Beam Instrumentation and Diagnostics (Lecture 2)

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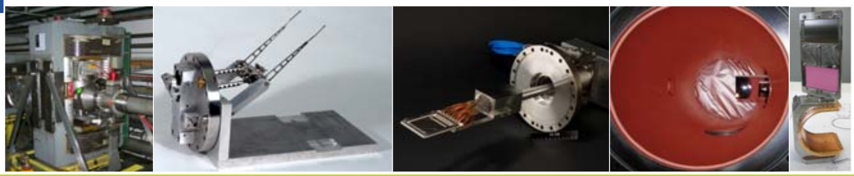
Introduction

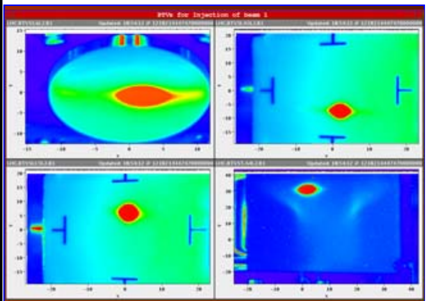
- Yesterday was dedicated to
  - Beam position measurement
  - Beam intensity measurement
  - Beam loss monitoring
- Today we'll continue with a look at
  - Beam profile monitoring & diagnostics
  - Tune, Coupling & Chromaticity measurement & feedback
  - Making Accelerators work using beam instrumentation



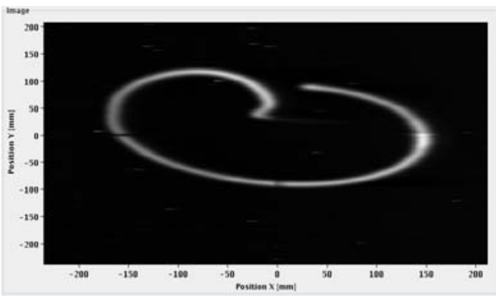
Beam Profile Monitors

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

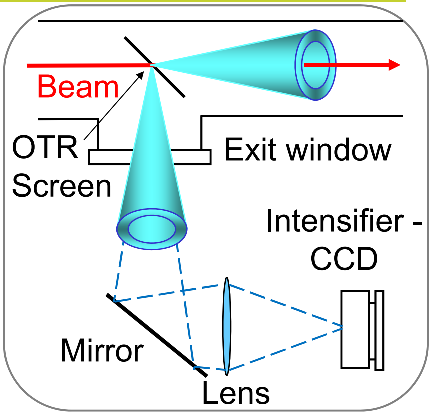


First Beam in the LHC 8/8/2008

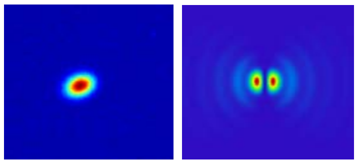


Profile Monitoring using Screens

- 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

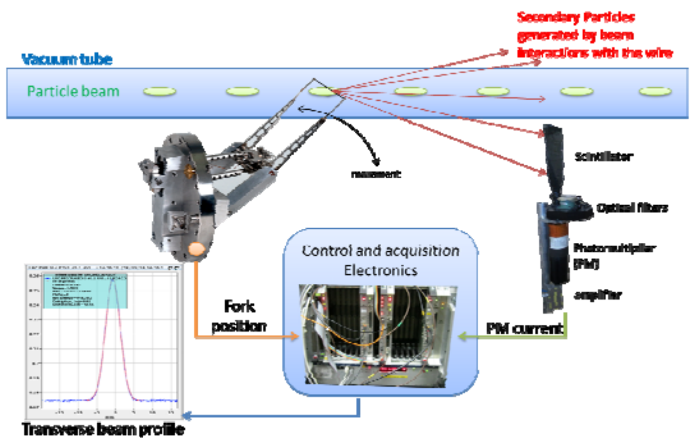


- OTR screens
  - Much less destructive (thin) but requires higher energy / intensity beam
  - Can be used for extremely high resolution measurements



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



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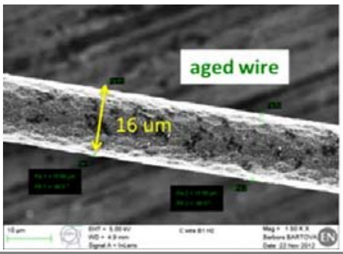
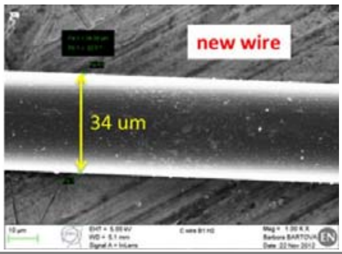
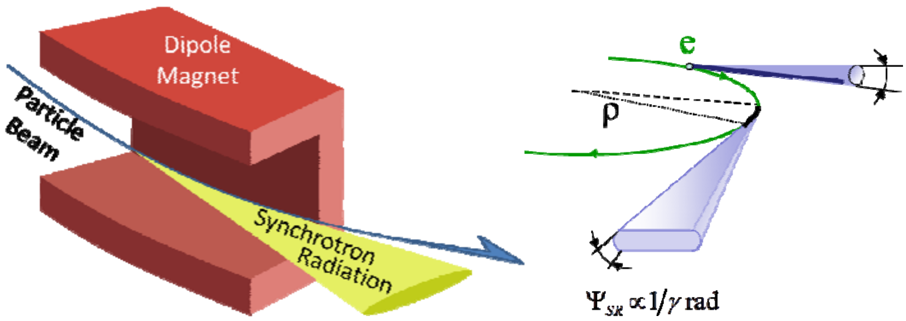
Limitation of WireScanners

- 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



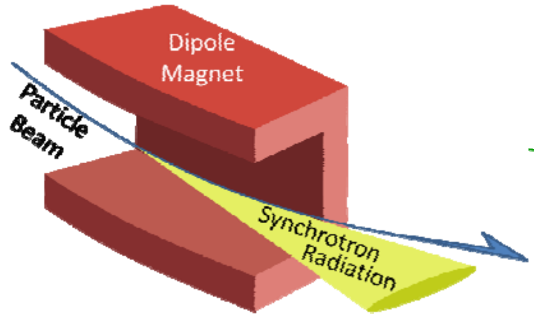


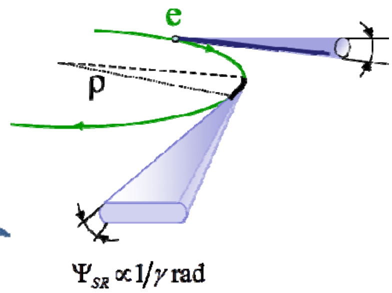
Synchrotron Light Monitors

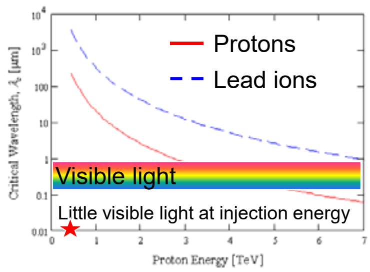


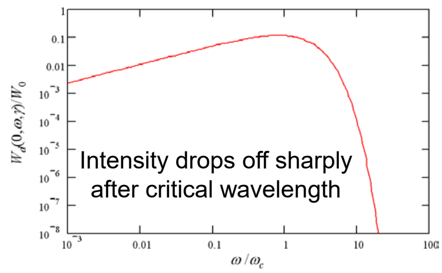
- Synchrotron light
  - Emitted from a moving charge bent in a magnetic field
  - The main "raison d'être" for light sources
  - Also a very useful, non-invasive, powerful diagnostic tool
  - Can even be observed with protons & lead ions in the LHC

