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PROGRESS IN ETA-II MAGNETIC FIELD ALIGNMENT USING STRETCHED WIRE AND LOW ENERGY ELECTRON BEAM TECHNIQUES*

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Abstract

Flux line alignment of the solenoidal focus magnets used on the ETA-II linear induction accelerator is a key element leading to a reduction of beam corkscrew motion. Two techniques have been used on the ETA-II accelerator to measure and establish magnet alignment. A low energy electron beam has been used to directly map magnetic field lines, and recent work has utilized a pulsed stretched wire technique to measure magnet tilts and offsets with respect to a reference axis. This paper reports on the techniques used in the ETA-II accelerator alignment, and presents results from those measurements which show that accelerator is magnetically aligned to within ~±200 microns.

Introduction

Alignment is a critical step in the assembly of any linac. Mechanical/optical alignment of accelerator hardware is only a part of the total process. It is equally important to assure that the magnetic flux lines produced by focus solenoids also be aligned to high accuracy. The magnetic axis of a magnet may not always be coincident with the mechanical axis, and thus it is important that the magnetic axis be used in the alignment criteria.

The ETA-II, as presently configured, is a 9.4m long accelerator, consisting of a total of 28 solenoidal magnets. Four solenoids are in the injector, and the accelerator sections are configured into two 10-solenoid cell blocks. The remaining four solenoids are used as intercell magnets in the transport regions between the cell blocks. Each of the solenoid magnets are fabricated with separate horizontal and vertical trim coils. The trim coils are used to correct for magnet tilts, but not for magnet offsets.

To minimize the buildup of beam corkscrew motion, we attempted to align the magnetic flux lines of ETA-II solenoids to a straight line. To accomplish this, a straight line reference axis on the mechanical center was first established between the injector and the end of the accelerator. Each solenoid's magnetic axis was then measured with respect to this reference, and where feasible, the magnets were physically moved to make their magnetic axis coincide with the reference axis. Additionally, for each magnet, a horizontal and vertical trim correction current was established to compensate for any inherent magnetic tilt. The manner in which the magnetic alignment was performed is described in more detail below.

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Magnet Alignment Techniques

Low Energy Electron Beam Alignment Technique

Since magnetic flux lines cannot be viewed directly, it is necessary that one resort to measuring the influence that a magnetic field has upon a measurable quantity. For instance, one way to map magnetic flux lines is to use a low energy electron beam. The low energy e-beam will closely follow a given magnetic field line, and a phosphor screen can be used to convert the e-beams energy to light. The light spot can then be digitized with a computer and TV camera to map the position of the field lines as a function of distance down the accelerator. This technique has already been successfully used during the initial assembly of ETA-II, and was reported earlier by Clark, et al.[1]. The difficulty with using this technique is that the entire accelerator assembly must be under vacuum, and all solenoids must be energized to properly transport the e-beam. Additionally, magnet offsets and tilts are not directly obtainable using this technique.

Stretched Wire Alignment Technique

An alternative technique for measuring magnet alignment is to sense the force produced on a current carrying conductor placed in a magnetic field. With this technique, a wire is stretched along the center reference of the accelerator through all the solenoidal magnets. A short current pulse, I, is then applied the wire, and if any transverse magnetic fields are present, the Lorentz force $\mathbf{dF}$ produced on an element $\mathbf{dl}$ of a conductor is given by equation (1) as:

$$\mathbf{dF} = I\,\mathbf{dl} \times \mathbf{B}_{\perp}. \qquad (1)$$

The force on the wire will cause the wire to deflect an amount proportional to the magnitude of the transverse field errors. This deflection propagates as a travelling wave along the stretched wire, and one can sense this deflection as a measure of magnet misalignment. Since a perfectly aligned solenoid will have no transverse fields on its axis, one attempts to null out the deflections of the stretched wire, and when the deflected signal is nulled, the wire then lies along the magnetic axis.

