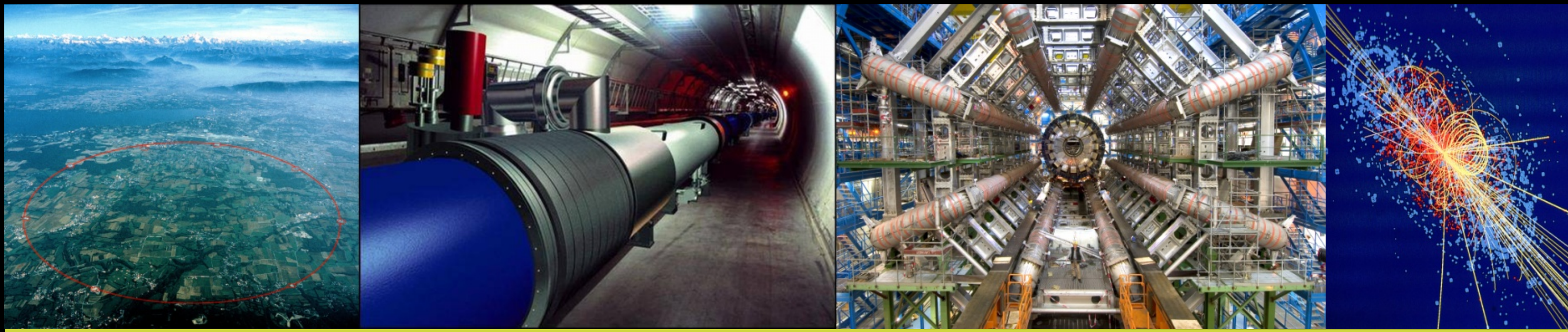


Beam Instrumentation and Diagnostics (Lecture 2)

CAS 2017

Royal Holloway, London

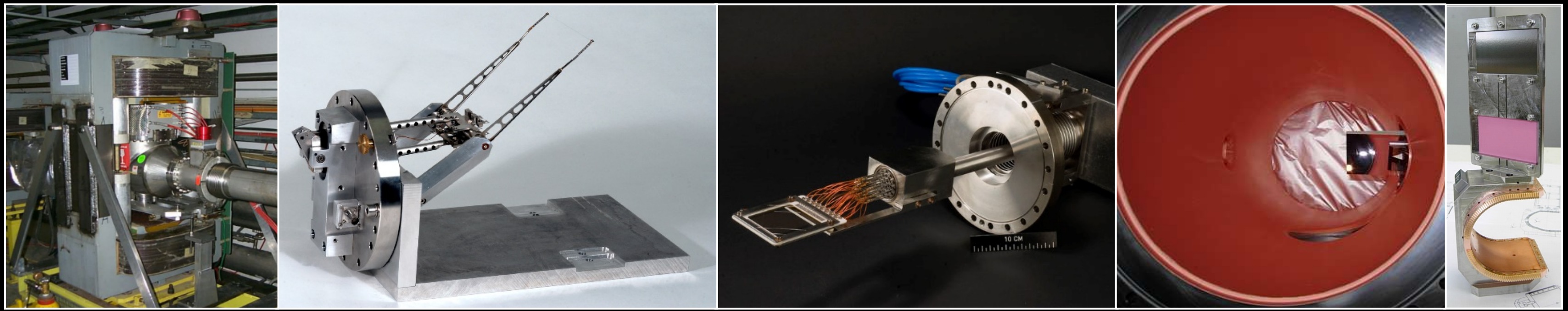
4th – 15th September, 2017

Dr. Rhodri Jones

Head of the CERN Beam Instrumentation Group

Introduction

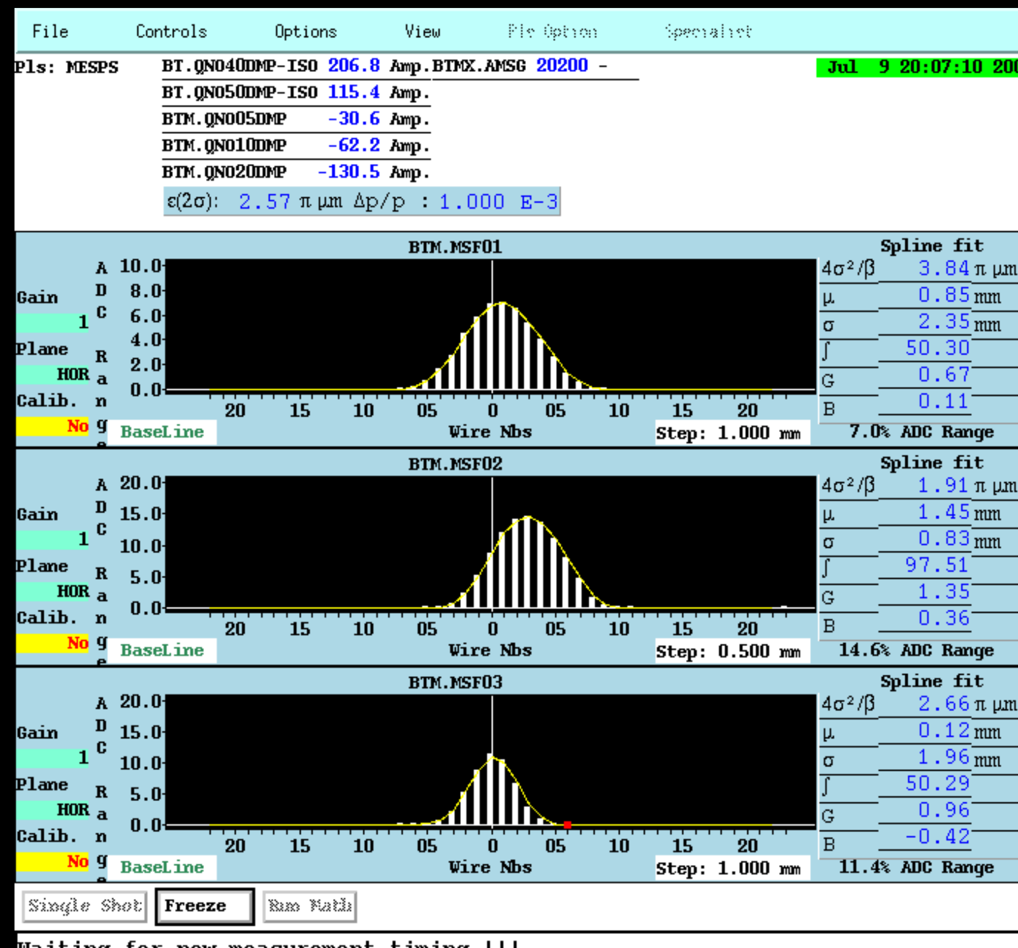
- Yesterday was dedicated to
  - Beam position measurement
  - Beam intensity measurement
  - Beam loss monitoring
- Today we'll continue with a look at
  - Beam profile monitoring & diagnostics
  - Tune, Coupling & Chromaticity measurement & feedback
  - Making Accelerators work using beam instrumentation



Beam Profile Monitors

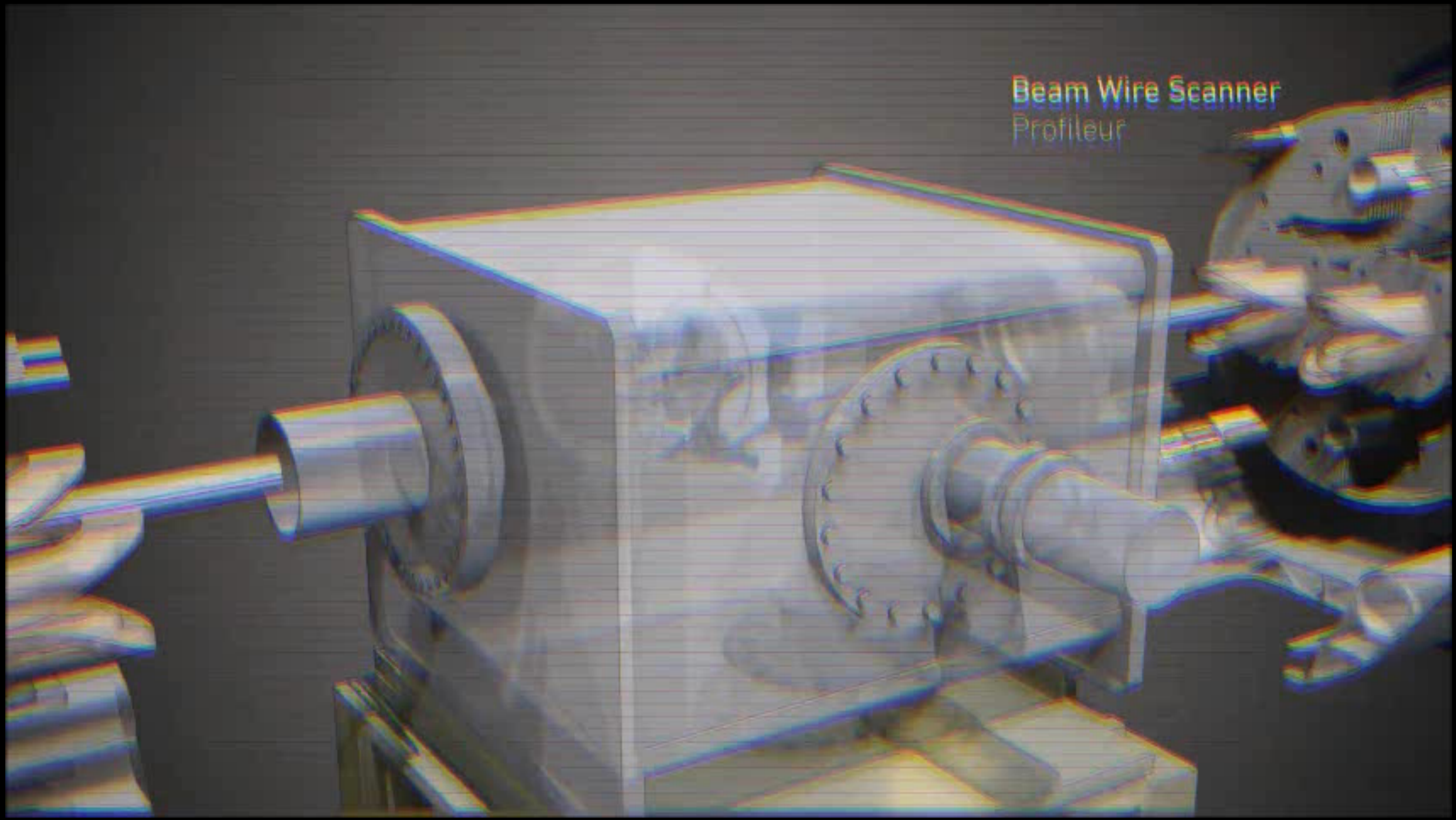
Profile Monitoring using Wires

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



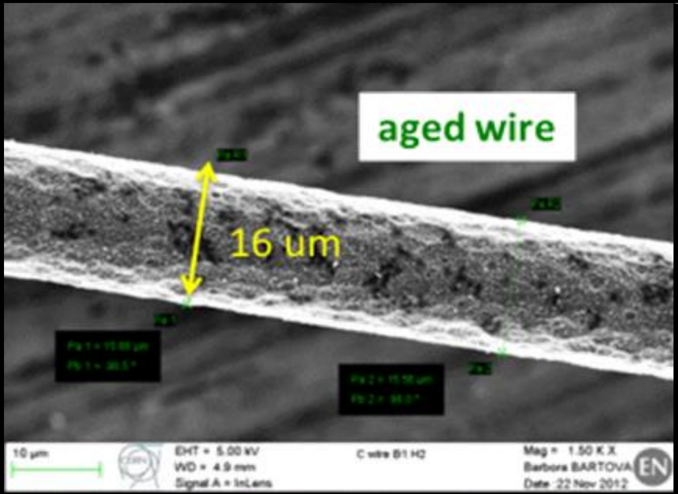
Profile Monitoring using Wires

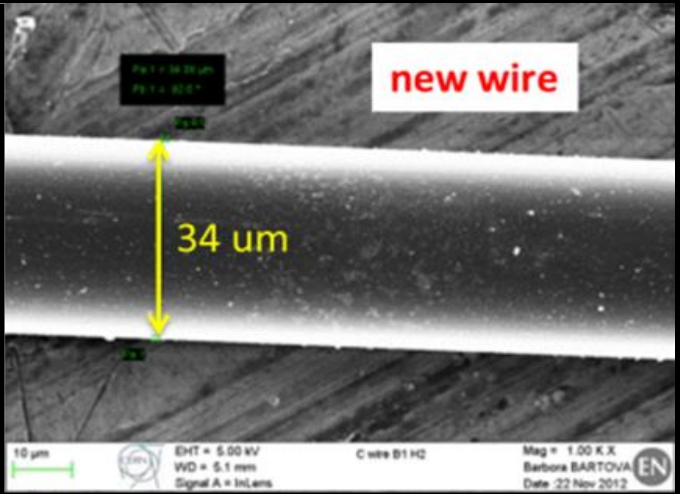
- Wire-scanners
  - Move thin wire across beam
  - Low energy : correlate wire position with secondary emission
  - High energy : correlate wire position with secondary shower



Limitation of Wire-Scanners

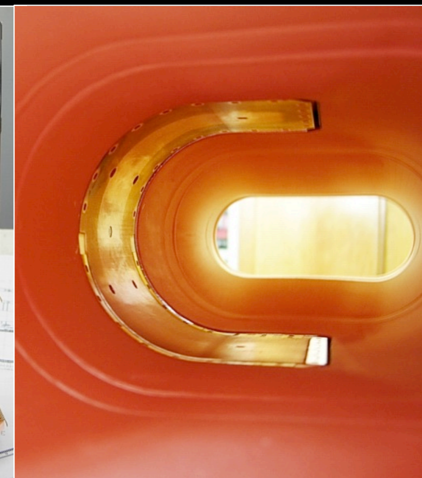
- Wire Breakage – why?
  - Brittle or Plastic failure (error in motor control)
  - Melting/Sublimation (main intensity limit)
    - Due to energy deposition in wire by particle beam
- Temperature evolution depends on
  - Heat capacity, which increases with temperature!
  - Cooling (radiative, conductive, 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

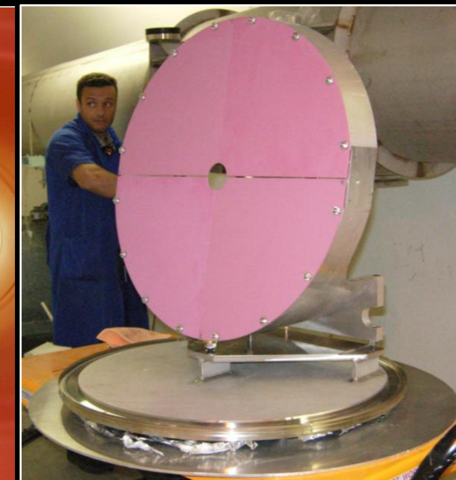


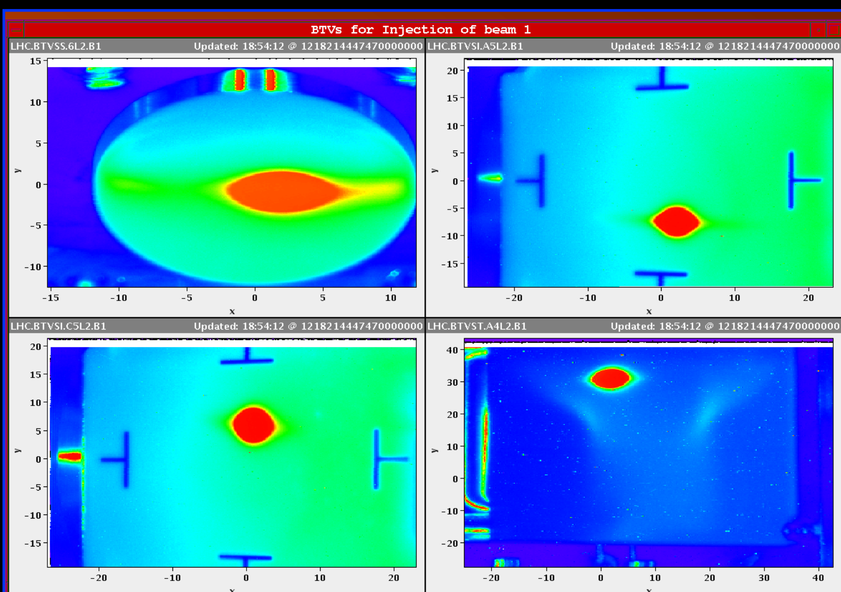


Profile Monitoring using Screens

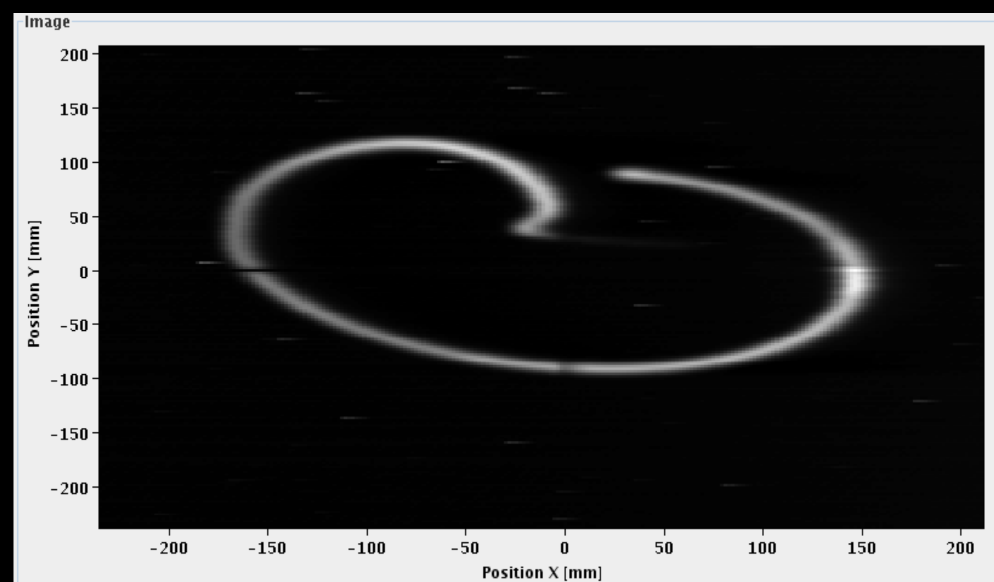
- Early Diagnostics
  - Luminescence / Scintillating Screens
    - Destructive (thick) but work with low intensities
- Advantages
  - Allows use of CCD camera
    - gives 2D information





