A cryogenic sensing element for measurement current transformers

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Abstract: The design of a cryogenic sensing element for superconducting DC current transformers working up to 100 kA at 4.2 K is proposed. Limitations of χ-metal magnetic characteristics at cryogenic conditions are overcome by a soft Ni 81-Mo 5-Fe magnetic alloy (referred to as cryogenic permalloy). An optimized geometrical design allows cores saturation due to mechanical constraints to be avoided. The effectiveness of the design is demonstrated through electromagnetic simulations exploiting measurement results from the characterization of cryogenic permalloy samples. Moreover, a preliminary lab-scale cryogenic DCCT prototype for a nominal current of 20 kA is implemented and characterized. A typical precision of the transducer below ±0.05% is achieved along with nonlinearity better than ±0.05%.

Keywords: Accelerator Subsystems and Technologies; Accelerator Applications; Acceleration cavities and magnets superconducting (high-temperature superconductor; radiation hardened magnets; normal-conducting; permanent magnet devices; wigglers and undulators)
1 Introduction

The theory of the zero-flux current transformer dates back to the fifties [1]. In the following years, the concept of magnetic flux compensation in a transformer’s core — to closely approximate the ideal current ratio — was largely extended. Nowadays, devices such as DC current transformers (DCCT) are available on the market, for a wide range of rated currents with bandwidth from DC to a couple of hundreds kHz. Careful calibration of these transducers leads to an accuracy of the order of ppm [2].
The applications of DCCTs include monitoring of power grid [3], intensity measurements of particle beam in high-energy physics accelerators [4], control systems for power supply [5], and so on. These applications operate at room temperature. Conversely, the increasing interest in superconductivity can spur the development of DCCTs for cryogenic temperatures (from liquid nitrogen to liquid helium). Indeed, the evolution of superconducting technologies for energy transmission [6], rotating machine [7], and transformers [8] could require an accurate current transducer for in-situ monitoring purposes.

The first development of a cryogenic DCCT is due to CEA-Saclay [9] for measuring the secondary current of a superconducting transformer [10]. The basic idea was to modify a well-settled commercial DCCT (MACC+ 600 A by Hitec [11]) in order to measure a rated current of 100 kA. The circuitry of the transducer is kept at room temperature while the sensing element is displaced in the cryostat at 4.2 K. The core saturation is mitigated via a shielding torus. The main issue is related to the sensing element, namely the three $\mu$-metal cores. The low temperature modifies the magnetic properties of the cores. In particular, the relative permeability decreases roughly by a factor two. This reduces the gain of the device for implementing the compensation mechanism. The high current can saturate the cores, due to geometrical constraints, limiting the DCCT operating range at 38 kA. This limit was increased up to 60 kA during latest experiments [12] where the improved centring and tightening of strands within the DCCT sensing element enhanced the rejection to saturation of the cores. However, the measurement of the full range, up to 80 kA, of transformer’s secondary current was missing. In this regard, a new sensing element capable of covering the extended range for the upgrade of the Facility for Research on Superconducting Cables at CERN [x1] exploiting that superconducting transformer would be of interest [12]. In particular, the characterization of new generation of Nb$_3$Sn superconducting cables would require currents above 60 kA in self and external field configurations [14–16].

In this paper, a cryogenic sensing element at 4.2 K for a DC current transformer measuring current up to 100 kA is proposed. In particular, the geometric design of the cores exploiting a soft Ni 81-Mo 5-Fe magnetic alloy (cryogenic permalloy [17]) allows a range of 100 kA and a typical precision of ±100 ppm to be achieved. In the following, after illustrating in section 2 the basic concepts of AC-DC compensation of current transformers, the leading concepts of the sensing element are given in section 3. The experimental characterization of the cryogenic permalloy is reported in section 4. In sections 5 and 6, the design of the sensing element and the numerical validation results, respectively, are illustrated. Finally, in section 7, the implementation of a preliminary lab-scale prototype of cryogenic DC current transformer based on cores of cryogenic permalloy, for a rated current of 20 kA, is reported. Experimental results from the metrological characterization of the implemented device, showing the effectiveness of the proposed approach, complete the paper.

2 Background on AC-DC compensation for current transformers

In figure 1, the basic equivalent circuit of a current transformer with magnetic core (assuming for simplicity constant permeability) for measurement applications is illustrated. In particular, the device can be seen as an ideal transformer, with current ratio of $N_2$ to $N_1$, in parallel with the magnetization inductance $L_0$. The primary current is transduced by means of the voltage drop on the burden resistor ($R_b$).
Beyond the other sources of non-ideality, the main error for such a device is the presence of the magnetization current:

\[ I_2 = -\frac{N_1}{N_2} I_1 + I_0 \]  

(2.1)

Common practice to reduce this error is to implement an AC compensation schema [18]. The basic idea is to sense the flux variation via an additional coil on the transformer secondary and to compensate it using a voltage-current amplifier that feeds the transformer secondary. In other words, the compensation current flows in the secondary coil of the transformer trying to short-circuit the magnetization inductance. Indeed, if the amplifier gain is infinite, the stable condition is achieved when \( V_2 \) (the voltage drop on the secondary coil) is zero and \( (N_1/N_2)I_1 = I_2 \), that is, the magnetic flux is nulled in the transformer core. This principle is referred to as zero-flux compensation. The advantage of this device is to reduce the magnetization current and to extend the low bandwidth limit of the current transformer. However, a DC component in the primary current cannot be sensed.

