LEP 2 Energy Calibration and the Spectrometer

- Goals of LEP 2 – m_W measurement
- LEP 2 Energy Model – the Magnetic Extrapolation
- Cross-checking with the Flux Loop
  (no details!)
- Cross-checking with the Synchrotron Tune
  (nor on this!)
- Cross-checking with the Spectrometer
- Conclusions

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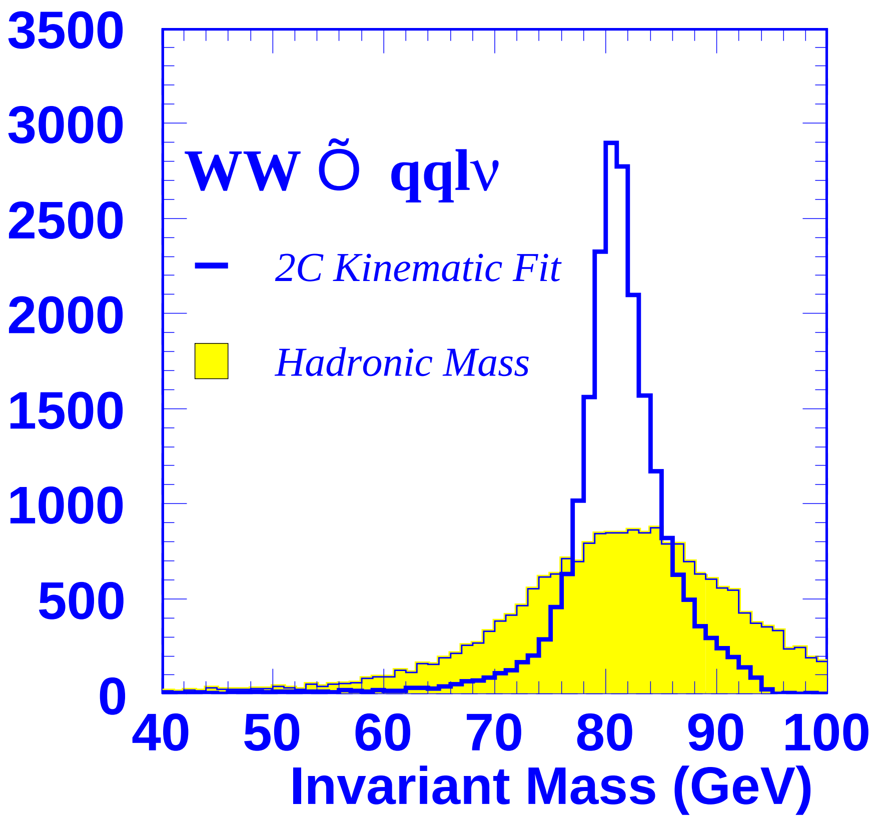
3 Sep 2002, Lausanne

Measuring the W boson mass

Higgs search aside, main goal of LEP 2 ('96 - 2000) has been high precision measurement of the W mass, m_W

m_W measured through reconstruction of W^+ & W^- within a kinematic fit, with beam energy (E_b) as constraint



How well should E_b be known?

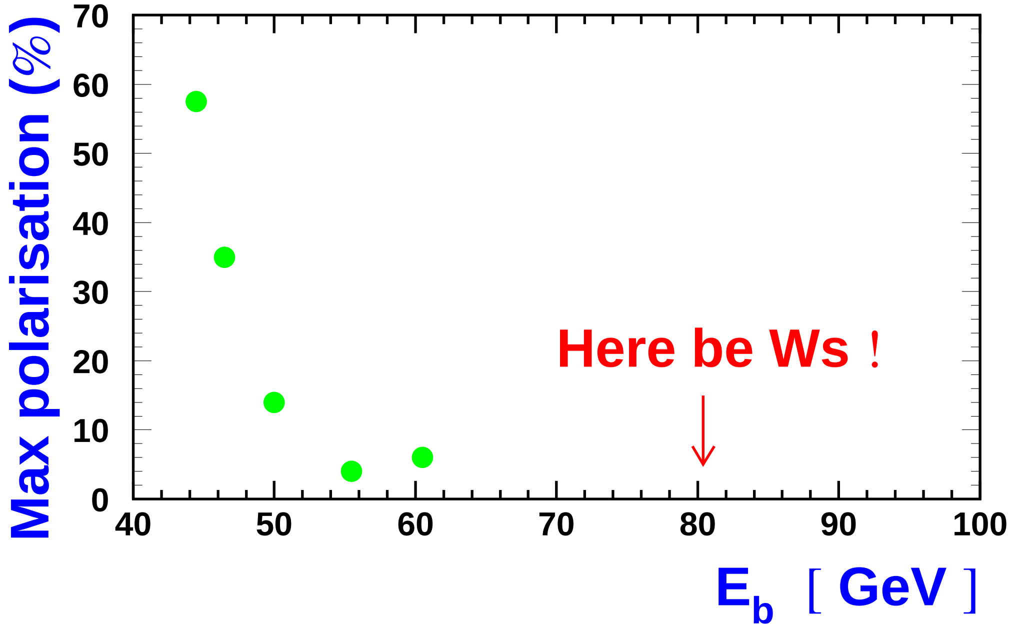
$$\frac{\delta m_W}{m_W} = \frac{\delta E_b}{E_b}$$

Statistical error of LEP 2 sample ~ 25 MeV. So should know E_b to 20 MeV (2×10^{-4}) or better... and 'know' means really know! Fully correlated between channels, experiments & years

Surely easy ? At LEP 1 E_b measured to 2×10^{-5} for m_Z

m_W and the end of spin

Not so! The prime tool of LEP 1 energy calibration was resonant depolarisation (RDP), but this no longer works!



Instead, recall $E_b \propto \oint B \, . \, dl$ & perform magnetic extrapolation

NMR probes

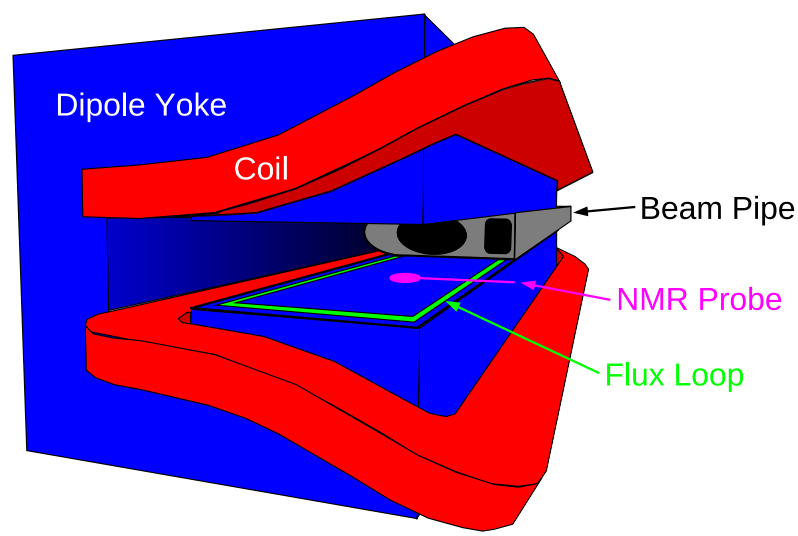
(precise, continual readout,

low sampling – only 16)

