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MEASUREMENT OF EDDY CURRENT TRANSIENTS IN FAST-CYCLED LINAC QUADRUPOLE MAGNETS AT CERN

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Abstract – The paper deals with a fast measurement technique of electromagnetic transients due to eddy currents in fast-cycled magnets for linear particle accelerators. First the context of the problem, related to the need for accurate control of the magnetic field quality in order to ensure the stability and performance of the particle beam in dynamic conditions (field ramps up to about 700 T/s) is outlined. Then the measurement technique and the setup employed are described by referring to a case study on a quadrupole magnet for Linac4, a new linear particle accelerator currently being built at CERN (European Organization for Nuclear Research). Finally, the results of the measurement campaigns carried out on a quadrupole magnet and on a reference air-core solenoid are discussed.

Keywords: eddy current measurement, pulsed resistive quadrupole magnet, linear accelerator

1. INTRODUCTION

A new linear particle accelerator (Linac4) is currently being built at the European Organization for Nuclear Research (CERN) to replace the existing Linac2 and provide a high-intensity, high-quality beam source for the Large Hadron Collider injector chain [1]. This machine includes a large number of narrow-aperture quadrupole electromagnets to keep the beam focused along the acceleration path. These magnets must provide a high gradient (of the order of 20 T/m) in a very limited space, and are therefore powered with relatively high currents up to 200 A. Size constraints make efficient water cooling difficult to achieve, therefore the field is switched on and off in synchronization with the passage of particle bunches in order to minimize the duty cycle and limit ohmic heating.

The so-called Type III quadrupole (Fig. 1), actually an old Linac2 spare laminated iron-core magnet, is going to be re-used in Linac4 (magnet parameters are listed in Table 1) [2]. The current ramp-up lasts about 200 μs and is followed by a flat-top of 600 μs, on which the field is required to be stable within 10^{-3} (see the excitation waveform in Fig. 2). The stability of the flat top is determined mainly by the decay of the eddy currents induced during the ramp, although it may be affected by also by the ripple of the power supply or other parasitic effects.

Eddy current effects are hard to predict accurately because they depend on a number of uncertain parameters, such as the microstructural and magnetic properties of the iron yoke, its temperature, the surface resistivity of the laminations, or the mechanical tolerances leading to unwanted air gaps in the magnetic circuit. As a consequence, laboratory testing is necessary to validate both design calculations and manufacturing quality.

A standard method to alleviate problems due to eddy currents in this kind of applications consists in applying a current overshoot at the end of the ramp-up, also known as *pre-emphasis compensation* (see [3] for a description of the method in a different context). This correction is already implemented in the power supply used for the tests, however accurate measurements were never done for Linac2 and, in addition, the nominal powering cycle for Linac4 is somewhat different. Therefore, the stability of the response of the magnet in the present conditions within the required tolerance has to be verified. to be defined.

In this paper, a measurement technique in view of future application to a number of similar cases concerning fast-pulsed accelerator magnets in operation or being designed at CERN is proposed. In particular, in Section 2 the proposed test method is described. In Sections 3 and 4, the measured response of the quadrupole magnet and of a reference solenoid are discussed. Finally, in Section 5, the effect of adding a conductive beam pipe inside the magnet is shown.

Table 1: Main physical and operating parameters of a CERN Linac 2 Type III quadrupole magnet

Parameter	Value
Length (mm)	56
Outer Ø (mm)	80
Aperture Ø (mm)	28
Central gradient (T/m)	16.5
Inductance (μH)	475
Resistance (mΩ)	73
Maximum Current (A)	200
Rise time (ms)	0.2
Flat-top duration (ms)	0.6
Stable field window length (ms)	0.2
Stable field tolerance (-)	10^{-3}

