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A Study of the Magnetic Dipole Field of LEP during the 1995 Energy Scan

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Abstract

In preparation for the 1995 LEP energy scan additional instrumentation was installed in two tunnel dipoles to monitor the time evolution of the magnetic field during experimental fills. Significant increases of the bending field superimposed by day-time dependent fluctuations on a minute time scale were revealed. These unexpected features could be correlated with earth currents captured by the LEP vacuum chamber and the ground cable. The currents are produced in particular by trains circulating in the Geneva area. This study presents a summary of our understanding of the LEP dipole field.

Geneva, Switzerland
August 1996

Contents

1 Introduction

After the 1993 energy scan [1, 2] some observed features of the LEP dipole field remained unexplained:

- There were indications for 2 sudden energy jumps in a long term energy calibration experiment [2] performed on August 29th 1993. These jumps could not be explained by the current LEP energy model.
- The analysis of the 1993 data from the **N**uclear **M**agnetic **R**esonance (NMR) probe in the reference magnet showed unexpected jumps corresponding to +5 MeV between two consecutive readings. Such jumps were observed in 5 to 10 % of all physics fills. In one case a jump could be confirmed to 50 % of the level change by a coincident beam energy measurement. It could not be clarified if all jumps corresponded to real field variations.
- Besides sudden jumps, the NMR showed field drifts during fills. These drifts could reach a few MeV after 12 hours. There was some evidence that these slow drifts were related to true field changes since in a further long term calibration experiment on 11th October 1993 a 2.5 MeV discrepancy between the measured and the extrapolated beam energy could be observed [2] if the NMR measurements were not taken into account.

Motivated by this lack of understanding the studies were pursued in 1995 with an improved monitoring of the B-field on the tunnel dipole magnets directly.

2 Magnetic Field Measurements

2.1 Instruments to Measure the Magnetic Field

In 1995 the magnetic field was measured simultaneously by 4 NMR probes and one rotating coil. Figure 1 shows the position of these probes around LEP.

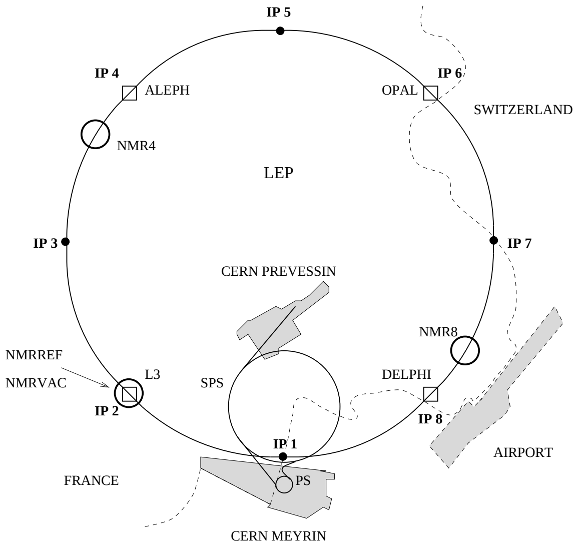

Figure 1: The LEP ring with the positions of the four NMR probes and the four experiments. NMROCT4 and NMROCT8 are mounted in two tunnel bending magnets. NMRREF and NMRVAC are installed in the reference magnet, which is located in a surface building and connected in series with the tunnel dipoles.

The rotating coil [3] and two NMR probes, called NMRREF and NMRVAC, are installed in the reference magnet. The magnetic field is measured simultaneously by rotating the coil within the magnet and varying the resonance conditions of the NMRs. The reference magnet is located in a temperature regulated ($\pm 1^o C$) room on the surface close to the power converters and is connected in series with the tunnel dipoles. The two other NMR probes are installed in dipole magnets (M418 and M818) close to IP4 and to IP8 in the tunnel. These two probes will later be referred to as NMROCT4 and NMROCT8 respectively. The rotating coil is in use since 1989 and NMRREF since the beginning of 1991. NMRVAC was installed in 1994 and the two NMRs in the tunnel dipole magnets in 1995. A detailed description of the functionality of the NMR probes can be found in [4]. Furthermore in each LEP octant a fluxloop [3, 5] is available for measurements of the magnetic field time derivative $\Delta B/\Delta t$. One fluxloop consists of induction wires connecting every dipole magnet in an octant. The wire is twisted between the dipoles. The total flux induced is integrated over a certain time period by the readout device and translated into a field change per time interval under the assumption of a constant cross section.

2.2 Installation of the Gauss-Meters

- **Installation in the reference magnet:**

The reference magnet has a C shaped yoke made of laminated iron. 1.5 mm thick iron plates alternate with 4 mm air gaps. Both reference magnet probes (NMRREF, NMRVAC) and the rotating coil are centred in the gap of the yoke. The NMRVAC probe is surrounded by a piece of the LEP vacuum chamber (Fig. 2, left). The probes in the reference magnet need a minimum field of 800 gauss for reliable operation. Since at 45 GeV the field in the magnets is only about 500 gauss, 2 field plates are installed around each NMR to increase the field. The B-field in the reduced gap is then roughly 860 gauss.

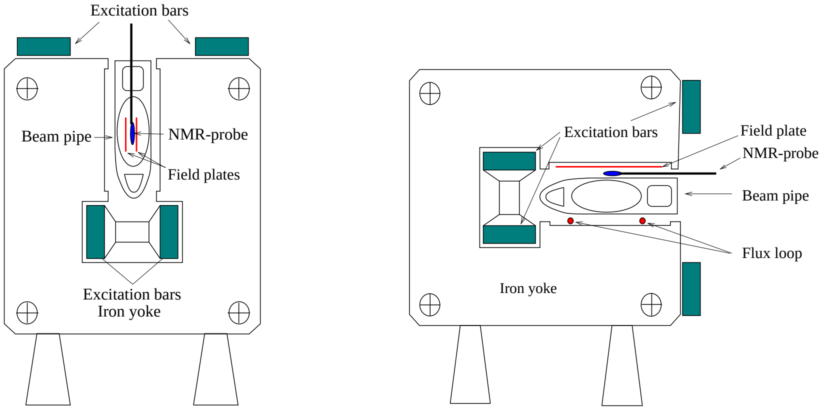

Figure 2: NMR location in the bending magnets. Left: Transverse section of the reference magnet with the probe inside the vacuum chamber and the field plates. Right: tunnel bending magnet with the NMR probe installed in the slit between the field plate and the vacuum chamber wall.

- **Installation in the tunnel magnets:**

The tunnel dipole magnets have the same plates and spacing as the reference one but the air gaps are filled with mortar [6]. The probes in the tunnel magnets are installed in a slit between the pole face of the magnet and the vacuum chamber wall (Fig. 2, right). At this off-centre position the field homogeneity is affected by the laminated structure of the yoke. To ensure the field homogeneity required for the operation of the NMRs, an iron plate (170 x 200 x 1.5 mm) had to be glued on the pole face. This plate increases the field by about 1.5 %. Since the type of NMR probe installed in the tunnel dipoles needs a minimum field of 400 gauss for reliable operation, no further gap reduction is necessary. The induction wires of the fluxloop are installed on the lower pole face.

3 Data Acquisition

3.1 The 1995 LEP Run

The 1995 LEP run was devoted to a three point energy scan around the Z resonance at Peak-2, Peak and Peak+2 energy settings (see Table 1). The total operation period of the '95 energy scan[1] consists of 72 fills. The accurate calibration of the LEP beam energy at "P-2" and "P+2" energy settings is provided by the resonant depolarization technique [7]. In total, 28 fills are calibrated, including 4 fills with a calibration at the beginning (BOF) and at the end (EOF) of the fill: 3022 (P+2), 3029 (P+2), 3030 (P-2), 3036 (P+2). In addition 2 MDs[2] are performed in fill 2929 (P-2) and 3064 (P+2) with frequent energy calibrations. From fill 2948 onwards a modulation of the bending magnets is performed at the beginning of every fill (in total 32) except for 2951, 2952, 3013 and 3016. A few fills include a bending modulation before as well as after the declaration of physics conditions.

