MAKING AN INEXPENSIVE ELECTROMAGNETIC WIGGLER USING SHEET MATERIALS FOR THE COILS*

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Abstract

An inexpensive electromagnetic wiggler, made with twenty-eight, 8 cm periods with a K of 1 and gap of 2.6 cm was made within 11 weeks after receipt of order by an industrial machine shop. The coil design used sheet and plate materials cut to shapes using water jet cutting and was assembled in a simple stack design. The coil design extends the serpentine conductor design of the Duke OK4 to more and smaller conductors. The coils are conduction cooled with imbedded cooling plates. The wiggler features graded end pole fields, trim coil compensation for end field errors, and mirror plates on the ends to avoid three dimensional end field effects. Details of the methods used in construction and the wiggler performance are presented.

INTRODUCTION

An electromagnetic (EM) wiggler with 28, 8 cm periods and a K of 1 was manufactured for us in a very short time, 11 weeks, for a purchase cost of $176,000. Even more unusual, the magnet was made entirely using machine shop technology without the use of traditional coils. We needed the wiggler as part of multi track program to reach the goal of 10 kW from our FEL. Half of the wiggler is shown in Figure 1

Figure 1, One Half of the EM Wiggler

We needed a back-up EM Wiggler for the low energy track of our expanded effort to obtain 10 kW at the FEL Upgrade Program at Jefferson Lab[1,2]. The characteristics of the wiggler, 8 cm period, and 0.134 T rms field are in the range of a normal conducting, electromagnetic wiggler, but design and production of coils in the required three month time frame was thought to be improbable.

A lunchtime conversation led to the possibility of using a new, inexpensive approach. Make the wiggler coils out of sheet copper cut in a serpentine pattern like the undulators used in the Duke OK-4 FEL[3] that use four large, internally water-cooled, alternating orientation, serpentine conductors in each wiggler half. Since our existing power supplies are limited to 220 A, we needed many more layers of a smaller conductor. Sheet copper, 1.5 mm thick that fits in the 2 cm space between poles is a workable cross section and has acceptable power loss.

The real breakthrough came when we realized the copper sheet could be cut to high precision using newly available, water jet cutting technology. Design began in mid February, aiming at having a wiggler in 10 weeks.

DESIGN

Four Main Coil Elements

We were ready to design after setting the wiggler gap, (2.6 cm) and the number of poles, (60). The first question is: How many ampere-turns are required to excite the poles of a wiggler with serpentine conductors? Does the missing portion of the coil turn result in not creating the full field of a full turn? We didn't have time to do a 3D magnetic model of this complexity. We checked on the current used for the OK4 and there seemed to be a small effect. (Our measurements show that before any saturation effects are seen, a factor of 10% more Ampere-turns are required). We chose 24 turns per pole per half of the wiggler, about 19 % more than theoretically required by our 2D magnetic model when operating at 200 A. The power supply had 20 A additional margin.

The second most important consideration in design was coil cooling. At our selected parameters, with a current density of 6.4 A/mm^2, effective cooling is still possible. Our sheet conductor design needed cooling plates that would cool by conduction through a layer of insulation. The cooling plate has to have enough surface area to transfer the heat and enough cross section to conduct the heat to a tube of flowing cooling fluid. Early in the design process we realized that the water jet cut process gives design freedom. Our conductor didn't look like a serpent. It followed the pole tip's square corners and had three times the electrical conduction width as well as heat transfer area outside the slots. See a typical conductor shape in Figure 2. We chose cooling plates made of the same 1.5 mm sheet copper as the conductor. We used a conservative philosophy of one cooling plate for every two conductors, leading to every conductor having one surface in contact with a cooling plate through insulation. The cooling plates are cooled by tubing brazed to their outside edges beyond the outer conductor edge. See the cooling plates in Figure 3.

We chose 76 μm Kapton as the insulation between conductors and between conductors and cooling plates.

