Curiosities and Operation of LEP/LHC

H.Schmickler, seminar CAS-Intro 2021

Slides assembled from old archives of M.Lamont, J.Wenninger and myself

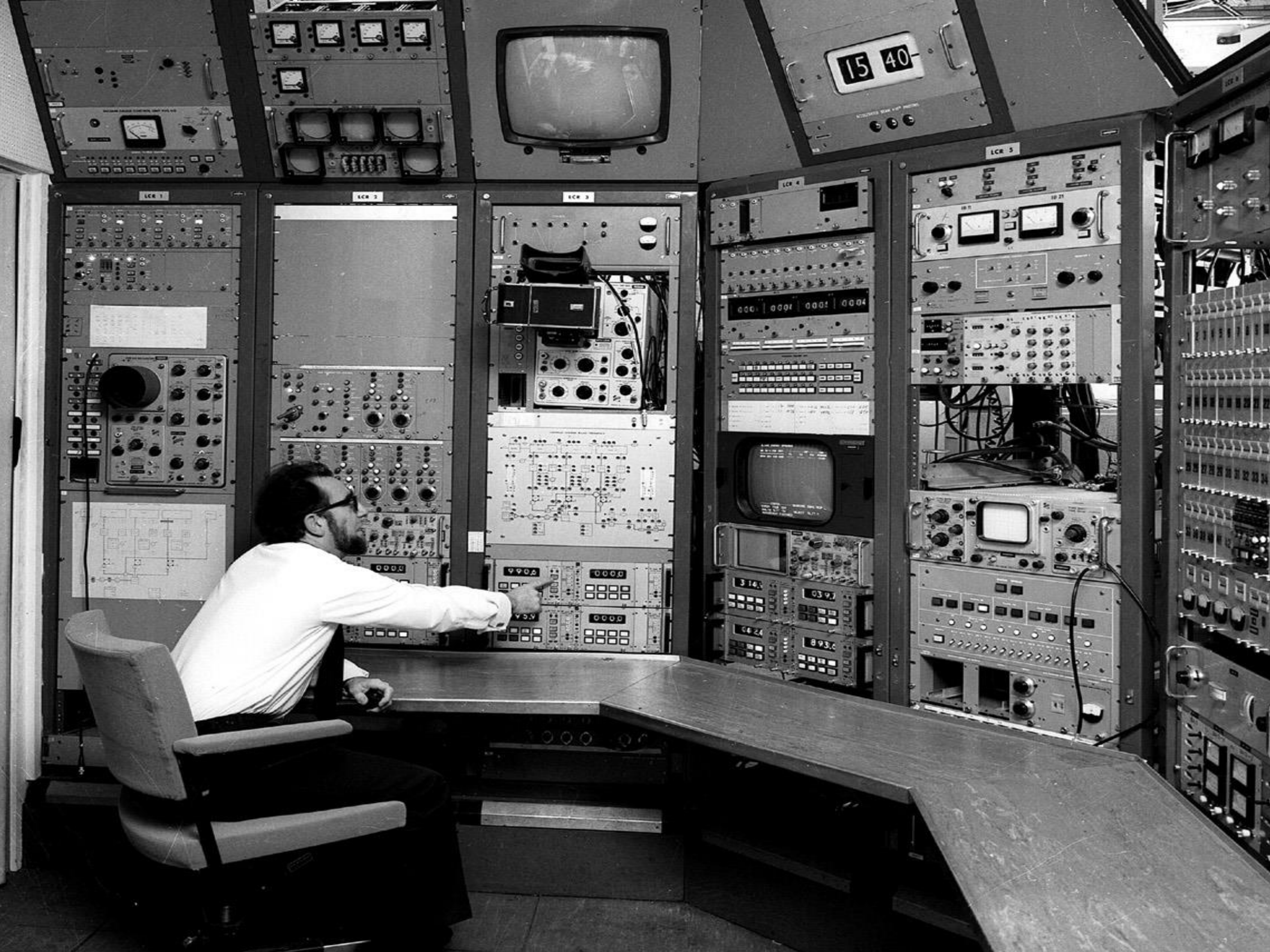
A Sort of Outline

- LEP controls group bashing
- Dynamic control of beam parameters (with beam in the accelerator
- 27 km of circumference… a perfect seismometer
- One of these (bad) days:
  - beams lost during beta squeeze
  - Beam does not circulate at all

most slides taken from J.Wenninger and M.Lamont

Controls technology

- …did barely exist in the « good old days ». Machines were small in size and all equipment control was routed via cables into a central control room.
- Switches, potentiometers and indicators (lampes, meters) were physically installed in the control room.
- Beam Diagnstics was done with instruments locally in the control room.



15 40
LCR 1
LCR 2
LCR 3
LCR 4
LCR 5

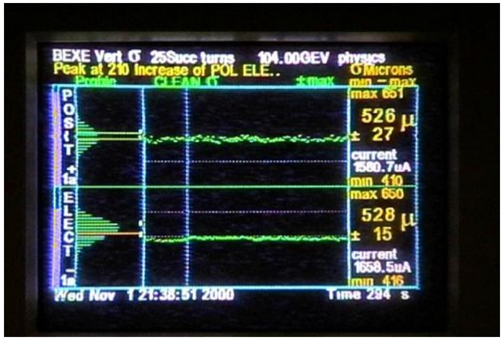
The intermediate period…

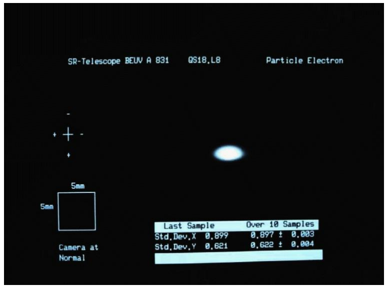
- Onset of computer control…
- No widely accepted industry standards existed for front-end computers and for console computers; low educational level of technical staff on computer technology
- Complete lack of standards for real time operating systems and systems intercommunication.
- Networking only in its beginning
- Performance limits of computers were significant.
  Still many systems (beam instrumentation and RF) with direct high frequency cables to control room.
- In terms of controls of beam parameters: a total mess

The LEP control system was in the beginning similar to a total mess, some of the mess has last until the very end.

Some amusement from beam signals in the control room

1) No fast updating information available on computer displays;
→generate signals locally in the equipment rack, put video camera in front of it and have a dedicated TV in the control room:





2) Synchrotron tune on a loudspeaker: approx 0.07 * 27khz = 1890 Hz
→ quite annoying (unless you try to play notes …)

3) Two controls groups and two control rooms on the injector side and on LEP control: Lepton profile measurements were transmitted by FAX!!!!

The CERN Control Center

Based on the experience of LEP the control system of the LHC was/is to be considered a modern functional control system.

Examples of beam parameter controls

Ability to control beam in terms of appropriate parameters

- Trim synchrotron tune, calculate total voltage change, trim total voltage.
- Trim tune calculate changes in K_{qf}, K_{qd}, I_{qf}, I_{qd}, and send to hardware - where in fact the current is delivered by 8 power converters
- Trim integrated B-field in wiggler, Calculate associated orbit correction, calculate associated optics change, calculate current changes in wigglers, wiggler compensation coils, orbit correctors and insertion quads.
- Plus user-definable KNOBS, e.g. orbit bumps, beta*squeeze etc etc

For either functions in the ramp or at steady state –

provide trim history, rollback, consistency etc… and the ability to carrying on ramping

Note: The ability to set a current is not considered sufficient.

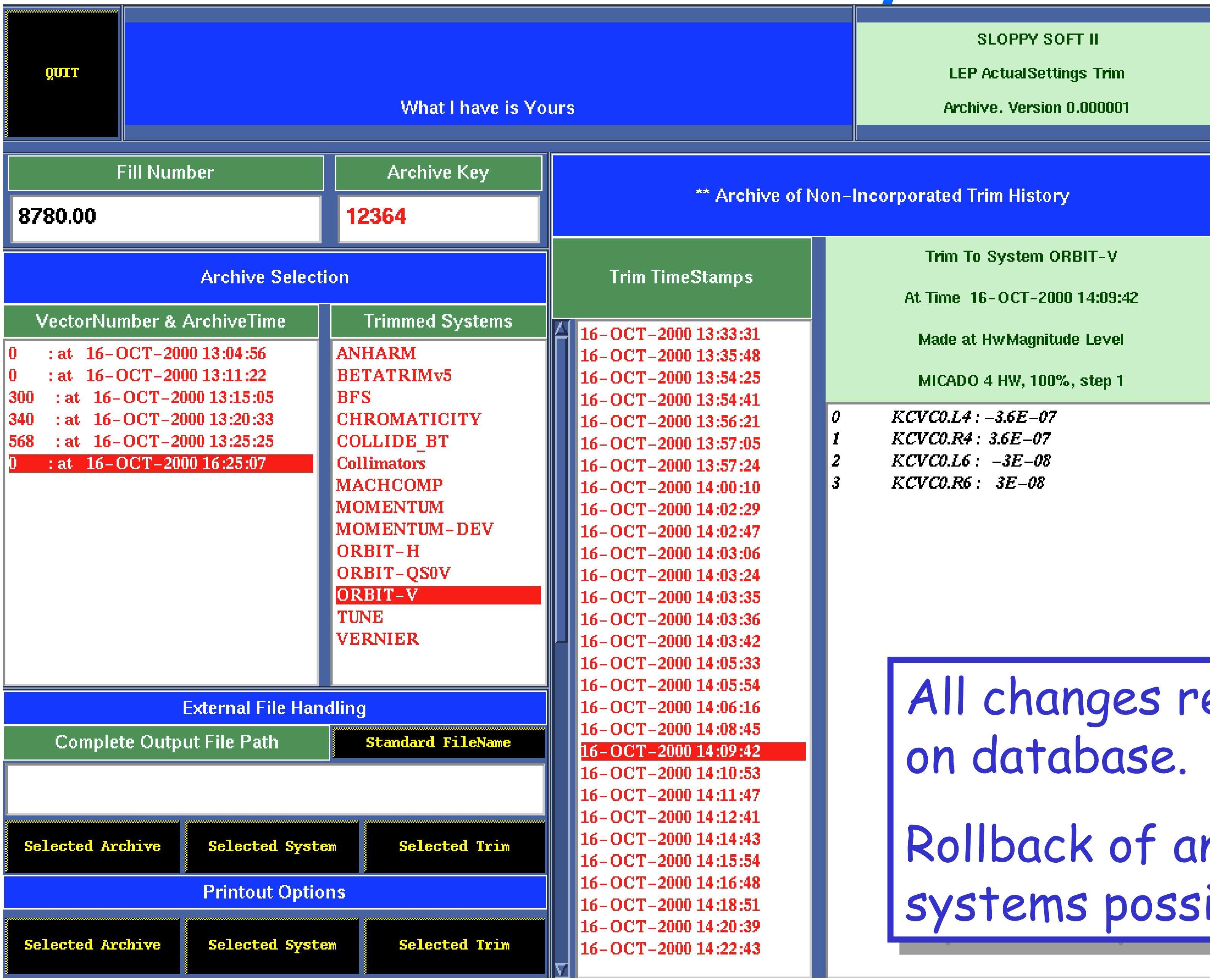
Combined controls/operation project

Controls provided fellows & support for the old system

Redesigned and re-implemented high level control system (on-line ORACLE controls database)

Successfully solved serious data management problem

Trim History



All changes recorded on database.

Rollback of any or all systems possible

Databases

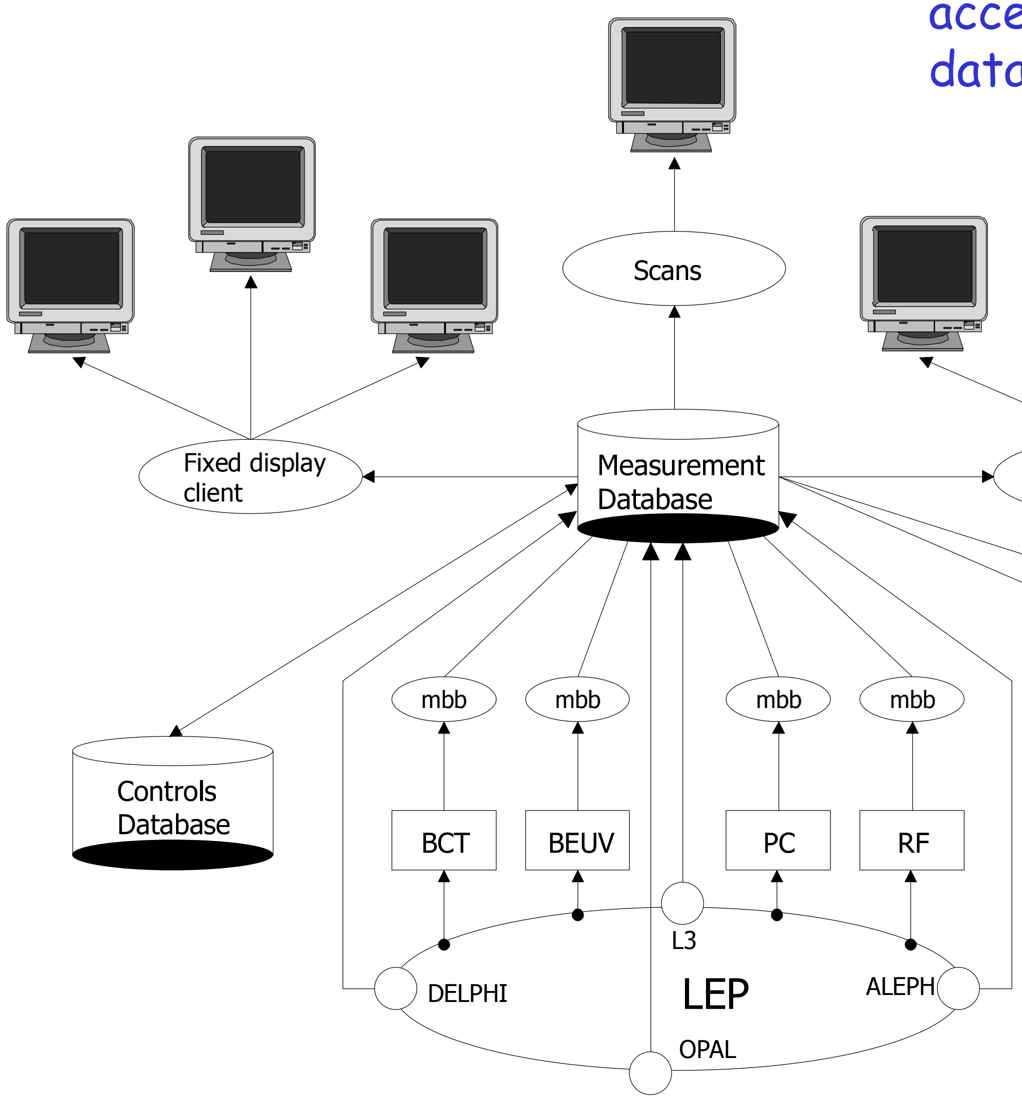
KEY FEATURE - THE USE OF DATABASES

Extremely useful, providing as they do…

Consistency, back-up, support of relational model, access mechanism, a lot of neat stuff, data management, etc…, CENTRAL RESPOSITORY

- Measurement database
  - beam, equipment, experiments, max rate 0.25 Hz, year's worth of history,
- Controls database
  - All settings, machine parameters, configuration, optics etc
  - All trims are recorded
- Logging database
  - many years, sparser than measurements plus environment etc etc
- RF logging database

