Design optimization of an ironless inductive position sensor for the LHC collimators

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ABSTRACT: The Ironless Inductive Position Sensor (I2PS) is an air-cored displacement sensor which has been conceived to be totally immune to external DC/slowly-varying magnetic fields. It can thus be used as a valid alternative to Linear Variable Differential Transformers (LVDTs), which can show a position error in magnetic environments. In addition, since it retains the excellent properties of LVDTs, the I2PS can be used in harsh environments, such as nuclear plants, plasma control and particle accelerators. This paper focuses on the design optimization of the sensor, considering the CERN LHC Collimators as application. In particular, the optimization comes after a complete review of the electromagnetic and thermal modeling of the sensor, as well as the proper choice of the reading technique. The design optimization stage is firmly based on these preliminary steps. Therefore, the paper summarises the sensor’s complete development, from its modeling to its actual implementation. A set of experimental measurements demonstrates the sensor’s performances to be those expected in the design phase.

KEYWORDS: Digital signal processing (DSP); Hardware and accelerator control systems; Accelerator Subsystems and Technologies; Instrumentation for particle accelerators and storage rings - high energy (linear accelerators, synchrotrons)

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1 Introduction

High-accuracy and high-precision linear position sensors are often required for reliable position and displacement measurements in harsh environments like nuclear plants, plasma control and particle accelerator facilities [1–5]. Such applications usually present a particular list of constraints for the sensor’s performances [1–7].

For high-precision position sensing in harsh environments (such as nuclear plants, plasma control or particle accelerator applications like the one described in the following subsections), the Linear Variable Differential Transformer (LVDT) is often the preferred choice [8]. It is a
high-accuracy and high-precision sensor when proper conditioning algorithms [9, 10] are used. It can be suitable for radioactive environments with specific sealing techniques and materials [11], it has virtually infinite resolution, very long lifetime due to contactless sensing [12] and good robustness [13]. Nevertheless, in spite of such good characteristics, this sensor has proved to be sensitive to external DC/slowly-varying magnetic fields [14, 15], due to the intrinsic non-linearity of its ferromagnetic materials [16].

A new linear position sensor design has been conceived to overcome the problem of LVDT magnetic interference, with the aim of fully rejecting the effect of external magnetic fields, and creating a device which exhibits complete immunity to such fields keeping the same good properties (mentioned above) as LVDTs. The Ironless Inductive Position Sensor (I2PS) has been proposed [8, 17] to be a valid alternative to LVDTs in magnetic environments. The I2PS presents the same excellent properties of LVDTs, adding the immunity to external magnetic fields, since the sensor does not involve the use of ferromagnetic materials.

After introducing the LHC Collimators application and its strict requirements, this paper presents the whole development of the I2PS, in terms of electromagnetic and thermal analysis, study of reading techniques and conditioning algorithms, and then exploits the results coming from these necessary points to successfully optimize the design of an Ironless Inductive Position Sensor for the LHC Collimators application.

Section 2 introduces the working principles of the LVDT and I2PS, stressing also the differences and analogies between the two solutions. Section 3 explains the results coming from the sensor’s characterization (electromagnetic, thermal and metrological), whereas section IV focuses on the proposed optimization procedure for the sensor’s application and its actual implementation.

1.1 The LHC collimators application: framework

The LHC Collimators are part of the complex machine protection system of the CERN Large Hadron Collider [1]. Their main function is to protect the machine from uncontrolled particle losses, absorb particles which are travelling outside the primary beam halo and reduce the noise for the LHC experiments [18–20]. Actually, given the high energy of the LHC beam, a beam loss can cause serious damage for the accelerators components along the ring (e.g. superconducting magnets’ quench [18]).

The active part of a collimator consists of a pair of graphite blocks (jaws) which can be positioned next to the beam to reduce its transverse size. The jaws are generally 1-meter long and can be moved in a perpendicular direction to the beam axis, with an aperture of several tens of millimetres [20]. It is possible also to specify a tilt angle with respect to the beam trajectory [19]. Each collimator has several electrical devices installed on, particularly stepper motors (for the jaw positioning), linear position sensors (for the position information), temperature sensors (thermal monitoring), and it hosts an ad hoc cooling system.

The operational environment of the LHC collimators is particularly challenging for any electromagnetic device. As a matter of fact, the intense nuclear radiation prevents any electronics from being installed nearby the collimator. Additionally, magnetic field leakage coming from nearby devices or cables can perturb the functioning of sensors.
1.2 The LHC collimators application: requirements

Given that the primary function of the collimator is carried out by the jaws, the most important requirement for it to be operational is the positioning uncertainty. The target uncertainty is one tenth of the nominal beam size at the collimator (200 $\mu m$), thus the jaws position has to be measured with a 20-$\mu m$ maximum target uncertainty. Actually, this is the specification for the linear position sensor.

Besides the uncertainty, a set of strict requirements for the linear position sensor are specified by the particular operational environment of the LHC collimators, described in the last subsection. The sensor has to be fully operational with intense nuclear radiation (i.e. integrated dose of 10 MGy over 10 years), it should have a very good robustness and long lifetime (of the order of 10 years). Finally, the position reading should not be affected by external magnetic fields.

Given the properties listed above, the LVDT is the choice which meets the majority of the requirements and it is actually installed on the LHC collimators. In particular, thanks to its outstanding performances, the LVDT position measurements performed in the LHC Collimators can reach an uncertainty of the order of a few micrometers, successfully meeting (and surpassing) the required limit.

Nevertheless, the sensitivity of LVDTs to external magnetic fields introduced above has been also verified. In particular, the problem has been first observed in particular location on the LHC ring and transfer lines, where the magnetic field generated by the power converter currents influenced the LVDT readings [14, 15]. Such high currents are dedicated to the pulsed magnet pre-cycles and can be considered as slowly-varying: the rise time is in the order of seconds, whereas the LVDT operational frequency is in the kHz range [15]. In spite of this, the external magnetic field produces a position drift on the LVDT readings which can reach several hundreds of micrometers [14, 15]. Given the abovementioned target uncertainty, this can be a serious issue.

2 Position sensing in harsh environments: working principles

As detailed in [8], several linear position sensors are not suitable for the harsh environment specifications listed in subsection 1.2. Some of them (e.g. potentiometers) cannot provide enough accuracy and precision, whereas numerous other solutions (e.g. encoders, capacitive sensors) can be seriously negatively affected by nuclear radiation [8]. The LVDT is, as anticipated, the solution which satisfies the majority of the requirements.

