A Vertical Path Proposal on Magnetic and Electromagnetic Phenomena and Superconductivity Based on Hands-on Experiments

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Abstract

Focusing on magnetic and electromagnetic phenomena offers a coherent teaching/learning path in a vertical curriculum perspective. Primary students start exploring the space around a magnet, and secondary school students analyze the concept of flux of a magnetic field and electromagnetic induction, ending with the analysis of superconductivity phenomena with exploration of the magnetic field in matter.

This learning environment at the workshop offers an experience of Conceptual Labs of Operative Exploration (CLOE Labs), engaging participants in working groups by means of semi-structured interviews and inquiry analyses to experience the way in which conceptual knots, known in literature, can be faced by means of inquiry-based learning (IBL) strategies. The IBL approach adopted in the workshop is based on a set of hands-on/minds-on explorative experiments designed with simple apparatus and multimedia tools.

Keywords: Physics education research, magnetism, electromagnetism, superconductivity, educational path, inquiry-based learning strategies

Introduction

Magnetic and electromagnetic topics have values on different levels since they are common phenomena allowing the construction of formal thinking. Moreover, they represent a context to step from observation to a description in terms of field. This paper aims at describing the structure of a hands-on and minds-on workshop in the form of a learning path on magnetism, electromagnetism and superconductivity.

Founding concepts (for example the distinction between field and force) can be addressed, finding out a spatial representation for the field and using the discovered representation to introduce the concept of flux that emerges to be constant from simple experimental explorations along a tube between two field lines. The concept of field is fundamental in physics to describing interactions (Vercellati, 2010a). It is useful in the static case, and it is of capital importance in dynamical situations, because we do not provide any other concept to describe phenomena, so the double nature of magnetic sources (magnets and currents) involving also electromagnetic induction (EMI), can be addressed. EMI plays a crucial role in physics (Nussbaum, 1972; Zuza et al, 2012; Galili & Kaplan, 1997; Galili, 2001) in the passage from static to dynamic fields, in the definition of time-depending magnetic fields as sources of electric fields and in the construction of the concept of electromagnetic field (EMF). EMI represents a fundamental prerequisite to many domains of modern physics, for example, in technological applications daily used in the real world (Dori & Balchner, 2005; Eckert et al, 2009) and that are present in educational labs (Torzo et al, 1986; Priest & Wade, 1992; McNeil, 2004; Jodl & Eckert, 1998; Tanner et al, 2001; Dori & Balchner, 2005; Ruiz, 2006; Fodor & Peppard, 2012), superconductivity (Bouquet et al, 2009; Kedzierska et al, 2010) and special relativity (Galili & Kaplan, 1997; Galili, 2001; Galili et al, 2006).

Magnetic and electromagnetic phenomena are also relevant topics in the physics curriculum due to their epistemological contribution as a new interpretative framework for common phenomena, the importance of the various applications in different fields, the perspectives that such topics open for interpreting the micro-world and the contribution on the historical plan regarding the scientific development of ideas. The analysis of magnetic and electromagnetic phenomena offers many opportunities for the development of formal thinking and for gaining ownership of the scientific way of thinking. The involved learning processes influence the analysis of the magnetic properties of matter, of the meaning of sources of the field, the interpretation of new phenomena such as the presence of an electromotive force, as well as the dealing with a new formalism and its meaning on different interpretative plans (from interactions between systems to the concept of field). Moreover, the topic of superconductivity is significant since it is framed in the wider context of modern physics: it is the macroscopic evidence of quantum processes that can be faced with simple and motivating experiments, involving technological applications, such as magnetic levitation analyzing magnetic properties of matter (ferro-, para-, dia-magnetism).

Literature on learning processes highlighted the importance to build a functional understanding of key concepts (McDermott, 1991; Jelcic et al, 2017) that make possible to describe electromagnetic phenomena from the description and interpretation of basic phenomena, creating the basis for the construction of the fundamental concept of an electromagnetic field (Bagno & Eylon, 1997; Albe & Venturini, 2001; Zuza et al, 2012; Michelini & Vercellati, 2012). The problem of effective learning does not regard knowledge plan only, but it has to be faced in broader cultural terms: the opportunity to understand what science is and what science is not has to be offered in order to understand what and how science deals with the cognitive processes and how to be aware potentials and limits of the scientific approach. The way in which this can be done represents another problem, but we cannot solve it by simple storytelling and passive delivery of information: scientific instruments and methods have to be known or re-known and meta-reflection plays an important role in this experience. Thinking on common experience is a good starting point: the exploration with mind, senses and sensors activate reasoning, explanations and the building of interpretative models. A vertical path in the curriculum builds the concepts in a step-by-step process starting from experience and does not provide a simple sequence of spiraling content views, which distracts from the conceptual development of scientific ideas.