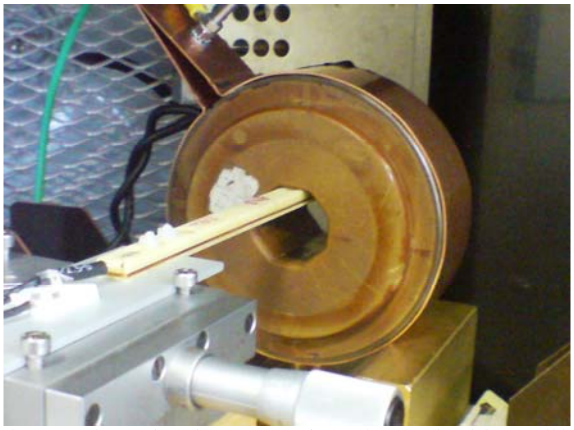

Figure 1: The quadrupole magnet on the test bench. The pick-up coil is mounted facing one of the four poles (embedded inside the insulation, hence not visible) to maximize flux linkage. The copper foil bracket fastened at the outside of the magnet is used to ground the iron yoke, both for safety and for signal integrity reasons.

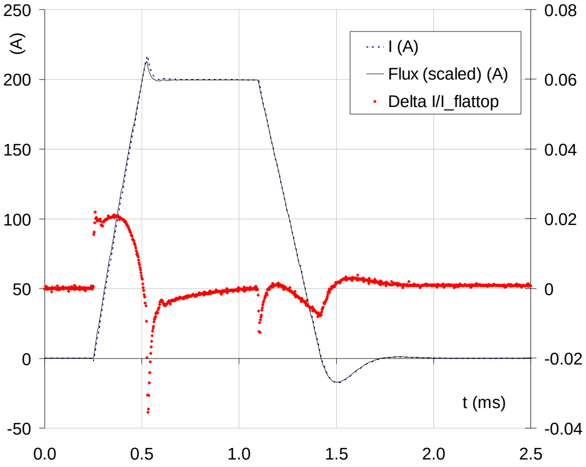

Figure 2: Measured waveforms of the excitation current $I(t)$ (continuous curve), the normalized magnetic flux $\phi(t)/L_{CM}$ (dashed) and their difference relative to the flat-top value $\Delta I/I_{flattop}$ (dotted). (see Section 2.3)

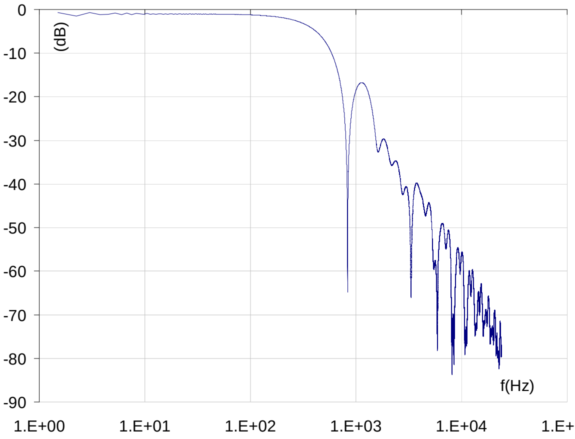

Figure 3: Power spectrum of the magnetic field signal.

2. MEASUREMENT METHOD

In the following, (i) the *design of the measurement method*, (ii) the *test set up*, and (iii) *treatment of acquired signals* are illustrated.

2.1 Design of measurement method

The simplest approach to the investigation of the dynamic response of a pulsed magnet consists in measuring the field transient, scaling it suitably, and comparing it to the excitation current history. Ideally, a close match points out the magnetic field follows faithfully the injected current, such as desired. Another possibility lies in the measurement of the full AC transfer function, in principle carried out by sweeping the range of frequencies of interest while recording amplitude and phase of the response. While potentially more informative, this method gives results of more difficult interpretation in a non-linear system such as an iron-dominated magnet, where saturation at high field plays a significant role. Moreover, for fast cycled linear magnets, this measurement would entail the practical difficulty of finding a power supply able to deliver a current sine wave of 400 A peak-to-peak at frequencies in the tens of kHz range. For this reason, tests have to be carried out in the time domain only; besides, in this way the information most relevant for beam control, i.e. whether (and when) the magnetic field becomes stable can be found straightforwardly.

