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Rapid Measurement of the Deformation of the Liner in a Superconducting Wiggler when the Magnets Transition to the Normal State

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Abstract—The liner of a superconducting wiggler is a thin-walled elliptical copper tube that is positioned inside the vacuum chamber and serves as a heat shield. When the wiggler magnets transition to the normal state, the liner is affected by vertical forces that are able to deform it. In this work, a system for the rapid measurement of the deformation of a liner is described and the measurement results for three different liners are reported.

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INTRODUCTION

A superconducting wiggler is a sequence of sign-variable superconducting magnets mounted along the path of a beam of electrons moving inside an accelerator's vacuum chamber and designed to generate powerful synchrotron radiation. The Institute of Nuclear Physics, Siberian Branch, Russian Academy of Sciences, is a world leader in creating high-field superconducting wigglers. A wiggler's superconducting magnets are mounted in a vessel filled with liquid helium. The vacuum chamber through which the electron beam travels is a part of this vessel and is made of stainless steel. If there were no heat shield between the beam and the vacuum chamber, considerable heat would be generated in the stainless steel chamber and thus to intense evaporation of the liquid helium. In order to reduce the heat losses due to the beam's induced currents, a so-called liner consisting of a thin-walled elliptical copper tube is placed inside the vacuum chamber, and the beam travels inside this tube (see Fig. 1). The resistance of copper, both electrical and thermal, is considerably lower than that of stainless steel. The heat generated in the liner is deflected to cryocoolers in heat contact with the liner at its ends at a temperature of about 10–20 K [1].

The transition of superconducting magnets to the normal nonsuperconducting state is not typical of experiments with wigglers, while operational practice shows that this does occur. When the wiggler transitions to the normal state, the liner is affected by powerful forces that can result in its vertical deformation and require expensive repairs. The aim of this work was to obtain data on the deformation of various liners upon magnets' transition to the normal state, and to develop a liner resistant to residual deformations.

THEORY OF LINER DEFORMATION

The emergence of a normal region in a particular magnet results in the heating of a winding region according to the Joule–Lenz law. Owing to heat transfer, the normal zone rapidly spreads over the winding and the neighboring poles. The magnet's transition to the normal state requires time on the order of a second (see Fig. 2).

An increase in resistance lowers the winding current and the magnetic flux in the space between the magnets in which the liner is positioned. Electromotive forces arise in the liner according to the law of electromagnetic induction, generating currents in it. In calculating the forces acting upon the liner, four currents can be discerned in every vertical cross-section of the wiggler perpendicular to the latter's axis: two in the upper and lower magnets and two in the upper and lower parts of the liner. The interaction of these currents described by Ampere's law results in

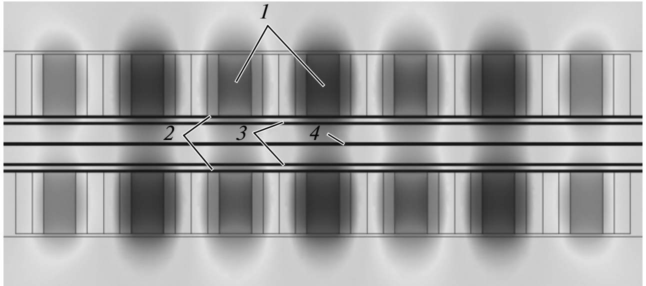

Fig. 1. Wiggler cross section: (*1*) superconducting magnets (the upper and lower magnet of each couple create a field in one direction, while the neighboring couples create one in the opposite direction), (*2*) vacuum chamber, (*3*) liner, (*4*) trajectory of electrons and synchrotron radiation.

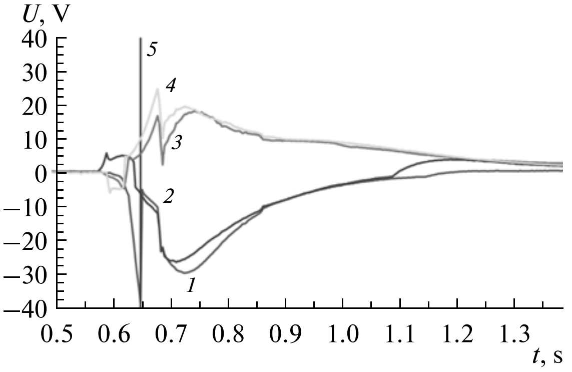

Fig. 2. Voltage on the pole windings during a transition to the normal state. (*1*) Upper internal, (*2*) lower internal, (*3*) upper external, and (*4*) lower external windings; (*5*) response of the transition detector.

