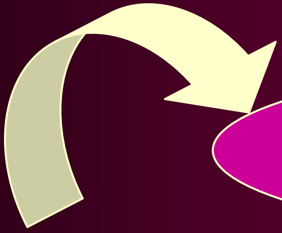
Beam Instrumentation
&
Beam Diagnostics



Today

CAS 2007

Hermann Schmickler & Rhodri Jones
(CERN)

Instrumentation---Diagnostics

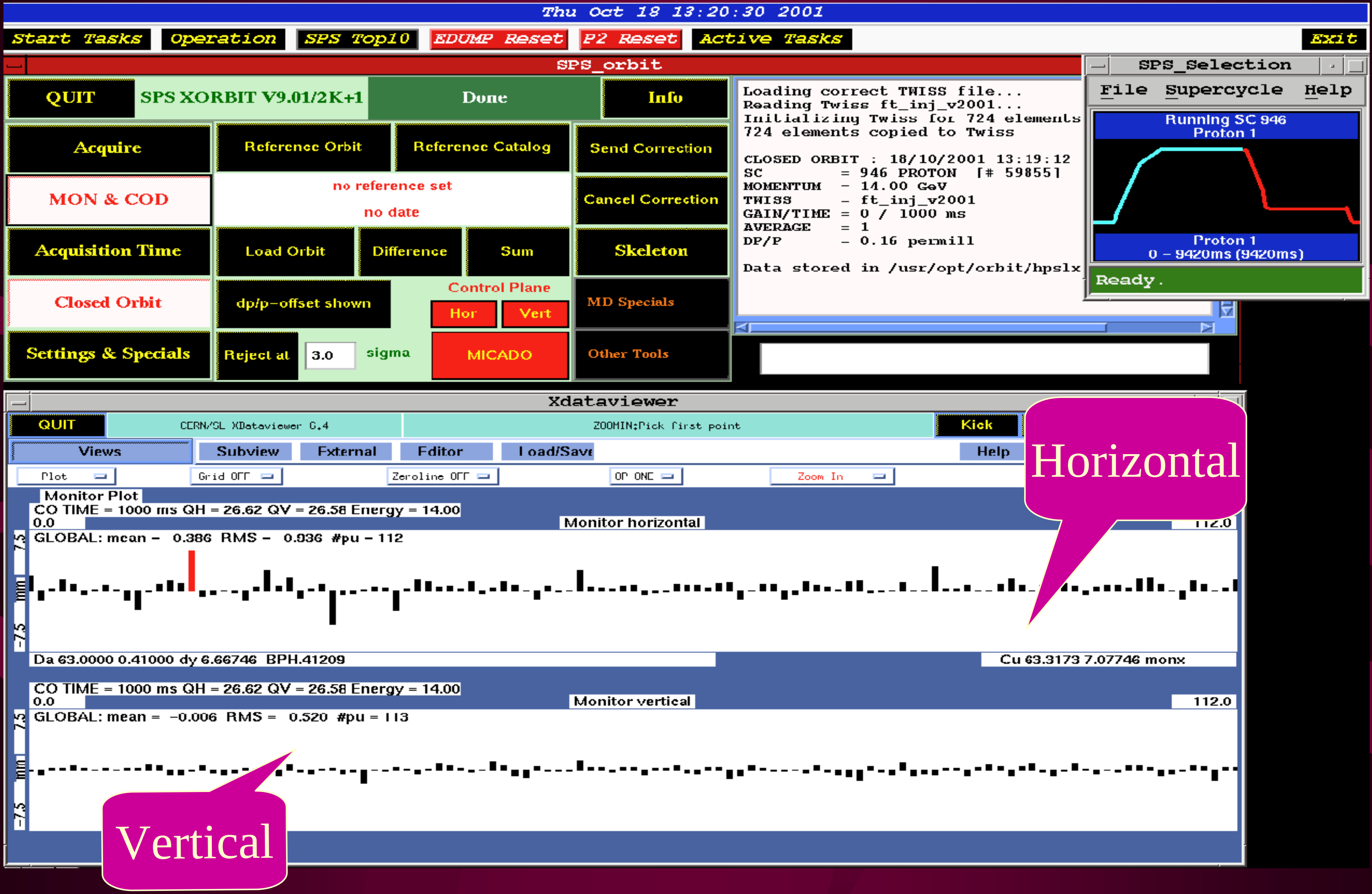
- Instrumentation: summary word for all the technologies needed to produce primary measurements of direct beam observables.
- Diagnostics: making use of these instruments in order to
  - operate the accelerators ex: orbit control
  - improve the performance of the accelerators
    ex: tune feedback, emittance preservation
  - deduce further beam parameters or performance indicators of the machine by further data processing
    ex: chromaticty measurements, betatron matching, bunch arrival time
- - detect equipment faults

Example: Instrumentation <-> Diagnostics

a BPM (yesterdays talk) delivers two values:
X,Y…the transverse position of the beam.
It delivers these values per machine turn/beam passage or per bunch passage in the BPM.
- Diagnostics usage:
Closed Orbit (=: CO)
- inspection/Correction
- automated real time feedback
- dispersion (CO for different momentum)
Turn by Turn data:
- machine optics (values of beta function, phase advances)
- tune, chromaticty

!!! The details of the diagnostics usage determine the specifications of the instruments. !!!

Orbit Acquisition



Thu Oct 18 13:20:30 2001

no reference set

no date

dp/p–offset shown

Reject at 3.0 sigma

```
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
```

Ready.

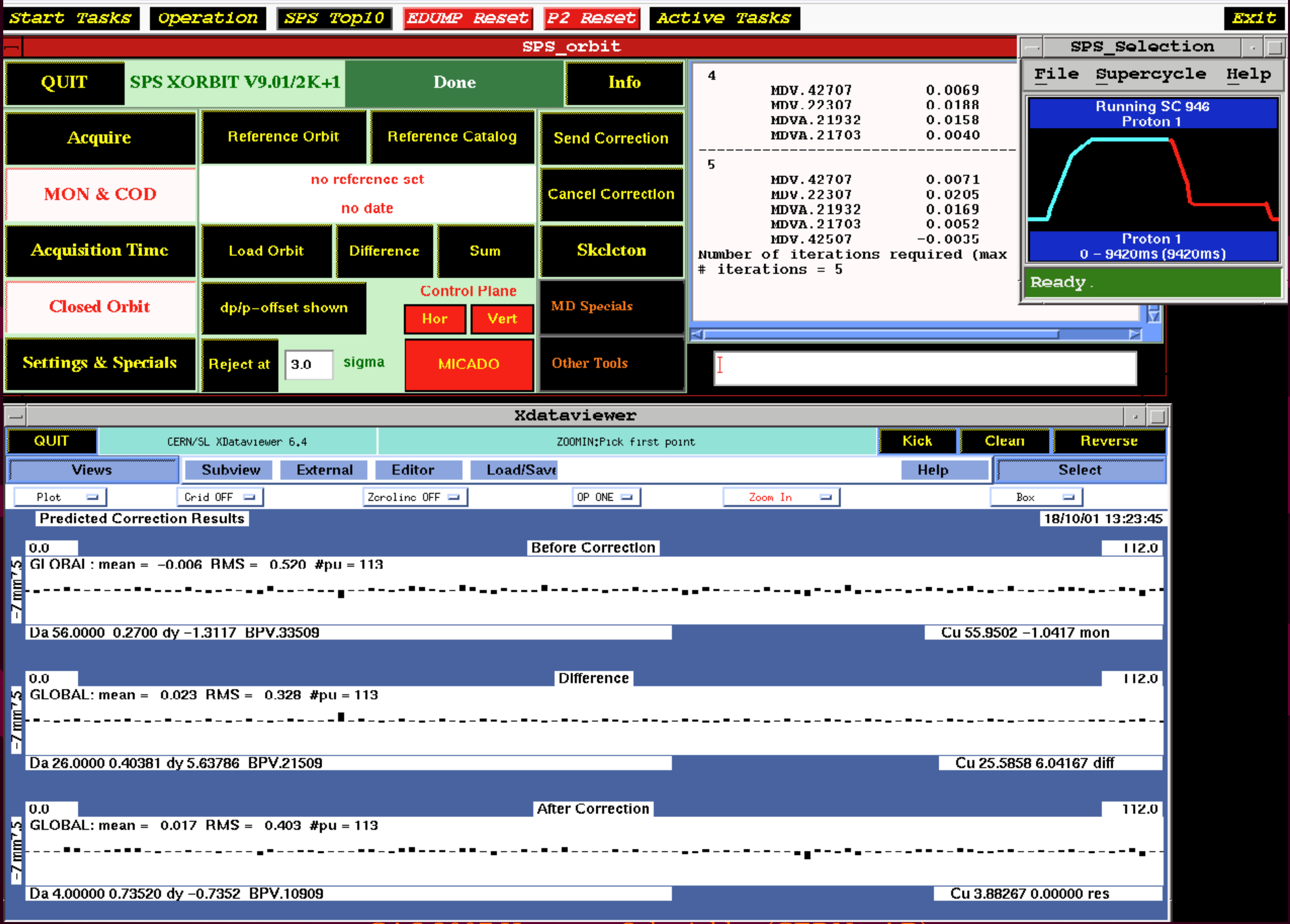
CERN/SL XDataviewer C.4

ZOOMIN:Pick first point

```
CO TIME = 1000 ms QH = 26.62 QV = 26.58 Energy = 14.00
0.0                                                  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                                                  112.0
GLOBAL: mean =  –0.006  RMS =  0.520  #pu = 113
```

Orbit Correction (Operator Panel)



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Reject at 3.0 sigma

```
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
```

Before Correction

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

Difference

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

After Correction

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)

Predicted Correction Results

18/10/01 13:23:45

Before Correction

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

Da 51.0000 1.13000 dy 4.38471 BPV.32509

Cu 50.9724 5.51471 mon

Difference

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

Da 51.0000 -0.4302 dy 4.25372 BPV.32509

Cu 50.8729 3.8235 diff

After Correction

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

Da 51.0000 0.69981 dy 6.80019 BPV.32509

Cu 51.1716 7.50000 res

Outline for Today

- Optimisation of Machine Performance
  ("the good days")
  - →Luminosity: basics + luminosity tuning, betatron ma
- Various Diagnostics
  ("the fun days")
  - → Tune & chromaticity measurements
  - → Dynamic effects: tune and chromaticity control
  - → Bunch arrival time in FEL

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*

Luminosity & Beam-Beam Tune Shift

- Luminosity
- Normalized emittance
- Beam-beam tune shift

Number of Bunches

Bunch Intensity

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

Beam size at the IP

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

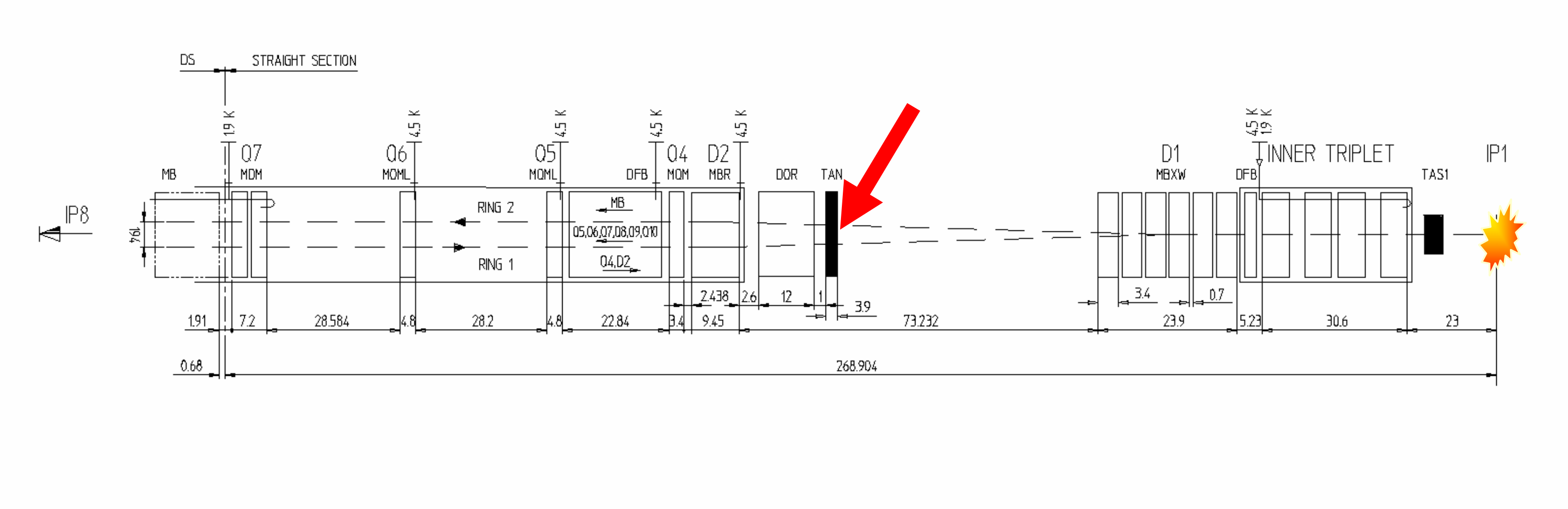
$$\Delta\nu_{bb} = \frac{Nr_p}{4\pi\varepsilon_N} \leq 0.006 \text{ (LHC)}$$

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

- To maximize L and minimize the stored energy, increase N to the tune shift limit, choose a large number of bunches (M) and a small β_*

Luminosity Measurements

In general: Measure flux of secondary particles produced in the collisions, for which the cross section of production is known. The fluxrate is a direct measure of Luminosity.



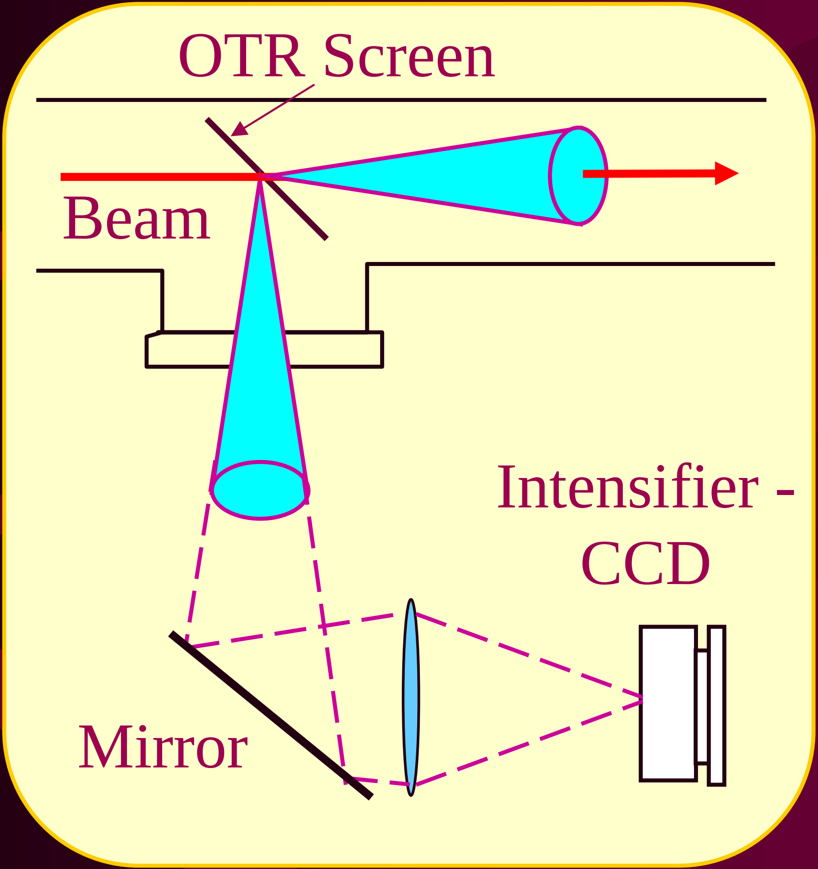
- The TAN absorbs forward neutral collision products (mostly neutrons and photons) and is placed in front of the outer beam separation dipole D2
- Ideal location to measure the forward flux of collision products
- The count rate is proportional to luminosity

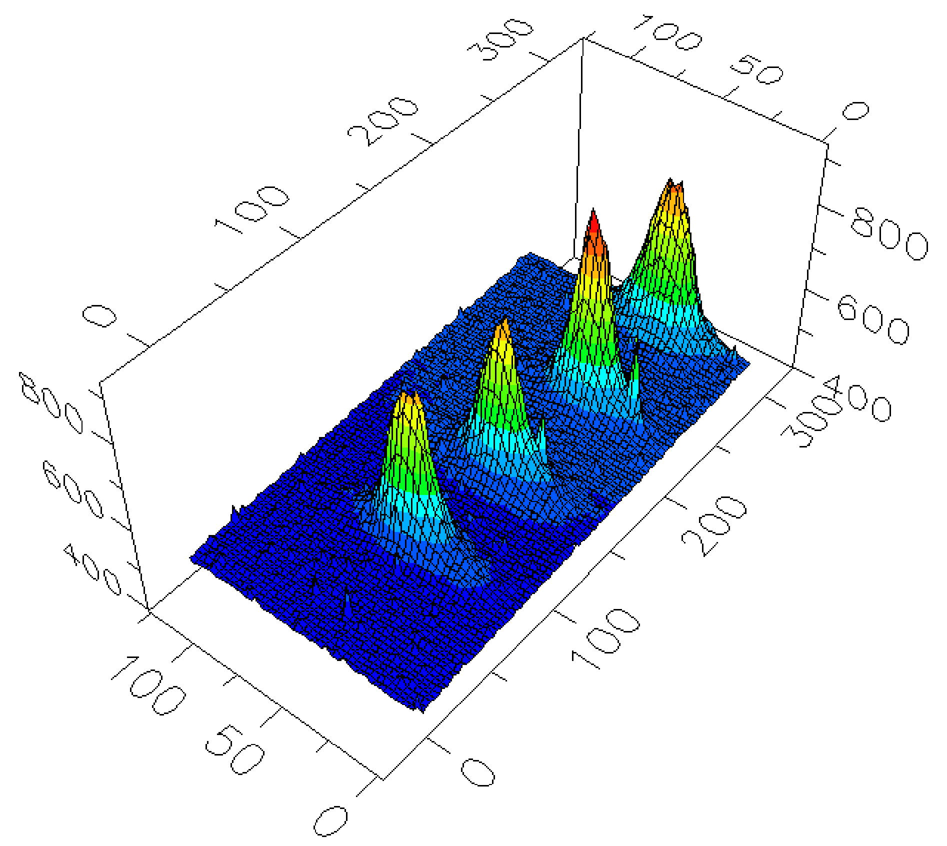
Improving luminosity

1) Stronger focusing insertions
→ transition from high beta optics at injection to low beta optics at collision (so called beta squeeze):
critical process with dynamic effects on orbit, tune and chromaticty
2) Smaller emittance and emittance preservation through the pre-injectors
→ measurements of beam size from low energy beams to high energy beams
→ betatron matching at injection
3) Higher intensity: sounds simple, but one needs diagnostics (and cures) for the onset of instabilities,
real time longitudinal and transverse feedback, control of radiation issues, i.e. beam loss monitors.

Optical Transition Radiation Monitors

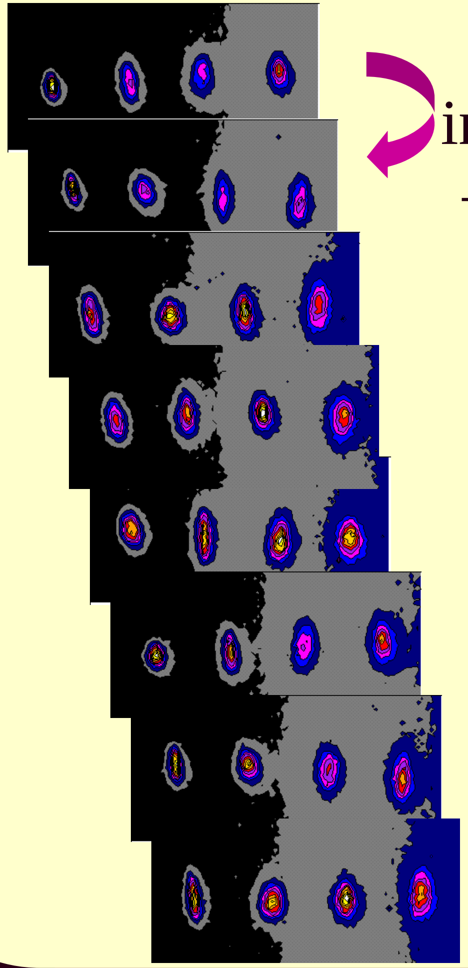
As Beam hits the 12µm Titanium foil 2 cones of radiation are emitted



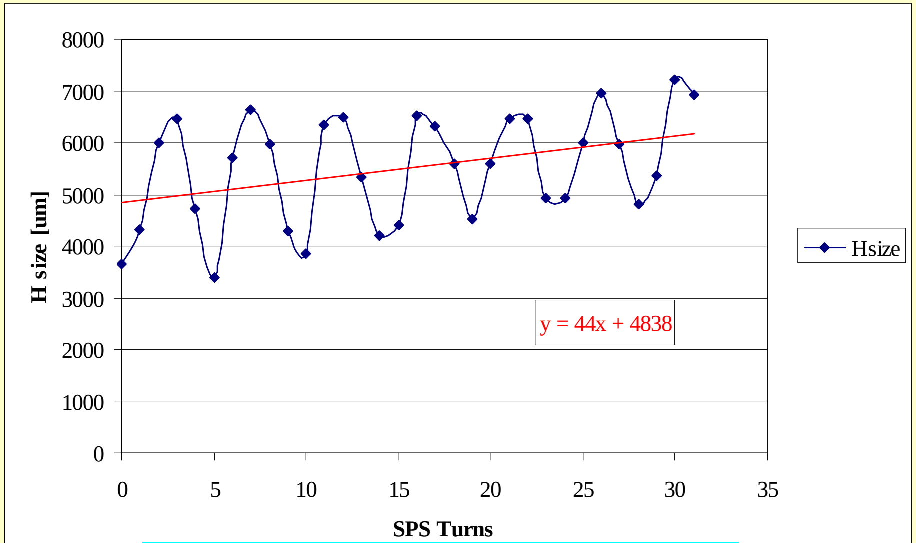


Capturing emitted radiation on a CCD gives 2D beam distribution

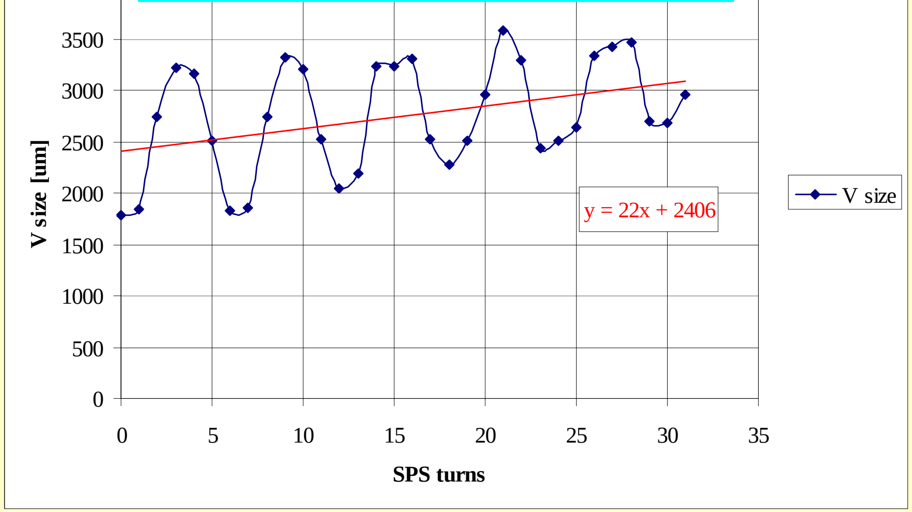
Turn-by-Turn OTR Results



Next injection +1 turn



Very poor matching!!

