Beam Instrumentation
&
Beam Diagnostics

Today

CAS 2003

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(CERN)

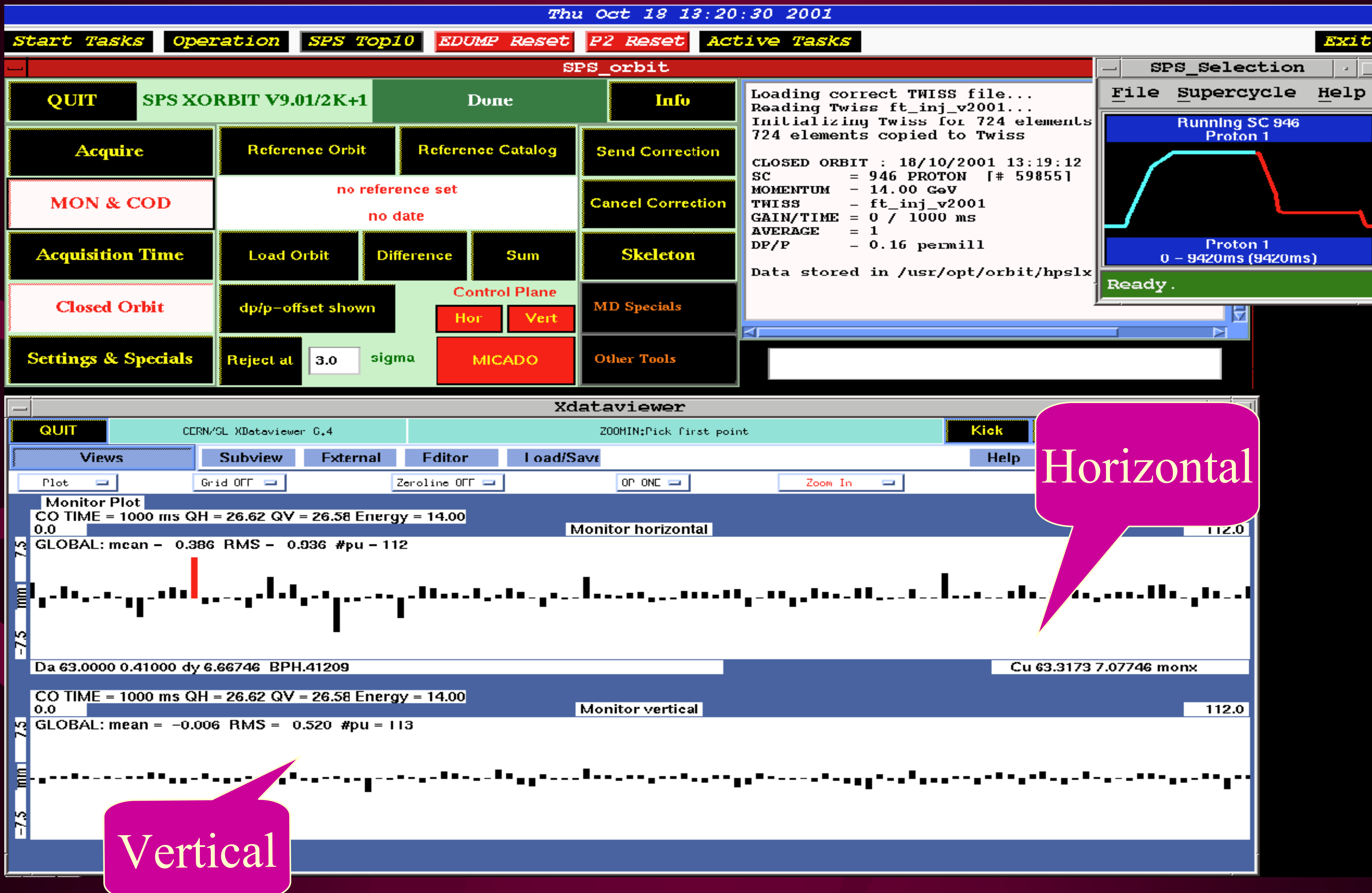
Outline for Today

- Optimisation of Machine Performance ("the good days")
  - → Orbit measurement & correction
  - → Luminosity: basics, profile and β - measurements
- Diagnostics of transverse beam motion
  - → Tune & chromaticity measurements
  - → Dynamic effects: tune and chromaticity control
  - → On-line β measurements

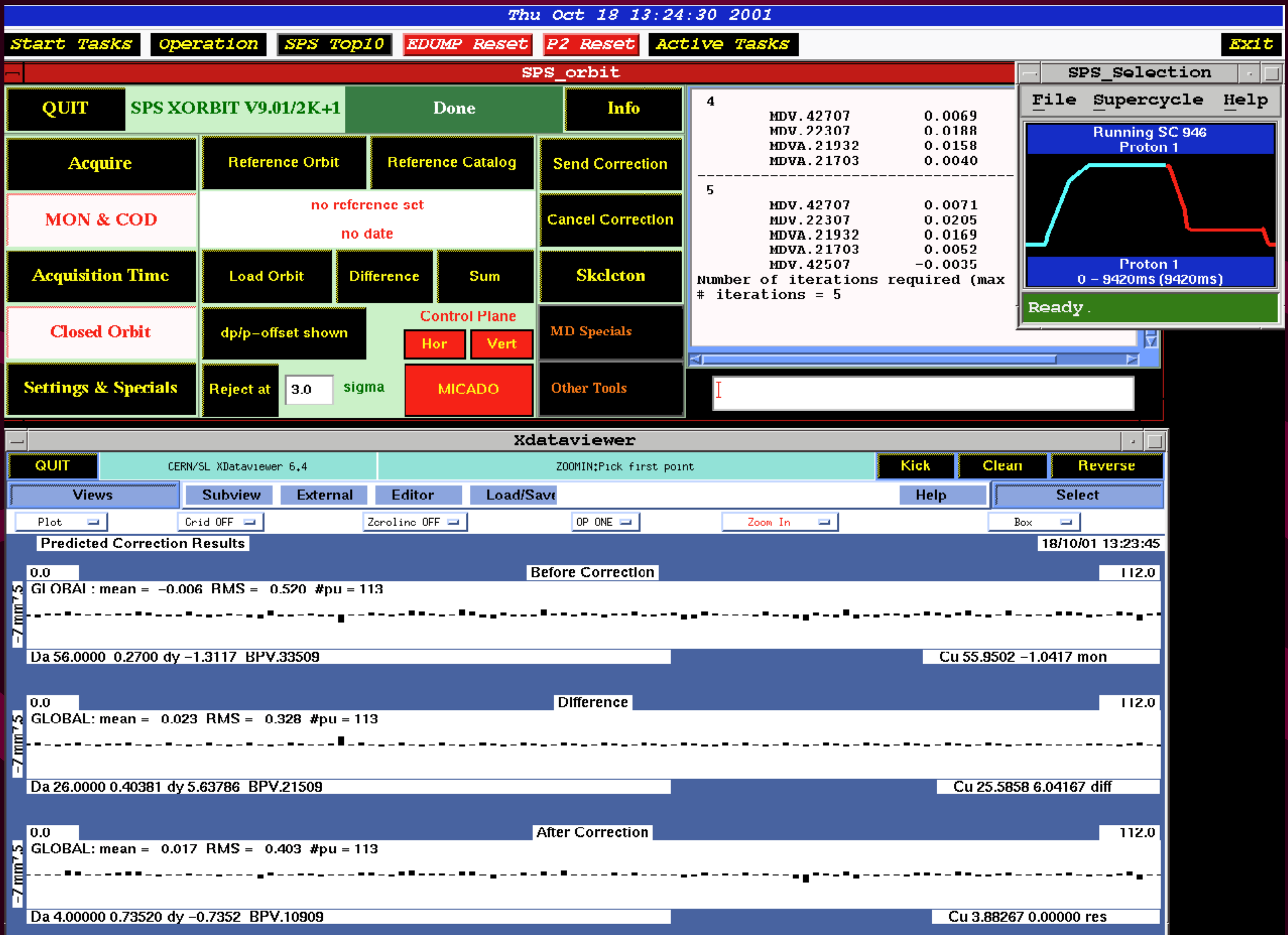
That is what gets reported on in conferences

- Trying to make the machine work ("the bad days")
  - → The beam does not circulate!
  - → The beam gets lost, when changing the beta*

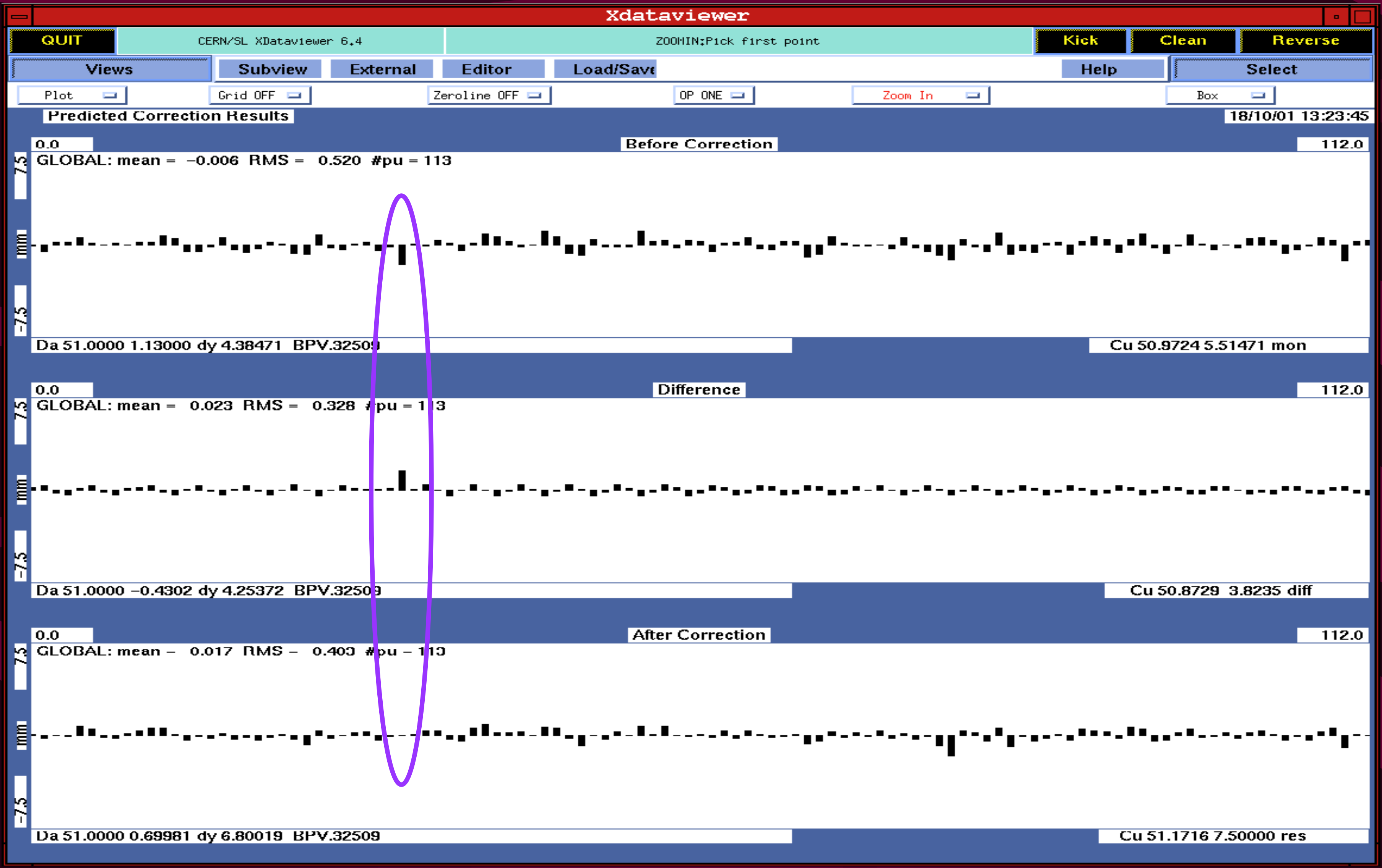
Orbit Acquisition



Orbit Correction (Operator Panel)



Orbit Correction (Detail)



Luminosity & Beam-Beam Tune Shift

- Luminosity
- Normalized emittance
- Beam-beam tune shift

$$L = f_{rev} \frac{MN^2}{4\pi\sigma_*^2}$$

$$\varepsilon_N = \gamma \frac{\sigma_*^2}{\beta_*}$$

$$\Delta\nu_{bb} = \frac{Nr_p}{4\pi\varepsilon_N} \leq 0.006 \text{ (LHC)}$$

$$\therefore \quad L = f_{rev} \frac{MN\gamma\Delta\nu_{bb}}{\beta_*}$$

- To maximize L and minimize the stored energy, increase N to the tune shift limit, choose large M and small β_*

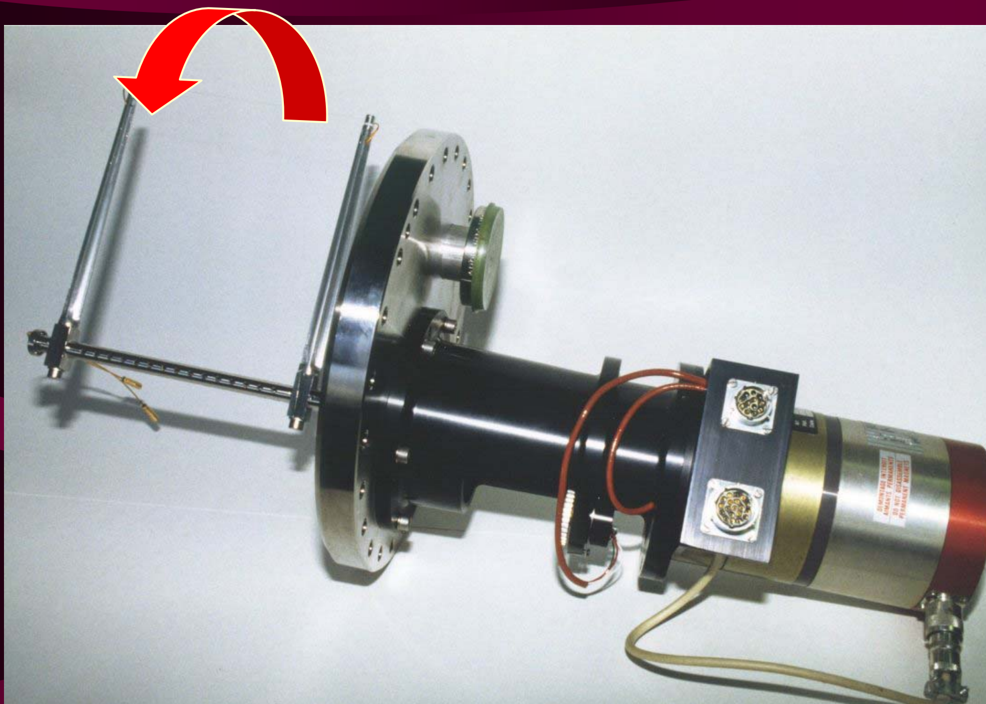
The LHC Emittance Budget

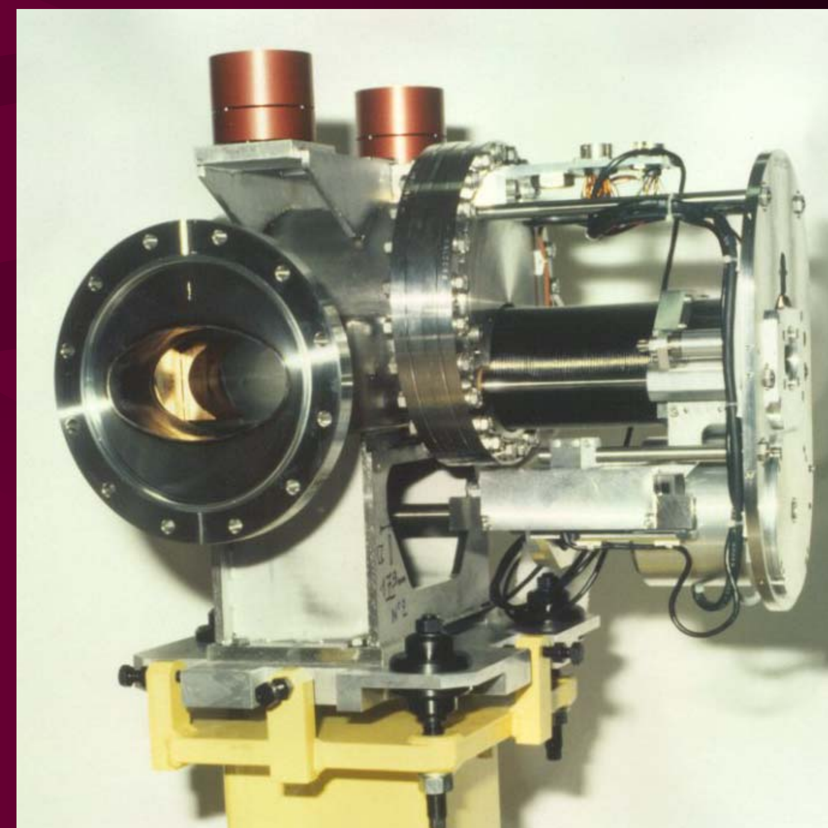
- From the particle source to "colliding beams" in the LHC the emittance may grow by 30% for nominal machine performance
  - → from LHC injection to collisions this means a "Budget" of 7%
  - → we have to measure emittance to a precision of a few (1..2) %
    - Precise profile measurements
    - On-line β measurements
  - → when:
    1) at the moment of injection
    2) with circulating beams

Measuring Beam Size

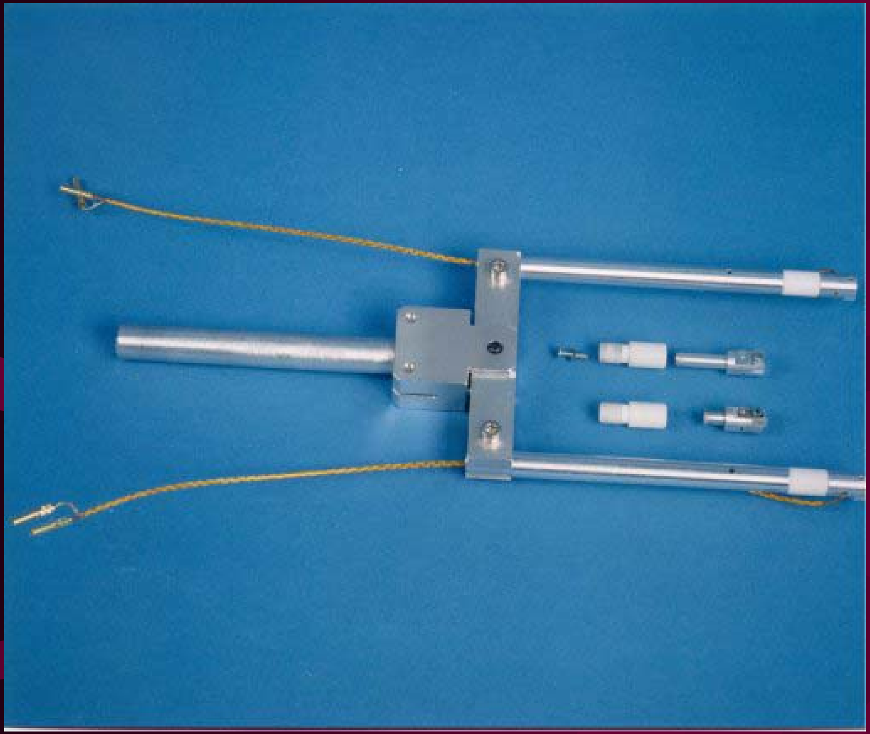
- Beam Profile Measurement Methods
  - → Wire Scanners
  - → Monitors based on interaction of beam with (rest)-gas in vacuum chamber
  - → Synchrotron light monitors
  - → Beam interaction with screen (semi or fully destructive)
  - → SEM monitors
  - → Others...