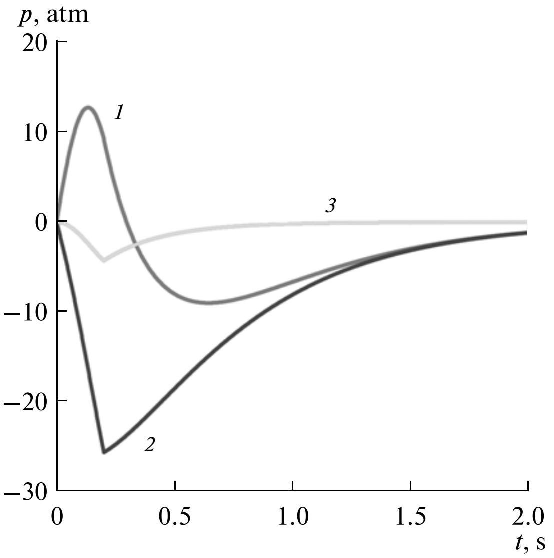

Fig. 3. Computer simulation of the pressures exerted on the liner. (*1*) Pressure on the upper side, (*2*) pressure on the lower side, and (*3*) pressure between the liner's currents.

vertical forces acting on the liner that are of interest to us. A computer simulation was performed, the results of which are presented in Fig. 3. It was assumed that the loss of superconductivity occurred in the upper magnet. The simulation results showed that the upper side of the liner stretches first upward and then downward. The lower side, however, always stretches downward. Finally, the liner must collapse and bend downward.

EXPERIMENTAL

In our experiments, we used a wiggler prototype consisting of seven magnets on each side and having a field of 7.5 T. Three central magnets generated a complete field of 7.5 T while two end couples generated three-fourths and one-fourth of the main field. Each pole was 100 mm long. The magnets were dipped into a 4-m deep vertical cryostat filled with liquid helium; since there was no vacuum chamber, the liner was also immersed in helium. The slots between the liner and the magnets, into which strain gauges were placed, were ~2 mm wide.

It is impossible to predict exactly at which of the central poles the transition to the normal state will begin, so at least seven gauges were needed for each side; three in the centers of the poles and four between the poles. The gauges had to be robust and operate at the temperature of liquid helium. The desired accuracy was 100 μm at slot widths of 0 to 10 mm; the sampling frequency had to be on the order of 10 kHz, since oscillations in the liner's audio frequency were likely to occur along with those caused by the loss of superconductivity that were of interest to us.

Capacitors with variable gaps were used as distance sensors. One plate common to all channels was the liner itself, which had the same point as the ground. The other plates, each 50 × 50 mm in size, were attached to the magnet. The nine such plates on each side of the liner were made on two-sided printed circuit boards; on the other side of each board, a common plate was formed to connect the generator. Aside from the printed circuit boards, only connecting wires were inside the cryostat, while the others were located outside it.

More than ten schemes that would allow us to measure the capacitor capacitance were considered, including those ones described in [2, 3]. However, the experiment imposed stringent requirements: it was necessary to simultaneously measure 18 conductively coupled channels; the signals traveled along 5-m long wires placed closely to each other with a capacitance comparable to that of the sensors; and no electronics could be placed inside the cryostat because of its low temperatures. Eventually, only three circuits were adopted: a potentiometer circuit, a bridge circuit, and a circuit with a diode bridge. They were all described in [3]. One disadvantage of the circuit with a diode bridge is its low sensitivity and need for a differential voltmeter; the bridge circuit is the most sensitive but it is suitable only for slightly changing the capacitance and does not register the absolute position of the liner. We therefore decided to use the potentiometer circuit shown in Fig. 4. A harmonic signal with a frequency of 100 kHz was generated by a G3-112 generator, its current was amplified by AD817 amplifiers, and it was applied to the common plates and to one of the inputs of eighteen AD835 multipliers. The signals from the middle plates were applied to the second input of these microcircuits and synchronous detection was enabled. The obtained signals passed through RC smoothing circuits and were digitized by an NI USB-6218 analog-to-digital converter with a sampling frequency of 5 kHz per each channel; the converter was connected to a computer.