2.1 The Linear Variable Differential Transformer

The working principle of a LVDT is illustrated in figure 1. It is a 3-coil structure, with an energized primary coil and two secondary coils. The supply can be performed either with a voltage or a current source [21]. The ferromagnetic core is physically attached to the element whose position is to be measured. When the core is in the center, the two secondary voltages are equal; on the contrary, when the core moves away from the center, the secondary voltages are not equal. Specifically, the voltage on the secondary coil in the direction of the movement is higher with respect to the voltage on the other secondary coil, since the displacement of the ferromagnetic core increases the mutual inductance between the primary and one secondary coil, whereas it decreases
the mutual inductance with the other secondary. The result is that the position of the core can be easily extracted by a simple differential reading of the secondary voltages, or by using a ratiometric reading technique [22, 23]. The advantages of using a ratiometric technique for the LVDT reading include a temperature-independent and primary-independent position measurement. In addition, if the secondary amplitudes are demodulated using a three-parameter Sine-fit algorithm (3PSF), the position uncertainty can be as small as a few micrometers [19]. A constant, so-called gain, gives the proportionality between ratiometric and position. A typical gain for LVDTs is 100 mm.

The advantages of the LVDT have been already listed. Furthermore, the simplicity of the working principle makes this solution even rather cost-efficient. The analytical study and the application of LVDTs in high-precision position measurements are a topic which has been widely documented in literature [24–26].

Regarding the materials, the core is not the only ferromagnetic part in the LVDT assembly. In fact, the external housing and the support bobbin are also usually ferromagnetic. The non-linearity of such materials (i.e. the non-linear relation between magnetic field and flux density, intrinsic of any ferromagnetic medium [27, 28]) makes an external DC/slowly-varying magnetic field polarize the materials in a different working point, modulating the secondary voltages accordingly [16]. Nevertheless, the description of the interaction of the external magnetic field with the magnetic materials’ ensemble is not trivial and depends on the magnetic properties of all parts. Measurements on standard LVDTs have however shown that position drifts of the order of hundreds of micrometers can be produced by an external flux density of 1 mT, which is the order of magnitude of the external field generated by the power converter currents next to the LHC Collimators [15, 21].

2.2 The Ironless Inductive Position Sensor (I2PS)

The structure of an Ironless Inductive Position Sensor (I2PS) is depicted in figure 2. It is a 5-coil structure, with two supply coils, two sense coils and a short-circuited moving coil. The two supply coils are energized so as to generate equal and opposite magnetic fields, as illustrated in figure 2. The supply signal can be either a voltage or a current [8]. As for the ferromagnetic core in a LVDT, the moving coil in an I2PS moves longitudinally, attached to the element whose position is to be measured. When the moving coil is in the center, the voltages induced on the sense coils are equal, since the current induced in the short-circuited moving coil is null (it is given by two
equal-and-opposite magnetic fluxes). When the moving coil moves away from the center, there is a non-null induced current in it, which generates a counter-acting magnetic field. This field perturbs the coupling between the supply and sense coils which the moving coil is facing. Therefore, the two sense voltages are not equal. As for LVDTs, the position of the moving coil can be extracted using a simple differential reading.

The presence of two supply coils (instead of a single coil, as for LVDTs) and the equal-and-opposite supply signals are a design choice to increase the sensitivity. For example, when the moving coil is facing Sense Coil 1 and Supply Coil 1 for the majority of its length, the magnetic field generated by this coil will perturb the coupling between these coils, but will enhance the coupling between Supply Coil 2 and Sense Coil 2. This gives a much better sensitivity to the sensor, with respect to the single-supply-coil solution, where the moving coil would always perturb the coupling between supply and sense coils, but by different amounts.

The I2PS coils are wound over non-conductive and non-magnetic supports. For this reason, an external DC/slowly-varying magnetic field cannot affect the position reading, which is performed selecting the voltage amplitudes at the operational frequency. In practice, all materials used for the I2PS exhibit a linear relation between magnetic field and flux density. This characteristic makes the I2PS immune to external magnetic fields.

Some additional remarks should be pointed out when comparing the I2PS to the LVDT. In a LVDT, the magnetically permeable core increases the coupling between the primary and secondary coil which is facing it. On the contrary, in the I2PS, the moving coil acts as a controlled disturbance on the inductive coupling between the supply and the sense coil which is facing it. The goal of the two sensors is nonetheless the same (i.e. to produce a spatially variable magnetic flux). In fact, the spatial modulation of the flux enables the estimation of the position.

Furthermore, figure 2 clearly shows that there is no contact between the moving coil and the fixed coil assembly. Therefore, the contactless sensing (which leads to a very long lifetime of the sensor), a well-known key-property of the LVDTs, is maintained in the I2PS. In addition, as for the LVDT core, the moving coil can move with virtually infinite resolution. Thus, the sensor’s reso-
solution is only determined by its conditioning electronics. The coils being wound on a cylindrical bobbin, the entire structure can be hermetically sealed with proper filling materials or resins, assuring a good robustness (as done for LVDTs). The wires of the coils can be insulated with polyimide and the bobbin supports for the windings can be made of appropriate plastic materials, so as to guarantee radiation hardness [11, 29]. Finally, as the number of signals acquired is the same as for LVDTs, the ratiometric technique enhanced with the three-parameter Sine-Fit algorithm can be used, so as to have position uncertainty of the order of a few micrometers [9].

In conclusion, the properties of contactless sensing, robustness, infinite resolution, very low position uncertainty and the possibility to have radiation hardness, which are typical advantages of LVDTs, are also satisfied by the I2PS. The added-value of the sensor is its immunity to external magnetic fields, which makes it a suitable choice in case of harsh magnetic environments.

3 Ironless inductive position sensor: modeling and reading techniques

This section presents the results of the complete sensor’s characterization. These will be of primary importance for the design optimization and procedure.