LEP Setting	Beam Energy (GeV)	# of calibr. fills (total of fills)	$\int \mathcal{L}$
Peak-2 ("P-2")	44.72	14 (26)	$\approx 10\ pb^{-1}$
Peak ("P")	45.59	1 (18)	$\approx 18\ pb^{-1}$
Peak+2 ("P+2")	46.51	13 (28)	$\approx 10\ pb^{-1}$

Table 1: Definition of the three LEP settings, the corresponding approximate beam energies, the number of calibrated fills and the delivered integrated luminosities.

3.2 Data Logging

The NMR probes provide measurements of the absolute B-field with a high precision of $\Delta B/B = 0.5 \cdot 10^{-5}$ [8]. Data from these probes are available for every fill from the 1995 scan period with a few exceptions. This note presents an analysis

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[1] later referred to as "scan period" 1995

[2] **M**achine **D**evelopment sessions

based on data obtained from a dedicated readout system of the NMR probes. During the scan period two independent systems are used. In one system, later referred to as "Snapshot Database"[3], data is taken every 7.5 minutes in form of a snapshot of the NMR readings. The other readout is realized with a sampling rate of 2 to 30 seconds. In the following discussion data based on the readout system with the fast sampling, compressed to one mean value in a 15 minutes time interval and an error estimated from the RMS scatter, are used. This procedure, later referred to as "Smooth Database", leads to a smoothed representation of the magnetic field evolution during a fill. Table 2 compares both samples. The scatter of the difference between two consecutive measurements for the two reference magnet probes is very small in both data samples ($<$ 0.3 MeV). The scatter from the probes in the tunnel magnets M418 and M818 is a factor of about 3 up to 5 larger with respect to the reference magnet probe (NMRREF) for both samples. The "Smooth Database" reduces the scatter by 30 % (NMRREF), 50 % (NMRVAC) and 40 % in the two tunnel probes. Gaps in this data sample are completed with data from the "Snapshot Database" if they were available. From fill 2901 to 2929 no NMROCT8 data were logged in neither system due to a hardware problem with the probe.

	Snapshot Database RMS [MeV]	**Smooth Database** RMS [MeV]	reduction
NMRREF	0.29	0.19	1.5
NMRVAC	0.27	0.13	2.1
NMROCT4	1.01	0.63	1.6
NMROCT8	1.41	0.91	1.5

Table 2: Scatter of two consecutive measurements from the four probes, evaluated from the data of the two databases.

NMR probe	conversion factor [MeV/G]
NMRREF	54.712 ± 0.007
NMRVAC	52.777 ± 0.004
NMROCT4	91.295 ± 0.010
NMROCT8	91.311 ± 0.005

Table 3: Conversion factors between the magnetic field in gauss and the equivalent beam energy in MeV for all NMR probes.

The absolute level of the measurements at the location of the probes increases due to the plates which are plugged in to ensure field homogeneity. Therefore a calibration of the instruments and a set of conversion factors to derive the beam energy equivalent in MeV from the magnetic field measurements are needed. The

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[3] i.e. the so called "LEP Logging Database"

normalization of the NMR readings nearest to the first beam energy measurement in the set of fills with BOF calibration and the two MD fills (in total 6 fills) is used to derive the different conversion factors. Table 3 summarizes the results. The quoted errors correspond to the RMS scatter of the different normalization factors in the 6 fills. The results from Table 3 are used in the data analysis presented in this note.

4 The Evolution of the LEP Dipole Field

This chapter summarizes the behaviour of the different NMR probes. The measurements from the four NMRs show a distinct time dependence. Examples are given in figures 3 and 5. In contradiction to the behaviour of the two tunnel NMR probes the two NMRs in the reference magnet do not display significant variations of the B-field with time.

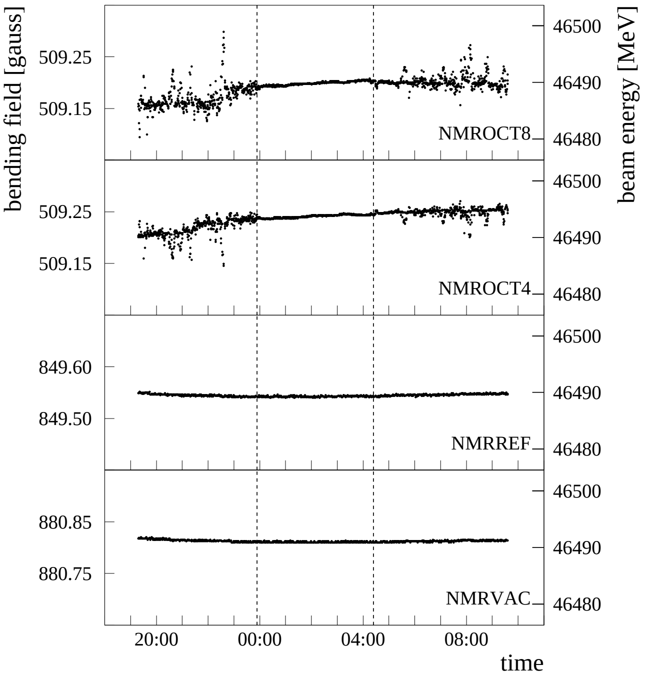

Figure 3: Bending field in gauss of all NMR probes in fill 2969 (P+2). The dotted lines denote the beginning and the end of a quiet period between 23h55 and 04h25. Apart from this time both NMRs in the tunnel show fast field fluctuations with time of the order of a few minutes. Both NMRs in the reference magnet record no time dependence.

4.1 Day-Night Effect

The two tunnel NMR show fast fluctuations between 4h30 and 24h00 (see Fig. 3). In the remaining time period they behave almost as the reference magnet probes. This period starts every day around midnight and ends between 4h00 and 5h00 in the morning. This pattern is observed with an uncertainty of ± 30 minutes in all fills which covered this particular time period and could be confirmed with flux-loop measurements (see [4] for more details). The NMR probes installed in the reference magnet do not show any fluctuation.

4.2 Short Term Behaviour (The Anti-Correlation)

While the period between midnight and 4h00 records only slow B-drifts, sudden variations up to 10 MeV equivalent beam energy are recorded outside this period of time. The duration of the fast field fluctuations is of the order of a few minutes (Δt $\leq$ 5 minutes) and the largest slope is measured to be roughly 0.3 MeV/seconds. As shown in figure 4 the difference between two consecutive measurements (ΔB) measured in the two tunnel magnets is strongly anti-correlated with a slope of -1.7. Hence the amplitude $\mathcal{A}$ of the perturbation at the two locations, where it is measured, is related with a scaling factor:

$$\mathcal{A}_{NMROCT8} \simeq -1.7\,\mathcal{A}_{NMROCT4} \tag{1}$$

The short term anti-correlated perturbation consists of field fluctuations with low frequency components of less than 1 Hz. This anti-correlation is confirmed with flux-loop measurements. See [4] for more details.

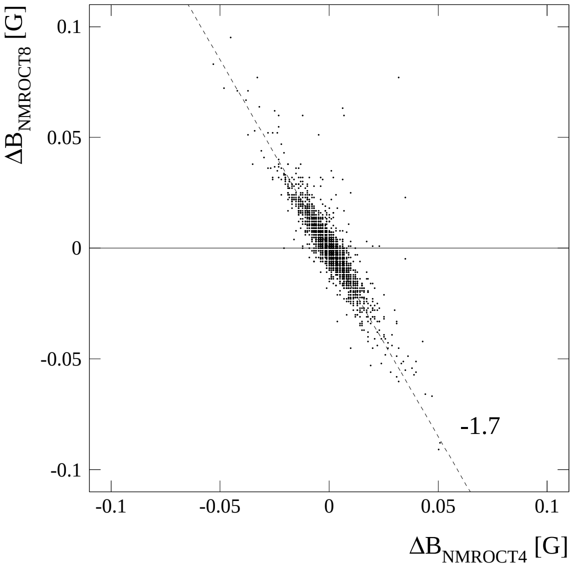

Figure 4: Correlation of the difference ΔB of two consecutive readings for NMROCT4 and NMROCT8. The slope is -1.7.

