MAGNETIC MEASUREMENTS OF PERMANENT AND FAST-PULSED QUADRUPOLES FOR THE CERN LINAC4 PROJECT

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Abstract

Linac4 is currently under construction at CERN to improve intensity and reliability for the whole accelerator chain. This machine will include about 120 permanent quadrupoles housed in the Drift Tube tanks, as well as about 80 electromagnetic quadrupoles. This paper describes the magnetic measurements carried out at CERN on the first batch of quadrupoles, including several prototypes from different manufacturers, as well as those done on several spare Linac 2 magnets reused in Linac 4's 3 MeV test stand. We first describe a prototype test bench based on technology developed for the LHC and able to carry out high-precision harmonic measurements in both continuously-rotating and stepping-coil mode. Next we present the first results obtained in terms of field strength, harmonics quality and effects of fast eddy current transients. Finally, we discuss the expected impact of these findings on the operation of the machine.

INTRODUCTION

Linac 4 is a 160 MeV, 352 MHz proton Linac currently being built at CERN and due to replace the ageing Linac 2 in 2015, providing higher intensity beams for the whole accelerator chain [1]. This ~100 m long machine and the associated transfer lines require about 230 magnetic elements, including prototypes and spares, essentially distributed as follows:

- 11 Electromagnetic Quadrupoles (EMQ) in the Chopper line. These are old refurbished Linac2 spare units.
- 111 new Permanent Magnet Quadrupoles (PMQ) in the Drift Tube Linac (DTL), along with 15 more in the Cell-Coupled Drift Tube Linac (CCDTL).
- 43 new EMQ in the Linac and transfer lines.
- 26 steerers, 7 bending magnets and 2 solenoids.

Many magnets, especially those in the transfer lines, have conventional resistive designs with apertures from 40 to 124 mm and can therefore be measured easily with well-established instrumentation. We expect to test only a small production sample of these units, which shall not be discussed further here. On the other hand, the PMQs and EMQs are at the same time potentially critical for the machine and rather difficult to measure precisely, so they will be the main focus of this paper.

First of all, these quadrupoles are characterized by a small aperture between ∅20 and ∅40 mm. While the available stretched wire system [2] provides integral Gdℓ even inside such small bores with good accuracy, to measure all other field parameters we had to develop a dedicated rotating coil system (for a given peak field the S/N ratio varies as $\varnothing^n$ with n=3~4, so small apertures are strongly penalized). In case of the EMQs the difficulty is compounded by the fast cycle rate, typically 2.4 ms which corresponds to a field ramp rate of more than 700 T/s. In all cases, the small size makes it possible to turn the magnet around in several orientations during the tests, which allows one to measure systematic offsets and thus improve the accuracy of the results [3].

CERN R&D activities for test instrumentation and procedures started in 2007. To date, a total of about 25 PMQs and EMQs have already been measured, the hardware of the test bench is finished and characterised, and the first batch of series PMQs is expected shortly. In the following sections we shall briefly describe the test bench, report the results obtained on PMQs and EMQs, and finally discuss their implications.

THE LINAC4 TEST BENCH

Linac2 magnets were measured in the '70s with a rotating coil system which, while still partly functional, can hardly be expected to provide the reliability needed in the long term. For this reason we have built a new test bench, shown in Fig. 1, based on novel PXI hardware and C++ software architecture [4].

The system is mechanically adaptable to a large range of small-aperture magnets, including all Linac4 elements. Harmonic measurements can be done in two basic modes, i.e.: standard continuously rotating coil, optimized for quasi-static fields; and stepwise rotating coil, which may be used for fast-cycling EMQs. The crucial component is a dual-mode incremental/absolute angular encoder which allows precise coil positioning within ~50 µrad.

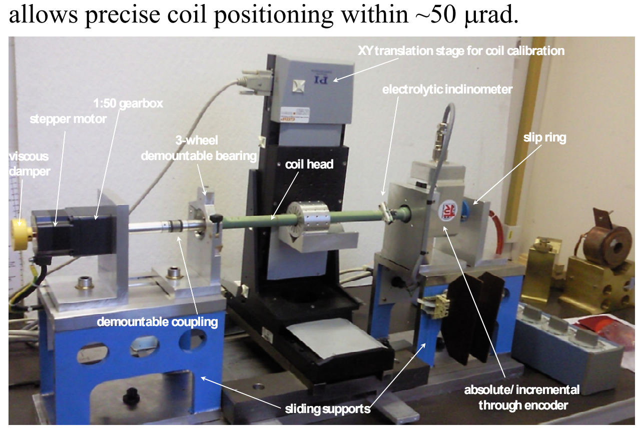

Figure 1: Linac4 harmonic coil test bench.

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The currently installed rotating shaft, including two thin nested coils, has a poor mechanical stability and is going to be replaced shortly by a more robust design, based on winding forms carved directly onto the outer surface of the shaft.