3.1 Electromagnetic analysis

As already mentioned in section 2 and depicted in figure 2, the Ironless Inductive Position Sensor can be energized either with a voltage or a current signal. However, the electromagnetic behavior of the sensor in these two situations can be analysed separately [30, 31]. In fact, adopting the number labels in figure 2, the general relations in phasor form linking the sense voltages with the supply currents are

\[
V_3 = j \omega \left( M_{31} I_1 + M_{32} I_2 - \frac{j \omega M_{35}}{Z_5} M_{51} I_1 - \frac{j \omega M_{35}}{Z_5} M_{52} I_2 \right)
\]

\[
V_4 = j \omega \left( M_{42} I_2 + M_{41} I_1 - \frac{j \omega M_{45}}{Z_5} M_{51} I_1 - \frac{j \omega M_{45}}{Z_5} M_{52} I_2 \right)
\]

where \( \omega \) is the angular frequency, \( Z_i \) is the impedance of coil \( i \) and \( M_{ij} \) is the mutual inductance between coil \( i \) and coil \( j \). Equations (3.1) are valid in any supply condition and neglect the effect of high frequency phenomena (skin and proximity effect, parasitic capacitances). The position dependence is given by the mutual inductance involving coil 5 (the moving coil).

Nevertheless, without fixing the supply type, it is impossible to understand if the supply currents in (3.1) are position-dependent. In current supply, \( I_1 = -I_2 = I \). Therefore, the supply currents are position-independent, whereas the sense voltages become

\[
V_3 = j \omega (M_{31} - M_{32}) I + \omega^2 I \left( \frac{M_{35} M_{51}}{Z_5} - \frac{M_{35} M_{52}}{Z_5} \right)
\]

\[
V_4 = -j \omega (M_{42} - M_{41}) I + \omega^2 I \left( \frac{M_{45} M_{51}}{Z_5} - \frac{M_{45} M_{52}}{Z_5} \right)
\]

which is a superposition of a constant term (the first one, position-independent) and a variable one, modulated according to the value of the mutual inductances involving the moving coil. In current supply, the voltages on the supply coils are also position-dependent.
Figure 3. Example of computation of I2PS sense voltages with (left) current supply and (right) voltage supply for illustrative values of winding parameters.

On the other hand, in voltage supply, \( V_1 = -V_2 = V \). Therefore, this time the supply current in (3.1) are position-dependent and the expression of the sense voltages becomes [30]:

\[
V_3 = j\omega \left[ \frac{V \left( \frac{A_1}{Z_1}M_{31} - \frac{A_2}{Z_2}M_{32} \right) - \frac{\omega C V}{Z_1 Z_5} (A_1 B_2 + A_2 B_1) (M_{31}M_{52} - M_{32}M_{51})}{j\omega Z_5 C \left[ 1 - \omega \cdot C \left( \frac{M_{51}}{Z_1} B_1 + \frac{M_{52}}{Z_2} B_2 \right) \right]} \right] \\
+ M_{35} \frac{V \left( \frac{A_2}{Z_2}M_{52} - \frac{A_1}{Z_1}M_{51} \right) \cdot C}{1 - \omega \cdot C \left( \frac{M_{51}}{Z_1} B_1 + \frac{M_{52}}{Z_2} B_2 \right)}
\]

\[
V_4 = j\omega \left[ \frac{V \left( \frac{A_1}{Z_1}M_{41} - \frac{A_2}{Z_2}M_{42} \right) - \frac{\omega C V}{Z_1 Z_5} (A_1 B_2 + A_2 B_1) (M_{41}M_{52} - M_{42}M_{51})}{j\omega Z_5 C \left[ 1 - \omega \cdot C \left( \frac{M_{51}}{Z_1} B_1 + \frac{M_{52}}{Z_2} B_2 \right) \right]} \right] \\
+ M_{45} \frac{V \left( \frac{A_2}{Z_2}M_{52} - \frac{A_1}{Z_1}M_{51} \right) \cdot C}{1 - \omega \cdot C \left( \frac{M_{51}}{Z_1} B_1 + \frac{M_{52}}{Z_2} B_2 \right)}
\]

(3.3)

where \( A_i \) and \( C \) are constant factors and \( B_i \) is a position-dependent term [30]. In this supply condition, the voltages on the supply coils are position-independent, whereas the currents in the same coils are position-dependent. In addition, from (3.3) it is evident that in voltage supply the sense voltages depend also on the impedance of the supply coils [31]. Figure 3 shows a computation of the sense voltages for illustrative values of winding and electrical parameters.

Equations (3.1)–(3.3) are a low-frequency description of the sensor’s electromagnetic behaviour. A high-frequency analysis on the magnetic and electric fields’ distribution in the coil layers has been performed [32] to take into account the skin and proximity effect, and in particular their effect on the electrical resistance and inductance. The corresponding frequency-dependent impedance, \( Z_i(f) \), can be included in equations (3.1)–(3.3) to take into account the high-frequency effects. Regarding the parasitic capacitances, the abovementioned models assume that the operational frequency is far enough from the resonance frequency of the device (i.e. 5 to 10 times smaller), so to fully exploit the inductive coupling and avoid capacitive effects.
In the framework of the I2PS design optimization, the electromagnetic analysis is crucial since it actually represents a design tool to respect the specifications (e.g. designed voltage swing, sensitivity, maximum non-linearity error, ratiometric swing, etc.).

3.2 Reading techniques

Different configurations of signal conditioning are available for LVDTs [33] and non-contact inductive sensors [34]. A way to perform the amplitude estimation of the voltages of a LVDT is using the three-parameter Sine-fit algorithm (3PSF) [9,35–37]. This algorithm is used to demodulate the LVDT voltages on the LHC Collimators and it is characterized by high accuracy and noise rejection [10,35–37]. The 3PSF algorithm estimates the amplitude, phase and offset of a sinusoid by minimizing the error quantity

$$e = \sqrt{\sum_{i}^{N} \left[y_i - A_c \cos(2\pi f_0 t_i) - A_s \sin(2\pi f_0 t_i) - O_o\right]^2}$$  (3.4)

where $N$ is the number of samples, $f_0$ is the working frequency, $t_i$ is the time instant and $y_i$ is the current sample value. The estimated quantities are

$$A = \sqrt{A_c^2 + A_s^2}$$

$$\varphi = \arctan(A_s/A_c)$$

$$O = O_o.$$  (3.5)

It has been observed [9] that the 3PSF algorithm can present important estimation errors when an additional sinusoid (with different frequency, especially if very low) is superimposed to the main one (figure 4). The estimation error leads to a position error. This issue is uniquely connected to the algorithm (in particular, to its frequency response). For example, in an I2PS, the additional signal
can be given by coupled magnetic fields coming from other sensors or electromagnetic devices placed nearby. The phenomenon is not fully observable in LVDTs, since the external magnetic field gives rise to magnetic drifts that mask this algorithmic issue, whereas on the I2PS this effect is evident, being insensitive to magnetic interference.

