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Magnetic measurements of a CEA/IPHI 28.5° dipole for the Linac4 diagnostic beam line

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Summary

This reports summarizes the results of a recent test campaign carried out on a spectrometer dipole for the Linac4 diagnostic line. These results include point-like measurements done with NMR and Hall effect probes and are intended as a cross-check of a more extensive campaign carried out at Sigma Phi. They are aimed specifically at the issue of the reproducibility of the field on different cycling conditions. In the Appendix, a field control algorithm which can be used to guarantee the requested 0.1% reproducibility is spelled out in full detail.

1. Introduction

A 28.5° bending dipole [1] made in 1976 by Danfysik for IPHI (CEA Saclay) and extensively measured at SigmaPhi in 2004 and 2010 [2][3], has been re-measured at CERN on a dedicated test bench in the I8 laboratory (bldg. 375) in the period from February to August 2011 (Fig. 1). This magnet is going to be installed in the Linac4 diagnostic line, where it will be used to calibrate beam energy at 3 MeV and 12 MeV. The corresponding field levels of interest, computed on the basis of the required deflection angle α=0.4974 rad, are given in Table 1. The corresponding approximate current levels, computed based on the nominal transfer function, are 65 A and 130 A. In the following, we refer only to the field measured on the central beam path at the nominal radius of curvature r = 1.5 m.

Fig. 1 – 28.5° IPHI dipole on the test bench in I8

Table 1

Energy [MeV]	**3**	**12**
γ	1.003132	1.012526
β	0.078954	0.15681
$B\rho$ [Tm]	0.24788	0.49691
$\int B\,d\ell$ [Tm]	0.12340	0.24717

The purpose of the test campaign at CERN was twofold: a) to verify the stability of the magnet w.r.t. the existing measurements and b) to measure the reproducibility of $\int B\,d\ell$ in the appropriate cycling conditions, in order to establish the control method needed to attain a required accuracy of 10^{-3}. The dipole has been powered with a spare 600 A/40 V LHC power supply, which guarantees control of the current within 10 ppm. The ramp rate used throughout was 20 A/s. The following probes have been used:

Dipole centre (B_0)	Metrolab NRM Teslameter PT2025 (Probes type #2 and #3)
Pole edges (B_1, B_2)	CERN-built ISR-type Hall probe teslameter [4]

2. Comparison with earlier measurements at SigmaPhi

The central field $B_0(I)$ has been measured with both Hall and NMR probes and has been compared to earlier results at SigmaPhi. In particular, the transfer function of the dipole is plotted in Fig. 2. On average, the measurements agree within 0.1% across the nominal range of the magnet i.e. from 10 A to 215 A, CERN results being higher by about 0.2 mT.

Between 60 A and 70 A the NMR result is up to 0.16% higher than what obtained at SigmaPhi; however, across the same range, the difference between the two Hall probe measurements is lower than 0.04%. The discrepancy can be attributed to the uncertainty linked to the exact position, orientation and averaging volume of the probe (about 1 cm^3 for the NMR). At the 130 A target level, the difference between CERN and SigmaPhi results is lower than 0.3%. In the end, the results obtained at SigmaPhi can be considered to be reliable within the given 0.1% tolerance.