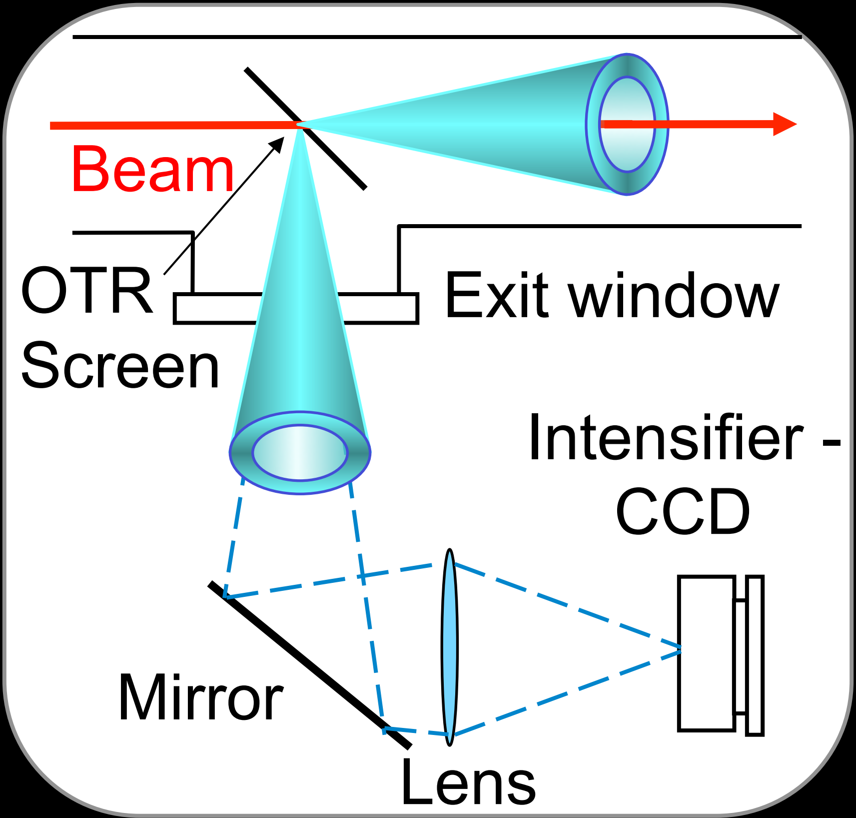


First Beam in the LHC 8/8/2008

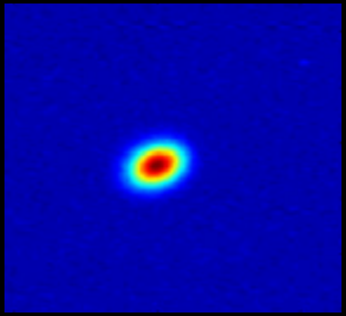


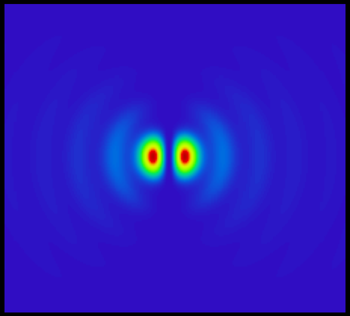
Profile Monitoring using Screens

- 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

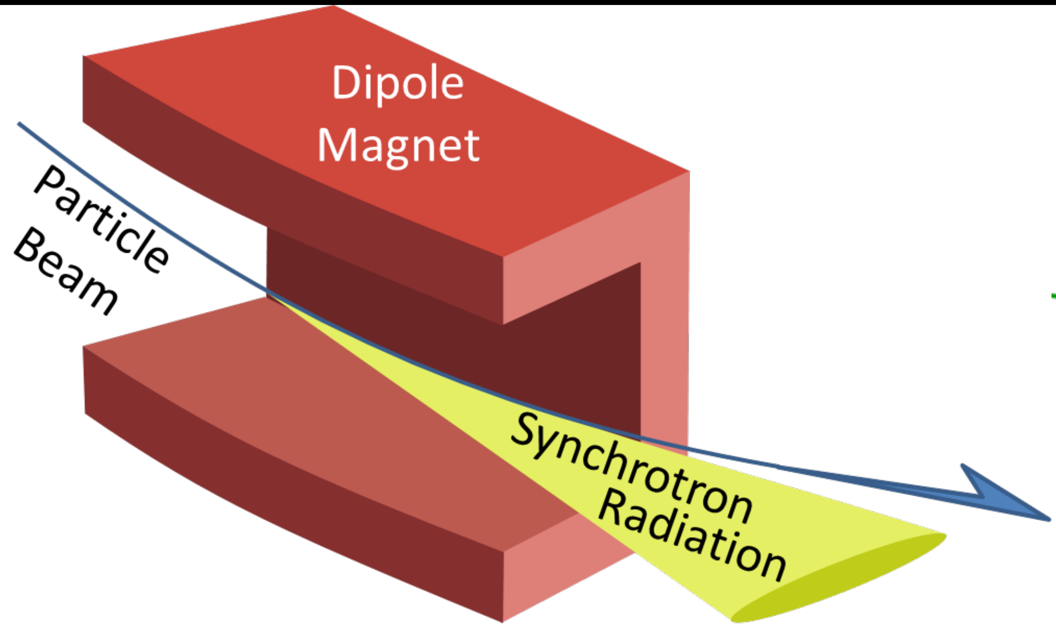


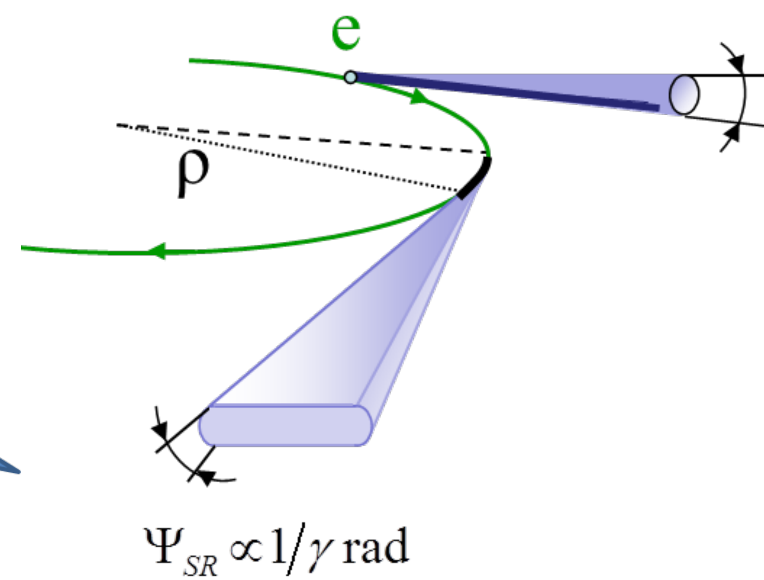
- OTR screens
  - Less destructive than scintillation but requires higher energy / intensity beam
  - Can be used for extremely high resolution measurements



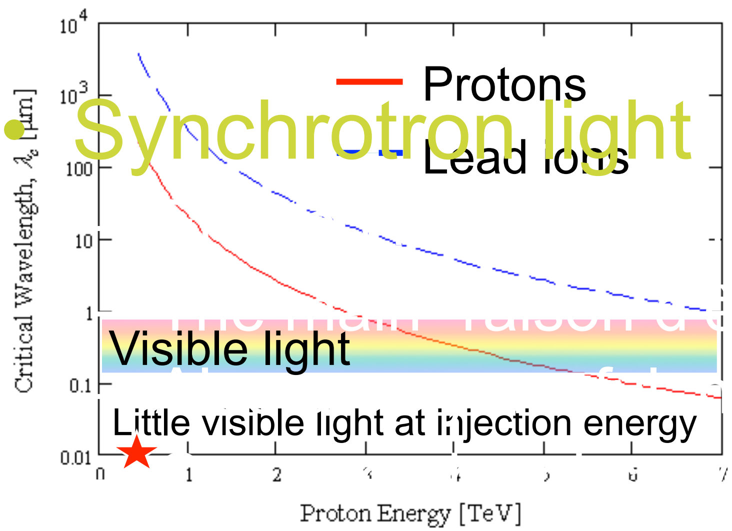


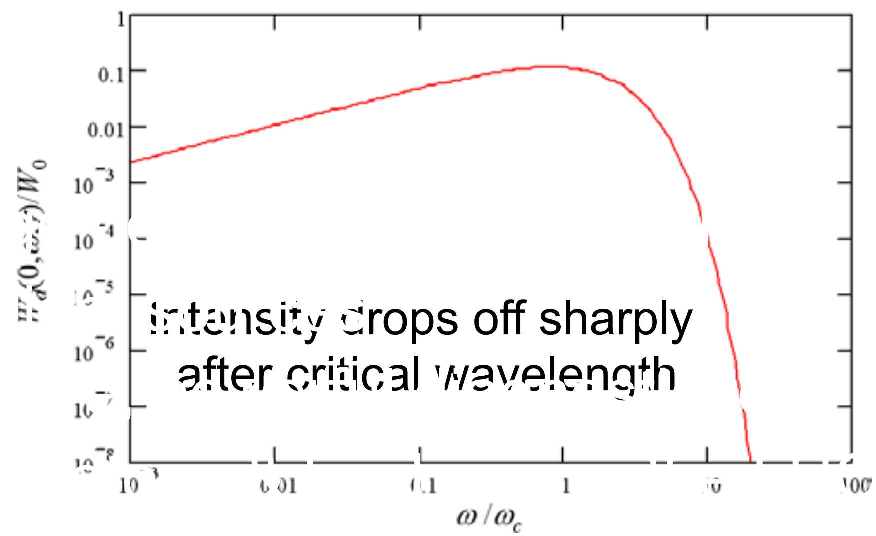
Synchrotron Light Monitors





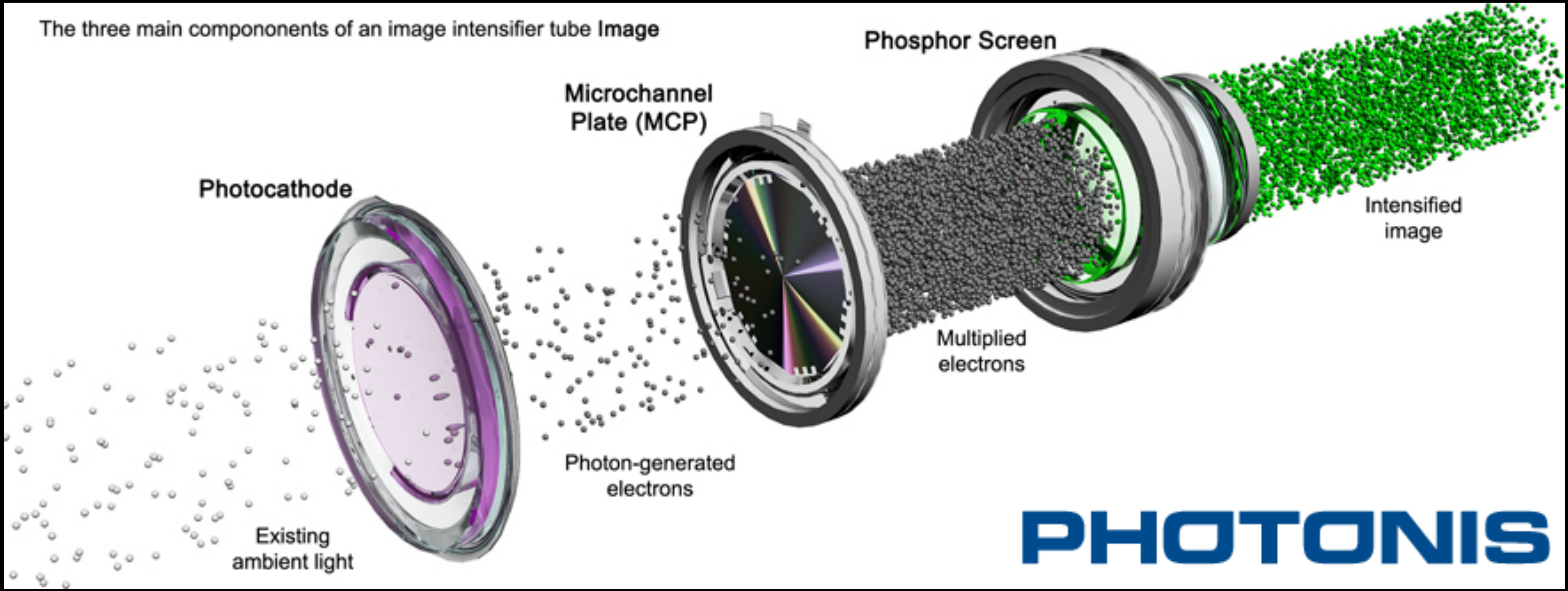
- Synchrotron light





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



Longitudinal Profile Measurement

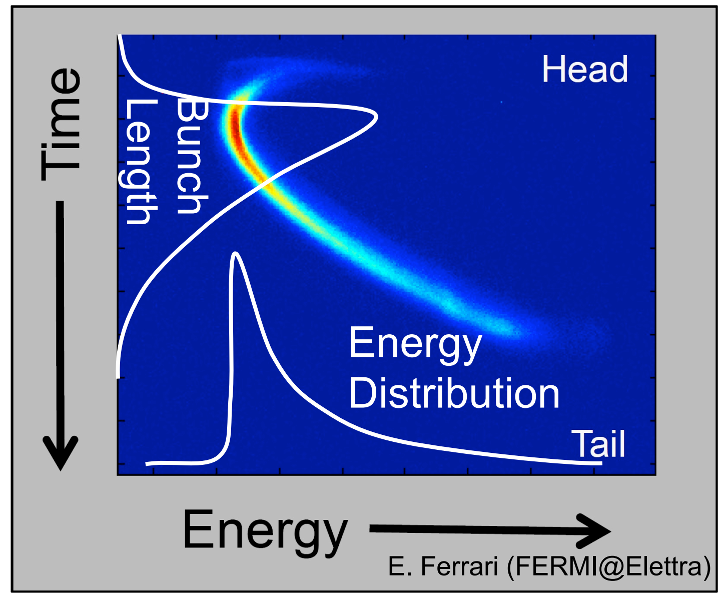
- Next Generation FELs & Linear Colliders
  - Use ultra short bunches to increase brightness or improve luminosity
- How do we measure such short bunches?

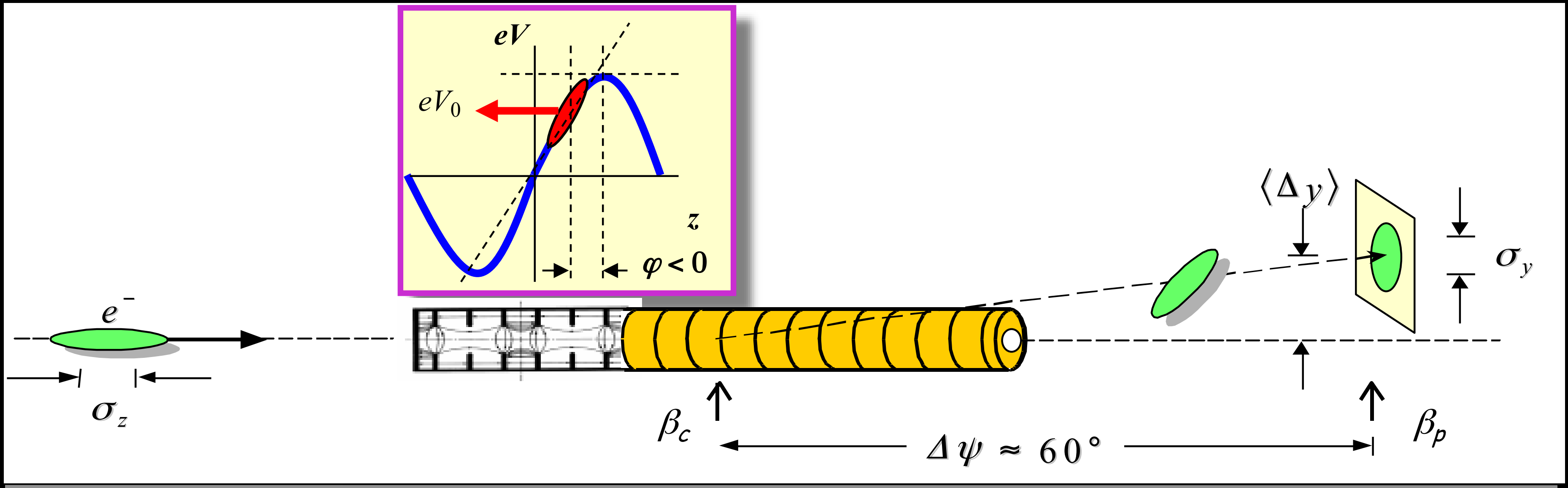
p^+ @ LHC	250ps
H^- @ SNS	100ps
e^- @ ILC	500fs
e^- @ CLIC	130fs
e^- @ XFEL	80fs
e^- @ LCLS	<75fs

  - Direct Observation
    - Synchrotron radiation observed with dedicated instruments
      - Streak camera resolution ~200fs
    - Use of RF techniques
    - Use laser pulses and sampling techniques
  - Indirect Calculation
    - Reconstruct bunch length from frequency spectrum
      - Either directly from the bunch or through its radiation spectrum

Measuring Ultra Short Bunches

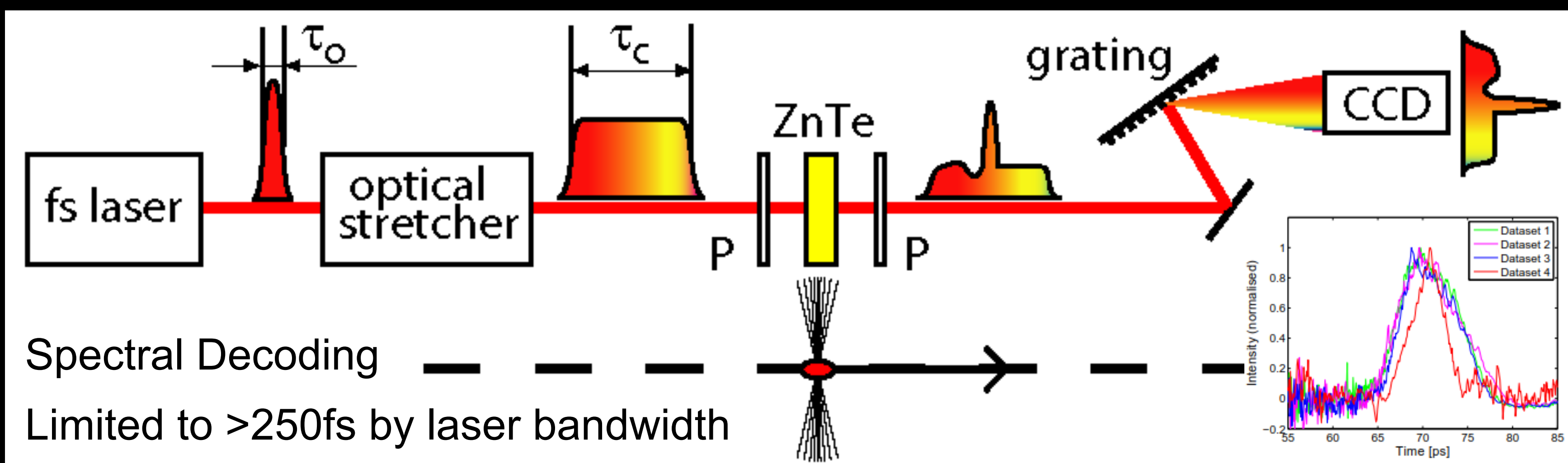
- RF Deflection
  - Converts time information to spatial information
  - Coupled to spectrometer also provides energy information
  - Destructive technique
  - Resolution down to 1.3 fs
    - X-band RF cavity
    - Linac Coherent Light Source (SLAC)