Flux loop

(high sampling – 96.5%,

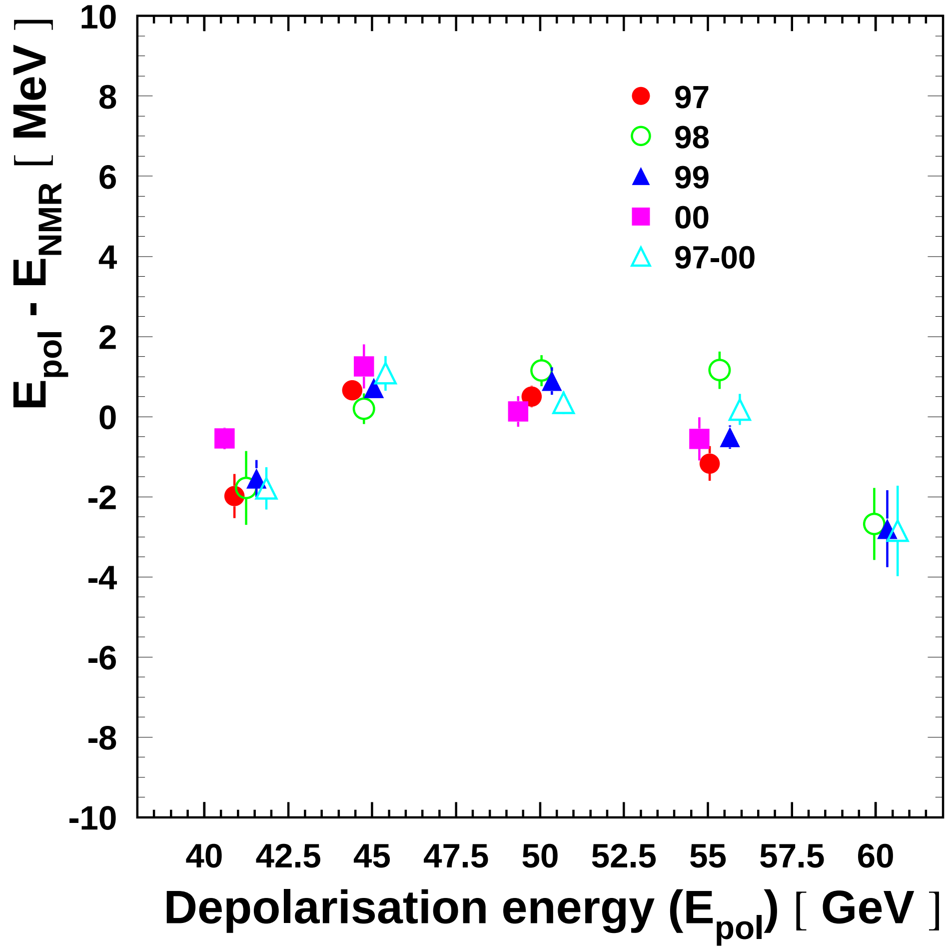
infrequent readout)



NMRs used in defining energy model, & flux loop to set error

Magnetic extrapolation method

Calibrate NMR readings against known energy in RDP region (40-60 GeV), and apply in W^+W^- regime (~ 100 GeV).



It works & is stable! However, how does above 'banana' evolve to 100 GeV, & is sampling representative of total $\oint B \, . \, dl$?

Cross-calibrate NMRs vs flux loop...

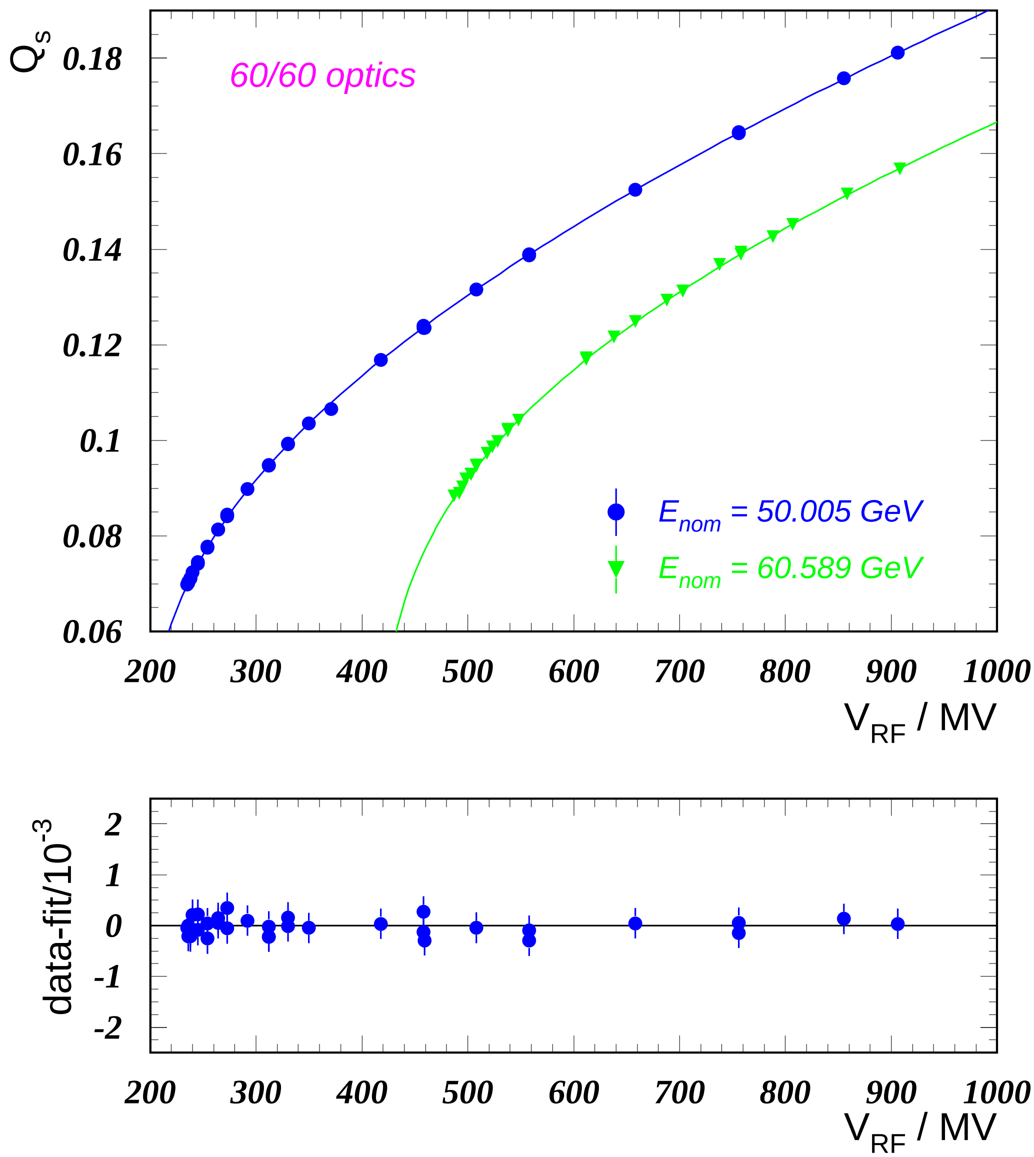
No significant non-linearity!

$$\rightarrow \delta \mathrm{E_b} \approx 20 \, \mathrm{MeV}$$

...but method indirect. Needs cross-checking!

