ISSN 1062-8738, Bulletin of the Russian Academy of Sciences: Physics, 2023, Vol. 87, No. 5, pp. 559–562. © Allerton Press, Inc., 2023.
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Ways of Minimizing Magnetic Integrals in Superconducting Insertion Devices

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Received November 28, 2022; revised December 15, 2022; accepted January 25, 2023

Abstract—Magnetic measurements using a stretched wire with a constant current are widely used in manufacturing insertion devices for generating synchrotron radiation. They allow the first and second magnetic field integrals to be measured and minimized along the trajectory of the beam inside the accelerator. The problem of wire sag is also considered.

DOI: 10.3103/S1062873822701702

INTRODUCTION

The Siberian Circular Photon Source (SKIF) is now being built in Russia. SKIF is a specialized source of synchrotron radiation (SR) of the fourth generation with an extremely low emittance. It is also planned to use such insertion devices (IDs) as superconducting wigglers and undulators [1] for generating SR. The Budker Institute of Nuclear Physics has two decades of experience in designing, manufacturing, commissioning, supporting, and upgrading such devices [2]. It participates in supplying IDs for the SKIF project.

INSERTION DEVICES

A multipole wiggler (or an undulator) is a sequence of magnets that generate an alternating magnetic field in the area of an electron beam's movement inside an accelerator. SR is generated as a result of accelerating electrons under the action of the Lorentz force [3]. Straight sections are normally left empty when designing ring accelerators, and IDs are mounted in them. If there is no ID or it is turned off, the beam trajectory within a straight section is a horizontal line segment. Changes caused by the ID in the trajectory at the output of a straight section can be described using two values: the angle and displacement in each plane (horizontal and vertical). It is easy to show that they are directly proportional to the first and second integrals of the magnetic field over displacement along axis *Oy*, respectively (*1*, *2* in Fig. 1). We must therefore minimize and measure the first and second integrals of the magnetic field when setting up an ID [4]. With IRs based on electromagnets (superconducting and otherwise), the device is set up by measuring the current in a specialized correcting coil:

$$I_1^x = \int_0^L B_z(y)\,dy, \tag{1}$$

$$I_2^x = \int_0^L dy \int_0^y B_z(y')\,dy'. \tag{2}$$

MAGNETIC MEASURING SYSTEMS

Several types of magnetic measuring systems are well-known. A Hall sensor is used for measuring a magnetic field, allowing us not just to calculate the magnetic integrals but to obtain the maximum amount of information on it. The main disadvantages of this system are long periods of scanning (40 min for a two-meter long magnet) and the instability of the sensor parameters for superconducting devices, due to rapid changes in temperature. Moving circuits (which generate the electromotive force according to Faraday's law) allow us to measure simultaneously only one integral, depending on the shape of the circuit; they are used to analyze permanent magnets with large gaps. A current-carrying wire stretched along the trajectory of electron beam propagation is best suited for measuring superconducting IDs with allowance for the geometrical dimensions of the system, since the internal height of the measuring chamber in today's

