

IMPROVED FOCUS SOLENOID DESIGN FOR LINEAR INDUCTION ACCELERATORS

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Abstract

Our FXR linear induction accelerator produces a 2 KA, 17 MeV electron beam of 60 ns duration. The beam is focused on a tantalum target to produce x-rays for radiography. The FWHM spot size of the focused beam is currently 2.2 mm. We strive to reduce the spot size by 30% by improving the field characteristics of focusing solenoids housed in each of 50 induction cells along the beamline. Tilts in the magnetic axis of the existing solenoids range up to 12 mrad (0.7 degrees). We are building new solenoid assemblies which include ferromagnetic homogenizer rings. These dramatically reduce field errors. A field tilt of under 0.5 mrad has been achieved.

Mechanical alignment of the rings is critical. We developed a novel construction method in which the rings are wound with 4 mil thick Si-Fe ribbon into grooves on an aluminum cylinder. The cylinder then becomes the winding mandrel for the focus solenoids. This forms a more accurate and compact assembly than the standard practice of pressing individual solid rings onto a tube.

Overall Design

An ideal focus solenoid would only produce a magnetic field along its axis. Real solenoids also produce transverse field components which kick the beam off-axis. These fields are caused by imprecisions in the practical winding of large conductor water cooled coils, by misalignment of the coils in the beamline, and by the coil leads [1]. Our strategy is to replace each existing solenoid in the FXR accelerator with the new solenoid assembly diagramed in Figure 1. The assembly consists of three parts:

Bifilar-Wound Water Cooled Solenoid Coil

A bifilar-wound coil has two advantages over more conventional coils. Due to inherent symmetries, it produces smaller transverse fields. It is also easier to cool, because the cooling channels are approximately one-half as long. Since the complete solenoid assembly must fit into the same space as an existing solenoid, the bifilar coils are 20% smaller, but must produce the same field. They generate more heat and require more cooling. Reference [1] discusses multifilar coils in depth.

Homogenizer Ring Assembly

Any transverse fields which are generated by the coils are reduced by as much as 10x by the ferromagnetic homogenizer

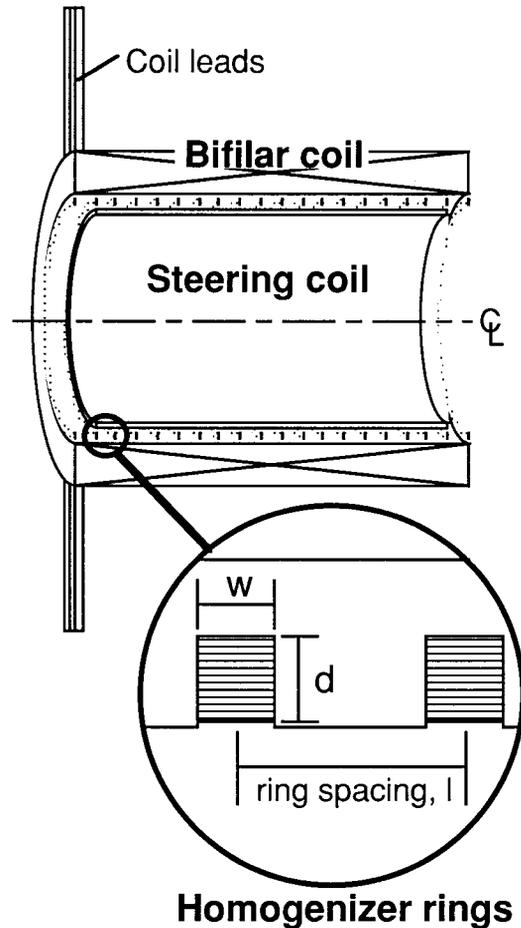


Figure 1: Cutaway sketch of an FXR solenoid assembly showing the location of the three major components.

rings [2]. The rings are so effective that their precise mechanical alignment becomes crucial. Rather than attempt to align individual solid rings to the coil axis, we machine grooves into an aluminum cylinder and wind ferromagnetic ribbon into the grooves to form the rings. All of the rings become a single precision part which can be aligned as a unit. This homogenizer ring design is the truly innovative part of the design and will be described in more detail in the remainder of this report.

Printed Circuit Steering Coils

Steering coils in each assembly correct any remaining field misalignment. The coils consist of 10 mil thick copper traces plated and etched on 5 mil Kapton polyimide film. They produce a maximum steering field of 730 G-cm. The homogenizer rings

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nearly double the field from these coils by providing an easy return path for the steering flux.