Checking the extrapolation – Q_s vs $V_{\rm RF}$

E_b obtainable by fitting synchrotron tune against RF volts



$\rightarrow$ E_b at 80 GeV with an error of $< 2 \times 10^{-4}$:

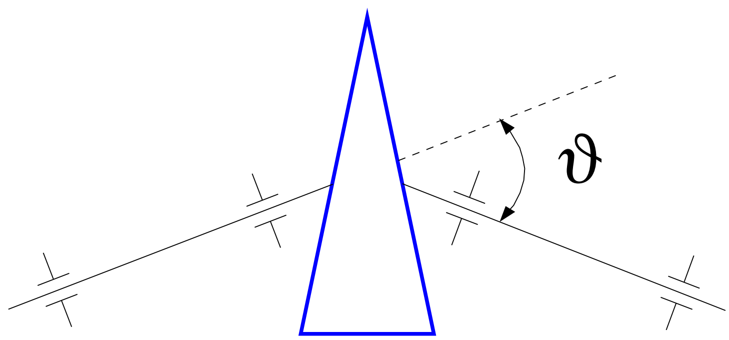
- Results need to be extrapolated (a little) to 100 GeV
- Appear to validate NMR model & agree with flux loop

Checking the extrapolation – the LEP spectrometer

Can we measure $\mathrm{E_b}$ *directly* to 1–2 $\times 10^{-4}$ in the W regime?

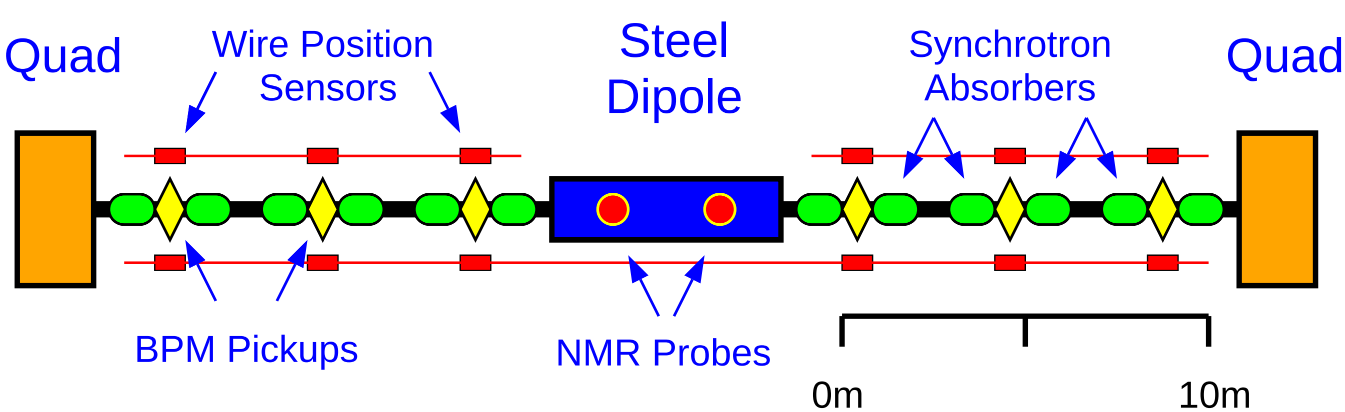
The idea (1997)

$$\Delta\theta \;\propto\; \frac{\oint B\,.\,dl}{E_{\mathrm{b}}}$$



Better still, measure *change* when going from 50 to 100 GeV

The reality (1999)



Such a measurement imposes extremely tight tolerances !

Main Spectrometer Topics

Brief overview on following issues:

- Knowledge of dipole bending field
- Knowledge / effect of field in 'field free' region
- Shielding of BPM blocks
- Wire position sensors
- RF Sawtooth
- BPMs – problems & global data analysis

All serious data taking took place in 2000 – not ideal as in competition with the Higgs search...

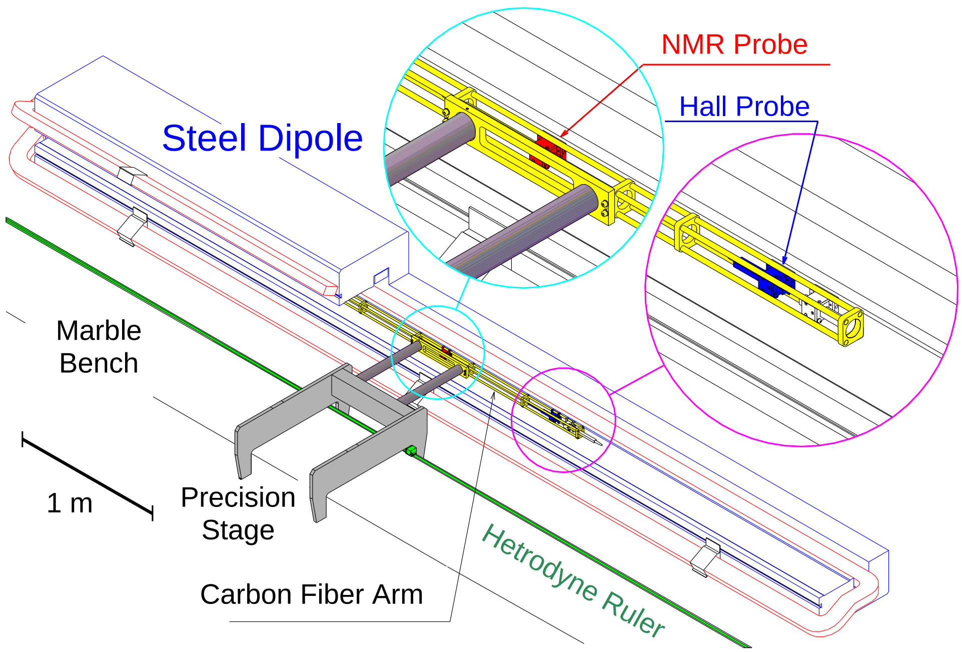
~ 17 fills in which spectrometer calibrated at low energy and ramped to ~ 93 GeV

Other experiments scanned low energy region to cross-check performance

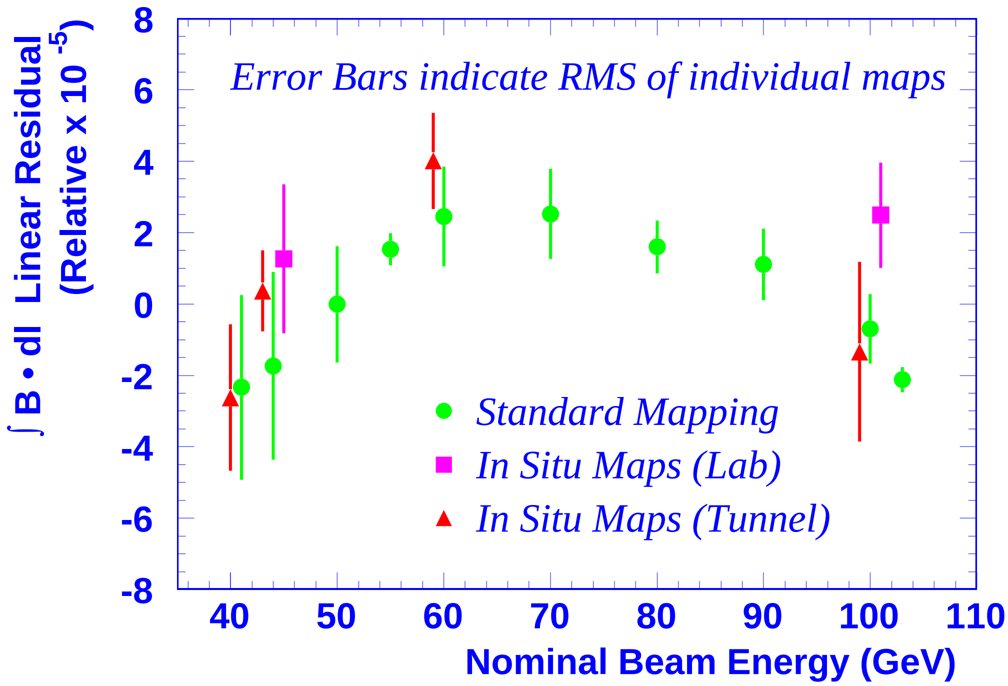
Plus several dedicated experiment to investigate systematic effects