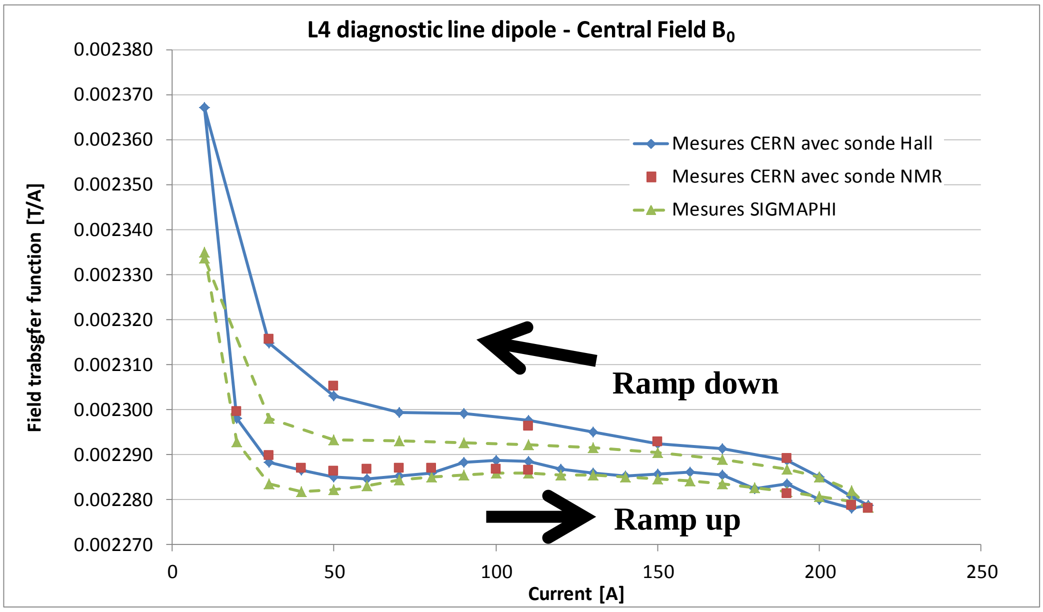


Fig. 2 – Hysteresis curve at the center of the magnet

3. Target current levels

The integral field measurements carried out at SigmaPhi, based on Hall probe field maps with a 13 mm step, cover only the four current levels I=50, 83, 130 and 251 A, meaning that the field integral at the lowest level has to be interpolated. A completely new field mapping would have been time-consuming and was deemed unnecessary. The field integral and magnetic length are plotted in Fig. 3 and 4. The target current levels given in Table 2 have been obtained by linear interpolation in the range from 50 A to 130 A (the range from 130 A to 250 A has not been used because the effects of non-linearity are more pronounced, as it can be seen in Fig. 2).

Table 2

Energy [MeV]	**$\int B d\ell$ [Tm]**	**B_0 [T]**	**I [A]**	
3	0.12340	0.1501	**65.607**	**I_{min}**
12	0.24717	0.3015	**131.933**	**I_{max}**

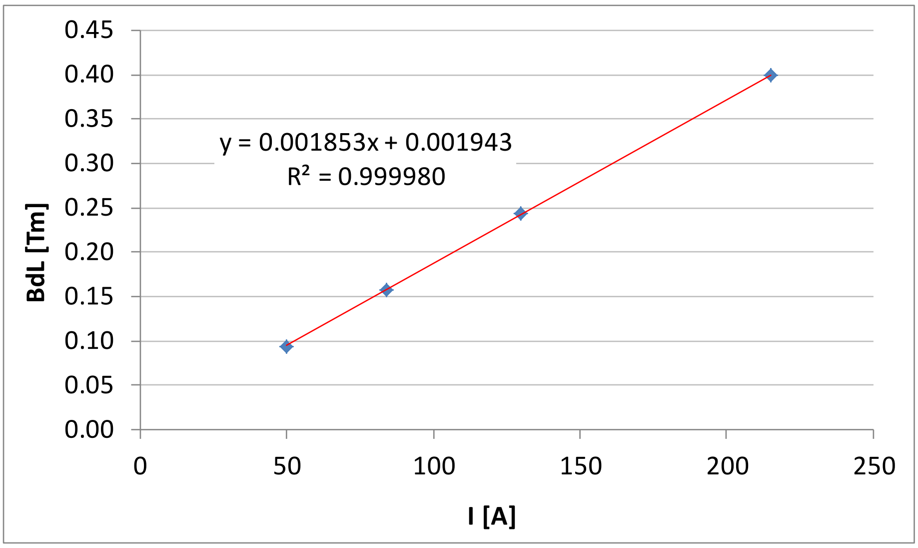


Fig. 3 – Integral field vs. current measured at SigmaPhi.