Homogenizer Ring Design

The homogenizer ring concept is simple. A series of ferromagnetic, high permeability rings fit along the axis inside a solenoid. Any transverse magnetic flux generated by the coil preferentially travels through the highly permeable rings and is shunted around

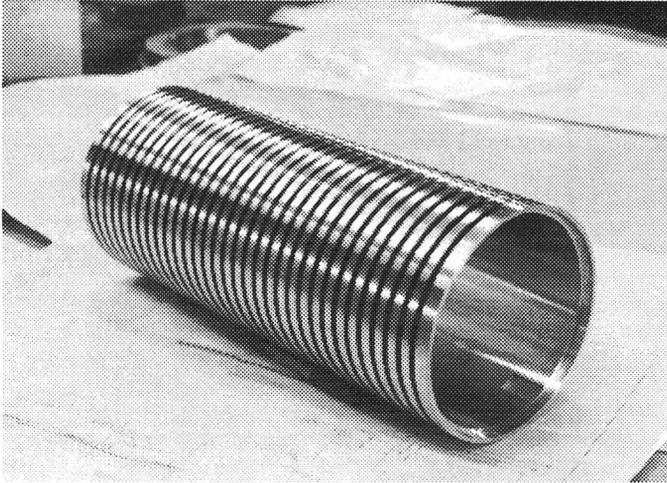


Figure 2: Homogenizer ring assembly used in the final design.

the beam area at the coil axis. The axial field is not shunted by the rings because of the air spaces between them. A picture of our ring assembly is shown in Figure 2.

Figure 1 defines parameters w (ring width), d (ring radial depth), and l (center-to-center ring spacing), which characterize a homogenizer ring design. Other dimensions of the rings are fixed by the coil size. Our choice of w , d and l involved a trade-off between the following considerations:

Reduction of Transverse Fields

The primary function of a homogenizer ring design is to attenuate transverse fields. The rings form a magnetic shield. From shielding theory we know that thick rings (large d) with small gaps (w/l approaching 1) will make the best shield. We performed a series of experiments to determine the best ring geometry for our application. Rings were fitted inside an existing FXR focus solenoid which had an uncorrected field tilt of 4 mrad. Field tilt is defined as the angle between the transverse field and the axial field.

Figure 3 shows the effect of 0.05" wide rings made from annealed pure iron ribbon. 5 mil thick ribbon was wound to a depth of 0.1" into grooves in a Lucite cylinder. With $w/d = 0.5$, the rings were in the shape of a washer. A 3x attenuation of transverse field was achieved with a ring spacing of 0.25" ($w/l = 0.2$).

We did another test series on rings wound from 0.1875" wide oriented silicon steel (Si-Fe) ribbon. This is the same 4 mil thick material we are using in our final design. Data for rings with $d = 0.15$ " ($w/d = 1.25$) is shown in Figure 4. As field tilts approached 0.5 mrad we began to reach the signal-to-noise limit

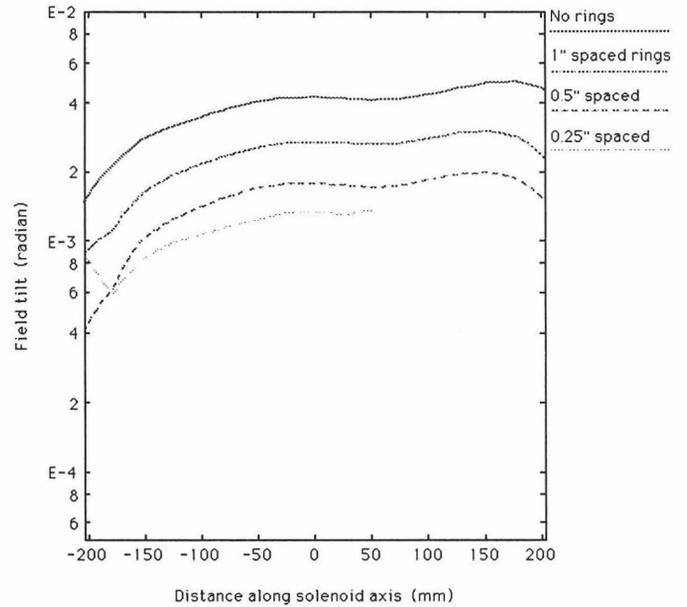


Figure 3: Reduction of field tilt by pure iron homogenizer rings at various center-to-center spacings, l , $w = 0.05$ " and $d = 0.1$ ". $z = 0$ at the center of the solenoid.

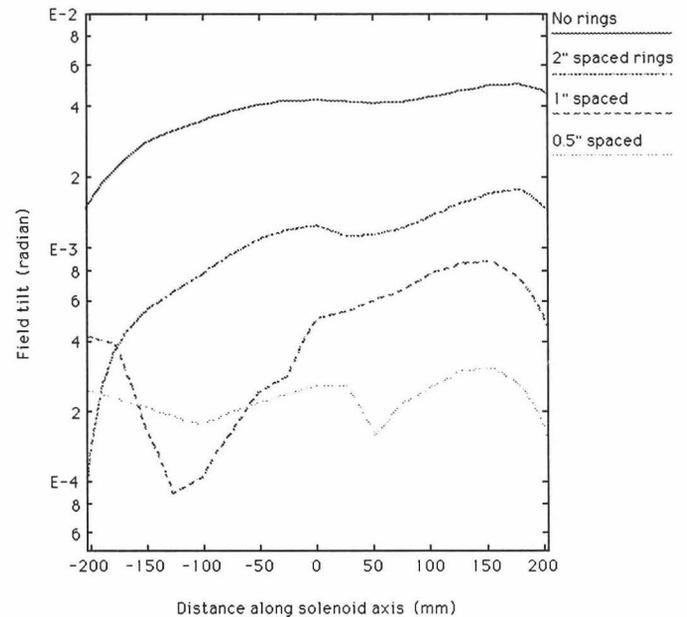


Figure 4: Reduction of field tilt by oriented Si-Fe homogenizer rings at various center-to-center spacings, l , $w = 0.1875$ " and $d = 0.15$ ".

of our testing apparatus. We achieved a better than 10x tilt reduction with rings spaced at 0.5" ($w/l = 0.375$).

