Beam Instrumentation and Diagnostics (Lecture 2)

CAS 2022

Sevrier, France

6th – 18th November 2022

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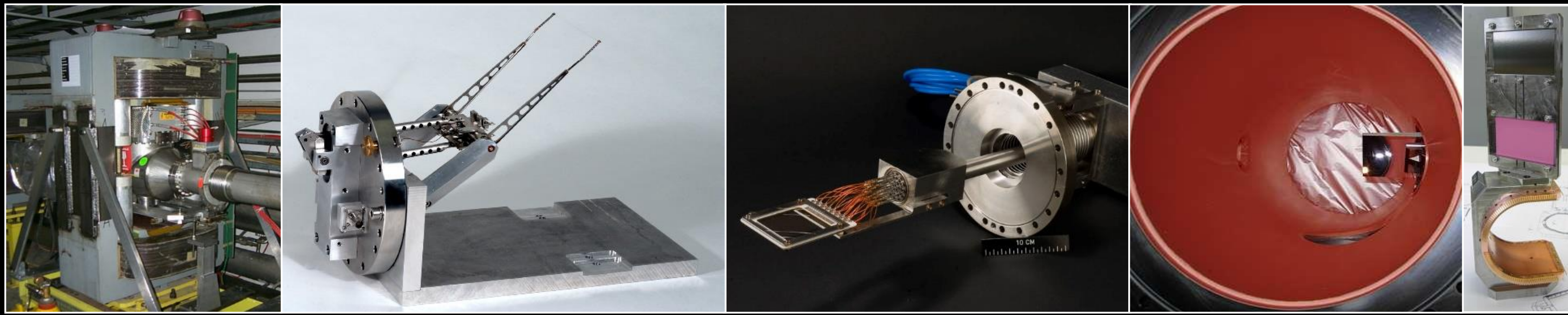
Introduction

- 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

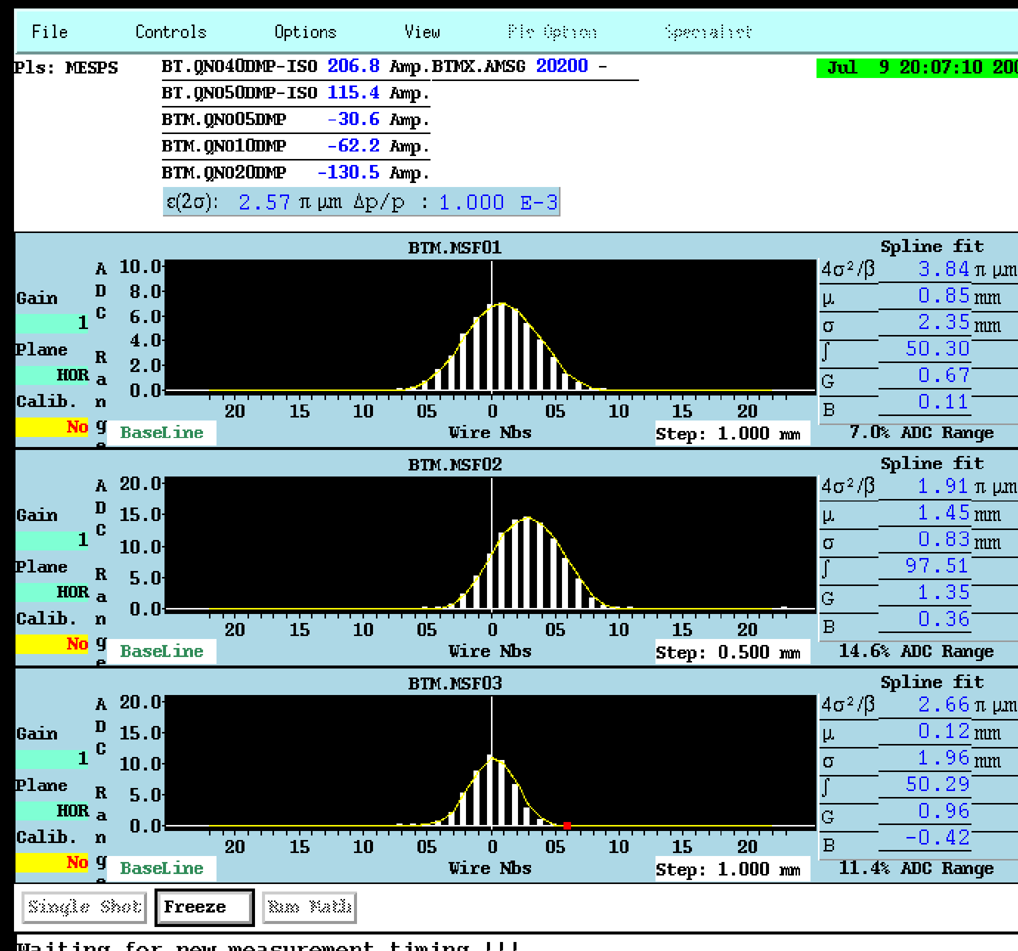


Beam Profile Monitors

(Longitudinal measurements covered next week by T. Lefevre)

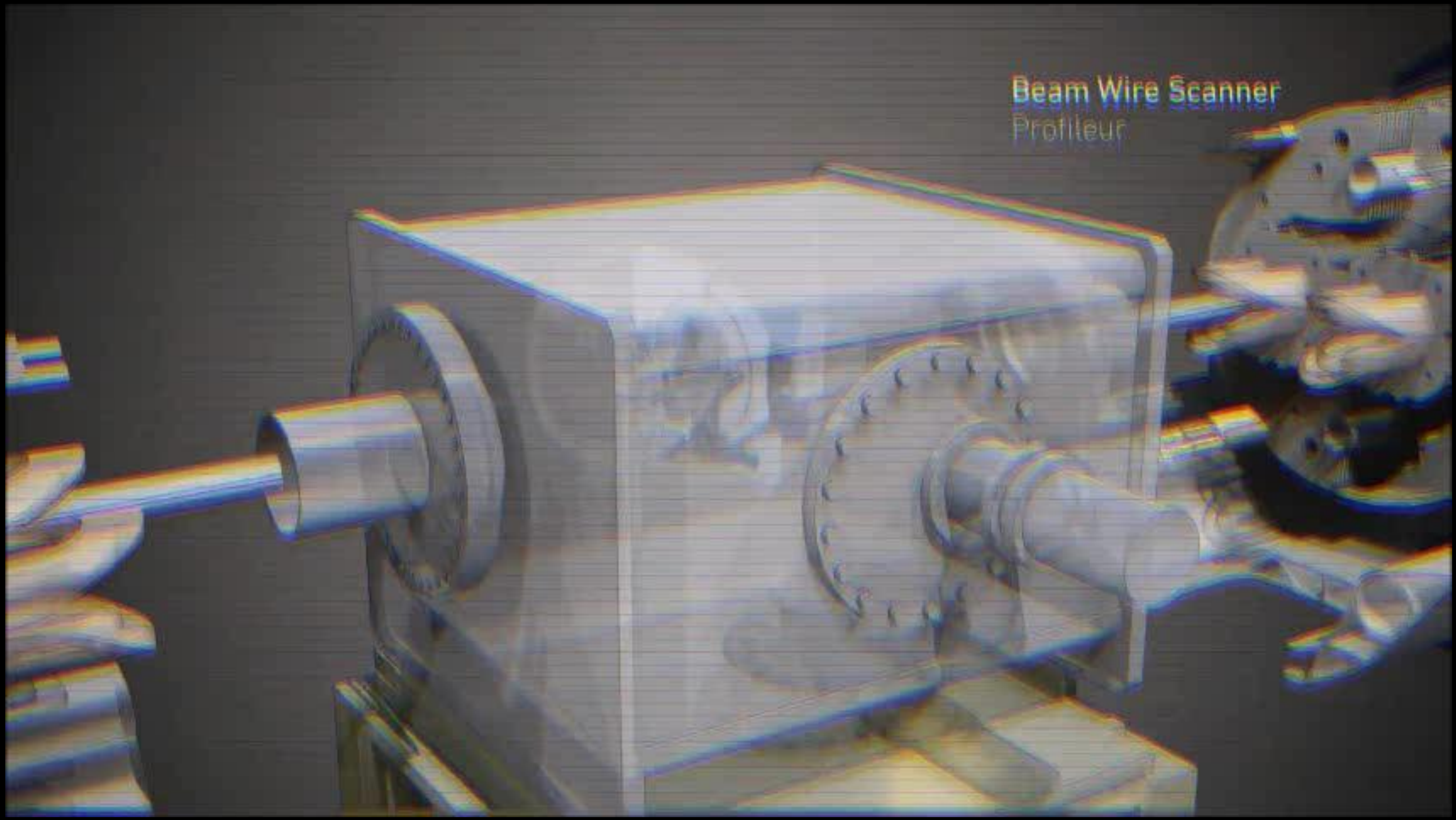
Profile Monitoring using Wires

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



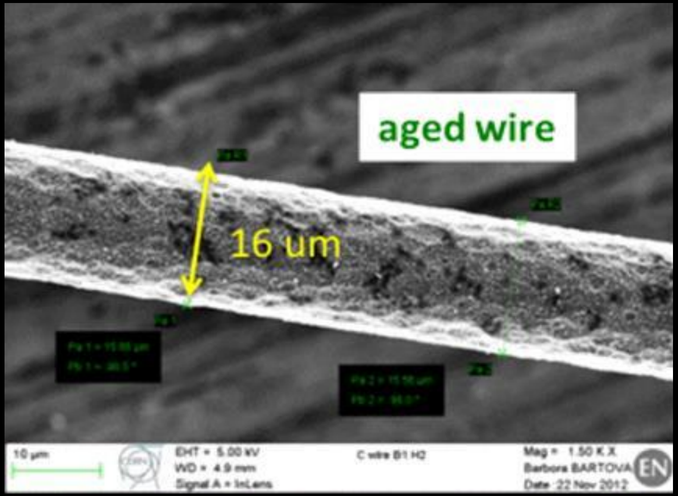
Profile Monitoring using Wires

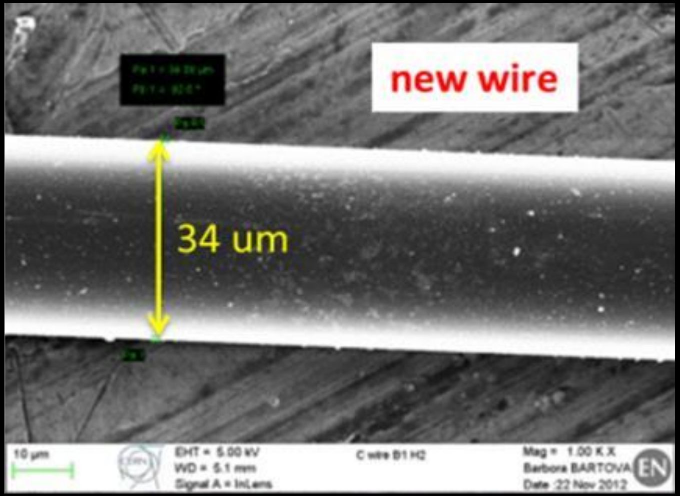
- Wire-scanners
  - Move thin wire across beam
  - Low energy : correlate wire position with secondary emission
  - High energy : correlate wire position with secondary shower



Limitation of Wire-Scanners

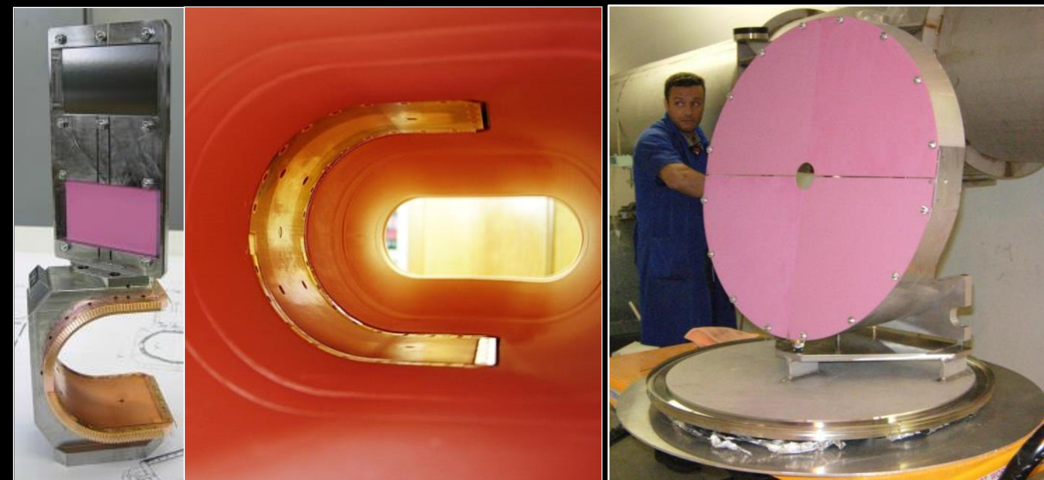
- Wire Breakage – why?
  - Brittle or Plastic failure (error in motor control)
  - Melting/Sublimation (main intensity limit)
    - Due to energy deposition in wire by particle beam
- Temperature evolution depends on
  - Heat capacity, which increases with temperature!
  - Cooling (radiative, conductive,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

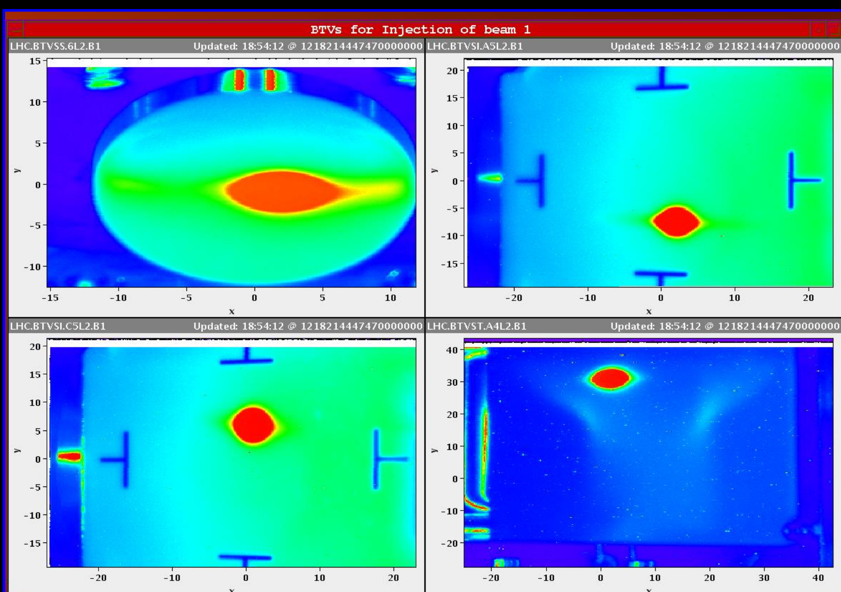




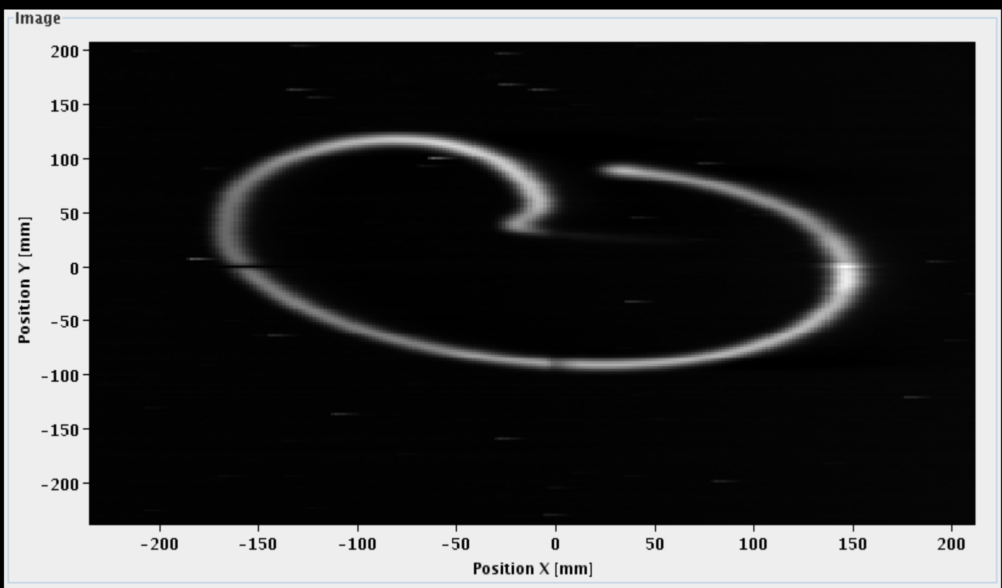
Profile Monitoring using Screens

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



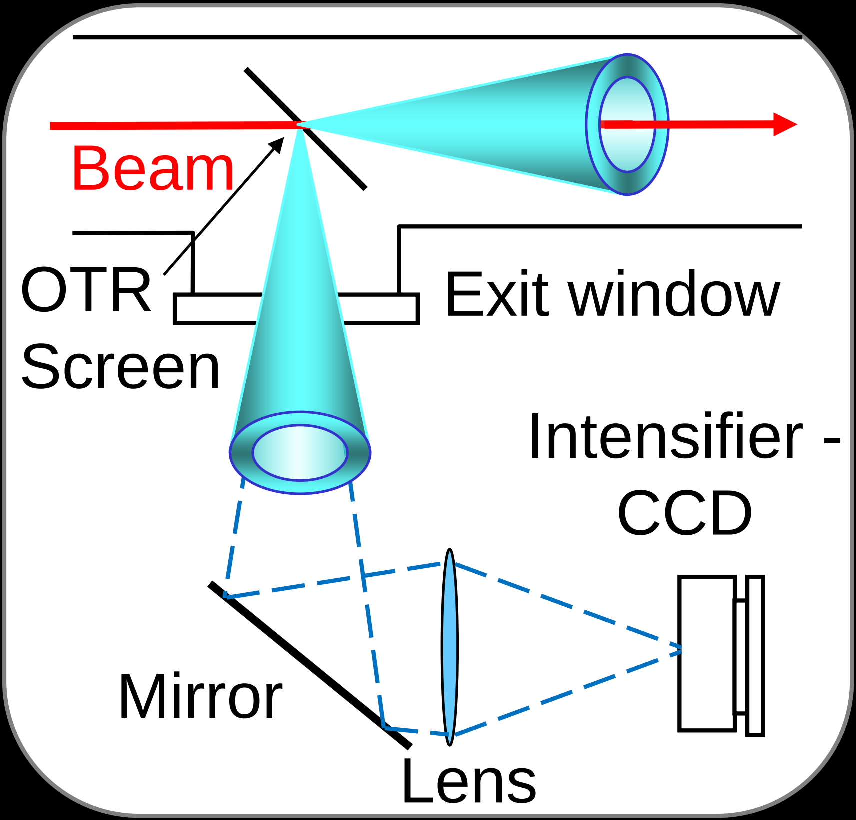


First Beam in the LHC 8/8/2008

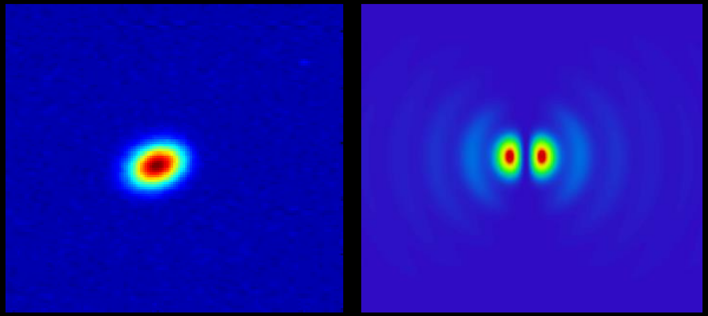


Profile Monitoring using Screens

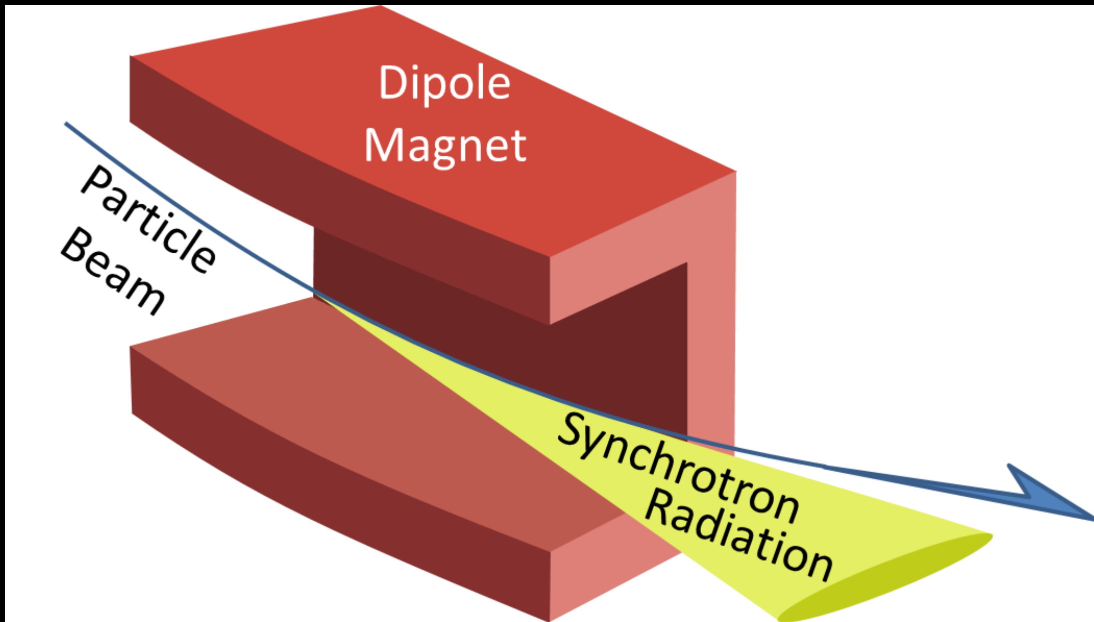
- Optical Transition Radiation
  - Radiation emitted when a charged particle goes through an interface with different dielectric constants
  - Surface phenomenon allows use of very thin screens (~10μm)
    - Can use multiple screens with single pass in transfer lines
    - Can leave it in for hundreds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

