Energy Calibration at LEP3
Lessons of LEP(2) 4 LEP3

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Acknowledgements: LEP Energy WG

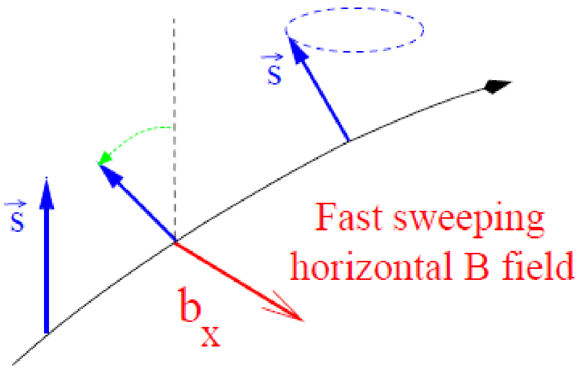
Resonant Depolarization

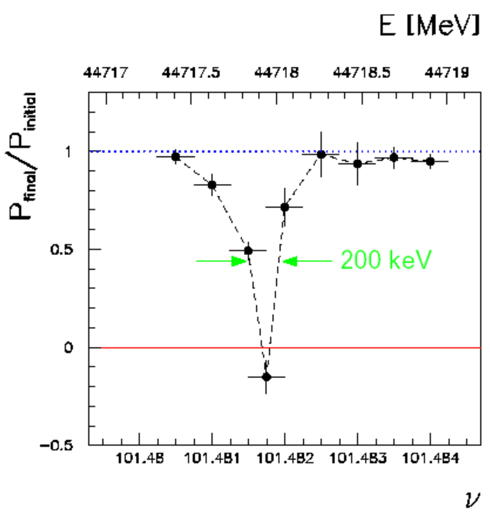
- Resonant depolarization was the workhorse and absolute reference for LEP(2) energy calibration. It relies on the relation between spin precession frequency (or tune ν_s) and energy E:

$$\nu_s = \frac{\mathrm{E}}{440.6486(1)\,[\mathrm{MeV}]}$$

- Even if other methods are also considered, it should be made available at LEP3 as absolute calibration reference.
  - *But it may not be available over the full energy range.*

- In practice it is first of all necessary to have a polarized beam. At LEP this required special machine configurations (tunes, orbit, no collisions etc).
  - *It may not be compatible with physics data taking at LEP3.*

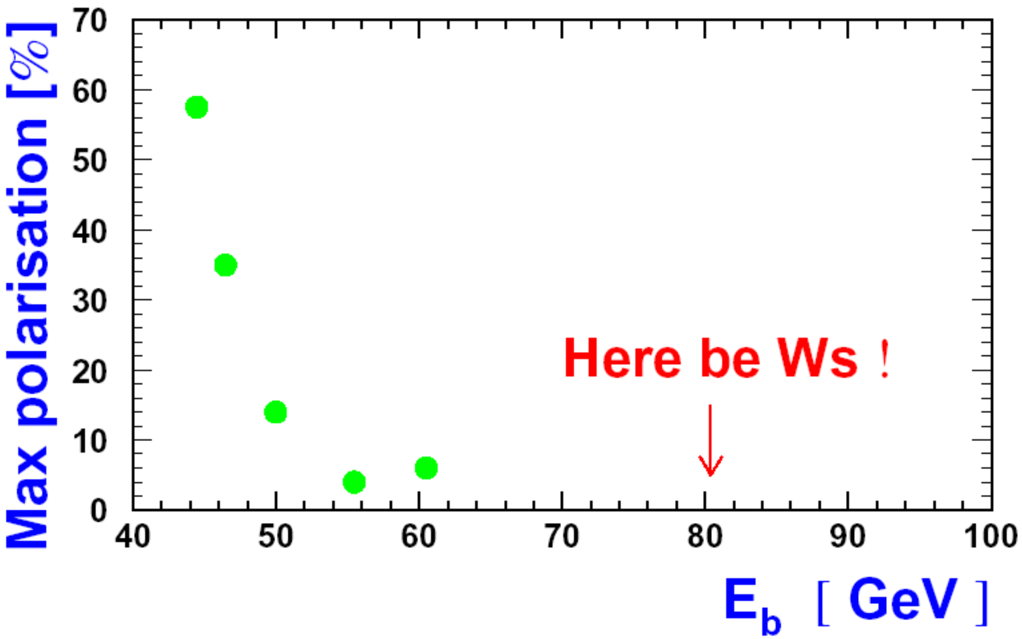




Principle of RDP:
- Get a fast transverse kicker.
- Sweep the B-field and observe $P_\perp$
- If the kicker frequency matches ν_s, $P_\perp$ is rotated away from vertical plane – spin/ flip or depolarization.

- Very high intrinsic (and practical) accuracy. At LEP the standard measurement accuracy was ±0.2 MeV.

- Under optimal machine conditions, a polarization $P_\perp$ of 57% was measured at LEP around the Z resonance.
- In practice most E calibrations were performed with $P_\perp$ ~5-15%.
- Above the Z the maximum polarization dropped quickly as the energy spread (and therefore ν_s spread) became large(r).
  - *No $P_\perp$ was ever measured above 60 GeV.*



The theoretical predictions were much more optimistic !