Series of applications accessing data via database



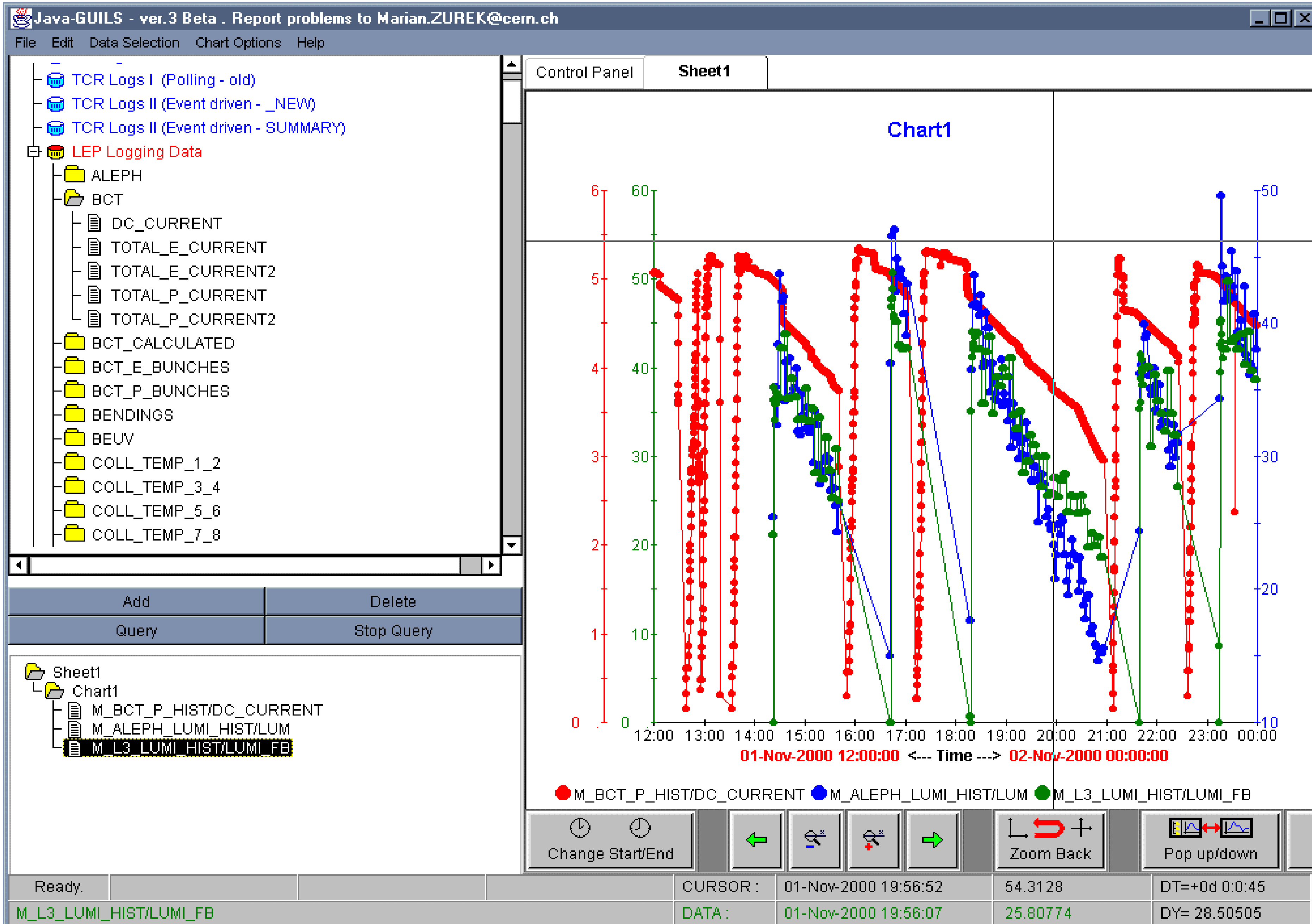
ORACLE database provides central repository

System dependent black boxes pushing data up at appropriate rates

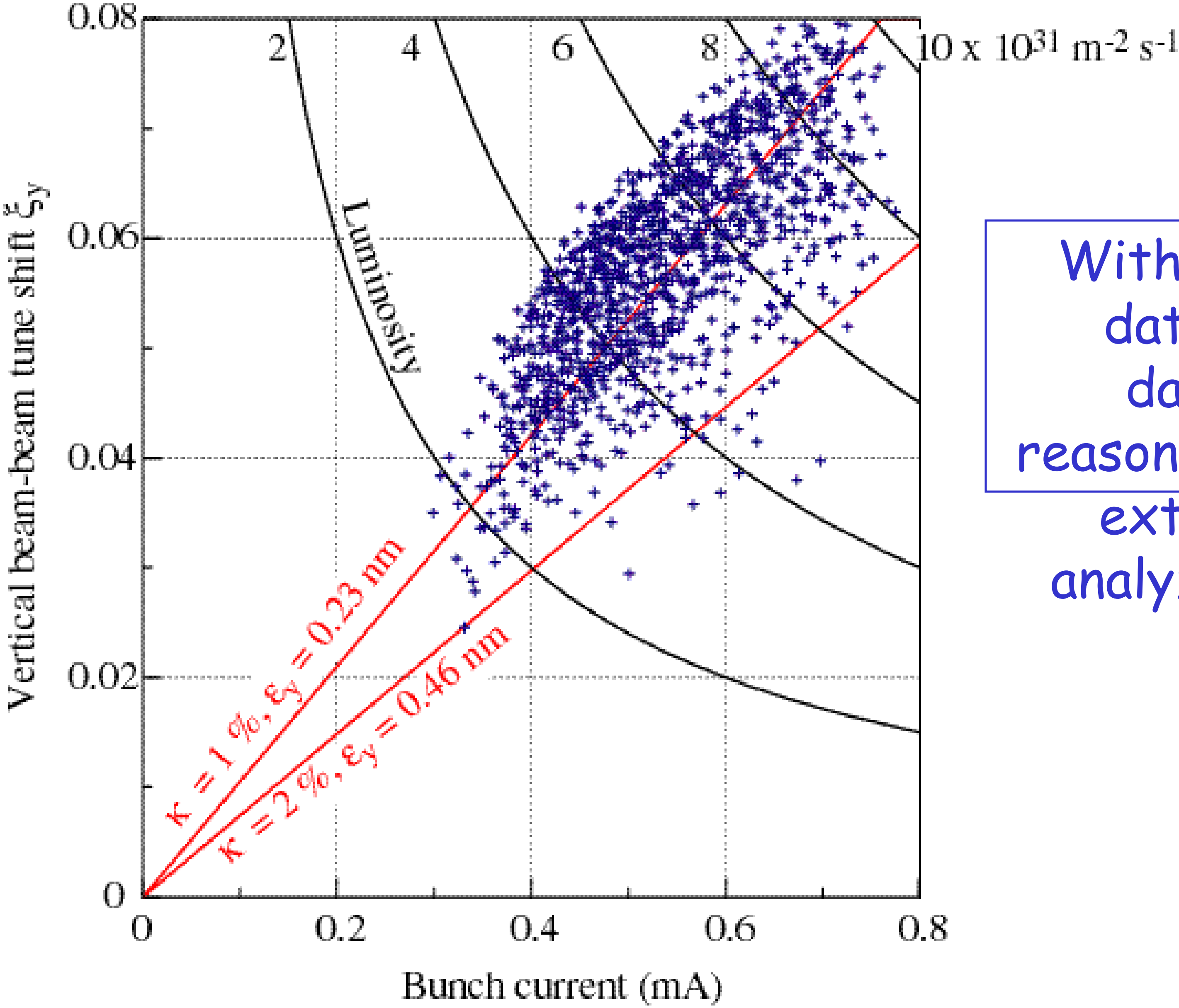
mbb = measurement black box
lbb = logging black box
BCT, BEUV, PC, RF : measurement subsystems

Experiments' communication system

DATA EXTRACTION - JAVA GUILS

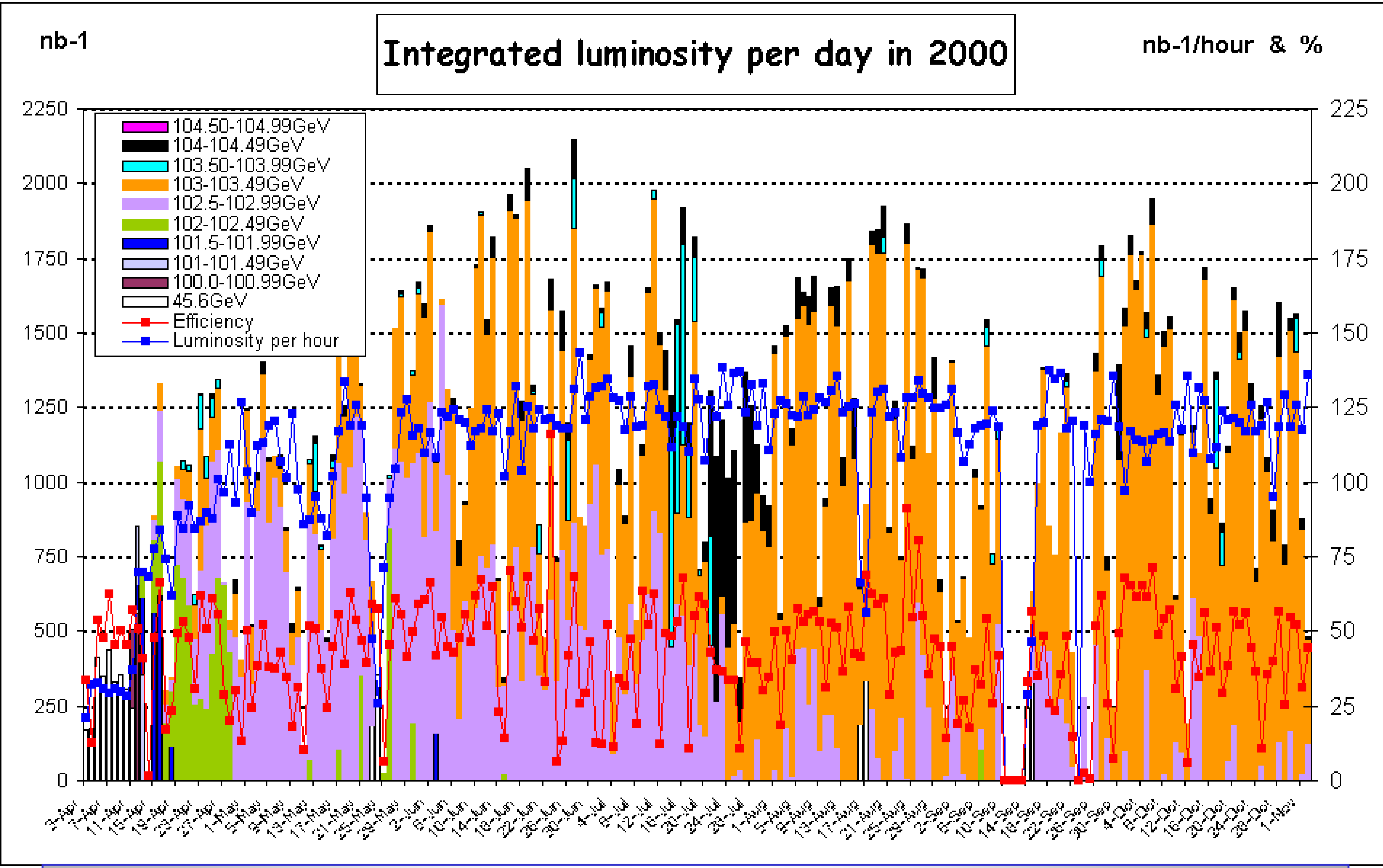


DATA EXTRACTION → POST RUN ANALYSIS



With historical data on the database, reasonably easy to extract and analyze off-line

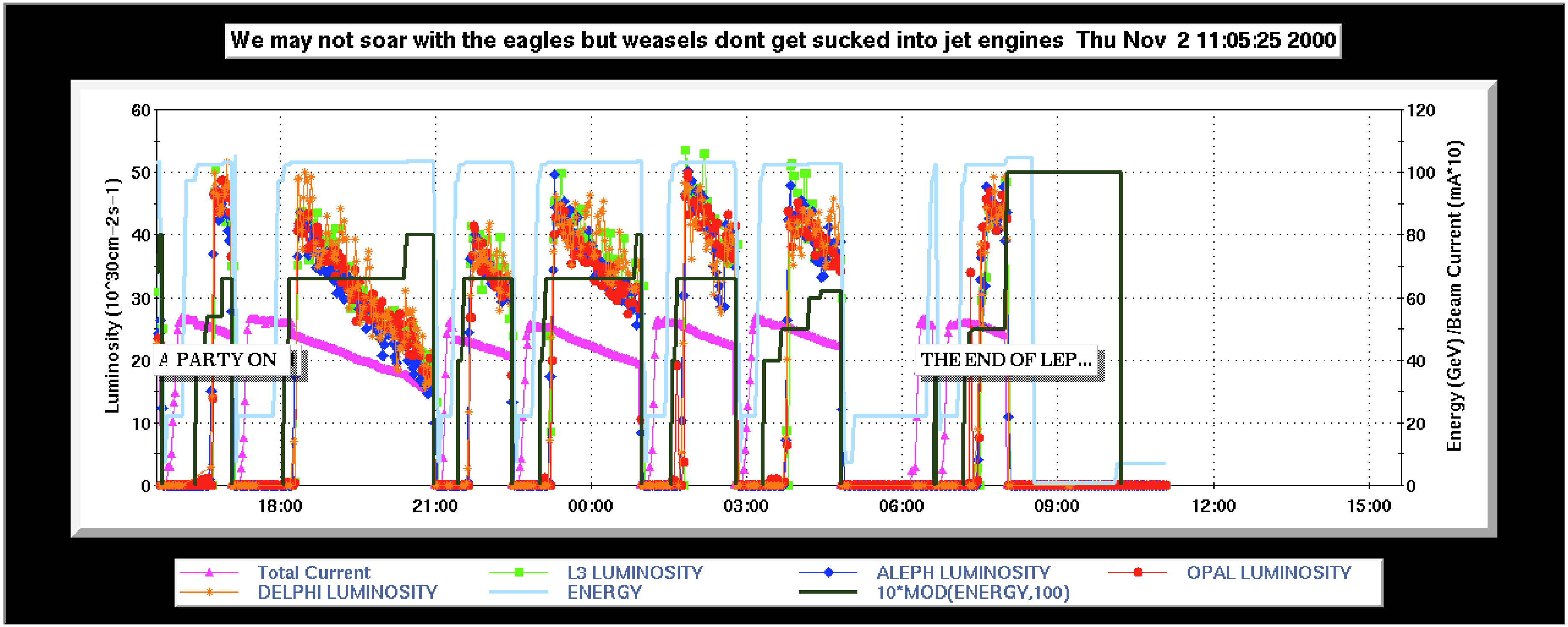
Statistics



Data hauled from database automatically at end of fill

Fixed Displays

Generic data driven application + dynamic SQL



+ backgrounds, radiation, beam-beam tune shifts, bunch currents, angle and positions, beam sizes, luminosities from various sources...

Back to LEP in one slide

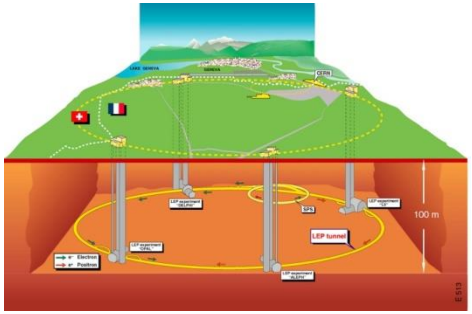
The **Large Electron Positron collider** (LEP) was build in the 1980's and operated between 1989 and 2000 at beam energies from **~43 GeV to 104 GeV**.

