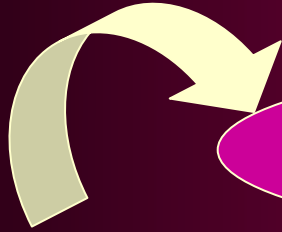


# Beam Instrumentation

&

Beam Diagnostics



Today

CAS 2003

Rhodri Jones [Hermann Schmickler]  
(CERN)



# Outline for Today

## ★ Optimisation of Machine Performance ("the good days")

- Orbit measurement & correction
- Luminosity: basics, profile and  $\beta$  - measurements

## ★ Diagnostics of transverse beam motion

- Tune & chromaticity measurements
- Dynamic effects: tune and chromaticity control
- On-line  $\beta$  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

Thu Oct 18 13:20:30 2001

Start Tasks Operation SPS Top10 EDUMP Reset P2 Reset Active Tasks Exit

SPS\_orbit

QUIT	SPS XORBIT V9.01/2K+1		Done	Info
Acquire	Reference Orbit	Reference Catalog	Send Correction	
MON & COD	no reference set no date			
Acquisition Time	Load Orbit	Difference	Sum	Skeleton
Closed Orbit	dp/p - offset shown	Control Plane Hor Vert		MD Specials
Settings & Specials	Reject at	3.0 sigma	MICADO	Other Tools

Loading correct TWISS file...  
Reading Twiss ft\_inj\_v2001...  
Initializing Twiss for 724 elements  
724 elements copied to Twiss

CLOSED ORBIT : 18/10/2001 13:19:12  
SC = 946 PROTON [# 59855]  
MOMENTUM - 14.00 GeV  
TWISS - ft\_inj\_v2001  
GAIN/TIME = 0 / 1000 ms  
AVERAGE = 1  
DP/P - 0.16 permill

Data stored in /usr/opt/orbit/hpslx

SPS\_Selection

File Supercycle Help

Running SC 946  
Proton 1

Proton 1  
0 - 9420ms (9420ms)

Ready.

Xdataviewer

QUIT CERN/CL Xdataviewer 0.4 ZOOMIN:Pick first point Kick

Views Subview External Editor Load/Save Help

Plot Grid OFF Zeroline OFF OP ONC Zoom In

Monitor Plot  
CO TIME = 1000 ms QH = 26.62 QV = 26.58 Energy = 14.00  
0.0 Monitor horizontal 112.0

GLOBAL: mean = 0.386 RMS = 0.936 #pu = 112

Da 63.0000 0.41000 dy 6.66746 BPH.41209 Cu 63.3173 7.07746 monx

CO TIME = 1000 ms QH = 26.62 QV = 26.58 Energy = 14.00  
0.0 Monitor vertical 112.0

GLOBAL: mean = -0.006 RMS = 0.520 #pu = 113

Vertical

Horizontal



# Orbit Correction (Operator Panel)

Thu Oct 18 13:24:30 2001

start Tasks    Operation    SPS Top10    EDUMP Reset    P2 Reset    Active Tasks    Exit

SPS\_orbit

QUIT	SPS XORBIT V9.01/2K+1	Done	Info
Acquire	Reference Orbit	Reference Catalog	Send Correction
MON & COD	no reference set no date		Cancel Correction
Acquisition Time	Load Orbit	Difference	Sum
Closed Orbit	dp/p-offset shown	Control Plane Hor    Vert	
Settings & Specials	Reject at 3.0 sigma	MICADO	Other Tools

SPS\_Selection

File    Supercycle    Help

Running SC 946  
Proton 1

Proton 1  
0 - 9420ms (9420ms)

Ready.

4	MDV. 42707	0.0069
	MDV. 22307	0.0188
	MDVA. 21932	0.0158
	MDVA. 21703	0.0040
5	MDV. 42707	0.0071
	MDV. 22307	0.0205
	MDVA. 21932	0.0169
	MDVA. 21703	0.0052
	MDV. 42507	-0.0035
Number of iterations required (max # iterations = 5)		

Xdataviewer

CERN/SL Xdataviewer 6.4    ZOOMIN:Pick first point    Kick    Clean    Reverse

Views    Subview    External    Editor    Load/Save    Help    Select

Plot    Grid OFF    Zorolino OFF    OP ONE    Zoom In    Box

18/10/01 13:23:45

Predicted Correction Results

0.0    Before Correction    112.0

GLOBAL: mean = -0.006 RMS = 0.520 #pu = 113

Da 56.0000 0.2700 dy -1.3117 BPV.33509    Cu 55.9502 -1.0417 mon

0.0    Difference    112.0

GLOBAL: mean = 0.023 RMS = 0.328 #pu = 113

Da 26.0000 0.40381 dy 5.63786 BPV.21509    Cu 25.5858 6.04167 diff

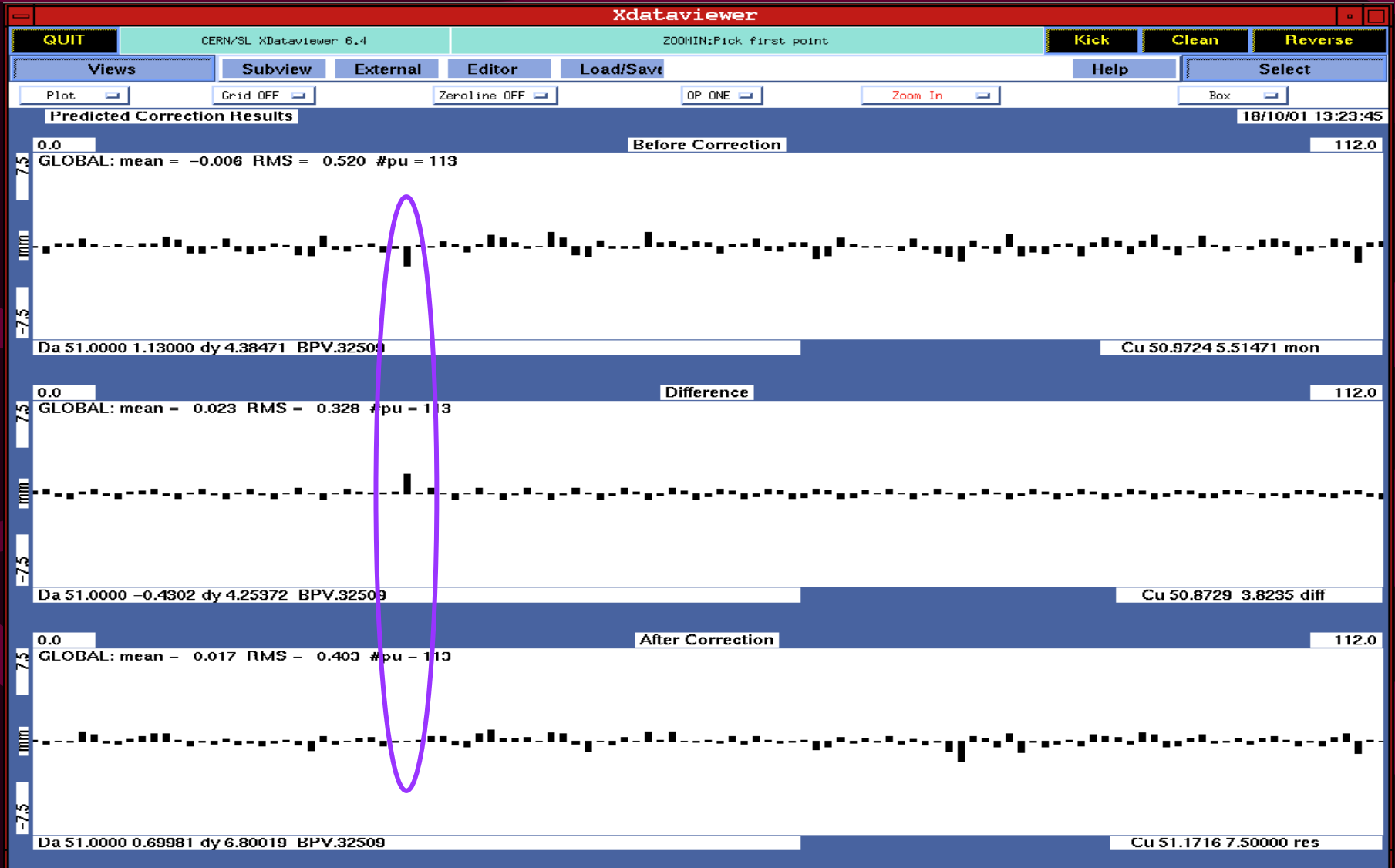
0.0    After Correction    112.0

GLOBAL: mean = 0.017 RMS = 0.403 #pu = 113

Da 4.00000 0.73520 dy -0.7352 BPV.10909    Cu 3.88267 0.00000 res



# Orbit Correction (Detail)





# Luminosity & Beam-Beam Tune Shift

- Luminosity
- Normalized emittance
- Beam-beam tune shift

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

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

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

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

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



# 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  $\beta$  measurements
  - when:
    - 1) at the moment of injection
    - 2) with circulating beams



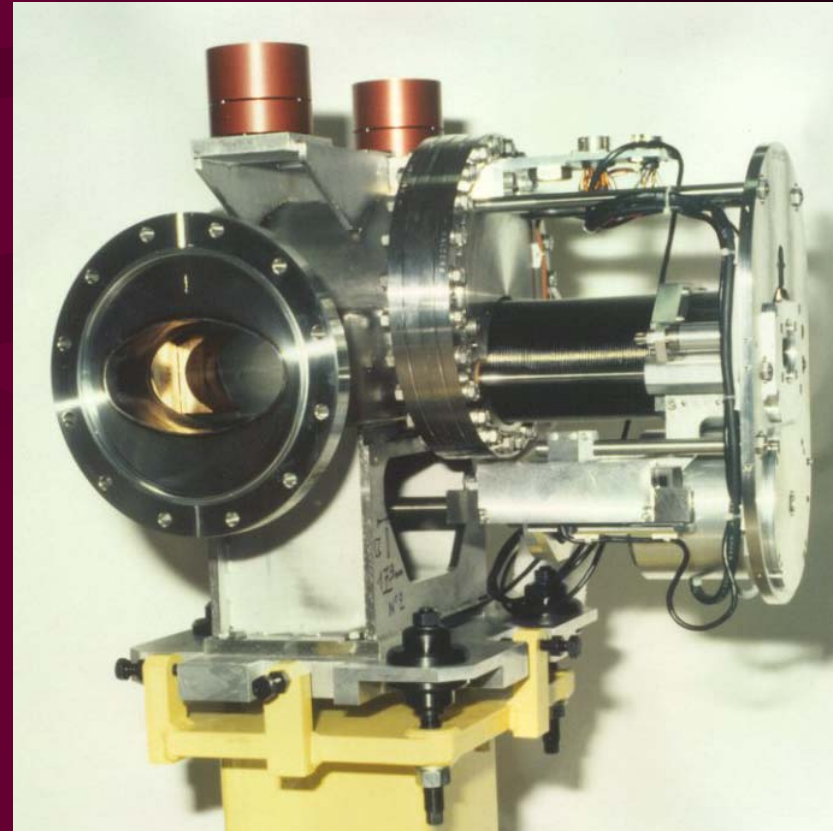
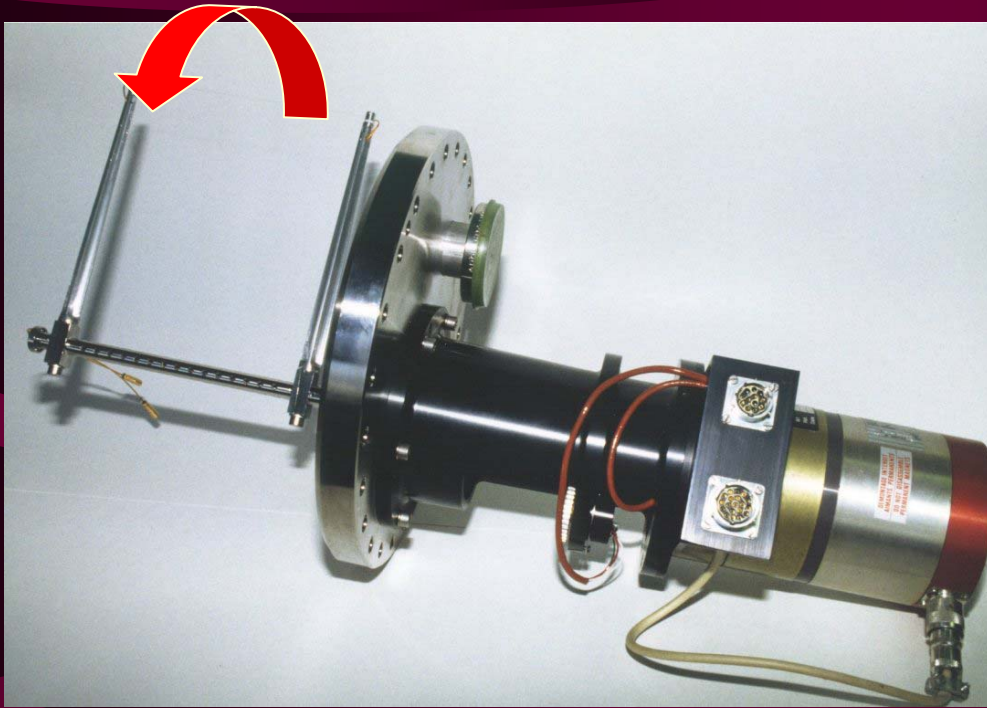
# Measuring Beam Size

- **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...



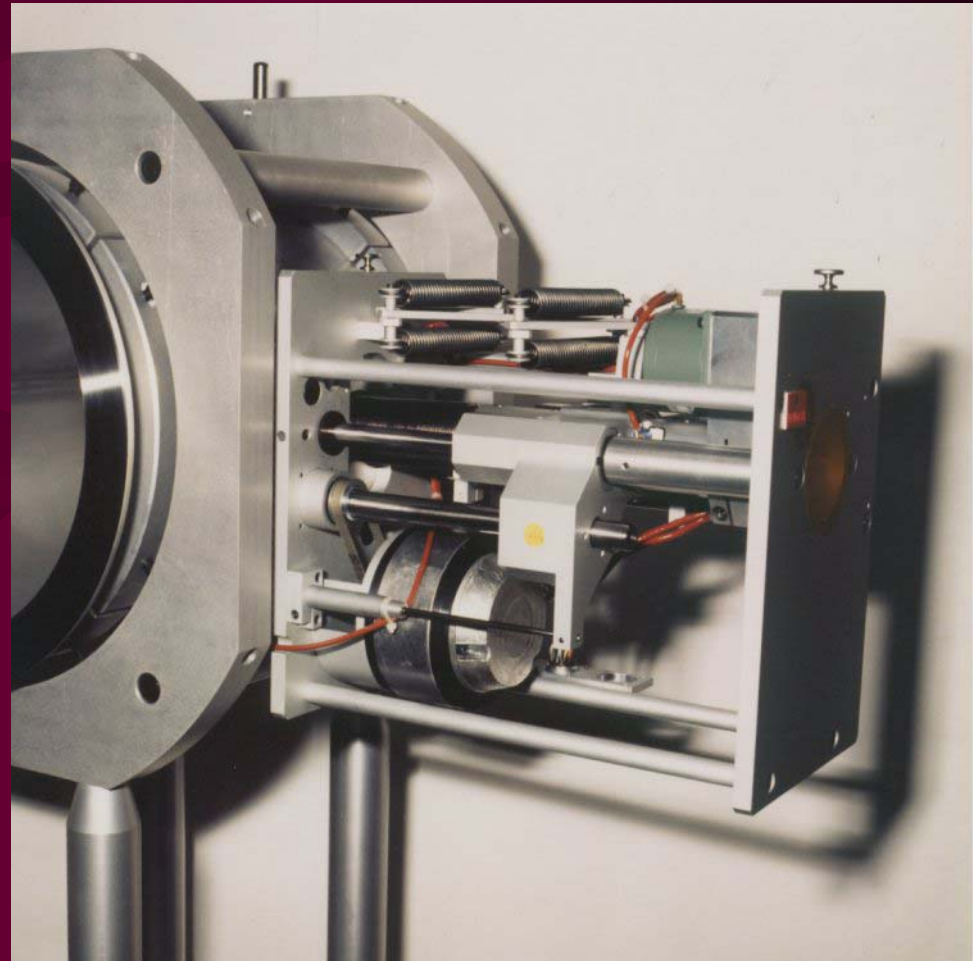
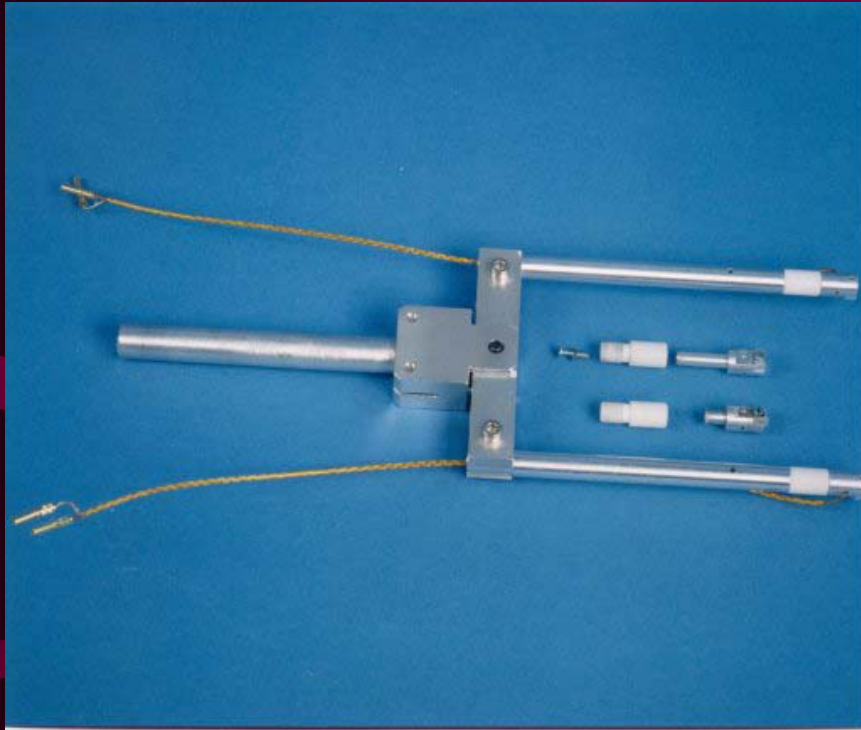


# Rotative Wire Scanner





# Linear Wire Scanner





# Measurement Results

Prof bwsh51995.rot EV:0x211b0101 SC:1240012 HV:1490 Mode:SLOW\_1ga pot.

18/10/01 15:42:09

IN profile

-29546.67

Position(um)

19160.0

3381.0612  
Amp  
-155.2653  
Sctime 96 ms  
Mean -6.228 mm  
Sigma 6.789 mm  
Norm 382060  
Ampl 3272  
Offst 40  
Acq.length 898

Da -1.53e+04 1471.00 dy 567.701

Cu -1.53e+04 2038.70 pl\_pr\_IN

OUT profile

-6687.273

Position(um)

39800.0

3410.1224  
Amp  
-155.0204  
Sctime 1096 ms  
Mean 16.162 mm  
Sigma 6.678 mm  
Norm 384623  
Ampl 3329  
Offst 40  
Acq.length 888

Da -6.56e+04 0.00 dy 2769.85

Cu 3.24e+04 2769.85 pl\_ft\_OUT

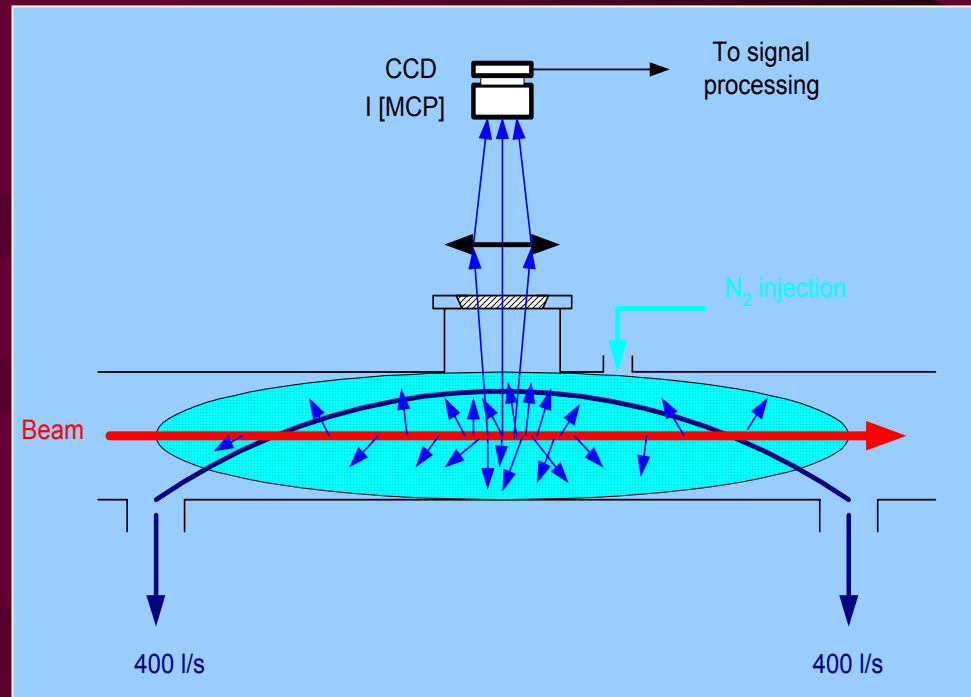
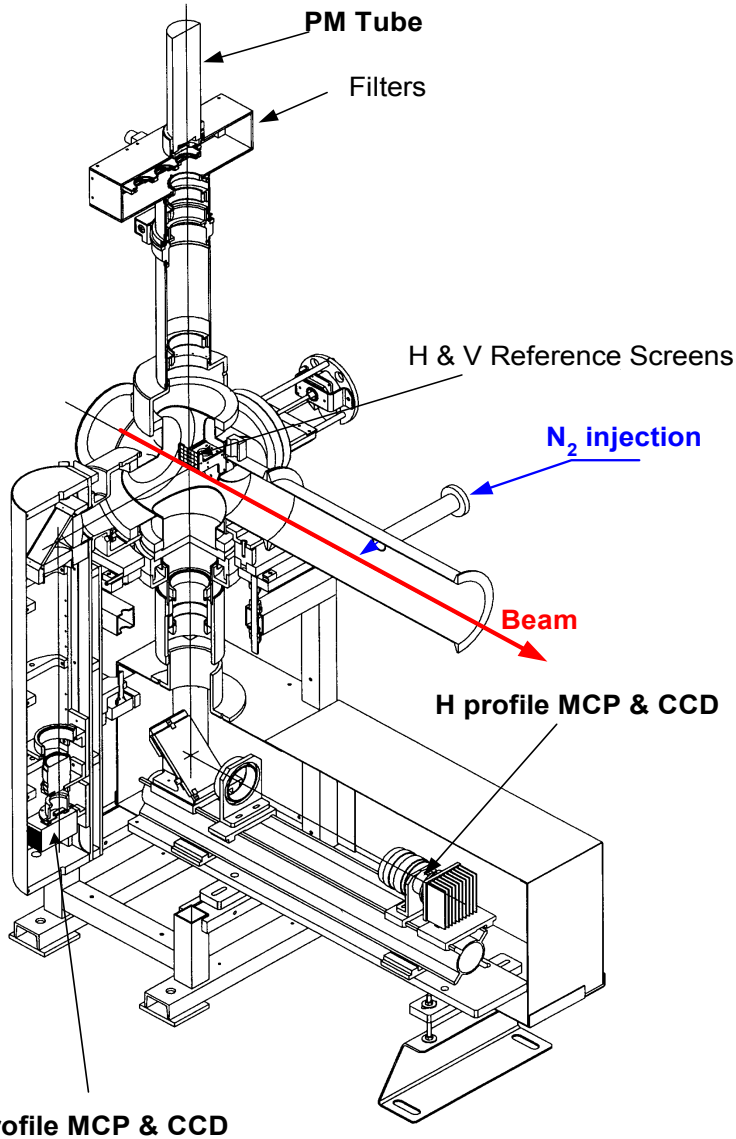