Synchrotron Light Monitors



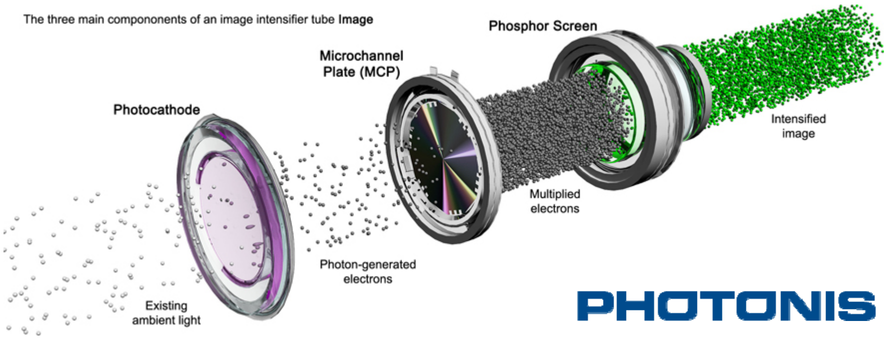






Synchrotron Light Image Acquisition

- Using various cameras
  - Standard CCD cameras for average beam size measurements
  - Gated intensified camera
    - For bunch by bunch diagnostics
  - Streak cameras
    - For short bunch diagnostics



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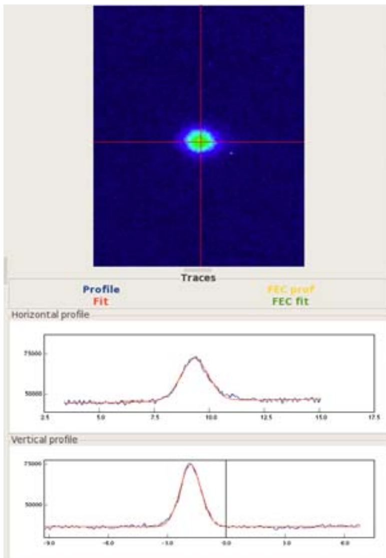
Synchrotron Light Imaging

- Proton Beam Example
  - LHC single bunch ~1.1e11p @ 3.5 TeV
  - Acquisition accumulated over 4 turns at 200Hz



- Limitations
  - Aberrations
    - Mitigated by careful design
  - Diffraction
    - Need to go to lower wavelengths as the beam size becomes smaller

Longitudinal Profile Measurement

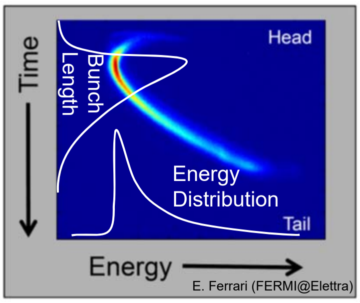
- Next Generation FELs & Linear Colliders
  - Use ultra short bunches to increase brightness or improve luminosity
- How do we measure such short bunches?

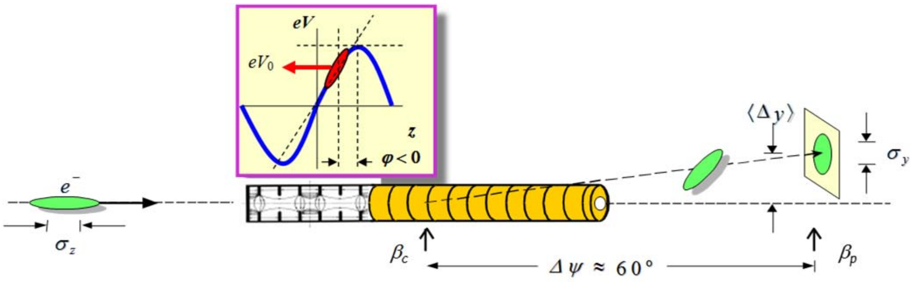
p^+ @ LHC	250ps
H^- @ SNS	100ps
e^- @ ILC	500fs
e^- @ CLIC	130fs
e^- @ XFEL	80fs
e^- @ LCLS	<75fs

  - Direct Observation
    - Produce light & observe 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

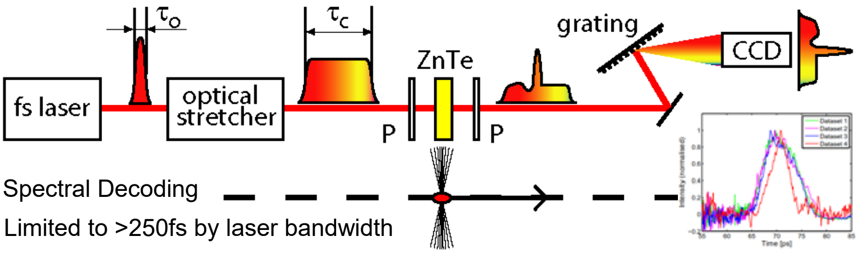
- RF Deflection
  - Converts time information to spatial information
  - Coupled to spectrometer also provides energy information
  - Destructive technique
  - Resolution down to 1.3 fs
    - X-band RF cavity
    - Linac Coherent Light Source (SLAC)





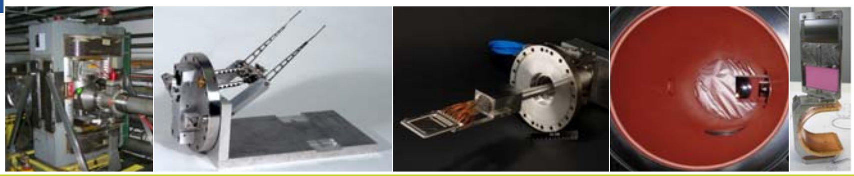
Measuring Ultra Short Bunches

- Electro-Optic Sampling
  - Birefringent crystal placed close to the beam
    - Non-destructive technique
  - Bunch passes simultaneous 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