Four large experiments (ALEPH, DELPHI, OPAL and L3) were installed in LEP, their experimental programs included the detailed **study of Z and W bosons**.

- *The maximum centre-of-mass energy of ~208 GeV was not sufficient to discover the Higgs as $e^+e^- \rightarrow HZ$ which requires ~215 GeV.*
- *The Z boson mass and width measurements, relying on an accurate determination of the beam energy, were an important part of the experimental program.*

Since energy losses by synchrotron radiation is a concern for circular e^+e^- colliders, the effective LEP bending radius was large, ρ = 3026 m.

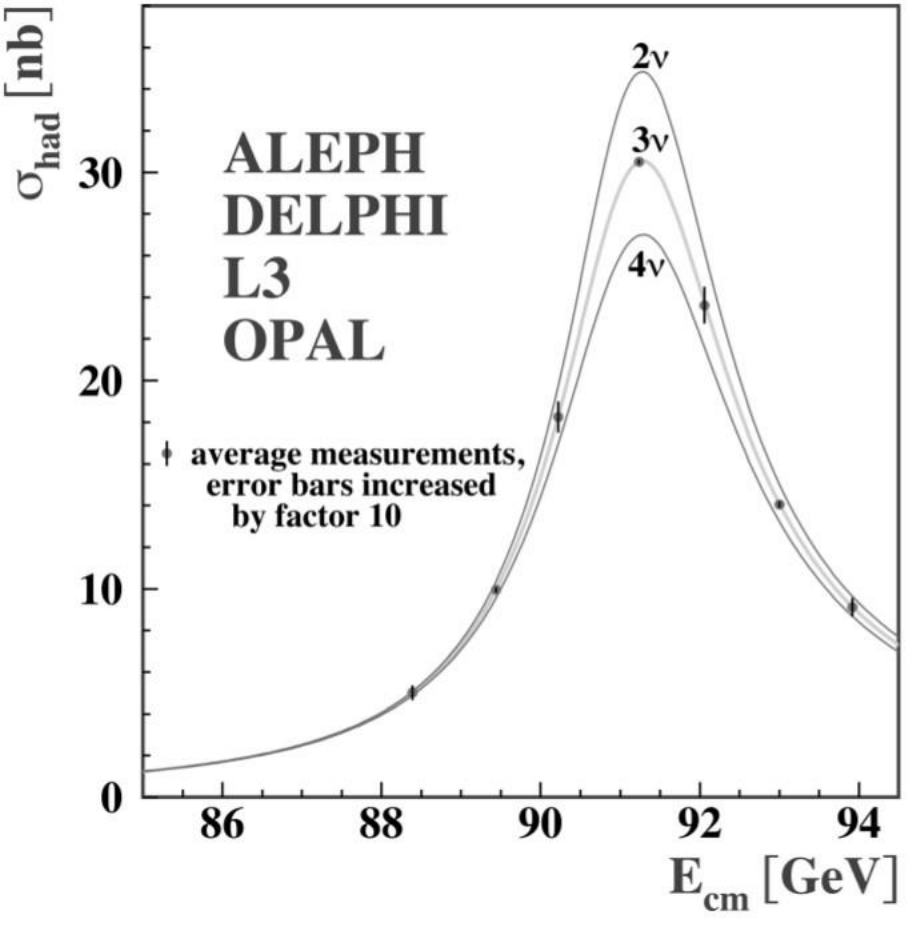
The dipole bending field of LEP was consequently very low, **B ≈ 50 – 120 mT**, rendering the machine more sensitive to stray fields.



Z line shape measurements

One of the main physics objectives of LEP:

Determine (within the Standard model) the number of lepton families



Beam energy

The average beam energy in a ring is given by the integrated magnetic field along the path of the beam(s).

Path / orbit closure

$$\oint_C d\theta = 2\pi = \frac{Ze}{P}\oint_C B(s)ds$$

$$d\theta = \frac{ds}{\rho(s)} = \frac{Ze\,B(s)ds}{P}$$

And therefore

$$P = \frac{Ze}{2\pi}\oint_C B(s)ds = Z \times 47.7[\mathrm{MeV/(cTm)}]\oint_C B(s)ds$$

It is challenging to determine the energy by simple 'summing up' of all fields when accuracies of $\Delta P/P \sim 10^{-5}$ are requested.

Polarization at LEP

As a side effect of synchrotron radiation emission, e^+/e^- beams polarize spontaneously (align their spins) in the transverse (vertical) direction, i.e. along the direction of the bending field.

Polarization is however a slow and delicate process which requires a lot of care in machine setup and special conditions.

Ideal machine :

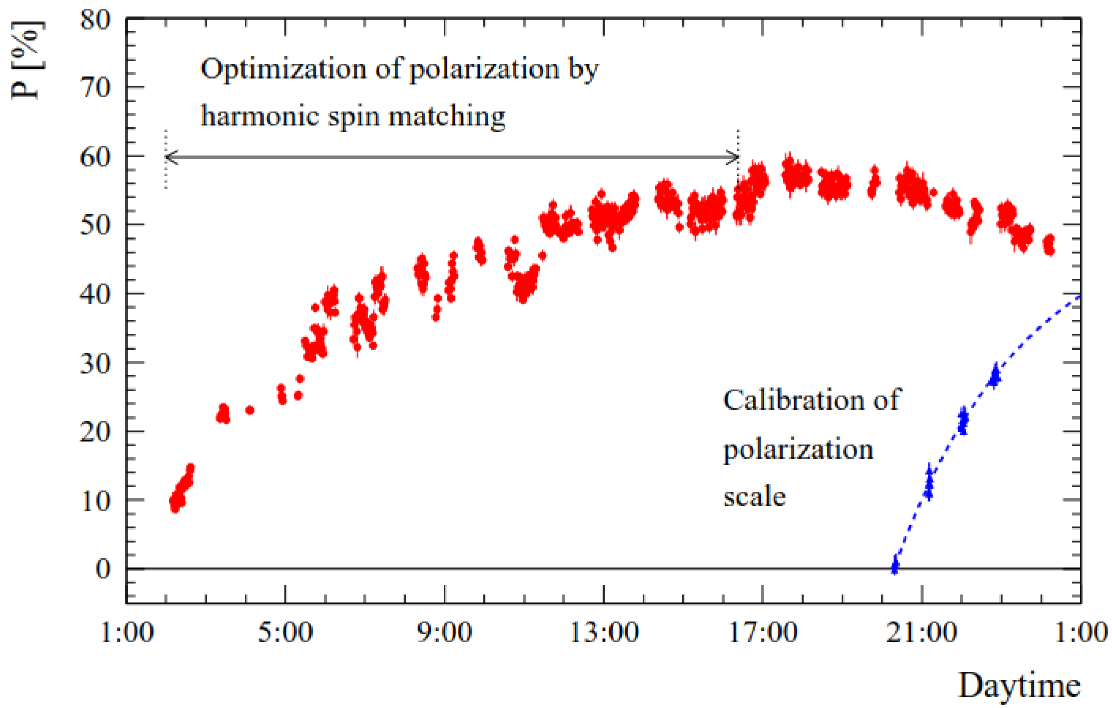
$P_T^{max} = 92.4\%$

At LEP :

record $P_T = 57\%$

routine $P_T = 5$ -10%

Up to 60.6 GeV



Resonant Depolarization

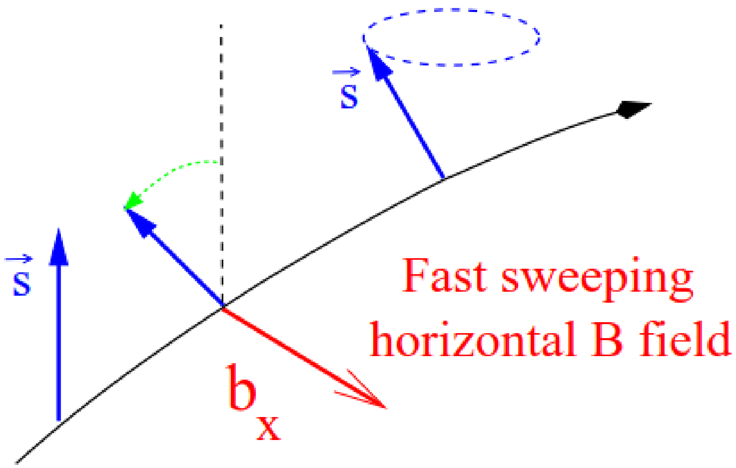
The interest of P_T : magnetic moments precess in B-fields

The **number of precessions/turn** ν, called the spin tune, is **proportional to the energy** :

$$\nu = \frac{g_e - 2}{2}\frac{E}{mc^2} = \frac{E[\mathrm{MeV}]}{440.6486(1)[\mathrm{MeV}]}$$

To determine the energy

Measure ν



Principle :

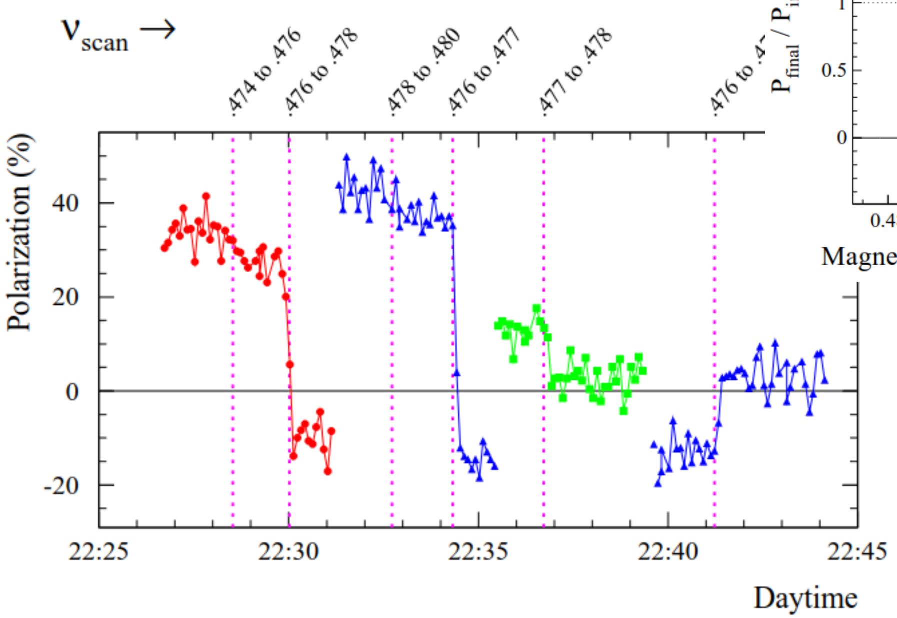
- Sweep the B-field of a fast pulsing magnet ("kicker") in frequency and observe P_T,
- If kicker frequency and ν match, P_T is rotated away from the vertical axis.

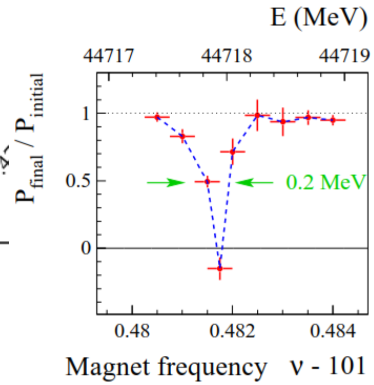
Resonant depolarization

Resonant Depolarization II

In practice :

- The kicker frequency is swept over a selected interval (~ 22 Hz).
- P_T can be destroyed or flipped when the kicker is in resonance.





Intrinsic accuracy :

$\Delta E < 0.4$ MeV
$\Delta E/E < 10^{-5}$

This technique is over an order of magnitude more accurate than any other method !

But it required a large amount of DEDICATED beam time as polarization was not compatible with physics data taking !

Z Resonance Scans

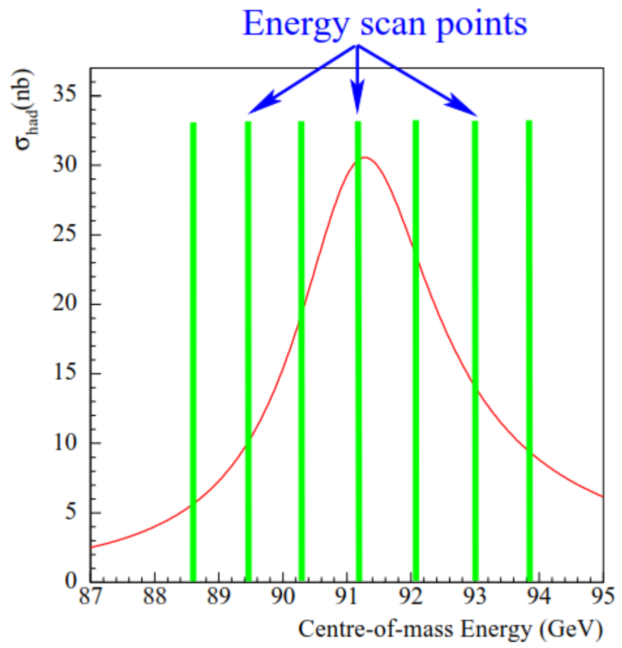
Good regions for P_T are ~ 50 MeV wide and spaced by 441 MeV.

Convenient for Z mass and width measurements !

Calibrations cannot be performed during "physics" (no P_T with colliding beams)

Extrapolation in time

Beam energy model



But 1991 :

the first calibrations revealed unexplained fluctuations of the beam energy.

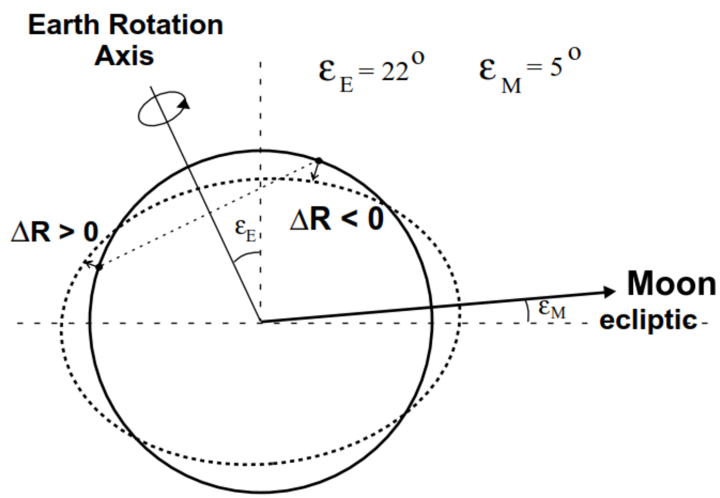
A SLAC ground motion expert suggested… tides !