K-Modulation

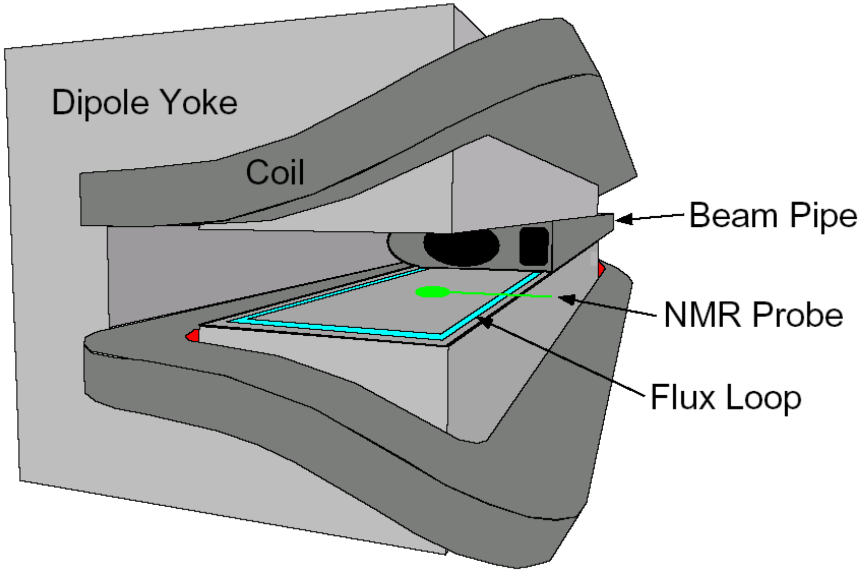
- The theoretical models also predicted that reducing the BPM offsets would yield significant increase of $P_\perp$ in the range 50-60 GeV where the measurements were difficult.
- Consequently special K-modulation windings were installed on all LEP quads, and the BPM offsets were measured with accuracies of 50 μm or less.
  - *Measurements were done during physics fills.*
- Unfortunately the results were a bit disappointing. The measured $P_\perp$ were much lower than hoped for…

Towards 80 GeV

- Since there was no direct energy calibration by RDP possible at W energies, we had to use indirect measurements.
  - *Cross-calibration wrt RDP in the range 44-60 GeV.*
  - *Interpolation to ≥ 80 GeV*
- Three methods were used:
  - *The flux-loop that was spanning all LEP dipoles,*
  - *A dedicated spectrometer,*
  - *Synchrotron tune measurements.*
- All three methods were used to establish corrections wrt to modeled energies (LEP model) based on 16 NMR probes, tide models, trains etc.
  - *See later for LEP energy model →*

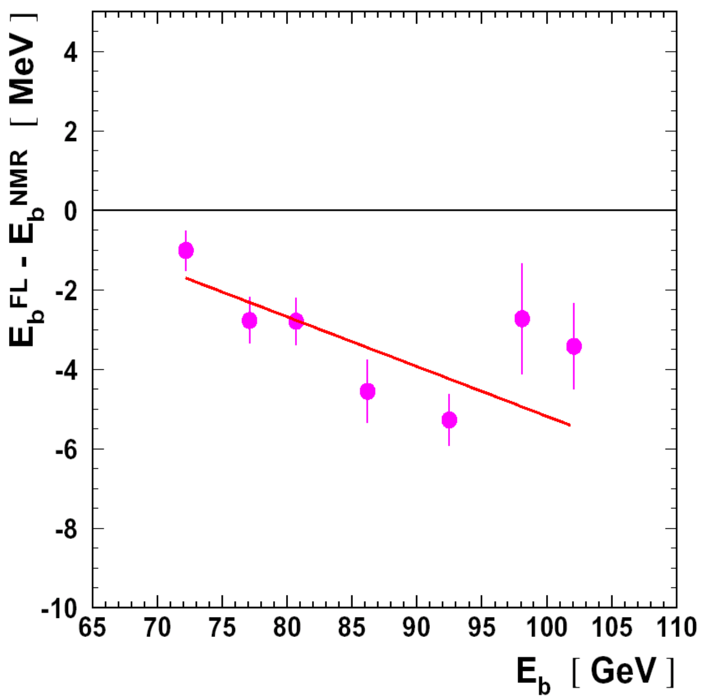
Flux-loop

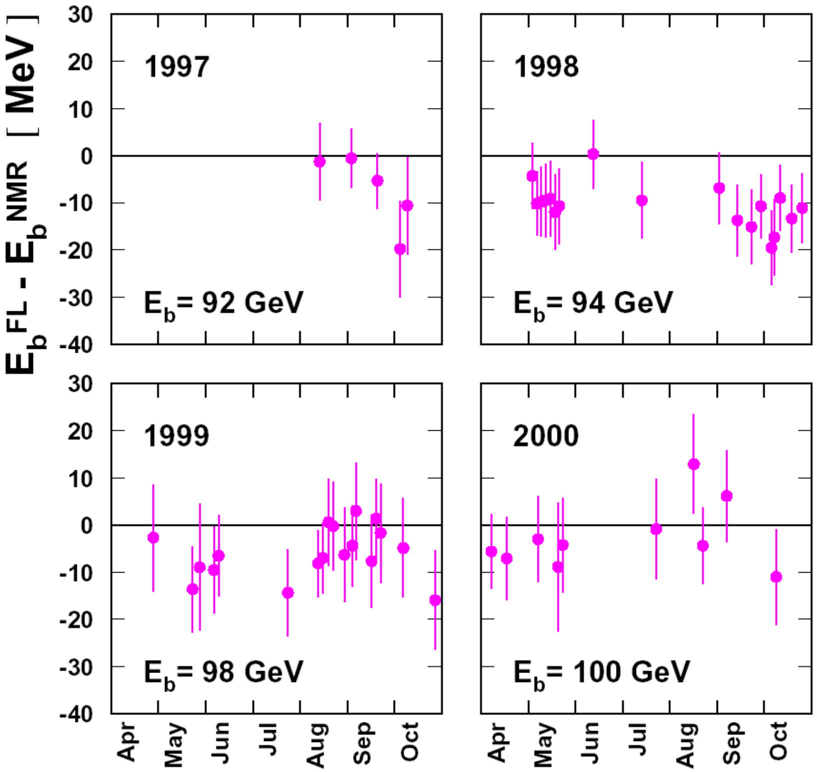
- A flux-loop was installed (and calibrated) from the beginning in all LEP dipoles. This loop was used for the first energy calibration at the Z resonance (before RDP).
  - *Relative accuracy of ~few 10^{-4}.*
  - *No absolute calibration.*
- The flux-loop was 'resurrected' for LEP2 where regular calibrations were performed at different energy levels, including the range of energies where RDP was available.