At this aim, the concept of magnetic modulator provides a suitable solution [18, 19]. Two additional ferromagnetic cores coupled with the primary are exploited for compensating the DC component. The two cores are brought into saturation, in phase opposition, by means of an oscillator. Figure 2 shows the shape of the magnetization current, due to the typical hysteretic behaviour of a core, when \( I_1 \) is zero (left) and not (right). In the former case, the combination of the signals from the two cores cancels out to each other (balanced condition). In the latter, a DC signal proportional to the DC component of \( I_1 \) arises producing at the output of the detection block a signal with no zero average, that is, the sought information to compensate the DC component.

A DC measurement current transformer (DCCT) combines the above-described AC and DC compensation mechanism to accurately measure currents.

3 The proposed sensing element

In the following, (A) the requirements, (B) the basic ideas, and (C) the design steps of the proposed sensing element are described.

3.1 Requirements

At CEA-Saclay, the room-temperature DCCT MACC+ 600 A by Hitec [11], with three toroidal cores of \( \mu \)-metal, was modified to achieve a current range of 100 kA at 4.2 K [9]. However, the following drawbacks arise:
Figure 2. Typical behaviours of the magnetization current on a core of a magnetic modulator for DC detection in current transformers: no current on the primary (left) and with DC component (right); the output of the detection block is highlighted in both the cases [9].

- At 4.2 K, the fall in the magnetic permeability of the $\mu$-metal cores gives rise to a reduction in the compensation gain. Moreover, the increase in the coercive field affects the hysteretic behaviour of the DC modulator of the MACC+, leading to a loss in precision by a factor two;

- Cores saturation due to geometrical constraints decreases the target of nominal current by a factor two, even with a precise centring of the primary cable, in spite of a shielding shell of FeSi-oriented grain for a background field of 0.5 T as well;

- Bandwidth reduction due to the shielding shell and of 10,000 turns for the compensation coil.

The work of CEA-Saclay [9] showed clearly how the simple modification of a commercial DCCT, to extend its operation range to 100 kA at 4.2 K, produces a performance loss.

Beyond cooling the DCCT sensing element, the increase in maximum primary current by two order of magnitudes results in the need for (i) a ferromagnetic shell, to avoid undesired local core saturation, and (ii) a higher number of turns for the secondary coil. Core’s saturation arises from either asymmetry of the field generated by the primary conductor (see section 5.1), or from interfering external field (e.g., from the return cable of the primary).
However, these items increase the secondary equivalent inductance. This leads to higher noise at the device output with a lower bandwidth. Indeed, the secondary voltage is proportional to the derivative of the compensation current via such an inductance. Moreover, by taking into account only the air core equivalent self-inductance on the secondary, this decreases the promptness of the secondary current to compensate the primary variation. Nevertheless, a higher number of turns results in a higher parasitic capacitance, limiting the bandwidth as well. On the other hands, the number of turns cannot be arbitrarily low, to not affect the current ratio. Thus, the secondary current can be measured via a low-resistance shunt (see the burden resistor in figure 1), and consequently, the primary current value can be retrieved. Therefore, the means to reduce the performance loss of a cryogenic DCCT, with respect the room temperature device, is also to limit as much as possible the unavoidable increase in the secondary inductance.

On this basis, the following requirements for a cryogenic sensing element are defined:

1. Magnetic characteristics at cryogenic temperature must be comparable with those of the $\mu$-metal at room temperature;
2. Core optimized geometry to avoid saturation at nominal current;
3. A ferromagnetic shell must be designed for off-centring immunity;
4. External field is to be shielded by exploiting superconducting materials to ensure correct cryogenic working and allowing the minimization of the thickness for the ferromagnetic shell;
5. The number of turns in the superconducting compensation winding has to be reduced.

3.2 Basic ideas

The ideal voltage across a $\mu$-metal core of a DCCT, modelled as a toroidal inductor with a ferromagnetic core of rectangular cross section, is:

$$V = \frac{d(\mu I)}{dt} \frac{N^2}{2\pi} h \ln \left( \frac{r_2}{r_1} \right)$$  (3.1)

where $\mu$ is the core magnetic permeability, $I$ the current in the coil, $N$ the number of coil turns, $h$ the height of the torus cross-section, and $r_2$ and $r_1$ the external and inner radii of the torus, respectively. For the design, the voltage is a function of the material properties $\mu$ and of a geometric term, $h \ln(r_2/r_1)$.

