The LEP Spectrometer Dipole Re-Mapping

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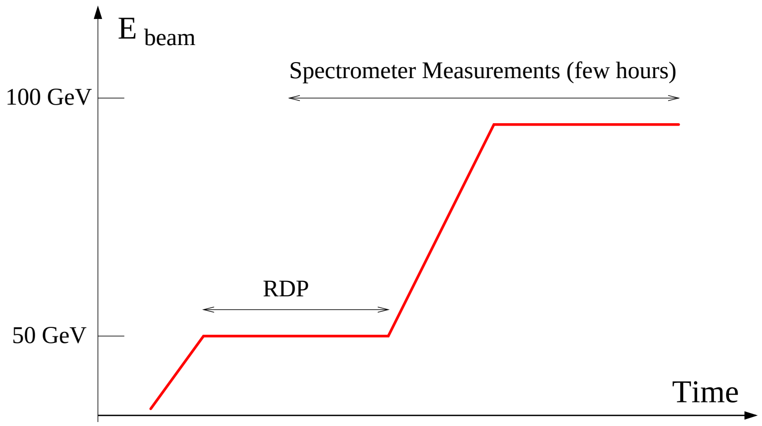
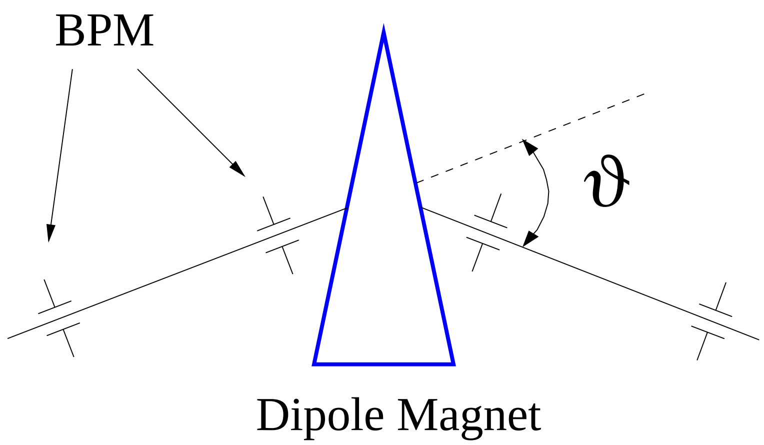
The LEP Spectrometer





- Evaluate the Ratio between two energies
- Prediction of the LEP beam energy with a relative accuracy of $1 \cdot 10^{-4}$
- The Beam Energy is depending on the Bending Angle and the Total Integral B-field:

$$\boxed{E_{beam} \propto \frac{\int_L Bdl}{\Delta\theta}}$$

- Main elements:
  - Beam Position Monitors (BPM) $\rightarrow$ $\Delta\theta$
  - Bending Magnet mapping $\rightarrow$ $\int_L Bdl$
- $\boxed{\frac{\Delta E}{E} \approx 1 \cdot 10^{-4}}$, $\boxed{\frac{\Delta(\int_L B \cdot dl Ratios)}{\int_L B \cdot dl Ratios} \approx 3 \cdot 10^{-5}}$

The Spectrometer Dipole

- Iron-Core Dipole 5.75 m long, manufactured by industry and assembled at CERN
- Core Field = 0.225 T @ I = 500 A
- C Shaped Gap 100 mm high
- Total Weight (Core + Girder) = 10.3 t
- Independent Temperature Regulated Cooling System (stabilized to $\pm .2\,^{\circ}C$)
- 4 Reference NMR Probes (Metrolab) permanently installed in the gap

