LEP Energy Calibration

OPAL Plenary

June 1998 – Pippa Wells

- The final word on LEP1 – “published”
  (CERN-EP/98-040, CERN-SL/98-012, submitted to Eur. Phys. J. C)
- The LEP2 energy model
  - Polarisation/NMR/flux-loop comparisons 1997 and 1998
  - Final central values for 1997
  - Close to final error estimates for 1997
- LEP Spectrometer Project

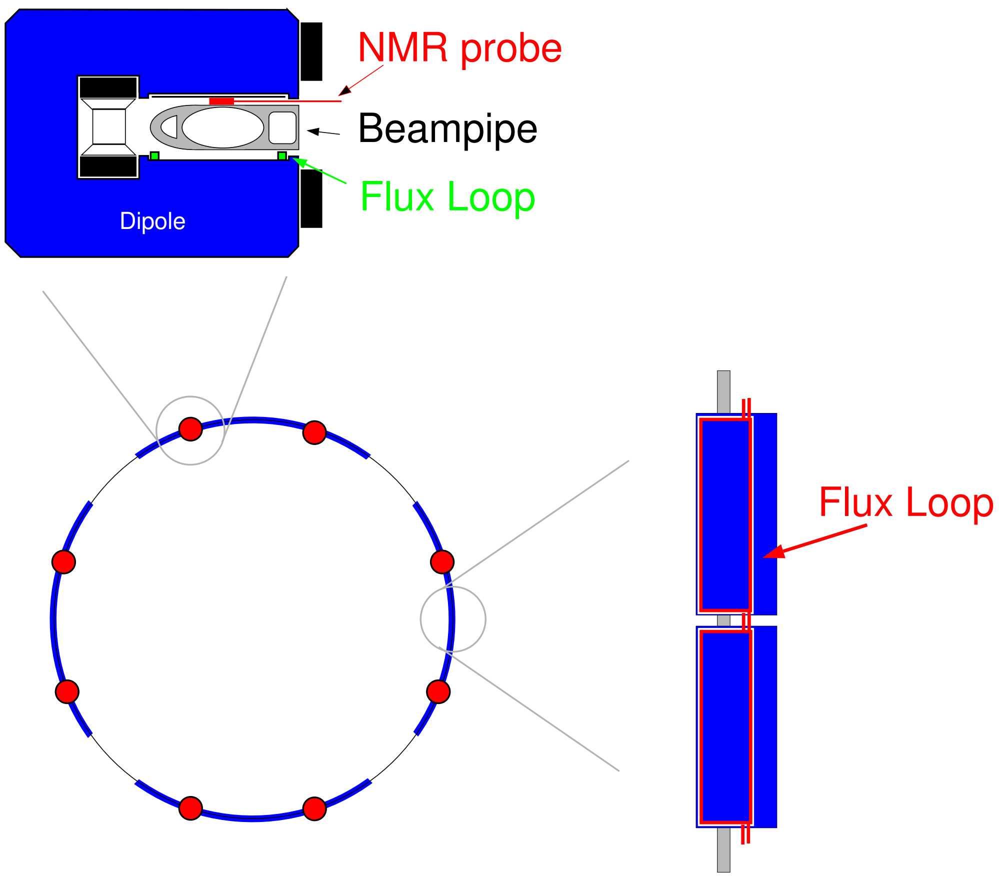
LEP2 energy model

- Aiming for total $\sigma(M_W) \approx 30$ MeV at LEP2 $\Rightarrow \Delta E_{\mathrm{beam}} 10 \approx 15$ MeV
- Many effects understood from LEP1. Some scale with energy. Energy loss per turn scales with E^4 $\Rightarrow$ care with logging RF system status.
- Resonant depolarisation gives most precise energy scale. Maximum RDP energy so far is 55 GeV. Physics running with E_{beam} 90–100 GeV.

$$\nu \propto E_{\mathrm{beam}} \propto \oint B \cdot \mathrm{d}\ell$$

- Magnetic extrapolation: compare E_{pol} with B_{NMR} in low energy range and predict E_{beam} at physics energy
- Flux loop measures total $\oint B \cdot \mathrm{d}\ell$, with NMR's read out at steps in the cycle
- Compare B_{NMR} with B_{FL} to test how well NMR's predict $\oint B \cdot \mathrm{d}\ell$ over full energy range (constrain non-linearity)
- If NMR's can predict B_{FL}, then they can provide E_{beam} at physics energy from E_{pol} at lower energy

