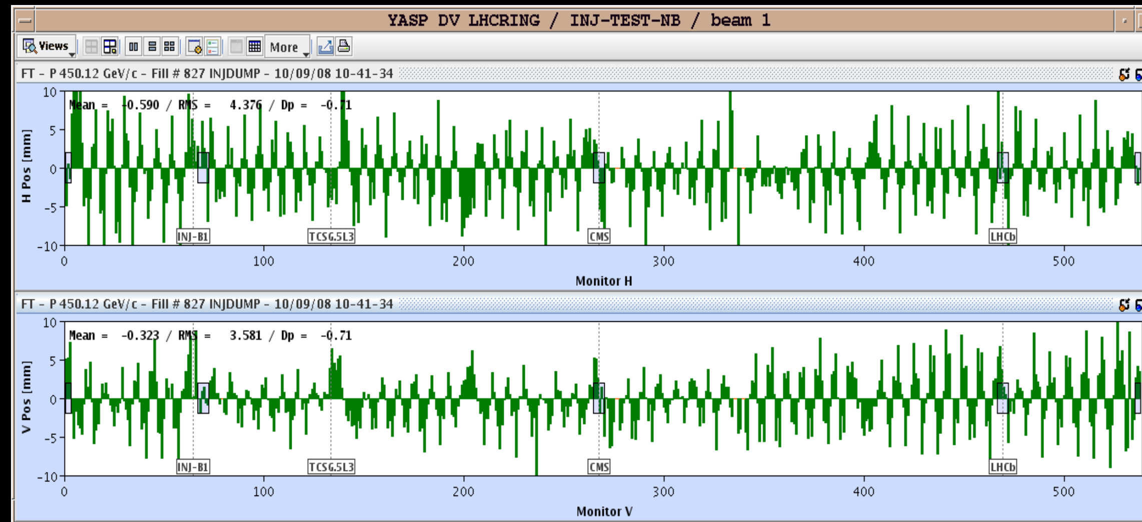


- Beam size
  - defined by incoherent betatron motion of all particles
- Particles have momentum spread
  - gives spread in focussing by quadrupoles
  - gives rise to spread in the frequency of the betatron oscillations (chromaticity)
- Coherent oscillations will de-cohere
  - Hadrons do not forget!
  - once hit they oscillate (practically) forever
  - any excitation must be kept very small

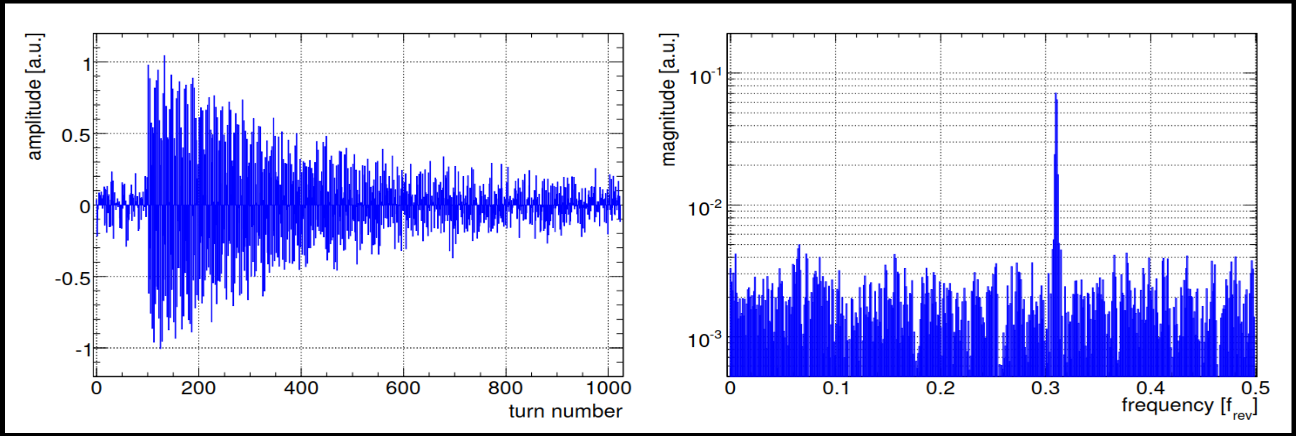




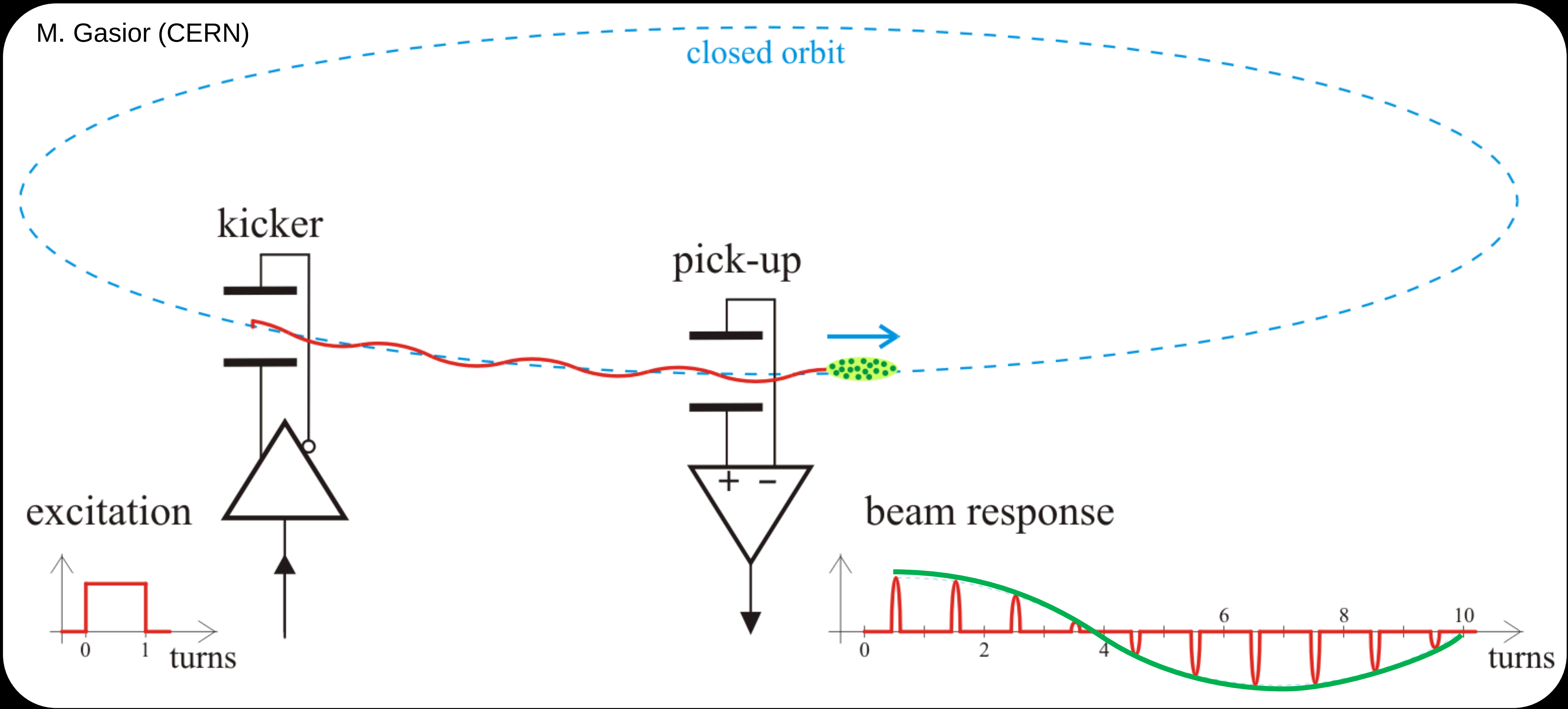
Tune Measurement



- Integer tune
  - seen in orbit response
  - ~550 dual plane BPMs
  - H: 59, V: 64 for LHC
- Fractional tune (q)
  - Seen from turn-by-turn signal of single BPM if beam is given a kick
  - Fast Fourier Transform (FFT) of oscillation data gives resonant frequency (q)



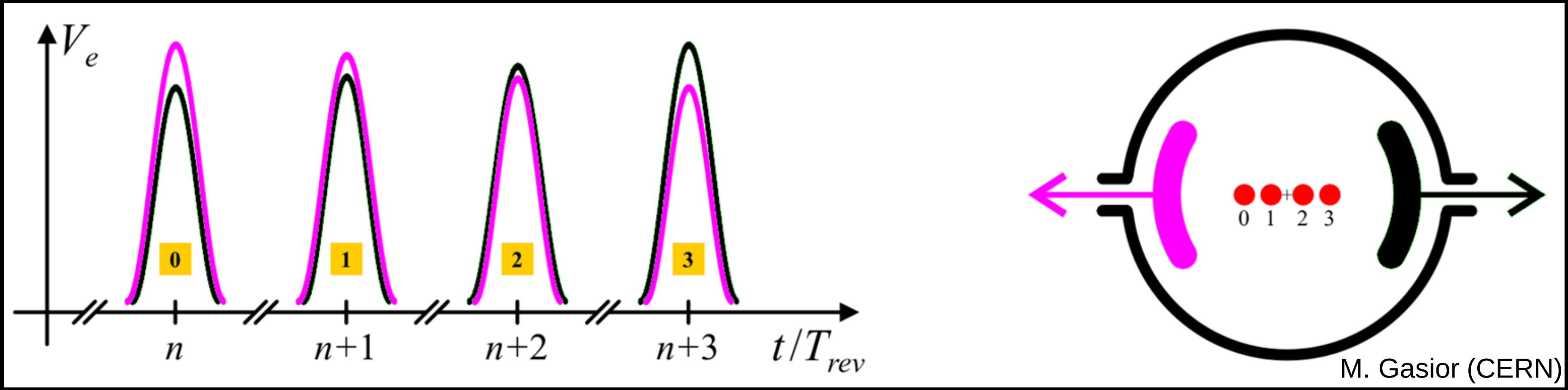
Tune Measurement – the principle



- A stimulus is needed to globally excite the beam
  - Resulting betatron oscillations observed on a position pick-up
  - Time domain signals usually converted to frequency domain
    - Displays which frequencies are present in the oscillations

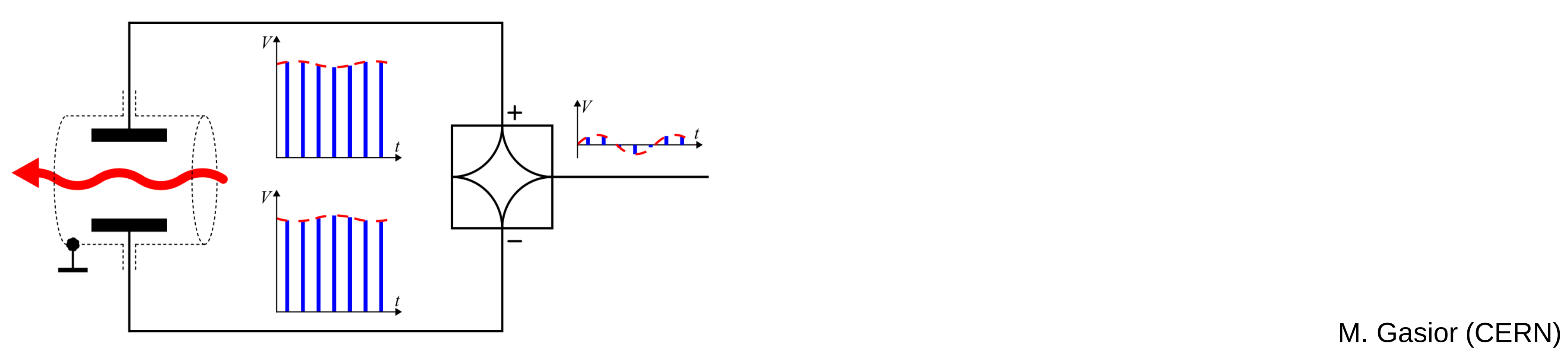
Tune Measurement – the principle

- Observable is the turn-by-turn position from a BPM
- BPM electrode signal has temporal shape related to the temporal structure (intensity profile) of the passing beam
  - Most of the signal produced is linked to intensity
- On top we look for very small variations linked to position
  - Such signals are very difficult to simulate in the lab

