MAGNETIC ALIGNMENT OF PULSED SOLENOIDS USING THE PULSED WIRE METHOD*

D. Arbelaez†, A. Madur, T.M. Lipton, W.L. Waldron, J.W. Kwan, LBNL, Berkeley, CA 94720, USA

Abstract

A unique application of the pulsed-wire measurement method has been implemented for alignment of 2.5 T pulsed solenoid magnets. The magnetic axis measurement has been shown to have a resolution of better than 25 μm. The accuracy of the technique allows for the identification of inherent field errors due to, for example, the winding layer transitions and the current leads. The alignment system is developed for the induction accelerator NDCX-II under construction at LBNL, an upgraded Neutralized Drift Compression eXperiment for research on warm dense matter and heavy ion fusion. Precise alignment is essential for NDCX-II, since the ion beam has a large energy spread associated with the rapid pulse compression such that misalignments lead to corkscrew deformation of the beam and reduced intensity at focus. The ability to align the magnetic axis of the pulsed solenoids to within 100 μm of the induction cell axis has been demonstrated.

INTRODUCTION

The induction accelerator NDCX-II, an upgraded Neutralized Drift Compression eXperiment for research on warm dense matter and heavy ion fusion, is currently under construction at LBNL. The induction cells contain pulsed solenoids, with maximum axial field of 2.5 T, which are necessary for transverse focusing of the beam. Precise alignment of these solenoids is essential for NDCX-II, since the ion beam has a large energy spread associated with the rapid pulse compression such that misalignments lead to corkscrew deformation of the beam and reduced intensity at focus [1]. The pulsed wire technique is used in order to determine the magnetic axis of the solenoids. The solenoids are then positioned inside of the cell such that the magnetic axis of the solenoid coincides with the mechanical axis of the cell. It has been shown that the magnetic axis of the solenoid can be aligned to the cell axis with an accuracy of better than 100 μm.

The pulsed wire technique has been chosen for the magnetic measurements since it naturally defines an axis by the location of the wire. This method was originally introduced by Warren [2] for the measurement and correction of wigglers. The method has not only been used extensively for the measurement of wigglers and undulators, but also for the magnetic axis measurement of DC solenoids ([3], [4], [5]). In this work, the pulsed wire measurement technique is adapted for the measurement of pulsed solenoids. It is critical to perform the magnetic axis measurement in a pulsed configuration since asymmetric eddy currents effects can shift the magnetic axis with respect to the axis obtained during DC operation. An analytical analysis of the method is applied to solenoid measurements, and experimental results are presented.

METHOD OVERVIEW

In the pulsed wire method, a wire is kept at constant tension between two points. While a section of the wire lies in an external magnetic field a current pulse is applied to the wire. The wire is subjected to the Lorentz force which induces a local motion in the wire. This motion then propagates as a traveling wave and is measured by a motion sensor at a specific location. For pulsed magnet measurements a current pulse is passed through the wire during the magnet pulse. For NDCX-II the ion beam pulse varies from approximately 500 ns at the front end of the accelerator to approximately 1 ns after completion of the pulse compression. The ion beam crosses the solenoid at the peak of the 5 ms magnet pulse; therefore, for the pulse wire measurements a short wire pulse is applied at the peak of the solenoid pulse. Figure 1 shows the NDCX-II magnet measurement facility, which includes: the induction cell on a cell mount, two wire stands on motion stages that move in the x and y directions, a wire motion sensor that detects both x and y motion, and wire location sensors (Metralight MICROXY laser micrometers) which can be used along with a laser tracker (Leica LTD500) to determine the position of the wire at the sensor location. For the measurements a 75 μm diameter Cu-Be wire is used with a maximum wire pulse amplitude of 4 A and a 400 g tensioning weight. The wire current pulse is applied over a 50 μs window at the peak of the 5 ms magnet pulse.

ANALYTICAL DESCRIPTION

The mechanics of the pulsed wire method can be described by using a one-dimensional theory for wave motion in a string. More sophisticated theories can take into account flexural rigidity effects that lead to dispersive wave motion. These effects are important for measurements where the magnetic field varies rapidly over short distances (e.g. short period undulators). For the NDCX-II solenoids, these effects are negligible and therefore ignored. The forced motion of a string can be described by

$$\mu\frac{\partial^2 u}{\partial t^2} = T\frac{\partial^2 u}{\partial z^2} + q(t,z), \qquad (1)$$

* This work was supported by the Director, Office of Science, Office of Fusion Energy Sciences, of the U.S. Department of Energy prepared by LBNL under Contract No. DE-AC02-05CH11231.