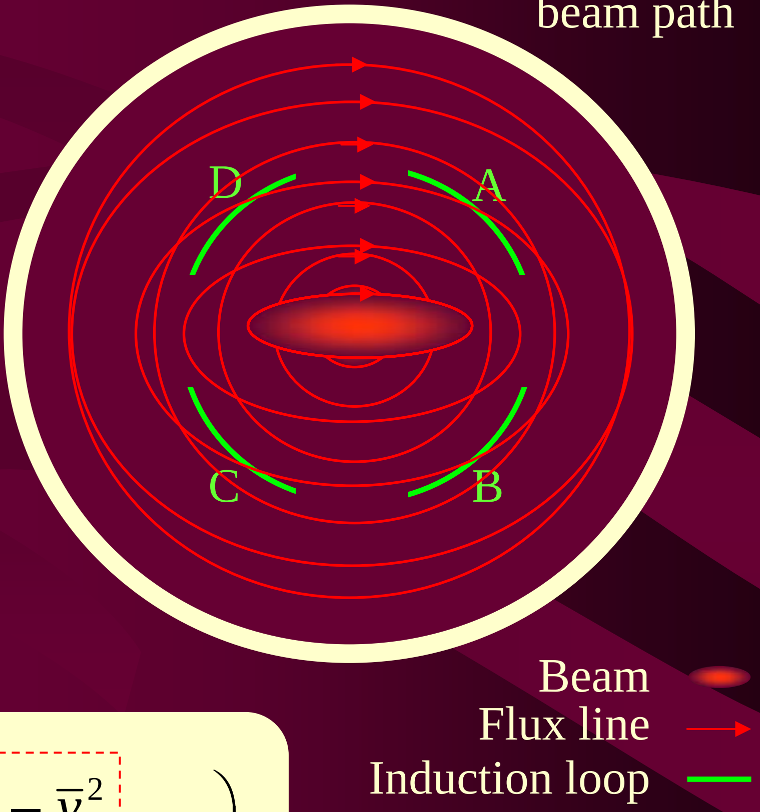


β-Mismatch at injection seen as a beating in the beam profile

Quadrupolar Pick-Up

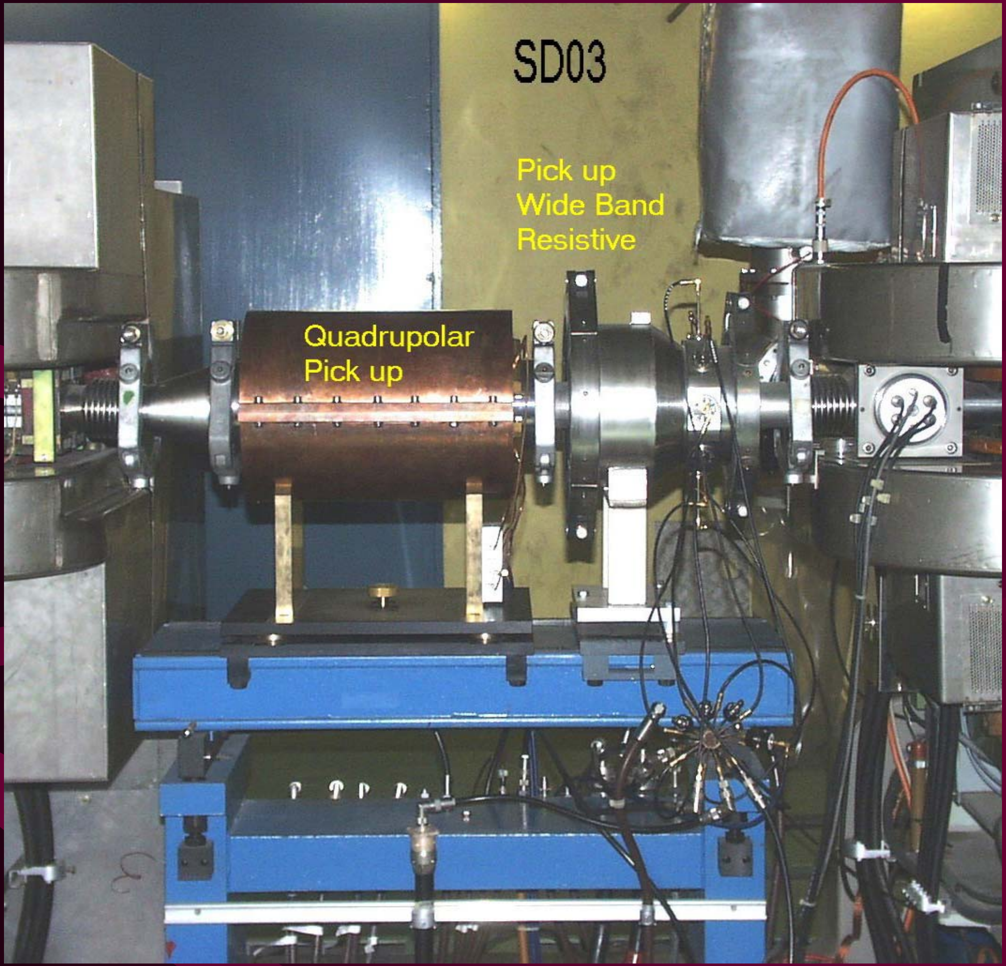
- Position contribution can not be avoided, but can be measured and subtracted.
- Design suppresses the dominating intensity signal by coupling to the radial magnetic field component.

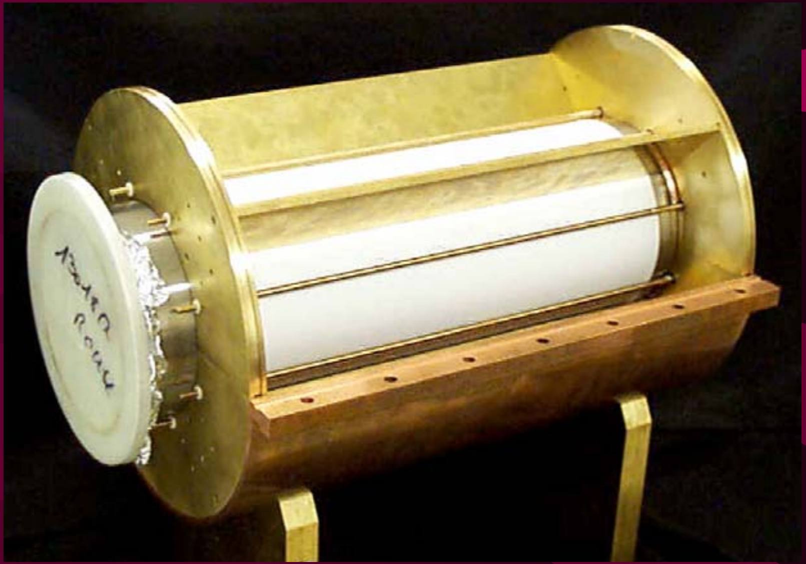
Pick-up seen along beam path



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

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

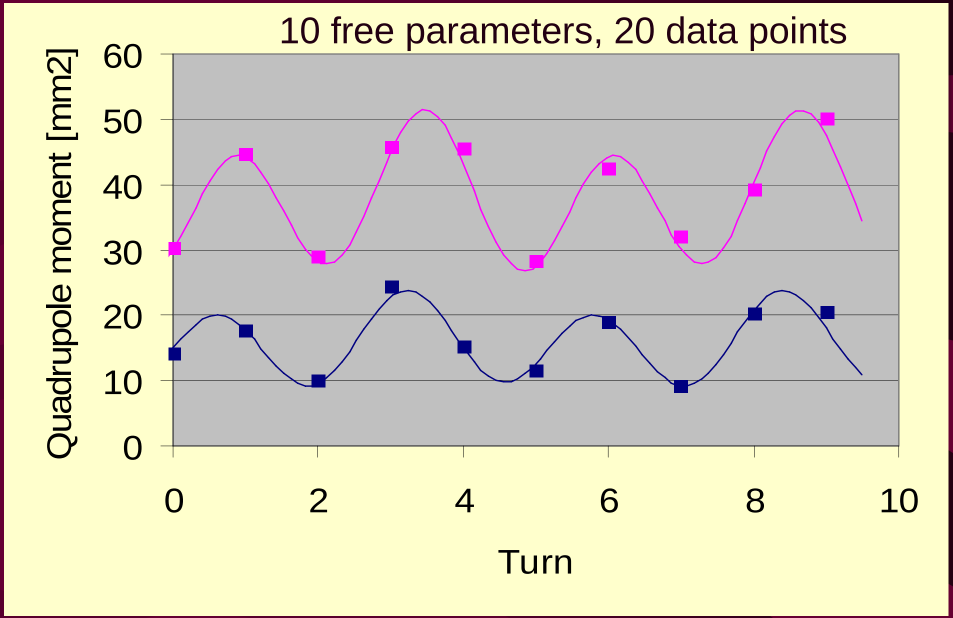
“One pick-up per plane”

Measurement of Matching

$$\kappa \propto \sigma_x^2 - \sigma_y^2 =$$

$$\varepsilon_x(\beta_x + \underbrace{\Delta\beta_x}_{2q_x}) - \varepsilon_y(\beta_y + \underbrace{\Delta\beta_y}_{2q_y}) +$$

$$+\sigma_p^2(D_x^2 + D_x\underbrace{\Delta D_x}_{q_x} + \underbrace{\Delta D_x^2}_{2q_x} - \underbrace{\Delta D_y^2}_{2q_y})$$

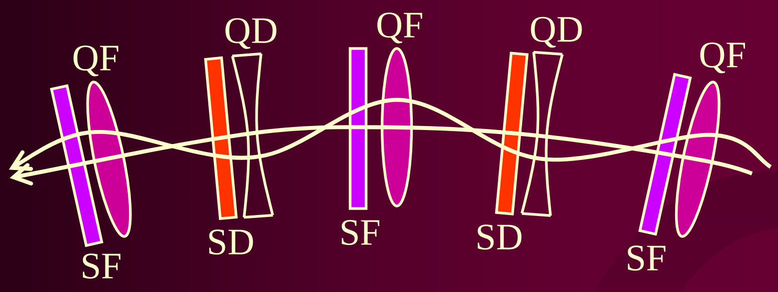


- Simultaneous fit to the two pick-up signals gives:
  - → Injected emittances.
  - → Betatron mismatches.
  - → Horizontal dispersion mismatch.
- Input parameters
  - → β_H, β_V, D_H
  - → $\Delta\mu_H$, $\Delta\mu_V$
  - → σ_p, q_h, q_v
- Most input parameters can be checked experimentally

Outline for Today

- Optimisation of Machine Performance
  ("the good days")
  - → Orbit measurement & correction
  - → Luminosity: basics + luminosity tuning, betatron matching
- Diagnostics of transverse beam motion:
  Important tools to stabilize performance at high levels
  - → Tune & chromaticity measurements
  - → Dynamic effects: tune and chromaticity control
- 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)

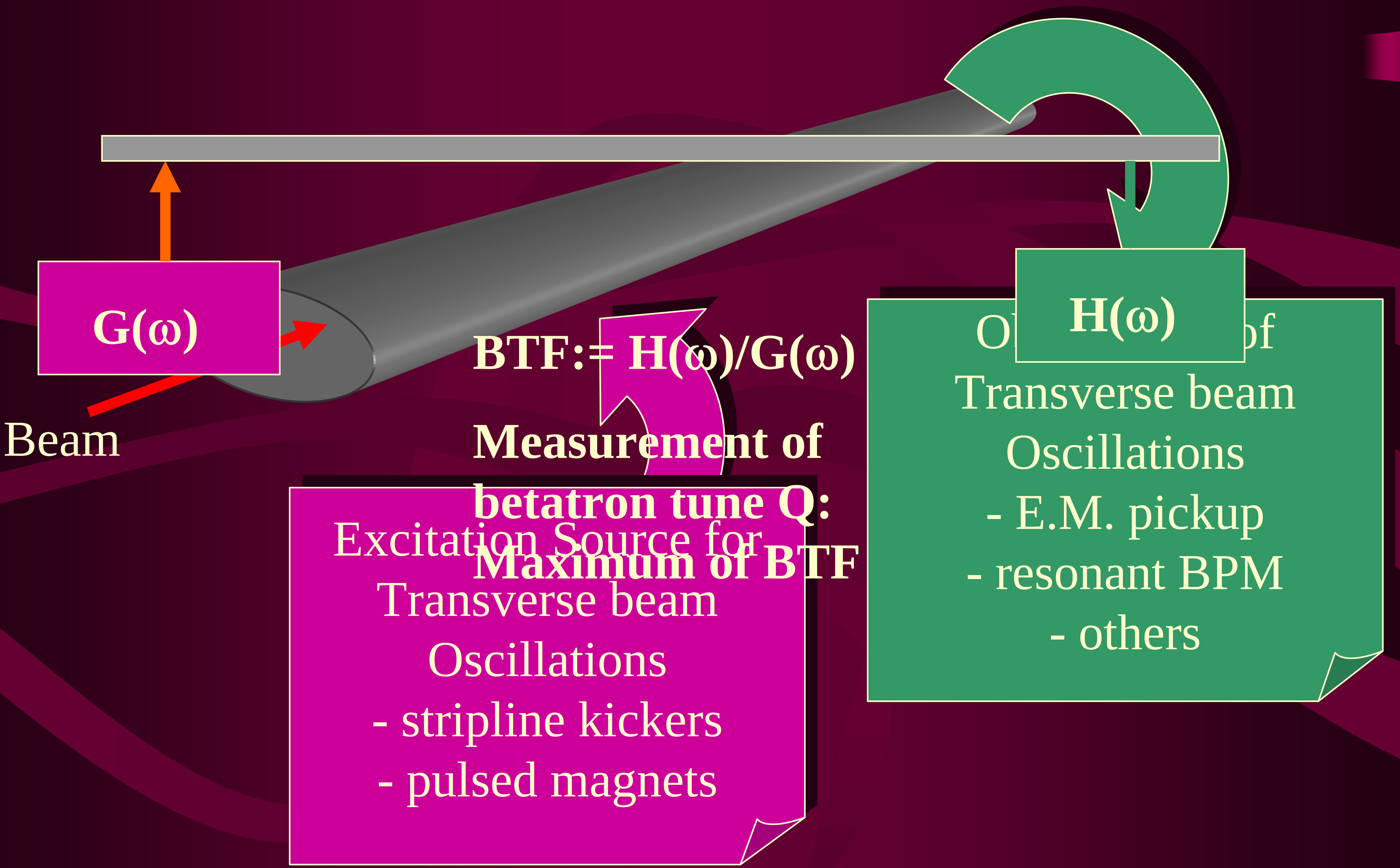


Characteristic Frequency of the Magnet Lattice

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



BTF:= H(ω)/G(ω)

Measurement of betatron tune Q: Maximum of BTF

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

O of
Transverse beam
Oscillations
- E.M. pickup
- resonant BPM
- others

Simple example: FFT analysis

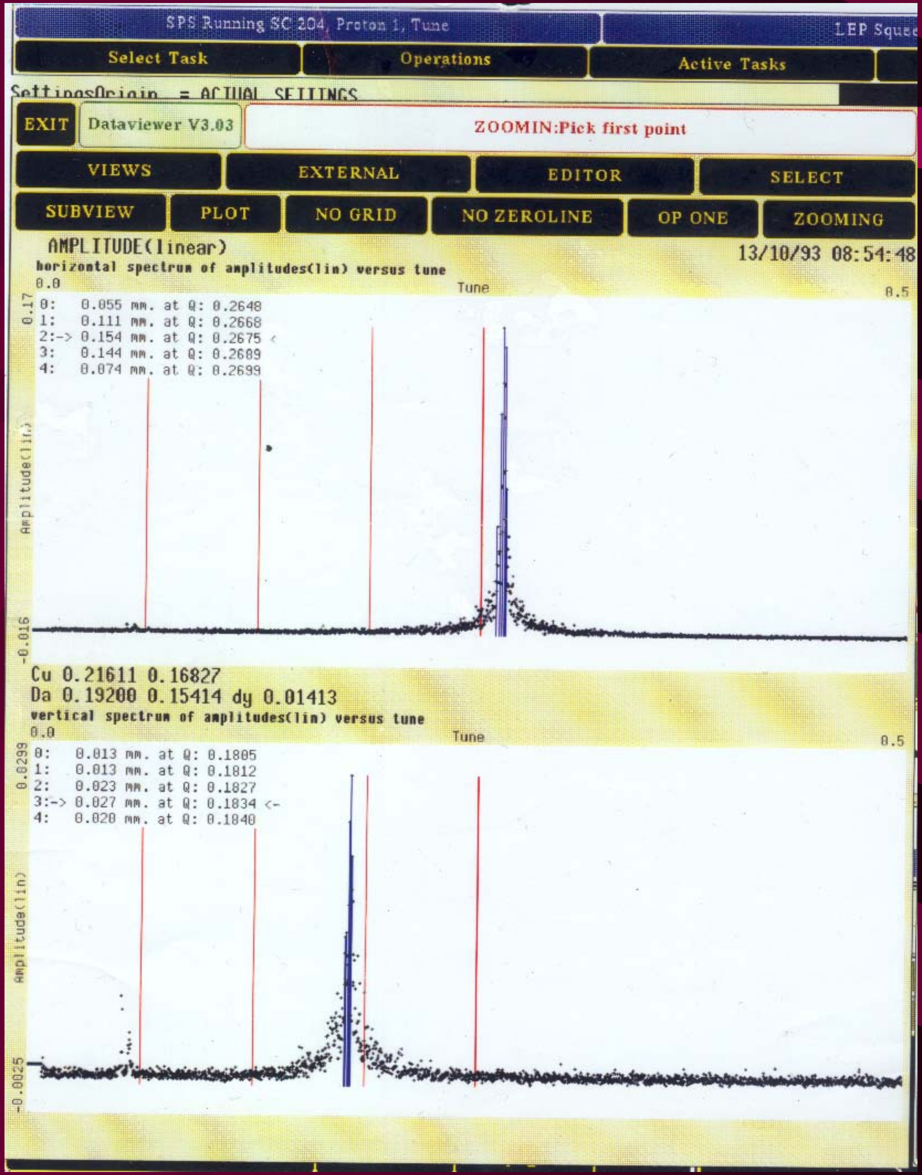
G(ω) == flat
(i.e. excite all frequencies)

Made with random noise kicks

Measure beam position over many consecutives turns

apply FFT → H(ω)

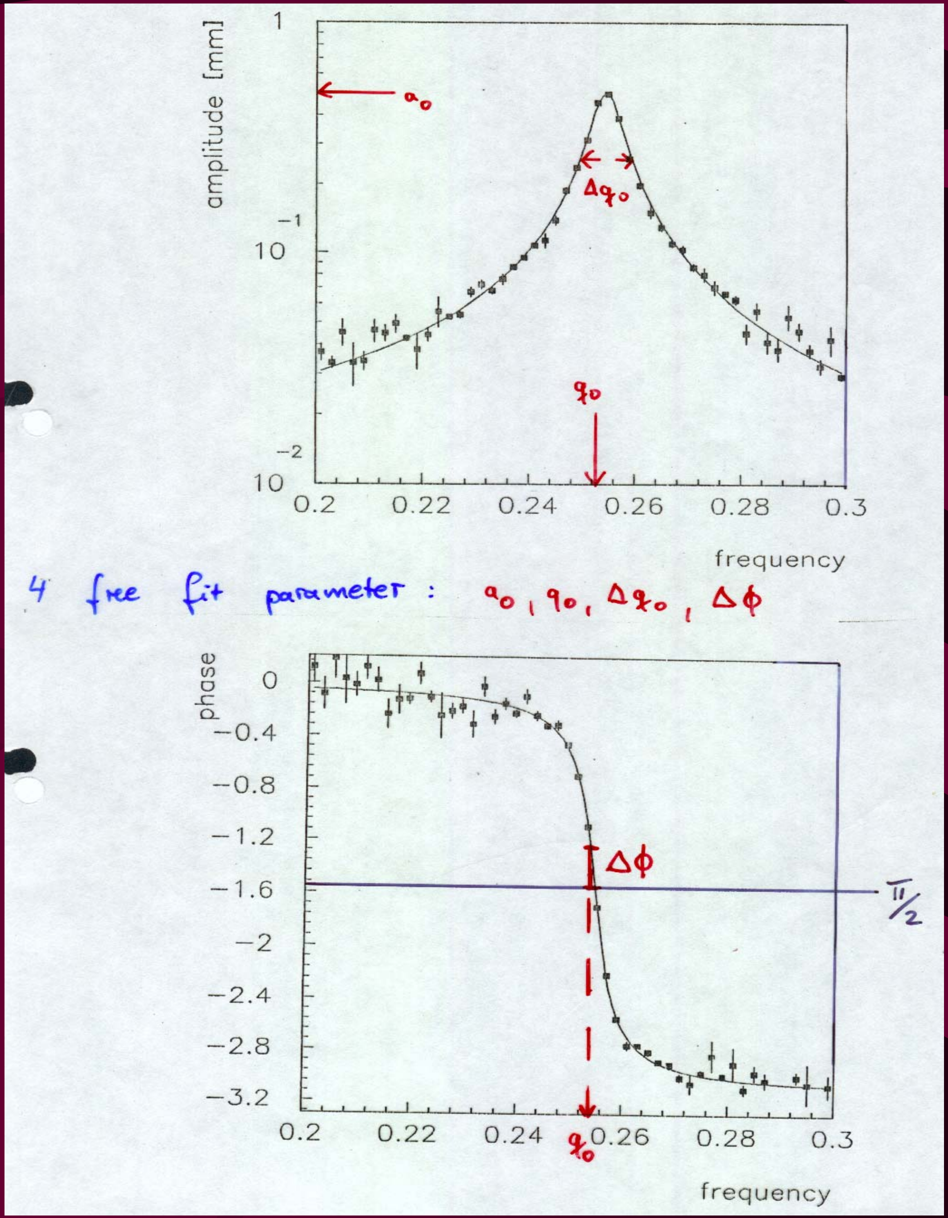
BTF = H(ω)



```
SettingsOrigin  = ACTUAL SETTINGS
AMPLITUDE(linear)                                        13/10/93 08:54:48
horizontal spectrum of amplitudes(lin) versus tune
0:    0.055 mm. at Q: 0.2648
1:    0.111 mm. at Q: 0.2668
2:-> 0.154 mm. at Q: 0.2675 <
3:    0.144 mm. at Q: 0.2689
4:    0.074 mm. at Q: 0.2699
Cu 0.21611 0.16827
Da 0.19200 0.15414 dy 0.01413
vertical spectrum of amplitudes(lin) versus tune
0:    0.013 mm. at Q: 0.1805
1:    0.013 mm. at Q: 0.1812
2:    0.023 mm. at Q: 0.1827
3:-> 0.027 mm. at Q: 0.1834 <-
4:    0.020 mm. at Q: 0.1840
```