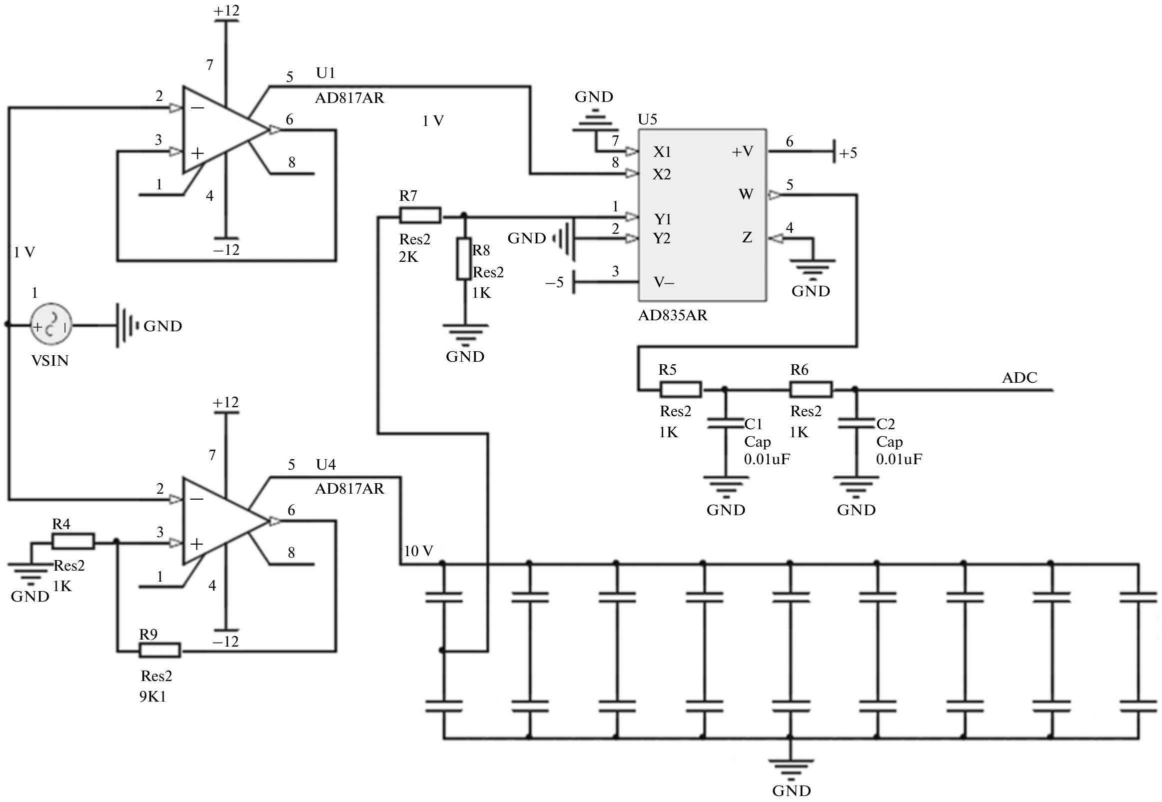

Fig. 4. Generator; equivalent scheme of one of the liner's sides with a printed circuit board; measuring channel.

If we ignore the phase shift, it is not difficult to find the dependence of the voltage at the output of the circuit on the distance between the plates. It is expressed by the formula $U(x) = k_1U_0^2\Big/\left(k_2 + \frac{1}{x}\right)$. The generator's squared voltage U_0 was due to the synchronous detection, coefficient k_1 was related to the declining signal amplitude in the resistance divider, and k_2 was determined by the ratio between the capacitance of the capacitors and connecting wires. With a zero gap, the voltage would also be zero and reach its maximum at an infinite x. When calibrating the system, it turned out that we had to introduce at least one more coefficient, that of voltage shift k_3. Our formula took the form $U(x) = \dfrac{k_1U_0^2}{k_2 + \dfrac{1}{x}} + k_3$. We did not investigate the physical meaning of this coefficient but introduced it phenomenologically.