† darbelaez@lbl.gov

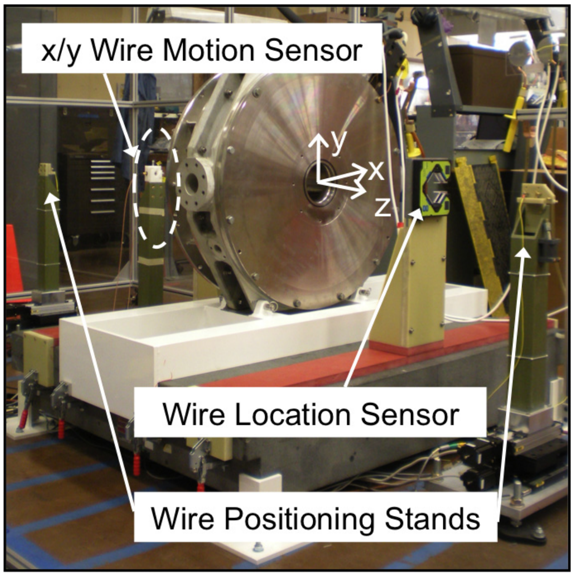

Figure 1: NDCX-II magnet measurement facility including wire stands on motion stages, a wire displacement sensor, and laser micrometers for determining the wire location.

where t corresponds to time, z is the position along the length of the wire, u is the transverse wire displacement, μ is the one-dimensional wire density, T is the tension in the wire, and $q(t, z)$ is the load on the wire.

For the pulsed wire method, $q(t, z)$ is given by $I(t)B_T(z)$, where $B_T(z)$ is the transverse field along the wire, and $I(t)$ is the time dependent current in the wire. Neglecting the effect of reflections and assuming a square current pulse with amplitude I_0 and pulse width δt, the solution to equation 1, obtained by using a Green's function approach [6], is given by

$$\hat{u}(t) = \frac{I_0}{2T} \int_{z=0}^{z=ct} \int_{z=\eta-c\delta t}^{z=\eta} B_T(\xi) d\xi d\eta, \qquad (2)$$

where $\hat{u}(t)$ is the wire displacement at the sensor location, $c = \sqrt{T/\mu}$ is the wave speed, and ξ and η are spatial integration variables. The wire pulse is chosen to start at $t = 0$, the sensor location is defined at $z = 0$, and the magnetic field is assumed to be non-zero only for $z > 0$ without loss of generality. For the wire pulse width, a very short pulse or a long pulse (DC) can be considered as limiting cases. For the measurement of the NDCX-II solenoids, only the short pulse is of interest since the critical information requires the measurement of the axis in a short time window at the peak of the magnet pulse. By letting $\delta t \rightarrow 0$, the wire motion for a short pulse can be described as

$$\hat{u}(t) = \frac{I_0 c \delta t}{2T} \int_{z=0}^{z=ct} B_T(\xi) d\xi, \qquad (3)$$

which states that the measured wire displacement as a function of time is proportional to the spatial integral of the magnetic field. For equation 3 to be valid in a measurement, the product of pulse width and wave speed should be considerably smaller than the characteristic length for the spatial variation of the field.

Figure 2 shows the characteristic signatures for the component of magnetic field that is transverse to the wire, when the wire is either translated (offset) with respect to the magnetic axis or rotated (tilt) about the center of the ideal axis. The transverse magnetic field was calculated using Biot-Savart law and corresponds to a peak solenoid axial field of approximately 1 T. For this example, an offset of 200 μm and a tilt of 1 mrad are used. As seen from figure 2,

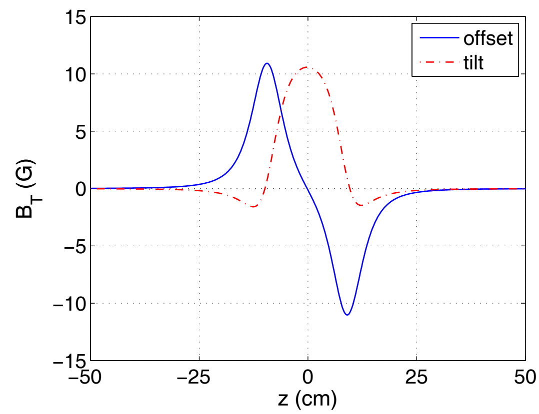

Figure 2: Characteristic transverse magnetic field for offset and tilt errors.

the transverse field for an offset error is an odd function while the transverse field for a tilt error is an even function. Therefore, an offset error has zero net integral over the length of the wire, while a tilt error has non-zero net integral. Since, for short pulses, the wire motion is proportional to the transverse field integral, the characteristic wire motion signatures are given by the field integrals that are shown in figure 3.

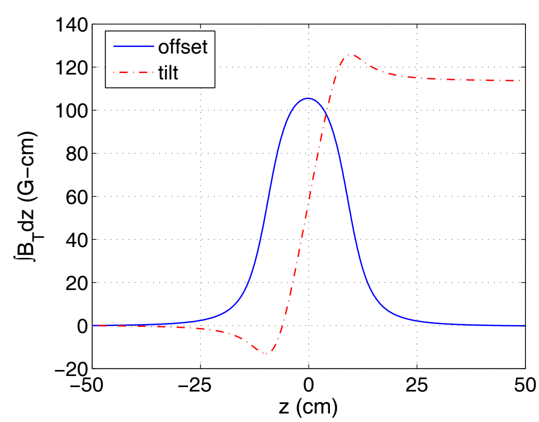

Figure 3: Characteristic transverse field integrals and wire motion for offset and tilt errors.