Magnetic measurements



NMRs:

- Precision: order 10^{-6}
- Read out: every 30 seconds
- Only measures B-field over small area, 16 probes for 3200 dipoles

Flux Loop:

- Precision: few 10^{-4}
- Read out: every few weeks. NMR's lock at steps in cycle
- Measures 96.5% of B-field. Missing:

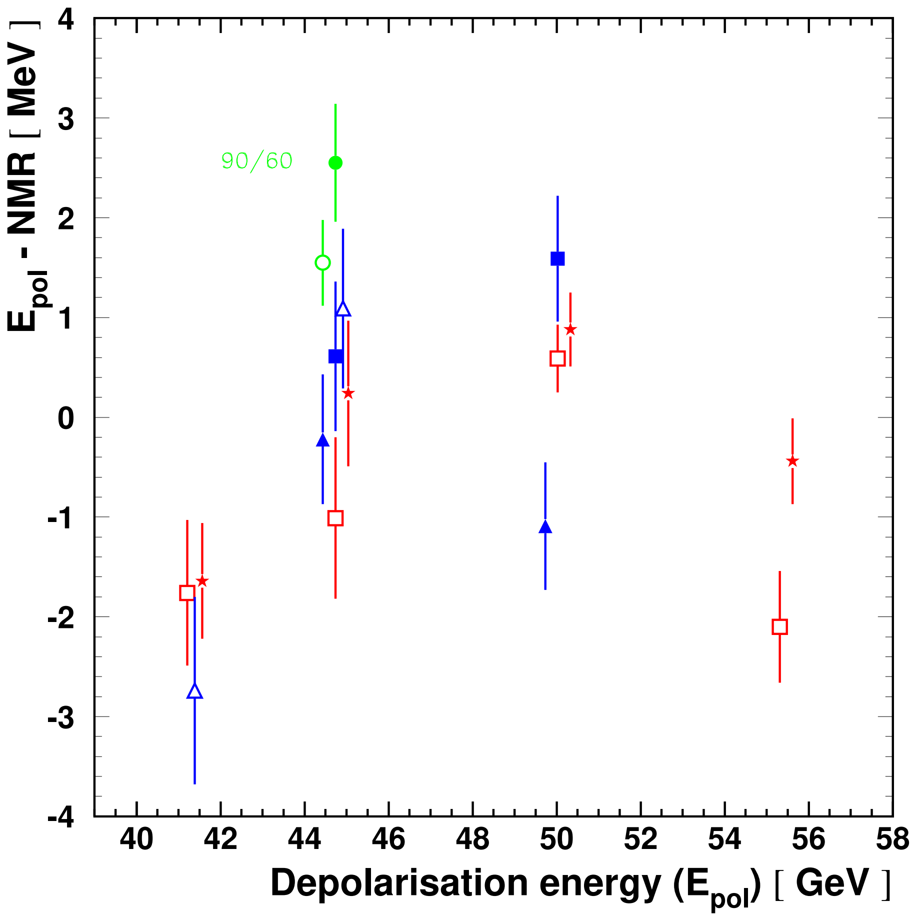
  "10%" dipoles (end of arcs)
  injection dipoles
  fringe fields
  quadrupoles ...

LEP2 polarisation measurements

Date	41 GeV	44 GeV	50 GeV	55 GeV	Optics
1996		●	●		90/60
17/08/97		●			90/60
06/09/97		●	●		60/60
30/09/97		●	●		60/60
02/10/97	●	●	●	●	60/60
10/10/97		●			90/60
11/10/97	●	●	●	●	60/60
29/10/97	●	●			60/60
14/06/98		●	●	●	60/60
18/06/98		?	???		102/90

- Only one fill with two energies in 1996.
- Several multi-energy fills and increased lever arm in 1997.
- Maximum measured energy 55 GeV. 2% polarisation at 60 GeV.