Measurement Setup I

- Before Spectrometer Operation

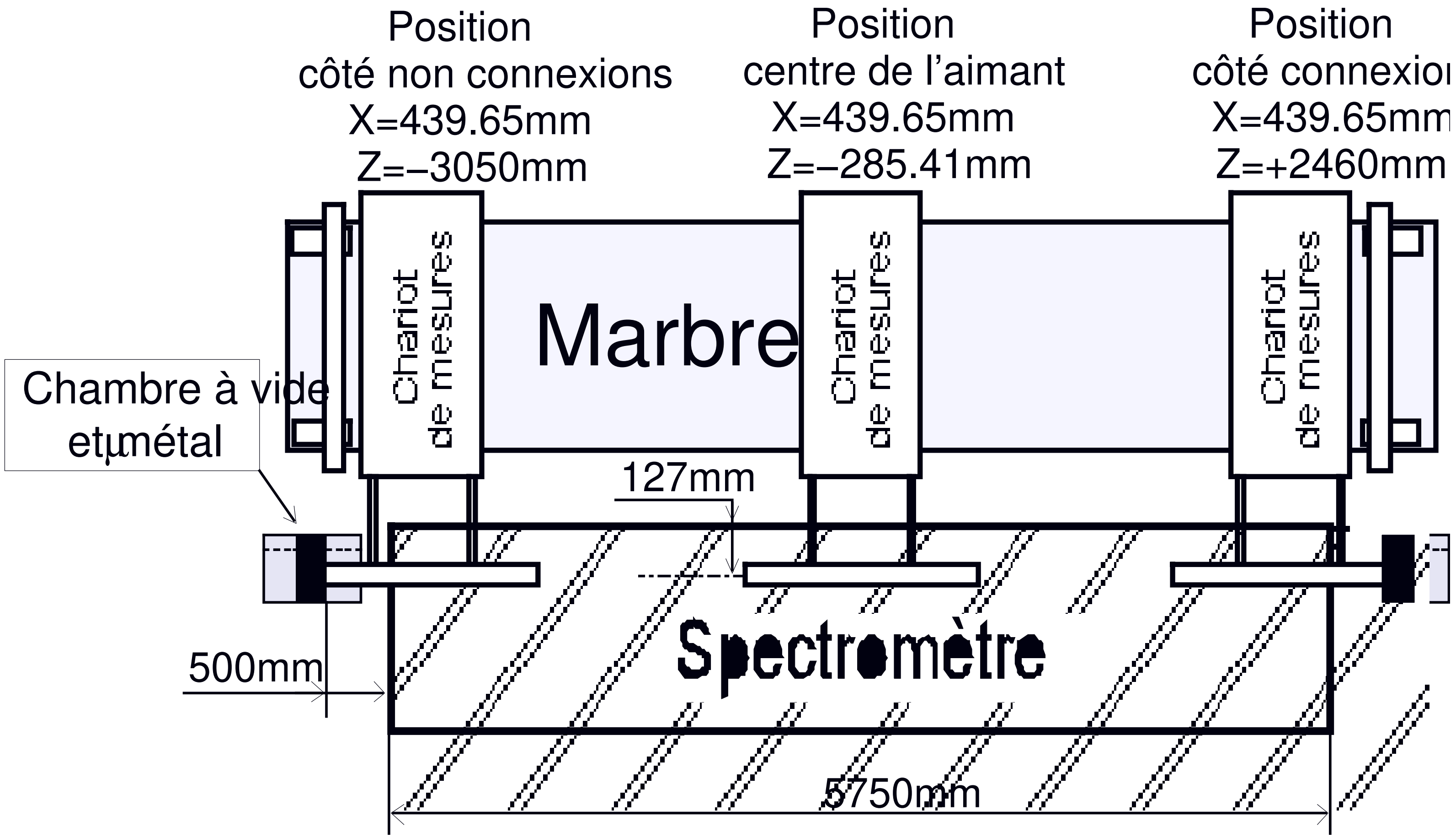
  "Field Map of the LEP Spectrometer With A Moving Carbon Fiber Arm" D.Cornuet, Proceedings of IMMXI, Brookhaven 1999

  "High Accuracy Field Mappings with a Laser Monitored Travelling Mole" F.Roncarolo et al., Proceedings of IMMXI, Brookhaven 1999

- After Spectrometer Operation:
  Re-assembly of the Carbon Fiber Arm measurement bench in a new hall

- Carbon Fiber Arm 2 m long
- Marble (High thermal inertia, 6000 kg)
- Optical Ruler
  (Heidenhain, accuracy $\pm 5 \mu m/m, C_t \approx 8 \cdot 10^{-6}/°C$)
- Magnetic Field Monitors (one NMR probe, two Hall Probes)

Measurement Setup II



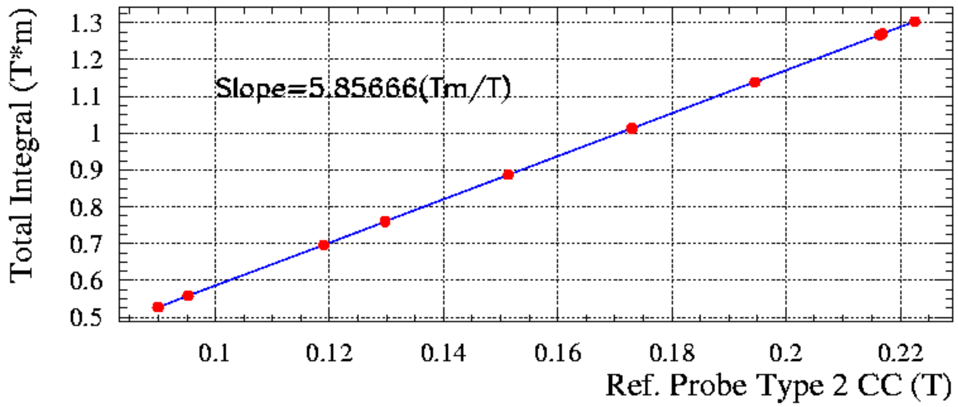
Previous Mapping Campaigns

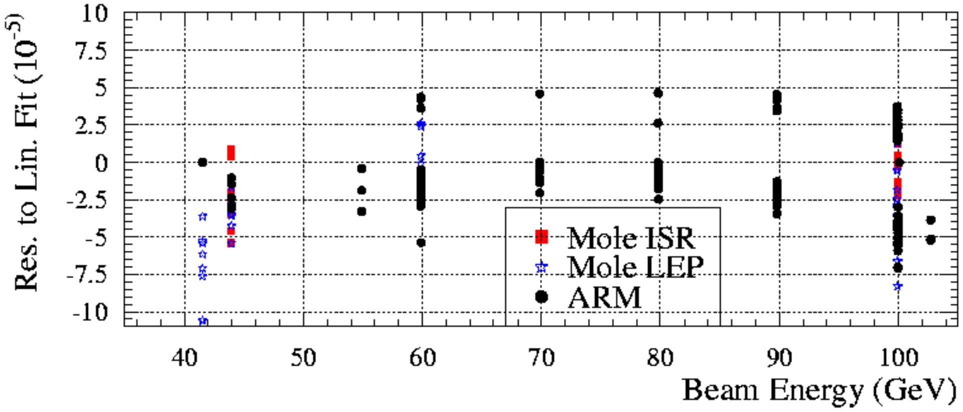
- Laboratory Measurements 1999 (Carbon-Fiber-Arm and Travelling Mole)
- LEP Tunnel Measurements 1999 (Travelling Mole)
- Final results within the requirements:

$$\frac{\int_L B \cdot dl - f(B_{ref})}{\int_L B \cdot dl} \approx 3 \cdot 10^{-5}$$

