DYNAMIC BEHAVIOUR OF FAST-PULSED QUADRUPOLE MAGNETS FOR LINAC4 TRANSFER LINE

S. Kasaei, School of Particles and Accelerators, Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
M. Buzio, L. Fiscarelli, CERN, European Organization for Nuclear Research, Geneva, Switzerland

Abstract

Linac4, recently built at CERN, is a linear normal conducting accelerator for negative hydrogen ions (H^-). A new transfer line will link Linac4 to the Proton Synchrotron Booster. This transfer line includes 21 quadrupole magnets characterized by fast excitation cycles, which make accurate magnetic measurements challenging. This paper describes the method used for the measurement, which is a combination of techniques based on rotating and fixed search coils. We show how these instruments can be used in a complementary way to derive information on different aspects of the magnetic behaviour of these quadrupoles, such as the impact of hysteresis and dynamic eddy current effects.

INTRODUCTION

The transfer line region of the Linac4 consists of 21 fast-pulsed quadrupoles in three different types of support plates, each containing two survey targets. The main properties of the fast-pulsed quadrupole magnets are given in Table 1 [1,2, 3].

Table 1: Main Transfer Line Quadrupole Parameters

Parameter	Value
Aperture ∅ (mm)	100
Good Field Region ∅ (mm)	75
Nominal peak current (A)	119.6
Nominal integrated gradient (T)	1.83
Integrated gradient tolerance	±0.5%
Stable flat-top duration (µs)	400
Harmonic error tolerance ($\|c_n\|$, n=3 to 10)	1%
Axis offset radial tolerance (mm)	0.2
Roll angle tolerance (mrad)	1
Yaw and pitch tolerance (mrad)	2

The possible large dynamic effects due to eddy currents and iron hysteresis make the measurement a challenge. In contrast to classical measurements of pulsed magnets carried out with a translating fixed coil [4], a shaft with the possibility of both step-wise and continuous mode rotation can vastly increase measurement range and accuracy in different magnet excitation modes such as DC, AC (sinusoidal) and pulsed.

The main purpose of this paper is to describe a new rotating coil instrument that enables us to simultaneously characterize the magnetic behaviour of the fast-pulsed magnets in the nominal pulsed condition as well as a low current DC mode. Moreover, this system allows us to cross-check the integrated field strength and to obtain harmonics as a function of excitation current or time.

MEASUREMENT SETUP

The setup and the reference system are shown in Fig. 1. We used a shaft with five tangential coils, 45 mm outer radius and 1200 mm length. This shaft is equipped with two non-magnetic 0.5 inch retro-reflectors mounted 180° apart at both ends for magnetic axis fiducialization. Data acquisition was done with two Fast Digital Integrators (FDI) [5] and a multifunction ADC device model NI USB-6366 (with 16 bits resolution and 100 kHz sampling rate).

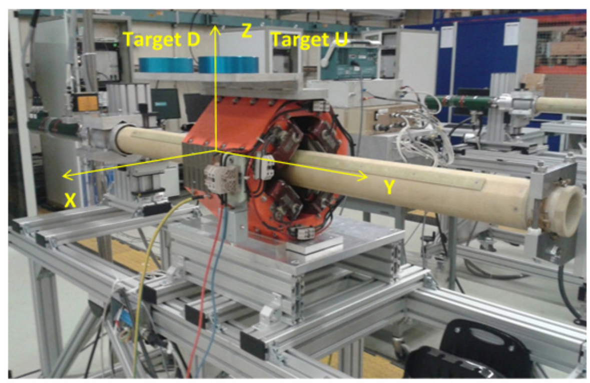

Figure 1: A transfer line quadrupole (TLQ) on the test bench.

The five tangential coils have been used in two different bucking schemes: the standard compensation mode plus the novel gradient mode to investigate dynamic effects and harmonic content. In standard compensation mode, a combination of 4 coils bucks out dipole and quadrupole terms and reduces the impact of the spurious higher harmonics caused by mechanical imperfections during rotation. The standard compensation scheme is sensitive to $n \geq 3$ harmonic components only. In this configuration, coils are rotated sequentially at 64 angular positions in the magnet aperture. At each position, the magnet is excited with the nominal current cycle generated by a CERN-developed prototype MAXIDISCAP capacitive discharge power supply [6]. Two output signals, i.e., absolute and compensated are fed to two FDIs to give main integrated gradient field and the field quality in the nominal beam conditions, i.e., at the end of the flat-top of the current cycle.