Knowing $\oint B \, . \, dl$

Prior to installation, conducted extensive mapping campaign



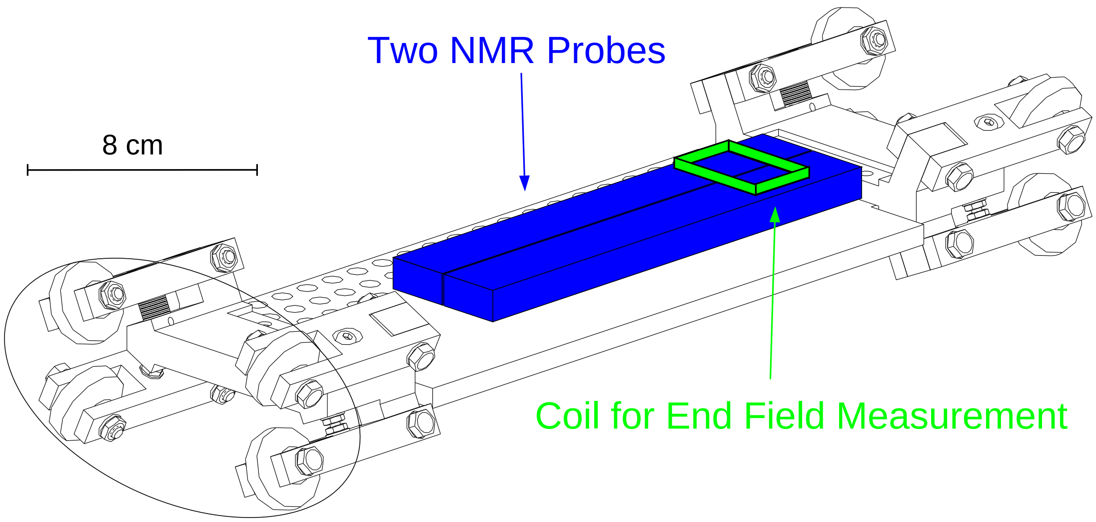
Model developed to relate $\oint B \, . \, dl$ to values of 4 reference NMRs in dipole as function of coil temperature etc



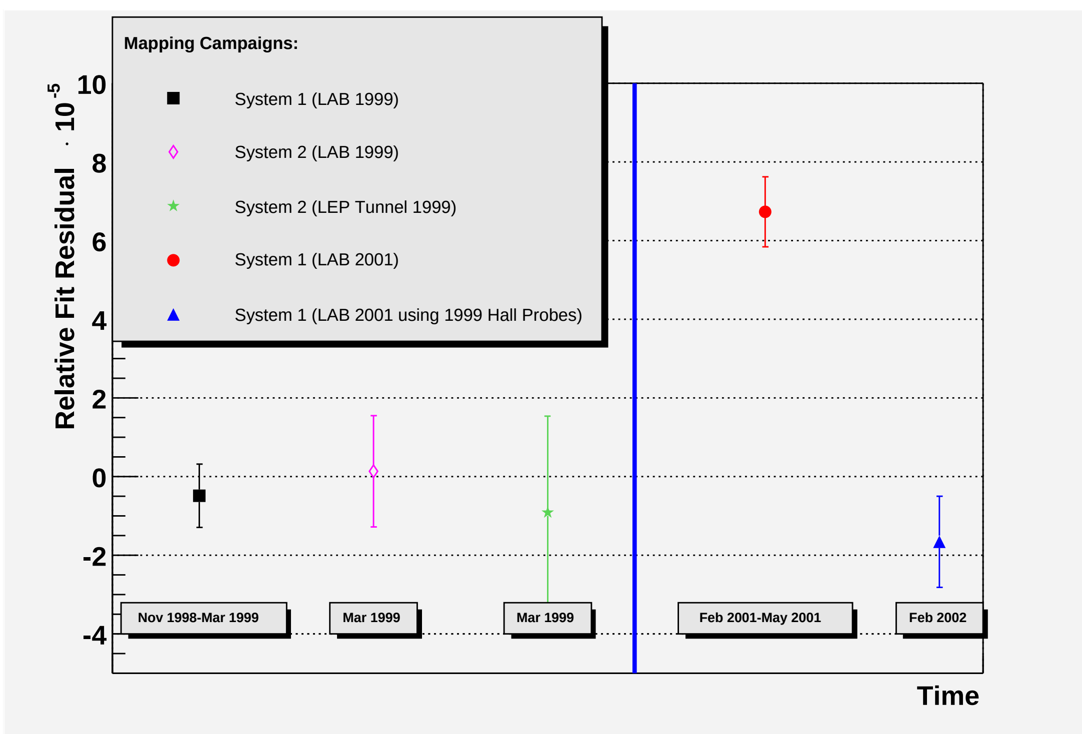
Value of model residuals 90 vs 50 GeV $\sim 1 \times 10^{-5}$

Knowing $\oint B \, . \, dl$

Cross-check in situ inside beam pipe with burrowing 'mole'