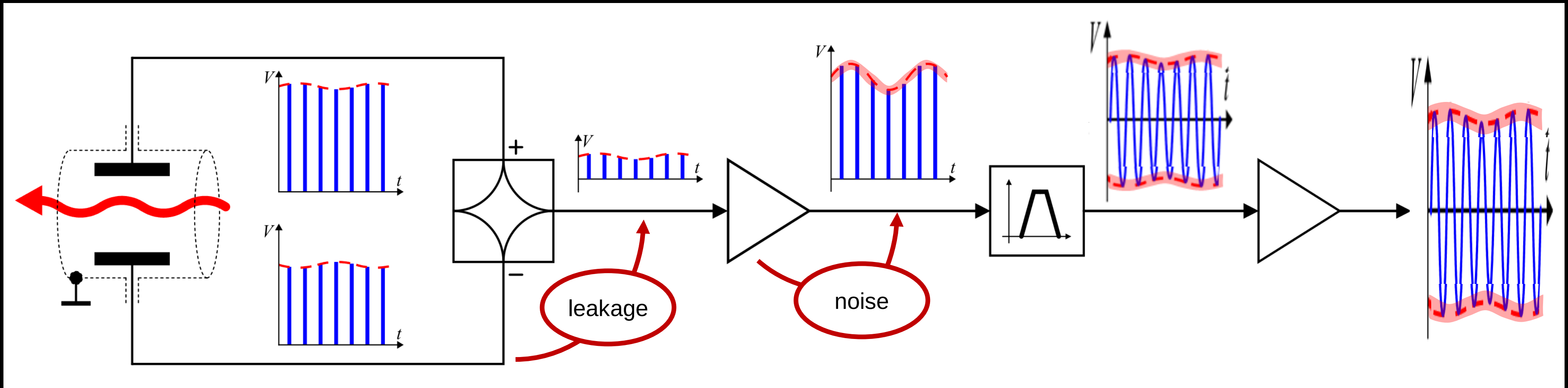


Tune Measurement – the principle

- A typical perfect detection scheme



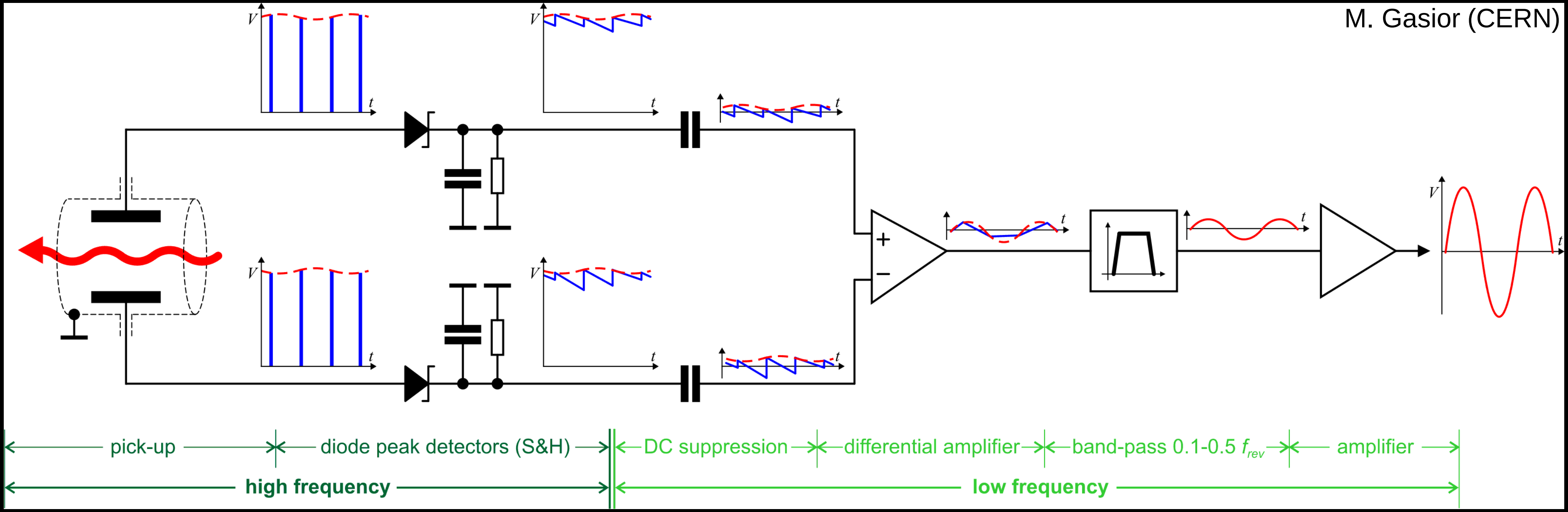
- Reality



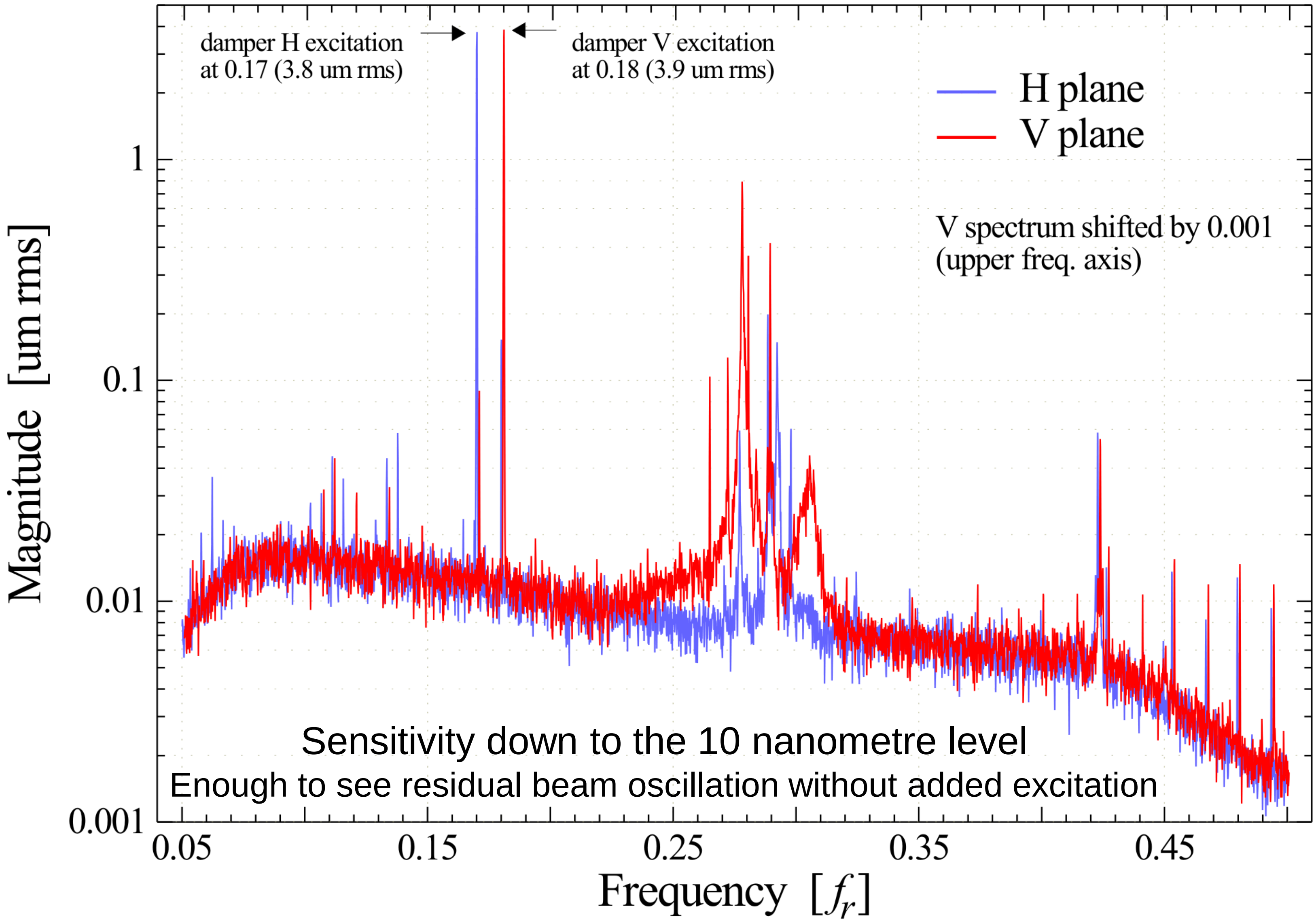
- Dynamic range issues
  - Signals related to betatron oscillations are small with respect to beam offset signals
  - Even for centred beam leakage is of order 1-10 % (of 100V!) for ns beam pulses

BaseBand Tune (BBQ) Measurement System

- Direct Diode Detection – the advantages
  - Single RF Schottky diode can handle up to 50 V pulses
    - Higher with a few diodes in series (LHC detector has 6 diodes)
  - Betatron modulation downmixed to below the revolution frequency
    - Allows efficient signal processing with inexpensive, high resolution ADCs
  - Just AM radio receiver – so what’s new?
    - Slow discharge & use of low noise, high impedance amplifiers
    - Brutal filtering of revolution line & everything outside band of interest