Therefore, the above requirements 1 and 2 are fulfilled (i) by a permalloy working at 4.2 K ideally as $\mu$-metal at room temperature, and (ii) by keeping the same $h \ln(r_2/r_1)$ for cores with different size (0.893 mm for the 600-A MACC+ by Hitec). Also the number of turns is assumed unchanged, 200, to preserve the order of magnitude of the equivalent inductance. In this condition, the performance of overall AC and DC compensation mechanisms, in principle, is not affected by replacing the ferromagnetic sensing coils.

The requirement 3 leads to a new design of the core. But the shell is made of pure iron in order to have satisfying magnetic performance at high field.
For requirement 4, a cylindrical superconducting magnetic shield ensures efficiency up to 100% at 4.2 K, for background fields up to few T. In particular, a NbTi/Nb/Cu multilayer composite [20] and a bulk of MgB$_2$ [21] are considered. In this way, a superconducting shield of thickness 6 mm is capable of screening up to 1 T [22] leaving the design of the iron shell concerned only with the off-centring issue.

Requirement 5 arises from limiting the unavoidable loss of bandwidth due to an increased secondary inductance and reducing the cryogenic load. 100 kA can be compensated by a coil wound with 8,000 turns, giving rise to an ideal maximum compensation current of 12.5 A. Moreover, from the new design of the sensing element a further reduction of the cross section area is achieved. The sensing element is designed to operate at the temperature of 4.2 K. Using a copper wire for the secondary coil turns into excessive power dissipation (about 1 W/kA), leading to high cryogenic load, namely, helium evaporation. At this aim, the power loss is reduced of several orders of magnitude by the use of a superconducting wire.

3.3 Design steps
According to the above basic ideas, the design of the new sensing element is split into four steps:

1. Choice of a core material operating at 4.2 K: the soft Ni 81- Mo 5-Fe magnetic alloy (cryogenic permalloy [17]) is selected for its typical magnetic induction at saturation of 0.8 T ($B_s$), coercive magnetic field of 1 Am$^{-1}$ ($H_c$), and maximum relative permeability of 70,000 ($\mu_{r,\text{max}}$) at 0.4 Am$^{-1}$.

2. Experimental characterization of DC magnetic permeability and hysteresis loop of the cryogenic permalloy at 4.2 K.

3. Conceptual and engineering design of the core, by optimizing the available space according to the geometric term $h \ln(r_2/r_1)$, and by setting the cores protection case, the wires geometry, and the iron shell between the cores and the compensation winding.

4. Validation by electromagnetic simulations to demonstrate the design effectiveness and to verify the operational margin due to the pure iron shell for cable off-centring.

4 Experimental characterization of cryogenic permalloy

A ferromagnetic material capable of providing performance at 4.2 K compatible with the $\mu$-metal at 300 K is the soft Iron-Nickel-Molybdenum alloy (Ni 81- Mo 5-Fe), produced by Aperam S.A. with the commercial name of CryoPhy® [17]. In table 1, its typical performance at 4.2 K is compared with $\mu$-metal at 300 K. The guaranteed maximum relative permeability, coercive field, and saturation field of the cryogenic permalloy differ from $\mu$-metal ones less than 15%. This increased performance will impact on the conditioning circuit of the final transducer, but far enough from the 50% degradation of the $\mu$-metal at 4.2 K.

The typical characteristics in table 1 were assessed in an experimental campaign at 4.2 K on several samples of cryogenic permalloy. In particular, reproducibility and repeatability of DC magnetic permeability and hysteresis loop were assessed. In the following, (A) the measurement set-up, (B) the DC magnetic permeability tests, (C) the hysteresis loop tests, and (D) discussion are reported.
**Table 1.** Typical and measured magnetic characteristics of cryogenic permalloy Ni 81- Mo 5-Fe at 4.2 K vs. nominal μ-metal at 300 K.

|                           | Typical cryogenic permalloy Ni 81- Mo 5-Fe at 4.2 K | Measured cryogenic permalloy at 4.2 K | Nominal μ-metal at 300 K |
|---------------------------|----------------------------------------------------|--------------------------------------|--------------------------|
| B_s (T)                   | H_c (Am⁻¹)                                         | μ_r, max (at 0.4 Am⁻¹)               |
| 0.8                       | 0.82                                               | 70,000                               |

|                           | Measured cryogenic permalloy at 4.2 K | Nominal μ-metal at 300 K |
|---------------------------|--------------------------------------|--------------------------|
| B_s (T)                   | H_c (Am⁻¹)                                         | μ_r, max (at 0.4 m⁻¹)   |
| 0.825 ± 0.005             | 2.52 ± 0.30                                   | 61,385 ± 7,813          |

|                           | Measured cryogenic permalloy at 4.2 K | Nominal μ-metal at 300 K |
|---------------------------|--------------------------------------|--------------------------|
| B_s (T)                   | H_c (Am⁻¹)                                         | μ_r, max (at 0.4 m⁻¹)   |
| 0.7                       | 1.00                                               | 60,000                   |

**Figure 3.** Sample for testing the magnetic properties of cryogenic permalloy at 4.2 K using a cryogenic insert: preparation (left) and installation (right).