- Calibration for the 1999-2000 LEP runs

$$B_{ref} \implies \int_L B \cdot dl$$





System Upgrades

The Hall Probes have been replaced by the sensors Siemens KSY 44

- Metal Organic Vapor Phase Epitaxy Hall sensor
- Built in an extremely flat plastic package (SOH)
- Integrated chip $0.35 \times 0.35\,mm$

Absolute Maximum Ratings

Parameter	Symbol	Limit Values	Unit
Operating temperature	T_A	– 40…+ 175	°C
Storage temperature	T_{stg}	– 50…+ 180	°C
Supply current	I_1	10	mA
Thermal conductivity	G_{thA}	≥ 1.5	mW/K
soldered, in air	G_{thC}	≥ 2.2	mW/K

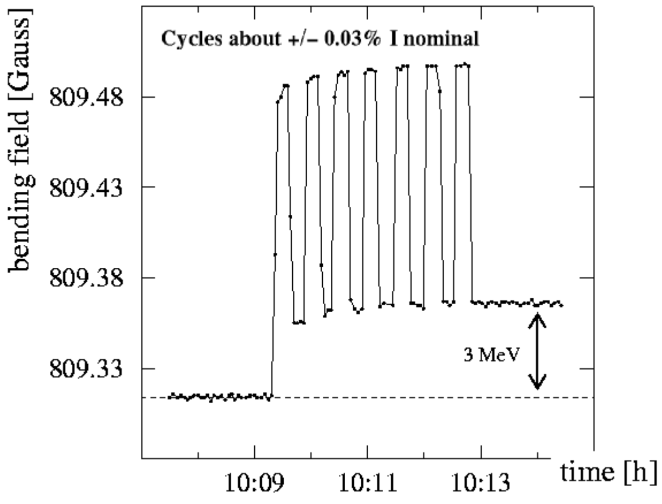
Electrical Characteristics (T_A = 25 °C)

Nominal supply current	I_{1N}	7	mA
Open-circuit sensitivity	K_{B0}	150…265	V/AT
Open-circuit Hall voltage $I_1 = I_{1N}$, $B = 0.1$ T	V_{20}	105…185	mV
Ohmic offset voltage $I_1 = I_{1N}$, $B = 0$ T	V_{R0}	≤ ± 15	mV
Linearity of Hall voltage	F_L		
$B = 0…0.5$ T		≤ ± 0.2	%
$B = 0…1.0$ T		≤ ± 0.7	%
Input resistance $B = 0$ T	R_{10}	600…900	Ω
Output resistance $B = 0$ T	R_{20}	1000…1500	Ω
Temperature coefficient of the open-circuit Hall voltage $I_1 = I_{1N}$, $B = 0.1$ T	TC_{V20}	~ – 0.03	%/K
Temperature coefficient of the internal resistance, $B = 0$ T	$TC_{R10,\,R20}$	~ + 0.3	%/K
Temperature coefficient of ohmic offset voltage, $I_1 = I_{1N}$, $B = 0$ T	TC_{VR0}	~ 0.3	%/K
Inductive zero component, I_{1N} =0	A_2 [1]	0.16	cm^2
Switch-on drift of the ohmic offset	dV_0 [2]	≤ 0.3	mV
voltage $I_1 = I_{1N}$, $B = 0$ T	ΔV_0 [3]	≤ 0.1	mV
Noise figure	F	~ 10	dB

Measurement Procedures & Strategies

Procedures

- Same schema as in the past, including:
  - Degaussing Cycles
  - Ramp
  - Bending Modulation



Bending Modulation

Strategies

- Scans at different excitation currents in order to check the linearity of $\int_L B \cdot dl$ with respect to the local field measured with the reference NMRs

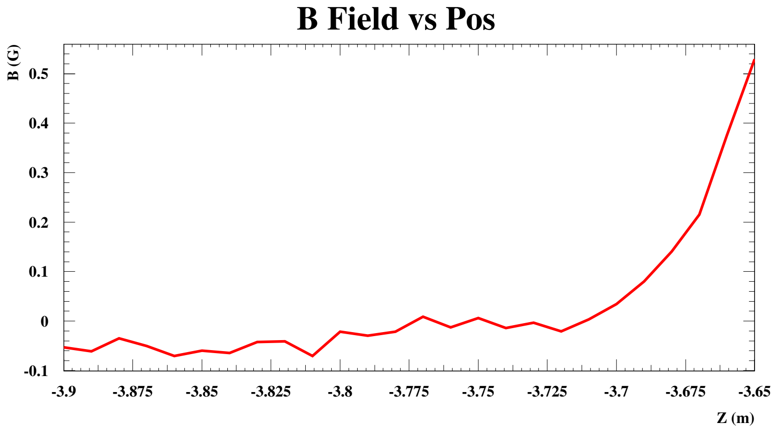
- Series of maps at two energy levels with ramp in between, in order to reproduce the Spectrometer operation