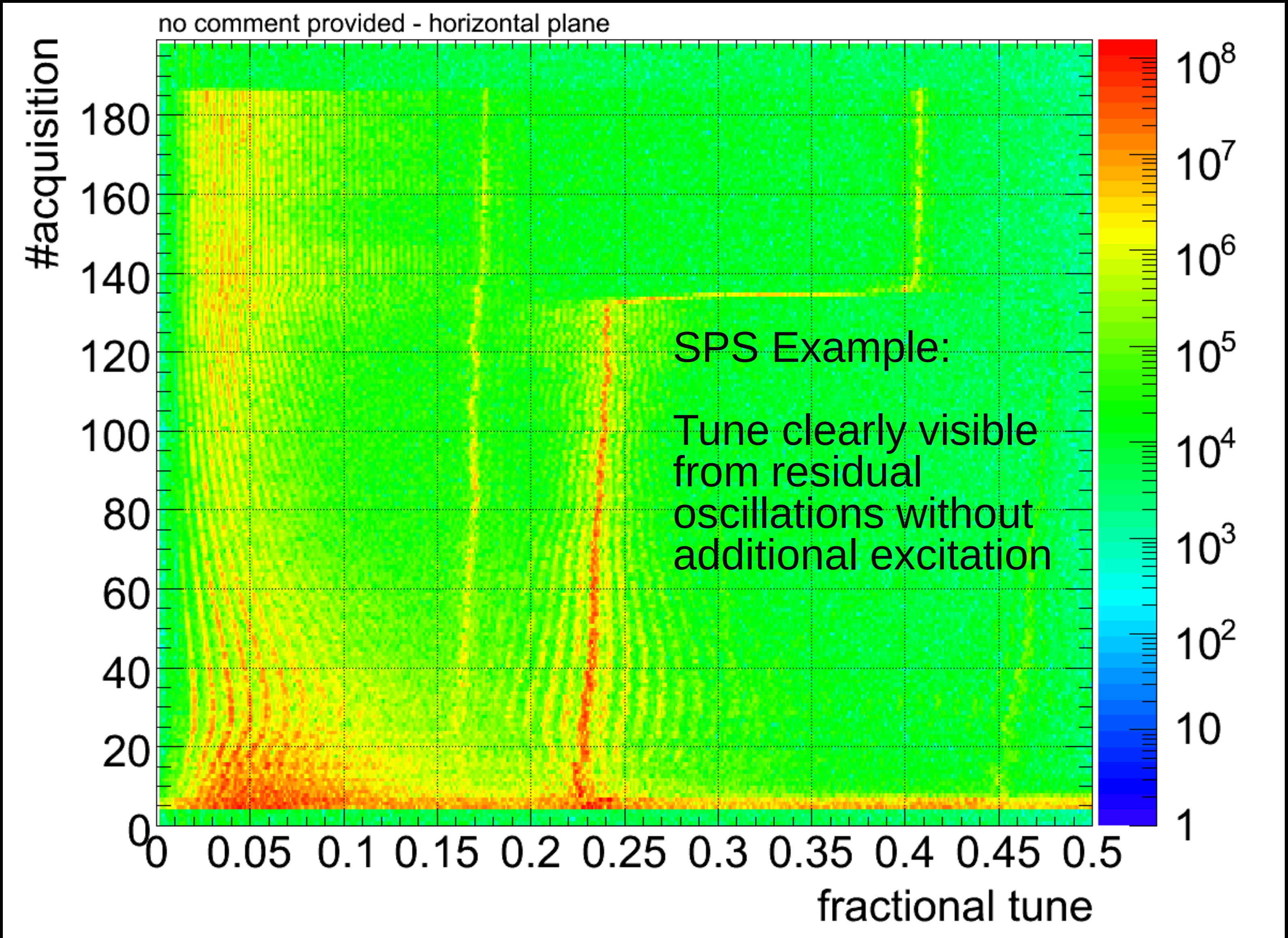
LHC BBQ System Performance



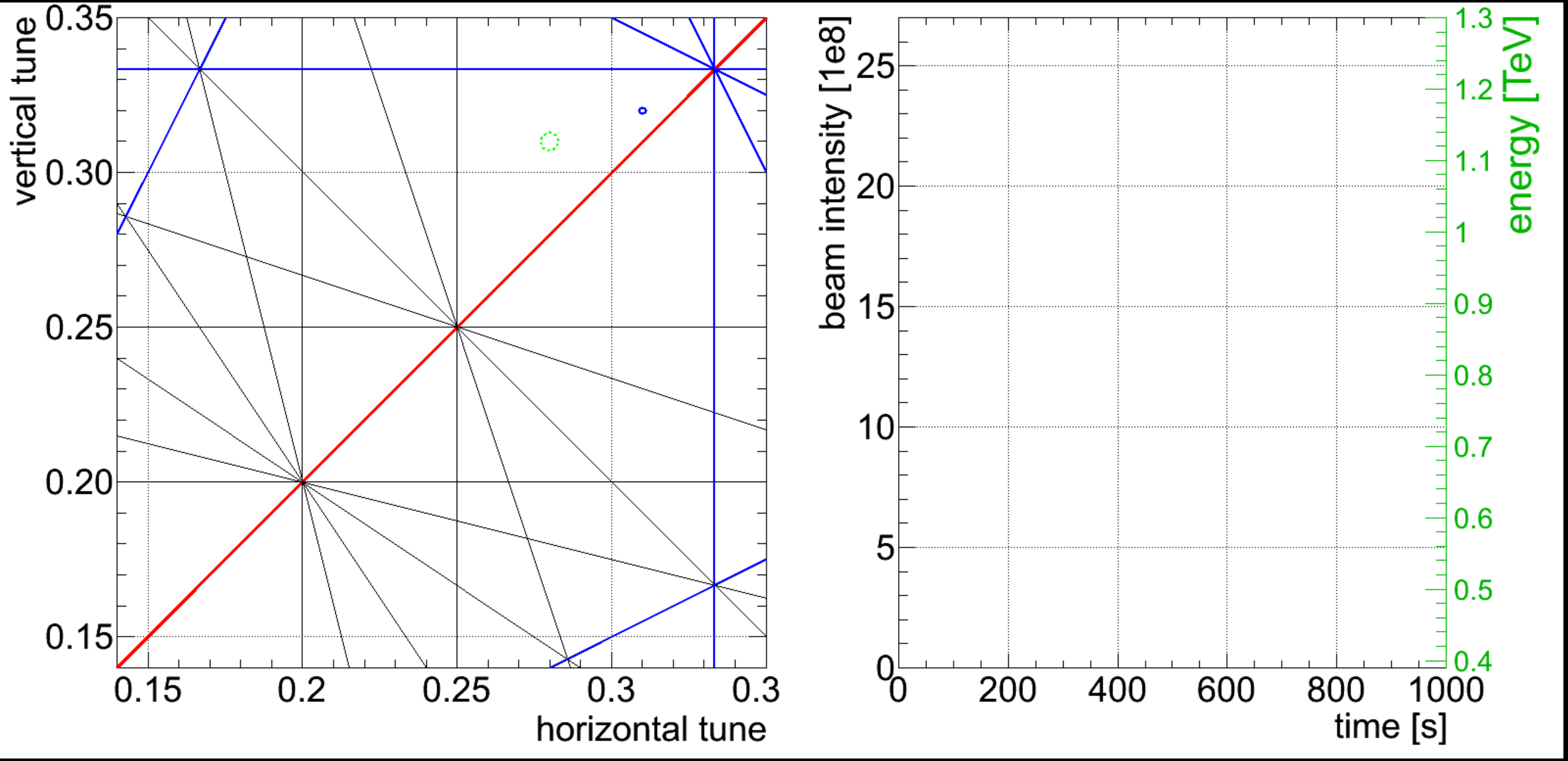
Sensitivity down to the 10 nanometre level

Enough to see residual beam oscillation without added excitation

Real-Time Tune Display

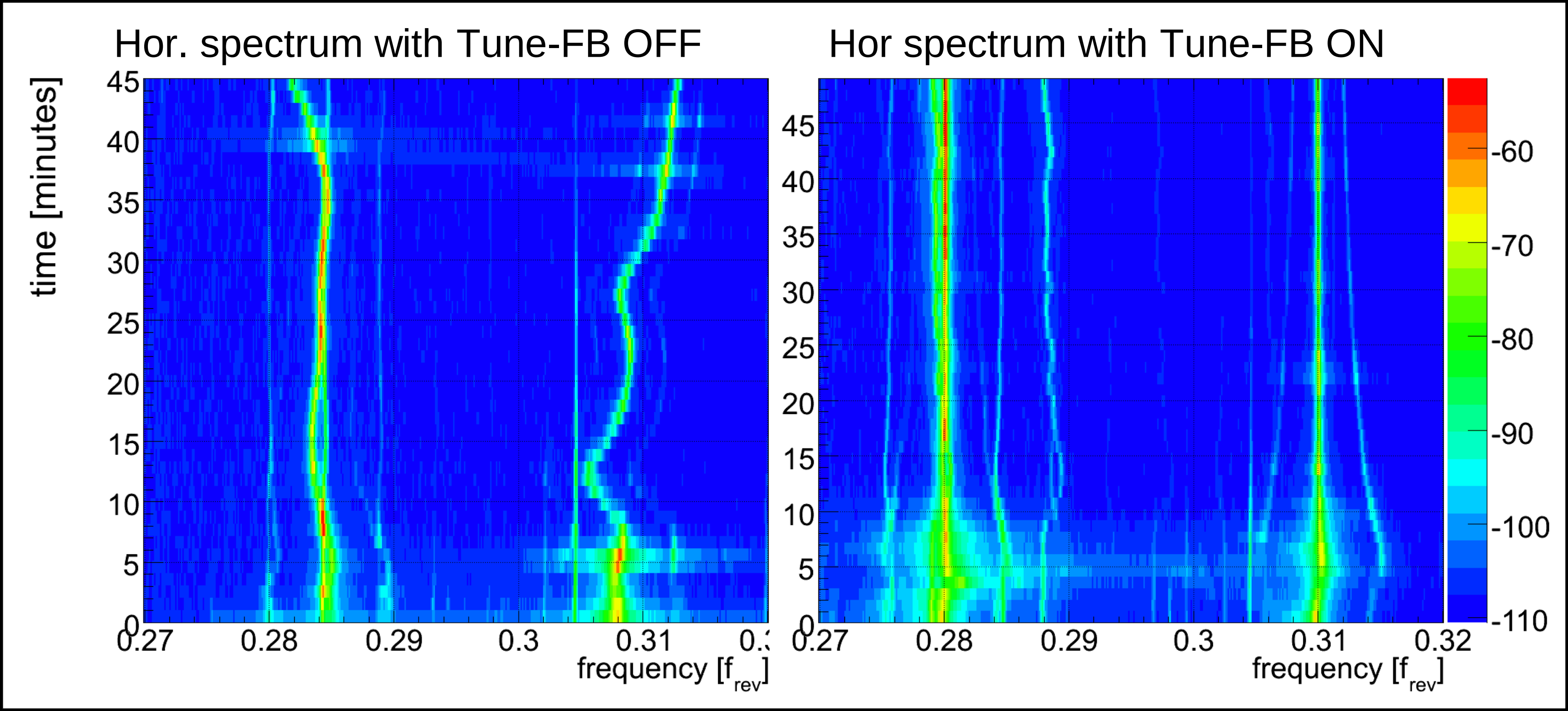


Tune Measurement in the LHC

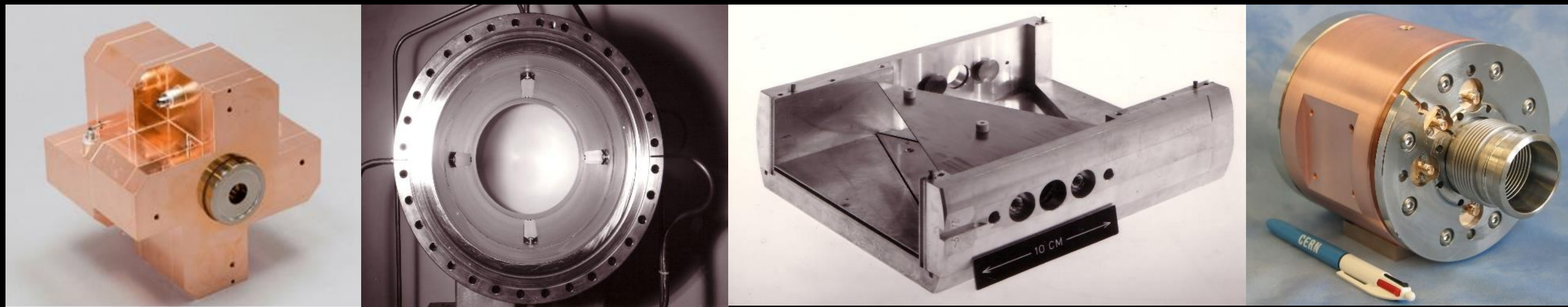


- Tune diagnostics throughout the ramp
  - Early ramps had poor tune control
  - Beam loss observed every time tune crossed a resonance line

Tune Feedback in the LHC



- Routinely used to compensate fill-to-fill variations
  - Uses peak fit on FFT with 0.1..0.3 Hz bandwidth
  - Feedback on trim quadrupoles