The bandwidth of the magnetic transient considered extends well into the 100 kHz range (see Fig. 3), thus the only viable sensors are either Hall effect plates or classic fixed-coil fluxmeters (see [4] for an example of a similar application). A pick-up coil has the main advantage of being sensitive to the whole integral of the magnetic field, which is the quantity affecting the particle beam. As long as the whole field is linked, the actual position of the coil is rather unimportant, provided of course that it is stable during a measurement. In addition, the output signal is proportional to the time derivative of the field, which in this case is so high (~ 700 T/s) as to guarantee a level of several Volts without the need for an expensive high-bandwidth instrumentation amplifier, as would be required for a Hall plate. Therefore, a house-made pick-up coil with N_T=4 turns, length L_C=200 mm and total area A_C=80 cm^2 was selected.

2.2 Test setup

The setup used for the tests is shown schematically in Fig. 4. The magnet is excited by a capacitive discharge power supply (CERN-design “Maxidiscap” type), triggered externally by a 30 V square pulse (this is a long-standing CERN standard aimed at distributing trigger pulses over cable lengths of several kilometers) and current-controlled via an internal Hitec MACCplus DCCT (Direct Current-to-Current Transformer). Two additional DCCTs (Pearson, Hitec Zero-Flux) have been added externally to cross-check the measurement (results are given in Section 4.2). This power supply, conceived for stable accelerator operation over a period of decades, does not allow easy manipulation of its output waveform parameters such as ramp rate or flat-top level, and this has somewhat limited the range of investigation.

Besides magnet current, the measured quantities include the output voltage of the pick-up coil and, as a term of comparison, the voltage at the terminals of the magnet coils.

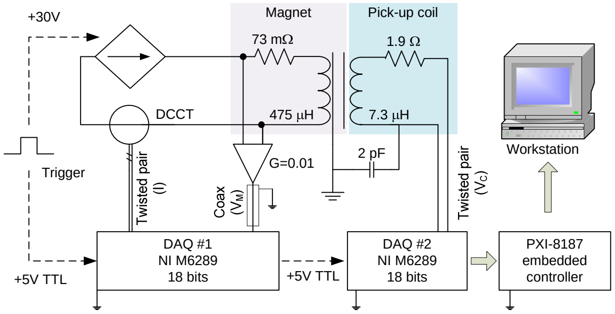

Figure 4: Measurement setup block diagram

The acquisition system is based upon a pair of 625 kHz, 18-bit PXI ADC cards (National Instruments M6289), connected via an embedded PXI controller to a PC running a custom LabView program and triggered synchronously to the power supply (the two ADCs are set in a master/slave configuration). The use of two cards is motivated mainly by the need to achieve up to 400 kHz sampling rate on two channels simultaneously, however it was remarked that splitting signals across different cards also helps eliminating cross-talk problems. While the pick-up coil signal V_C does not need special conditioning, the magnet coil tension signal V_M reaches about 500 V and must be divided. The signal transmission lines use either a standard twisted pair or coaxial cable with grounded shields (swapping cables proves that choosing one or the other does not affect appreciably the measurement).

2.3 Treatment of acquired signals

The e.m.f. V_C induced in the coil has to be integrated to obtain the linked flux ϕ. Assuming that the quadrupole is excited starting from a demagnetized state at $t=t_0$, ϕ is calculated as:

$$\phi(t) = \frac{1}{N_t}\int_{t_0}^{t} V_C(t)dt \tag{1}$$

In the ideal (linear) case, this flux would be simply proportional to the excitation current via the mutual inductance L_{CM}, which depends on the geometry and on the magnetic permeability of the iron core [5]:

$$\phi\,(\mathrm{t}) = L_{CM}\, I(\mathrm{t}) \tag{2}$$

In reality, an effective current difference ΔI can be defined:

$$\Delta I = \frac{\phi(t)}{L_{CM}} - I(t) \tag{3}$$

that will be in general nonzero, containing contributions from all non-ideal effects. In Fig. 2, the rough invariance of $\Delta I(t)$ during the ramp-up can be argued, then it undergoes a rapid transient and finally decays on the flat-top. Assuming that the transient has completely died out at the end of the flat top, i.e. $\Delta I(t_S)=0$, the mutual inductance is derived:

$$L_{CM} = \frac{N_T I(t_s)}{\int_{t_0}^{t_s} V_C(t)dt} \tag{4}$$

Considering that the measured signals are affected by electrical noise, mains hum, power supply ripple etc., the accuracy of this calculation can be increased by averaging both terms over a short time interval $t_S - \Delta t \le t \le t_S$.

3. ANALYSIS OF THE MAGNETIC RESPONSE

Measurement results are best interpreted by comparing the excitation current I to the normalized flux ϕ/L_{CM}, expressed in Amperes, as shown in Fig. 1 and Fig. 5. The relative difference $\Delta I/I_{flattop}$ can then be compared directly to the required stability tolerance. The following features of the magnetic response can be observed:

- eddy currents in the iron yoke screen field changes in the magnet aperture. As it is well-known, the field lags the current by a time Δt proportional to the permeability and to the conductivity of the material (and not dependent on the ramp rate). In this case the delay in the initial (linear) part of the ramp is about 2µs.
- when the iron is in its linear (constant permeability) range, the coil voltage and the time lag will be constant. As the material starts to saturate, the dB/dt and hence the coil voltage drop, while the apparent lag increases (Fig. 5).
- At the end of the pre-emphasis transient current and magnetic field oscillate briefly. The phase delay between field and current is consistent with Δt
- As the current stabilizes, eddy currents are expected to decay exponentially with a time constant of the same order as Δt.

The measured $\Delta I(t)$ waveform, in fact, shows on the flat-top a large exponential decay effect with time constant of about ~100 µs which is dramatically inconsistent with both the time constant estimated above and expectations based on eddy-current calculations. The source of this measurement artefact to date is not clear, however but is believed to be due to either a parasitic capacitance, EMC coupling or transmission line mismatch the acquisition chain. This belief is supported by the following findings:

- the effect is present also when the magnetic field is generated by an air-core solenoid (see Section 4.2),

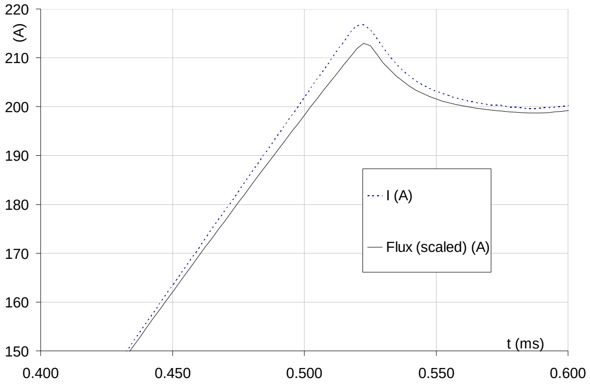

Figure 5: Measured waveforms of the excitation current and the normalized magnetic flux (detail of Fig. 1).

- the effect is independent from iron yoke temperature, so magnetic viscosity-type effects [6][7] can be excluded (see the results of oven tests in Fig. 6).

The following sources of perturbation have also been ruled out:

- current flowing in the pick-up coil (the ADCs have a very high input impedance about 10 GΩ)
- high-frequency effects in the magnet conductor (the copper skin depth at a few kHz is of several millimetres, compared to the ~1 mm size conductor)
- thermal effects in the conductor (the temperature rise due to ohmic heating is less than 0.1 °C)
- parasitic capacitance between the pick-up coil and the iron yoke (the capacity is very small, about 2 pF; moreover, grounding or not the yoke has no effect on the measurement)
- 50 Hz mains hum (digital notch filtering does not change the results, consistently with the spectrum shown in Fig. 3)

To summarize, the decay artefact masks completely the exponential decay of the eddy currents on the flat-top, however we believe that the time constant of the eddy currents can be estimated reliably from the time lag measured during the ramp. Moreover, in any case the measured flux can be observed to stabilize within the required 10^{-3} about 400 μs into the flat-top, which proves the viability of the magnets for the accelerator (let us also recall that these particular magnets have already been in operation for three decades without problems).