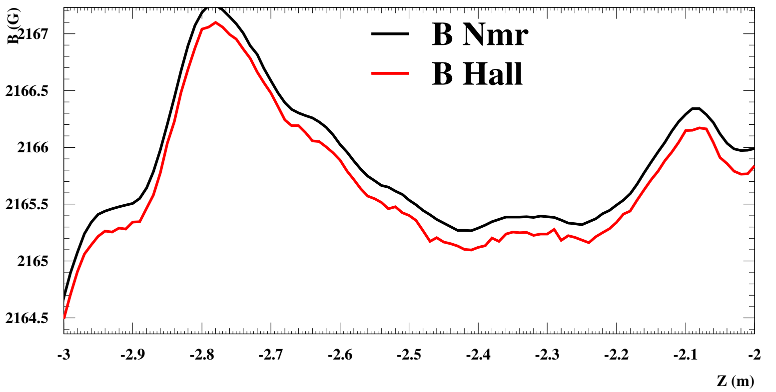
Hall Probes Calibration I

- Off-line Calibration has been performed by mean of the NMR probes
  → Polynomial approximation of the transfer function

$$\boxed{V_{hall}\,[V] \longrightarrow B_{hall}\,[T]}$$

- Hall sensors drift in offset and gain



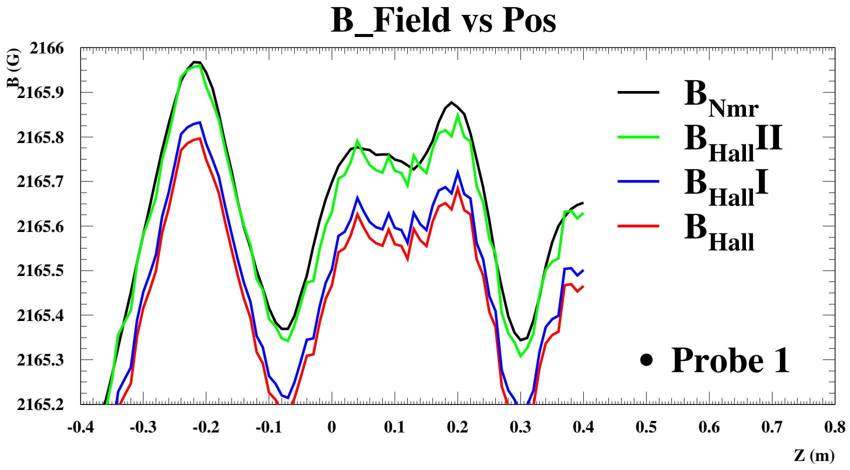


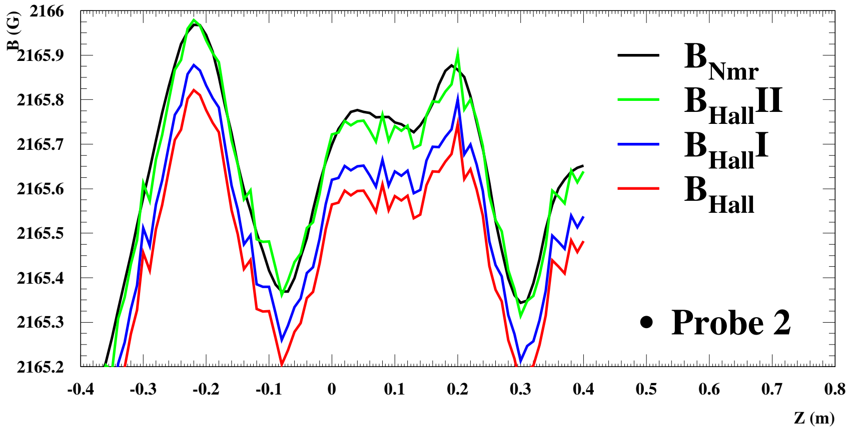
Hall Probes Calibration II