NMR–polarisation comparison

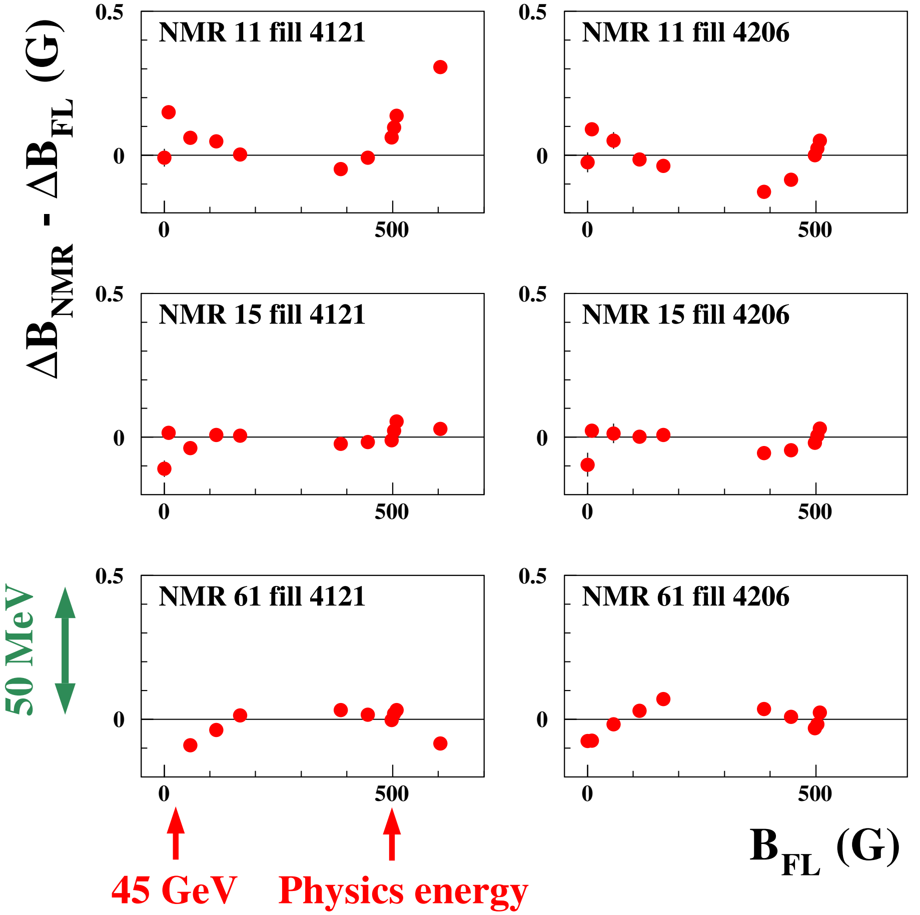


- Make fit of E_{pol} to
  $E^i_{\text{NMR}} = a^i + b^i B^i_{\text{NMR}}$
  for each NMR $i = 1, 16$
- Plot residuals
  $E_{\text{pol}} - E^i_{\text{NMR}}$
- Different probes show different behaviour, but reproduced from fill to fill.
- Error bars from rms/sqrt(Nprobes).
  Significant "banana" shape