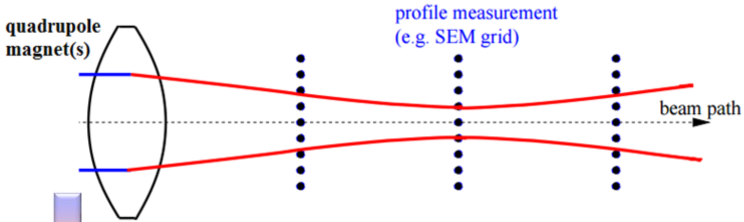
Spectral Decoding

Limited to >250fs by laser bandwidth

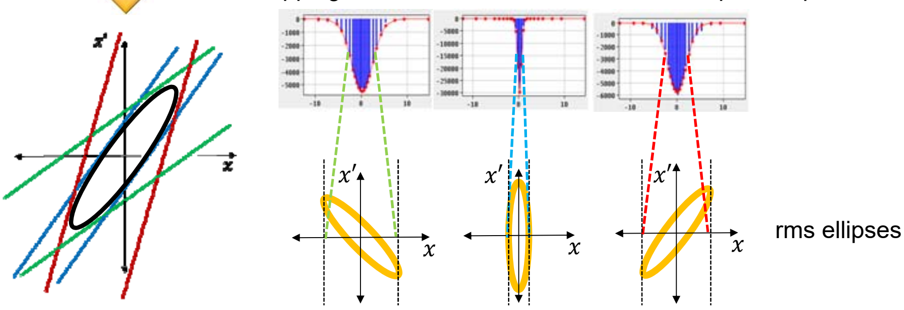


Diagnostics using Beam Profile Monitors

Optics Measurement in LINACs

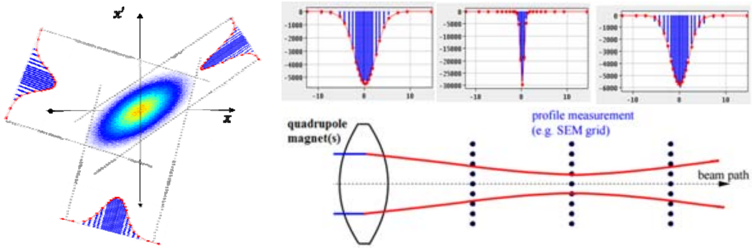


Linear Mapping of measured beam size onto initial phase space

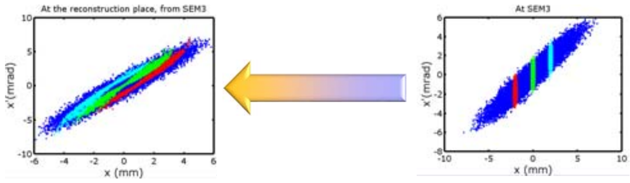


Optics Measurement in LINACs

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

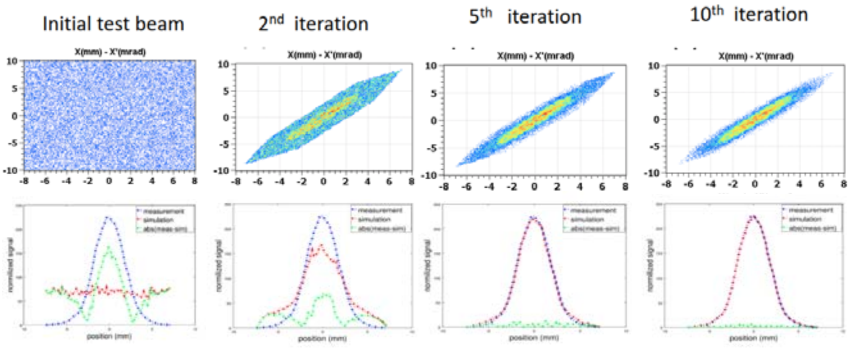


- Things get more complicated when you add space charge



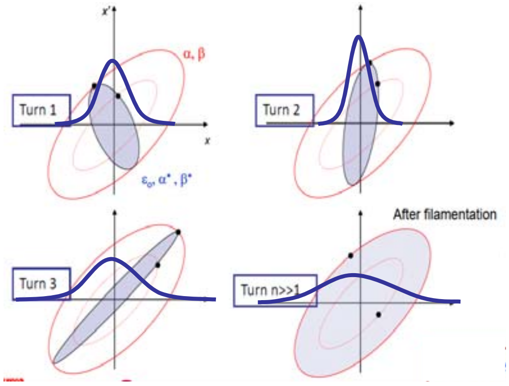
Optics Measurement in LINACs

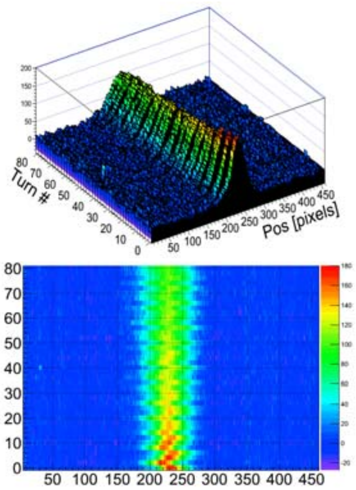
- Method
  - Iteratively vary Twiss parameters & track to the measurement locations including space-charge
  - Comparing measured & simulated rms beam sizes
  - Continue until the simulated beam sizes converge to measured profiles
- Hybrid Phase Space Tomography in Linac4
  - Deduce new distribution of density in phase space from which particles fall on which wires
  - Generate new beam distribution & use for next iteration



Measurements with Screens

- Injection matching measurements with OTR
  - Filamentation
  - Machine Settings Mismatch

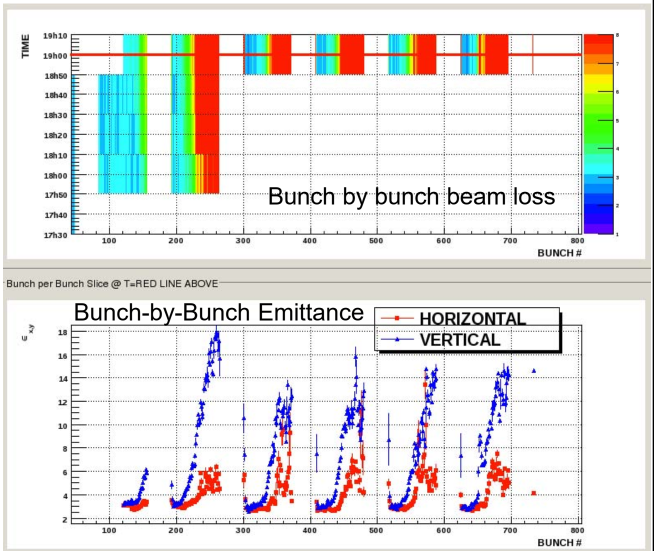


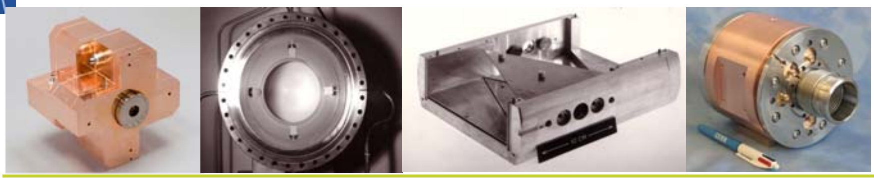


Bunch by Bunch Diagnostics

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
- Machine parameters adjusted to counter this effect
  - Chromaticity
  - Transverse feedback