A specific reading algorithm has been designed [9] to avoid this effect, combining the 3PSF algorithm and a time windowing technique. In practice, before being submitted to the Sine-fit, the signal is first multiplied by a Bartlett window [38] in time domain. The windowing allows the low-frequency sinusoids, superposed to the main one, to be placed in the null-point of the frequency response of the algorithm to external tones (figure 4). In this way, the estimation error is null. Furthermore, the minimization of the estimation error occurs for all frequencies far from the main one (as in figure 4).

Figure 5 (left) shows that the reading uncertainty of the sense voltages depends on the signal-to-noise ratio (and, therefore, on the signal’s amplitude) for the described algorithm, just as for the standard 3PSF. Figure 5 (right) also shows the relation (with ratiometric reading and a gain of 200) between the voltage reading uncertainty and the position uncertainty of the sensor, an important performance indicator for the LHC collimators application. These two graphs should serve as primary design tools for predicting the sensor’s uncertainty.

For the sensor’s design optimization, the reading algorithm has to be designed (in terms of choosing sampling frequency, number of samples and operational frequency) so as to respect the real time constraints of the application without affecting the sensor’s performances (i.e. accuracy and precision).

3.3 Thermal analysis and compensation technique

The electromagnetic analysis recalled in subsection 3.1 is valid for a constant ambient temperature. In fact, the ambient temperature modulates the resistivity of the wires, changing the electrical
resistance value of the coils. Therefore, since the sense coils’ amplitudes depend on the coils’ impedance (as from (3.1)–(3.3)), the ambient temperature may represent a source of position drift. Furthermore, since equations (3.3) exhibit a dependence on all coils’ resistances (whereas equations (3.2) only have a dependence on the moving coil resistance), the case of voltage supply is the most exposed to this problem.

Introducing the analytical dependence of copper resistivity in (3.1)–(3.3), in particular in the expression of the coils’ electrical resistance, it is possible to observe [39] that measured position drifts of hundreds of micrometers can occur with ambient temperature variations of some 20 degrees. To overcome the problem and reject the temperature dependence, a compensation algorithm has been designed for the current supply case [39], which is the reasonable design choice for minimizing temperature dependences. In particular, a measurement of the ambient temperature is made by means of a DC current injected in the primary coils. The corresponding DC voltage variation will represent a measurement of the average temperature variation along the sensor [39]. In this way, the temperature acquisition is performed without the need of additional probes or wires.

Adopting the ratiometric reading technique, the compensation relation is the following

\[
r_0 = \frac{r(T)}{1 + \zeta \cdot \Delta V_{DC}(T)}
\]

(3.6)

where \( r(T) \) is the ratiometric value affected by the ambient temperature variations, \( \zeta \) is a correction factor which can be obtained with a sensor calibration [39] and \( \Delta V_{DC}(T) \) is the DC voltage variation measuring the average temperature. It is demonstrated [39] that by applying this compensation technique the temperature sensitivity of the position reading can be decreased by a factor of 25.

Besides this compensation algorithm, typical actions have to be taken in order to guarantee the thermal stability of the windings (i.e. foresee a sufficiently large wire diameter to limit the current density inside the wires).

In the framework of the sensor’s optimization, the thermal model is crucial to choose the supply type (voltage or current), its amplitude, the wire radii and the DC signal amplitude used to measure the average temperature.

4 I2PS design optimization

This section presents the design procedure used to design an optimal Ironless Inductive Position Sensor for the LHC Collimators application. In addition, the results coming from experimental measurements are also shown, demonstrating the effectiveness of the design and the performances of the sensor.

The choice of the optimization algorithm strongly depends on the cost function to maximize/minimize and on the nature of the free parameters which determine it. Therefore, the optimization procedure which is proposed in this section is not unique. However, even if it is presented and successfully applied for the LHC collimators application, the procedure can be seen as a general approach for the I2PS optimization with the considered cost function. For this reason, the optimization steps are presented in a general way, particularizing the results for the LHC collimators applications just at the end of each.
### Table 1. List of optimization parameters (divided by family) of the I2PS.

| Symbol | Description                                      |
|--------|--------------------------------------------------|
| $r_c$  | Inner radius of the moving coil                  |
| $a_C$  | Moving coil semi-length                          |
| $a_P$  | Supply coil semi-length                          |
| $a_S$  | Sense coil semi-length                           |
| $N_c$  | Number of turns of the moving coil               |
| $N_p$  | Number of turns of the supply coils              |
| $N_s$  | Number of turns of the sense coils               |
| $d_{wc}$ | Diameter of the moving coil wire                |
| $d_{wp}$ | Diameter of the supply coil wire                |
| $d_{ws}$ | Diameter of the sense coil wire                 |
| $f_0$  | Operational frequency                           |
| $I$ or $V$ | Supply signal amplitude                      |
| $f_S$  | Sampling frequency                              |
| $N_{samples}$ | Number of acquired samples                 |

### 4.1 Parameters and constraints

From the electromagnetic model (in particular, from equations (3.2) and (3.3)), it is possible to extract the design parameters for the sensor, defined as those quantities (geometrical, physical or dimensionless) that can be tuned in order to achieve a certain performance of the device. In addition, other parameters (related to acquisition, voltage range etc.) come also into play. The parameters list is shown in table 1.

For the Ironless Inductive Position Sensor, since the harsh environment specifications of the LHC Collimators (listed in subsection 1.2) are already intrinsically met, the required performance is to maximize the sensitivity and minimize uncertainty, keeping the dimensions within the limits of common LVDTs. Maximizing the sensitivity translates into the maximization of the ratiometric swing (i.e. the value of the ratiometric at the extreme positions), since the ratiometric technique is used to perform the position reading.

The design parameters, categorized as belonging to the sensor part or to signals’ acquisition, are given in table 1. The supply signal amplitude is actually present in both categories. In practice, the choice of these parameters completely defines the sensor and its performance.

Regarding the supply type, given the sensitivity of electrical resistance to ambient temperature variations (subsection 3.3), the supply signal should be a current sine-wave. This is anyway a design choice that can be adapted to the environment (it can be changed whether the expected operational conditions of the sensor are not critical from the thermal point of view, for example in closed spaces with very little temperature variations).