Coupling Measurement

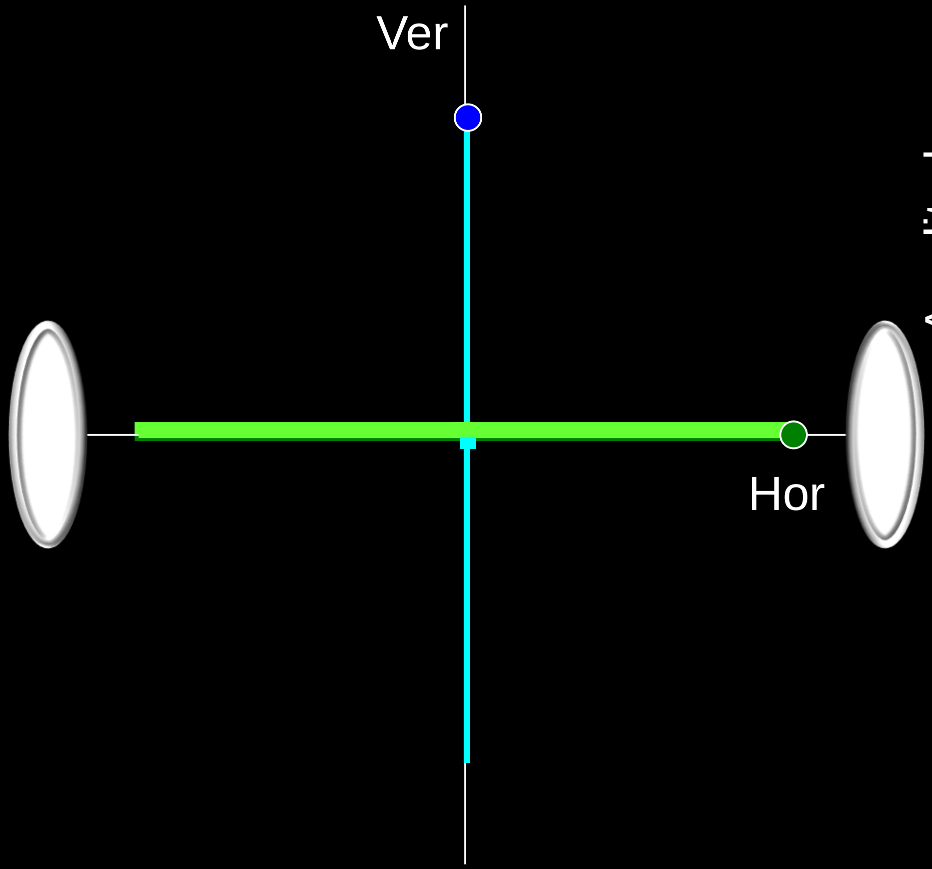
Coupling

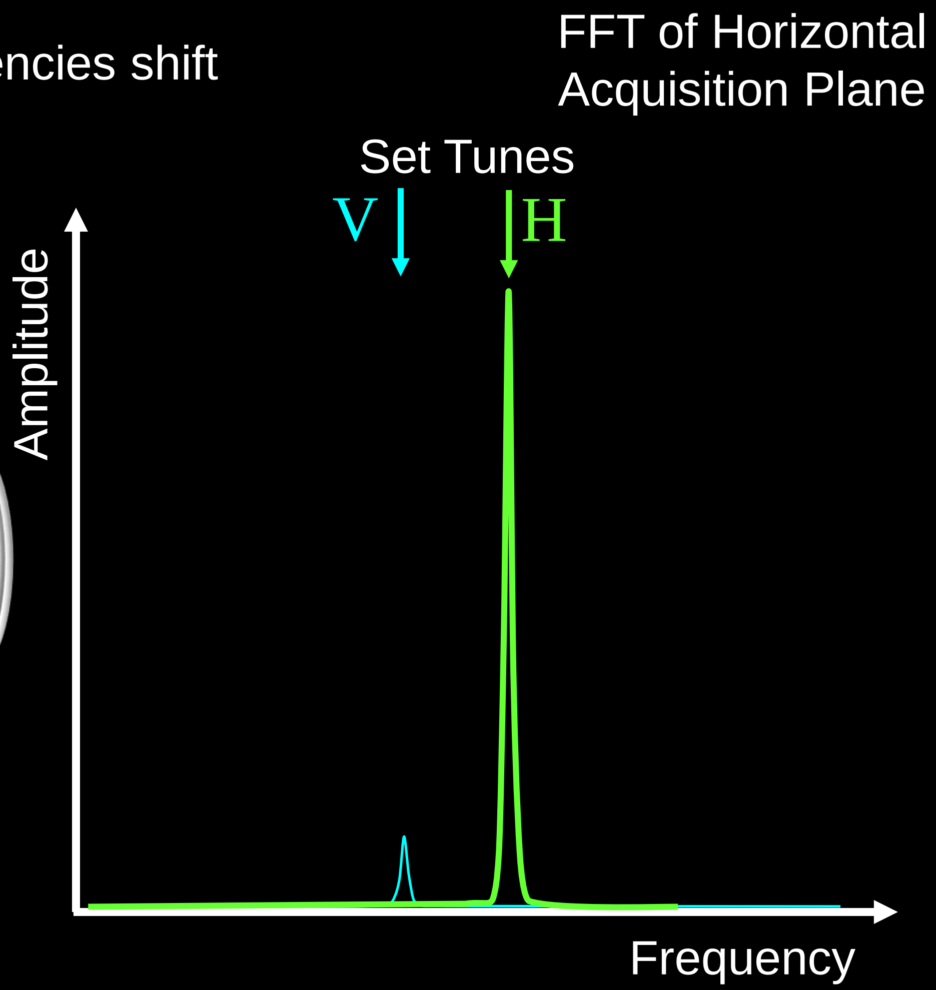
$$\overbrace{Q_{I,II}}^{\text{Measured Tunes}} = \frac{1}{2}\left(\overbrace{Q_x + Q_y}^{\text{Set Tunes}} \pm \sqrt{\left(Q_x - Q_y\right)^2 + |C^-|^2}\right)$$

- 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 horizontal & vertical 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 Measurement

- Start with decoupled machine
  - Only horizontal tune shows up in horizontal FFT
- Gradually increase coupling
  - Vertical mode shows up & frequencies shift





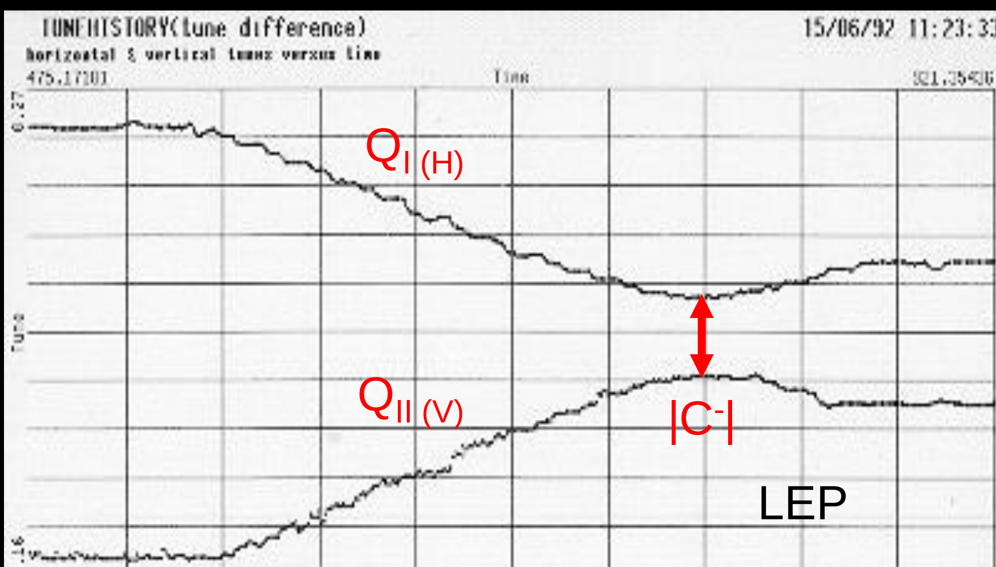
Measuring Coupling

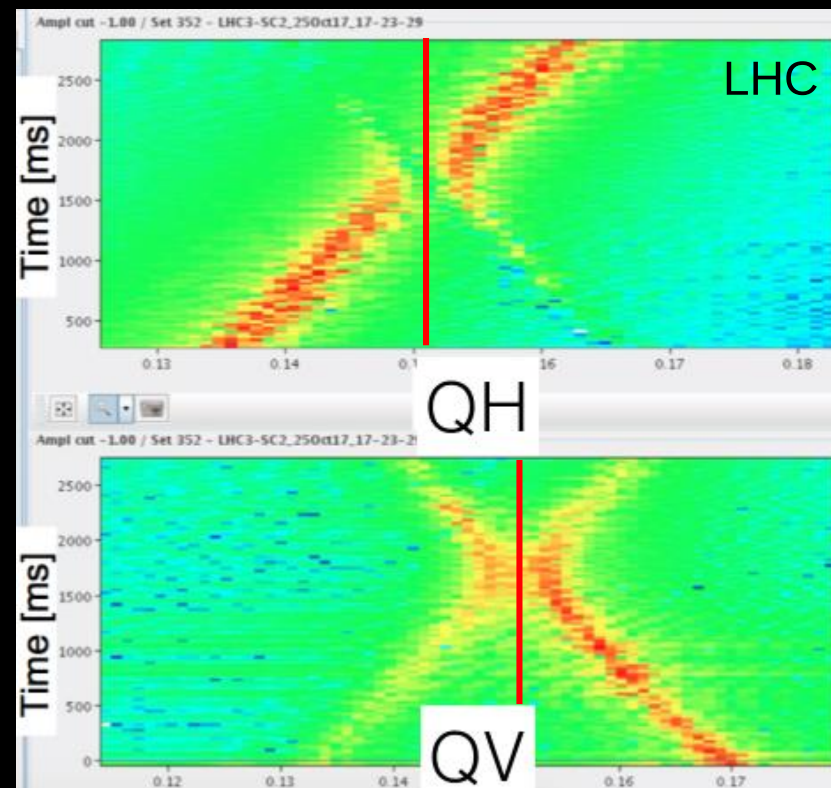
- 3 Main Methods
  - Orbit changes
    - Change orbit in one plane by exciting steering correctors or by changing injection conditions & measure effect in other plane
    - Large coupling sources identified as locations where horizontal orbit change generates a vertical kick & vice versa
    - Acquire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

Measuring Coupling – Closest Tune Approach

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

- Measure tunes while changing the quadrupole strength
  - Coupling Measurement in LEP using Phase Locked Loop tune measurement
  - Coupling measurement in LHC using base band tune measurement