On-Line Calibration

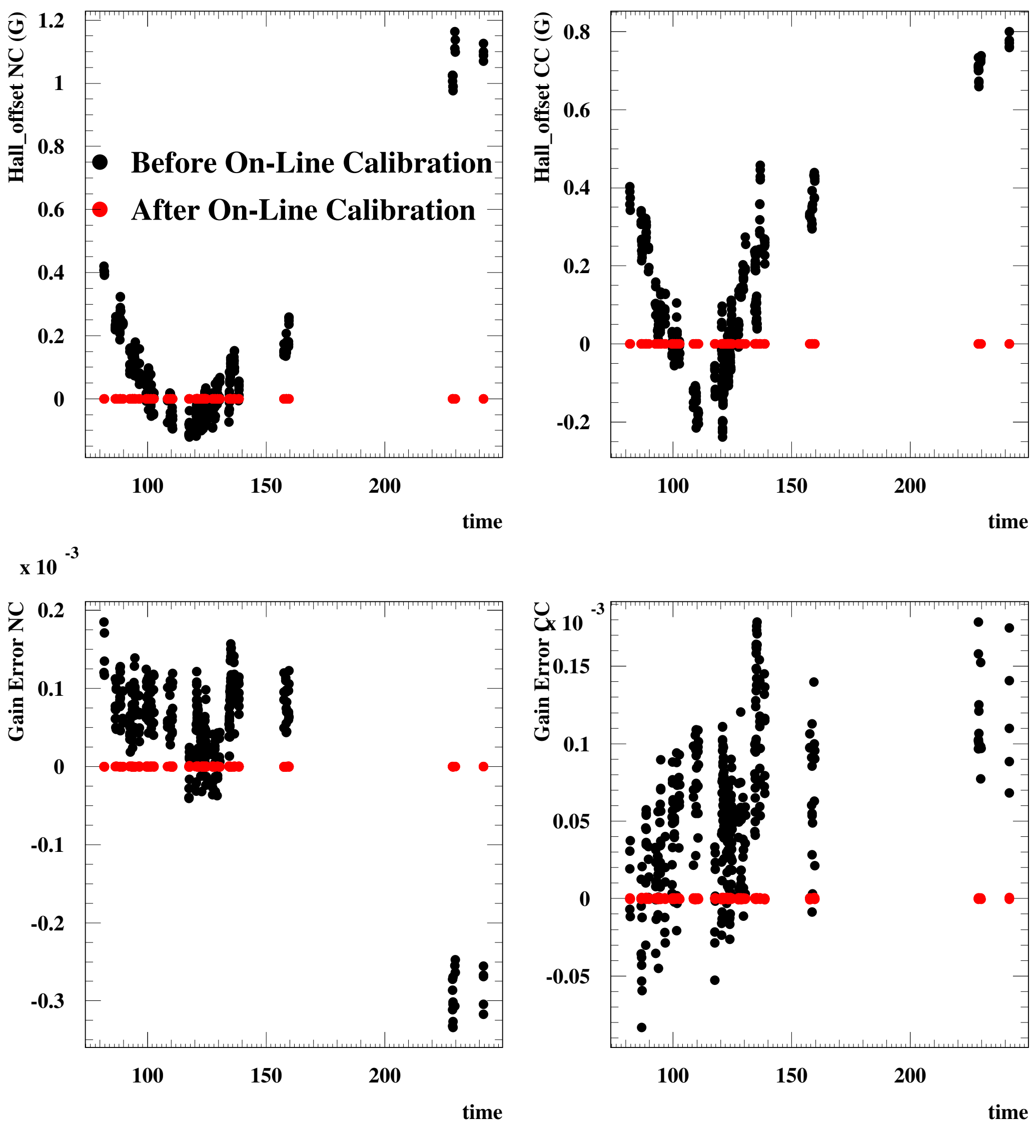
Correction for the Hall Probes Offset and Gain by mean of the known "zero field" in the μ-metal region and "Core Field" read by the NMR Probe.

$$
\begin{aligned}
B_{hall} &= B_{offs} + g \cdot B_{nmr} \\
B^{I}_{hall} &= B_{hall} - B_{offs} \\
B^{II}_{hall} &= \frac{B_{hall} - B_{offs}}{g} \quad (\Leftarrow \; B_{nmr})
\end{aligned}
$$