PERMANENT MAGNET QUADRUPOLES

Linac4 PMQs are made by enclosing 8 or 16 suitably magnetized blocks of radiation-resistant Sm_2Co_{17} in a cylindrical aluminium shell. (Fig. 2). The design with segregated blocks allows for fine tuning of their radial position, carried out iteratively by the manufacturer to achieve individually prescribed integrated gradients in the range of 1 to 3.3 Tm/m within 0.5%. The quadrupoles will be inserted into copper Drift Tubes (DT), which will be electron-welded and mounted into three DTL tanks.

In order to assure the desired quality, all PMQs shall be tested at CERN both upon reception and after installation in the DTs. Once the DT is mounted into the tank, in fact, no further adjustment is possible and so any degradation of $Gd\ell$ or magnetic centring must be carefully verified. Preliminary tests indicate that localised heating due to the welding does not affect appreciably the $Gd\ell$. Production statistics will be monitored closely during series tests, taking also into account any complications due to the splitting of the contract between multiple firms.

Magnetic direction and axis must be controlled within 1 mrad and 0.1 mm respectively throughout the assembly operation. Ideally, also the orientation of the magnetic axis in terms of pitch and yaw should be contained within 2 mrad. However, the measurement of these angular parameters over so short a length appears to be very difficult and has not been attempted so far. Field errors, specified to be less than 1% at 7.5. mm on each harmonic, can be measured accurately enough by the rotating system in its current configuration.

The measurement of magnetic axis of individual PMQs once inside a tank is being considered as an additional safeguard against mechanical uncertainties. To date, no instrument is available at CERN to carry out a magnetic axis measurement in such a small aperture over a length of ~2 m. However, potentially suitable systems such as vibrating wires are being studied for future applications (e.g. CLIC) and in principle could be adapted to this task.

Presently, a total of 15 prototype and pre-series PMQs from four manufacturers have been measured. The results obtained, summarized in Table 1, show that both field quality and strength are well within tolerances. The only outstanding issue is the measurement of the field direction, which in the current test bench configuration is affected by a poor reproducibility around 0.6 mrad (expected to improve with the new coil in preparation).

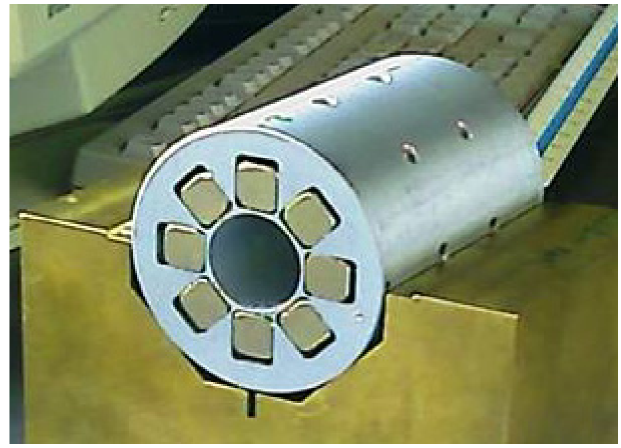

Figure 2: Prototype 80 mm PMQ.

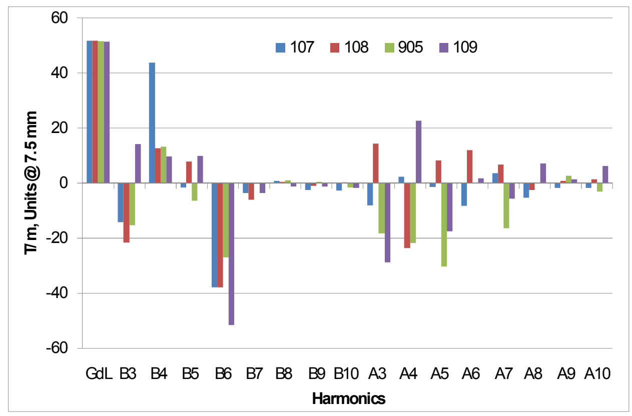

Figure 3: Typical field harmonics in 45 mm PMQs.

Table 1: Summary of magnetic test results of PMQs.

Field Error	Pre-series (4× 45 mm 1× 80 mm)	Estimated uncertainty (RMS)	Tolerance
$Gd\ell$ (%)	0.04~0.30	0.20	1
Direction (mrad)	0.01~0.60	0.60	1
Axis (mm)	0.02~0.05	0.03	0.1
Harmonics up to n=10 (%)	0.06~0.12	<0.06	1

ELECTRO-MAGNETIC QUADRUPOLES

The EMQs are compact, air-cooled laminated iron-core magnets, powered with up to 300 A for a very short time to fire up in synch with the passing bunches. Each quadrupole is individually powered and mechanically accessible once installed in the machine, therefore field and alignment tolerances are less critical. The primary concern in this case is the time lag between field and excitation caused by eddy currents, which should be known within a few 10 µs.