### 4.1 Measurement set-up

The measurement set up [23], based on a high-performance digital integrator [24] and on a software framework [25], is part of the new platform for magnetic measurement developed at CERN in cooperation with the University of Sannio. A controlled voltage power supply (±40 A, ±10 V) is used to magnetize the specimen housed in a cryogenic insert [26]. In figure 3, the preparation of a sample (left), and the insert bottom with the current leads and the cables for the signal measurement (right) are illustrated.

*Magnetic Shields Electromagnetic Engineering ltd* supplied 28 rings of cryogenic permalloy with inner diameter of 76 mm, outer diameter of 114 mm, and thickness of 1 mm, namely, the standard size of the samples used for the CERN permeameter. The rings were annealed and stacked in sets of 7 units to prepare a toroidal sample (figure 3, (left)). During cool-down, the contraction of the windings on the top of the cores must be reduced as much as possible because mechanical stress could lead to deterioration of magnetic material properties. Therefore, the samples were packed into an aluminium box.
4.2 DC magnetic permeability

In figure 4, the measured relative magnetic permeability of four samples (S1, S2, S3, and S4) after demagnetization is shown. The magnetization current was ramped at 0.5 As\(^{-1}\) periodically between symmetrical positive and negative plateaus (5 s) with increasing amplitude. S1 shows permeability at low field up to \(17 \times 10^3\) higher than the other samples. This could arise from either a residual magnetization or from non-uniformity in the material production. At excitation fields higher than \(6 \text{ Am}^{-1}\), the permeability of the four samples exhibits the same behaviour. Despite S1, the material shows satisfying magnetic DC characteristics at 4.2 K. The maximum permeability of the samples under test is always higher than \(10 \times 10^4\), typical of a fairly good \(\mu\)-metal.

In figure 5, the measured magnetic induction (B) versus the excitation field (H) is shown. The maximum measured B is 0.83 T for a maximum H of 370 Am\(^{-1}\). This is in agreement with the saturation value in table 1. The maximum permeability of 68,000 at 0.4 Am\(^{-1}\) is attained by S1. For S4 is of the order of 54,000.

The assessed non-uniformity in the magnetic permeability of the samples affects the DCCT behaviour. In particular, for the DC compensation, this results in an asymmetry in the currents in the magnetic modulator, leading to an output offset [27]. This offset gives rise to a fictitious primary current, bringing the AC core to a non-null magnetization, and thus producing a loss in gain. This effect can be minimized by matching the cores of the DC magnetic modulator and adjusting suitably the offset of the power amplifier.
4.3 Hysteresis loop tests

In figure 6, the measured hysteresis loops of the samples with a maximum excitation field of 25 Am$^{-1}$ are illustrated. The excitation current rate was set at 0.16 As$^{-1}$ to limit eddy currents for coercive field assessment. The loops and permeability results agree. S1 (continuous line in figure 6) exhibits the sharper loop, owing to its higher permeability. The loops for S2 (dashed line) and S3 (dotted line) are similar. The S4 (thinner line) with the lowest permeability has a loop with the lowest level of B. The measured $B_r$ is 0.3 T.

The coercive magnetic field varies from 2.1 Am$^{-1}$ (S1) to 2.8 Am$^{-1}$ (S4). The maximum $B_m$ is 0.73 T for S1, 0.72 T for S2 and S3, and 0.7 T for S4.

4.4 Discussion

In table 1, the results of the four samples are compared with the typical performance of cryogenic permalloy and $\mu$-metal. Measured and typical performance of permalloy shows a satisfying agree-
The higher coercive field, a factor two and half, could be related to eddy currents. But, this value is compatible with the $\mu$-metal coercive field measured at room temperature in [9], i.e., between 2 and 4 Am$^{-1}$. Thus, the precision of the device should not be affected. In comparison with $\mu$-metal, only a 15% higher saturation is significant. This results in the requirement of increasing the module of the current driving the magnetic modulator, namely, to achieve a proper saturation of the cores. However, higher saturation results in a better rejection of the permalloy to the external interfering field.

5 Sensing element design

For the design of the cores, the type of cable passing through the DCCT, i.e. the transformer primary, has to be specified. The main limitation experimented by CEA-Saclay arose from a rectangular cross section [9], owing to its square edges concentrating the field lines. Furthermore, this section allows the issue related to the symmetry — non cylindrical — of the generated field distribution to be highlighted. For these reasons, a cross-section cable of 26.26 mm $\times$ 4.60 mm was considered. Finally, cable off centring must be taken into account also, though a suitable ferromagnetic shell.

In the following, (A) the conceptual design and (B) the engineering layout of the sensing element are reported.

5.1 Conceptual design

The basic design idea is to increase the core’s inner radius as much as possible, in order to avoid saturation at nominal current. Thus, in the design, the available space must be optimized according to the geometrical term $h \ln(r_2/r_1)$ of (3.1).