The basic problem for scientific learning regards the fact that attention should be focused on setting up strategies to achieve an effective conceptual change from common sense to the scientific knowledge of the topic (Michelini, 2010). Reference situations, materials and methods are never neutral, but dynamic evolution of internal logic of reasoning (Gilbert, 1998), following problematic stimulus.

The building of formal thinking acts on three directions: (a) informal learning and the role of hands-on and minds-on activities to interpret phenomena, models (tools to bridge common sense to physics ideas) and representations in learning process; (b) Information and Communication Technologies (ICT), Real-Time Labs (RTL) and modeling activities contribution; (c) building a formal theoretical way of thinking.

In our Research Unit in Physics Education from University of Udine, the context of informal learning research comes from an operative proposal with simple materials, easy to reproduce and computer on-line sensors as sense extensions to explore phenomena: in the Games, Experiments and Ideas (GEI) exhibit (Michelini et al 2003; Michelini, 2005), which consists of 650 hands-on experiments, a structured environment allows pupils, students and teachers to play and do experiments, exploring ideas and use such ideas to explore phenomena. This context of playing offers a great opportunity for subject’s development and learning providing the transition from the concrete context of action and the abstract thinking. Moreover, the de-contextualization of play, stimulates and activates personal learning processes and achieves a connection with ludic-symbolical abilities. Thus, using play, the learner amplifies the vision of the world and learns the way in which thought is structured with relation to the experience. In other words, the place of experimentation becomes the place of learning.

Conceptual Labs of Operative Exploration (CLOE) represent a bridge between research and school praxis and are carried out providing an open work environment in which problem-solving situations on specific different topic are proposed to students using semi-structured interviews and tasks following an Inquiry-Based Learning (IBL) approach (McDermott, 1996). During a CLOE activity, discussions of ideas in working group, interactive explorations and discussions and maps production take place under the guide of the researcher (or teacher) that follows a semi-structured protocol providing stimuli key questions. Working sheets in which students are guided to make a prevision on a phenomenon, the exploration of it and the comparison with the prevision (PEC - Prevision, Exploration, Comparison cycle) are frequently used.

Conceptual knots on magnetism and electromagnetism

Conceptual learning difficulties, known also as "conceptual knots" are to be taken into consideration in structuring an educational path (Vercellati, 2010b). Research literature in Physics Education Research (PER) highlights several conceptual knots related to magnetic field (i.e. static field) and to electromagnetic induction (i.e. dynamic field). In the latter case, the difficulties include magnetic flux and its time variation, Lenz's law (i.e. the sign of induced electromotive force), the motion of conductors in a magnetic field and the mathematical description of the phenomenology.

In the static case, the conceptual knots include: (a) the reciprocity of the interaction (i.e. the third law of dynamics) (Guisasola et al, 1999), (b) the field representation (Guisasola et al, 1999; Michelini & Vercellati, 2012) and nature (Michelini & Vercellati, 2012): related to the following questions: is the field material or is it a state of space? If it is a material entity, how it is possible to create or destroy it by means of current or the motion of something else? Which exact properties has this entity? (c) the recognition of magnetic fields generated by currents (sources and geometry of the field), (d) the concept of field superimposition (Rainson & Viennot, 1992), (e) the relation between field lines and the trajectory followed by objects interacting with magnetic field (Tornkwist et al, 1993): difference between field lines and forces, and (f) the relation between magnetic field and currents, and the nature of the field itself (Thong & Gunstone, 2008).

If we move from the static case, where electrostatics and magnetostatics are different phenomenological areas, to the dynamic case (where the electric and magnetic field are the components of the electromagnetic field) we amplify the panorama of the recalled problems about field concept. General conceptual knots regard the sources of the field and the role of relative motion (Maloney et al, 2001), the Lorenz force (its nature and identification of the effects related to charges in motion) (Maloney et al, 2001) and the Lenz's law with particular regard to the direction of the induced field (Bagno & Eylon, 1997).

Conceptual knots related to magnetic flux and its time variation regards the facts that magnetic flux is usually confused with magnetic field (Saarrelainen et al, 2007; Thong & Gunstone, 2008) and the concept of magnetic flux is not distinguished from its time variation (consequently most of students do not recognize the role of magnetic field flux time variation) (Kesonen et al, 2011; Sanchez & Loverdue, 2012; Salvesberg et al, 2011; Secrest & Novodvorsky, 2005). Time-depending magnetic field is not identified as a source of electric field (Kesonen et al, 2011) while induced current is associated mainly to relative motion between magnets and coils and there is little awareness that there is no EMI in the case in which no flux variation is observed even when a relative motion occurs between a magnet and a coil (Maloney et al, 2001; Secrest & Novodvorsky, 2005; Guisasola et al, 2013). It is not recognized that EMI can be observed also when an electric circuit is warped in presence of a magnet (Maloney et al, 2001), when it is rotated near a magnet (Maloney et al, 2001), or in the case of two coupled circuits without any kind of relative motion (Peters, 1984; Thong & Gunstone, 2008).