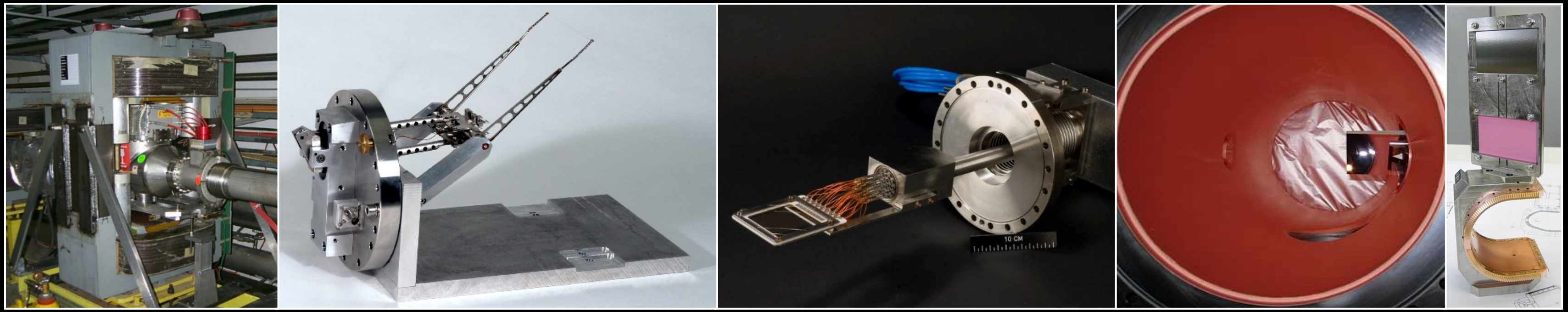




Measuring Ultra Short Bunches

- Electro-Optic Sampling
  - Birefringent crystal placed close to the beam
    - Non-destructive technique
  - Bunch passes simultaneous a to chirped (time varying wavelength) laser pulse
  - Intensity of bunch electric field modifies polarisation of light in crystal
    - Longitudinal bunch distribution mapped to wavelength
  - Wavelength v. Intensity gives longitudinal bunch distribution
    - Can be done in a variety of ways (simplest example below)
    - Resolution down to 30 fs possible



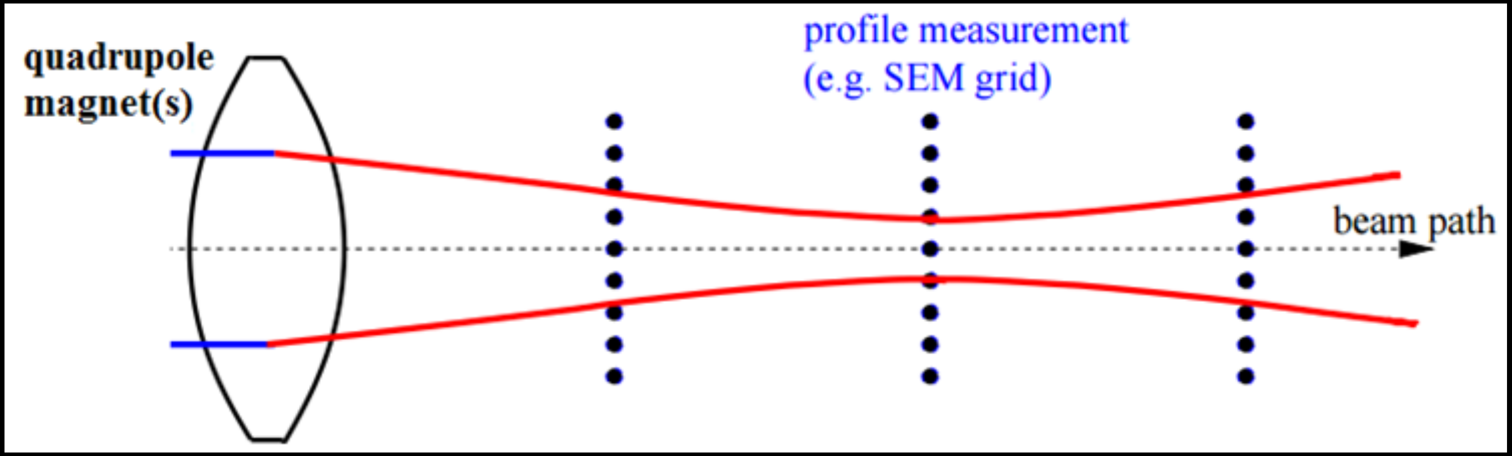


Diagnostics using Beam Profile Monitors

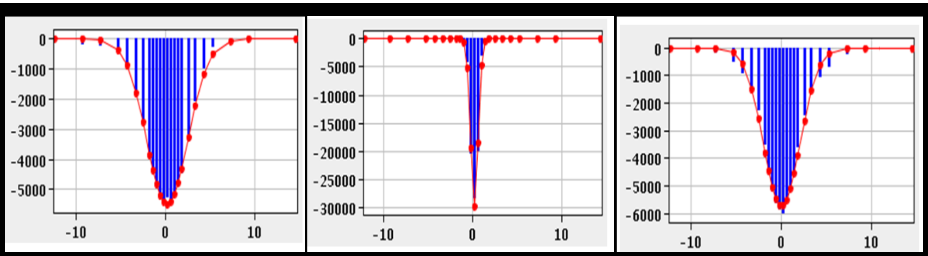
Optics Measurement in LINACs

3 Monitor Method

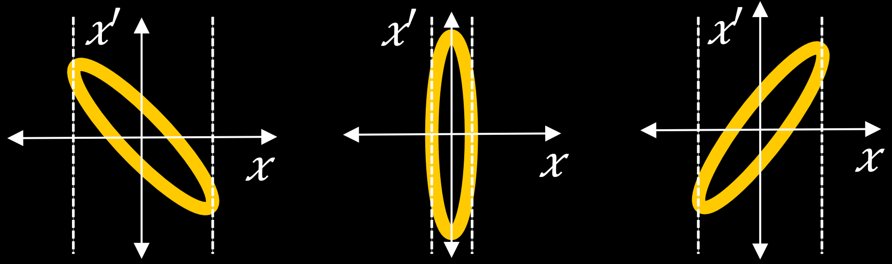
– Optics functions & initial emittance reconstructed using transport matrix



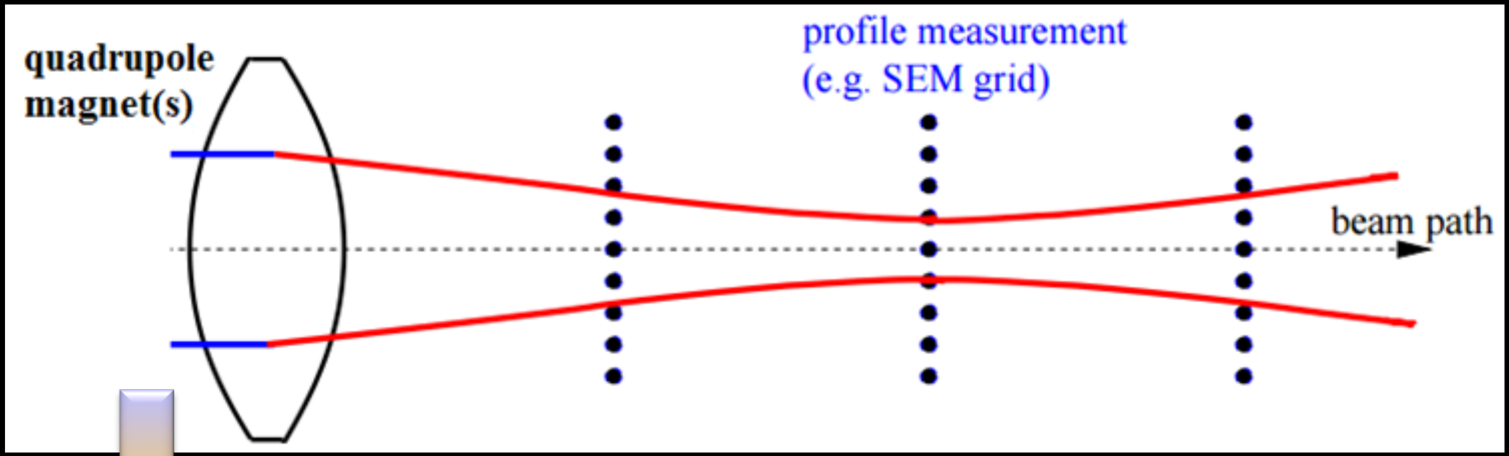
Measured Beam Profiles



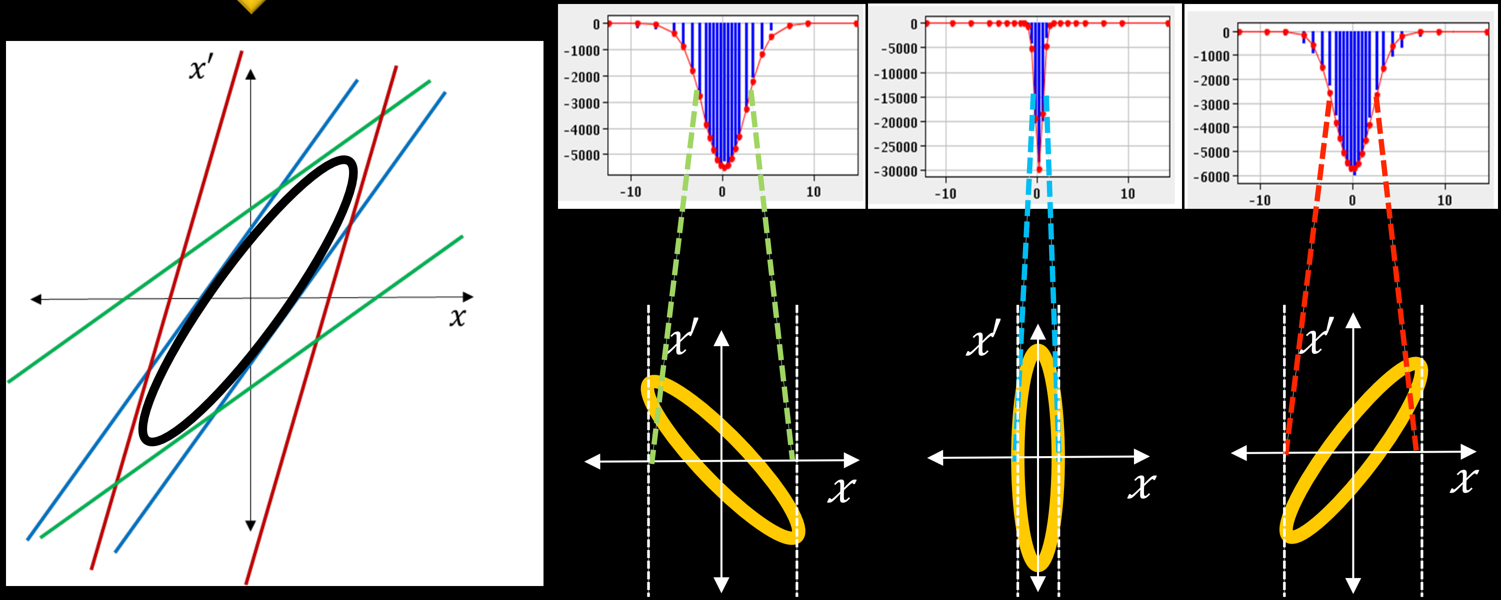
rms ellipses



Optics Measurement in LINACs

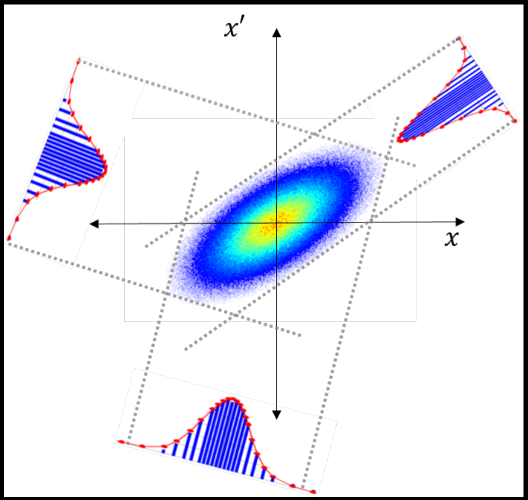


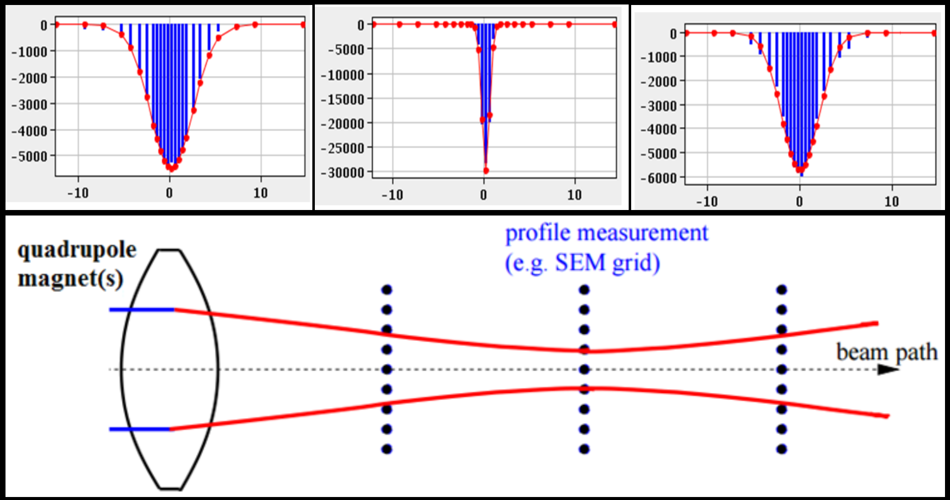
Linear Mapping of measured beam size onto initial phase space



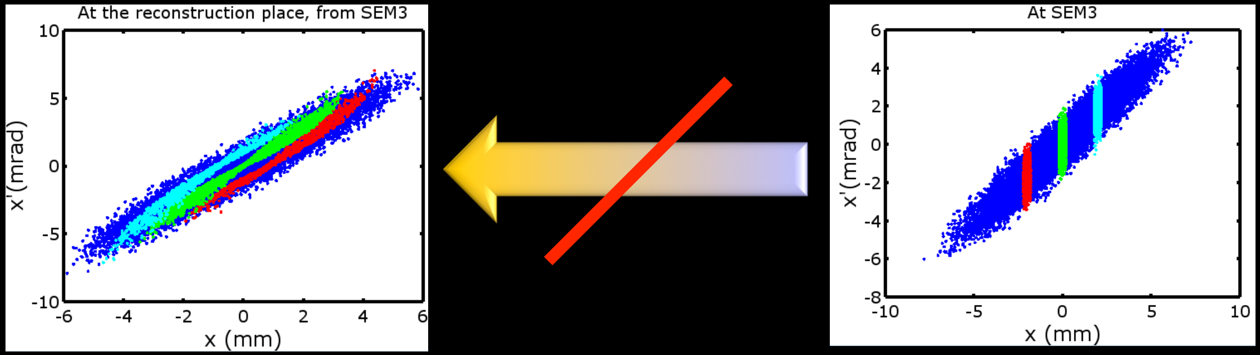
Optics Measurement in LINACs

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



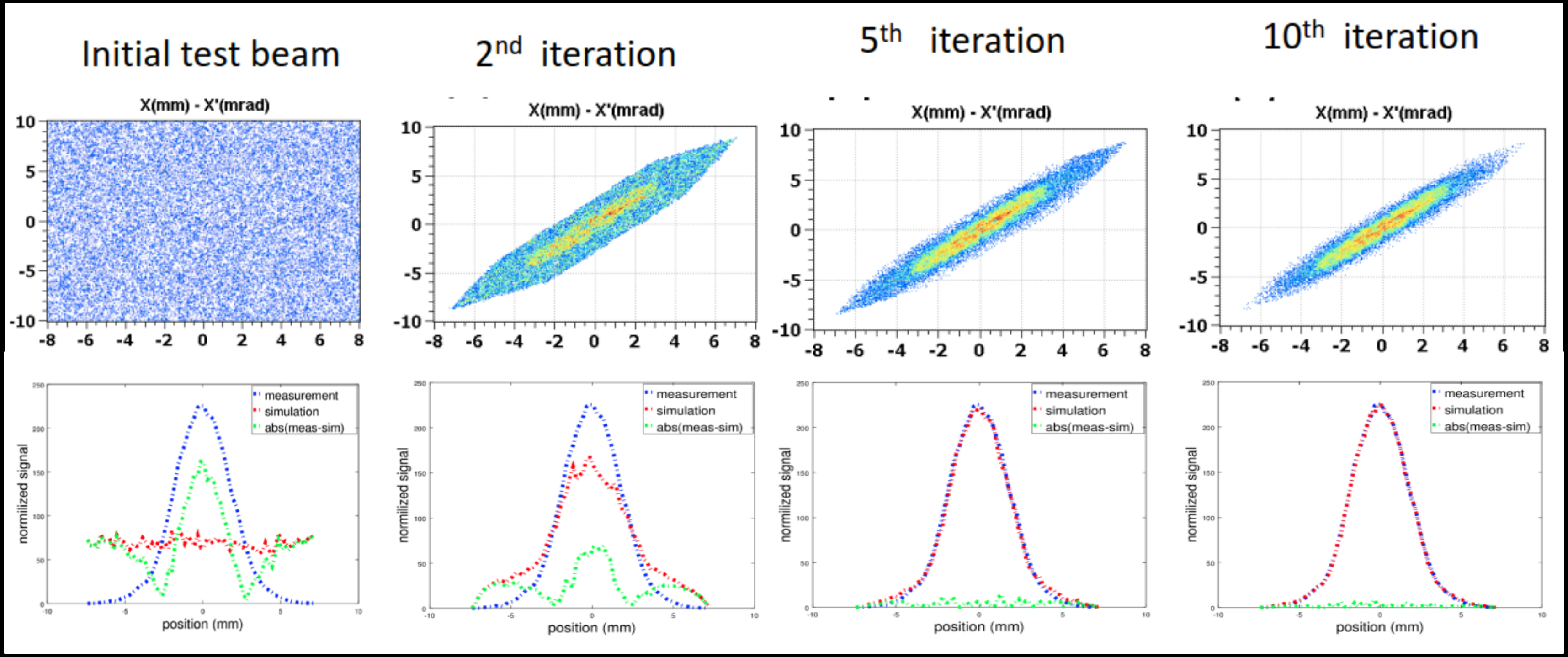


- Things get more complicated when you add space charge



Optics Measurement in LINACs

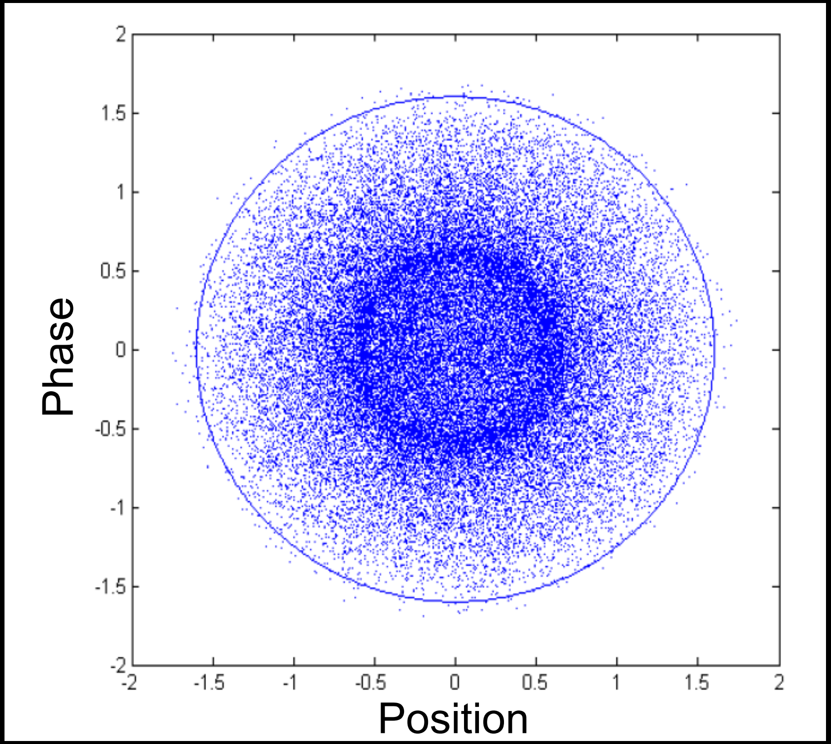
- Hybrid Phase Space Tomography in Linac4
  - Iteratively vary Twiss parameters
  - Track to the measurement locations including space-charge
  - Deduce new distribution of density in phase space from which particles fall on which wires
  - Generate new beam distribution & use for next iteration