NMR–polarisation comparison

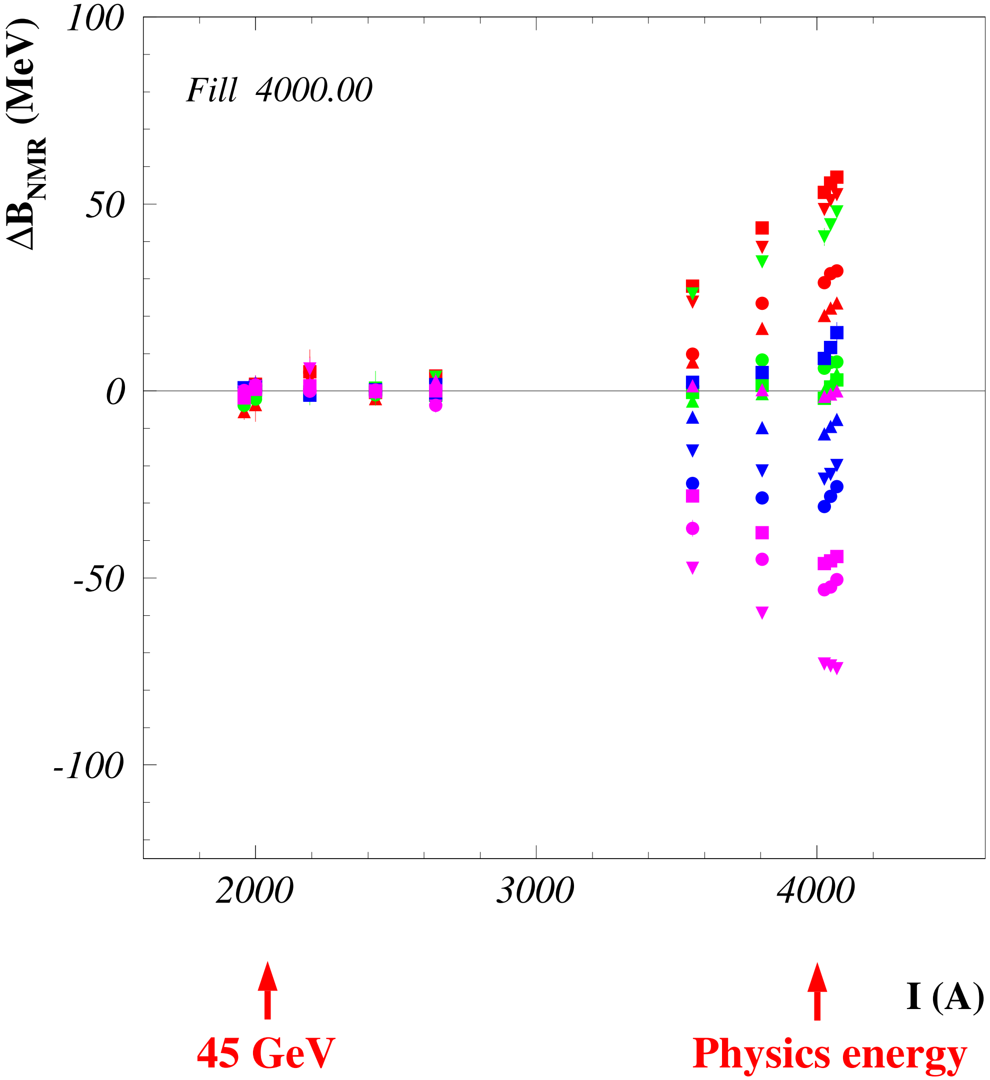
- Each NMR can predict energy in physics $\Rightarrow$ 10 MeV uncertainty from 40 MeV rms scatter over 16 NMR's
- Fitting to subsets of RDP fills $\Rightarrow$ additional 5 MeV uncertainty.
- Estimate of non-linearity effect: Increase errors until χ^2/dof=1. Extrapolated uncertainty at physics energy is 7 MeV.

NMR flux-loop raw data



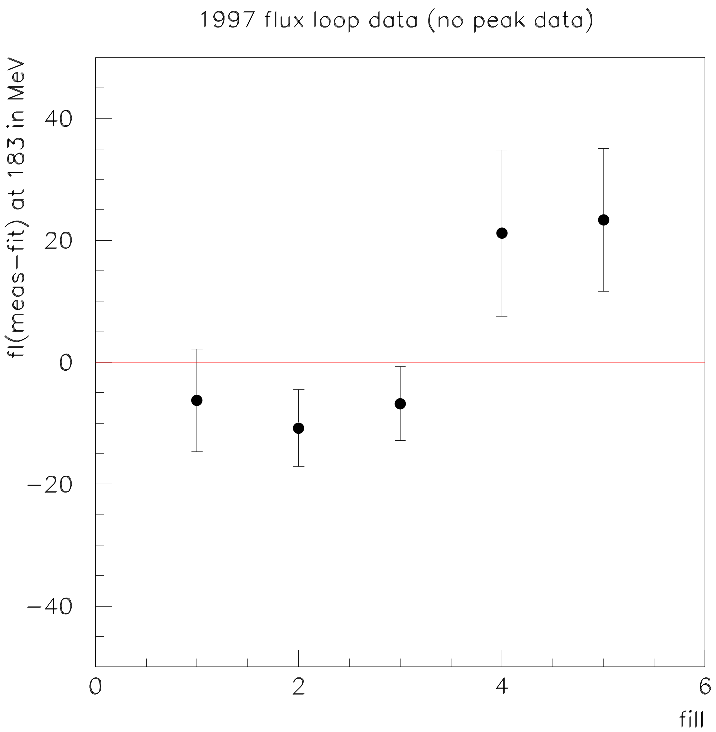
- Fit $B_{\mathrm{NMR}} = c + dB_{\mathrm{FL}}$.
- Plot residuals from this line as a function of ΔB_{FL} (0 G at 40 GeV, 500 G at physics energy)
- Behaviour varies octant-to-octant and magnet-to-magnet, but is reproduced from fill-to-fill
- Slopes are not constant with energy