Earth Tides

Tide bulge of a celestial body
of mass M at a distance d :

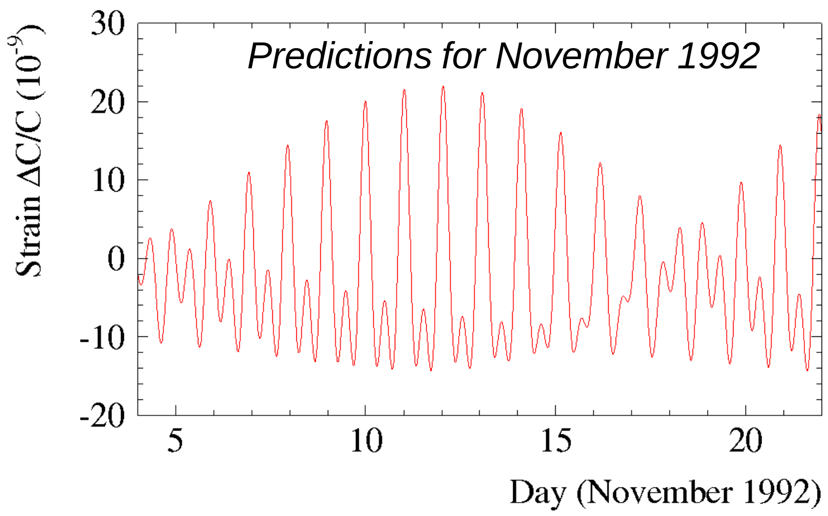
$$\Delta R \sim \frac{M}{2d^3}(3cos^2\theta - 1)$$

θ = angle(vertical, the celestial body)



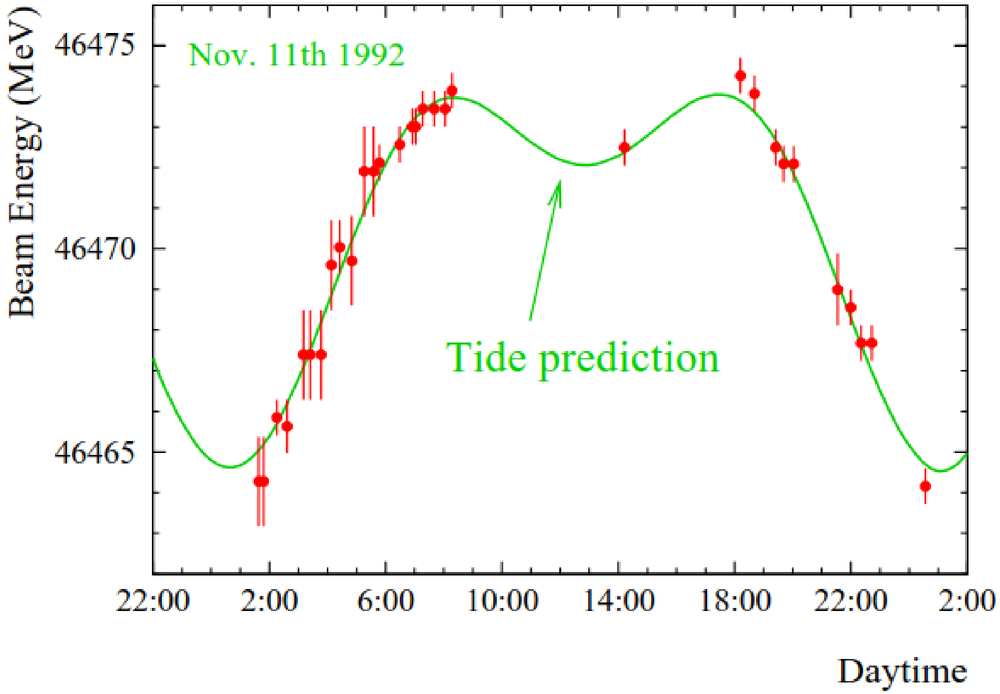
Earth tides :

- The Moon contributes 2/3, the Sun 1/3.
- Not resonance-driven (unlike Sea tides !).
- Accurate predictions possible (~%).



Moonrise over LEP

November 1992 : A historic tide experiment during new moon



The total strain is 4 x 10^{-8} (ΔC = 1 mm)

Success in the Press !

Moon Found Behind Particle-Accelerator Puzzle

By MALCOLM W. BROWNE

In Physics, the Moon Factor

GENEVA (IHT) — Scientists at the European Laboratory for Particle Physics will have to consult the phase of the moon in future before calibrating instruments on the Large Electron Positron collider outside Geneva.

Long puzzled by variations in the energy of the circulating beam made up of hundreds of millions of subatomic particles, physicists have now discovered that these correspond exactly to minute deformations in the Earth's crust caused by lunar attraction. Over the 27 kilome-

SCIENCES

Au LEP, près de Genève

Les effets de Lune dévoilés par les physiciens

Dans le grand accélérateur européen de particules, les mesures ...

Physicists look to the moon for atomic answers

PHYSIQUE DES PARTICULES Mystère élucidé

Comment la lune a trompé le CERN : les physiciens expliquent

Les scientifiques ont enfin trouvé l'origine d'une imprécision qui entachait leurs expériences : des « marées terrestres » provoquées par la lune

La lune trouble le CERN

L'énergie des particules circulant dans l'anneau du LEP se modifie en fonction des phases lunaires.

Physicists are always curious:
What is the mechanism by what the tides vary the beam energy?

Good guess: By lengthening of the closed orbit.

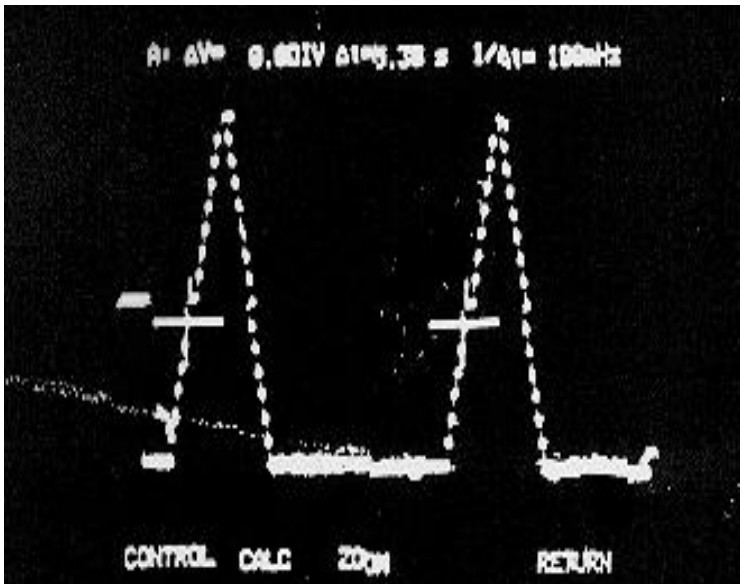
Need about 2mm/27km to explain effect.

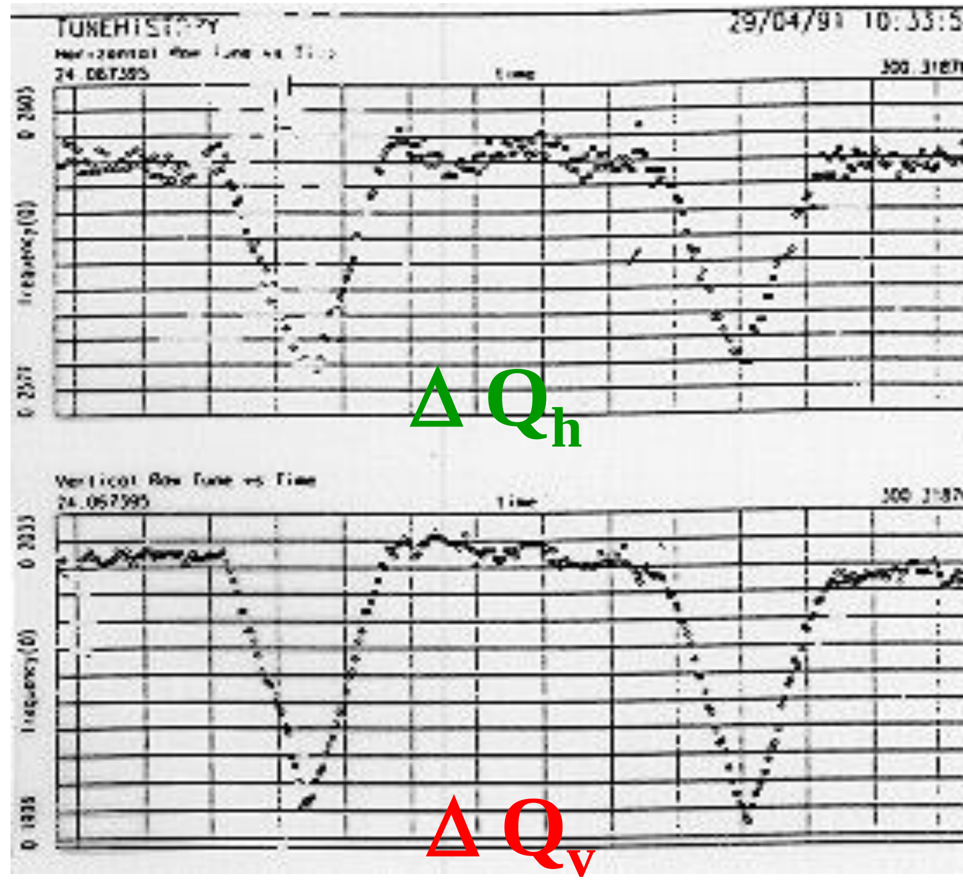
But how to measure this?

Idea (Albert Hoffmann): Detect the orbit by which the beam passes on average through the centre of all sextupoles (which are mounted on the same girder as the quadrupoles).

In practice: PLL-tune tracking during the modulation of the RF frequency …and this procedure for different chromaticity values.

…because if you pass through the centre of the sextupoles they should not have an effect on the beam.

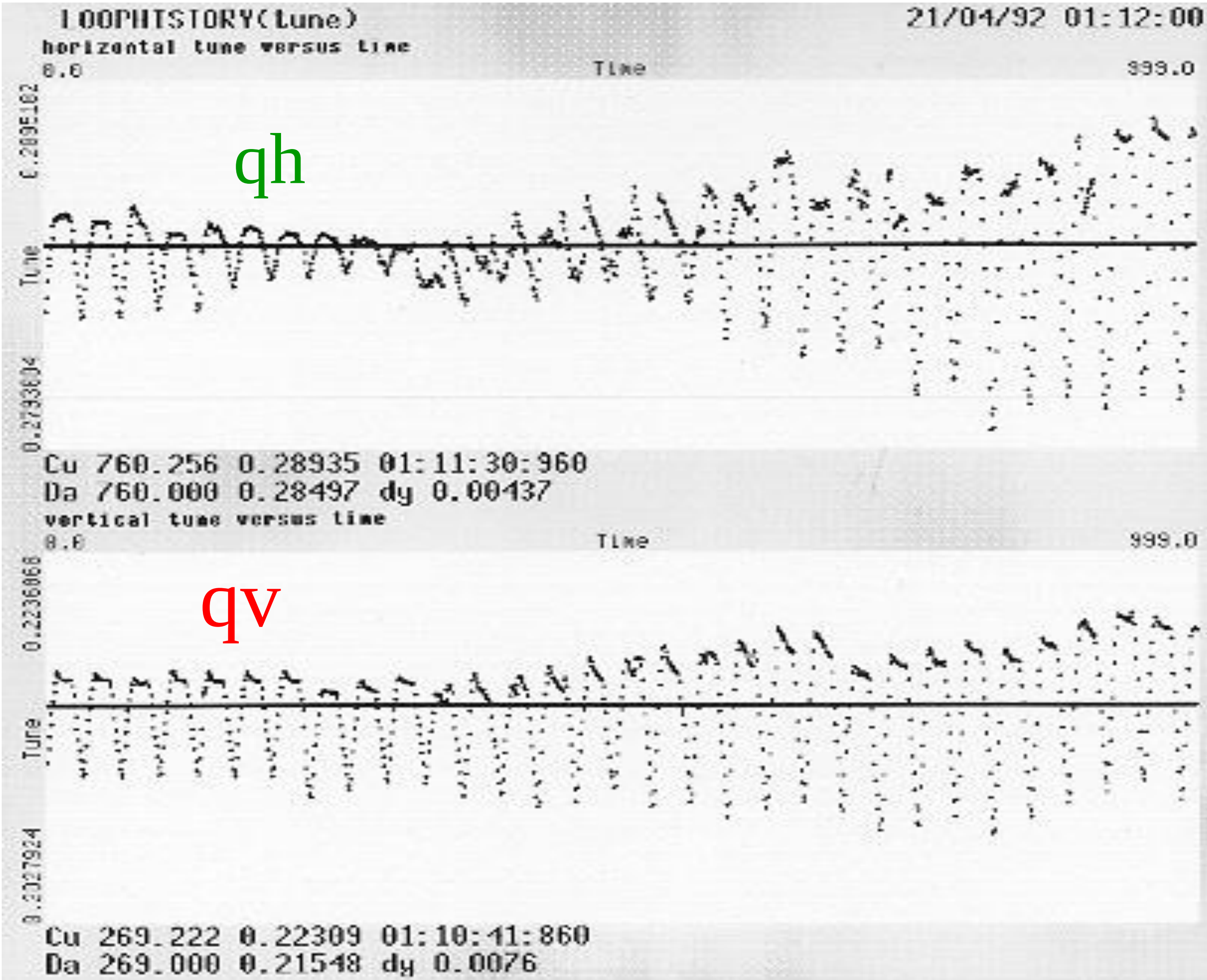




Applied Frequency Shift
Δ F (RF)

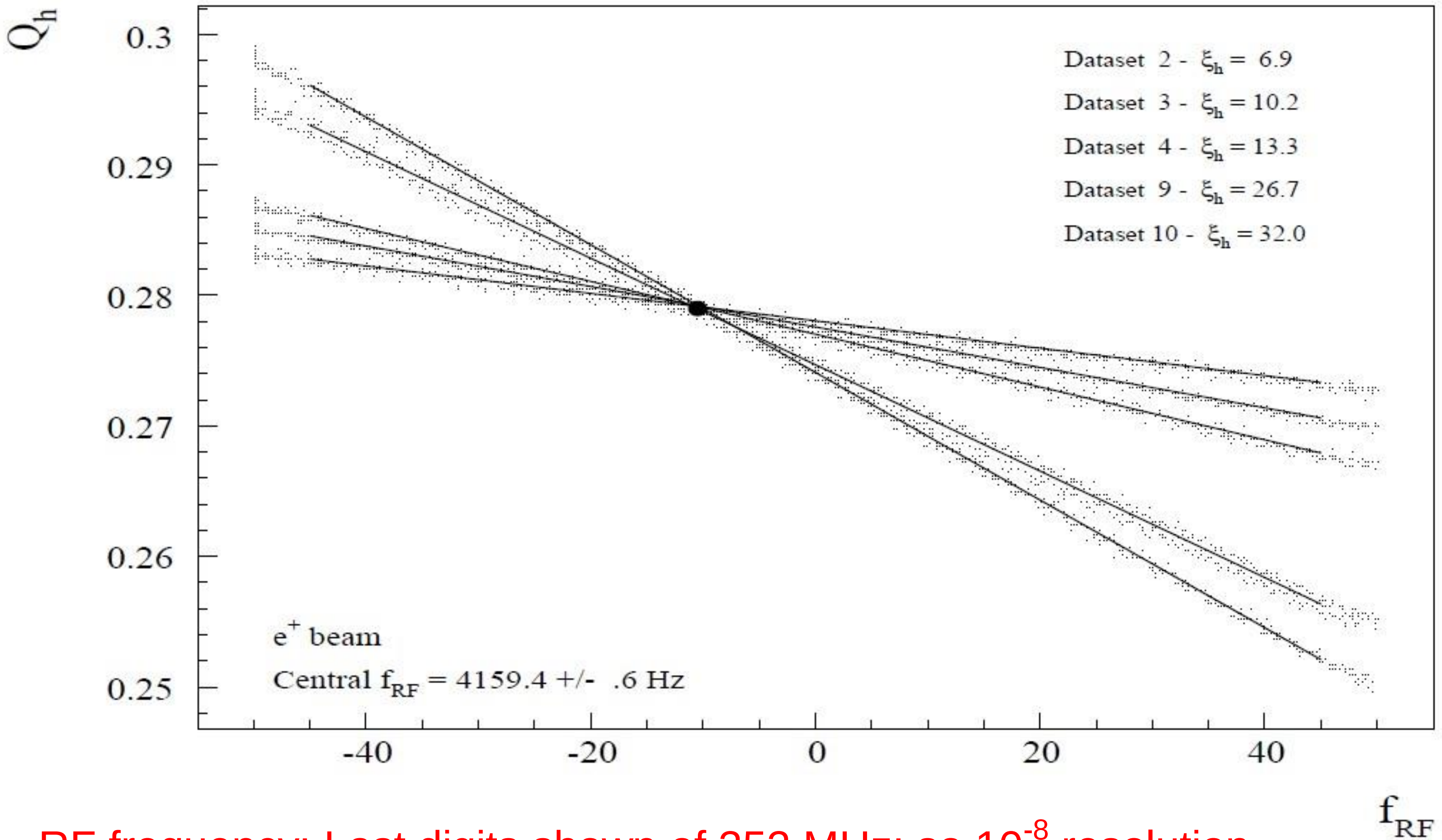
Amplitude & sign of chromaticity calculated from continuous tune plot