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Figure 2, Conductors

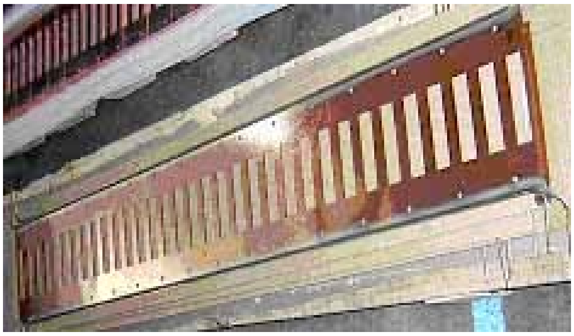

Figure 3, Cooling Plates

This is a robust insulation, with high dielectric strength, no cold flow under pressure and capable of withstanding several hundred °C in case of marginal cooling performance. An insulation sheet is shown in Figure 4.

Figure 4, Insulation Sheet

We used 6.3 mm aluminum clamp plates on the outsides of the conductor stacks to package and press the conductors, insulation and cooling plates into a unit where thermal conduction could take place reliably. A set of sixty-four 6.3 mm brass and bronze bolts and studs, run through the stacks provide uniformly distributed clamping force.

We extended our water jet cutting philosophy. We made all four of the major coil components of this complex electromagnetic wiggler very rapidly and accurately using a computer controlled water jet, the modern rendition of the jigsaw.

Simple calculations of the potential power dissipation came to 8 kW, well within the limits of the available power supply. One dimensional thermal calculations of the heat flow through the insulation, the thermal contact resistances and the heat flow through the copper conductor and cooling plate showed that temperature differences between the copper conduction strip at the center of the slot (highest temperature point) and the cooling water were limited to several degrees K.

End Complexities

We have to thank Stepan Mikhailov of the Duke University FEL Center for very constructive discussion on wiggler design at this point in the design. We copied the OK4 design's grading of end pole field's strengths, aiming for 25% field integral at the end poles and 75% at the second poles. One fourth of the conductors that serpent through the poles of the body of the wiggler end in a connection-loop around the end poles, exciting them to 25% of full field. Half of the remaining serpentine conductors end in a connection-loop around the second poles. They are excited to 75% by these turns combined with the second undulation of the quarter of the conductors looping around the end poles. The remaining one quarter of the conductors end in connection-loops around the third poles, exciting them and all subsequent poles to full field. With our chosen 24 conductors (turns) per pole in the main body of the wiggler, the ratios for end pole grading led us to stacks of 6-12-6 of the three progressively shorter serpentine conductor styles.

A simple method of connecting the 24 alternating serpentine conductors was the next design hurdle. We copied a design used on the coils of the Spreader-Recombiner Dipoles of CEBAF. At the head and tail of each serpentine conductor, we added tabs to extend the conductor termination outside the bounds of conductor/cooling plate stack. The silver plated tabs have a hole in their center and are designed to stack over one another. A series coil is formed when an insulator film is slipped between every other tab-to-tab interface and the stack of tabs is compressed to make electrical contact between the non-insulated tabs. A single bolt passing through the hole in the tabs provides the compression force. The bolt is insulated from the edges of the tab holes by an epoxy fiberglass sleeve and isolated from the end tabs by thick epoxy fiberglass washers.

The cable lug connections to the wiggler coil are made directly to the tab of a top or bottom serpentine conductor of a stack. The same bolt used to compress the tabs provides the compression force to make good electrical contact with the lug.

The grading of field in the end poles added complexity to the above connections. The stacks of tabs at each end come out of the conductor stack in three positions. The first is from the six conductors ending around the first pole. The second stack of 12 tabs is comes out at the second pole. The third stack of 6 tabs comes out at the third pole. We added jumper strips between tab stacks to form the 24-turn coil. These stacks and connections are shown in Figure 5.

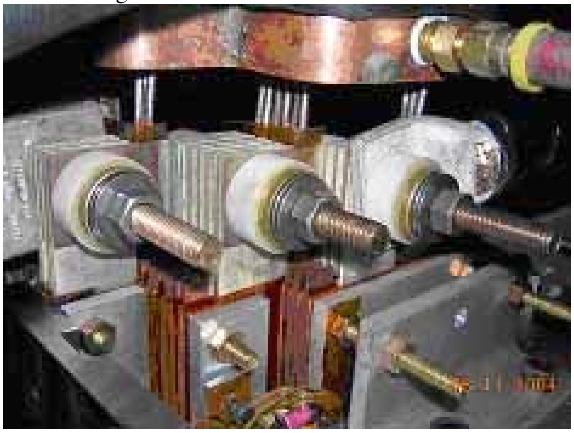

Figure 5, Lead Tabs & Bolts with Manifold

This system of tab and lug contacts and the jumpers enabled a very complex connection problem to be solved within a very small volume.