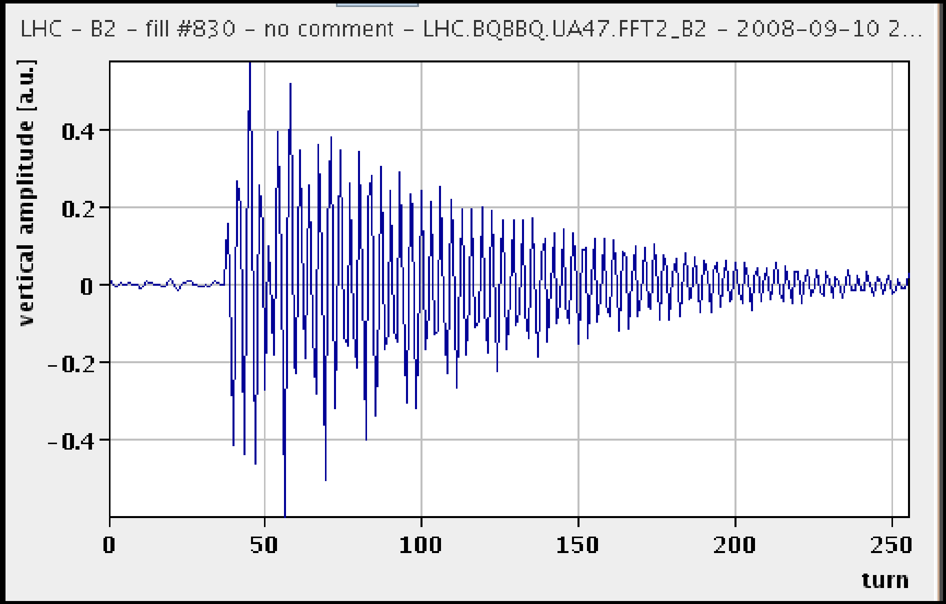


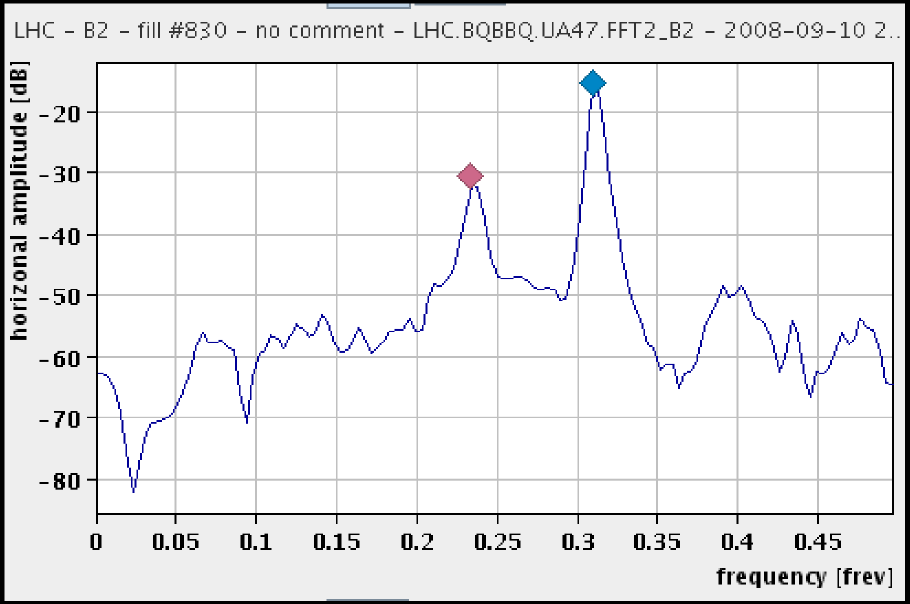


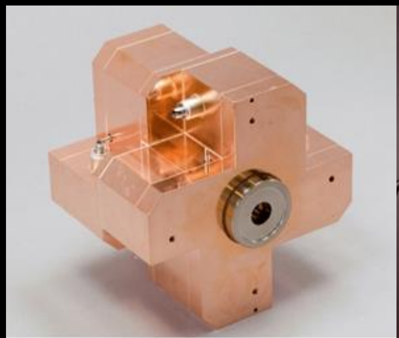
Measuring Coupling – Kick Response

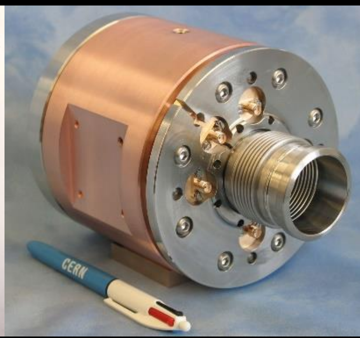
- Kick Beam in one plane and measure oscillations in other
  - Observe with tune measurement system
  - Magnitude of local coupling can be derived from amplitude ratios of tune peaks

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







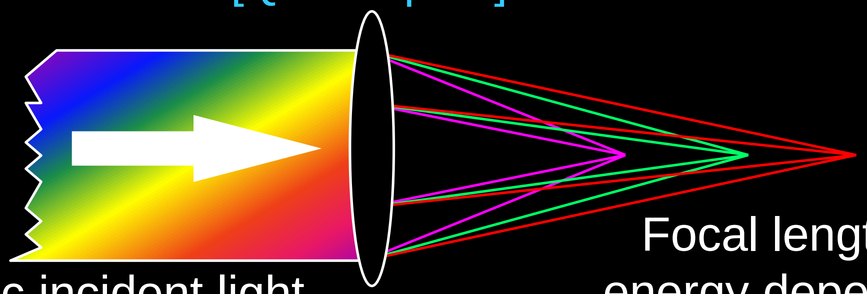


Chromaticity Measurement

Chromaticity

- Machine Chromaticity

Optics Analogy:



Spread in the Machine Tune due to Particle Energy Spread

Controlled by Sextupole magnets

First Order

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

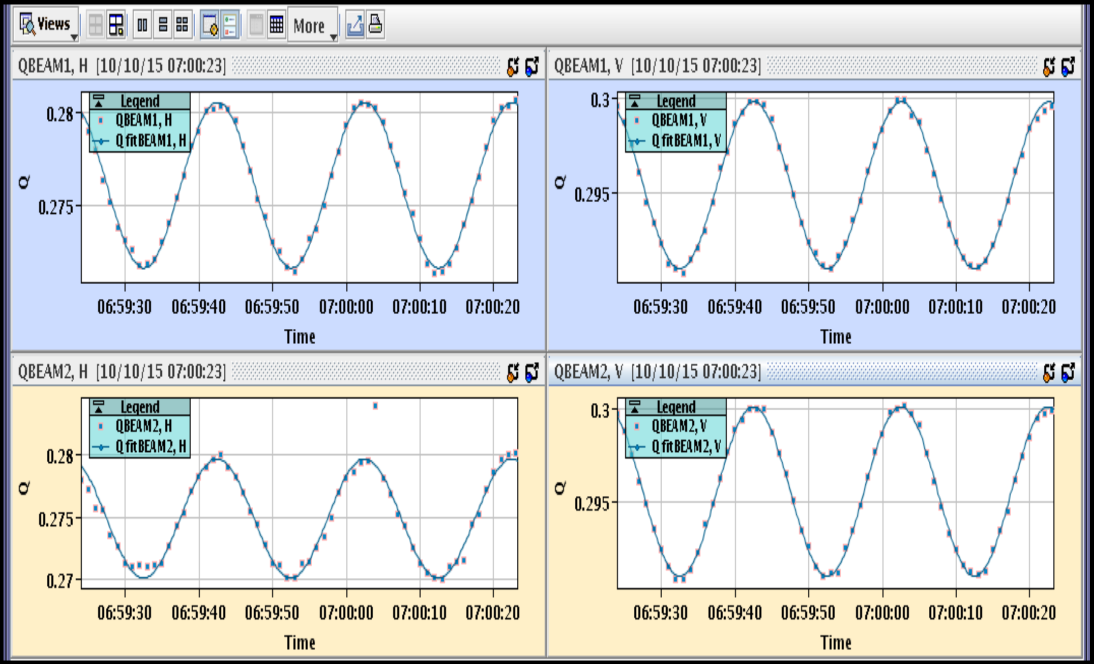
$$\xi = \frac{Q'}{Q}$$

Measurement Techniques

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 to exploit in hadron machines with low synchrotron tune, Influence of collective effects
Width ratio of Schottky sidebands	⇔	Used on many machines & ideally suited to unbunched or ion beams. Measurement is typically very slow
Bunch spectrum variations during betatron oscillations	⇔	Difficult to disentangle effects from all other sources – e.g. bunch filling patterns, pick-up & electronics response
Head-tail phase advance (same as above, but in time domain)	⇔	Good results on several machines but requires kick stimulus $\Rightarrow$ emittance growth!

RF Momentum Modulation Techniques

- Slow RF Variation
  - Apply time varying RF modulation
  - Continuously measure the tune
    - Amplitude of tune variation proportional to chromaticity

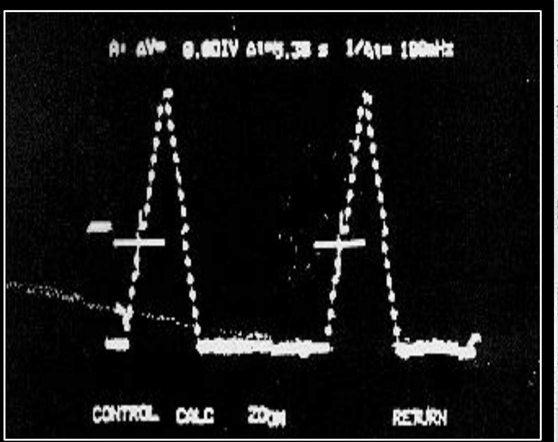


Example from the LHC

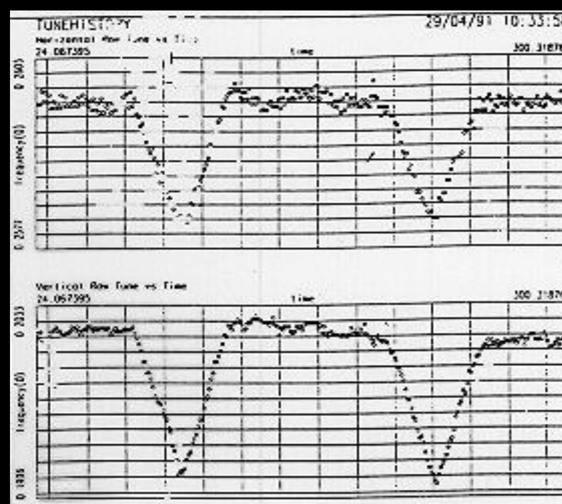
- Sinusoidal RF modulation at 0.05Hz
- Tune continuously tracked in all planes of both beams
- Chromaticity calculated once acquisition complete

RF Momentum Modulation Techniques

- Slow RF Variation
  - Apply time varying RF modulation
  - Continuously measure the tune
    - Amplitude of tune variation proportional to chromaticity