Network Analysis

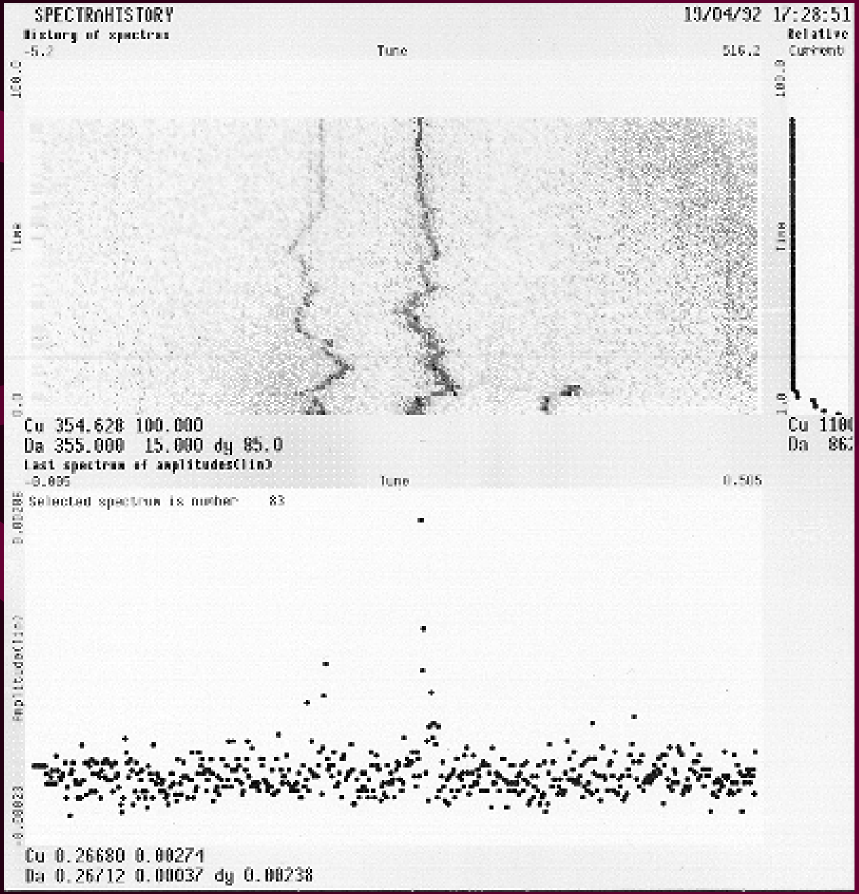
1. Excite beams with a sinusoidal carrier
2. Measure beam response
3. Sweep excitation frequency slowly through beam response

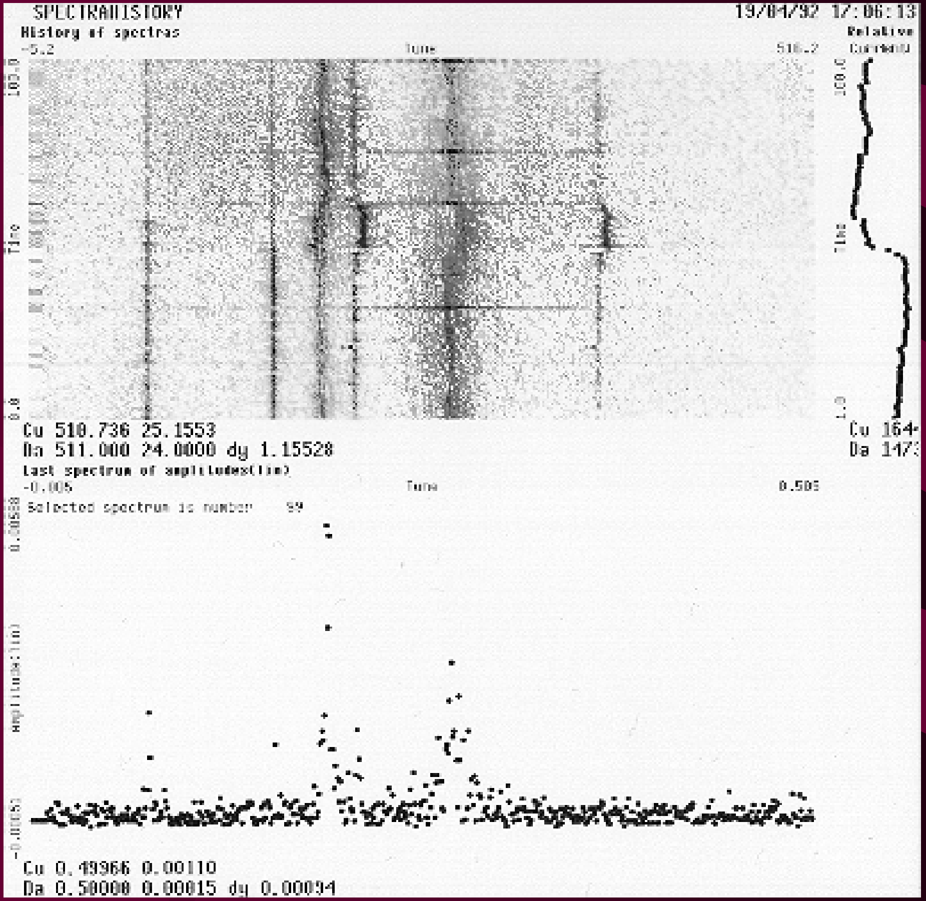


4 free fit parameter : a_0, q_0, Δq_0, $\Delta\phi$

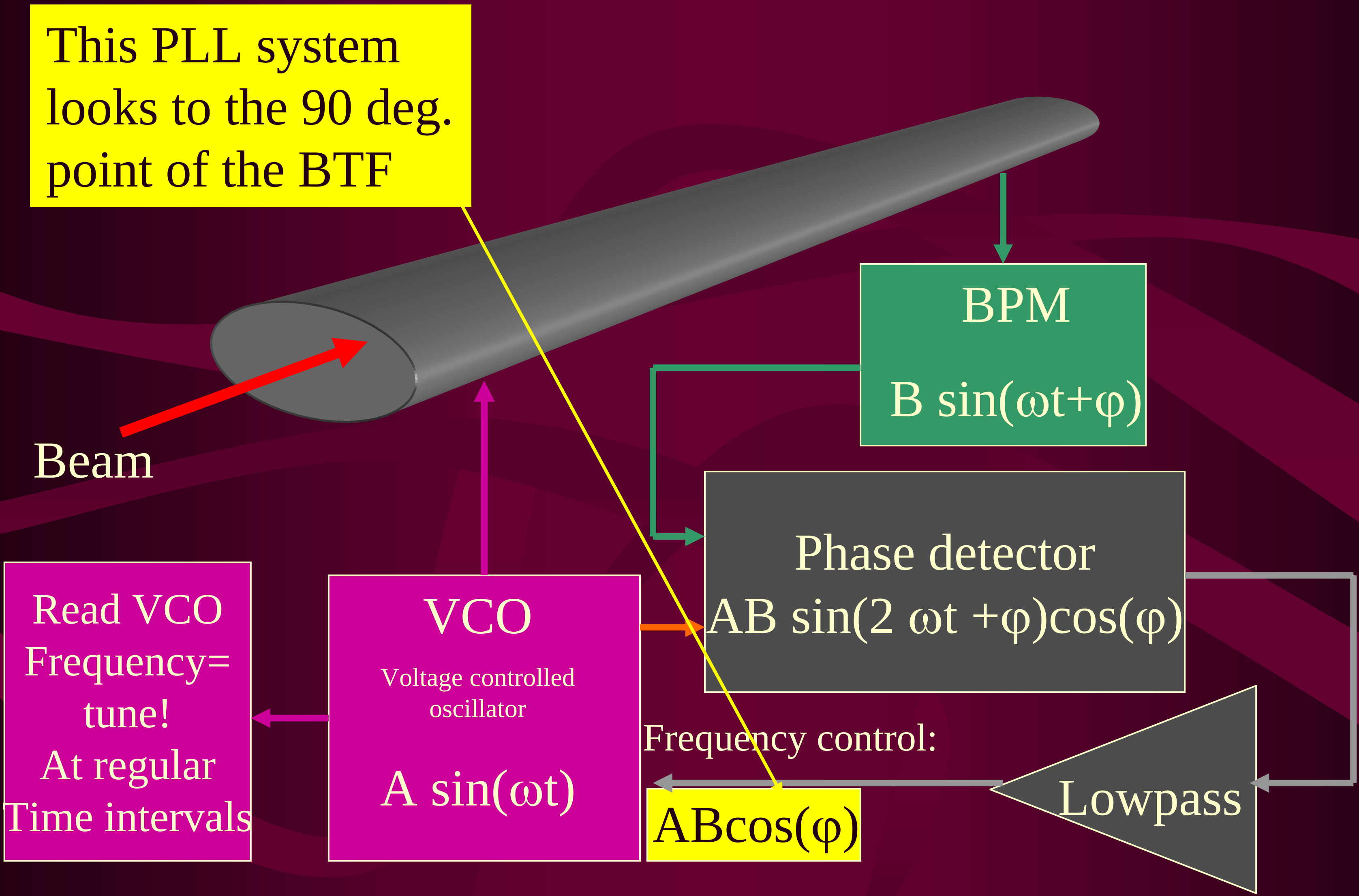
Time Resolved Measurements

- 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

BPM

$B \sin(\omega t+\varphi)$

Phase detector

$AB \sin(2\,\omega t+\varphi)\cos(\varphi)$

Lowpass

Frequency control:

$AB\cos(\varphi)$

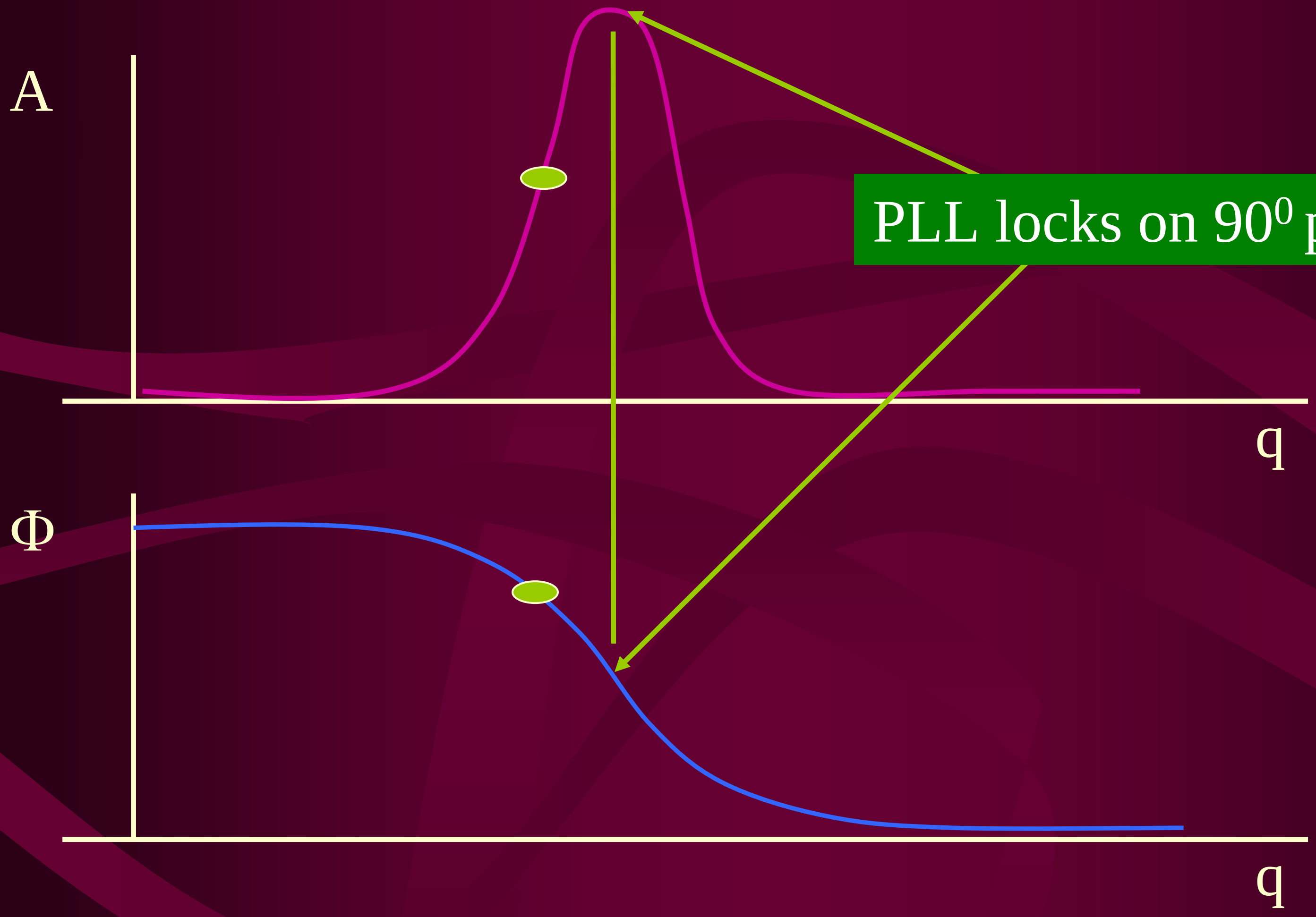
VCO

Voltage controlled oscillator

$A \sin(\omega t)$

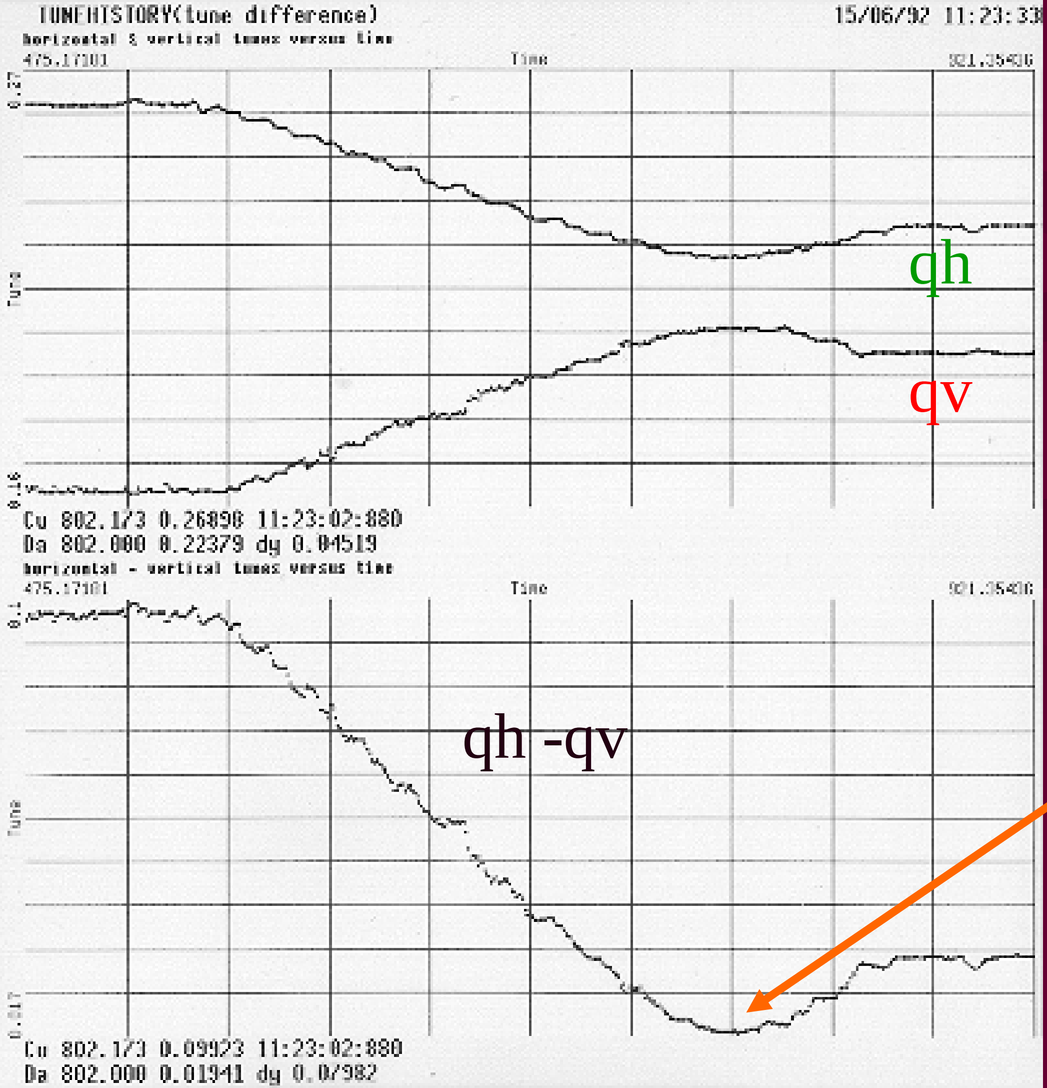
Read VCO Frequency= tune! At regular Time intervals

Illustration of PLL tune tracking



PLL locks on 90^0 point of BTF

Example of PLL tune measurement



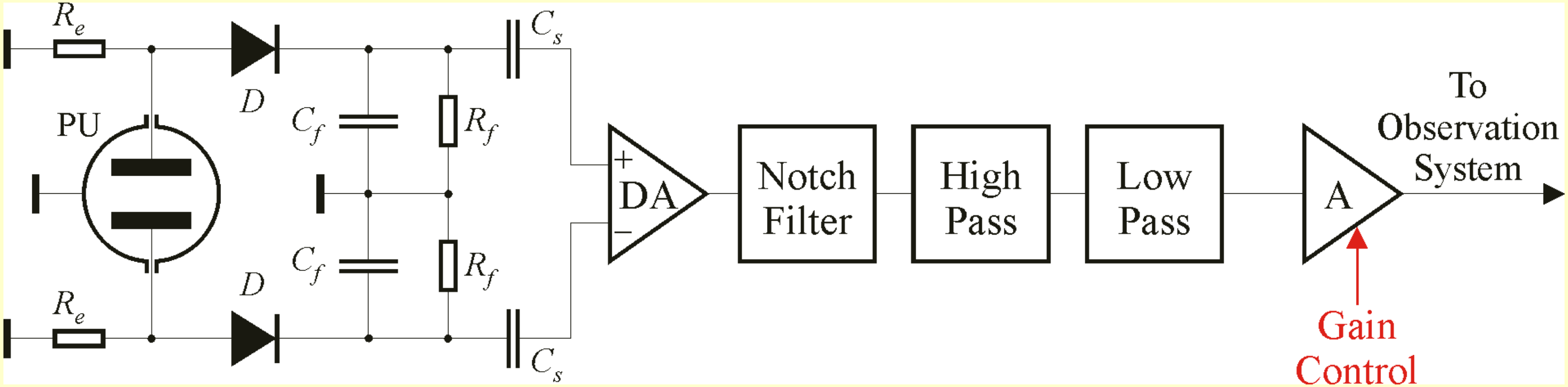
```
TUNEHISTORY(tune difference)                15/06/92 11:23:33
horizontal & vertical tunes versus time
Cu 802.173 0.26898 11:23:02:880
Da 802.000 0.22379 dy 0.04519
horizontal - vertical tunes versus time
Cu 802.173 0.09923 11:23:02:880
Da 802.000 0.01941 dy 0.07982
```

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

Tune Measurement Systems

- Standard Tune Measurement (FFT) and PLL tune tracker will use a new BaseBand Tune (BBQ) system developed at CERN using Direct Diode Detection (3D)



3D Method Advantages / Disadvantages

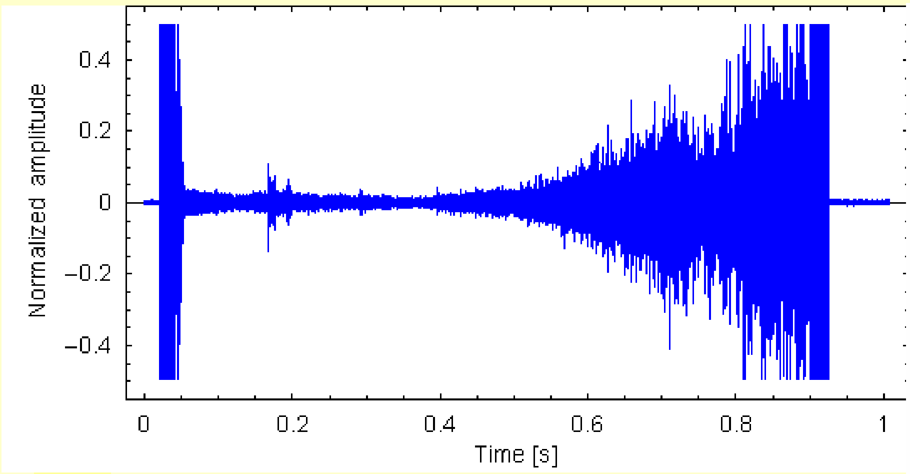
Advantages

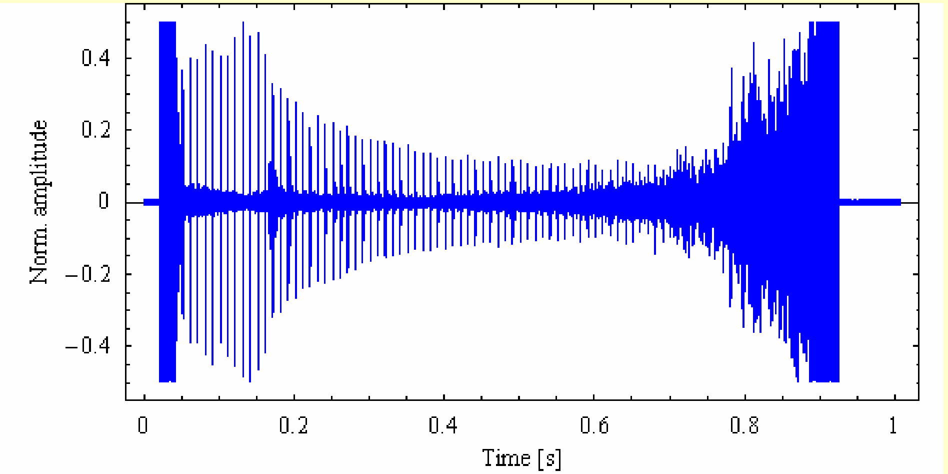
- Sensitivity (noise floor measured at RHIC in the 10 nm range!!)
- Virtually impossible to saturate
  - → large Frev suppression already at the detectors + large dynamic range
- Simplicity and low cost
  - → no resonant PU, no movable PU, no hybrid, no mixers, it can work with any PU
- Base band operation
  - → excellent 24 bit audio ADCs available
- Signal conditioning / processing is easy
  - → powerful components for low frequencies
- Independence from the machine filling pattern guaranteed
- Flattening out the beam dynamic range (small sensitivity to number of bunches)

Disadvantages

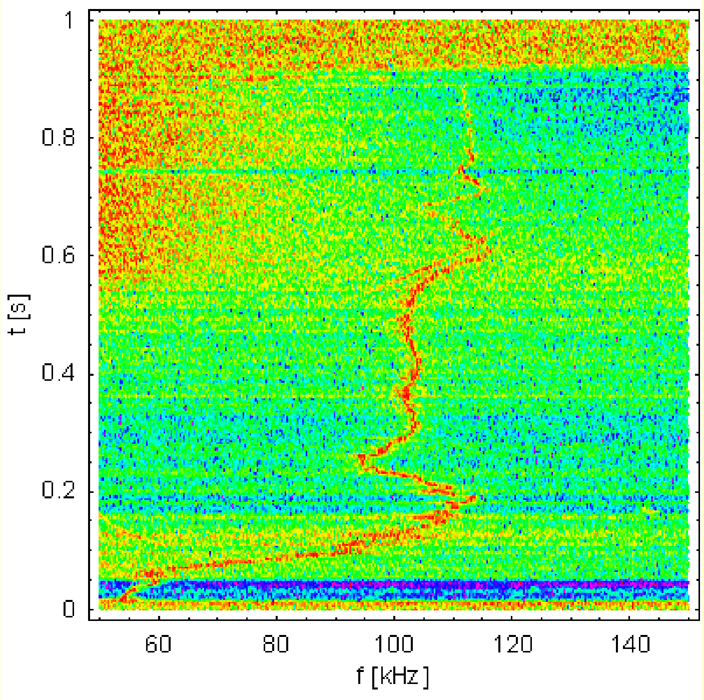
- Operation in the low frequency range
  - → More susceptible to EMC
- It is sensitive to the “bunch majority”
  - → gating needed to measure individual bunches