Example of corrections to the LEP model energy based on the flux-loop measurements.

- *Typically ~5 MeV.*

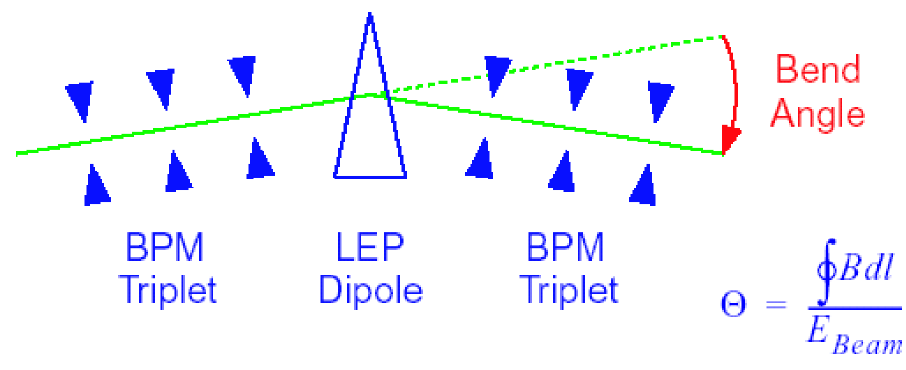


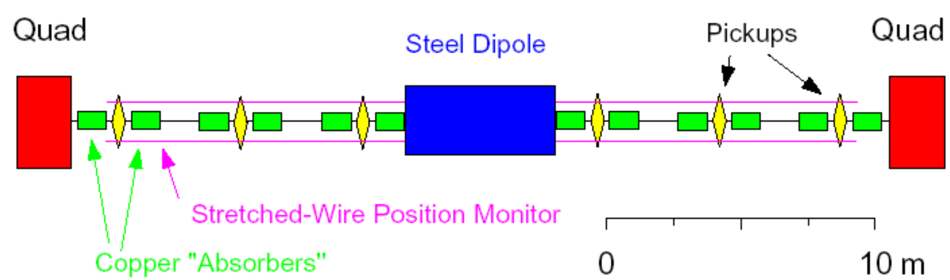


- A dedicated spectrometer was designed and installed in the LEP ring for LEP2 energy calibration.

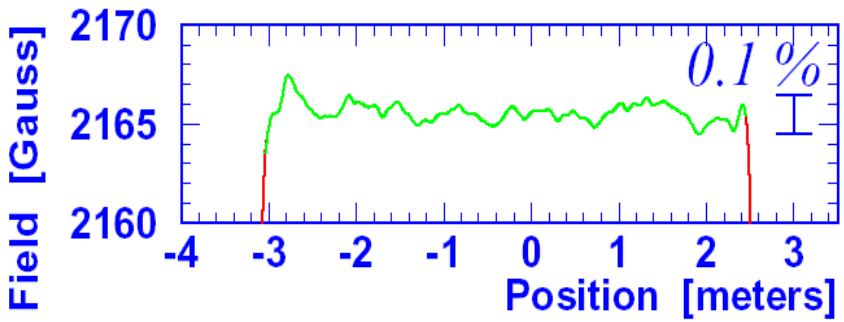
Principle:

- *Dedicated dipole magnet*, calibrated with very high accuracy, and instrumented with NMRs.
- On either side 3 *high precision and high resolution BPMs*.
- Alignment drifts are controlled with a *stretched wire system*.
- BPMs are cross-calibrated wrt RDP in the range 44-6 0GeV.
- The energy is determined from the bending angle.



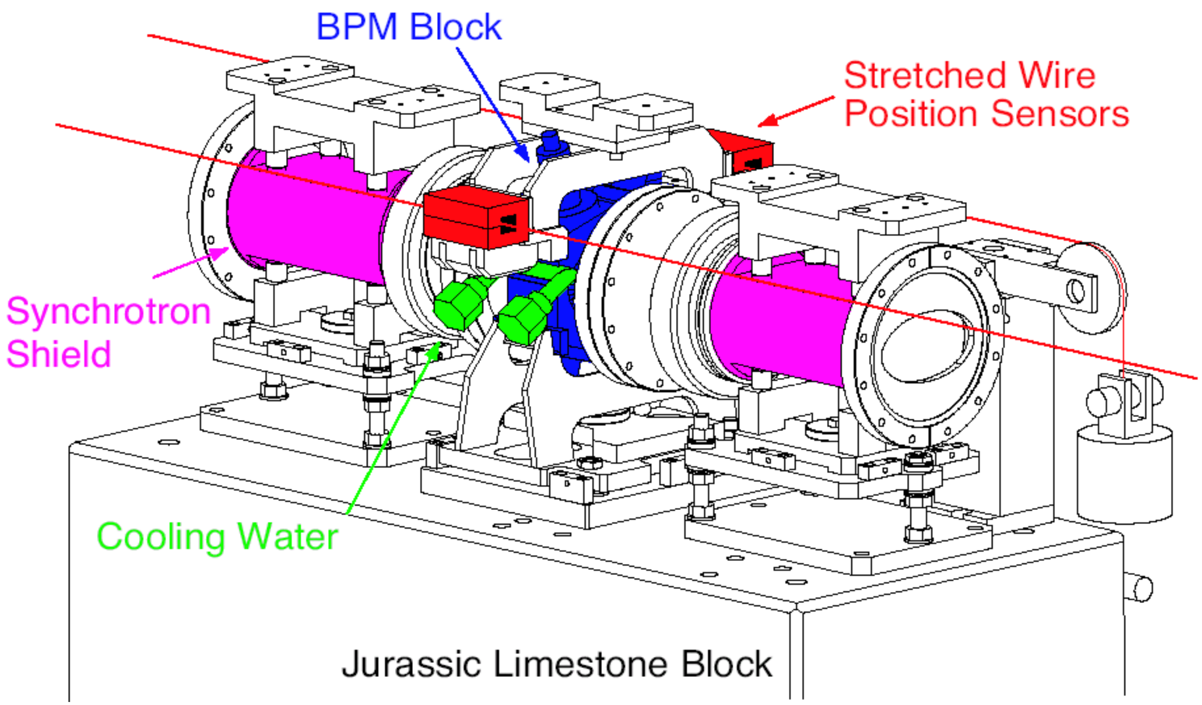


- The spectrometer magnet was a custom built 5.75m steel dipole.
- Temperature regulated and stabilized with dedicated water-cooling.
- Local field measurements from 4 NMRs.
- Integral field maps with relative accuracy ~10^{-5}.