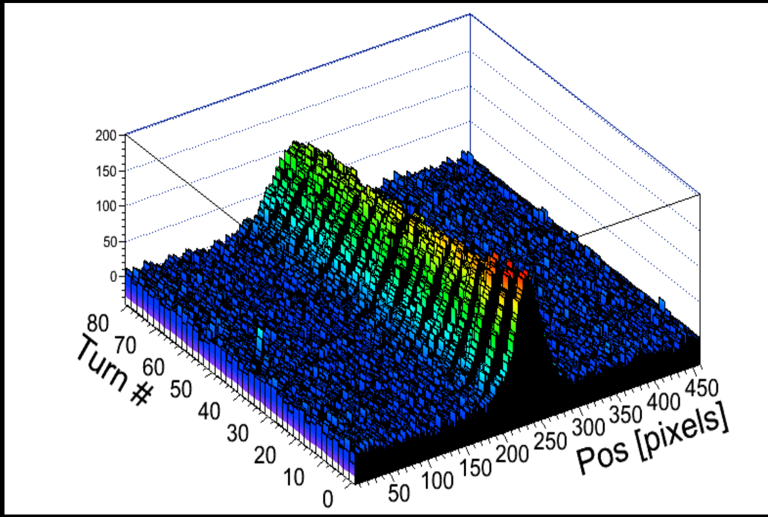


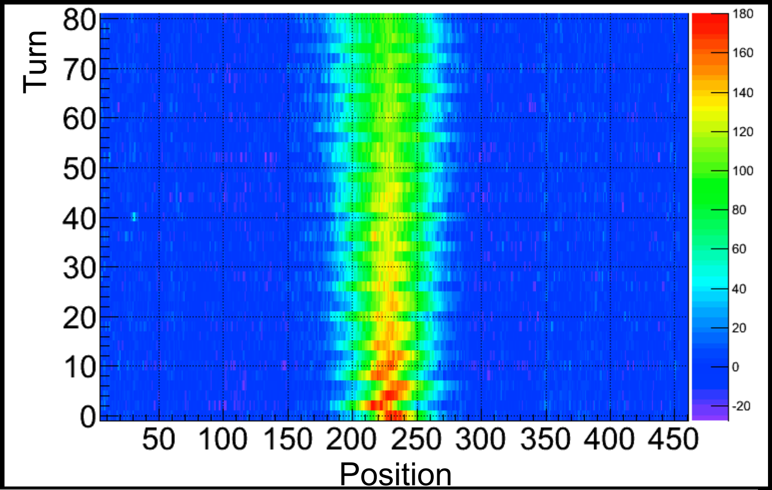
Reconstructed & Measured profiles at last SEM grid

Measurements with Screens

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







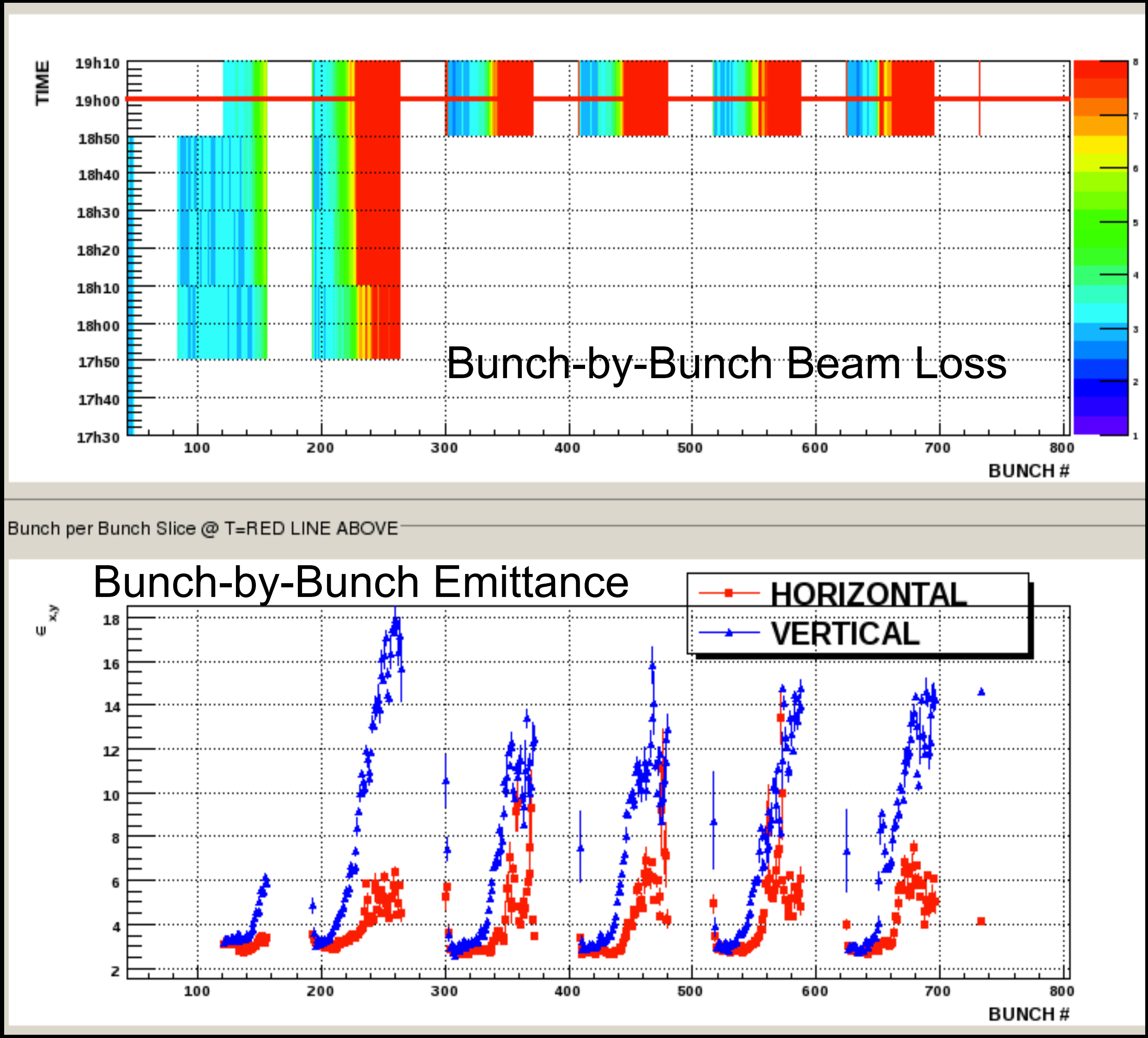
Bunch by Bunch Diagnostics

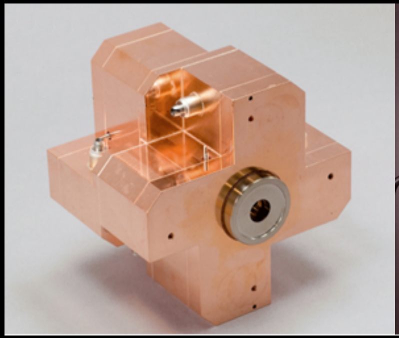
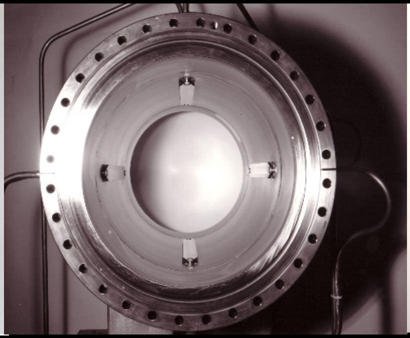
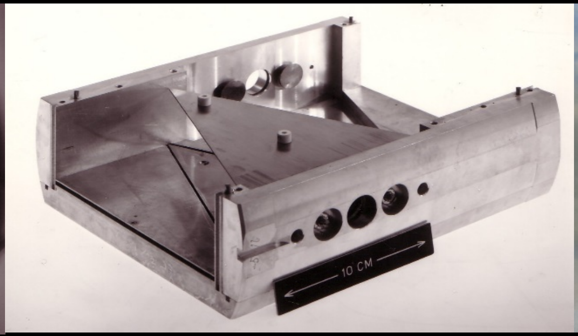
LHC Synchrotron Light Diagnostics

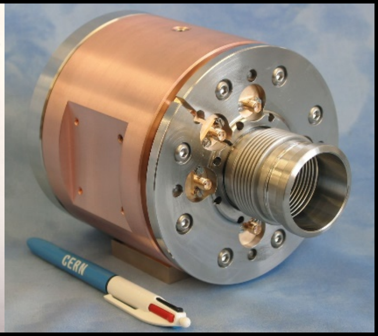
- Gated intensified Camera
- Allows bunch by bunch profile measurement

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



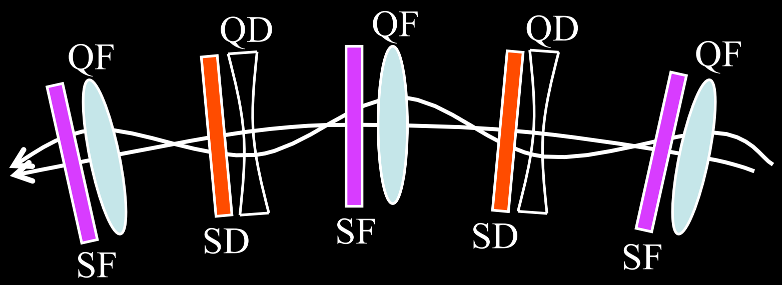




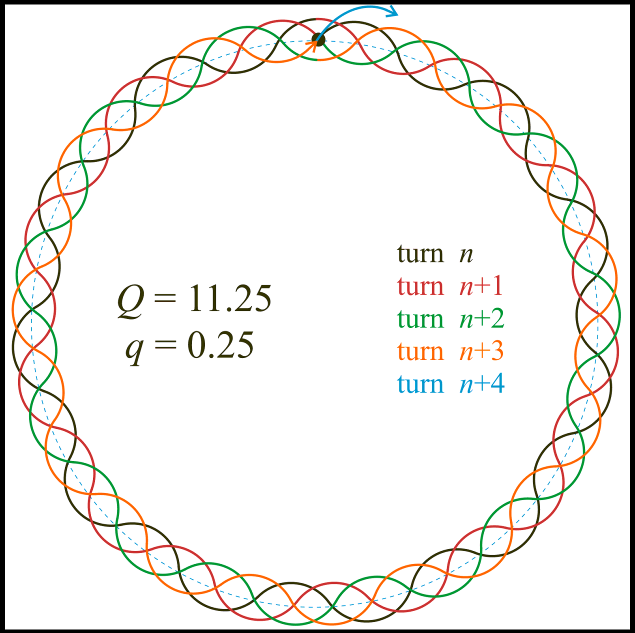
Tune, Coupling & Chomaticity Measurement

Machine Tune

- ## Machine Tune



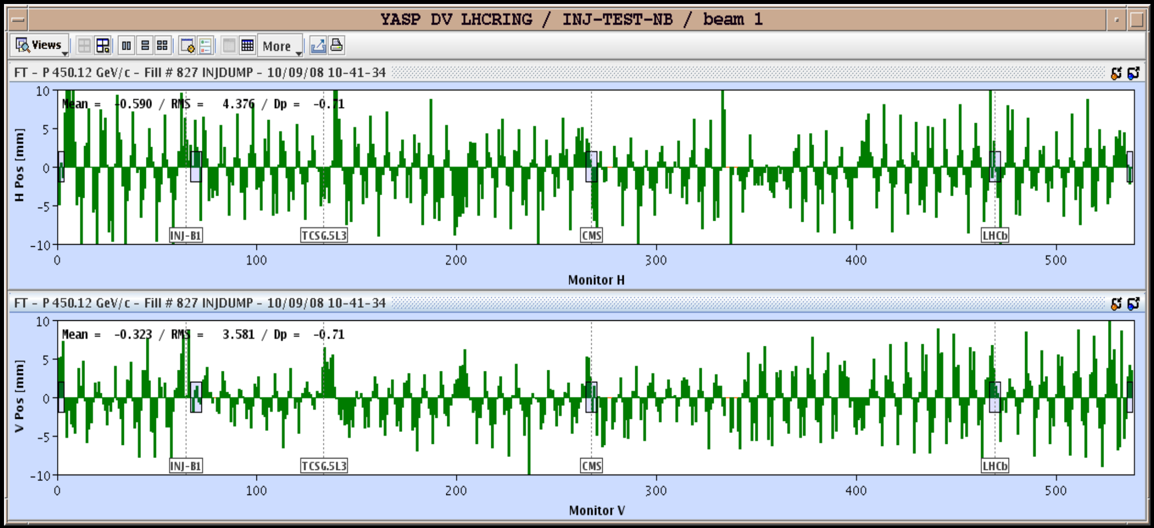
Characteristic Frequency
of the Magnetic Lattice
Given by the strength of the
Quadrupole magnets



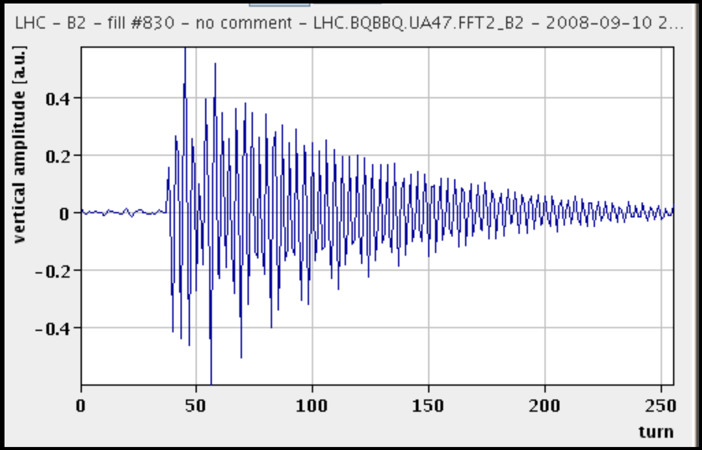
- Parameters per plane
  - Q : Full betatron tune
  - q : Fractional tune (operating point)
- Real life more complex
  - horizontal & vertical oscillations couple
  - betatron motion at large amplitudes non-linear

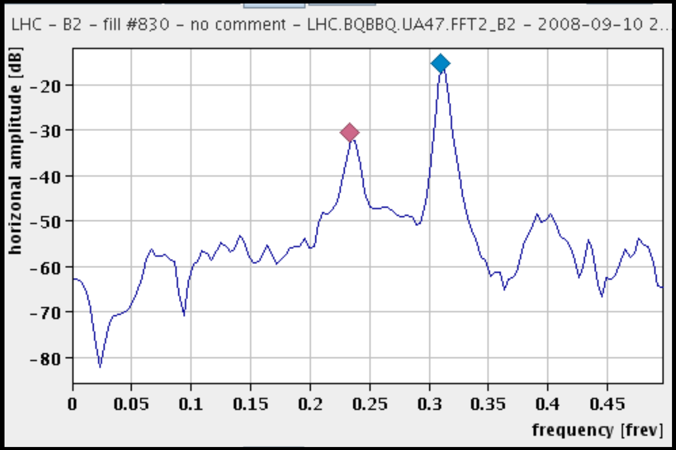
Tune Measurement

- Integer tune
  - can be seen in orbit response
  - H: 59, V: 64 for LHC

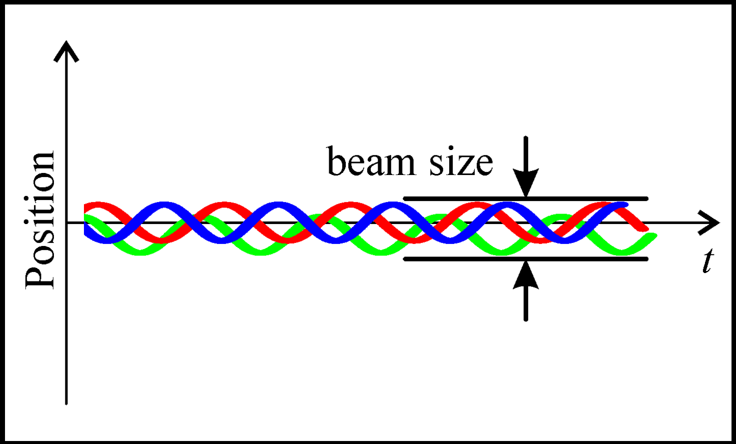


- Fractional tune (q)
  - Seen from turn-by-turn signal of single BPM if beam is given a kick
  - Fast Fourier Transform (FFT) of oscillation data gives resonant frequency (q)

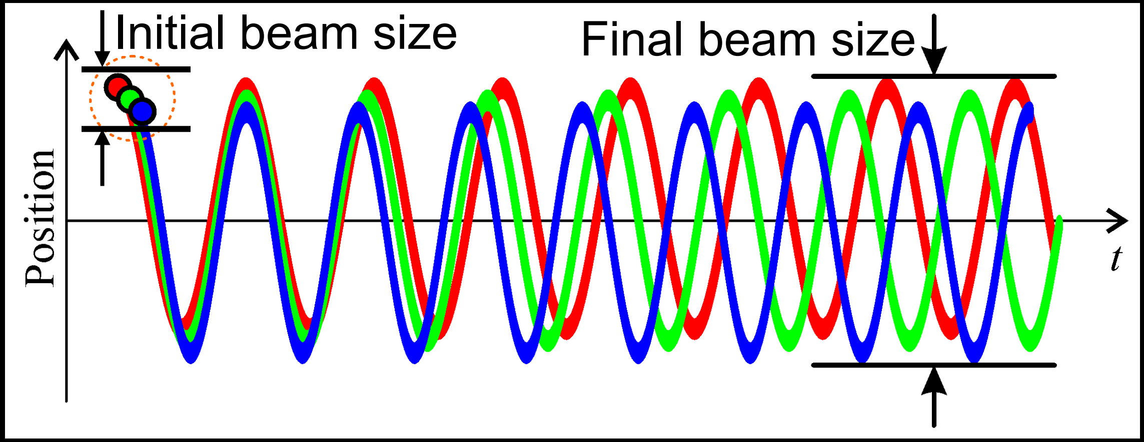


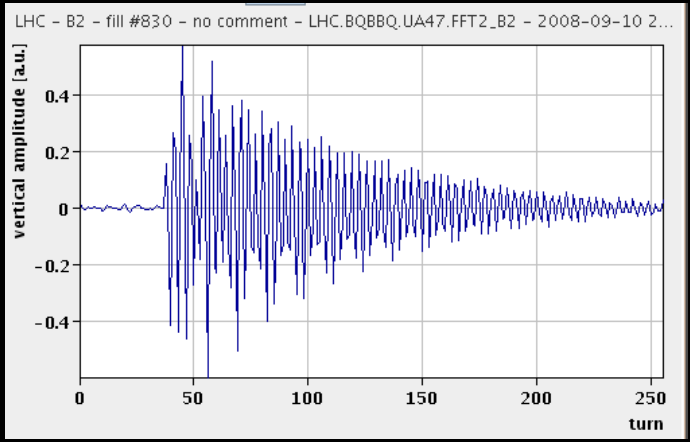


Tune Measurement – the principle



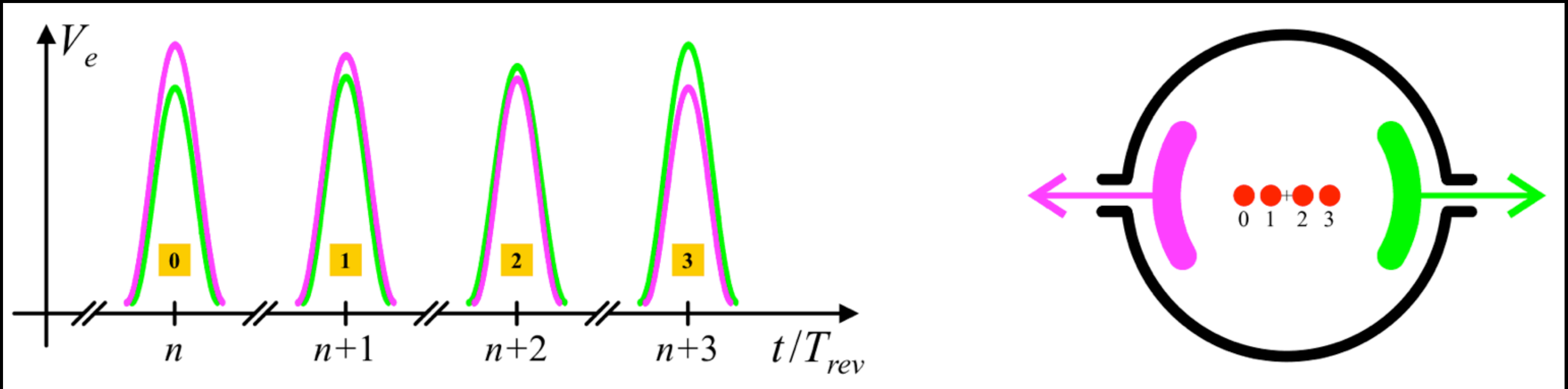
- Beam size
  - defined by incoherent betatron motion of all particles
- Particles have momentum spread
  - gives spread in focussing by quadrupoles
  - gives rise to spread in the frequency of the betatron oscillations (chromaticity)
  - coherent oscillations will de-cohere
- Hadrons do not forget!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