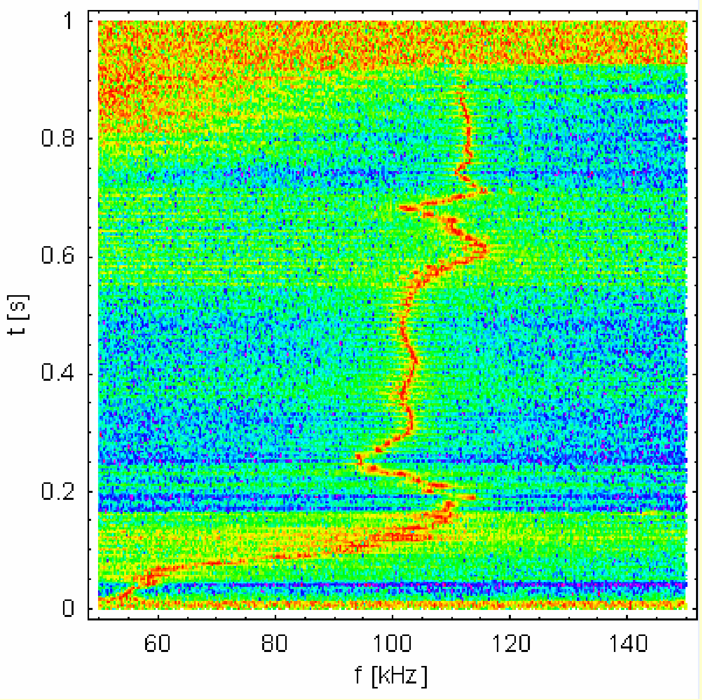
Results from the PS (AD cycle)





No explicit beam excitation





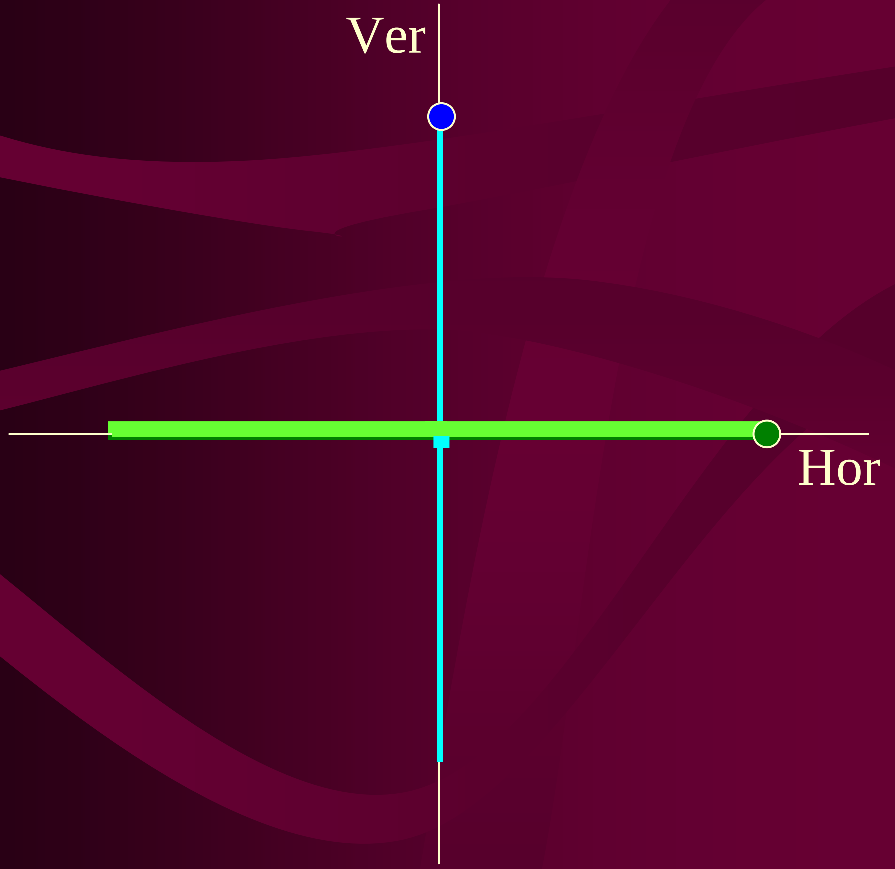
Q Kicker set to minimum

Measurement of Coupling using a PLL Tune Tracker

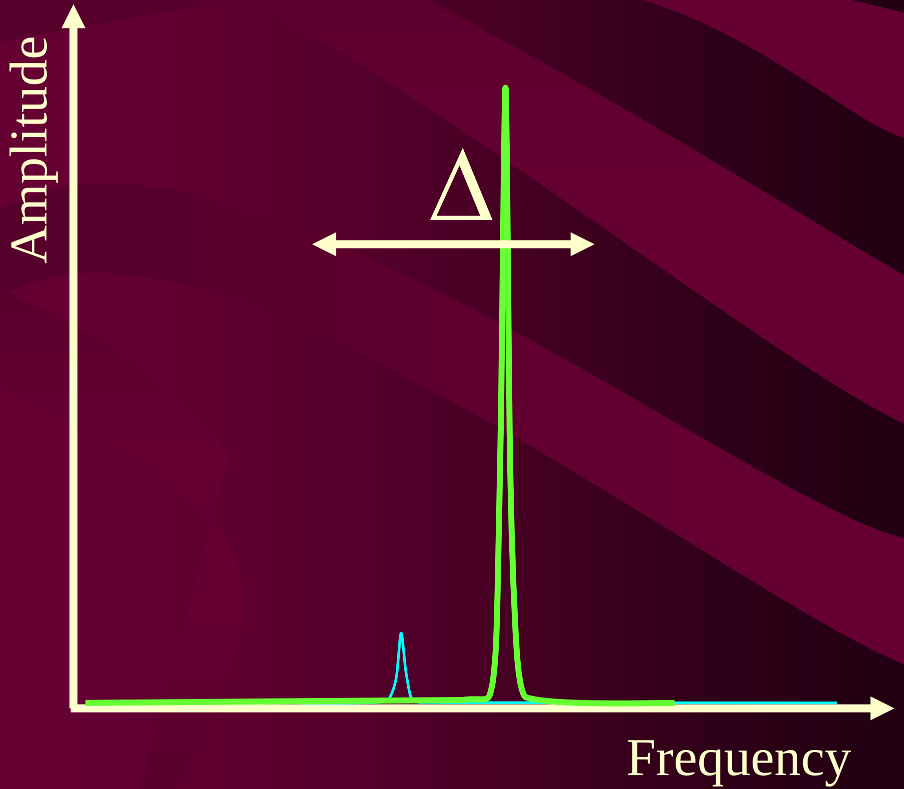
Start with decoupled machine ➡ Only horizontal tune shows up in horizontal FFT

Gradually increase coupling ➡ Vertical mode shows up & frequencies shift

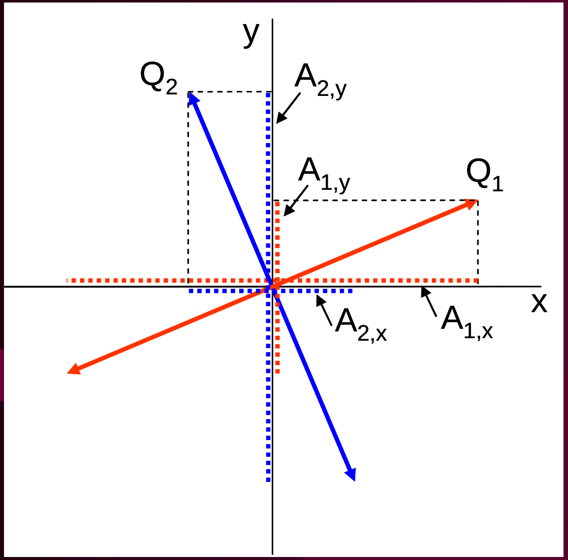
Fully coupled machine: $\Delta = |C^-|$

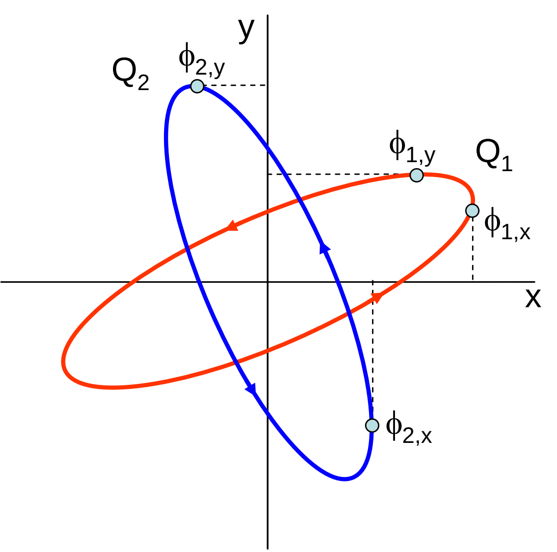


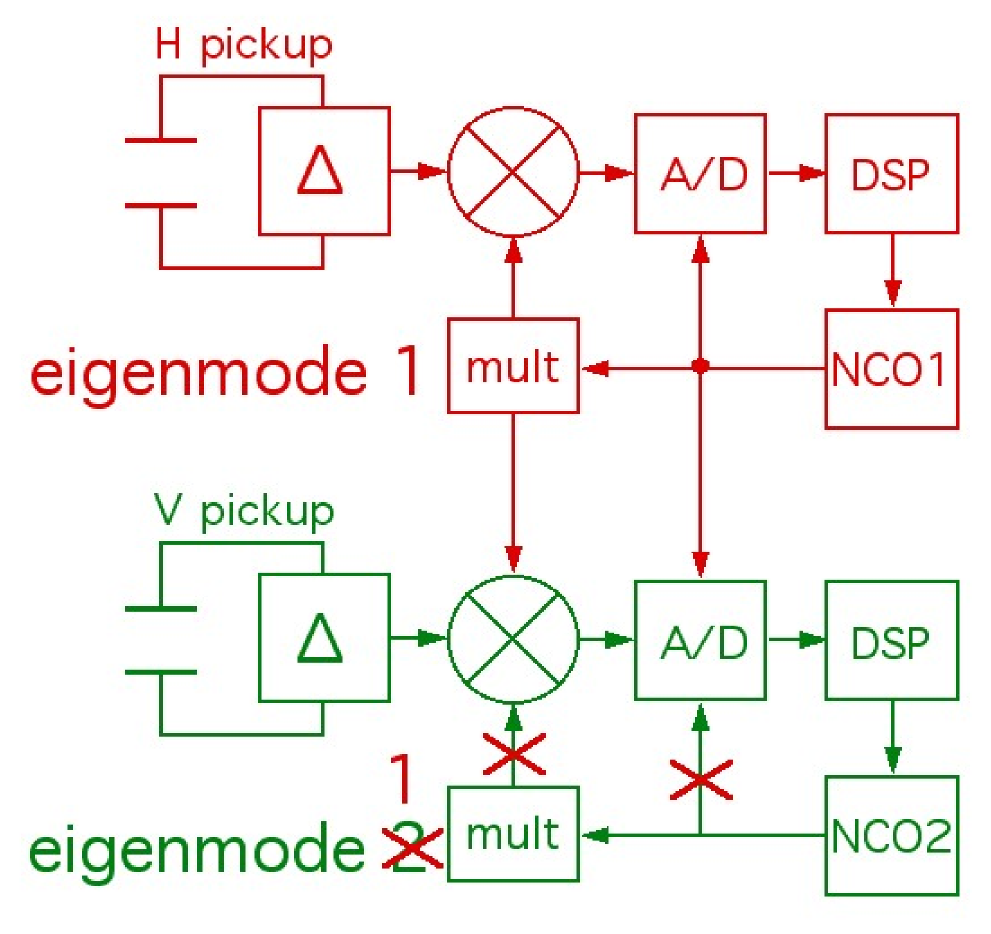
FFT of Horizontal Acquisition Plane



Measurement of Coupling using a PLL Tune Tracker

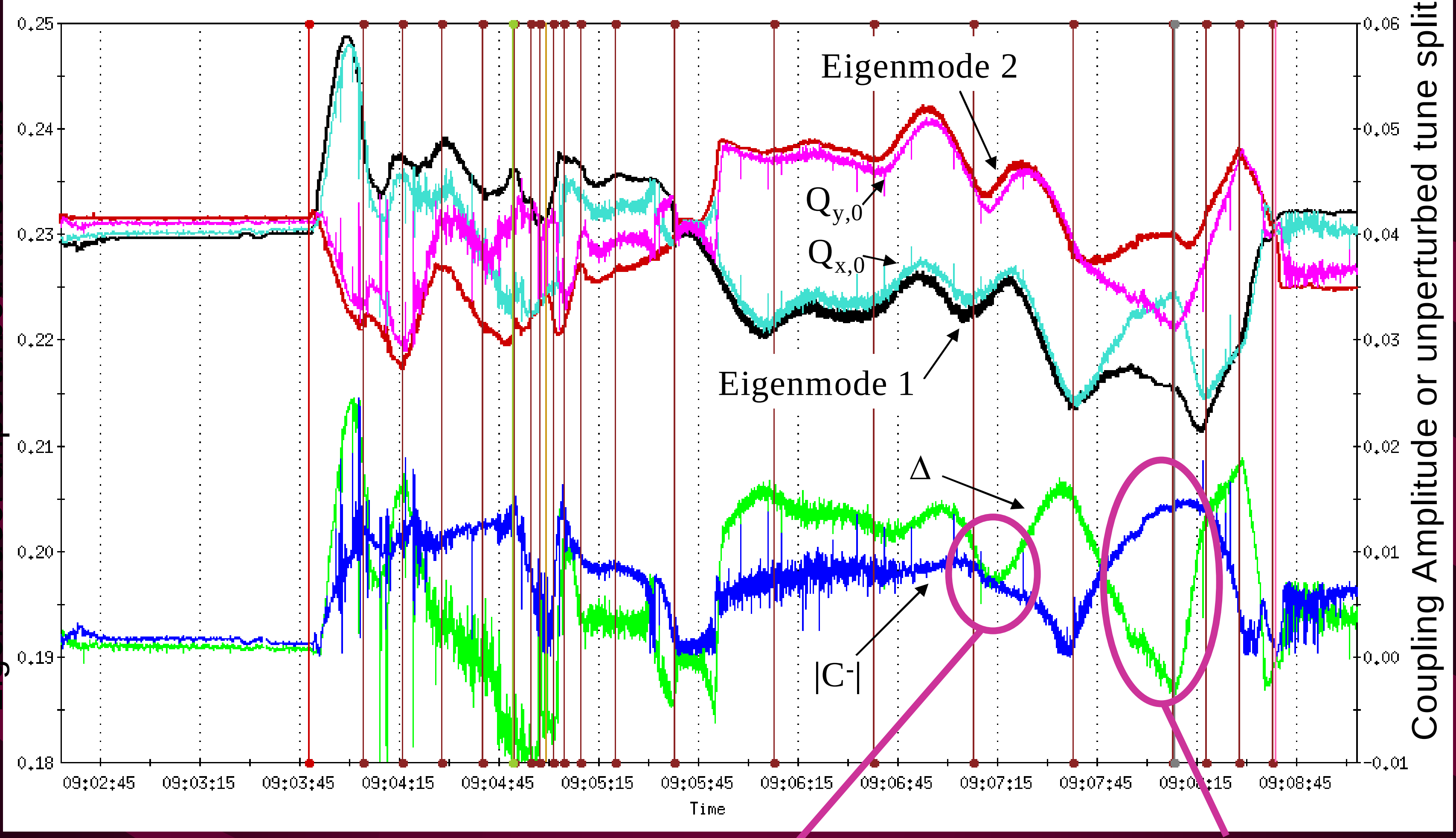






Tracking the vertical mode in the horizontal plane & vice-versa allows the coupling parameters to be calculated

Measurement of Coupling using a PLL Tune Tracker (RHIC Example)



Fully coupled

Tunes entirely defined by coupling

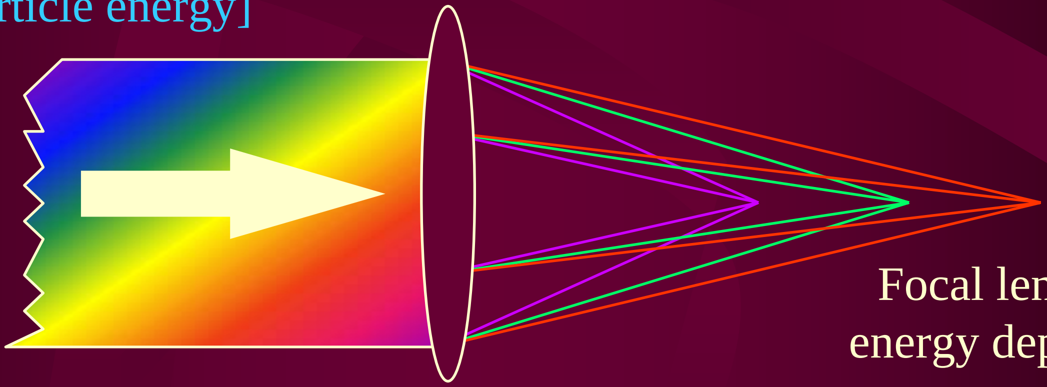
Chromaticity (Q’ or ξ)

Spread in the Machine Tune
due to Particle Energy Spread
Controlled by Sextupole magnets

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

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

Optics Analogy:



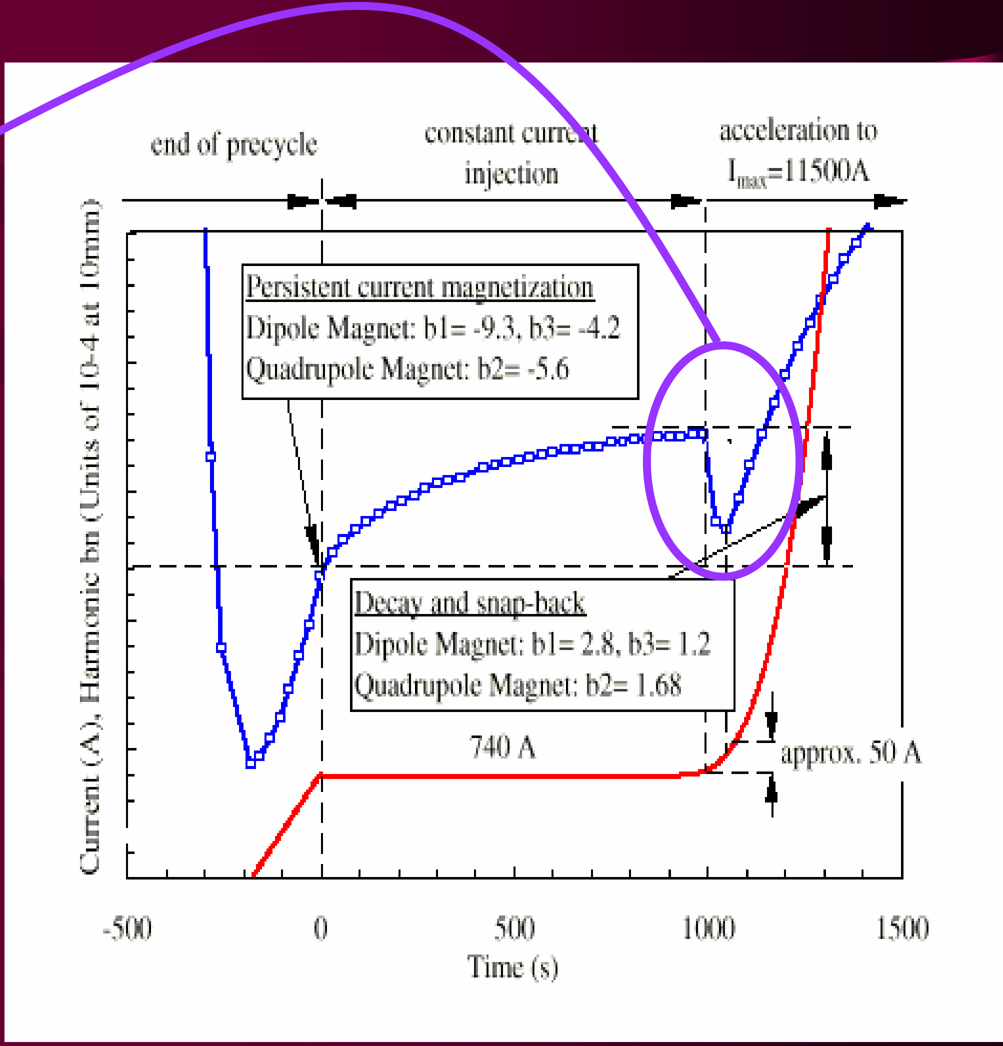
Achromatic incident light
[Spread in particle energy]

Focal length is
energy dependent

Lens
[Quadrupole]

Chromaticity – Its Importance for the LHC?

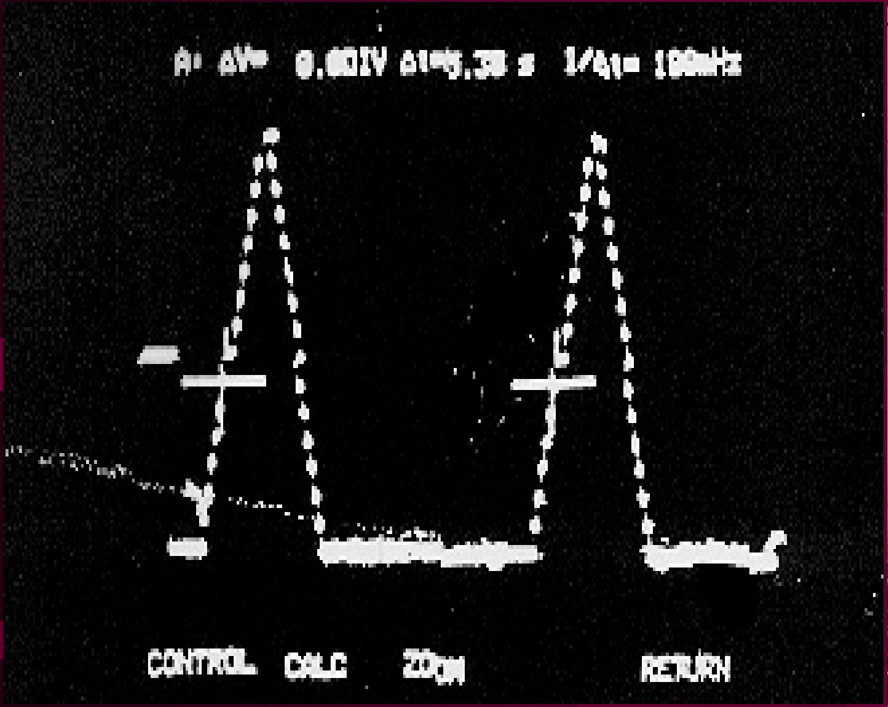
- Change in b3 during snap-back
  - → Change in Q’ of ~150 units
- Nominal operation requires ΔQ’ < 3
- Correction by:
  - → Feed-forward tables from magnet/chromaticity measurements
  - → On-line feedback from b3 measurements on reference magnets
  - → Possible on-line feedback directly from chromaticity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

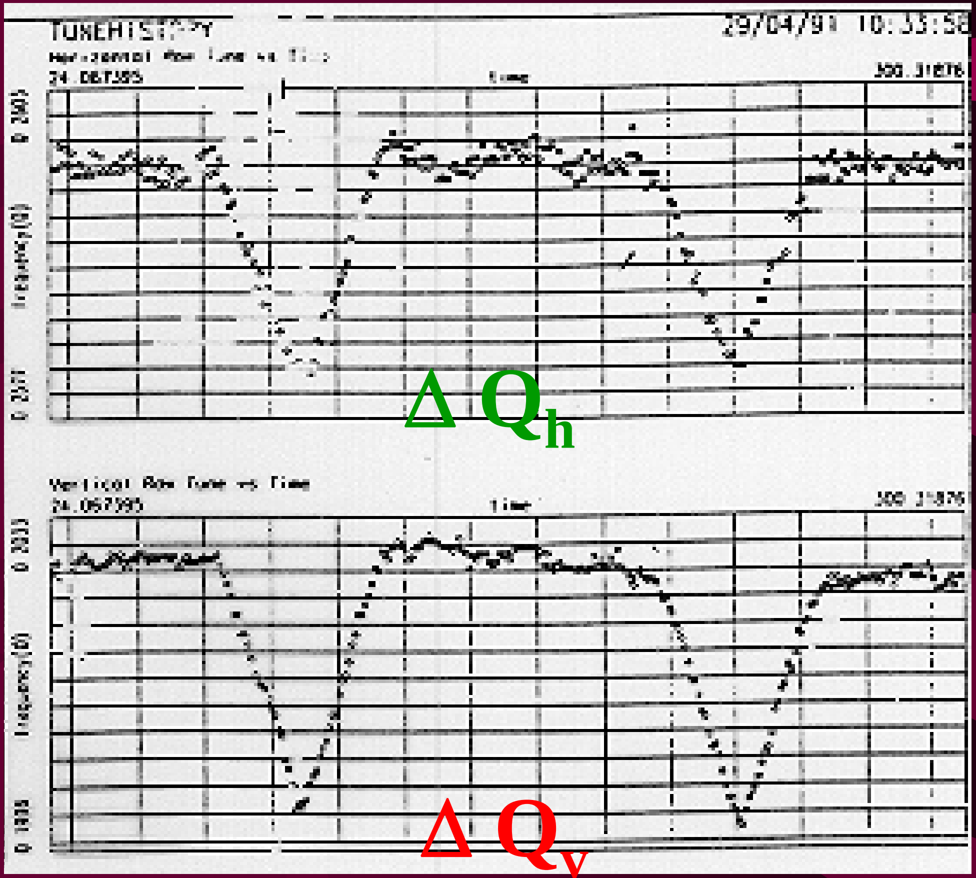


Chromaticity - What observable to choose?