Despite its educational and social relevance, recent researches in PER highlighted various difficulties in the comprehension of Faraday-Neumann-Lenz (FNL) law, demonstrating that the involved concepts and models are particularly problematic for students. There is a general agreement on the fact that the concepts related to FNL law are “highly abstract and their understanding is model-dependent” (Guisasola et al, 2007; Venturini & Albe, 2002; Huang et al, 2008; Sanchez & Loverdue, 2012). In particular Lenz’s contribution to FNL law is fundamental for an in-depth comprehension of electromagnetic interactions, since it represents an expression of the energy conservation. It represents another conceptual knot for students in the comprehension of EMI phenomena (Secrest & Novodvorsky, 2005; Jones, 2003; Kesonen et al, 2011): students have difficulty in determining the versus of the induced magnetic field (Bagno & Eylon 1997). The major source of difficulty could be related to a fuzzy encoding, probably due to an incorrect interpretation, of textbook sentences like ‘‘The induced current resists its cause’’ or “it opposes the changes”, that could be interpreted as being “in the opposite direction”. This implies that the induced magnetic field is always in the opposite direction of the inductor magnetic field.

Conceptual knots concerning the motion of conductors in a magnetic field, arise due to difficulties emerging in interpreting magnetic flux changes when it is not evident/explicit which kind of flux-changes happens (Bringuer, 2003; Maloney et al, 2001; Feynman et al, 1964; Duit, 1985; Galili & Kaplan, 1997; 2006; Zuza et al, 2012).

Also the needed formalism to deal the aforementioned concepts is linked to some difficulties: students reach partial knowledge of the basic concepts of electromagnetism (fields, flux, induction) while they are not able to associate the mathematical formalism (vectors, integrals) to the physical description of such key concepts, so the comprehension of the relationships between these concepts as well as the construction of formal models become very difficult for learners, even though the recurring use of mathematical procedures is observed (Albe et al, 2001; Venturini & Albe, 2002; Salvesberg et al, 2002).

From a general point of view, most researches related the difficulties about FNL with students’ partial and local vision of observed phenomena (Jelecic et al, 2017; Salvesberg et al, 2002; Sanchez & Loverdue, 2012). Some research results (Bagno & Eylon, 1997; Duit, 1985; Guisasola et al, 2004) demonstrate that some student difficulties regarding EMI arise from incoherent conceptualization of magnetic field and its representation through field lines, magnetic flux and divergence. The vision of field lines as concrete objects (real entities) accordingly to Faraday who “seemed to attributed more reality to the field lines than we nowadays find acceptable” (Tornkvist, 1993; Guisasola et al, 2004) affect the comprehension of EMI phenomena: students believe that it is necessary to have contact between magnetic field lines and coils to get EMI (Thong & Gunstone, 2008; Michelini & Viola, 2008; Loftus, 1996).

The learning environment and the strategies designed to overcome those conceptual knots are presented in a workshop described hereafter.

Structure of the workshop

The workshop on magnetism, electromagnetism and superconductivity is organized in three main sections: a first explorative section focuses on the presentation of a path on magnetic phenomena, based on magnetic field lines as conceptual referent to identify magnetic field, to distinguish between magnetic field and magnetic force. Inquiry interviews based on Observe-Do-Understand (ODU) strategy will encourage the personal involvement of the participants in exploring the experimental situations on interactions between magnets and between magnets and other objects made of ferromagnetic, diamagnetic, paramagnetic matter. The compass, as a magnet itself, becomes the explorer of the properties of the space around a magnet, gives the opportunity to investigate the interactions between magnets and build a sort of map of the space in terms of flux (Vercellati, 2012).

In the second section, electric current will become the source of magnetic field: through the Oersted experiment and by using a platform of compasses, participants explore the new characteristics of field lines and individuate the analogy between a magnet and a solenoid. This gives the opportunity to measure a magnetic field in fundamental units and to explore the electromagnetic induction with relative applications (Michelini & Vercellati, 2010; Michelini & Viola, 2010).

The final section of the workshop focuses on the phenomenology of superconductivity which offers many opportunities to explore a relevant phenomenology perceived as a challenge stimulating the construction of models, activating a critical re-analysis of magnetic and electrical properties of materials. The changes in the electric and magnetic properties of a YBCO (yttrium barium copper oxide) sample, a material showing superconductive properties, at phase transition emerge, employing probes designed to explore resistivity versus temperature of solids with on-line measurements. The problematized analysis of the phenomenology aims at constructing models for the Meissner effect, using the field line representation.