Local saturation and off centring mainly arise from the field asymmetry generated by the rectangular cross section. The 2D map of B field norm close to a rectangular cable with uniform current density distribution has an elliptical distribution (figure 7, simulated through COMSOL®).
In Figure 7, the cylindrical field geometry is restored at about 50 mm from the cable centre. In Figures 8(a) and 8(b), the norm of B along y and x, respectively, are reported. This simulation highlights that (i) the B values are practically the same for x and y higher than 50 mm, and (ii) the inner radius of the cryogenic permalloy core must be higher than 50 mm (assuming a perfect cable centring).

5.2 Engineering layout

In the engineering design, a protection case for the cores, the geometry of the wires, and an iron shell between the cores and the compensation winding were considered.

In Figure 9, the cross section view of the proposed sensing element is illustrated (length in mm). The inner and the outer radii of the cores are chosen in order to maximize the distance from the cable and to have enough space in radial direction for other elements. Each core has to be endowed with a thin layer (1 mm) of Epoxy to bear mechanical stresses during winding. The
height $h$ is chosen to preserve the geometric term in $h \ln(r_2/r_1)$ in (3.1) of the MACC+ $\mu$-metal cores ($h = [0.893/\ln(r_2/r_1)]$ mm). The detection coil is wound with 200 turns of an insulated copper wire with a diameter of 0.315 mm. Therefore, the gains of the AC and DC compensation mechanisms should be as close as possible to the commercial device working at room temperature (see section 3.2).

The iron shell has a thickness of 2 mm in order to provide ideally a screening factor of 20. The compensation coil can be wound with 8,000 turns of type 1 LHC corrector strand [28] (estimated thickness of 5.22 mm), outer diameter 0.435 mm. The strand has a critical current of 76.2 A at 4.2 K and for an external field of 4 T (parallel and orthogonal directions). The equivalent air-core inductance of the secondary is 0.17 H (five times lower than the CEA-Saclay solution [9]).

6 Numerical results

The designed sensing element has 8,000 turns for the compensation coil, with a current ratio of 8,000:1. For a perfect compensation of 100 kA in the cable under test, a current of 12.5 A is required. However, such a current level could give rise to saturation in the core of the cryogenic permalloy, namely 0.8 T. Moreover, any residual field gives rise to a DC component, generating a measurement error. Finally, an off centring of the cable under test could lead to a performance loss of the DCCT, and, even to core saturation. An iron shell between the three cores of the sensing element and the compensation coil provides a reasonable margin.

On this basis, twofold 2D simulations for the design validation were carried out at nominal operating conditions: (A) without the pure-iron shell, in order to demonstrate the design effectiveness; and (B) with the shell, in order to verify the rejection to off-centring condition.

6.1 Without iron shell

In this case, the iron shell absence and a perfect centring are assumed. The compensation coil is powered with 12.5 A for an ideal compensation. The cryogenic permalloy is modelled using the relation between $H$ and $B$ during the first magnetization curve of S2 in figure 5, by assuming full saturation at $800 \text{Am}^{-1}$. This is because the simulation is carried in DC condition (from a demagnetized state), with negligible hysteresis losses around the demagnetized state.

In figure 10, the 2D field map of $B$, when the DCCT’s sensing element surrounds the cable carrying 100 kA, is shown. As expected, the cores do not saturate as highlighted by the dark blue region, i.e. corresponding to a value of 0.5 T, i.e. 0.3 T below the saturation value of the cryogenic permalloy. The maximum magnetic induction field inside the core is 0.125 T, corresponding roughly to 1 Am$^{-1}$ of residual magnetic field. If the feedback mechanism of the DCCT would compensate such a field, an increment of the compensation current of 45 $\mu$A is required. This implies accuracy in the current measurement of the order of $10^{-6}$.

In figure 11, the effects of an off centring of 2 mm for the cable in both the directions $x$ and $y$ are highlighted. In this case, the maximum field in the core is 0.72 T (figure 11 (left)), close to the saturation. Figure 11 (right) illustrates also the regions with field higher than 0.71 T. The equivalent magnetic field is of the order of 26 Am$^{-1}$. The accuracy decreases to $10^{-4}$.
Figure 10. B field map generated by a cable of rectangular cross section carrying 100 kA and DCCT compensation coil with 12.5 A (dark blue region inside the core at low field region: flux compensation).

Figure 11. (Left) B field map for a rectangular cable off-centred symmetrically by 2 mm carrying 100 kA with 12.5 A in the compensation coil. (Right) Field regions higher than 0.71 T.

6.2 With iron shell

In figure 12, the simulation for a perfect cable centring, with a core surrounded by a 2 mm-thick iron shell, is shown. The maximum field value inside the core is 0.017 T, a factor 10 lower than in figure 12. A significant increase in compensation performance is achieved.