Tune Difference for different beam momenta	⇔	used at HERA, RHIC and Tevatron 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	⇔	Operationally used at RHIC and Tevatron; prepared for LHC
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)

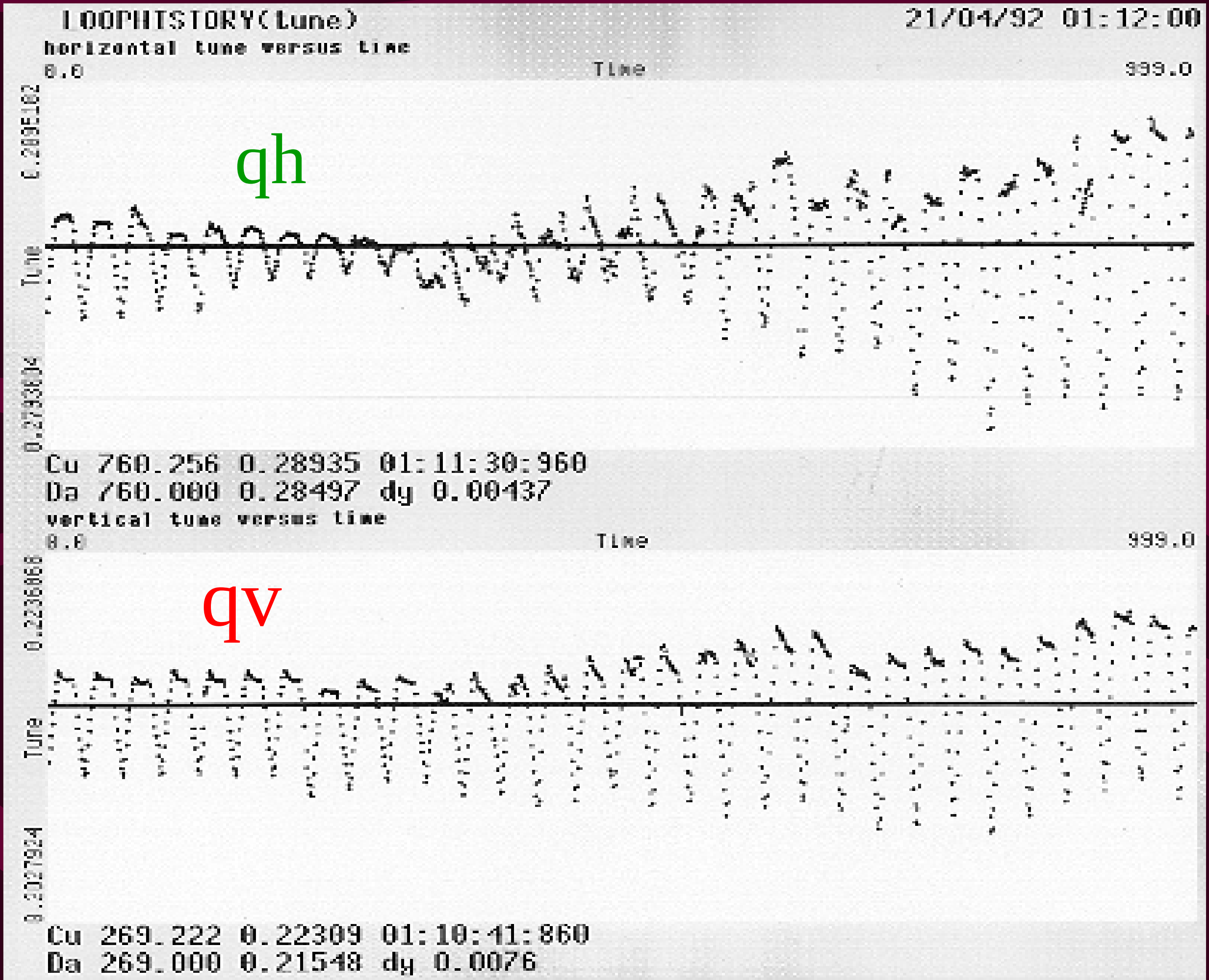




Applied Frequency Shift
Δ F (RF)

Amplitude & sign of chromaticity calculated from continuous tune plot

Measurement Example during LEP β-squeeze



LOOPHISTORY(tune) 21/04/92 01:12:00

horizontal tune versus time

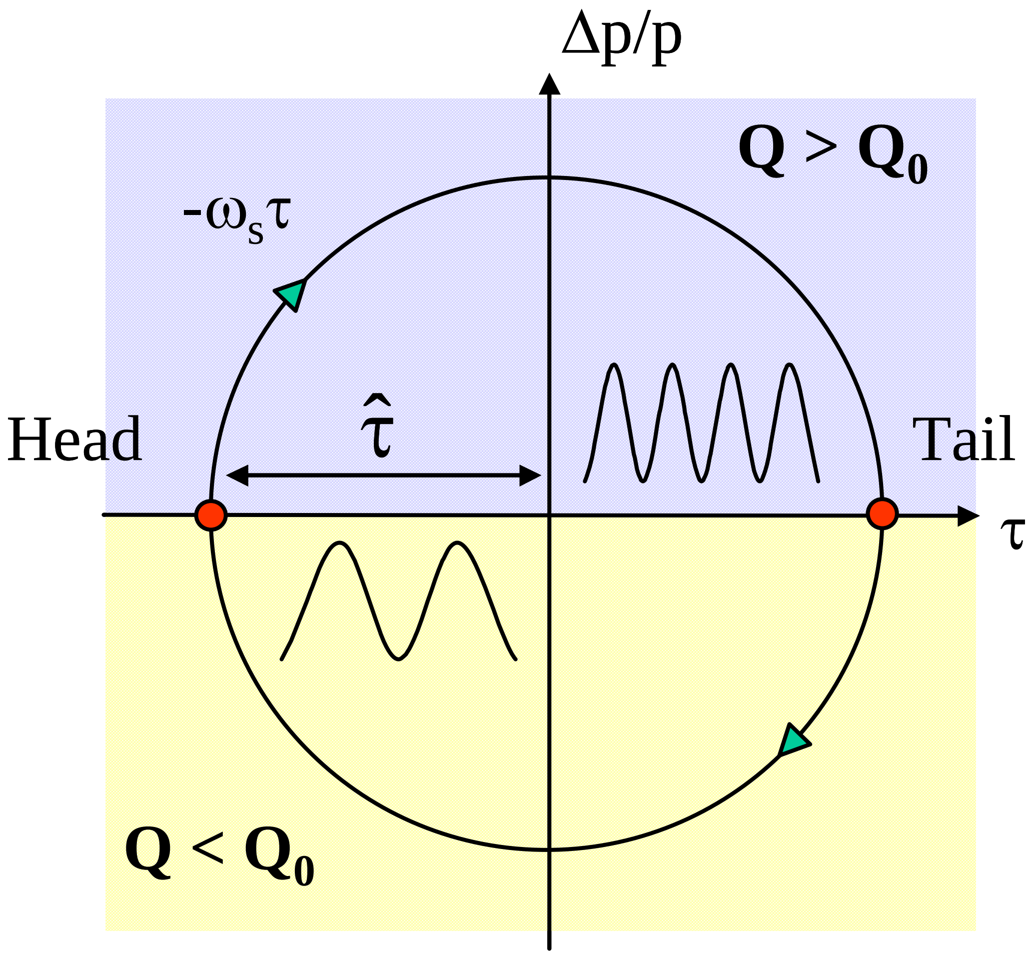
Cu 760.256 0.28935 01:11:30:960
Da 760.000 0.28497 dy 0.00437

vertical tune versus time

Cu 269.222 0.22309 01:10:41:860
Da 269.000 0.21548 dy 0.0076

Chromaticity & Head-Tail Motion

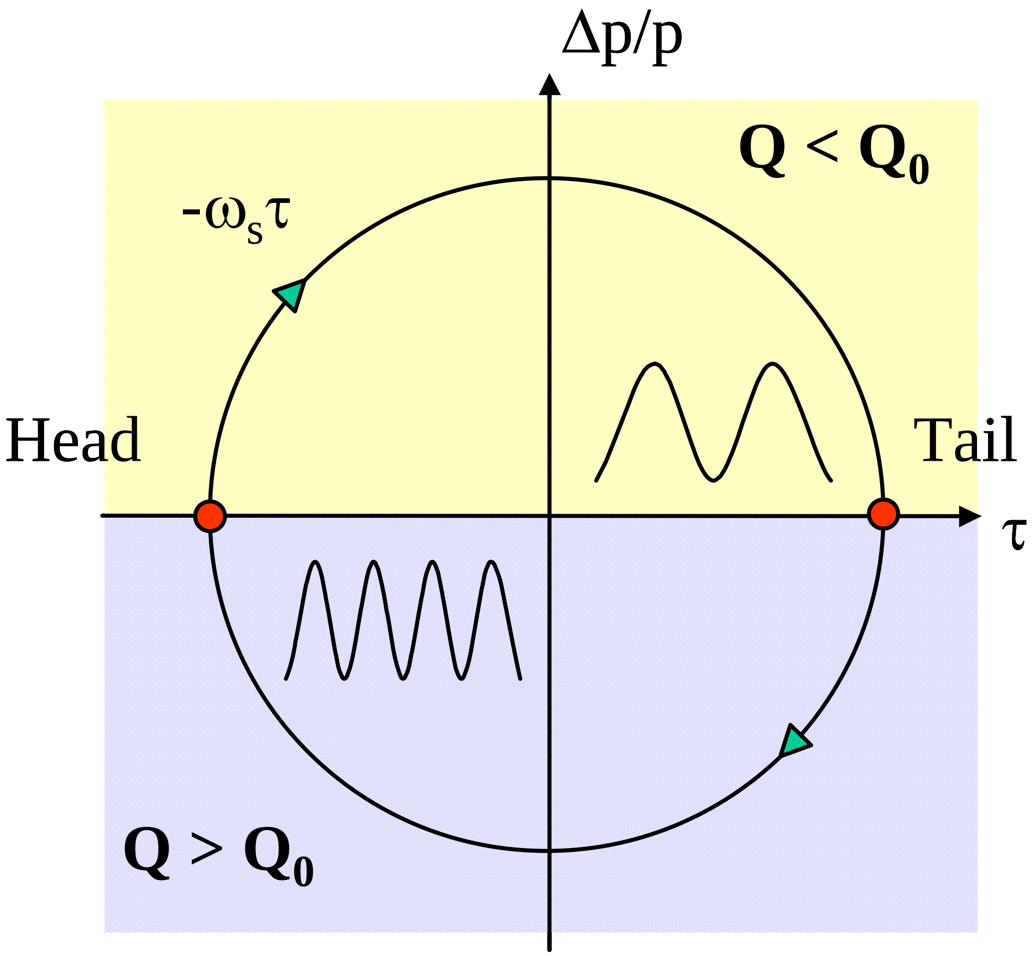
Positive Chromaticity (Above Transition)



Longitudinal Phase-Space

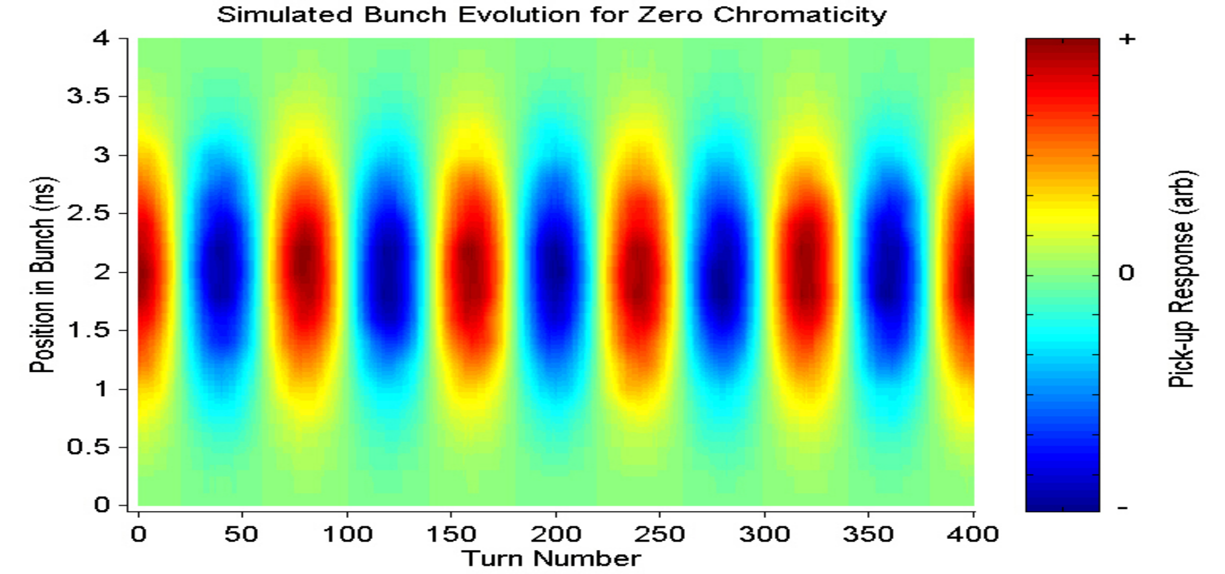
Chromaticity & Head-Tail Motion

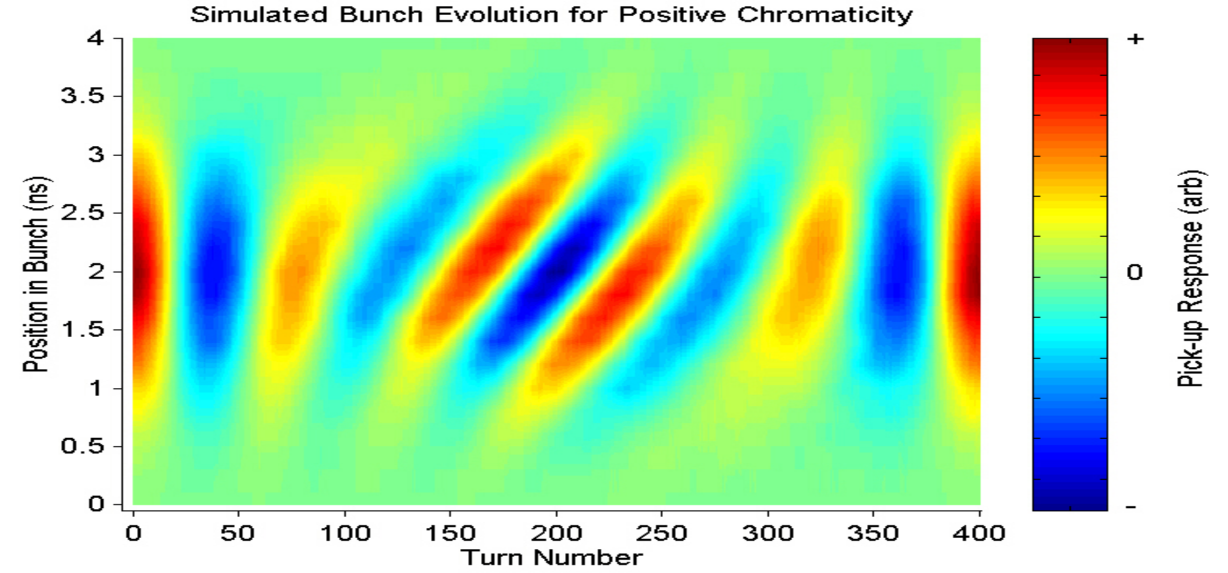
Negative Chromaticity (Above Transition)



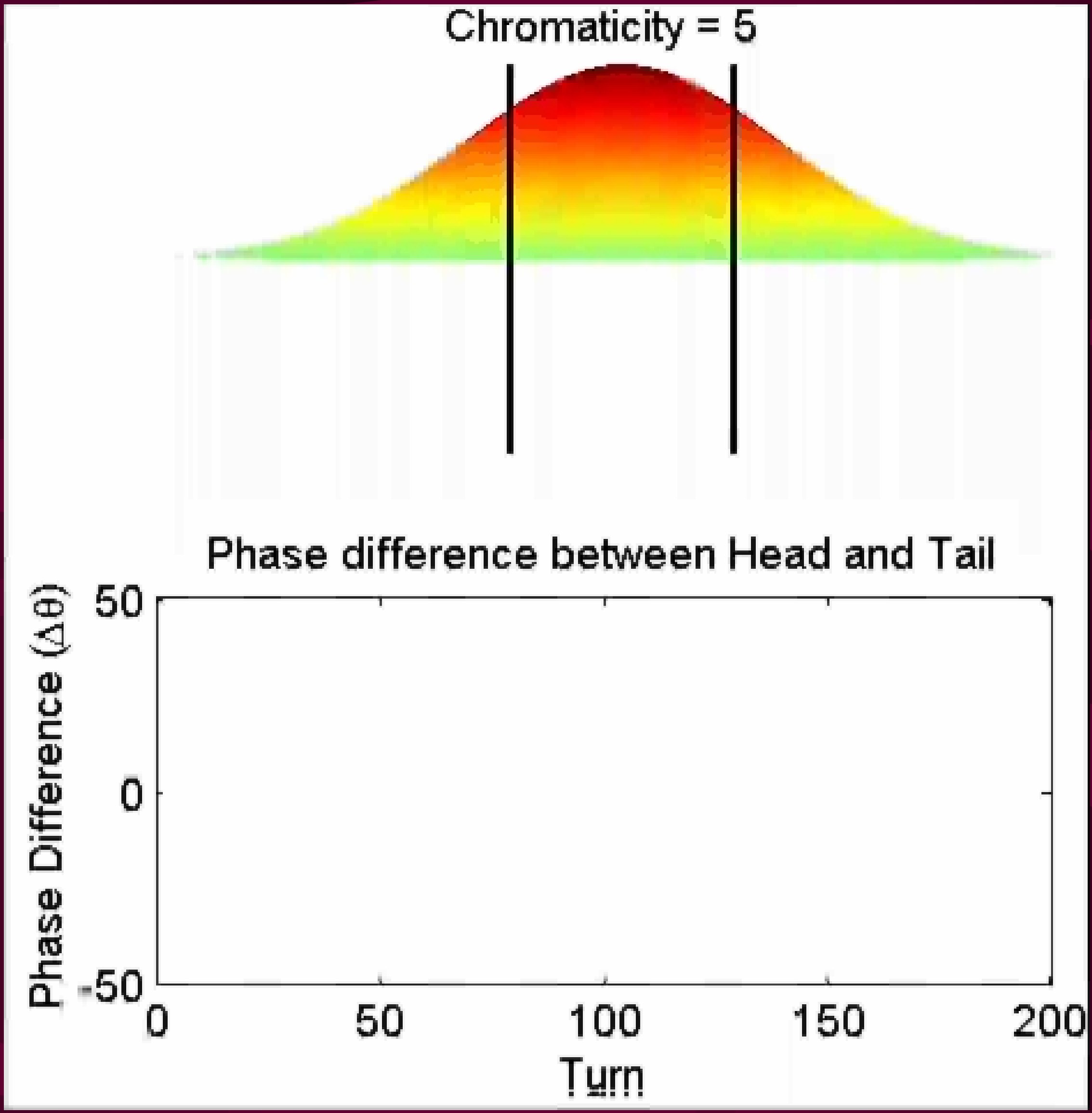
Longitudinal Phase-Space

Simulated Response


Simulated Bunch Evolution for Zero Chromaticity

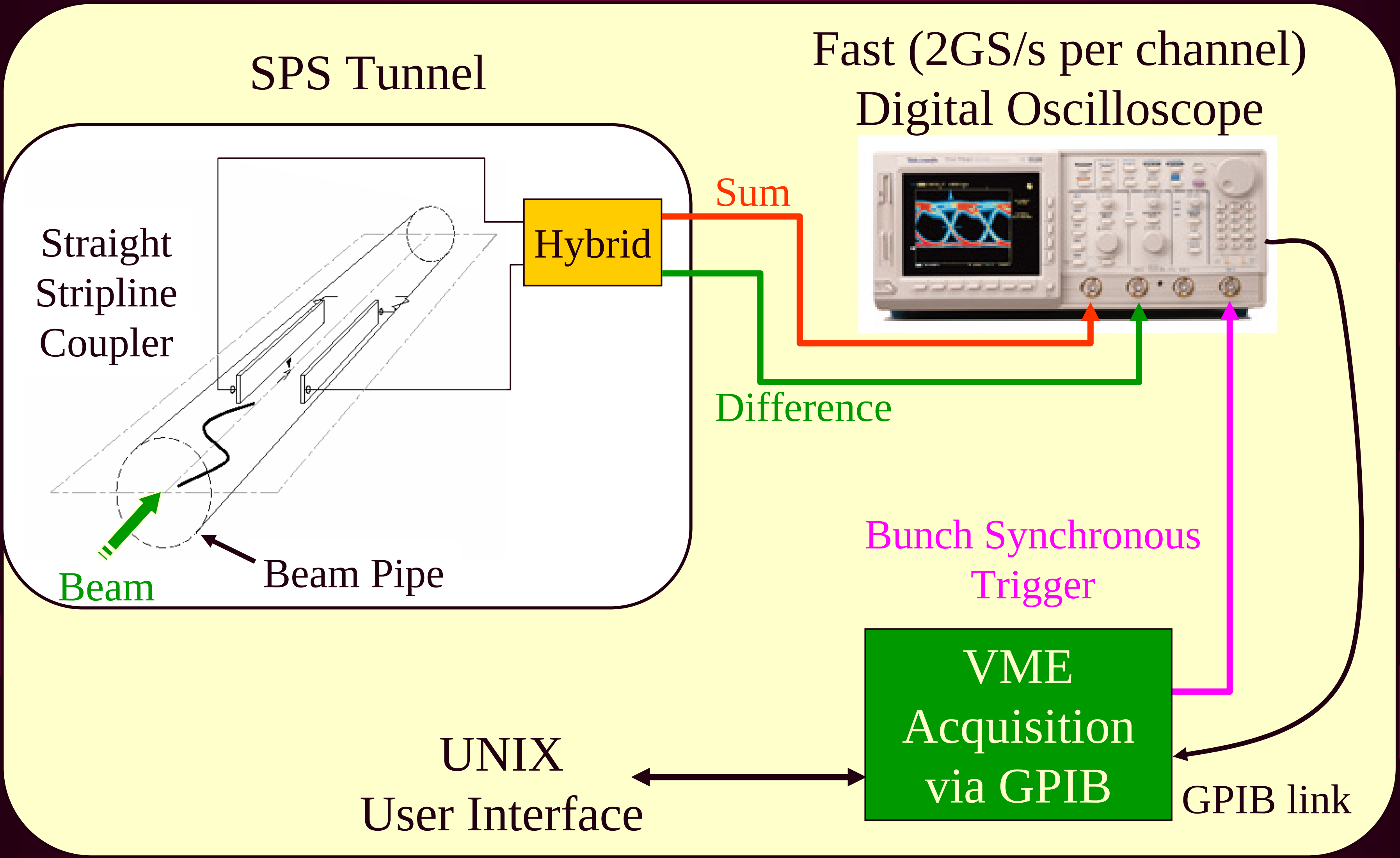

Simulated Bunch Evolution for Positive Chromaticity

The Head-Tail Measurement Principle



Start movie

Head-Tail System Set-up (SPS)