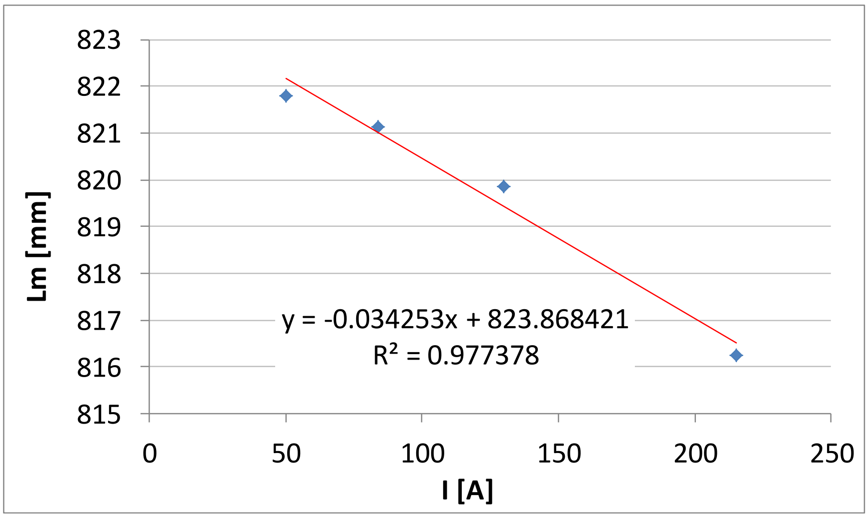


Fig. 4 – Magnetic length measured at SigmaPhi.

4. Field reproducibility

The reproducibility of the field has been tested by cycling repeatedly the magnet between the two target levels I_{min} and I_{max}. The position of the probes is visible in Fig. 5. The two NMR probes, which are needed to measure the two different field levels, were placed symmetrically to the mid-plane so as to have the same offset due to the normal sextupole. The two Hall probes, placed at the beam entry and exit points on the central path (r=1.5 m), are more sensitive to the possible effects of iron saturation at the edge of the poles and are intended to give an indication whether the local reproducibility is different w.r.t. the reproducibility at the center.

Three runs of 7 cycles each have been made, switching the power supply off between cycles to simulate the magnet behavior that should be expected when resuming operation after a machine stop. With reference to Fig. 6, the first run starts from and undefined point E on the I=0 axis, then the current is increased up to point F and the cycle FAF is then repeated, keeping the current constant for the time necessary to take readouts. The results are plotted in

Fig. 7 and 8 at 3 MeV and 12 MeV respectively and are also summarized in Table 3 (the values I_{min} and I_{max} tested are slightly different from those given in Table 2, however this bears no impact on the results that follow). In the Table, the inequality sign indicates that the measurement is limited by the resolution of the Hall probe acquisition electronics

The behavior of the magnet is essentially the same in the three runs. During the first three cycles we observe a transient corresponding to the point F gradually joining the downwards (i.e. upper) limit branch of the hysteresis curve, with B_0 increasing by about $0.5 \cdot 10^{-3}$ in relative terms. This transient, which is above tolerance at 3 MeV, is negligible at 12 MeV. This is consistent with the general finding that operation at higher field i.e. closer to saturation tends to reset the magnetic state and is less sensitive to perturbations.

During the subsequent 4 cycles the field appears to be very stable, with fluctuations of only a few ppm at the center i.e. well within the resolution of the NMR probe (0.1 ppm). On the other hand, the stability at the pole edges cannot be evaluated accurately since the Hall probe instrumentation is working below its own resolution limit; however, the upper bound i.e. $0.7 \cdot 10^{-3}$ at 3 MeV is within tolerance.

Table 3

Energy [MeV]	**Stability ΔB/B relative to steady-state value (cycle n. 7)**			
	ΔB/B over first 3 cycles		**ΔB/B after first 3 cycles**	
	B_0 *(central field)*	**$B_{1,2}$** *(pole edges)*	**B_0** *(central field)*	**$B_{1,2}$** *(pole edges)*
3	5.4×10^{-3}	7.5×10^{-3}	7.1×10^{-6}	$\leq 0.7 \times 10^{-3}$
12	0.1×10^{-3}	$\leq 0.3 \times 10^{-3}$	2.1×10^{-6}	$\leq 0.3 \times 10^{-3}$