The optimization procedure should define the values of the parameters listed above in order to satisfy the specifications. Generally, the specifications of the sensor performances can involve a required accuracy or precision, linearity or strict space occupancy. For the LHC collimators, the specifications can be translated in numbers as in table 2.
Table 2. List of specifications and constraints (divided by family) for the linear position sensor to be optimized (LHC collimators application).

| Parameter   | Value                  |
|-------------|------------------------|
| Geometry    |                        |
| Max Diameter| 26 mm                  |
| Max Length  | 220 mm                 |
| Position Range | [-25 mm, 25 mm]         |
| Acquisition |                        |
| Survey Time | 10 ms                  |
| Voltage Range | 10 V                  |
| Performace  |                        |
| Non-Linearity Error | 0.5% – 0.6%     |
| Max Uncertainty | ∼ 1 µm (best if < 1 µm) |

The 10-V amplitude constraint is imposed to respect the data acquisition channels’ range, whereas the specified survey time guarantees 100 position readings per second. The definition of non-linearity error will be given in section 5.

4.2 The optimization problem

The number and nature of the design parameters listed in the last subsection makes the optimization process non-trivial. Some of them are even inter-linked, so that the influence on the objective function cannot be in principle estimated considering them one by one (e.g. if the winding length is fixed, the number of turns per layer will depend on the wire diameter and vice versa). In addition, as explained in [30, 31], the computation of the mutual inductances involve the evaluation of elliptic integrals of first and second kind. Therefore, the calculation of the objective function involves the numerical computation of these integrals, as well as non-linear operations (such as the complex modulus, or the ratiometric computation). Last but not least, several parameters are not defined in the entire real (or complex) axis, but they rather admit only integer values (e.g. the number of layers), leading to integer optimization problems, which are particularly hard to solve [40, 41]. All these circumstances make a simple optimization run (i.e. an automatic algorithm that searches for the maximum or minimum of the objective function [41]) an ineffective and time-consuming choice. Even with more sophisticated optimizations, e.g. genetic algorithms [42], the possibility of finding a local maximum/minimum in the cost function, together with the integer nature of many parameters, make the problem be greatly demanding and possibly unsolvable.

However, an optimization procedure can be prepared by fixing some relationships between the parameters (e.g. imposing equal length for the supply and sense coils) for geometrical or linearity reasons, so as to decrease the number of unknowns, or imposing first the most critical constraints (e.g. thermal stability) and then optimizing the new parameters sub-set.

The procedure which is presented here is a valid choice for a fast and effective I2PS optimization. It does not merely use existing algorithms, but exploits the results coming from the sensor’s characterization to perform the design steps in a proper way. The appropriate combination of such steps (as depicted in figure 6) brings then to the complete procedure.

The advantages of such an approach lie in the reliability of its results, being each step based on sound analytical models previously verified and validated, and in its flexibility, since it can
be modified and adapted to different cases by adding/removing steps. This nature of modularity further underlines the generality of the proposed approach (i.e. it can be used also for different applications) and its preference over standard optimization procedures.

4.3 Supply type and position range

The optimization process considers the current supply case and takes as objective function the ratiometric of the sensor at one of its extreme positions. This is actually the first design choice, which involves the use of a current signal for the supply (for thermal reasons, as explained in subsection 3.3) and the choice of the ratiometric technique (because of its good properties [22], as discussed in subsection 3.2). From what has been said, the first specification to fix for the device’s optimization is the position range $[−p_{\text{MAX}}, p_{\text{MAX}}]$ (as in the chart in figure 6). As anticipated, for the LHC Collimators application, $p_{\text{MAX}} = 25 \, \text{mm}$.

4.4 Wire diameters

As the second step, the wire diameters should be chosen, in order to have good thermal stability of the coils (as explained in section 3). In particular, in the case of the moving coil, the wire diameter should be chosen in order to have the least resistance (i.e. maximize the induced current in the coil) according to the space constraints.

To keep the current density in the wires at a low level for thermal stability, the wire diameter of the supply coils have to be bigger than the sense coils’ one. The latter can be chosen small since no current is flowing into the sense coils. The moving coil’s wire diameter has also to be big since this will keep the resistance small, but given the high number of layers which is expected, the space constraints should be respected.

For the LHC collimators, the values chosen are $d_{\text{wp}} = 0.2 \, \text{mm}$ for the supply coils, $d_{\text{ws}} = 0.05 \, \text{mm}$ for the sense coils, $d_{\text{wc}} = 0.4 \, \text{mm}$ for the moving coil.

4.5 Space occupancy

As the next step, the radial and longitudinal dimensional constraints have to be considered to determine the upper bounds of the coils’ radii and lengths.

For the LHC Collimators application, given the constraint of maximum length listed in subsection 4.1, the upper bound for the supply and sense coils’ lengths is about 90 mm. With this value, the winding assembly will have a length of 180 mm. 20 mm on each side are left for connections and washers. Given the big moving coil’s wire diameter, the corresponding winding support should have a tiny diameter and, at the same time, the total diameter of the moving coil should reserve enough space for the sense and supply coils to stay within the maximum sensor’s diameter. In addition, at least 1 mm of air-gap between the moving coil and the fixed coils’ (sense and supply)
bobbin has to be left, in order to guarantee contactless sensing. For these reasons, the upper bound for the outer diameters of moving coil and supply coils are fixed to 15 mm and 22 mm respectively. 2 mm of space on each side for the sensor’s housing has been left.

The inner diameter of the moving coil is chosen to be 4 mm. Smaller values would lead to technical difficulties in the manufacturing of the support bobbin, which would be too thin to withstand the winding process anyway.

Given that the sensor’s mutual inductances increase with the radial dimensions (subsection 3.1), the upper bounds are also taken as design choices. Instead, for the longitudinal dimensions, a more complicated process has to be followed for choosing the optimal values.

4.6 Winding layers

With the chosen radial dimensions, 14 winding layers are expected for the moving coil. Leaving a 1-mm air-gap on each side to assure contactless sensing, the fixed coils’ support bobbin has a diameter of 17 mm. Its thickness can be fixed at 1.5 mm, and therefore the inner diameter of the sense coils is 20 mm. For this reason, 1 mm on each side is available for the winding of sense and supply coils. This space is enough for three 0.05-mm layers (sense) and four 0.2-mm layers (supply), leaving 0.05 mm for the insulator in-between. The number of layers is small enough to guarantee a good winding regularity.

4.7 Optimal coil semi-lengths

From figure 3 it is evident that there exists a position for which the sense voltage exhibits a maximum. The presence of this maximum inside the nominal moving coil position range leads to a decrease of the sensitivity (the voltages have a lower slope with the position) and breaks the duality of the two sense coils (i.e. there are some points where both voltages are decreasing or increasing with the position). It also increases the non-linearity. For these reasons, such a maximum should be kept as far as possible from the null point. The ideal would be to relegate it outside the desired position range.