SPS Tunnel

Fast (2GS/s per channel)
Digital Oscilloscope

Straight
Stripline
Coupler

Hybrid

Sum

Difference

Beam

Beam Pipe

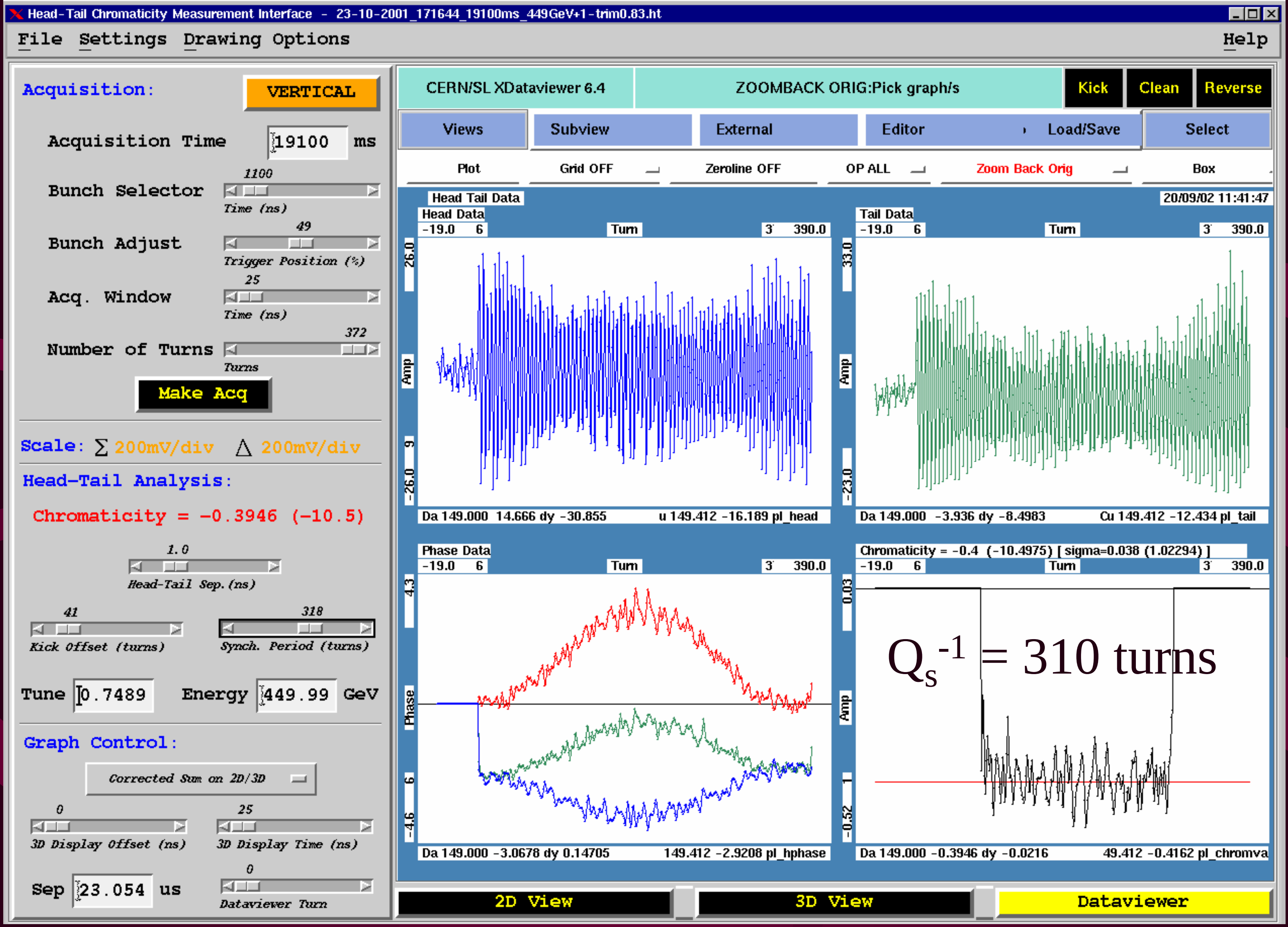
Bunch Synchronous
Trigger

VME
Acquisition
via GPIB

GPIB link

UNIX
User Interface

Measuring Q’ (Example 1: low Qs)



Head-Tail Chromaticity Measurement Interface - 23-10-2001_171644_19100ms_449GeV+1-trim0.83.ht

Acquisition Time 19100 ms

Bunch Selector 1100 Time (ns)

Bunch Adjust 49 Trigger Position (%)

Acq. Window 25 Time (ns)

Number of Turns 372 Turns

Scale: Σ 200mV/div Δ 200mV/div

Head-Tail Analysis:

Chromaticity = -0.3946 (-10.5)

1.0 Head-Tail Sep. (ns)

41 Kick Offset (turns)

318 Synch. Period (turns)

Tune 0.7489 Energy 449.99 GeV

Graph Control:

Corrected Sum on 2D/3D

0 3D Display Offset (ns)

25 3D Display Time (ns)

Sep 23.054 us

0 Dataviewer Turn

20/09/02 11:41:47

Da 149.000 14.666 dy -30.855 u 149.412 -16.189 pl_head

Da 149.000 -3.936 dy -8.4983 Cu 149.412 -12.434 pl_tail

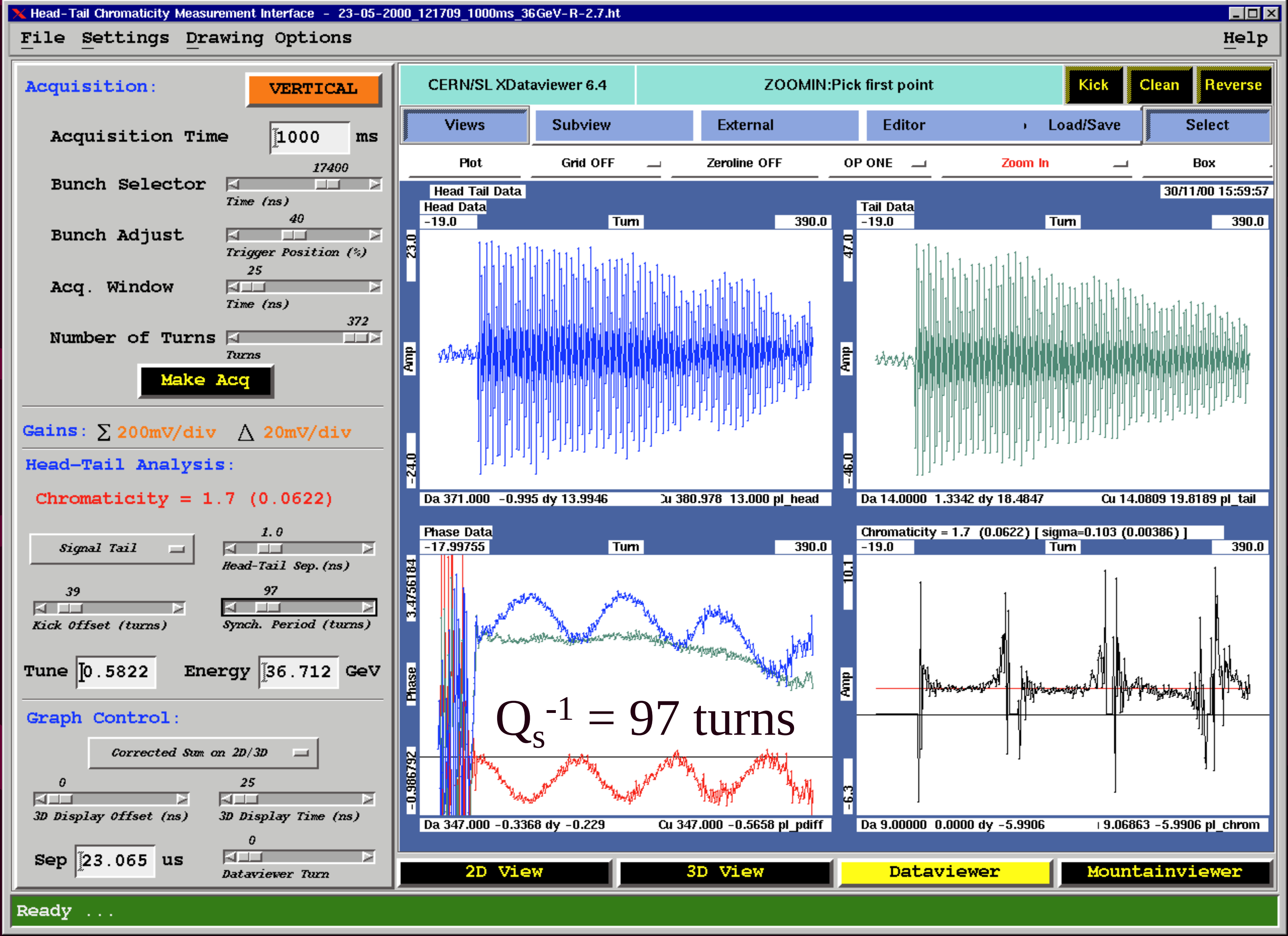
Da 149.000 -3.0678 dy 0.14705 149.412 -2.9208 pl_hphase

Chromaticity = -0.4 (-10.4975) [sigma=0.038 (1.02294)]

Da 149.000 -0.3946 dy -0.0216 49.412 -0.4162 pl_chromva

Q_s^{-1} = 310 turns

Measuring Q’ (Example 2: high Qs)



Head-Tail Chromaticity Measurement Interface - 23-05-2000_121709_1000ms_36GeV-R-2.7.ht

Acquisition: VERTICAL

Acquisition Time 1000 ms

Bunch Selector 17400 Time (ns)

Bunch Adjust 40 Trigger Position (%)

Acq. Window 25 Time (ns)

Number of Turns 372 Turns

Gains: Σ 200mV/div Δ 20mV/div

Head-Tail Analysis:

Chromaticity = 1.7 (0.0622)

Signal Tail

1.0 Head-Tail Sep. (ns)

39 Kick Offset (turns)

97 Synch. Period (turns)

Tune 0.5822 Energy 36.712 GeV

Graph Control:

Corrected Sum on 2D/3D

0 3D Display Offset (ns)

25 3D Display Time (ns)

Sep 23.065 us

0 Dataviewer Turn

CERN/SL XDataviewer 6.4

ZOOMIN:Pick first point

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

Head Data: Da 371.000 -0.995 dy 13.9946 Cu 380.978 13.000 pl_head

Tail Data: Da 14.0000 1.3342 dy 18.4847 Cu 14.0809 19.8189 pl_tail

Phase Data: Da 347.000 -0.3368 dy -0.229 Cu 347.000 -0.5658 pl_pdiff

Chromaticity = 1.7 (0.0622) [sigma=0.103 (0.00386)]: Da 9.00000 0.0000 dy -5.9906 Cu 9.06863 -5.9906 pl_chrom

Ready ...

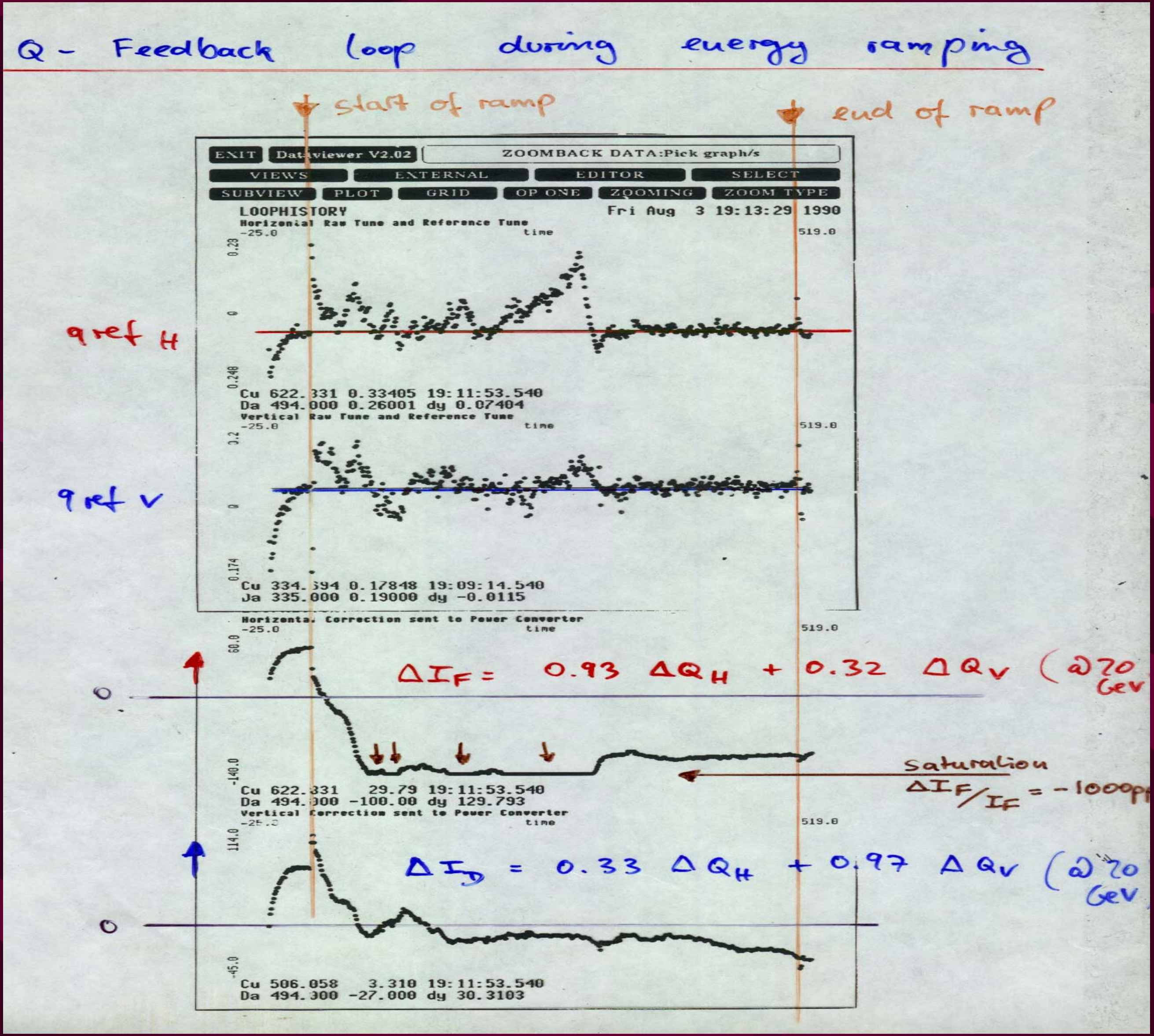
$Q_s^{-1} = 97$ turns

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
  - → System used at HERA until last days→ following movie
  - → RHIC, Tevatron and LHC perspectives

Early example from LEP



Q - Feedback loop during energy ramping

start of ramp

end of ramp

LOOPHISTORY Fri Aug 3 19:13:29 1990

Horizontal Raw Tune and Reference Tune

qref H

```
Cu 622.331 0.33405 19:11:53.540
Da 494.000 0.26001 dy 0.07404
```

Vertical Raw Tune and Reference Tune

qref V

```
Cu 334.594 0.17848 19:09:14.540
Ja 335.000 0.19000 dy -0.0115
```

Horizonta. Correction sent to Power Converter

$\Delta I_F = 0.93\ \Delta Q_H + 0.32\ \Delta Q_V$ (@ 20
GeV

saturation

$\Delta I_F / I_F$ = -1000p

```
Cu 622.331    29.79 19:11:53.540
Da 494.000 -100.00 dy 129.793
```

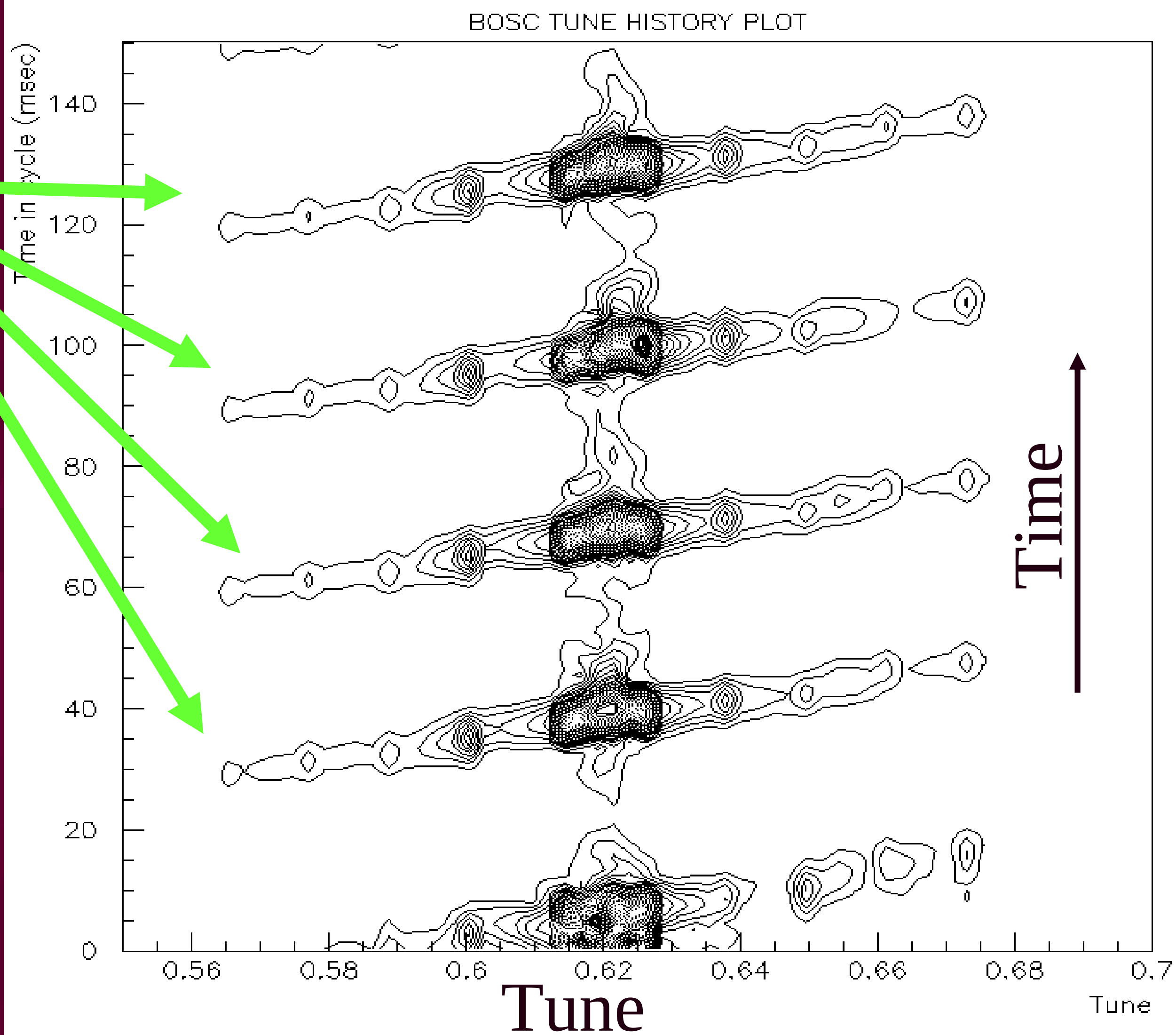
Vertical Correction sent to Power Converter

$\Delta I_D = 0.33\ \Delta Q_H + 0.97\ \Delta Q_V$ (@ 20
GeV

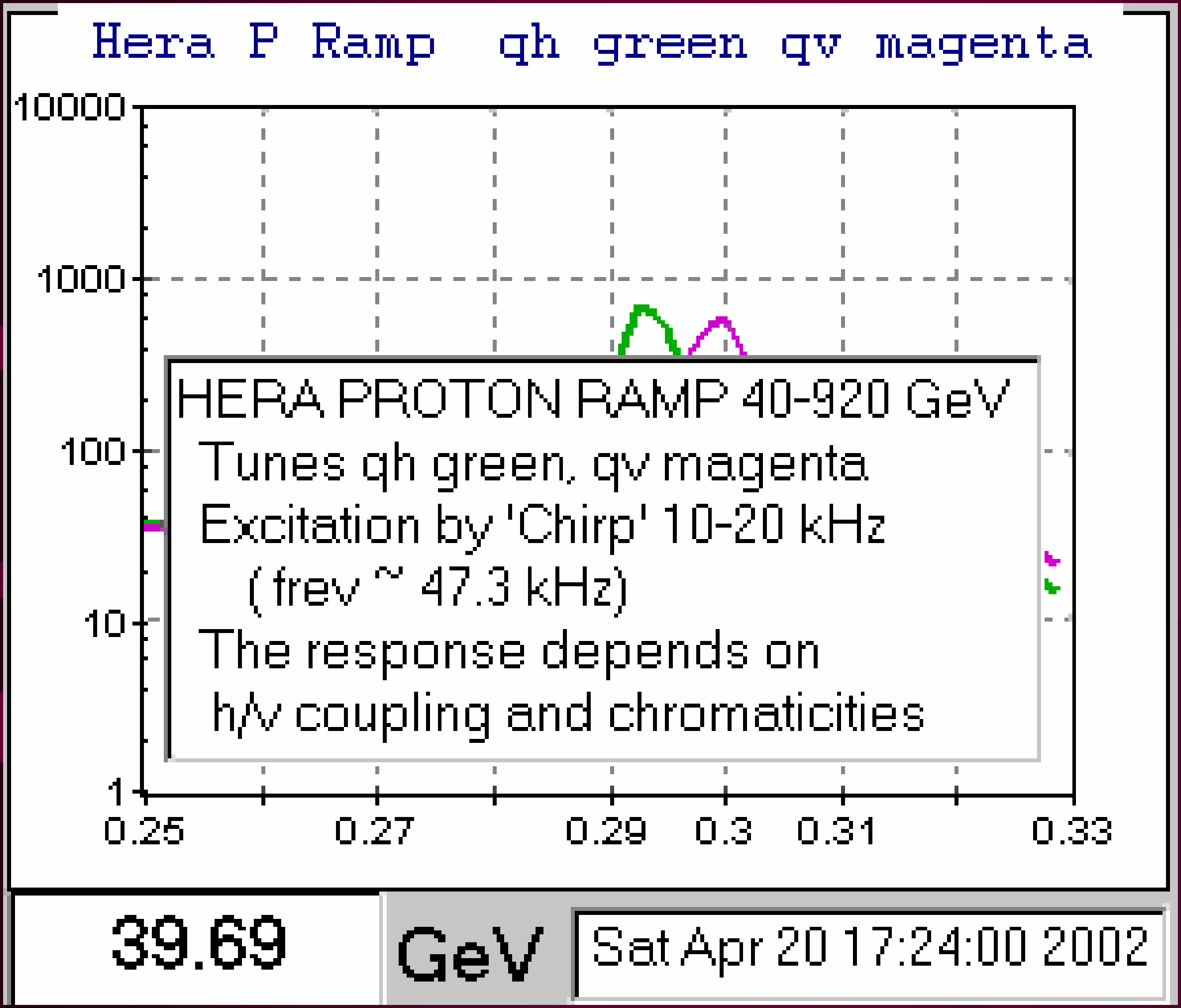
```
Cu 506.058    3.310 19:11:53.540
Da 494.300 -27.000 dy 30.3103
```

HERA-p solution:

- “Chirp” tune measurements
- Online display
- Operator “joystick” feedback to quadrupole and sextupole power-supplies (BLL = brain locked loop)



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



HERA PROTON RAMP 40-920 GeV
Tunes qh green, qv magenta
Excitation by 'Chirp' 10-20 kHz
(frev ~ 47.3 kHz)
The response depends on
h/v coupling and chromaticities

39.69 GeV Sat Apr 20 17:24:00 2002

Courtesy of Steve Herb (DESY)

Femto-Second Synchronization

The operation of ultra-violet and X-ray free electron lasers requires a bunch arrival-time stability on the order of several tens of femto-seconds between the X-ray pulses and laser pulses of external probe lasers, to be able to take full advantage of the fs-short X-ray pulses in pump-probe experiments.