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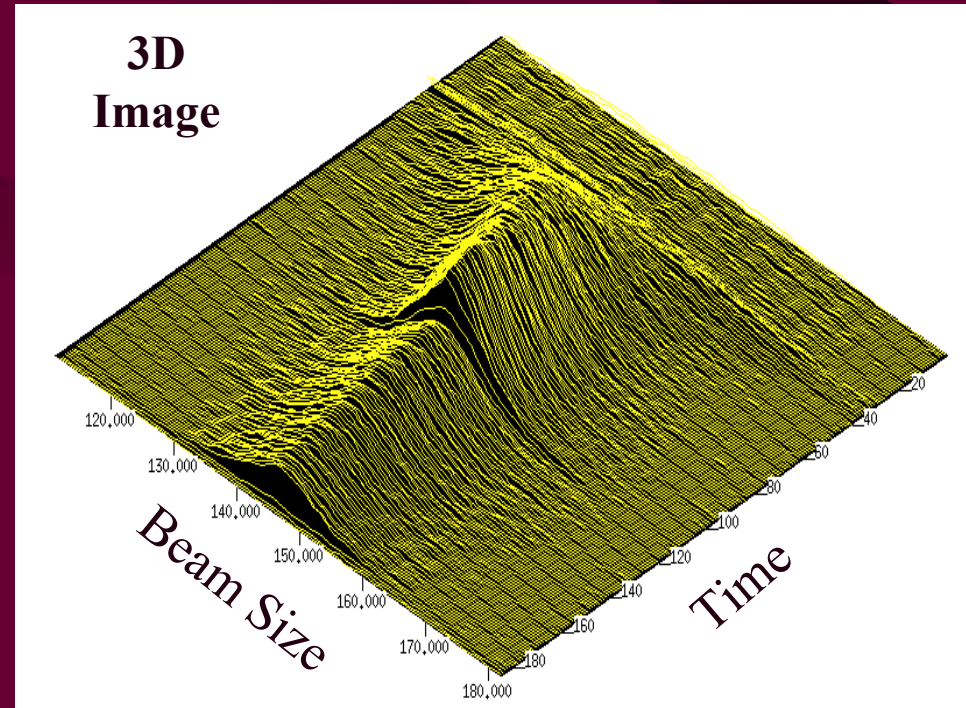
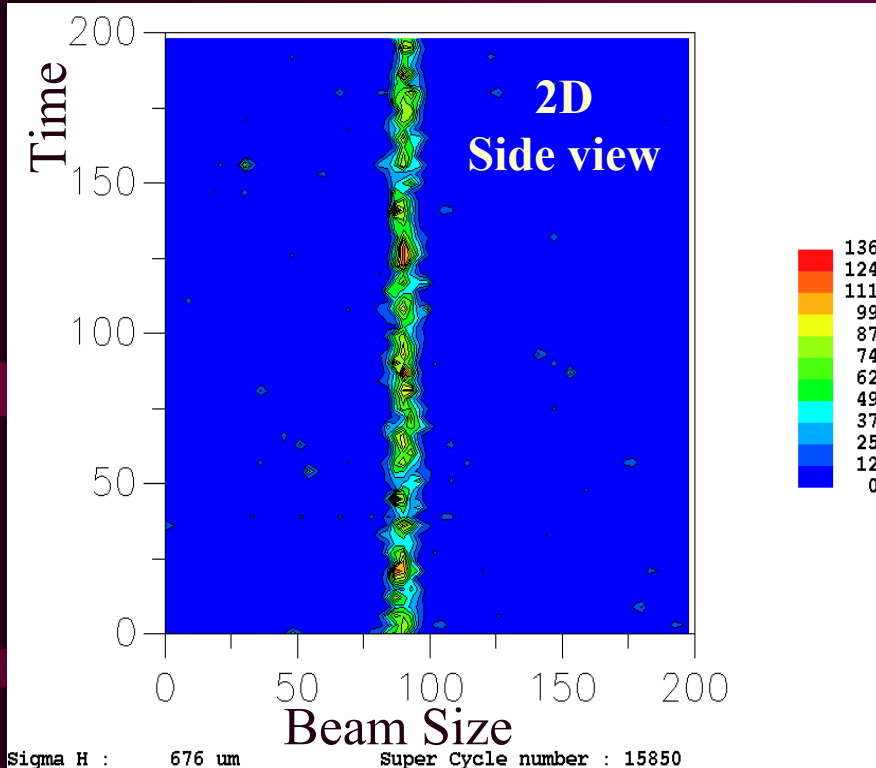


# Luminescence Profile Monitor





# Luminescence Profile Monitor

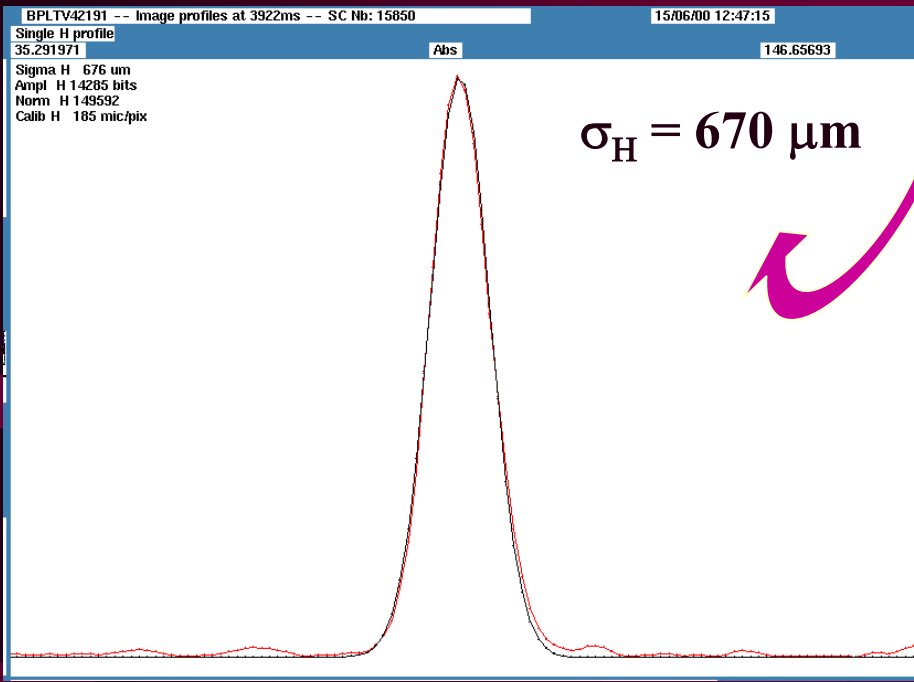


## CERN-SPS Measurements

- Profile Collected every 20ms
- Local Pressure at  $\sim 5 \times 10^{-7}$  Torr



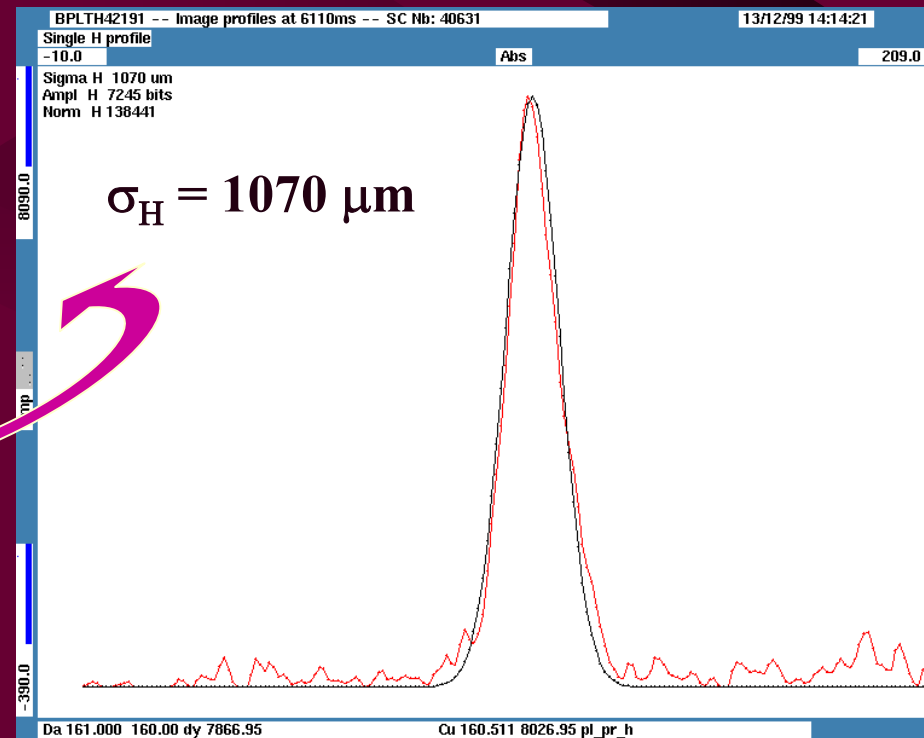
# Luminescence Profile Monitor



**Single shot (840 SPS turns)**

→  $6 \times 10^{-5}$  Pa (  $5 \times 10^{-7}$  Torr )

→  $2 \times 10^{13}$  protons (140 mA) at 450 GeV



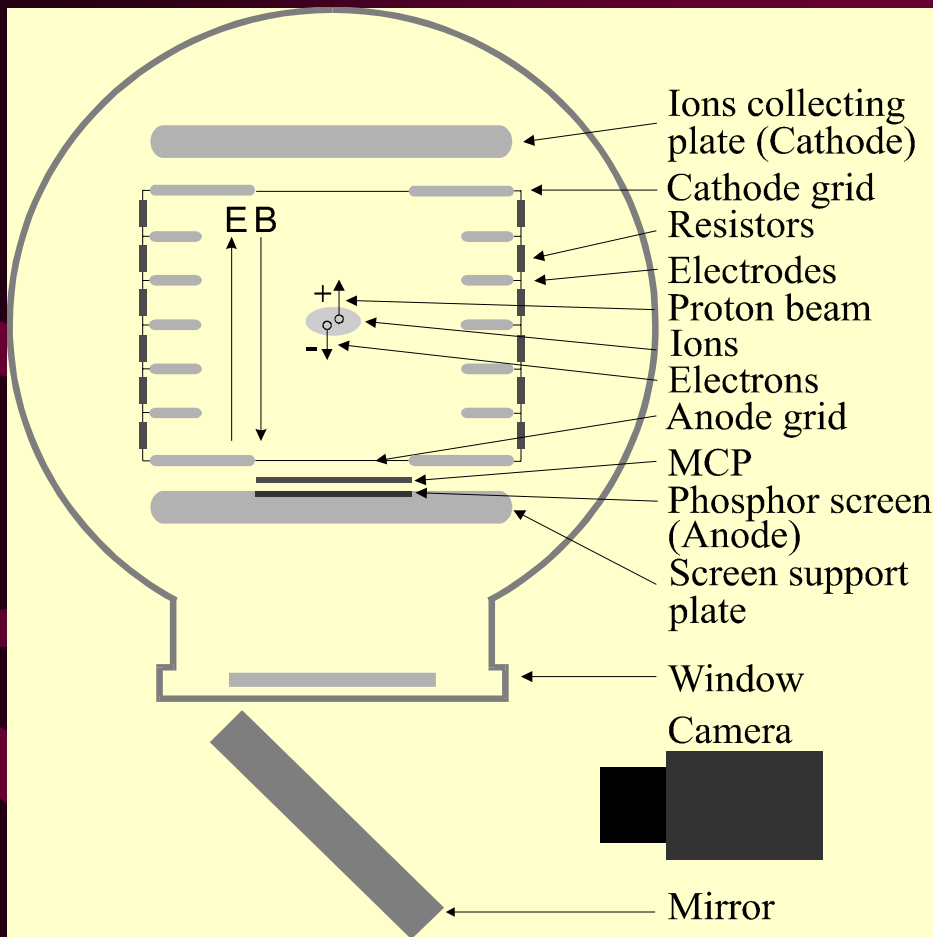
**Single shot (840 SPS turns)**

→  $8 \times 10^{-5}$  Pa (  $6 \times 10^{-7}$  Torr )

→  $9 \times 10^8$  Pb ions (540 mA) at 450 GeV



# (Rest Gas) Ionisation Profile Monitor - IPM



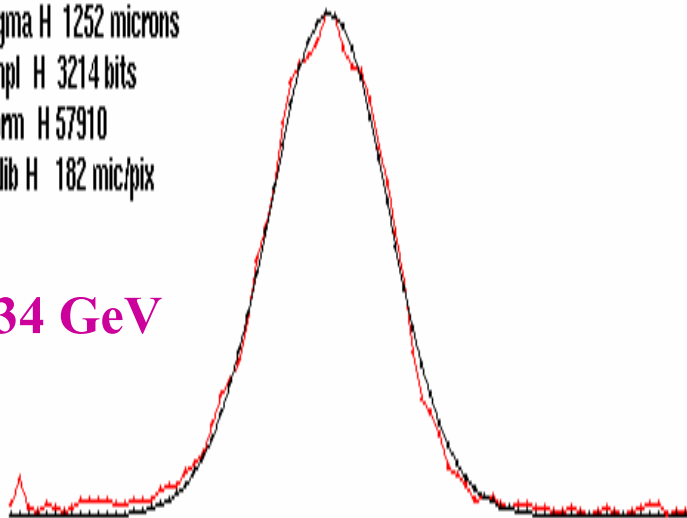




# IPM Beam Profiles during Acceleration

Sigma H 1252 microns  
Ampl H 3214 bits  
Norm H 57910  
Calib H 182 mic/pix

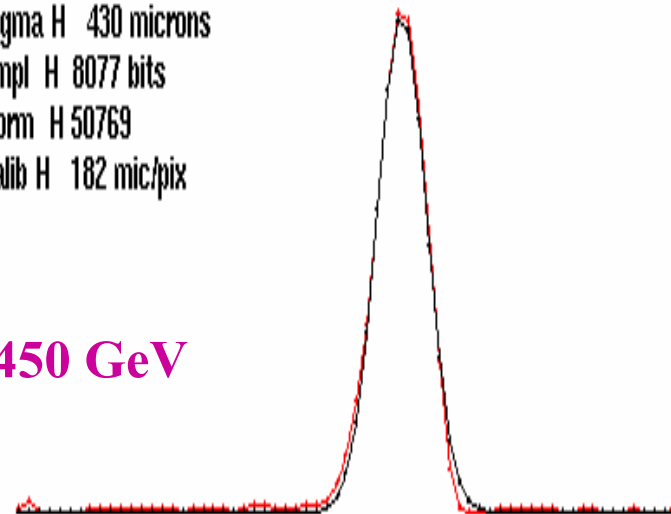
**34 GeV**



CCD camera  
20ms per profile

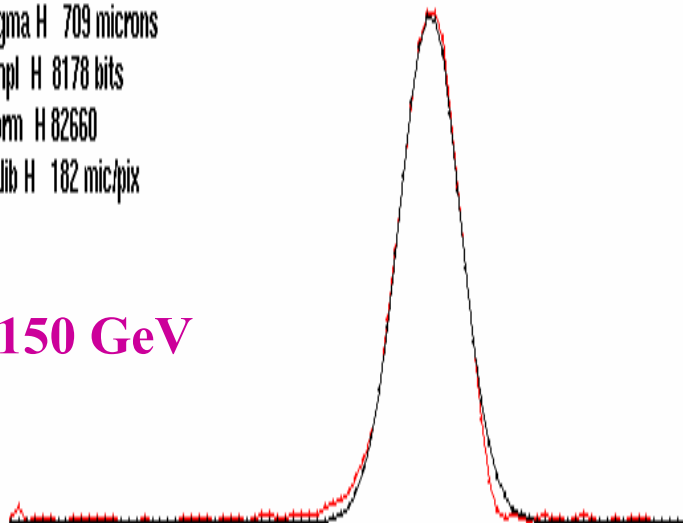
Sigma H 430 microns  
Ampl H 8077 bits  
Norm H 50769  
Calib H 182 mic/pix

**450 GeV**



Sigma H 709 microns  
Ampl H 8178 bits  
Norm H 82660  
Calib H 182 mic/pix

**150 GeV**

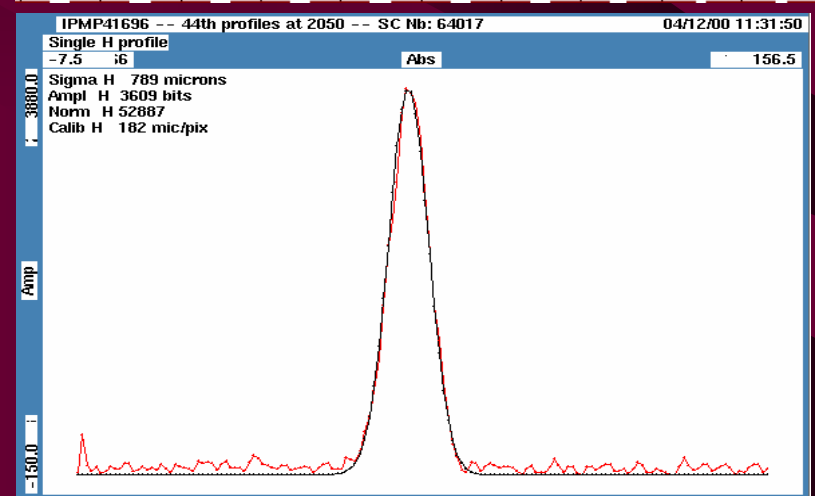
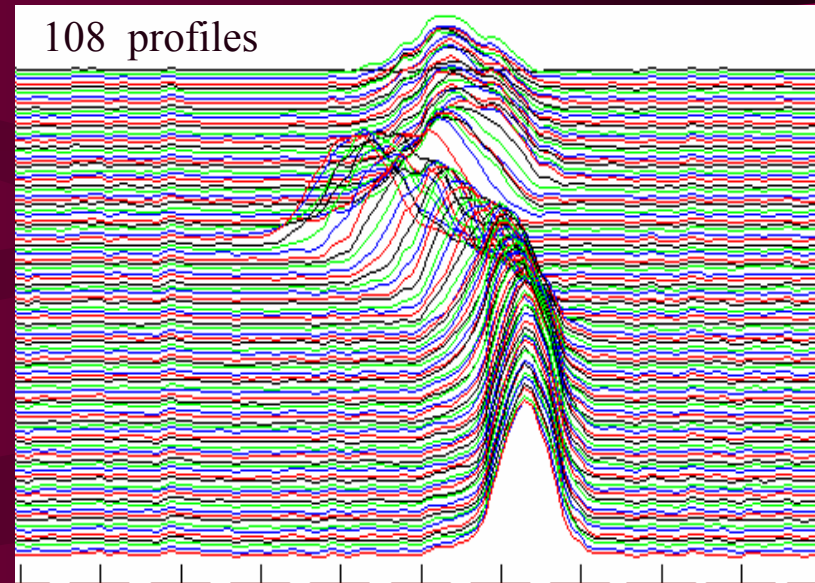
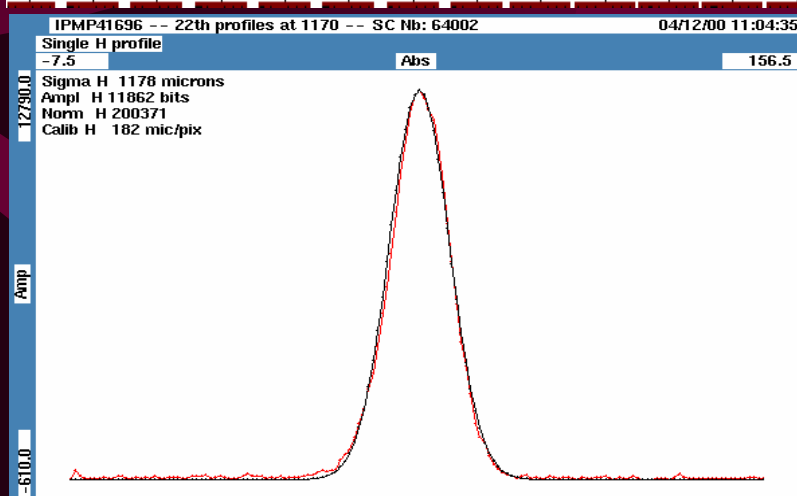
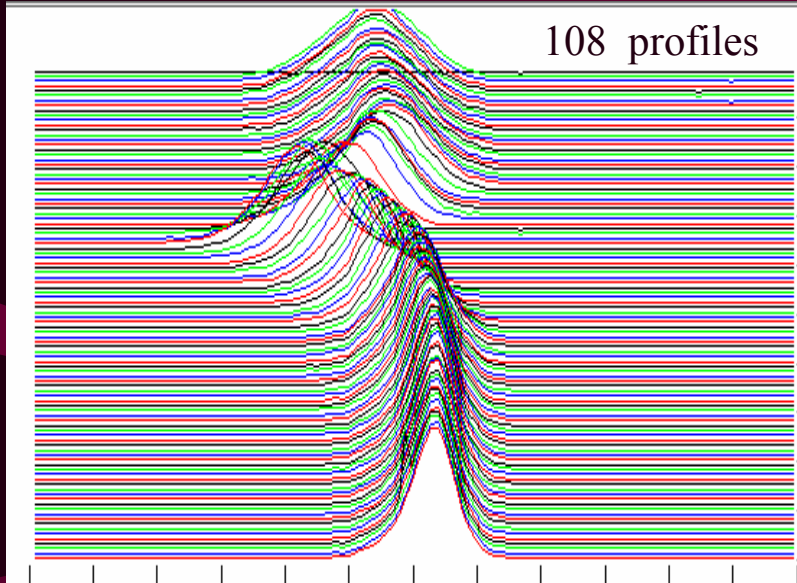




# IPM Single Bunch Measurements ( CCD - 870 SPS turns (20 ms) per profile )

$6 \times 10^{10}$  p/bunch

$2 \times 10^{10}$  p/bunch



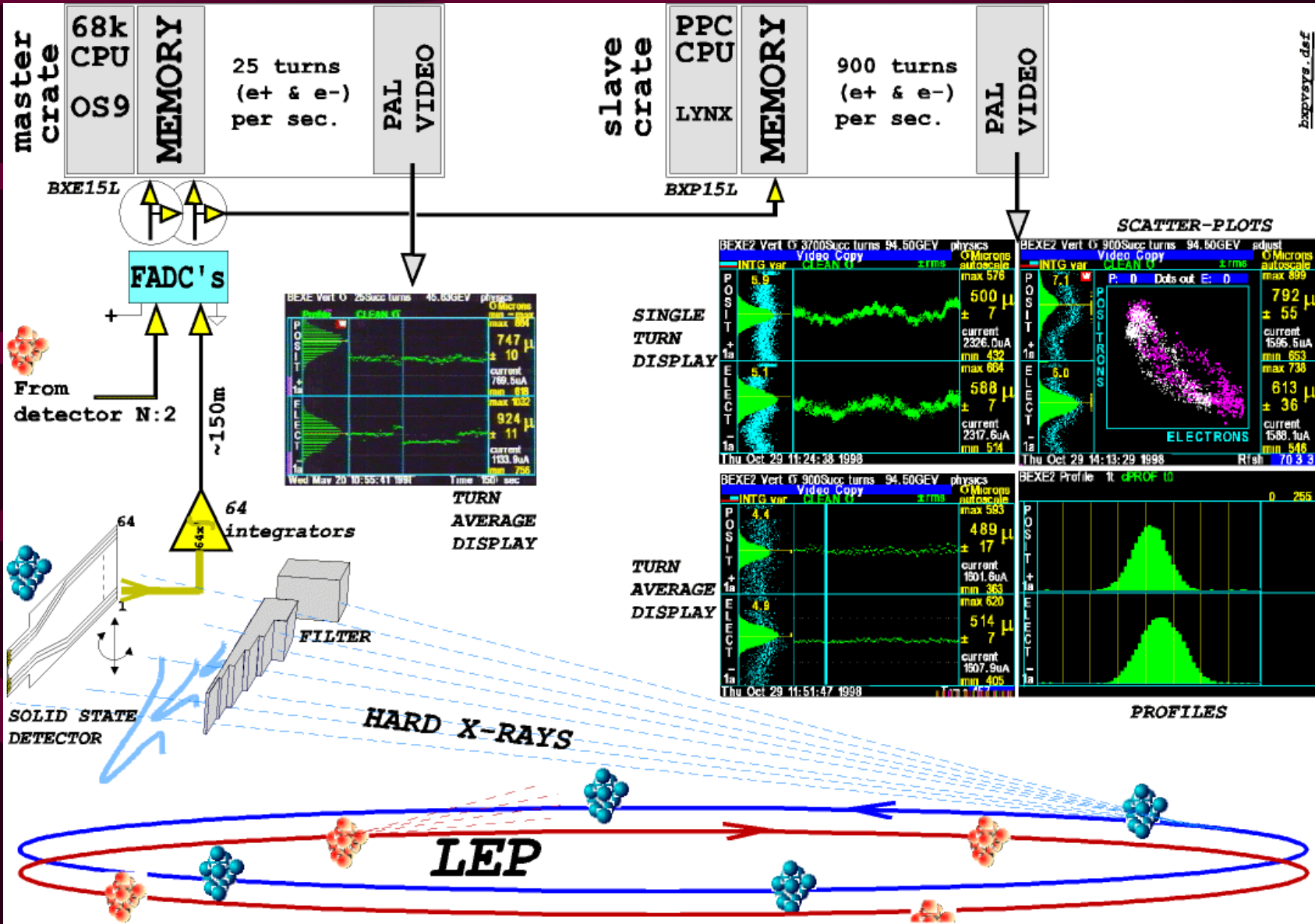


# Measuring Beam Size

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  - Others...