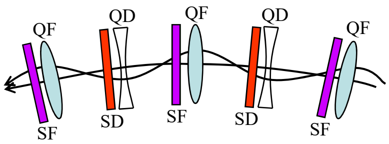




Tune, Coupling & Chomaticity Measurement

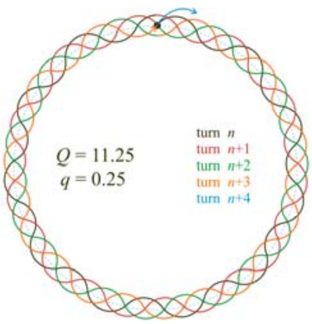
Machine Tune

- Machine Tune



Characteristic Frequency of the Magnetic Lattice

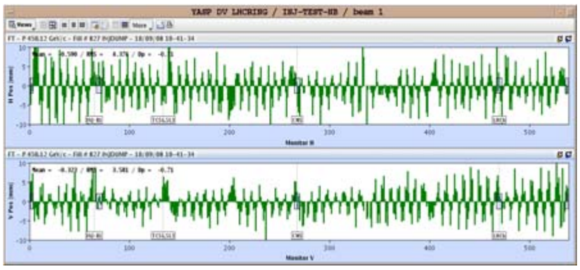
Given by the strength of the Quadrupole magnets



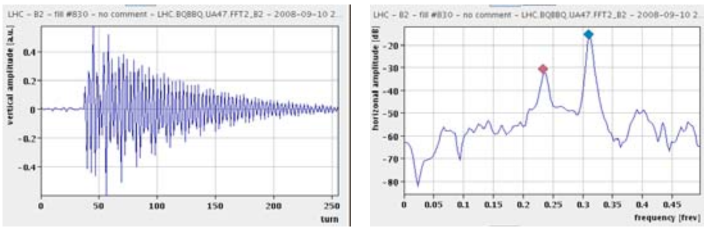
- Parameters per plane
  - Q : Full betatron tune
  - q : Fractional tune (operating point)
- Real life more complex
  - horizontal & vertical oscillations couple
  - betatron motion at large amplitudes non-linear

Tune Measurement

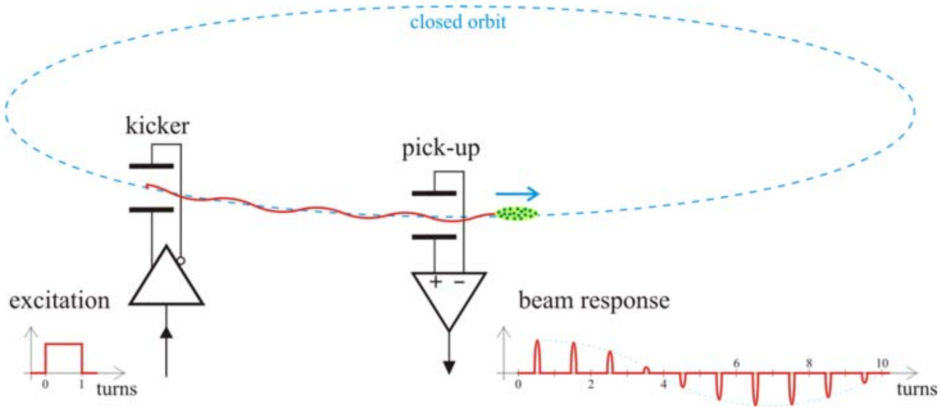
- Integer tune
  - can be seen in orbit response
  - H: 59, V: 64 for LHC



- Fractional tune (q)



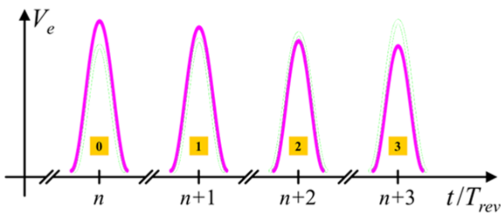
Tune Measurement – the principle

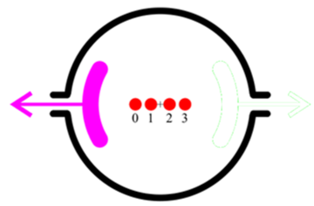


- Beam betatron oscillations are observed on a position pick-up
- Oscillations of individual particles are incoherent
  - an excitation needed for globally exciting the beam
- Betatron oscillations usually observed in the frequency domain

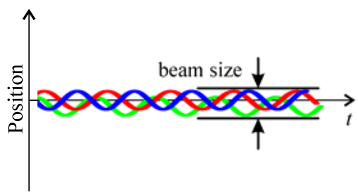
Tune Measurement – the principle

- BPM electrode signal has temporal shape corresponding to temporal structure of the passing beam
  - For LHC nominal beams that means nanosecond pulses with amplitudes up to ~100 V
  - Such signals are very difficult to simulate in the lab

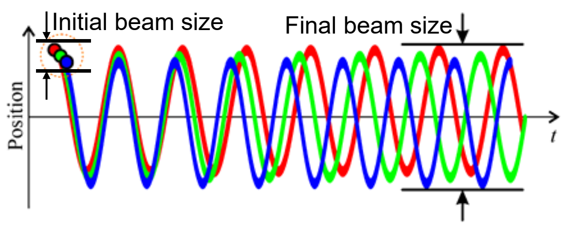


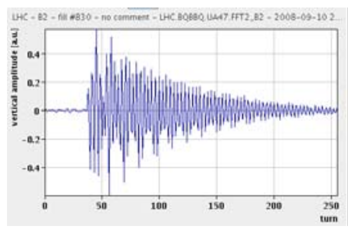


Tune Measurement – the principle



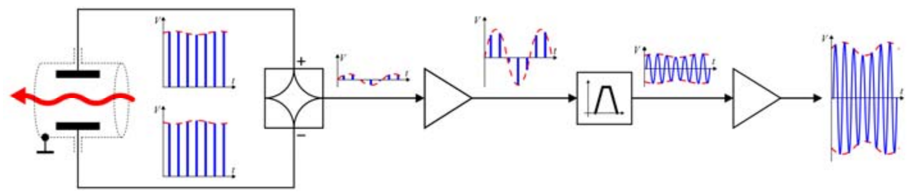
- Beam size
  - defined by incoherent betatron motion of all particles
- Particles have momentum spread
  - gives spread in focussing by quadrupoles
  - gives rise to spread in the frequency of the betatron oscillations (chromaticity)
  - coherent oscillations will de-cohere
- Protons do not forget
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