4. CHARACTERIZATION OF THE ACQUISITION SYSTEM

In the following, (i) the *dynamic comparison of the DCCTs*, and (ii) the *reference measurement in an air-core solenoid* are illustrated.

4.1 Dynamic comparison of the DCCTs

Both magnetic field and excitation current, contrary to expectations, do not appear to be perfectly stable during the flat-top, thus it was decided to investigate the dynamic performance of the internal DCCT by comparing it to two external units. The measurement was carried out with all three different sensors at the same time. As shown in Fig. 7, the sensor with the highest nominal bandwidth (Pearson) shows a large 3% drop on the flat-top that is not confirmed by the other two, which makes it unsuitable for our purposes. The Hitec Zero-Flux, conversely, is very stable on flat-top but exhibits a clear delay of about 8 μs on the ramp-up, which again is not acceptable. The Hitec MACCplus DCCT in-built in the power supply, on the other hand, shows no adverse effects (besides some negligible fluctuations on the flat-top) and has been therefore used as a reference throughout the test.

4.2 Reference measurement in an air-core solenoid

The acquisition chain has been tested by running the measurement inside an air-core solenoid having roughly the same resistance and inductance as the quadrupole magnet (although the field is an order of magnitude smaller). Since no iron yoke is present, the magnetic field is expected this time to follow very closely the excitation current. However, from the results shown in Fig. 8 one can see that is indeed not the case. In particular:

- on the ramp-up the current measurement *lags* the field by a delay $\Delta t_{REF}=5.5\pm0.5$ μs, where the uncertainty derives from the fact that the lag appears to increase with time. As there is no physical reason why the field should anticipate the excitation, this effect can be ascribed to the limited bandwidth of the DCCT output amplifier (note that the same problem affects the Pearson sensor, as shown in Fig. 7). A time shift equal to $-\Delta t_{REF}$ can be used therefore to correct all Hitec MACCplus measurements taken in the quadrupole magnet, in particular those shown in Fig. 1 and 5.
- on the flat-top, an exponential decay with amplitude and rate similar to those measured in the quadrupole magnet can be observed (see Fig. 8). This confirms that the artefact is linked to the acquisition system and does not represent the behaviour of the magnet under test.