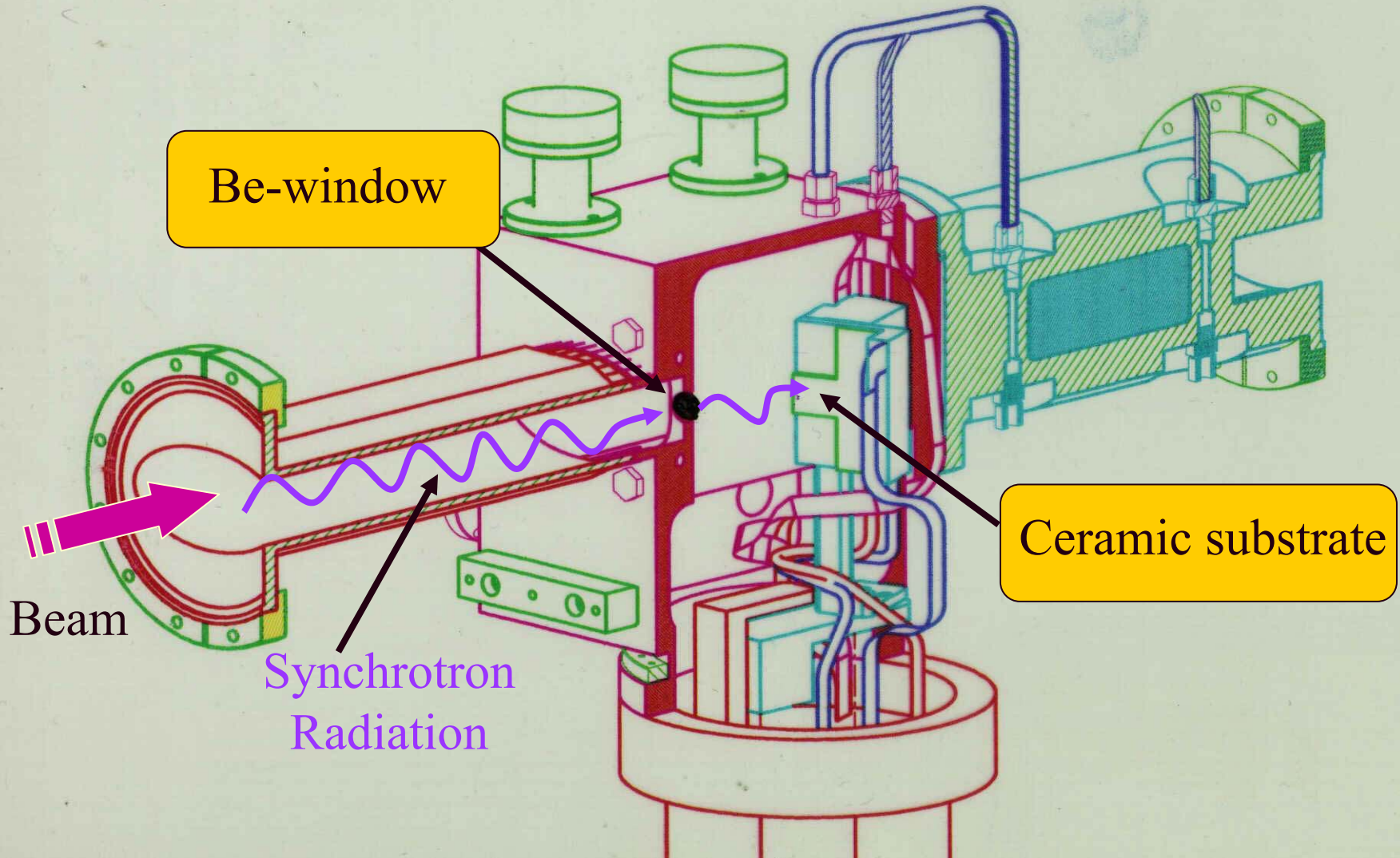


# LEP X-Ray Monitor (BEXE system)



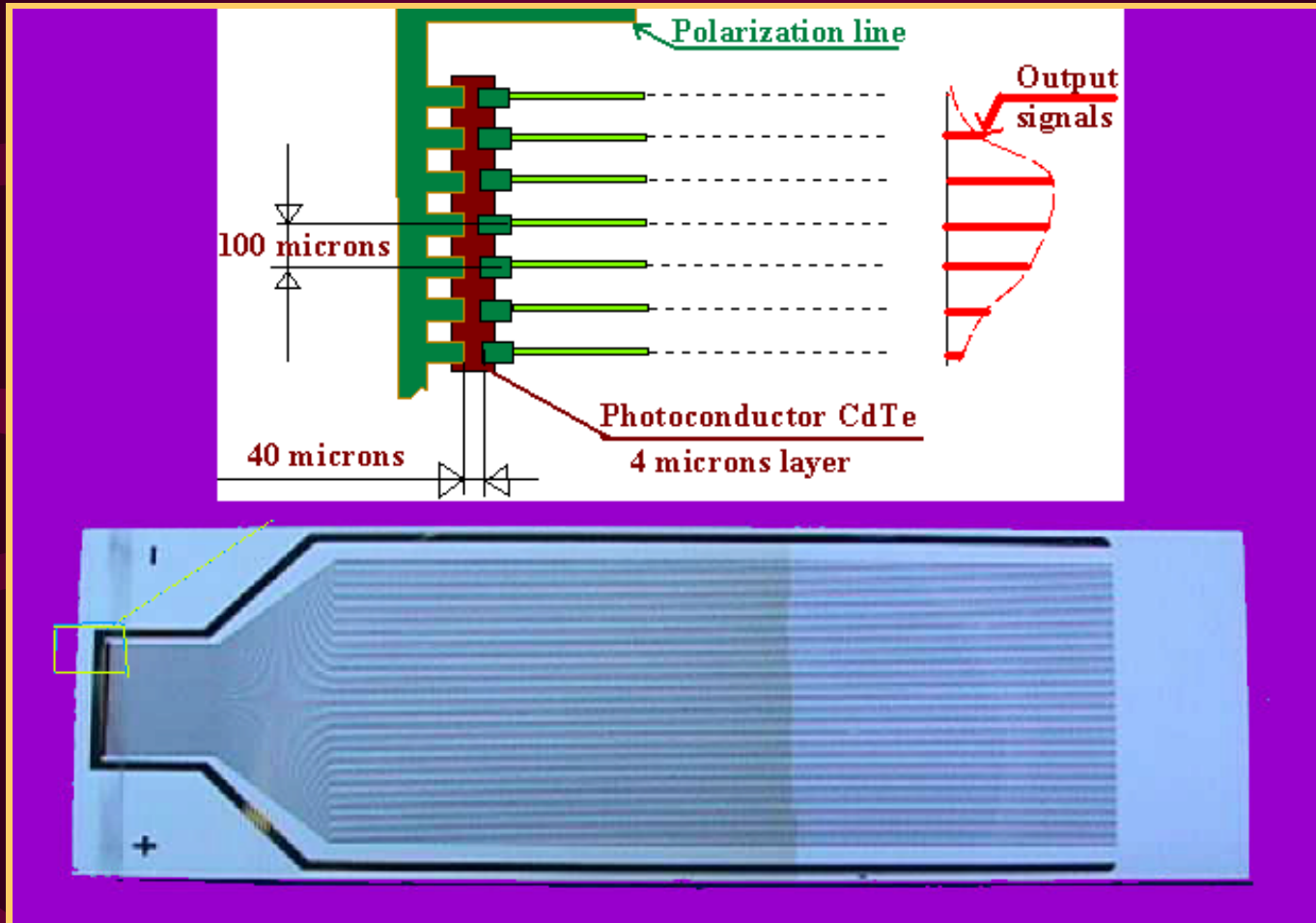


# The BEXE Detector





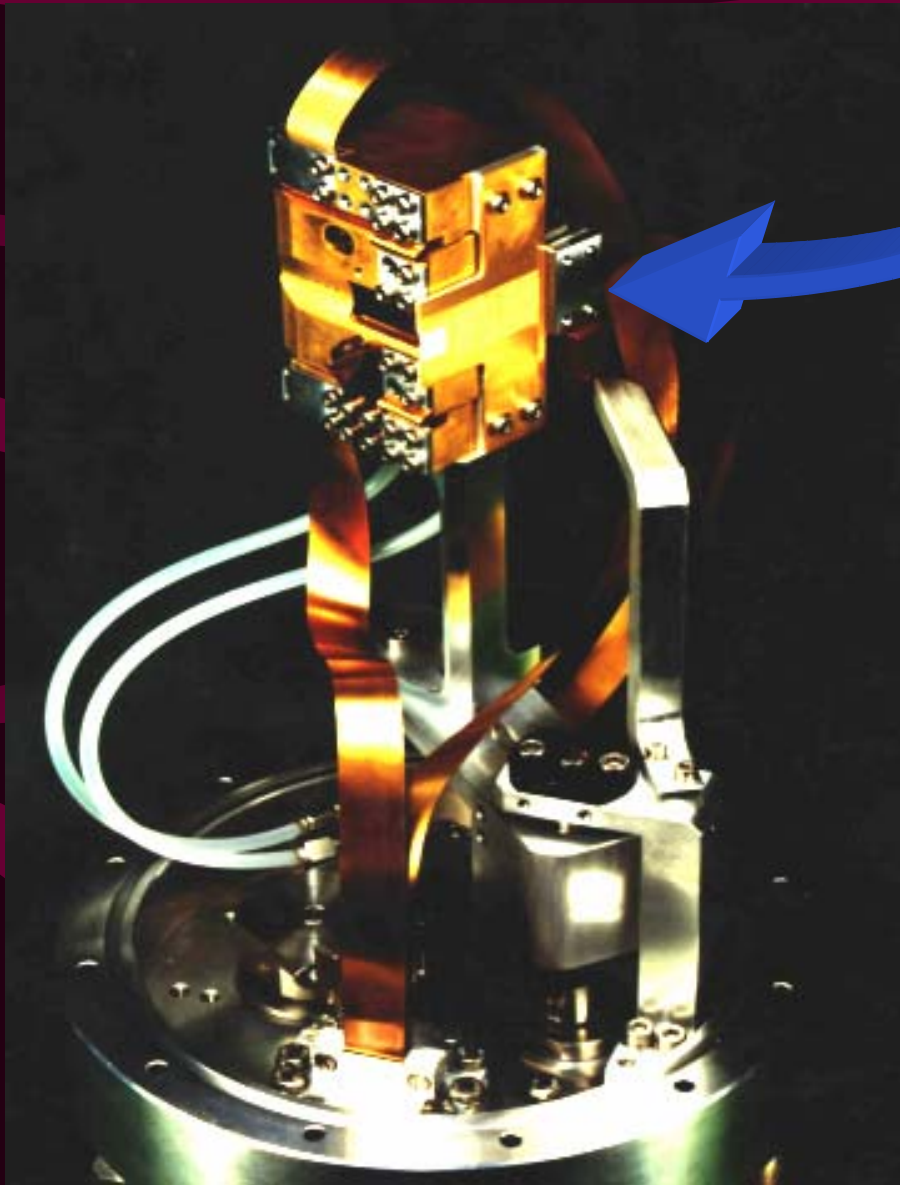
# X-ray Beam Intercepting Strip Line Detector (Cd-Te photo-conductors)



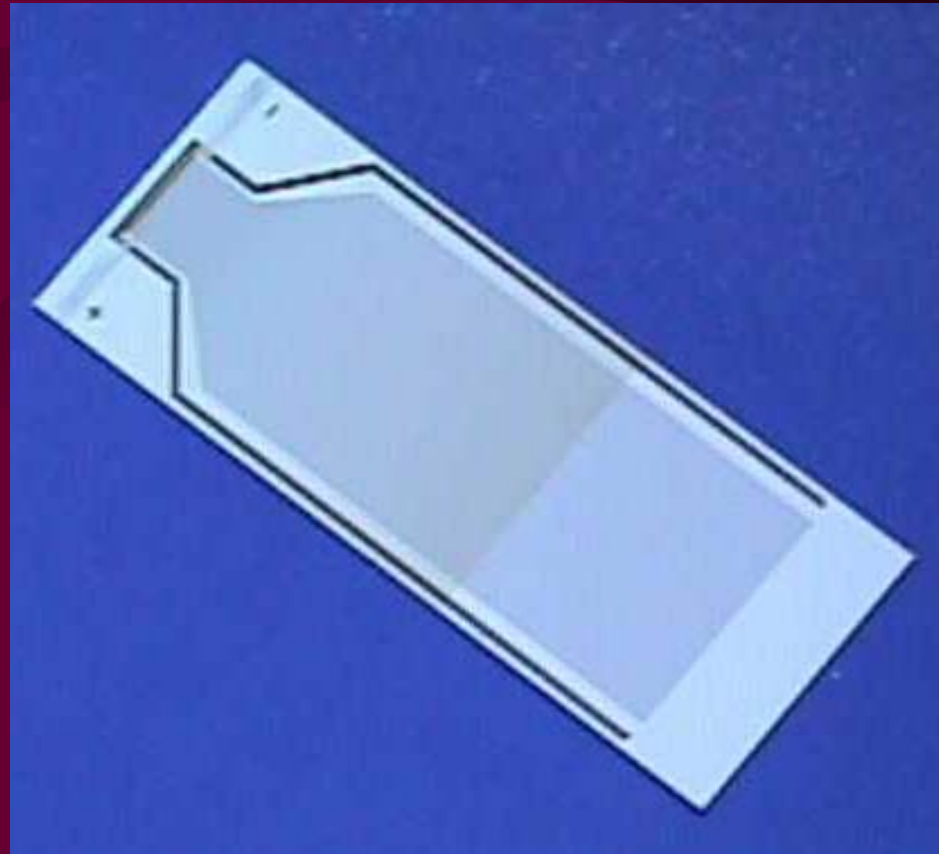
The detector is made from a 4 micrometer layer of photoconductive CdTe deposited on a 20 X 50 mm ceramic substrate



# The BEXE Detector



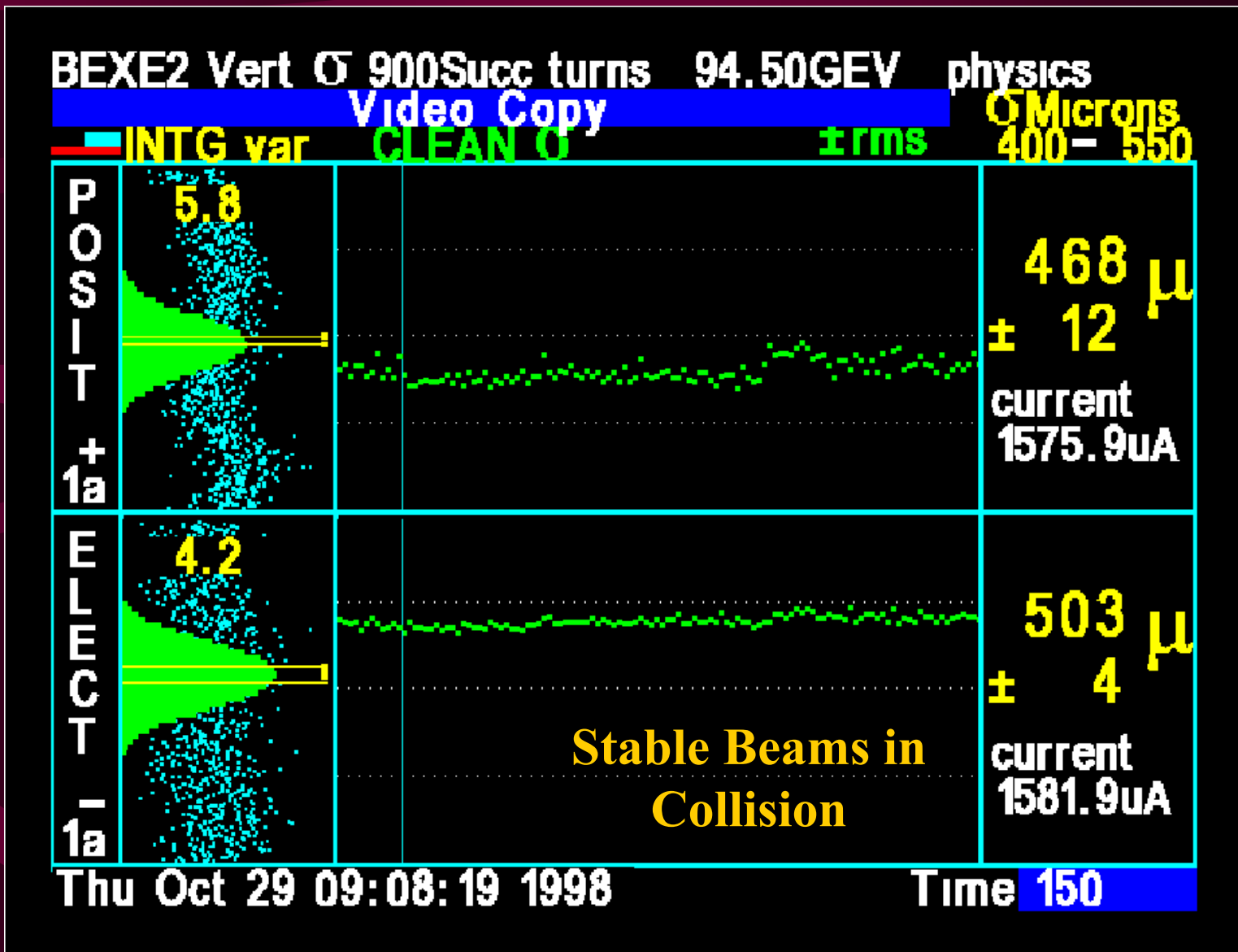
Ceramic substrate





# Online Display in LEP Control Room

( e<sup>+</sup> & e<sup>-</sup> vertical beam size versus time )



Histograms of Individual Cd-Te Channels





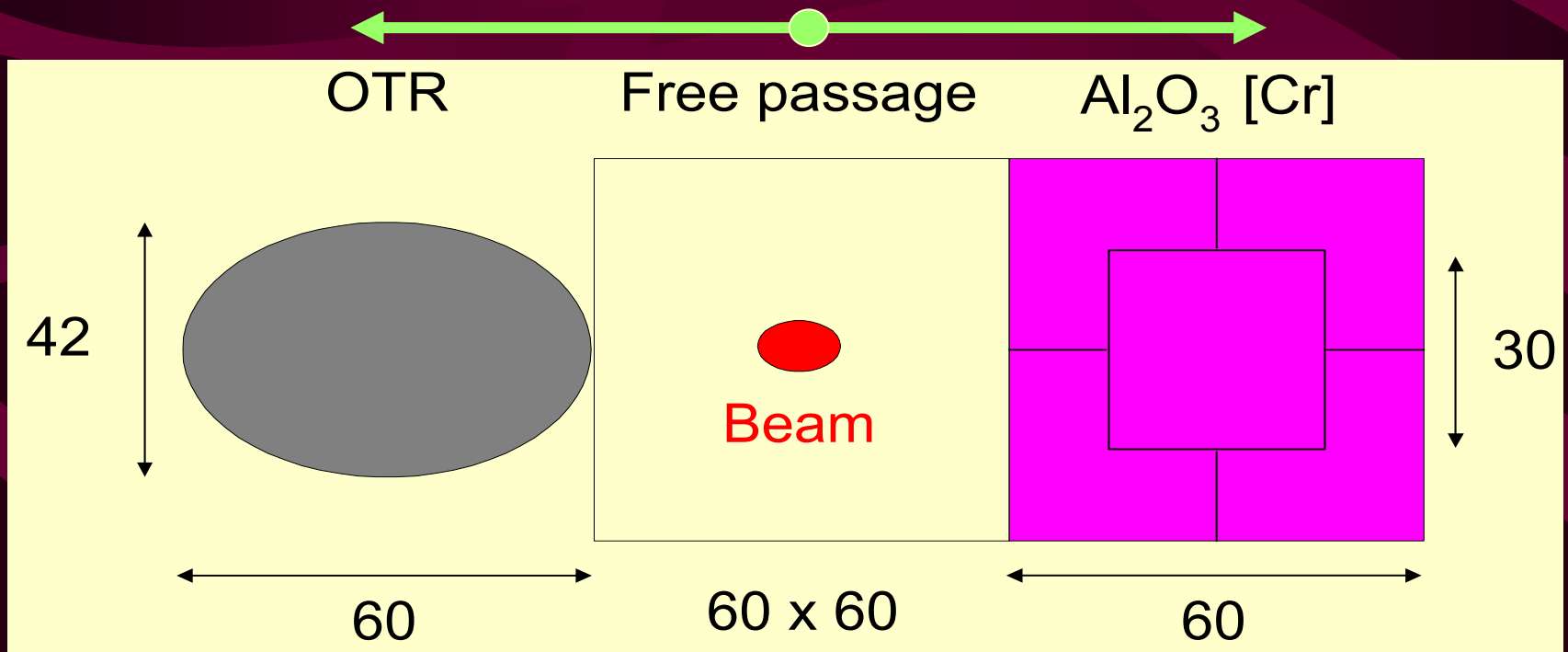
# Measuring Beam Size

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(semi or fully destructive)
  - SEM monitors
  - Others...



# Measuring Profiles using Screens

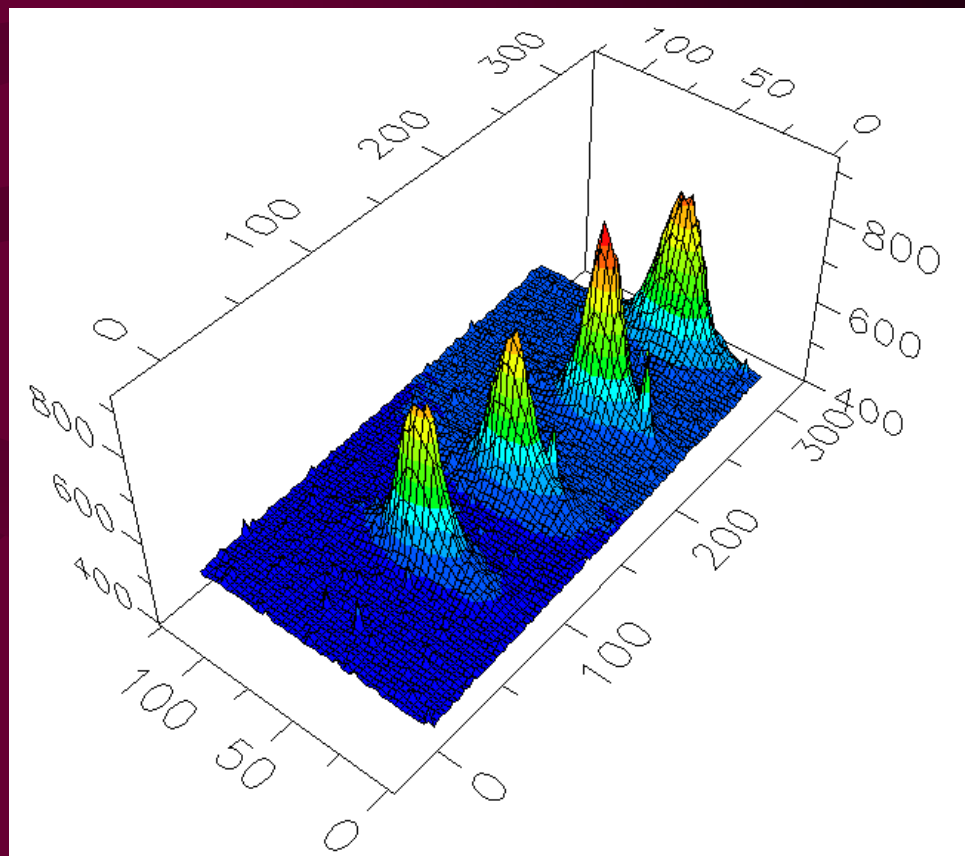
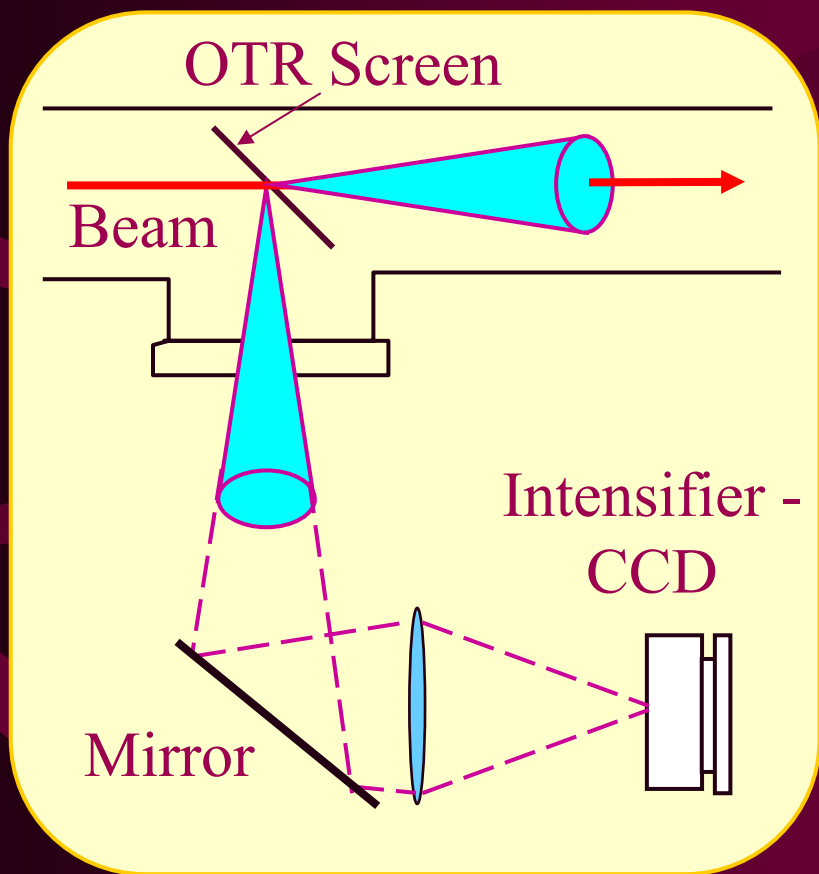
- Al<sub>2</sub>O<sub>3</sub> screens for set-up and “bad days”
- OTR screens for nominal operation
- Can combine both into one instrument