Spectrometer BPM

- For stability reasons, the BPMs were installed on Limestone Blocks and connected by a stretched wire system.
  - *Quite some issues with synchrotron radiation effects on the wire system.*
- The BPM electronics had an accuracy of ~ 1 μm. But it took a while to get it.

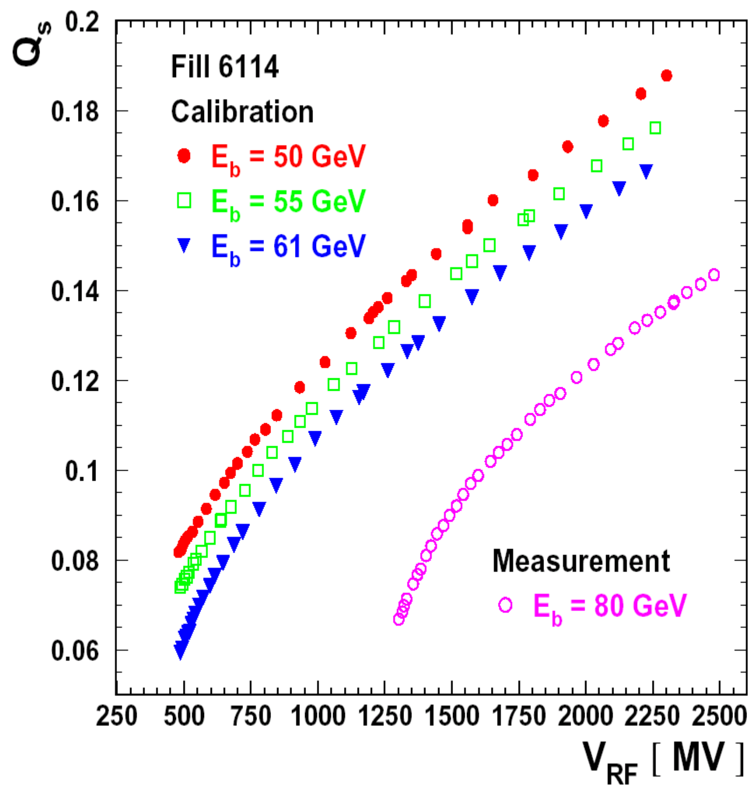


Synchrotron tune

- In parallel ideas were tested to take advantage of the strong energy dependence of the energy loss by synchrotron radiation, $\propto E^4$, to determine the energy.
- After some trial and error, the synchrotron tune Q_s was identified as a good handle on the beam energy.
  - *Depends directly on energy loss,*
  - *Can be measured accurately (frequency).*

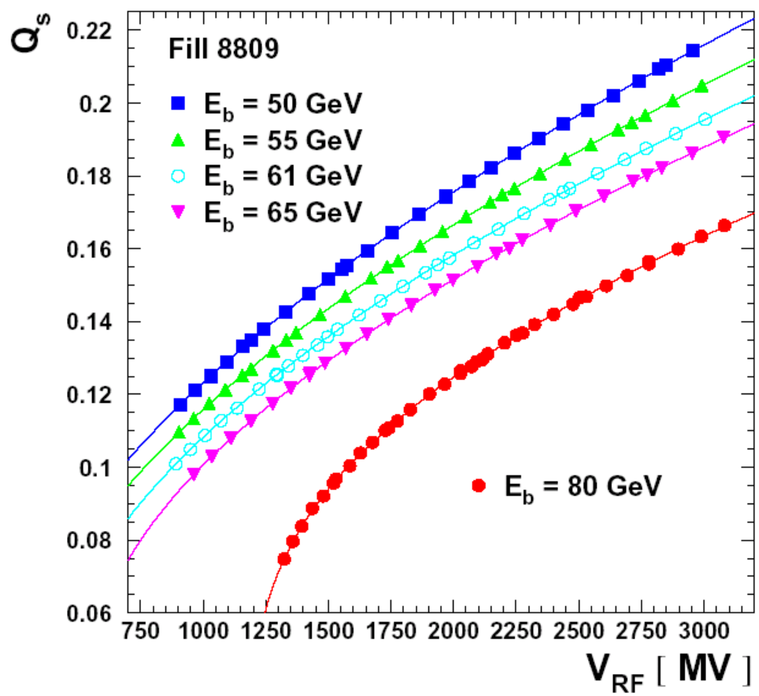
Principle:

- Measurement of Q_s versus RF voltage V_{RF} at known energy points. Provides a calibration for V_{RF}.
- Repeat the measurement at energy of interest, use the V_{RF} calibration to extract energy from a fit.