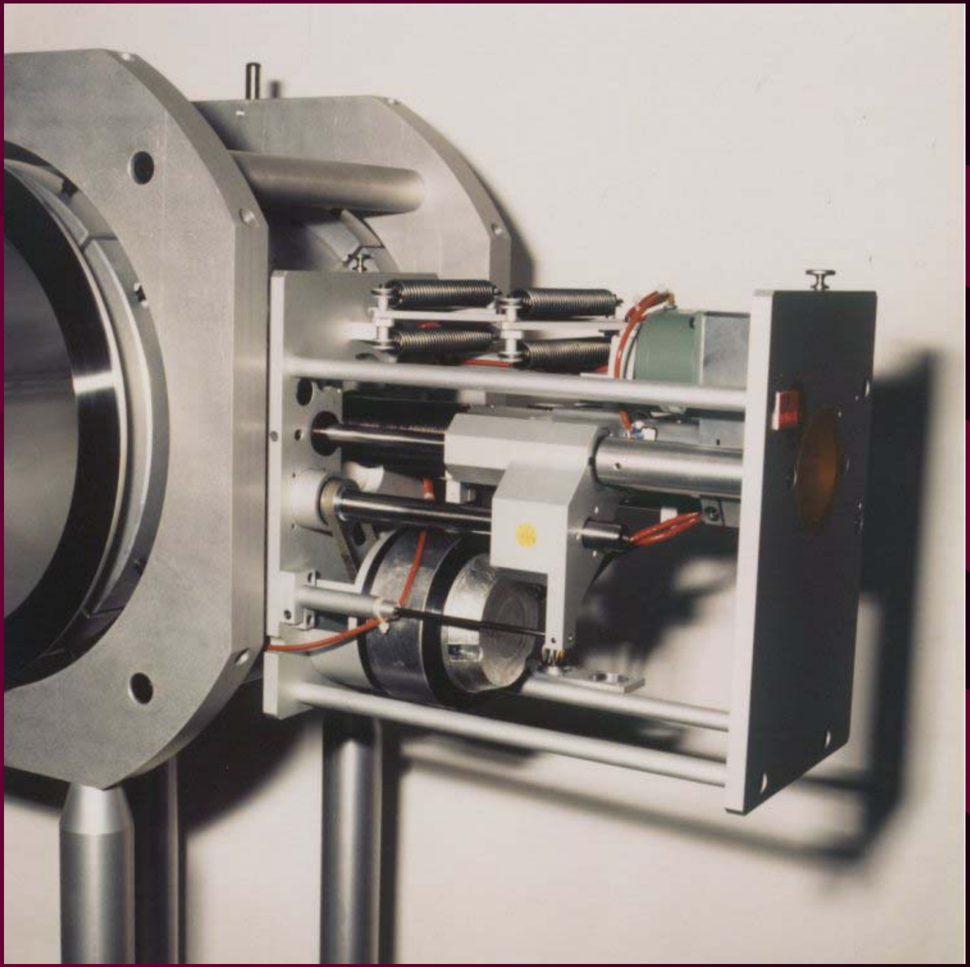
Rotative Wire Scanner



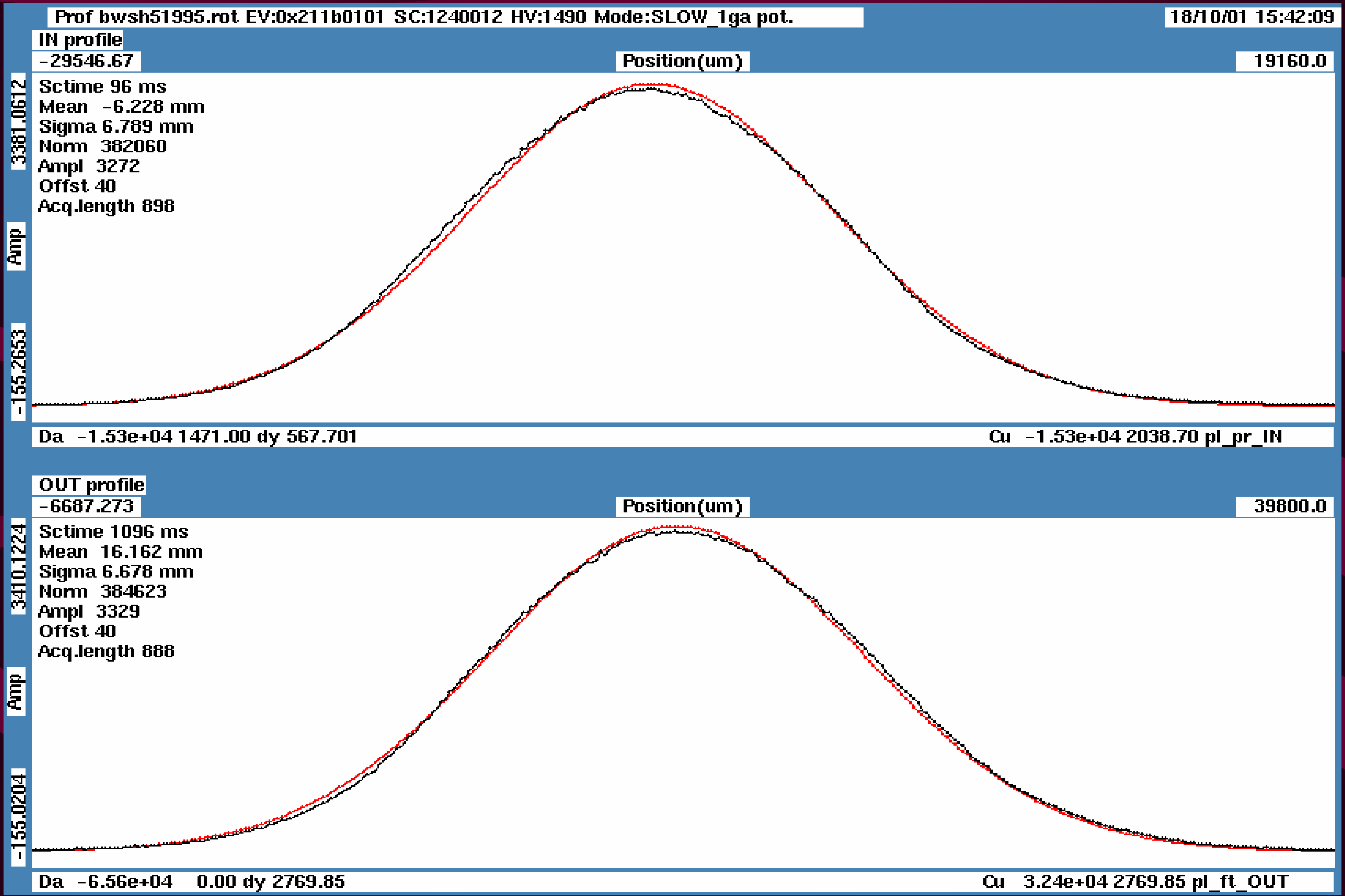


Linear Wire Scanner





Measurement Results



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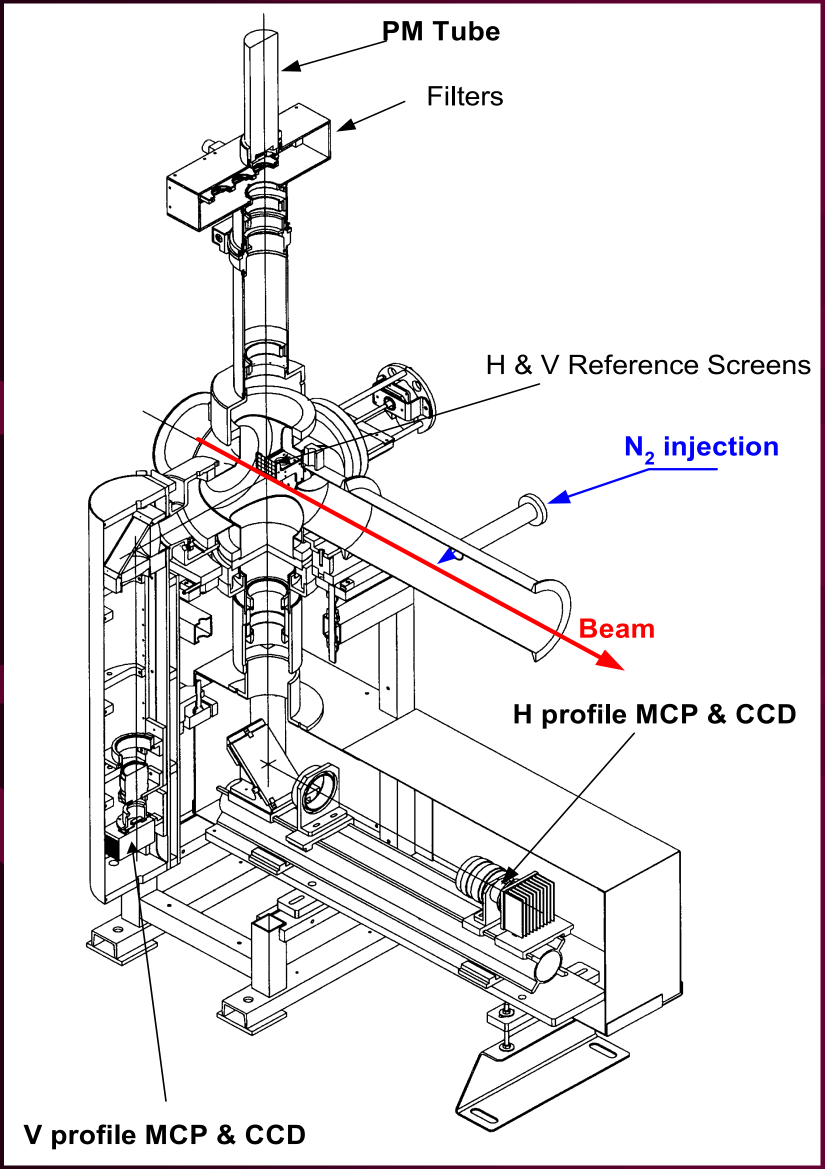
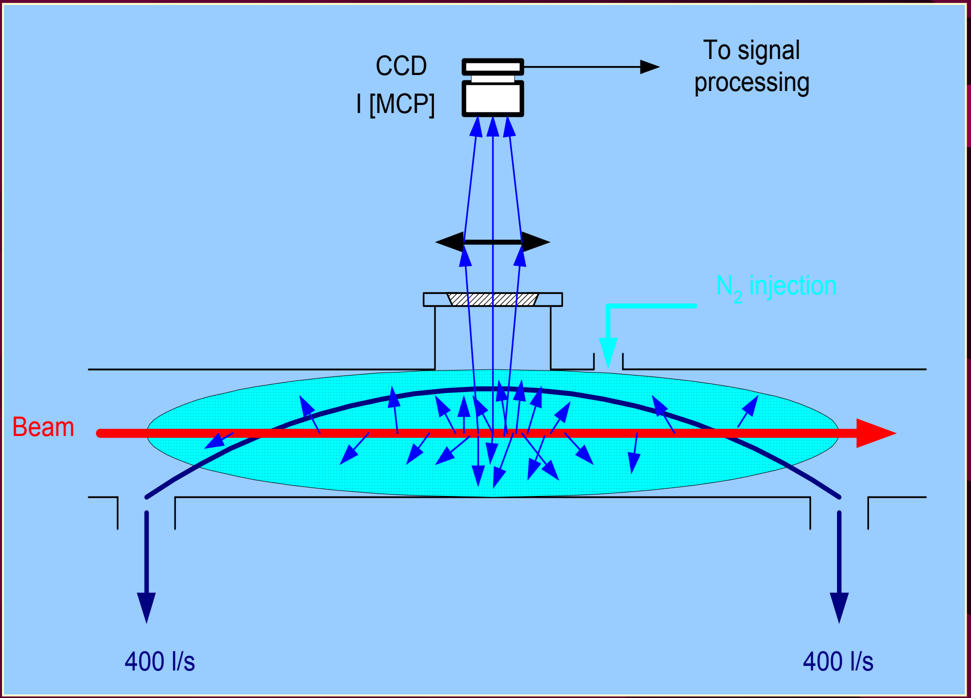
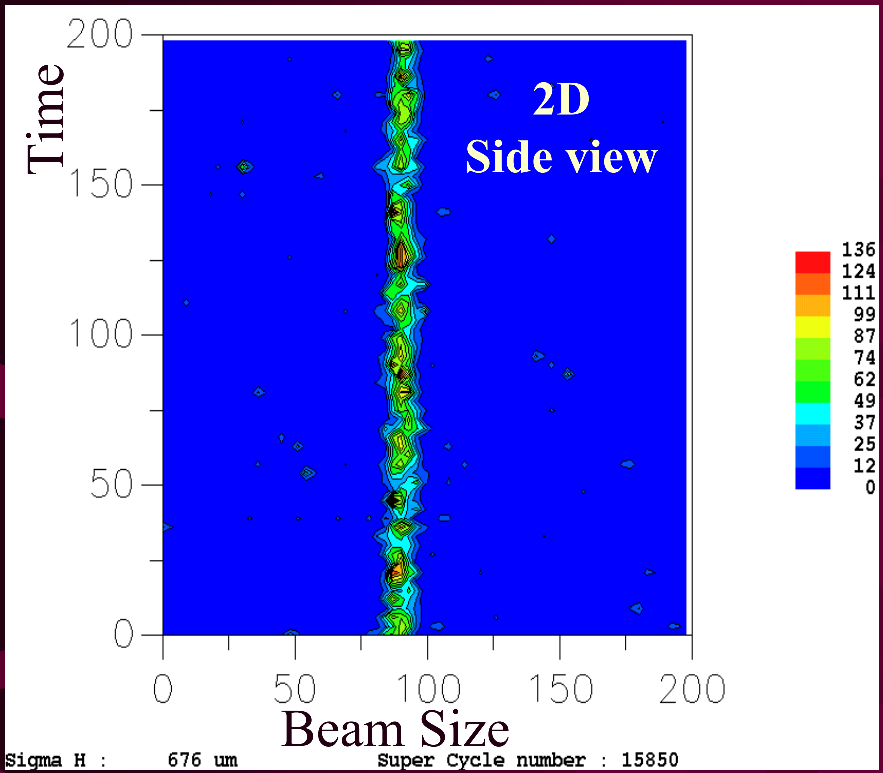
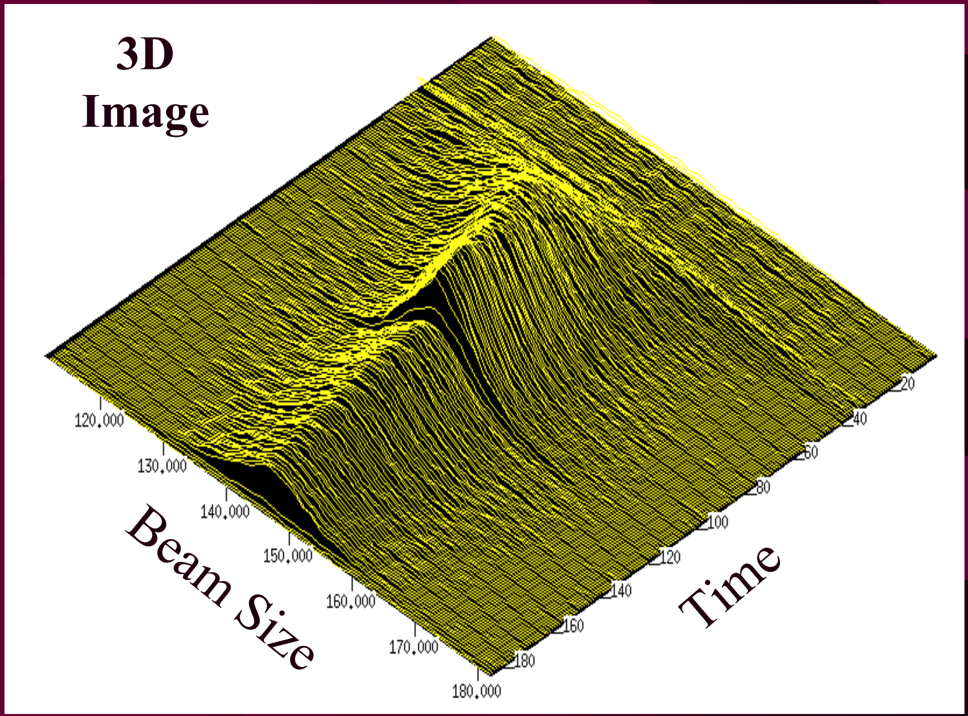
Luminescence Profile Monitor





Luminescence Profile Monitor

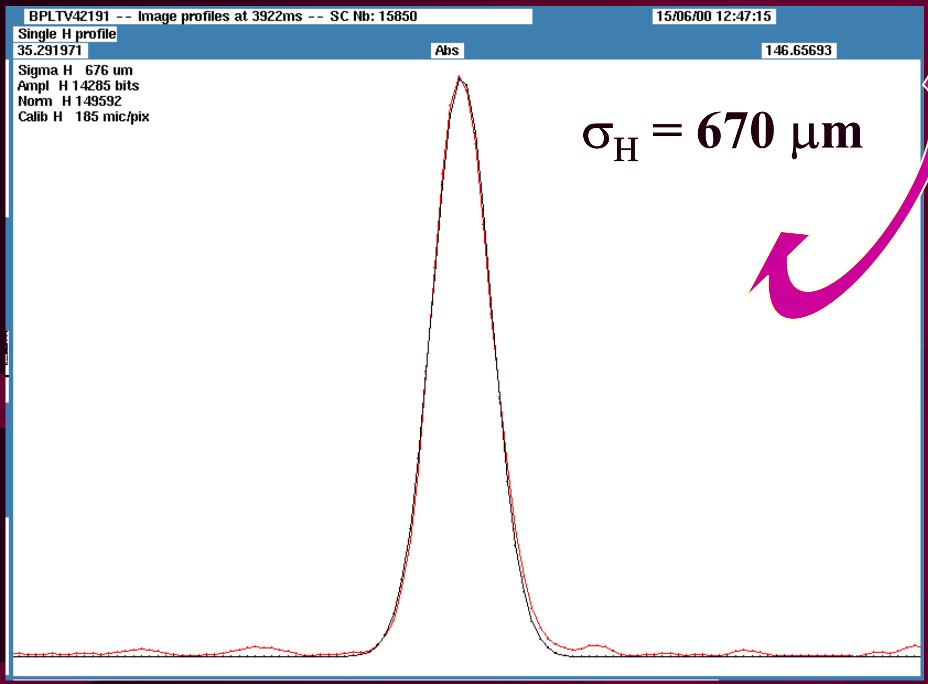




CERN-SPS Measurements

- Profile Collected every 20ms
- Local Pressure at ~5×10^{-7} Torr

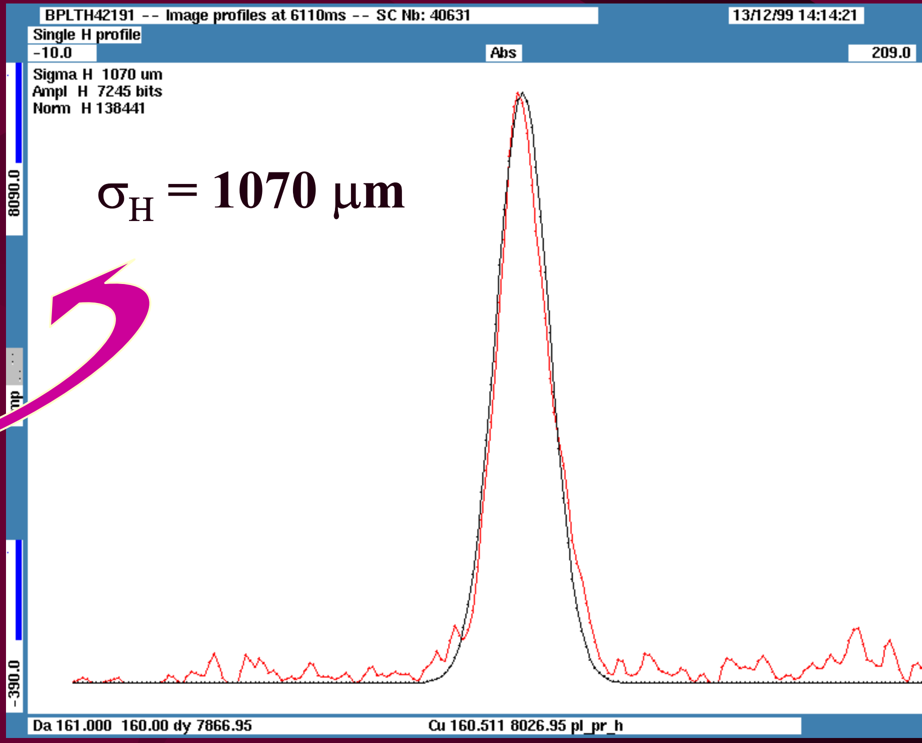
Luminescence Profile Monitor



Single shot (840 SPS turns)

→ 6×10^{-5} Pa (5×10^{-7} Torr)

→ 2×10^{13} protons (140 mA) at 450 GeV

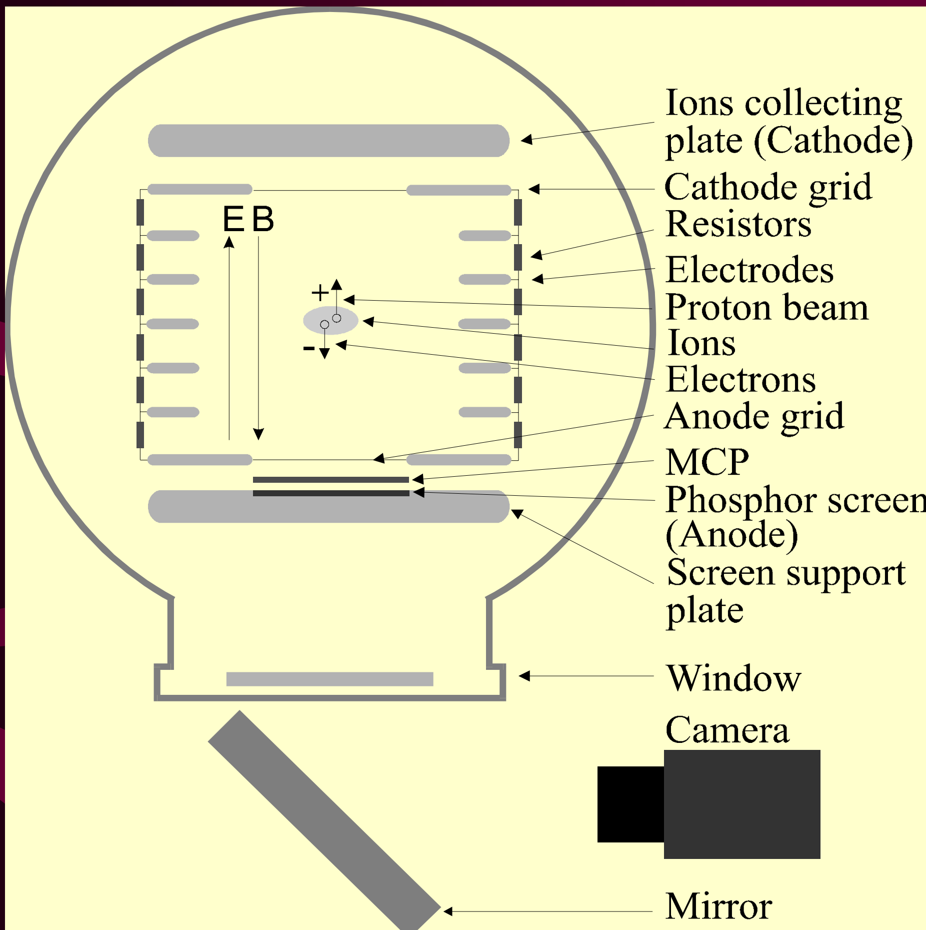


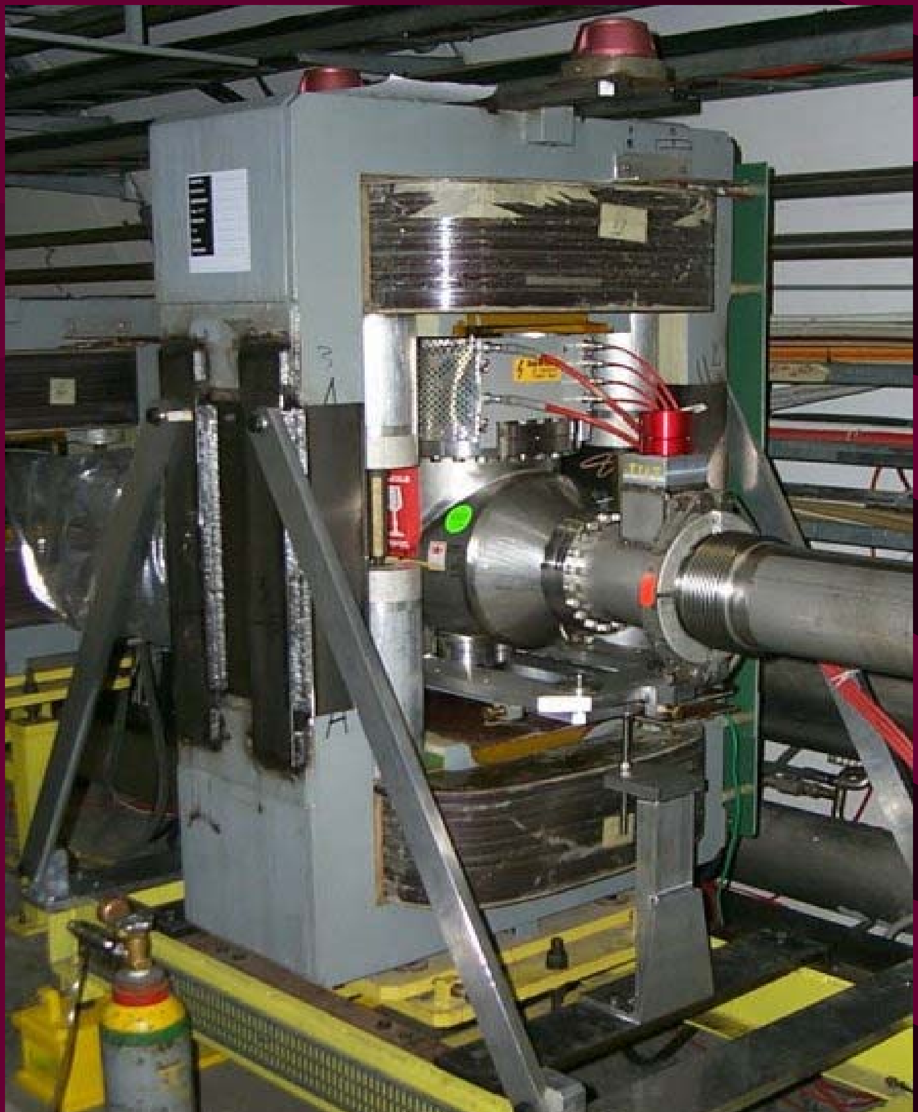
Single shot (840 SPS turns)

→ 8×10^{-5} Pa (6×10^{-7} Torr)

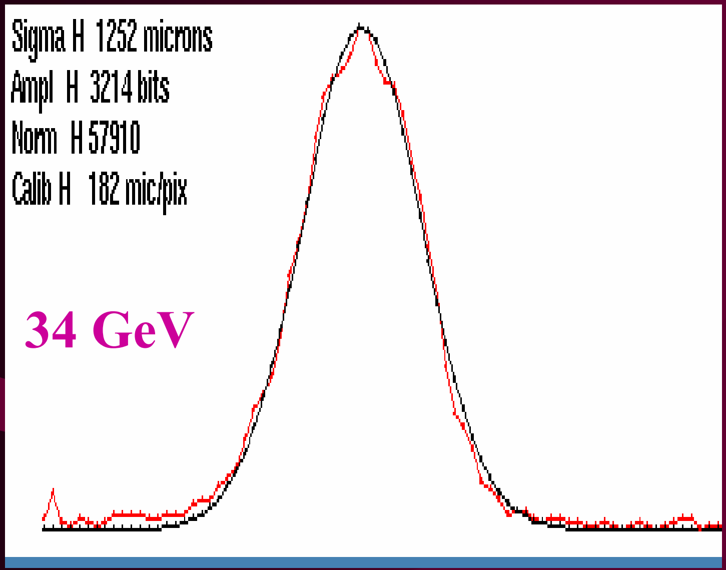
→ 9×10^{8} Pb ions (540 mA) at 450 GeV

(Rest Gas) Ionisation Profile Monitor - IPM

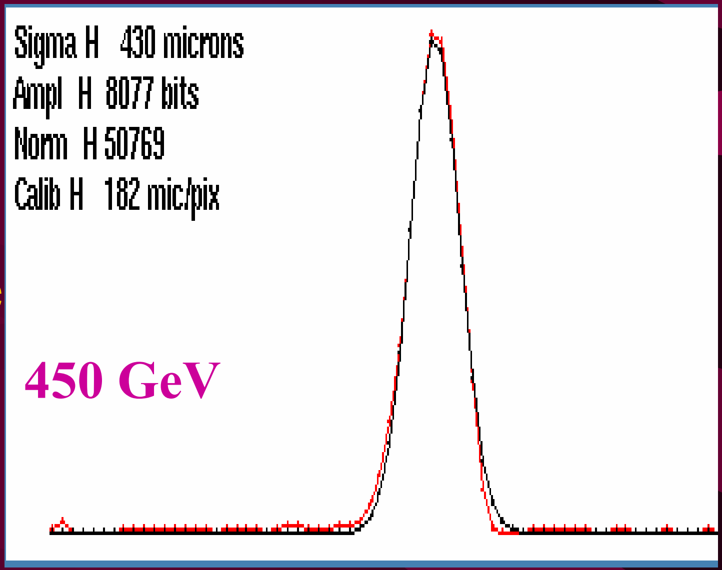


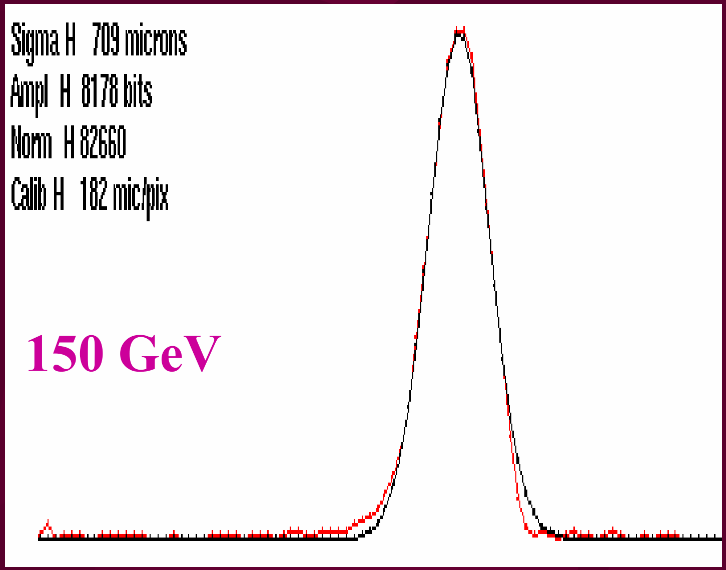


IPM Beam Profiles during Acceleration



CCD camera
20ms per profile

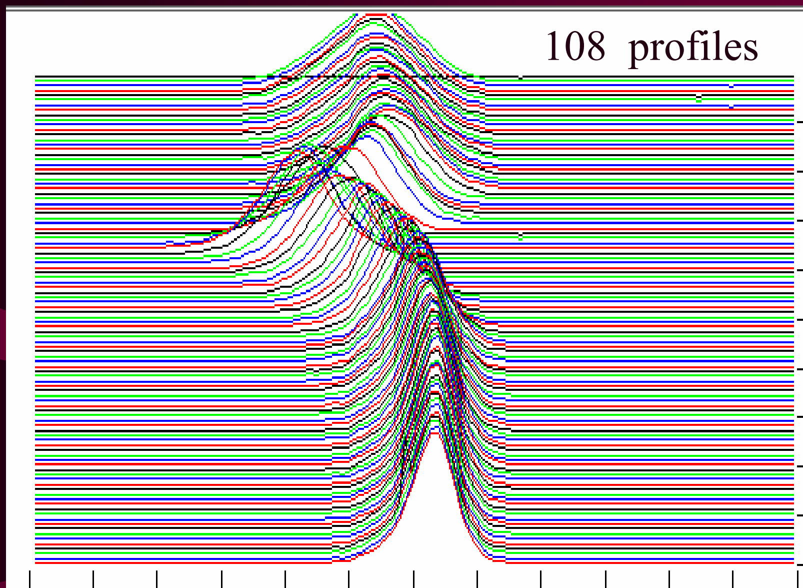


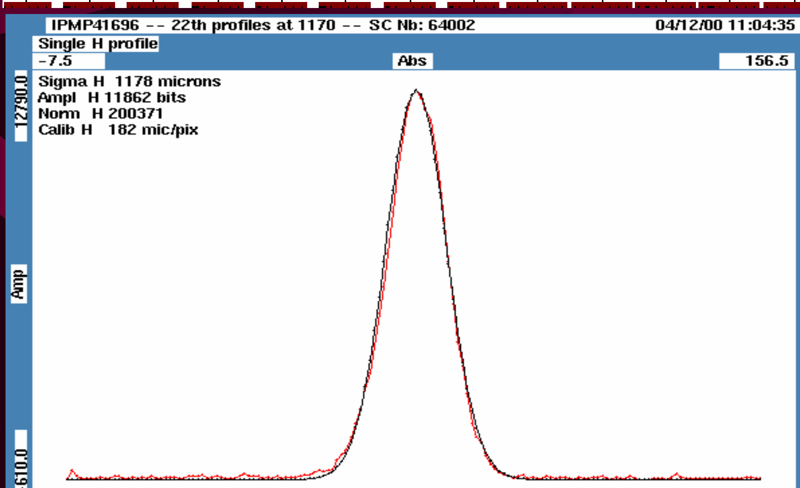


IPM Single Bunch Measurements

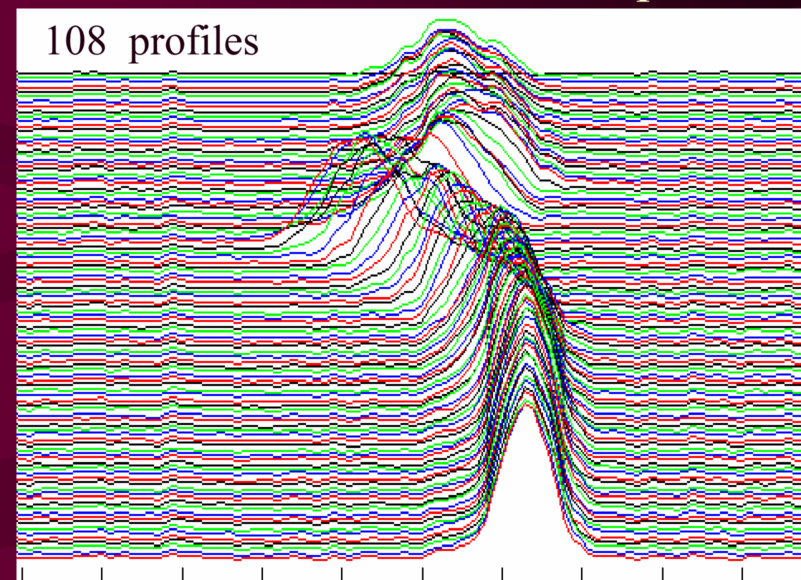
(CCD - 870 SPS turns (20 ms) per profile)