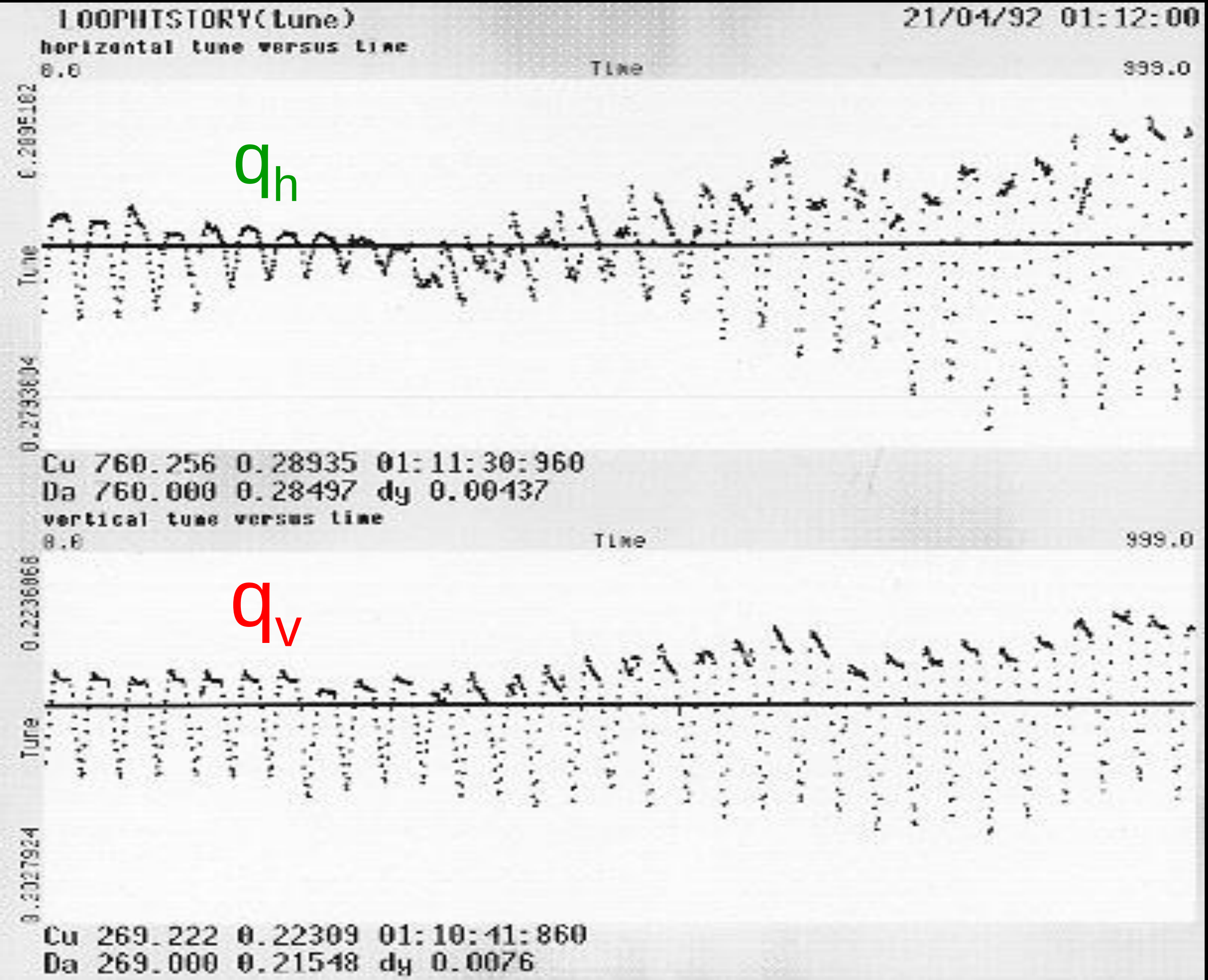
Applied Frequency Shift



Q_h & Q_v Variation

Example from CERN-LEP
- Triangular RF modulation
- Allows sign of chromaticity to be easily determined

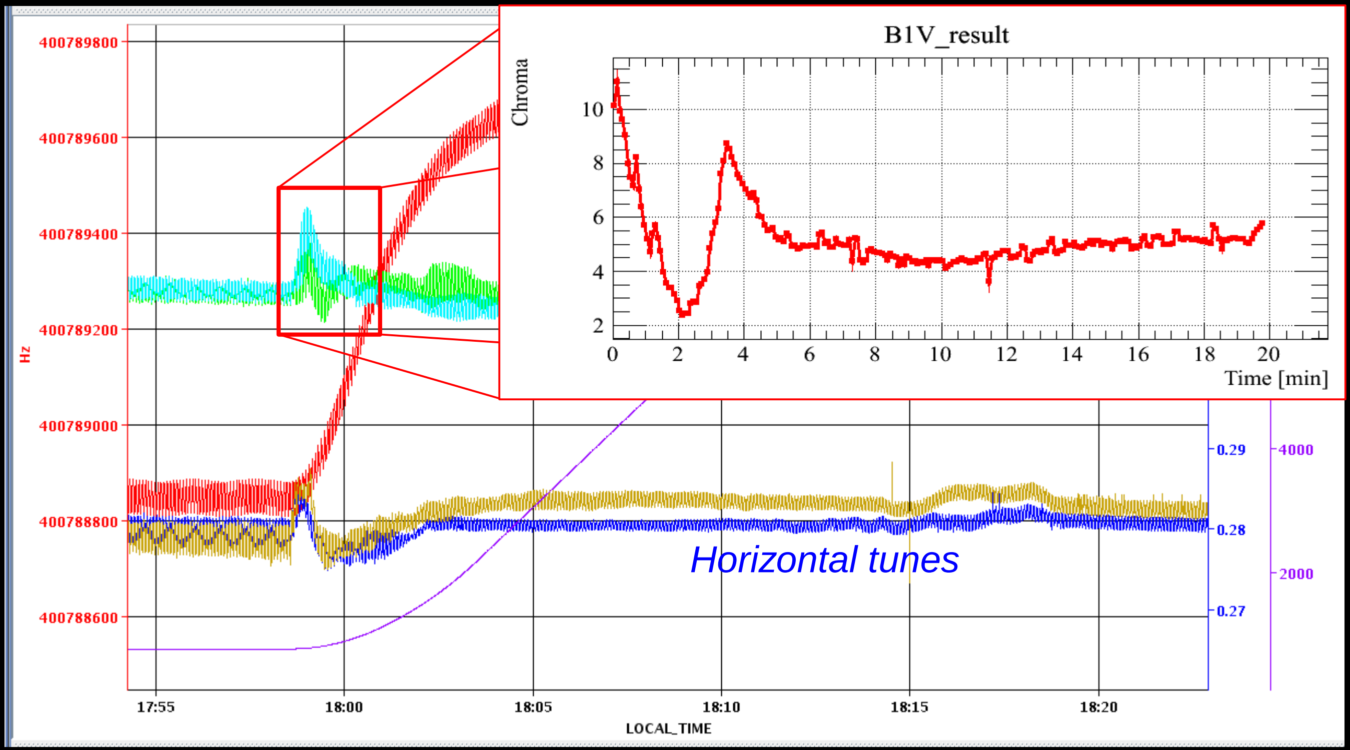
Example from LEP β-squeeze



Example from LHC Acceleration Ramp

- Dynamic Measurement Examples
  - LHC Ramp
    - RF continuously modulated
    - Tune measured continuously
    - Chromaticity calculated from tune modulation amplitude

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



Measurement Techniques

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 to exploit in hadron machines with low synchrotron tune, Influence of collective effects?
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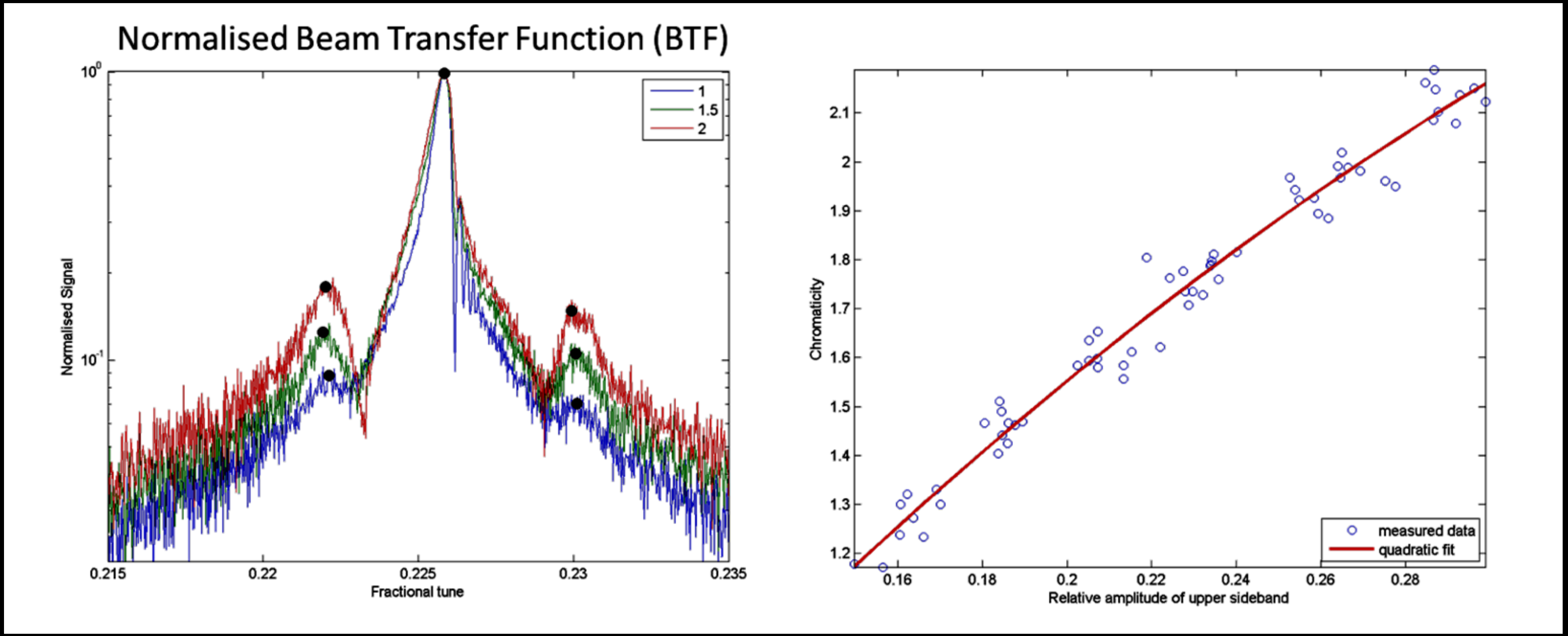
Head-tail phase advance (same as above, but in time domain)	⇔	Good results on several machines but requires kick stimulus ⇒ emittance growth!