Referring to equations (3.2), writing $Z_5$ as $R_5 + j\omega L_5$ and taking the supply current $I$ as reference for the phases, the modulus of one of the sense voltages is

$$|V_3| = \left|\frac{\omega I (M_{31} - M_{32})}{Z_5} - \frac{\omega^2 I \cdot L_5}{|Z_5|^2} \cdot M_{35} (M_{51} - M_{52})\right|^2 + \left|\frac{\omega^2 I \cdot R_5}{|Z_5|^2} \cdot M_{35} (M_{51} - M_{52})\right|^2 \quad (4.1)$$

whereas the derivative with respect to the position, taking into account that all mutual inductances involving the moving coil (i.e. winding 5) are position-dependent, is

$$\frac{\partial |V_3|}{\partial p} = \frac{\frac{\partial f(M)}{\partial p} \cdot \omega^3 L_5}{|Z_5|^2} \left[f(M) - L_5 (M_{31} - M_{32})\right] \sqrt{\left[M_{31} - M_{32}\right] - \omega^2 L_5 \cdot f(M)} + \left[\frac{\omega R_5}{|Z_5|^2} \cdot f(M)\right]^2 \quad (4.2)$$

where $f(M) = M_{35} (M_{51} - M_{52})$. To find the maximum of (4.1), one of the following relations has to be satisfied in (4.2)

$$\frac{\partial f(M)}{\partial p} = 0 \quad \quad f(M) = L_5 (M_{31} - M_{32}) \quad (4.3)$$
The second condition in (4.3) is impossible. As a matter of fact, \( f(M) \) is by definition the product between two factors which are position dependent (\( M_{35} \) and the difference between \( M_{51} \) and \( M_{52} \)). In particular, as detailed in [30, 31], the mutual inductances involving the moving coil exhibit linear dependence with the position. Therefore, \( f(M) \) should exhibit a quadratic dependence on the position. On the other hand, the second condition in (4.3) says that \( f(M) \) should be a constant function (none of the parameters in the second term are position-dependent), which is impossible.

Therefore, the first condition in (4.3) has to be satisfied in order to find the maximum of the sense voltage. This means that the following relation has to be imposed (the position dependence is highlighted)

\[
\frac{\partial [f(M)]}{\partial p} = \frac{\partial}{\partial p} [M_{35}(p) \cdot (M_{51}(p) - M_{52}(p))] = 0.
\] (4.4)

Given the linear dependence of the mutual inductances with respect to the position and their symmetry with respect to the null-point, they can be generically written as

\[
M_{35}(p) = a + bp, \quad M_{51}(p) = c + dp, \quad M_{52}(p) = c - dp
\] (4.5)

where \( a, b, c \) and \( d \) are constants. Imposing (4.4), one can find that the position at which the sense voltage exhibits its maximum value is

\[
p^* = \frac{a}{2b}.
\] (4.6)

Thus, this position value depends just on the mutual inductance \( M_{35} \) (or \( M_{45} \), if the other sense coil was considered) and on its dependence with the position.

The value of \( p^* \) can be related to the moving coil semi-length \( a_C \). If \( p^* \) is calculated using (4.6) for several values of \( a_C \), it is possible to observe that the voltage maximum always occurs in the position

\[
p^* \approx -\frac{a_C}{2}.
\] (4.7)

The demonstration is shown in figure 7, where the mutual inductance \( M_{35} \) and the value of (4.6) without sign are computed for different values of \( a_C \) and illustrative values of other parameters.
Figure 8. Computation of the ratiometric at 30 mm for different values of $a_C$ and $a_S$. (Left) 3D surface plot. (Right) Projection from the top. The area around the dotted line individuating the choice $a_C = a_S$ gives the best sensitivity.

Figure 7 (right) also shows the linear interpolation of the model data, which gives a slope of 0.5 and a negligible offset, confirming (4.7).

Therefore, once (4.7) has been demonstrated, the following design rule can be followed in order to keep the voltage maximum away from the desired position range

$$a_C \geq 2p_{\text{MAX}}.$$  \hfill (4.8)

Values of $a_C$ smaller than $2p_{\text{MAX}}$ but anyway not far from the limit given by (4.8) may be also chosen for space occupancy reasons.

Regarding the supply and sense coils, the design choice

$$a_S = a_P$$  \hfill (4.9)

can be adopted for symmetry and manufacturing purposes. The design process thus focuses on $a_C$ and $a_S$ (the number of turns per layer can be computed afterwards). The optimal values can be found following two techniques:

- Calculate the ratiometric value at $p_{\text{MAX}}$ from (3.2) and run an automatic optimization process with $a_C$ and $a_S$ as free variables (e.g. using genetic algorithms, in order not to find local maxima [41]) to maximize the value of the ratiometric.

- Calculate the ratiometric at $p_{\text{MAX}}$ from (3.2) for different values of $a_C$ and $a_S$ in their boundaries and plot it as a surface. Identify the area of maximum sensitivity.

Both techniques give the same result, even though the second is faster. The dependence of the ratiometric on $a_C$ and $a_S$ is shown in figure 8. It is clear that the locus which gives the maximum sensitivity (i.e. maximum absolute value of the ratiometric) is around the line

$$a_S = a_C$$  \hfill (4.10)
Figure 9. High-frequency electromagnetic model results for the moving coil resistance.

as also highlighted in the top view in figure 8 (right). Nevertheless, for big values of $a_S$, $a_C$ can be chosen smaller, since the optimum slightly deviates from (4.10) in this region. In addition, the ratiometric exhibits big values (in modulus) for small winding semi lengths ($< 35 \text{ mm}$). However, when the semi-lengths become too small, the calibration curve of the sensor is not monotonic (i.e. it is not possible to extract the position).

Specifying these results for the LHC collimators application and, in particular, following (4.8) for the optimization of the sensor, the moving coil semi-length $a_C$ should be at least 50 mm. In addition, for (4.9)–(4.10), the fixed coils would have a total length of at least 100 mm. Nevertheless, these values would lead to unacceptable longitudinal dimensions of the sensor. Therefore, the value of $a_C$ is chosen to be 45 mm and $a_S$ and $a_P$ will be 40 mm, to decrease the dimensions and at the same time not to diverge from the optimum. In this way, the total assembly length of the coil will be 160 mm, which is below the limit and gives a margin for uncertainty.