The stretched wire alignment technique has been used successfully at LANL by Warren and Elliot[2] in the fabrication and testing of wigglers, and by Liska, et al.,[3] in the precision alignment of permanent-magnet drift tubes. The inherent simplicity of the stretched wire alignment technique is an attractive feature. No high vacuum conditions are required as with the e-beam technique, and both the offset and tilts can be obtained for each individual magnet.

Stretched Wire Implementation We use a thin (4-mil) BeCu wire stretched through the bore of the linac and positioned on the mechanical center reference axis at the two ends of the accelerator. The wire is attached to a X-Y translation stage at each end so that the wire can be moved by measurable amounts off the reference axis to determine how far the magnetic axis of a given solenoid is off the mechanical axis. While the wire is tensioned near its tensile strength to minimize the catenary droop from the vertical axis, we calculate the amount of catenary offset at each solenoid, and include this as a correction to the vertical offset data.

Two photo-optical sensors positioned 12.8 cm away from the termination point are used to sense the minute wire deflections. One of the sensors is used to measure vertical motions, and the other sensor measures horizontal deflections. The sensor itself is a very simple, low cost, and a readily available component used in industries as diverse as computers to textiles. It consists of a GaAs infrared emitting diode illuminating a silicon phototransistor across a 0.1 inch gap. The detector senses the deflection of the wire in the gap by the wire's affect on the light transmission. Figure 1 shows typical detector sensitivity curves obtained for 4 and 8 mil wires. We position the wire at a point of maximum slope on the detector curve to give the greatest sensitivity, which in the case of a 4 mil wire is on the order of 25 millivolts per micron of motion.

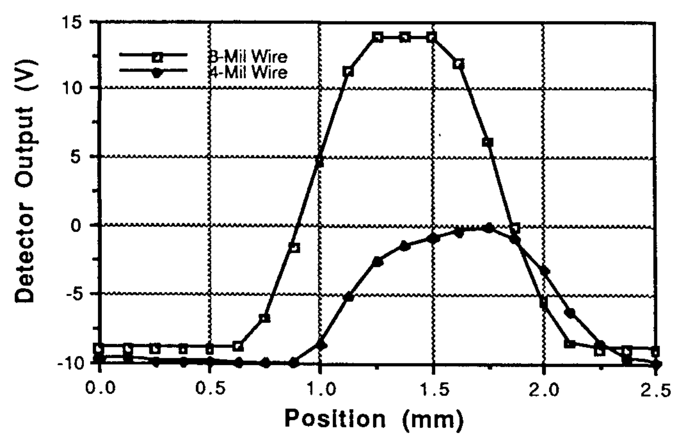

Figure 1. Detector output response for 4mil and 8mil wire.

Figure 2 shows a block diagram of electronics used in the data acquisition system. The horizontal and vertical detector circuits are simple opamps to increase the sensitivity, and the oscilloscope is a digital storage unit with signal averaging to improve signal to noise ratios. A single solenoid is energized at one time, and a 1 millisecond long current pulse of 1-2 amperes is typically applied to the stretched wire. Any transverse magnetic fields due to magnet misalignments will cause the wire to be perturbed off axis by the Lorentz force on the wire during the time that the current pulse is applied. This deflection pulse propagates down the wire at the acoustic velocity in the wire and passes the photo-optical position sensors.

By viewing the wire deflection waveforms it is possible to distinguish magnet tilts from offsets, since tilts and offsets have different waveform signatures as shown in figure 3.

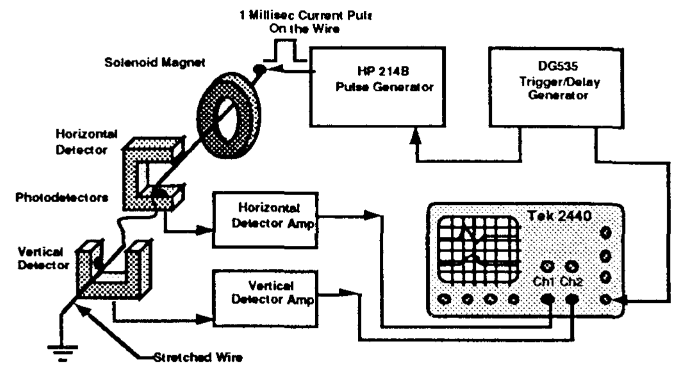

Figure 2. Block diagram of detector circuit.