The gradient mode, which is obtained by the connecting two equal and parallel coils in series opposition, is sensitive only to even harmonics. In this mode, the coils were kept fixed facing two opposite poles and the signal was fed to the high-speed ADC, in order to measure dynamic effects and to check the correlation with continuous rotating coil in DC mode. The error on the gradient due to the octupole component is at most 1.6 units and is therefore negligible compared to the required tolerance.

MEASUREMENT RESULTS

Eddy Current Effects

Due to the finite conductivity of the magnet core, a time varying excitation current will induce eddy currents that will attenuate and affect the uniformity of the gradient. In order to reduce this undesirable effect, the core was made of 0.5 mm thin laminations electrically insulated from each other. However, the high ramp rate of dB/dt ≈ 150 T/s still gives rise to measurable eddy current effects. Figure 2 shows the profiles of the excitation current *I(t)* and of the scaled integrated gradient. To compare the integrated gradient and *I(t)*, the integrated gradient is scaled to coincide with the excitation current at the end of flat-top $t=t_s$:

$$I^{*}=I(t_s)\int G\,ds/\left(\int G\,ds(t_s)\right). \quad (1)$$

Due to eddy currents, magnetic field lags excitation current during rise time. If there were no eddy currents, I^* and I should superpose at the end of ramp-up. The difference (I^*-I) which is representative of the non-linearities, shows clearly an exponential decay with a time constant $\tau_e = 0.8\ ms$ and a relative amplitude of 0.3% at the end of the ramp-up. This means that the entire flat-top is stable enough for the passage of the beam. The final offset of about 0.3% between the initial and final value of the field can be attributed to remanent field. Since the magnet was preliminarily subject to several excitation cycles, the remanent field is expected to be stable. However, the current oscillations at the end of each pulse are not controlled by the power supply, and this may have an impact on the reproducibility of the magnetic behaviour during operation.

Integrated Gradient

The impact of eddy currents and of lower-than-nominal excitation was investigated thoroughly on a sample of several units, which provided consistent results. We show in Fig. 3 the dynamic transfer function (TF), i.e., the ratio of the instantaneous integrated gradient to the excitation current. The TF during any given ramp can be modelled by:

$$TF=\frac{\int G\,ds}{I}=\frac{\int G\,ds_0}{I}+TF_{\infty}. \quad (2)$$

where $\int Gds_0$ is the remanent field in the absence of current and TF_∞ is the asymptotic transfer function assuming linear behaviour of magnet. The remanent field, which is responsible for the divergent behaviour of the curves at I=0, depends critically on the excitation history. This was in practice very difficult to control during series tests. In operation, the cycling is expected to be much more stable due to the excitation cycles being repeated millions of times.

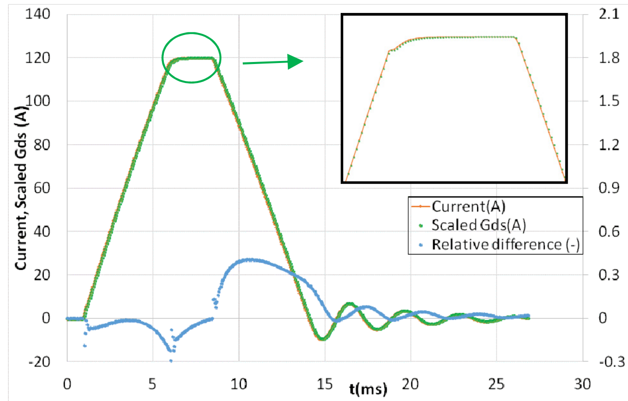

Figure 2: Current and normalized field integral profiles showing the exponential transient due to eddy currents. (highlighted by the blue arrow).