In figure 13, the effects of a cable off centring of 2 mm along both the directions x and y are investigated. The maximum magnetic induction is 0.25 T (figure 13 (left)), twice than in figure 6, but still matching the required accuracy of $10^{-5}$. Moreover, 0.25 T is three times lower than figure 11, by highlighting an operational margin for off centring. The field value inside the core is comparable with perfect centring a no surrounding shell. In figure 13 (right), the field’s regions higher than 0.24 T are illustrated.
Figure 12. B field map of a rectangular cable carrying 100 kA with 12.5 A in the DCCT compensation coil and iron shell surrounding the core.

Figure 13. (Left) B field map for a rectangular cable off-centred symmetrically by 2 mm carrying 100 kA with 12.5 A DCCT compensation coil and iron shell surrounding the core. (Right) Field regions higher than 0.24 T.

From the above results, the insertion of the iron shell leads to an overall performance enhancement, by giving rise to a larger immunity to off-centring problems.

7 Experimental proof demonstration

In this section, the experimental validation of a lab-scale cryogenic DCCT prototype is reported. In particular, (A) the requirements, (B) the design, (C) the experimental setup, and (D) the metrological characterization of the prototype are illustrated.
7.1 Requirements

The proposed sensing element is aimed at implementing a cryogenic DCCT to accurately measure currents up to 100 kA at 4.2 K. Testing the final transducer would require a superconducting cable with 100 kA in external magnetic field at liquid helium temperature. This is not feasible without involving an ad-hoc complex facility. Furthermore, the iron shell can be disregarded because simulation showed its marginal impact on performance without significant off-centring. Likewise, the superconducting shield is needed only with a high external field. Finally, a superconducting wire is required only when cryogenic load is of concern.

Under the above assumptions, the following requirements arise for the lab-scale prototype:

- Maximum primary current 20 kA, to keep cryogenic load not higher than 20 W;
- Maximum secondary (compensation) current of 10 A;
- Maximum sensing element diameter of 70 mm to avoid disturbance field from the powering current leads.

7.2 Design

For keeping the sensing element diameter below 70 mm, the cryogenic permalloy cores have to be designed according to eq. (3.1). In particular, by leaving the height $h$ equal to 17.3 mm (see section 5.2), the geometric factor $h \ln(r_2/r_1)$ in (3.1) is unaltered if the logarithmic ratio is preserved with respect to the proposed design. Halving the lengths of the radii of the final cores provides: $r_2 = 29.8$ mm and $r_1 = 23.3$ mm. Then, a primary current of 20 kA is compensated with 10 A, if a secondary coil of 2,000 turns is implemented, with a current ratio of 2,000:1.

In figures 14, the scaled core of cryogenic permalloy (a), the three cores with the 200 turns sensing coil (b), and the sensing element assembly (c) of the prototype are shown. The three cores are insulated mutually with Teflon tape. The compensation coils is realized with a copper wire with $\phi = 0.315$ mm.

The prototype can be tested with a primary current of 20 kA by exploiting an extra coil wound on top of the sensing element. Using a power supply of 20 A with a primary coil of 1,000 turns gives rise to the desired equivalent maximum current, namely 20 kAt. The excitation coil is wound on the top of the secondary coil using a copper wire of $\phi = 0.315$ mm. The coils are insulated mutually by a Kapton tape.

For the sake of clarity, in figure 15 the conceptual architecture of the cryogenic DCCT is recalled. The voltage $V_{DCCT, out}$ is the output of the conditioning electronics that drives the power amplifier to generate the required compensation/secondary current ($I_2$) of the device. The signals from the sensing element are exploited to implement the feedback mechanism for the AC and DC components of the primary current ($I_1$) under test.

The power amplifier available from the commercial MACC+ provides a maximum current of about 1 A. The circuit is based on a push-pull configuration with two complementary Darlington transistors and a biasing resistors network [9]. The same design is used to implement a new power amplifier for higher current, up to 20 A, guaranteeing noise level of the same order of the commercial device.
Figure 14. The prototyping steps of the cryogenic DCCT sensing element: the cryogenic permalloy core (a), the stack of the three cores insulated with Teflon tape (b), and the 2,000-turns secondary coil (c).

Figure 15. Cryogenic DCCT conceptual architecture.

7.3 Experimental setup

In figure 16, the experimental setup for the characterization of the cryogenic DCCT prototype is illustrated. The Power Supply is a SM 7020-D DELTA ELEKTRONIKA capable of providing a primary current up to 20 A. The reference DCCT is a MACC+ [11]: output $\pm 10$ V for a primary of $\pm 120$ A (12 A V$^{-1}$). The value of $I_1$ is retrieved via the output voltage $V_{MACC+}(I_1)$ and the reading is carried out by means of the 61/2-digits multimeter KEITHLEY 2000 (Digital Voltmeter). The sensing element is placed in a cryostat using a cryogenic insert. The top plate of the cryostat provides the connections of the cables from/to the sensing element, the DCCT conditioning electronics, and the primary. The power stage is connected to the compensation coil, linked to the burden resistor ($R_b = 50$ m$\Omega$). The voltage drop on the burden, due to the $I_2$, is amplified with an ideal gain $G$ equal to 16. The voltage output of the instrumentation amplifier ($V_{CryoDCCT}(I_2)$) is proportional to $I_2$: $V_{CryoDCCT}(I_2) = G R_b I_2$, i.e. $\pm 8$ V for a primary of $\pm 20$ kA (2500 A V$^{-1}$). The reading of this voltage is carried out by means of a further multimeter KEITHLEY 2000.
7.4 Metrological characterization

The metrological characterization is aimed at assessing in a steady state condition the difference between the primary current measured by the prototype and the reference of the MACC+ at room temperature.