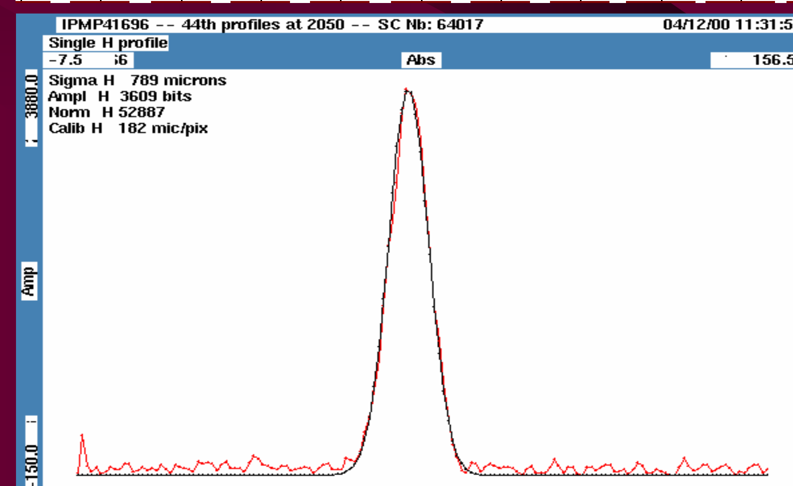
6×10^{10} p/bunch





2×10^{10} p/bunch





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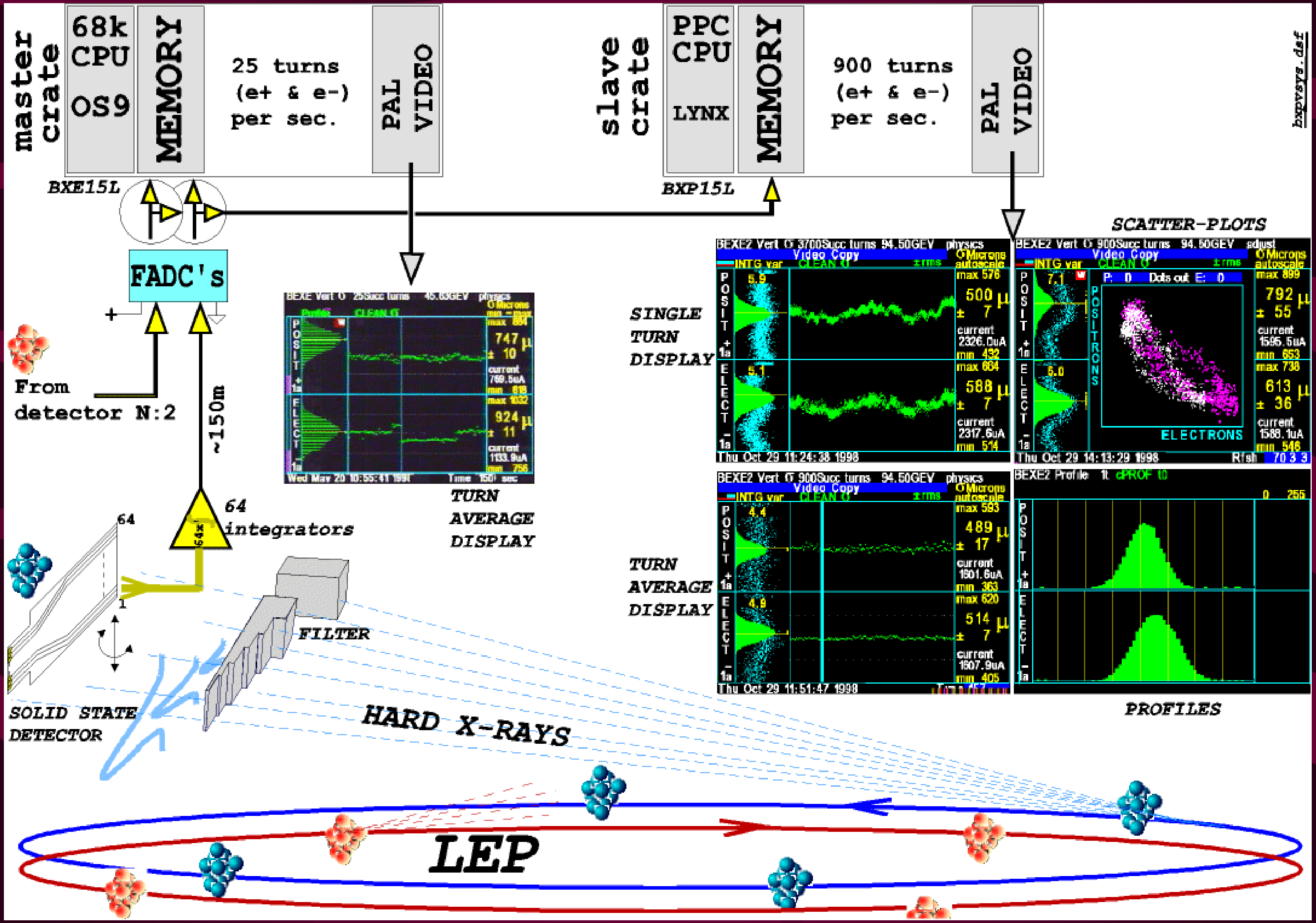
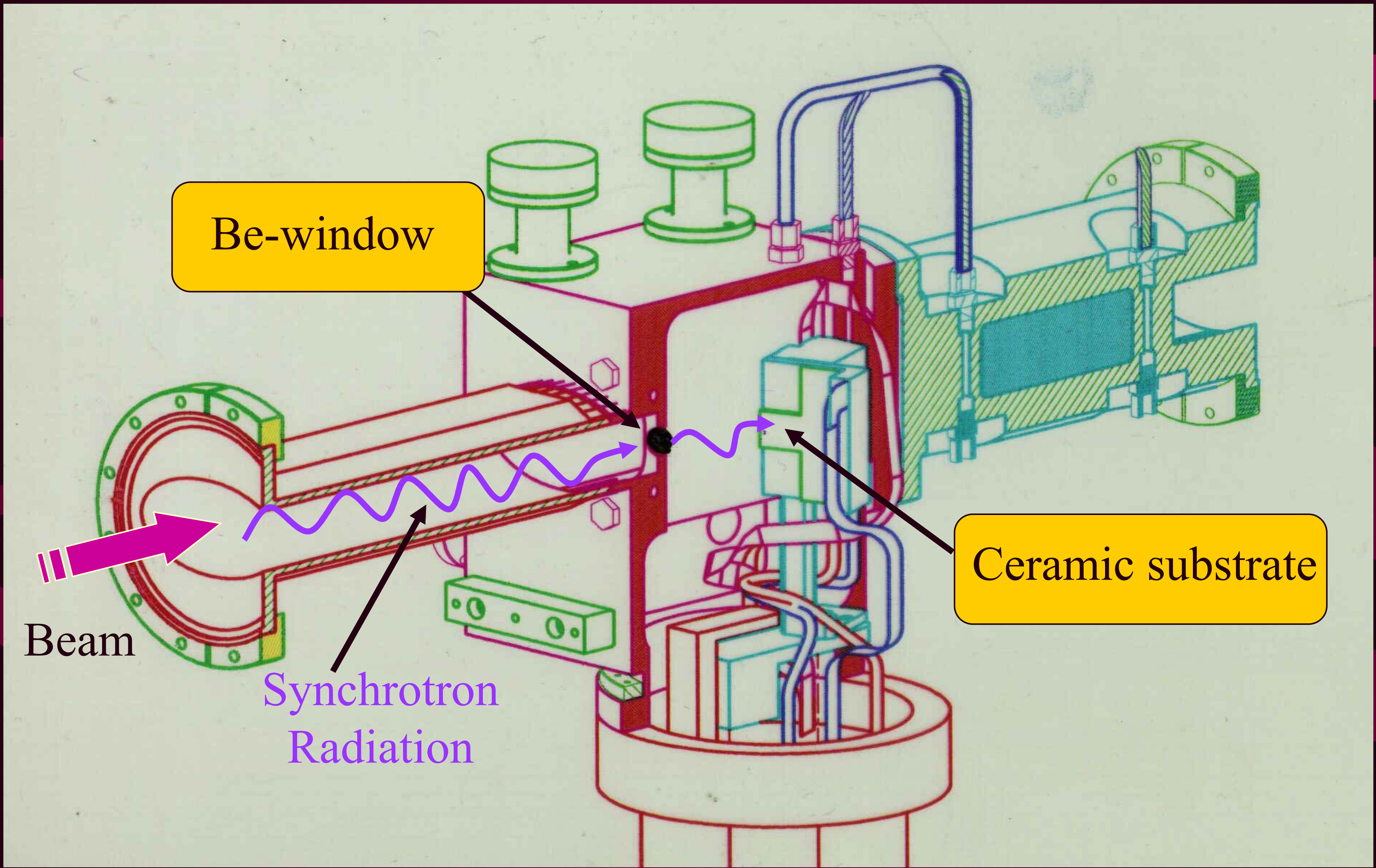
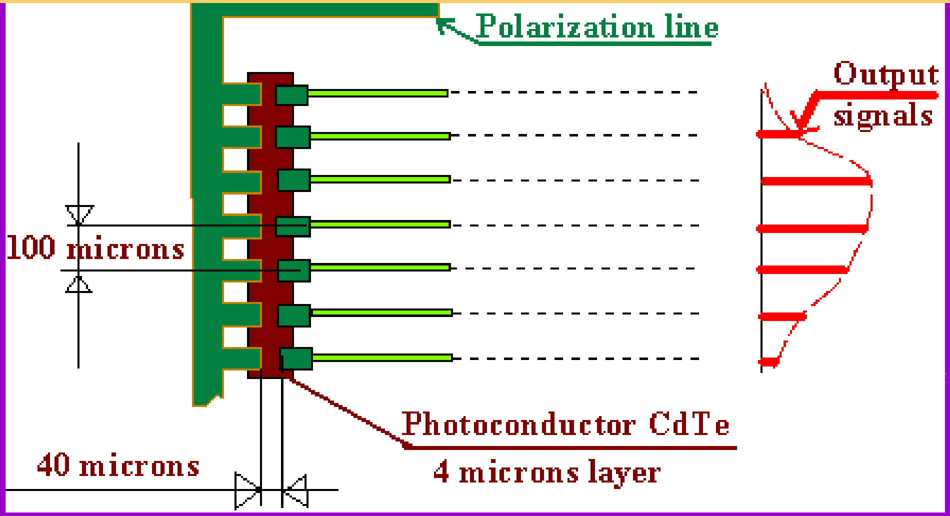
LEP X-Ray Monitor (BEXE system)

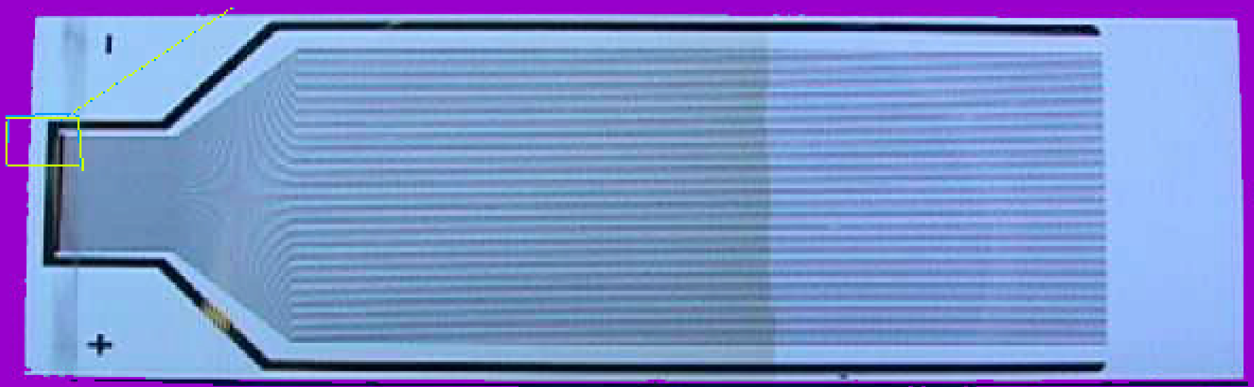


The BEXE Detector



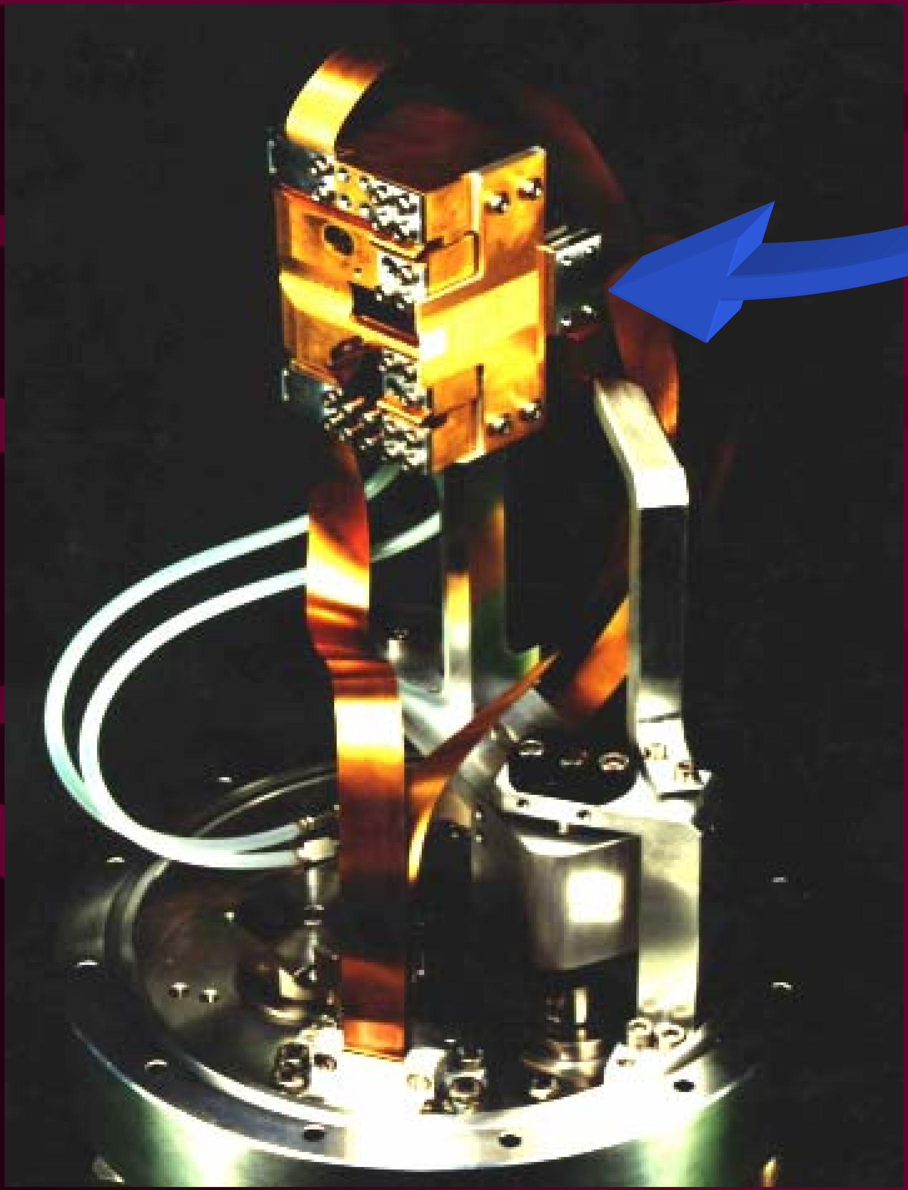
X-ray Beam Intercepting Strip Line Detector (Cd-Te photo-conductors)



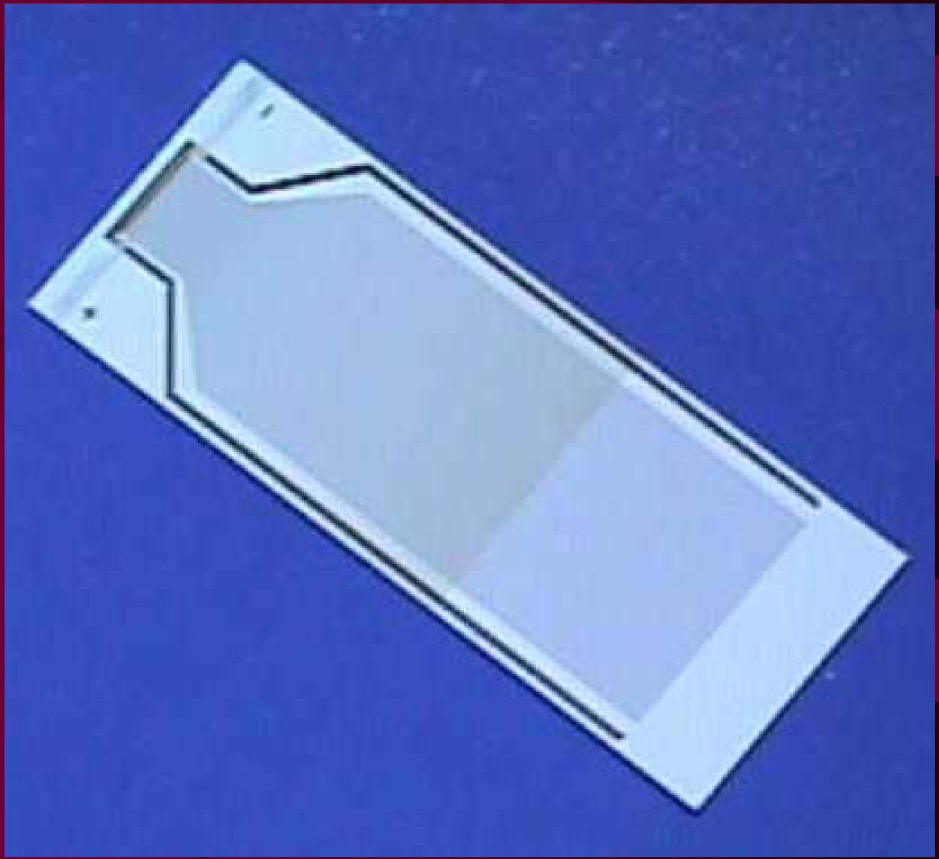


The detector is made from a 4 micrometer layer of photoconductive CdTe deposited on a 20 X 50 mm ceramic substrate

The BEXE Detector



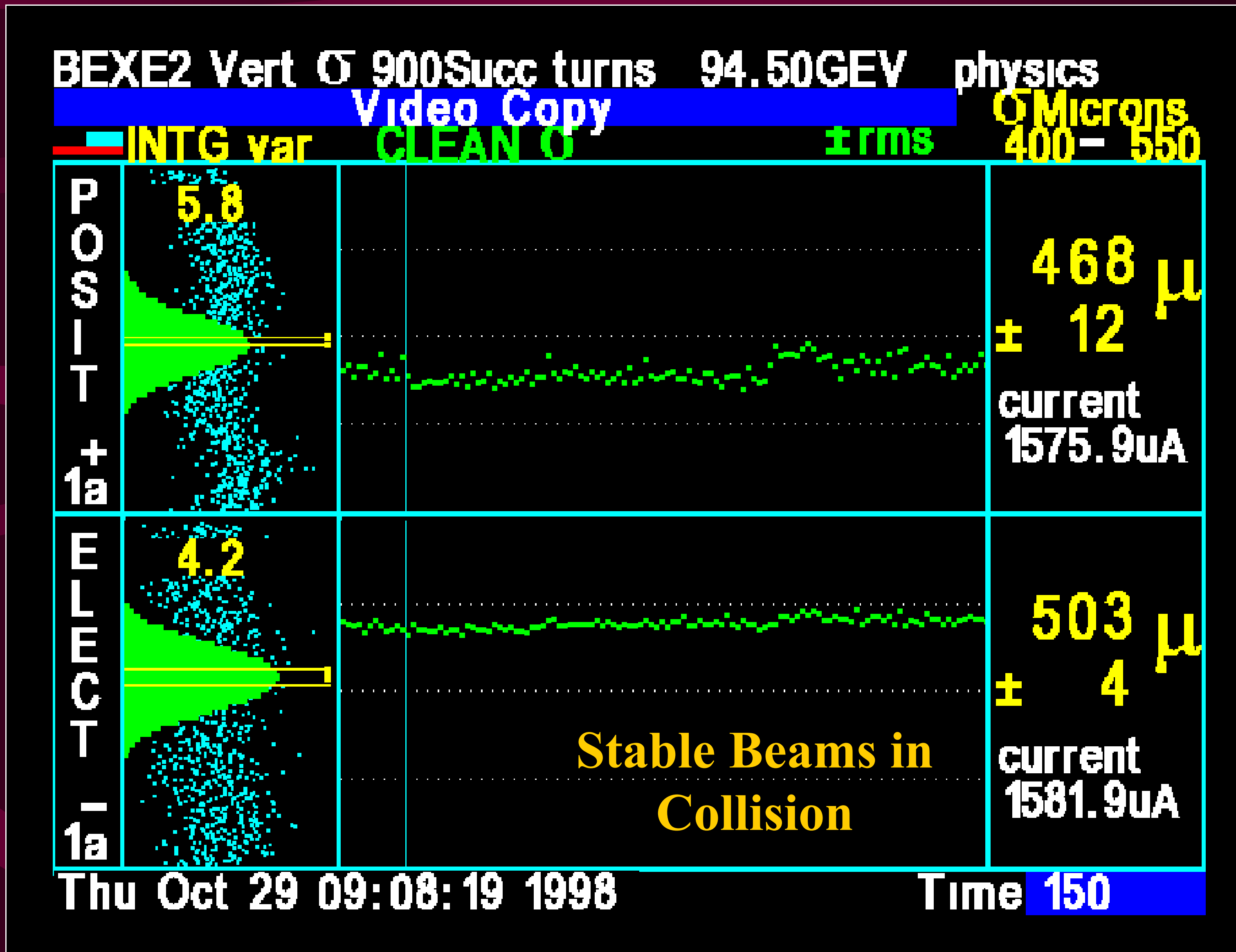
Ceramic substrate



Online Display in LEP Control Room

(e^+ & e^- vertical beam size versus time)

Histograms of Individual Cd-Te Channels



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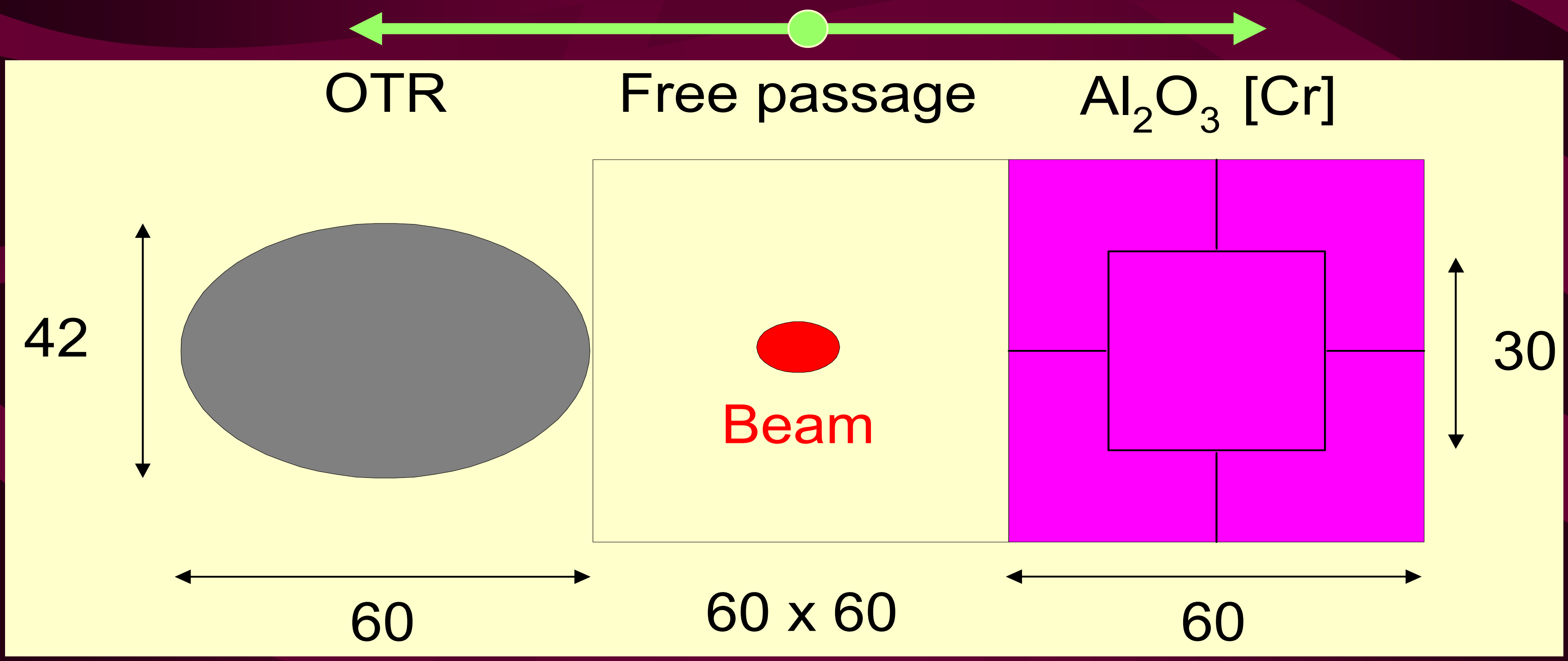
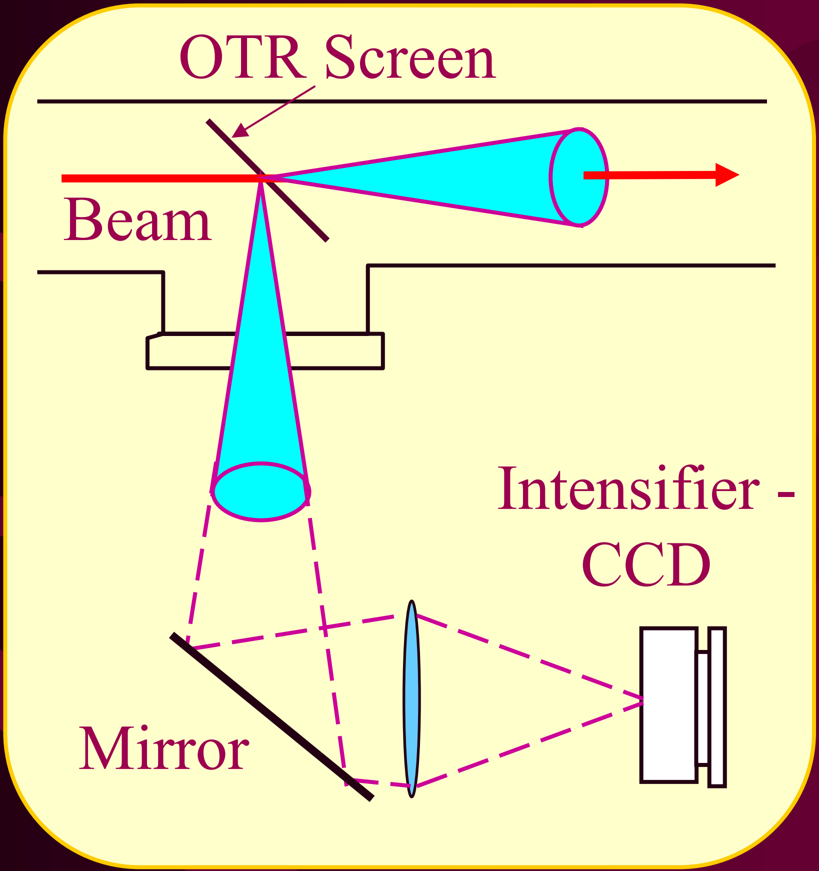
Measuring Profiles using Screens