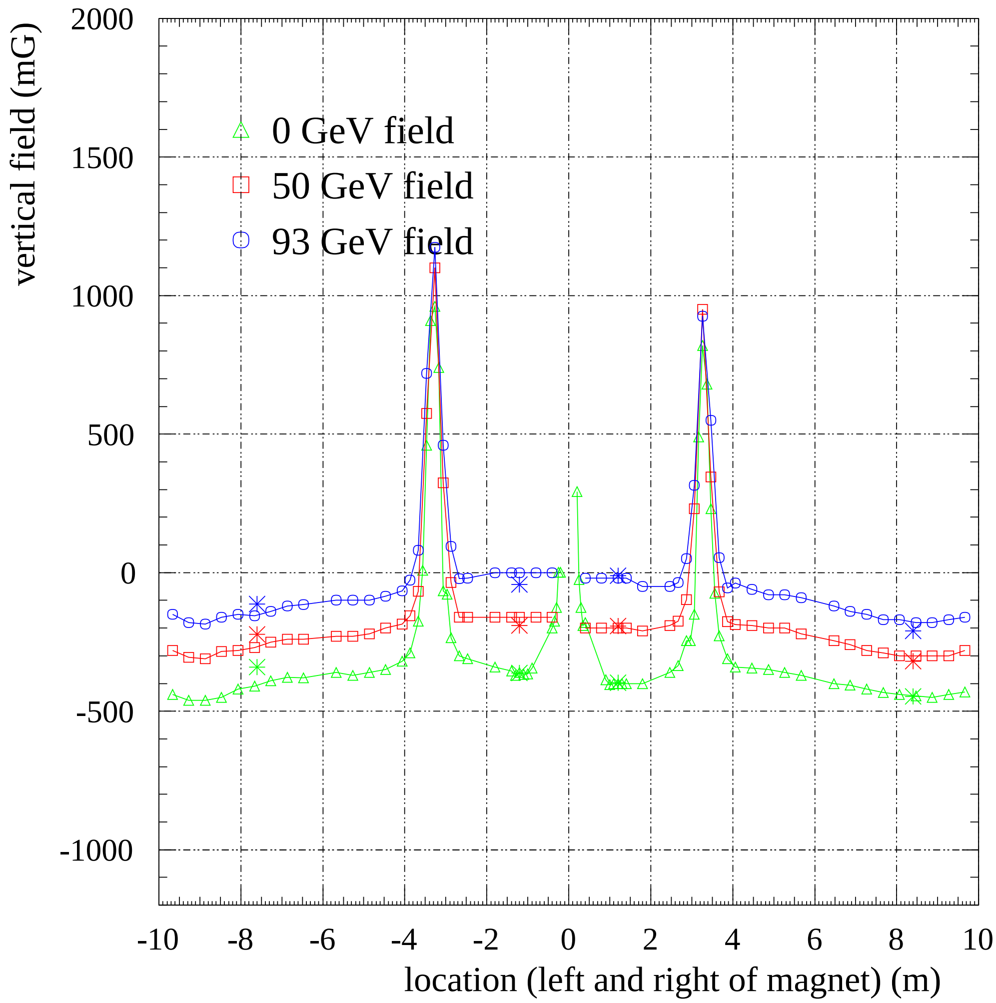
Further mapping in 2001 and 2002 with improved Hall probes



Results seen are very consistent. Excursion understood as Hall probe systematic. Max uncertainty induced on $E_{\mathrm{b}} < 2 \times 10^{-5}$!

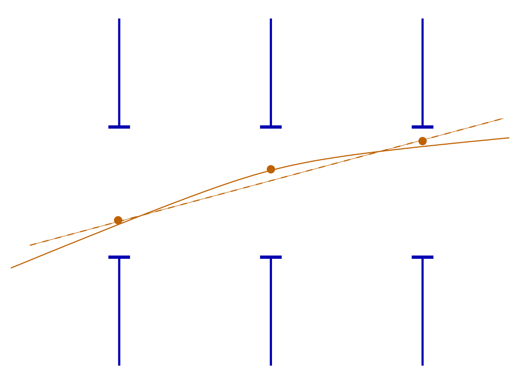
Environmental fields

Field free arms of BPM triplets are not field free!



(Spikes come from permanent magnets in vacuum pumps. Energy variation from currents in magnet cables.)

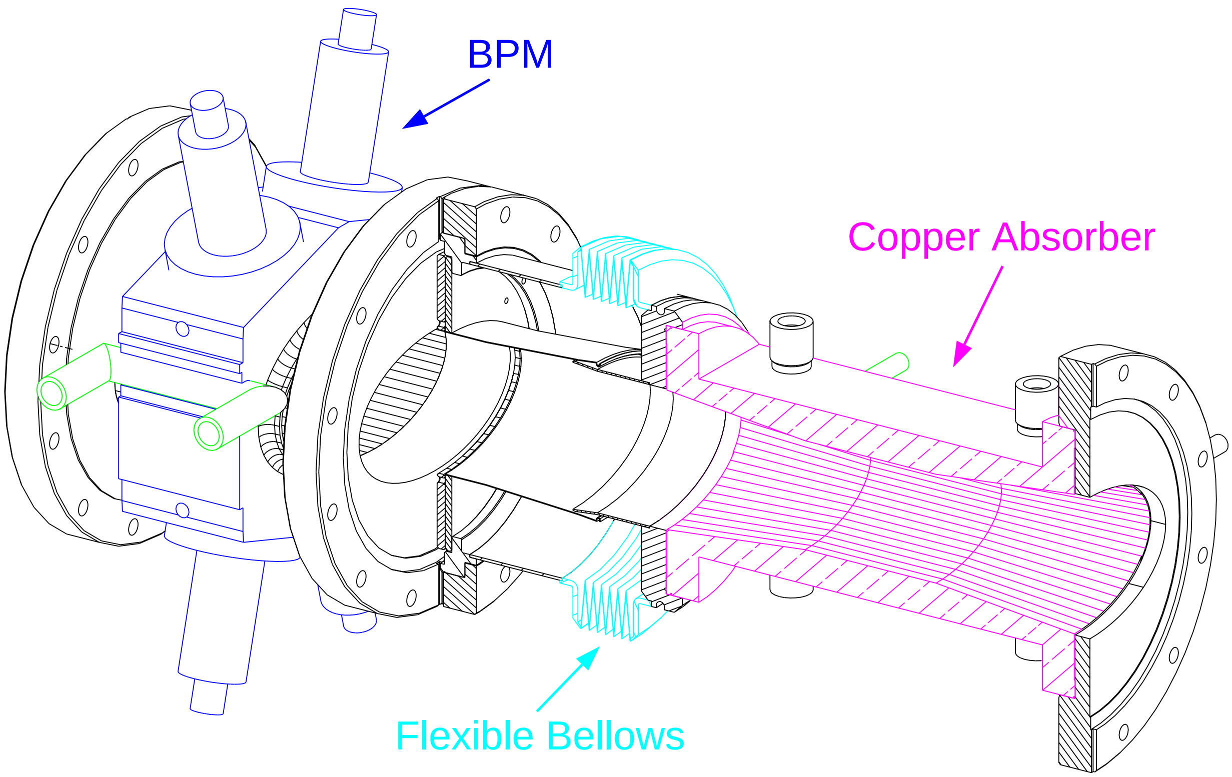
Causes a bias which must be accounted for in analysis:



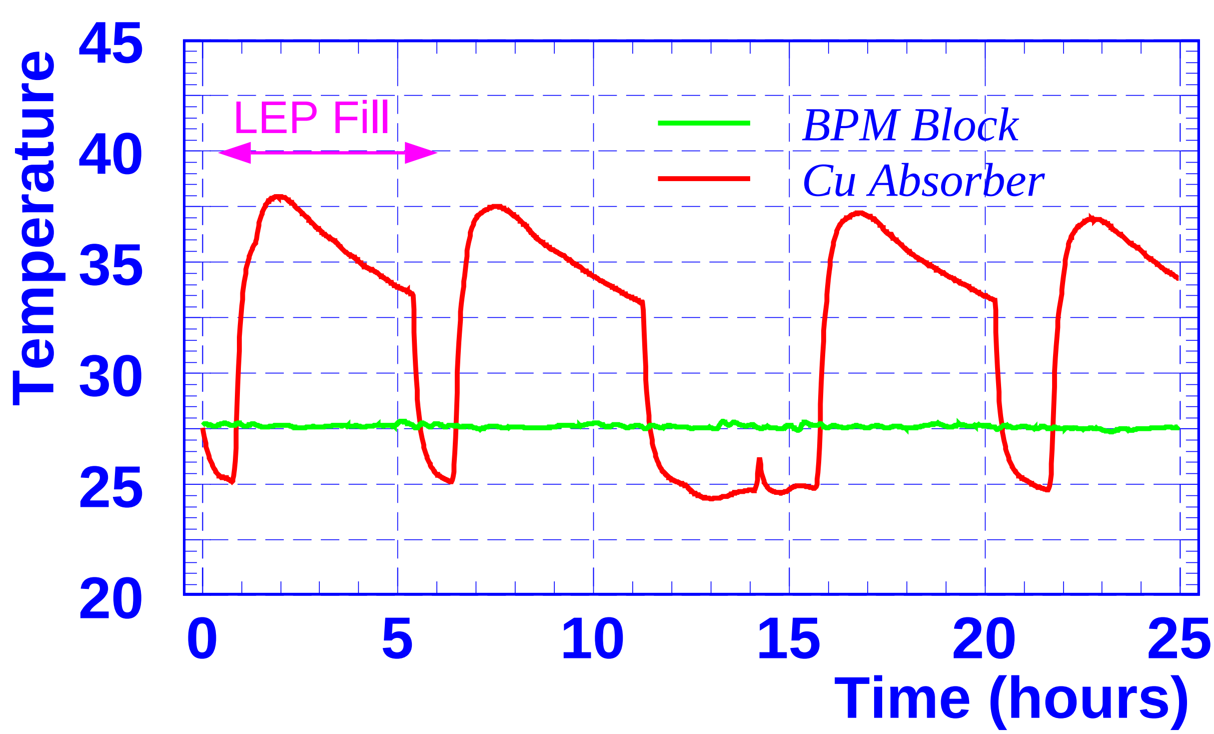
Field magnitude monitored fill to fill with flux gates → stable

Synchrotron shielding

Synchrotron power $\propto E_{\rm b}^4$ – reaches kW/m

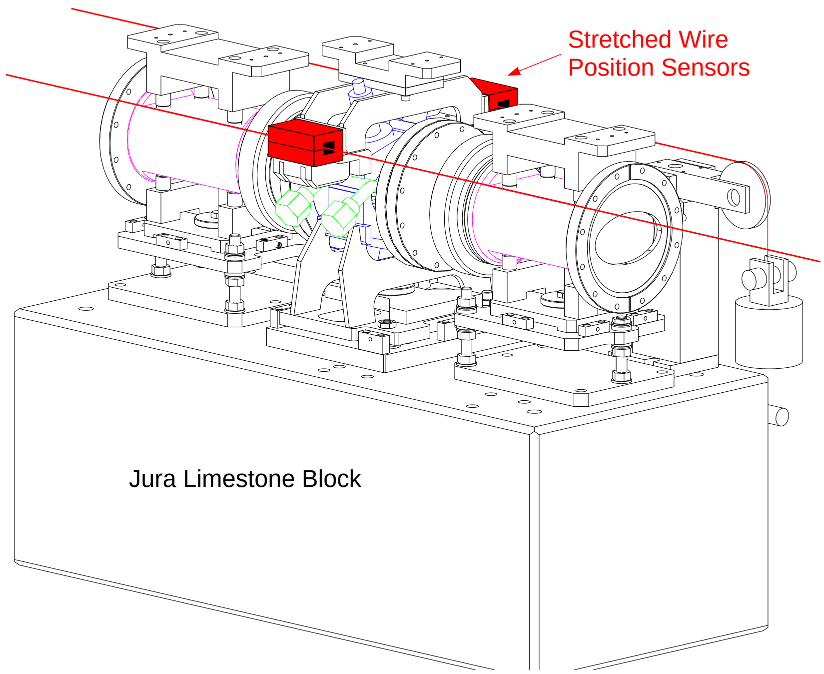


BPMs stable to $< 0.2^\circ{\rm C}$ $\rightarrow$ block expansion $< 1.5\mu{\rm m}$