We are again indebted to Stepan Mikhailov for two additional suggestions that we adopted in our wiggler. We added trim coil sets, one set to the four end poles and a second set to the second poles. They allow us to zero out the first field integral. The second suggestion was to add mirror plates to the end of the wiggler to cancel out the 3 dimensional end field distortions.

We will run the power lead cables from or back to the power supply and to or from the opposite half of the wiggler via drops from an over-head cable tray. The pairs of opposing current cables are tied next to one another along these paths to minimize the flux lines of the 0.7 mT field created between the leads at operating current.

Cores

We planned to substitute our new wiggler for the upstream wiggler of the installed Optical Klystron (OK). We would reuse the mounting features of the common strong-back that supports both OK wigglers. This substitution requirement determined the new wiggler core's vertical dimension (10 cm thickness), the same as the core of the OK wiggler with the 20 cm periods. We reasoned that transverse field uniformity would be as good or better. We had a surplus slab of 1006 magnet steel from CEBAF's 3 m dipole program that we split in half to form the two multi poled core halves. This guaranteed identical magnetic properties in the two halves. We annealed the cores just before final machining using our standard vacuum oven, slow cool method for iron cores.

Insulation Details

We decided to forego insulating our coil packs with conventional cast epoxy-fiberglass. The chosen Kapton film is capable of holding off 30,000 V as a 2 dimensional insulation. Our challenge with this 2 dimensional insulation was to prevent arc-over to the grounded cooling plates and clamp plates from the conductor edges. These edges are found around all sixty poles, at all 64 bolt penetrations and the outer edges running the length and width of the conductor. As a design philosophy, we decided that a nominal insulation overhang of 1 mm would be applied to all such edges. Thus, at the poles, the conductors were withdrawn from the surface of the pole edge by 1 mm plus a 0.25 mm manufacturing tolerance. The Kapton film's holes to fit over the poles included only a 0.25 mm assembly tolerance. For this philosophy to succeed we would have to keep the voltage low, say below 100 V, to minimize the possibility of flash over along a surface path between conductor and ground. Fortunately, the water jet process achieved tolerances of ± 130 μm in cutting the film insulation to make the concept a reality.

The second part of the philosophy of extending 2 dimensional Kapton insulation to a 3 dimensional wiggler was to directly insulate the surfaces of the two classes of objects penetrating the conductor stacks. The pole tips are insulated with pre-formed, 76 μm Mylar sleeves and the bolts through the stacks are insulated with 50 μm Mylar tape.

To build redundancy into the insulation system, we also specified that the cores and cooling plates be coated with Sherman Williams "Clear Coat", an organic coating.

Cooling Details

We developed a compact manifold system that distributes the cooling water to the twelve parallel cooling circuits on each side of the conductor stacks and still fits within the confines of the installed strong back. The 3.2 mm outside diameter copper water tubes were bent outward in unison at the ends of the cooling plates. The manifolds are made of two parts, a pan-like vessel and a sealable cover. The pan-vessels were made with 12 holes in their bottom. The design calls for impaling the pan bottoms over the 12 tube ends and soldering the tubes into the holes from the inside of the pan while it is concave outward. Applying the sealed covers to the pan completes the manifold vessel. See figure four. This method of soldering from the front assures the small tubes are not plugged and the joints are leak free.

MANUFACTURING

We were fortunate to have a relationship with an excellent manufacturing company to make our wiggler. Process Equipment Co. (PECo) of the Dayton Ohio area machined the cores of 400 CEBAF dipoles and had performed their assembly. They were also familiar with wigglers, having machined the four core halves of the original OK Wigglers and built their strong-back. They had the additional advantage of routinely using a very good Dayton water jet company (Kerf Water Jet Co.) and a noted furnace brazing company (Wall Colmonoy).

After supplying PECo with preliminary sketches in early February followed by actual details, a contract was placed for the Electromagnetic Wiggler on March 8 per a fixed price bid and promised 10 to 12 week delivery. This period was not our original 10 weeks from lunchtime conversation, but close to it.