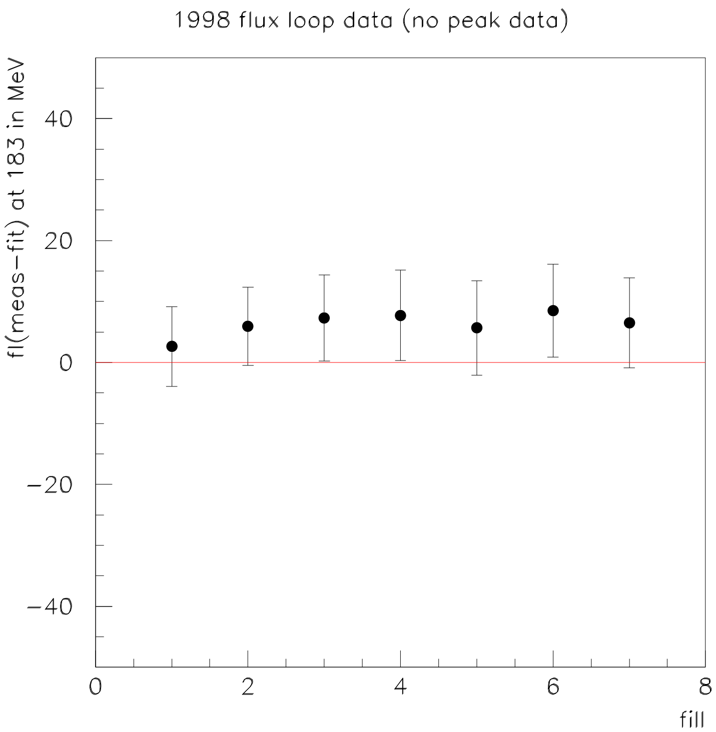
FL test of extrapolation with NMR's



- Restrict fit of $B_{\text{NMR}} = c + dB_{\text{FL}}$ to 40–55 GeV range.
- Good correlation between slopes of flux-loop and polarisation fits
- This plot is for one flux-loop measurement. Each symbol corresponds to a different NMR