The sensitivity of the system is enormous at narrow gaps and low at wide ones. Once calibrated, its relative error for distance is lower the higher the value of the latter is; it was therefore possible to measure only two points with sufficient accuracy: zero and infinite distances. This yielded two coefficients for each channel, k_1 and k_3. Calibration thus did not yield any numerical dependence of the distance on the measured voltages. In order to get at least some idea of the gaps, the experimental data were processed in the following manner: assuming k_2 to be equal for all channels and considering the obtained k_1 and k_3, we performed a linear transformation of the $U(t)$ graphs. The graphs of the nine lower channels were then reflected relative to the time axis so that the top and bottom of the voltage axis corresponded to the top and bottom of the wiggler for all channels, rather than the increase and decrease in the distance between the liner and the magnet. The graphs were then displaced along the voltage axis so that they all passed through one point directly before the loss of superconductivity, as though the deformation there were zero. For subsequent transitions to the normal state, in every experiment two versions of the graphs were made that also passed through one point and started where the previous graphs ended. Finally, one more visualization was performed: various channels were displaced relative to each other in both time and voltage, and the image became three-dimensional. Because of the large number of graphs and lack of quantitative differences between them, only the results of one measurement are given here. Figure 5 presents the processed results of the last transition to the normal state in the third experiment.