Characterizing magnetic field by experimental explorations

The typical starting situation provides a cluster of different objects of different materials and shapes and a magnet. The forecast regards the interactions between the magnet and the objects that are classified according to the different magnetic behaviour after trails. Performing the explorations, it is possible to stress out that not all metallic materials are attracted by the magnet but only the ones containing iron (ferromagnetic attraction), the modalities in which a magnet can be recognized out of other materials, due to its characteristic properties of attracting iron, and the properties of the reciprocal interactions between a magnet and an iron object (it is not simply that magnet attracts the object, but the vice-versa is also true, since forces appear always in pairs).

Interactions between magnets are subsequently explored: magnets have two different poles and the interaction can be attractive or repulsive only in the case of bonded systems. If the magnets are free (or floating), the interactions are of two types: attraction and rotation followed by attraction: no repulsion occurs, and this is at the basis of the fact that magnetic field is not a field of forces, but rather a field of torques, which is deeply linked to the fact that in a magnet it is not possible to break apart the two single poles (Fig. 1).

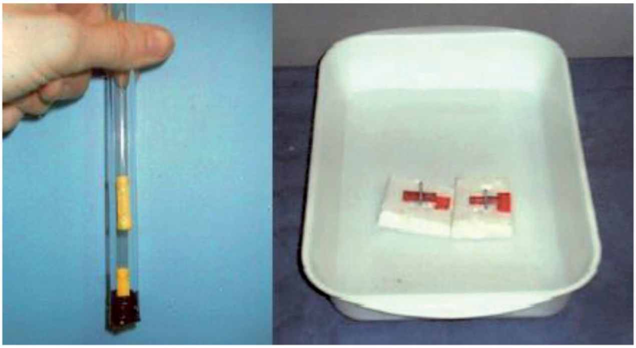

Fig. 1. Magnets do not attract or repeal each other according to the poles: this is true only if they are constrained. If the magnets are free, only attraction or rotation followed by attraction occur.

The idea of field as an entity permeating the space can be addressed since magnets feel each other at a distance apart with no physical contact, that can be demonstrated by the pattern assumed by iron filing placed around a magnet. The observation that a magnet can influence the needle of a compass is the starting point of using the compass as an explorer of the magnetic field around a magnet in different positions and at different distances, drawing down the field lines. From the description of field lines, the evidence that there is no intersection between lines emerges as well as the fact that they appear to be closed and that the distance between two lines is not constant (Fig. 2).

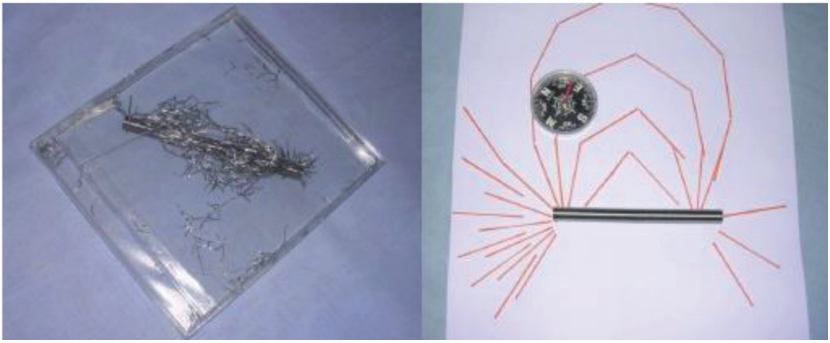

Fig. 2. Field lines are visible thanks to iron filing around a magnet or using a compass as an explorer, according to the direction of its needle in different points.

If the magnet is rotating by 90 degrees, the field lines pattern changes due to the composition of its magnet field with the terrestrial one, creating the first idea of a vectorial - not scalar - composition. Moreover, the situation proposed in Fig. 3 (left) enables us to answer the question “how will the orientation of the compass’ needle change from point 5 to a point near a pole of one of the two identical magnet?”. From 45 degrees in the starting position, the angle changes due not only to the fact that the magnetic field is not only a versor, but is has also an intensity, and the composition rules are the ones of the vector sum. The other evidence is provided by the experiment in which a compass approaches the pole of a magnet and noticing that the orientation of its needle changes with distance, due to the changing of the transversal component of the field. This behaviour can be explored by means of a magnetic field sensor: the intensity of the magnetic field increases approaching the magnet along a field line, demonstrating that it is not constant along one of them (Fig. 3, right).

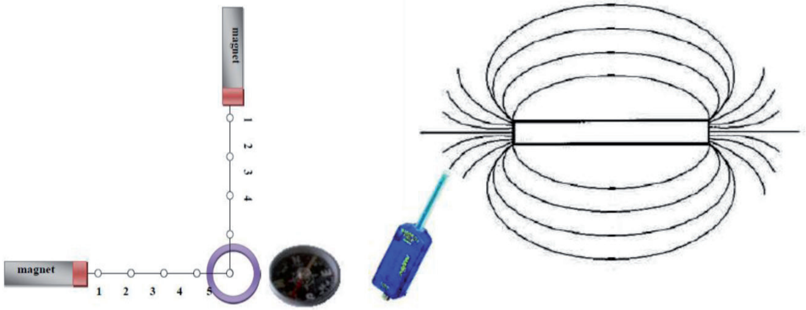

Fig. 3. A simple exploration proving the vector nature of the magnetic field (left) and the use of a magnetic field sensor to measure the intensity of the field along a previously sketched line (right).