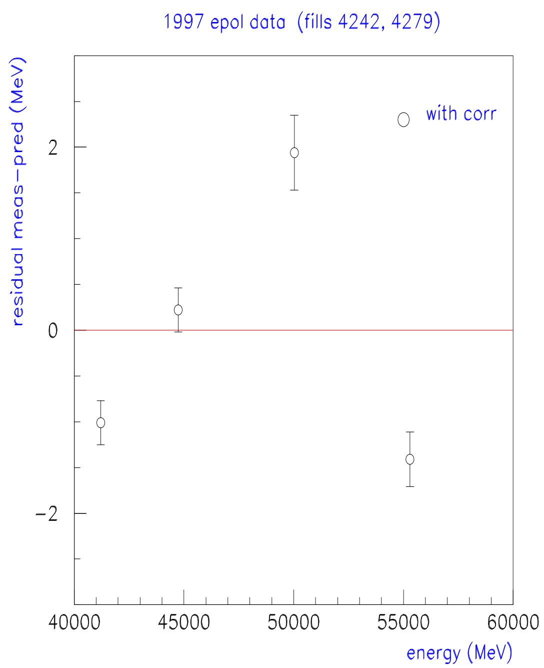
FL test of extrapolation with NMR's

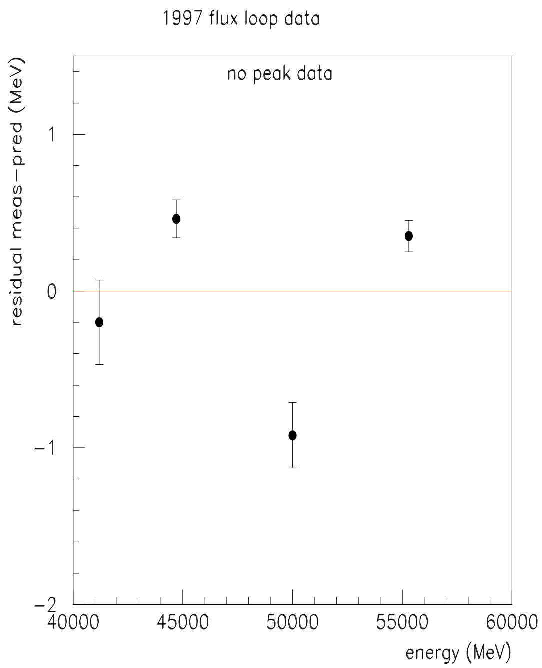


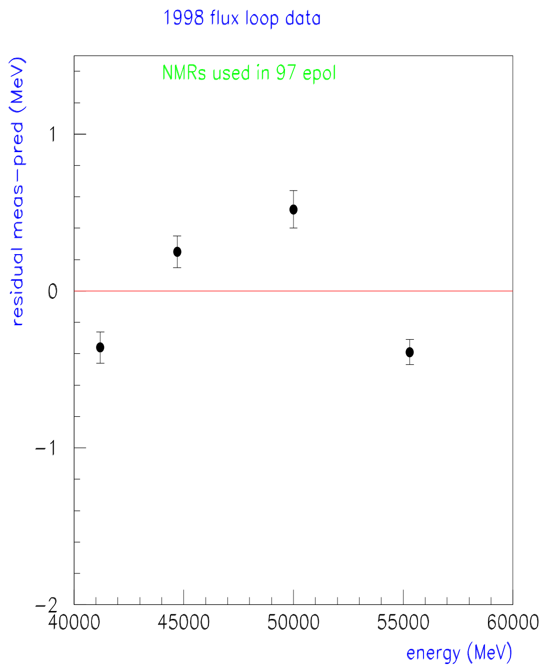


- Compare B field measured by flux loop at physics energy to B field predicted by NMR's from fit in the 40-55 GeV region. Convert to energy difference.
- Average shift –10 to +20 MeV, varying during 1997. Test repeated in 1998.

Compare polarisation and flux loop bananas







- Flux loop does not reproduce the polarisation banana, but this is perhaps beyond the systematic precision of the device.

Optics difference

Most of the 4 MeV measured energy difference at 45 GeV is explained by different QF and QD excitation currents and by horizontal orbit correctors.

- Remaining discrepency at 45 GeV is about 1 MeV.
- Difference expected to scale with energy $\Rightarrow$ uncertainty of 2(?) MeV

Field outside flux loop

For Moriond, assumed 1% uncertainty on the 3.5% of $\oint B \cdot \mathrm{d}\ell$not measured by the flux loop (12 MeV error). Now:

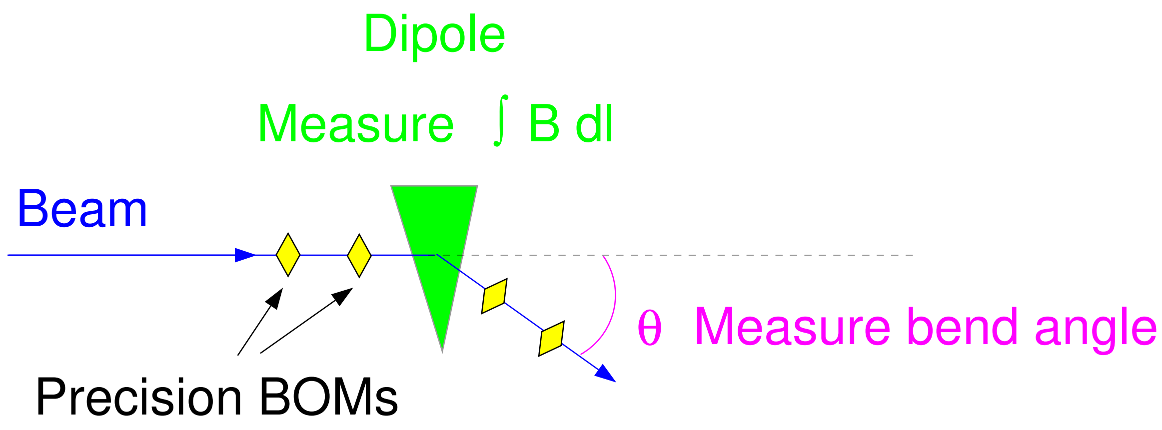
- Fringe fields of main bend dipoles $\Rightarrow$ 5 MeV error
- 10% bending dipoles at ends of arcs are 0.2% of total field $\Rightarrow$ negligible effect
- Injection dipoles are instrumented with NMRs in 1998. Field proportional to main bend field to better than 10^{-3} $\Rightarrow$ negligible effect

Preliminary error summary

Source	Moriond	Now
Polarisation systematic	1	1
e^+e^- energy difference	2	2
Optics difference	4	4
Extrapolation from NMR–polarisation		
NMR rms/sqrt(N) at physics energy	10	10
Non-linearity systematic (new)		7
Different E_{pol} fills	5	??
Flux-loop test of extrapolation		
NMR flux-loop difference at physics energy	20	20
NMR scatter (double counted)	10	0
Field not measured by FL	12	5
Corrector effects	6	6?
Tide	1	1
Dipole rise modelling	1	1
RF frequency shift (15 min sampling)	3	0
IP specific corrections ($\sigma(E_{\mathrm{CM}})/2$)		
RF model	3	3
Dispersion	2	2
Total	29	??