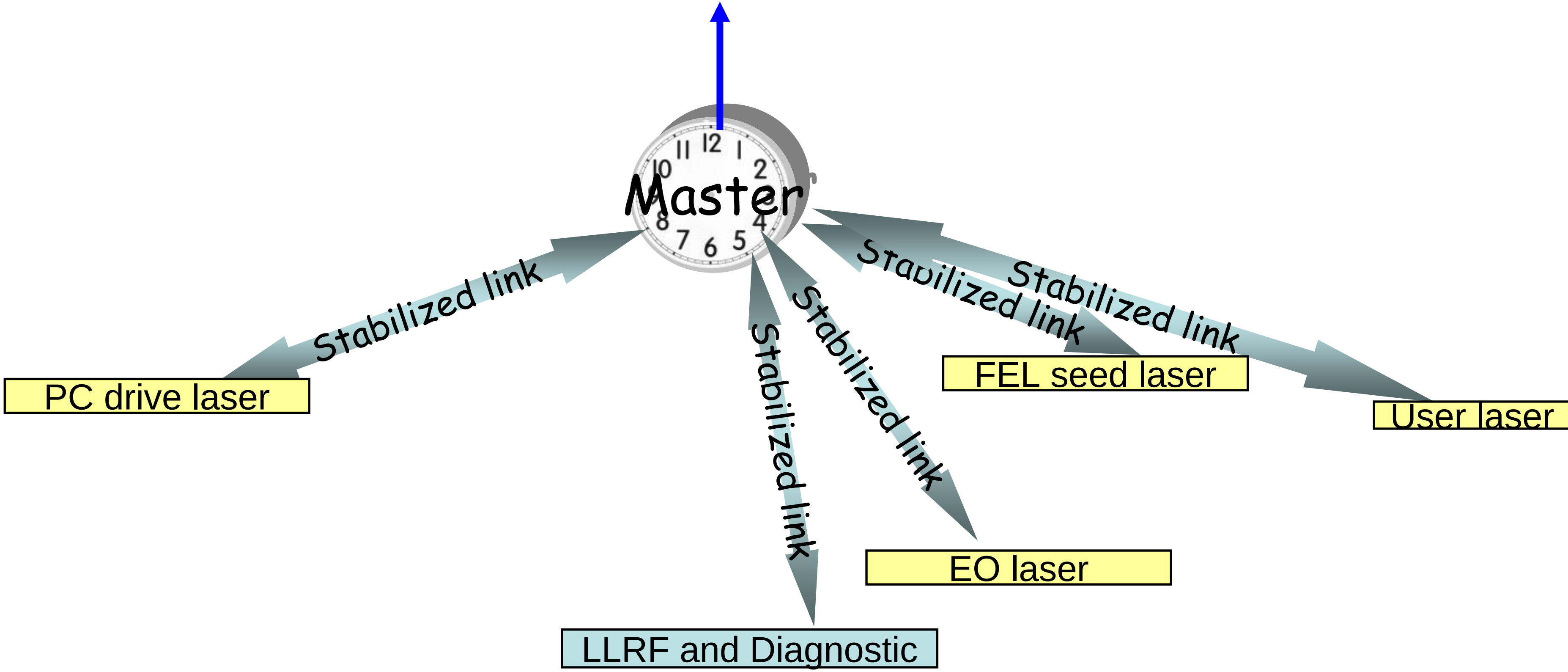
- **What is the currently achievable signal jitter for a reference signal?**
- **How do we measure it?**
- **How do we use it with beam?**

Courtesy of K.Wittenburg (DESY) and J.Byrd (LBNL)

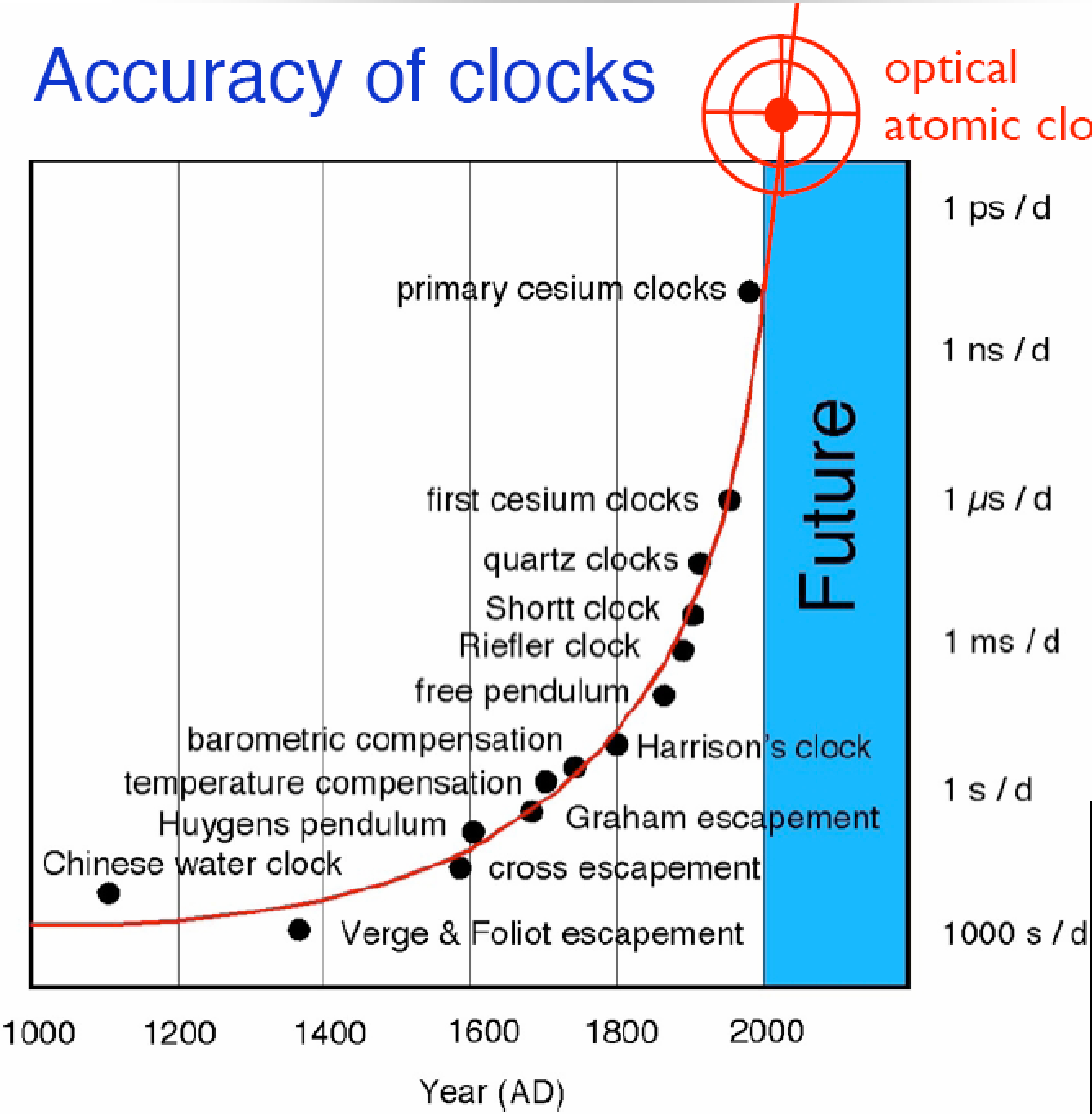
All based on stable Synch. Signal

2005 Nobel Prize in Physics awarded to John L. Hall and Theodor W. Hänsch "for their contributions to the development of laser-based precision spectroscopy, including the optical frequency comb technique"

This technology is *nearly* ready for applications in precision synchronization in accelerators (J. Byrd, BIW2006)



Accuracy of clocks


optical
atomic clocks

Nobel Lecture
Passion for Precision
Theodor W. Hänsch
December 8, 2005, at Aula Magna, Stockholm University.
http://nobelprize.org/nobel_prizes/physics/laureates/2005/hansch-lecture.html

All based on stable synch. signal and stabilized links

The timing system will play a crucial role in achieving the expected performance in Linac based FELs due to the sub-ps electron bunch length and to the expanded use of fs-lasers as key components in future light sources.

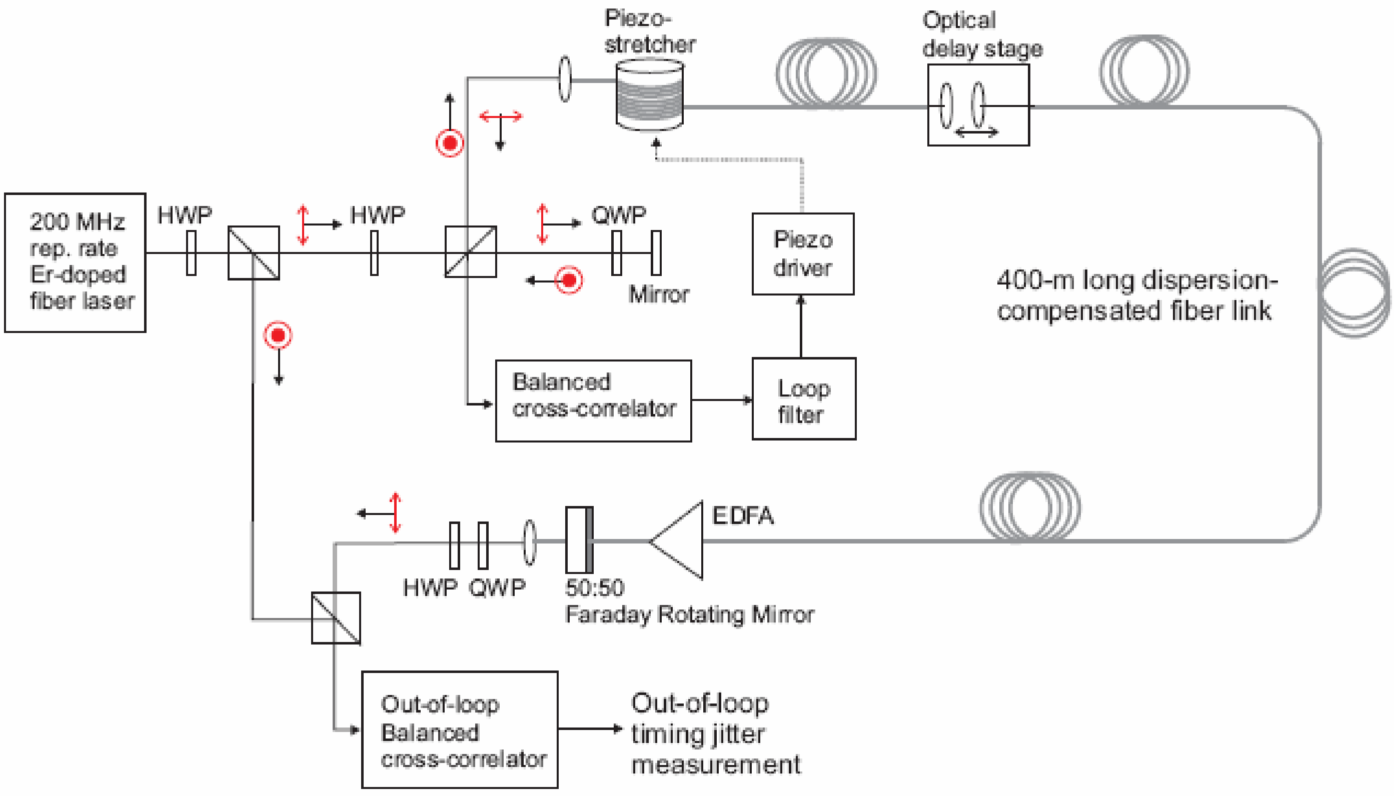
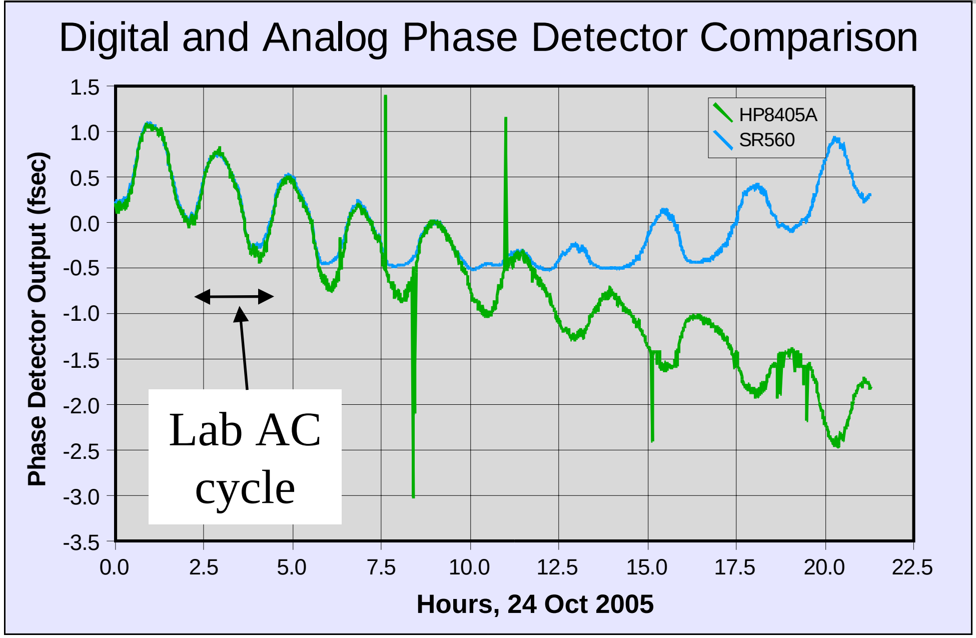


Figure 2: Experimental setup for the fiberlink stabilization.

Compare phase at the end of fiber with reference to establish stability.



Measure slow drift (<1 Hz) of fiber under laboratory conditions

Compensation for several environmental effects results in a linear drift of 0.13 fsec/hour and a residual temperature drift of 1 fsec/deg C.

Environmental factors

- Temperature: 0.5-1 fsec/deg C
- Atmospheric pressure: none found
- Humidity: significant correlation
- Laser Wavelength Stabilizer: none
- Human activity: femtosecond noise in the data

J. Byrd, *Progress in femtosecond timing distribution and synchronization for ultrafast light sources* BIW06

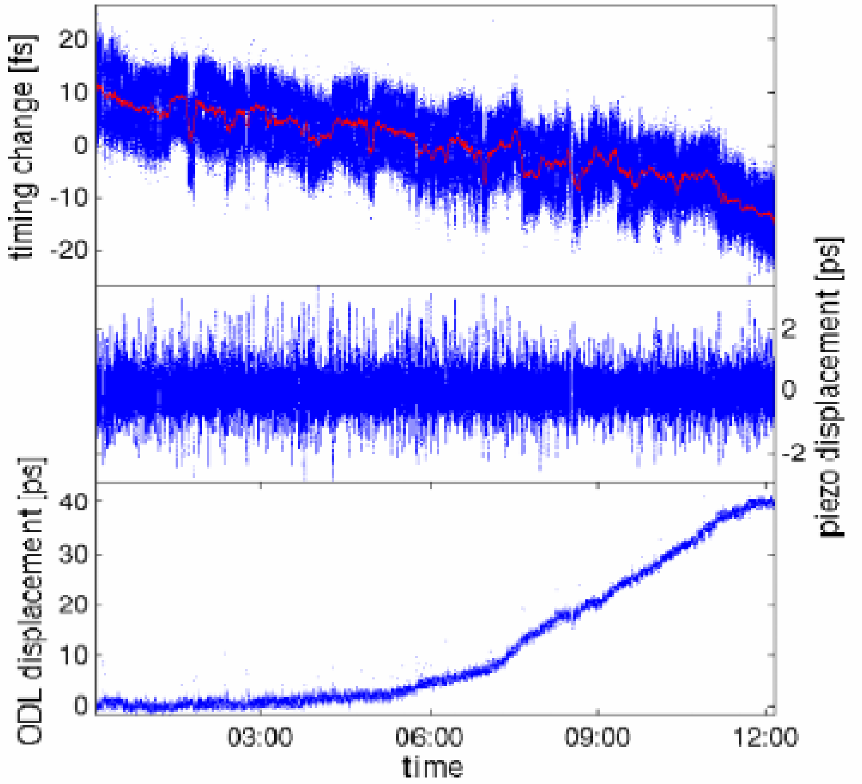
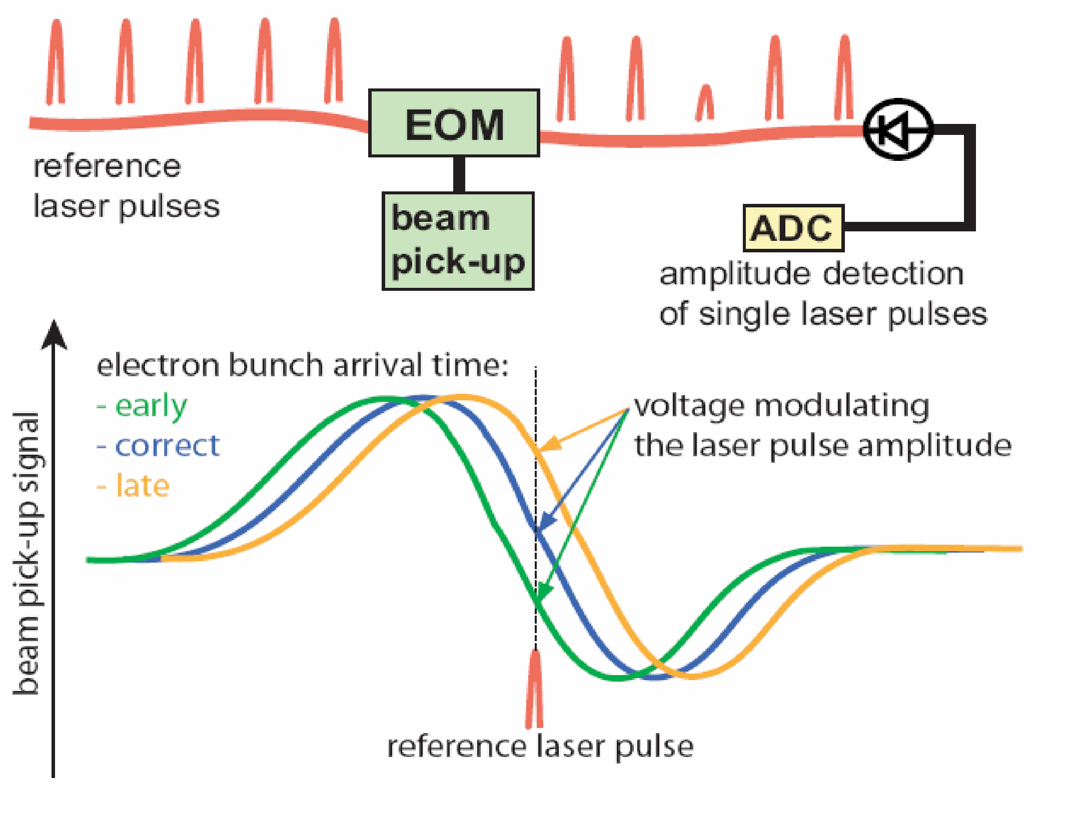


Figure 5: Out of loop drift measurement of a 400 m long fiberlink. Top: end of link timing change (blue). Over 12 hours the rms jitter is (7.5 ± 1.8) fs with a timing drift of 25 fs. The red line indicates changes with a time constant of 100 s. The timing jitter faster than 100 s is (4.4 ± 1.1) fs

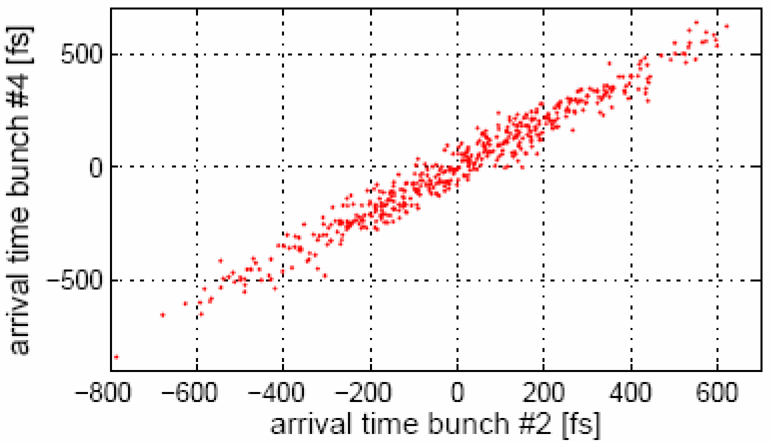
First prototype of an optical cross-correlation based fiber-link stabilization for the FLASH synchronization system; Florian Loehl, Holger Schlarb (DESY, Hamburg), Jeff Chen, Franz Xaver Kaertner, Jung-Won Kim (MIT, Cambridge, Massachusetts), DIPAC07

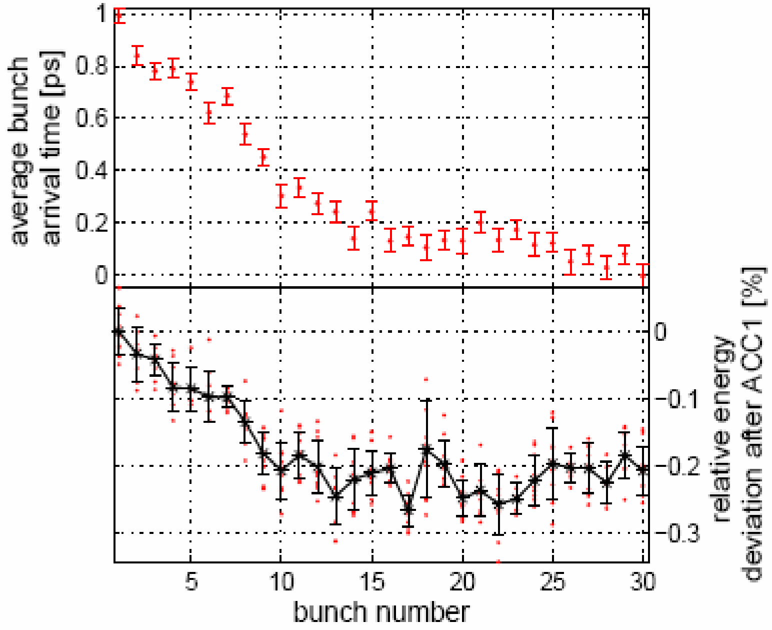
Measurement: Bunch arrival monitor (Σ)



Principle of the arrival time detection. Reference laser pulses traverse an electro-optical modulator which is driven by the signal of a beam pick-up (top). Arrival time changes of the electron beam cause different modulation voltages at the laser pulse arrival time (bottom), leading to laser amplitude changes that are detected by a photo detector.