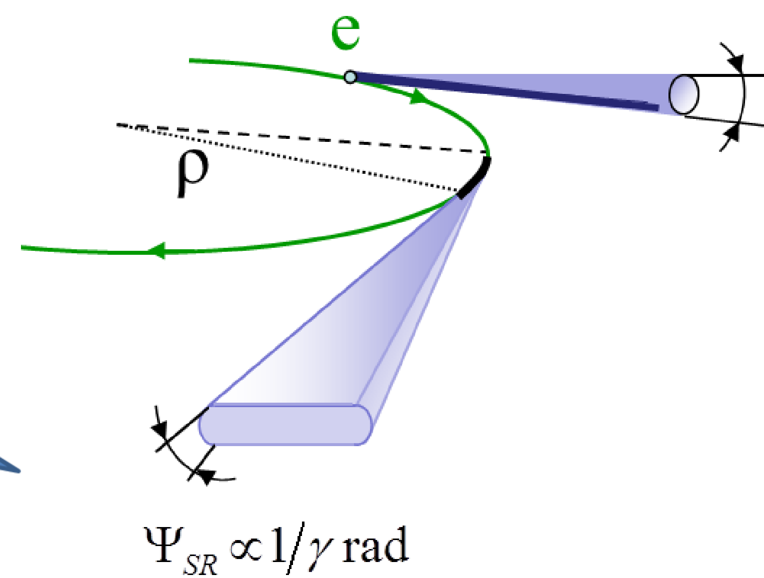


- OTR screens
  - Less destructive than scintillation but requires higher energy / intensity beam
  - Can be used for extremely high resolution measurements

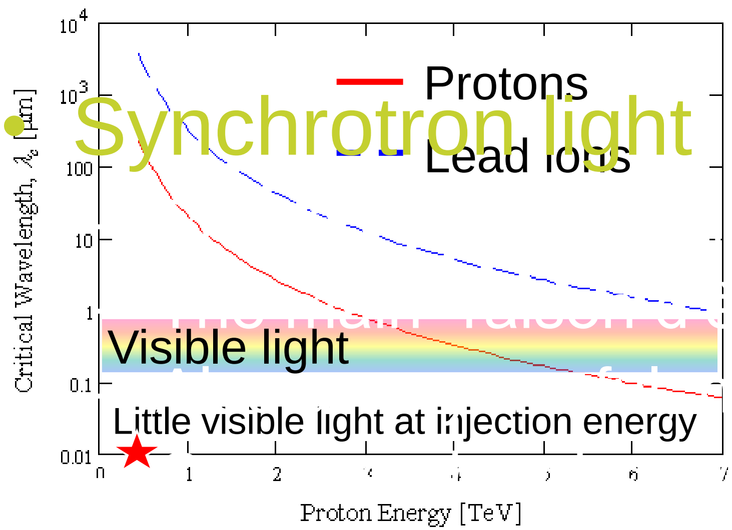


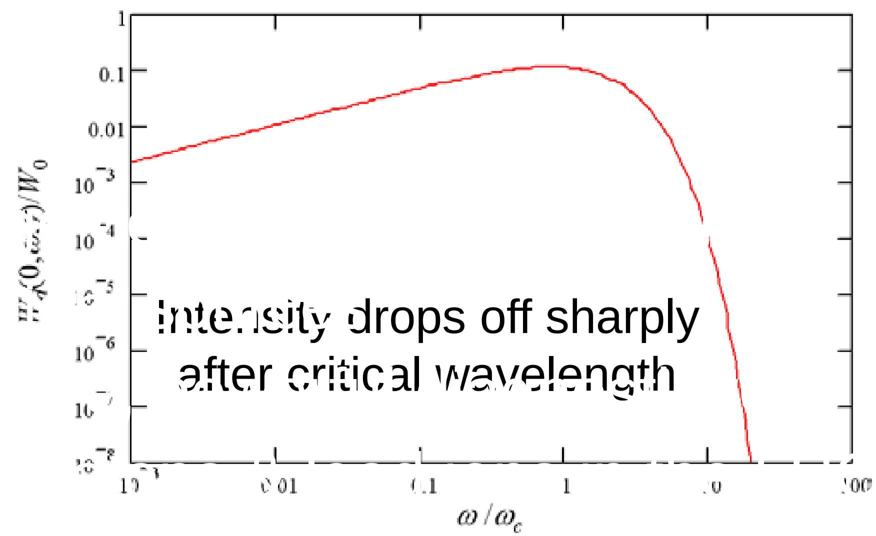
Synchrotron Light Monitors





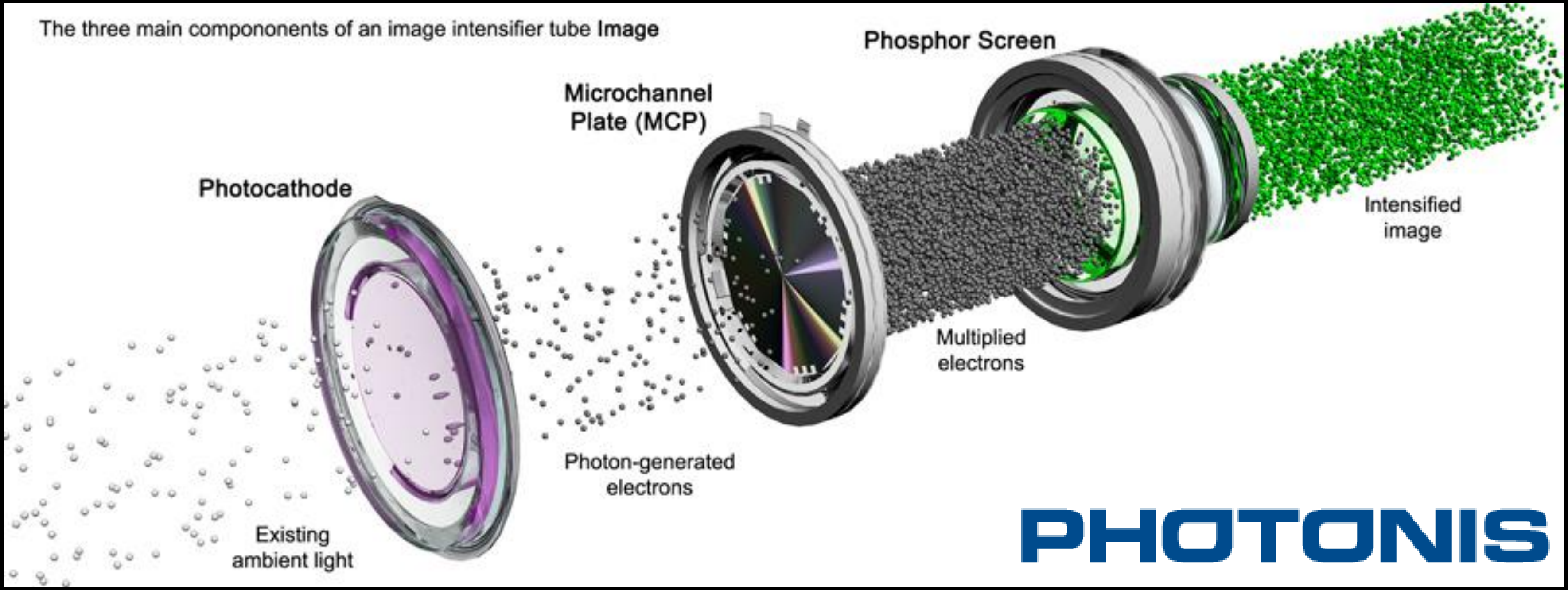
- Synchrotron light

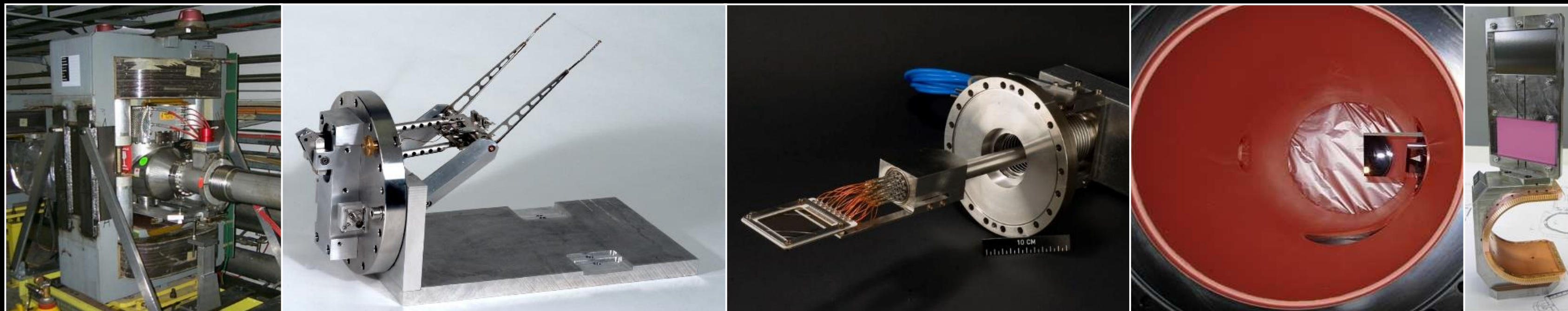




Synchrotron Light Image Acquisition

- 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



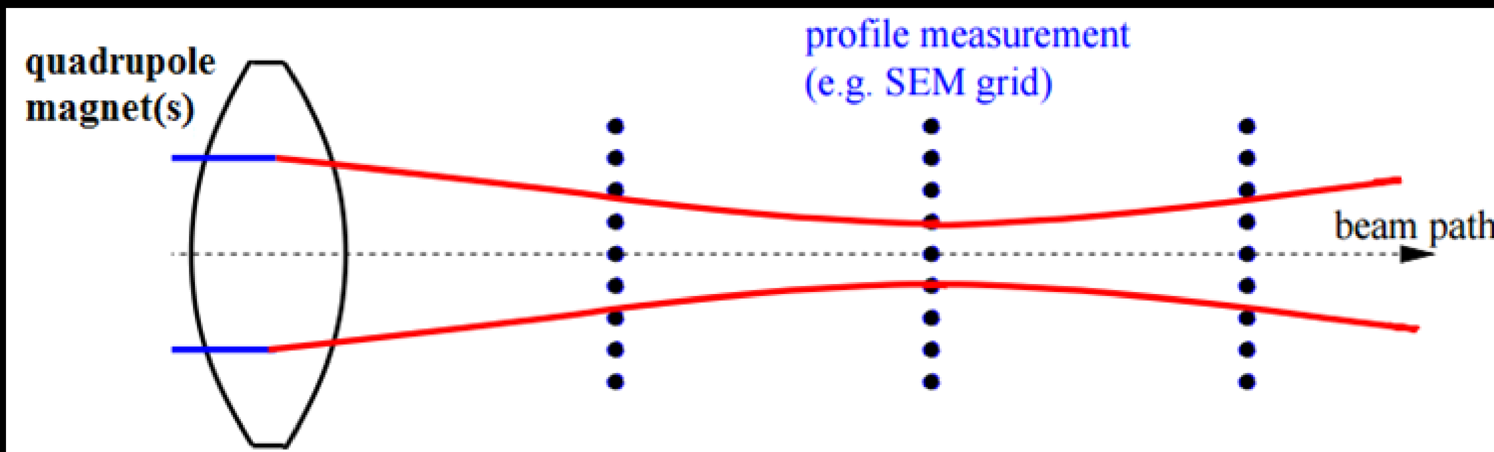


Diagnostics using Beam Profile Monitors

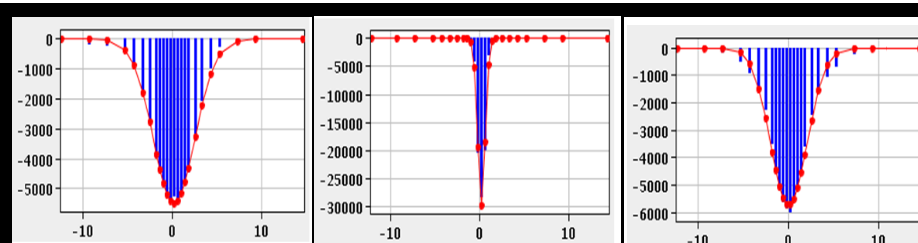
Optics Measurement in LINACs

3 Monitor Method

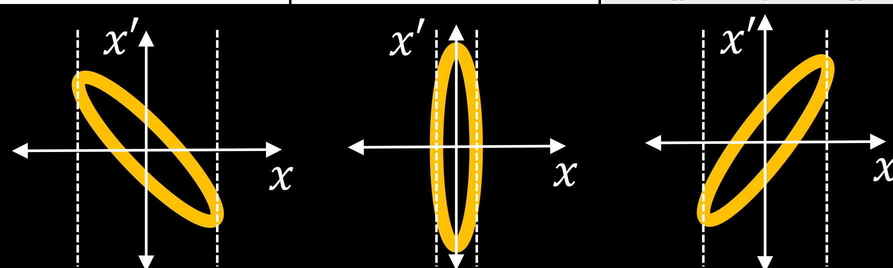
– Optics functions & initial emittance reconstructed using transport matrix