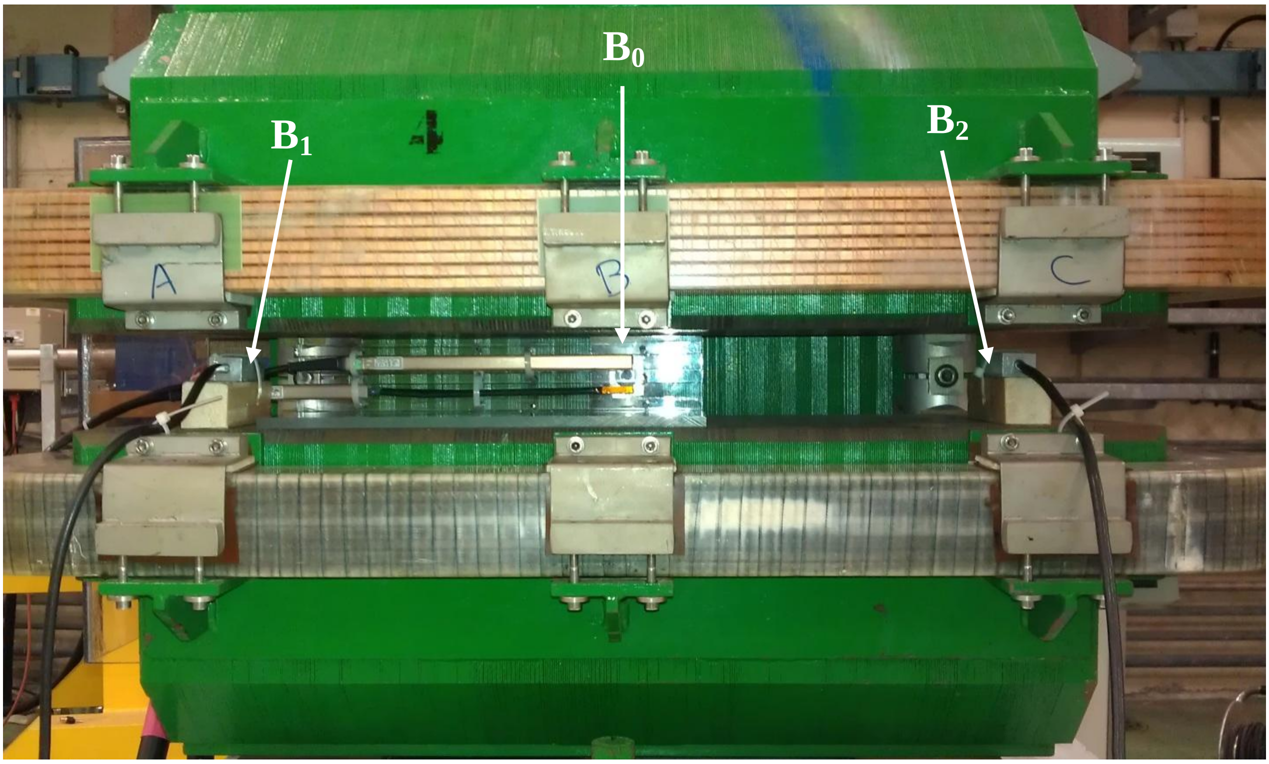


Fig. 5 – Probe placement for reproducibility measurement. B_1 and B_2 are measured with Hall probes, B_0 is measured with two NMR probes.