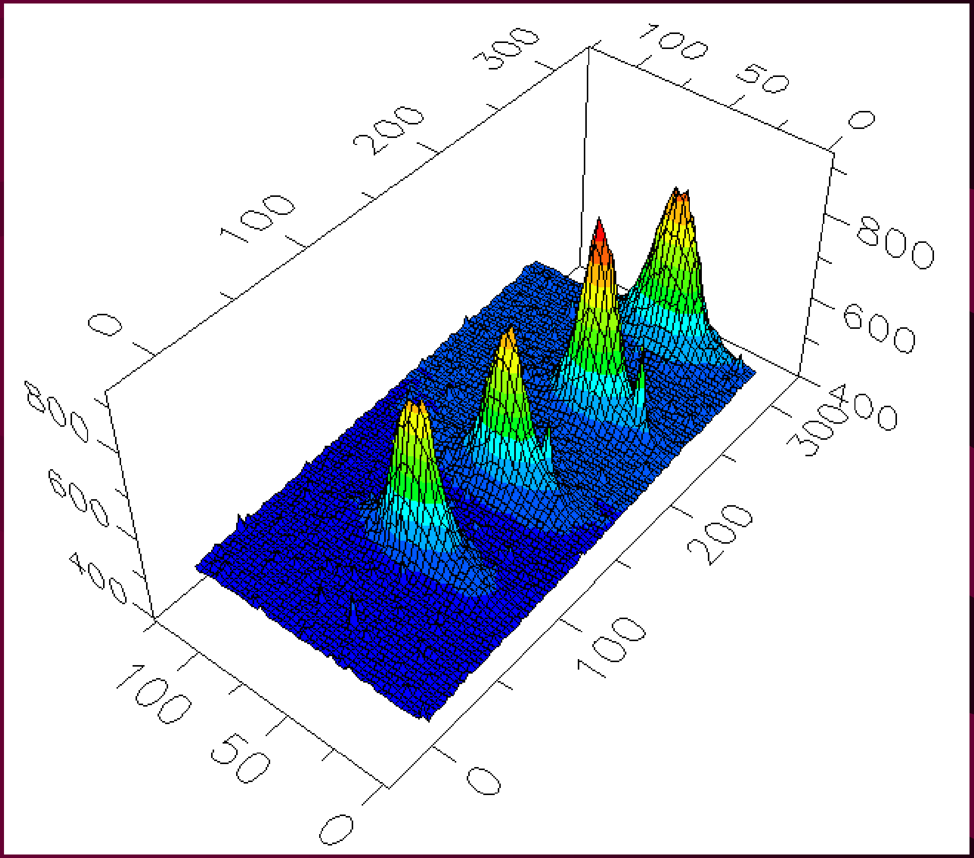
- Al2O3 screens for set-up and "bad days"
- OTR screens for nominal operation
- Can combine both into one instrument



Optical Transition Radiation Monitors

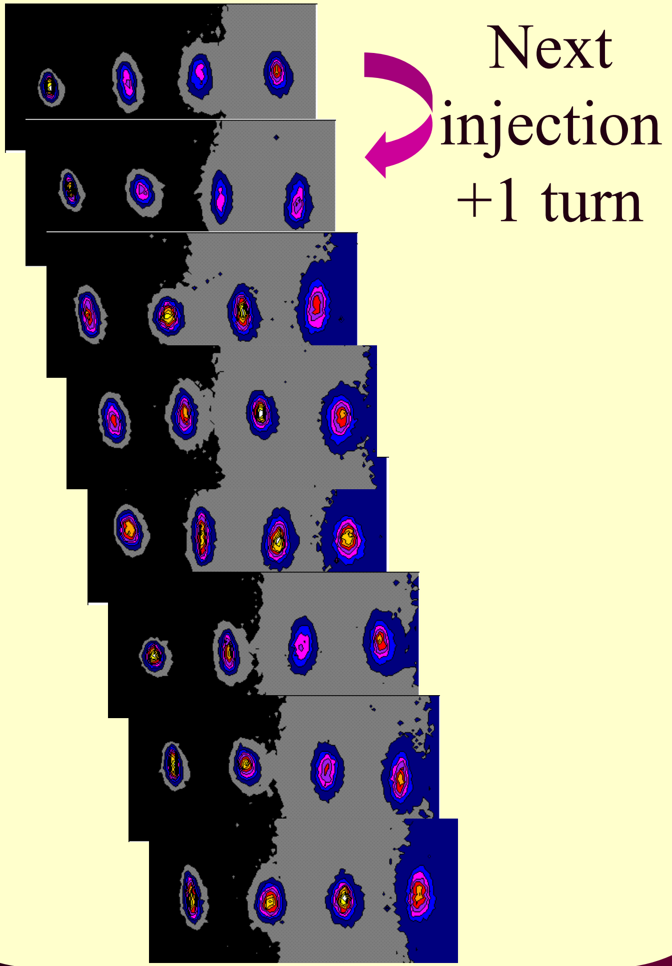
As Beam hits the 12μm Titanium foil 2 cones of radiation are emitted

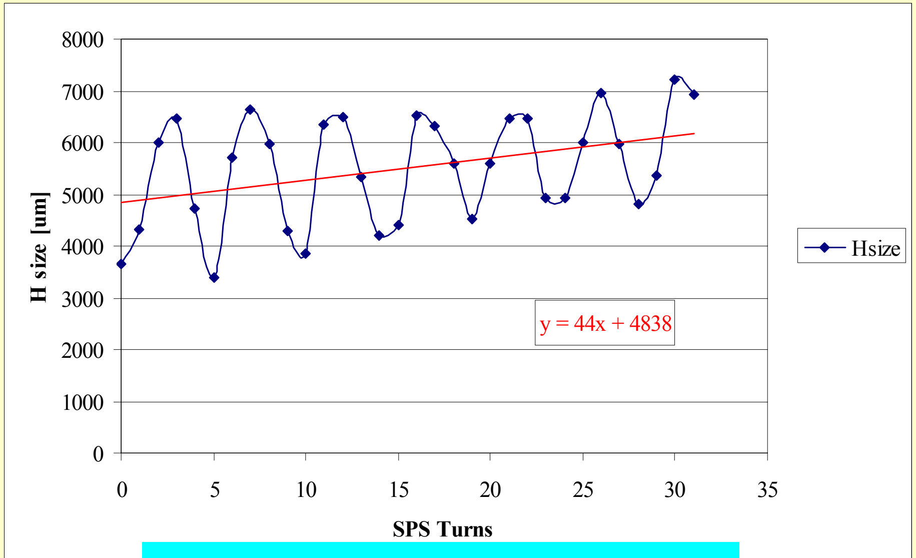




Capturing emitted radiation on a CCD gives 2D beam distribution

Turn-by-Turn OTR Results



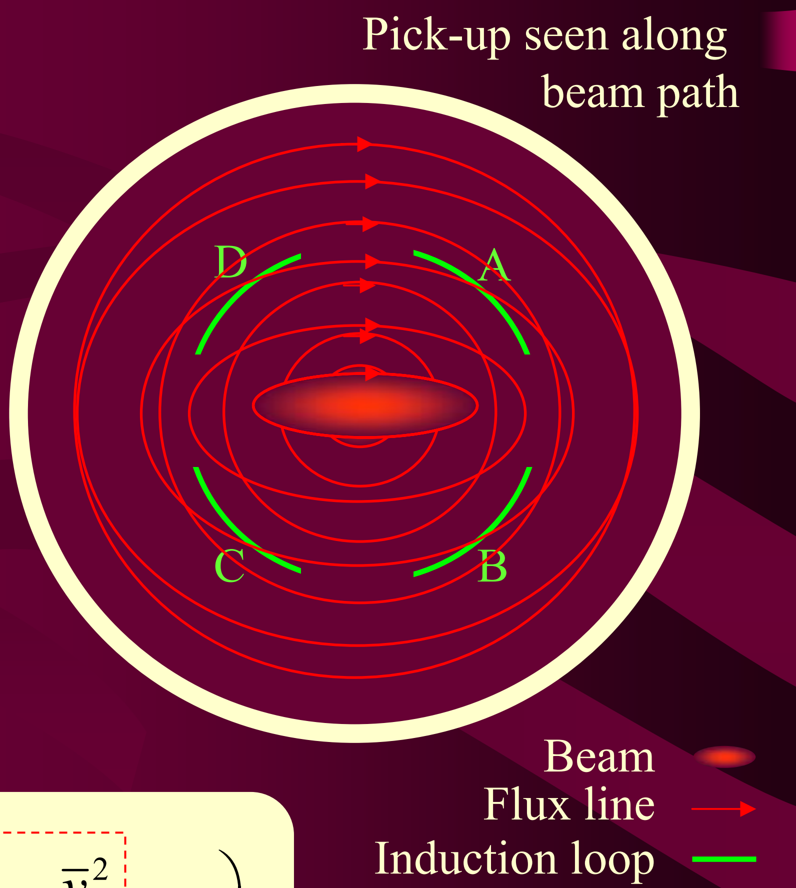


Very poor matching!!

β-Mismatch at injection seen as a beating in the beam profile

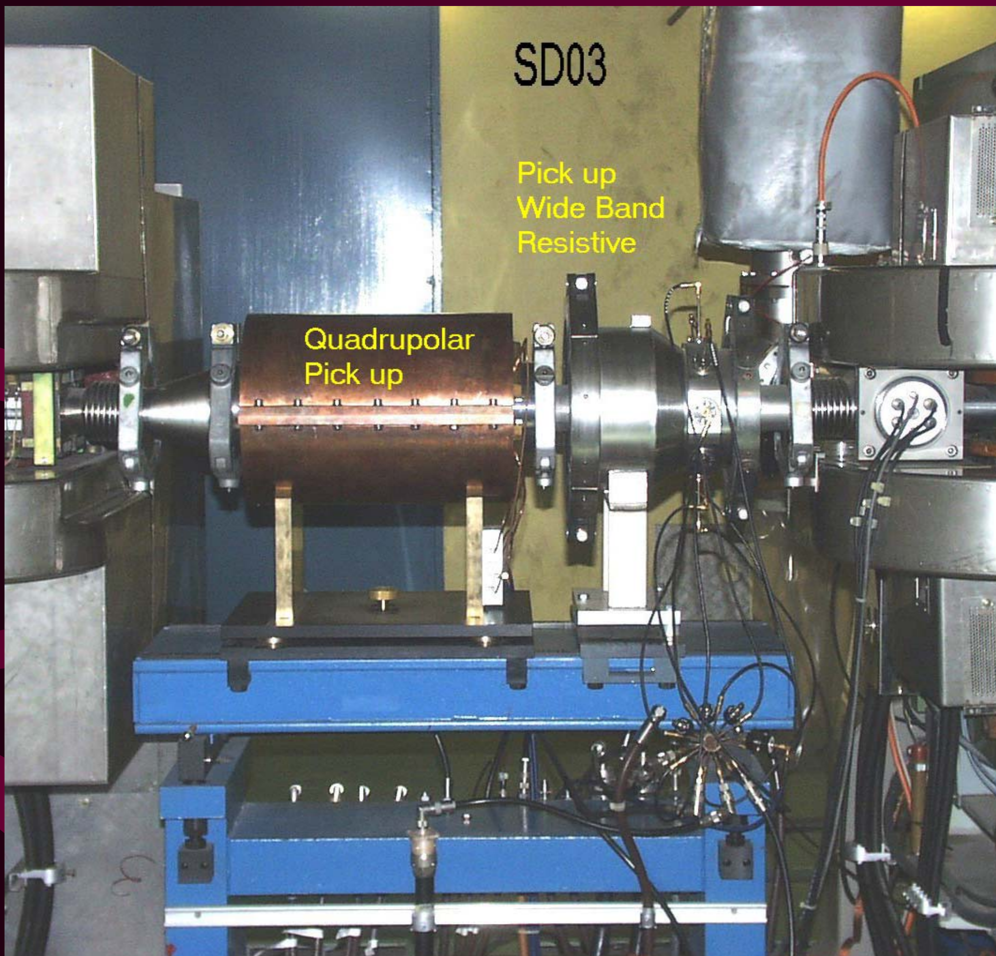
Quadrupolar Pick-Up

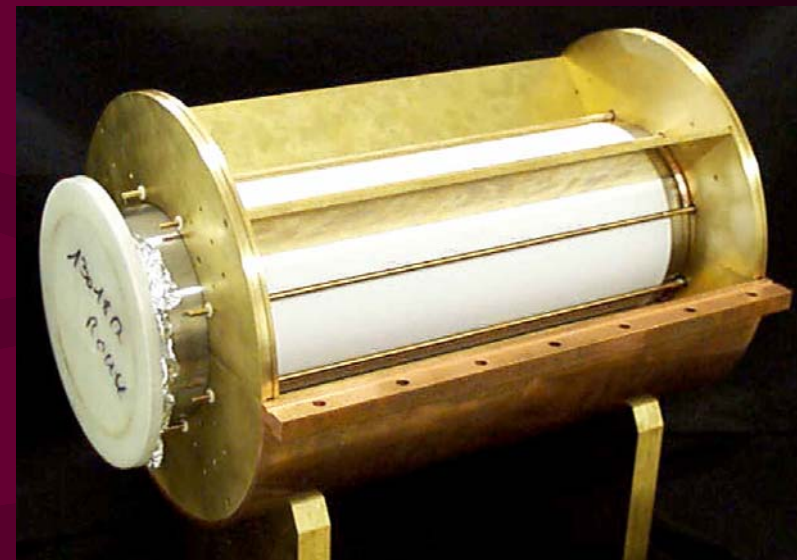
- Position contribution can not be avoided, but can be measured and subtracted.
- Design suppresses the dominating intensity signal by coupling to the radial magnetic field component.



$$A \propto i_b \left(0 + 0.41 \left(\frac{\bar{x}}{r} - \frac{\bar{y}}{r} \right) + 1.23 \frac{\sigma_x^2 - \sigma_y^2 + \bar{x}^2 - \bar{y}^2}{r^2} + \dots \right)$$

Installation in the CERN-PS



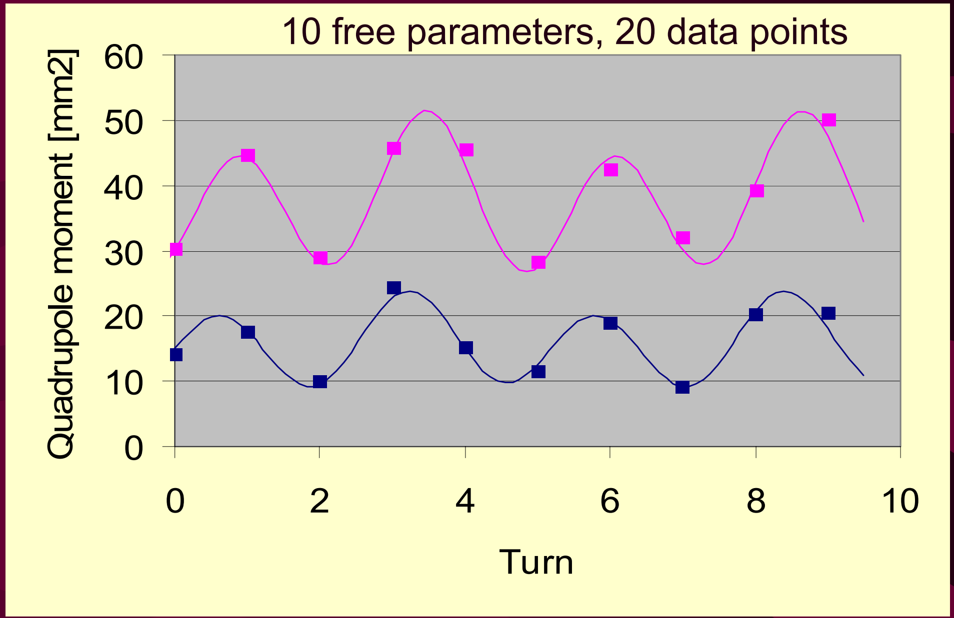


	β_h	β_v	D_h
SS 03	22 m	12 m	3.2 m
SS 04	12 m	22 m	2.3 m

"One pick-up per plane"

Measurement of Matching

$$\kappa \propto \sigma_x^2 - \sigma_y^2 =$$
$$\varepsilon_x(\beta_x + \underbrace{\Delta\beta_x}_{2q_x}) - \varepsilon_y(\beta_y + \underbrace{\Delta\beta_y}_{2q_y}) +$$
$$+\sigma_p^2(D_x^2 + D_x\underbrace{\Delta D_x}_{q_x} + \underbrace{\Delta D_x^2}_{2q_x} - \underbrace{\Delta D_y^2}_{2q_y})$$



- Simultaneous fit to the two pick-up signals gives:
  - → Injected emittances.
  - → Betatron mismatches.
  - → Horizontal dispersion mismatch.

- Input parameters
  - → β_H, β_V, D_H
  - → $\Delta\mu_H$, $\Delta\mu_V$
  - → σ_p, q_h, q_v
- Most input parameters can be checked experimentally

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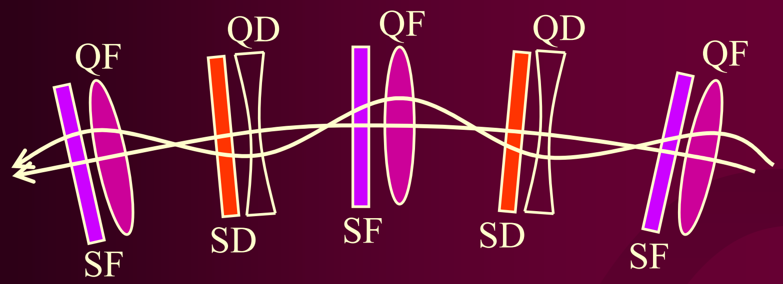
Measurement of Q (betatron tune)

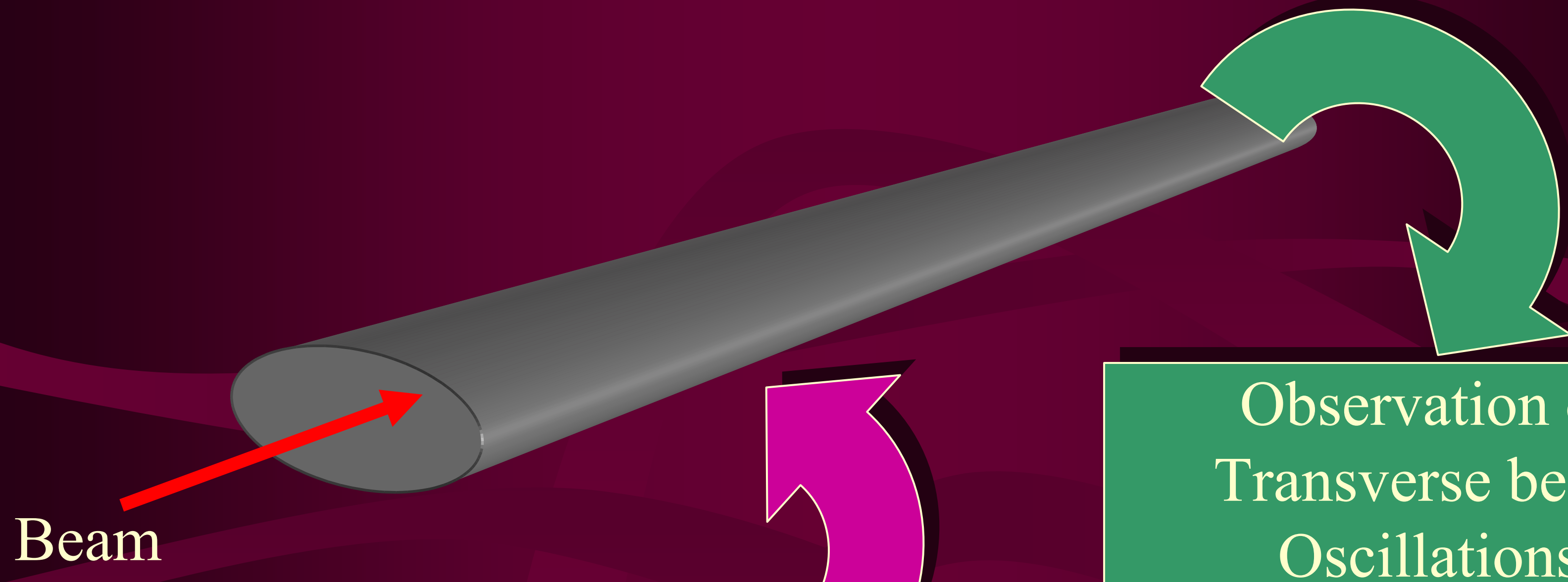


Characteristic Frequency of the Magnet Lattice

Produced by the strength of the Quadrupole magnets

- Q – the eigenfrequency of betatron oscillations in a circular machine
  - → One of the key parameters of machine operation
- Many measurement methods available:
  - → different beam excitations
  - → different observations of resulting beam oscillation
  - → different data treatment

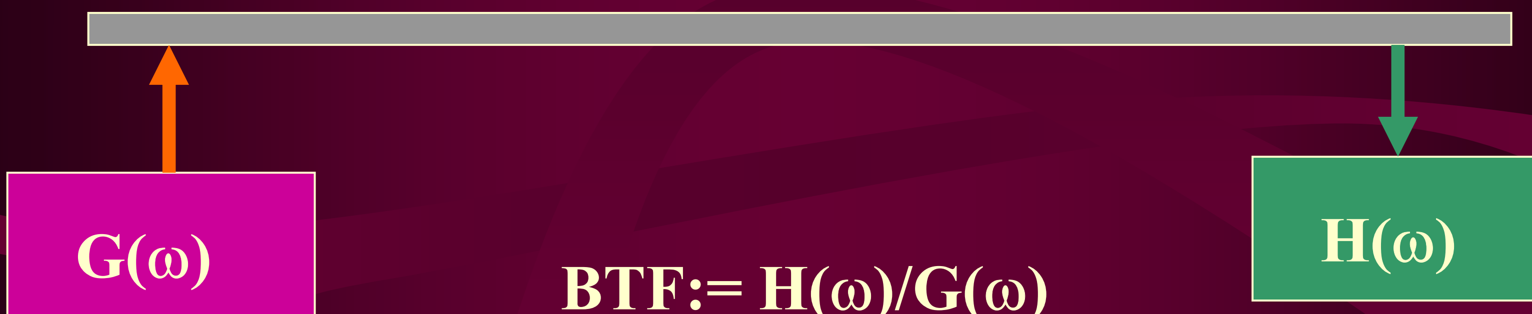
Principle of any Q-measurement



Observation of
Transverse beam
Oscillations
-e.m. pickup
- resonant BPM
-others

Excitation Source for
Transverse beam
Oscillations
- stripline kickers
- pulsed magnets

Principle of any Q-measurement



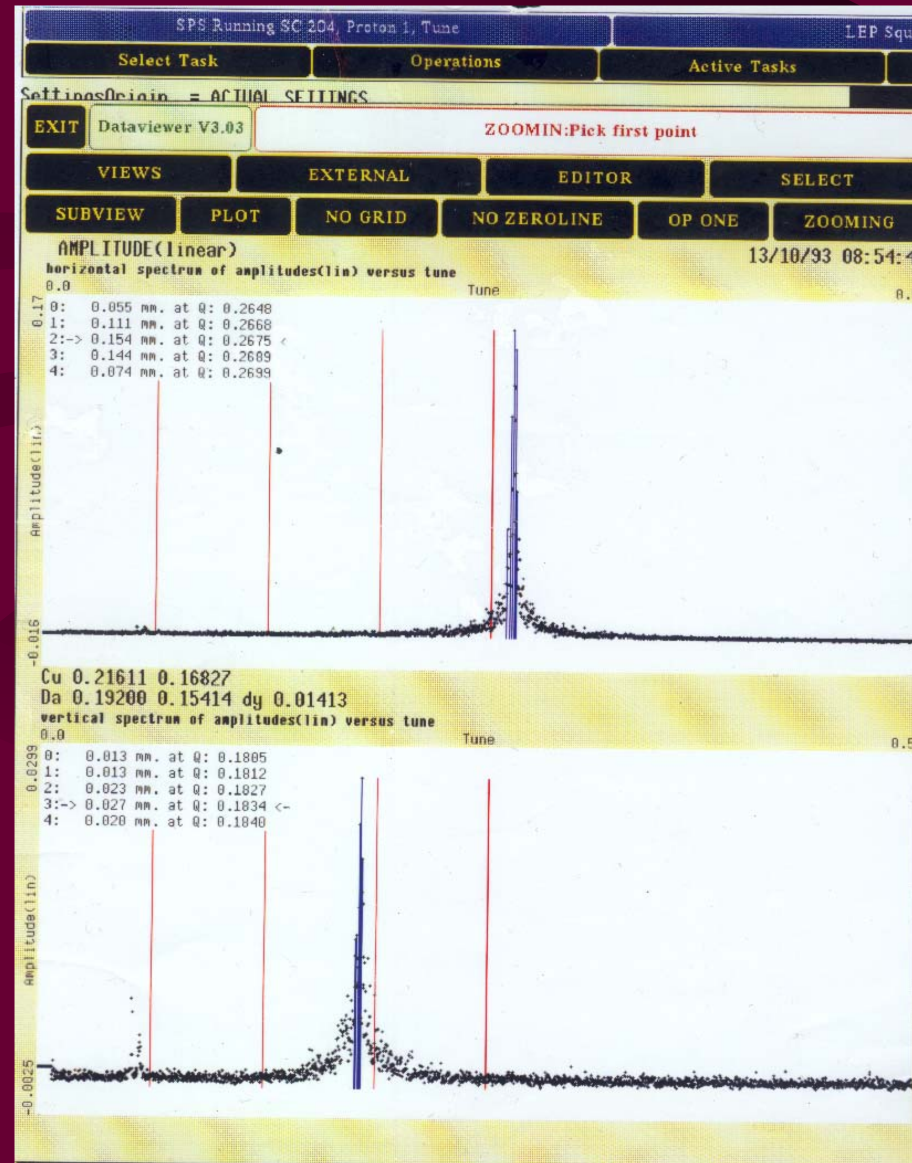
BTF:= H(ω)/G(ω)

Measurement of betatron tune q: Maximum of BTF

Simple example: FFT analysis

G(ω) == flat;