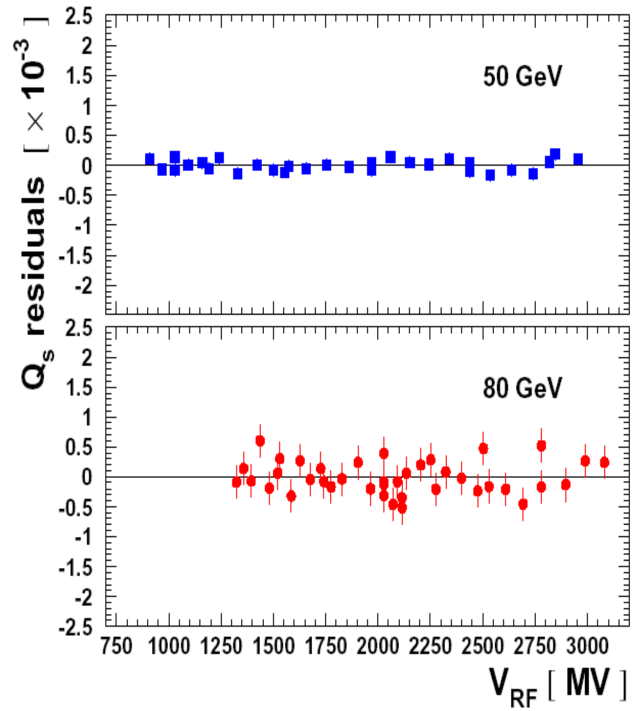


Synchrotron tune

- Example of a Qs energy measurement, with calibration and measurement fill.



Fit residuals



LEP2 calibration summary

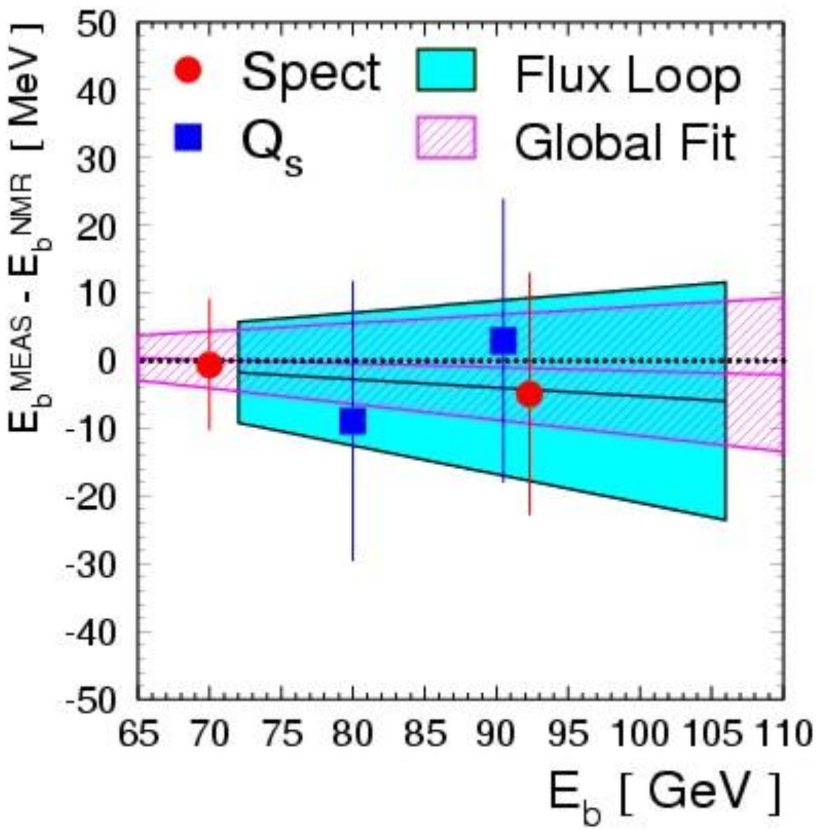
- The 3 methods eventually yielded very consistent corrections, but a lot of analysis and systematic studies had to be made.
  - *Not sure that we would have been convinced by our results without this triple redundancy*.

- Eventually the consistency gave us confidence that the results were correct.

Final uncertainty:

± 10 MeV

in the range 80-100 GeV.



LEP energy model

- The energy calibration experiments provided calibration at fixed points in time.
  - *For the Z width measurements, LEP was operated at 3 alternating energies, and we tried to calibrate each off-peak fill (at the end).*
- But for the physics analysis (e.g. Z or W), it was necessary to provide energy information for the time of each events.
  - *Need a model to predict the energy at any time t !*
- With experience it became possible to predict the energy based on 16 local NMR probes installed throughout the LEP ring.
  - *The NMRs are cross calibrated (RDP etc) to provide a base energy.*
  - *The NMR energy is corrected for tides, circumference changes, local energy shifts at the IPs from the RF, etc*