We also contracted with PECo for prototype efforts of water jet cutting of both insulation and copper sheets. During this phase we transmitted CAD generated outlines of the parts directly to the water jet vendor. That vendor's software transferred the outlines into cutting code without translation error. We also funded prototype brazing of tubes to cooling plates. The prototyping gave PECo and their vendors the confidence to rapidly proceed with production once the production run materials arrived.

The production water jet cutting took about three weeks. Prototyping showed that water jet cutting forms a burr on the edges of the sheets that had to be removed. The radius left by the water jet turned out to be large enough to minimize the tear-from-an-inside-corner property of the Kapton film. This was very important; there are 240 inside corners per sheet and we only had to use tape to fix a hand full of tears. Brazing the tubes to the cooling plates took about two weeks.

As part of our contractual agreement with PECo, we designed a simple assembly tool to ease the draping of the conductors, insulation sheets and cooling plates over the 60 poles. The tool has comb like teeth. It supports the coil pieces while lowering them between the poles and can then be withdrawn. The tool was made of a sheet of polycarbonate and also cut by water jet.

Assembly took about three weeks by several skilled assembly workers and their project manager. Each coil pack was assembled twice because the first assemblies had low resistance to ground. Small chips were found embedded in the Kapton film in at least four interfaces, even though the assembly took place with extensive wiping-down in a relatively clean assembly area. They performed the second assembly in the plant's clean-room-like metrology lab.

The wiggler was received at Jefferson Lab 11 weeks after receipt of order.

RESULTS

The Jefferson Lab semi-automatic hall probe scanning table is used to measure the wiggler We removed the upper gap spacer blocks and brought the poles back to parallel using clamps. We are still qualifying the wiggler and calibrating the trim coil values vs. K. as this paper is written

Vertical scans at lower fields show excellent uniformity of the fields in the body of the wiggler. We also found that the field has a 2.5% third harmonic component that reduces the peak field for a given rms field. The new peak field for an rms K of one is 0.1850 T.

A marginally acceptable trajectory (30 µm peak to peak) for an rms K of .85 is shown in figure 6, indicating the wiggler is capable of qualification. The first trial at a trajectory for the design rms K of 1.0 is shown in Figure 7. The offset and entry angle are already quite small and the trajectory is straight to 50 microns peak to peak. In both scans, a superposed saw-tooth field along the wiggler's length, increasing at higher fields leads to the S-shaped electron trajectory. The trim coils on the first and second poles do not cancel it. We are exploring several approaches, some involving trim coils. Fortunately, we left a 3 mm space between the coil pack and the bottom of the coil slot to add the coils.

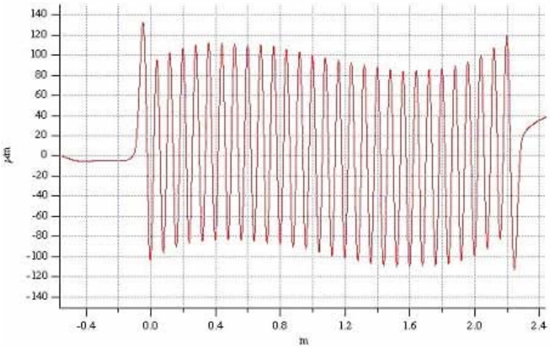

Figure 6, Trajectory for a K = 0.85

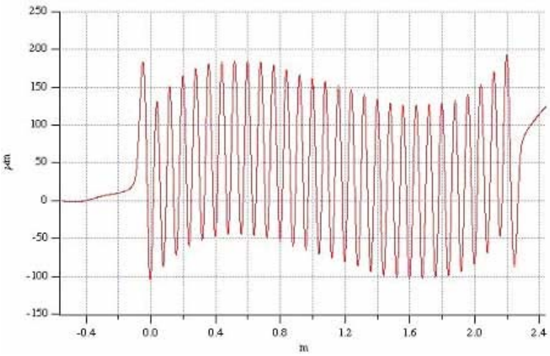

Figure 7, Trajectory for a K = 1

CONCLUSIONS

- An inexpensive wiggler may be made very rapidly using water jet cutting technology.
- Transverse field quality is not compromised by the use of serpentine conductor in this configuration.
- Field quality for this wiggler is limited by a small saturation effect - this is correctable by trim coils.
- This manufacturing method may be extended to more complicated wigglers with higher fields and shorter periods using of 3D magnetic and thermal modeling.

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