LEP Spectrometer Project

- Measure bend angle of electron and positron beams each time they go through a particular dipole.



$$\theta \propto \frac{\int B \mathrm{d}\ell}{E_{\mathrm{beam}}}$$

- Cross calibrate with RDP at low energy.
- Dipole current ramps with E_{beam}, along with the rest of the machine.
- Monitor $\theta \Rightarrow$ calculate change in E_{beam} relative to nominal setting value.

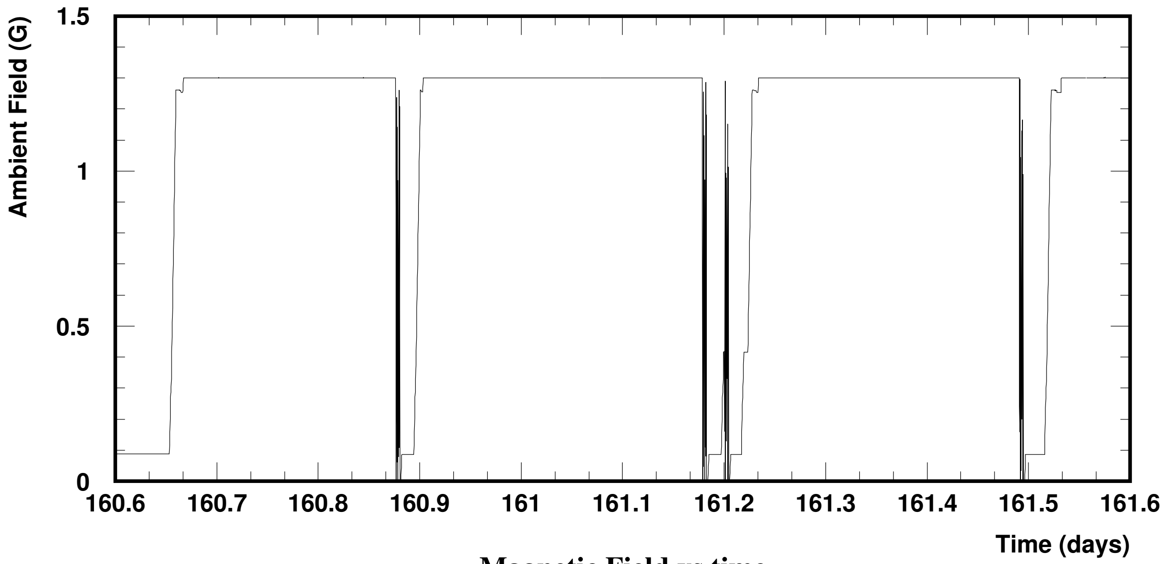
Spectrometer realisation

- Aim for 10^{-4} precision $\Rightarrow$ ± 10 MeV at 100 GeV
- Find a place in the LEP lattice with space for BOMs
  - 1998: two concrete dipoles near point 3. Equip with 4 NMR's
  - 1999: replace with a single, precisely mapped, steel "injection" dipole
- $\theta \approx 3.8$ mrad, lever arm ≈ 10 m $\Rightarrow$ required BOM precision 1 micron