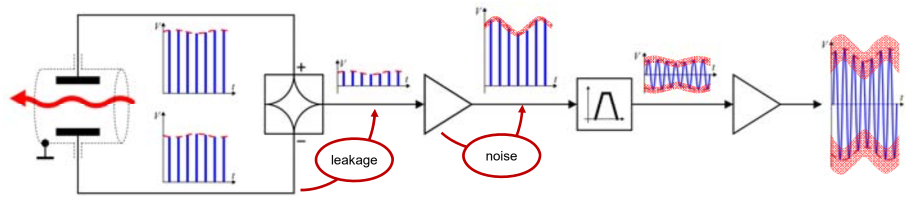


Tune Measurement – the principle

- A typical perfect detection scheme



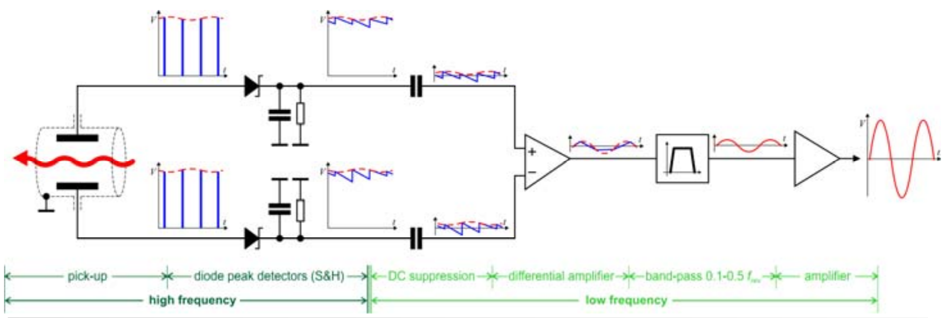
- Reality



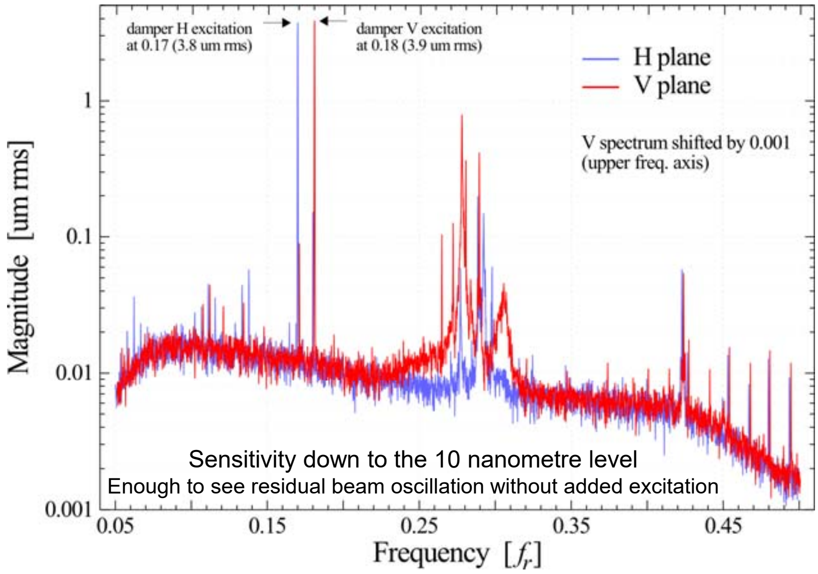
- Dynamic range issues
  - Signals related to betatron oscillations are small with respect to beam offset signals
  - Even for centred beam leakage is of order 1-10 % (of 100V!) for ns beam pulses

The LHC Tune Measurement System

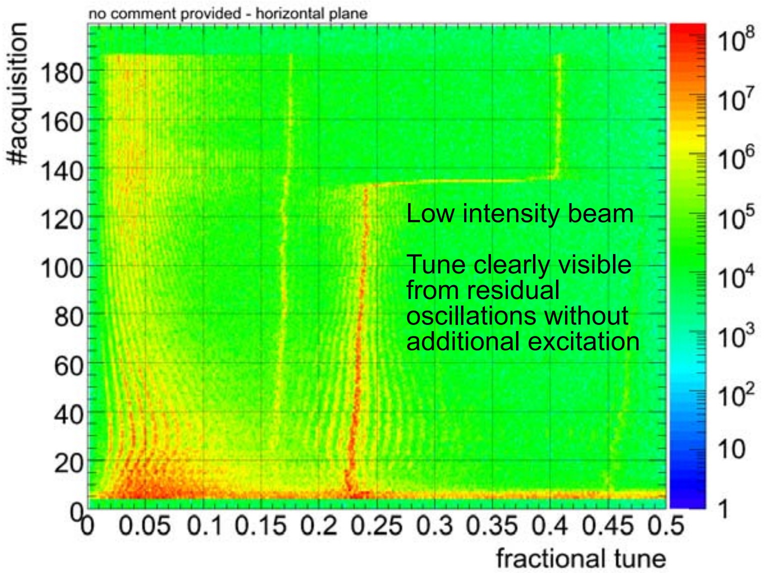
- Direct Diode Detection – the advantages
  - RF Schottky diode can handle up to 50 V from beam pulses
    - more possible with a few diodes in series (LHC detectors has 6 diodes)
  - Betatron modulation downmixed to low frequency
    - Allows efficient signal processing with inexpensive 24-bit audio 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