7.4.1 Procedure

The characterization procedure is summarized as follow:

1. Setting of the current reference $I_1$ on the primary, by regulating the current of the power supply in order to read always the same output voltage, $V_{MACC+}(I_1)$, from the MACC+ up to the fourth decimal digit of the voltmeter’s display (the last stable one for $V_{MACC+}(I_1)$). In table 2, the reference current values are reported.

2. Reading of the $V_{CryoDCCT}(I_2)$ from the voltmeter in order to retrieve the $I_2$ value; once the current on the primary is properly set, the voltage $V_{CryoDCCT}(I_2)$ from the instrumentation amplifier is read when the transient is negligible.

Repeat the points 1 and 2 for several values of $I_1$ by following the standard practice to limit hysteresis phenomena in the instrumentation. The readings are carried out on the way from the minimum up to the maximum of $I_1$ and from the maximum down to the minimum. This alternation should be repeated 15 times to collect 30 readings for each value of $I_1$ in table 2. Despite of this, the number of readings per primary current value was limited to 6 providing already satisfactory results: helium loss is the main factor of time limitation.

7.4.2 Characterization results

In table 3 the measured value of $I_2$, are reported with the corresponding experimental uncertainty $u$. These results are defined using the 6 readings available for each $I_1$ value. The relative uncertainty is better than $\pm 10^{-3}$. 

![Figure 16. Experimental setup for the cryogenic DCCT characterization.](image)
Table 2. Reference $I_1$ values.

| $V_{\text{MACC}+}(I_1)$ (V) | $I_1$ (A) |
|-----------------------------|-----------|
| 0.1630                      | 1.9560    |
| 0.2463                      | 2.9554    |
| 0.3328                      | 3.9936    |
| 0.4108                      | 4.9290    |
| 0.5000                      | 6.0000    |
| 0.5765                      | 6.9180    |
| 0.6647                      | 7.9764    |
| 0.7470                      | 8.9640    |
| 0.8296                      | 9.9552    |
| 0.9120                      | 10.9440   |
| 1.1646                      | 13.9752   |

Table 3. Measured secondary current $I_2$ for the $I_1$ values of table 2.

| $I_2$ (A) | $u$ (A) |
|-----------|---------|
| 1.0147    | ± 0.0005|
| 1.5014    | ± 0.0014|
| 2.0178    | ± 0.0011|
| 2.4870    | ± 0.0002|
| 3.0230    | ± 0.0002|
| 3.4822    | ± 0.0006|
| 4.0102    | ± 0.0001|
| 4.5033    | ± 0.0009|
| 4.9977    | ± 0.0008|
| 5.4904    | ± 0.0012|
| 6.9944    | ± 0.0024|

The ideal relationship between $I_2$ and $I_1$ is the classical transformer current ratio:

$$I_1 = -\frac{N_2}{N_1} I_2$$  \hspace{1cm} (7.1)

where $N_2$ and $N_1$ are the secondary (2,000) and primary (1,000) turns of the transformer, respectively. The current ratio of the cryogenic DCCT prototype is then 2:1 or equivalently 2,000:1 by considering the primary ampere turns current ($N_1 I_1$). In table 4, the reference $I_1$ values, the measured $I_{1,m}$ according to (7.1), and the measurement errors ($I_1 - I_{1,m}$) are reported. The assessed experimental uncertainty of the primary current measurements is at least one order of magnitude lower than the error: it has not to be taken into account for evaluating the static characteristic of the prototype.
Table 4. Reference primary current $I_1$ along with the measured values $I_{1,m}$ and the error ($I_1 - I_{1,m}$).

| $I_1$ (A) | $I_{1,m}$ (A) | $I_1 - I_{1,m}$ (A) |
|-----------|---------------|---------------------|
| 1.9560    | 2.0295 ± 0.00096 | -0.0735            |
| 2.9554    | 3.0029 ± 0.00276 | -0.0475            |
| 3.9936    | 4.0355 ± 0.00220 | -0.0419            |
| 4.9290    | 4.9740 ± 0.00037 | -0.0450            |
| 6.0000    | 6.0460 ± 0.00038 | -0.0460            |
| 6.9180    | 6.9644 ± 0.00121 | -0.0464            |
| 7.9764    | 8.0203 ± 0.00025 | -0.0439            |
| 8.9640    | 9.0067 ± 0.00179 | -0.0427            |
| 9.9552    | 9.9954 ± 0.00150 | -0.0402            |
| 10.9440   | 10.9807 ± 0.00234 | -0.0367            |
| 13.9752   | 13.9888 ± 0.00487 | -0.0136            |