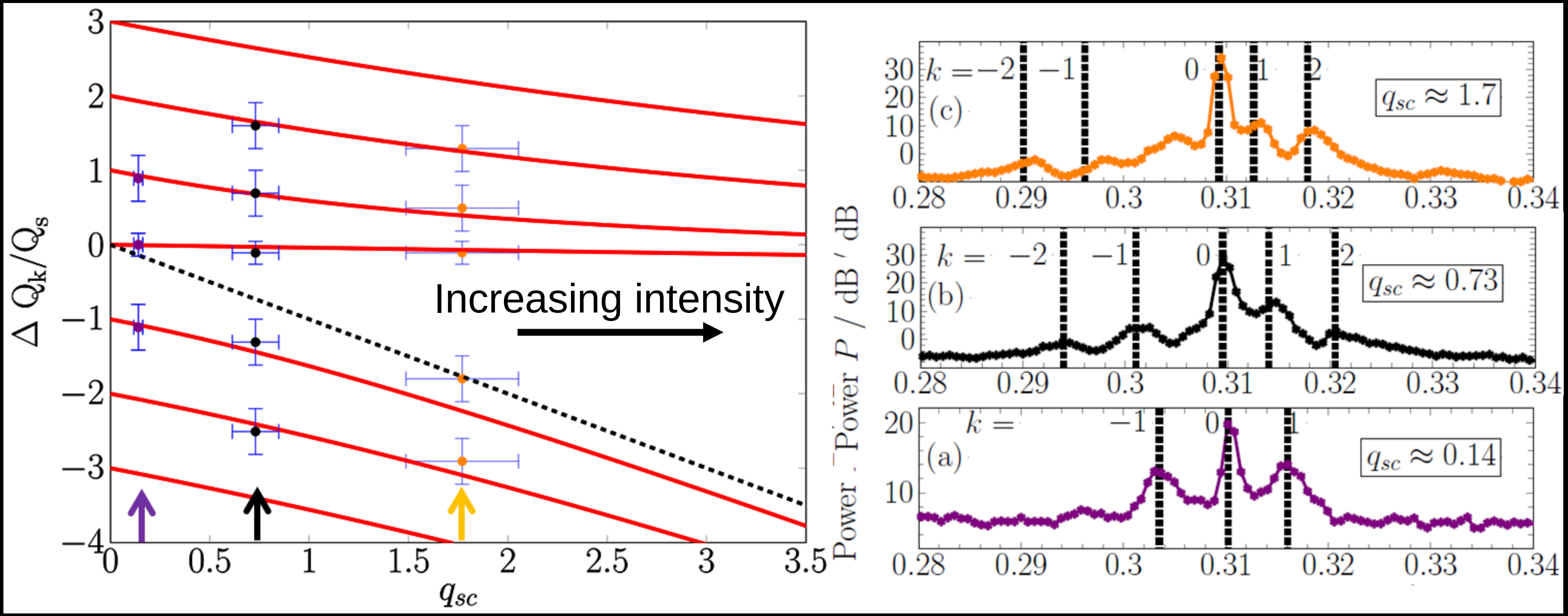
Amplitude of Synchrotron Sidebands

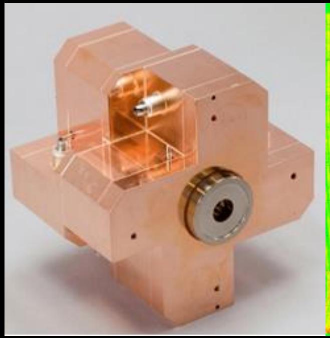
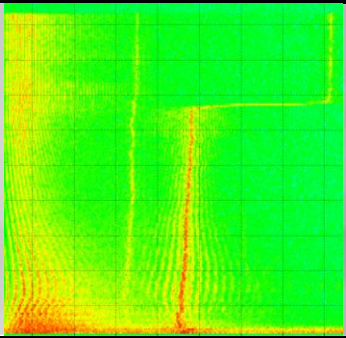
- Recently demonstrated at DIAMOND
  - RF modulation changes orbit - not compatible with user operation
  - Looking for technique to measure chromaticity on-line
    - Measure Beam Transfer Function (BTF) on single bunch
      - Using transverse bunch by bunch feedback system
      - Emittance blow-up of single bunch irrelevant

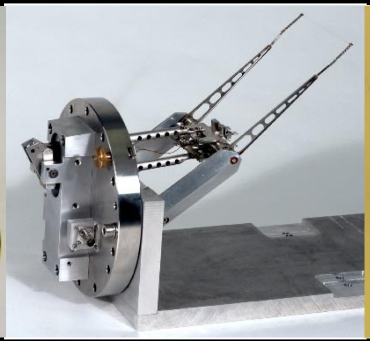
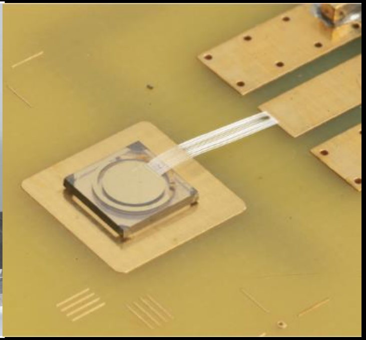


Amplitude of Synchrotron Sidebands

- Must be Careful with High Intensity Effects
  - Modification of tune spectra by space charge & impedance
    - Measurements performed at GSI
  - Relative heights & mode structure given by chromaticity
    - Can be calculated with simplified analytical models



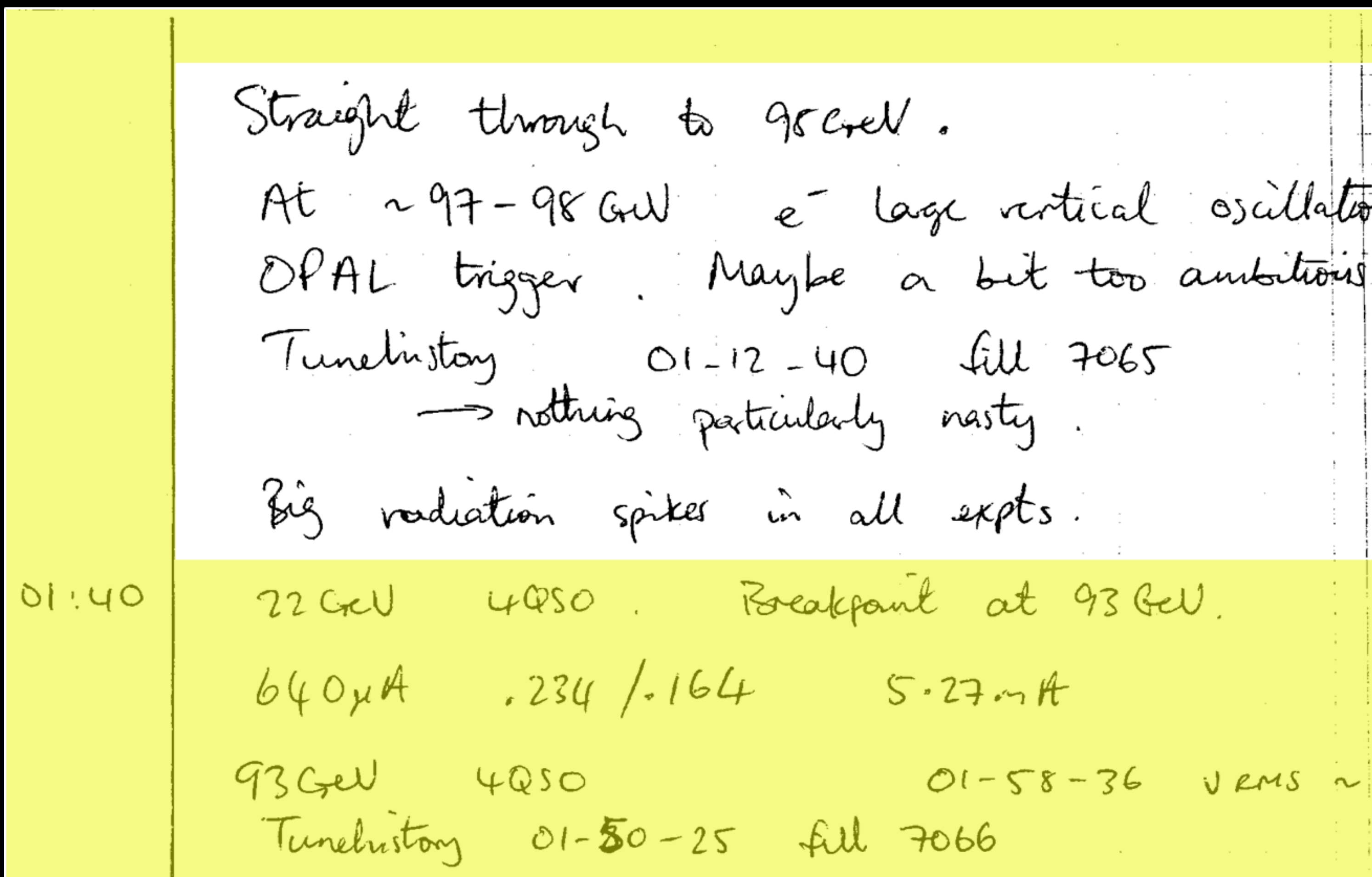



Diagnosing Machine Issues using Beam Instrumentation

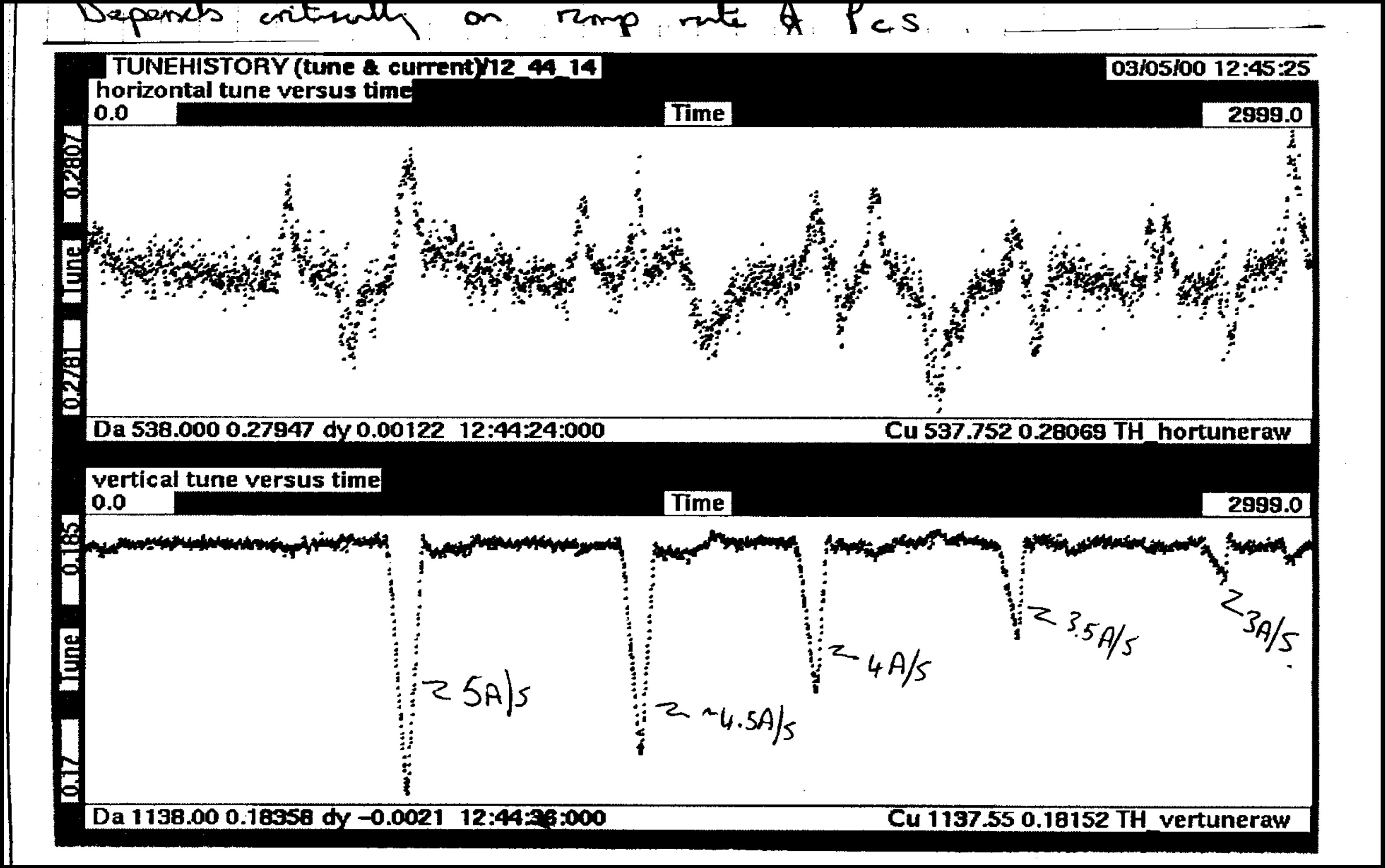
LEP Beams Lost During β-Squeeze

- Extract from LEP logbook (when pen & paper still used!)
  - OK when stepping through the β-squeeze slowly
  - Beams lost when attempting to go straight through


Straight through to 95 GeV.
At ~97-98 GeV e^- large vertical oscillatio
OPAL trigger. Maybe a bit too ambitious
Tunehistory 01-12-40 fill 7065
→ nothing particularly nasty.
Big radiation spikes in all expts.
01:40 22 GeV 4QS0. Breakpoint at 93 GeV.
640μA .234/.164 5.27mA
93 GeV 4QS0 01-58-36 V RMS ~
Tunehistory 01-50-25 fill 7066