The vector represents a magnetic property of space, orienting the needle of a compass. Magnetic field lines thus assume both the roles of representation and model, a conceptual tool to interpret magnetic interactions, to distinguish magnetic field and magnetic force (which have the same direction only for electrostatic interactions): it is enough to put a small metallic ball in proximity of a field line and noticing that the direction of the starting motion is different from the field line in that point: magnetic field and the acting force in a given point are different quantities (Fig. 4).

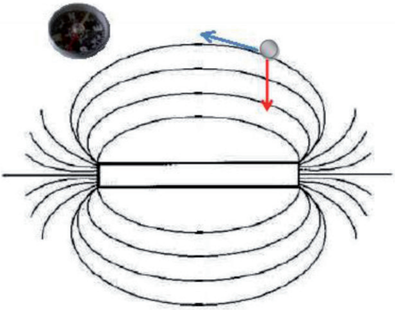

Fig.4. The force acing on an iron sphere (red) is different from the direction of the magnetic field in the same point (blue).

The magnetic field sensor also allows to measure the intensity of the magnetic field B between two field lines with respect to the relative distance D between the two lines, discovering that field lines are more distant as the field along one of them decreases. It is thus suggested to correlate the intensity of B with the area D^2 of the tube between two lines. The linear relationship between B and D^2 produces a reasoning in terms of flux, since the evidence that the product BD^2 is constant and representative of the field itself, and it is called "flux" (Fig. 5).

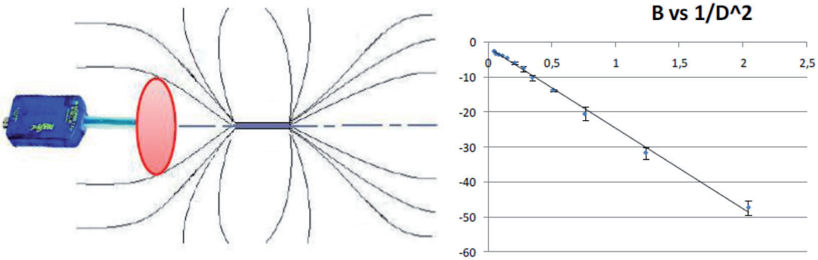

Fig. 5. The correlation between the intensity of the magnetic field (B) between two lines and the area between them (D^2) turns out to be linear. The flux of the magnetic field (proportional to B times D^2) is thus a constant.

Exploring the magnetic effects of currents and the electromagnetic induction

The second part of the workshop analyzes the sources of the magnetic field (Michelini & Vercellati, 2010; Michelini & Viola, 2010). The Oersted experiment provides the evidence that a current flowing in a rectilinear wire produce the same effects on a compass' needle that the ones produced by a magnet. In this way it is possible to explore and draw down the magnetic field lines produced by a current flowing in a rectilinear wire. The prevision of the pattern of field lines around a current loop can be foreseen and visualized both via simulation and with the tangent compass, allowing also to visualize the field pattern produced by a solenoid with the aid of a compass inside the solenoid itself (Fig. 6).

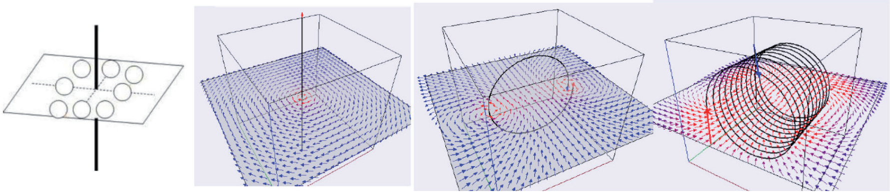

Fig. 6. An ensemble of compasses or a computer simulation allow to visualize the geometry of the magnetic field around a rectilinear wire, inside a loop or a solenoid.

This representation guides to find out a very important similarity between the magnetic field lines pattern of a magnet of the one produced by a solenoid: the two objects behave similarly from a magnetic point of view.

Since this similarity is pointed out, interactions between the new source of magnetic field, are explored: solenoid carrying current attract or repel each other according to the direction of the flowing current, a solenoid carrying current is able to attract ferromagnetic objects, and magnets are attracted by current flowing in solenoids. Interactions between different sources of magnetic field are explored by semi-structured questions as "two magnets are sources of magnetic field and interact with each other, do you think that two wires/coils/solenoids will do the same (being also them sources of magnetic field)? Perform the experiment and describe the observed phenomena".