4.3 Long Term Behaviour

A typical field time dependence for a long LEP fill is shown in Figure 5. On a time scale Δt > 1 h both NMR probes in the tunnel measure a long term rise of the magnetic field regardless of the superimposed anti-correlated perturbation. This pattern can be observed in many fills. This 15 hour long fill shows a total increase of the B field corresponding to 12 MeV equivalent beam energy with a tendency to saturation towards the end. This increase is not monotonic but shows variations of the slope and steps of various sizes. The jumps occur after a strong fluctuation of the B field. Figure 6 shows one example for a successful verification of the magnetic field measurements in the tunnel with BOF and EOF energy calibration data. In this fill BOF and EOF calibrations with the resonant depolarization method were performed to confirm the field rises measured by the tunnel NMR probes. While NMRREF and NMRVAC do not exhibit a considerable deviation from the start value, both tunnel NMRs rise during the fill. The rise is confirmed

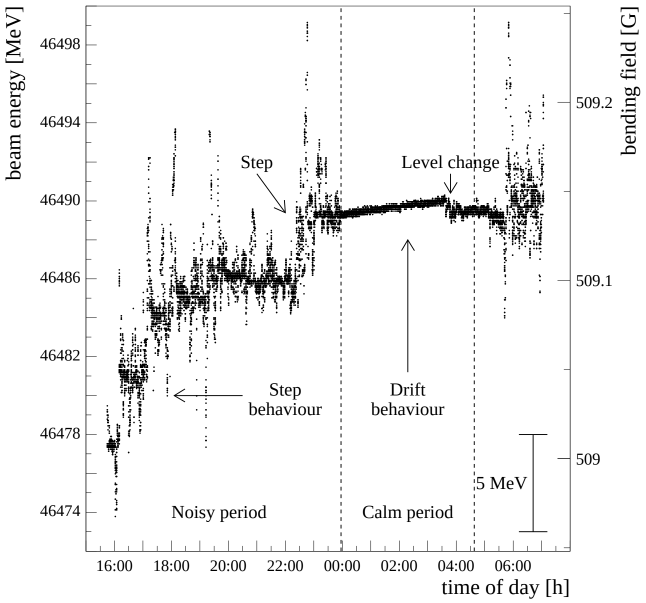

Figure 5: Magnetic field measured in the tunnel with a high sampling rate of 2 seconds at the location of NMROCT8 as a function of the time of the fill. The field increase in this fill is not continuous in time but with variations of the slope and steps of various sizes. Usually the jumps occur after a strong fluctuation of the B field.

by the energy calibration data E_{pol}, although in this experiment, which is one of the six performed in 1995, the calibration data somewhat exceed the field measurements. All such experiments verify that on a long term time scale the magnetic bending field is rising, but the ratio of the energy calibration data and the rise measured by NMROCT4 on one hand and NMROCT8 on the other hand differs from case to case. These differences are still under study.

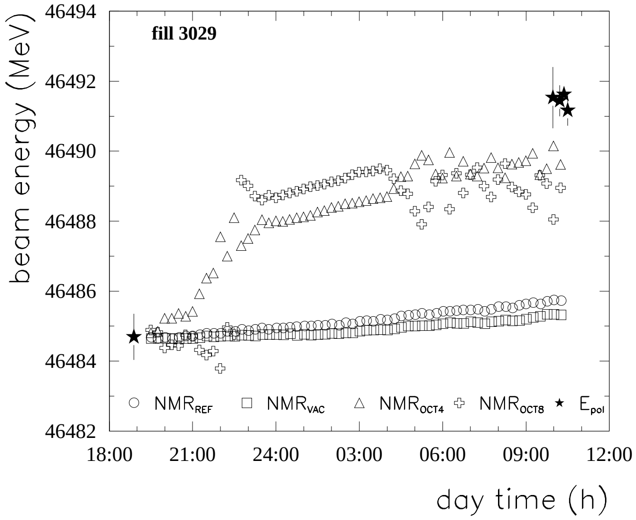

Figure 6: The beam energy, measured by the resonant depolarization method and the dipole field, measured by the four NMR probes, as a function of time. The NMR data, converted into units of beam energy, are from the “Smooth Database” and normalized to the first energy calibration measurement. Between 22h00 and 23h00 a jump in the B-field is recorded from NMROCT8 while the field in OCT 4 rises smoothly.

5 The Current of the Main Dipoles

The main bending magnets are series connected and powered by two power converters in a master/slave configuration installed in a surface building at IP2. The bus bar that carries the current of the dipole magnets consists of 2 loops connecting the windings of the magnets from IP2 to IP6 via IP4 and IP8 respectively

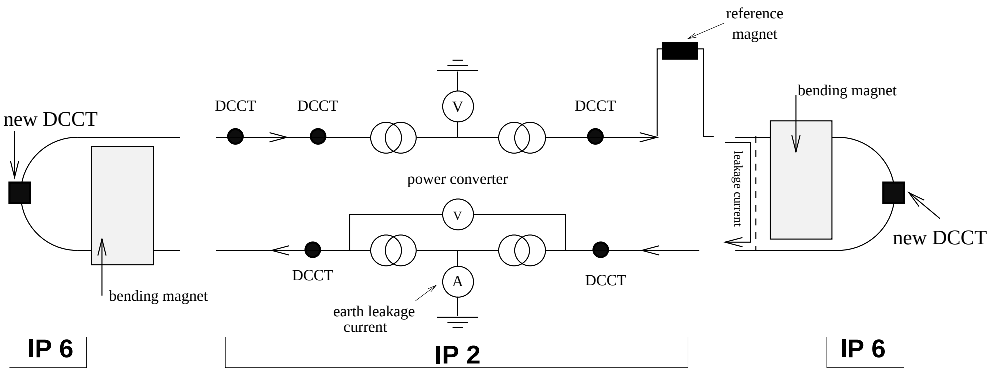

Figure 7: Schematic view of the dipole power converters with the bus bars carrying the current from IP2 to IP6 and back in two loops. All magnets are connected in series. Two new DCCTs were installed in IP6 for the 1995 scan period.

(see figure 7). The current is monitored by DCCTs[4] [9] with a resolution of $\Delta I/I \simeq 2 \cdot 10^{-5}$. Up to 1995 all DCCTs were installed around the power converters at IP2. It could not be excluded that some current is leaking between the bus bars from IP2 to IP6 and the return line, resulting in a lower current and therefore a lower B-field towards the extreme points of the loop. For that reason two new DCCTs with an improved resolution of $\Delta I/I = 10^{-6}$ were installed at the extreme points of the two loops in IP6. The observed relative fluctuations of the currents are between 10^{-5} and 10^{-6} for all fills. Figure 8 shows the readings from one the DCCT on the left side of IP6 in one particular fill (2899) and the corresponding measurements of NMROCT8. The variation of the current is about $2 \cdot 10^{-5}$ while the magnetic field increases during the same time by $3 \cdot 10^{-4}$. Fluctuations of the excitation current can thus not explain the variation of the dipole field inside a fill.

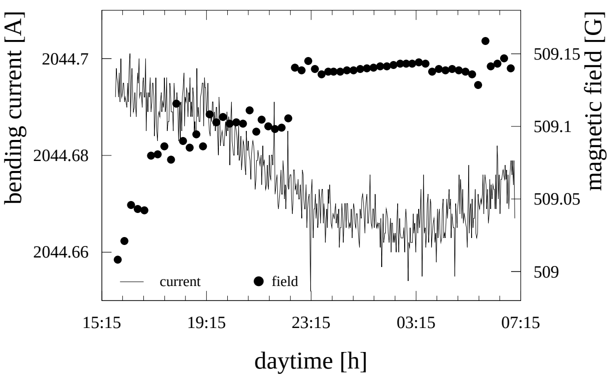

Figure 8: Data from the left DCCT at IP6 and from NMROCT8 for fill 2899. The variation of the current is $2 \cdot 10^{-5}$ while the magnetic field increases by one order of magnitude more $(3 \cdot 10^{-4})$.