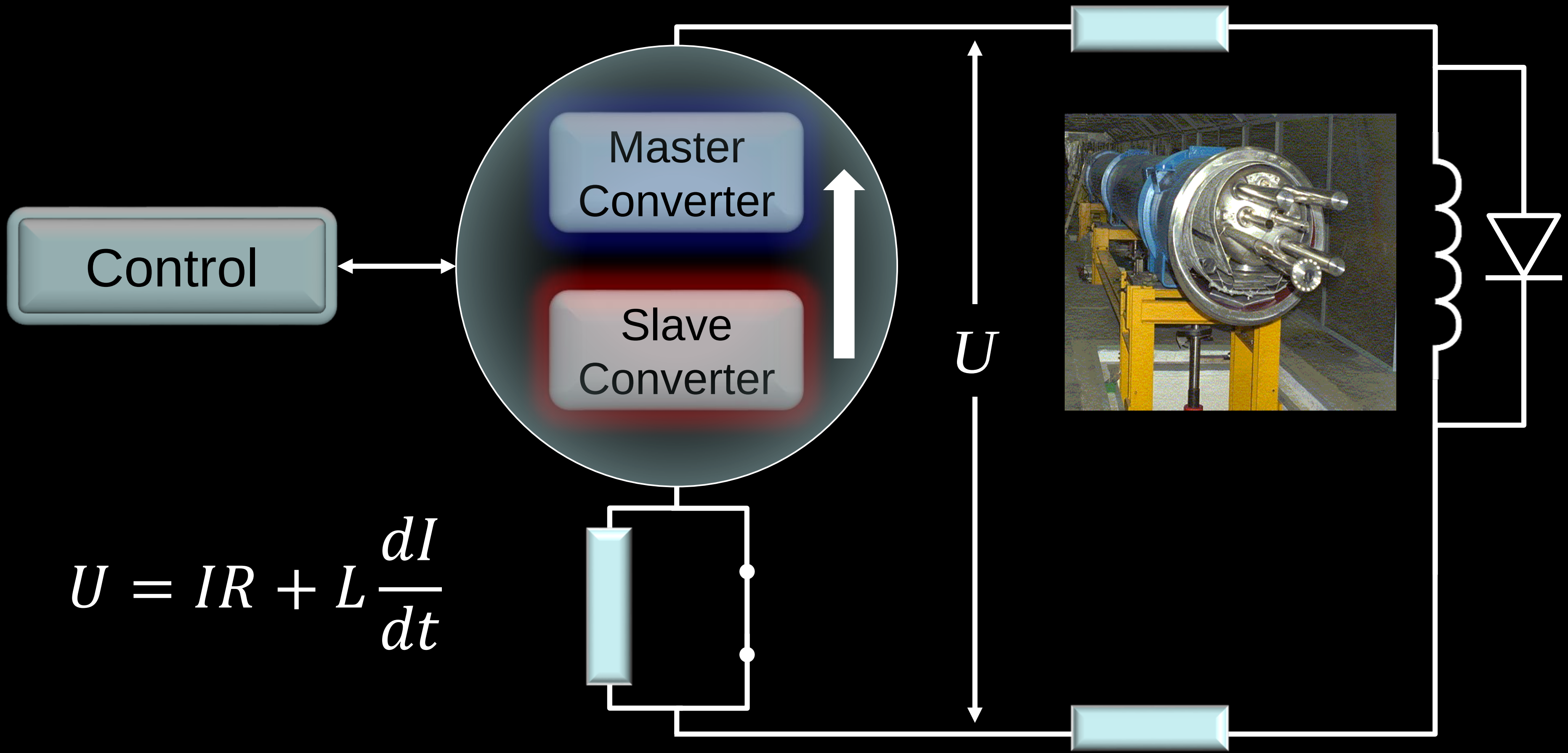
The Diagnostics

- Tune Variation
  - Tracked for different power converter ramp rates



The Explanation

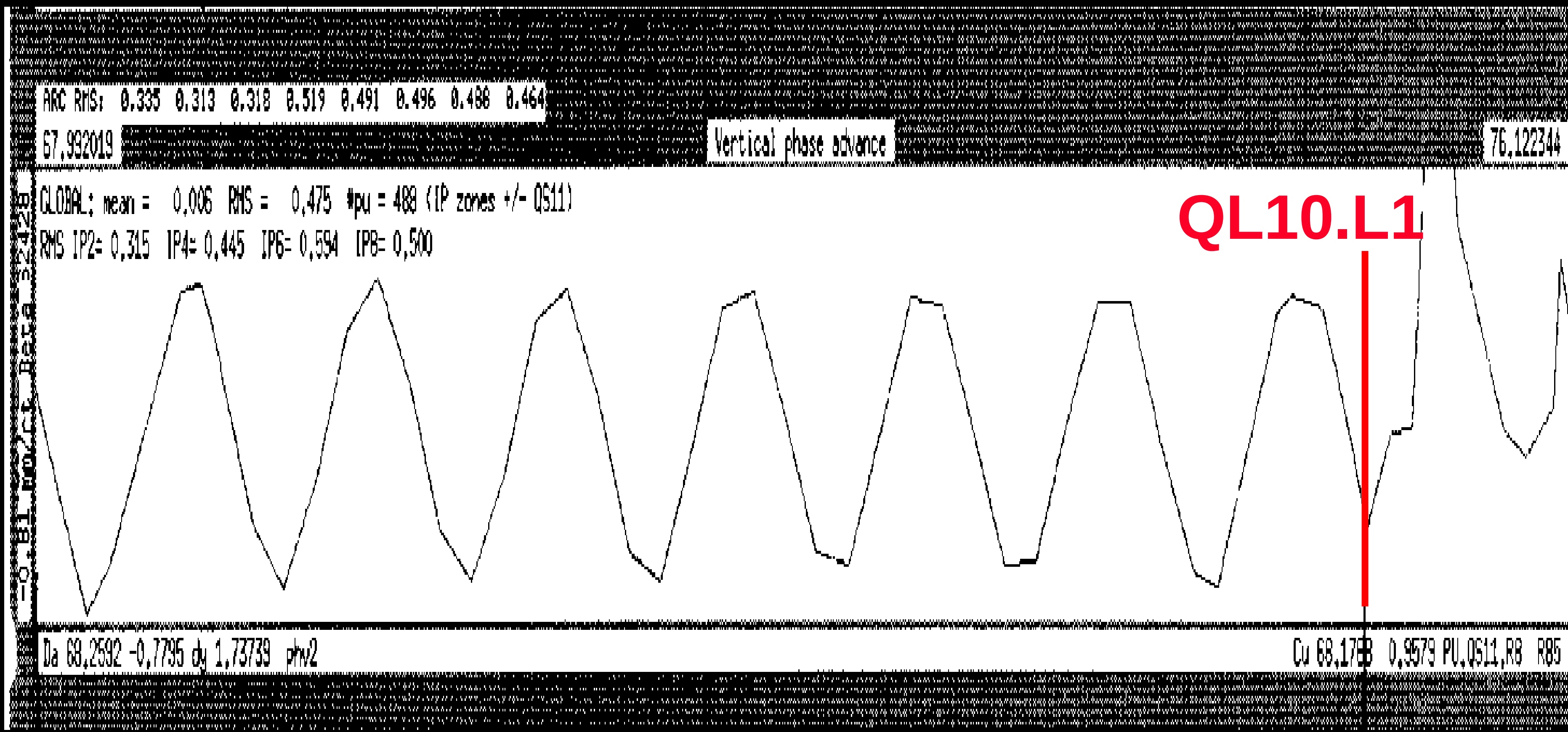
- Master-Slave Configuration for Power Converter
  - Each converter can deliver full DC current
  - Slave converter not working
    - Slave only needed to give increased voltage for fast current changes



$$U = IR + L\frac{dI}{dt}$$

LEP – No Circulating Beam

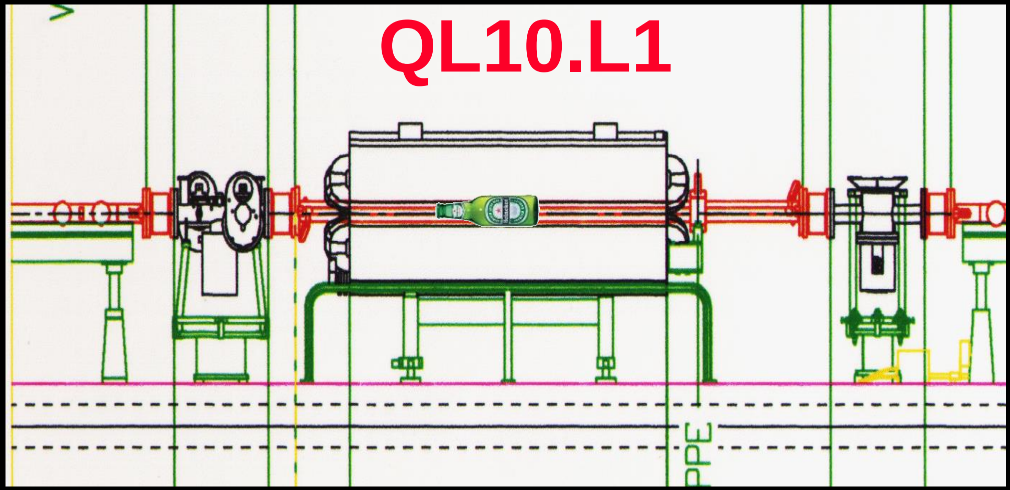
- No Circulating Beam after Technical Stop
  - Phase advance from BPMs show that optics no longer correct after specific quadrupole

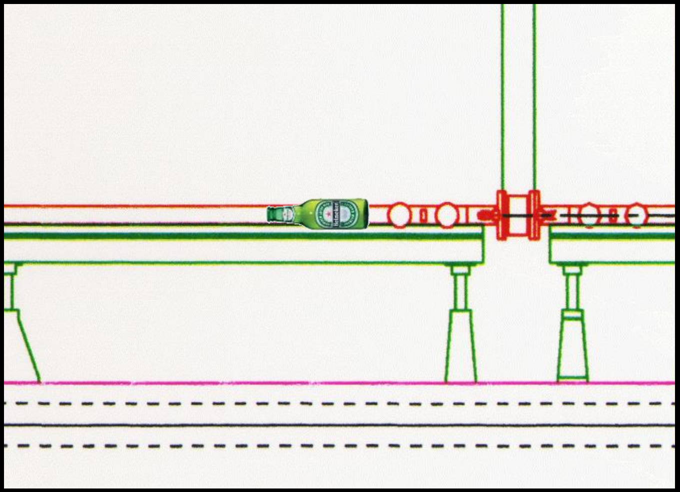


Positrons →

The Explanation

- After many trials - open vacuum chamber in QL10.L1
  - & 10m to the right ….





- Unsociable sabotage
  - Both bottles were empty!!

Summary

- You now hopefully have a first impression of how to build and use beam instrumentation to run & optimise accelerators
- It should also be clear that there are two distinct types
  - "Bread & butter" instrumentation for standard operation
  - Innovative instrumentation to address specific requirements or new techniques to use traditional instrumentation in non-conventional ways

For those that want to know more then I hope you've joined the Beam Instrumentation Afternoon Course!

- 3 Sessions on BPM design
  - Simulation software & "hands-on" laboratory measurements
- 1 Session on Tune Measurement
  - Simulate your own tune measurement system
- 2 Sessions on Profile Measurements
  - "Hands-on" laboratory measurements of transverse & longitudinal profile
- Final Session
  - Group presentation of your BI proposals for an accelerator