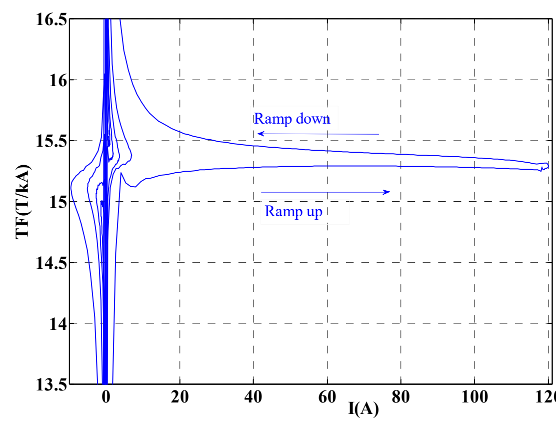

Figure 3: Dynamic integrated gradient TF in pulsed mode.

The transfer function was measured with the stepwise rotating integral coil. The results show a good linearity of the quadrupole up to the nominal current, with as little as 0.2% saturation and 0.7% of hysteresis in spite of the eddy current losses. The results are consistent across the whole series as they depend essentially upon the overall geometry and the quality of the steel, which is typically very uniform. We should remark also that the messy transfer function lines around *I*=0 are caused by the oscillations at the end of ramp-down, which make a sort of degaussing albeit not in a well-controlled fashion.

Conditions throughout the flat-top are equivalent to DC within the given tolerance. We can therefore derive the integrated gradient in operating conditions from DC measures at the maximum allowed DC current of 9.2 A, which are much simpler and quicker. DC measurements were performed at ±9.2 A to cancel out both external DC perturbations and residual field contributions. The average TF over the whole series is 15.23 T/kA, which is less than 0.1% higher than the nominal design value [7]. We observed RMS magnet-to-magnet fluctuations about

ISBN 978-3-95450-182-3

0.5%, which include three contributions: measurement repeatability, reproducibility of the residual field and uncertainty of current reading by DCCT.

Magnetic Axis

The two reflectors at the ends of the coil shaft are surveyed by means of a LEICA laser tracker LTD500. The centers of the circular profiles described by each reflector during a 360° rotation define the rotation axis of the coil. The rotating coil measurement at ±9.2 A DC gives the centering offset of the magnetic axis with respect to the two fiducial targets on the top of magnet. DC measurements were found to be sensitive to interference from background fields as low as 0.2 G, measured along the exposed part of the rotating coil with a Fluxgate magnetometer. This external field corresponds to a systematic offset of 0.14 mm vertically and 0.13 mm horizontally, which was subtracted from the final results.

The average and standard deviation of the magnetic axis for the whole series are 89±93 μm and 10±51 μm along x and z respectively, which is consistent with the specified mechanical tolerances. The total uncertainty of centering offset is estimated by the root sum square of repeatability, rotating coil systematic error and optical target offset. The systematic horizontal error was easily estimated by turning the magnet by 180° around its vertical axis and we assumed vertical errors to be statistically of the same order. Rotating coil repeatability over 2 measurements is about 35 μm, while the nominal uncertainty of the optical survey is 20 μm. Only two quadrupoles were significantly out of specifications and they were corrected by adjusting the central keyway accordingly on the final supports.

The change of magnetic axis offset as a function of current was measured dynamically in rotating coil stepwise mode on TLQ #6 (Fig. 4). The difference between flat-top and 9.2 A is of about 30 μm, however, this can be attributed to hysteresis effects.

Field Quality

Due to practical constraints such as finite permeability and finite current density, designed magnets are not ideal but include higher harmonic errors that are required to be less than a given tolerance. The multipole results at nominal current are essentially consistent with standard DC measurement at ±9.2 A on all quadrupoles. The normalized coefficients (b_n, a_n) are the dimensionless multipole coefficients, which are normalized to the main field (B_2) and are expressed in units of 10^{-4}. The most significant components are, as expected from symmetry constraint, b_6 and b_{10}. These harmonics are allowed based on symmetry of quadrupole magnet. We see also a relatively large sextupole $\|c_3\| = \sqrt{a_3^2 + b_3^2}$=1.7 units, which is usually an indicator of mechanical assembly asymmetries. The total error is one order of magnitude below than the tolerance and can be neglected.

Figure 5 shows the behaviour of the normal sextupole versus current for TLQ #6. We observe that during the ramp-up b_3 is constant within 0.13 units, but shows several units of hysteresis during the ramp down. While the hysteresis of the main harmonic is clearly linked to energy dissipation, no similar simple argument can be derived for the variation of field harmonics, which is presumably determined by the geometry and the patterns of saturation and eddy currents across the poles. At any rate, the field quality is not affected by these considerations during the passage of the beam.