A small time dependence on a fill to fill time-scale of the mean excitation current is observed. The mean current is decreasing by about $2 \cdot 10^{-5}$ between the beginning and the end of the scan period. This corresponds to a decrease of the beam energy by 1 MeV [4]. This observation is confirmed by a cross check with the recordings of the DCCTs around IP2. If any leakage current between both lines in one branch occur, a deviation from the nominal bending current and a difference

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[4] Direct Current Current Transformers

between the two points left and right from IP6, where the two half circles end, will be expected. Figure 9 shows the mean difference between the right and left DCCT as a function of the fill number. The average difference is measured to be constant. The evolution in figure 9 shows no time dependence. Furthermore no significant time dependence can be observed in the evolution of the earth leakage currents either. Hence variations of the main dipole excitation current can be excluded to be the origin of any of the observed magnetic field variation.

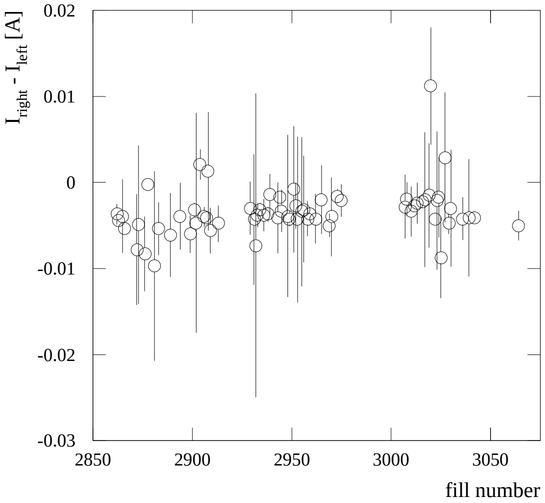

Figure 9: Distribution of the mean current differences measured with the newly installed high resolution DCCTs versus the fill number. Error bars correspond to the RMS scatter in the whole fill.

6 The "Train Effect"

Investigations to understand the behaviour of the NMRs installed in the LEP tunnel showed that a current of up to a few amperes was circulating on the vacuum chamber and on all parallel conductors in LEP as for instance the ground cable, which is installed along the vacuum chamber and connected to earth at the 8 IPs. The origin of these currents is in fact a known problem of DC railroads [10]. In principle, the current supplied by the power stations to the locomotive returns to the power stations over the railway tracks. In fact, a certain fraction of this current (up to 25 %) leaks into the ground and flows back to the generator along other "roads". The currents affecting LEP are mostly due the railway line between Geneva and Bellegarde which is powered with DC voltage (1500 V) while the swiss CFF[5] lines use 15000 V AC (Fig. 10, upper part). For the same electrical power the DC line requires 10 times higher currents. In our case, some of the return currents from trains passing on that railway line flow back to the generator via the good conductors installed in LEP: the ground cable, the vacuum chamber or the metallic struts in the concrete of the tunnel wall itself. A controlled experiment was performed during the LEP high energy run after the scan period to confirm the so called "train effect". Correlation measurements (Figure 10, lower part) of these currents between different parts of the ring showed that they enter or exit the LEP ring through the transfer lines from the SPS around IP1 and over a relatively large zone around IP6. The potential difference between rails and ground, the voltage on the vacuum chamber and and the magnetic field

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[5] Swiss railroad company: Chemin de Fer Fédéraux

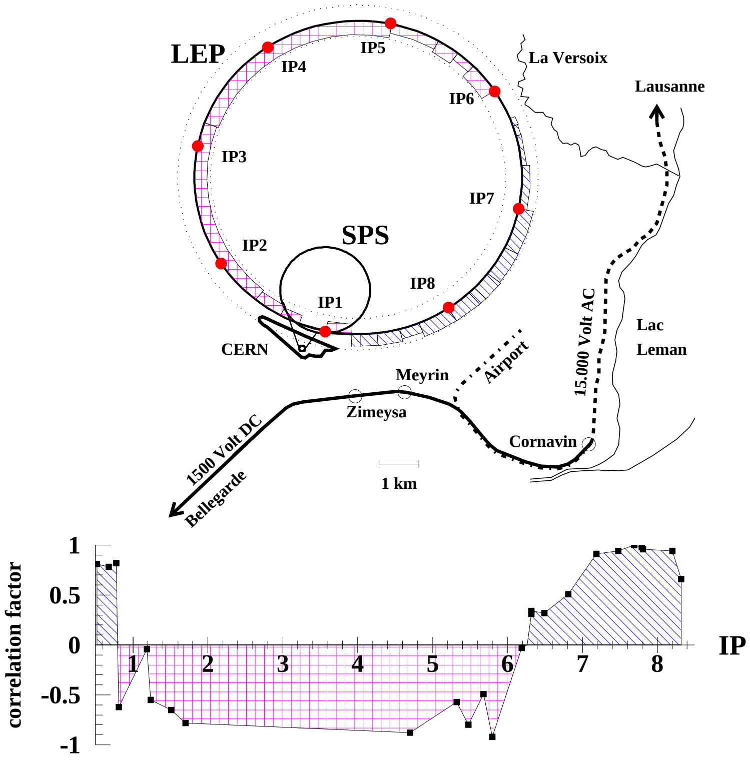

Figure 10: Schematic View of LEP with the 8 interaction points and the railroads in the Geneva area. Below the correlation factor of the "vagabond" currents with respect to the position of NMROCT8 as a function of the position along the ring. The correlation factor changes sign around the injection lines (i.e. close to IP1) and the interaction point IP6.

in the tunnel were measured simultaneously. A typical result over 15 minutes is shown in figure 11 during a "busy" afternoon at the time a "TGV" type train is passing. The correlation between the three distributions is evident. Thus the "train effect" explains several observed features of the magnetic field at the same time:

- **day-night effect**
  The observed quiet periods between 00h00 and 04h00 correspond to a time window where no trains circulate.
- **anti-correlation**
  The anti-correlation of the field fluctuations is due to the fact that the sign of the current is opposite in the two parts of LEP (relative to the direction of the main bending current). Since the currents enter/leave LEP in IP1 and around IP6 (Figure 10, upper part), they separate LEP into two parts with a length ratio of 5/3. These two parts behave like a parallel resistor system. This explains the amplitude ratio of $1.7 \simeq 5/3$ between the field fluctuations in NMROCT4 and NMROCT8.
- **long term behaviour**
  The current carried by the beam pipe changes the local magnetic attributes of the two dipoles M418 and M818 (and all other LEP dipoles) and is thus able to induce a change in the magnetic field of the bending magnets surrounding the vacuum chamber. The total rise in the field depends most likely on the frequency and amplitude of the current fluctuations although some features of the observed drift behaviour can not be explained by the train effect (chapter 9).

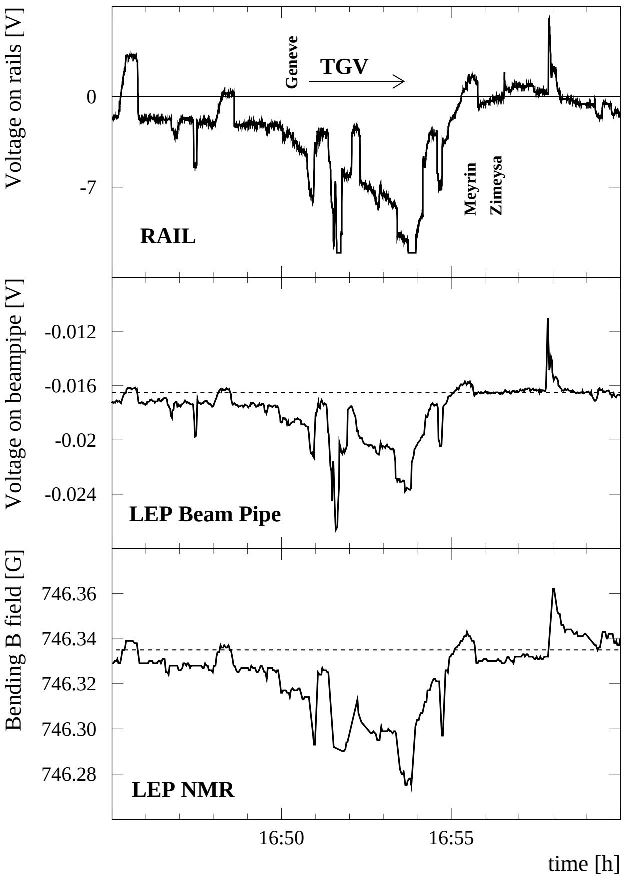

Figure 11: In a controlled experiment, the potential difference between the rails and a reference ground were measured simultaneously with the magnetic field in the tunnel and the voltage on the vacuum chamber for 15 minutes during a "busy" afternoon.