# Optical Transition Radiation Monitors

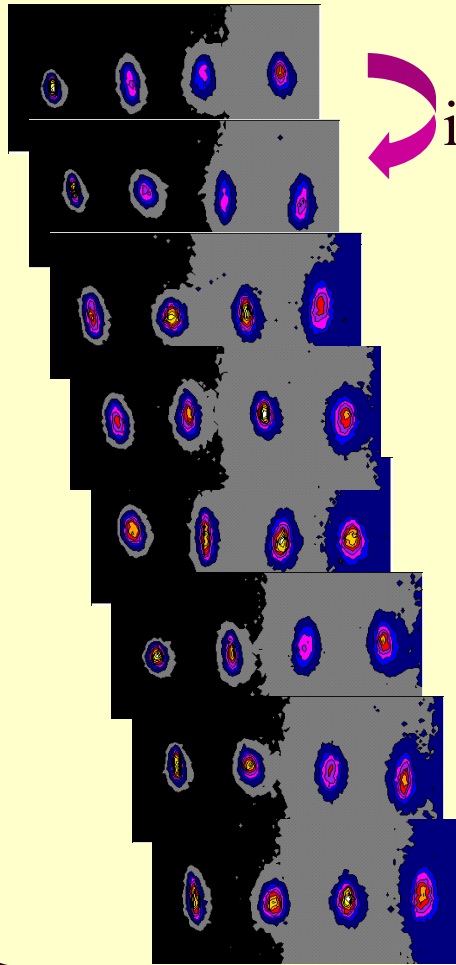
As Beam hits the  $12\mu\text{m}$  Titanium foil 2 cones of radiation are emitted



Capturing emitted radiation on a CCD gives 2D beam distribution

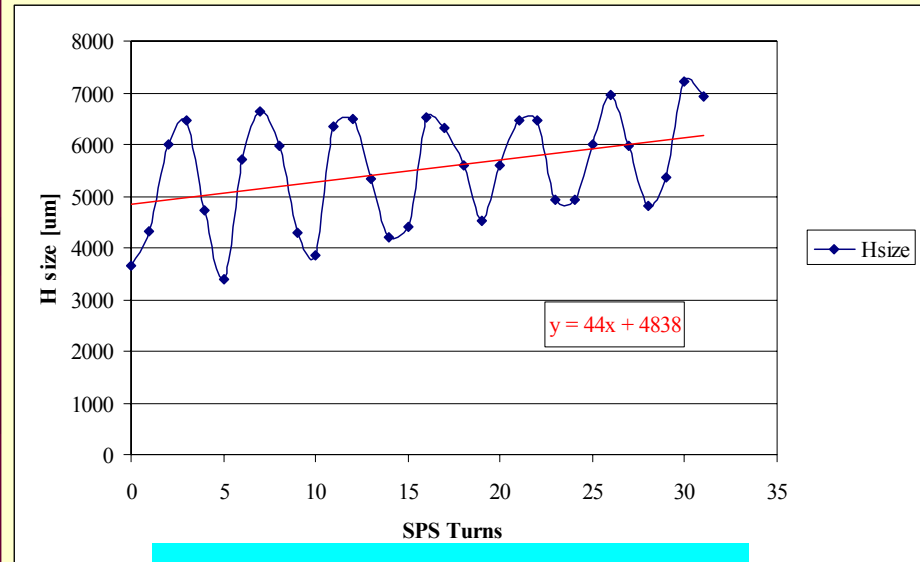


# Turn-by-Turn OTR Results

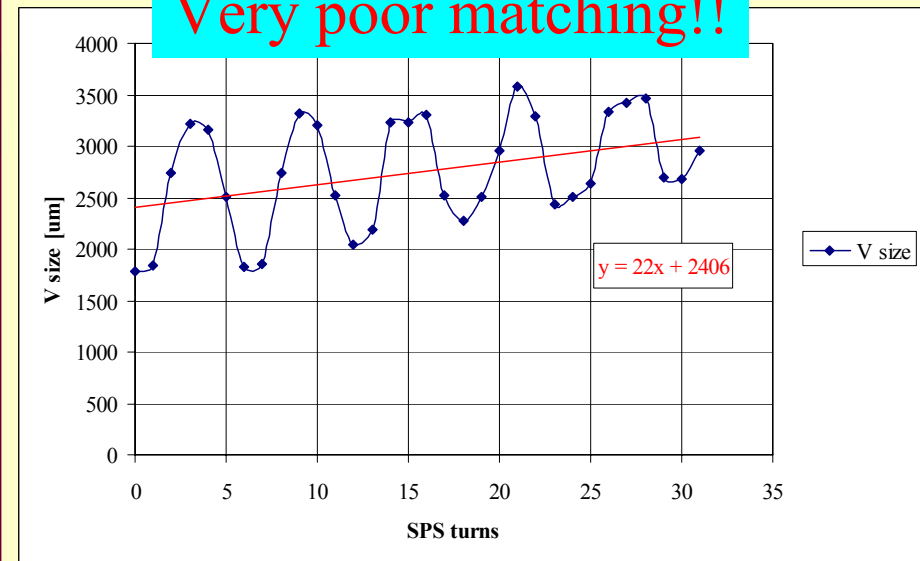


Next injection  
+1 turn

$\beta$ -Mismatch at injection seen as a beating in the beam profile



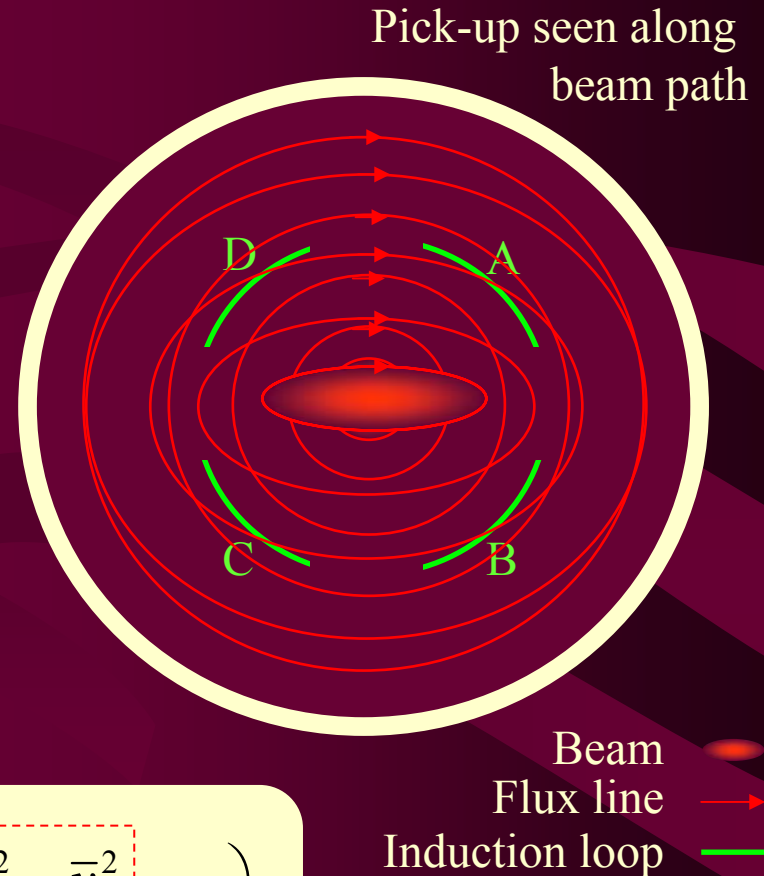
Very poor matching!!





# Quadrupolar Pick-Up

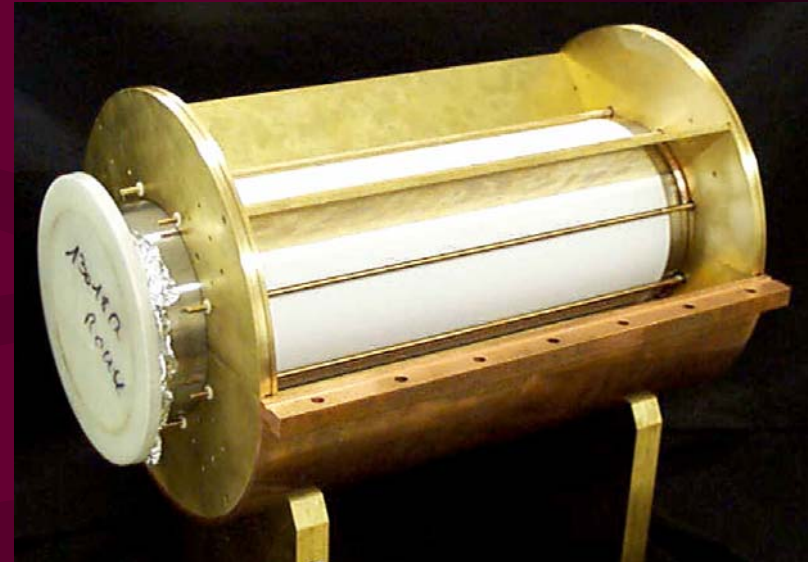
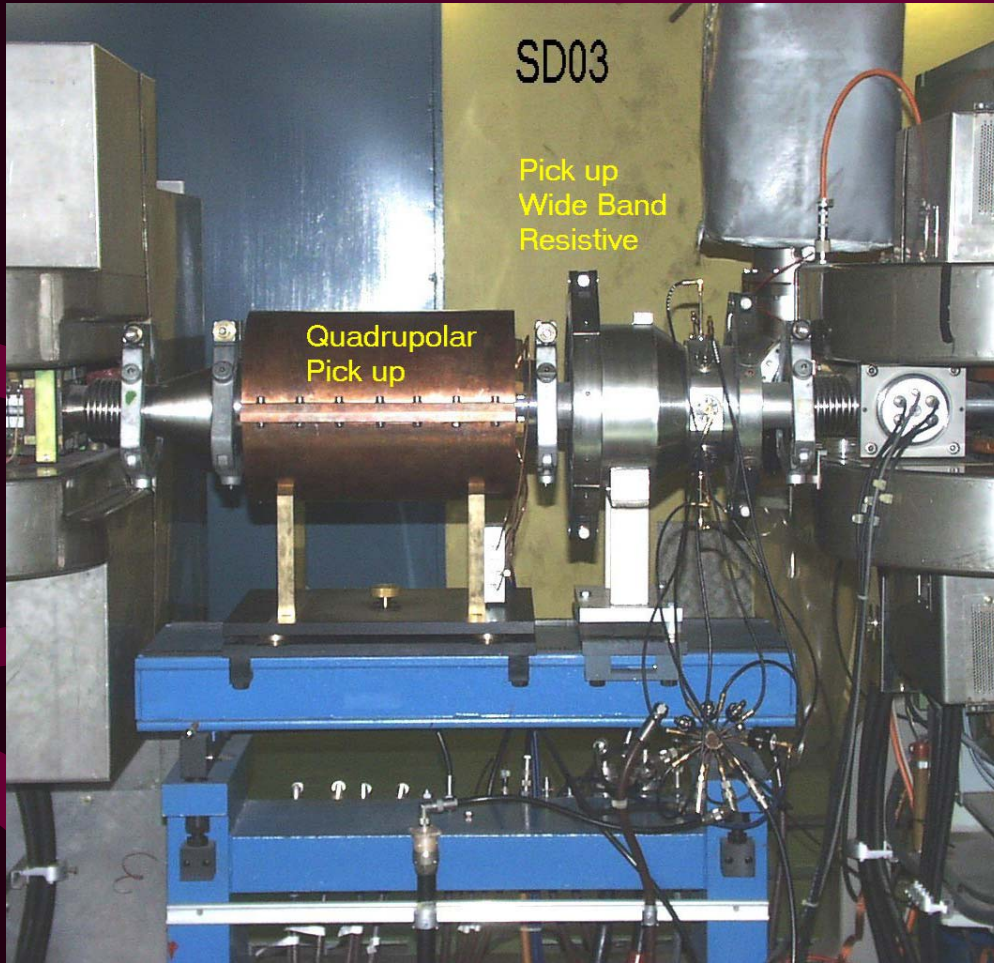
- Position contribution can not be avoided, but can be measured and subtracted.
- Design suppresses the dominating intensity signal by coupling to the radial magnetic field component.



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



# Installation in the CERN-PS



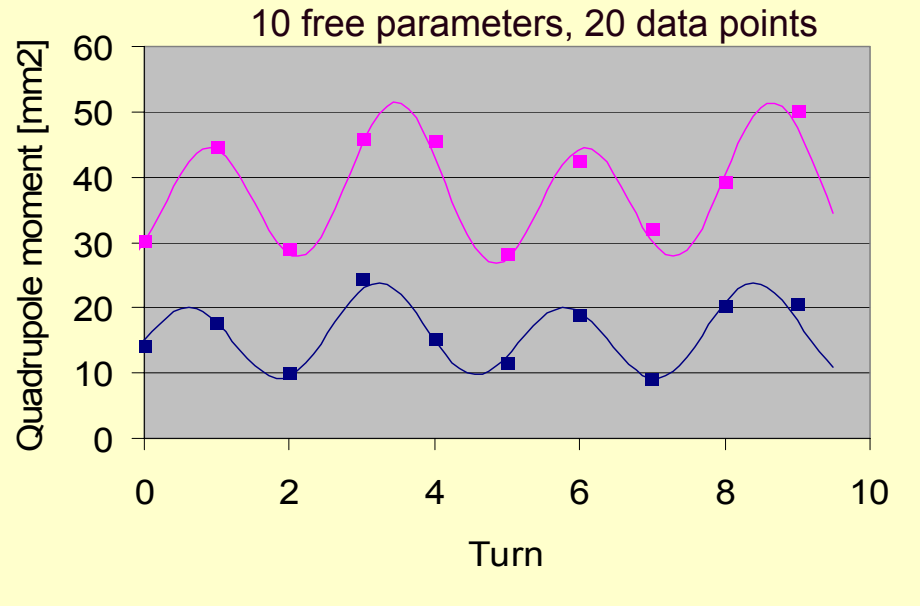
	$\beta_h$	$\beta_v$	$D_h$
<b>SS 03</b>	22 m	12 m	3.2 m
<b>SS 04</b>	12 m	22 m	2.3 m

“One pick-up per plane”



# Measurement of Matching

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



- Simultaneous fit to the two pick-up signals gives:

- Injected emittances.
- Betatron mismatches.
- Horizontal dispersion mismatch.

- Input parameters

- $\beta_H, \beta_V, D_H$
- $\Delta\mu_H, \Delta\mu_V$
- $\sigma_p, q_h, q_v$

- Most input parameters can be checked experimentally



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## ★ Diagnostics of transverse beam motion

- Tune & chromaticity measurements
- Dynamic effects: tune and chromaticity control
- On-line  $\beta$  measurements

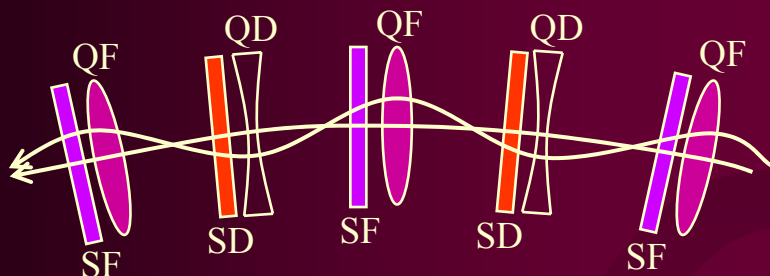
## ★ Trying to make the machine work ("the bad days")

- The beam does not circulate!
- The beam gets lost, when changing the beta\*





# Measurement of Q (betatron tune)

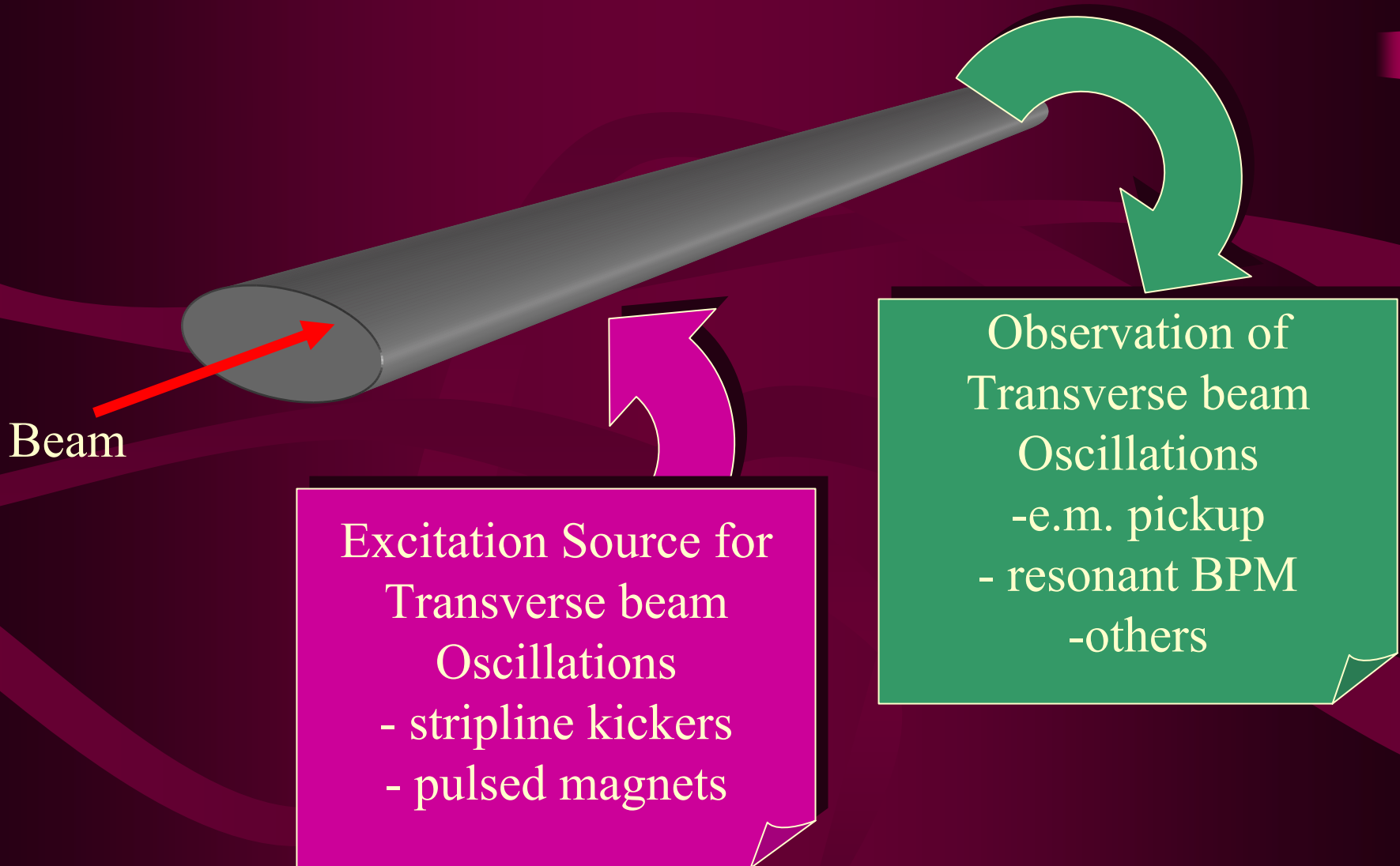


Characteristic Frequency  
of the Magnet Lattice  
Produced by the strength of the  
Quadrupole magnets