A more subtle shielding question is whether many small rings are preferable to several large rings with the same w/l ratio. Our measurements of the FXR solenoid indicated that the transverse field it generated could change in radial direction by more than 10 degrees per inch along the coil axis. By decreasing the ring spacing along the axis, we get a more localized shielding effect to counteract this variation.

Minimum Effect on Axial Field

Even greater reductions in transverse fields would result with w/l approaching 1. However, as the air gap between rings is reduced, more axial flux is shunted through the rings and the focus field in the beam region decreases. We performed computer-generated 2D magnetic field simulations to assess this effect and saw little difficulty for $w/l < 0.5$. Nor did we see any detectable degradation of axial field during our experiments.

Proper Field Levels Within Rings

Close spacing of the rings also increases the axial field within the rings, which could saturate the ring material. Although the cross field characteristics of the ring materials were unknown, we wanted to avoid saturation. We performed computer simulations which showed that tubular rings ($w/d > 1$) concentrate more axial field inside than washer shapes ($w/d < 1$). Our final design calls for $w/d = 1.25$ and a maximum central focus field of 2.5 KG. This would place a 7 KG axial field within the rings, which is well below their saturation induction.

Circumferential fields within the rings must also be considered. These fields result from the transverse fluxes shunted by the rings. A low reluctance path for these fluxes should be maintained. This means that the ring material should exhibit high permeability at the field levels of operation. A low coercivity material has the advantage of providing high permeability even at low field levels. This is desirable. We want the rings to shield effectively even small transverse fields.

Using a low coercivity ring material has the additional advantage of minimizing remnant fluxes which can sometimes add to the transverse fields generated by the coil. We saw this effect when we made some rings from a material which was much too hard magnetically. Degaussing coils could be added to the ring assembly, but we felt the added complexity was not warranted. The coercivity of the Si-Fe ring material is low enough that we did not detect remnant fields during testing.

The effective permeability of the rings is enhanced by avoiding ring cross sections ($w \times d$) which are too large. Smaller rings require smaller transverse fields to bias them into their high permeability range where they shield more effectively. Obviously, the ring cross section must be kept large enough to avoid saturation.

Space Available For Rings

In our application, where we had a fixed space for the coil assemblies, the radial depth, d , of the rings was critical. The

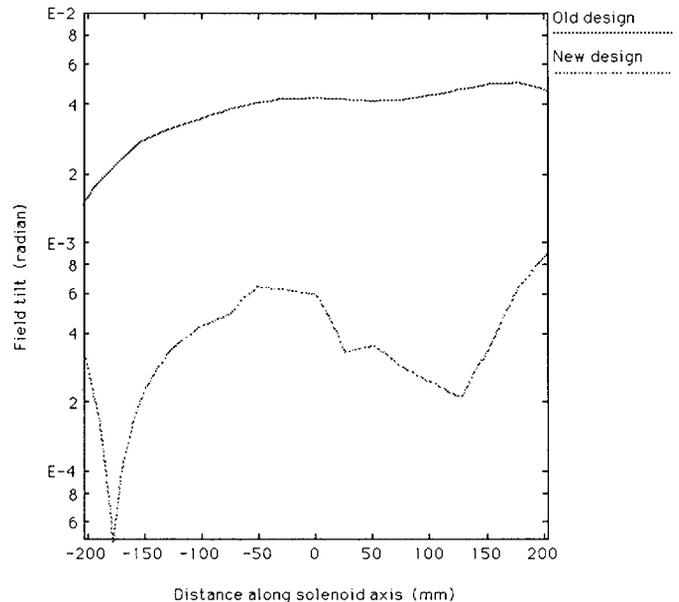


Figure 5: Field tilt from our new solenoid assembly compared to an existing FXR focus solenoid.

maximum we found we could tolerate was $d = 0.15''$. The solenoid coil was wound directly onto the ring assembly.

Our final homogenizer ring design uses 32 Si-Fe rings with $w = 0.1875''$, $d = 0.15''$, and $l = 0.5''$.

Performance

Figure 5 shows the measured field tilt from one of our new focus solenoid assemblies. The solenoid was producing an axial field of a little over 1 KG at the time, and the steering coils were not energized. A tilt of 0.5 mrad was achieved. Installation of the assemblies into FXR has begun and we expect completion by April 1994.

References

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2. B. Feinberg, I. G. Brown, K. Halbach, W. B. Kunkel, A Method for Improving the Quality of the Magnetic Field in a Solenoid, Nuclear Instruments and Methods, v. 203, (1982), pp. 81-85.