To quantify magnet offsets, the wire end points are moved in unison until a null occurs in the offset waveform signature. To determine magnet tilt angles, we apply current to the trim coils, and we convert trim current to an equivalent tilt angle by using equation 2 below:

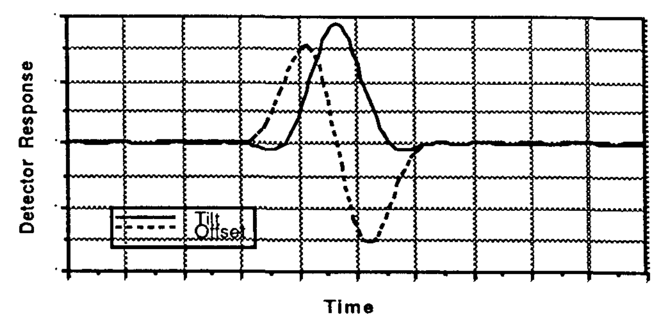

Figure 3. Response signatures for magnet tilts and offsets.

Magnet tilt angle can then be calculated as

$$\alpha = -2 \frac{\int_{-\infty}^{\infty} B_{\perp} dz}{\int_{-\infty}^{\infty} B_z dz} \qquad (2)$$

where we have measured the relationship between trim current and the perpendicular magnetic field, $B_{\perp}$ produced by the trim coils, and measured B_z as a function of solenoid current.

ETA-II Alignment Results

This section summarizes the alignment data on ETA-II. All alignment work was performed for a Bz field of 1.3kG in the accelerator and 540G in the injector. We believe the injector, intercells and accelerator 10-cell blocks are aligned to within ±400μm with an rms misalignment of 270μm in the horizontal direction and 120μm in the vertical direction. Figures 4a and 4b show the measured offset values for each of the solenoids. The alignment measurements were repeated a number of times in order to obtain confidence in the repeatability of the measurements. Magnets in the injector and 10-cell blocks are not individually adjustable mechanically, since the assemblies are pin aligned at the time of assembly. Therefore, we adjusted the position of the entire cell block to the best linear fit through the measured data. We accounted for the catenary deflection of the wire by calculating the catenary value for each cell, and raised the wire end points an appropriate amount to compensate for the droop. Individual magnets in the intercells were moveable, and we positioned these coils by locating the wire on the reference axis at the coil, and then moved the solenoids so as to null the stretched wire response. This adjustment was not completely successful, however, because of difficulties arising from over-constraints in the mechanical design.

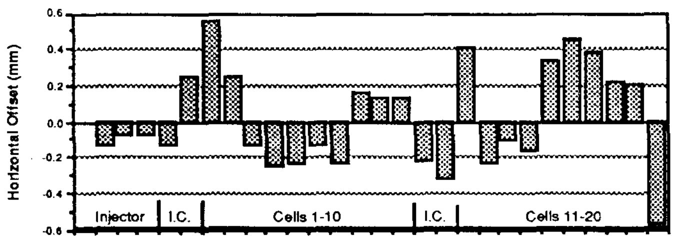

Figure 4a Measured ETA-II solenoid horizontal offsets.

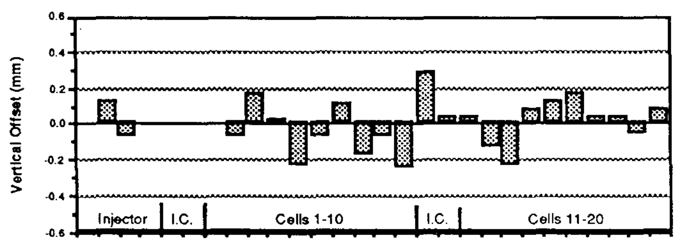

Figure 4b Measured ETA-II solenoid vertical offsets.