- 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

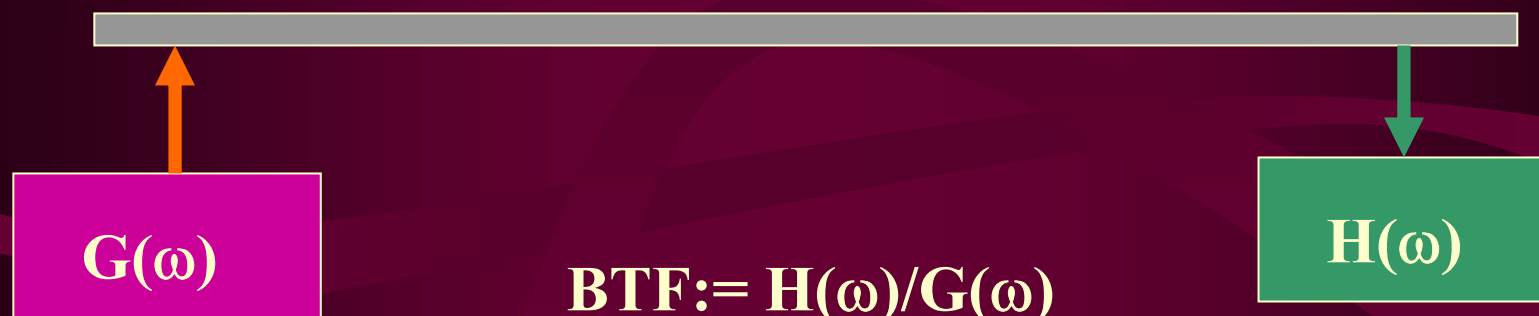


# Principle of any Q-measurement





# Principle of any Q-measurement



$$\text{BTF} := H(\omega)/G(\omega)$$

**Measurement of  
betatron tune  $q$ :  
Maximum of BTF**



# Simple example: FFT analysis

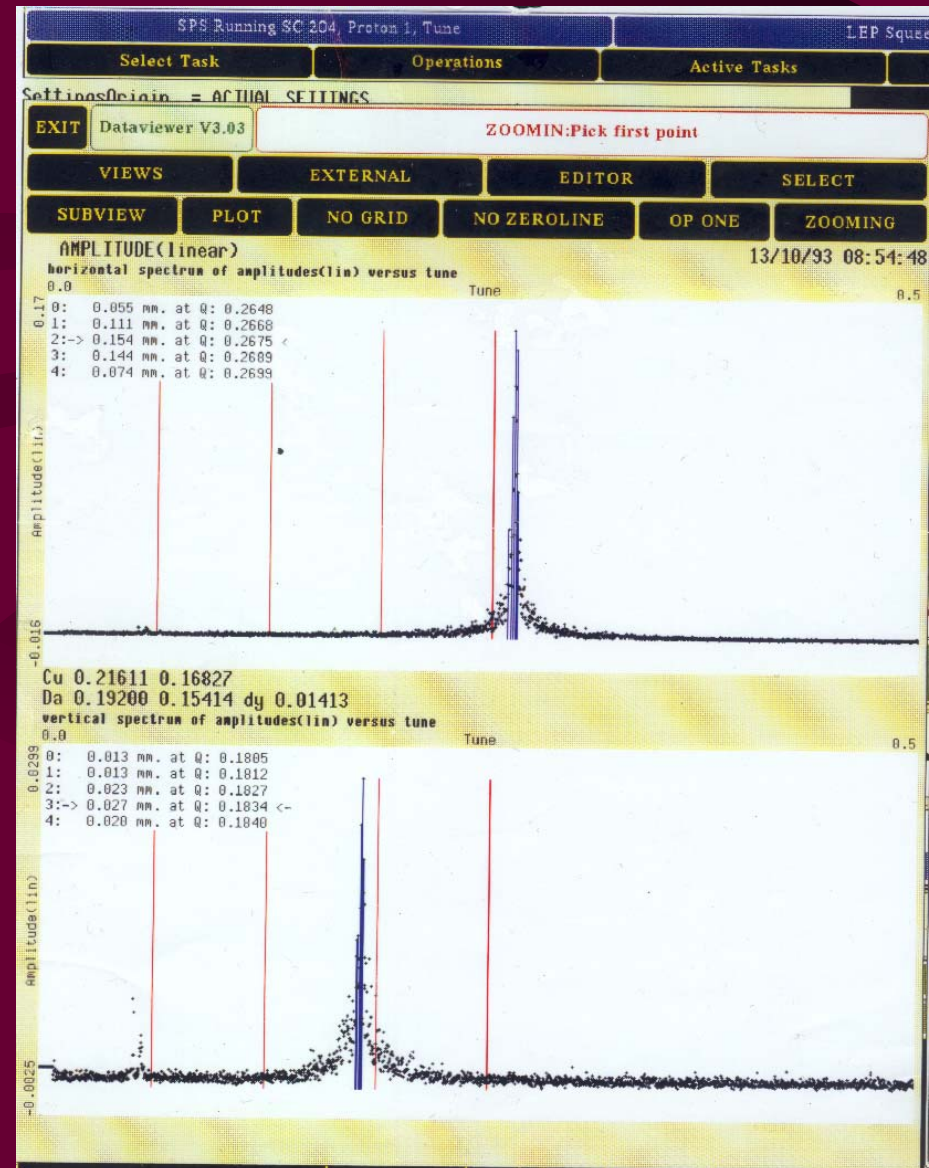
$G(\omega) == \text{flat};$

Made with random noise kicks

Measure beam position over many consecutive turns

-> apply FFT ->  $H(\omega);$

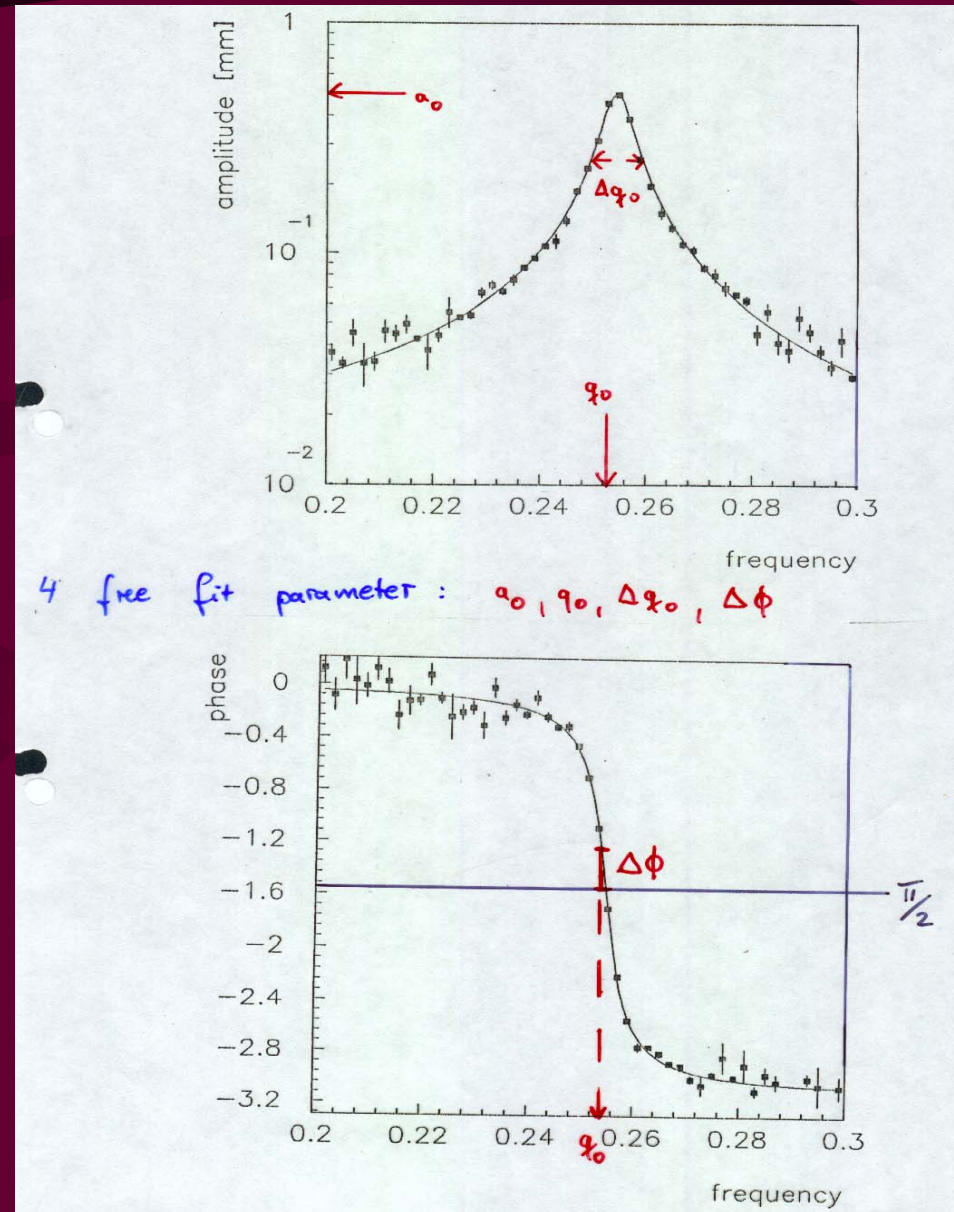
$\text{BTF} = H(\omega)$





# Network Analysis

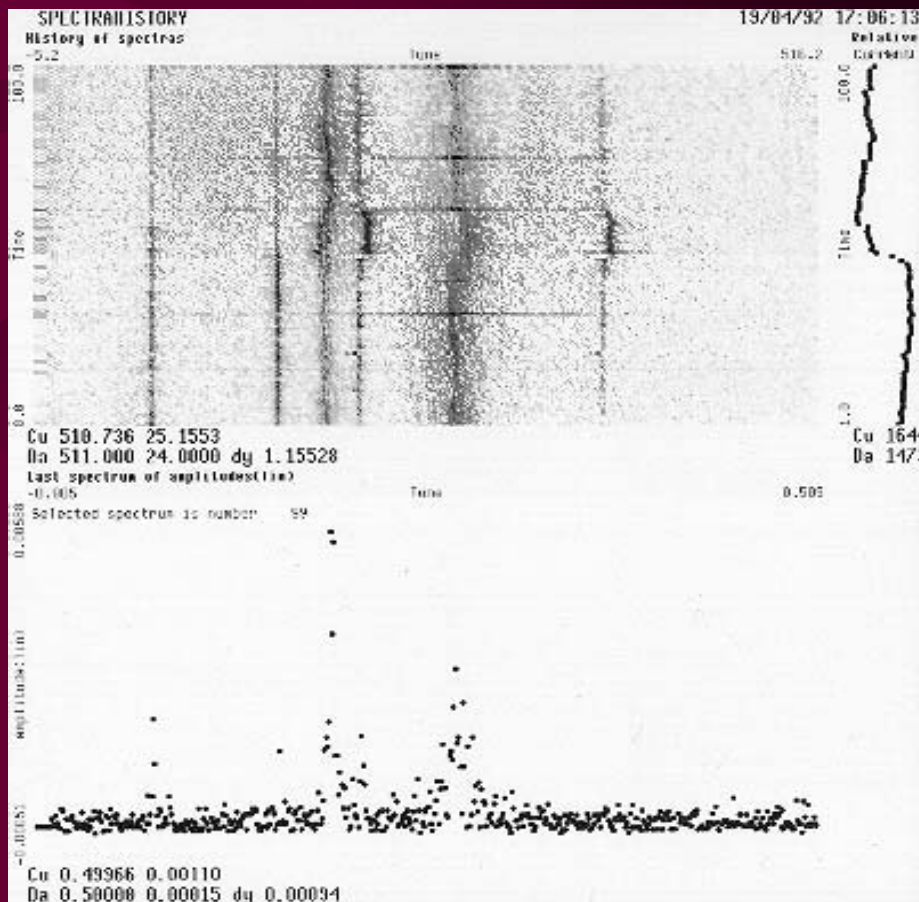
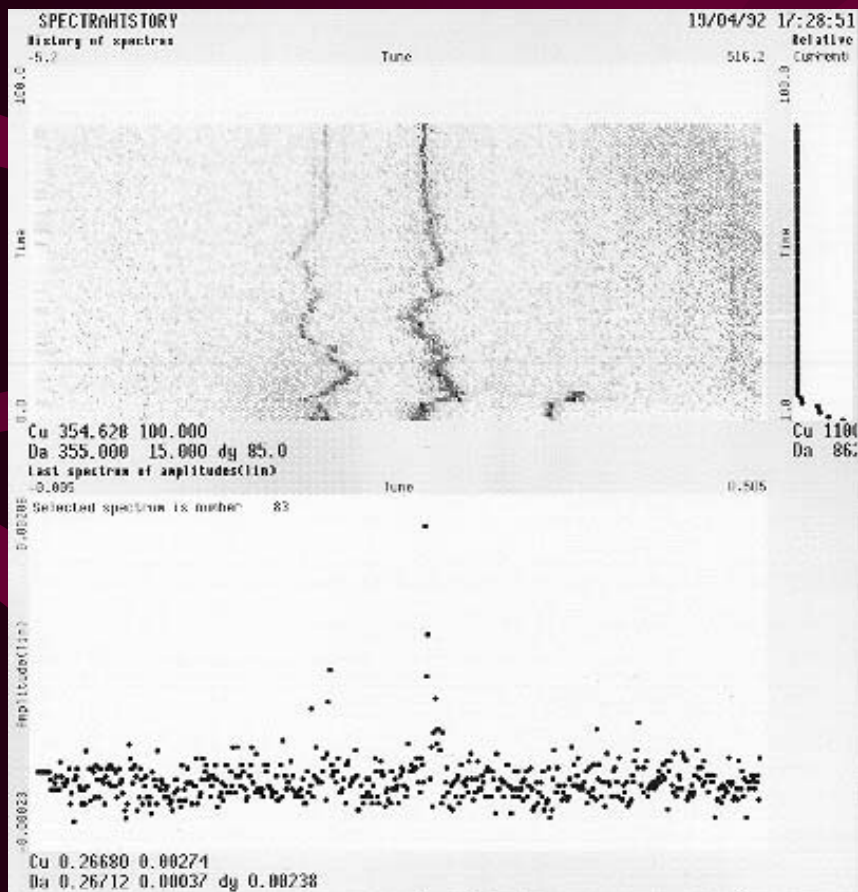
1. Excite beams with a sinusoidal carrier
2. Measure beam response
3. Sweep excitation frequency slowly through beam response





# Time Resolved Measurements

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

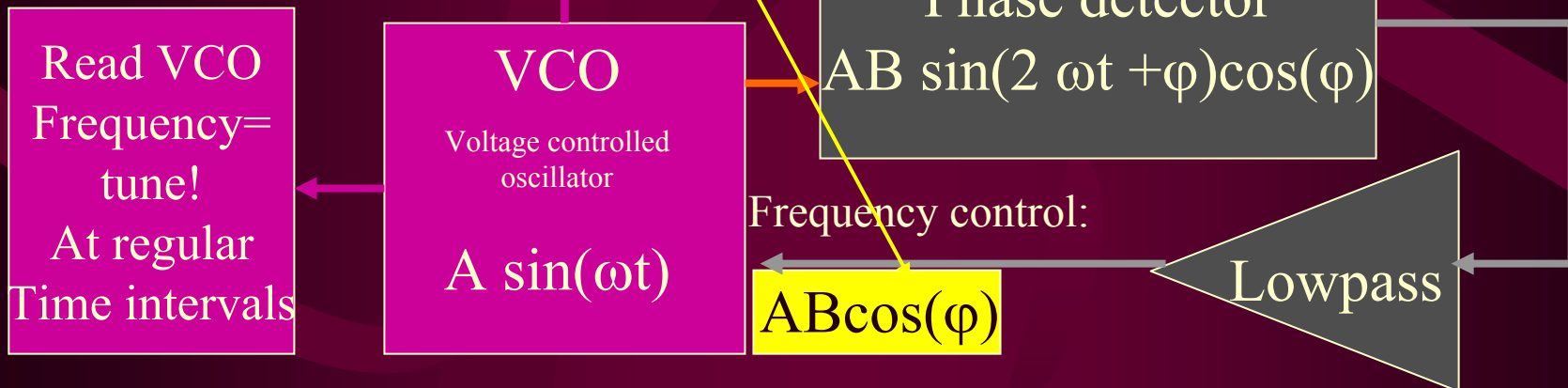




# Principle of PLL tune measurements

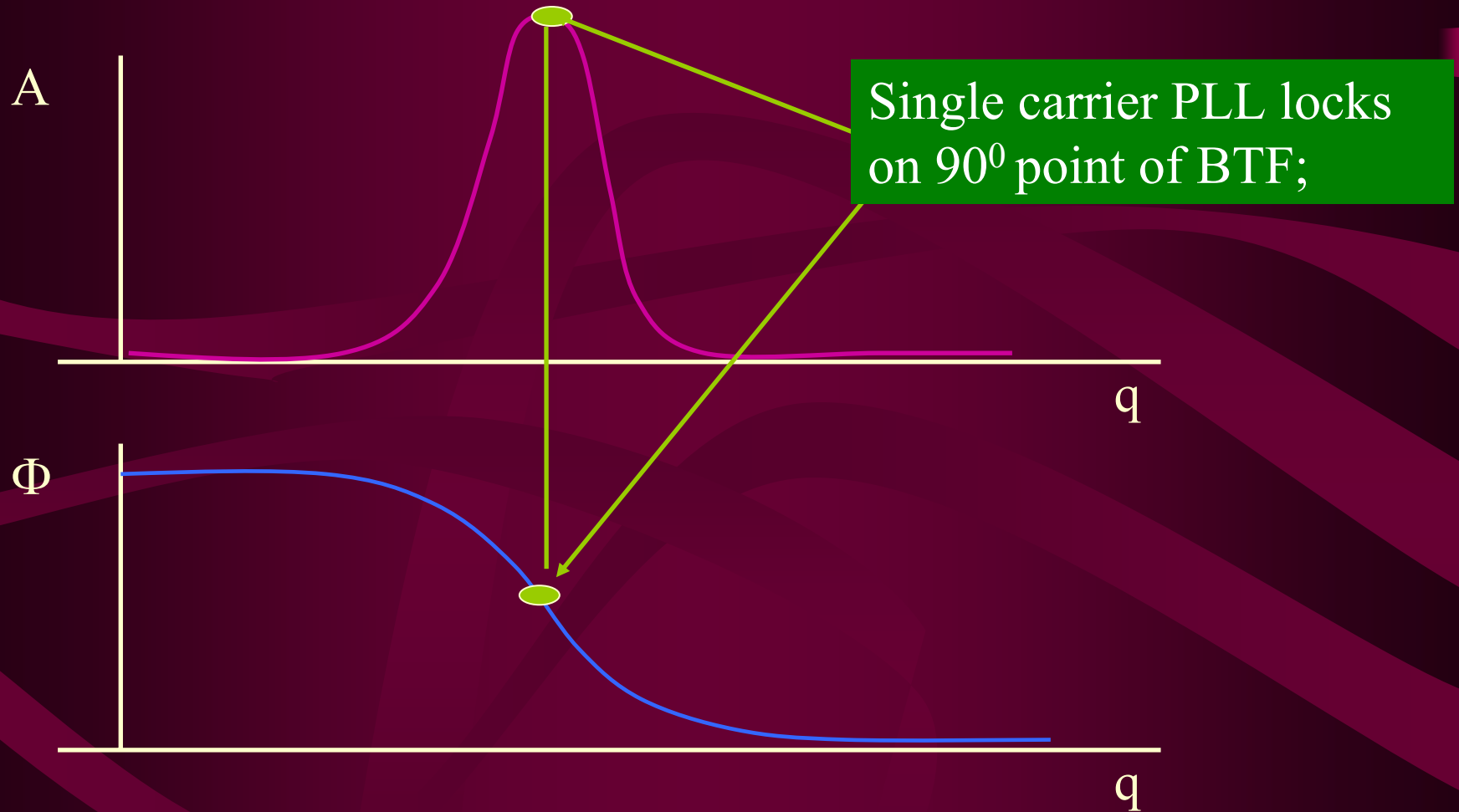
This PLL system looks to the 90 deg. point of the BTF

Beam





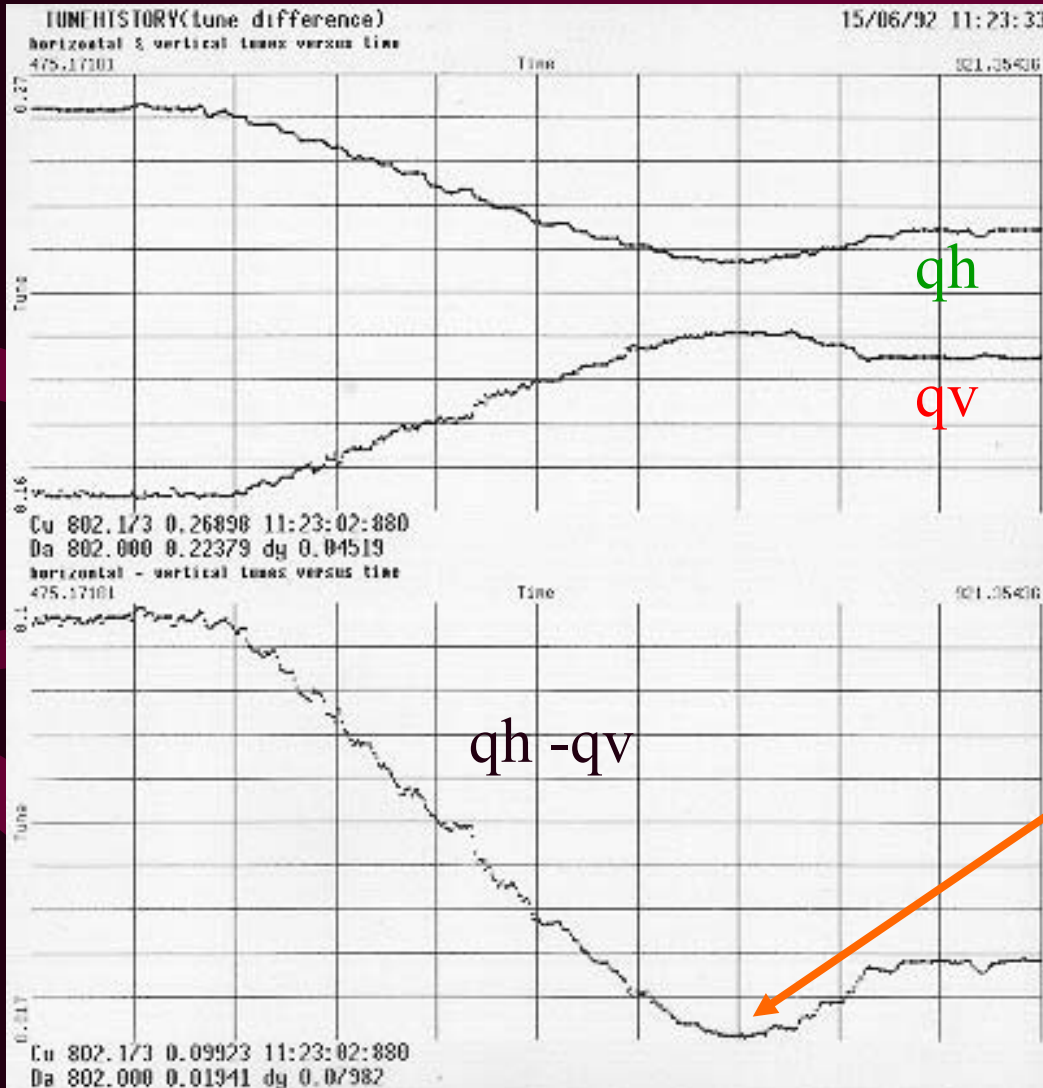
# Illustration of PLL tune tracking







# 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



# $\beta$ Function Measurement by k-Modulation

- Purpose:

- measurement of  $\langle \beta \rangle$  within a quadrupole
- optics knowledge
- emittance determination:  $\varepsilon = \sigma_{\text{rms}}^2 / \beta$

- Principle:

- a (small) strength variation  $\Delta k$  within a quadrupole induces a tune variation  $\Delta Q$

$$\Delta Q = \Delta k / 4\pi \int_{\text{Quad}} \beta(s) ds$$
$$\langle \beta_{H,V} \rangle = (4\pi \Delta Q_{H,V} / L \Delta k) (1 + \varepsilon(\Delta Q))$$

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

- L is the quadrupole magnetic length
- $\Delta Q$  is small enough to keep second order term contribution  $< 1\%$

- $\Delta k$  modulated using k-modulation facility in LEP to test:

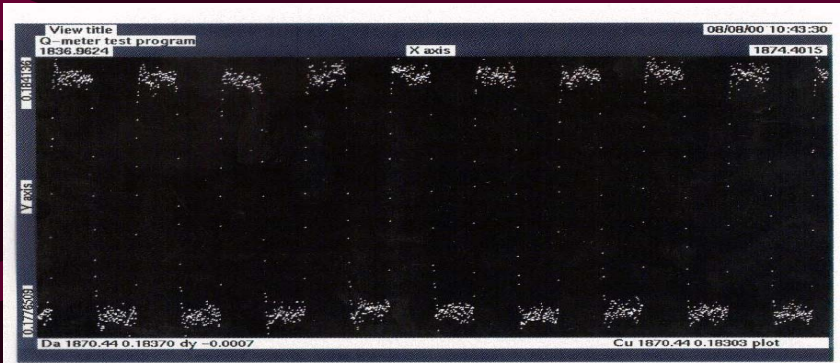
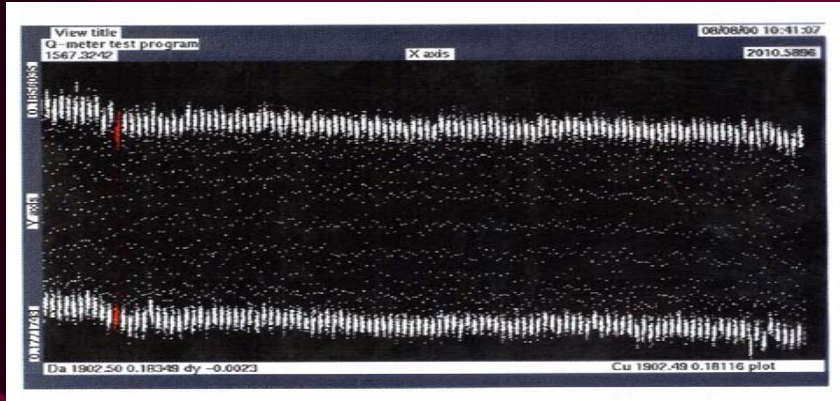
- What is the smallest possible perturbation? (LHC emittance budget)
- Can it work with beams colliding head ON ?