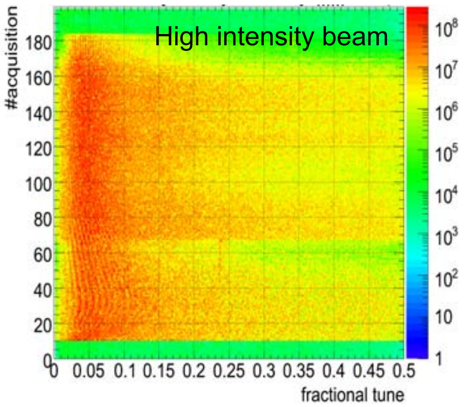


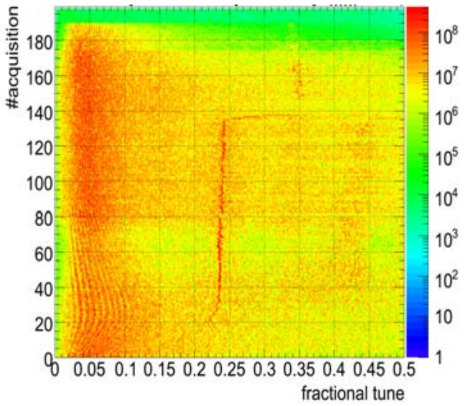
Tune Measurement in the SPS



Tune Measurement in the SPS

- Real-time Tune Display

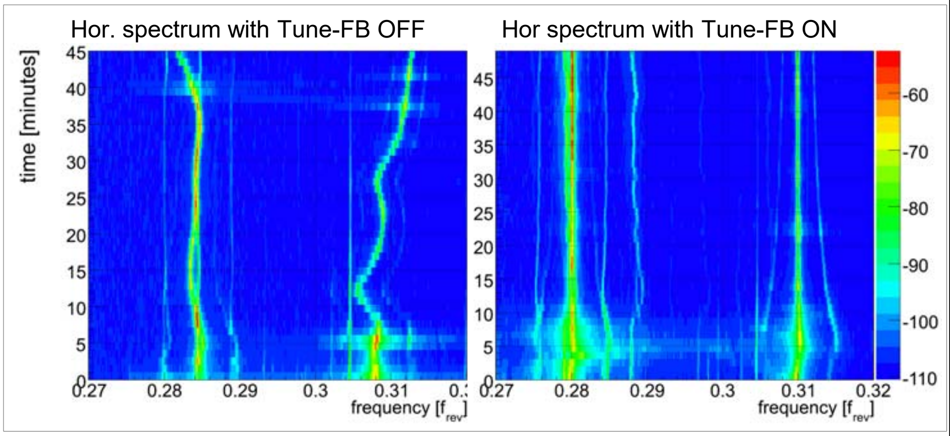




Nominal Beam - Excitation OFF
– Tune hardly visible

Nominal Beam - Excitation ON
– Tracking achieved throughout cycle

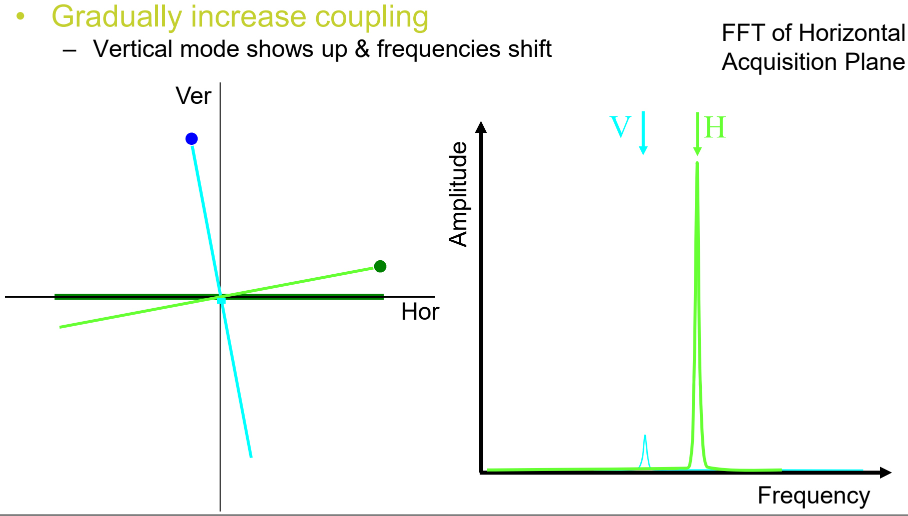
Tune Feedback in the LHC



- 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

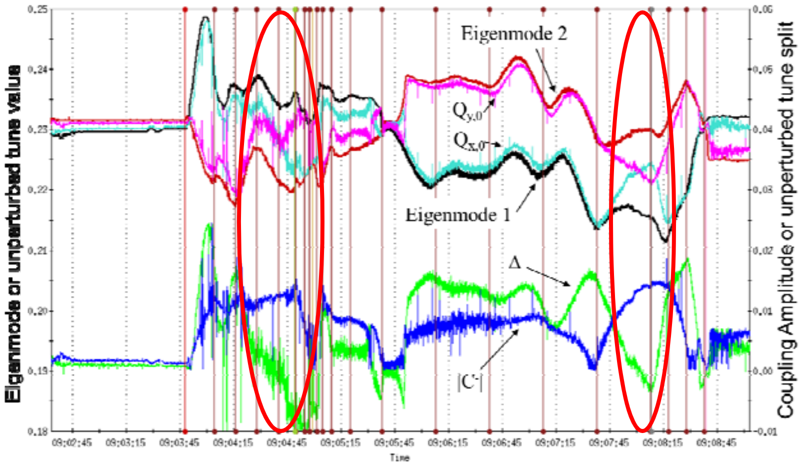
Set   Measured

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

- 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

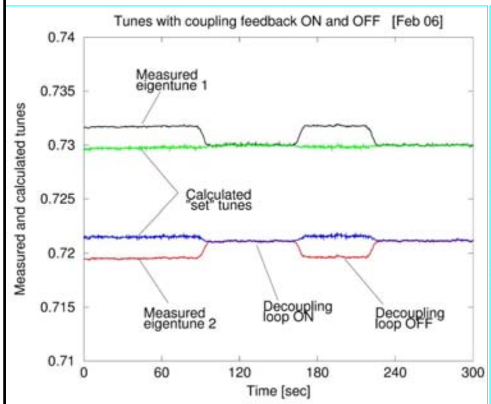
Coupling & Tune Feedback

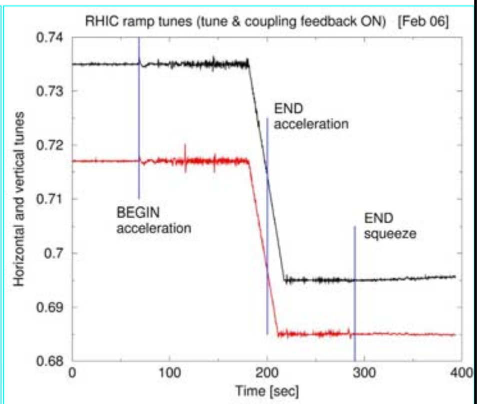
- Measurement from RHIC during acceleration cycle
  - At several points measured tune is defined by coupling
  - Tune feedback breaks down at these points



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

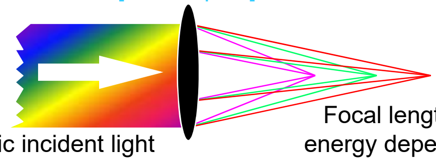




Chromaticity

- Machine Chromaticity

Optics Analogy:



Spread in the Machine Tune due to Particle Energy Spread

Controlled by Sextupole magnets

First Order

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

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

Generalised

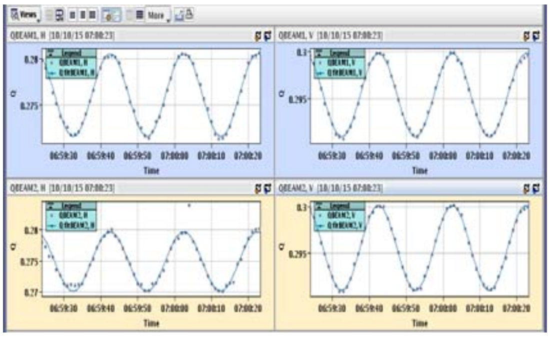
$$Q^{(n)} = \frac{\partial^{(n)} Q}{\partial \delta^{(n)}} \qquad \delta := \frac{\Delta p}{p}$$