Figures 5a and 5b show the resulting magnet tilts found by evaluating equation 2. It should be noted that the tilts shown are for coils with no correction currents applied. When trims are applied, the field tilts are compensated to better than ±1 milliradian based upon our confidence in the repeatability of the measurements.

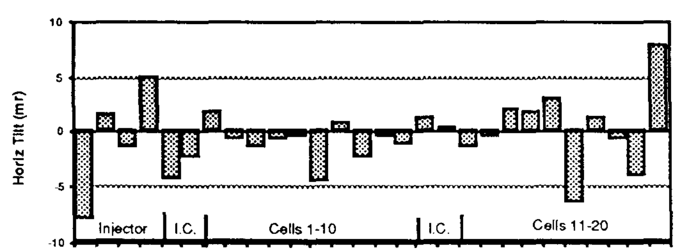

Figure 5a Measured ETA-II solenoid horizontal tilts.

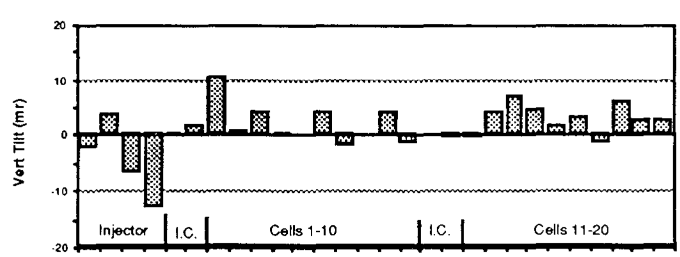

Figure 5b Measured ETA-II solenoid vertical tilts.

While the magnet offsets and tilts as determined by the stretched wire alignment technique do not directly provide us with a plot of the magnetic field lines through the accelerator, we have measured the field for each of the magnets used on ETA-II, and this data can be used along with the tilt and offset data to obtain an equivalent flux line pattern based upon a superposition of the individual field components. This plot is shown in figure 6.

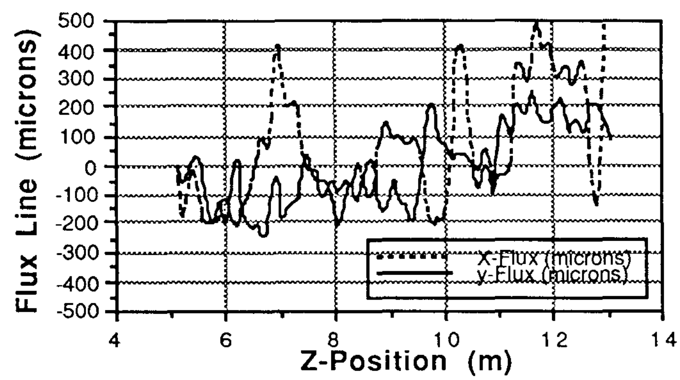

Figure 6 Calculated horizontal and vertical flux line based upon magnet tilts and offsets.

Conclusions

We have found the stretched wire alignment technique to be very useful in measuring the alignment of ETA-II. Measurement times for the 28 solenoids is on the order of 4 hours, with potential improvements requiring even less time. The technique lends itself well to establishing magnetic alignment during the fabrication and assembly stage of the accelerator cell blocks, and this will be implemented in the future.

Our interpretation of the tilt and offset waveforms has been based upon that of an experienced user. Work is currently underway to develop an on-line digital signal processing capability to extract offsets and tilts directly from the waveforms. When some of the operator's subjectivity is removed, it is believed that even greater accuracies will be obtained.

References

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2. R. Warren and C. Elliot, "New System for Wiggler Fabrication and Testing", Los Alamos National Laboratory, Los Alamos NM, LA-UR 87-2981.

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