Table 3 shows the list of dimensional parameters obtained with the optimization.

4.8 Optimal frequency

The operational frequency of the sensor has been found combining the results from the high-frequency electromagnetic model and those coming from an experimental campaign on a prototype, which has been manufactured according to the dimensions given in table 3.

Skin and proximity phenomena modify the resistance value of a coil at high frequency. In particular, with current supply, the resistance of the moving coil is critical (the other coil resistances do not enter the computation of the sense voltages, as seen in (3.2) and [30]). As a matter of fact, as demonstrated in [32] and illustrated in figure 9, the resistance of the designed moving coil shows a monotonic increase with the frequency. A higher moving coil resistance leads to smaller induced current in this coil, and therefore worse sensitivity. Thus, it is important to keep this resistance small so as to have a small impedance $Z_S$. Calculating $Z_S$ for the LHC collimator applications and imposing a maximum variation of 10 % with respect to the computation using the DC resistance, the limit is around 7 kHz.
Table 3. Optimized dimensional parameters of the Ironless Inductive Position Sensor coils for the LHC Collimators application.

| Winding       | Parameter        | Value  |
|---------------|------------------|--------|
| Moving Coil   | Wire diameter    | 0.4 mm |
|               | Inner diameter   | 4 mm   |
|               | Outer diameter   | 15 mm  |
|               | Number of layers | 14     |
|               | Number of turns per layer | 225     |
|               | Length           | 90 mm  |
| Sense Coils   | Wire diameter    | 0.05 mm|
|               | Inner diameter   | 20 mm  |
|               | Outer diameter   | 20.3 mm|
|               | Number of layers | 3      |
|               | Number of turns per layer | 1600  |
|               | Length           | 80 mm  |
| Supply Coils  | Wire diameter    | 0.2 mm |
|               | Inner diameter   | 20.4 mm|
|               | Outer diameter   | 22 mm  |
|               | Number of layers | 4      |
|               | Number of turns per layer | 400     |
|               | Length           | 80 mm  |

As a further study of the frequency limit, experimental measurements have been performed on a sensor prototype. These measurements also take into account the parasitic capacitances which come into play at high frequencies, therefore giving a limit on the excitation frequency also from this viewpoint.

Figure 10 shows the impedance measured at the supply electrodes as function of the frequency. The measurement has been carried out with an impedance analyser. The magnitude measured is then an equivalent impedance, since it takes into account all mutual couplings between coils which are seen at the supply electrodes.

It is evident that after about 8 kHz, the high-frequency effects of parasitic capacitances start playing the major role, masking the inductive coupling. The same phenomenon happens for several moving coil position values. From figure 10 (right) it is also evident how the sense voltages are affected. In fact, below 8 kHz they always present a maximum inside the position range (as the theory predicts). Nevertheless, at 10 kHz the maximum does not appear anymore and the amplitudes start decreasing already after 6–7 kHz. For frequencies above 10 kHz, the measurements showed that the voltages do not even exhibit symmetry anymore. Therefore, the operational frequency should be well below 8 kHz.
The high-frequency effects influence also the sensitivity. Figure 11 shows the measured position-ratiometric curves for different frequencies in the range [−30 mm, 30 mm]. The curves have been obtained starting from the measurements in figure 10. A small slope indicates a more remarkable sensitivity of the device. The slope decreases when the frequency increases, but again after 7–8 kHz the trend changes and the slope starts increasing. Therefore, from this other point of view, even if a high frequency is advisable, this should not be higher than 7–8 kHz.

Taking into account all the frequency trends which have been described so far, the choice of the frequency should thus be the result of a compromise between them. As a result of such an analysis, the frequency of 1 kHz has been chosen for the LHC collimators application. It is far enough from 7 kHz to avoid high-frequency effects but still guarantee good sensitivity.

4.9 Supply current amplitude

The supply signal amplitude can be chosen taking into account the thermal stability (current densities smaller than 4 A/mm$^2$ are preferred, in order not to give rise to significant internal heat generation) and the simulations on the precision shown in figure 5 (with higher amplitudes, the signal-to-noise ratio increases, and the uncertainty on the signal’s amplitude estimation decreases).

Additionally, the voltage range has to be considered. The amplitude of the sense voltages increases as the supply current amplitude increases (subsection 3.1). Therefore, the amplitude has to give a sense voltage which does not exceed the limits of the readout system (amplitude not bigger than 10 V) in any of the position values of the desired range, as imposed in subsection 4.1.

For the LHC collimators, with 1-kHz operational frequency, a 30 mA-peak sinusoidal signal and 10 mA DC current for temperature measurement have been chosen. As it can be foreseen from the model and simulations (nominally, equation (3.2) and figure 5), these values satisfy the cited requirements: the current density is about 0.8 A/mm$^2$, the voltage levels are under 10 V (taking...
Figure 11. (Left) Position-ratiometric curves obtained with calibration of the I2PS sensor at different frequencies. (Right) The slope of the calibration curves gives the sensor’s gain at each frequency.

Table 4. Optimized electrical parameters and acquisition settings of the I2PS.

| Parameter                | Value   |
|--------------------------|---------|
| Operational Frequency    | 1 kHz   |
| Excitation Current Amplitude | 30 mA  |
| Sampling Frequency       | 250 kS/s|
| Number of Samples        | 2000    |

into account both DC and AC) and big enough for a sub-micrometric uncertainty with a 50-dB signal-to-noise ratio (typical value for the application [19]).

4.10 Acquisition parameters

For the acquisition parameters, a sampling frequency of 250 kS/s has been chosen in order to have enough samples in a period. Given the relation between signal-to-noise ratio, number of samples and uncertainty [9], 8 periods (2000 samples) of the signals can be acquired, leaving 2 ms for the time windowing and 3PSF processing. These choices give good accuracy and precision for the reading algorithm described in subsection 3.2 (figure 5), respecting the survey time specification given in subsection 4.1.

Table 4 lists the electrical and acquisition parameters which have been chosen in the design. At this stage, the design of an Ironless Inductive Position Sensor for the LHC Collimators application is complete. The choice of the housing material is not crucial from the design viewpoint (as long as it is non-magnetic and exhibits a high resistivity to minimize the eddy currents) and it can be performed a posteriori, as well as the measurement of the correction factor $\zeta$ and reference DC voltage for the temperature compensation in (3.6).
Figure 12. Optimized prototype with a metal shield which can be used as housing.