Tune Measurement – the principle

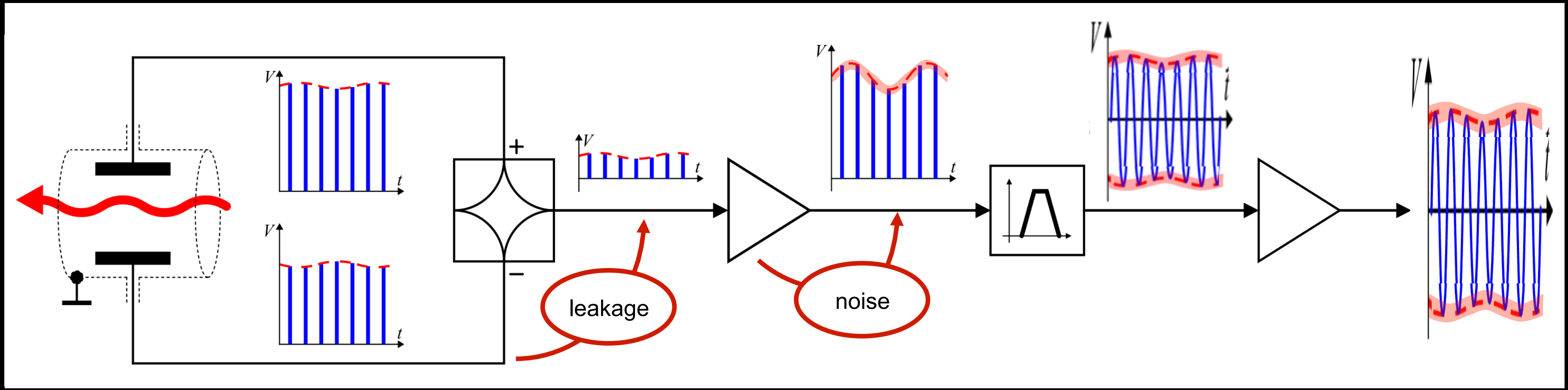
- Observable is typically turn-by-turn position from a BPM
- BPM electrode signal has temporal shape related to the temporal structure (intensity profile) of the passing beam
  - Most of the signal produced is linked to intensity
- On top we look for very small variations linked to position
  - Such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



Tune Measurement – the principle

- A typical perfect detection scheme

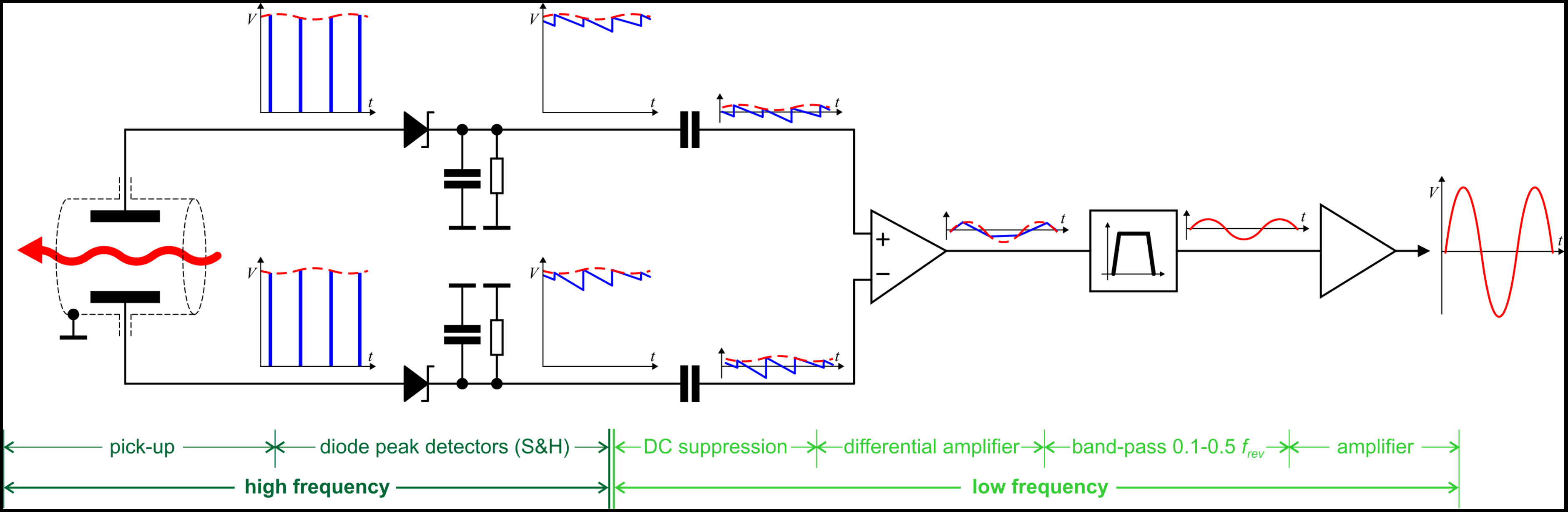
- Reality



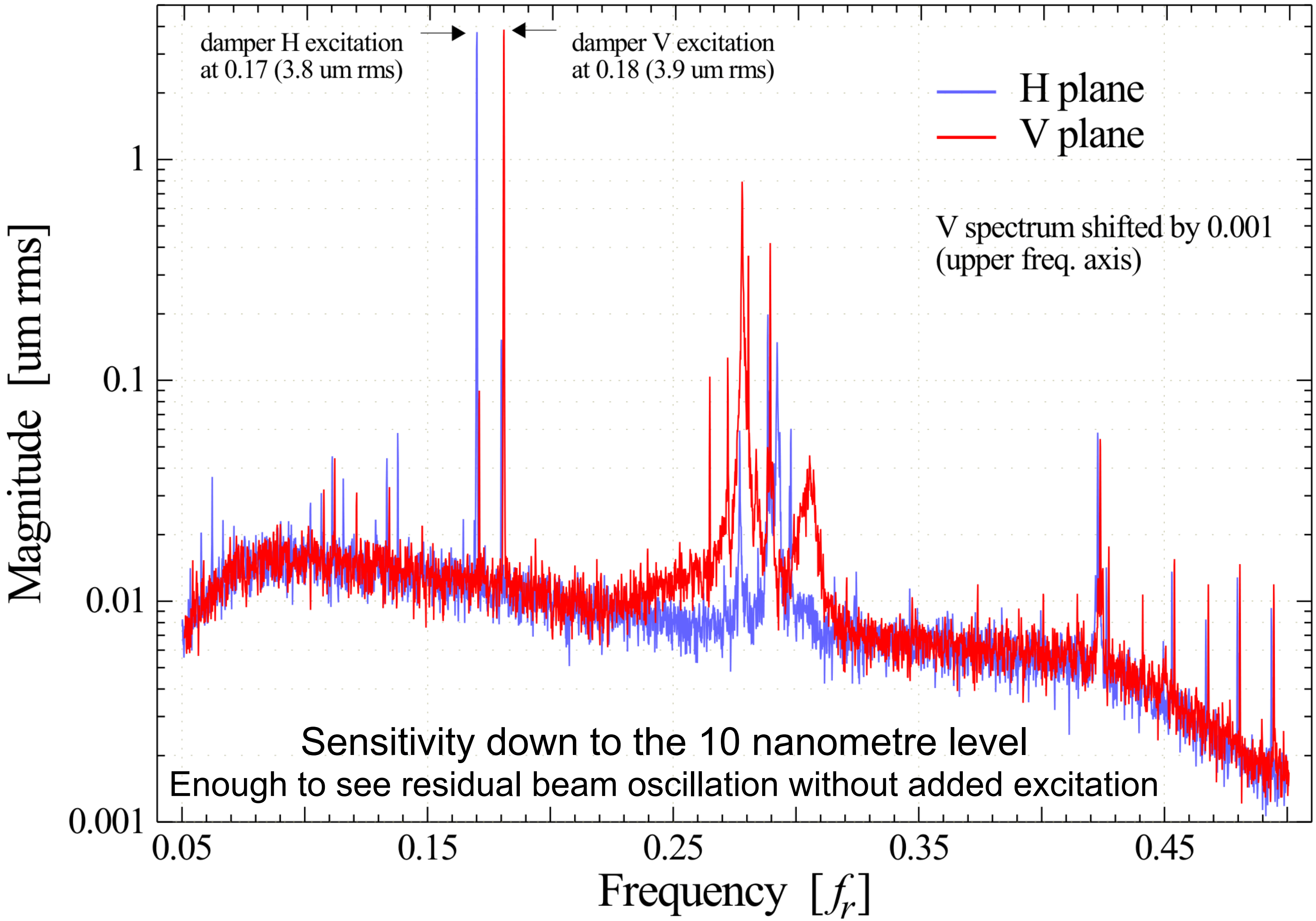
- Dynamic range issues
  - Signals related to betatron oscillations are small with respect to beam offset signals
  - Even for centred beam leakage is of order 1-10 % (of 100V!) for ns beam pulses

The LHC Tune Measurement System

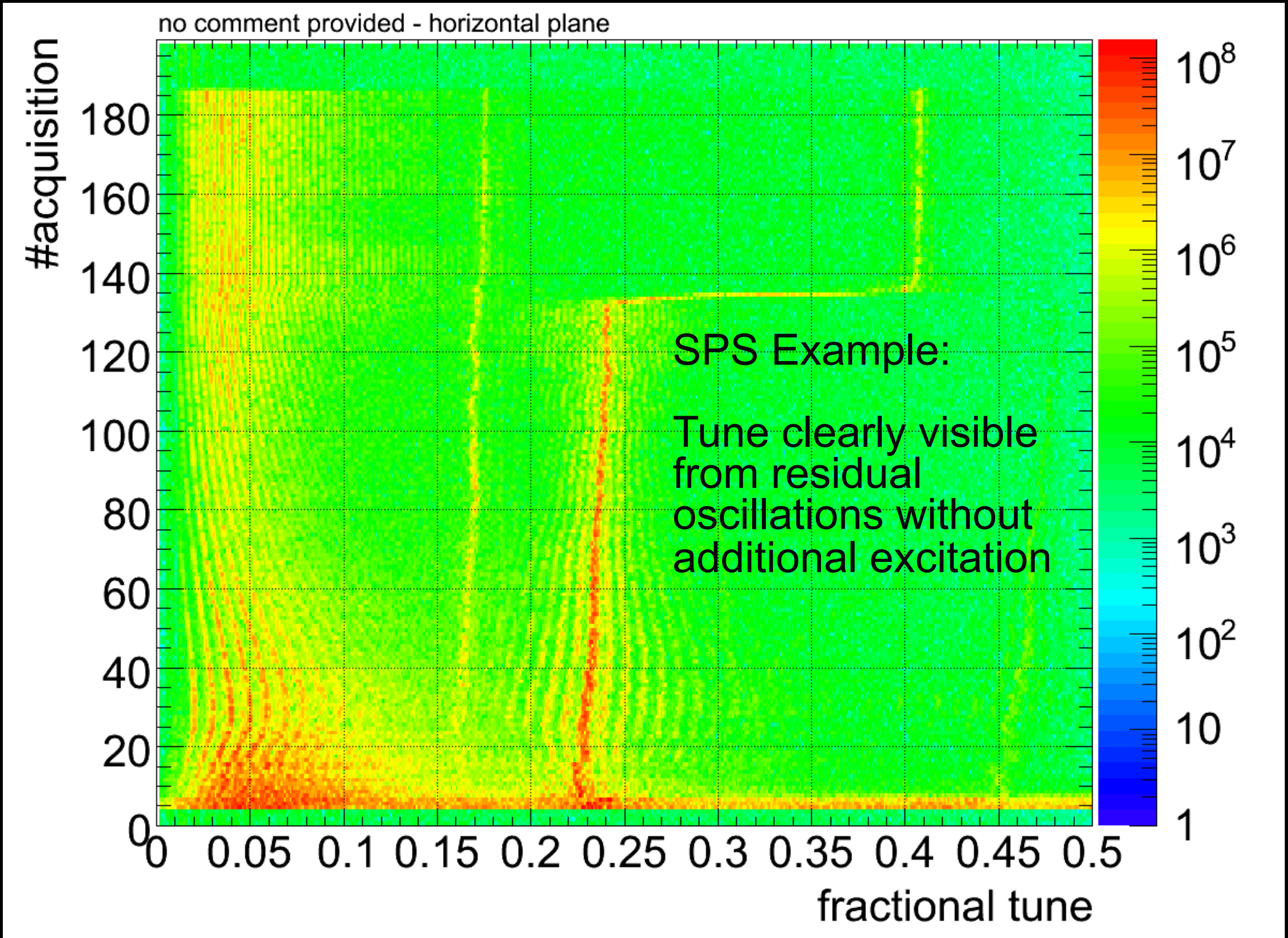
- Direct Diode Detection – the advantages
  - Single RF Schottky diode can handle up to 50 V pulses
    - Higher with a few diodes in series (LHC detector has 6 diodes)
  - Betatron modulation downmixed to below the revolution frequency
    - Allows efficient signal processing with inexpensive, high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