Measurement example during changes on very strong quadrupoles in the insertion: LEP β-squeeze



LEP central frequency

The same measurement as before for different chromaticity settings



RF frequency: Last digits shown of 352 MHz: so 10^{-8} resolution

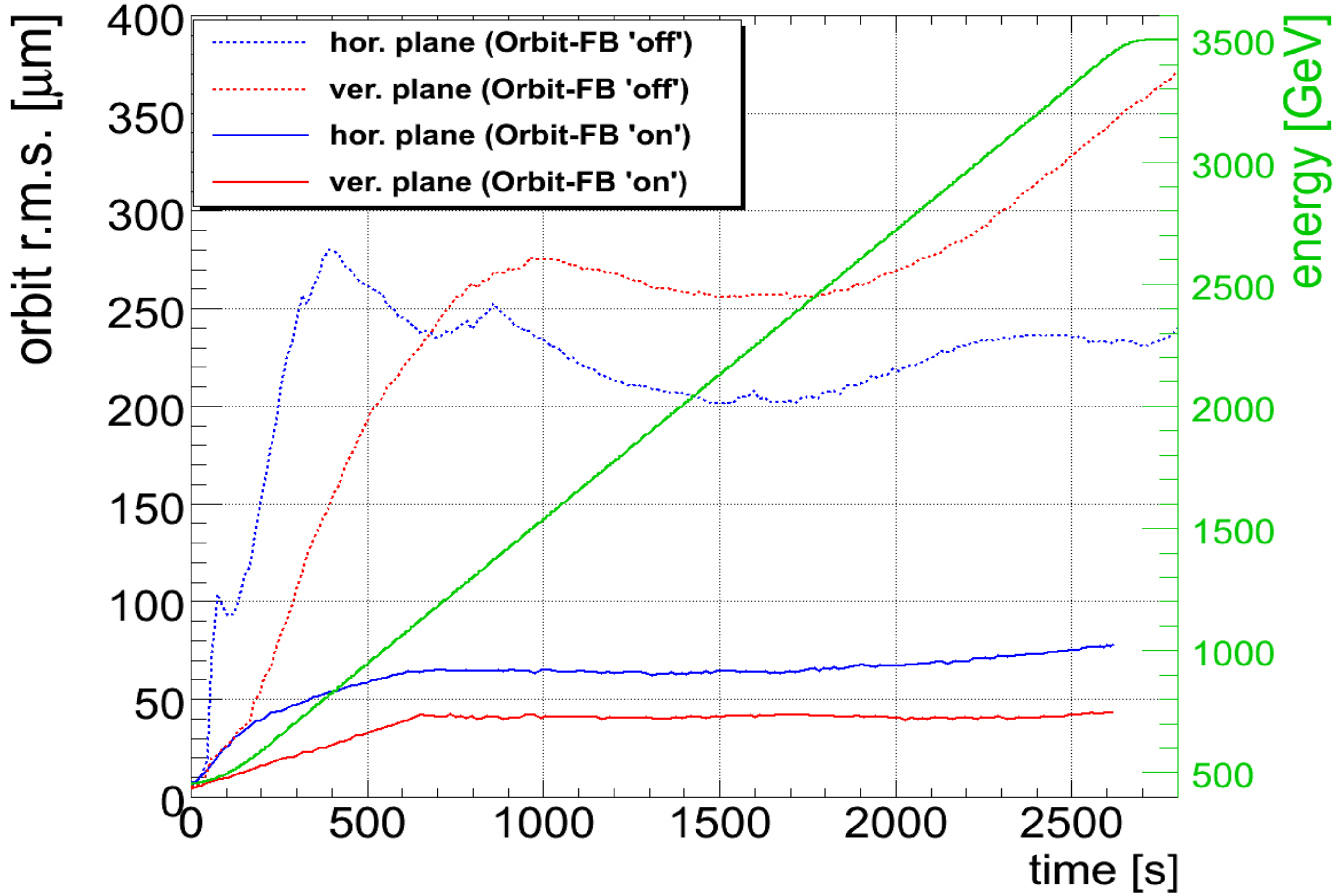
Moon deformations in the LHC?

Of course…it is the same tunnel.

Do we care: Not at all for physics…,

but to some extend for orbit stability (in particular at critical collimators close to the beam

Orbit Feedback in the LHC

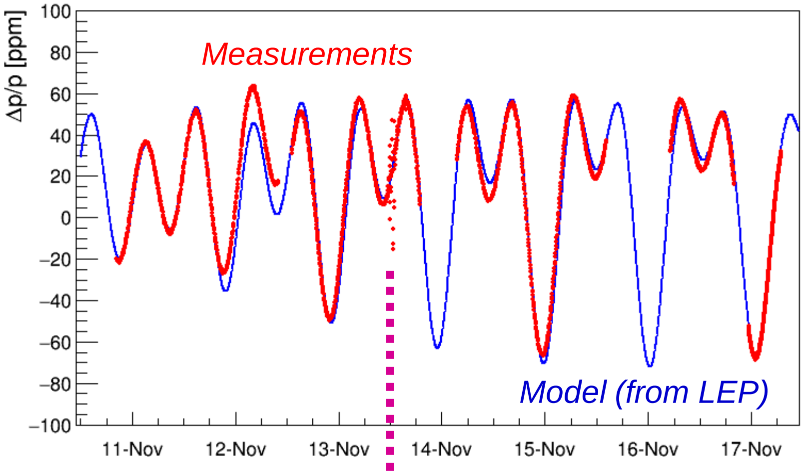


- Bandwidth of 0.1 Hz with BPM data supplied at 25Hz
- Regularised SVD approach to calculate applied correction
- Can maintain orbit stability to better than ~70μm globally & ~20μm in the arcs

Tides and Earthquakes at LHC

Tides are also observed very clearly on the LHC circumference since it is the same ring !.

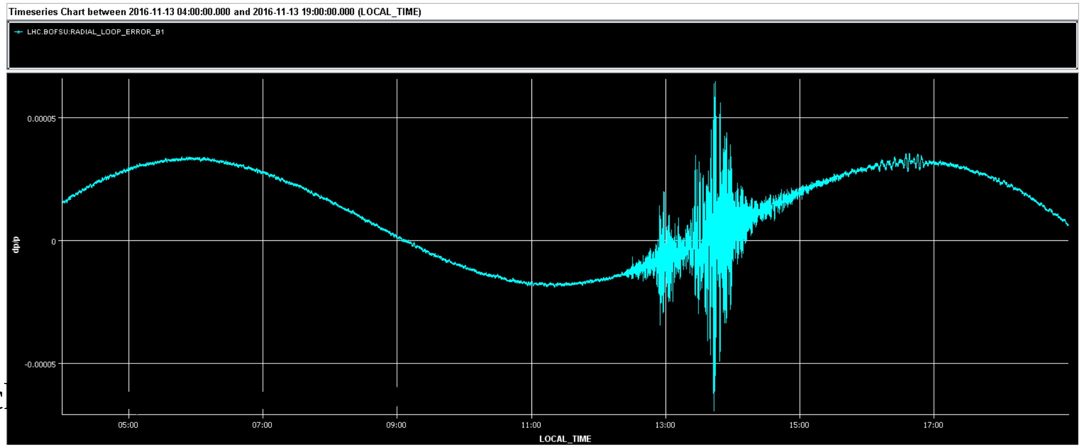
During a 6 day special LHC run in 2016 the feedback on the circumference was switched off to observe tides using the beam position monitors.



Tide observations during the 2016 pPb run at 4 TeV

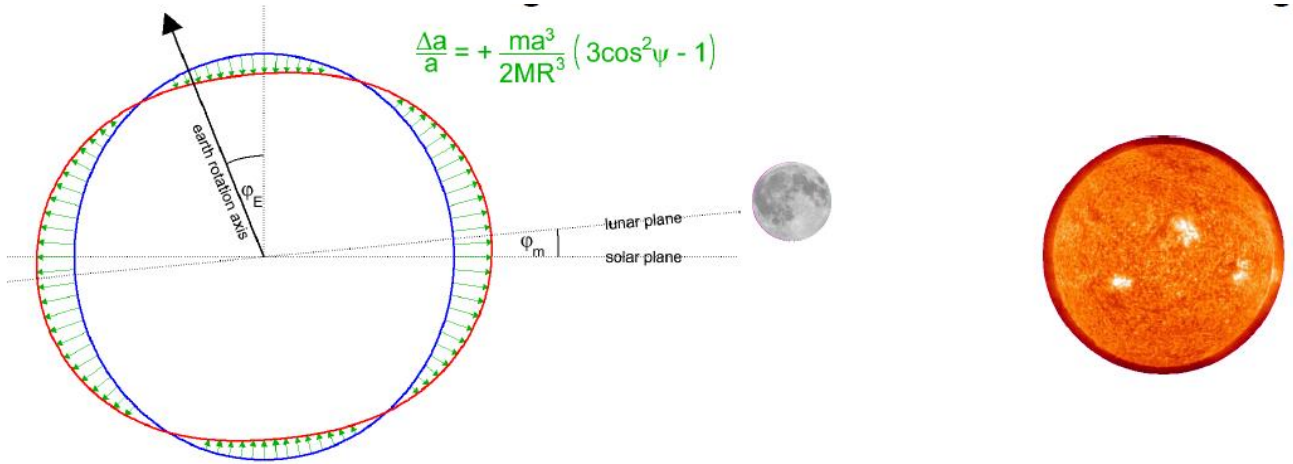
Earthquake in New Zealand

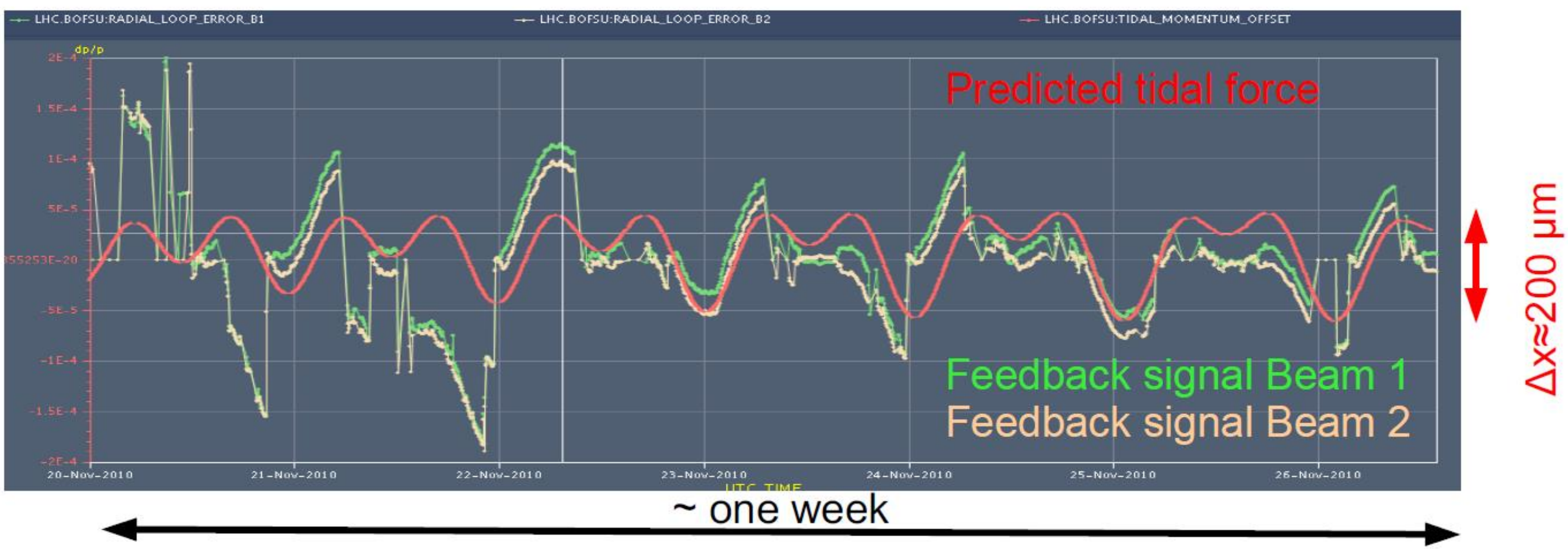
The pressure waves induce a modulation of the circumference



Orbit Feedback in the LHC

- Earth Tides dominating Orbit Stability during Physics



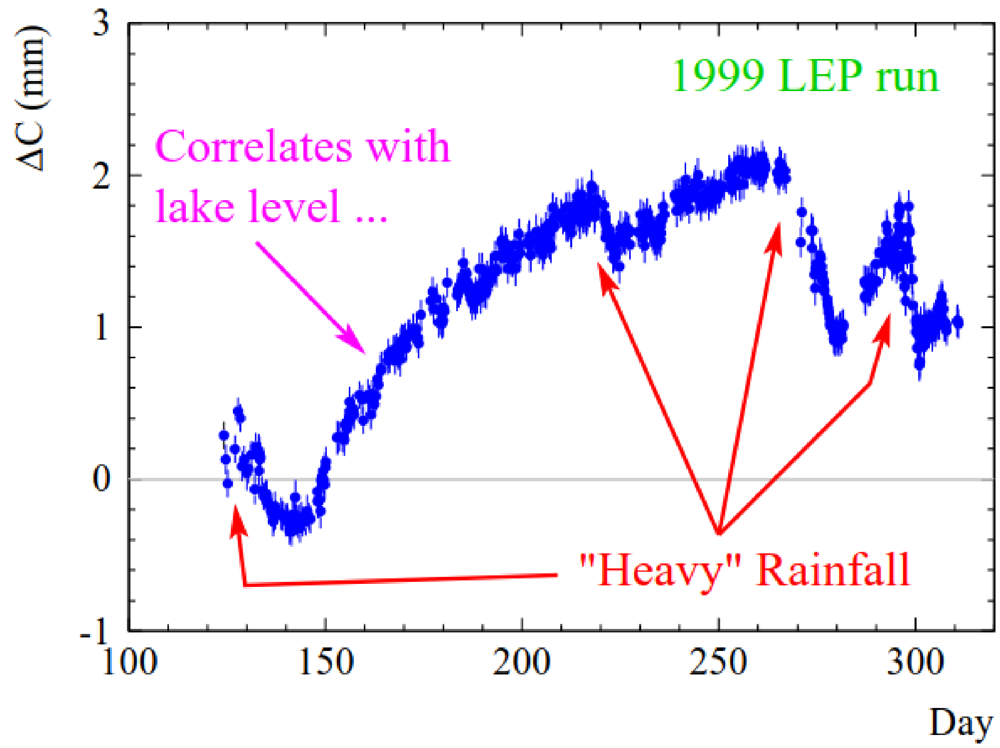


Underground Water

1993 : Unexpected energy "drifts" over a few weeks were traced to cyclic circumference changes of ~ 2 mm/year.

Driving "forces" :

- Underground water
  → Rainfall
- Lake levels ?
- Other ?