About 10 old Linac2 spares are included in the Linac4 Chopper line, now completed, and most of them have been tested magnetically for eddy currents before and/or after installation. The test setup, shown in Fig. 4, is based on the comparison between the excitation current and the magnetic flux, integrated and scaled to coincide with the excitation current at the end of the flat-top, as shown in Fig. 5 [5]. As the beam is present only on the flat-top of the cycle, the main parameter of interest is the time constant τ_E of the exponential decay of the difference signal. As it happens, τ_E is independent from the position of the measuring coil, which has greatly facilitated the measurement inside the ~6 m long beam pipe of the Chopper line.

The results obtained show that for typical "Type III" quadrupoles the response can be approximated by the superposition of a slow decay with $\tau_E \approx 190$ μs, due to the eddy currents in the yoke, and a fast one with $\tau_E \approx 30$ μs due to the eddy currents in the beam pipe (Fig. 6). In the majority of cases this is not a concern since a sufficiently long and stable plateau (error ≤ 1% over 400 μs) can be easily obtained. The only exception are the so-called Type VII quadrupoles (see Fig. 5), which are about three times larger than Type III and exhibit a peak error of about 30% at the end of ramp-up.

At present, all EMQs are planned to be tested upon reception at CERN for eddy current effects, in addition to magnetic strength and axis. The first prototypes are expected to arrive at the end of 2010.

CONCLUSIONS

The magnetic design of PMQs has been proven sound and the quality of the first pre-series is well within specifications. The stability of $Gd\ell$ over more than 2 years and after integration in a DT has been measured to be within a few 10^{-4}, which is very reassuring; however, further tests concerning the possible long-term effects of galvanic Cu-Al corrosion are still pending.

A measurement method to evaluate eddy current transients on the scale of a few microseconds has been developed. As a first result, the screening effect of the Cu chopper plates has been measured to be negligible. The timing of the excitation of Type VII quadrupoles shall be adapted to the measured lag in the magnet's reponse.

The new Linac4 test bench performs very satisfactorily, despite some shortcomings of the current rotating coil that can be recovered by an adapted calibration procedure and an improved coil design.

ACKNOWLEDGEMENT

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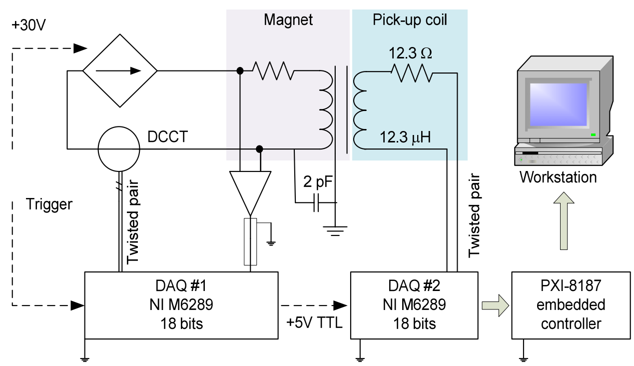

Figure 4: Test setup for eddy current effects.

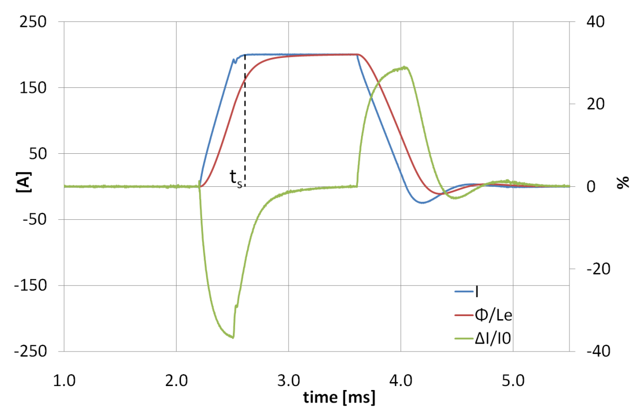

Figure 5: Excitation current, scaled field and their difference in a Type VII Linac2 quadrupole.

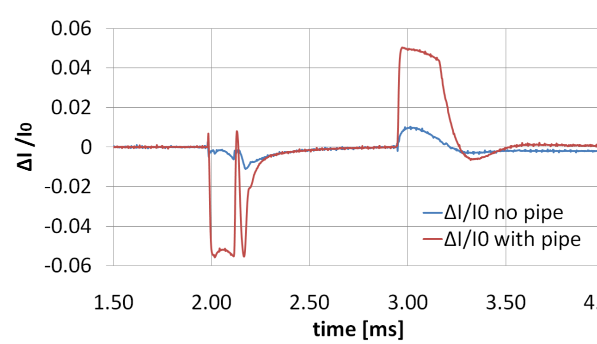

Figure 6: Difference between scaled field and current in a Type III Linac2 quadrupole, showing the further field attenuation due to the beam pipe.