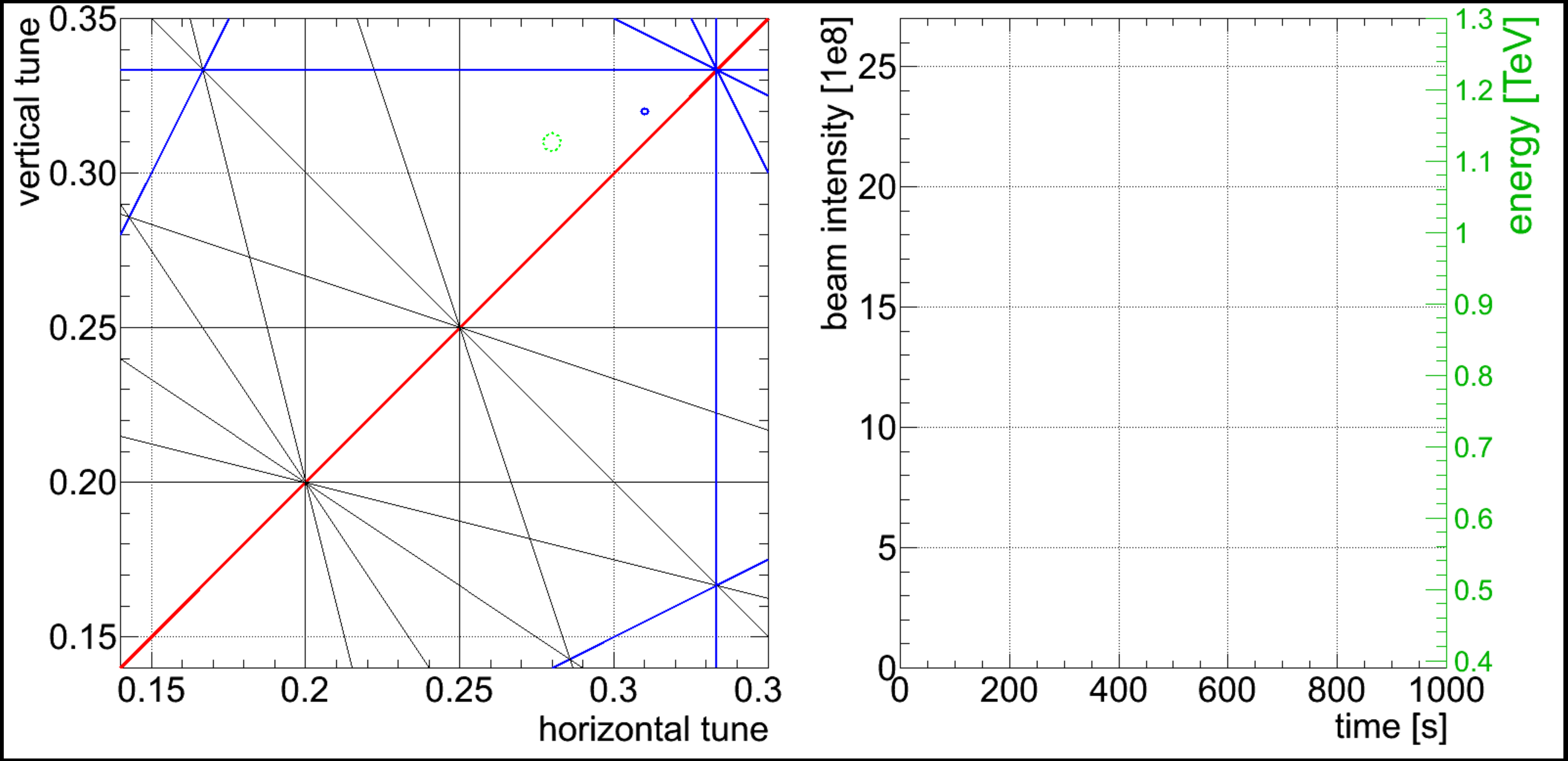
LHC Tune System Performance



Real-Time Tune Display

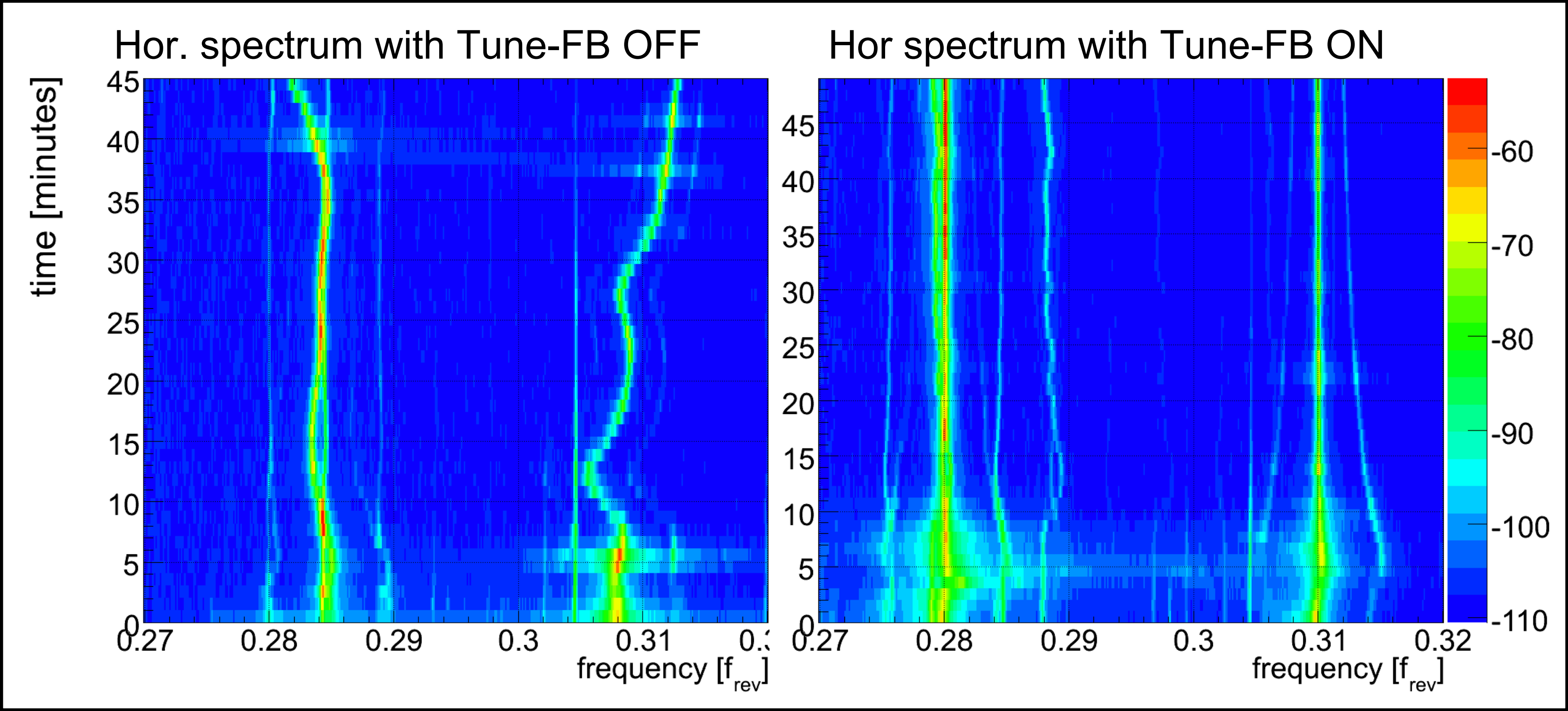


Tune Measurement in the LHC



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

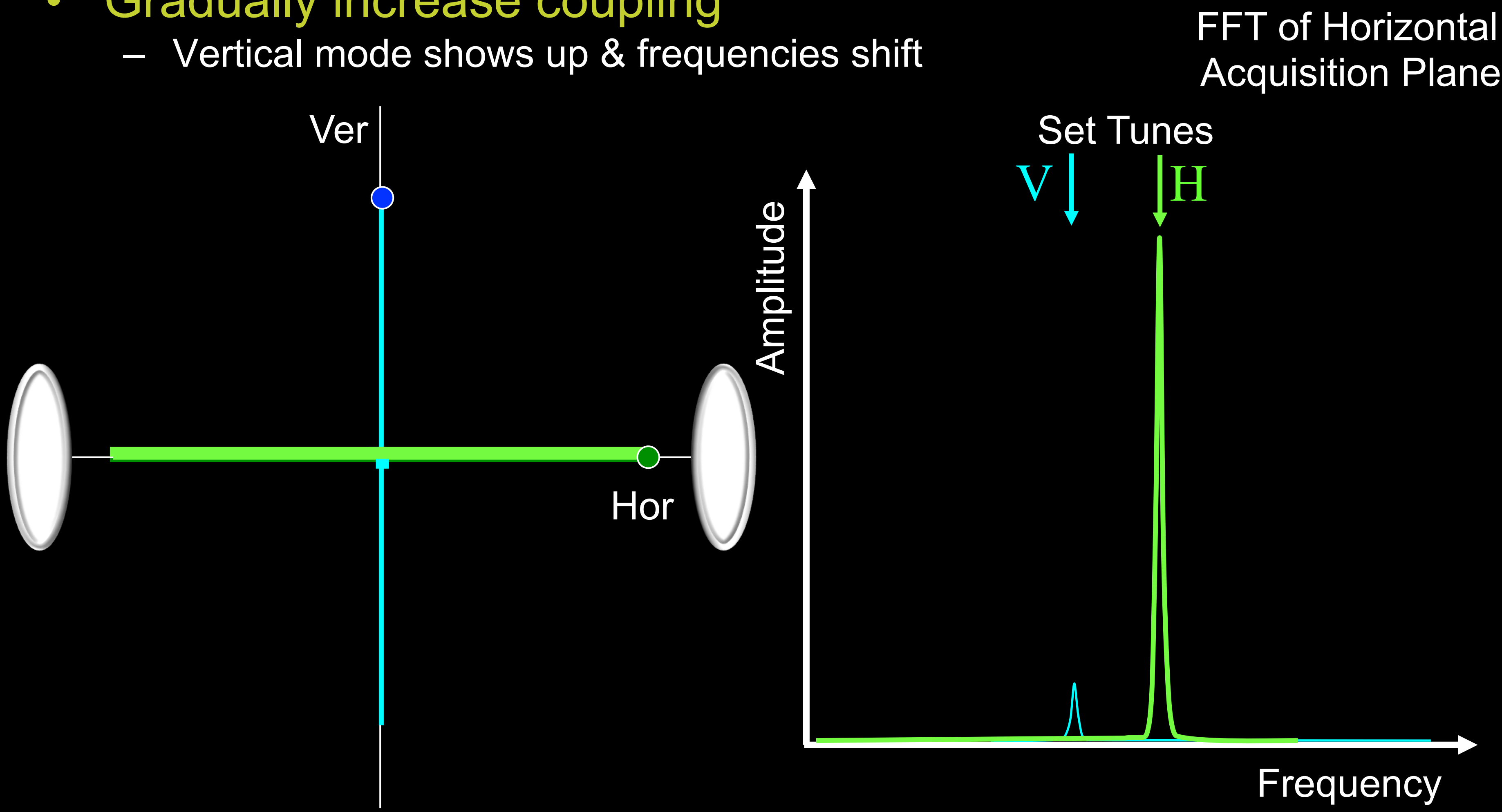
Tune Feedback in the LHC



- 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

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



Coupling & Tune Control

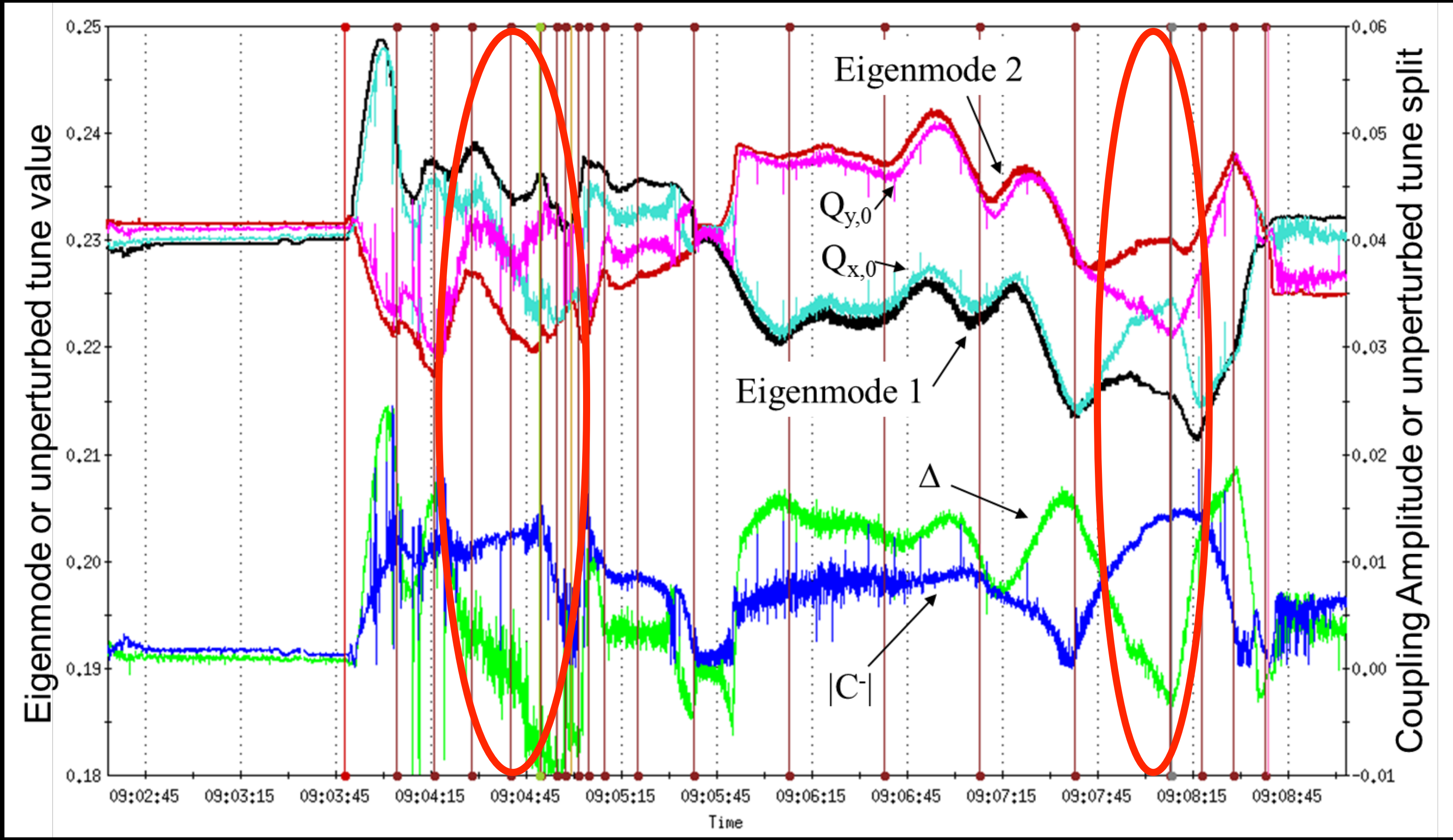
Set Measured

$$Q_{x,0} = Q_1 + \tfrac{1}{2}\Delta - \tfrac{1}{2}\sqrt{\Delta^2 + \left|C^-\right|^2}$$

- Measured tunes - the physical observables
  - Often called the 'normal modes' or 'eigenvalues'
- Set tunes
  - What tunes would be in absence of coupling
  - Can be calculated with knowledge of coupling
- The coupling coefficient C^-
  - Often called 'minimum tune split' or ΔQ_{min}
  - 'Forbidden zone' in a system of coupled oscillators
- Set tune split Δ
  - Difference between the set horizontal & vertical tunes
- When C^- greater than Δ
  - Conventional tune control no longer works
  - Magnet system applies correction to the wrong plane
  - Tune feedback becomes unstable

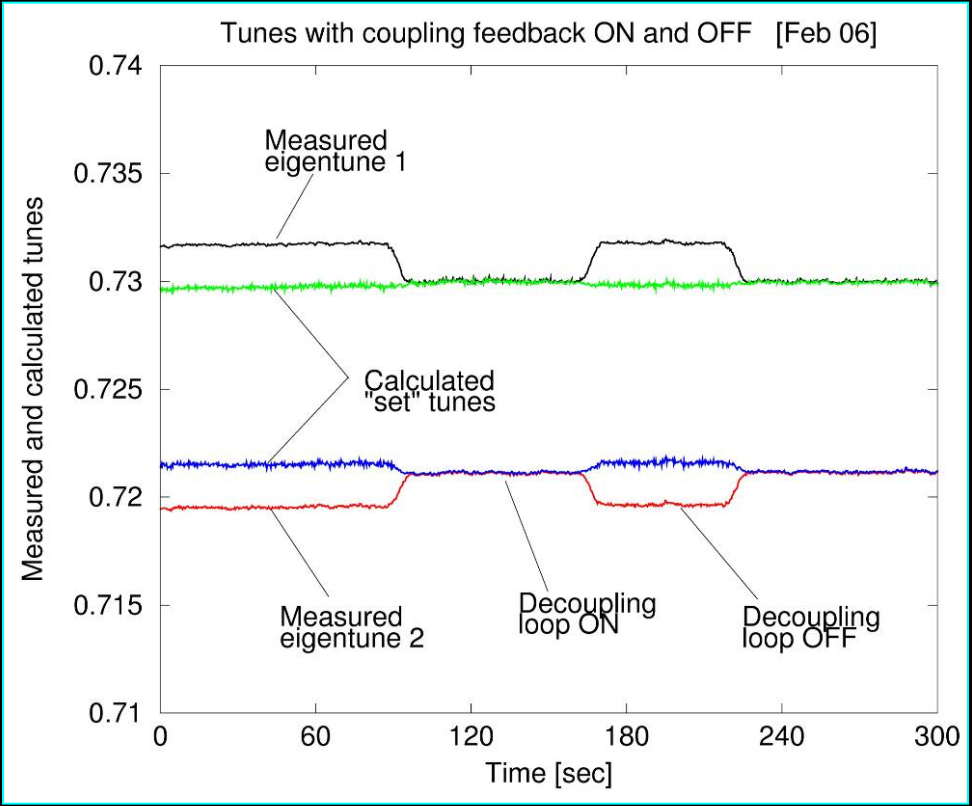
Coupling & Tune Feedback

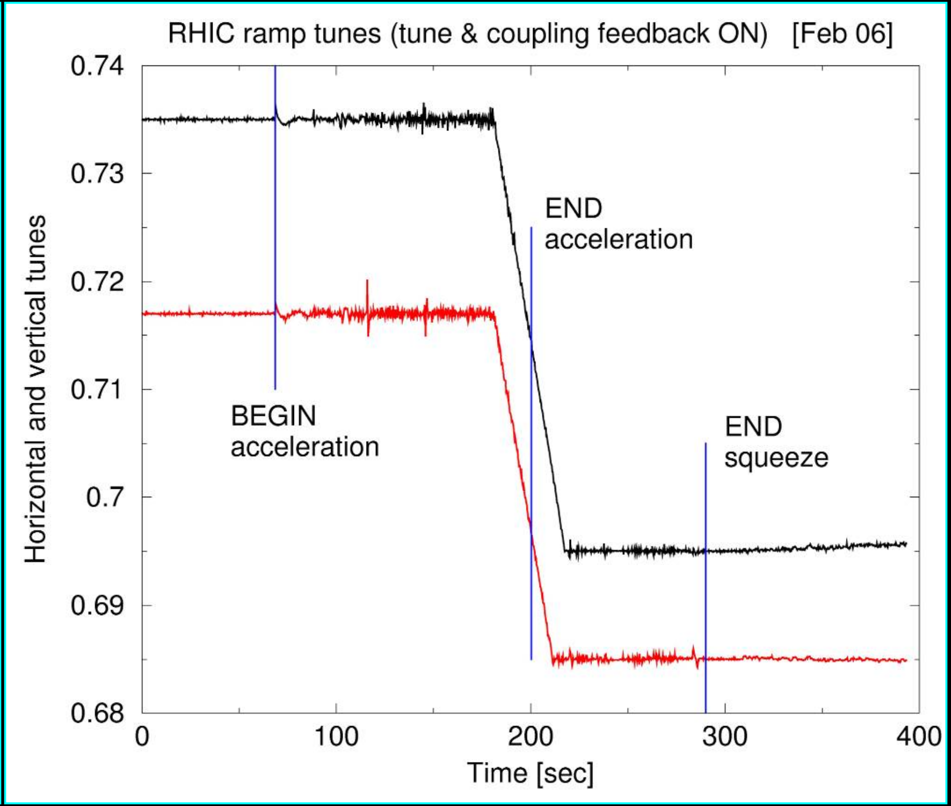
- Measurement from RHIC during acceleration cycle
  - At several points measured tune is defined by coupling
  - Tune feedback breaks down at these points



Coupling & Tune Feedback

- Coupling Feedback at RHIC
  - Measure coupling & feed-back on skew quadrupole families
    - Maintains a decoupled machine
  - Coupling & Tune feedback ON
    - Easily tracks & correct tune throughout acceleration cycle

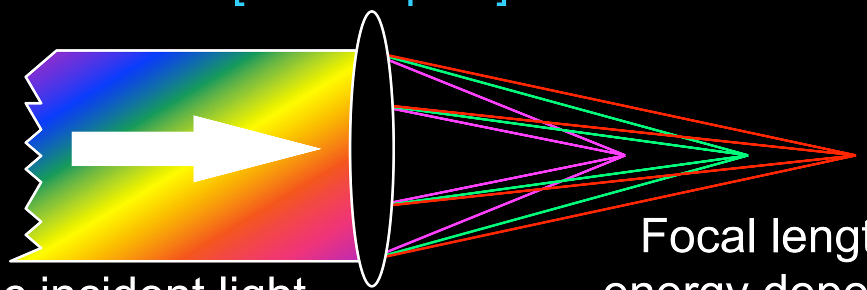




Chromaticity

- Machine Chromaticity

Optics Analogy:



Spread in the Machine Tune due to Particle Energy Spread

Controlled by Sextupole magnets

First Order

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

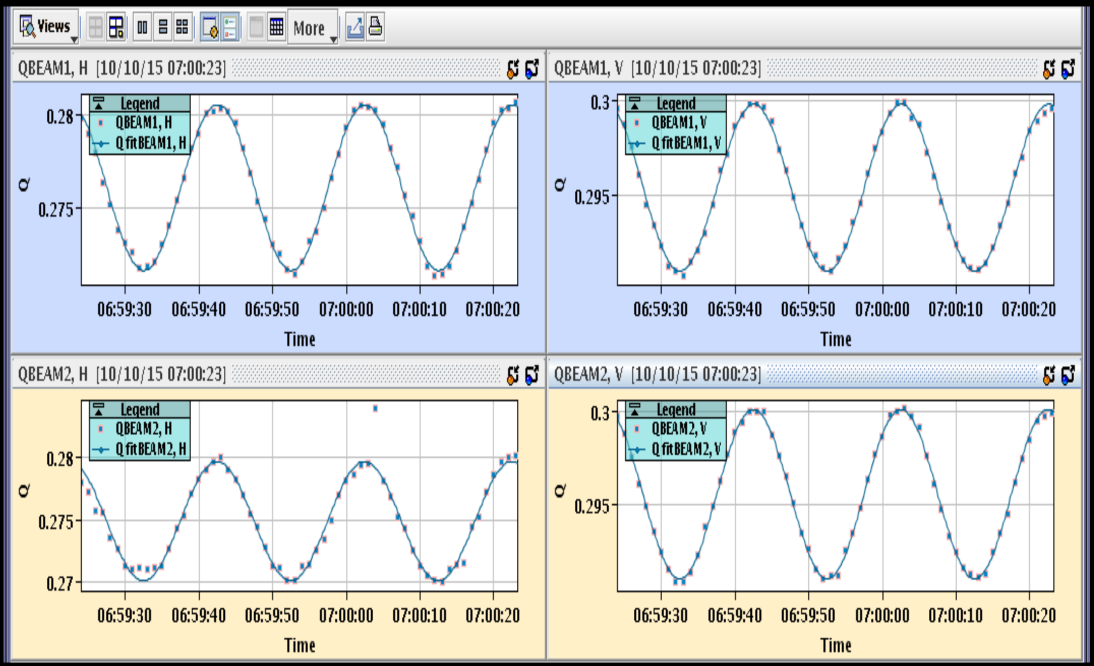
$$\xi = \frac{Q'}{Q}$$

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 ⇒ 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