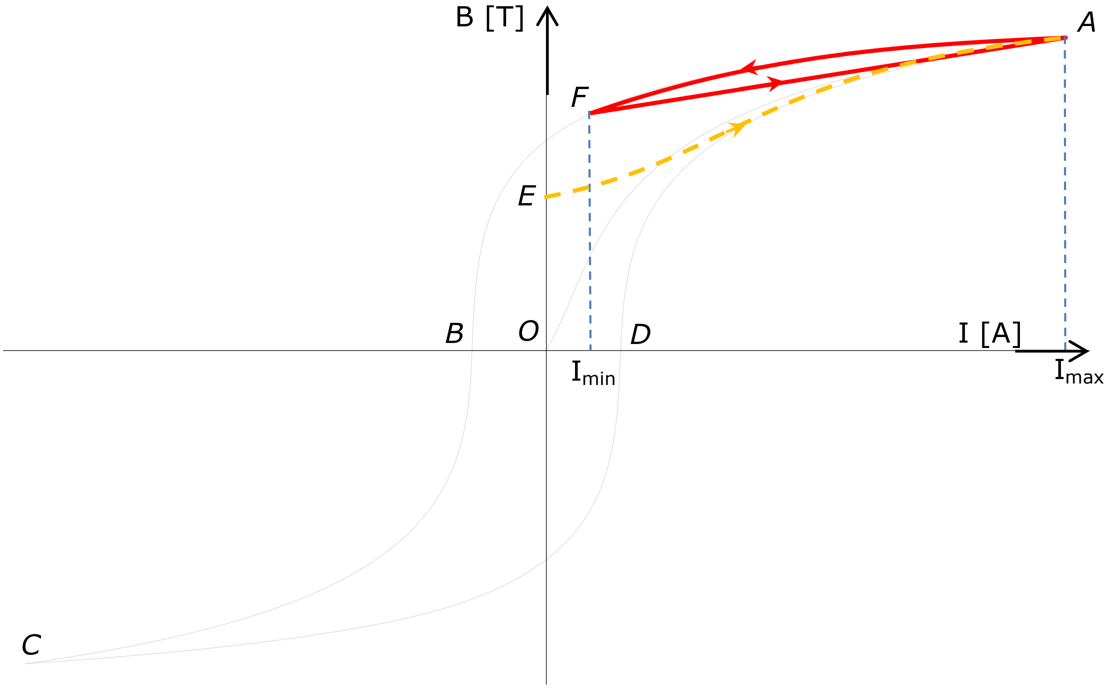


Fig. 6 – Current cycle representation on the (*I*,*B*) hysteresis curve

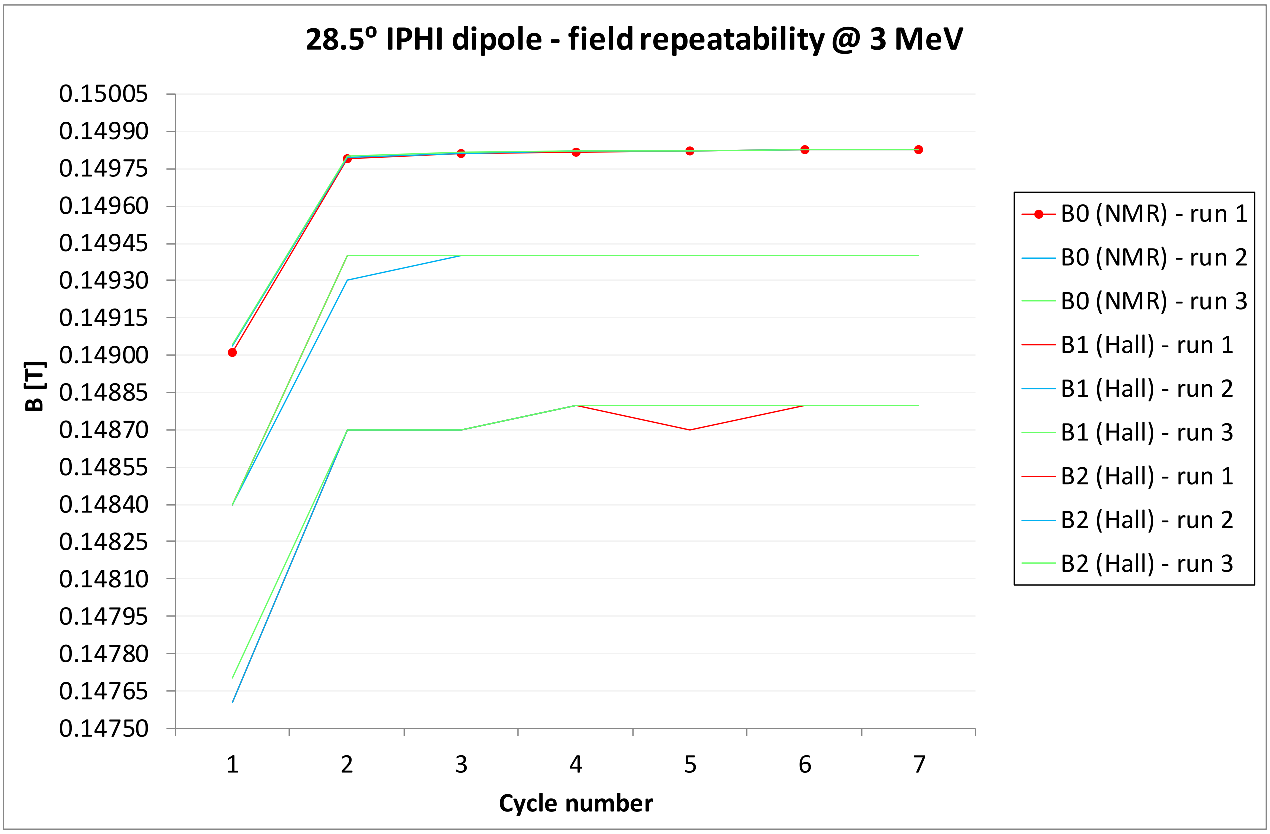


Fig. 7

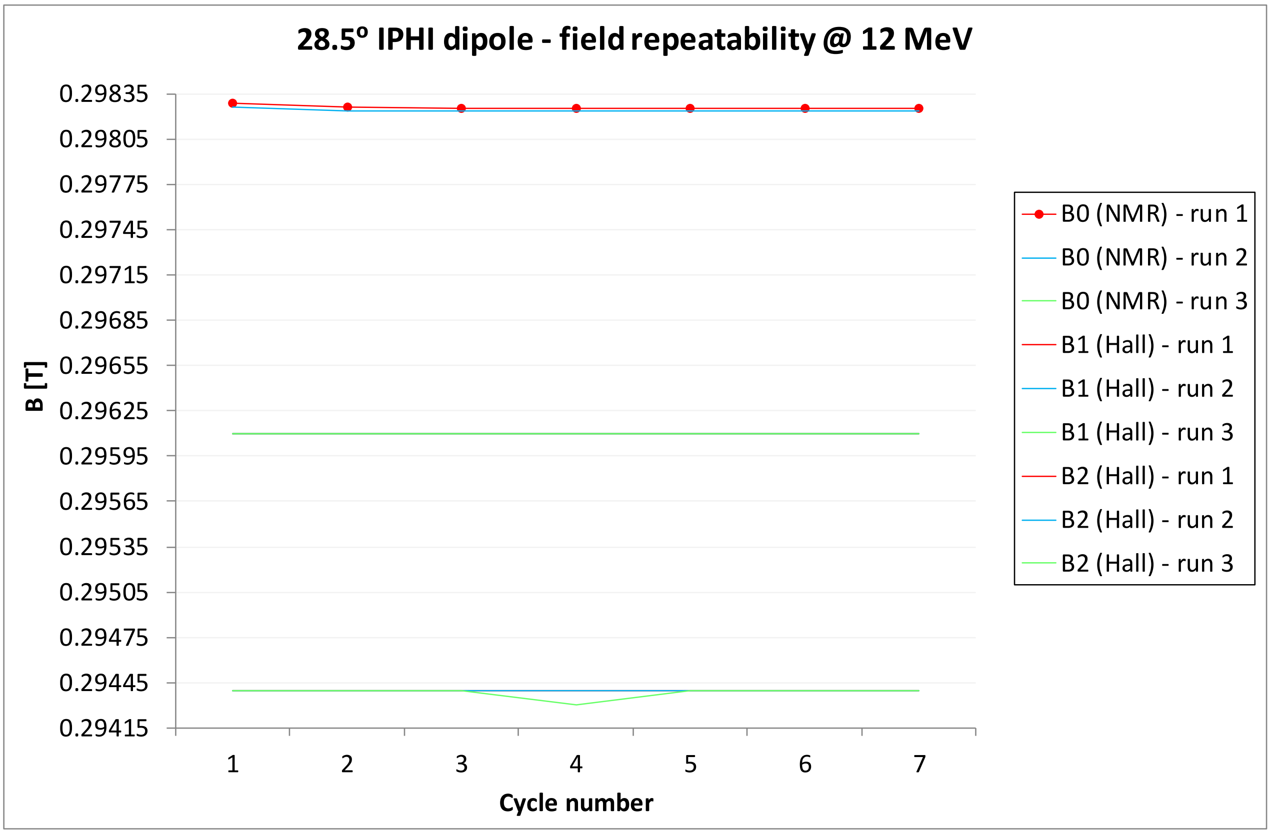


Fig. 8

5. Field control

The results above show that the required field reproducibility can be achieved in open loop, without having to resort to real-time field measurement and the associated complex feedback power supply control. The following prescriptions must be observed:

a) Upon restart: three pre-cycles from I_{min} to and I_{max} and back.
b) Ramp rate = 20 A/s
c) Never exceed the I_{min} and I_{max} limits
d) In case of intermediate plateau at $I_{min} \leq I \leq I_{max}$: always resume cycling on the same up or down ramp, i.e. always follow counterclockwise the FAF cycle (Fig. 6)
e) In case b), c), or d) are not respected (e.g. power supply trip, operation error etc.): reset the magnetic state with three pre-cycles

The pseudo-code needed to implement these prescriptions is given in the appendix.