Made with random noise kicks



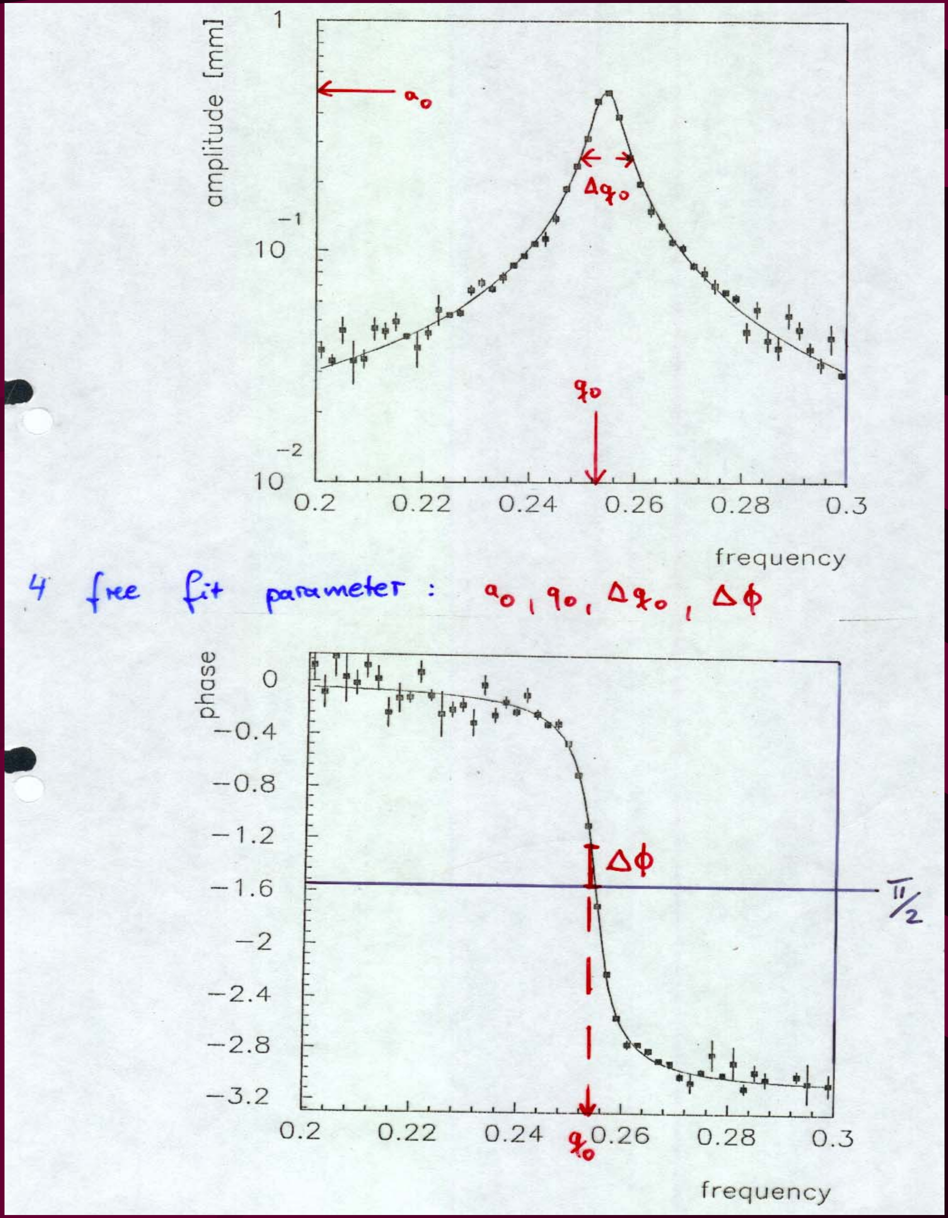
Measure beam position over many consecutives turns

-> apply FFT ->H(ω);

BTF = H(ω)

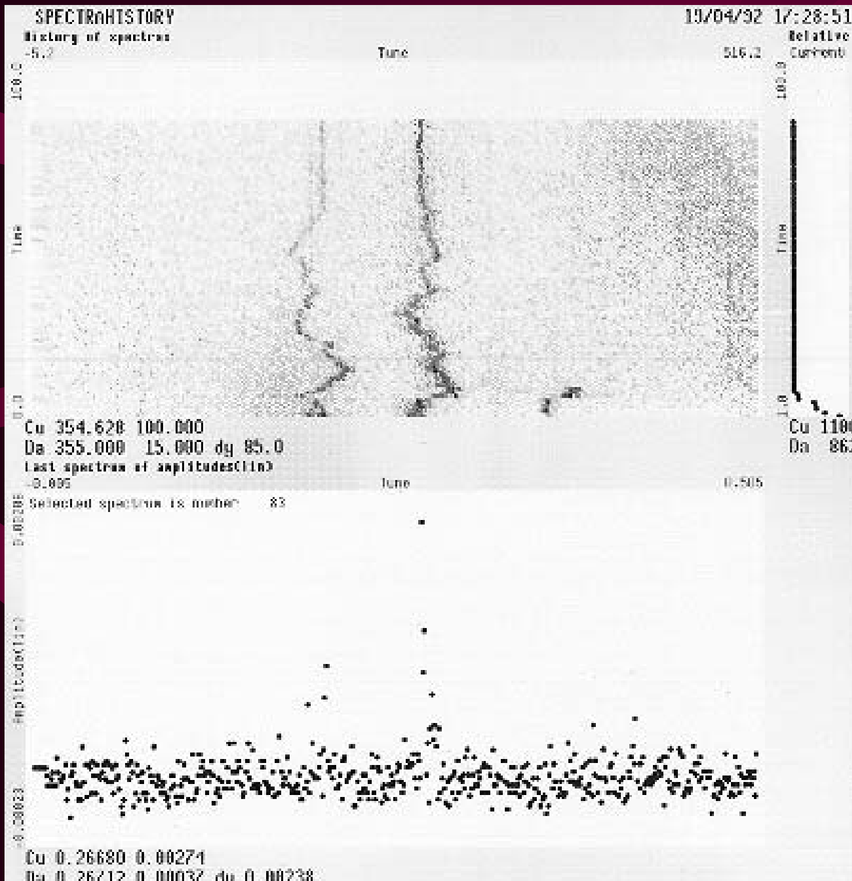
Network Analysis

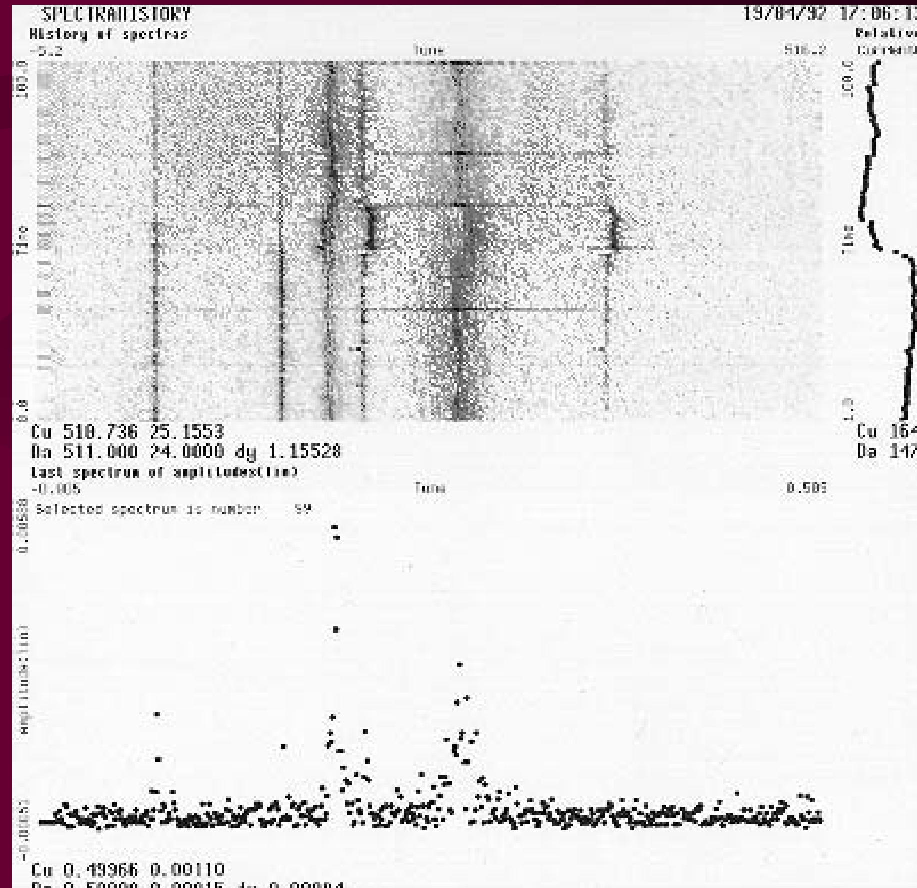
1. Excite beams with a sinusoidal carrier
2. Measure beam response
3. Sweep excitation frequency slowly through beam response



Time Resolved Measurements

- To follow betatron tunes during machine transitions we need time resolved measurements. Simplest example:
  - → repeated FFT spectra as before (spectrograms)





Principle of PLL tune measurements

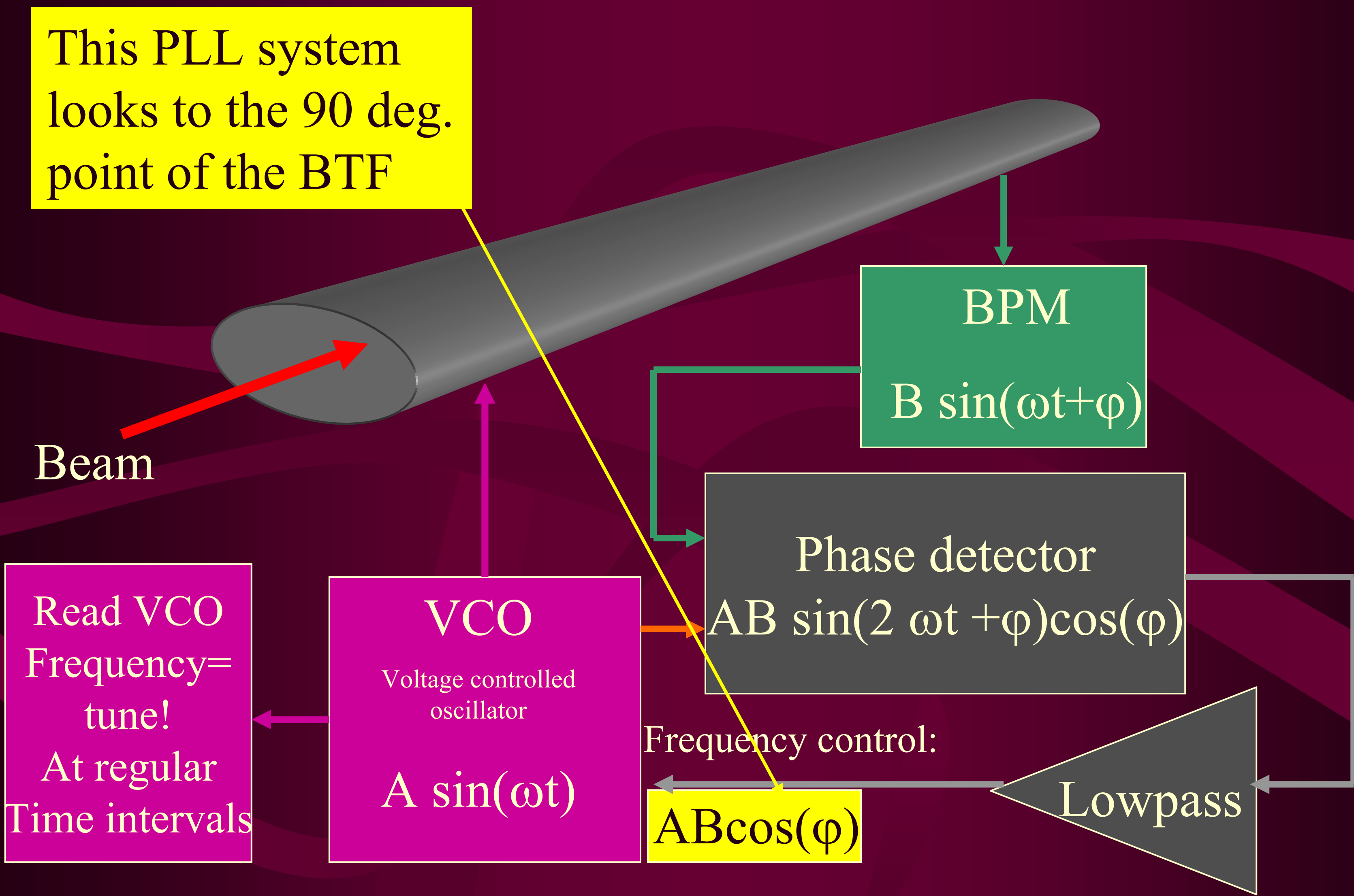
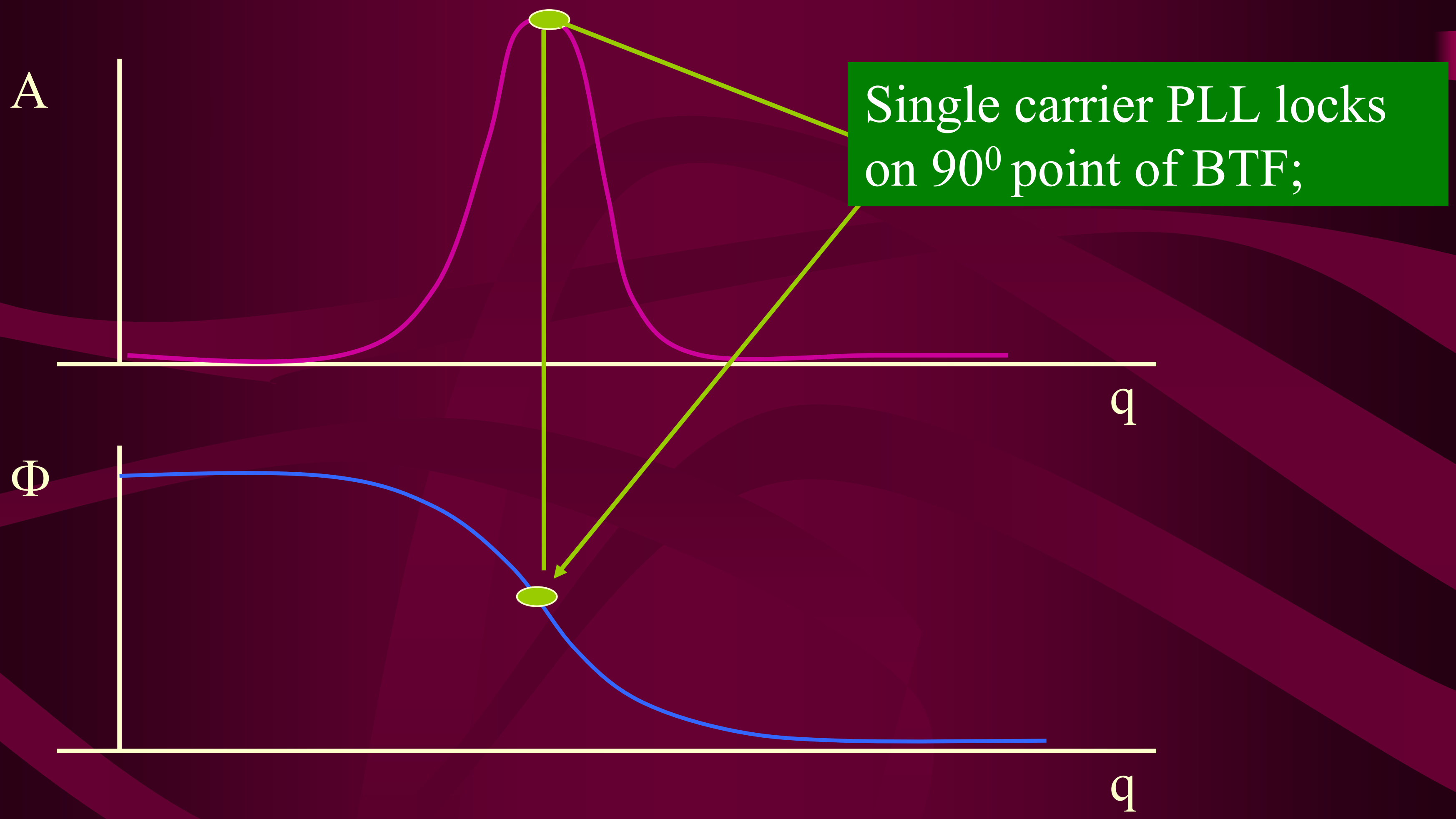
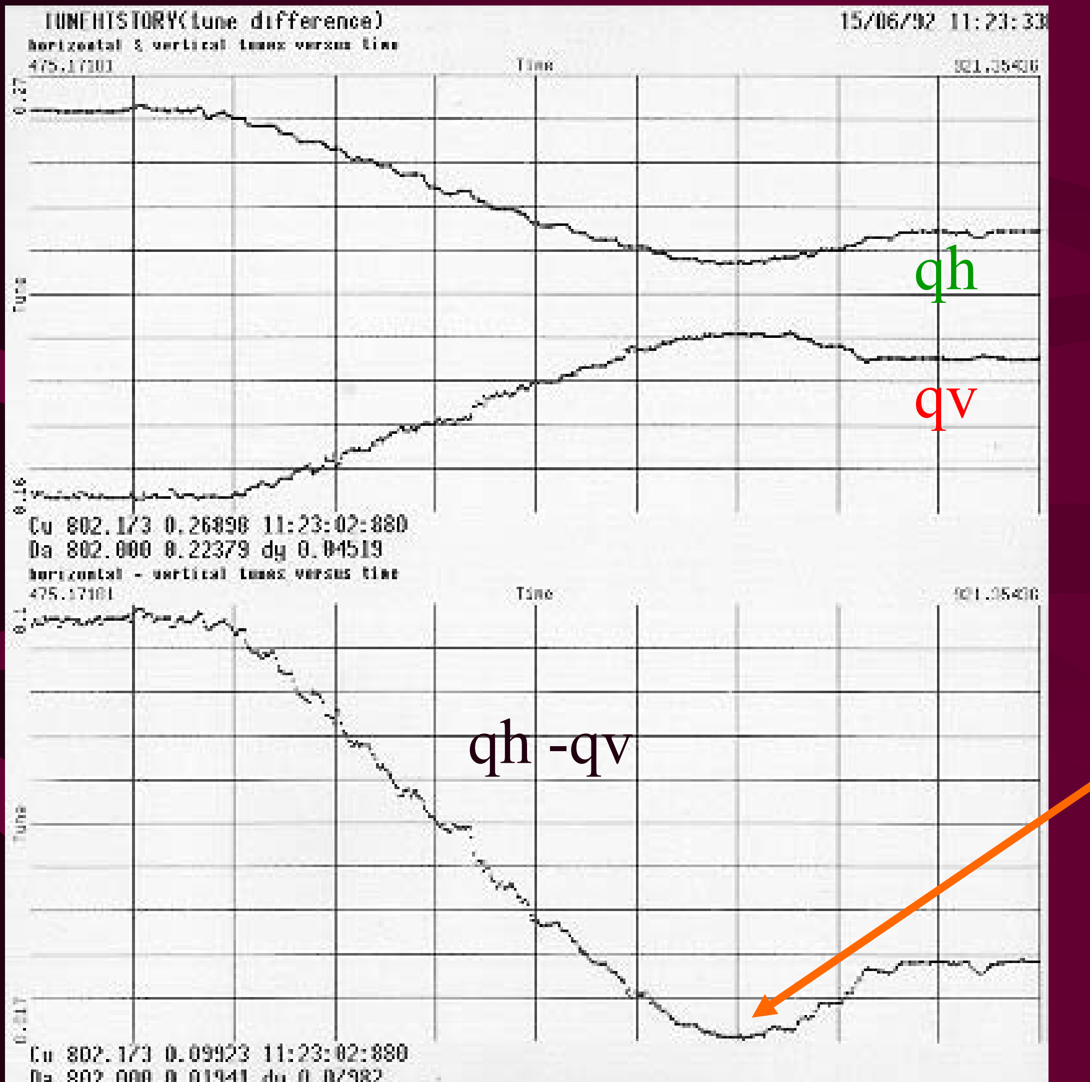


Illustration of PLL tune tracking



Example of PLL tune measurement



In this case continuous tune tracking was used whilst crossing the horizontal and vertical tunes with a power converter ramp.

Closest tune approach is a measure of coupling

β Function Measurement by k-Modulation

- Purpose:
  - → measurement of $< \beta >$ within a quadrupole
  - → optics knowledge
  - → emittance determination: $\varepsilon = \sigma^2_{rms} / \beta$
- Principle:
  - → a (small) strength variation Δk within a quadrupole induces a tune variation ΔQ

$$\Delta Q = \Delta k / 4\pi \int_{Quad} \beta(s)\, ds$$

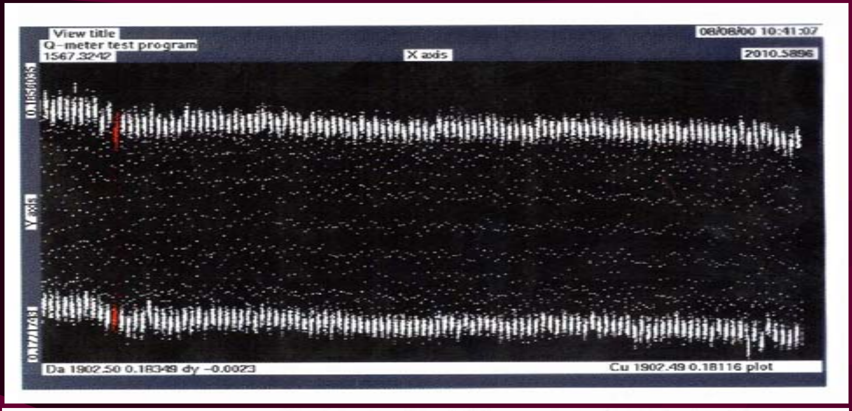
$$< \beta_{H,V} > = (4\pi\, \Delta Q_{H,V} / L\Delta k)\,(1+\varepsilon(\Delta Q))$$

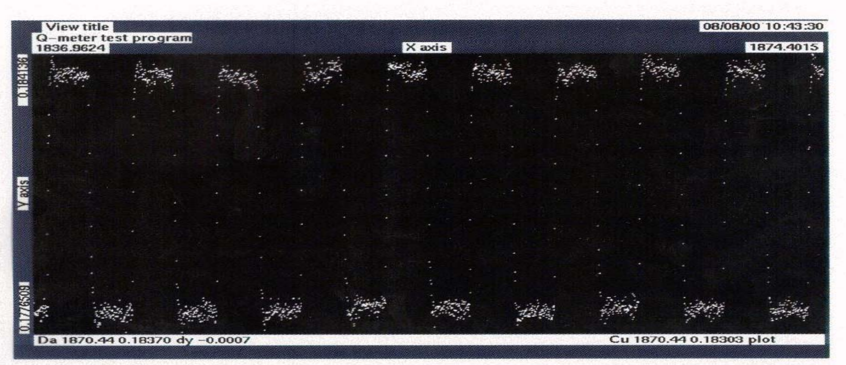
$$\frac{\delta\langle\beta\rangle}{\langle\beta\rangle} = \left[2\left(\frac{\delta k}{\Delta k}\right)^2 + 2\left(\frac{\delta q}{\Delta q}\right)^2 + \left(\frac{\delta L}{L}\right)^2\right]^{1/2}$$

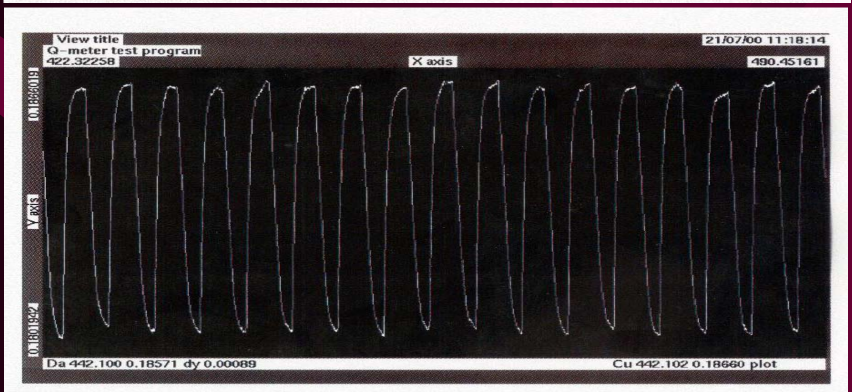
  - L is the quadrupole magnetic length
  - ΔQ is small enough to keep second order term contribution < 1%

- Δk modulated using k-modulation facility in LEP to test:
  - → What is the smallest possible perturbation? (LHC emittance budget)
  - → Can it work with beams colliding head ON ?