Table 5. Reference $I_1$, measured $I_{1,m}$ corrected by offset, and percentage error.

| $I_1$ (A) | $I_{1,m}$ - Offset (A) | Error % |
|-----------|------------------------|---------|
| 1.9560    | 1.9587                 | 0.05    |
| 2.9352    | 2.9321                 | 0.50    |
| 3.9936    | 3.9648                 | 0.82    |
| 4.9290    | 4.9032                 | 0.60    |
| 6.0000    | 5.9753                 | 0.48    |
| 6.9180    | 6.8937                 | 0.41    |
| 7.9764    | 7.9496                 | 0.38    |
| 8.9640    | 8.9359                 | 0.36    |
| 9.9552    | 9.9247                 | 0.34    |
| 10.9440   | 10.9100                | 0.35    |
| 13.9752   | 13.9181                | 0.44    |

The linear interpolation of $I_{1,m}$ results in the fitting line with expression:

$$LI = 0.9963 I_1 + 0.07072 \text{ (A)}$$

(7.2)

prospects for further increases in the metrological performance of the final prototype.

This relation highlights an offset error for the cryogenic DCCT equal to 0.0707 A and a gain error of almost 0.4%. Indeed, correcting the measurement data from the offset, the percentage difference between reference and measured $I_1$ is of the same order for the overall measurement points, table 5 (uncertainty are not reported).

In figures 17, the 1-$\sigma$ repeatability (top) of $I_{1,m}$ and the nonlinearity (bottom) are illustrated. The nonlinearity is better than ±0.05% for $I_1$. These results highlight that the gain error is mainly due to the implementation of the instrumentation amplifier (discrete components and resistors with
uncertainty of 1%). Moreover, a potential significant loss in metrological performance can arise from temperature drifts of resistors. In the final prototype, resistors with tolerances on the order of 0.01% and a temperature coefficient less than 2 ppm/C will be used. The offset error could be due to an unbalance of the cryogenic permalloy cores. In synthesis, the static characterization shows the effectiveness of the cryogenic DCCT design and the prospect of further increases in the metrological performance of the final prototype.

Finally, in figure 18, as a visual example, the measured current curves on the primary (red) and secondary (black) using the MACC+ and the Cryogenic DCCT prototype are shown, respectively. The current curves from the cryogenic DCCT prototype and the reference MACC+ were recorded by means of an oscilloscope Tektronix DPO 2024 (the image of figure 18 is only a visual qualitative indication). In particular, three current steps were used to ramp up to a maximum equivalent primary current of 17 kA. The current values are expressed in terms of equivalent At.

According to the previous metrological characterization, the behaviour of the reference device and the prototype are compatible.
Figure 18. Visual example of the measured current by means of the reference MACC+ (red) and cryogenic DCCT prototype (black) during a current cycle.

8 Conclusions

A cryogenic sensing element for commercial measurement current transformers up to 100 kA is proposed. The design is based on a soft magnetic alloy, the Ni 81-Mo 5-Fe, referred to as cryogenic permalloy. Magnetic characterization measurements at 4.2 K show properties of cryogenic permalloy for the DCCT sensing element, in some extent, even better than $\mu$-metal at room temperature. The geometrical dimensions of cores’ sensing element are defined according to an optimization criterion. This allows ideally the room temperature performance of a commercial transducer to be preserved for a rated current of 100 kA at 4.2 K.

The design has been validated via 2D electromagnetic simulations of the sensing element, at nominal working conditions, exploiting the data from the experimental characterization of the cryogenic permalloy. The results show the effectiveness of the sensing element by promising the transducer accuracy of the order of $10^{-5}$. A screening shell of pure iron is also considered to increase the overall performance. A large immunity margin for facing off-centring problems is achieved.

Afterwards, a lab-scale cryogenic DCCT was prototyped for validating on the field the design basic ideas. The prototype was manufactured to achieve a current ratio of 2,000:1 for a maximum primary current of 20 kA. In the experimental setup, the primary of the transformer is wound with a 1,000 turns coil in order to reach 20 kAt for an excitation of 20 A. The reference primary current is retrieved using a commercial DCCT. The characterization results show a 1-$\sigma$ repeatability of the measured current practically better than $\pm0.05\%$. The characterization highlights also a gain error with respect the reference DCCT of 0.4% and an offset referred to the primary current of 7.0 mA. The gain error is mainly due to the implementation of the instrumentation amplifier. The offset error could be due to an unbalance of the cryogenic permalloy cores. By correcting this error, nonlinearity better than $\pm0.05\%$ is achieved. These preliminary results show the effectiveness of the cryogenic DCCT design and the prospect for further increase in the metrological performance of the final 100 kA prototype.

Further research in this field will be aimed at realizing and testing the final 100-kA cryogenic DCCT prototype based on the proposed sensing element in a measurement test station.
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