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

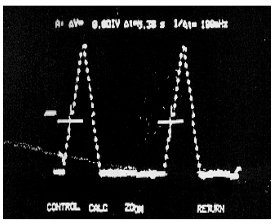


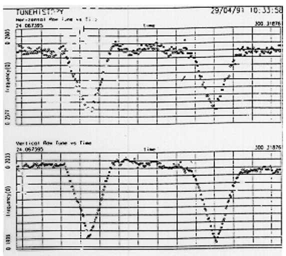
Example from the LHC

- 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

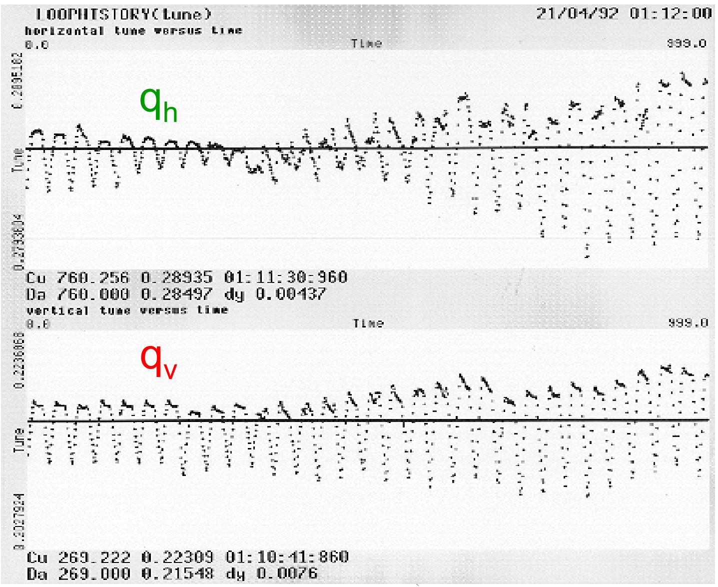




Example from CERN-LEP

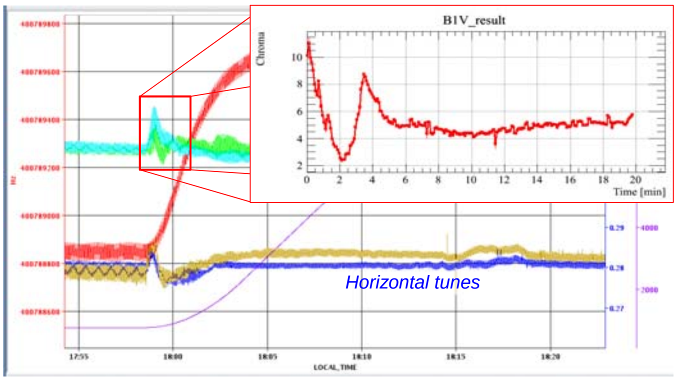
- Triangular RF modulation
- Allows sign to be easily determined

Example from LEP β-squeeze



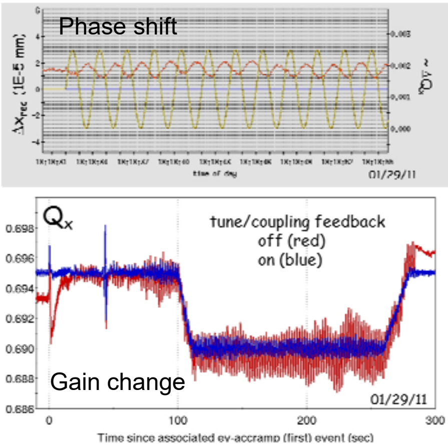
Example from LHC Acceleration Ramp

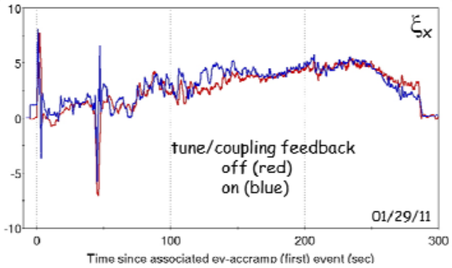
- Dynamic Measurement Examples
  - LHC Ramp
    - RF continuously modulated
    - Tune measured using the very sensitive Base Band Tune (BBQ) system
    - Tune calculated from peak fitting of resulting frequency spectrum
    - Tune feedback is switched off (rely on Q feedforward)
    - The orbit FB can cope with the modulation as it subtracts the RF offset



Example from RHIC

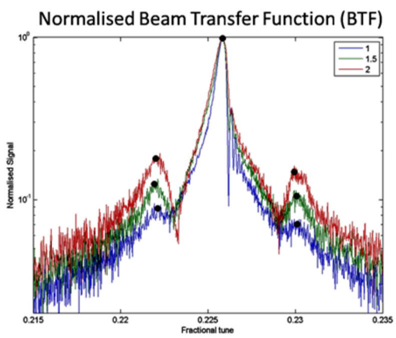
- Chromaticity measurement in presence of feedbacks
  - RHIC
    - Algorithm needs to be calibrated for use with tune feedback
    - Tune & coupling feedback introduce both phase shift & gain change

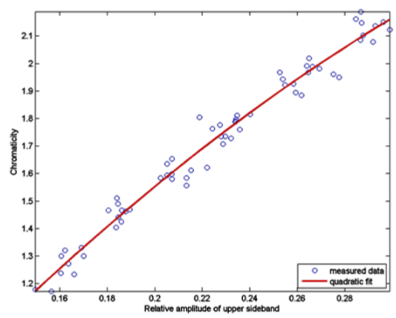




Amplitude of Synchrotron Sidebands

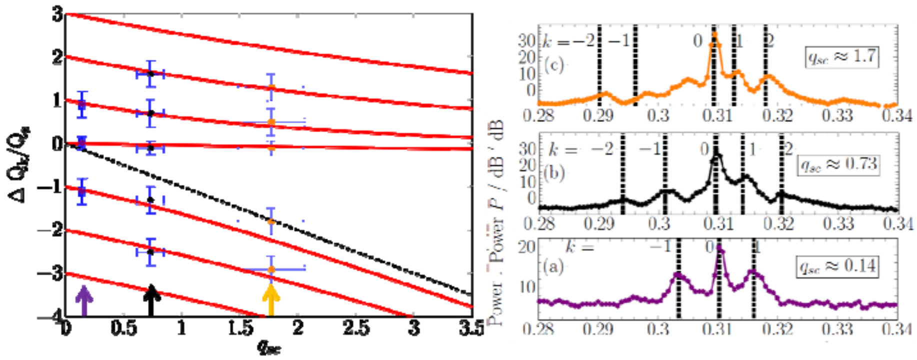
- Recently demonstrated at DIAMOND
  - RF modulation changes orbit - not compatible with user operation
  - Looking for technique to measure chromaticity on-line
    - Measure Beam Transfer Function (BTF) on single bunch
      - Using transverse bunch by bunch feedback system
      - Emittance blow-up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