β Measurement using k-Modulation in LEP







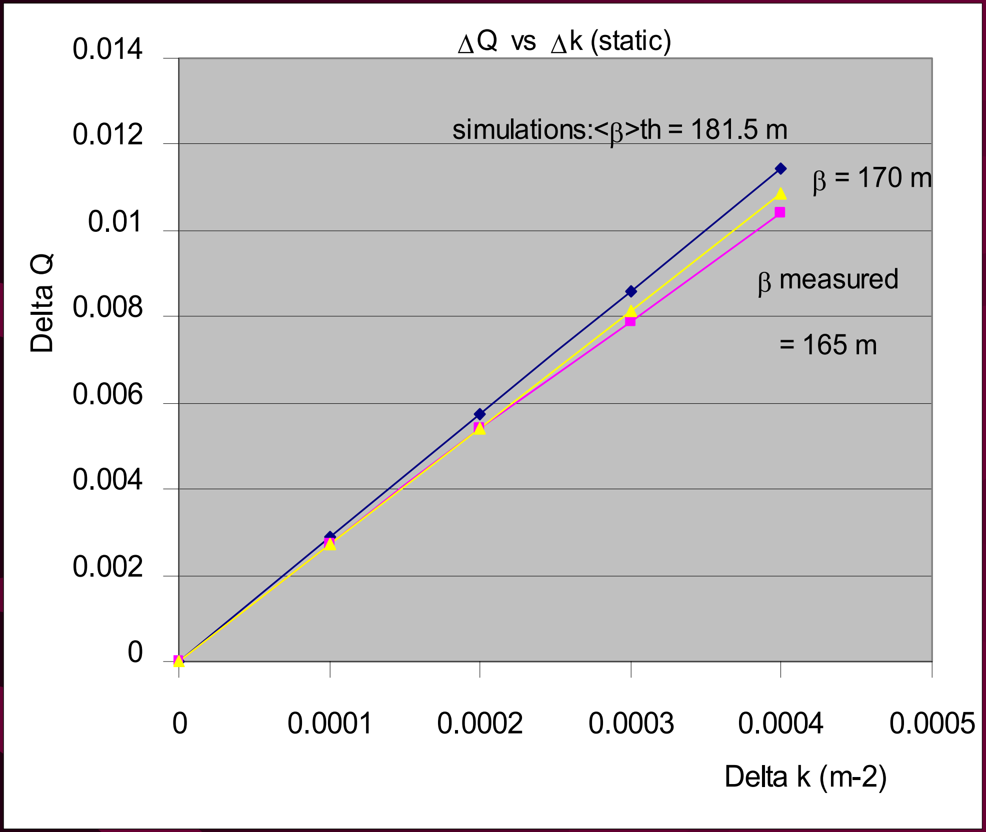
Effect of Q feedback loop speed (PLL mode)

→ ΔI = 1A, 0.25 Hz

→ " fast" mode: 20 Hz

→ "normal" mode: 12 Hz

β Measurement using k-Modulation in LEP



Comparison between static Δk , 1000 turns and k-modulation

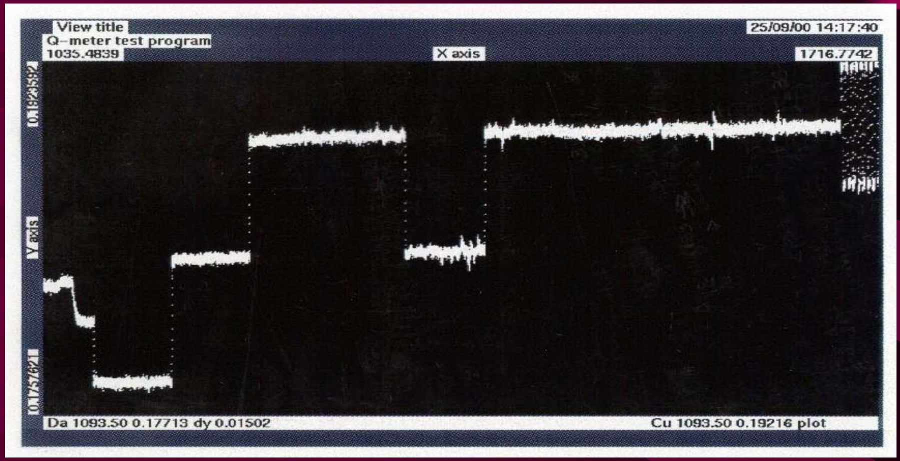
LEP: 85GeV, 800mA, 4 bunches

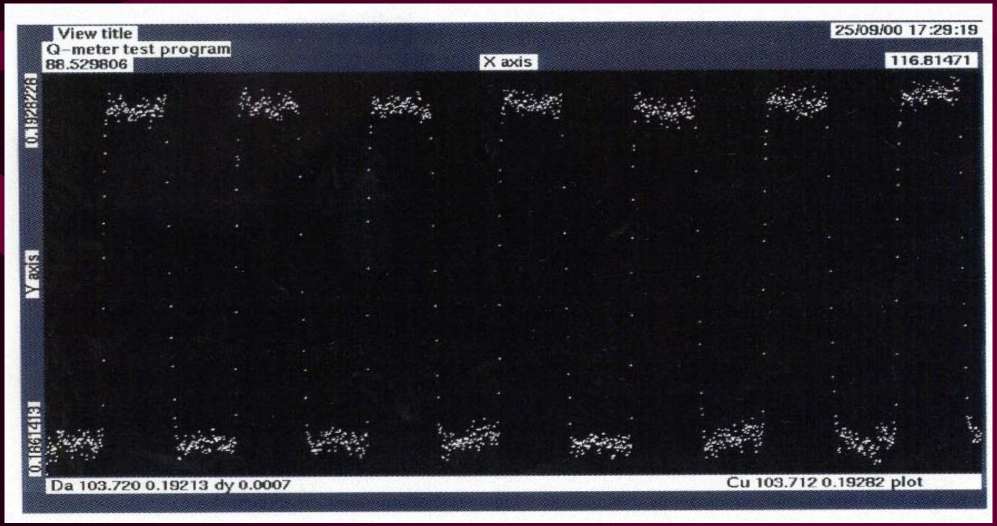
- 1000 turns:
  - → β_{middle} QUAD = 175.4 m
  - → β-beating: -9.2%
  - → <β> =164.8 m
- k-modulation:
  - → 1A (5×10^{-4}), 0.25 Hz
  - → <β> = 162.9 m

Comparison between static Δk and k-modulation with colliding beams in LEP

[103.3 GeV, 1860 μA on 1860 μA]

- Static Δk:
  - → I0 + 0.5 A : <β> = 383.9 m
  - → I0
  - → I0 - 0.5 A : <β> = 392.8 m





- k-modulation:
  - → I0 + ΔI
  - → ΔI = 1A, 0.25 Hz
  - → <β> = 389.4 m

Chromaticity (Q’ or ξ)

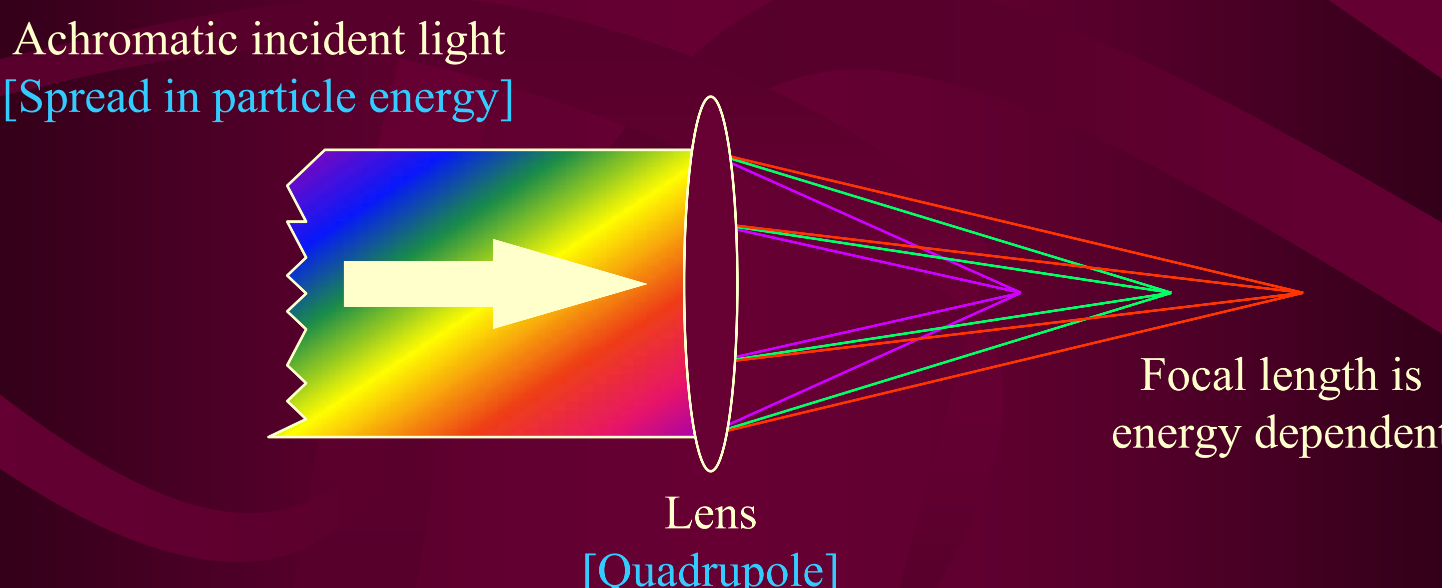
Spread in the Machine Tune due to Particle Energy Spread

Controlled by Sextupole magnets

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

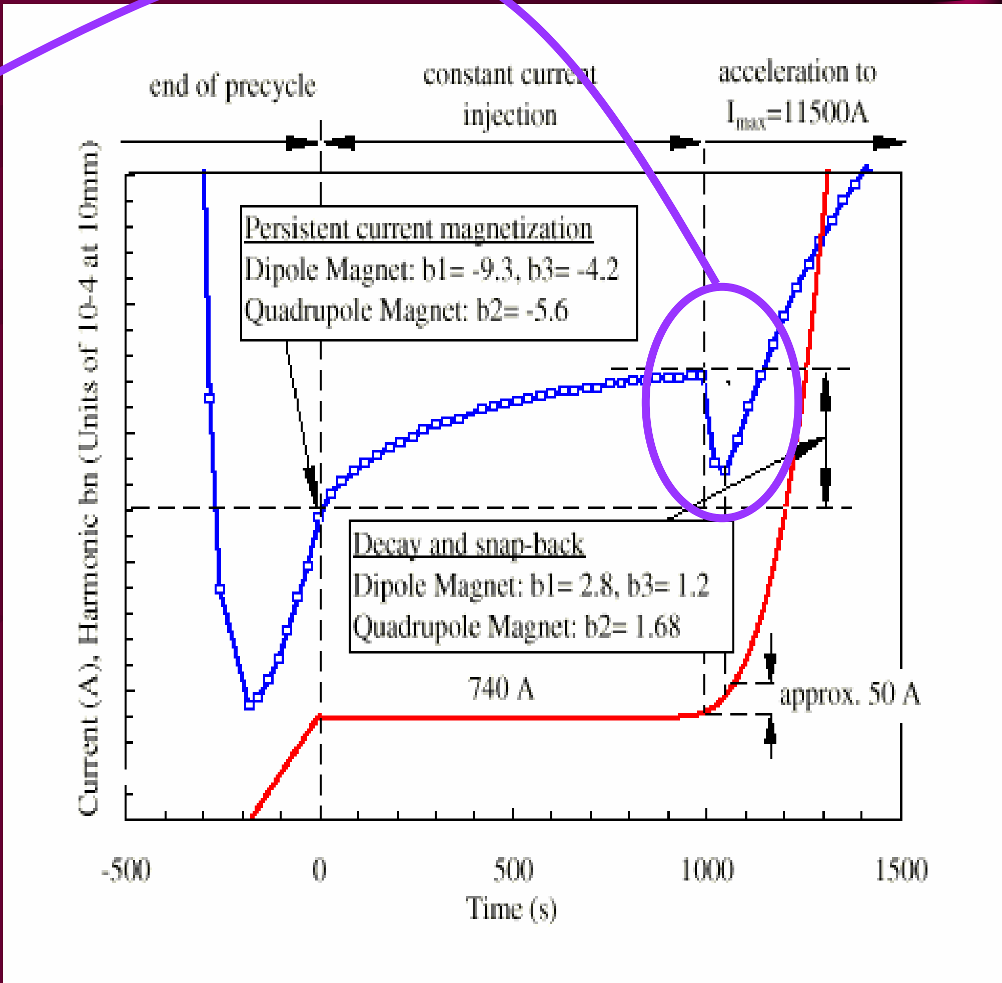
$$\xi = \frac{Q'}{Q}$$

Optics Analogy:



Chromaticity – Its Importance for the LHC?

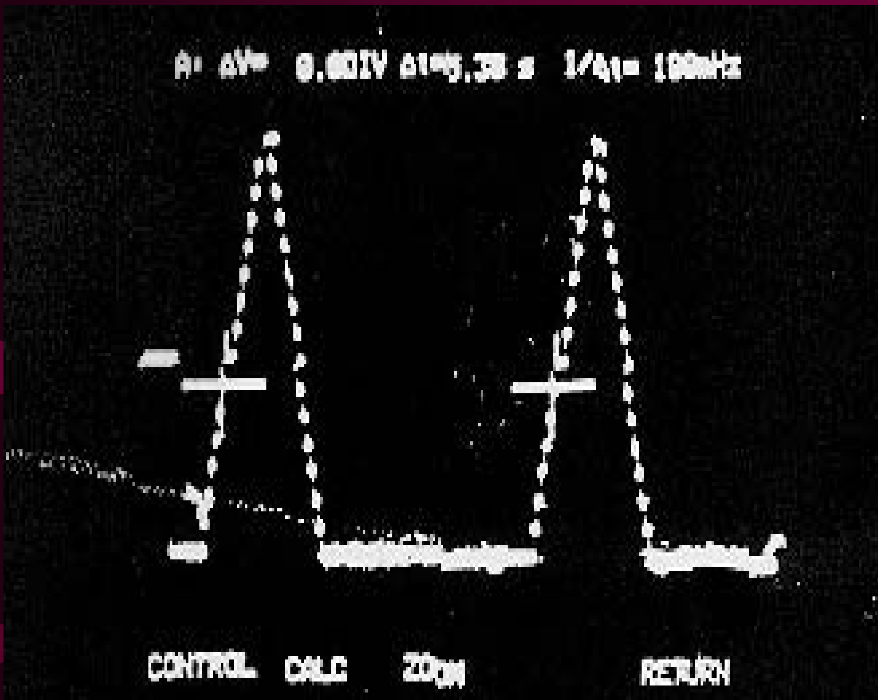
- Change in b3 during snap-back
  - → Change in Q’ of ~150 units
- Nominal operation requires $\Delta Q' < 3$
- Correction by:
  - → Feed-forward tables from magnet/chromaticity measurements
  - → On-line feedback from b3 measurements on reference magnets
  - → Possible on-line feedback directly from chromaticity measurements

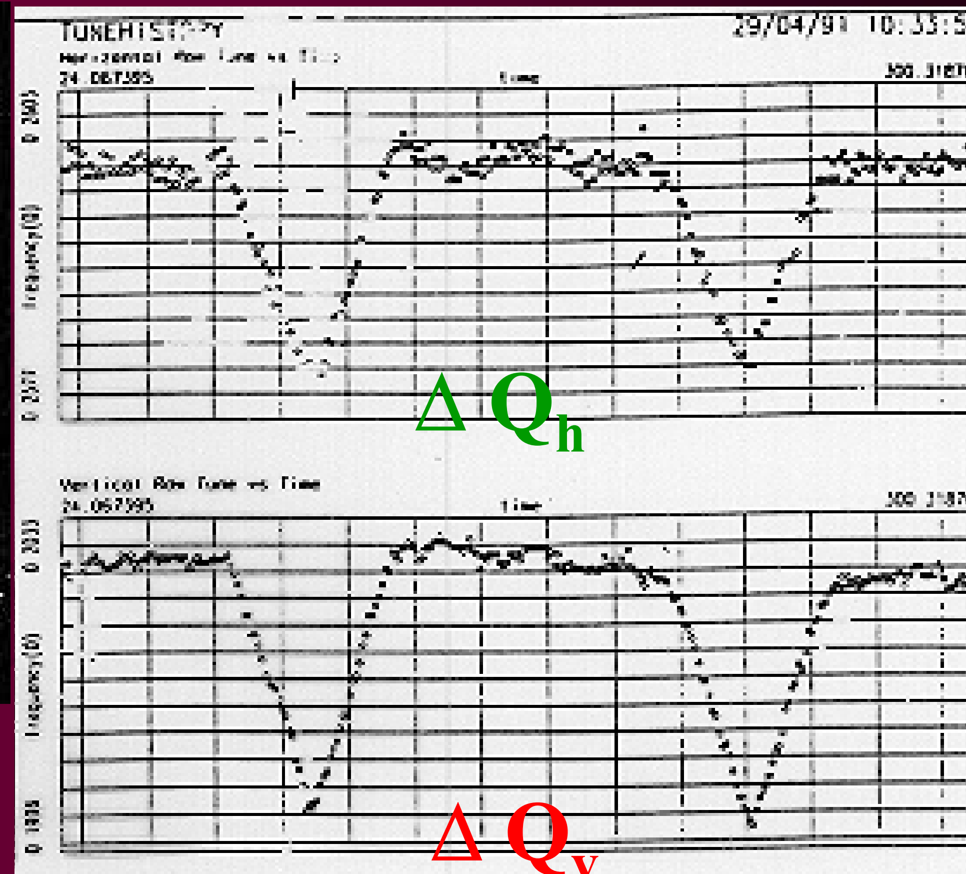


Chromaticity - What observable to choose?

Tune Difference for different beam momenta	⇔	used at HERA, LEP, RHIC in combination with PLL tune tracking
Width of tune peak or damping time	⇔	model dependent, non-linear effects, Used extensively at DESY
Amplitude ratio of synchrotron sidebands	⇔	Difficult of exploit in hadron machines with low synchrotron tune, influence of lattice resonances?
Excitation of energy oscillations and PLL tune tracking	⇔	First promising steps in the SPS
Bunch spectrum variations during betatron oscillations	⇔	difficult to measure
Head-tail phase advance (same as above, but in time domain)	⇔	very good results but requires kick stimulus ⇒ emittance growth!

Q' Measurement via RF-frequency modulation (momentum modulation)

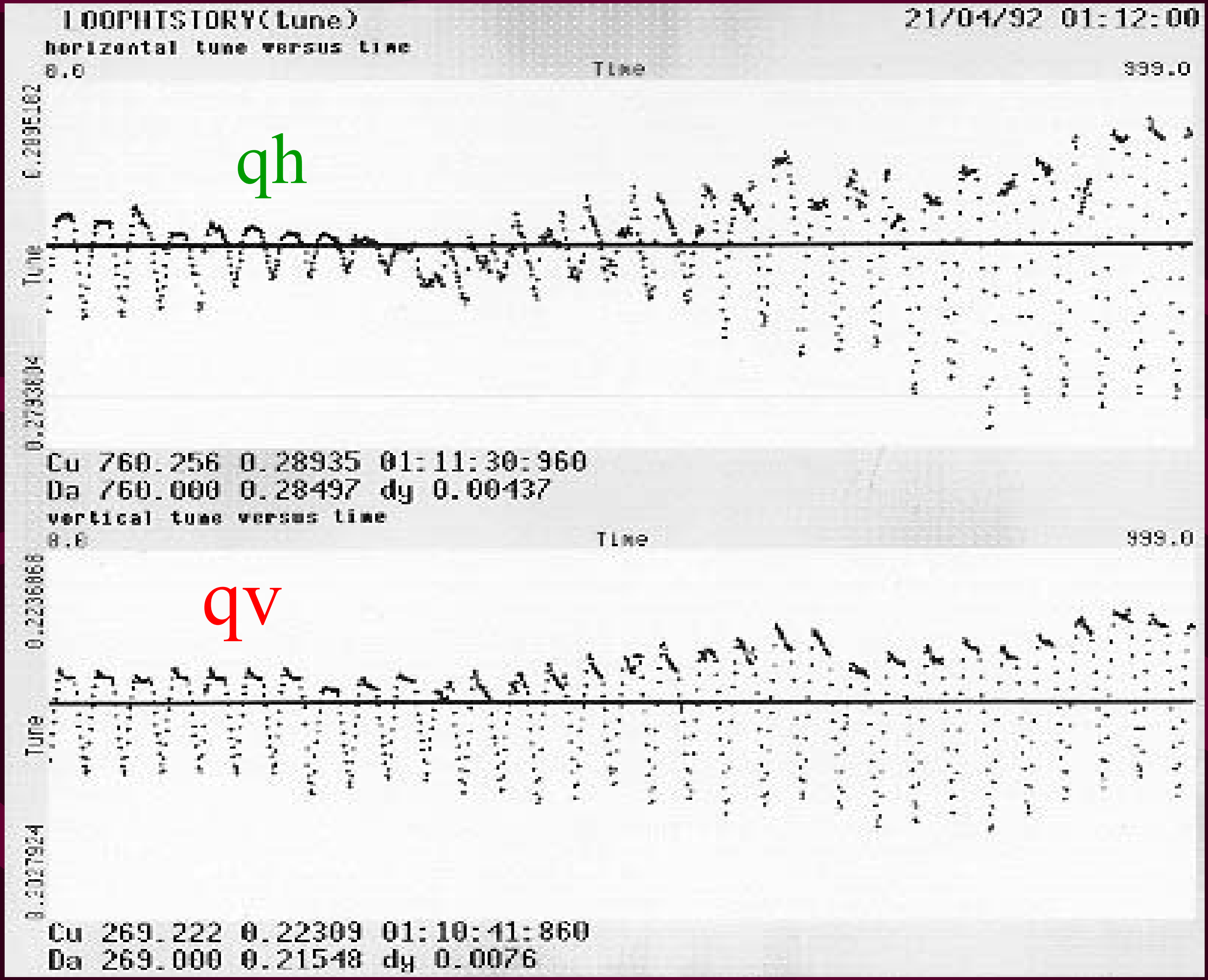




Applied Frequency Shift
Δ F (RF)

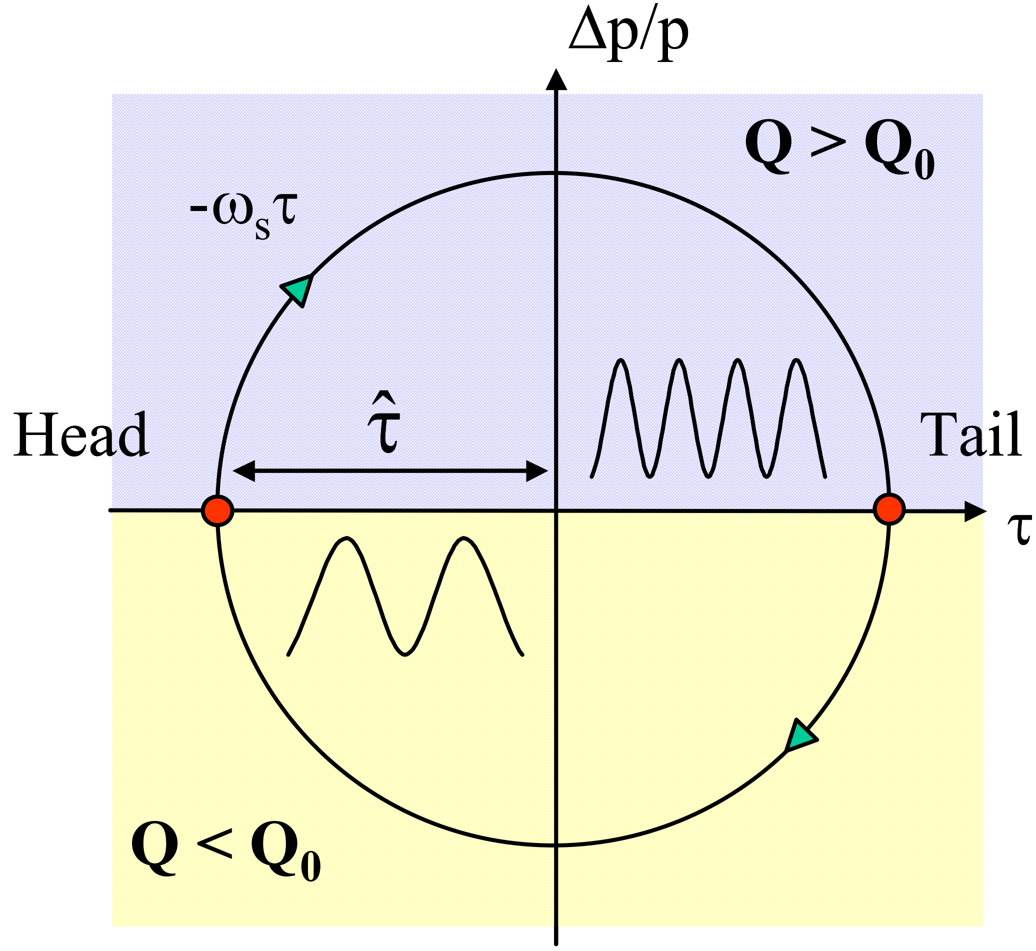
Amplitude & sign of chromaticity calculated from continuous tune plot

Measurement Example during LEP β-squeeze



Chromaticity & Head-Tail Motion

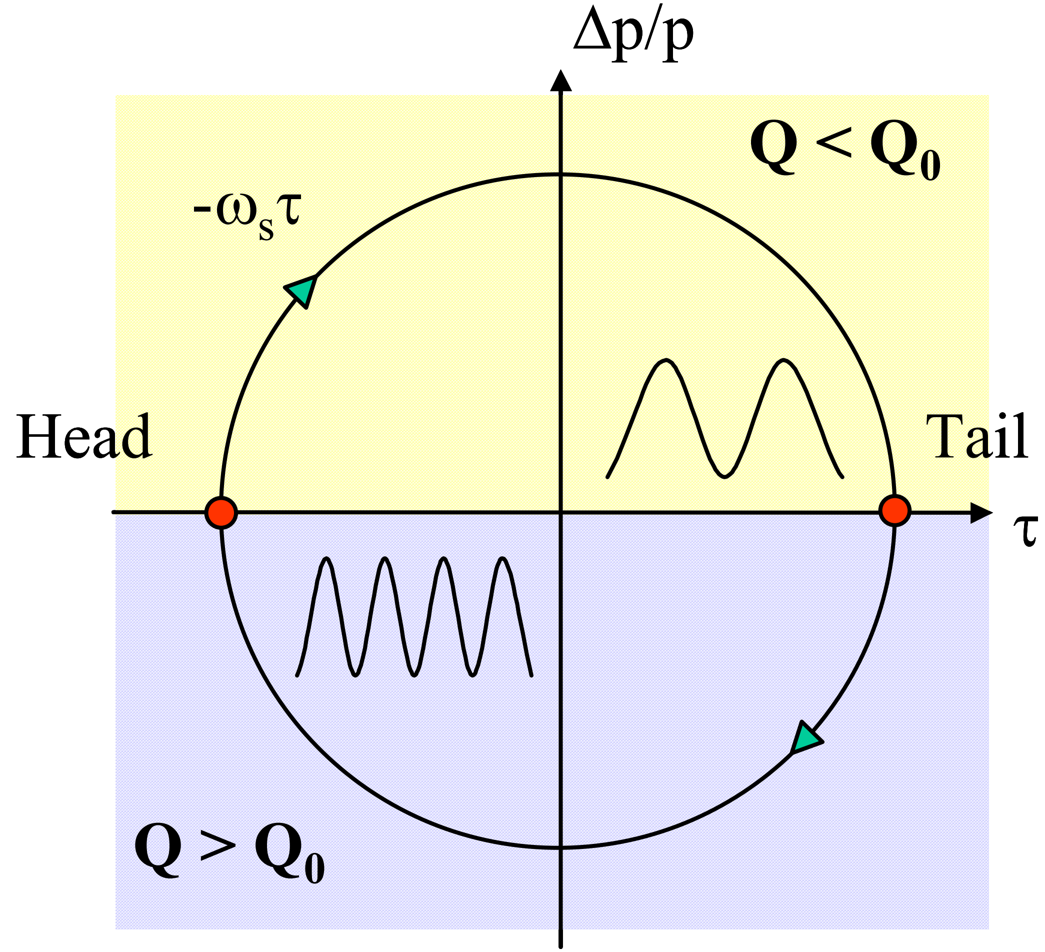
Positive Chromaticity (Above Transition)