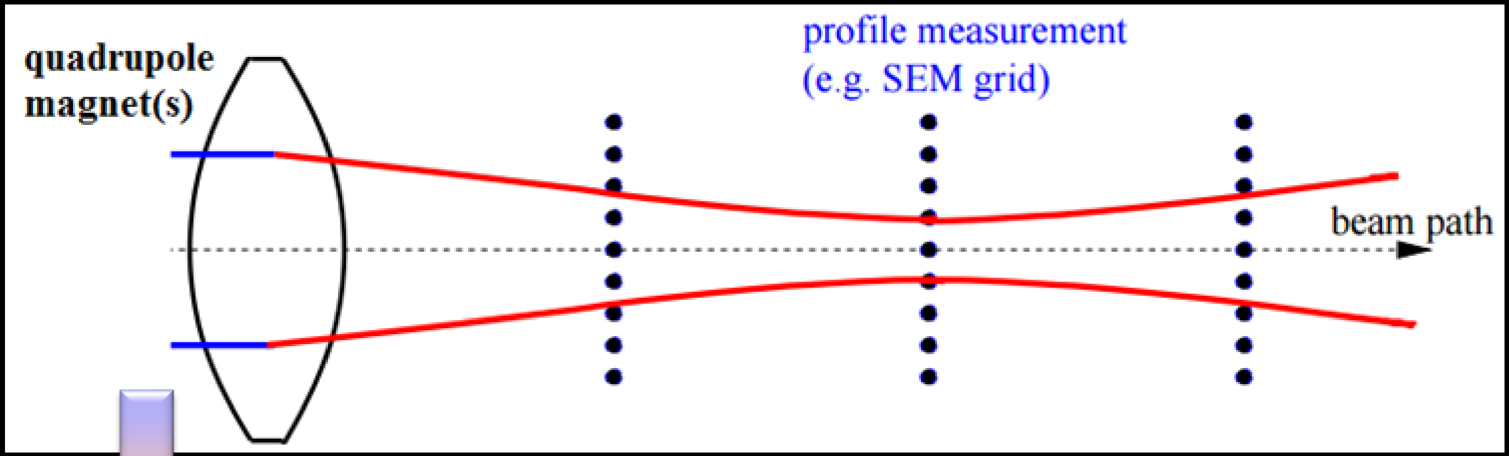
Measured
Beam Profiles



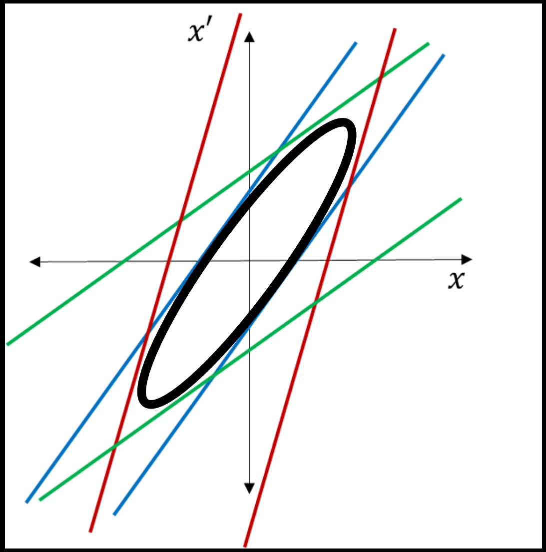
rms ellipses

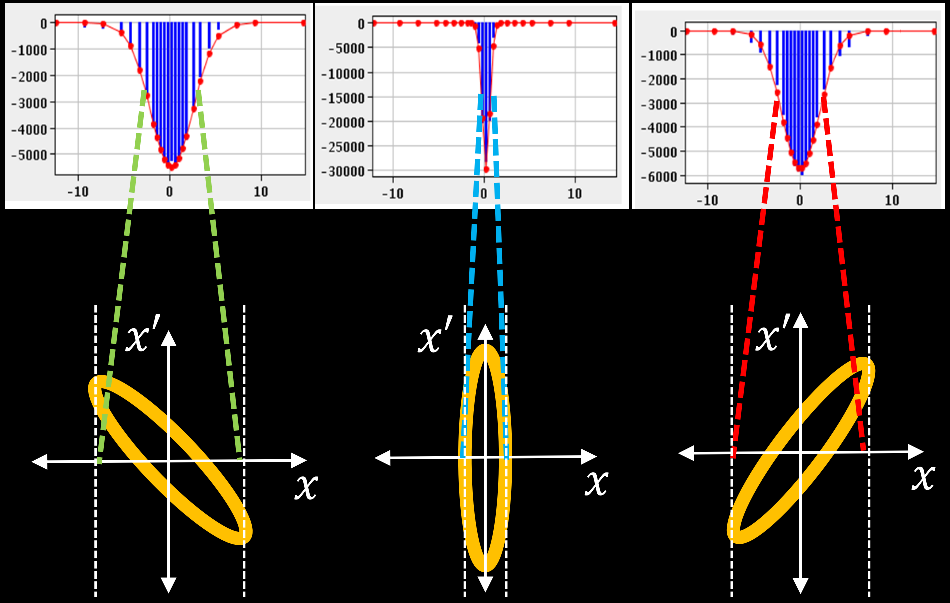


Optics Measurement in LINACs



Linear Mapping of measured beam size onto initial phase space





Measured Beam Profiles

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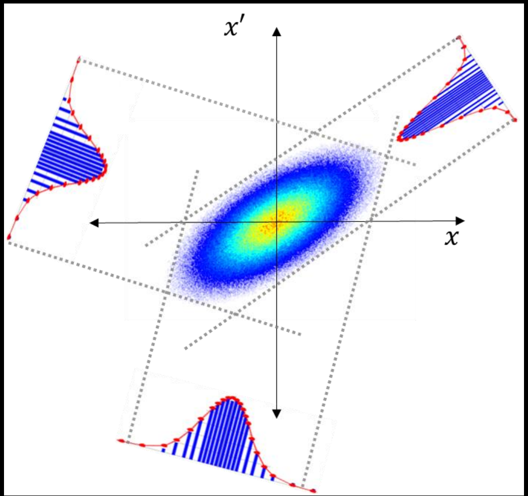
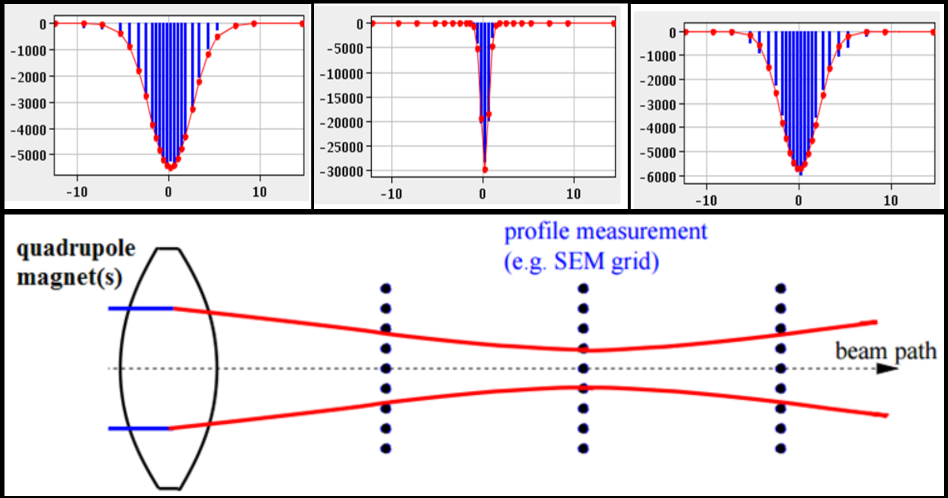
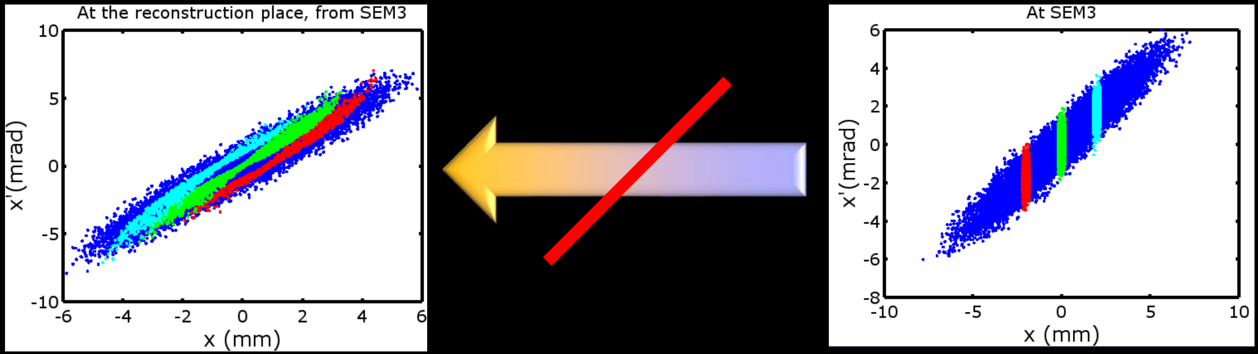
Optics Measurement in LINACs

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



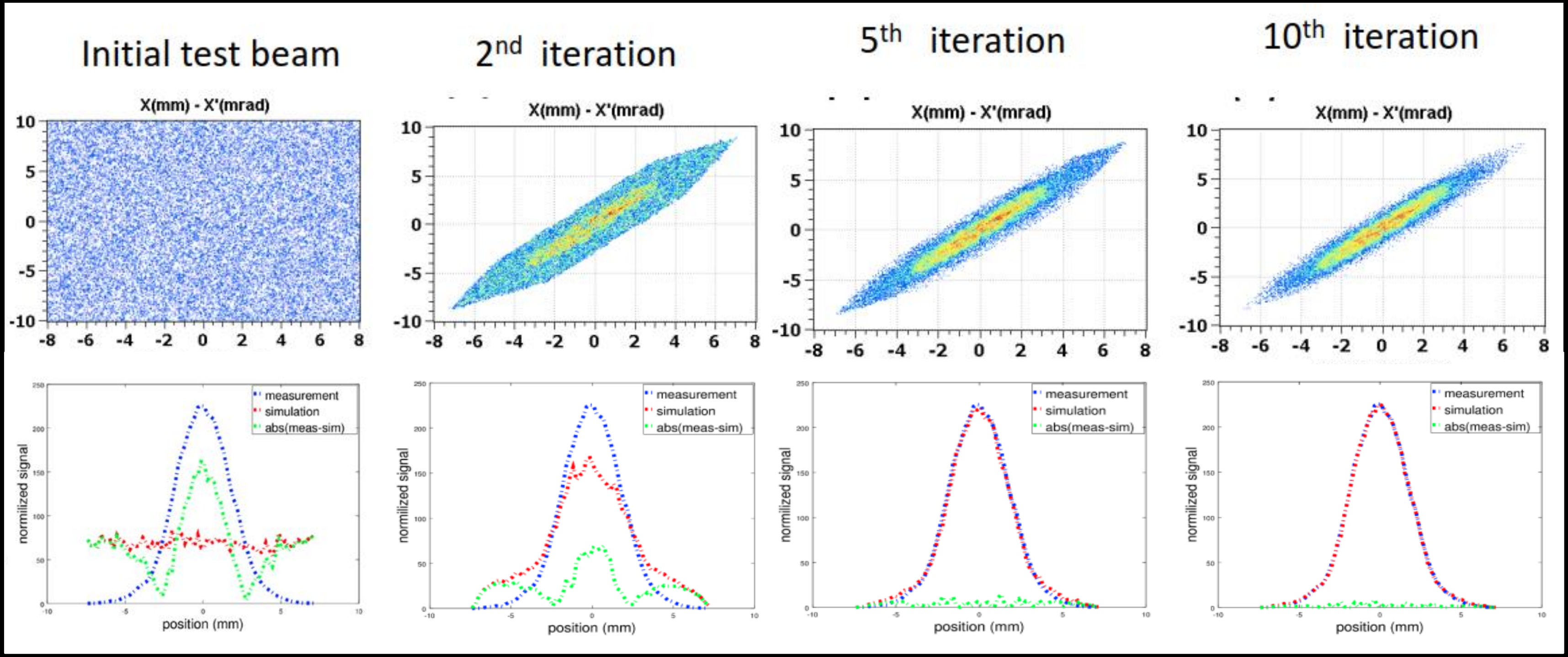


- Things get more complicated when you add space charge



Optics Measurement in LINACs

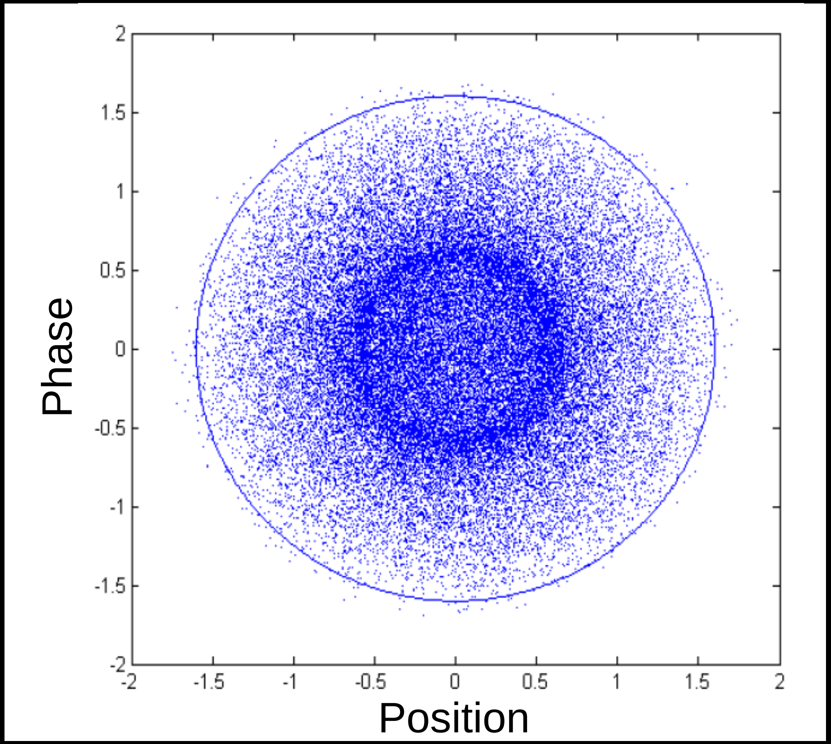
- Hybrid Phase Space Tomography in Linac4
  - Iteratively vary Twiss parameters
  - Track to the measurement locations including space-charge
  - Deduce new distribution of density in phase space from which particles fall on which wires
  - Generate new beam distribution & use for next iteration

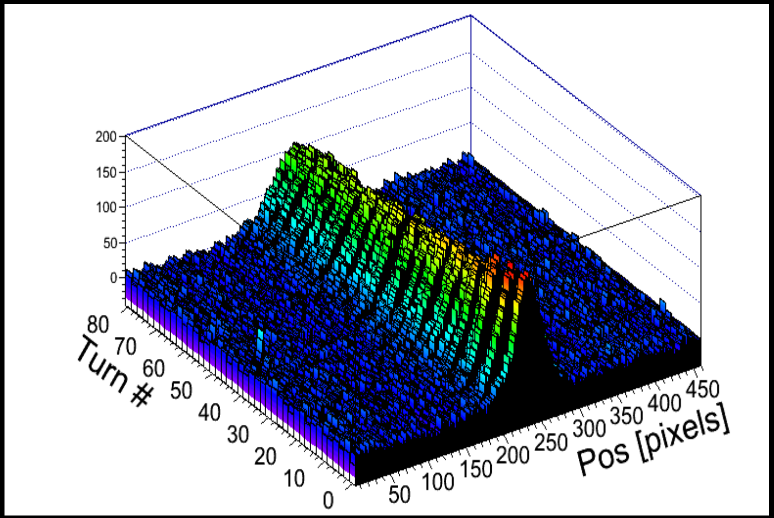


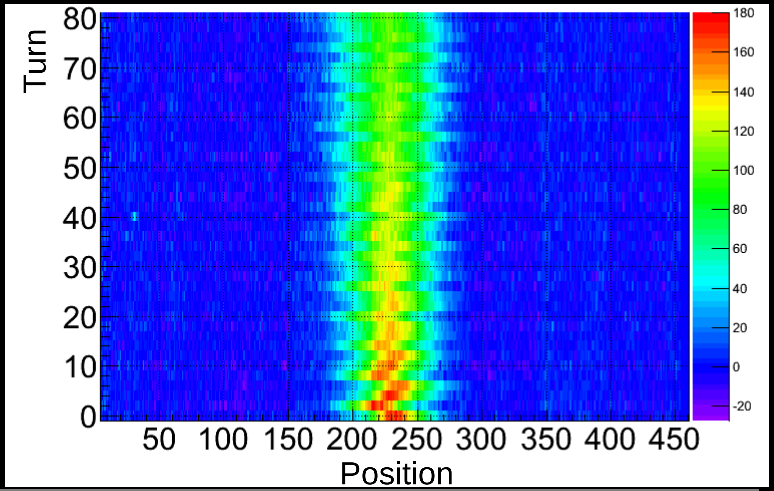
Reconstructed & Measured profiles at last SEM grid

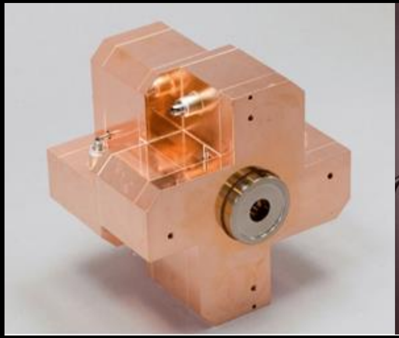
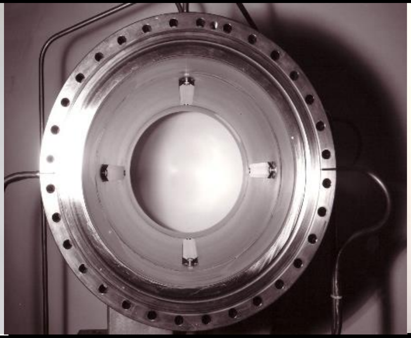
Measurements with Screens

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





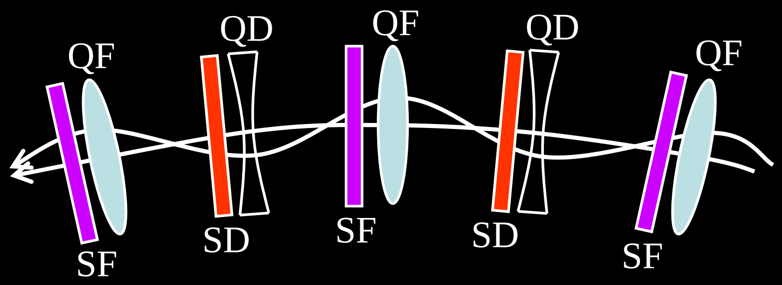



Tune Measurement

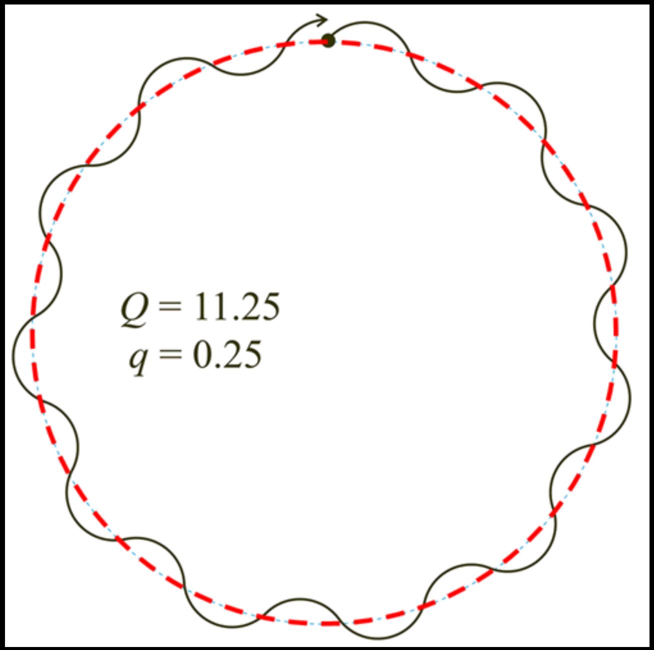
Machine Tune

- Machine Tune



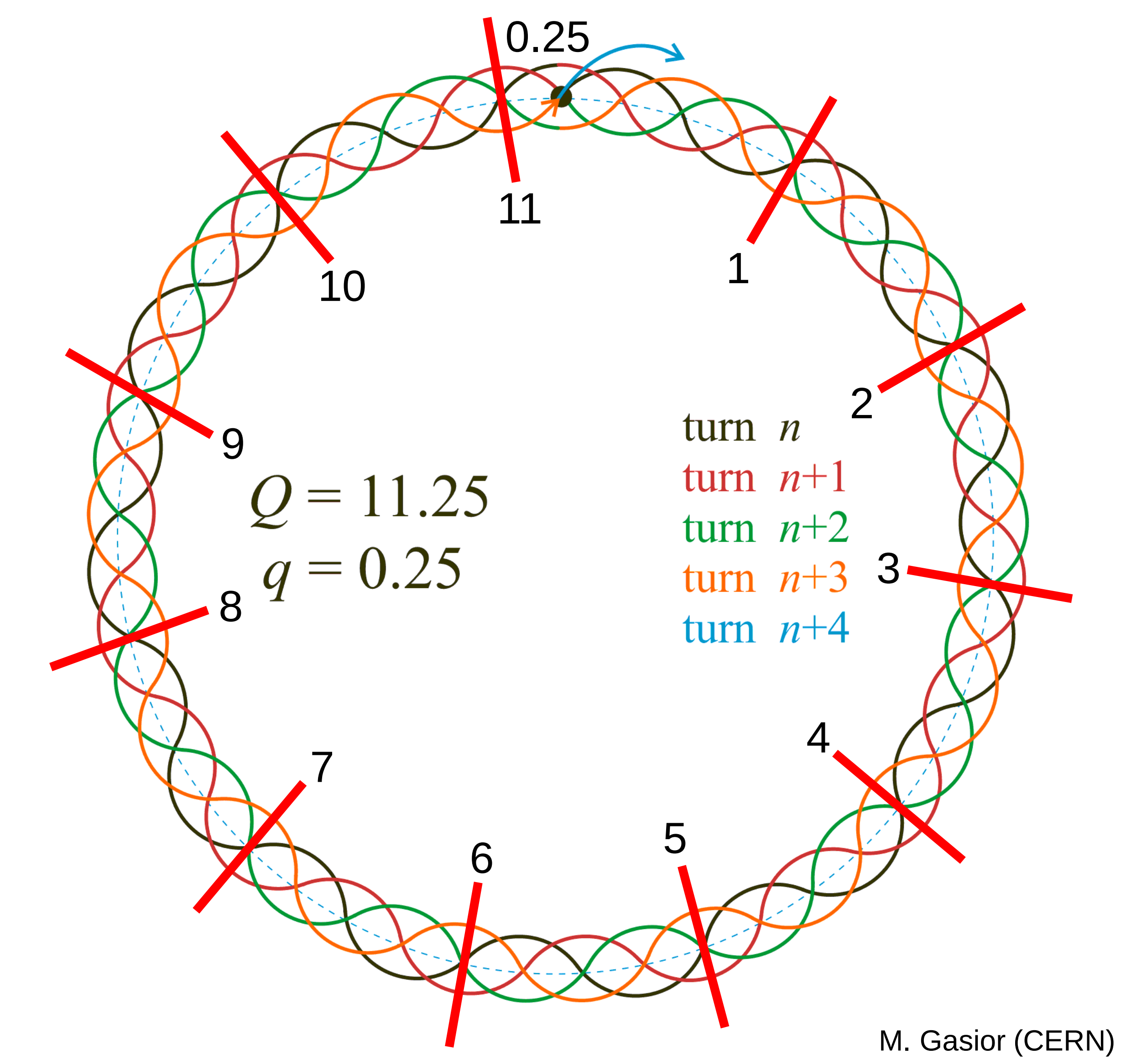
Characteristic Frequency of the Magnetic Lattice