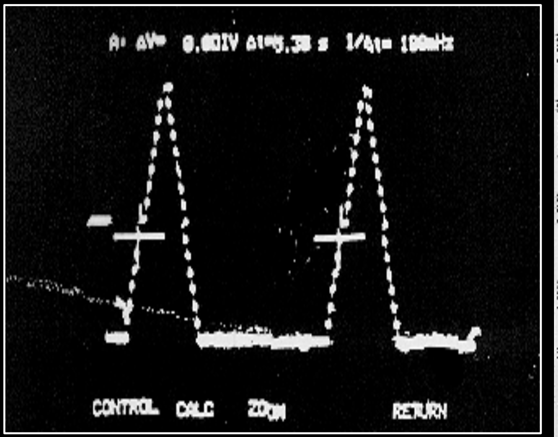


Example from the LHC

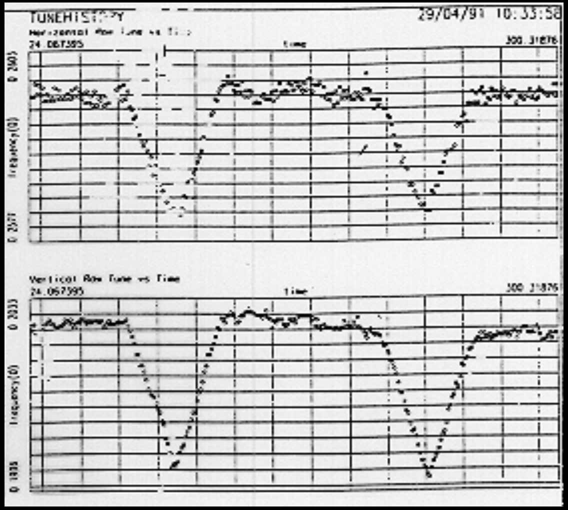
- Sinusoidal RF modulation at 0.05Hz
- Tune continuously tracked in all planes of both beams
- Chromaticity calculated once acquisition complete

RF Momentum Modulation Techniques

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



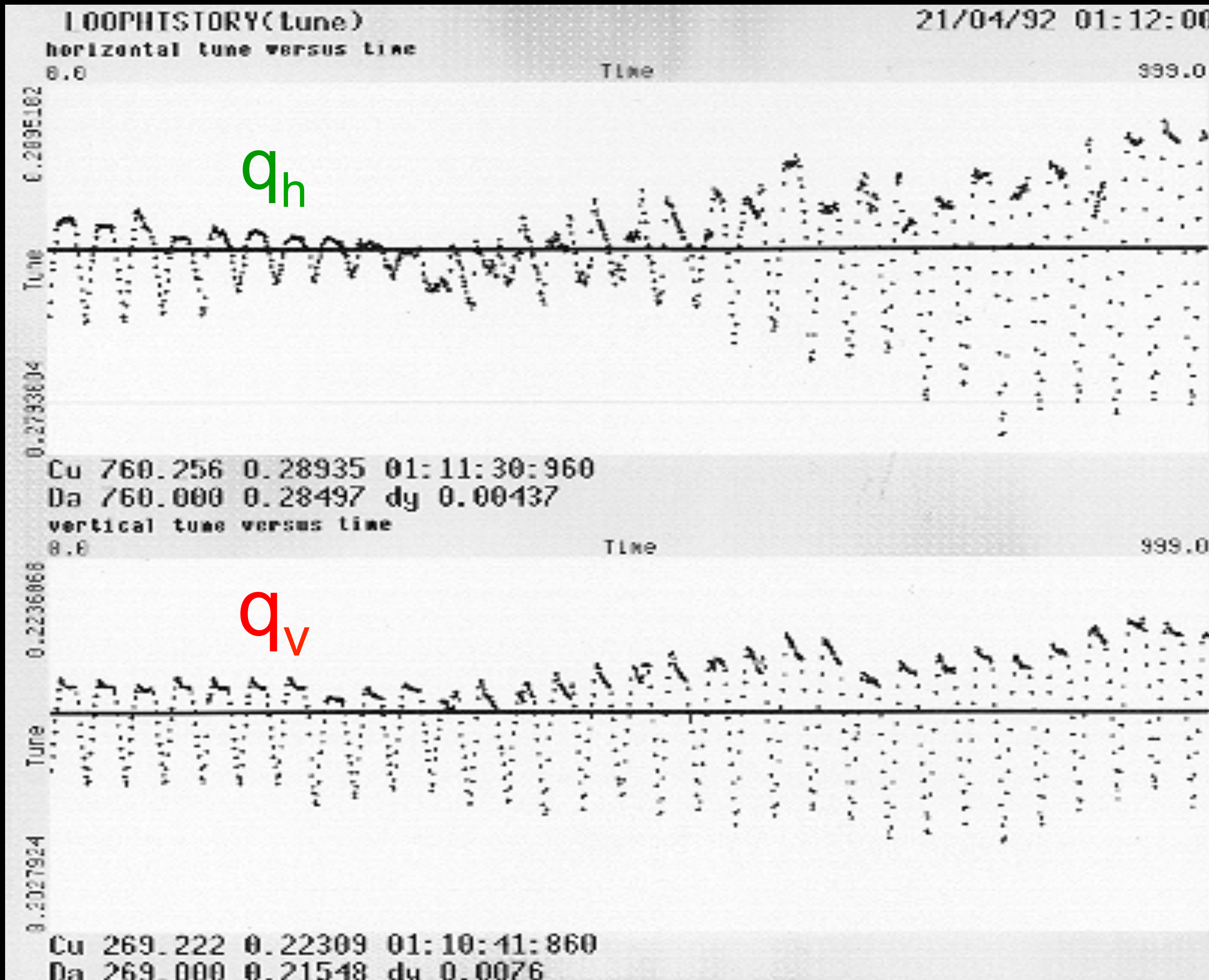
Applied Frequency Shift



Q_h & Q_v Variation

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

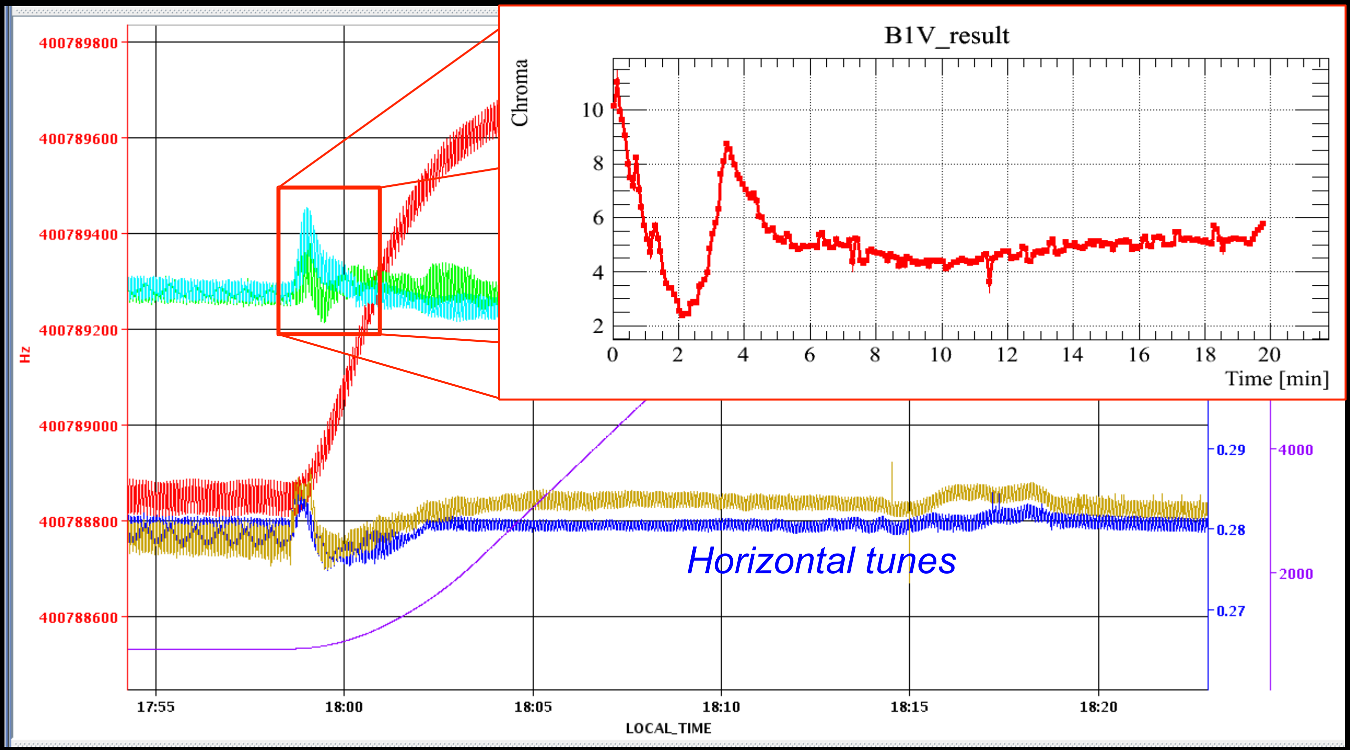
Example from LEP β-squeeze



Example from LHC Acceleration Ramp

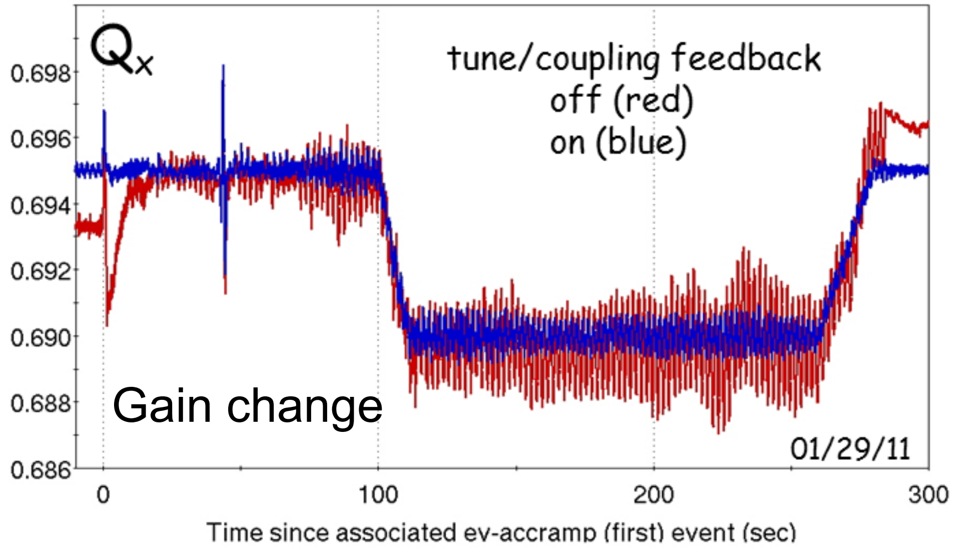
- Dynamic Measurement Examples
  - LHC Ramp
    - RF continuously modulated
    - Tune measured continuously
    - Chromaticity calculated from tune modulation amplitude

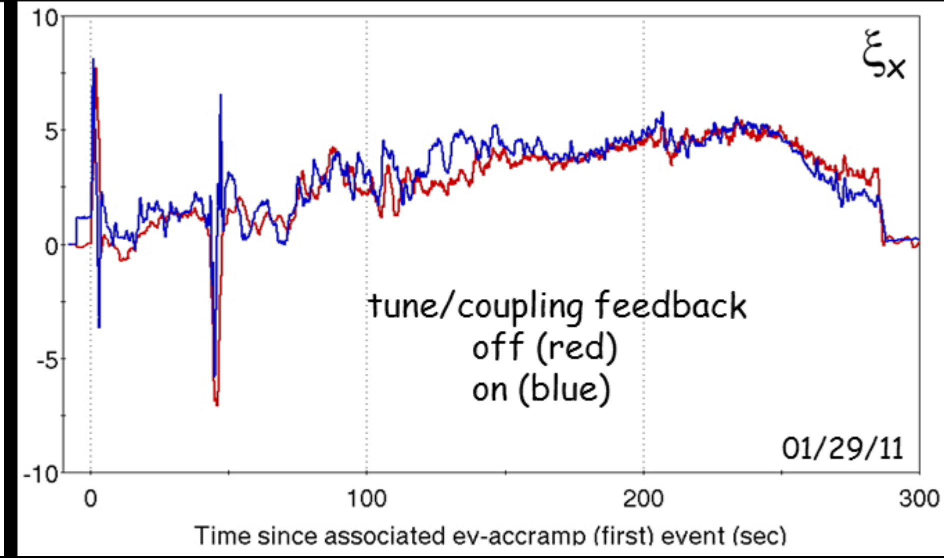
$$\Delta Q = Q'\frac{\Delta p}{p} = \left(\frac{1}{\gamma^2} - \alpha\right)^{-1} Q'\frac{\Delta f}{f}$$



Example from RHIC

- Chromaticity measurement with feedbacks on
  - RHIC Example
    - RF continuously modulated
    - Tune feedback maintains tunes constant
    - Chromaticity calculated from feedback corrections to tune





- Chromaticity still well computed with effects of other feedbacks taken into account

Measurement Techniques

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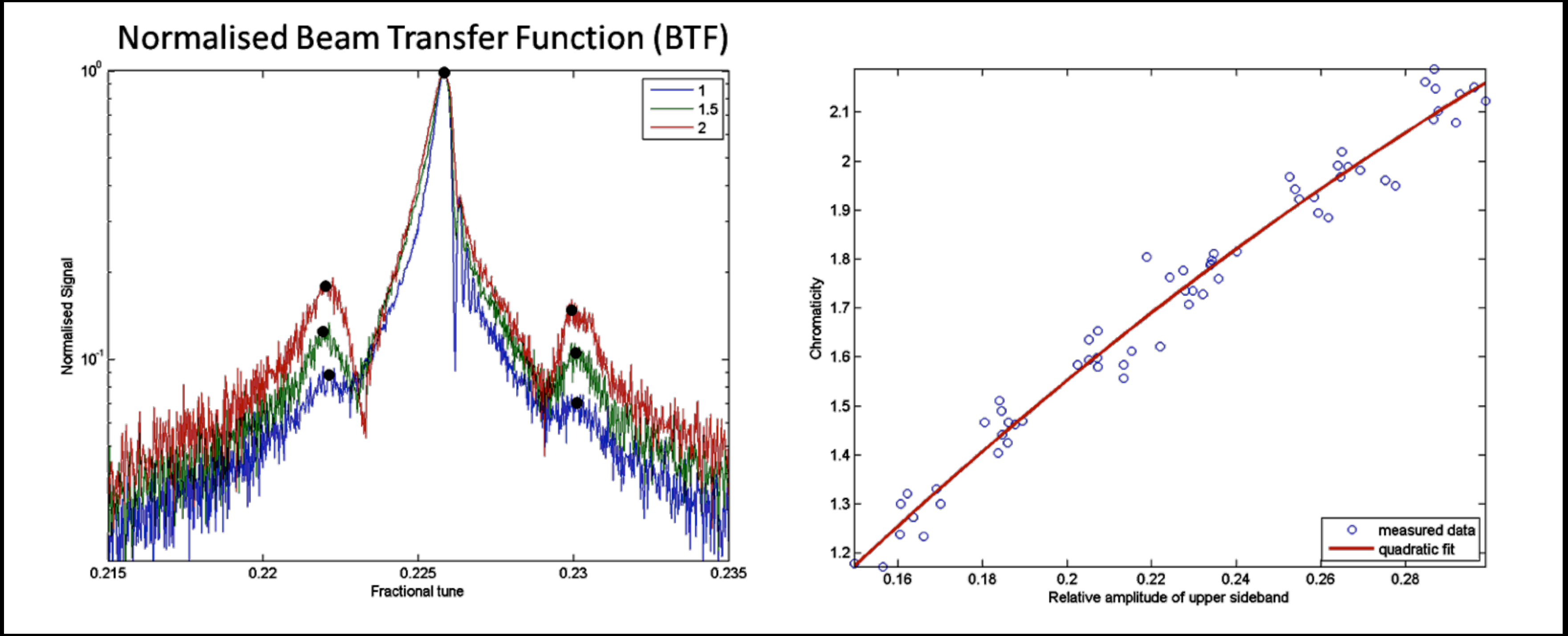
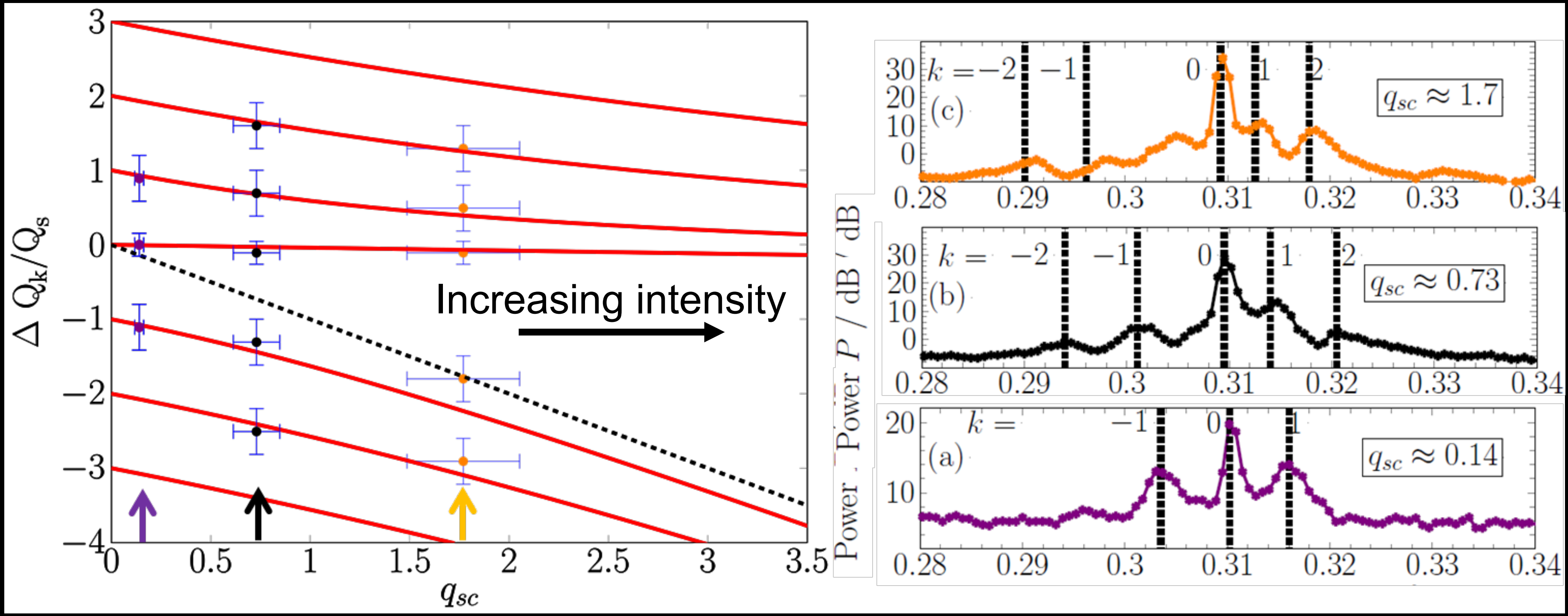
Amplitude of Synchrotron Sidebands