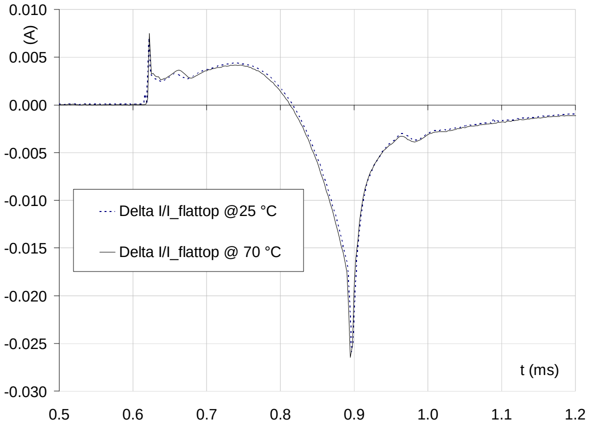

Figure 6: Essentially identical ΔI curves measured at 25 °C and 70 °C

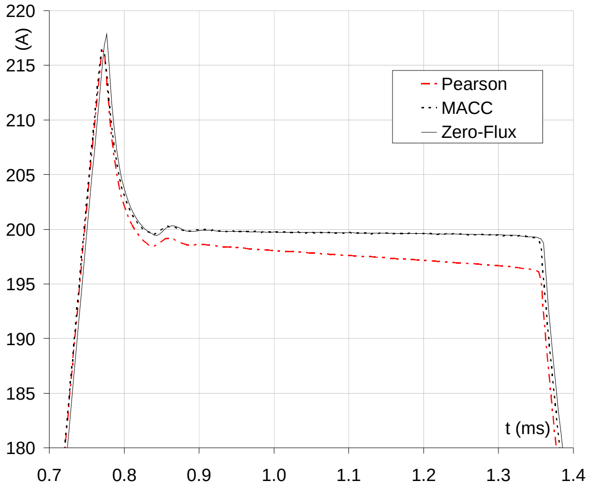

Figure 7: Comparison between the three different current sensors (detail)

5. EFFECT OF BEAM PIPE INSERTION

The magnet tests were repeated with its aperture occupied by a vacuum chamber (Ø 25mm) which, despite being made of relatively resistive stainless steel, has a significant screening effect upon the inner magnetic field.

The results plotted in Fig. 9 show that the amplitude of the transient effects is much larger, which is consistent with the field lag on the ramp (not shown in the figure) being increased to about 10 µs. At any rate, the magnitude of the perturbations on the flat-top, which is important for the beam, is unaffected.

6. CONCLUSIONS

The method presented in this paper allows the acquisition of very detailed information about the transient behaviour of accelerator-type magnets during fast excitation cycles. It is clear that, in this range of frequency, we have been working at the limit of the capabilities of our present instrumentation. In particular, parasitic effects can evidently affect the measurement precision at the percent level, i.e. one order of magnitude above our goal.

The dynamic measurement of the signals on the ramp-up can provide, it is felt, a reliable indication on the time constant of the eddy currents that were our primary concern. Their behaviour on the flat-top, which is important for the operation of the accelerator, is however completely masked by a spurious exponential decay.

While the viability of the present magnets is proven, future test campaigns scheduled for similar cases require all acquisition artefacts to be eliminated. To help doing so, we intend to investigate transmission line effects with a network analyser, and to use more flexible power supplies to carry out more easily parametric studies of magnetic field response to different ramp rates and current levels.

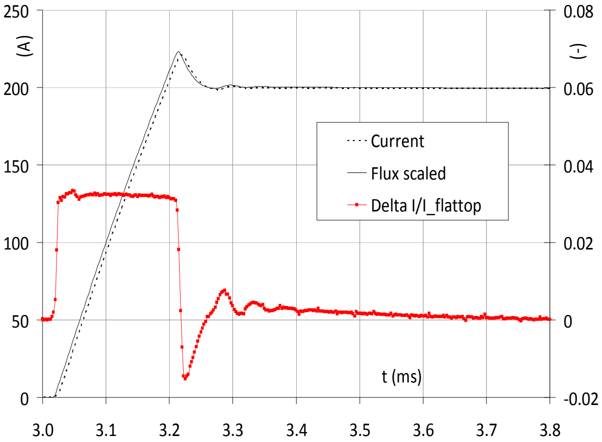

Figure 8: flux and current measured and their difference in an on air solenoid.

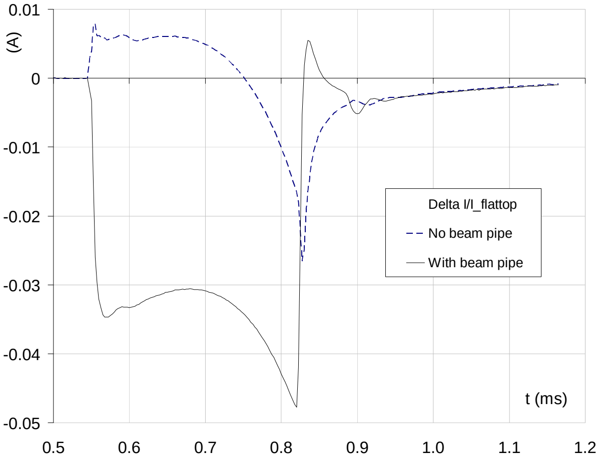

Figure 9: Comparison between ΔI measured with and without beam pipe.

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