Given by the strength of the Quadrupole magnets

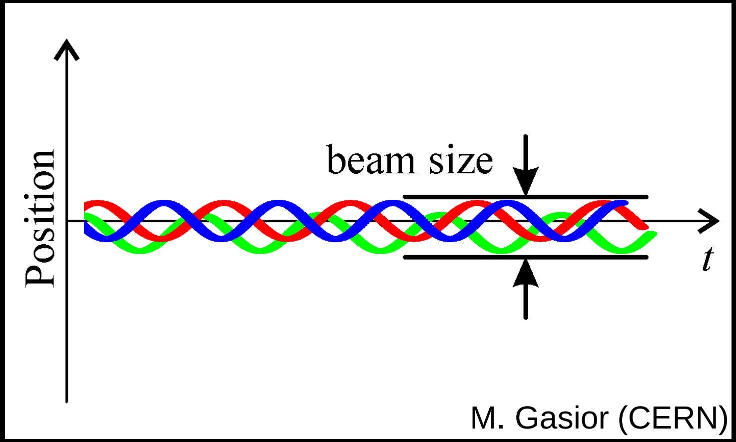


- Parameters per plane
  - Q : Full betatron tune
  - q : Fractional tune (operating point)
- Real life more complex
  - horizontal & vertical oscillations couple
  - betatron motion at large amplitudes non-linear

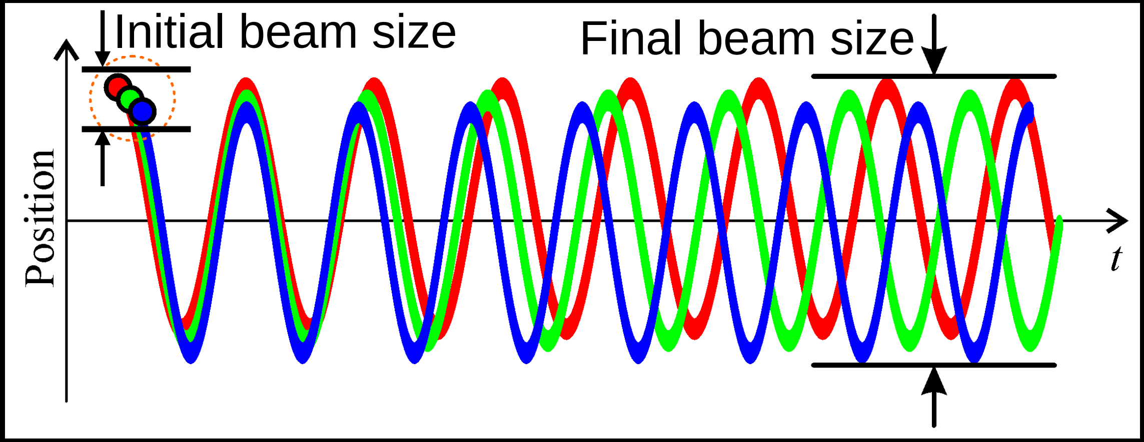
Betatron motion and the Tune

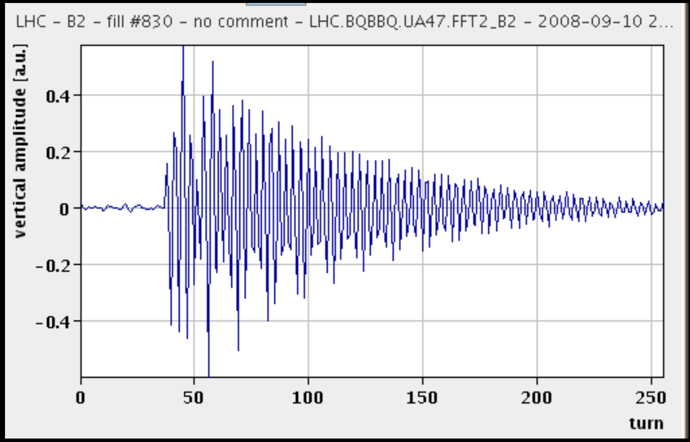


Betatron motion and the Tune



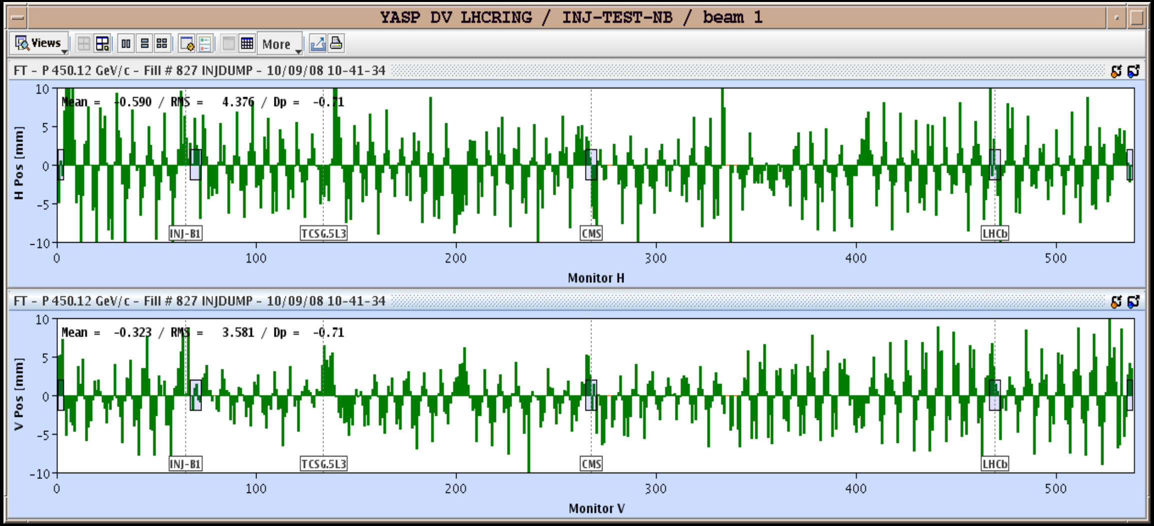
- Beam size
  - defined by incoherent betatron motion of all particles
- Particles have momentum spread
  - gives spread in focussing by quadrupoles
  - gives rise to spread in the frequency of the betatron oscillations (chromaticity)
- Coherent oscillations will de-cohere
  - Hadrons do not forget!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



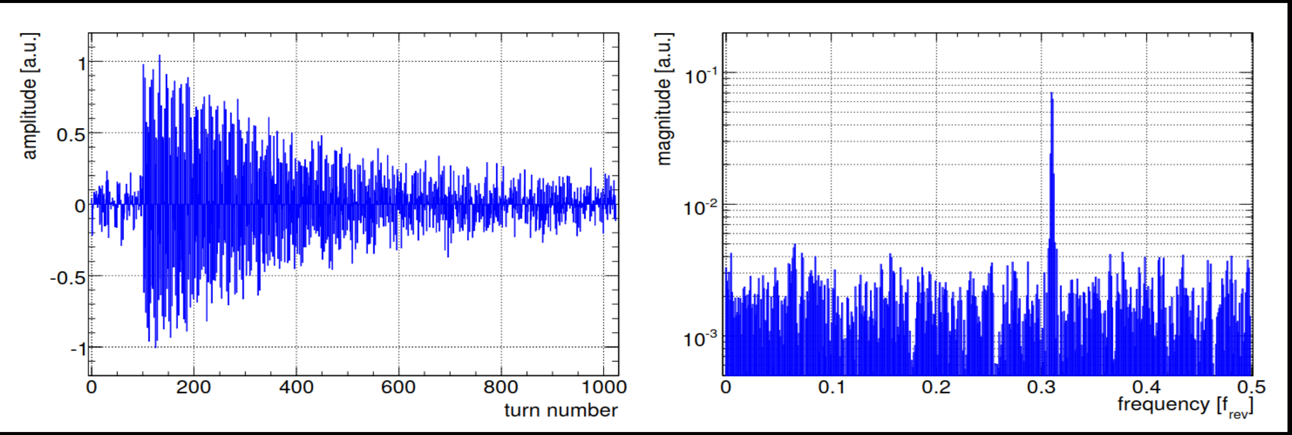


Tune Measurement

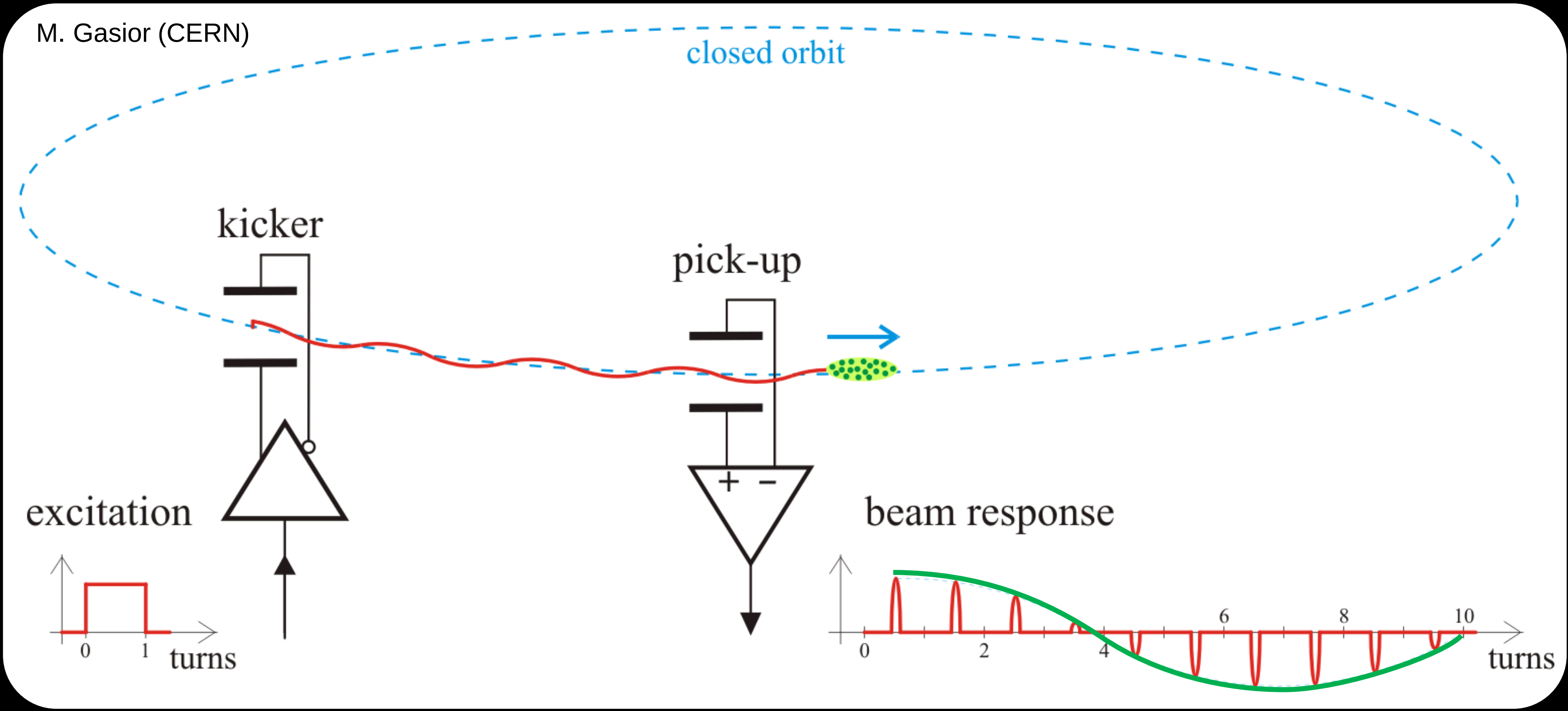
- Integer tune
  - seen in orbit response
  - ~550 dual plane BPMs
  - H: 59, V: 64 for LHC



- 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)