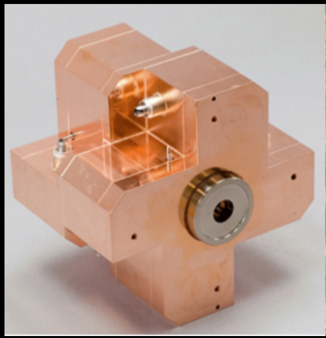
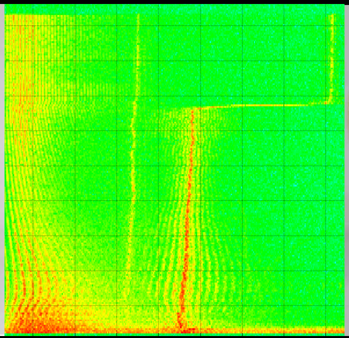
- Recently demonstrated at DIAMOND
  - RF modulation changes orbit - not compatible with user operation
  - Looking for technique to measure chromaticity on-line
    - Measure Beam Transfer Function (BTF) on single bunch
      - Using transverse bunch by bunch feedback system
      - Emittance blow-up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

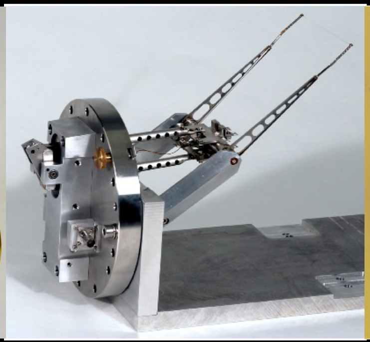
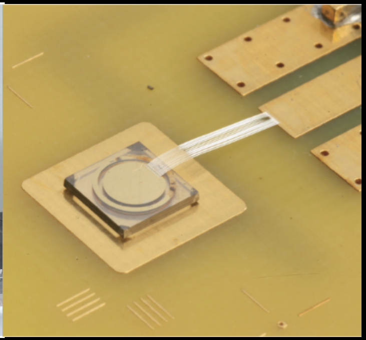


Amplitude of Synchrotron Sidebands

- 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



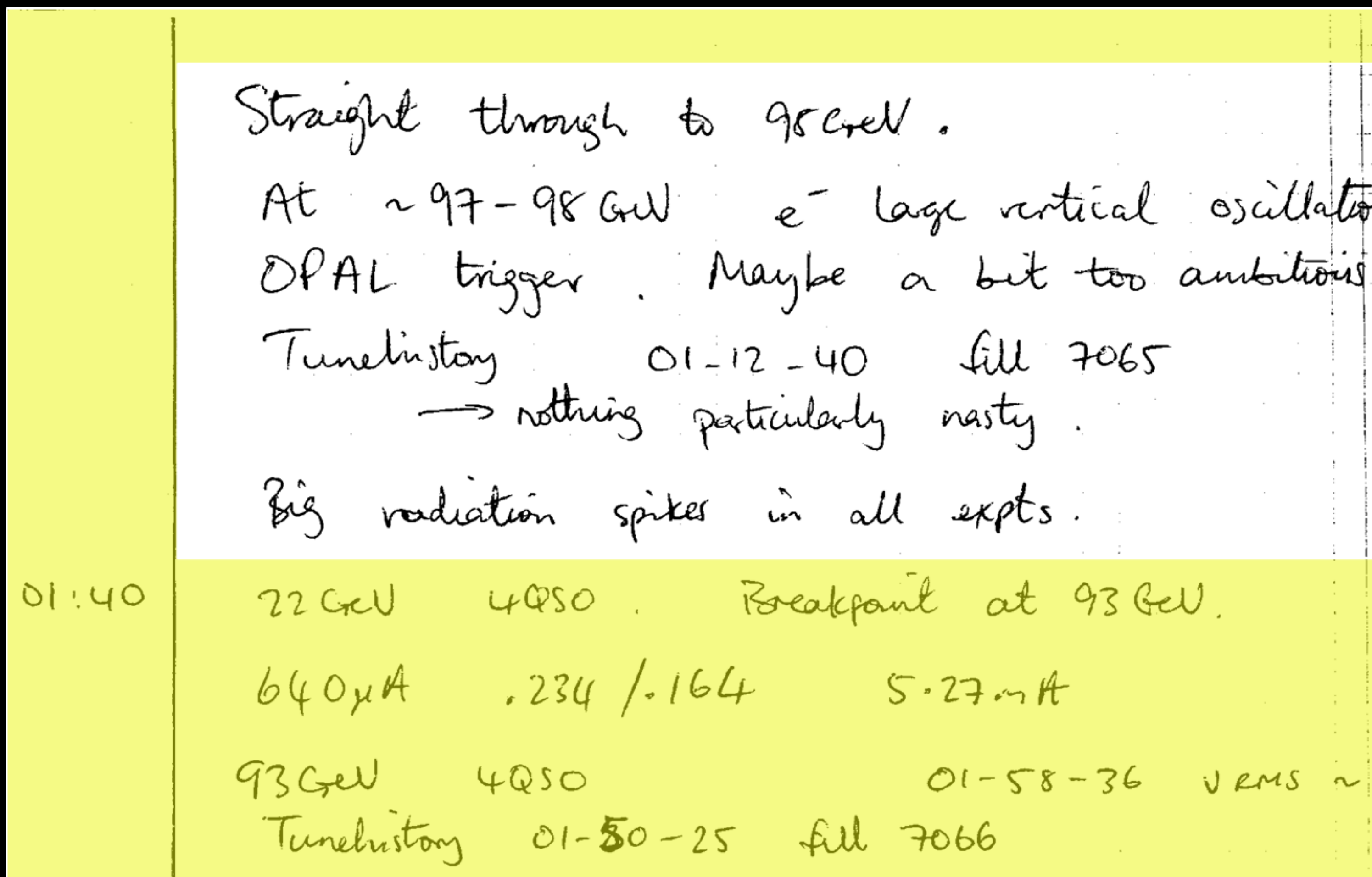



Diagnosing Machine Issues using Beam Instrumentation

LEP Beams Lost During β-Squeeze

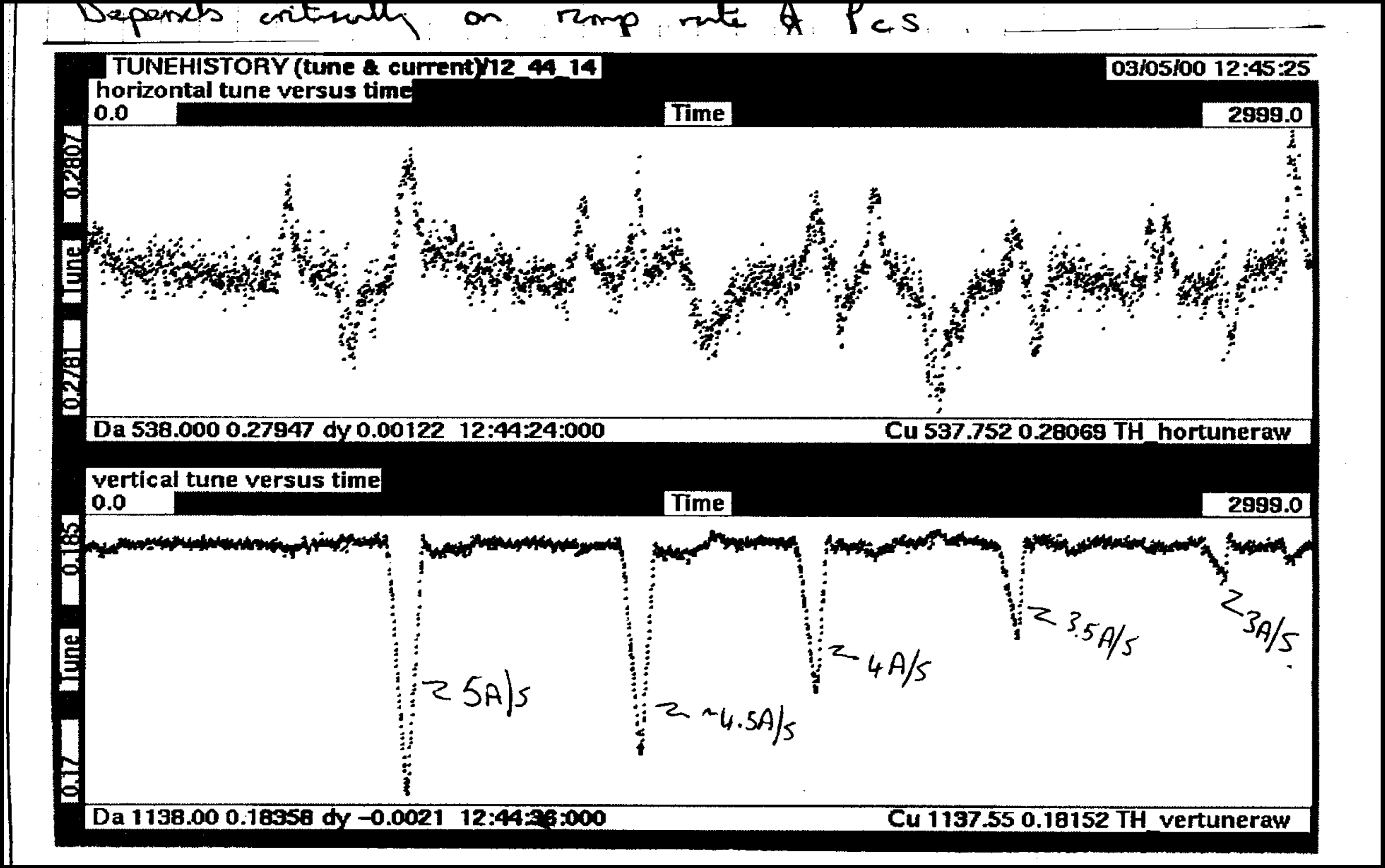
- Extract from LEP logbook (when pen & paper still used!)
  - OK when stepping through the β-squeeze slowly
  - Beams lost when attempting to go straight through



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

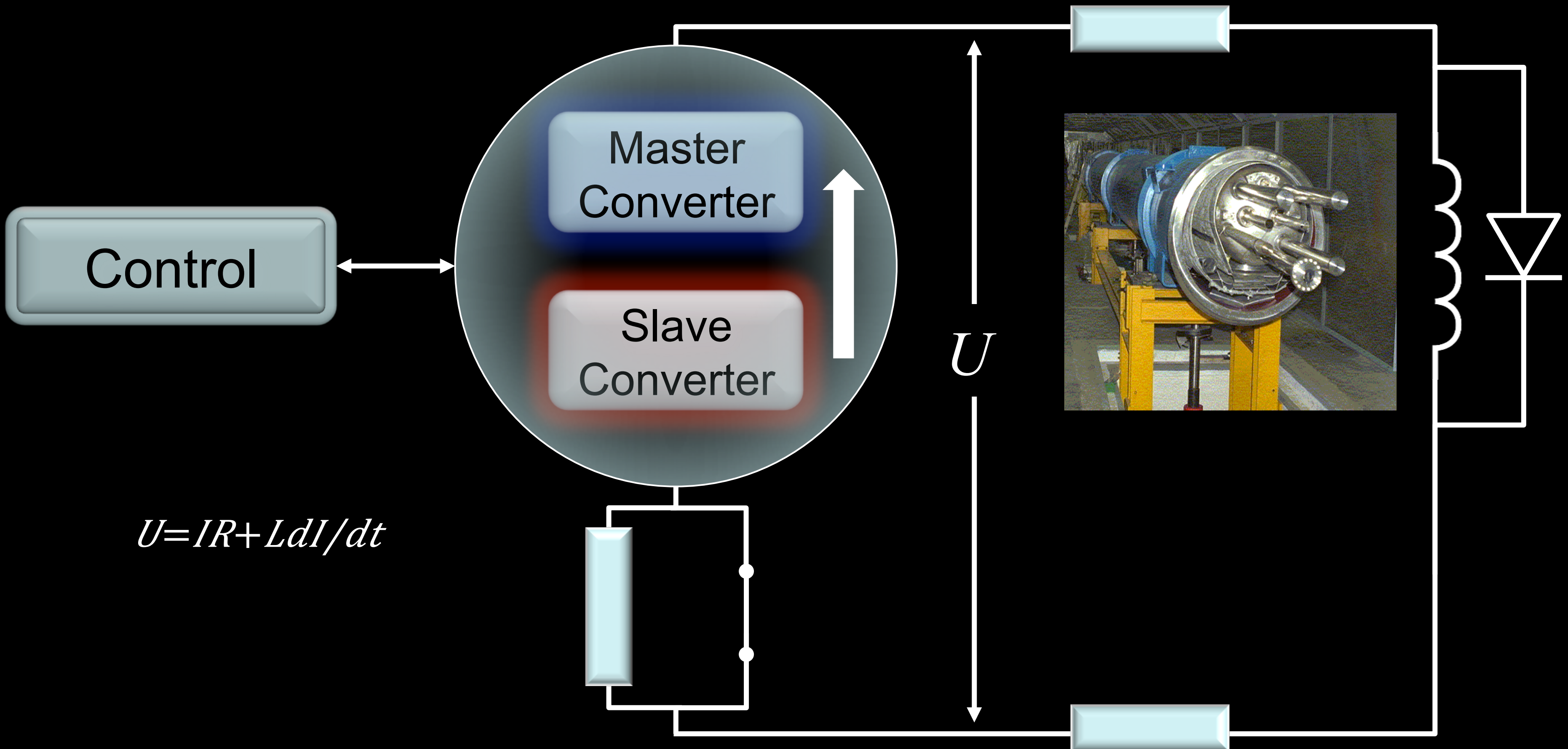
The Diagnostics

- Tune Variation
  - Tracked for different power converter ramp rates



The Explanation

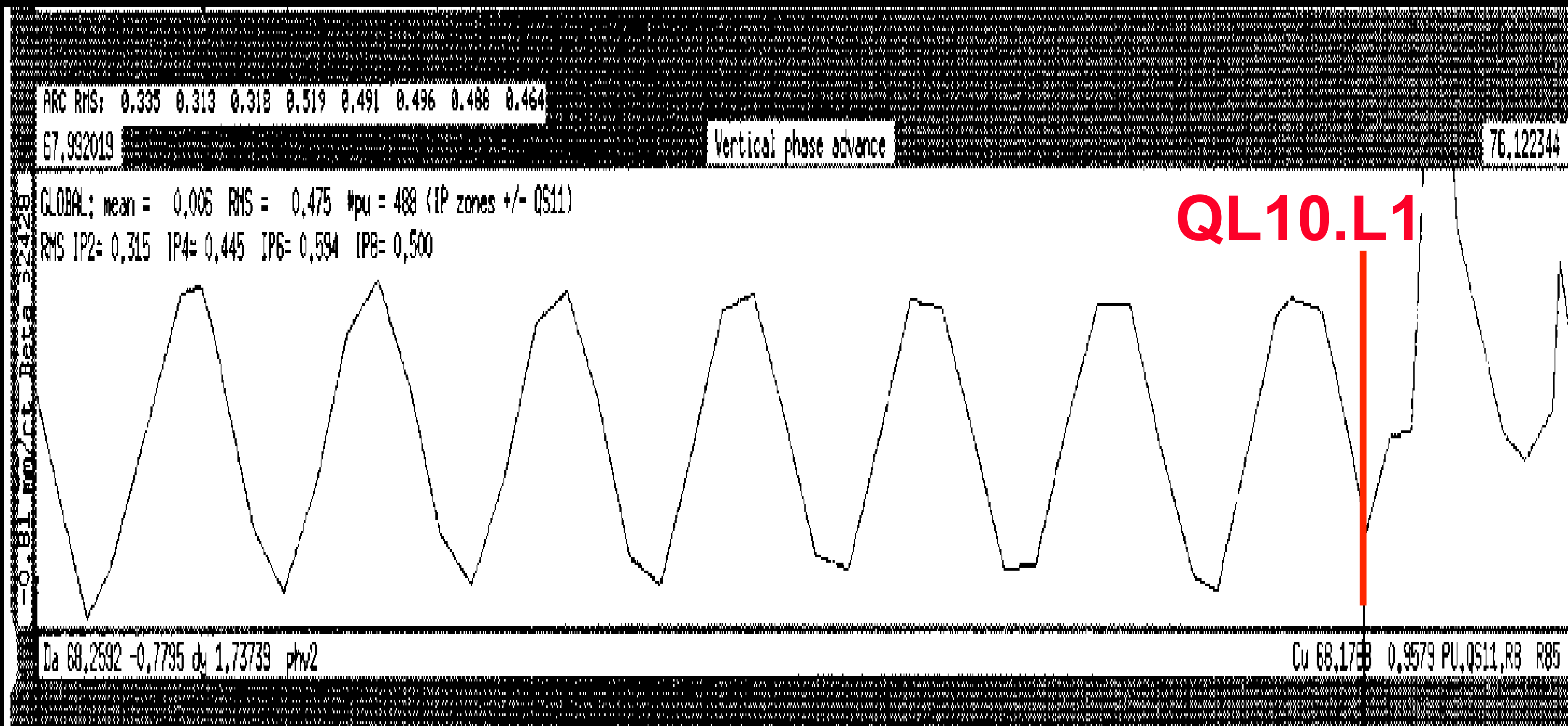
- Master-Slave Configuration for Power Converter
  - Each converter can deliver full DC current
  - Slave converter not working
    - Slave only needed to give increased voltage for fast current changes



$U = IR + L dI/dt$

LEP – No Circulating Beam

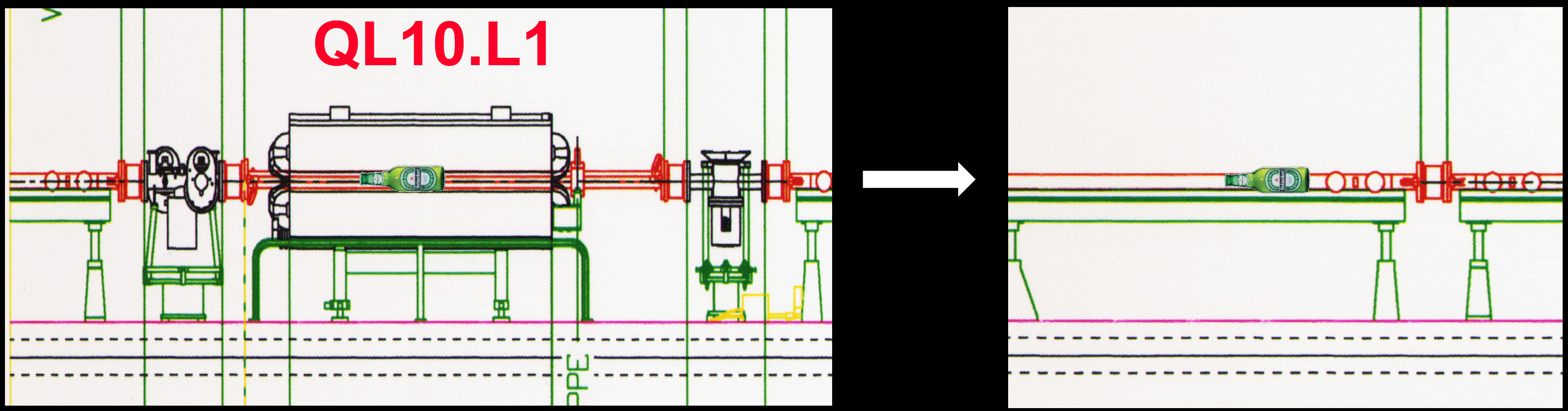
- No Circulating Beam after Technical Stop
  - Phase advance from BPMs show that optics no longer correct after specific quadrupole



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

Want to know more?
Then Join the Beam Instrumentation Afternoon Course

- 3 Sessions on BPM design
  - Simulation software & “hands-on” laboratory measurements
- 1 Session on Tune Measurement
  - Program and measure using your own DSP
- 2 Sessions on Profile Measurements
  - “Hands-on” laboratory measurements
- Final Session
  - Group presentation of your BI proposals for an accelerator