6.1 The Effect of the Leakage Current on the Bending Field

A current travelling on the vacuum chamber produces transverse B-field lines surrounding the beam pipe. The field lines traverse the iron yoke of the bending magnet because of its high permeability. The transverse field depends on the current density on the vacuum chamber. The **short term** fluctuation of the magnetic field is explained by a superposition of the transverse field produced by the leakage currents and the actual LEP dipole field. The **long term** behaviour can be modelled with nonlinear effects of the iron hysteresis. The transverse superimposed field shakes the magnetic domains of the bending magnets. After the excitation the domains realign themselves with a chance to achieve a lower potential energy than before what corresponds to a higher magnetic field. In terms of cycles in the (H,B) plane of the hysteresis loop [11], an increase of the current (i.e. $\Delta H > 0$) causes the magnet to increase its B-field. After the excitation a non zero $\Delta B = \Delta B_{final} - \Delta B_{inital}$ remains due to the nonlinearity of the hysteresis loop. A downward excitation of the current finally leads to an increased B-field as well. Repeating a large number of identical hysteresis cycles results in a vanishing magnetic field change ΔB per cycle. The saturation of the magnetic field rise with the number of excitation cycles is the approach to the understanding of the long term field rise.

The long term field rise is the most important consequence of the "train effect" on the beam energy. On the other hand, the anti-correlated short term fluctuations are not supposed to affect the average beam energy since the current integrated over the propagation length between IP1 and IP6 along both semi-circles balances.

7 Bending modulation

Studies [12] performed during the 1993 energy scan to understand the jumps and drifts of the field in the reference magnet showed that a series of current spikes applied to the magnet lead to an increase in the field which saturates after a few spikes. This behaviour suggested that it might be possible to stop or reduce the increase of the field in the dipoles if a few deliberate current spikes are applied at the beginning of each fill. Following some tests in the first part of the scan period this technique (called "bending modulation") was applied in all fills since fill 2948. It should be noted that, to avoid beam losses, the quadrupoles have to be modulated at the same time. The default parameters for the "bending modulation" technique are chosen such that the current of the main power supply of the dipoles is modulated by a square pulse train excitation with 7 pulses and an amplitude of 1.0 ampere per pulse corresponding to a relative change $\Delta B/B = 5 \cdot 10^{-4}$. The pulse length is 17 s. Figure 12 shows a bending modulation test. Every modulation pulse is clearly visible in form of a peak in the magnetic field. In this test experiment the pulse length was 30 seconds. The saturation effect after the second excitation pulse is clearly visible. The resulting increase in the magnetic field is about 0.055 gauss which corresponds to 3 MeV in beam energy.

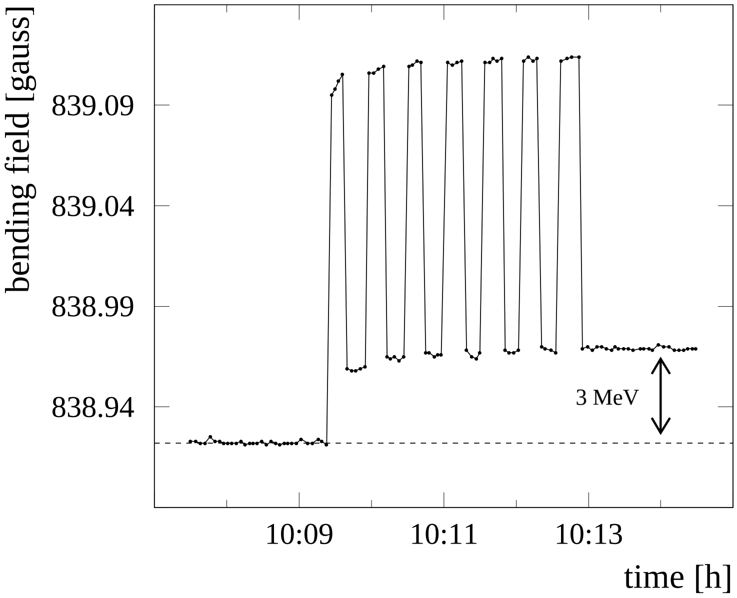

Figure 12: Magnetic field (NMRVAC) as a function of time during one dedicated "bending modulation" test.

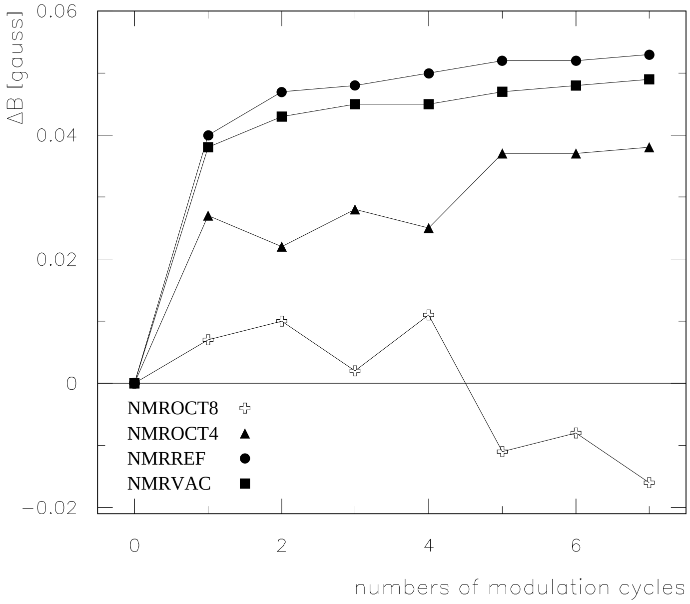

Figure 13: Increase of the magnetic field with respect to the first reading as a function of the number of the excitation pulse for all NMRs.

Figure 13 compares the effect of bending modulation as measured by all NMR probes during this particular test. The figure shows the increase of the magnetic field with respect to its start value as a function of the number of excitation pulses. The reference magnet exhibits a clear response after the first pulse, followed by a saturation of ΔB with more modulation cycles. The NMROCT4 probe records almost the same behaviour as the reference magnet probes but with a reduced change in the level of the magnetic field. In contrary to the other probes, NMROCT8 shows no field increase but a slight decrease with the number of excitation pulses. The bending modulation pulses seem to be compensated by another disturbing effect. Our present understanding of this behaviour is that a superimposed magnetic field change resulting from the currents carried by the vacuum chamber disturbs the modulation pulses. The different behaviour of NMROCT4 and NMROCT8 is most likely explained by the different amplitude of the perturbation (Equation 1) for both magnets.