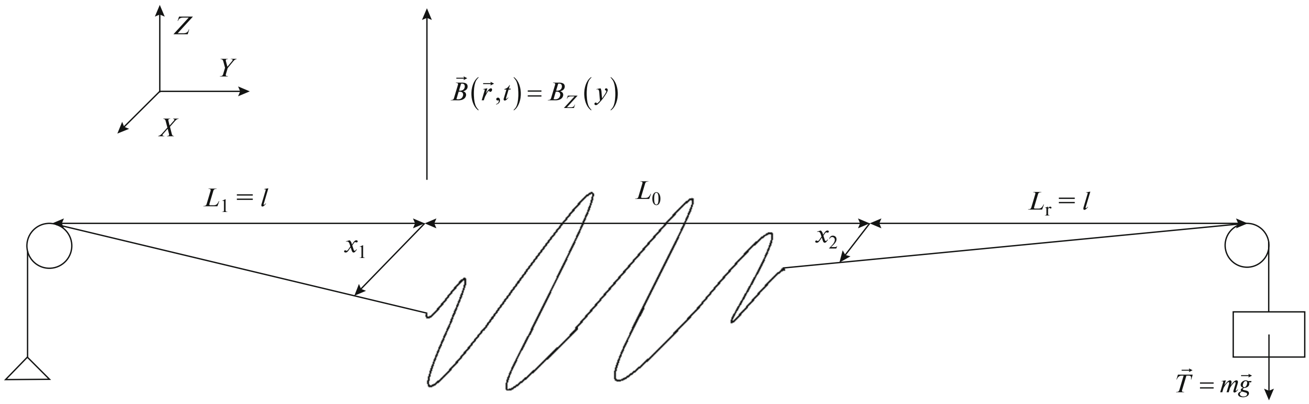

Fig. 1. Scheme of the measuring system. If the magnetic field has only vertical component B_z and there is no wire sag, the wire is curved only in horizontal plane *XY*.

IDs can be 5 mm or less. This system in turn comes in several varieties, depending on the shape of the current. An alternative to the model with the use of a Hall sensor, the pulse current technique places extremely high demands on the quality of the wire (constant thickness, no ellipticity or impurities). The resonant swinging technique allows us to measure multiple integrals simultaneously (which is important when dealing with undulators), since it is extremely sensitive to the way the ends of the wire are fixed. This work focuses on the constant current technique [5, 6], which is both simple and efficient in measuring both magnetic integrals and other characteristics of a magnetic field.

A measuring system based on a stretched wire with a constant current is shown in Fig. 1. The wire rests on rollers placed at the same height at distance L_w from each other, and is stretched by a load of mass m with force mg. At distance L_l from the left roller, the wire's position sensor is located as close as possible to the left side of the measuring chamber, which determines its displacement x_1 along axis Ox when constant current (I) is on within the wire. A similar sensor (measuring displacement x_2) is placed at the distance of L_r from the right roller. The distance between the sensors (the length of the measuring chamber) is L_0 ($L_w = L_l + L_0 + L_r$), and the analyzed magnet with length L_m is located within this gap. Let us assume that $L_r = L_l = l$; $x_1, x_2 \ll l$. In addition, the magnetic field has a vertical component only and depends solely on coordinate y ($B(x, y, z, t) = B_z(y)$, where y lies inside L_m). The sag of the wire is ignored. It is then well-known [5] that the X-component of the first integral of the magnetic field is proportional to the sum of displacements x_1 and x_2, while the X-component of the second one is proportional to their difference (3, 4). With component B_x of the magnetic field, the Z-components of the magnetic integrals are determined in the same way as the functions of displacements along axis Oz:

$$I_1^x = \frac{T}{Il}(x_1 + x_2), \tag{3}$$

$$I_2^x = \frac{TL_w}{2Il}(x_1 - x_2). \tag{4}$$

To improve the accuracy of this measuring system, we must improve its sensitivity by reducing the tension or raising the current. If the material of the wire remains the same, its cross-sectional area must be be enlarged in order to increase the current. This contributes to the wire's linear density and its sag. Choosing the appropriate wire (its material and thickness), the amperage of the current, and the force of the tension is a major problem. Along with the problem of sag, the stiffness of the electron beam, the focusing effect [5], and the requirements imposed on the accuracy of measuring (which depend on the characteristics of the given ID but not of the wire) must also be considered. There should be no interaction between the wire and the magnetic field when there is no current within the former. This is not always so in practice, due probably to impurities in the wire's material. The minimum wire thickness is related to the position sensor that is used. In our case, it is 200 μm for a Metralight MicroXY laser micrometer. There is thus no "ideal" wire; for each ID, the characteristics of the measuring system (including the material and the thickness of the wire) must be selected individually.