Amplitude of Synchrotron Sidebands

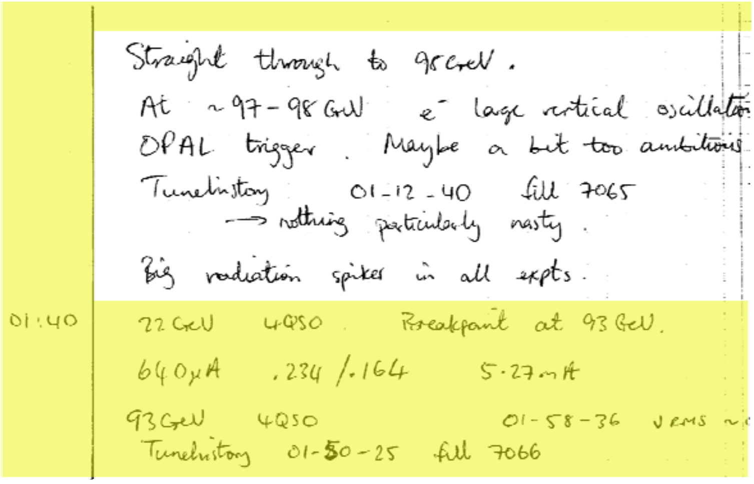
- Dealing with High Intensity Effects @ GSI
  - Modification of tune spectra by space charge & impedance
  - Measured using Base Band Tune system
  - Relative heights & mode structure given by chromaticity
    - Can be calculated with simplified analytical models



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

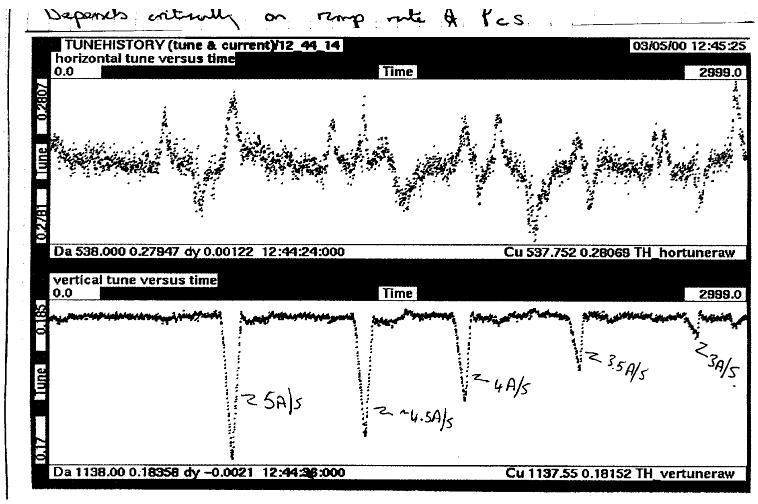


Straight through to 98 GeV.
At ~97–98 GeV e⁻ large vertical oscillation
OPAL trigger. Maybe a bit too ambitious
Tunehistory 01-12-40 fill 7065
→ nothing particularly nasty.
Big radiation spikes in all expts.

01:40 22 GeV 4Q50 Breakpoint at 93 GeV.
640 μA .234 / .164 5.27 mA
93 GeV 4Q50 01-58-36 V RMS
Tunehistory 01-50-25 fill 7066

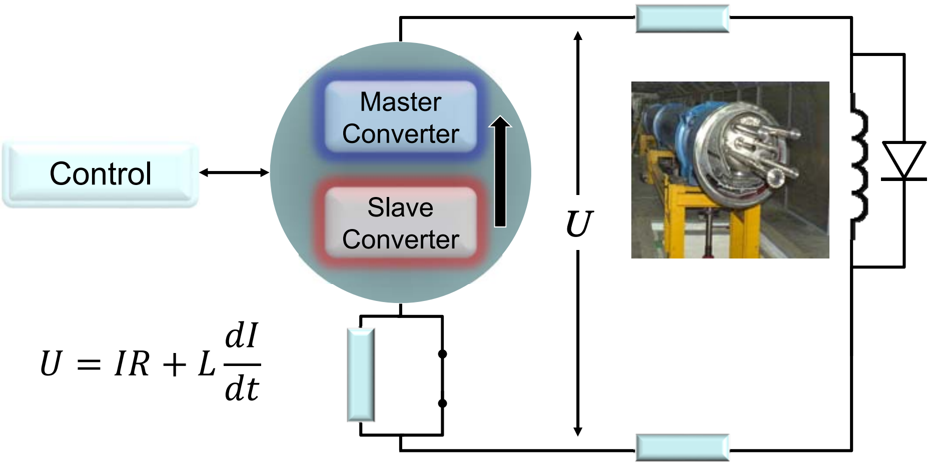
The Diagnostics

- Tune & Chromaticity
  - Tracked for different power converter ramp rates



The Explanation

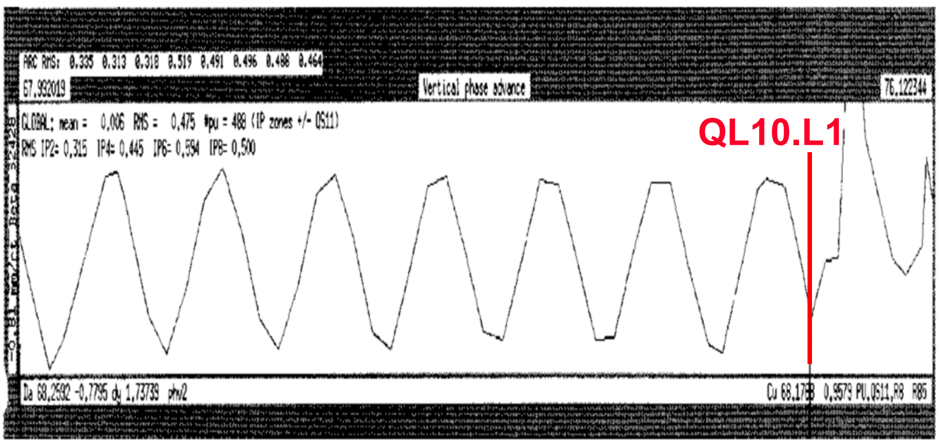
- Master-Slave Configuration for Power Converter
  - Each converter can deliver full current
  - Slave only needed to give increased voltage for fast current changes



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

LEP – No Circulating Beam

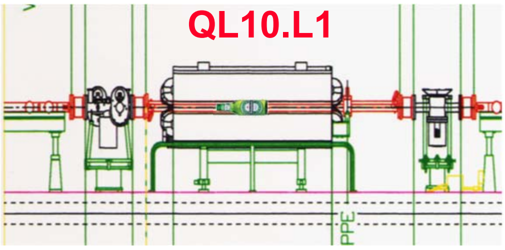
- No Circulating Beam after Technical Stop
  - Phase advance from BPMs show that optics no longer correct after specific quadrupole



Positrons →

The Explanation

- After opening 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