Longitudinal Phase-Space

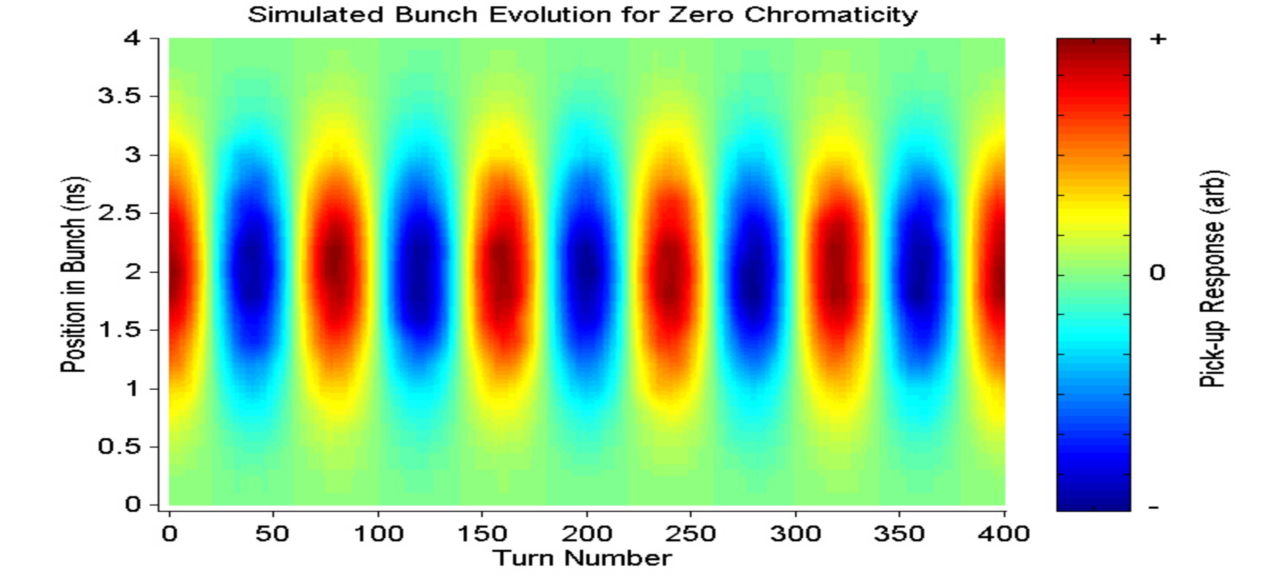
Chromaticity & Head-Tail Motion

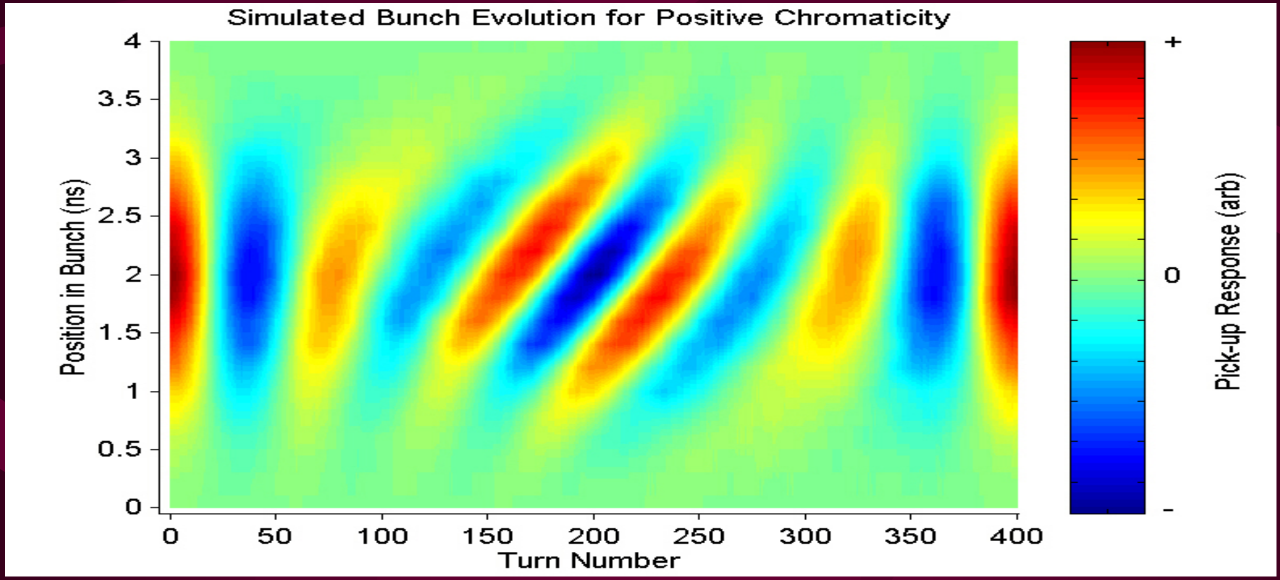
Negative Chromaticity (Above Transition)



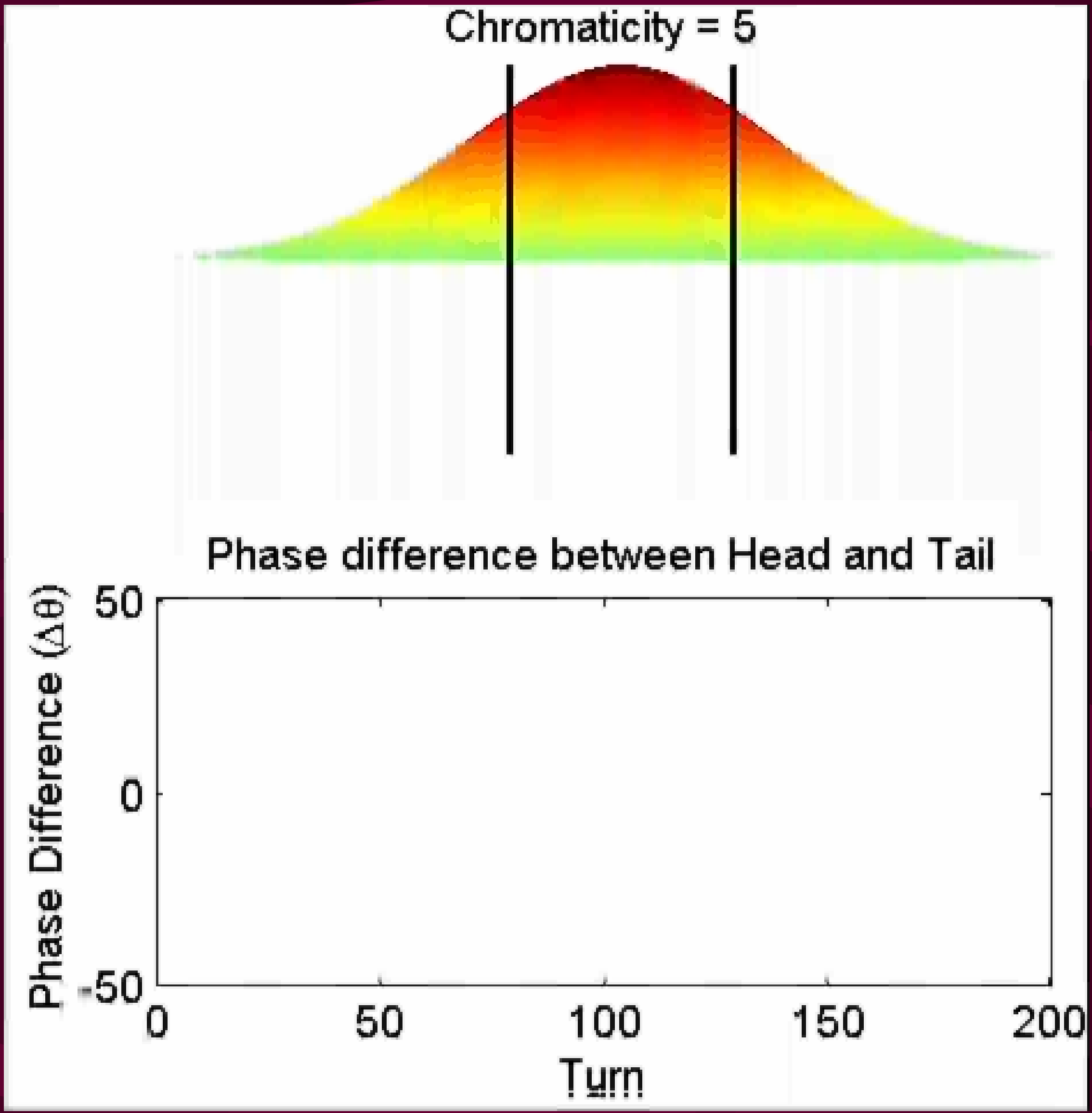
Longitudinal Phase-Space

Simulated Response

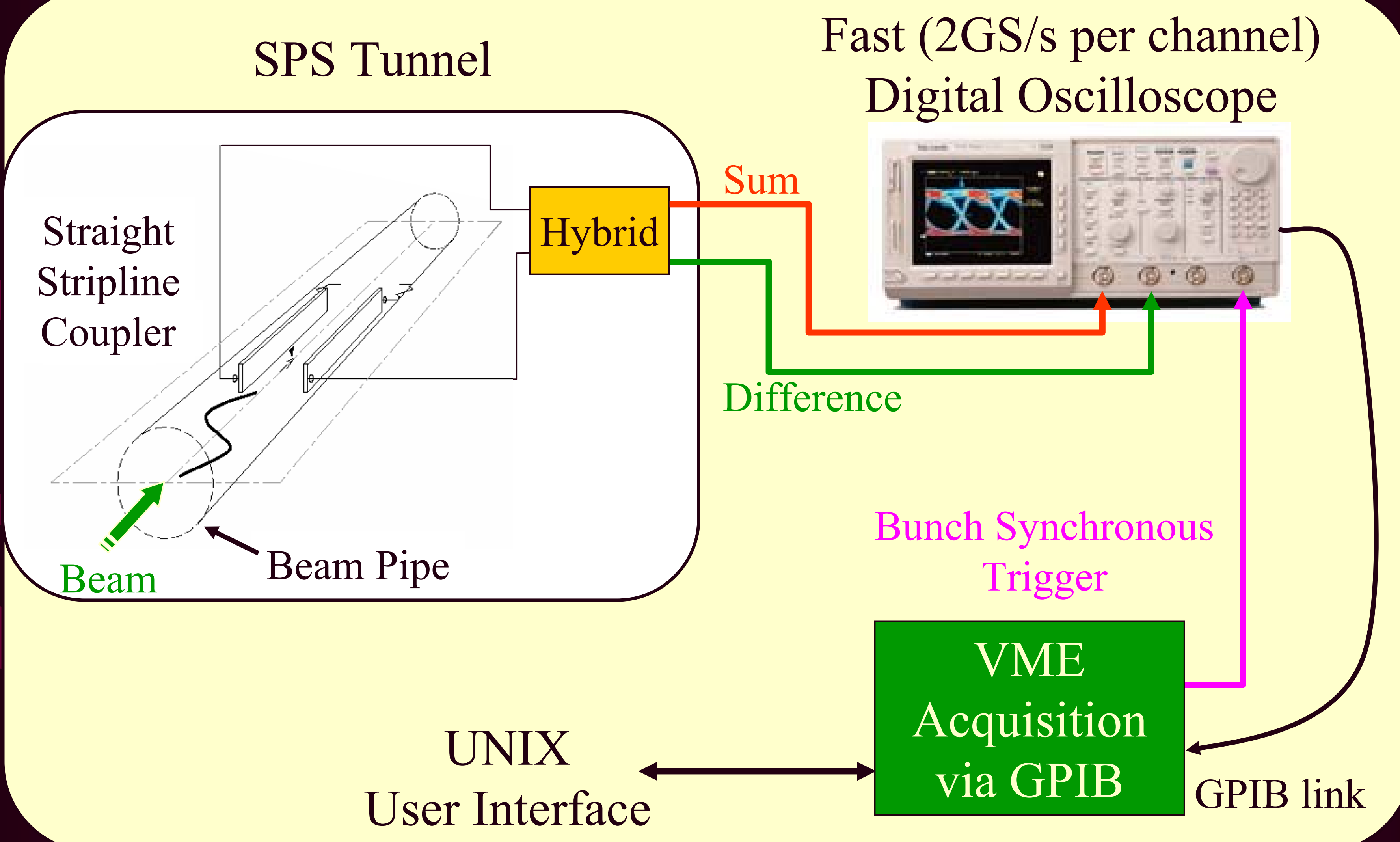




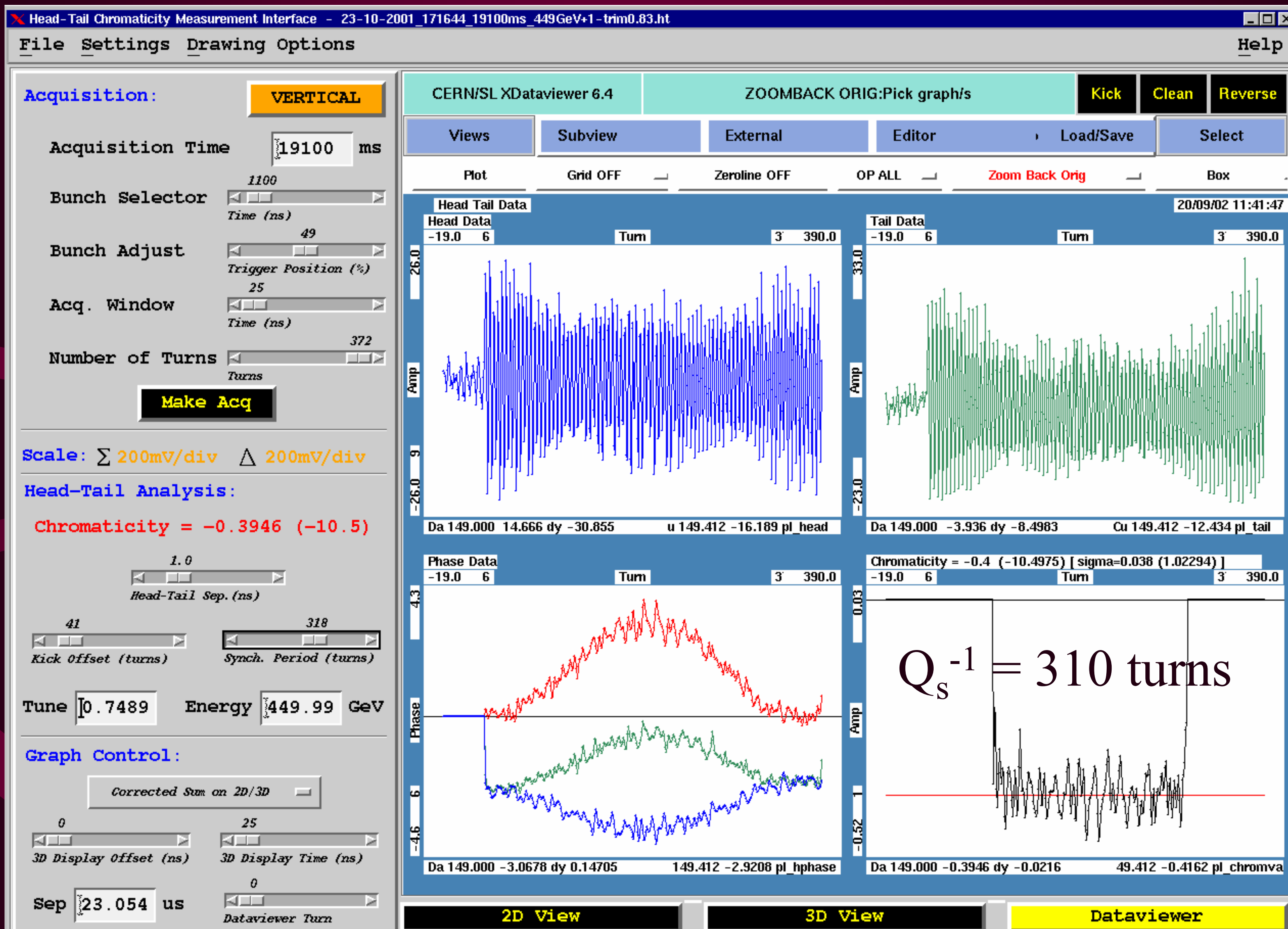
The Head-Tail Measurement Principle



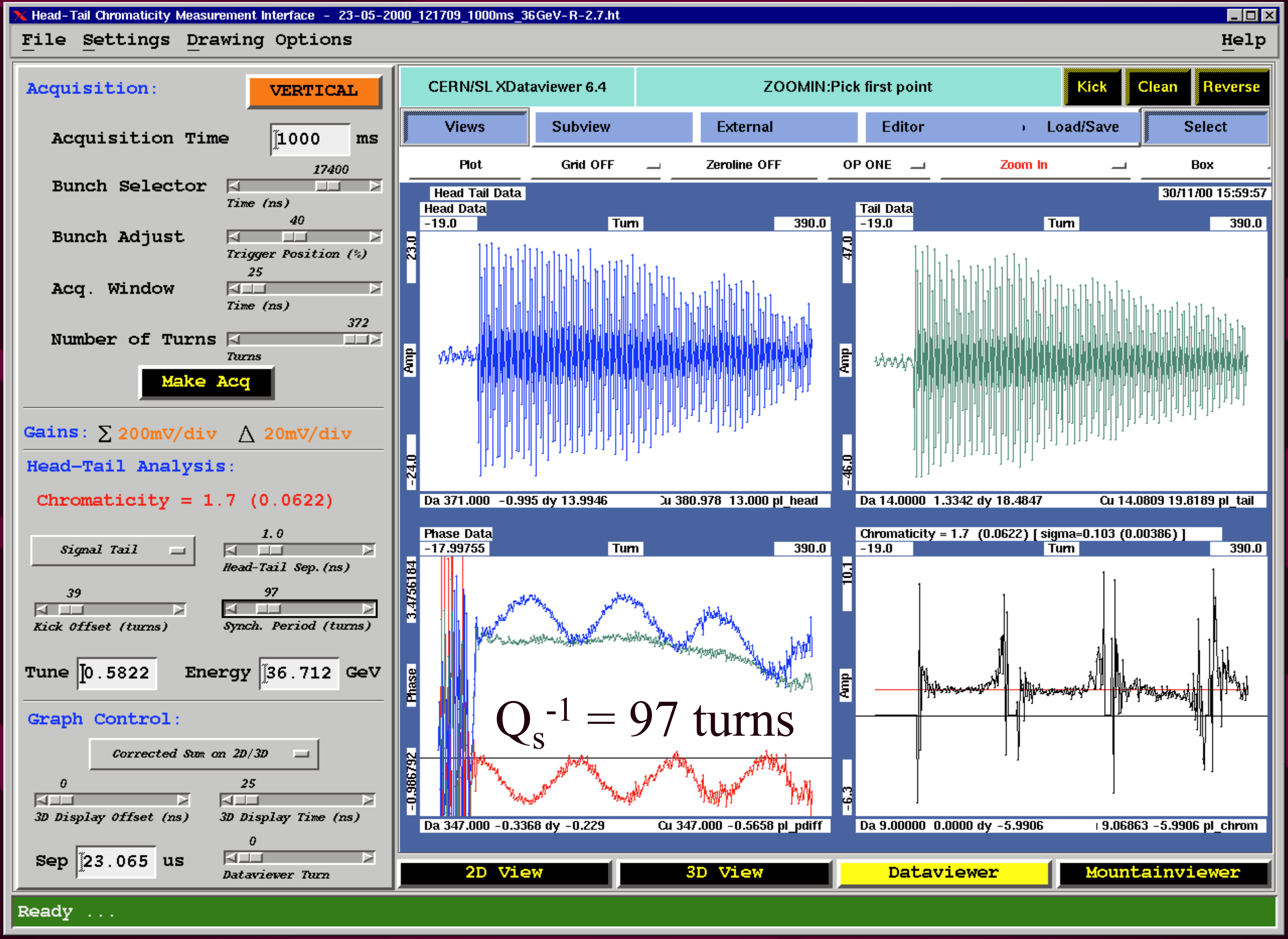
Head-Tail System Set-up (SPS)



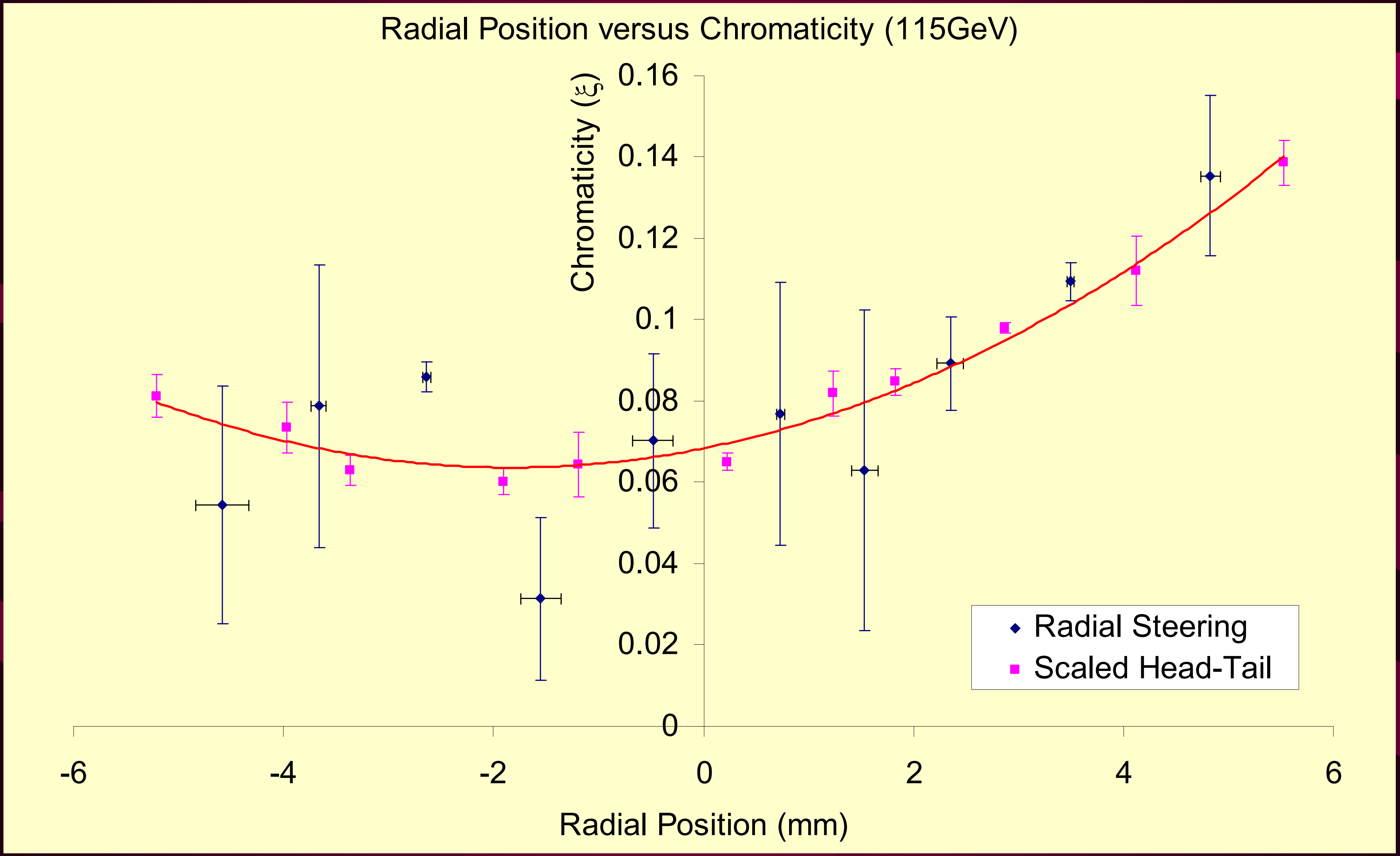
Measuring Q’ (Example 1: low Qs)



Measuring Q' (Example 2: high Qs)



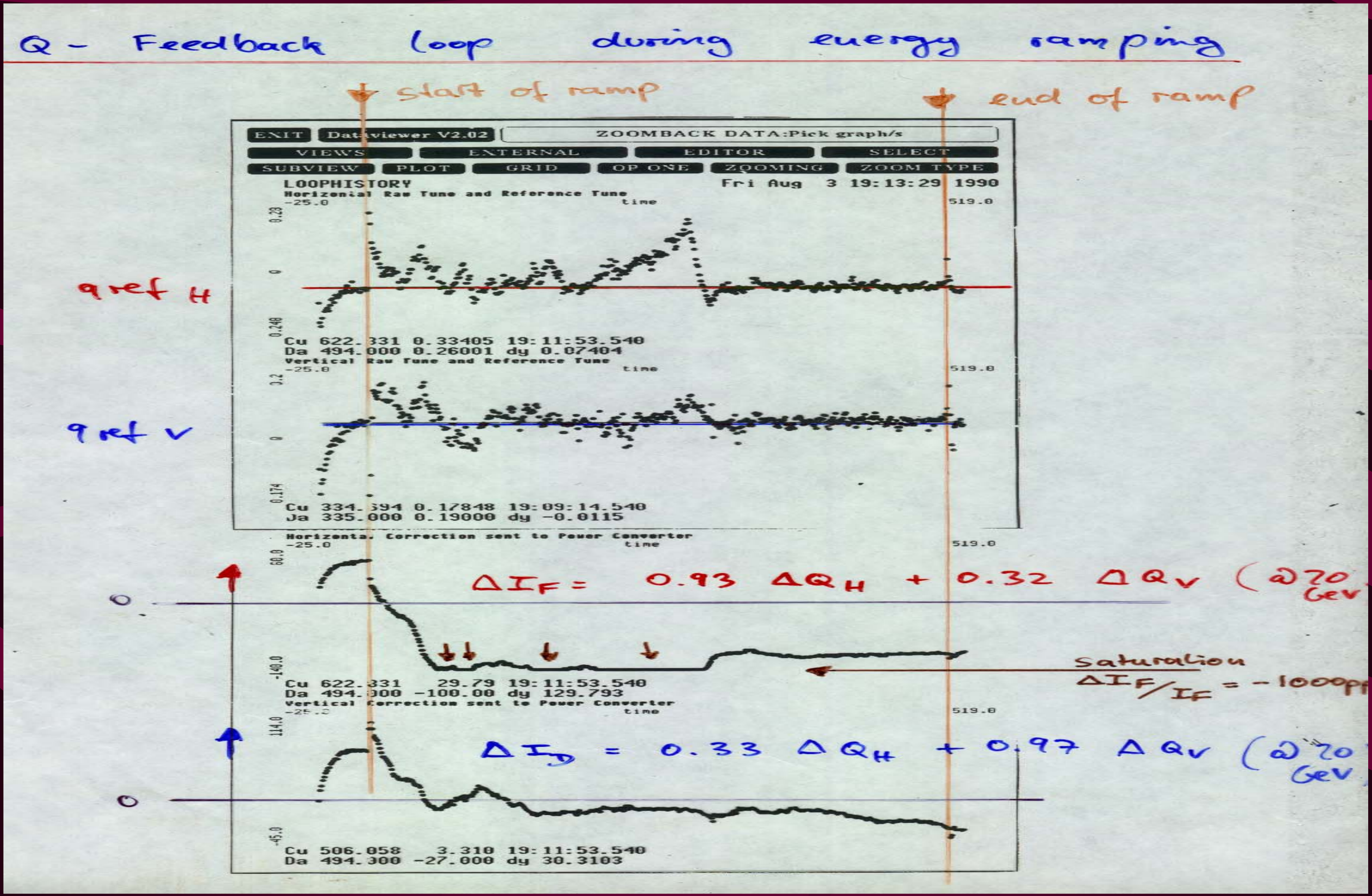
Measuring Q'' and Q'''



Online measurement and feedback of Q & Q'