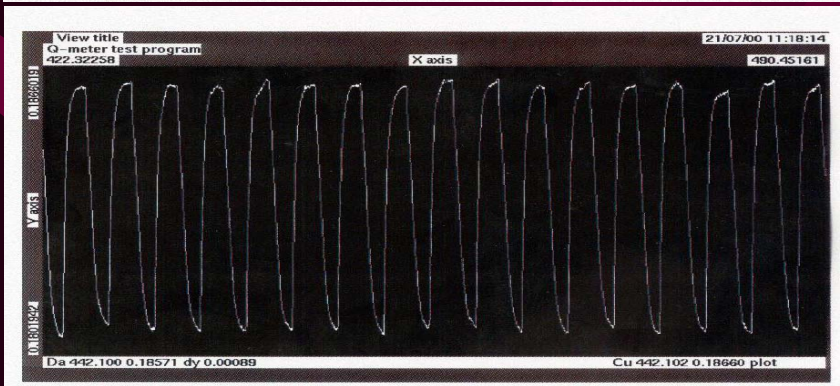
# $\beta$ Measurement using k-Modulation in LEP

Effect of Q feedback loop speed  
(PLL mode)

→  $\Delta I = 1\text{A}$ , 0.25 Hz



→ “fast” mode: 20 Hz



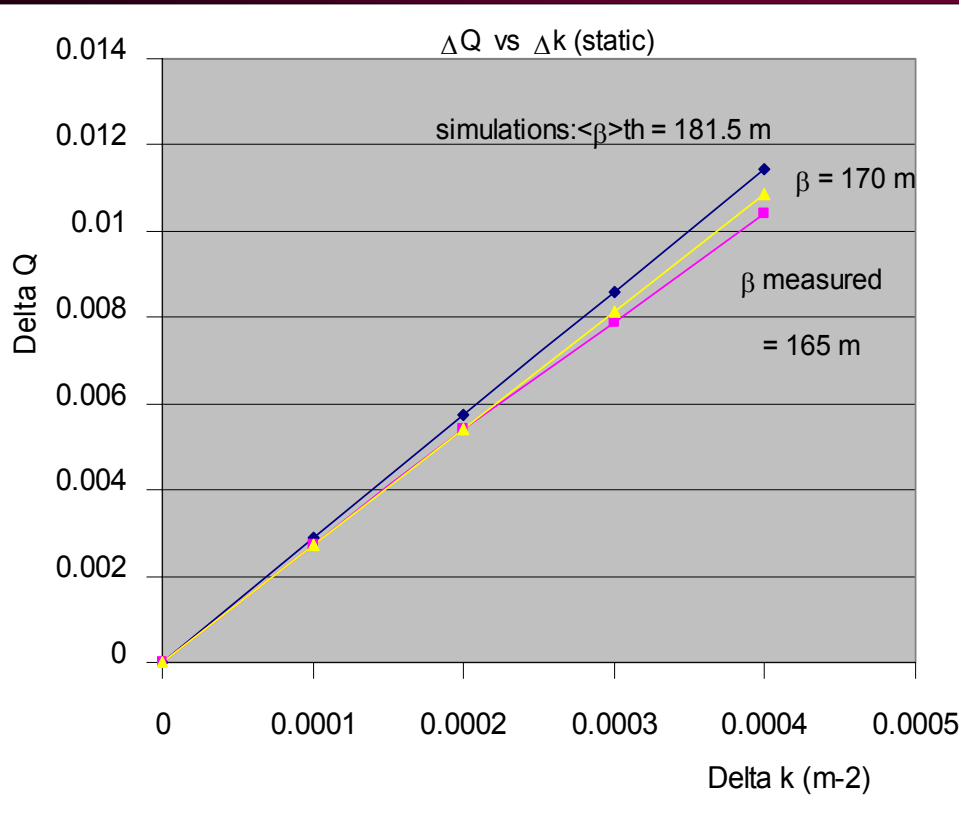
→ “normal” mode: 12 Hz



# $\beta$ Measurement using k-Modulation in LEP

Comparison between static  $\Delta k$ ,  
1000 turns and k-modulation

LEP: 85GeV, 800mA, 4 bunches



- 1000 turns:

→  $\beta_{\text{middle QUAD}} = 175.4 \text{ m}$

→  $\beta$ -beating: -9.2%

→  $\langle \beta \rangle = 164.8 \text{ m}$

- k-modulation:

→ 1A ( $5 \times 10^{-4}$ ), 0.25 Hz

→  $\langle \beta \rangle = 162.9 \text{ m}$



# Comparison between static $\Delta k$ and k-modulation with colliding beams in LEP

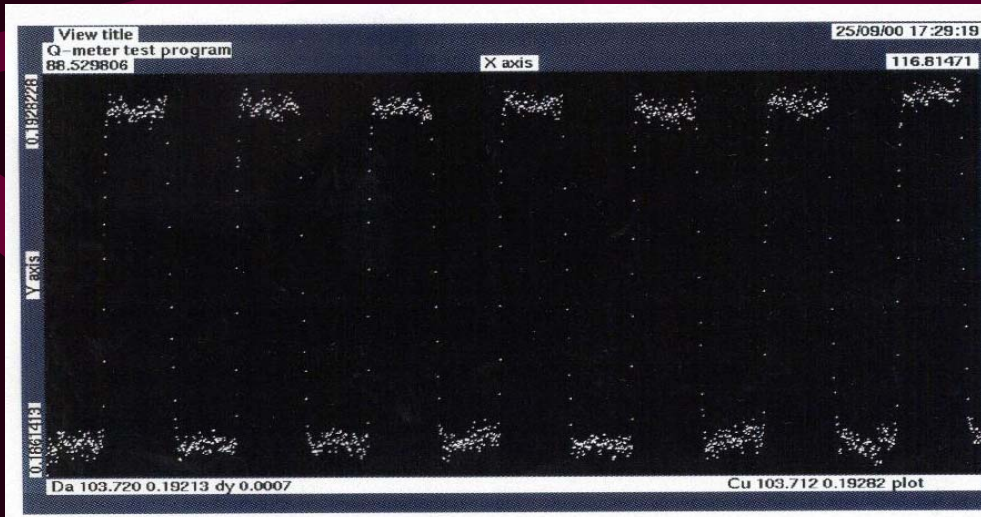
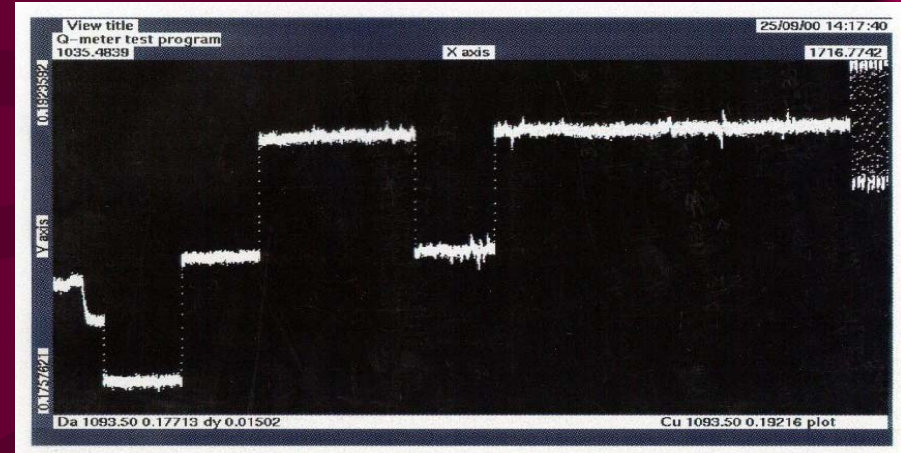
[103.3 GeV, 1860  $\mu\text{A}$  on 1860  $\mu\text{A}$  ]

- **Static  $\Delta k$ :**

→  $I_0 + 0.5 \text{ A} : \langle \beta \rangle = 383.9 \text{ m}$

→  $I_0$

→  $I_0 - 0.5 \text{ A} : \langle \beta \rangle = 392.8 \text{ m}$



- **k-modulation:**

→  $I_0 + \Delta I$

→  $\Delta I = 1 \text{ A}, 0.25 \text{ Hz}$

→  $\langle \beta \rangle = 389.4 \text{ m}$



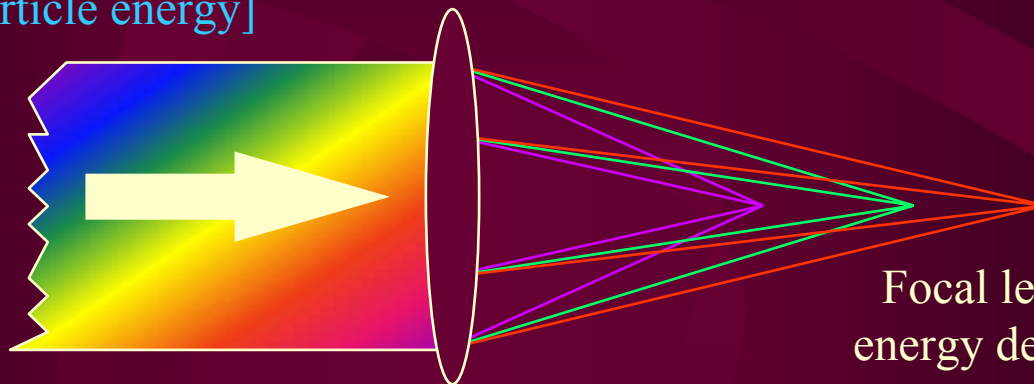
# Chromaticity ( $Q'$ or $\xi$ )

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:

Achromatic incident light  
[Spread in particle energy]



Lens

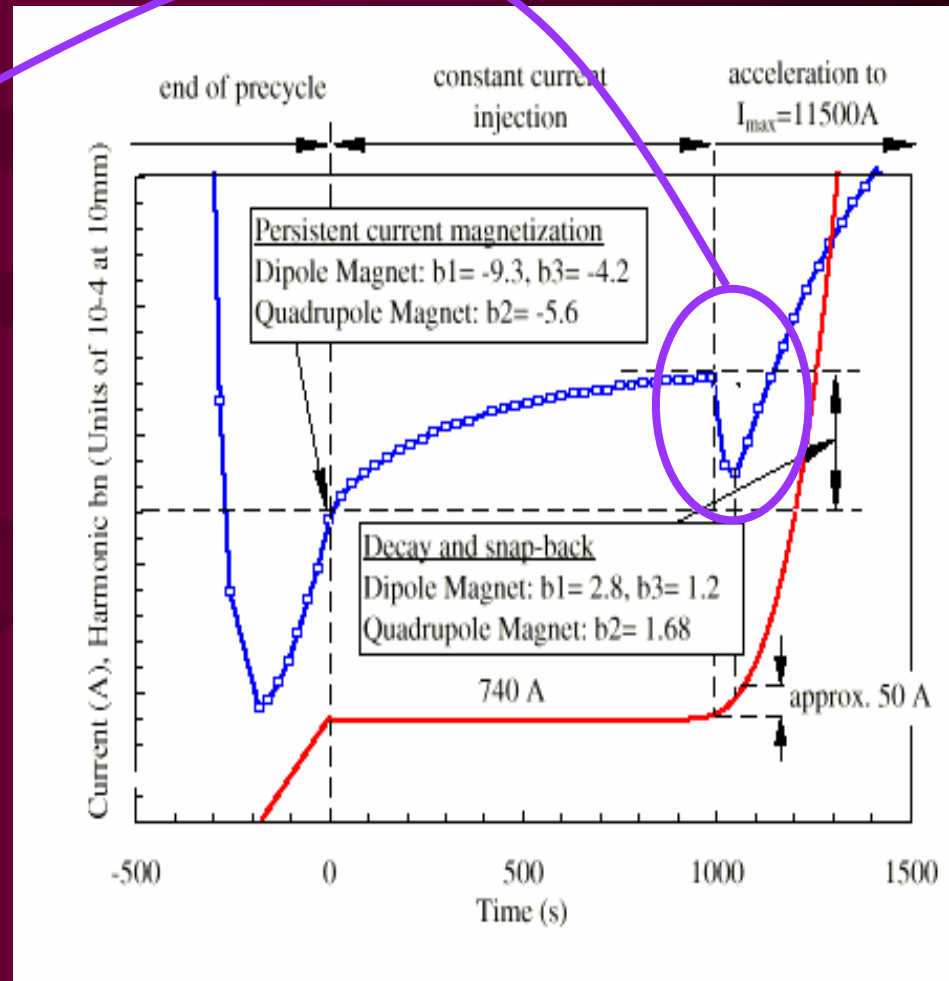
[Quadrupole]

Focal length is  
energy dependent



# Chromaticity – Its Importance for the LHC?

- Change in  $b_3$  during snap-back
  - Change in  $Q'$  of  $\sim 150$  units
- Nominal operation requires  $\Delta Q' < 3$
- Correction by:
  - Feed-forward tables from magnet/chromaticity measurements
  - On-line feedback from  $b_3$  measurements on reference magnets
  - Possible on-line feedback directly from chromaticity measurements





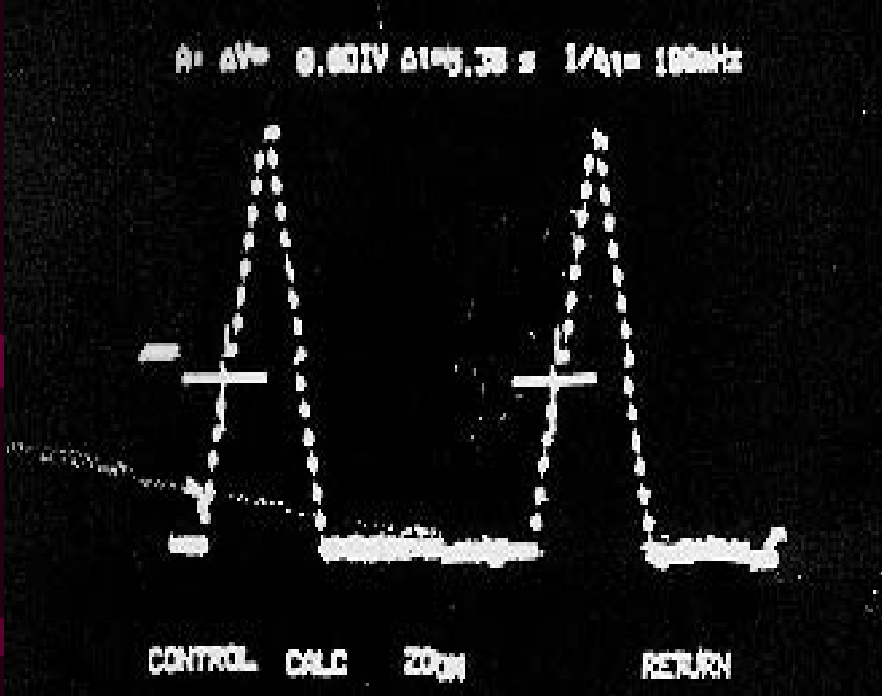
# Chromaticity - What observable to choose?

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 $\Rightarrow$ emittance growth!

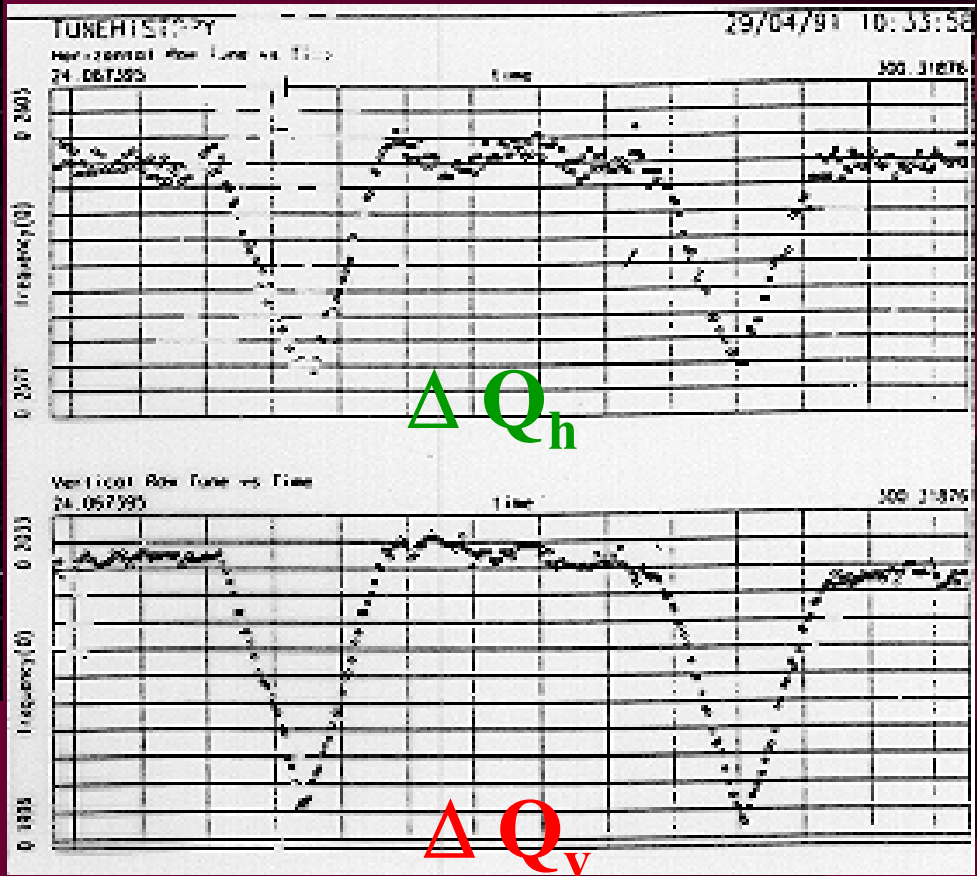




# Q' Measurement via RF-frequency modulation (momentum modulation)



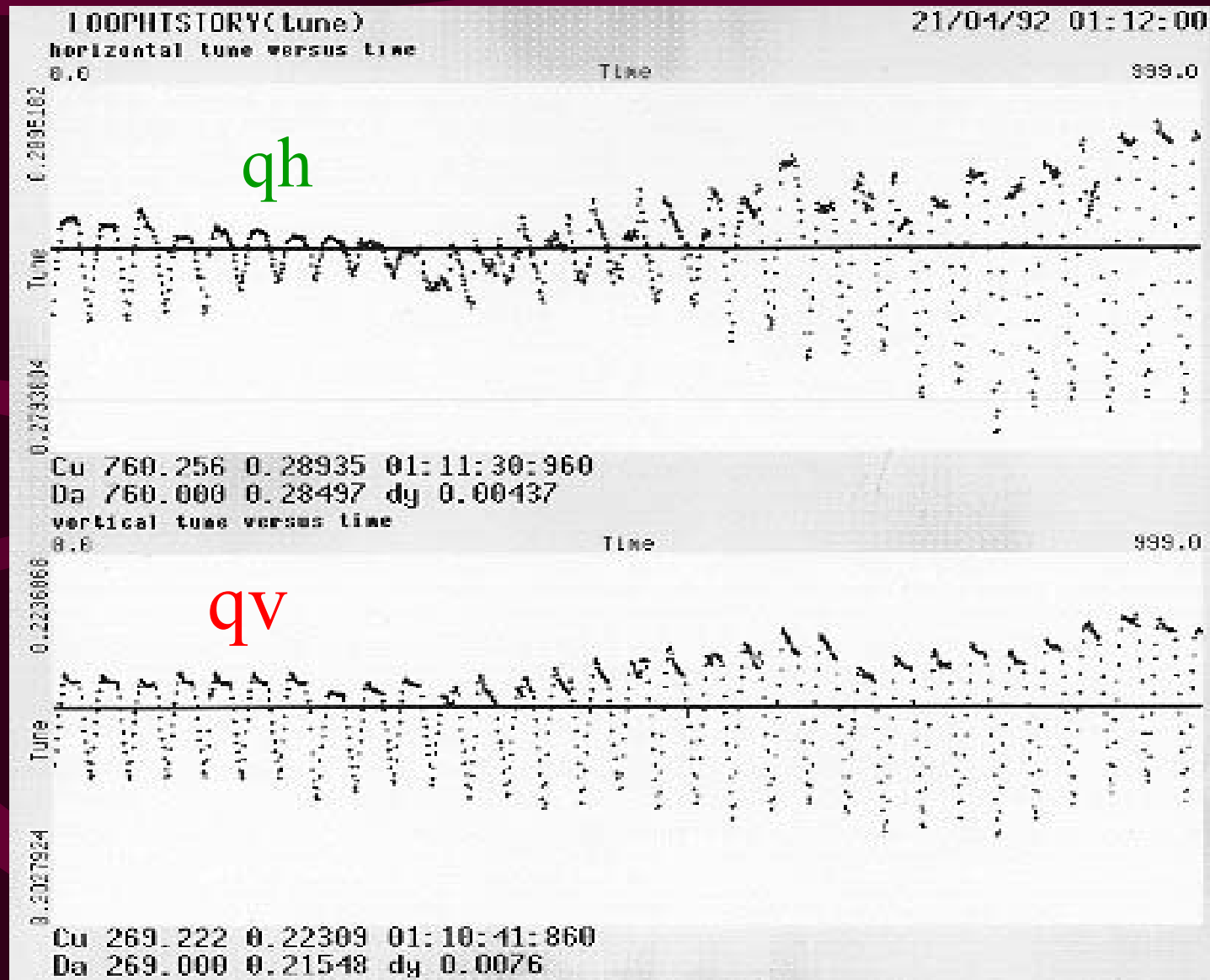
Applied Frequency Shift  
 $\Delta F$  (RF)



Amplitude & sign of chromaticity  
calculated from continuous tune plot



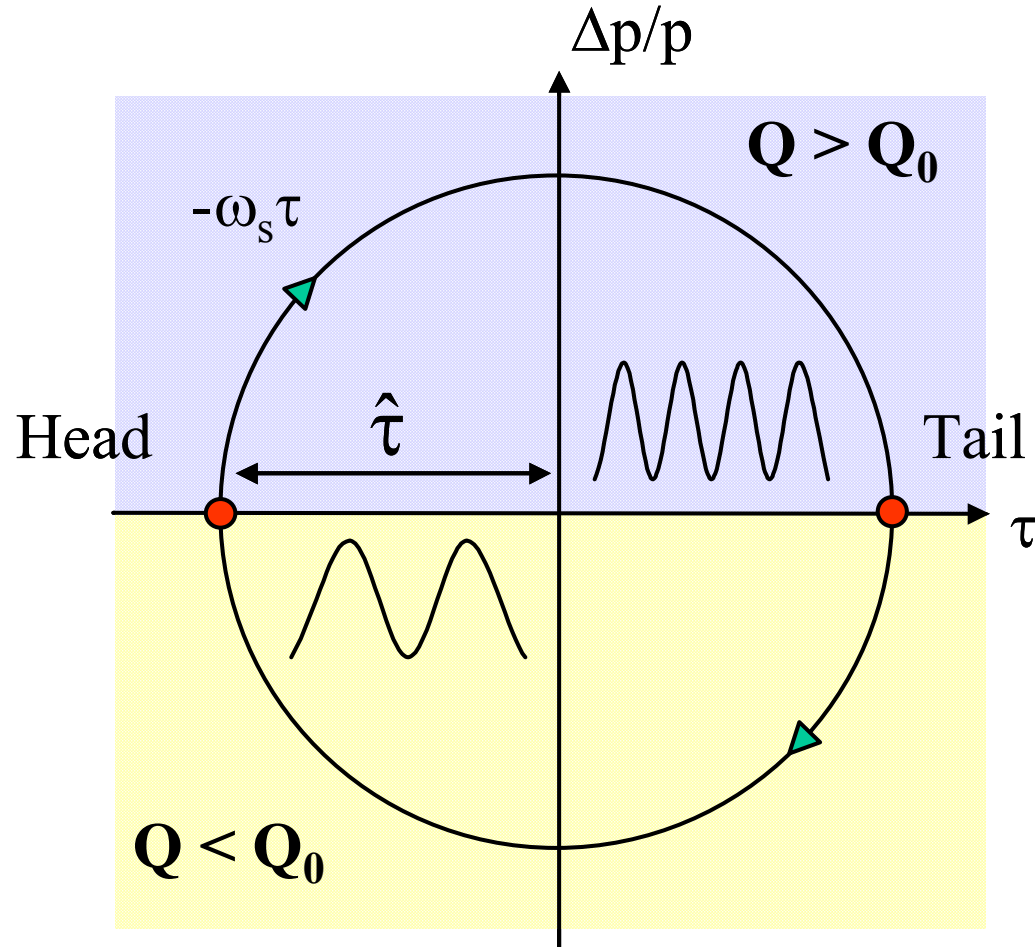
# Measurement Example during LEP $\beta$ -squeeze





# Chromaticity & Head-Tail Motion

Positive Chromaticity (Above Transition)