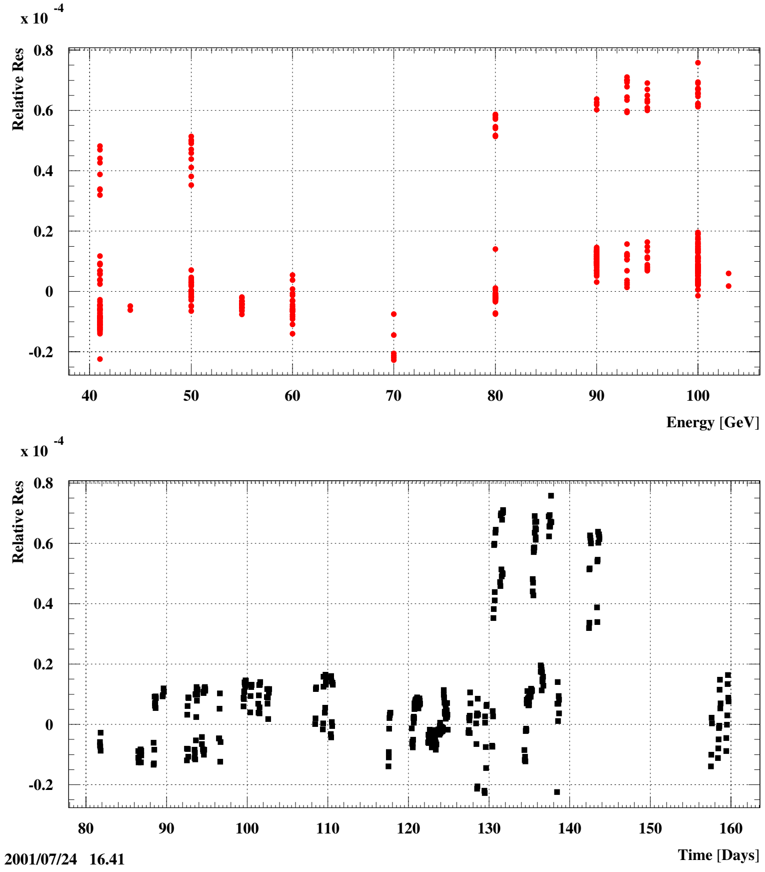
Hall Probes Calibration III



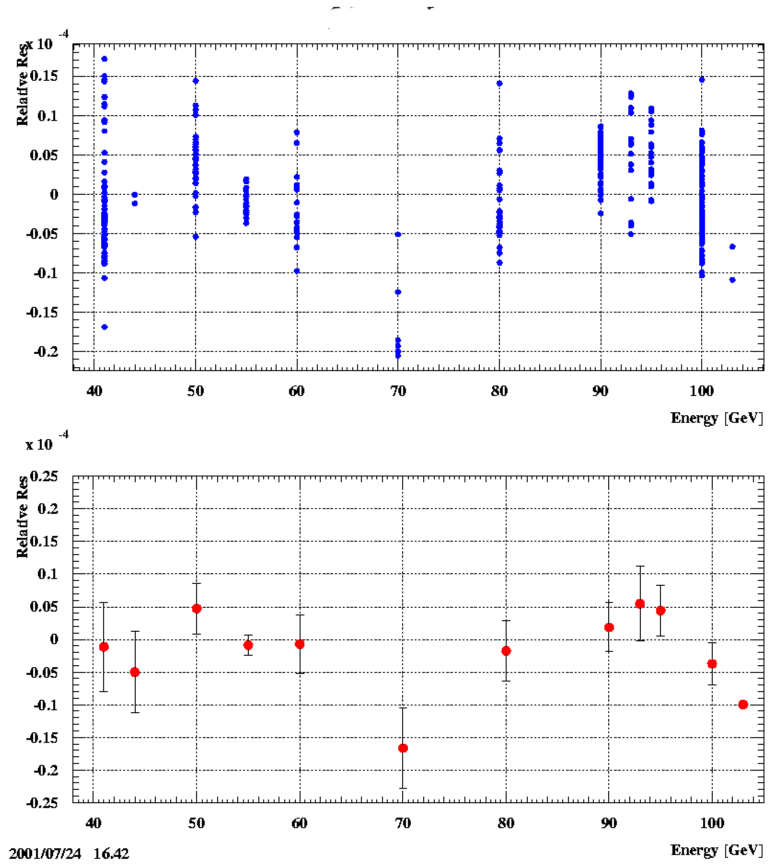
$$Hall_{Offset} = \langle B_{Hall} \rangle_{\mu metal}$$

$$Gain_{Error} = 1 - \frac{B_{Hall}}{B_{Nmr}}$$

Reproducibility of the Re-Mapping Measurements

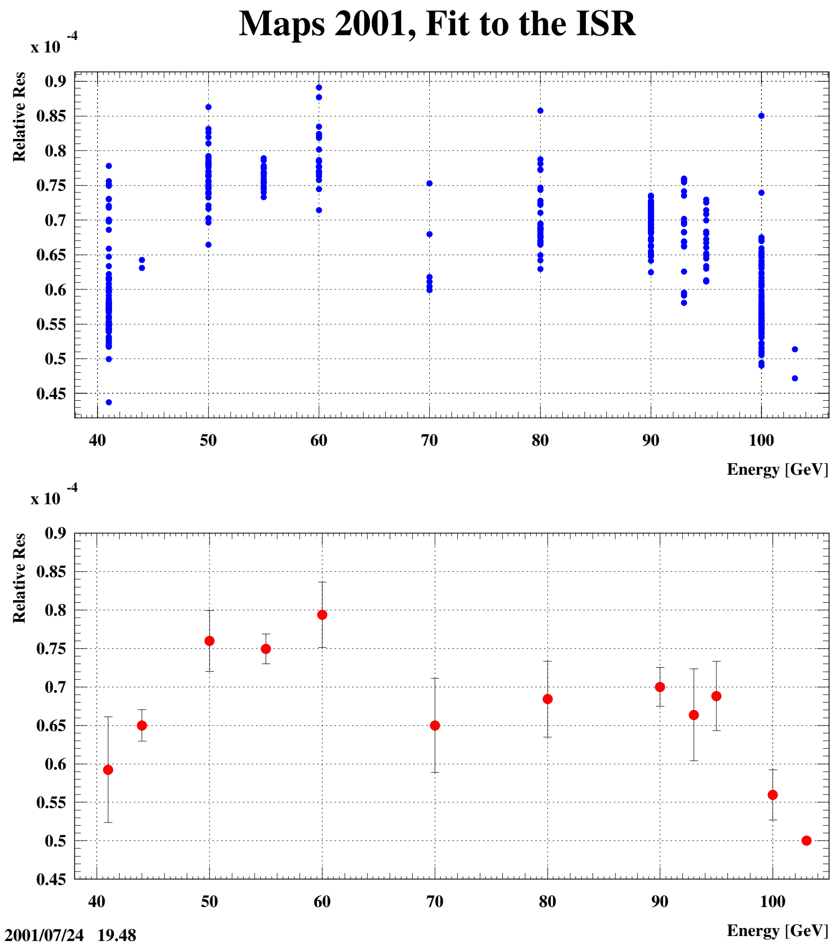


All maps, relative residuals to linear fit (local vs integral field)
as function of Beam Energy and Time



Residuals after Temperature Correction

Mapping/Re-mapping Comparison



- Residuals of linear fit using the first mapping campaign calibration:

$$\int_L B \cdot dl|_{predicted} \;=\; f(B_{local}) = a \cdot B_{local} + b$$

a, b from mapping campaign
(carbon-fiber-arm + Mole)