We have tested the following wires in practice (all designations here and below based on Russian State (GOST) standards): a superconducting NbTi cable, a BrB2 bronze wire, an L63 brass wire, and a copper cable (Table 1). The mechanical fluctuations of the wire's position are no more than ±3 μm per minute when the sensors are mounted on separate pillars, and no more than ±7 μm per minute when the sensors are installed on the body of a superconducting ID (the

Table 1. Characteristics of our wires.

Material	Diameter, μm	Tension, N	Current, A
NbTi	300	73	5
L63	200	4	2
L63	300	18	3
BrB2	200	37	2
BrB2	400	20	5

increased number of fluctuations is due to vibrations of the ID caused by the operation of cryocoolers and vacuum pumps). When tuning the integrals, their values are no greater than 10^{-5} T m for I_1 and 10^{-5} T m^{-2} for I_2, which correspond to the sum and the difference of wire displacements up to 10 μm. During integral measurements while enhancing and reducing the magnetic field, they are no greater than 10^{-4} T m and 10^{-4} T m^{-2} (except for small fields generally below 0.5–1.0 T, where the remnant magnetization plays an important role). These values are typical of superconducting wigglers.

The wire's sag is limited first by the height of the measuring chamber, which the sag cannot be above on the interval of L_0 (the length of the chamber). In reality, however, the ID's field depends on coordinate z (Fig. 2), especially at the distance from the center along axis Ox that is needed for, e.g., measuring the sextupole component of the magnetic field. Let us introduce the concept of a median plane, on which the magnetic field of an ID has only the Z-component. In an ideal case, this plane is horizontal and halfway between the poles. A practical algorithm for finding the median plane was described in [5]. The algorithm considers the wire's movement in the vertical plane, which imposes much stricter requirements on the sag. It is well-known that the sag curve is represented by a non-linear chain line. The sag on interval L_m (the length of the magnet) differs from that on interval L_0 (the length of the chamber) disproportionally to ratio L_m/L_0. For most superconducting wigglers, the acceptable sag at length L_m (1–2 m) is 0.5 mm (and up to 1.5 mm in some cases).

A SUPERCONDUCTING UNDULATOR

The Budker Institute of Nuclear Physics is currently developing and launching a superconducting undulator that has a number features not seen in superconducting wigglers manufactured earlier. A strong field (B_y) emerges at the ends of an undulator due to the presence of passive poles, displacements of active poles in the lower and upper parts of the magnet [7], and the configuration of the correcting coil. This field interacts with the non-horizontal sections of the wire and distorts results from measuring the X-components of the magnetic integrals. It is planned to reduce the sag at length $L_m = 2$ m down to 0.1 mm, which was impossible with wires used earlier while maintaining the acceptable accuracy of measurements.

A possible solution is to use a composite wire. A one-wire copper cable with a cross-sectional area of 1 mm^2 serves to carry the current, allowing us to use one of more than 10 A for longer periods of time. The cable is placed inside a Kevlar sheath that withstands tension of more than 300 N. The system of stretching the wire is upgraded because of the increased mechanical loads. An additional pair of rollers is added at the edges. Almost all the load falls on them, while the internal rollers (which determine the position of the wire with motorized 2-coordinate transport modules) experience loads of less than 10 N.

The above system has been tested in studying a superconducting undulator with the maximum field of 1.2 T. It has been determined experimentally that tuning the integrals with a wire that has a constant current is possible only within the range of 0.72–0.87 T. Computer modeling has proved this cannot be done in strong fields even when there is zero sag, due to different positions of the median plane in the neighboring pairs of poles. Magnetic measurements of the superconducting undulator finished with a series of tests using the Hall sensor in different positions on axis Oz.