It should be remarked that an attempt has been made to measure the field with the vacuum vessel installed inside the magnet gap, with the aim of understanding if the option of real-time measurement is viable should it become necessary in the future. NMR measurements were not possible in the available volume due to the field inhomogeneity exceeding the NMR probe specifications (about 1.2×10^{-3} cm^{-1} in the field range being tested). The measurement is of course always possible using Hall probes, although issues of long-term stability and temperature drifts may be critical and should be further investigated.

5. Conclusions

Measurements of the 28.5° CEA/IPHI dipole carried out at CERN confirm those done at SigmaPhi within the required 10^{-3} tolerance. Open-loop control of the power supply between the values I_{min} and I_{max} corresponding to 3 MeV and 12 MeV, found by linear interpolation of SigmaPhi results, allows to achieve a field stability well within the tolerance, provided the powering prescriptions given above are followed. In particular, three simple precycles between the two extreme current levels have been found to provide excellent stability; however, the procedure for a complete degaussing is also given in the Appendix, should it be needed in special cases.

References

[1] NORMA database: http://norma-db.web.cern.ch/cern_norma/magnet/idcard/?id=7421

[2] M. Duval, A. Lemarie, MESURES MAGNETIQUES DIPOLE, Internal Report SigmaPhi, 2004

[3] Magnetic measurement report CEA – IPHI 28.5° Dipole magnet (ref 76141), Internal Report SigmaPhi, 2010

[4] K. Brand, G. Brun, « A digital teslameter », CERN Yellow Report ISR Division 79-02 http://cdsweb.cern.ch/record/133084/

Appendix – Open-loop field control algorithm

Integrated field vs. current: $\int B\,d\ell$ [mTm]$=1.943 + 1.853\, I$
Beam energy vs. current: E [MeV]$= -5.90244 + 0.135693\, I$

State variables:

I		actual value of magnet current
prev_dir	{up,down}	direction followed to get to I (must be updated at every ramp)

Routines:

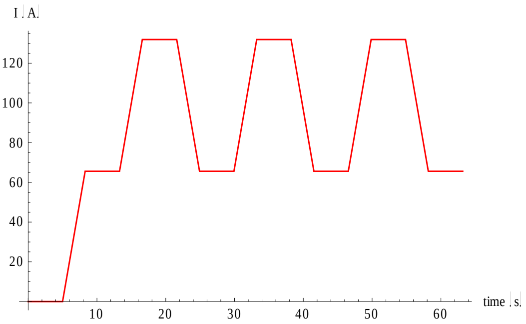
rampto(I_{new})

```
power converter ramp to $I_{new}$ at ramp rate $\pm dI/dt$
if $I_{new} > I$ then prev_dir=up else prev_dir=down end
$I = I_{new}$
```

Aim: execute a basic ramp while updating state variables

precycle

```
for j=1 to 3 do rampto($I_{min}$); wait(5 s); rampto($I_{max}$)
end
rampto($I_{min}$)
```



Aim: put the magnet is a reproducible magnetic state by means of three consecutive cycles between I_{min} and I_{max}
The precycle must be done:
- upon power-up
- when new values of I_{min} or I_{max} are set
- after any deviation from normal powering occurs, e.g. after a power converter trip

cycleto(I_{new})

```
if $I_{new} > I$ then
      if prev_dir==up then rampto($I_{new}$)
      else rampto($I_{min}$); rampto($I_{new}$) end
else
      if prev_dir==up then rampto($I_{max}$); rampto($I_{new}$);
      else rampto($I_{new}$) end
end
```

Aim: ramp the magnet to the desired current level while respecting the cycling prescriptions given in Section 5

degauss(I_{new})

```
rampto($I_{max}$)
do rampto($-\frac{2}{3} I$) while($|I| > I_{tol}$)
```

Aim: put the magnet in a reproducible magnetic state as close as possible to zero remanent magnetization.
Warning: this procedure requires more time and a more precise/stable power supply than the `precycle` procedure and does not automatically guarantee better results.

Parameters:

I_{tol} [A]	0.5	tolerance corresponding to the precision of the power supply control in the vicinity of zero (must be confirmed by TE/EPC depending, on the specific power converter used)
I_{min} [A]	65.607	3 MeV beam
I_{max} [A]	131.933	12 MeV beam
dI/dt [A/s]	±20	fixed ramp rate (should not be increased to avoid eddy current effects)