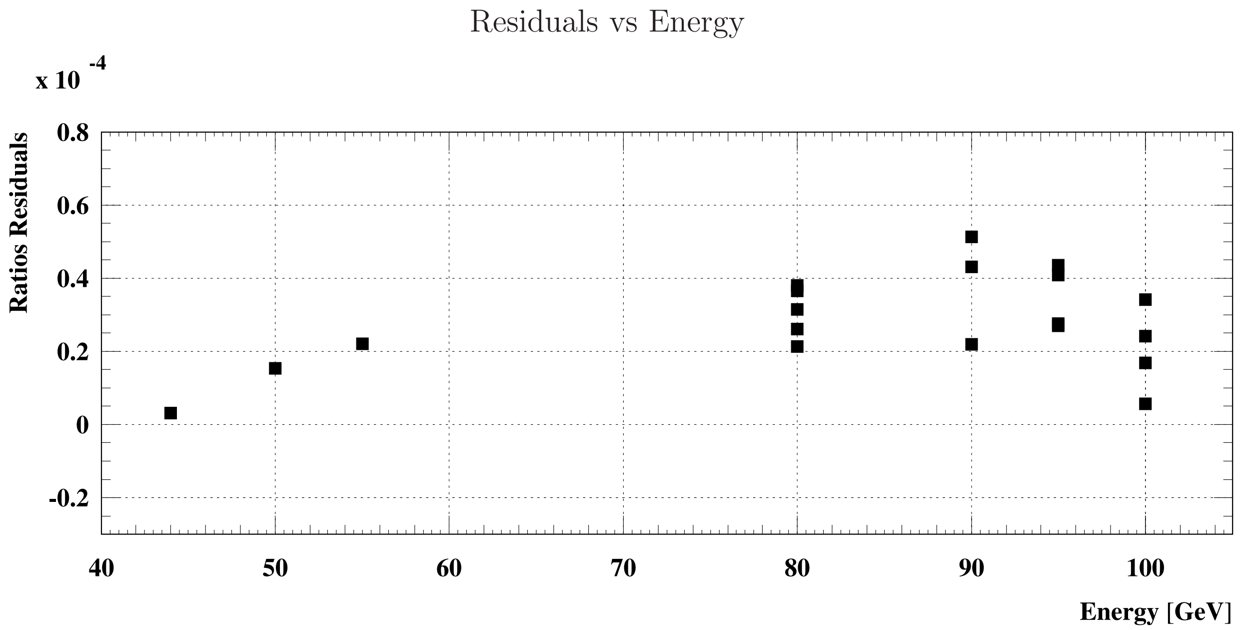
$$Residual \;=\; \frac{\int_L B \cdot dl|_{re-mapping} - \int_L B \cdot dl|_{predicted}}{\int_L B \cdot dl}$$

- Energy Dependence

- Mean Relative Residual $\boxed{\approx 7 \cdot 10^{-5}}$

→ Total $\int_L B \cdot dl$ variation between the two mapping campaigns

Ratios

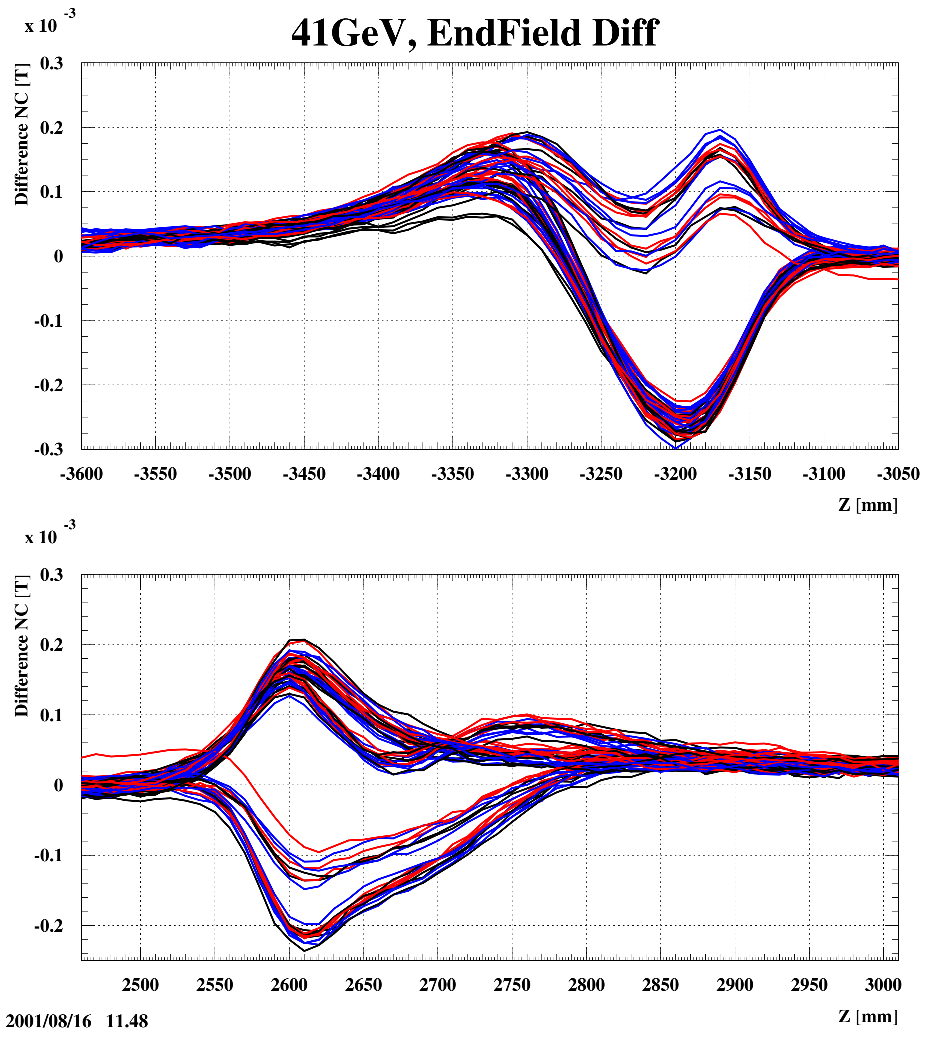


$$Residuals = \frac{\int_L B \cdot dl|^{E_2}}{\int_L B \cdot dl|^{E_1}} - \frac{\int_L B \cdot dl|^{E_2}_{predicted}}{\int_L B \cdot dl|^{E_1}_{predicted}}$$