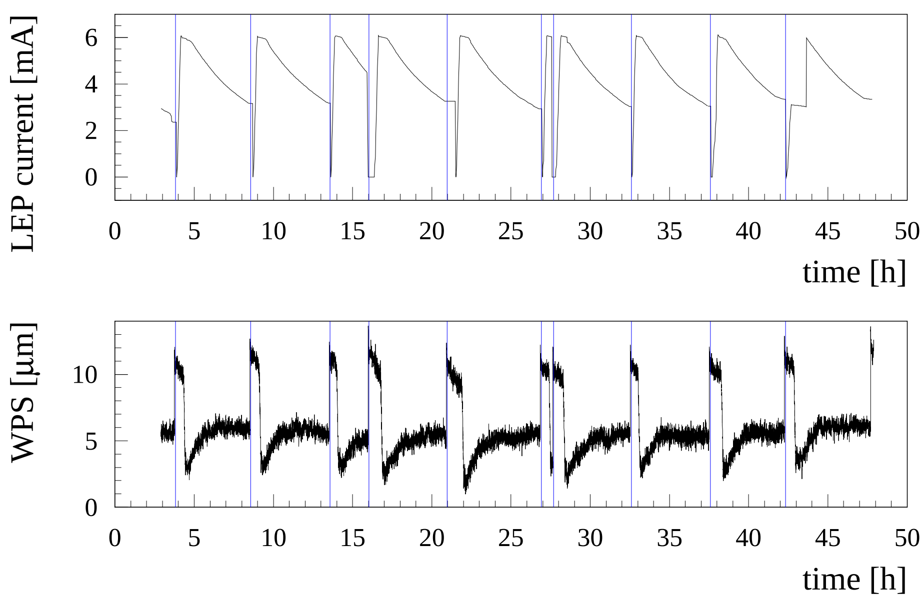


Wire Position Sensors and Synchrotron Radiation

Stability of BPMs monitored by stretched wire sensors



These showed alarmingly large jumps at start of fill



Not real! Artefact caused by ionisation of air

→ Cured with shielding and careful centring of wires

Real movements found to be small → corrected for in analysis

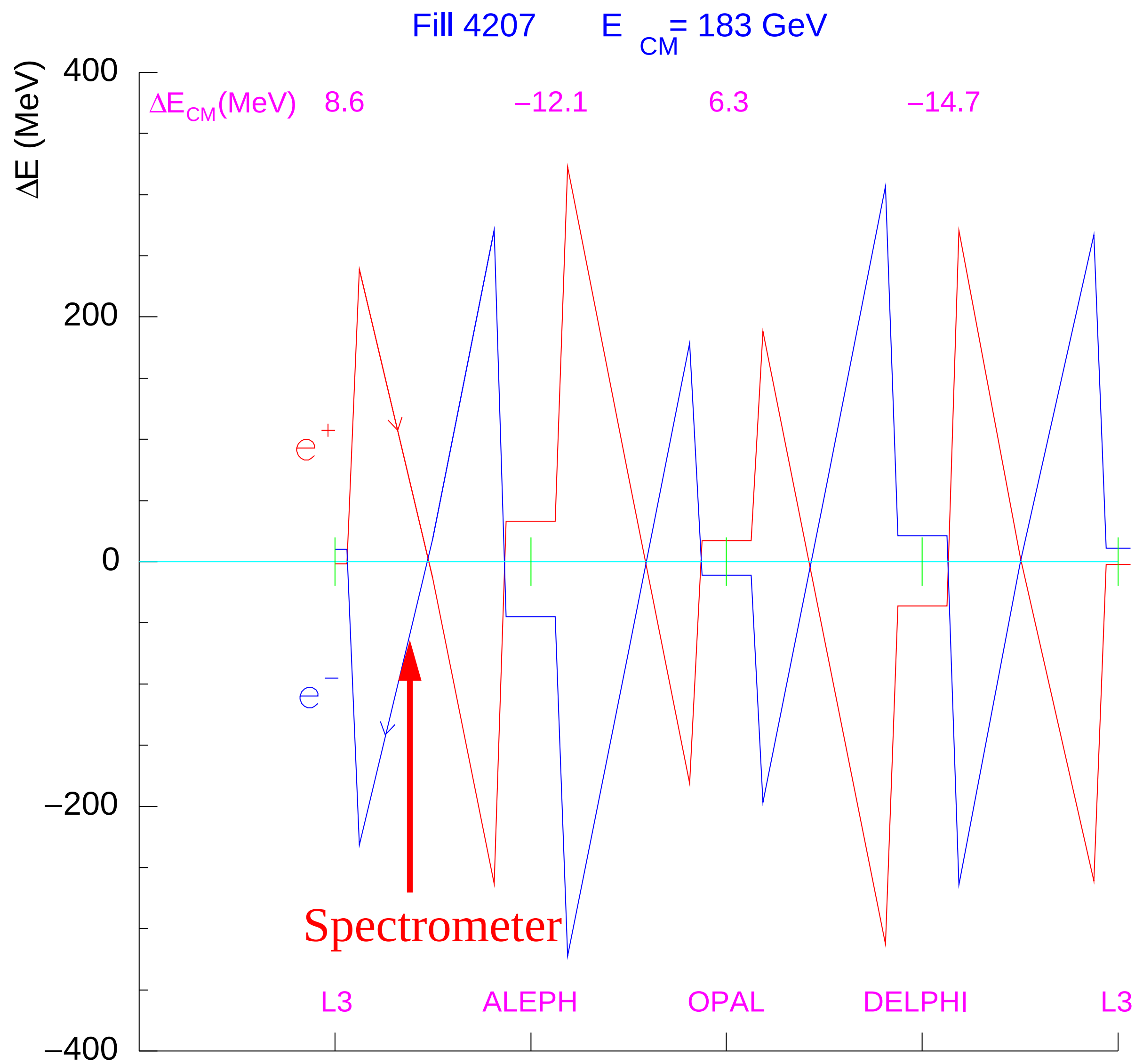
RF sawtooth

Nearly 3 GeV lost and replenished per revolution at 100 GeV

- Need to relate *local measurement* of spectrometer to *mean energy* measured by resonant depolarisation

  $\longrightarrow$ Correction of 20–50 MeV

- Dependent on misalignments, misphasings, voltage scale

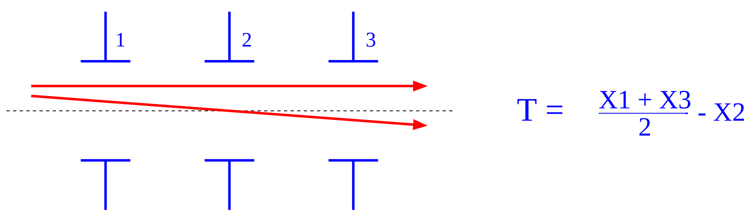


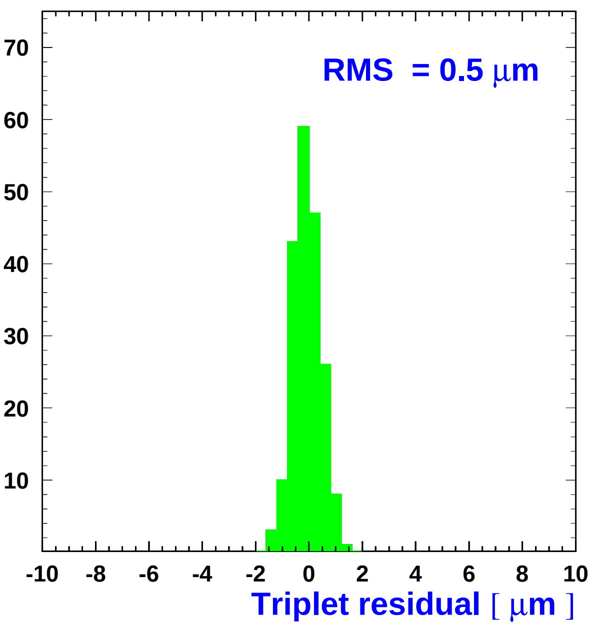
Model calibrated through orbit measurements in dedicated experiments, and controlled through comparing e^- vs e^+

$\longrightarrow$ Residual error of 5 MeV

Beam Position Monitor performance

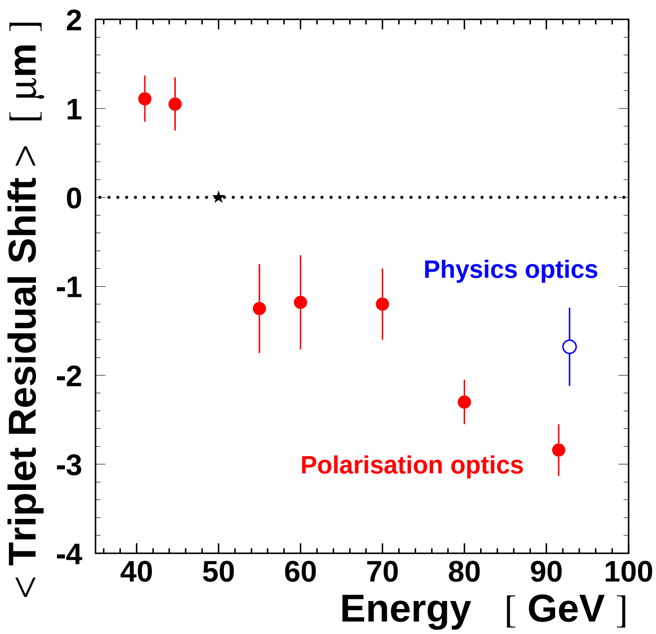
Use normal LEP BPMs, but with high precision electronics





Triplet residuals demonstrate required μm resolution achieved !

BUT "large" shifts are seen BETWEEN energy points!