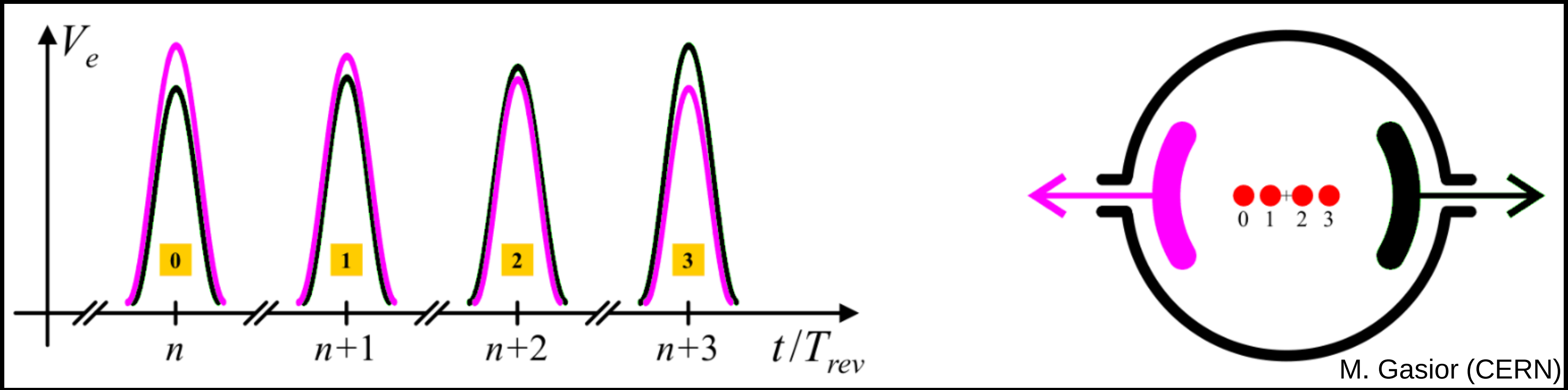
Tune Measurement – the principle



- 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

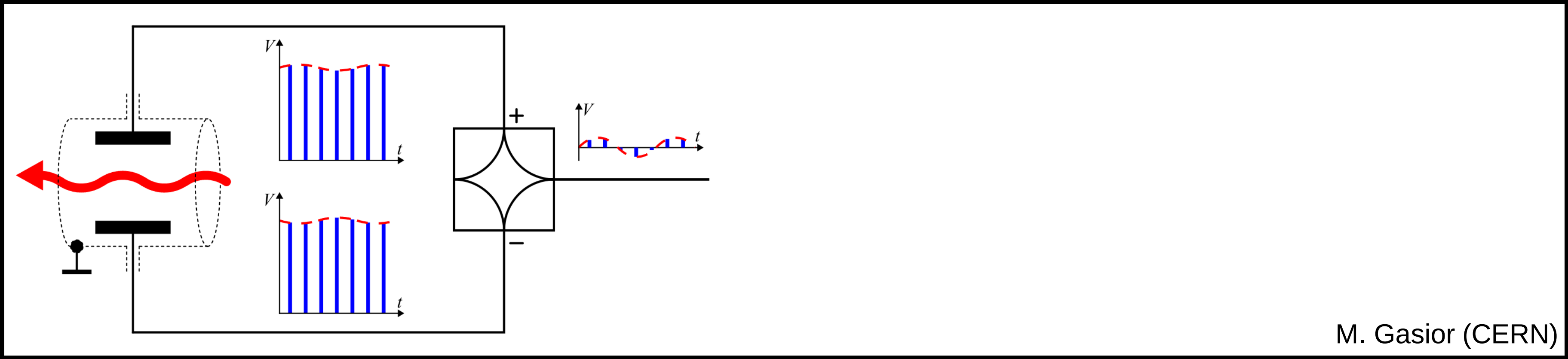
Tune Measurement – the principle

- 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

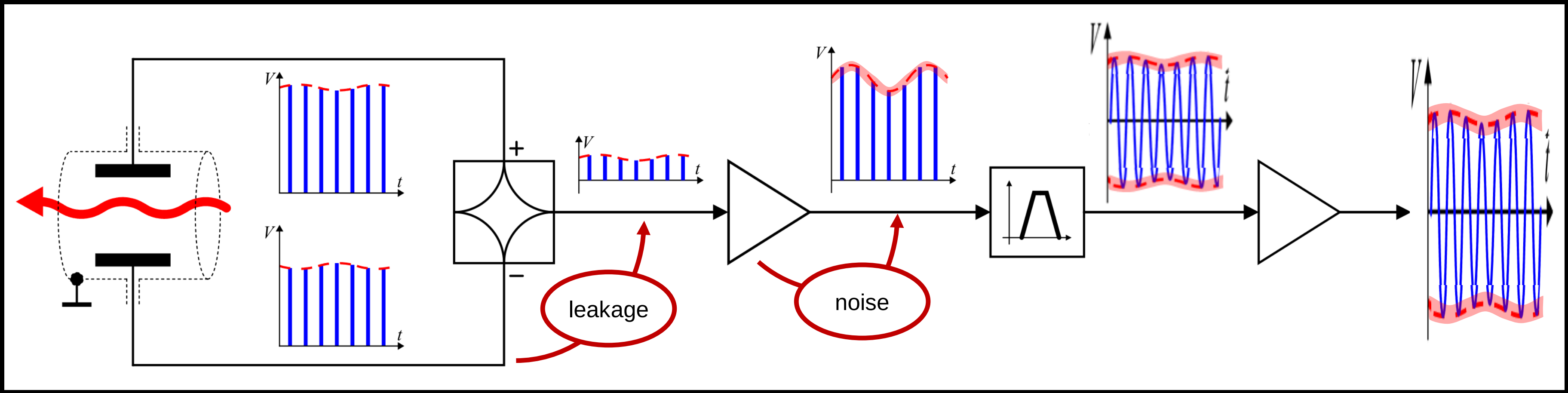


Tune Measurement – the principle

- A typical perfect detection scheme



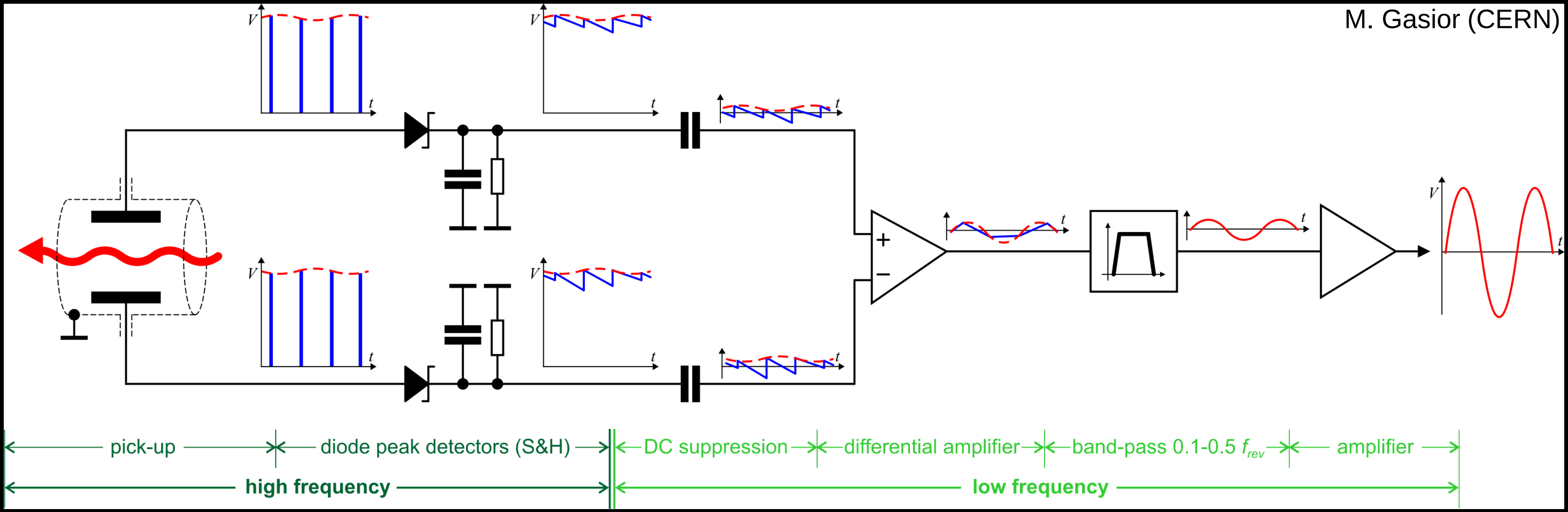
- Reality



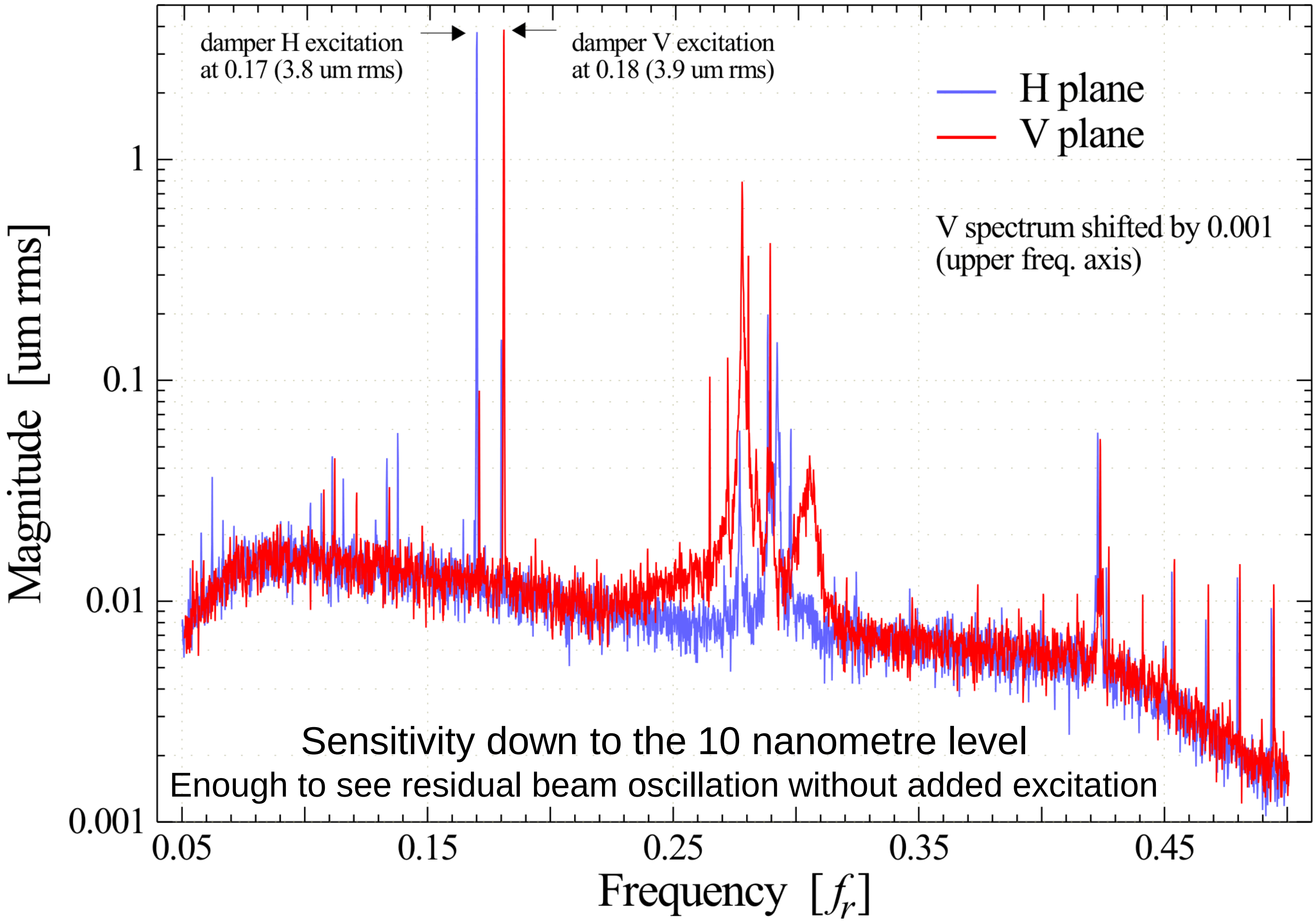
- Dynamic range issues
  - Signals related to betatron oscillations are small with respect to beam offset signals
  - Even for centred beam leakage is of order 1-10 % (of 100V!) for ns beam pulses

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



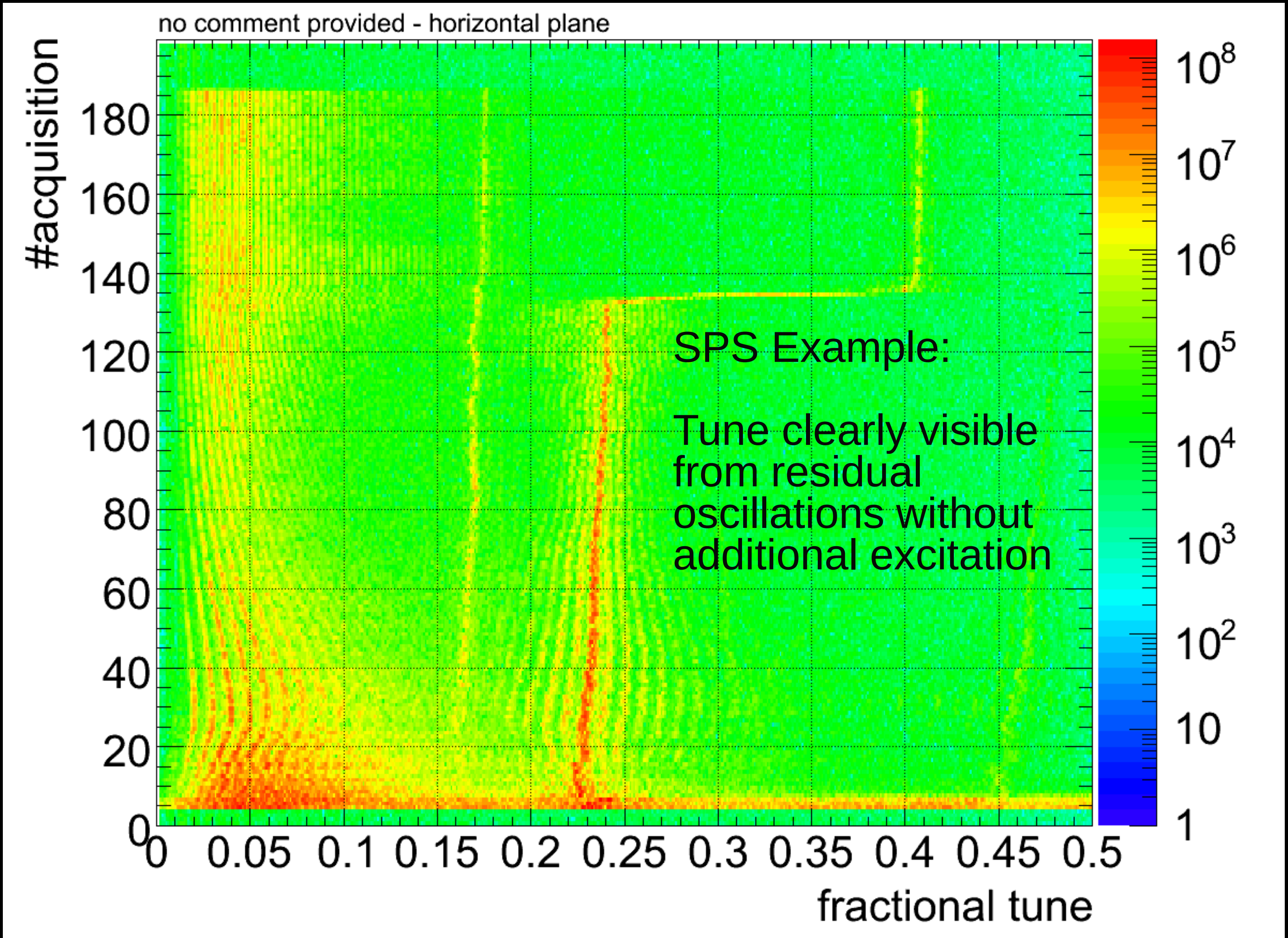
LHC BBQ System Performance



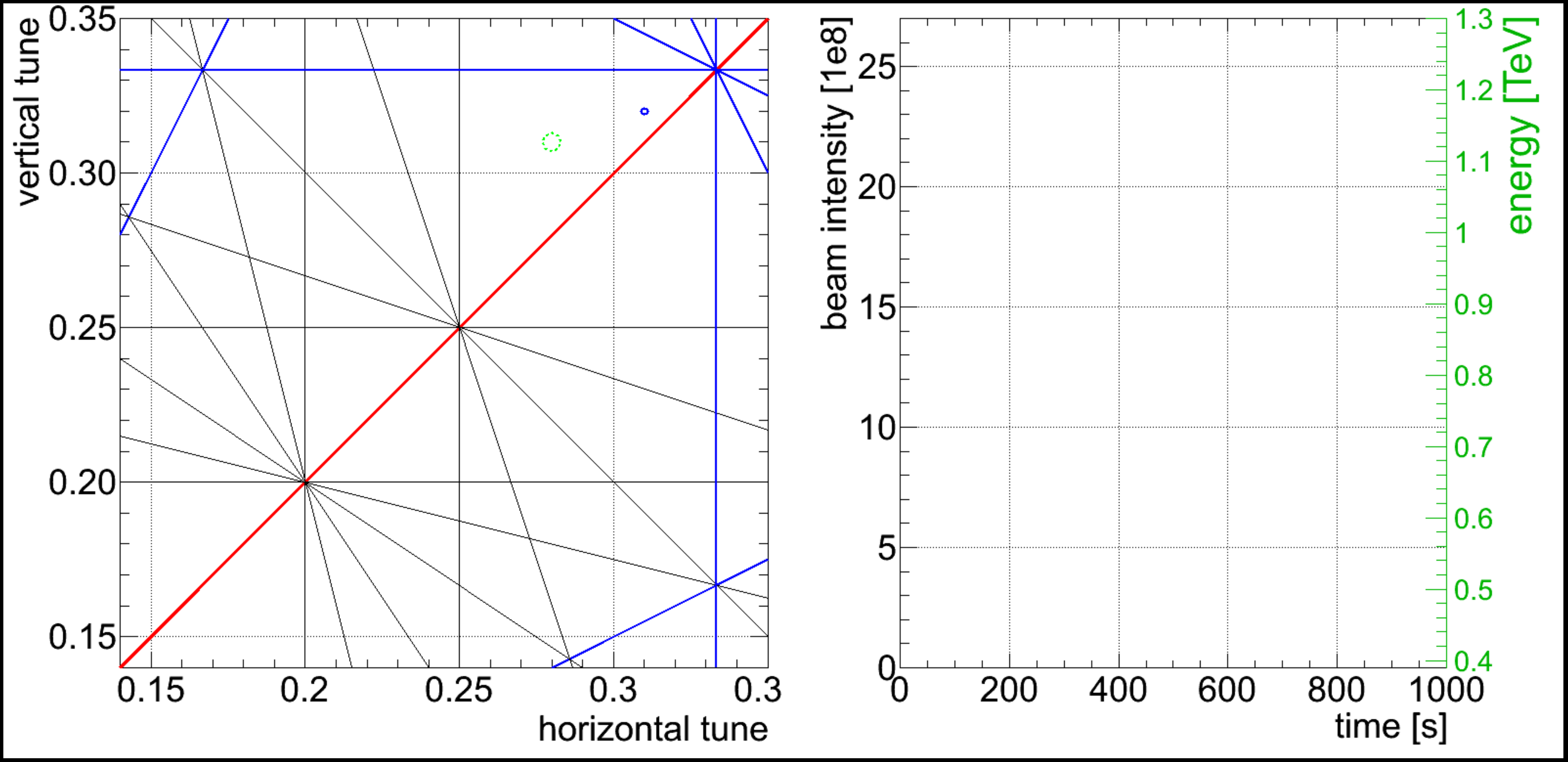
Sensitivity down to the 10 nanometre level

Enough to see residual beam oscillation without added excitation

Real-Time Tune Display

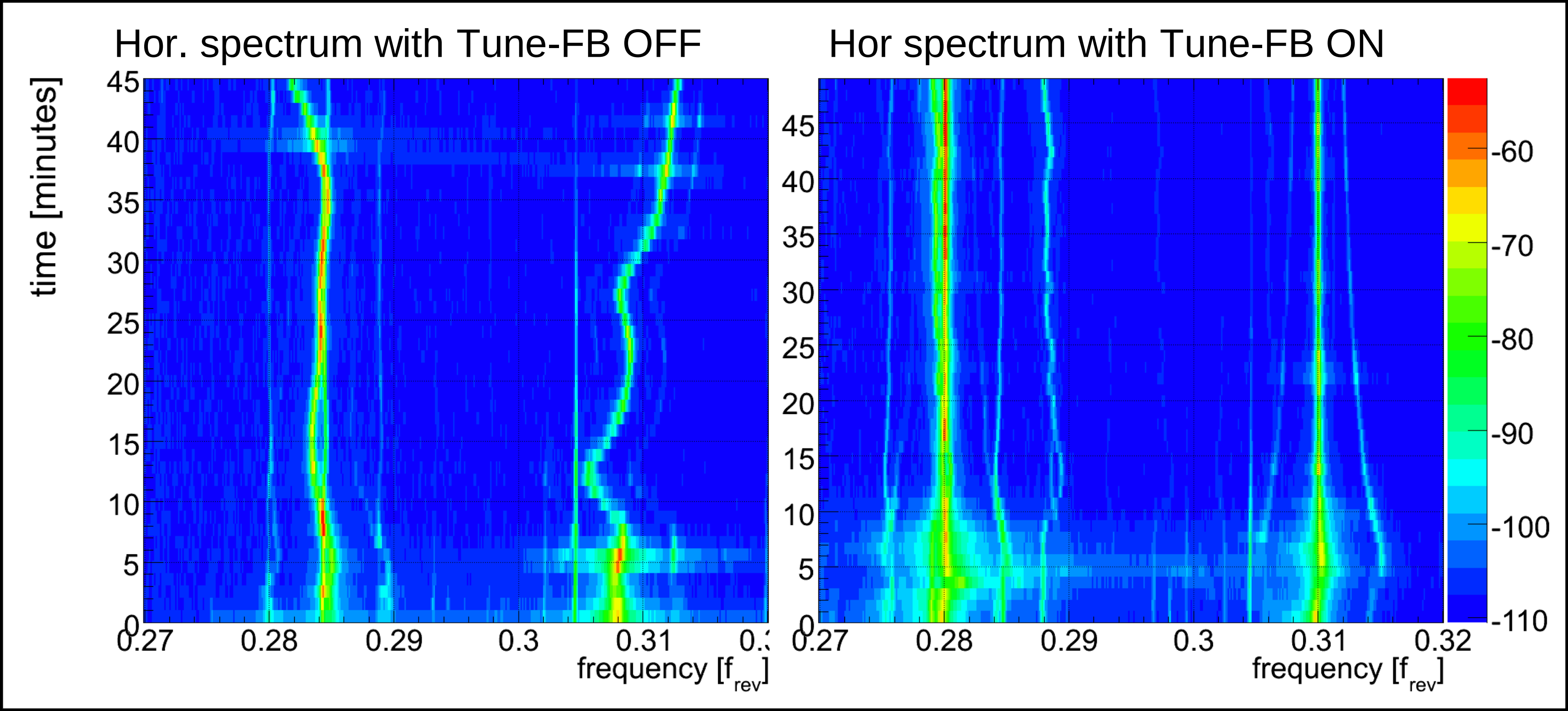


Tune Measurement in the LHC

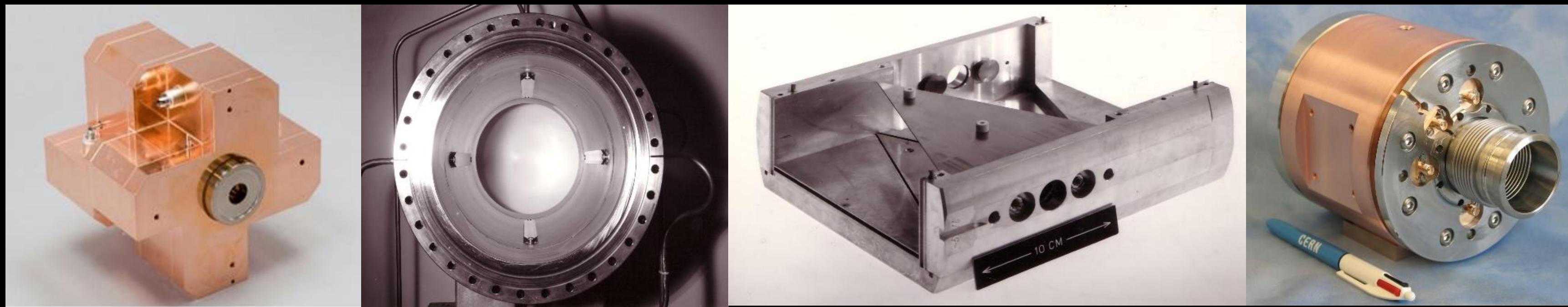


- Tune diagnostics throughout the ramp
  - Early ramps had poor tune control
  - Beam loss observed every time tune crossed a resonance line

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

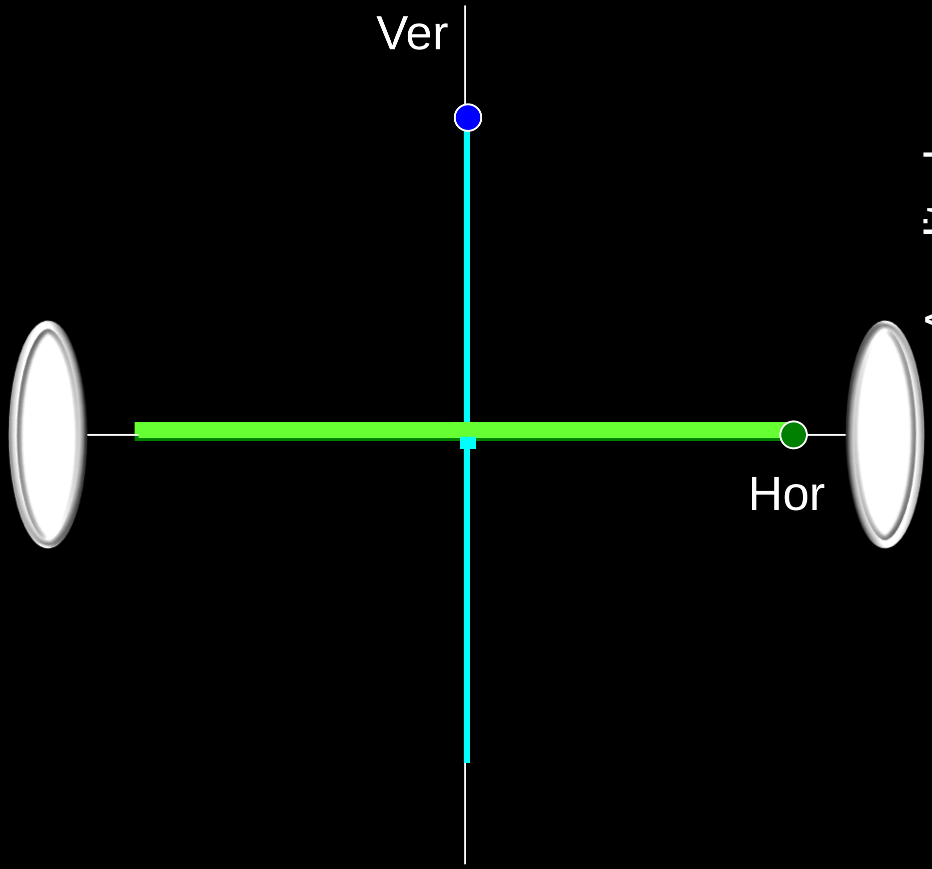
Coupling

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

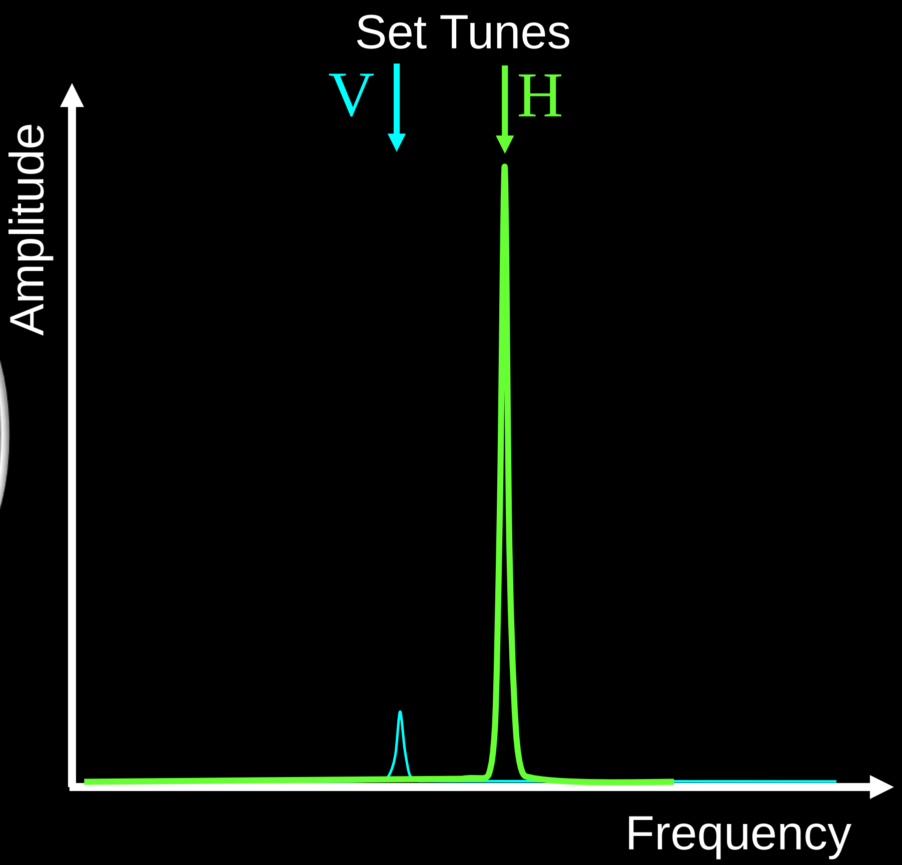
- Measured tunes - the physical observables seen in FFT
  - Often called the ‘normal modes’ or ‘eigenvalues’
- Set tunes
  - What the tunes would be in absence of coupling
  - Tune split $\Delta = (Q_x - Q_y)$
    - Difference between the set horizontal & vertical tunes
- Magnitude of the coupling coefficient $|C^-|$
  - 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