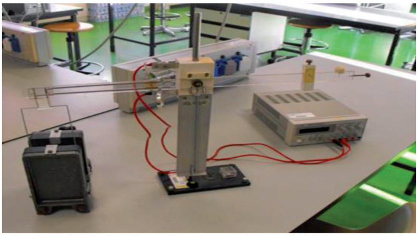

Fig. 7. EMI can be explored analyzing the behavior of a current loop inside a magnetic field: the direction of the force acting or the balance's arm depends on the versus of the current.

The next step is the experimental exploration of EMI: a coil connected to one of the two arms of a balance is placed between two magnets; the wire is connected to a voltage supply and the current flows first in one sense and then in the other (Fig. 7). The arm of the balance curves towards or far away from the magnets according to the versus of the current. This experimental exploration is performed having in mind flux tubes in order to interpret the observed behavior.

The next point is to explore the vice-versa: if a current produces a magnetic field, can a magnetic field produce a current? The role of magnetic flux and its time variation is explored considering the role of the different parameters (magnetic field, area and orientation) placing different coils with different number of loops and different areas between two magnets. The coils are connected to a galvanometer, measuring the current flowing, and the relationships between the induced current and the parameters comes after qualitative and quantitative exploration by means of on-line sensors (Fig. 8).

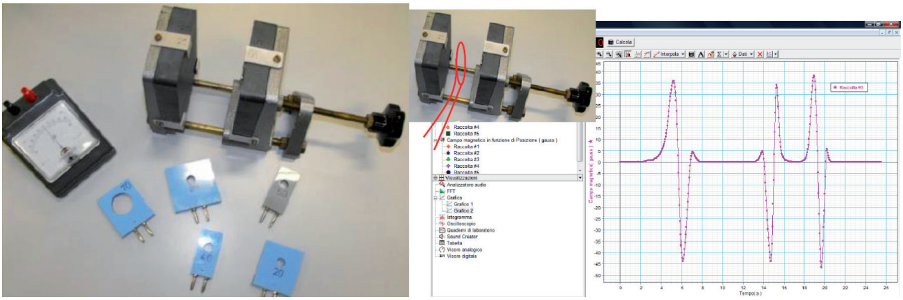

Fig. 8. Quantitative and qualitative analysis of EMI. The former can be performed using a galvanometer connected to different loops moving inside a magnetic field (left) while the latter can be performed using an on-line sensor measuring the voltage to the heads of the loops (right).

A simple experiment clarifying the phenomenology of EMI is illustrated in Fig. 9: a cart moves under the weight of a magnet falling into a coil. The voltage across the coil and the cart's velocity are measured with sensors connected to a PC. Two peaks of voltage are measured: the former corresponding to the magnet entering the coil, and the latter corresponding to the magnet exiting the coil. Peaks are different, but they are linearly correlated with the velocity (the second peak is, in absolute value, greater than the first one, since the motion is an accelerated one). The areas of the two peaks are equal since the total variation of flux is zero (magnet first enters the coil, and then the same magnet comes out of the coil).

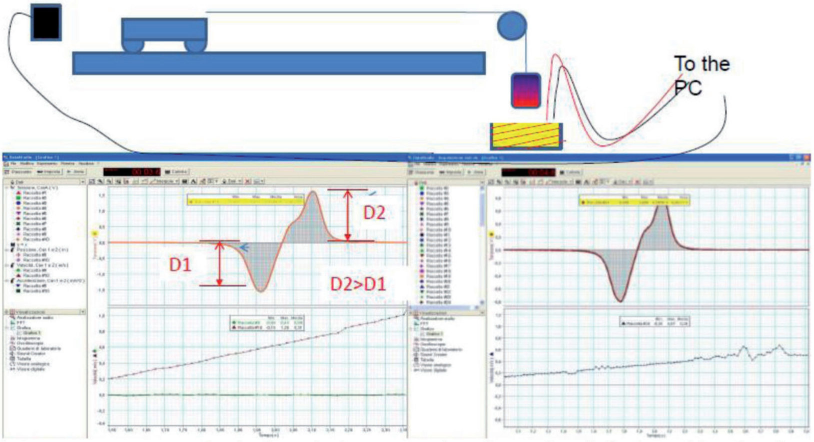

Fig. 9. Experimental setup to measure the induced electromotive force (emf) induced by the free falling of a magnet inside a solenoid. Graphs allows to observe that the net flux variation is zero and that the emf is linearly correlated with the speed of the falling magnet.

A research-based path on superconductivity

The last session of the workshop explores phenomena related to superconductive behavior of certain materials in the light of magnetic interactions and EMI phenomena previously analyzed.

By means of simple torsion balances is possible to explore the interaction of a magnet with different kind of materials (aluminum, copper, water, wood, graphite) hanging to the balances and see if they are attracted, repulsed or not affected by the magnet. This exploration allows to demonstrate the different behavior of the materials in the proximity of a magnet: ferro-, para- and diamagnetic properties are explored, noticing that some materials (for example pirolitic graphite) are repelled. It is thus shown that diamagnetic materials show repulsive magnetic properties only in the presence of a magnet. The usage of a torsion balance is needed since diamagnetic effects are very weak.