A Sub-50 Femtosecond bunch arrival time monitor system for FLASH; F. Loehl, Kirsten E. Hacker, H. Schlarb (DESY, Hamburg) DIPAC07





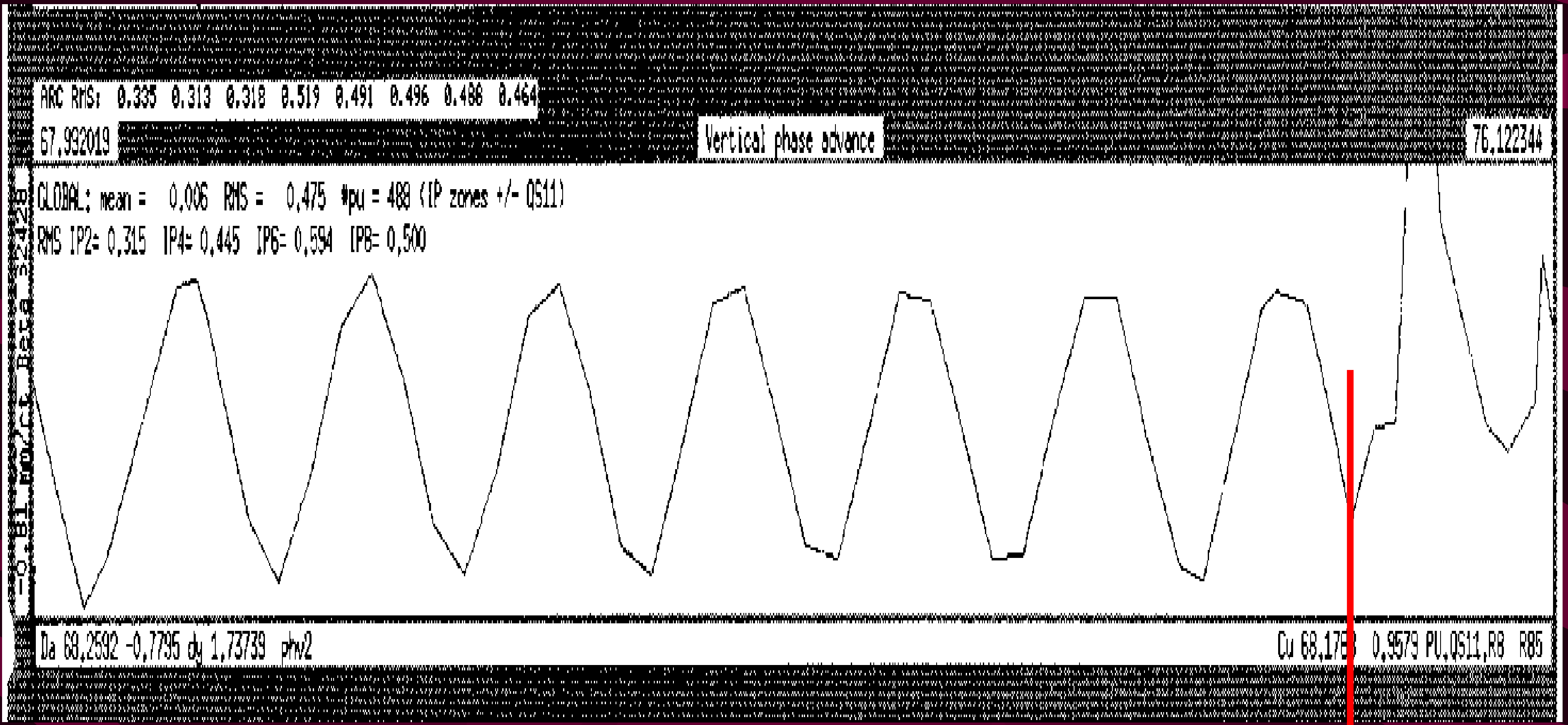
Comparison of the average bunch arrival time over the bunch train at the end of the machine with the average beam energy after the first accelerating module ACC1.

Outline for Today

- Optimisation of Machine Performance
  ("the good days")
  - → Orbit measurement & correction
  - → Luminosity: basics, profile and β - measurements
- Various Diagnostics : the fun days
  - → Tune & chromaticity measurements
  - → Dynamic effects: tune and chromaticity control
  - → Bunch arrival time

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

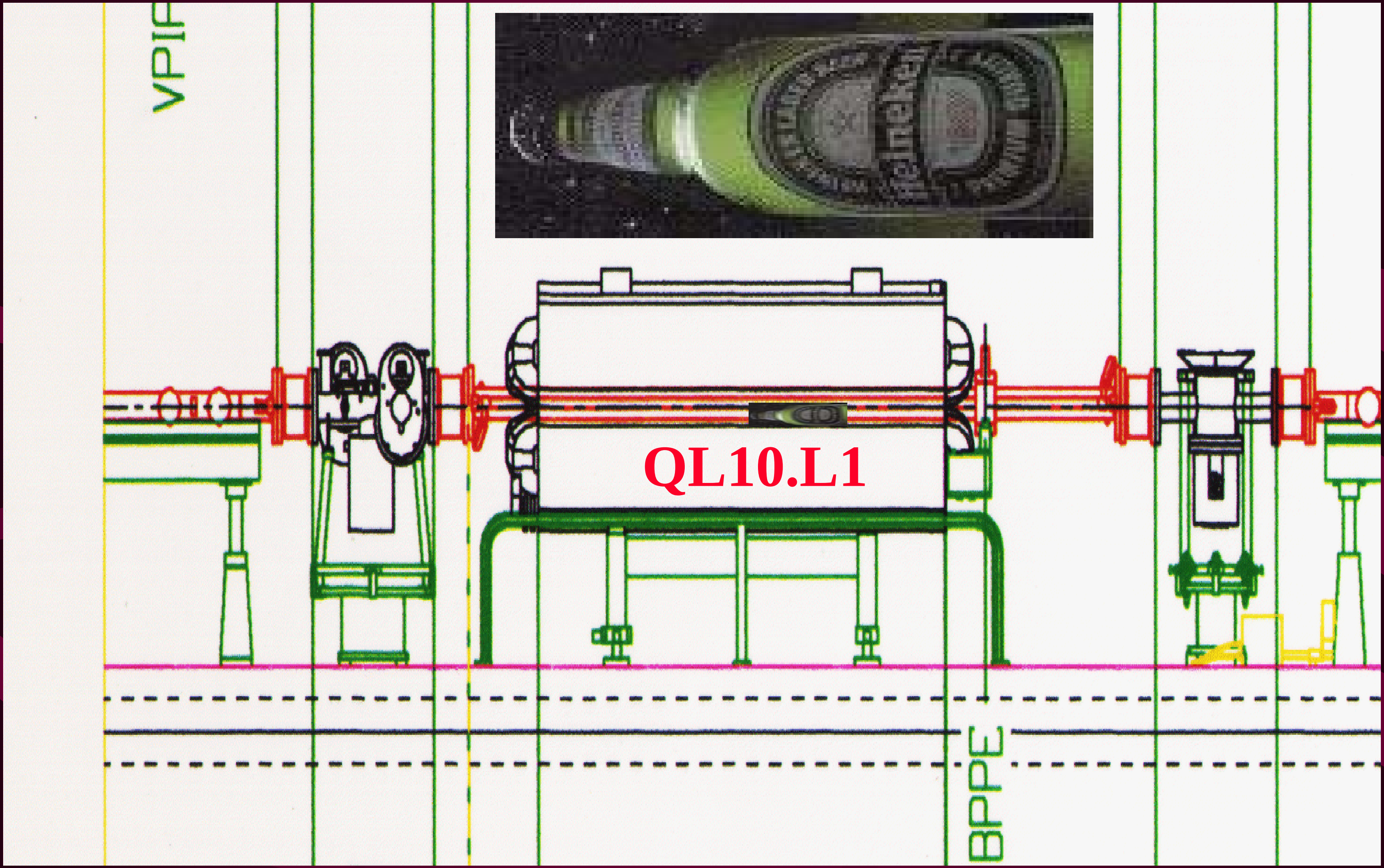
LEP – No Circulating Beam



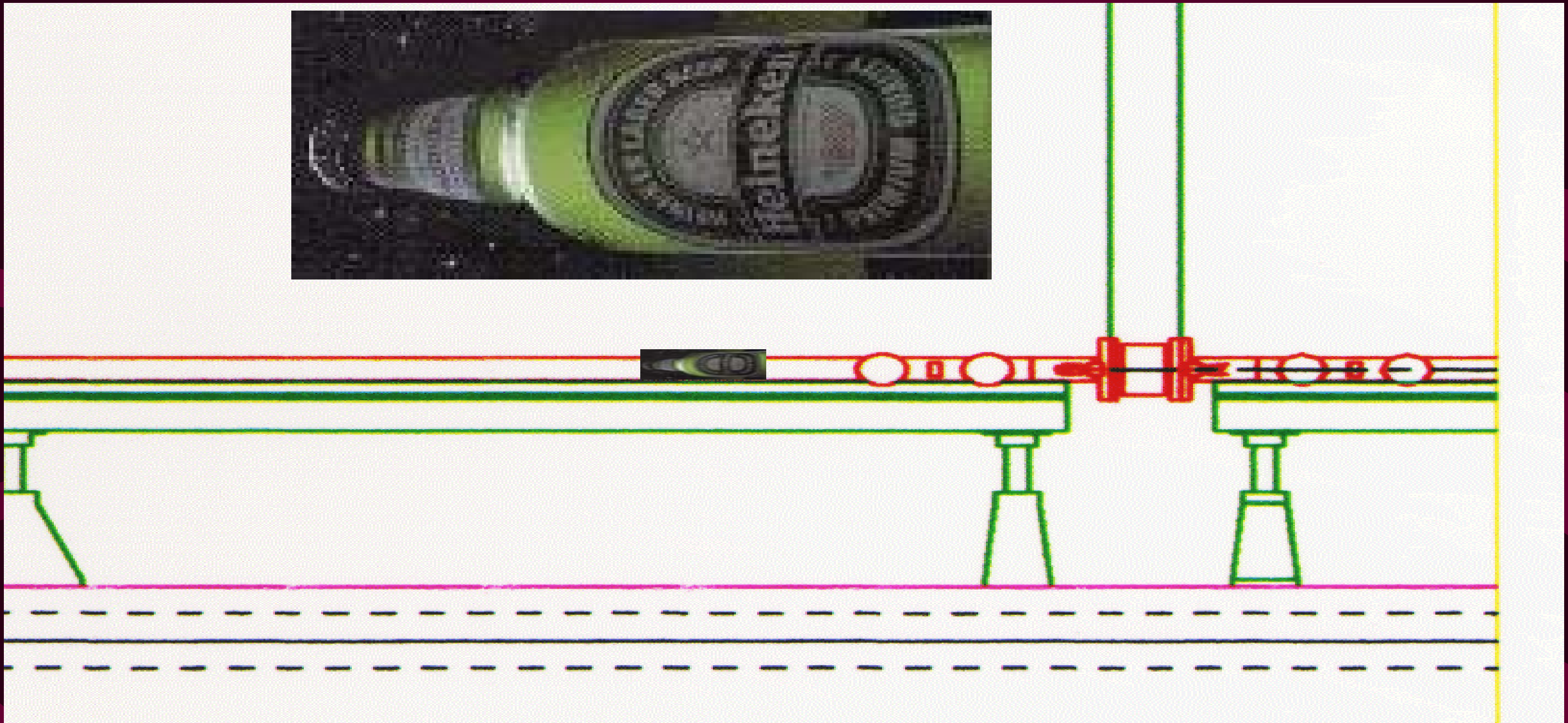
Positrons →

QL10.L1

Zoom on QL10



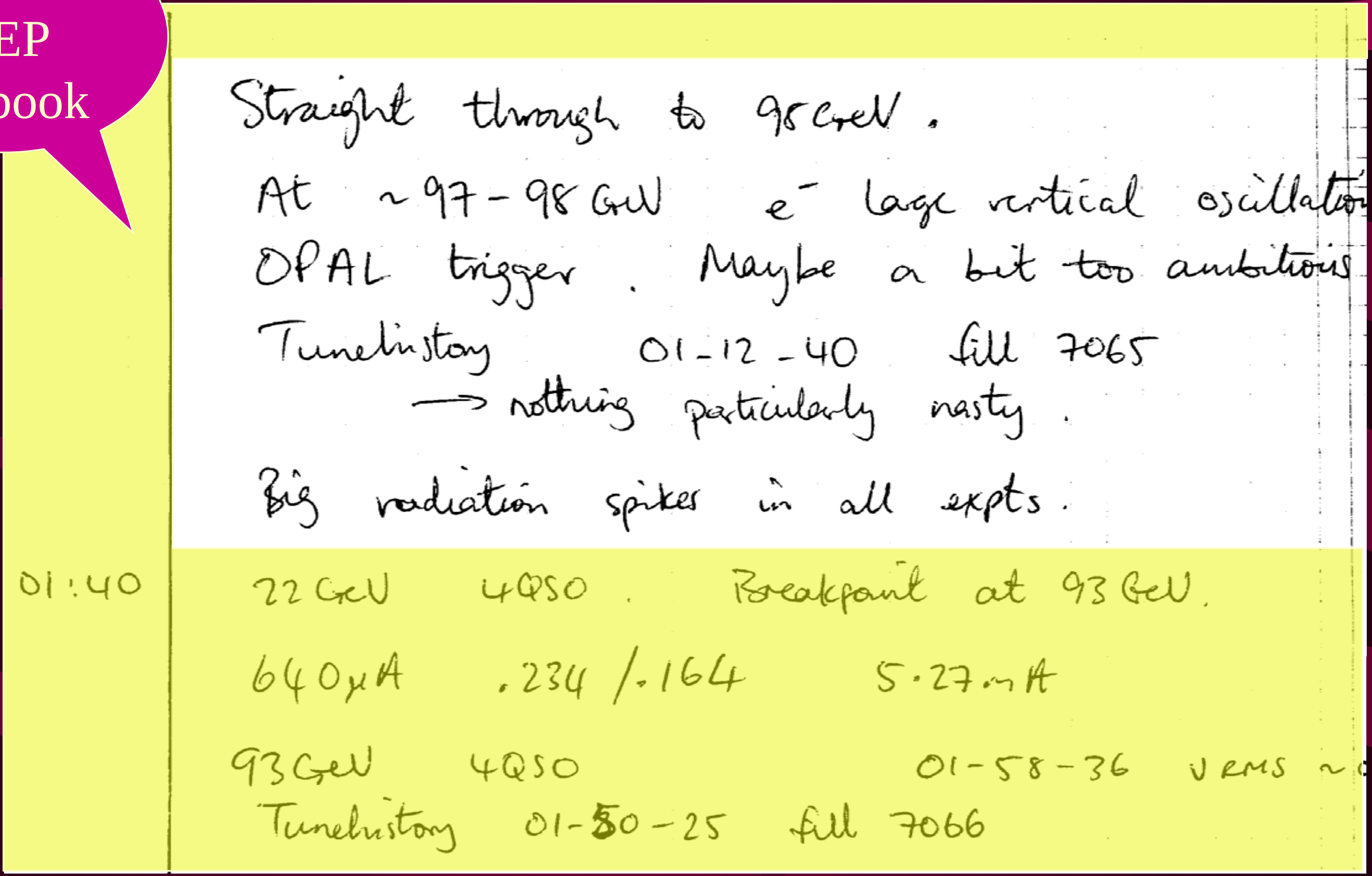
& 10 metres to the right …



Unsociable sabotage: both bottles were empty!!

LEP Beams Lost During Beta Squeeze

From
LEP
logbook



Straight through to 95GeV.

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.

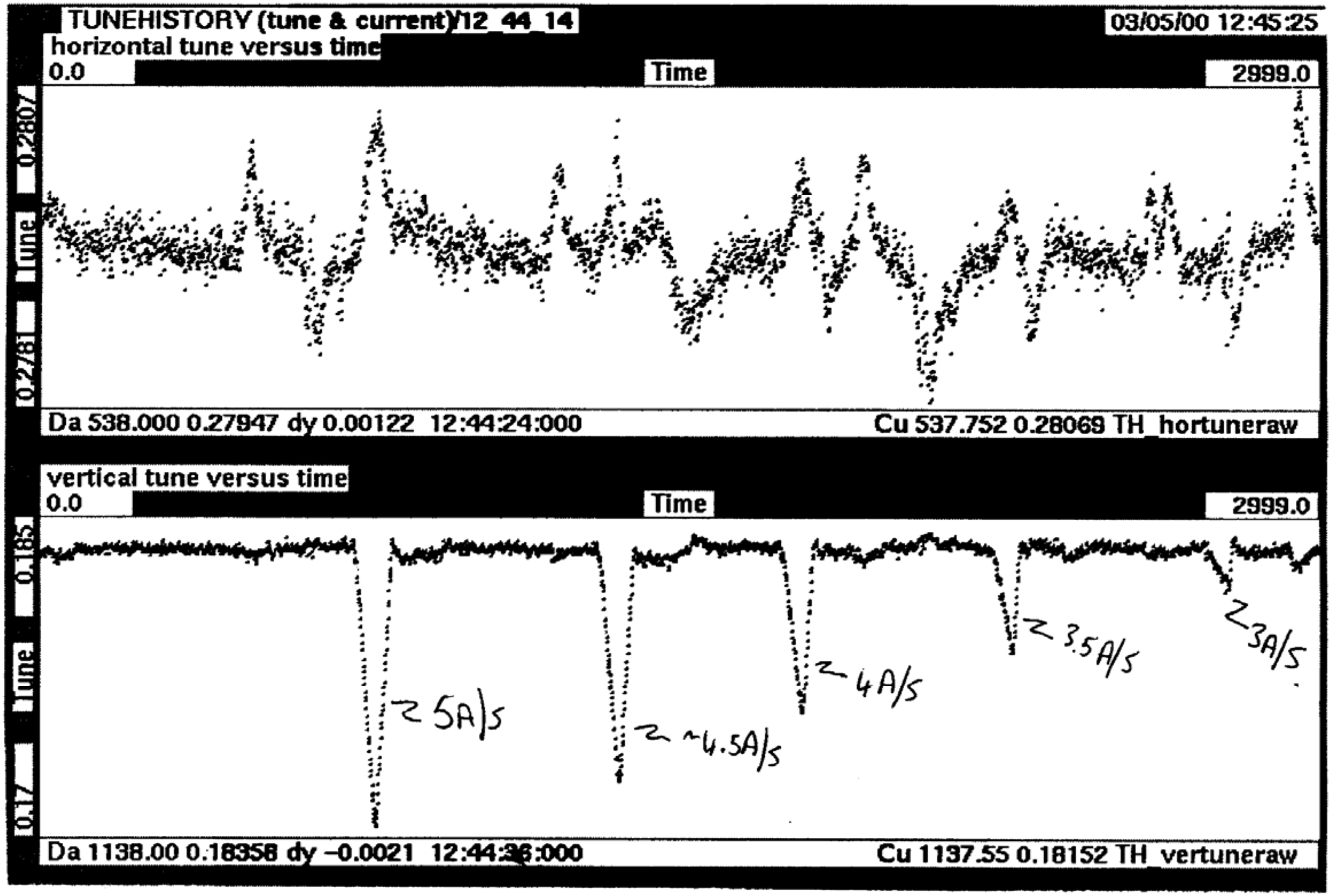
01:40 22 GeV 4QSO. Breakpoint at 93 GeV.

640μA .234 /.164 5.27mA

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

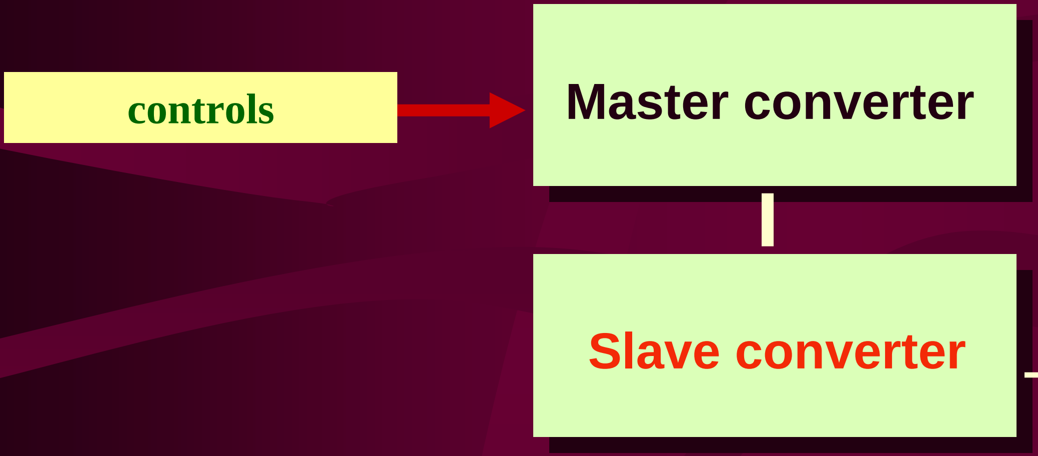
…and the corresponding diagnostics

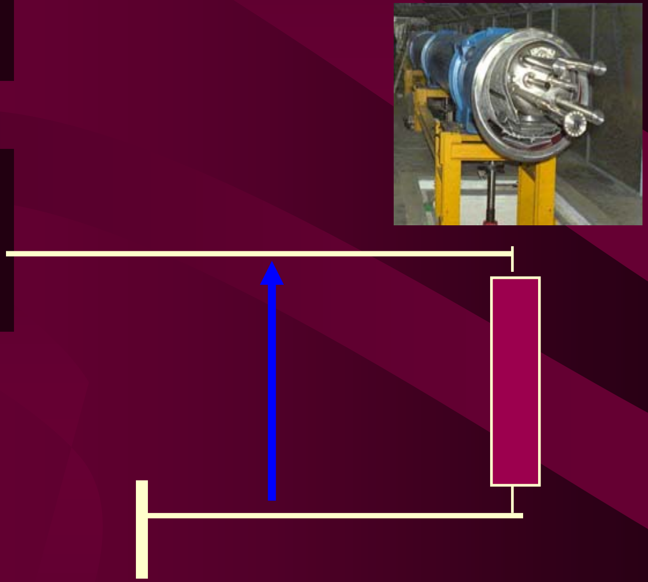
Depends critically on ramp rate of PCs.



Explanation

Master-Slave Configuration for power converter; each converter can deliver full current, slave only needed to give double voltage for fast current changes.





$$U \text{ magnet} = R * I \text{ magnet} + L * d I \text{ magnet}/dt$$

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

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

Slides available on the CAS website