FFT of Horizontal Acquisition Plane



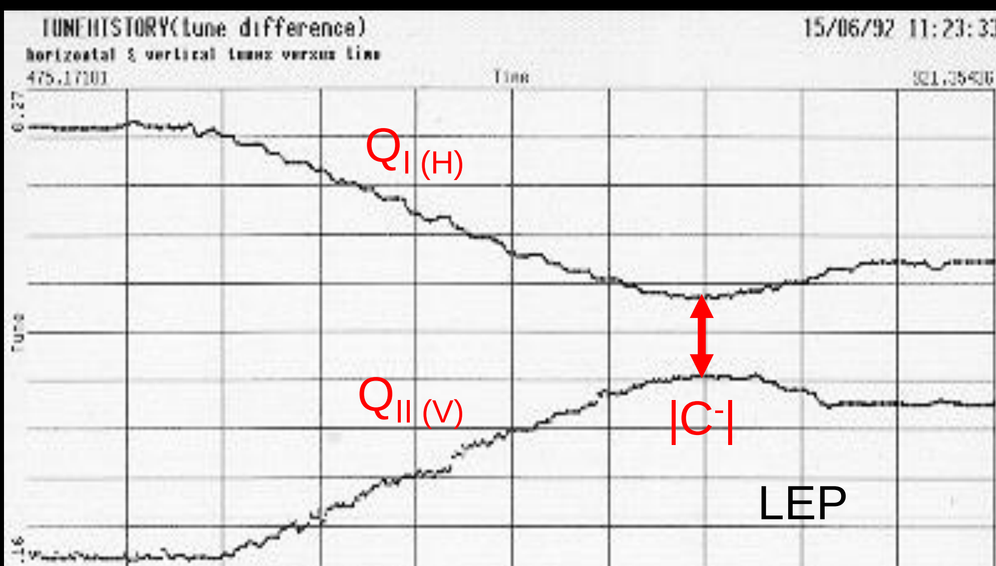
Measuring Coupling

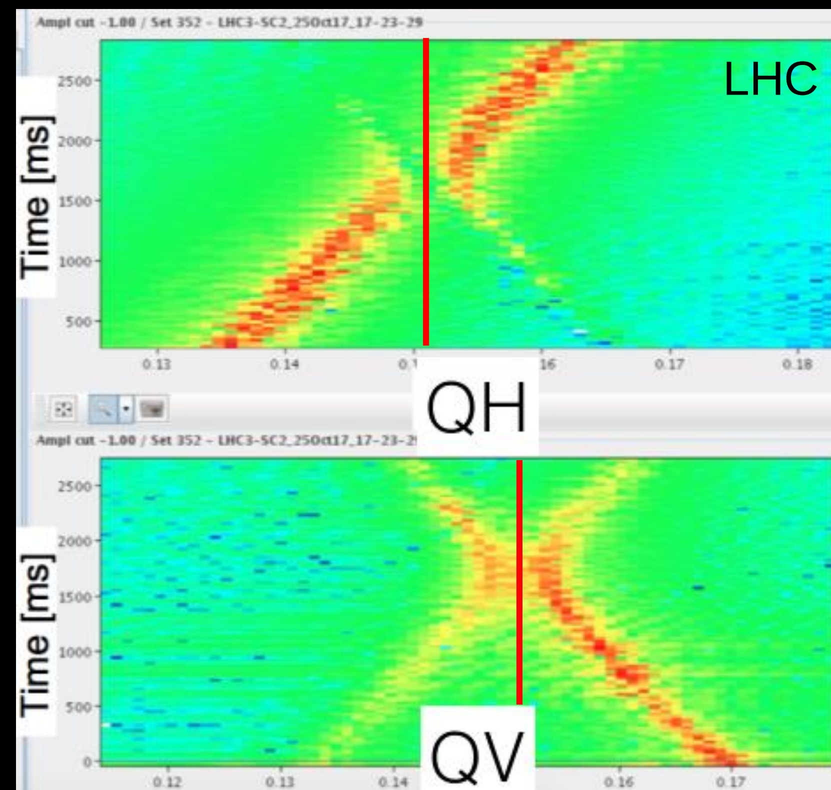
- 3 Main Methods
  - Orbit changes
    - Change orbit in one plane by exciting steering correctors or by changing injection conditions & measure effect in other plane
    - Large coupling sources identified as locations where horizontal orbit change generates a vertical kick & vice versa
    - Acquire 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

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

- 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

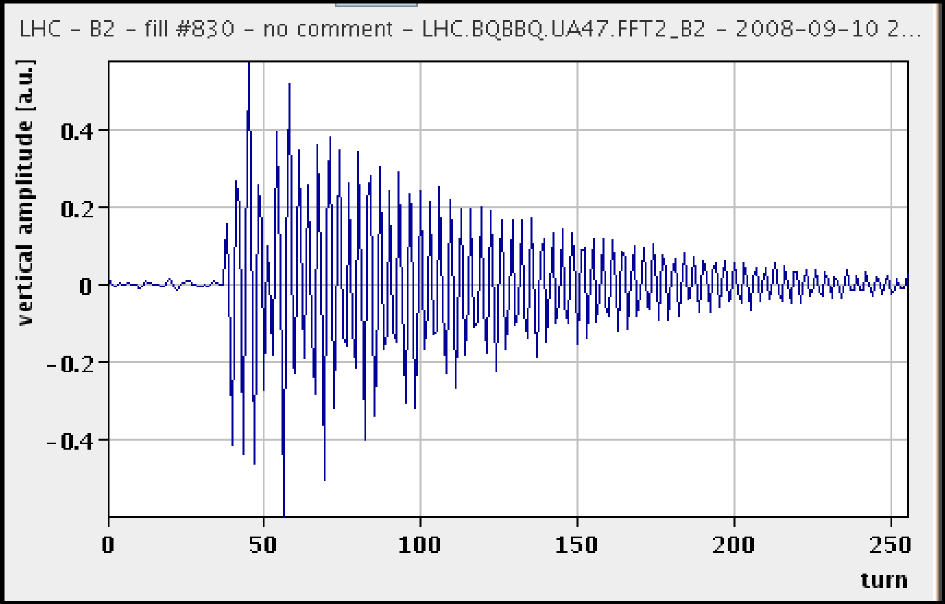


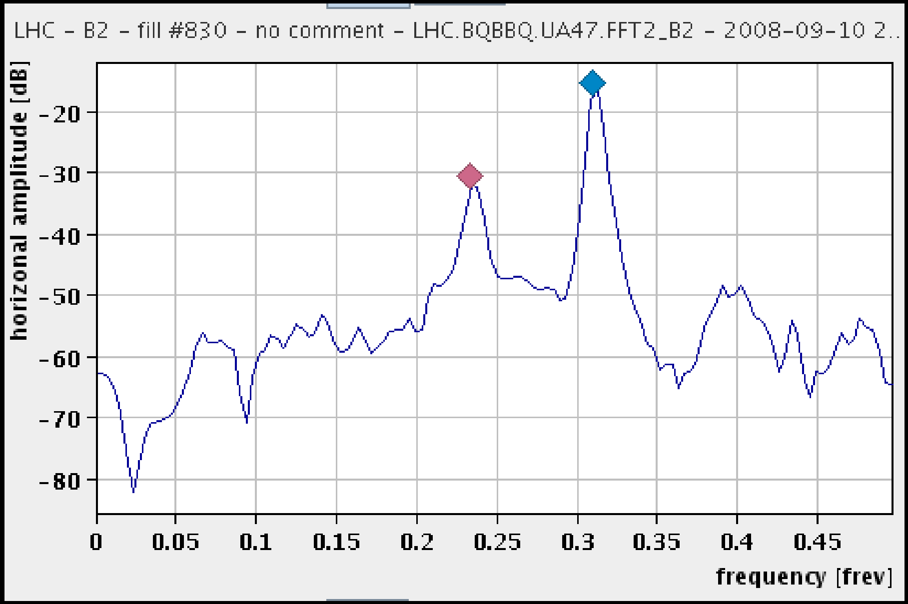


Measuring Coupling – Kick Response

- 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

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



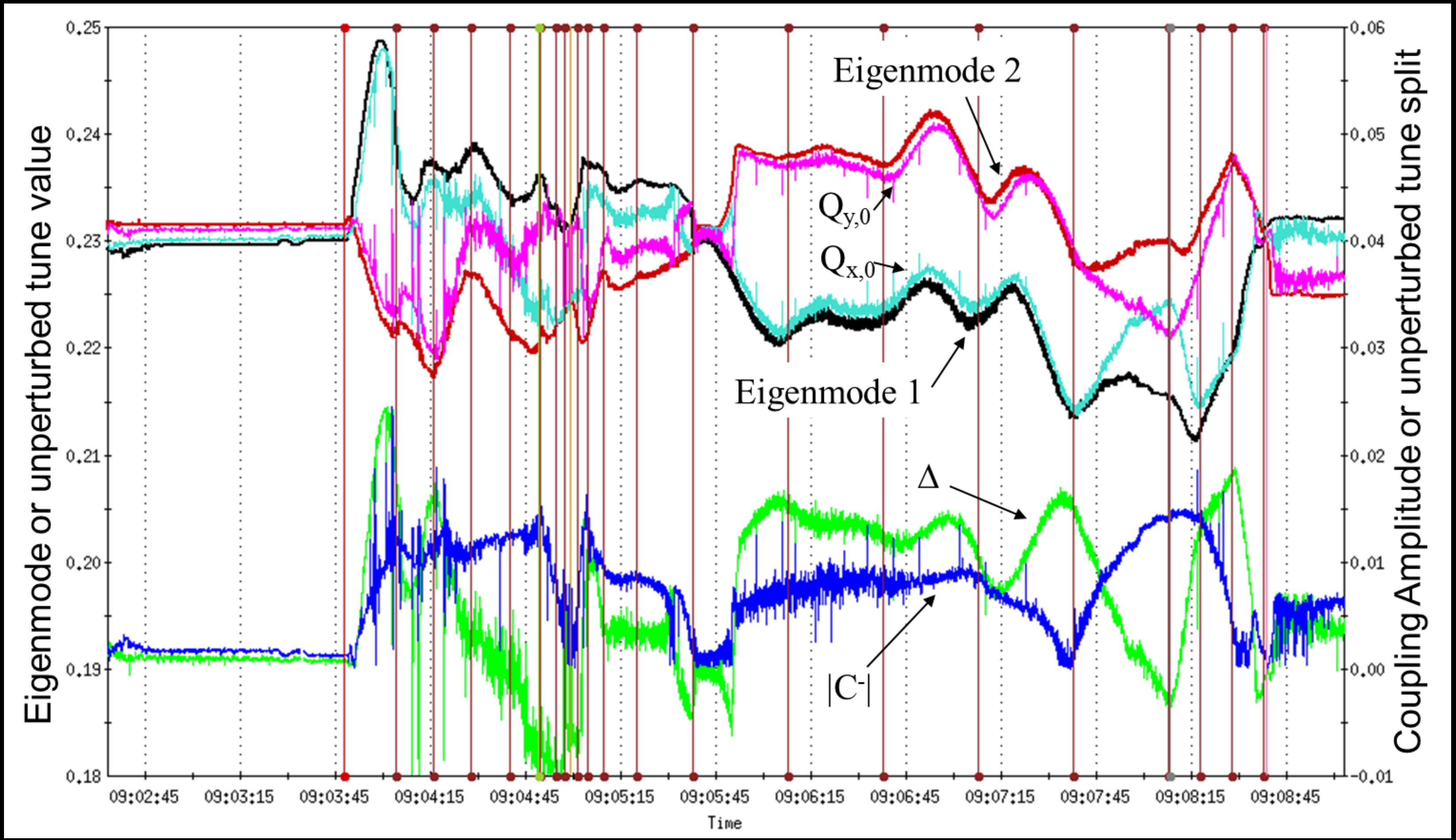


Understanding Tune Feedback Systems

A RHIC Example

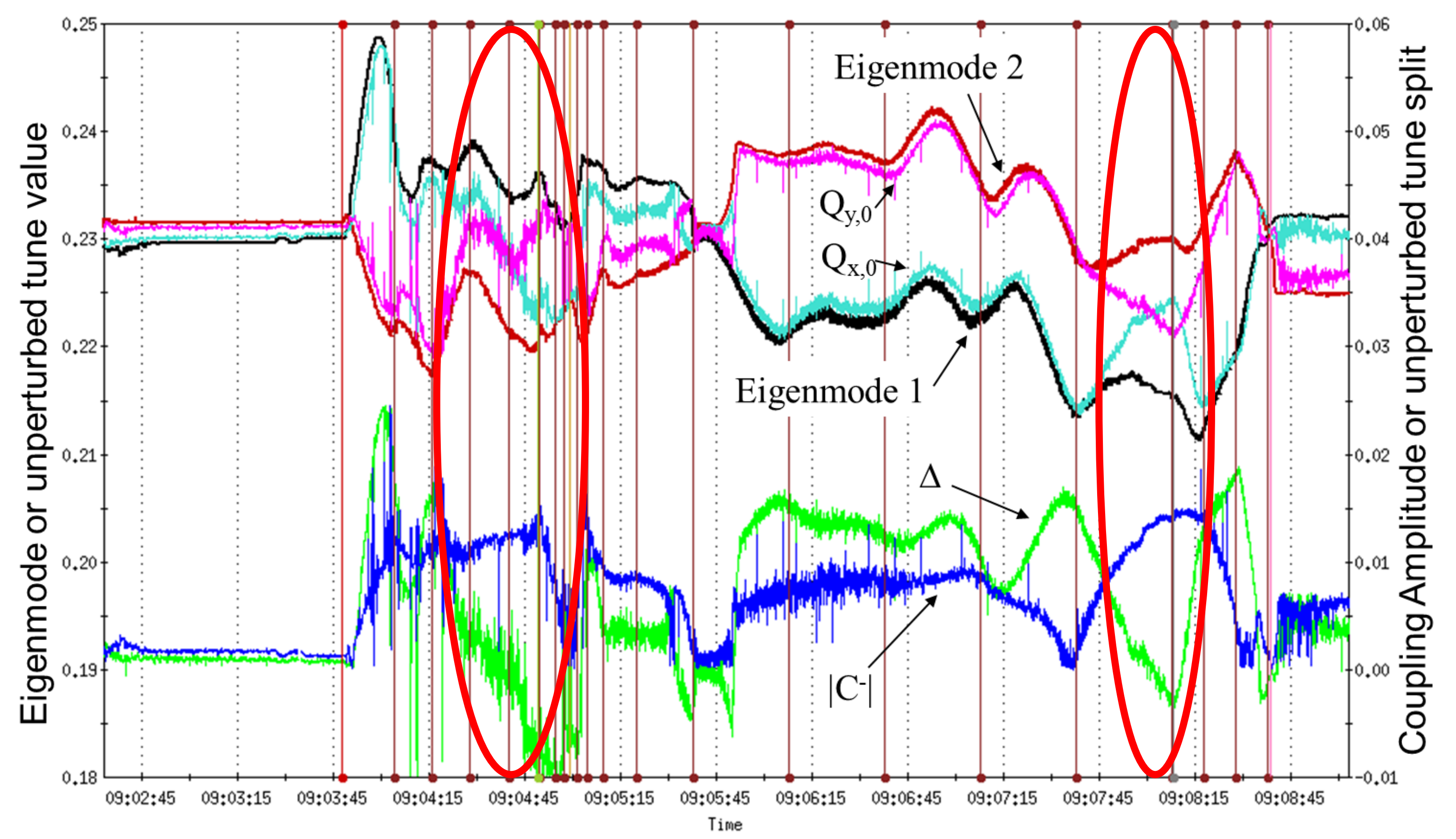
Coupling & Tune Feedback

- Measurement from RHIC during acceleration cycle
  - Tune & coupling measurement using 4 phase locked loops
    - Q_H loop (excite H, observe H) : Q_V loop (excite V, observe V)
    - $Q_{H,V}$ loop (excite H, observe V) : $Q_{V,H}$ loop (excite V, observe H)