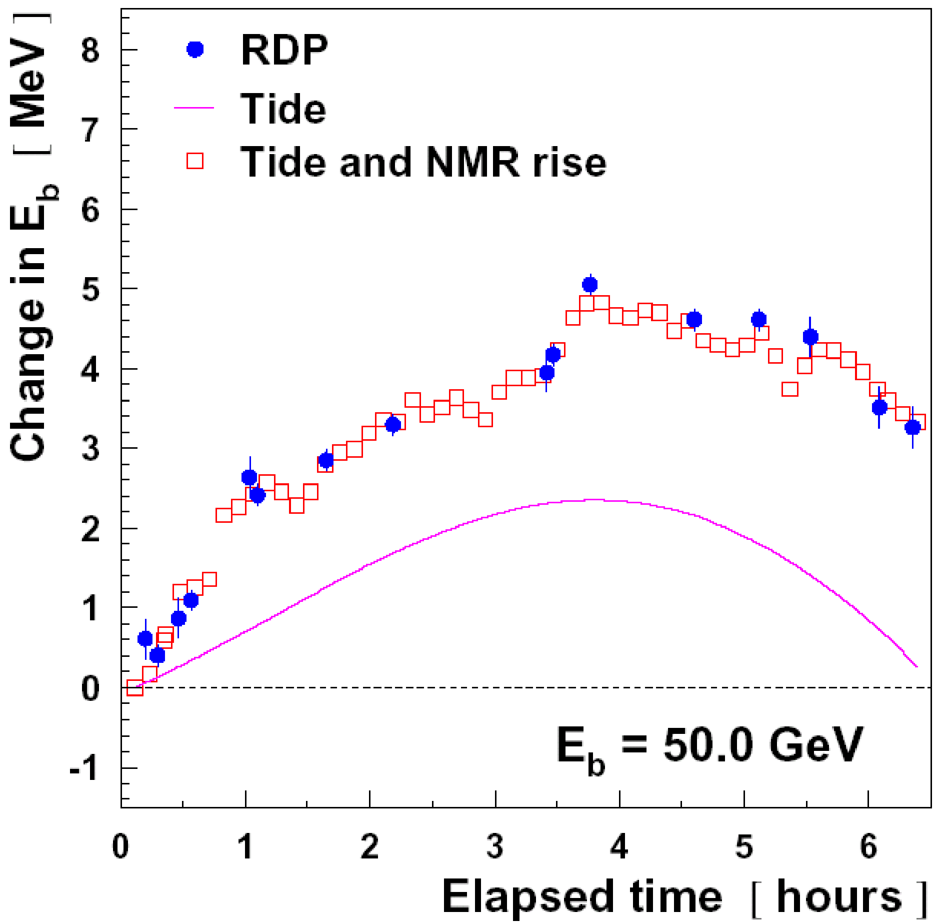
➔ The LEP energy model

Interpolation

- Example of a LEP energy model test during a fill where the energy was measured at regular intervals.

  Very good agreement !

- Energy rise in fill is due to trains ➔



The Field Ghost

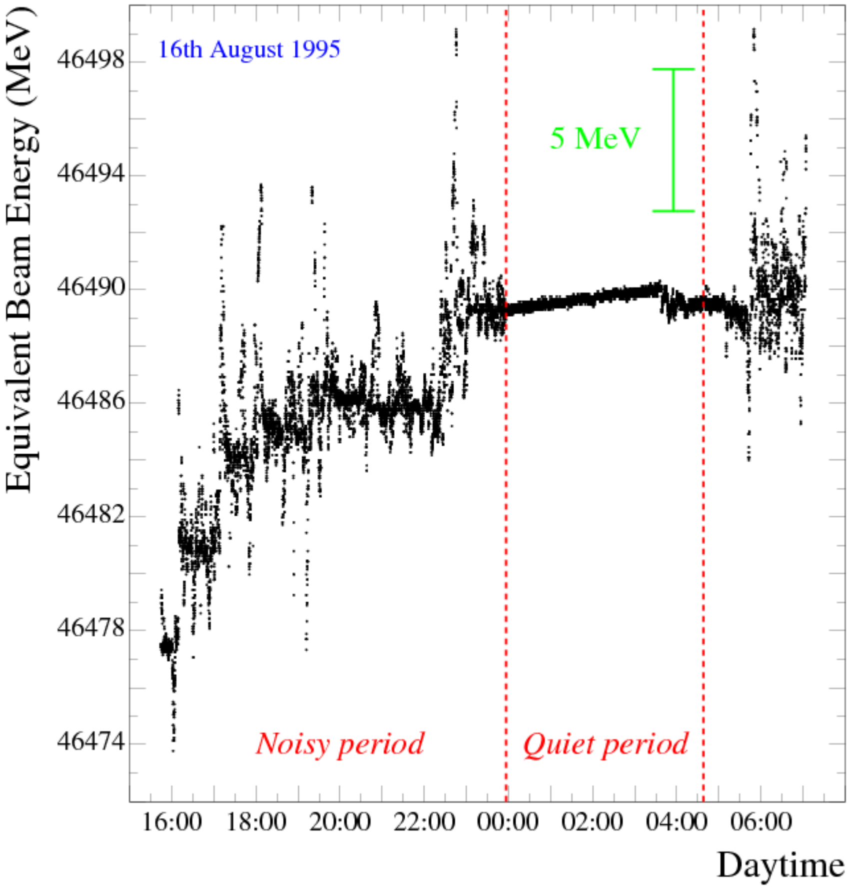
Summer 1995 : the first field measurements inside ring dipoles.

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 ??

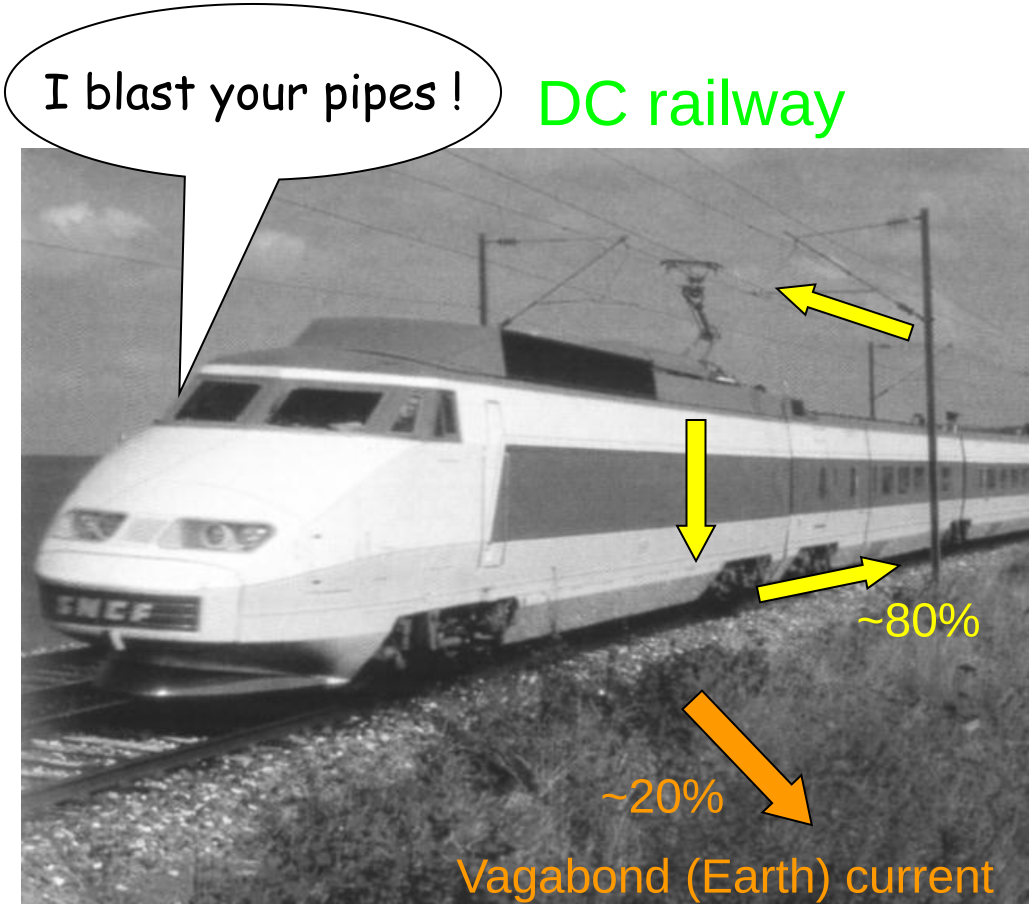


Pipebusters

The explanation was given by the Swiss electricity company EOS...