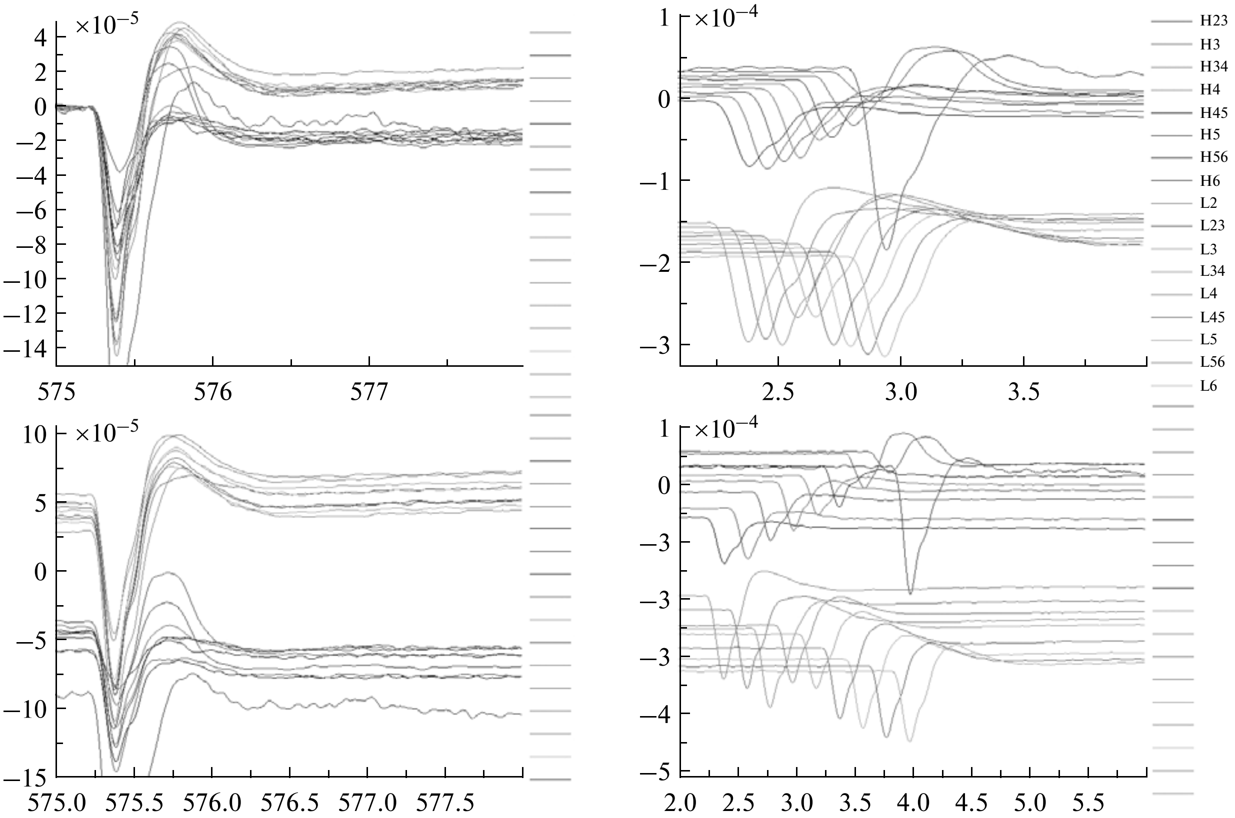

Fig. 5. The initial deformation on top is assumed to be zero; the initial deformation on the bottom corresponds to the end of the previous measurement. The figures on the right are three-dimensional: each consecutive channel is shifted with respect to the previous one in both time and voltage. The horizontal axis shows the time in seconds; the vertical axis, the voltage in volts. Key to measuring channels: H, upper side; L, lower side. The numbers denote the pole numbers; the double digits, the interpole spaces.

RESULTS AND DISCUSSION

Experiments with three liners were conducted: one with a conventional copper liner, one with a copper liner coated with a sputtered nichrome film to add resilience, and one with a copper liner that had longitudinal slots to reduce induced current.

Conventional Liner Experiment

The unmodified copper liner was used in the first experiment. It was known beforehand that it would eventually be flattened and flexed, so the experiment was aimed first of all at testing the system for measuring deformation. Two measurements were conducted and in both cases the system revealed both oscillations of the liner upon transitioning to the normal state and residual deformation.

Sputtered Nichrome Film Experiment

For the second experiment, a 300-μm thick nichrome film was sputtered on the outer surface of the liner, the thickness of the copper in its narrowest spot being 500 μm. The specific conductivity of nichrome is lower than that of copper by several orders of magnitude; the forces that acted upon the liner should therefore have not increased substantially. It was, however, assumed that the liner's mechanical strength would increase greatly. The experiment, which consisted of three measurements, showed that this was not the case: the deformation appeared to be approximately the same as it was the first time.

Slotted Liner Experiment

In the third experiment, we used a liner on each side of which there were two parallel 500-mm-long slots spaced 40 mm from each other. The current induced across the liner was thus separated into three independent areas, which should have reduced the forces acting on the liner manyfold.

Five measurements were conducted altogether. Qualitatively, the pattern was the same as in the previous experiments: each time, some deformation was observed. Disassembly of the wiggler showed that the residual deformation was considerably less than in the preceding experiments. It was predominantly the strips between the slots that changed their shapes; the liner as a whole did not bend and only the cross section through the thickness was reduced. In the previous experiments, it disappeared completely.

CONCLUSIONS

Rapid measurement of the deformation of a superconducting wiggler liner upon transitioning to the normal state is a new problem for the Institute of Nuclear Physics that is of great importance in building liners more resistant to the intense operating conditions of wigglers. A measuring system was developed that enabled us to conduct experiments with a wiggler prototype in a submersible cryostat. Unfortunately, we managed to obtain only a qualitative pattern of deformation that was nevertheless consistent with the theoretical calculations.

It was established that two opposite Ampere forces acted upon the liner component nearest to the magnet that had transitioned to the normal state: first, the attraction toward the magnet predominated since it was a change in the current strength in the magnet that induced the current in the liner; with time, this force became weaker and the liner started collapsing due to the interaction of the currents in its two halves. The deformation of the liner depended on many factors, e.g., the position of the magnet at which the transitions to the normal state started, the pattern of how the normal state included other wiggler magnets, the design of the liner itself, and its previous deformations. In general, however, the liner always sought to collapse at least in the region of the pole, causing transitions to the normal state.

A total of three liners were tested: a conventional copper liner, a copper liner with a sputtered nichrome film, and a copper liner with longitudinal slots. The first two liners were deformed in an almost similar and unacceptably severe fashion, so the sputtered nichrome coating did not have any appreciable effect on the liner's mechanical strength. The third liner experienced only slight deformation; consequently, the longitudinal slots, providing infinite resistance to induced currents, considerably improved the resistance of the liner to the magnets' transitions to the normal state.

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