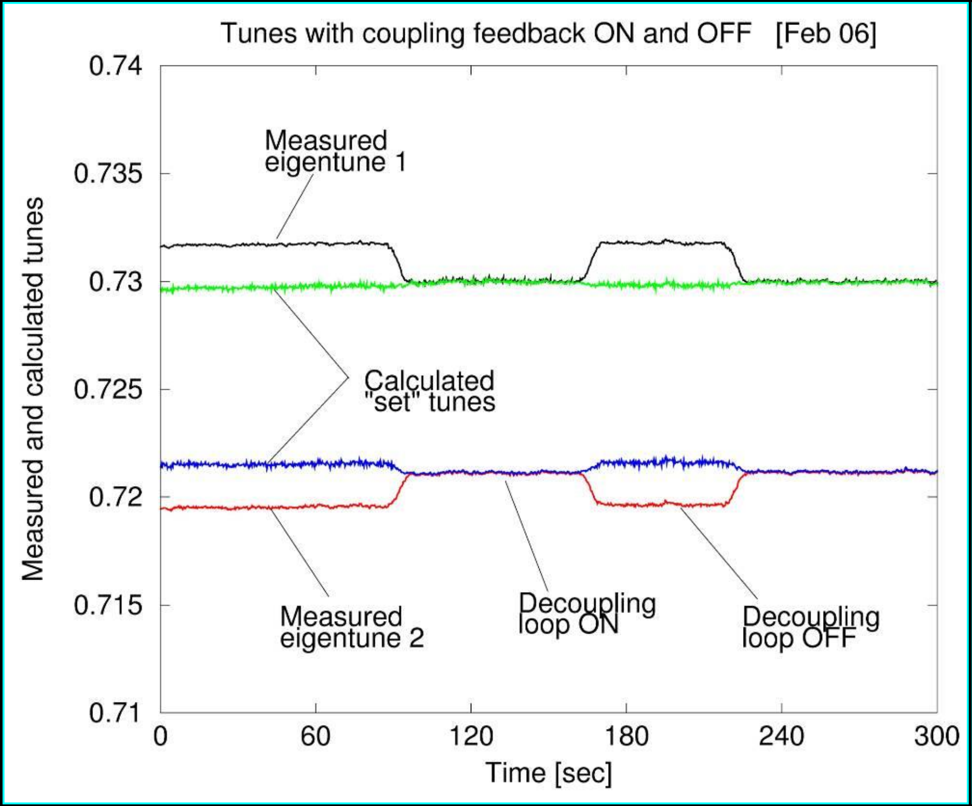
Coupling & Tune Feedback

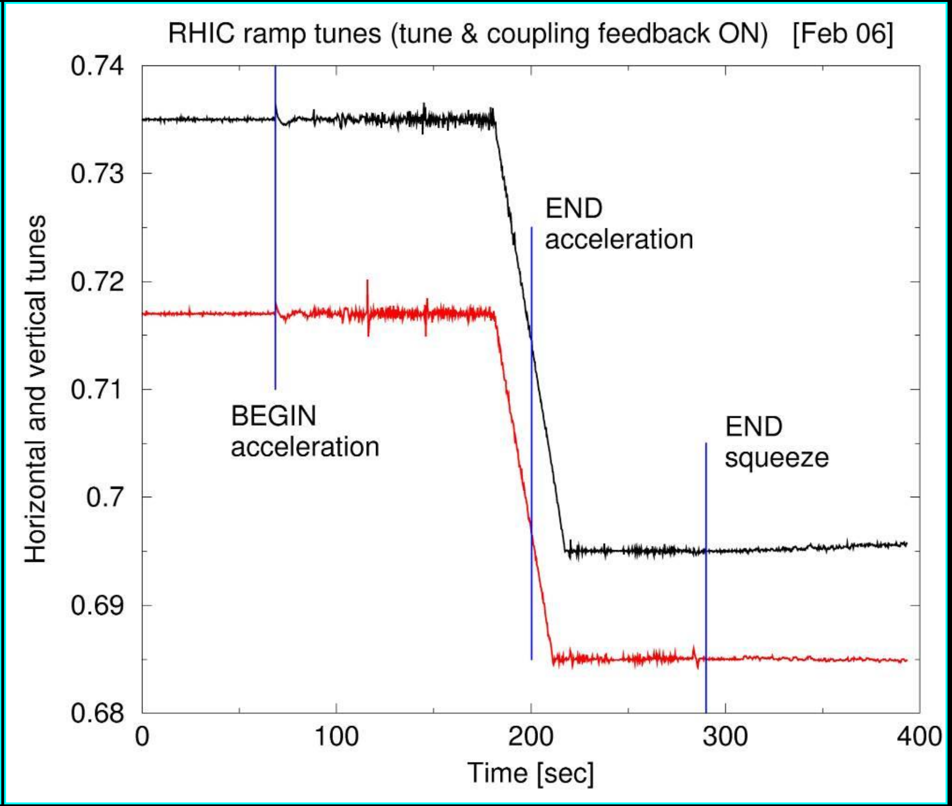
- Measurement from RHIC during acceleration cycle
  - At several points measured tune is defined by coupling
  - Tune feedback breaks down at these points
    - Need to correct coupling first

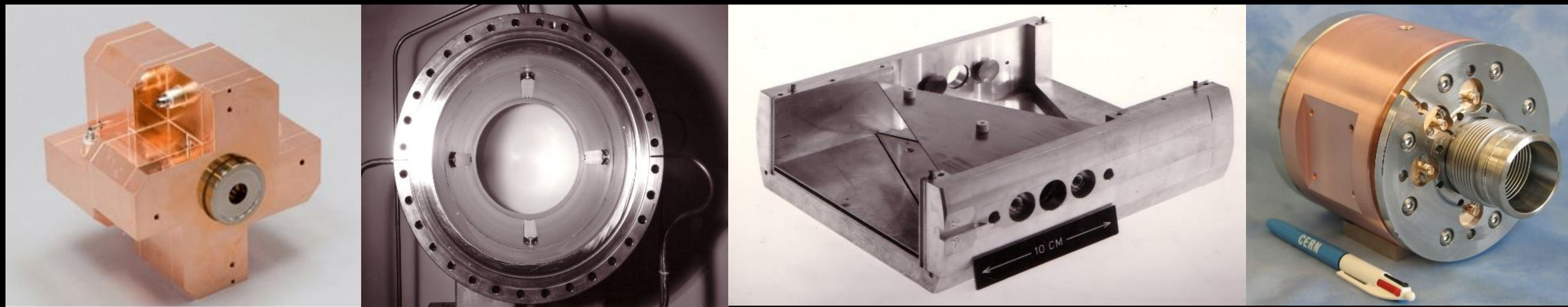


Coupling & Tune Feedback

- 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





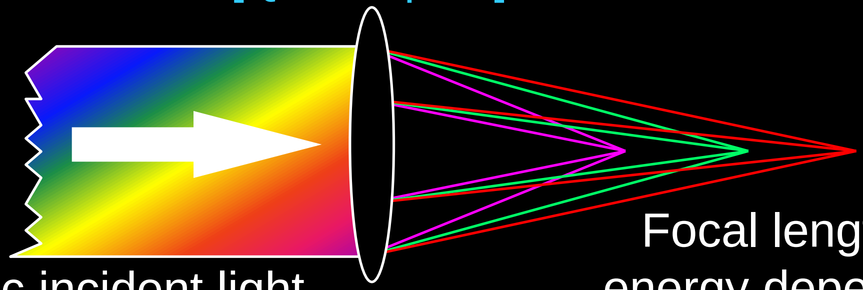


Chromaticity Measurement

Chromaticity

- Machine Chromaticity

Optics Analogy:



Spread in the Machine Tune due to Particle Energy Spread

Controlled by Sextupole magnets

First Order

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

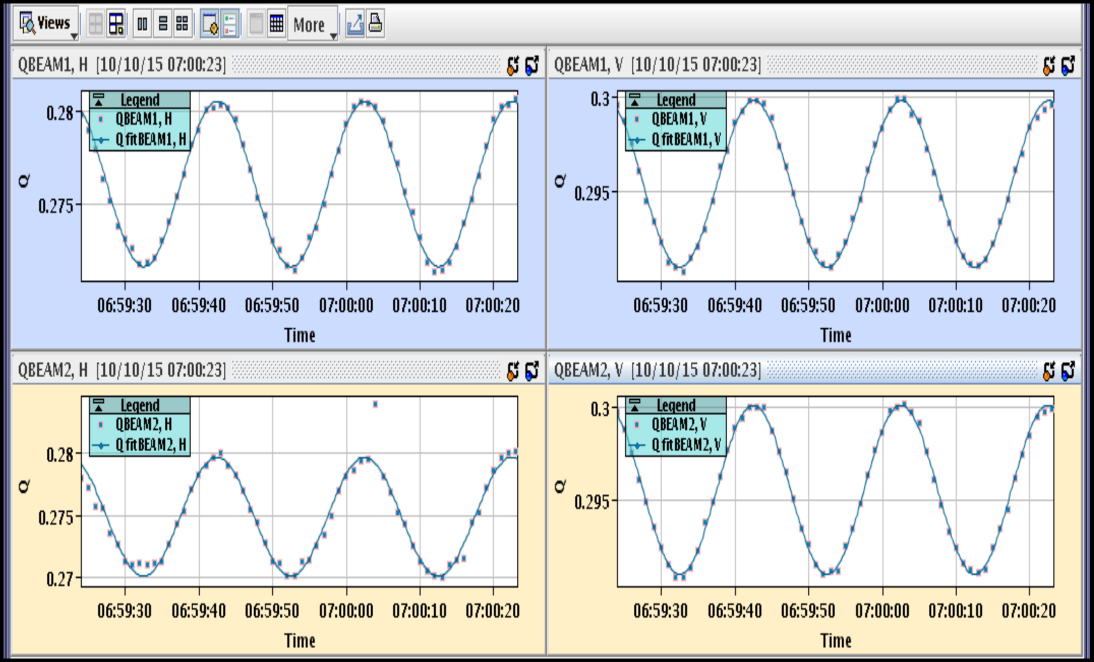
$$\xi = \frac{Q'}{Q}$$

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

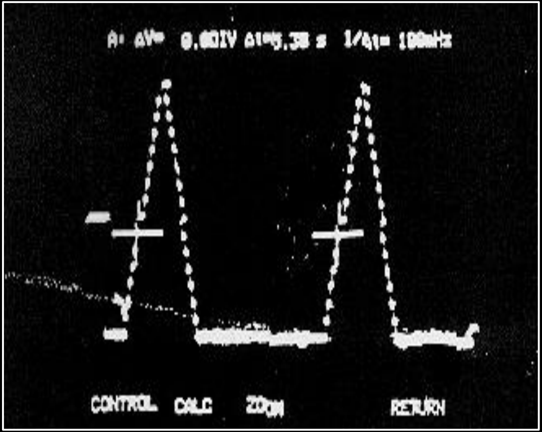


Example from the LHC

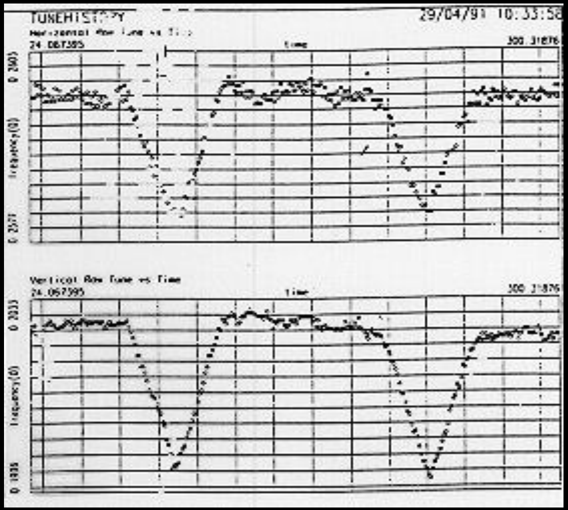
- Sinusoidal RF modulation at 0.05Hz
- Tune continuously tracked in all planes of both beams
- Chromaticity calculated once acquisition complete

RF Momentum Modulation Techniques

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



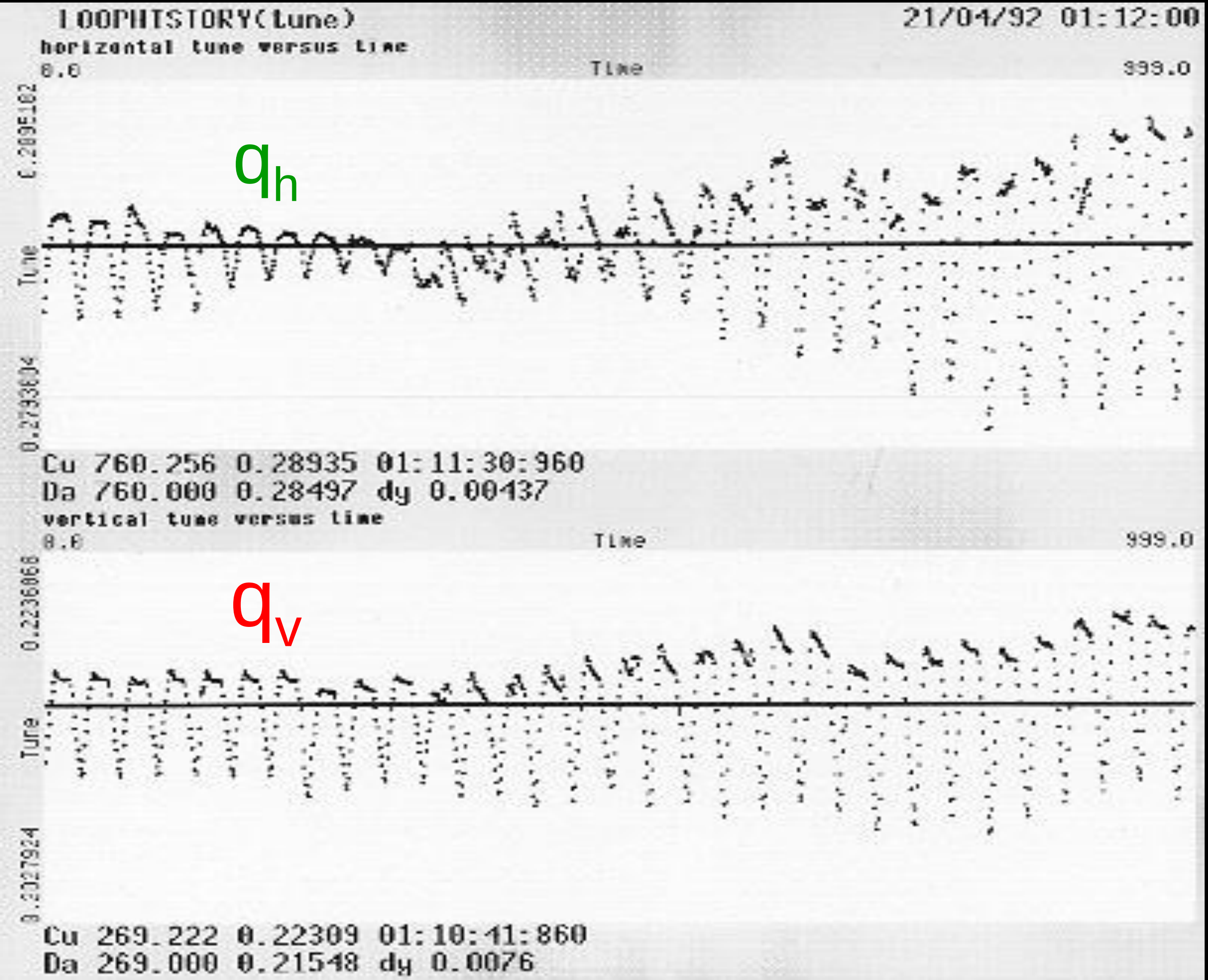
Applied Frequency Shift



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

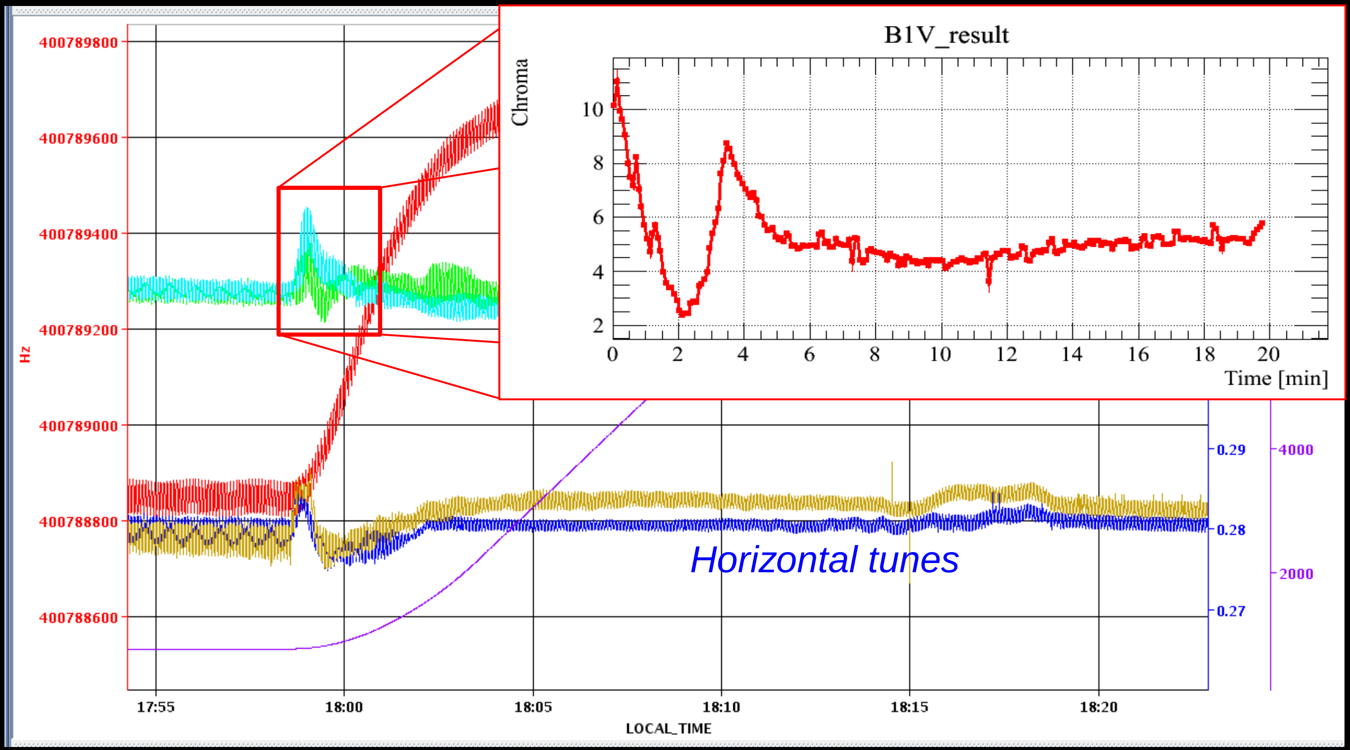


BI)