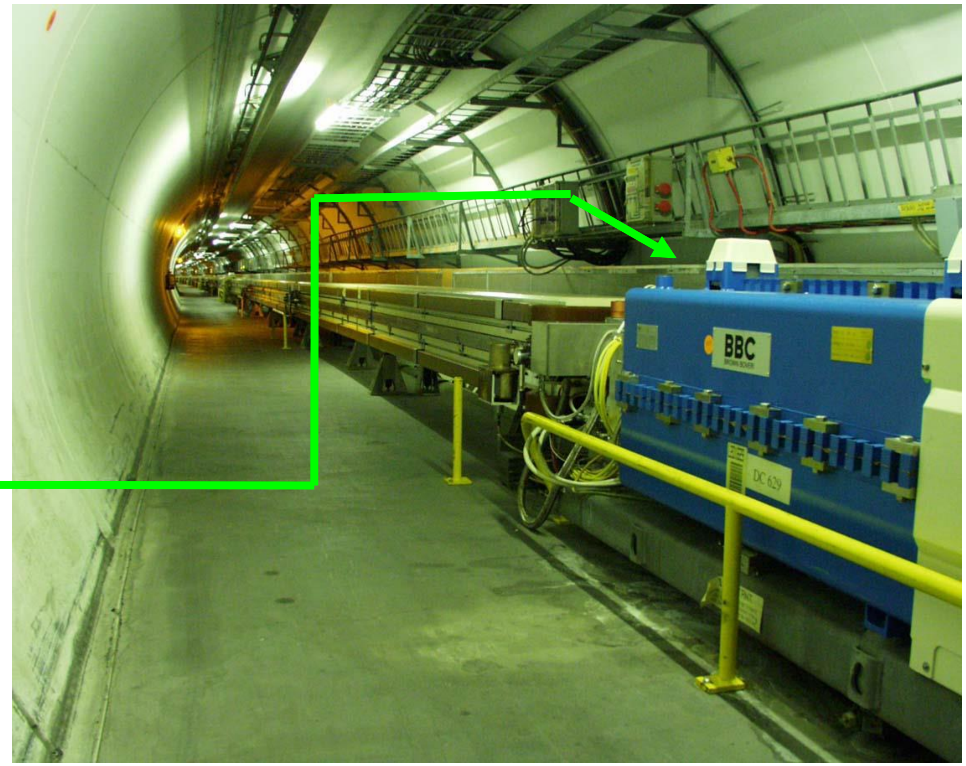
Circumference change measured with the beam position monitors.

First Energy Model

1993 run : following an extensive energy calibration campaign over many fills, a first model of the beam energy evolution emerged.

The model included:

- Tides,
- Seasonal circumference changes,
- Tunnel temperature induced energy changes ($\Delta E/E \sim 10^{-4}$ / K),
- Stray fields from the bus-bars ($\Delta E/E \sim 3\times10^{-5}$),
- Reference magnet field,
- RF system corrections: from beam to centre-of-mass energy.

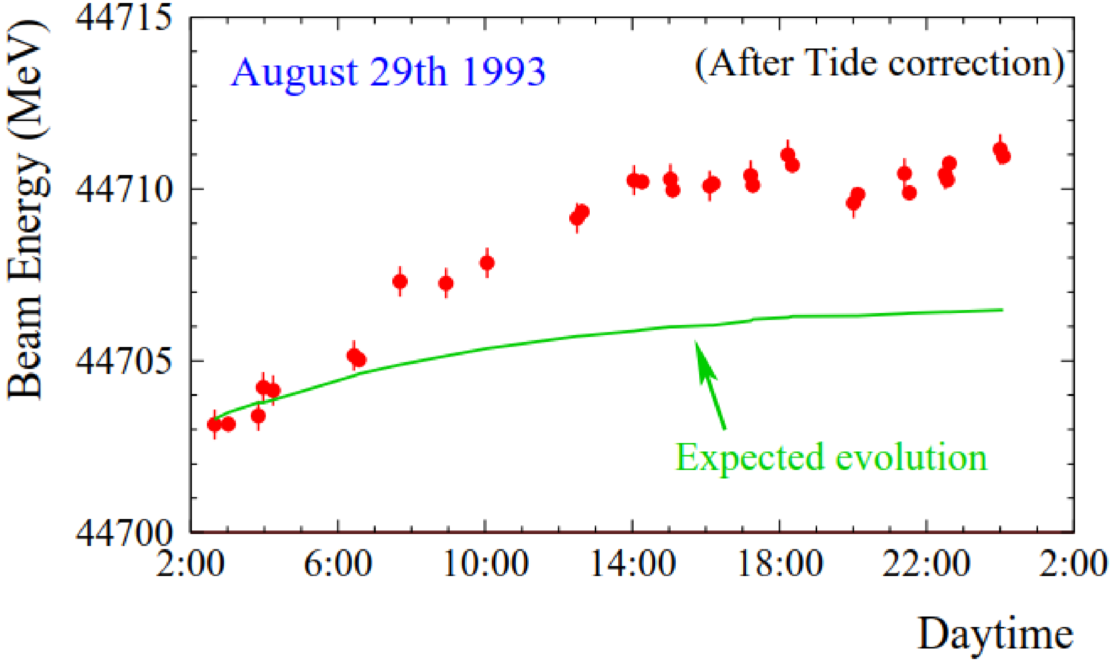


A Crack in the Energy Model

Spring of 1994 : the beam energy model seemed to explain all observed sources of energy fluctuations...

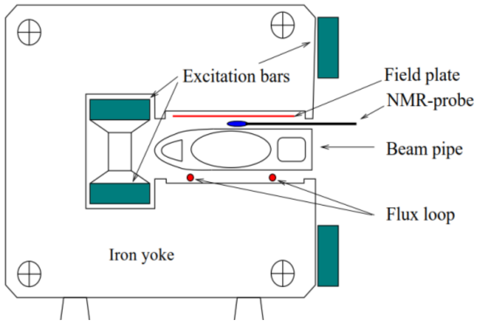
EXCEPT :

An unexplained energy increase of 5 MeV was observed in **ONE** experiment.



It will remain unexplained for two years…

The Field Ghost



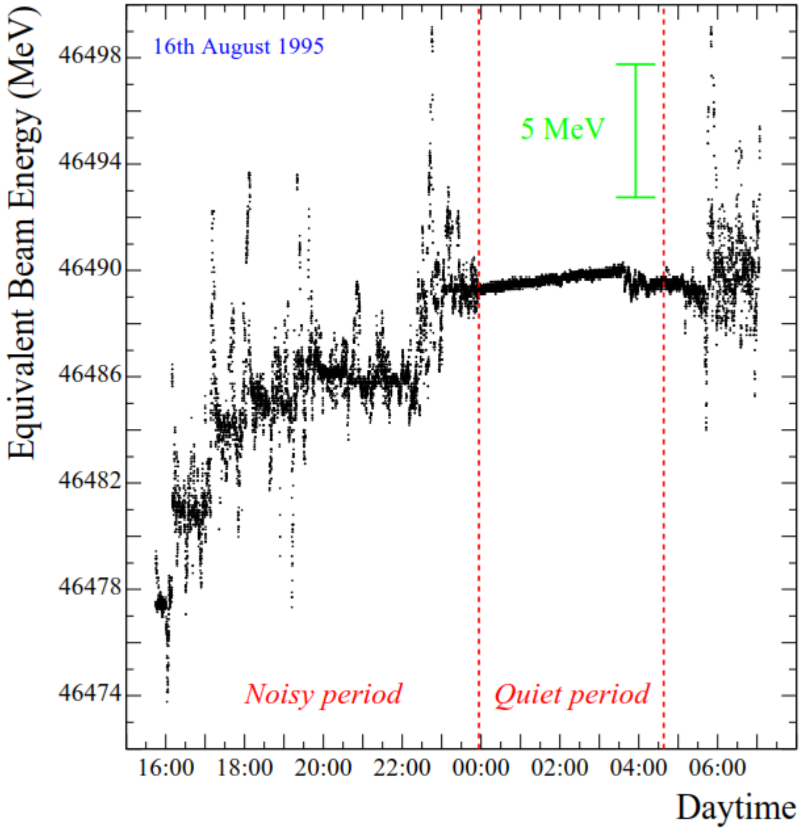
Summer 1995 : NMR probes were installed in some dipoles providing the first in-situ field measurements during operation

The data showed (unexpected) :

- Short term fluctuations,
- Long term increase (hysteresis), Energy increase of ~ 5 MeV over a LEP fill.
- Quiet periods in the night !

Human activity !

But which one ??



Pipe-busters

The explanation was provided by an electrician from the Swiss electricity company EOS: he knew that effect well !

Vagabond currents from trains and subways

Source of electrical noise and corrosion (first discussed in 1898)

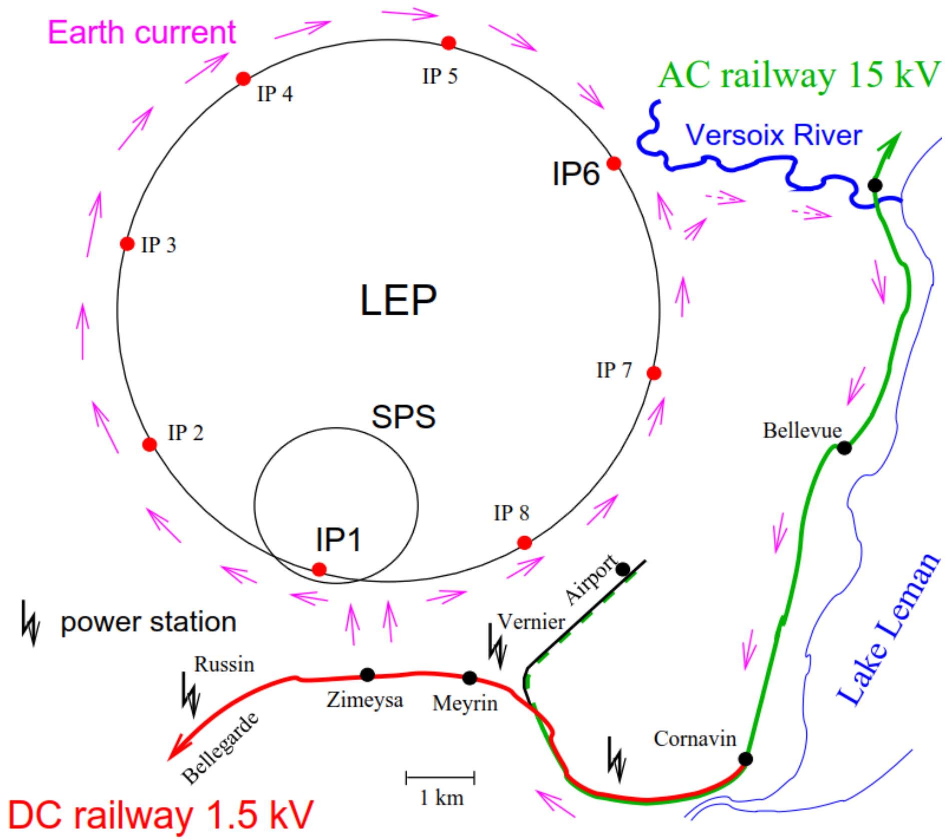
DC railway

I blast your pipes !

Vagabonding Currents

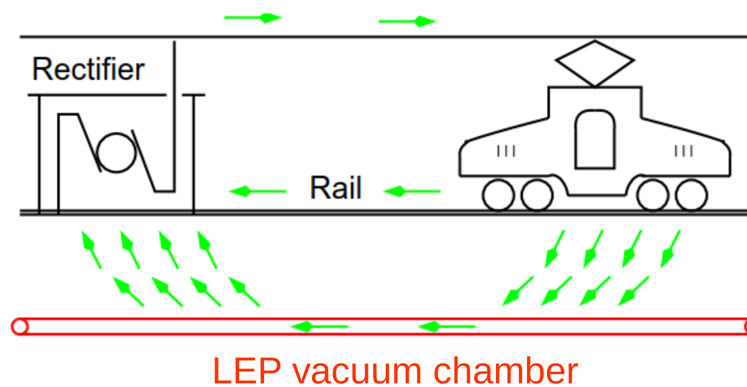
LEP was affected by the French DC railway line Geneva-Bellegarde (it was just recently upgraded to AC operation !)

A DC current of 1 A was flowing on the LEP vacuum chamber.



Entrance/exit points :

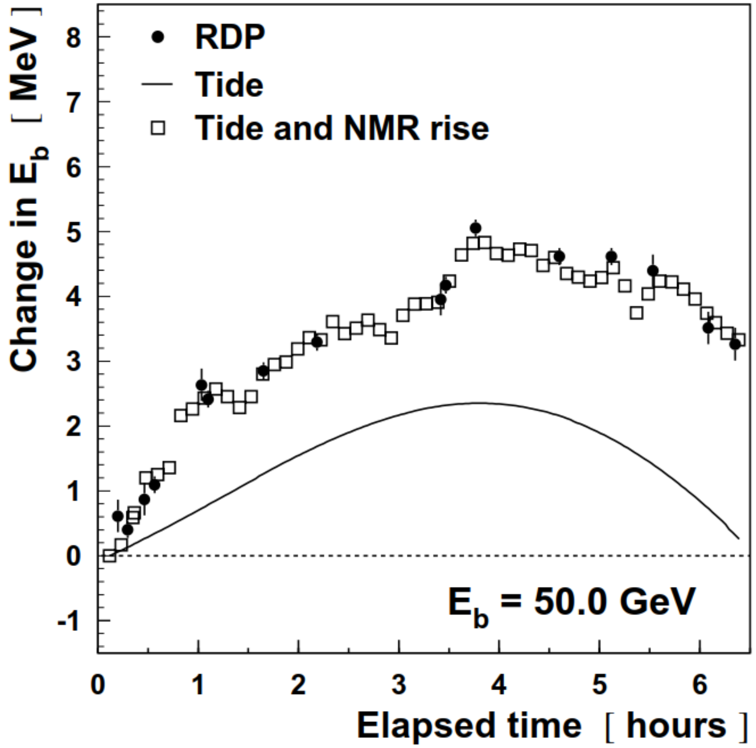
- Injection lines (Point 1)
- Point 6 (Versoix river)



Final Energy Model

1996-2000 : The LEP energy description was completed with a model of the train effects and NMR measurements.

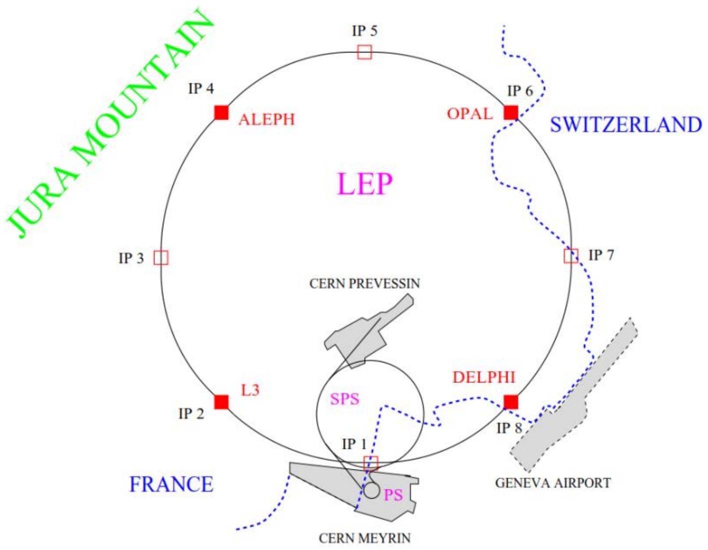
In the second half on the 1990's we were finally able to interpolate the LEP beam energy with sub-MeV precision !