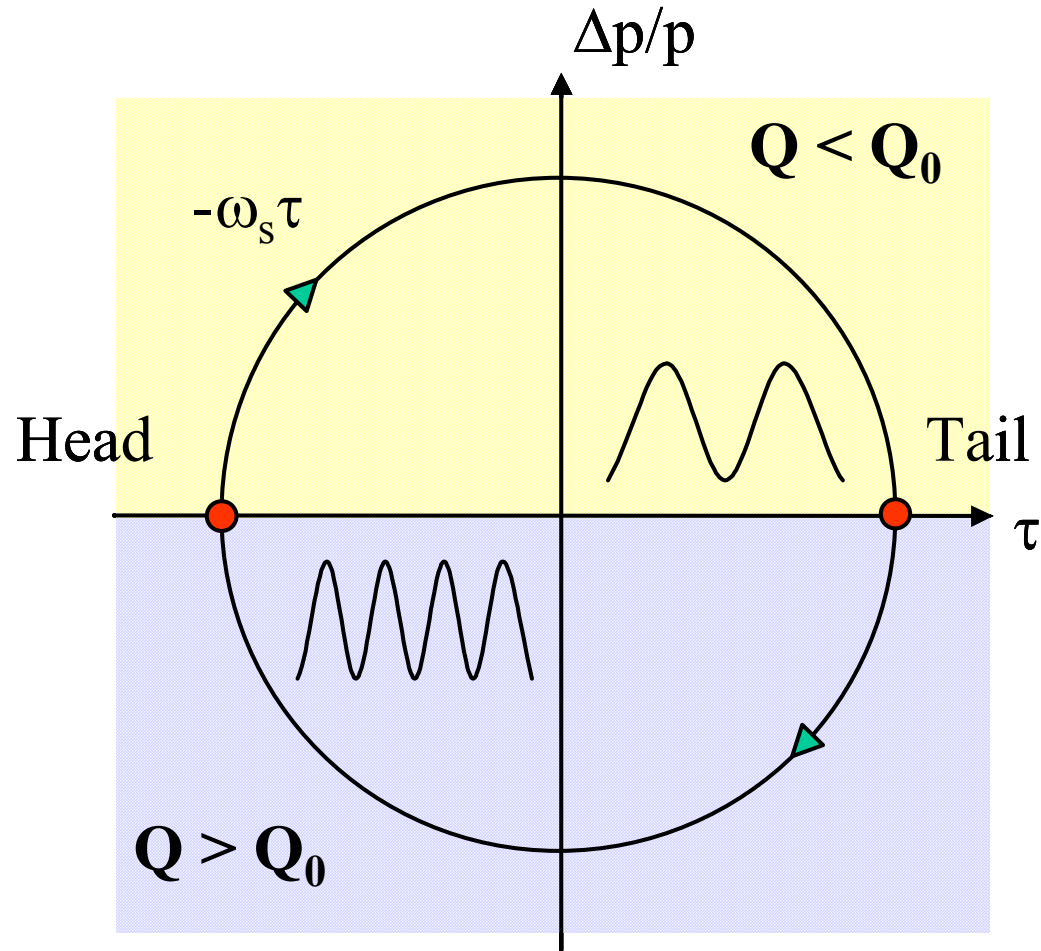


Longitudinal Phase-Space



# Chromaticity & Head-Tail Motion

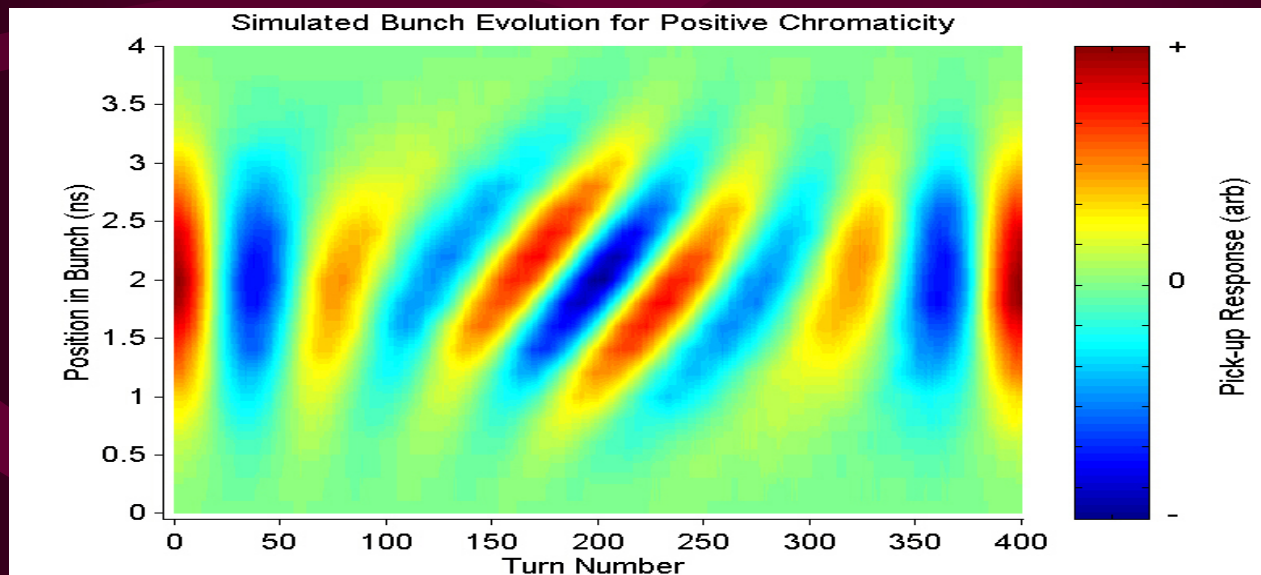
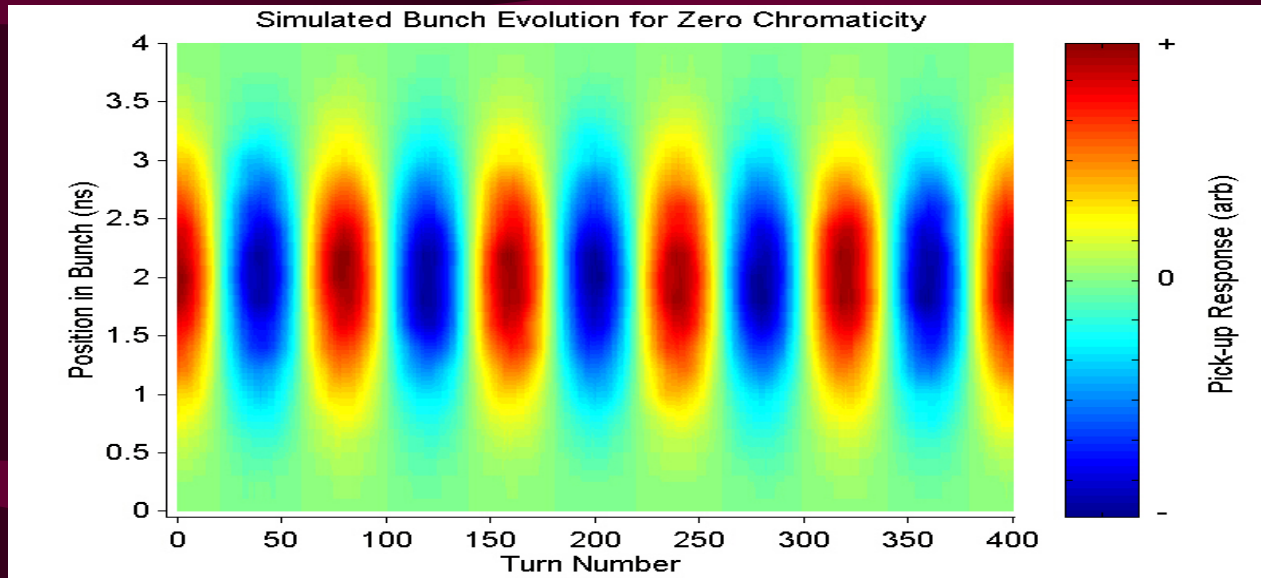
## Negative Chromaticity (Above Transition)



Longitudinal Phase-Space

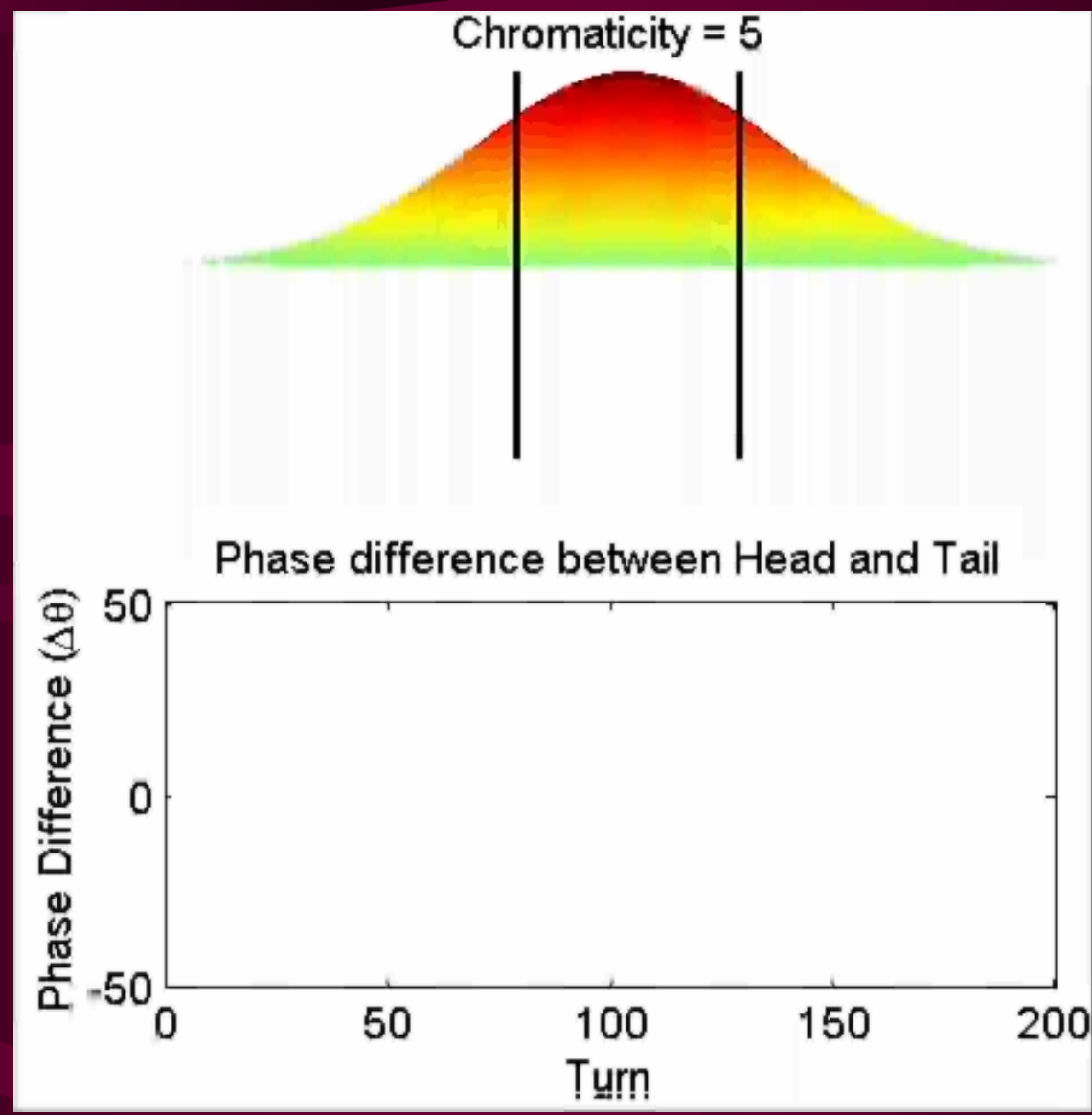


# Simulated Response



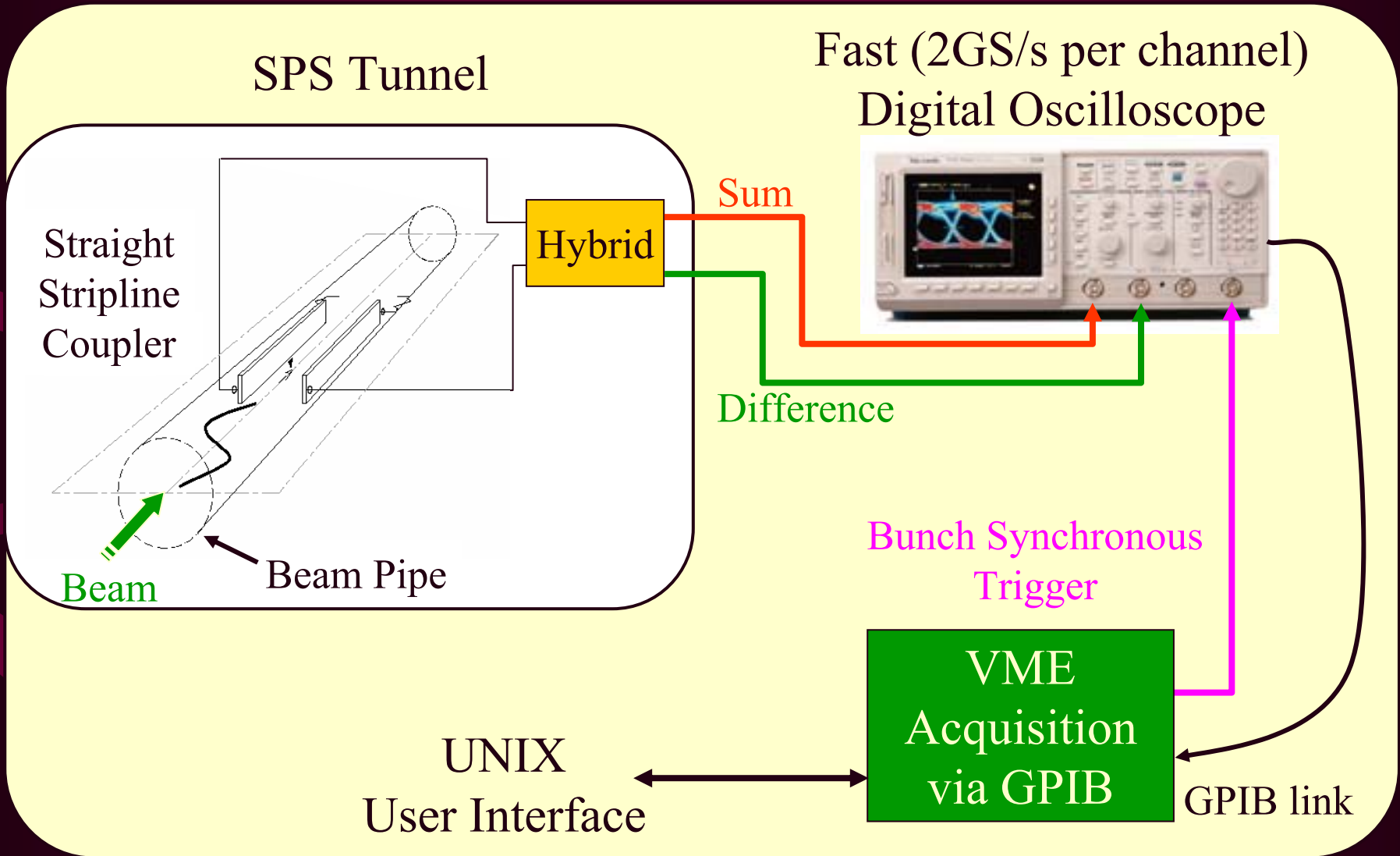


# The Head-Tail Measurement Principle



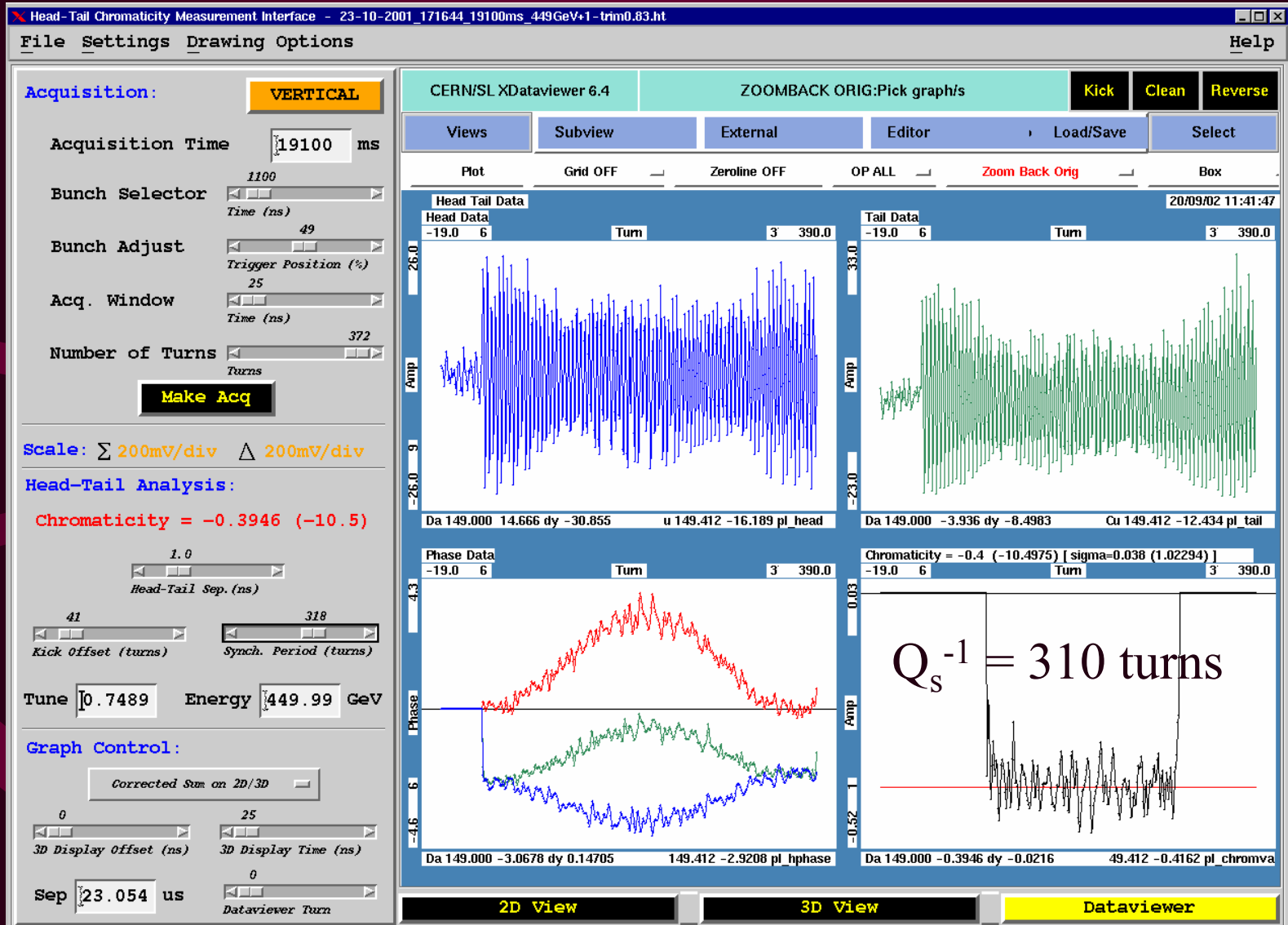


# Head-Tail System Set-up (SPS)





# Measuring Q' (Example 1: low Qs)







# Measuring Q' (Example 2: high Qs)

Head-Tail Chromaticity Measurement Interface - 23-05-2000\_121709\_1000ms\_36GeV-R-2.7.ht

File Settings Drawing Options Help

Acquisition: **VERTICAL**

Acquisition Time: 1000 ms

Bunch Selector: 17400

Bunch Adjust: 40

Acq. Window: 25

Number of Turns: 372

**Make Acq**

Gains:  $\Sigma$  200mV/div  $\Delta$  20mV/div

Head-Tail Analysis:

Chromaticity = 1.7 (0.0622)

Signal Tail: 1.0

Kick Offset (turns): 39

Head-Tail Sep. (ns): 97

Synch. Period (turns): 97

Tune: 0.5822 Energy: 36.712 GeV

Graph Control:

Corrected Sum on 2D/3D

3D Display Offset (ns): 0

3D Display Time (ns): 25

Sep: 23.065 us

Dataviewer Turn: 0

Ready ...

CERN/SL XDataviewer 6.4 ZOOMIN:Pick first point Kick Clean Reverse

Views Subview External Editor Load/Save Select

Plot Grid OFF Zeroline OFF OP ONE Zoom In Box

Head Tail Data 30/11/00 15:59:57

Head Data -19.0 Tum 390.0

Tail Data -19.0 Tum 390.0

Phase Data -17.99755 Tum 390.0

Chromaticity = 1.7 (0.0622) [sigma=0.103 (0.00386)]

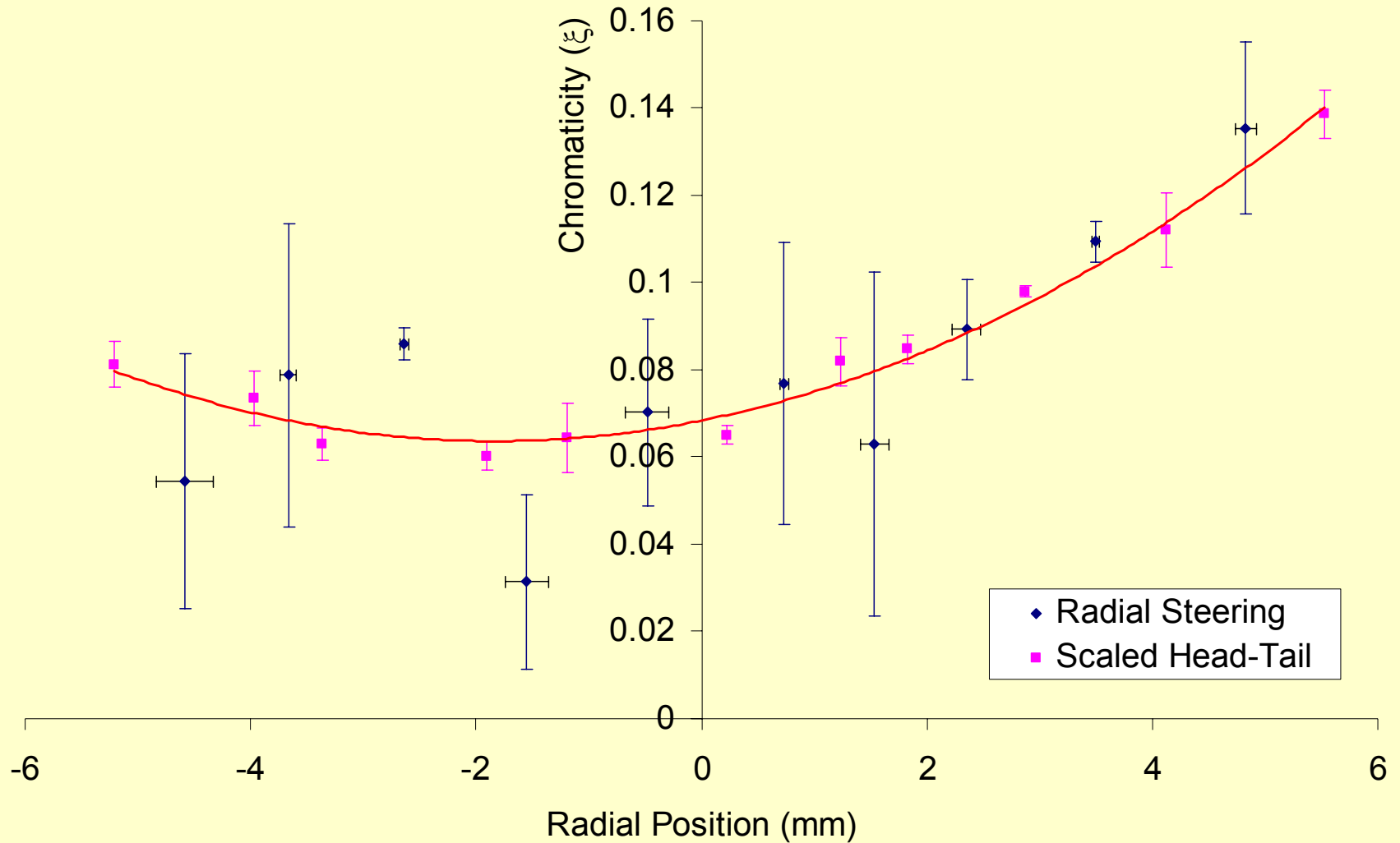
$Q_s^{-1} = 97$  turns

2D View 3D View Dataviewer Mountainviewer



# Measuring $Q''$ and $Q'''$

Radial Position versus Chromaticity (115GeV)





# 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

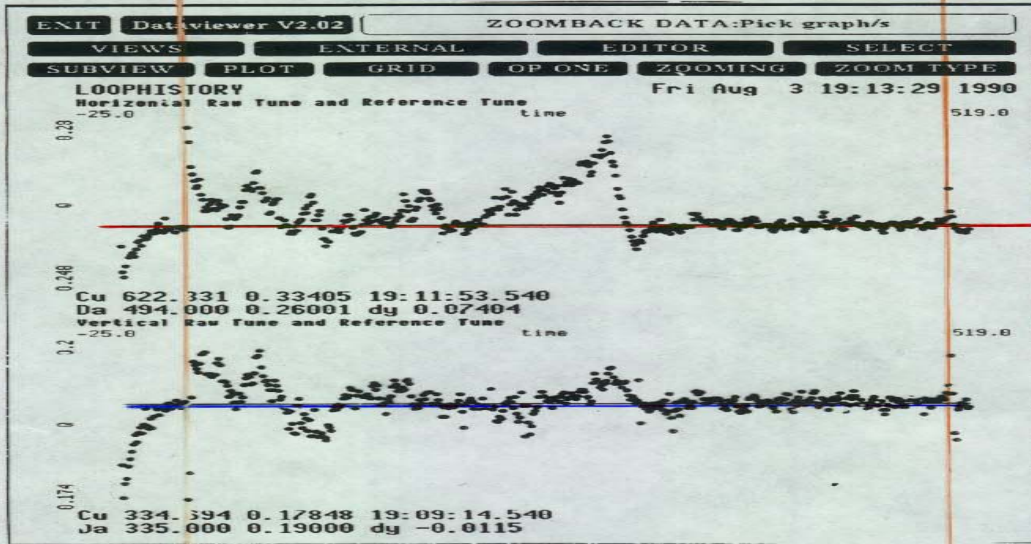


# Early example from LEP

Q - Feedback loop during energy sampling

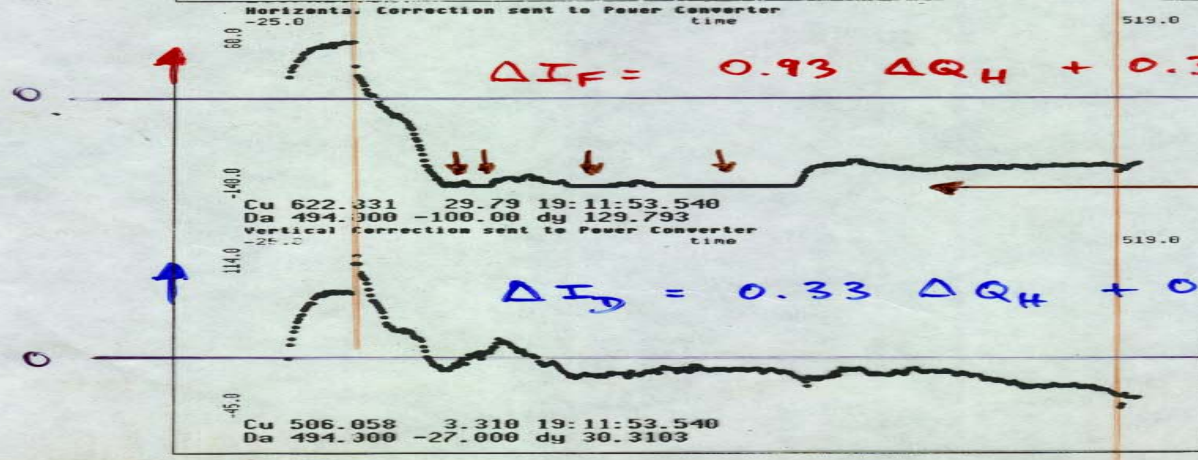
start of ramp

end of ramp



q<sub>ref</sub> H

q<sub>ref</sub> V



$$\Delta I_F = 0.93 \Delta Q_H + 0.32 \Delta Q_V \quad (\text{at } 70 \text{ GeV})$$