7.1 Bending Modulation at BOF and EOF

To verify the saturation of the field after the bending modulation at the beginning of a fill, the bending modulation was repeated at the end of 6 particular fills[6]. As expected, the level change in the magnetic field due to bending modulation at the end of a fill was much smaller than the change at the beginning of the fill (see Table 4). In particular a reduction by a factor of 3 to 4 in the average jump level for NMRREF and for NMRVAC was measured. Both tunnel magnets demonstrate a slightly weaker reaction to the BOF bending modulation. The change due to magnet conditioning at BOF, compared with the mean change at

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[6] 2948, 2965, 2970, 2973, 2975, 3012

EOF, is reduced by a factor of 4 at NMROCT4 and a factor of 9 at NMROCT8. Taking the statistical significance into account, no important difference remains between the four NMR probes. On the other hand, both tunnel probes record a somewhat larger scatter of the average bending field variation due to magnet conditioning at BOF with respect to the NMRREF probe: a factor of 2 for NMROCT4 and a factor of 4 for NMROCT8. For the bending modulation at EOF the scatter is roughly the same for all probes. According to our present understanding the weak reaction to the magnet conditioning at BOF and the larger scatter are due to the frequent perturbation of the tunnel magnets caused by the current flow on the beam pipe resulting from the train effect. The difference between the probes vanishes at the end of the fills. Since the reference magnet is not affected by the trains, saturation effects and thus a reduction of the jump level at the end of a fill are caused by the intentional modulations at the beginning of a fill only. This demonstrates that the bending modulation at the beginning of the fills reduces the sensitivity of the magnets to current spikes by a factor of 3 to 4.

	BOF			**EOF**			
	N_{mod}	mean [MeV]	RMS [MeV]	N_{mod}	mean [MeV]	RMS [MeV]	reduction
NMRREF	33	3.4	0.5	6	0.9	0.7	4 ± 1
NMRVAC	33	2.9	0.4	6	1.0	0.6	3 ± 1
NMROCT4	32	2.3	1.0	6	0.6	0.7	4 ± 1
NMROCT8	31	2.8	2.2	6	0.3	0.5	9 ± 6

Table 4: Evaluation of the average bending field variation after a bending modulation at the beginning of a fill (BOF) and the end of a fill (EOF) in MeV. N_{mod} denotes the total number of performed bending modulations. Quoted errors are statistical.

8 Magnetic Field Drifts

8.1 Drift as a Function of Day-Time

The tunnel dipoles are affected by the currents on the vacuum chamber while the reference magnet is not. Thus a variation of the field change with the time of the day for the tunnel probes was expected, since the number of trains passing in the area around CERN per unit of time is not constant during the day (according to the time table of the SNCF[7] trains and some local trains from CFF). The variations in the reference magnet should not depend on the day time since the beam pipe does not cross the reference magnet. Figure 14 shows the distribution of the absolute difference between two consecutive readings in the "Smooth Database", averaged over all physics fills of the 1995 scan period, as a function of the day time. This difference of the magnetic field readings is a measure for the intensity of the disturbance and has been converted into the equivalent change

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[7] French railroad company: Societé Nationale des Chemins de Fer

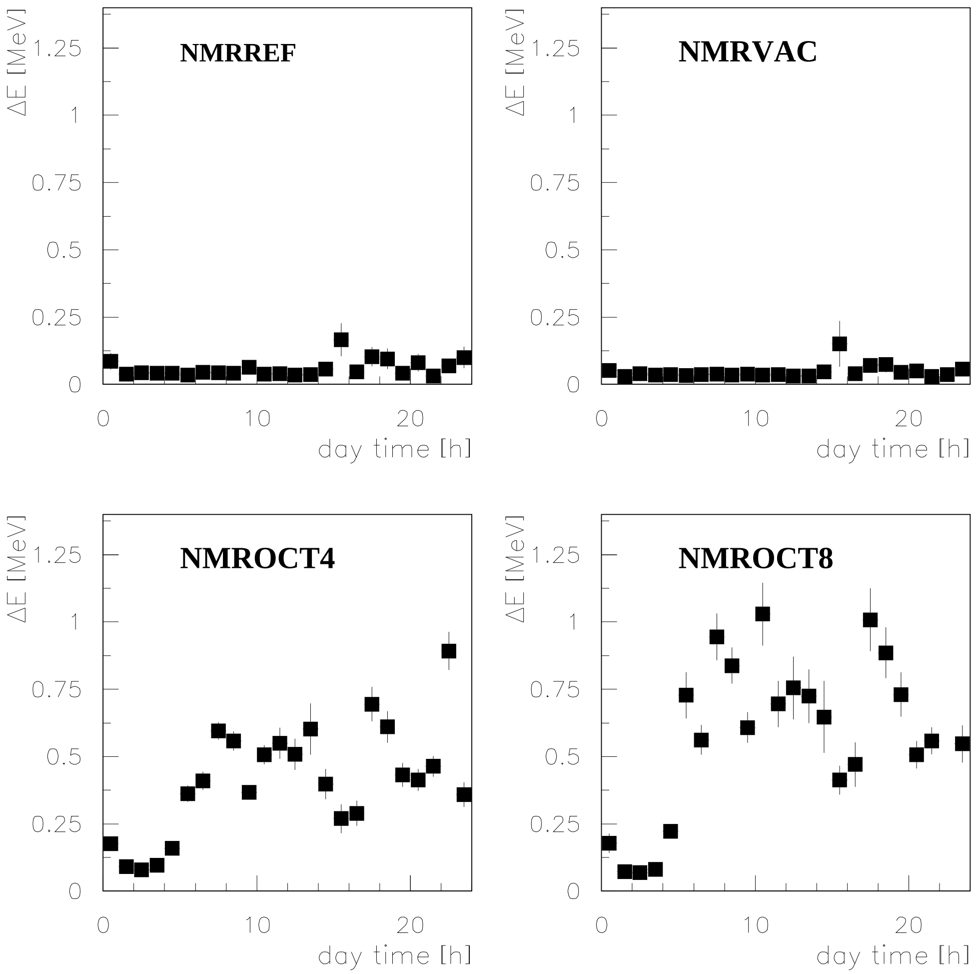

Figure 14: Change of the average magnetic field as a function of the daytime for all NMR probes in units of equivalent beam energy. ΔE corresponds to the absolute difference between two consecutive readings.

of the beam energy ΔE. The fluctuation in both reference magnet probes is very small ($\Delta E\ < 0.2$ MeV/h) during the whole day. The exceptional but still small peak in the distribution between 15h00 and 16h00 correspond to the data from 2 fills where a jump in the magnetic field of the reference magnet occurred. The fluctuations of NMROCT4 and NMROCT8 are much larger. The variation as a function of daytime is similar for the two tunnel probes. They show the same daily peaks (around 08h00, between 11h00 and 14h00, around 18h00 and 23h00) but differ in the absolute level. This level is smaller in NMROCT4 than in NMROCT8 due to the different amplitudes (equation 1) of the earth leakage currents in both octants. As expected from train effect predictions, the fluctuations in the tunnel probes during the quiet period (00h00 - 05h00), where no trains circulate, are very small. Both probes fluctuate by about 0.1 MeV/h during this period. This value corresponds to the fluctuation seen by the reference magnet probes. After 06h00, when the railway traffic starts, the perturbation in the tunnel dipoles increases roughly by one order of magnitude.