MAGNETIC ALIGNMENT

The magnetic alignment of the induction cells consists of magnetic measurements with the pulsed wire system, laser tracker measurements to determine the locations of the various components, and the mechanical adjustment of the solenoid's position inside of the cell.

Magnetic Axis Determination

Tilt and offset errors can be cancelled independently in order to align the wire with the magnetic axis of the solenoid. Figure 4 shows an example of the alignment of the wire with the magnetic axis of the solenoid. Initially the wire motion signal contains both the offset and tilt signatures. First the tilt error is cancelled by performing a 5 mrad rotation followed by the cancellation of the offset error by translating the wire 1.5 mm. As can be seen in figure 4 the wire motion is not cancelled completely which is attributed to magnetic field errors due to a number of factors, such as: the current leads, the winding end transitions, winding imperfections, and asymmetric eddy current effects. Since a perfect magnetic axis can not be obtained, the magnetic axis is defined as having zero total first and second field integrals. With respect to the wire motion, this corresponds to the wire displacement returning to zero after the motion pulse has passed as well as zero net first integral of the displacement. Figure 5 shows the calculated horizontal

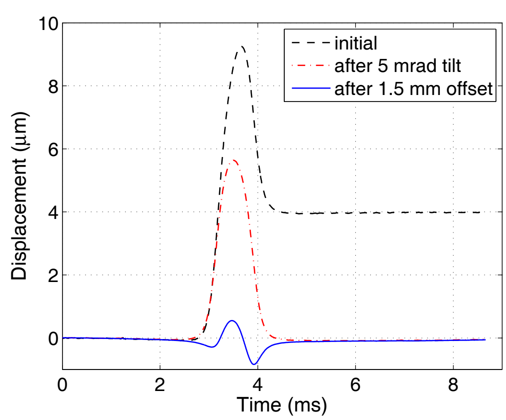

Figure 4: Alignment of the wire with the magnetic axis. A 5 mrad rotation and a 1.5 mm translation are performed from the initial wire location.

(x) and vertical (y) transverse components of the magnetic field with respect to the defined axis of the solenoid. The calculation of the residual fields is performed using equation 3 by taking the time time derivative of the wire motion signal and performing the proper scaling.

Solenoid Alignment

Once the wire is aligned with the solenoid's magnetic axis, its position must be related to fiducial points on the solenoid. This is accomplished by using a laser tracker

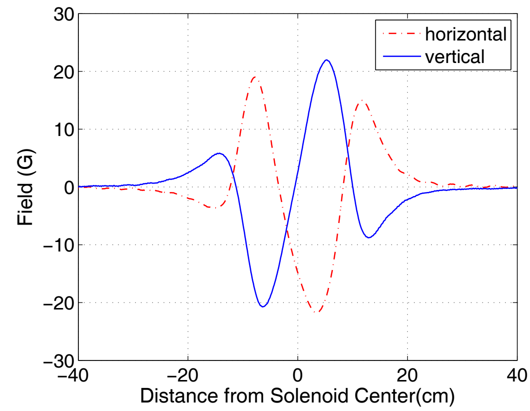

Figure 5: Calculated transverse magnetic field along the stretched wire at the defined magnetic axis. The non-zero transverse field is due to imperfections and asymmetries in the magnet.

along with calibrated laser micrometers (see wire location sensor in figure 1) in order to find the location of the wire at two points and relate this to the fiducial points on the solenoid. The relation between the magnetic axis and the solenoid fiducials is then used to align the magnetic axis of the solenoid with the cell axis.

CONCLUSIONS

A magnet measurement facility has been constructed for the alignment of the NDCX-II pulsed solenoids. The pulsed wire technique has been implemented to determine the magnetic axis of the solenoids at the peak of the magnet pulse. Due to the high magnetic field of the solenoids, the pulsed wire measurements are highly sensitive. Offset errors as small as 25 μm and tilt errors as small as 0.1 mrad can be distinguished after averaging over only a few pulses. The alignment of the solenoids inside of the cell has been demonstrated with an accuracy of better than 100 μm.

REFERENCES

[1] A. Friedman et al, "Beam dynamics of the Neutralized Drift Compression Experiment-II, a novel pulse-compressing ion accelerator," Physics of Plasmas. 17(5) (2010).

[2] R.W. Warren, "Limitations on the use of the pulsed-wire field measuring technique," Nuclear Instruments and Methods in Physics Research Section A. 272 (1988), p. 257.

[3] J.G. Melton, M.J. Burns, and D.J. Honaberger, "Pulsed taut-wire measurement of the magnetic alignment of the ITS induction cells," PAC'93, `http://www.JACoW.org`.

[4] C. Bonnafond and D. Villate, "Alignment techniques for the high current AIRIX accelerator," PAC'99, p. 1381, `http://www.JACoW.org`.

[5] D. Zhi-Yong et al, "Alignment techniques for DRAGON-I LIA," Chinese Physics C. 33(9) (2009), p. 789.

[6] K.F. Graff, Wave Motion in Elastic Solids, Dover Publications Inc. (1991).