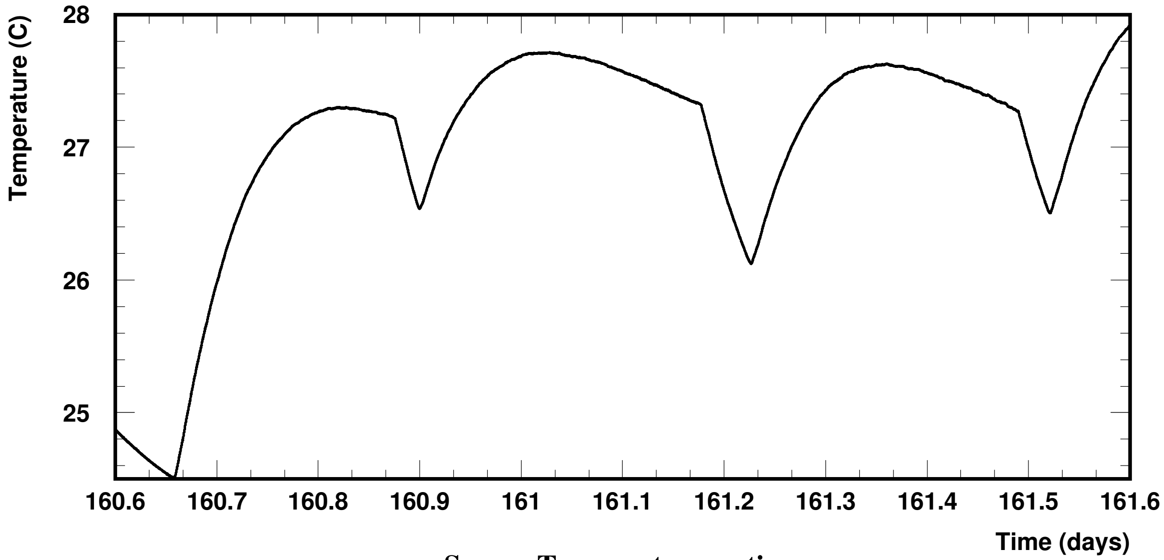
  Possible with standard pickups, equipped with new electronics
  - 1998: only one side (will be) equipped with new readout
  - 1999: both sides equipped
- Stretched wire system to measure relative alignment
- Thermal and mechanical stability an issue
  - 1998: phase 1 – check relative precision of BOM measurements
  - 1999: available for energy calibration

Spectrometer Data, June 12-13

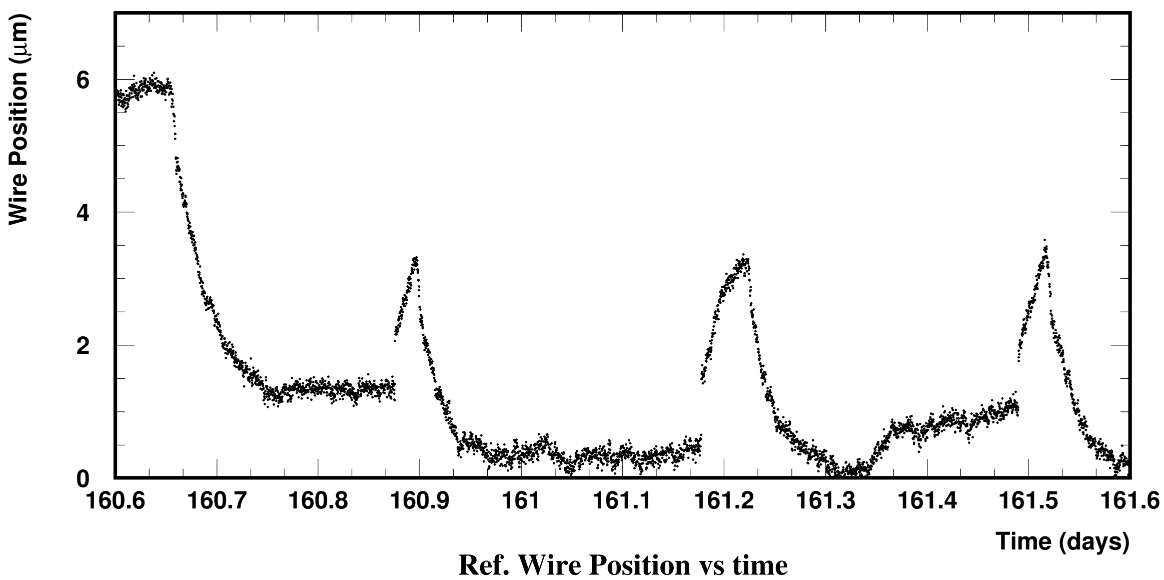
98/06/17 14.22



Magnetic Field vs time



Sensor Temperature vs time



Ref. Wire Position vs time

Conclusions and plans

- Progress for 1997 data:
  - Consistency of polarisation data and flux-loop vs. NMR's firmly established at the 20–30 MeV level at physics energy. Final error and paper soon.
- Magnetic extrapolation in 1998
  - Attempt to increase lever arm with RDP at 60 GeV (60/60 optics)
  - More fills with many/different energy points in the same fill
  - Cross-calibrate polarisation (60/60) and new physics (102/90) optics
  - Control field outside flux loop (injection dipoles measured)
- Improve Monte Carlo modelling of radiative returns
- Spectrometer commissioning and tests parasitic on physics and on RDP
- 8 days of machine development time have been allocated for energy calibration