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
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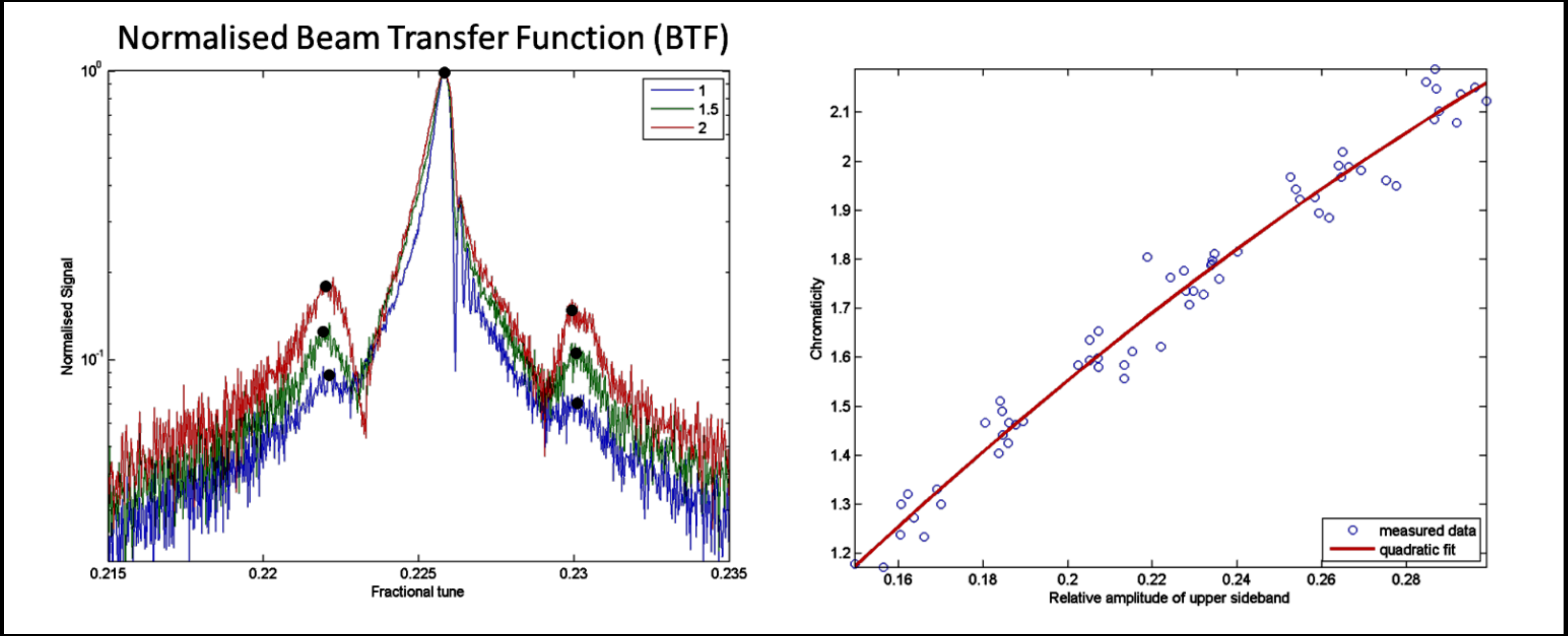
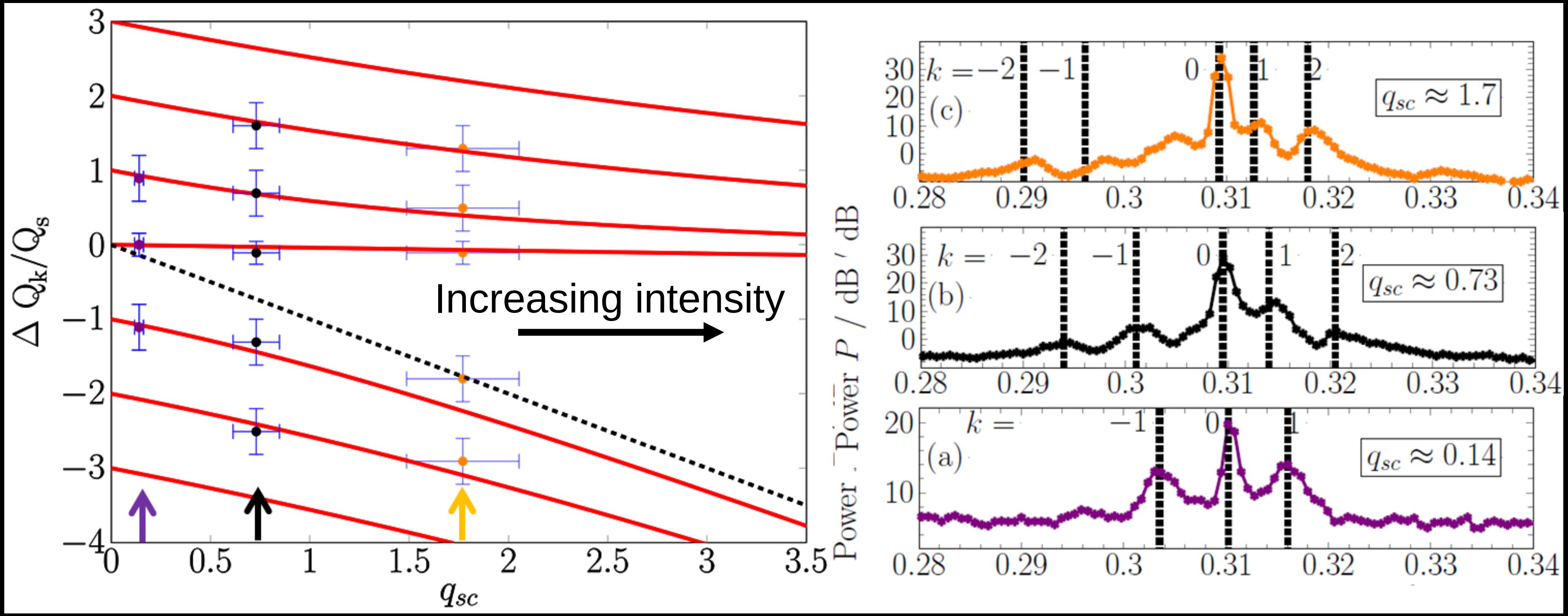
Amplitude of Synchrotron Sidebands

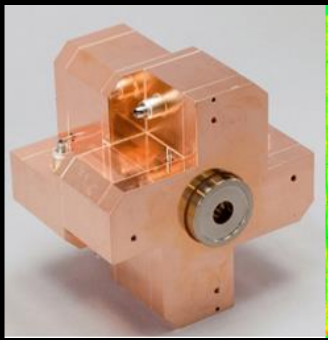
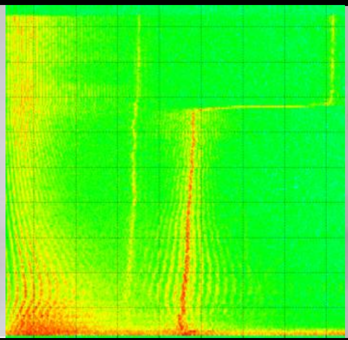
- Recently demonstrated at DIAMOND
  - RF modulation changes orbit - not compatible with user operation
  - Looking for technique to measure chromaticity on-line
    - Measure Beam Transfer Function (BTF) on single bunch
      - Using transverse bunch by bunch feedback system
      - Emittance blow-up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

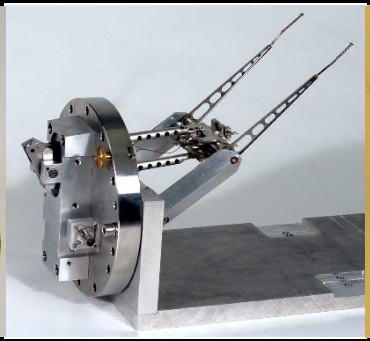
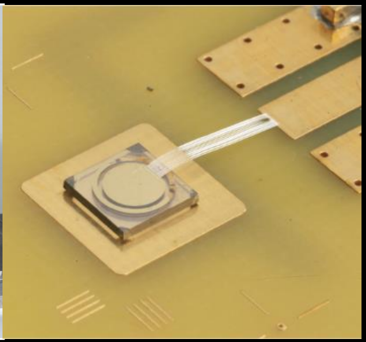


Amplitude of Synchrotron Sidebands

- 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.

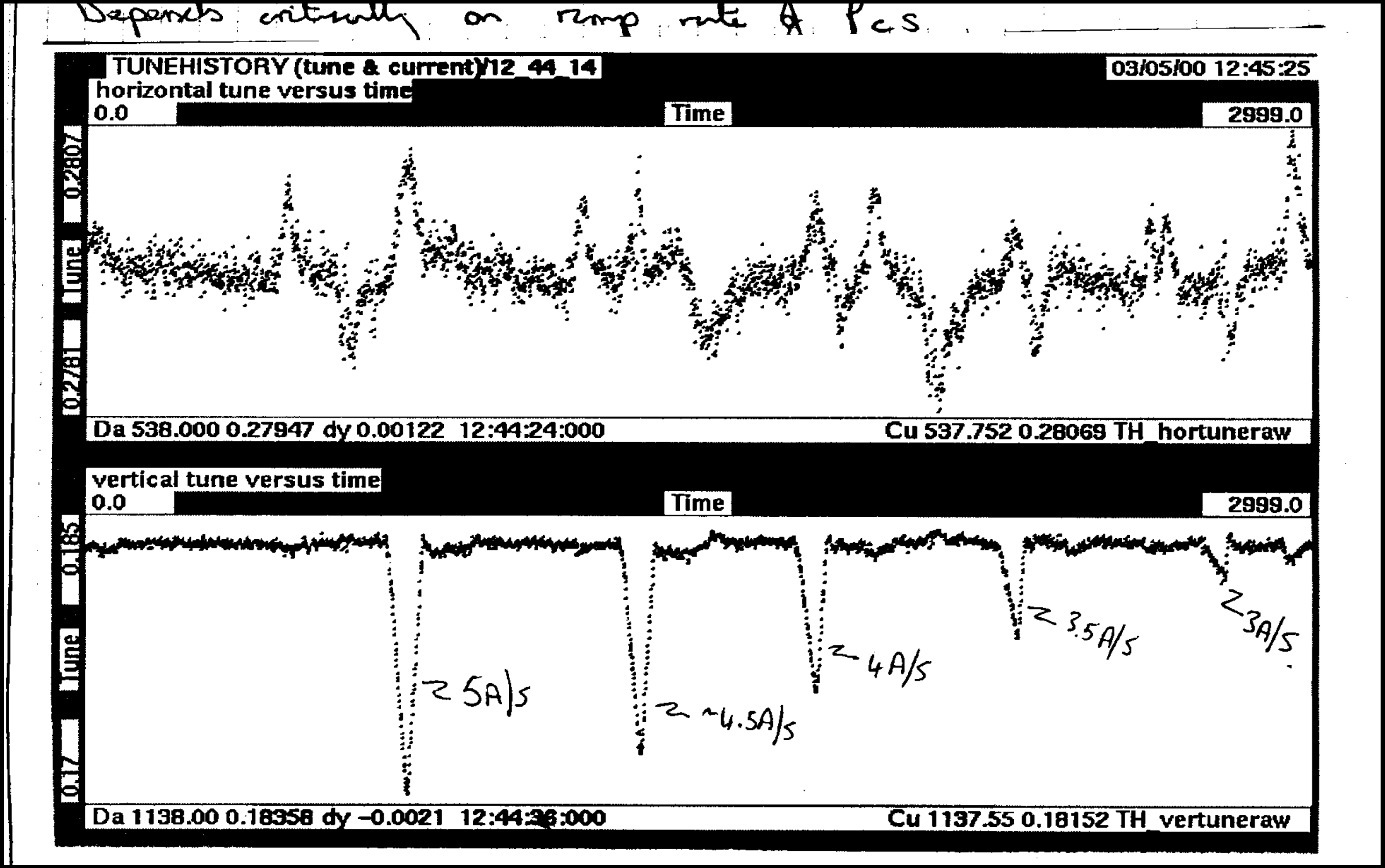
01:40 22 GeV 4QS0. Breakpoint at 93 GeV.

640μA .234/.164 5.27mA

93GeV 4QS0 01-58-36 V RMS ~
Tunehistory 01-50-25 fill 7066

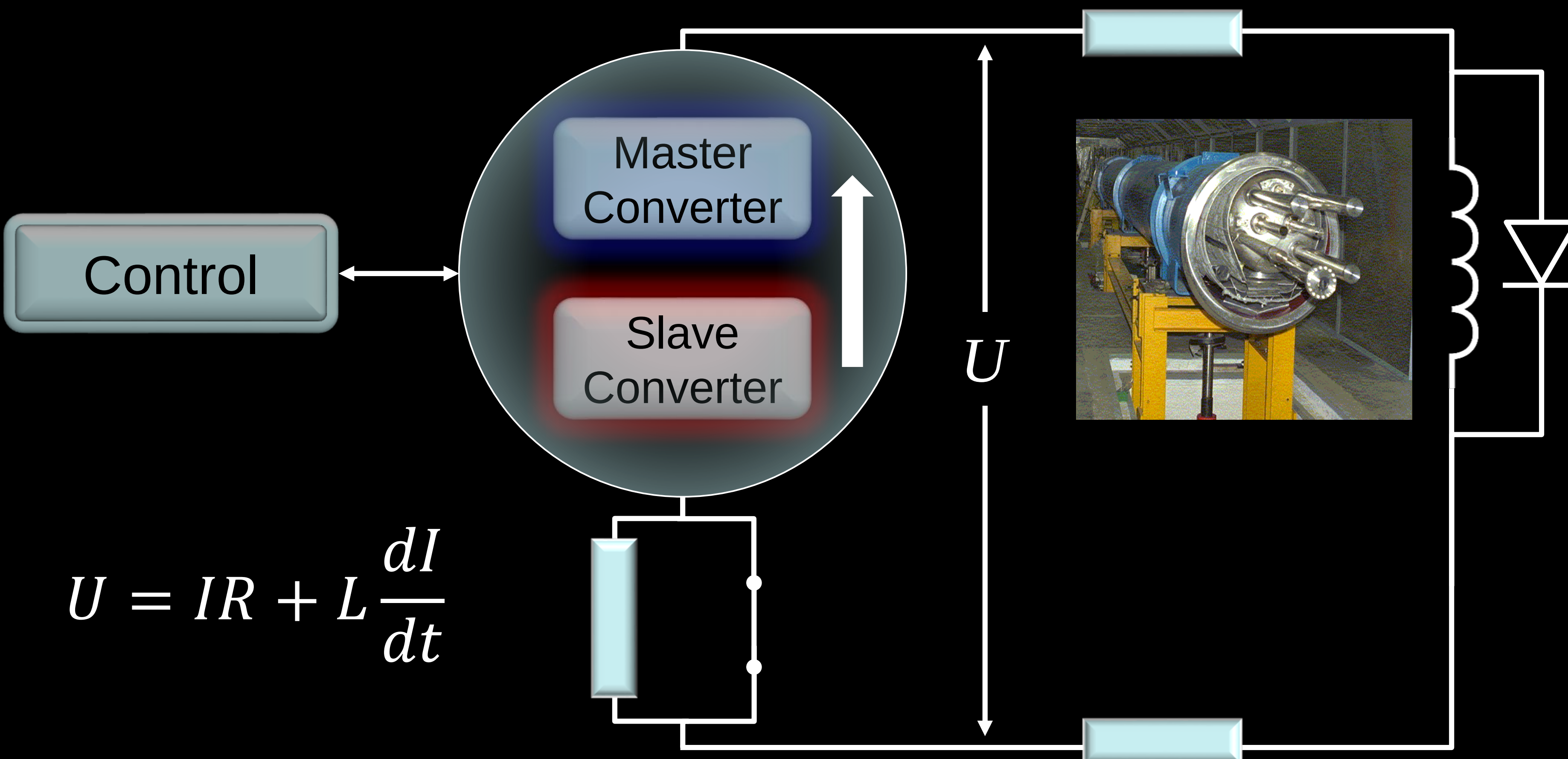
The Diagnostics

- Tune Variation
  - Tracked for different power converter ramp rates



The Explanation

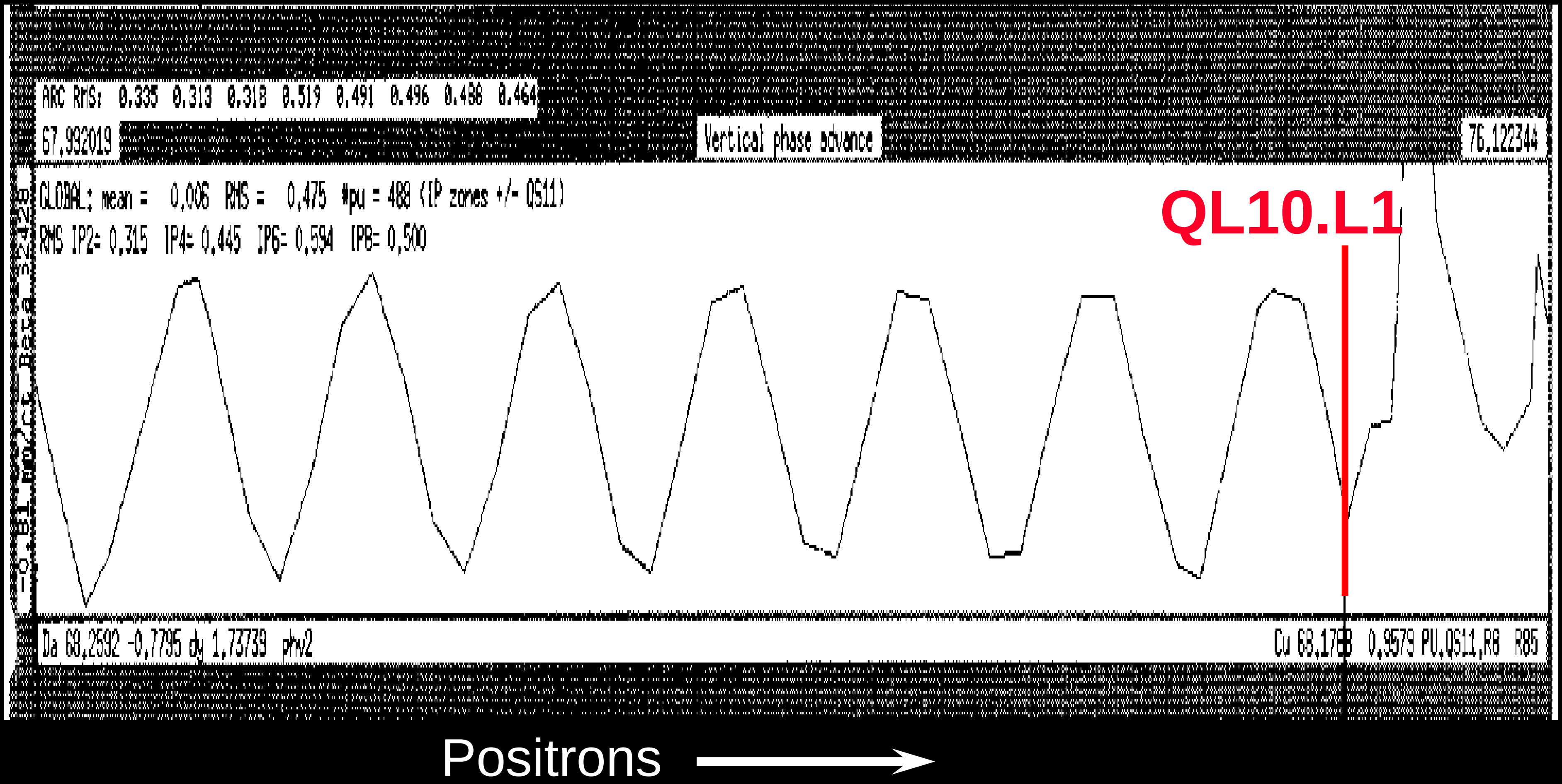
- Master-Slave Configuration for Power Converter
  - Each converter can deliver full DC current
  - Slave converter not working
    - Slave only needed to give increased voltage for fast current changes



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

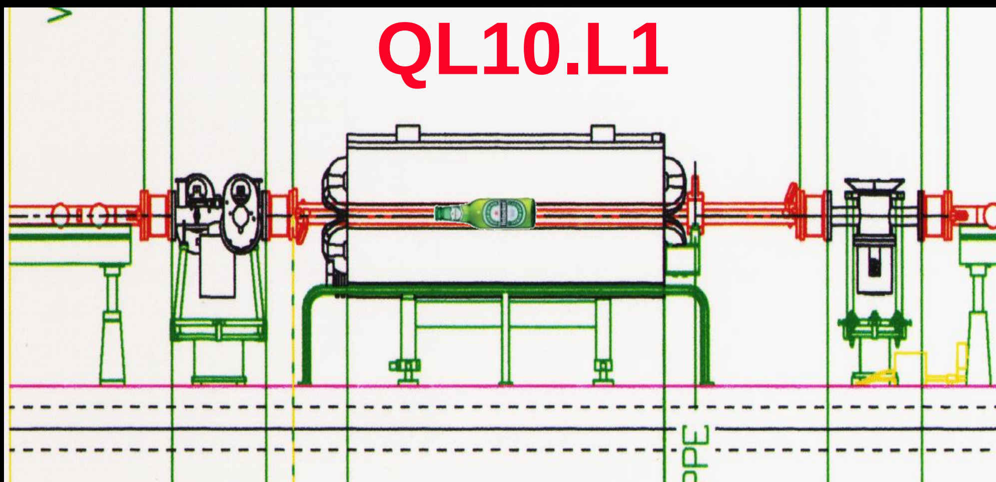
LEP – No Circulating Beam

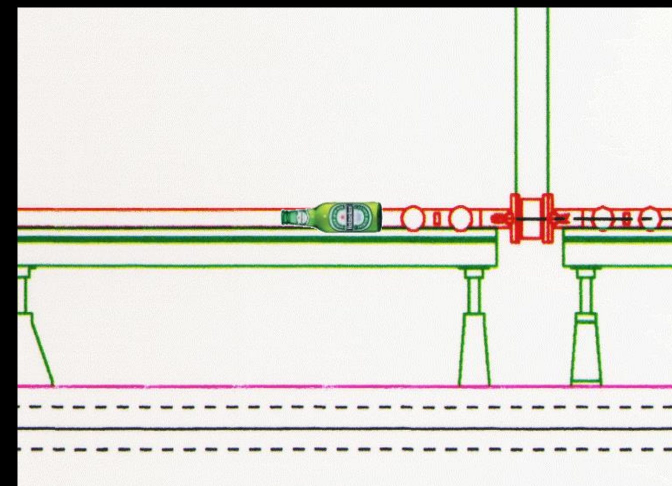
- No Circulating Beam after Technical Stop
  - Phase advance from BPMs show that optics no longer correct after specific quadrupole



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
  - 2 days simulating a beam position acquisition system
  - 1 day "hands-on" laboratory measurements
- 3 Sessions on Profile Measurements
  - A series of different "hands-on" laboratory experiments