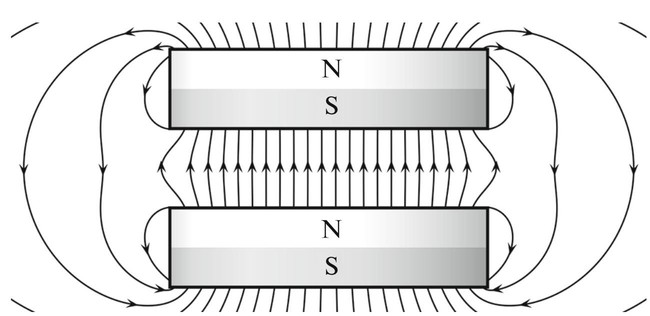

Fig. 2. Magnetic field lines of a pair of coils without allowing for the magnetic conductor.

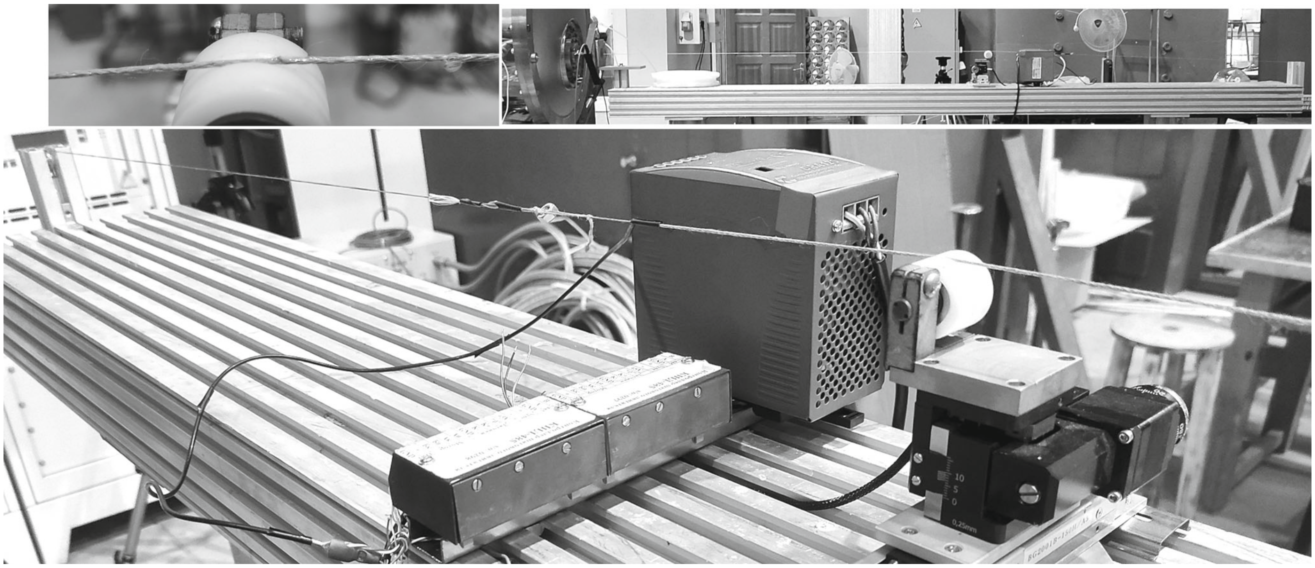

Fig. 3. Scheme of stretching a composite wire. A current-carrying copper cable emerges from a Kevlar sheath between the rollers. The roller on the motorized transport modules experiences a minimal load.

CONCLUSIONS

We have described different ways of making magnetic measurements in regard to insertion devices for generating synchrotron radiation. A measuring system using a stretched wire with a constant current was described in detail. The problem of wire sag was considered. The experience from using different wires at the Budker Institute of Nuclear Physics in manufacturing superconducting wigglers was generalized. A modification of the system based on a composite wire and additional rollers was proposed. The upgraded system was tested in examining a superconducting undulator.

FUNDING

This work was performed as part of Agreement no. 075-15-2021-1359 with the RF Ministry of Science and Higher Education, and as part of a State Task no. FWUS-2021-0004 for the Institute of Chemistry of Solid State and Mechanochemistry.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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Translated by A. Shishulin