5 Experimental tests

The optimized prototype is shown in figure 12 once the coil winding is performed according to the optimal parameters of table 3. Radiation-hard plastic materials have been selected for the winding supports (for moving, sense and supply coils) [42]. Figure 12 also shows the metal case which can be used as external housing of the sensor (for improving mechanical robustness).

The optimized prototype has been tested in order to draw its characteristic curves, examine its performances and verify the magnetic immunity. The sense voltages at different positions are reported in figure 13 (left). Symmetry is clear, testifying to accurate sensor manufacturing. In addition, the maximum of the sense voltages occurs at about 22.5 mm, as the theory in section 4 predicted. This curve is depicted in figure 13 (right), together with the position reading uncertainty for all the position values in the range. The non-linearity error can be calculated in the position range as

\[
NLE = 100 \cdot \max \left( \frac{p' - \overline{p}}{MCPR} \right)
\]

where \(\overline{p}\) is the moving coil reference position, \(p'\) is the position calculated through linear interpolation of the calibration curve, \(MCPR\) is the moving coil position range considered. For the optimized prototype, the \(NLE\) is 0.6 % in the full position range and reduces to 0.2 % in [-18 mm, 18 mm]. These values are not far from common non-linearity errors of LVDTs. The sensor’s gain (i.e. the slope of the linear interpolation of the calibration curve), which also gives an indication on the sensitivity, is 225.4 in the full position range, whereas it is 225.0 in [-18 mm, 18 mm], once again confirming the linearity. From this value, the sensitivity of the sensor is about \(1/225 = 4.4 \cdot 10^{-3}\) mm\(^{-1}\). LVDTs exhibit sensitivities of the same magnitude [21]. This testifies that even if the maximum of the sense voltages is slightly inside the position range, it is still far enough from the center so as not to perturb significantly the sensitivity and the non-linearity.
Figure 13. (Left) Sense voltage curves at different positions for the optimized sensor. (Right) Position-ratiometric curve for the optimized prototype and its corresponding position uncertainty, calculated as the standard deviation on 30 repeated measurements with a coverage factor 3.

From figure 13 the nominal uncertainty of the position reading can also be discussed. With the optimized parameters (mainly excitation current and operational frequency) a position uncertainty of less than 1 µm has been achieved. This value is well within the specifications given in section 4. However, if the uncertainty has to be even lower, the frequency can be slightly increased (adjusting the excitation current so as not to have voltage amplitudes of more than 10 V), improving in this way also the sensitivity (as from figure 11). Additional measurements showed that with 2 kHz and 20 mA of excitation current, the uncertainty is 0.6 µm and the sensitivity is $5.4 \times 10^{-3}$ mm$^{-1}$. This solution can be adopted as a backup choice in the case when an operational frequency of 1 kHz is not possible (e.g. because of an isofrequency environmental noise). However, frequencies higher than 2 kHz have to be discarded because they approach the limit of 7 kHz.

The last matter to be discussed is the magnetic field immunity of the optimized prototype. This further test is useful for 2 main reasons:

- The main advantage of I2PS sensors over LVDTs is the intrinsic immunity to external magnetic fields, achieved by avoiding magnetic materials in the structure. Therefore, a verification of the immunity also for the optimized prototype is mandatory to complete the sensor design;

- An external magnetic field can cause estimation issues on the 3PSF algorithm, as discussed in subsection 3.2. Therefore, a test with a sinusoidal magnetic field can stress and confirm the effectiveness of the algorithm described in subsection 3.2 with the optimized acquisition parameters chosen in section 4.

Experimental measurements with external longitudinal magnetic fields have been performed with a ramped magnetic field reaching 800 A/m (i.e. approximately 1 mT in air) with different ramp rates and with a sinusoidal profile at different frequencies. The external magnetic field has been
chosen to be longitudinal since the longitudinal interference is the major cause of position drifts in LVDTs [14].

The results which have been observed on the optimized sensor are similar to the ones presented in [8] for a sample prototype (with illustrative parameters) and are depicted in figure 14 for two cases where the moving coil position is 10 mm. The ramp rate is 0.3 mT/s and the frequency of the sinusoidal field is 2 Hz. It is evident that the position drift (computed as the difference between the position read in presence of the external interference and the position read in absence of the interference) stays always around the zero within its uncertainty. This happens with slowly-varying fields (i.e. during the ramp and the sinusoid) and with constant field (i.e. when the ramp reaches the maximum value). The two spikes in figure 14 (right) are due to the discontinuity of the derivative of the magnetic field profile (which contains all frequencies). The same results have been observed with different ramp rates, frequencies of the interfering sinusoidal signal and moving coil positions.

From what has been observed, the results coming from the experimental tests carried out on the optimized structure confirmed the expected values of sensitivity and non-linearity. In addition, the sensor satisfies the dimensional and operational constraints given in subsection 4.1. Finally, the magnetic field immunity and algorithm efficiency with the optimized parameters have also been confirmed.

6 Conclusions

The design optimization of an Ironless Inductive Position Sensor for use in the harsh magnetic environment of the LHC Collimators’ has been proposed in this paper. The optimization procedure relies on the results coming from the complete sensor’s characterization, in terms of electromagnetic and thermal modelling, as well as the choice of a smart reading technique. Unlike common simple or sophisticated optimization algorithms, which are anyway inapplicable given the number and the nature of the design parameters, the proposed procedure presents a modular approach, combining different design steps in an appropriate way to quickly and effectively design an Ironless Inductive Position Sensor with the performances within the specifications.
The optimization procedure has been derived taking the ratiometric swing (i.e. the sensor’s sensitivity) as target function and performing optimization actions devoted to reduce the number of design parameters and find the optimum values for the remaining ones. Nominally, the design optimization leads to the optimal choice of dimensional and electrical parameters.

An optimized prototype has been manufactured and experimental measurements have been executed, verifying the sensor prototype’s performances (in terms of sensitivity, non-linearity, magnetic immunity and uncertainty). The results showed the effectiveness of the optimization algorithm, all constraints being respected and the sensor’s performances satisfactory, and confirmed the magnetic immunity also with the optimized parameters.

Although the specific application concerns the use of an I2PS in the LHC Collimators, given its modularity and flexibility, this optimization process may be followed also as a general example for different kinds of applications (e.g. with more relaxed space constraints but stricter limits on the voltage amplitudes) where the ratiometric swing constitutes the objective function to optimize.

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