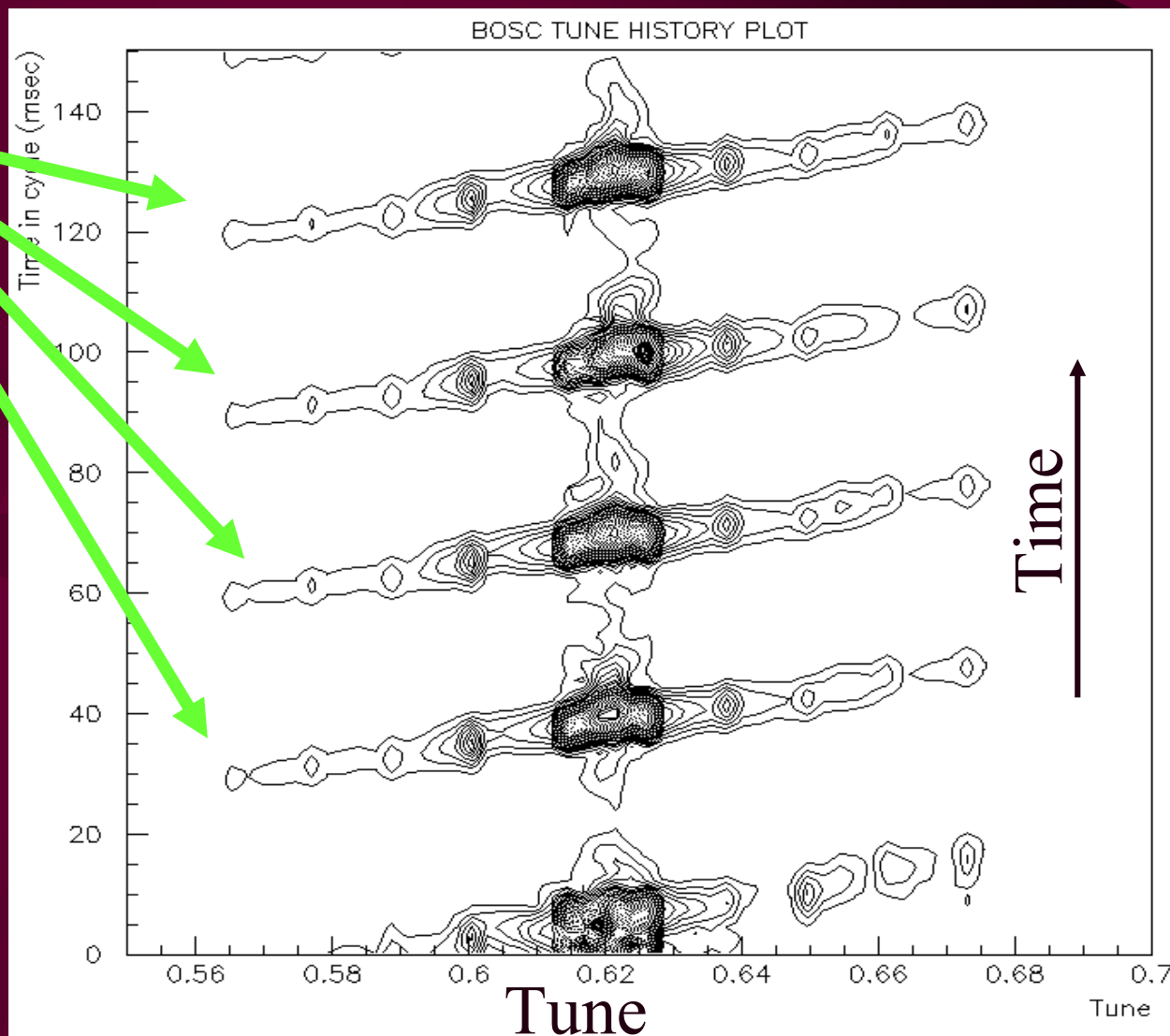
saturation  
 $\Delta I_F / I_F = -1000 \mu\text{p}$

$$\Delta I_D = 0.33 \Delta Q_H + 0.97 \Delta Q_V \quad (\text{at } 70 \text{ GeV})$$



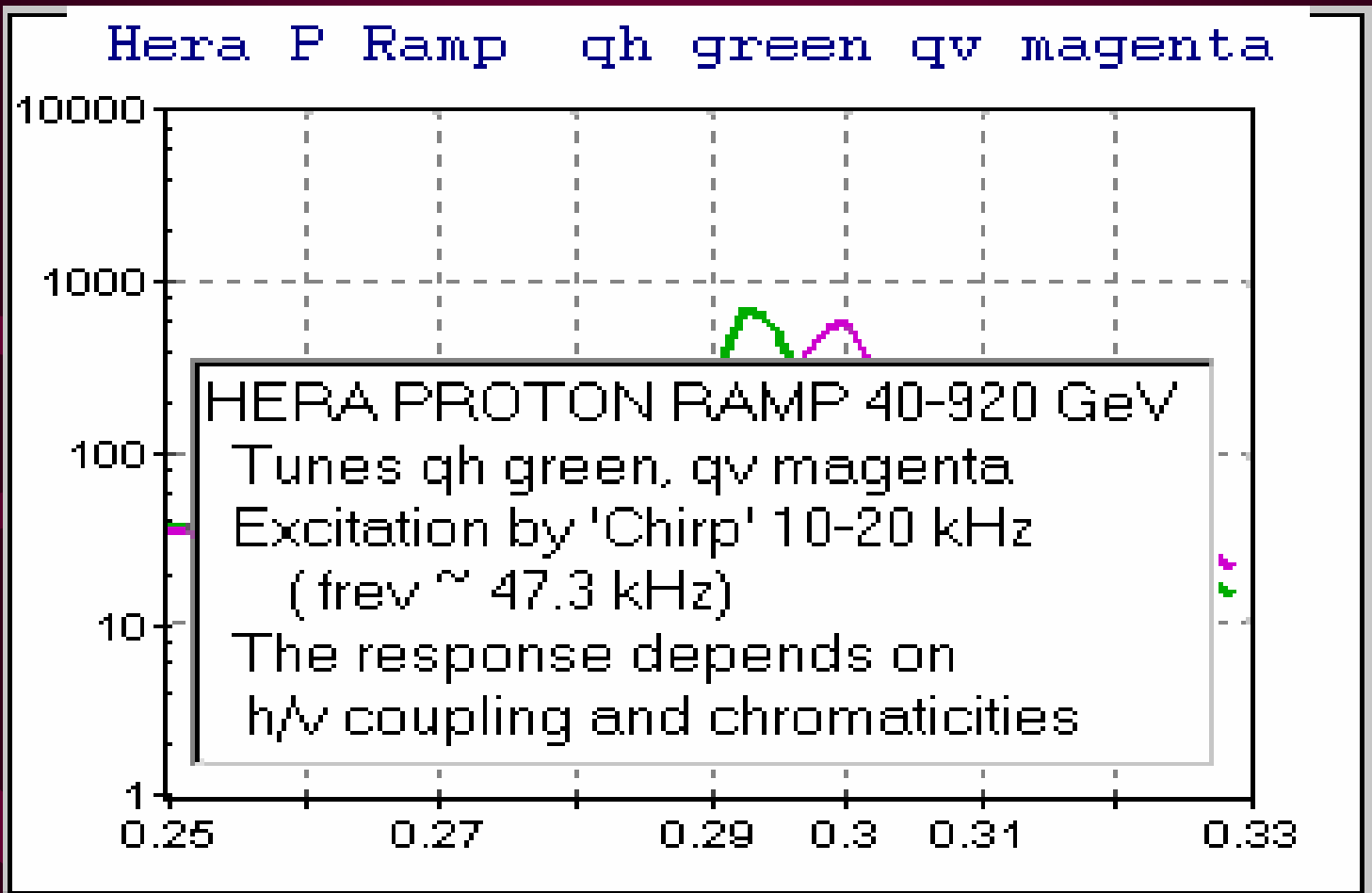
# HERA-p solution:

- “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)



39.69

GeV

Sat Apr 20 17:24:00 2002



# Outline for Today

## ★ Optimisation of Machine Performance ("the good days")

- Orbit measurement & correction
- Luminosity: basics, profile and  $\beta$  - measurements

## ★ Diagnostics of transverse beam motion

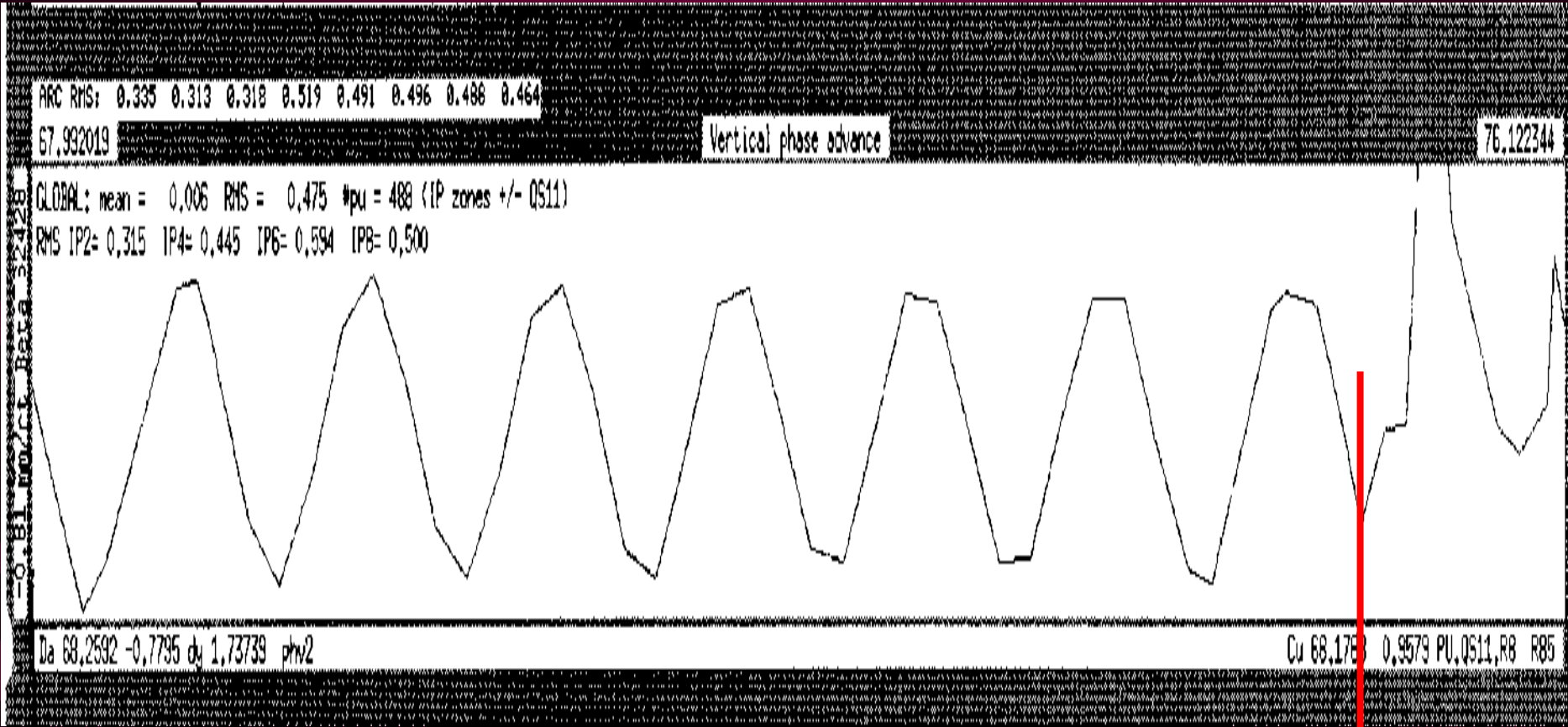
- Tune & chromaticity measurements
- Dynamic effects: tune and chromaticity control
- On-line  $\beta$  measurements

## ★ 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



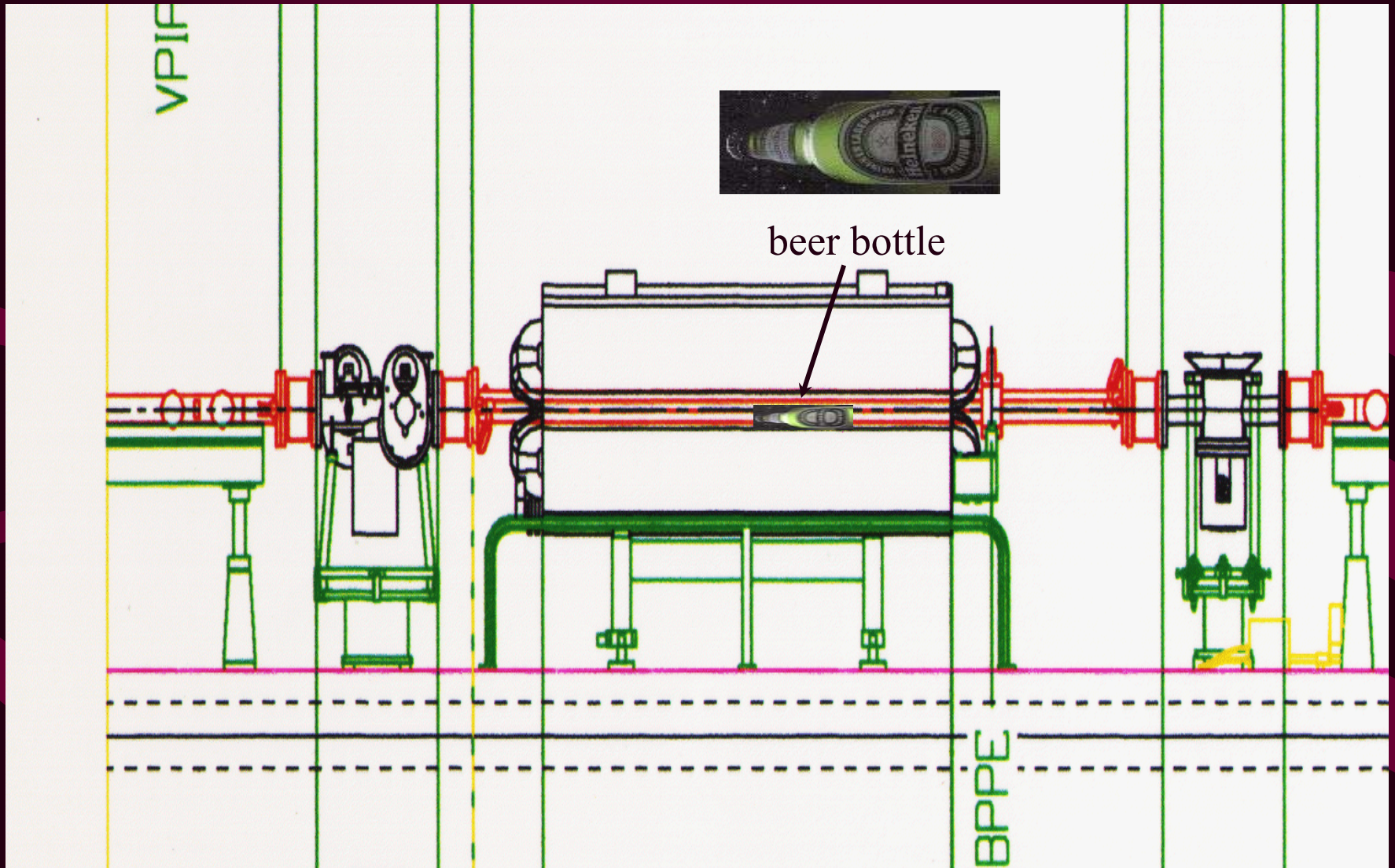
Positrons →

QL10.L1



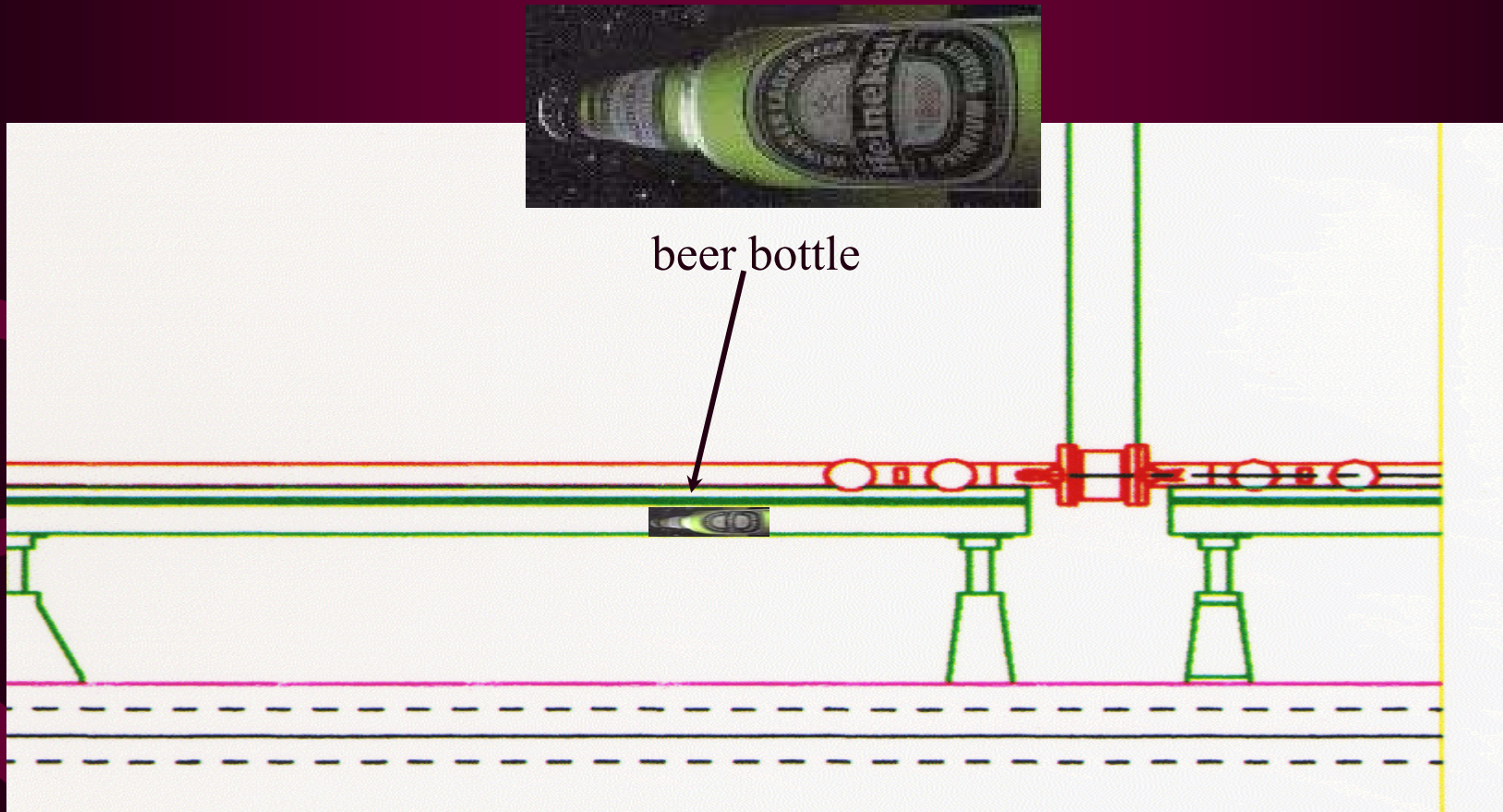


# Zoom on QL1





# 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  $\sim 97-98$  GeV  $e^-$  large vertical oscillation  
OPAL trigger. Maybe a bit too ambitious

Tune history 01-12-40 fill 7065  
→ nothing particularly nasty.

Big radiation spikes in all expts.

01:40

22 GeV 4QSO Breakpoint at 93 GeV.

640  $\mu$ A .234 / -164 5.27 mA

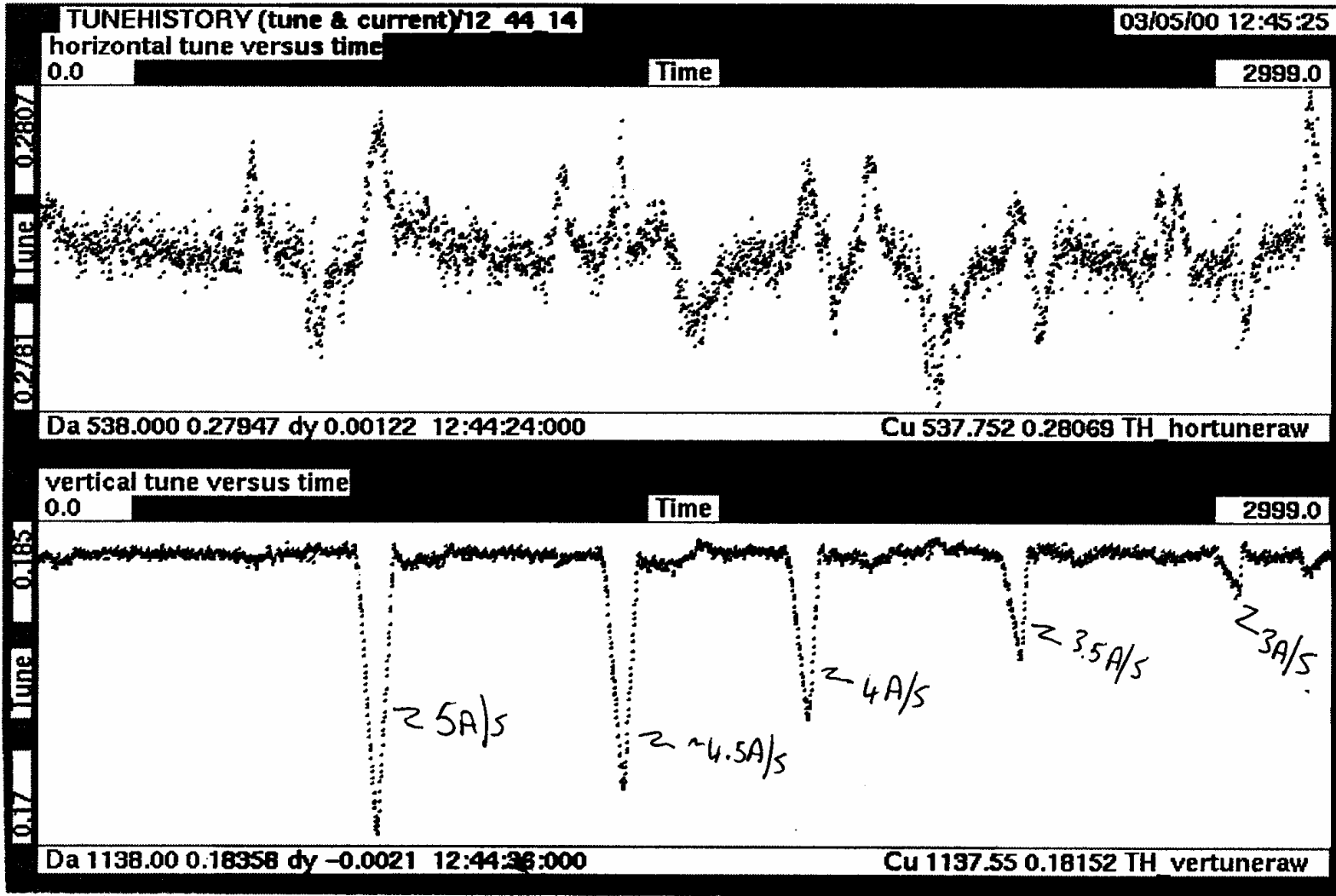
93 GeV 4QSO 01-58-36  $\nu$  RMS  $\sim$

Tune history 01-50-25 fill 7066



# ...and the corresponding diagnostics

Depends critically on ramp rate of Pcs





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%20lecture/>