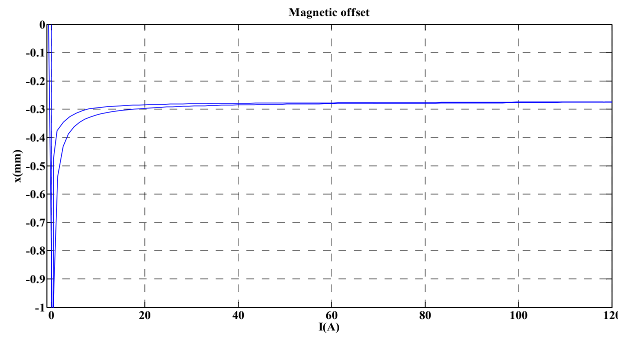

Figure 4: Magnetic axis offset with respect to the coil axis as a function of the current for TLQ #6.

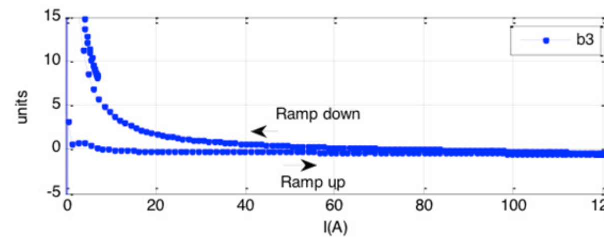

Figure 5: Dynamic behaviour of sextupole harmonic in pulsed mode for TLQ #6.

CONCLUSION

The impact of eddy currents on the integrated field has been measured to be negligible, leaving large margin for the 400 μs window of stability that must be synchronized with the beam. In particular, conditions at the end of the flat-top are equivalent to DC mode. This justifies replacing stepwise with DC measures for magnetic axis and integrated gradient.

However, we have seen that hysteresis effects depend, in a critical manner, upon certain details of the excitation cycle such as the reproducibility of the oscillations at the end of ramp-down. It must be remarked that this work presents for the first time the dynamic behaviour of individual high-order field harmonics with a resolution of a few microseconds.

Also the magnetic axis of the quadrupoles was measured in the DC mode. The impact of systematic errors and the external field in the low current were estimated and corrected. All the quadrupoles have been accepted and are currently being installed, with only two out of 21 being in need of transversal axis offset adjustment.

ACKNOWLEDGEMENT

We wish to thank R Beltron Mercadillo, O. Dunkel, S. Joffe, L. Gaborit, D. Giloteaux, G. Golluccio, G. Deferne (CERN) for their support during this measurement campaign.

REFERENCES

[1] A. M. Lombardi *et al.*, “Linac4 Technical Design Report”, CERN, Geneva, Switzerland, Rep. CERN-2006-022-HIPPI, 2006.

[2] L Vanherpe, “Linac4 Transfer Line Quadrupole Electromagnets”, CERN, Geneva, Switzerland, Rep. CERN-2012, Jan. 2012.

[3] L Vanherpe, “Magnetic Measurements Specification for the Linac4 Transfer Line Quadrupole Electromagnets”, CERN, Geneva, Switzerland, Rep. CERN-2014-01, Jan. 2014.

[4] R. Chritin *et al*., “Measuring Eddy Current Contributions in Normal Conducting Magnets”, in *Proc. Internal Magnetic Measurement Workshop (IMMW17)*, La Mola, Spain, Sep. 2011.

[5] P. Arpaia *et al.*, “Performance of a fast digital integrator in on-field magnetic measurements for particle accelerators”, *Rev. sci. Instrum*, vol. 83, p. 024702, Feb. 2012.

[6] J. M. Cravero, “Design of The DC-DC Power Stage of the Capacitor Charger for MAXIDISCAP Power Converters”, CERN, Geneva, Switzerland, Rep. CERN-2014-01, Jan. 2014.

[7] M Buzio, S. Kasaei, L. Fiscarelli, “Magnetic Measurements of Fast Pulsed Electromagnetic Quadrupoles for Linac4 Transfer Line”, CERN, Geneva, Switzerland, Rep. CERN-2015-03, Mar. 2015.

ISBN 978-3-95450-182-3