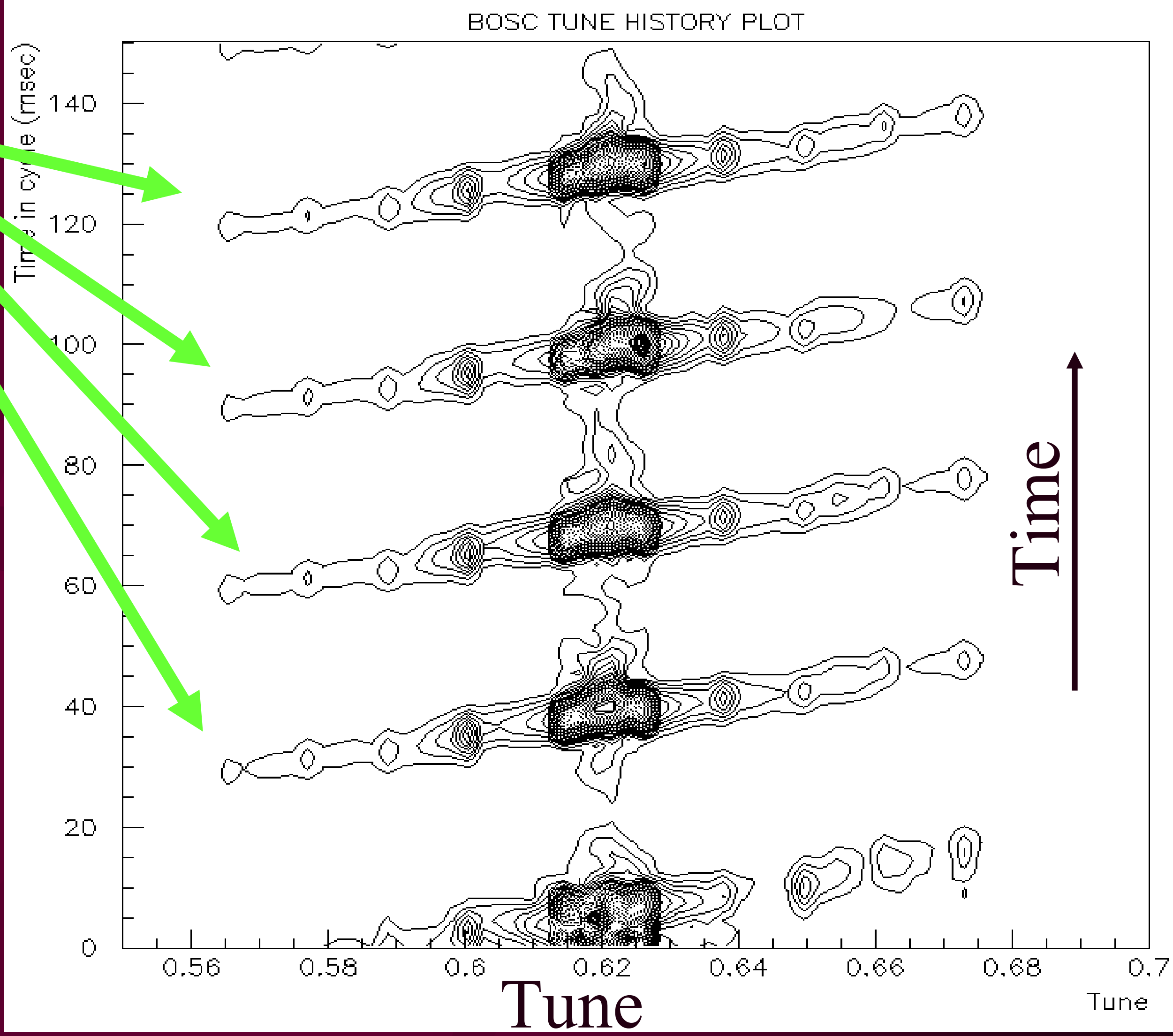
- The aim for the LHC:
  - → Permanent Q & Q' measurements with hard constraints on:
    - emittance preservation
    - insensitivity to machine-parameter changes (orbit, coupling…)
  - → Online feedback to power supplies of quadrupole and sextupole magnets (bandwidth < 10 Hz)
- What has been done so far:
  - → Early example from LEP → next slide
  - → Present situation at DESY → following movie

Early example from LEP

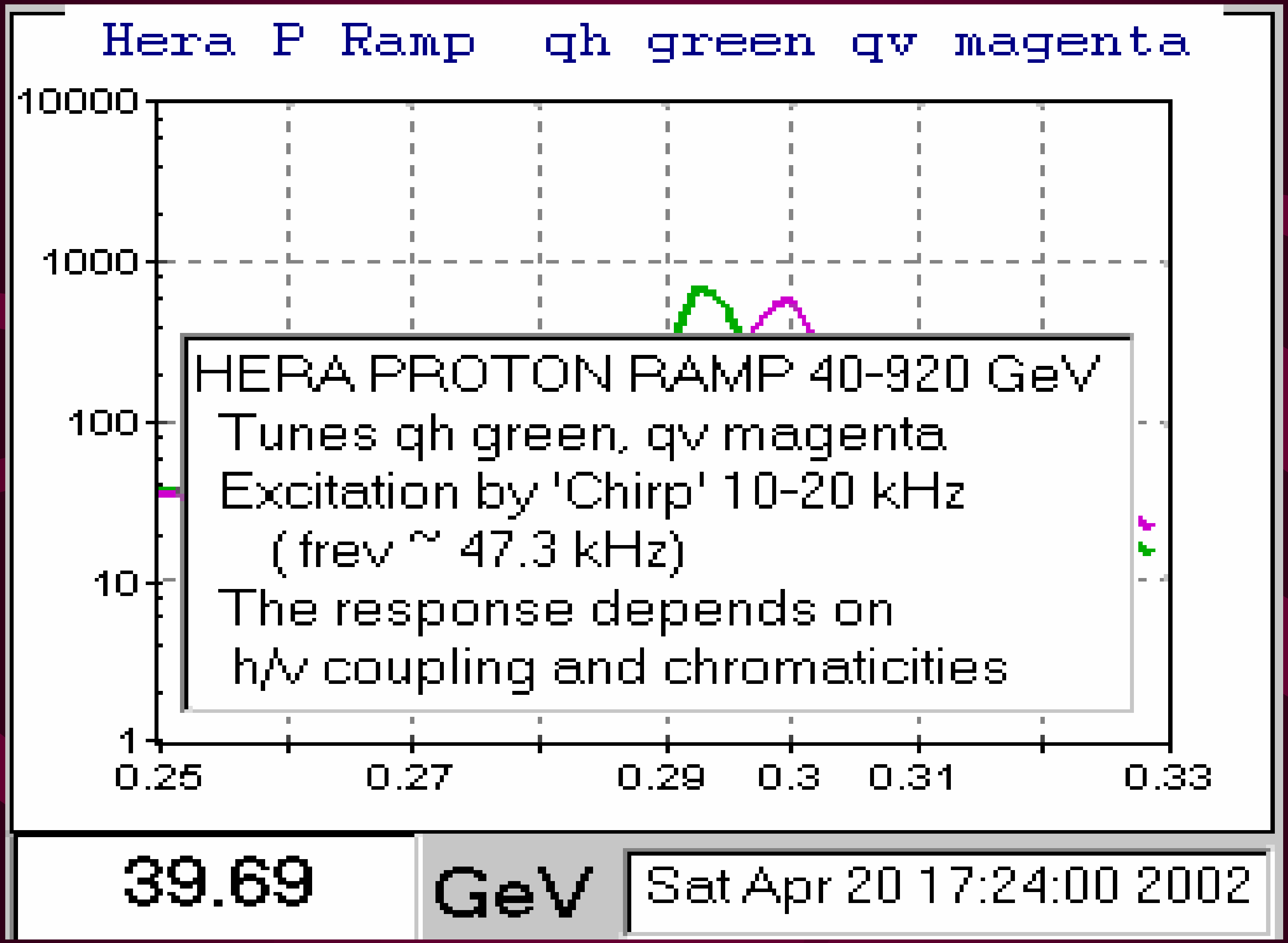


HERA-p solution:

- "chirp" tune measurements
- Online display
- Operator "joystick" feedback to quadrupole and sextupole power-supplies



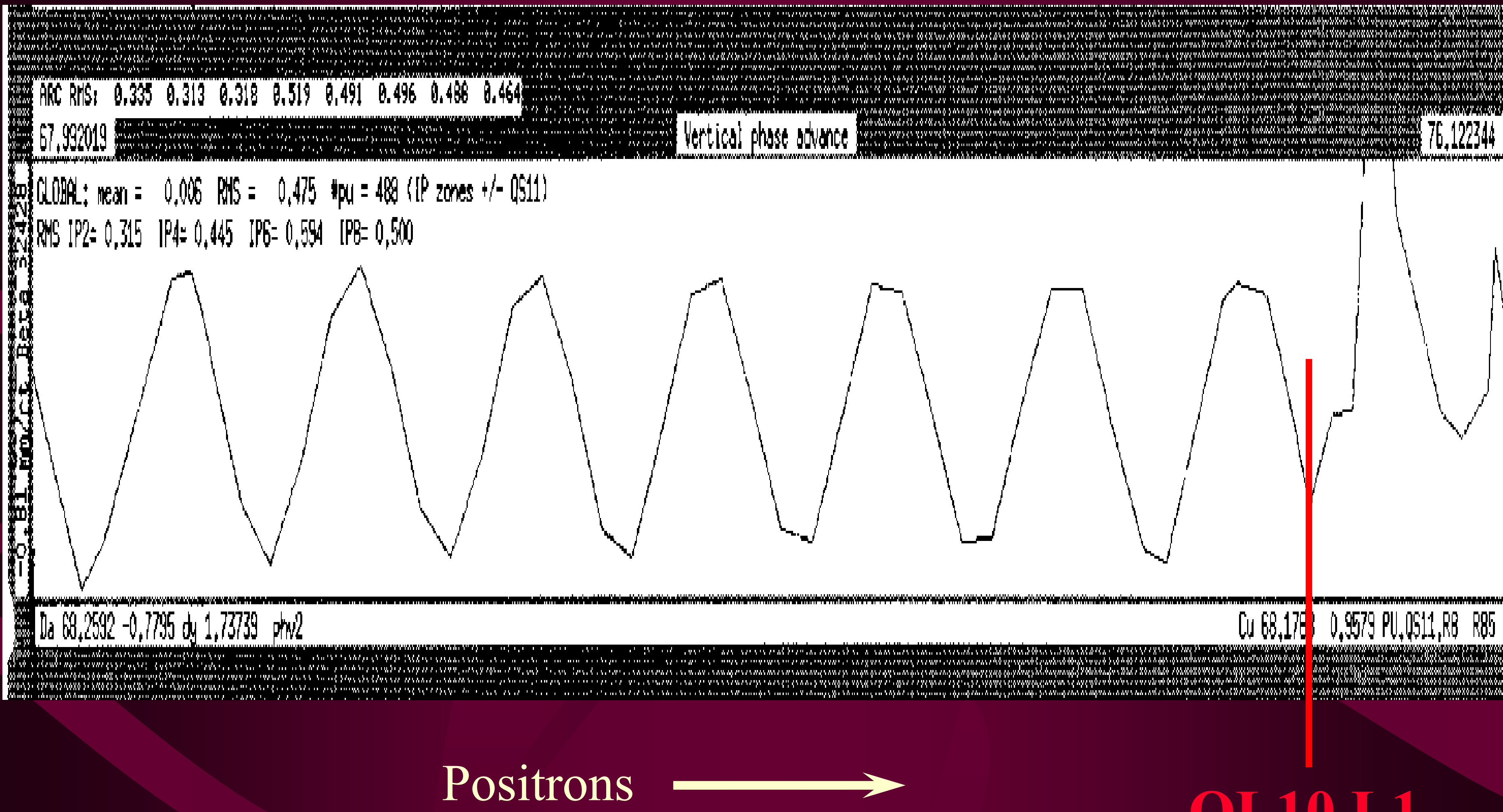
Online Q-display at HERA-p with "BLL" as control (brain locked loop)



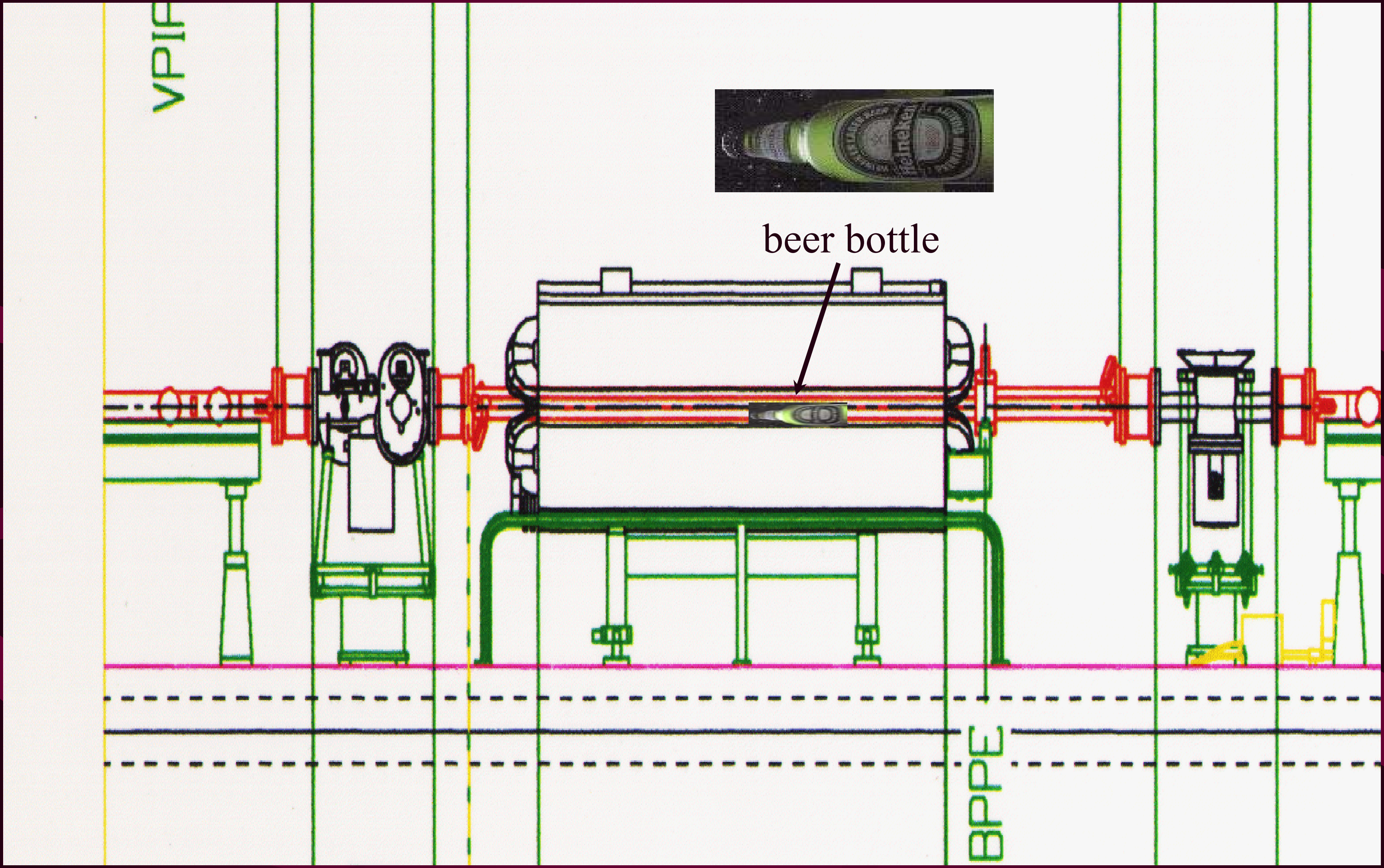
Outline for Today

- Optimisation of Machine Performance ("the good days")
  - → Orbit measurement & correction
  - → Luminosity: basics, profile and β - measurements
- Diagnostics of transverse beam motion
  - → Tune & chromaticity measurements
  - → Dynamic effects: tune and chromaticity control
  - → On-line β measurements
- Trying to make the machine work ("the bad days")
  - → The beam does not circulate!
  - → The beam gets lost, when changing the beta*

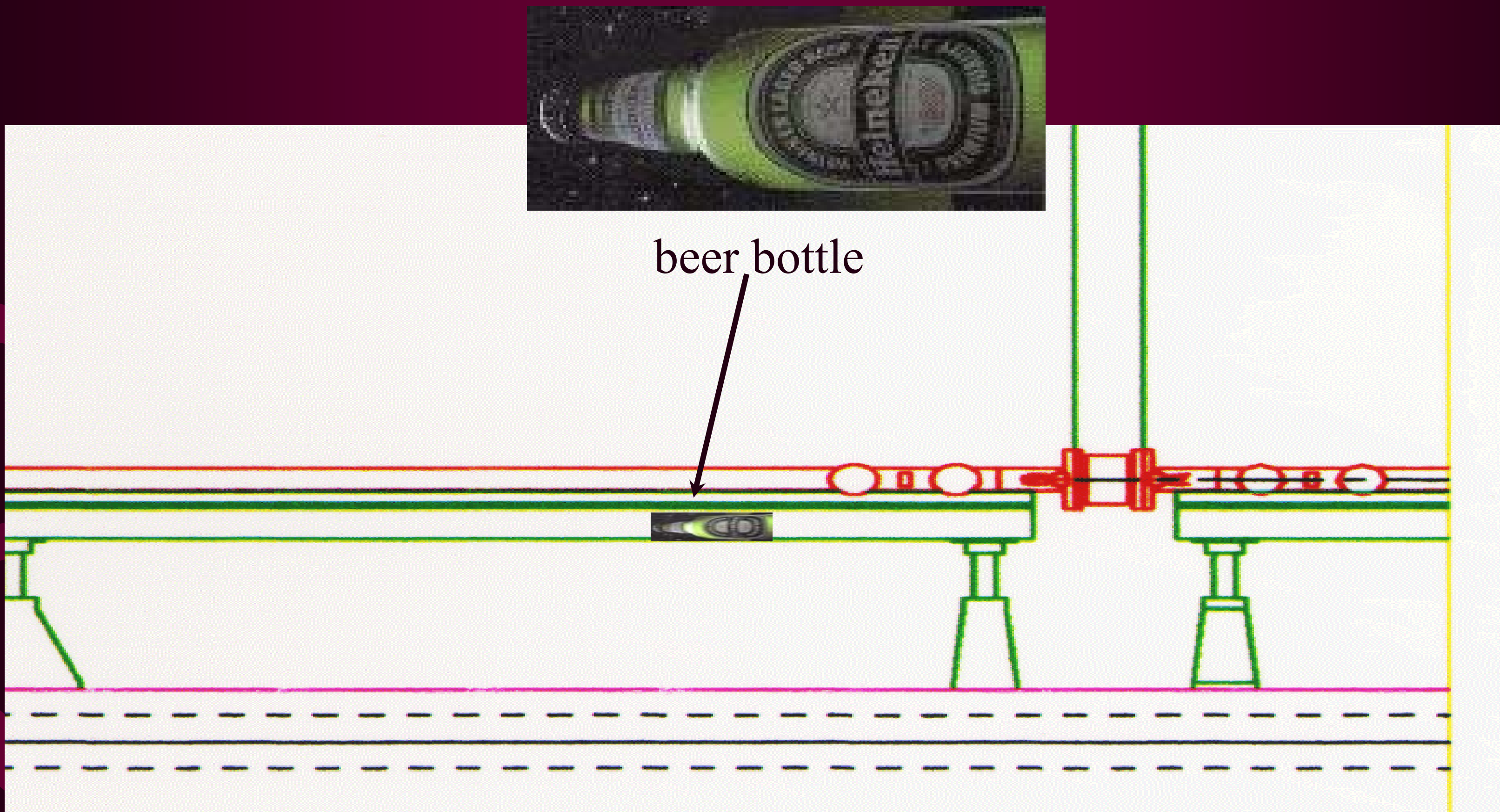
LEP – No Circulating Beam



Zoom on QL1



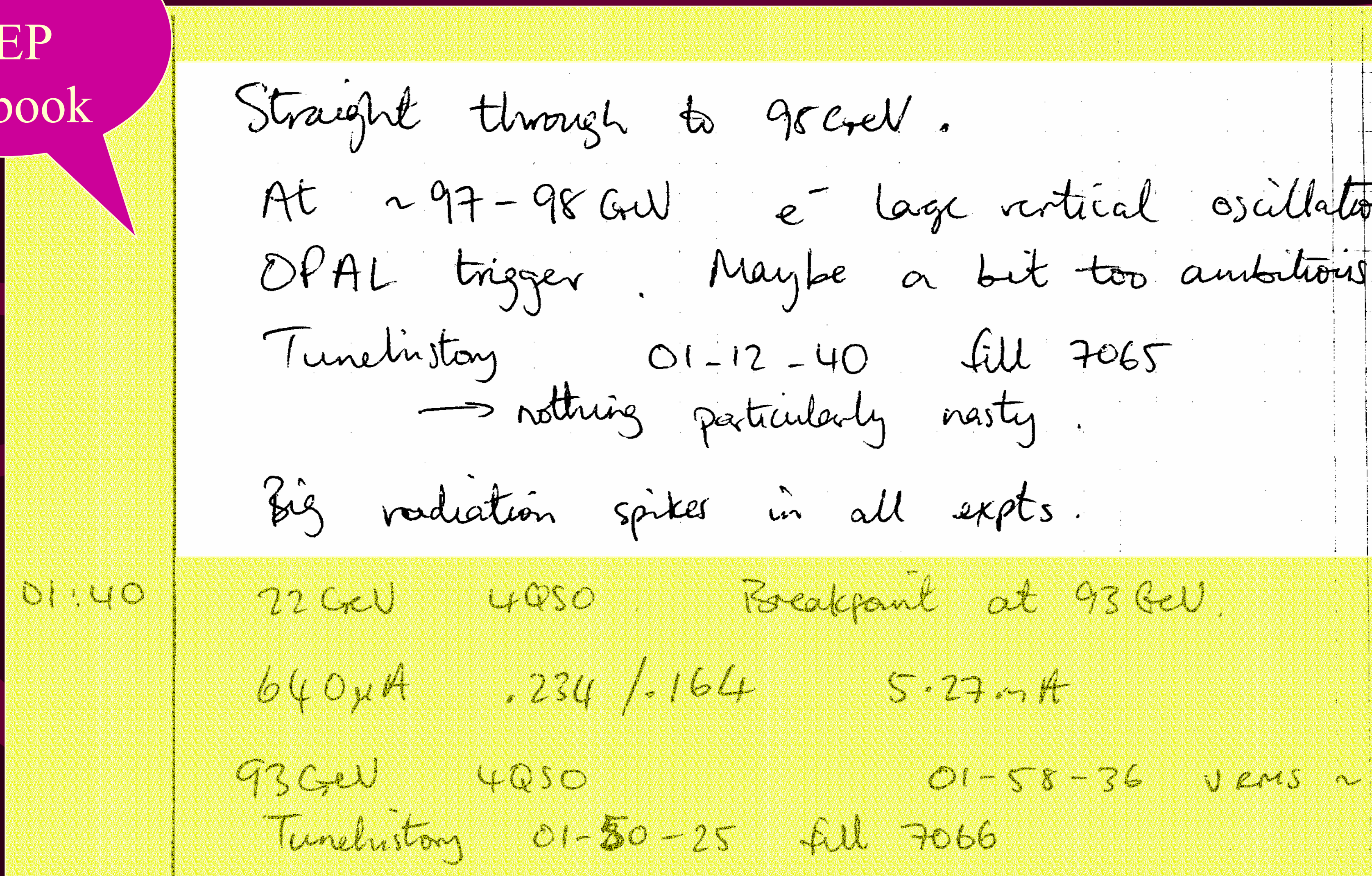
10 metres to the right



Unsociable sabotage: both bottles were empty!!

LEP Beams Lost During Beta Squeeze

From LEP logbook



Straight through to 95 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.

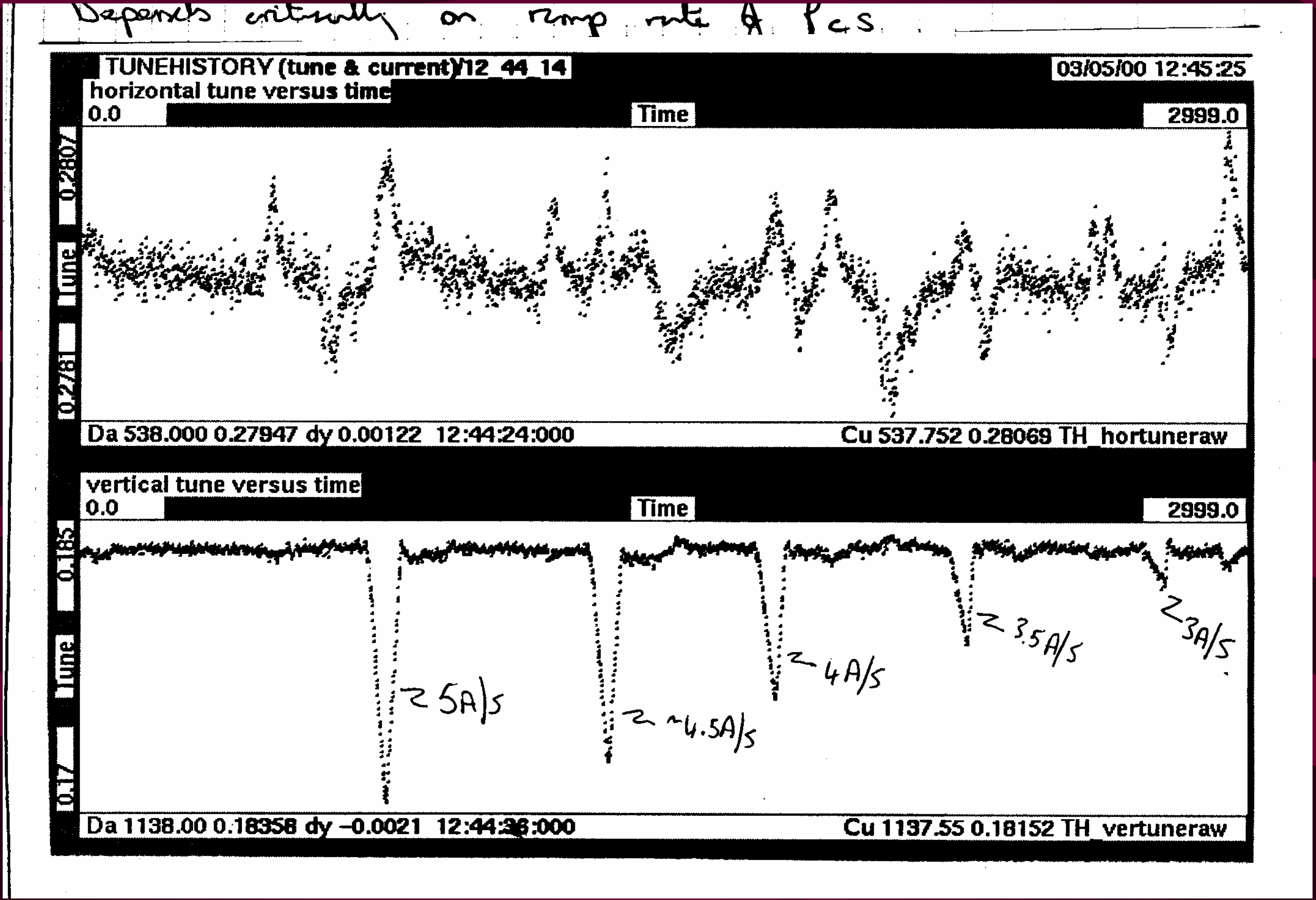
Big radiation spikes in all expts.

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

640μA .234/.164 5.27mA

93 GeV 4QSO 01-58-36 v RMS ~
Tunehistory 01-50-25 fill 7066

…and the corresponding diagnostics



In these two lectures we have seen how to build and use beam instrumentation to run and optimise accelerators

Hopefully it has given you an insight into the field of accelerator instrumentation and the diverse nature of the measurements and technologies involved

http://sl-div.web.cern.ch/sl-div-bi/CAS%20/lecture/