8.2 Drift as a Function of Time in a Fill

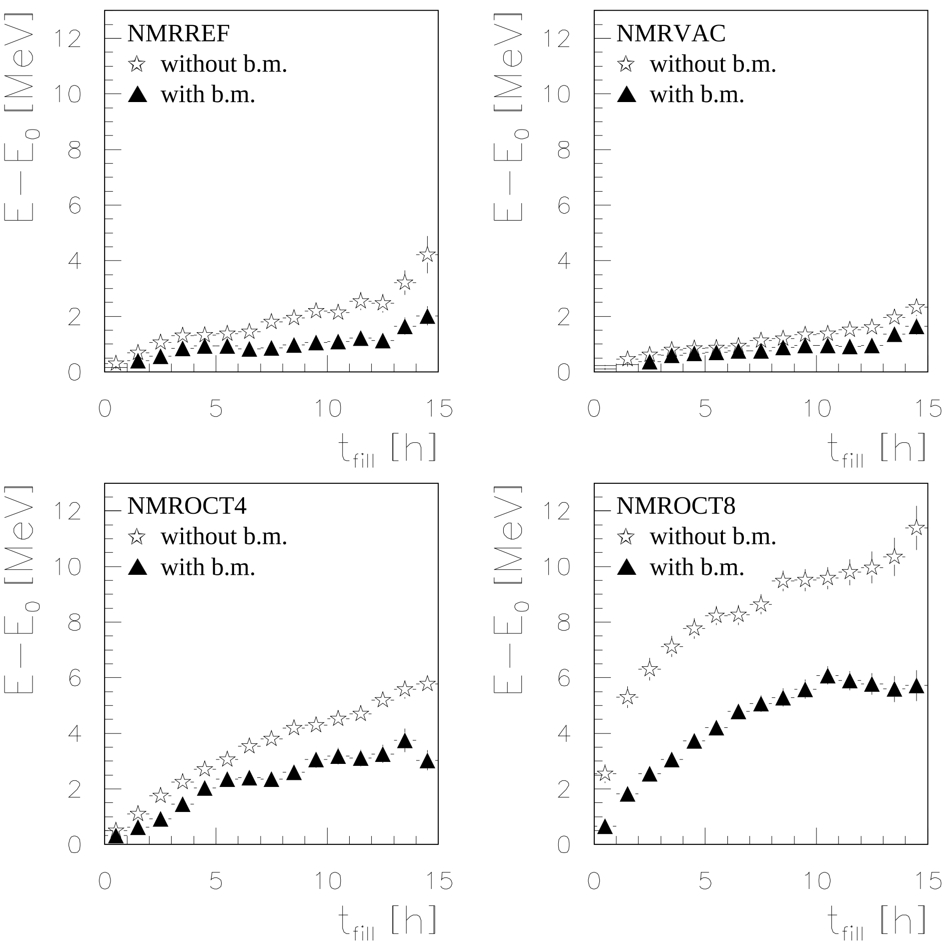

Figure 15: Variation of the B field (in units of beam energy) for two fill samples with and without **b**ending **m**odulation (b.m.) as a function of time after the ramp to the final energy and the time after the realization of a bending modulation respectively. E_0 denotes the beam energy at the time the fill starts.

The rise of the magnetic field for the different probes as a function of the length of a fill is derived for the whole scan period. Thus it is expected, that a bending modulation at the beginning of a fill would have an effect on the drift behaviour, the fills from the scan period are separated into two sets, with and without magnet conditioning. The time of a fill without bending modulation is considered to be the time after the ramp to the final energy while for a fill with bending modulation it is the time after the conditioning of the magnets. In figure 15 the results for the two samples are superimposed. It turns out that bending modulation more or less eliminates the rise of the magnetic field in the reference magnet while it only reduces the rise by roughly 30% in M418 and 50% in M818. Without bending modulation the field seen by NMROCT4 does not saturate after 15 hours of a fill and the magnetic field increases more or less linearly up to about 6 MeV. The same magnet tends to saturate at the end of the 15 hours period if it was conditioned. NMROCT8 saturates in both cases after a rise of about 6 MeV and 10 MeV respectively. The bending modulation reduces the slope significantly during the first hours of a fill. Table 5 summarizes the results for other selected data subsamples:

selected data	NMRREF [MeV/h]	NMRVAC [MeV/h]	NMROCT4 [MeV/h]	NMROCT8 [MeV/h]
all	0.20 ± 0.03	0.13 ± 0.02	0.37 ± 0.04	0.74 ± 0.08
00h00-04h00	0.11 ± 0.02	0.09 ± 0.01	0.17 ± 0.03	0.03 ± 0.02
without b.m.	0.32 ± 0.04	0.08 ± 0.01	0.42 ± 0.05	0.91 ± 0.14
with b.m.	0.08 ± 0.03	0.01 ± 0.01	0.30 ± 0.06	0.49 ± 0.08
P-2	0.14 ± 0.02	0.11 ± 0.01	0.29 ± 0.08	0.70 ± 0.16
P	0.20 ± 0.02	0.15 ± 0.02	0.44 ± 0.09	0.75 ± 0.17
P+2	0.19 ± 0.05	0.14 ± 0.03	0.40 ± 0.06	0.71 ± 0.15

Table 5: Mean of the average B-field rise measured by the NMR probes. The error is the statistical error of the mean.

- **all**
  All fills from the scan period are selected without cuts. Drifts are small in NMRREF and a factor of 2 respectively 4 bigger in the two tunnel probes. The ratio between the drifts in NMROCT4 and NMROCT8 is about 2.
- **00h00-04h00**
  Only data out of the “quiet period” between midnight and 04h00 are taken into account. Residual drifts ($\simeq$ 50 % of the “all”-data values) are measured in NMRREF and NMROCT4. The drift vanishes only in NMROCT8. No rise resulting from the “train effect” is expected in that period for any magnet. However, drifts in the reference magnet have been observed already in 1993 [2] (chapter 1) and no explanation could be found.
- **without/with bending modulation (b.m.)** (Figure 15)
  Fills with and without magnet conditioning at the beginning are selected. The mean rise in the magnetic field is larger for all probes if fills without bending modulation are selected rather than fills with bending modulation. With bending modulation the drift is vanishing for NMRREF and reduced by about 30% and 50% respectively for the two tunnel probes.
- **P-2, P, P+2**
  All fills at one of the energy points are taken into account at a time regardless of bending modulation or not. The rise is slightly larger at the Peak setting because most of these fills were made at the beginning of the scan

period before the conditioning of the dipole magnets became operational. NMROCT4 records a slightly smaller mean rise at "P-2" energy setting rather than at "P+2". Taking the errors into account these deviations become non significant. From the "train effect" model no dependence on the energy point is expected.

9 Unexplained Features

However, a few features remain to be investigated:

Classification of jump types:

In the reference magnet sporadic jumps are observed with and without a coincident change in the tunnel magnets. In cases where jumps are observed at all probes (see figure 16), it is most likely due to a current spike in the main bending power converter. It remains unknown what could cause a several MeV jump in the reference magnet without a corresponding level change in the tunnel probes. An example for this type of jump is given in figure 17. This kind of jump is observed twice during the 1995 scan period.

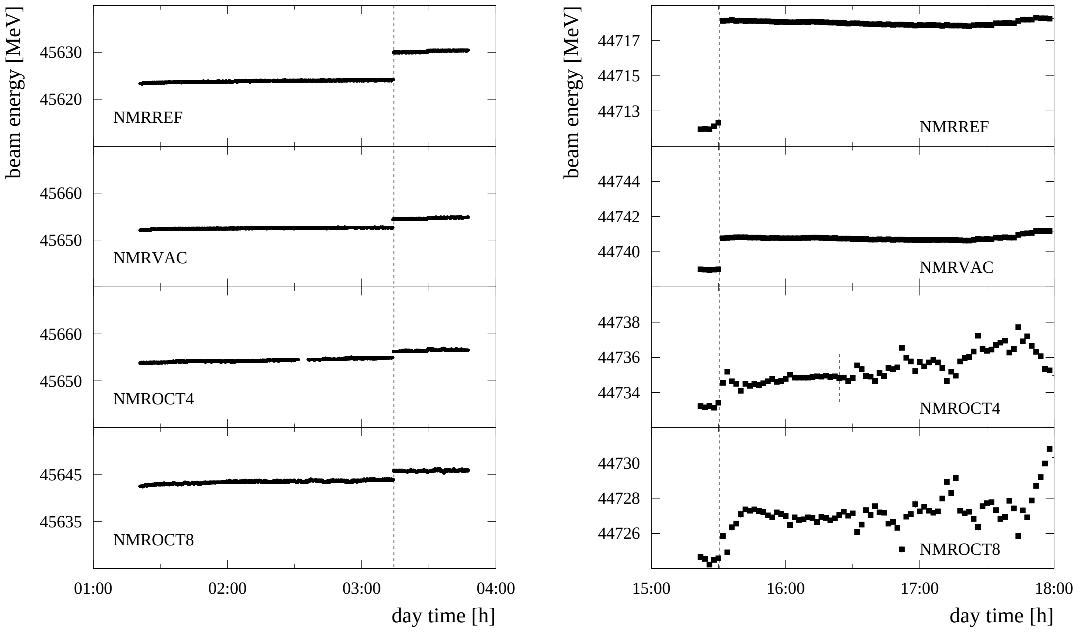

Figure 16: Bending field in units of equivalent beam energy in fill 2819 (left) and 2856 (right) as a function of day time. In fill 2819 all four probes register a coincident jump around 03h15 during the quiet period. In fill 2856 the coincident jump happens around 15h30 during the afternoon.

