SSCL-Preprint-387

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May 1993
Distribution Category: 400

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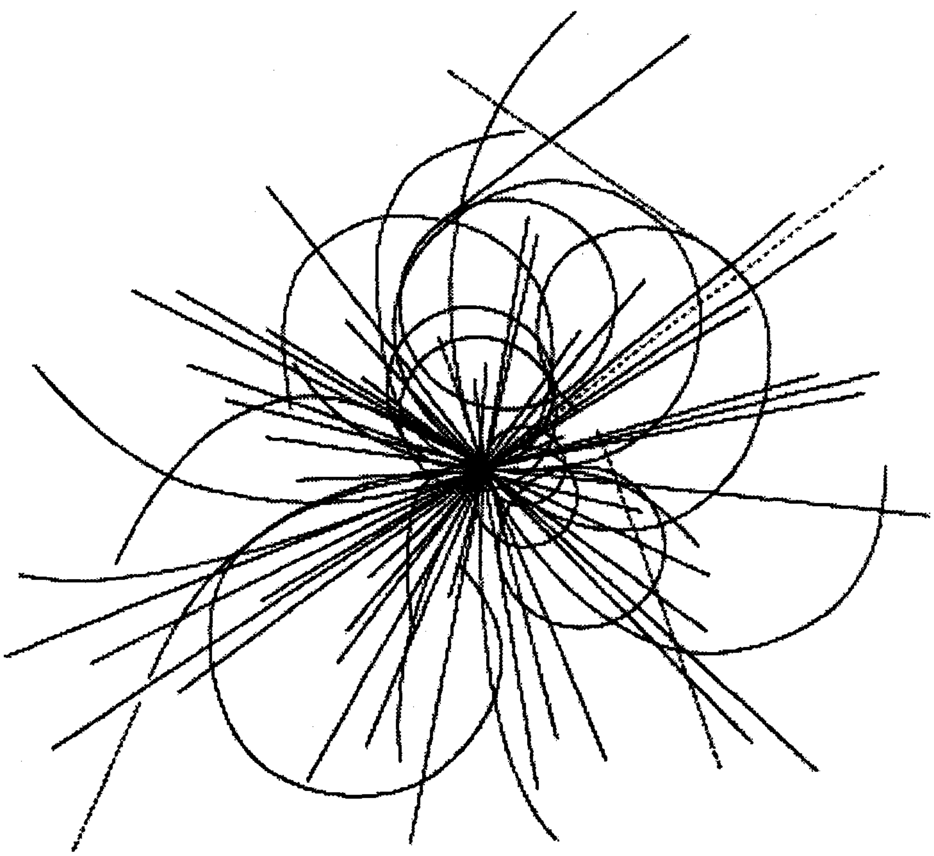

Superconducting Super Collider Laboratory

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Lamination and End Pack Design Studies of SSC Low Energy Booster Magnet Prototypes*

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May 1993

*To be presented at the 1993 IEEE Particle Accelerator Conference on May 17–20, Washington, D.C.
†Operated by the Universities Research Association, Inc., for the U.S. Department of Energy under Contract No. DE-AC35-89ER40486.

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I. INTRODUCTION

The LEB machine includes six kinds of laminated magnets and 4 kinds of laminations. The main quadrupole magnet and low field and high field corrector quadrupoles use the same lamination shape. The chromaticity sextupole, corrector dipole, and main dipole have different lamination designs. To test the physical design and production procedure for the magnets, it is necessary to build 2 or 3 prototypes for each kind of magnet.

The ZVI plant in Moscow, manufactured all 4 kinds of lamination punching dies for the LEB magnets. Each die takes 3 to 5 months to fabricate. SSCL manufactured laser cut laminated magnet prototypes in the SSC shop at the same time.

Since the LEB cycles at 10 Hz, the high frequency current and laminated end plate design causes a delamination problem on the magnet end. This problem is of concern and will be addressed.

II. LASER CUT LAMINATION

A. Quality of the laser Cut Lamination

To speed up prototype production and in order to offer some magnetic field information to the Russian collaborators; the SSC shop used laser cut laminations to build the LEB magnet prototypes.