- Prediction always done using the first mapping calibration
- $E_1 = 41.6\,\mathrm{GeV}$
- $E_2 = 50,\ 55,\ 80,\ 90,\ 95,\ 100\,\mathrm{GeV}$
- Energy Dependence of total $\int_L B \cdot dl$ residuals

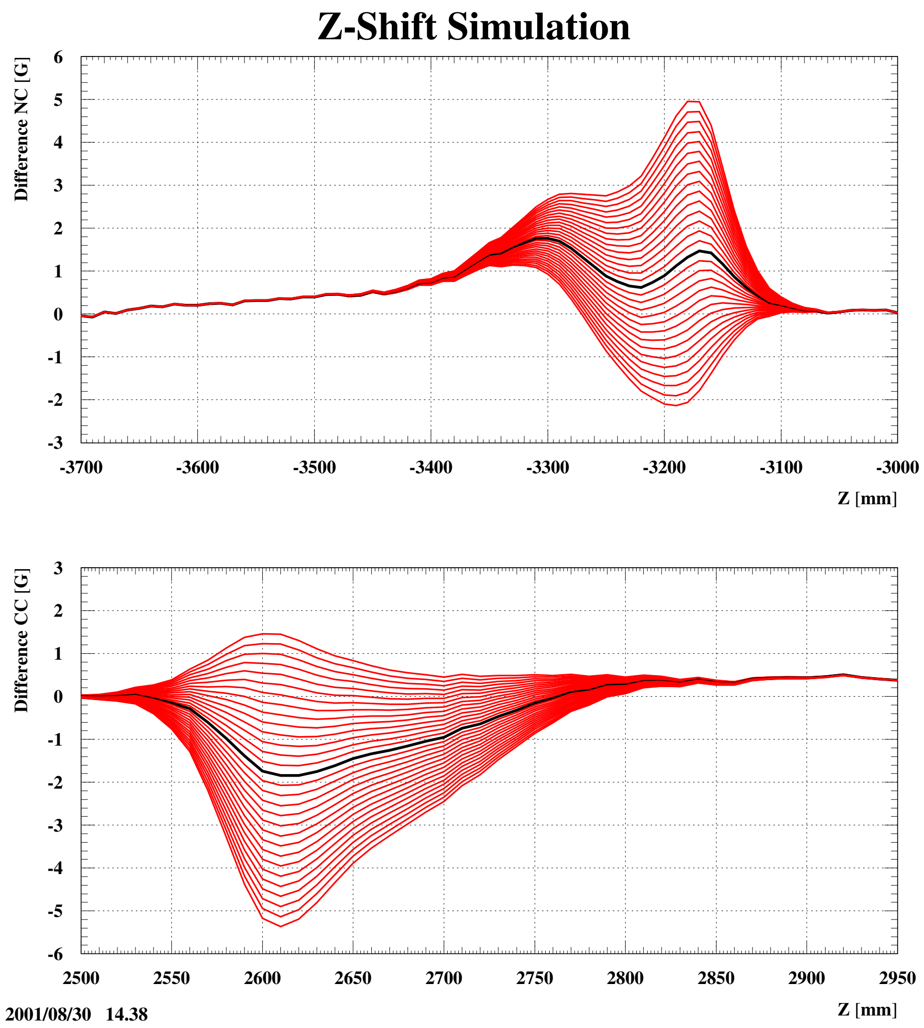
$\boxed{\Longrightarrow \text{Ratio Residuals} \neq 0}$

End Field Investigations I



- Differences between local field values (Mapping-ReMapping)
- Zoom in the two end-field regions with maximum gradient
- Integral of such differences corresponds to $\approx 7 \cdot 10^{-5}$ relative to the total $\int_L B \cdot dl$
- Field differences change shape in time
- Differences variations of the two endfields regions are correlated

End Field Investigations II



- Simulation to look for possible causes of local field differences
- Assumption of wrong correlation Field-Position
- Scan between $\pm .5\,mm$
- Possible causes of error:
  - Misalignment Marble-Magnet
  - Misalignment Marble-Ruler
  - Ruler Non-linearities
- Measured differences fit inside simulations

Conclusions

- The integral field of the Spectrometer Dipole Magnet has been measured before its installation in the LEP tunnel in order to produce a calibration local field $\rightarrow$ integral field
- A Re-mapping Campaign was necessary to check field variation during the Spectrometer operation
- The measurement system (equipped with new Hall Probes) shows a reproducibility of $\approx 2 \cdot 10^{-5}$ (relative) when collecting all the results of the re-mapping
- The total $\int_L B \cdot dl$ changed of a factor $7 \cdot 10^{-5}$ (relative)
- Ratios between the total integrals at high and low energies changed of a factor $3 \cdot 10^{-5}$ (relative)
- Possible causes for this changes are under investigation