Vagabond currents from trains and subways

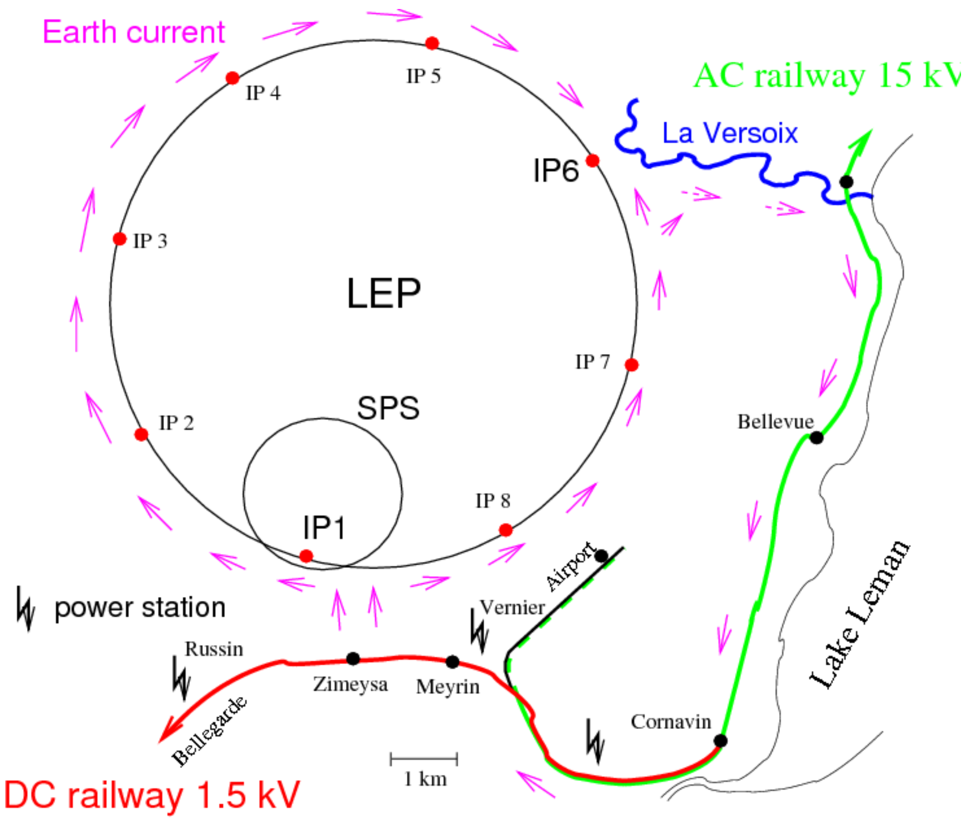
Source of electrical noise and corrosion (first discussed in …1898 !)



Vagabonding Currents

LEP is affected by the French DC railway line Geneva-Bellegarde

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



Entrance/exit points :

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

TGV for Paris

November 1995 : Measurements of

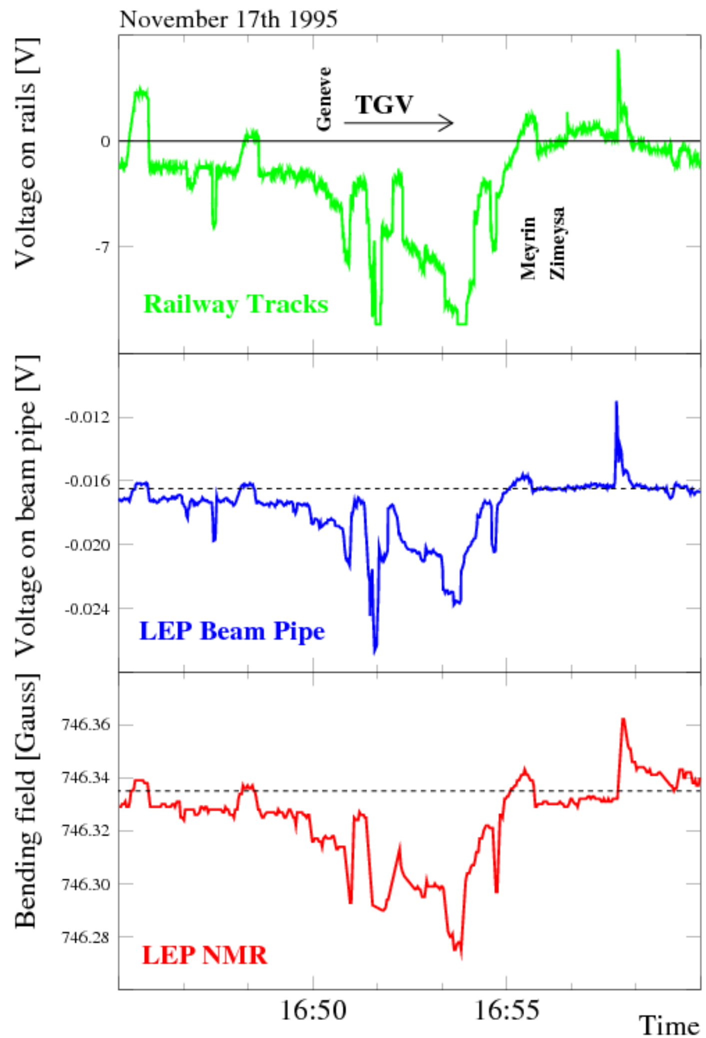
- The current on the railway tracks
- The current on the vacuum chamber
- The dipole field in a magnet

correlate perfectly !