Possible reasons:

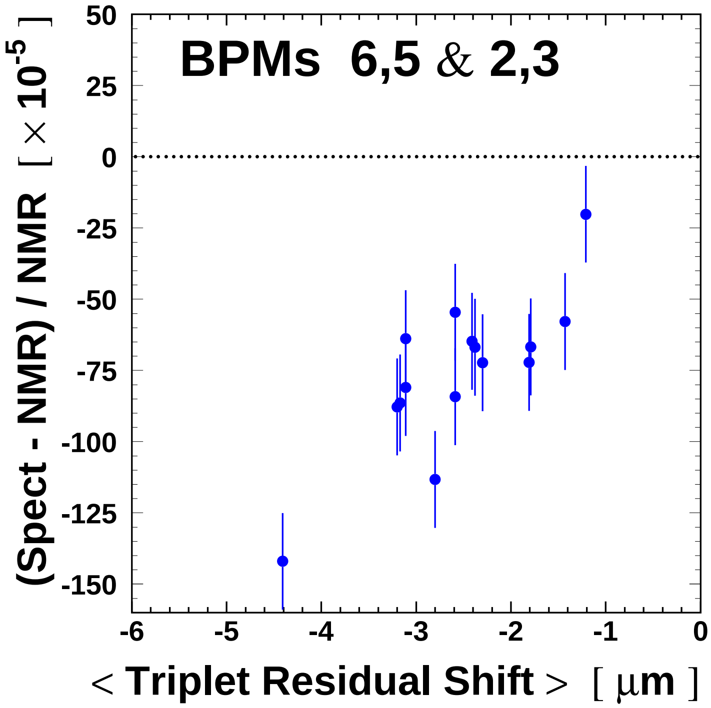
- Bunch length ?
- Beam size ?
- Drift with time ?

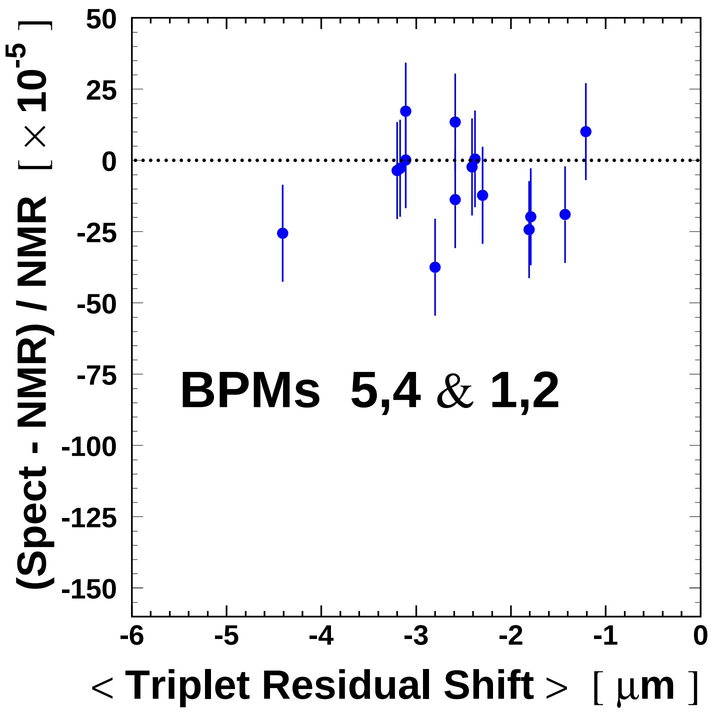
→ No certain answer on mechanism, but can be calibrated out

Global analysis of Spectrometer Measurements

System of 3 + 3 BPMs gives 9 different energy estimates.
Because of BPM systematics these are not identical.

Study results from each combination vs size of systematic...

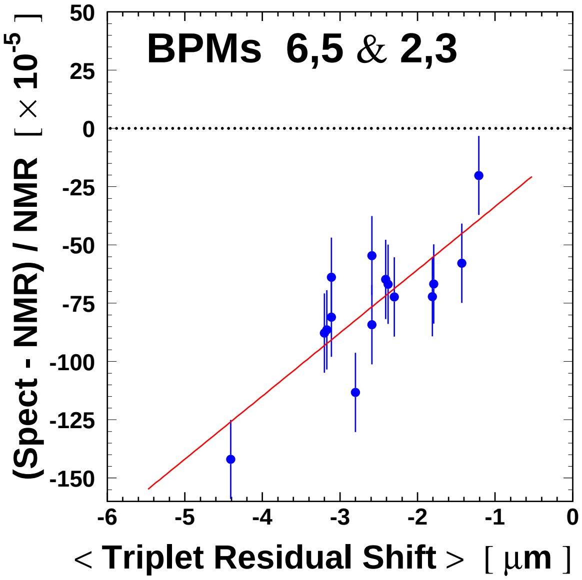


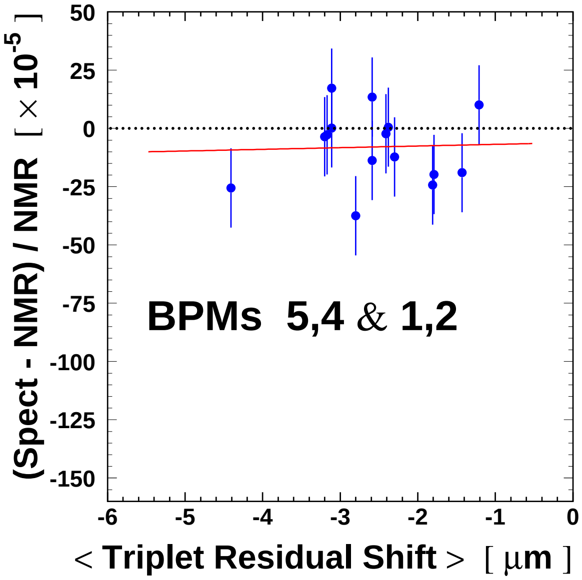


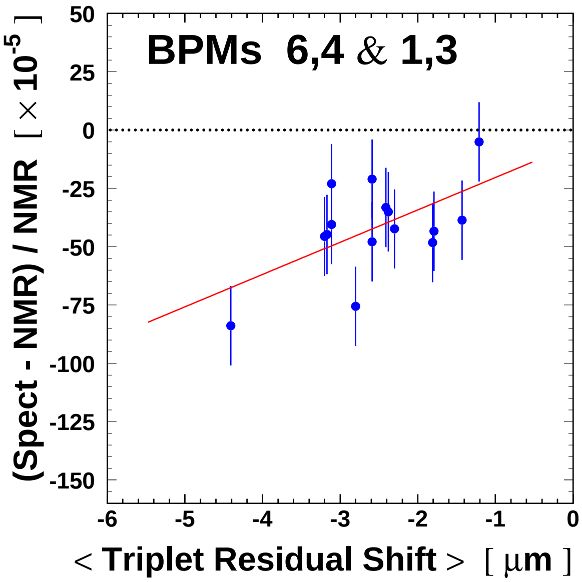
...observe some combinations more stable than others

Global analysis of Spectrometer Measurements

Linear fit allows extrapolation back to zero systematic...







...all combinations give same result

Conclusions confirmed in parallel analysis at low energy

Conclusions

Analysis of spectrometer data, & other LEP 2 energy calibration measurements, are very close to completion.

Verdict on spectrometer:

- 'Crash programme' carried out very efficiently
- Understanding of (relative) dipole field to $1 - 2 \times 10^{-5}$
- Stability ($\sim 2\mu\mathrm{m}$) and monitoring ($< 1\mu\mathrm{m}$) of apparatus in fierce environment
- BPMs – very high performance achieved, but systematics at $2 - 4\mu\mathrm{m}$ level
- Final result looks likely to have a precision of $\leq 2 \times 10^{-4}$

And in wider context:

- Checks on magnetic extrapolation from flux loop, synchrotron tune and spectrometer appear to be consistent, with similar precisions
- Likely final uncertainty on E_{b} to be $1 - 1.5 \times 10^{-4}$
- Becomes a small error contribution to m_W

Nice result from many years of close collaboration between (a few) machine physicists, particle physicists & engineers!