Differences in the rise behaviour:

The two tunnel probes record a distinct type of rise behaviour. Figure 18 (left) shows one example for the different magnetic field rises during the quiet period as measured by the four NMR probes during fill 3027. Comparing the behaviour of the tunnel magnets, some discrepancies has been observed. In average (see

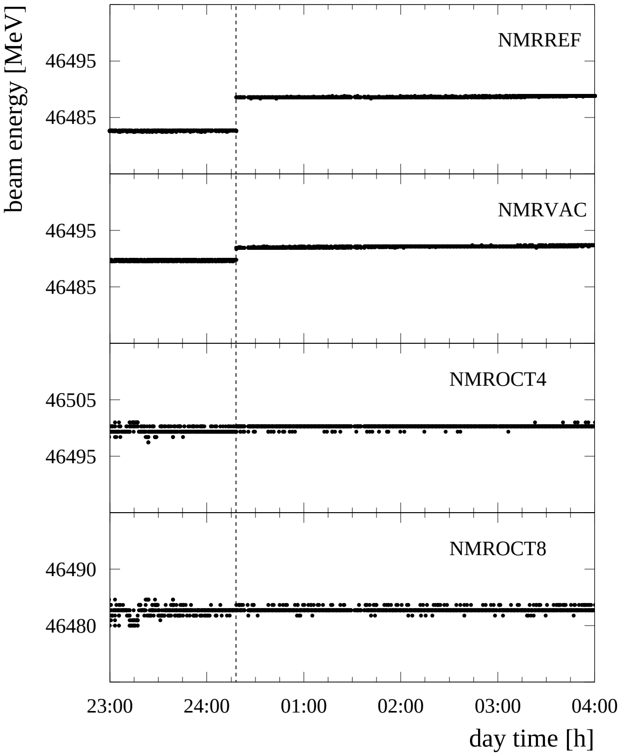

Figure 17: Bending field in units of equivalent beam energy as measured by all NMR probes in fill 2859. A few minutes after midnight, during the quiet period, a sudden change in the level of the magnetic field in the reference magnet is visible while no variations are observed in the tunnel magnets.

Table 5) a drift of 0.17 ± 0.03 MeV/h remains for the quiet period in NMROCT4 while the drift vanishes in NMROCT8 (0.03 ± 0.03 MeV/h). In this particular fill, NMROCT4 shows a continuous rise in the quiet period whereas no variations is expected from the "train effect" model. Such a rise behaviour could be recorded in a few other fills during the scan period and can not be explained by the simultaneous rise of the temperature ($\Delta T^{M418} = T(04h00) - T(00h00) = 0.7^{o}C$ in fill 3027) in Magnet M418. However, the magnetic field of a dipole magnet can possibly be affected by the core temperature: for a material with a non zero temperature expansion coefficient a rise in temperature leads to a change of the gap size and causes thus a variation of the magnetic field at the position of the probe. But in this particular fill the observed drift is larger than any expectation and larger than in all other fills, where drifts during the quiet period happen. In contrary to NMROCT4, NMROCT8 does not drift during the quiet period and it starts rising in discontinuous jumps once the noise started again after 04h00.

Figure 18 (right) shows an example, where the B-field, measured in OCT 4, rises smoothly between 08h00 and 18h00 and the B-field, measured in OCT 8, increases in discrete jumps. The first jump is significantly bigger than the later ones. The magnetic field increase added up during this time period is almost equal for both magnets. This type of rise behaviour during day time can be observed in many other fills in the 1995 scan period. However, only the behaviour of the magnet in OCT 8 agrees with our expectation from the "train effect" model. A mechanism what could cause such a difference in the rise behaviour needs still to be investigated.

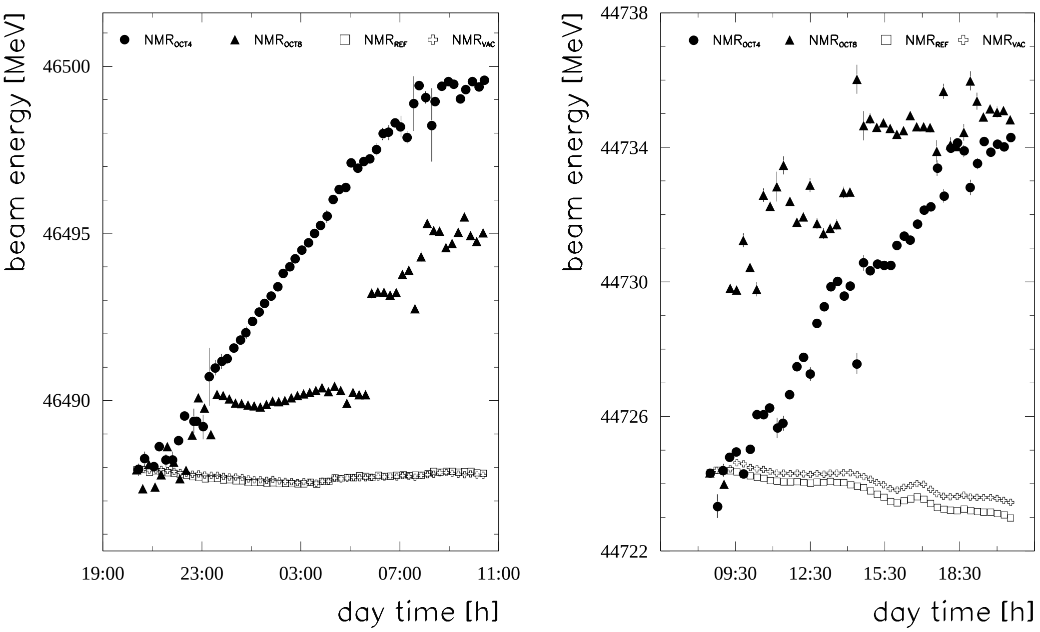

Figure 18: Evolution of the beam energy as measured by all four NMR probes with respect to the start of the fill as a function of the day time for fill 3027 (left) and fill 2948 (right). Every data point corresponds to a mean value over 15 minutes ("Smooth Database"). Left: The B-field measured in OCT 4 rises continuously during the quiet period while no rise is expected from the "train effect" model. Right: During day time, the B-field measured in OCT 8 increases in discontinuous jumps, the B-field measured in OCT 4 rises smoothly.

10 Conclusions

For the first time since LEP has been commissioned, the magnetic field was measured with NMR probes mounted in bending dipoles in the tunnel. The unexpected effects of the field measurements as short term fluctuations, day-night effect and long term variations could be traced back to earth leakage currents flowing on the LEP vacuum chamber. It was shown that these currents result from railway trains circulating in the area around LEP. Other possible sources could be excluded.

- According to the "train effect" explanation, the two observed energy jumps during the long term energy calibration experiment in 1993 (chapter 1) can now be interpreted as a result of typical magnetic field fluctuations peaked around 08h00 and around 12h00 (Figure 14).
- Since only one probe was available, jumps could in '93 be observed in the reference magnet only [2]. In '95 all four NMR probes registered coincident jumps (Fig. 16) in the tunnel and the reference magnet. These coincident jumps are considered to be most likely due to spikes in the main bending power converter. No explanation is found for jumps registered from the reference magnet probes only (Fig. 17).
- Drifts towards higher fields, already known in '93 to happen in the reference magnet (chapter 1), were observed in all probes in 1995. These drifts, mainly

due to magnet hysteresis effects, are much higher in the tunnel magnets than in the reference magnet. The assumption, that these slow drifts are related to true field changes could be proved (Fig. 6) with energy calibrations.

A method to reduce the magnetic field drifts and the frequency of sudden field jumps was presented. A few features of the magnetic field still remain unexplained.

11 Acknowledgements

We would like to thank the LEP operations team for their excellent work and their patience in the difficult (and never ending) task of getting more and more understanding of the magnetic dipole field behaviour. We thank Jörg Wenninger for his support and for many discussions.

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