Because energy calibrations were usually performed :

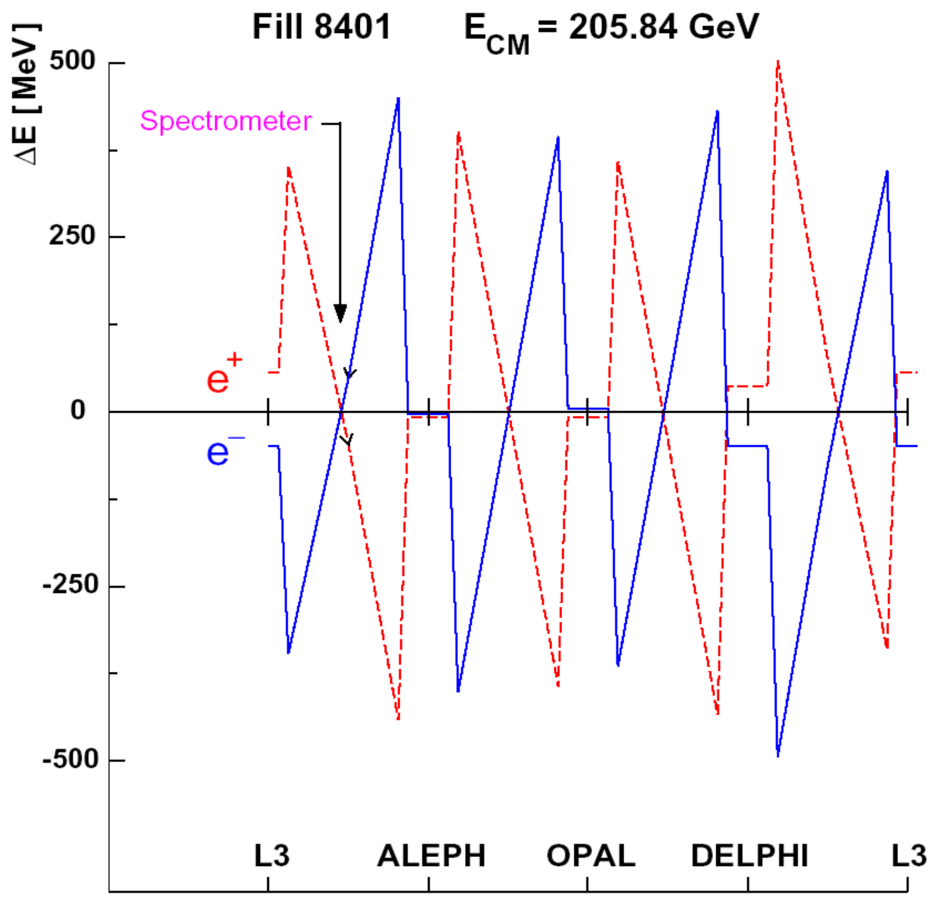
- At the end of fills (saturation)
- During nights (no trains !)

We "missed" the trains for many years !



RF sawtooth

- Local RF asymmetries, voltage or phase errors may lead to local energy shifts at the IPs.
  - *Different at each IP.*
- Such effects had to be modeled. They were cross-checked using Q_s and special voltage and phase calibration fills.



The LEP Energy Calibration Working Group

- The LEP Energy Calibration Working Group was a highly successful and exiting collaboration between the LEP machine and experiments. All the studies of the LEP energy were coordinated within this WG.
  - *At peak periods it had ~40 members, at the last meeting in 2004 only 5 of us were left over to discuss the last LEP2 paper !*
  - *A similar collaboration should be set up for LEP3 if it is every built…*
- The precise energy calibration for such a large ring was a fascinating detective work, where we (re-)discovered a lot of basic physics - tides, vagabond currents from trains, etc.
  - *Each year we used 5 to10% of the scheduled time for calibration.*
  - *The LEP(2) experience gives a head-start for future LEP3 energy studies.*

‘Ideas & Recommendations’ : LEP(2) 4 LEP3

- The obvious: you want to use RDP for absolute calibration.
- Design a good, reproducible and fast polarimeter. Consider separate polarimeters for e- and for e+.
- Be ready to work with lower than anticipated polarization.
- Consider offset measurements by K-modulation for all BPMs.
- Provide sufficient BPM redundancy for good orbit correction.
- Install NMR probes in a subset of your dipoles as field reference.
  - *Trains may come back…*
- In anticipation of possible absence of polarization, consider a spectrometer-like device. Read carefully the LEP papers to learn from the LEP experience and do it better (more than 3 BPMs on each side…).

‘Ideas & Recommendations’ : LEP(2) 4 LEP3

- In a systematics dominated regime, watch out for dangerous ‘correlations’ or ‘sampling effects’.
  - *We missed the train effect for years because we almost always measured at nights or during week-ends !!*
- Explain your future physics coordinator that a precise energy calibration requires lot’s of (MD) beam time.

References

A page with many papers and notes:

http://jwenning.home.cern.ch/jwenning/ECAL.html

The Energy Calibration WG:

http://lepecal.web.cern.ch/LEPECAL/

Main papers – LEP1:

L. Arnaudon et al., Z. Phys. C 66 (1995) 45.
R. Assmann et al., Z. Phys. C 66 (1995).
A. Blondel et al., Eur. Phys. J. C 11 (1999), 573-585.

Main papers – LEP2:

R. Assmann et al., Eur. Phys. J. C 6 (1999) 2, 187-223.
R. Assmann et al, Eur. Phys. J. C39 (2005), 253-292.

LEP Laser Polarimeter