The laser cutting technique is advertised to have a very high machining accuracy of 0.01 mm tolerance over a 200 mm length. But for the 5 kinds of laser cut laminations, only the main quadrupole laminations have reached the +/- 0.0125 mm design tolerance requirements for the critical segments. The corrector quadrupole lamination (the same design as the main quatrupole but made by a different company) pole segment error is around a factor of 10 larger than the requirements. The deviation of the main dipole pole segment on the straight part is around 15 times larger than the design. Even for the very simple shaped trim dipole, one pole on the straight part is still 4 times over the tolerance band. This situation attracted our attention. The laser cutting technique can cut very complex parts, such as the main quadrupole laminations. But this does not necessarily mean that it will have the necessary accuracy. Industry is familiar with conventional industry standards. It is a rather new thing for them to cut accelerator magnet laminations which are thin and have big transverse dimensions; the shape is rather complicated as well. If we do not carefully choose a good company and do not have a test program for laminations, but just simply believe in the laser cutting technique itself; it is very likely we will have poor quality laminations, even worse than one would expect from conventional tooling methods. When we have poor quality laminations to make the prototype, the physical design problems will be mixed with the mechanical tolerance problems, and it will be hard to separate the physical design errors from the mechanical fabrication errors. The result is that the prototype can only offer a production procedure study but not a physical design study.

From our experience, the conclusion is that using laser cutting techniques to cut laminations may be a good method to build laminated magnet prototypes. It saves time, but it is a very sensitive method as well. Special attention must be paid to the programming and the program running lamination samples.

B. Different Property between Laser Cut Laminations and Die Punched Laminations

The laser cut laminations have a major difference from the die punched laminations. The laser cut laminations have no burrs, so the stacked core can easily reach almost 100% packing factor. But the die punched lamination core will have a rather lower packing factor. Our laser cut main quadrupole prototype has a 99.8% packing factor and the die punched lamination prototype has a 98.5% packing factor.

The burr characteristic also gives the core stacked from the laser cut laminations a high resistance under high voltage. But the die punched lamination core definitely can not obtain the same value. For the die punched lamination core, the stack resistance is composed of 3 factors: 1. the resistance of lamination coating insulation which is very high; 2. the resistance of steel sheet which is much lower than the coating one, if the stacking

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compression is reasonable, this resistance can be ignored; 3. the resistance of the lamination edge area which is caused by burrs and can be considered as the steel resistance. When you test the lamination stack insulation, in fact, you can only observe the lamination edge area resistance. Therefore, it is a non-comparable value with the resistance value of laser cut lamination stack. The 10 cm thick stack insulation test shows that the resistance value of the main quadrupole prototype made by the die punched laminations is 2.8 to 4.0 ohm under 5 kg/cm^2 compression at 50 V, the dipole is 0.9 to 1.0 ohm under the same condition. But the 3.0 cm*3.0 cm*0.9 cm testing samples obtained $1.11*10^5$ ohm resistance at 1.0 V/mm.

As stated above, the packing factor and the insulation value which were achieved from the prototype made by laser cut laminations can not be used as a criterion to judge the die punched laminations. Otherwise, the two kinds of prototypes made by different laminations should share the same mechanical tolerance and the same magnetic field results.

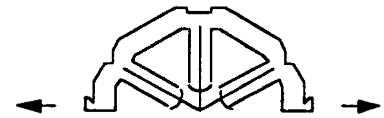
III. PUNCHED LAMINATION

A. Quality of the Die Punched Lamination

The LEB quadrupole, main dipole, and the chromaticity sextupole lamination punching dies have been developed and several thousands laminations have been punched. Inspections show the laminations have very good quality. All 3 kinds of laminations are qualified for the +/- 0.0125 mm tolerance requirements on the critical segments. It is a real surprise that they are much better than the laser cut laminations. ZVI chose the refined die method for the LEB magnet lamination fabrication. There is no clearance between the guide pins and bushings; pins and bushings are never out of touch with each other; the clearance between the die and the punch is as small as 0.02 mm. ZVI built the main quadrupole lamination die and the punch as one solid piece. ZVI took full advantage of the EDM technique and took the risk as well. If any spot of the die or punch cutting edge is broken, the only way to repair the die is to build a brand new piece. It will cost significant money and time. This adventure obviously supplied a very high quality die and, of course, very high quality laminations. The burrs are as small as 0.02 mm, this means that the deburring procedure can be total eliminated.

B. Th Sextupole Lamination

The sextupole laminations show something very interesting. The LEB sextuple design is composed of 2 half cores, i. e. each half has 3 poles, so it is kind of a C shaped lamination.



C shaped lamination is assumed to tend to open
Figure 1. LEB Sextupole Lamination

It is a common knowledge that this kind of lamination tends to open after punching because of the materials inner-stress. In general, it is suggested to use two steps to punch the lamination. First, a rough shape stamp that allows the release of the material's inner-stress and then a punch step to achieve a accurate size pole segments and packing reference segments on the lamination. For the LEB sextupole, its outline dimension is about 479*220*0.5 mm; it is rather small and thin. The ZVI plant designed only one die to punch the lamination. They did not adjustments to the die for the opening problem. The inspection results by ZVI in Moscow showed very good quality laminations. Opening did not occur on the laminations at all. The lamination samples were then delivered to the SSC, we re-measured them. The inspection values were different from ZVI report, but in the tolerance band. The interesting thing is that the right and the left poles of the lamination and the right and the left clamping ears of the lamination consistently demonstrated that the lamination did open slightly. I believe there may be ageing. I will continue to study more samples during the sextupole lamination lot production; if the phenomenon indicated above exists in the majority of inspected laminations, it may give us some new information about the opening problem of the C shape lamination. We will get some experimental data between the lamination size and the opening ratio. We may find that we can ignore the opening problem for certain size laminations.