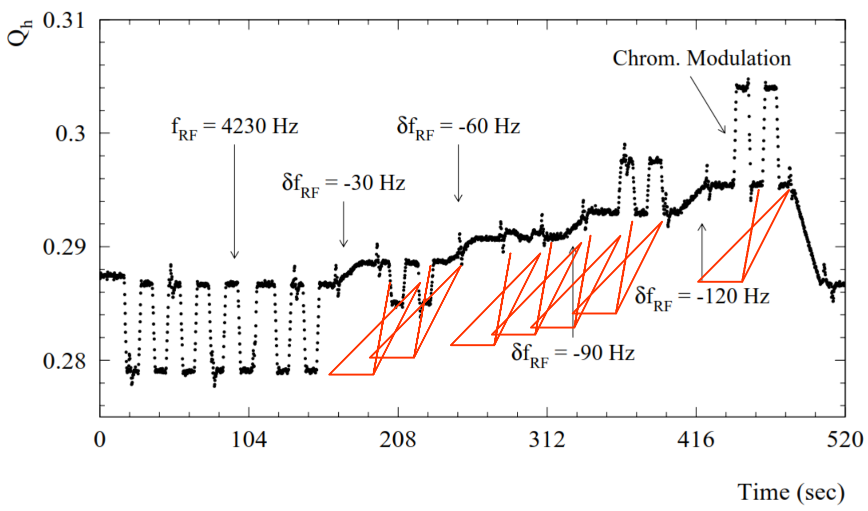


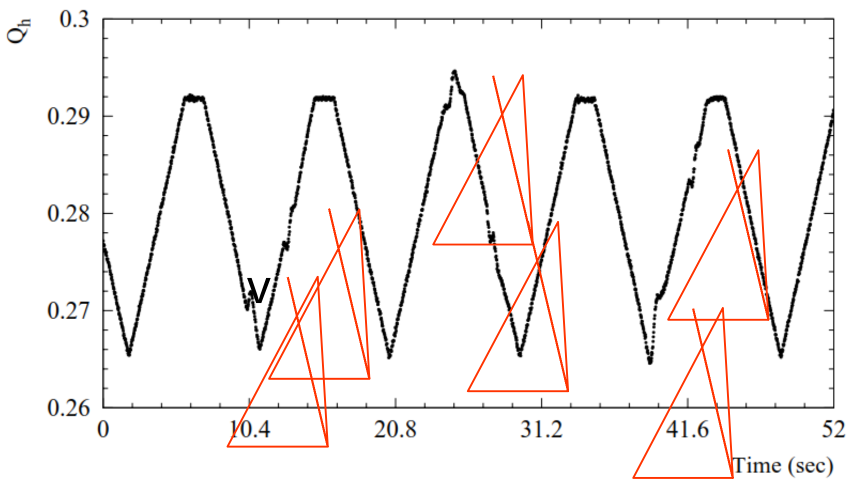
SPS – LEP coupling: the worlds biggest transformer

The SPS magnetic cycle (B_{max} ~ 2 T) affected LEP by generating periodic perturbations of the machine tunes during the ramp-down phase from its flat top (at the time once per 14.4 s).

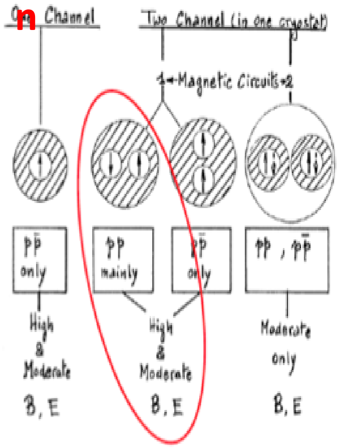
At 45 GeV the induced δQ ~ 0.002 – far from negligible !





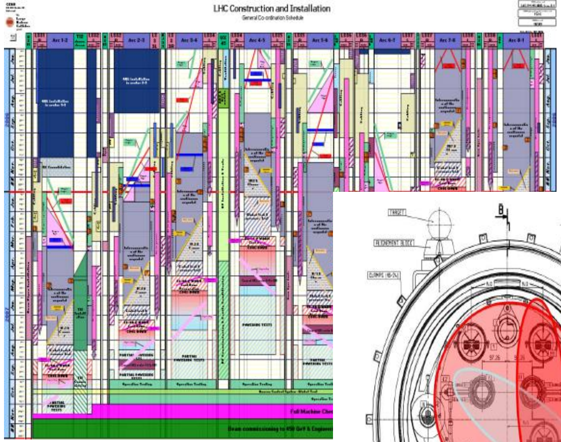


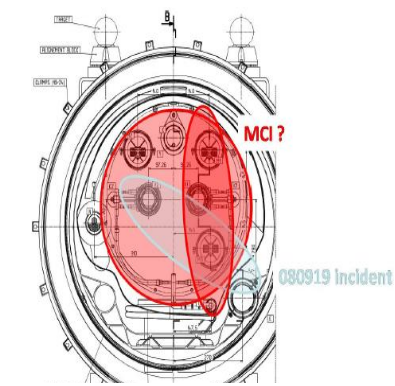
Conception



Initiation

LHC approved by the Elders





Birth – overdue

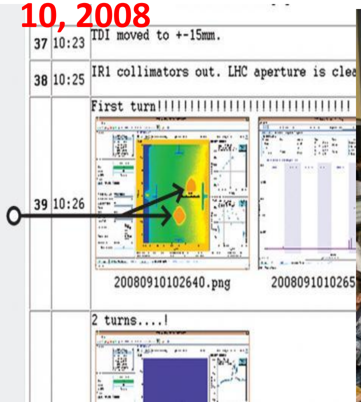
Withdrawal from community for mediation and preparation

Rival stumbles

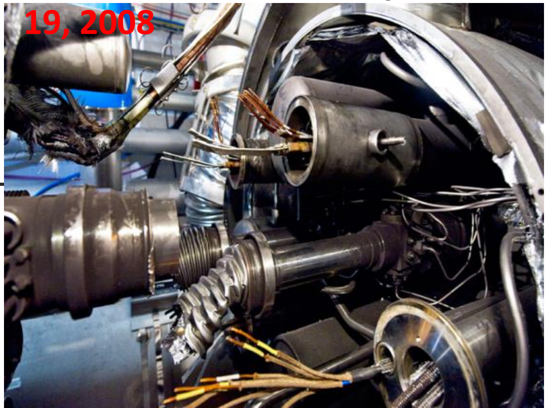
SSC cancelled

1984	//	90	91	92	93	94	95	96	97	98	99	00	01	02	03	04	05	06	07	08	09	10

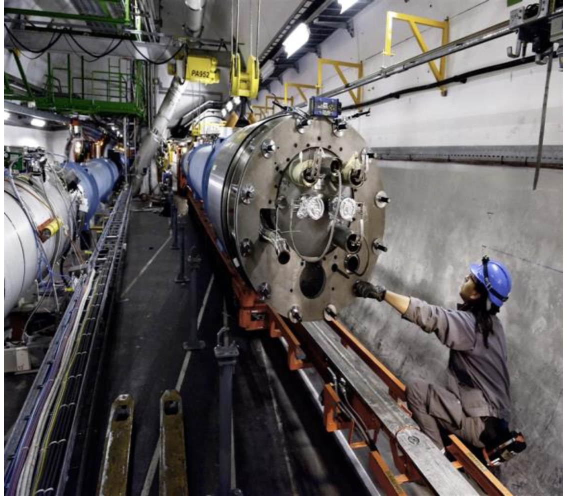
Hubris (?) September 10, 2008



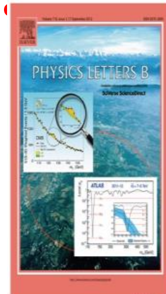
Nemesis September 19, 2008



LHC



Apotheosis and atonement



Trial/descent in the underworld

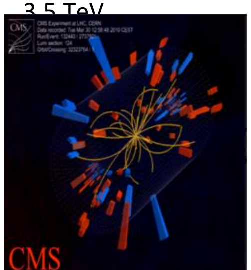
4 July, 2012

November 29, 2009

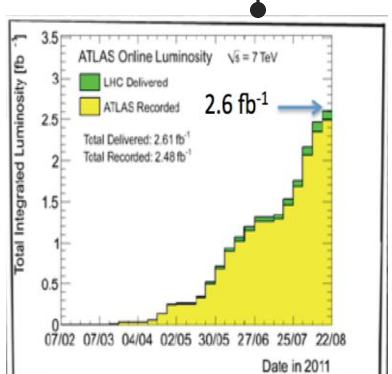
Resurrection and rebirth

2009	2010	2011	2012	2013

March 30, 2010
First collisions at 3.5 TeV



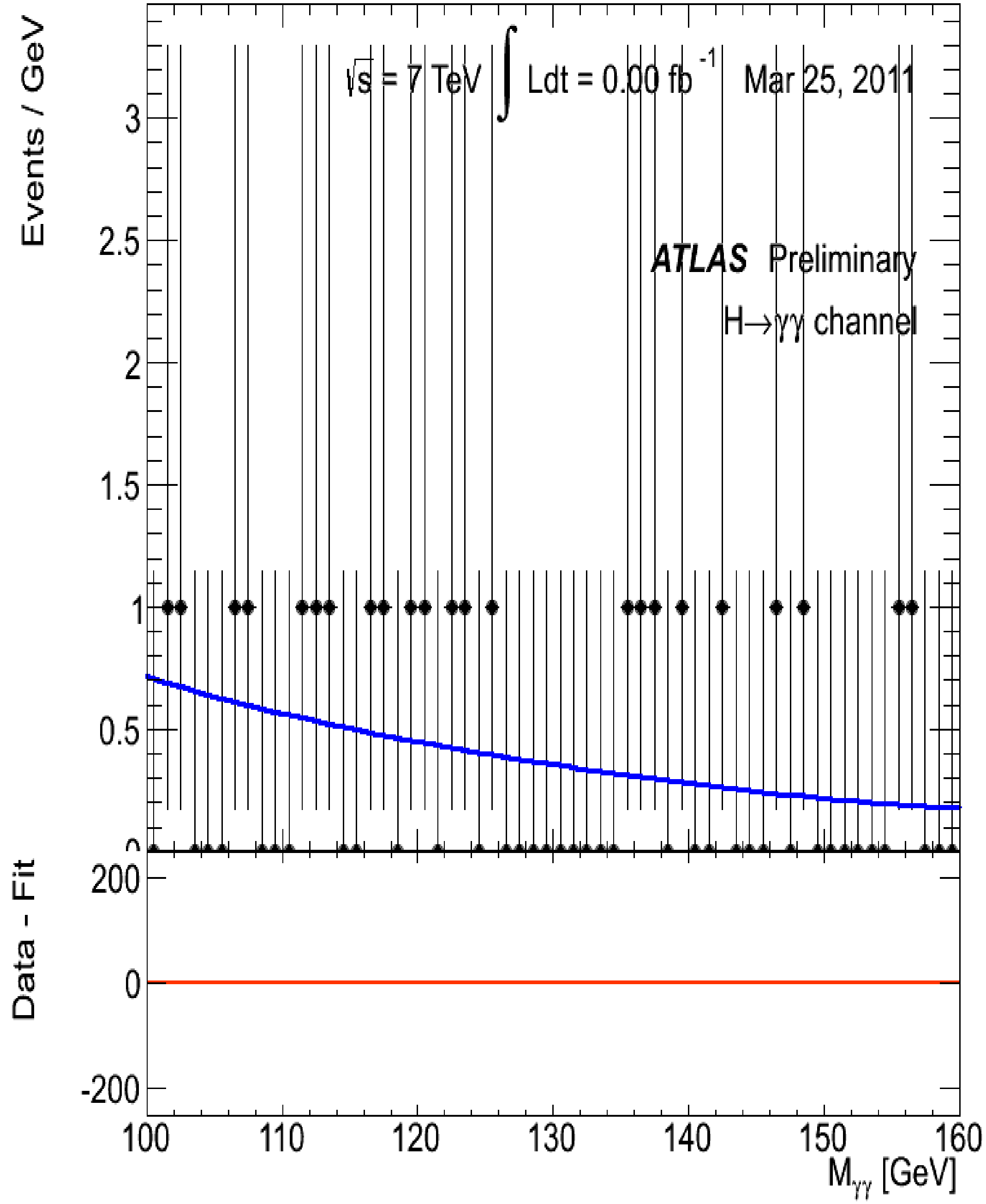
Ascensi



Heroic subplot

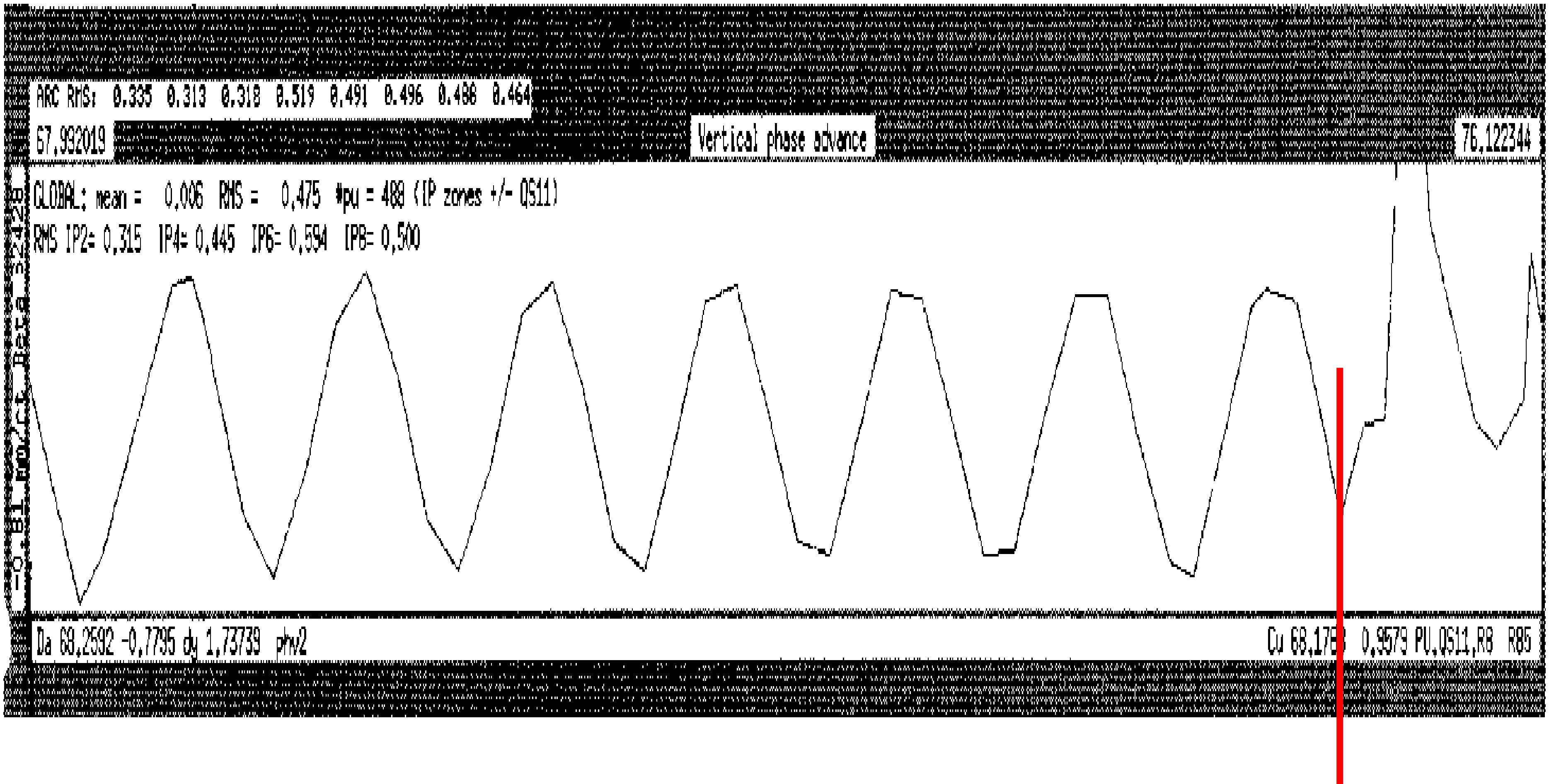
And let us not forget Fortuna

- Late
- Over budget
- Blew it up after 9 days
- Costly, lengthy repair
- Rival coming up fast on the outside (Higgs search at FNAL)
- Had to run at half energy
- And yet…