The next step is the analysis of three phenomena apparently different from each other: (a) the free fall of a flat magnet on a diamagnetic metal, for example copper, ground, (b) the motion of a flat magnet on an inclined diamagnetic metal and (c) the free fall of a flat magnet inside a tube of the same material. In all the cases, the magnet slows down till reaching a constant velocity, despite in static conditions it interacts very weakly with the material used. Tubes of different materials can be used and the velocity reached by the magnet depends from the material. It turns out that the lower is the resistivity of the material, the lower is the velocity of the magnet. The phenomenon is interpreted in the light of the EMI phenomenology and eddy (induced) currents: the conceptual tools used are the operative definition of field lines, the flux of the magnetic field and the FNL law: Induced currents interact with the magnetic field of the magnet producing a force, i.e. a lifting (braking) effect (Fig. 10).

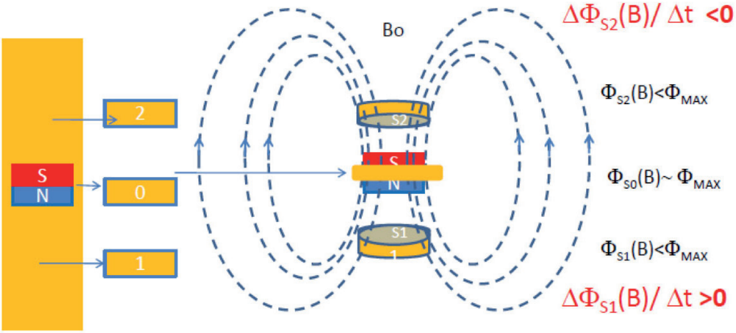

Fig. 10. A round magnet falling inside a metallic tube creates eddy currents, due to the variation of flux, resulting in a force that slows down the magnet. The lower the resistivity of the material, the higher the eddy currents and the braking effect is more evident. This effect does not depend on the magnetic properties of the tube, that can be either a para- or diamagnetic material.

The exploration of a peculiar behavior of a YBCO (Yttrium-Barium-Copper-Oxide) tablet allows to explore the Meissner effect: preliminary exploration with magnets or compasses show that the YBCO does not interact with any magnets nor it shows any magnetic properties at room temperature, but when the tablet is in thermal equilibrium in a bath of liquid nitrogen at a temperature of T_{LN} = 77K, it strongly interacts with the magnet and levitation occurs: the magnet is repelled by the cooled YBCO and it oscillates around its equilibrium position (Fig. 11).

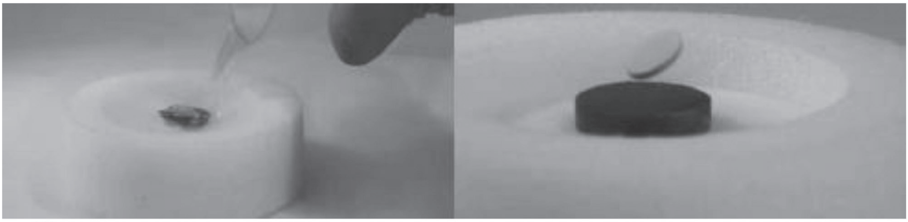

Fig. 11. A cooled tablet of YBCO interacts in a new way with a magnet.
How can be this behavior interpreted?

Only the magnetic property of the YBCO are changed, since both at room temperature and at T_{LN} the magnet interactions with other objects (not YBCO) are essentially unchanged, and the magnetic field measured around the magnet with a probe has the same intensity and direction. Hypotheses concerning the changing in the magnetic properties of the YBCO are discussed: has the YBCO become a ferromagnetic object? If the magnet is reversed (undergoing a 180 degrees rotation), levitation occurs in the same way: there always is a repulsive effect. The YBCO does not become a ferromagnetic object since when a magnet interacts with a ferromagnetic object there is an attractive effect. Maybe the YBCO becomes a magnet and it interacts with the other magnet as they are facing with the same polarity (i.e. the levitation a case of suspended magnets)? The answer is no, the YBCO tablet does not become a magnet since two magnets repeal each other only when they are constrained to be faced with the same polarity. Two free magnets facing the same polarity rotate to attract each other. In levitation the magnet and YBCO are free and repulsion occur with no rotation (Fig. 12).