IV. LAMINATION INSPECTION

A. The Principle for Set Up of the Inspection System

There are many ways to set up the lamination inspection system, i.e. the measuring coordinates. But the system that most accurately and directly reflects the possible deviation of the critical part of laminated core after packing should be the favorable one. Such as for the quadrupole magnet, the pole diameter and the gap size between the adjacent poles are the most critical mechanical values to ensure good magnetic field quality. And the datum features of the lamination to reflect these values are the 2 yokes , i. e. the mating surfaces between adjacent quarter cores. So the measuring system should be set on these two features. Then inspection numbers will demonstrate exactly the pole diameter and the gap value. Using the same principle for the dipole lamination inspection, measurement should use the features which will be chosen for the core packing datum as the X and Y axis. For the sextupole we should choose the bottom most edge and the symmetrical line of the lamination to be the X and Y axis.

To take just the LEB main quadrupole prototype lamination as an example :

The SSC inspection sets up the measuring system as indicated in the left side of figure 2; the ZVI inspection sets up the measuring system as on the right.

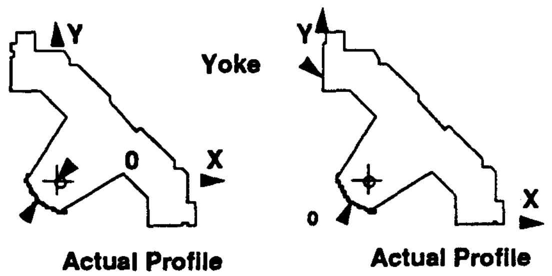


Figure 2. Setup Measurement System

The two inspections show different results. The laminations measured by the SSC system were out of tolerance on the pole tip and the laminations measured by the ZVI system were in tolerance. Of course, the right system is reasonable and reliable. This example shows us that since the magnet laminations have very tight tolerance requirements, an inappropriate measurement system may lead to a wrong conclusion.

The establishment of a lamination inspection system should be thoughtfully considered for each individual magnet .

B. The Inspection Programing

Apart from the trim dipole, the LEB magnet lamination poles are a broken line type of design. This kind of design raises a question of lamination inspection: there are two normal lines crossing at the intersecting point of 2 adjacent small straight lines; which one should the inspecting indicator trace? The best way is to write a program which smooths each two intersected broken lines on the pole into an arc and therefore the normal line of the tangent line of this arc will be the trace of the inspecting indicator.

VI. END PACK DESIGN

To save LEB machine space and avoid eddy currents, the LEB magnets all adopt the glued and laminated end plate type of design. As the LEB is a 10 Hz machine, it is assumed that the high frequency vibration will cause the delamination of the end plates. The glue is not reliable under radiation and for long life times. ZVI made an experiment on a special main dipole model for studying the delamination problem. This model has two different end plates. One is glued and another is not glued. The laminated, unglued end plate was shaking baddly and each lamination was dancing crazily under the 10 Hz power. Just a little tremble could be felt on the glued end plate. But the tear resistance of the glued end plate obviously is a negative factor over the machine life time with such strong split forces.

The INP people proposed a new design to improve the unity property of the LEB dipole magnet end plates. They put a frame of low carbon steel on the top of the laminated end plate and this frame will be welded with the bending plate, which will make it and the core a single element. The frame pushes a solid block of G10 type material toward the laminated end plate and this G10 block is fixed to the pole tip of the end plate by two insulated screws made of non-magnetic stainless steel.

For the main quadrupole end plate, there is a stud through the hole on the pole tip of the core to hold tight the laminated packs and end plate as an entire piece. But since the end plate is chamfered, the end plate will still tend to be split by the 10 Hz vibration. The delamination was observed when we were trimming the end plate chamfer of the main quatrupole prototype even before running AC measurements. The reason is that the glue did not permeate into the gap between laminations thoroughly, and the adhesion was partly destroyed during milling the chamfer. We are going to make some structural change to improve the main quatropole end plate rigidity to ensure it will work as a solid plate.The laminated end plate design was used by Fermi Lab for their DC machine. But there is no experience for use of this design on AC machines.We will continually study problems and find ways to solve them.