$\sqrt{s}$ = 7 TeV $\int$ Ldt = 0.00 fb^{-1} Mar 25, 2011
ATLAS Preliminary
H→γγ channel
Events / GeV
3
2.5
2
1.5
1
0.5
0
Data - Fit
200
0
-200
100
110
120
130
140
150
160
$M_{\gamma\gamma}$ [GeV]

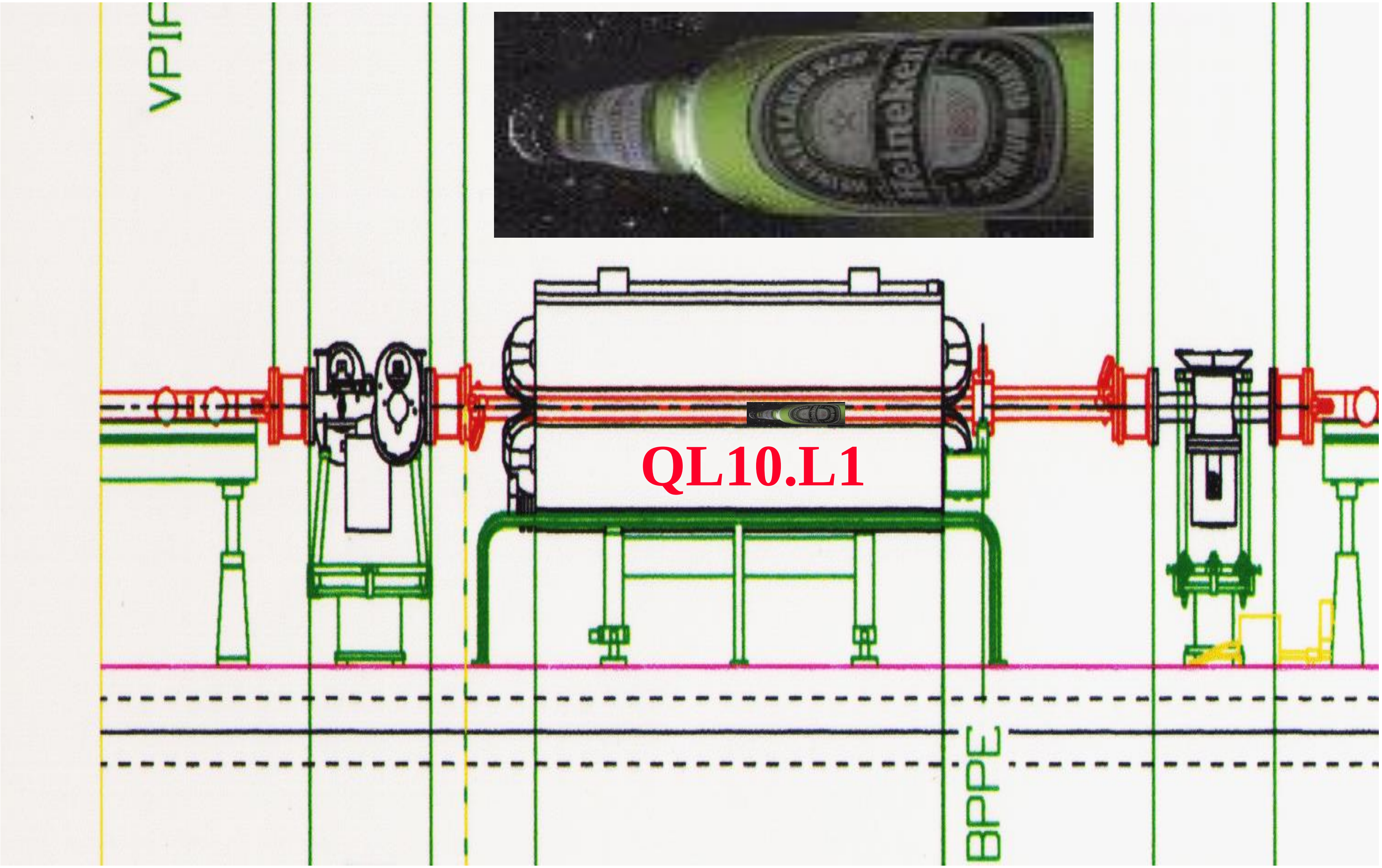
The most important at the end: beam diagnostics



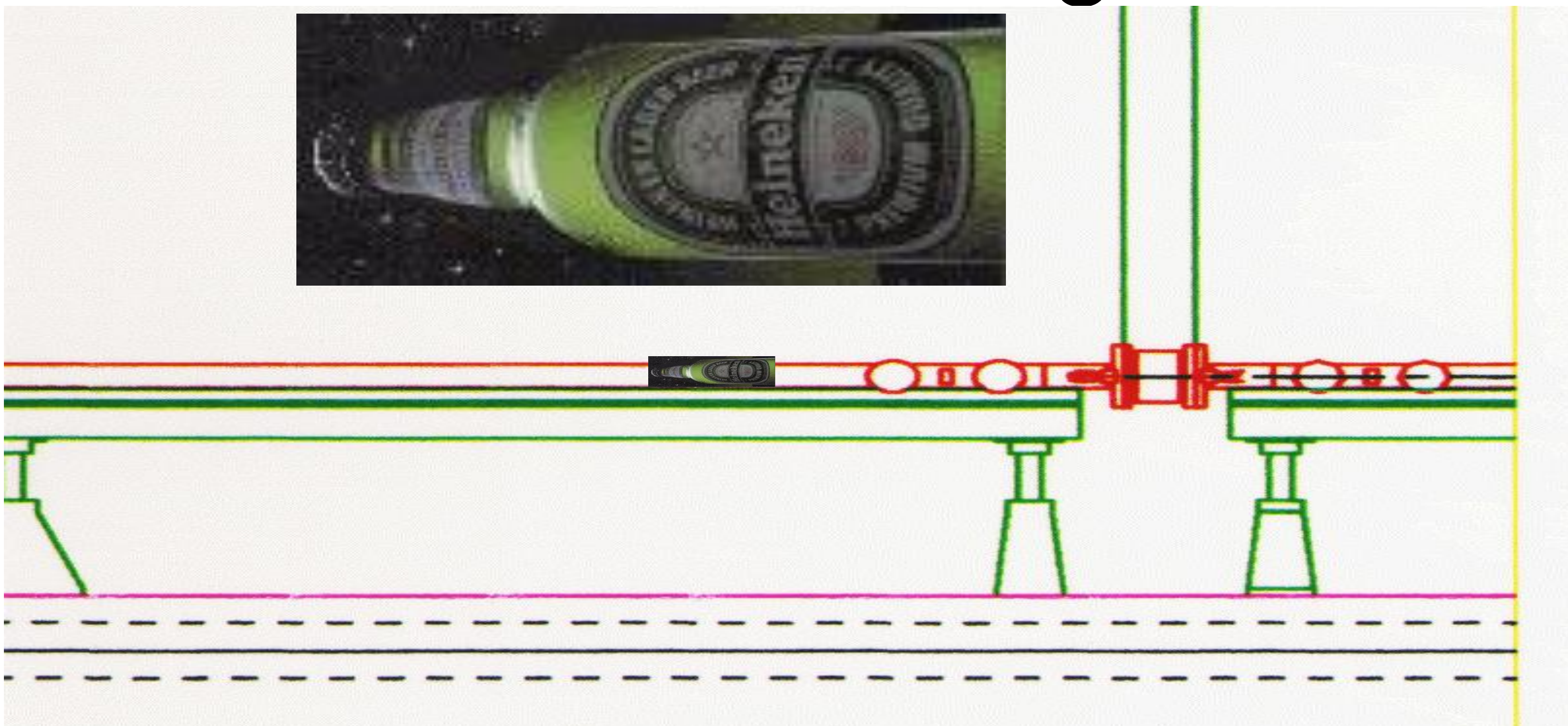
Positrons →

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 ~97 – 98 GeV e^- large vertical oscillatio[n]
OPAL trigger. Maybe a bit too ambitious
Tunehistory 01-12-40 fill 7065
→ nothing particularly nasty.

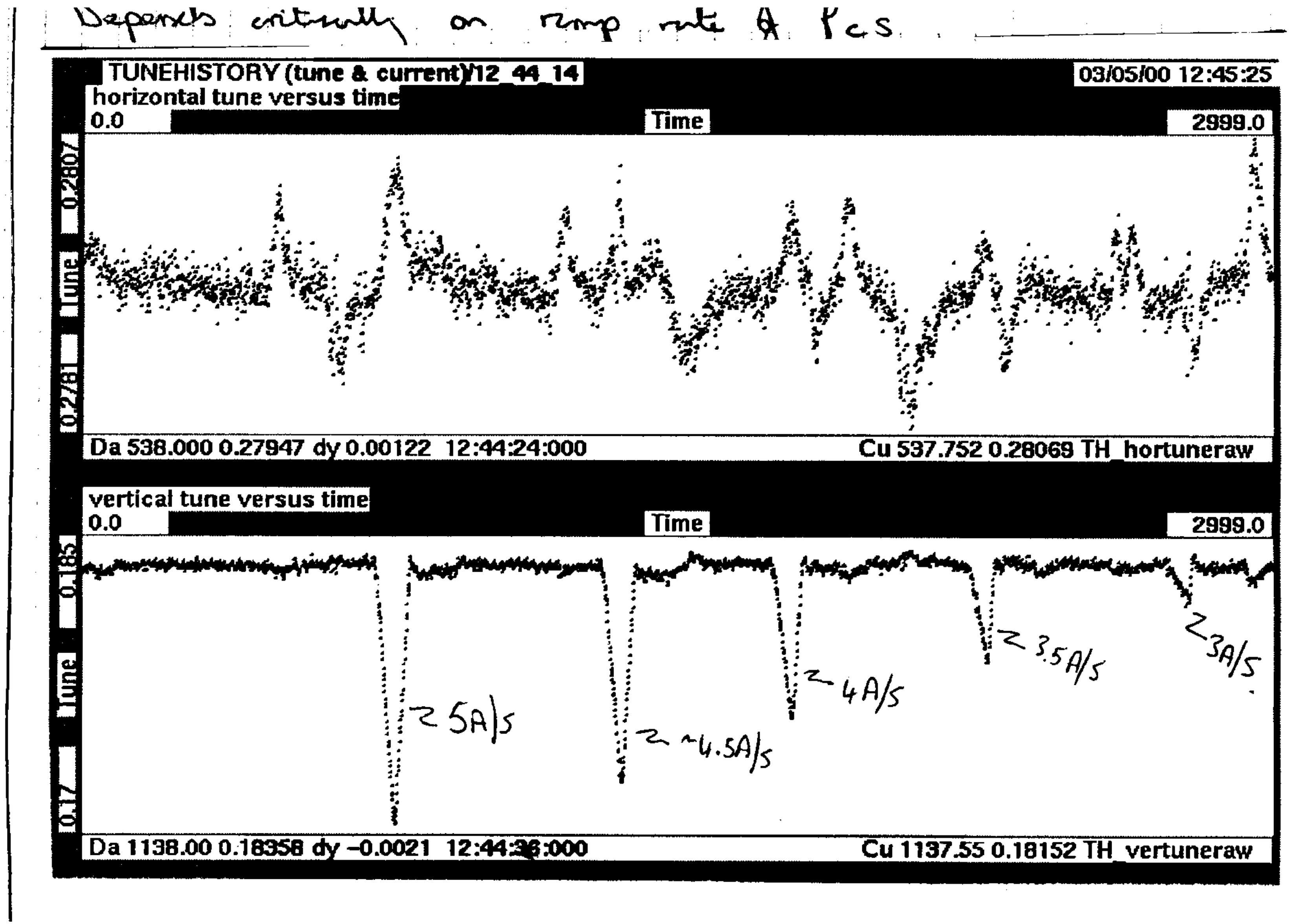
Big radiation spikes in all expts.

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

640μA .234 / .164 5.27mA

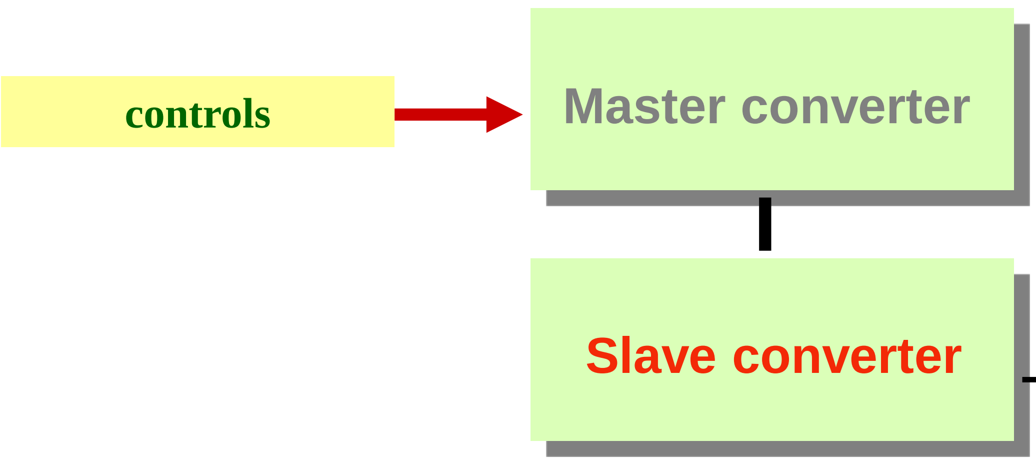
93GeV 4QSO 01-58-36 vRMS ~
Tunehistory 01-50-25 fill 7066

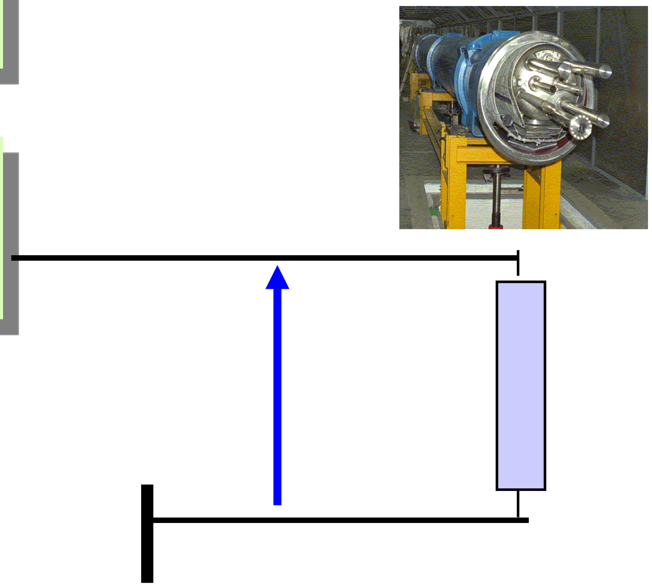
…and the corresponding diagnostics



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 magnet = R* I magnet + L * d I magnet/dt