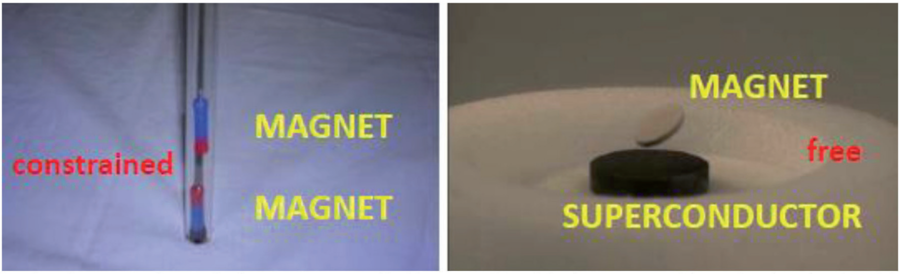

Fig. 12. The phenomenology of a free magnet repelled by a YBCO tablet is not amenable to the situation in which two constrained magnets interacts repelling each other.

The next question is: does the YBCO at T_{LN} act magnetically with no magnet close to it, i.e. can we expect an interaction between an iron clip and the YBCO tablet? An experimental test will be in any case dramatically negative: nothing happens in any case, so the YBCO does not “act magnetically” with no magnet close to it. Does thus the YBCO become diamagnetic at T_{NL} since diamagnetic material repeals magnets? Analyzing the levitation phenomenon characteristics emerges that if the magnet is changed, the height of that it is very weak or negligible through the YBCO.

The magnetic behavior of the YBCO appears to be induced; an analogy can be used in order to interpret the phenomenon, recalling the situation of a falling magnet on a copper bar or inside a copper tube that gradually decreases its velocity till reaching a constant velocity. EMI and eddy currents are used for interpretative analogies in order to discuss about the Meissner effect: the analogy between the “braking” of the magnet in presence of a conductor and the levitation, appears to work if the conductor is “perfect” (i.e. with zero resistance), so the current initially induced by the magnet never stops. A superconductor turns out to be a system with zero resistance and zero magnetic field inside it. A match between the braking of the magnet in the presence of a conductor and levitation has been built!

It is possible to see if a change in the electrical properties of the superconductor with respect to its temperature occurs using an on-line system (Gervasio & Michelini, 2009), allowing the study of the relationship between resistivity and temperature in a superconductor (Fig. 13, left). A sample of superconductor is cooled down to TNL and the transition to the superconductive state (i.e. with zero resistivity) is observed in real time below a certain critical temperature (Fig. 13, right).

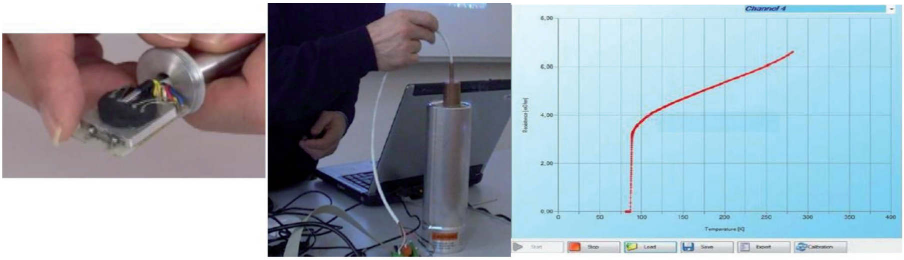

Fig. 13. The on-line system used to measure in real time the dependence of the resistivity of a superconductor (left) with respect to its temperature (right). The sample is put in a case and immersed in liquid nitrogen to gradually decrease the temperature (middle). The system is constituted by an interface card for USB connection with PC.

Conclusions

Literature presented several student difficulties on magnetic phenomena quoting specific learning knots, and evidences of the way to overcome them, as for example offering field lines as conceptual referent for the field and monitoring dynamical evolution of reasoning.

Concerning magnetic phenomena, starting from the analysis of the interactions of a magnet approaching objects made out of different materials it is possible to recognize the different kinds of interactions, and explore the idea of a magnetic property in the space around a magnet.

Experiments used as anchor referents for building interpretative models, are proposed and performed: the interaction between floating magnets, the pattern assumed by iron filing placed around a magnet, the use of the compass as an explorer of the magnetic properties and the experiment of the broken magnet become pivotal conceptual referents upon which explanatory model coming out from hypotheses, testing and comparisons can be built. The compass is used to draw down the field lines, used as a conceptual referent, and it is understood both as an explorer of the magnetic properties of space and as a magnet itself. The concept of flux spontaneously emerges from the qualitative analysis of the mathematical relation between the intensity of the field and the area of a flux tube. The learning path provides also a set of experiences and observations that allows to experimentally explore the phenomenology of the EMI, starting from the previous explanatory model based on the idea that magnetic field is thought as the region of space in which the presence of the magnet is felt and that could be represented using field lines. Even if only in a qualitative way, the main phenomenological characteristic of the process of EMI highlighting the dependence from the different parameters are explored. The presence of a main direction in the magnetic propriety that influences the production of current into a coil is highlighted as well as the relation between the sign of the inducted current and the way in which it interacts the field lines.

The phenomenology of superconductivity is analyzed in the light of the addressed concepts and the Meissner effect is interpreted as a phase transition to the superconductive state of an YBCO tablet, after having analyzed its magnetic and electrical properties.

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