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# DESIGN CALCULATIONS AND MEASUREMENTS OF A DIPOLE MAGNET WITH PERMENDUR POLE PIECES*

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## ABSTRACT

A redesign of the SLC South Linac-to-Ring beam line required that the width of a good field of three of the bending magnets be increased while utilizing the same yoke and coils. Further requirements were that the resulting magnets should have the same strength at two different operating currents as the original magnets. The idea of replacing the steel poles with pole pieces of the high permeability material Permendur was investigated. Design calculations were done using TOSCA and POISSON. An existing prototype magnet was modified with Permendur poles, and magnetic measurements were done. The new magnets were completed, and measurements agreed well with the calculations.

## INTRODUCTION

The SLAC Collider South Linac-to-Ring beam line has been redesigned to incorporate an energy compressor.[1] An increase in magnet aperture width was required at several points in the beam transport line. One of the requirements was that the good field width of three identical bend magnets be essentially doubled. There were several important constraints. The magnets would be wired in series with other un-altered bend magnets and would have to achieve the same strength ($\int B_y\,dz$) as these magnets at two different energy settings. The original plan was to remove the magnets during a shut-down period and modify the poles. This meant that the new design would have to utilize the old yoke and coils. Previous computer studies on similiar magnets had shown that replacing the steel poles with Permendur would give an increase in good field because of the high saturation induction properties of that material. Because of the constraints mentioned above and a critical time path, we decided to use this material. So far as we know, previous magnet designs utilizing this material have been mainly for wiggler magnets and were relatively small in size. Our pole pieces were of the order of $2 \times 4 \times 12$ inches.

## PERMENDUR

Permendur, an alloy of steel and cobalt in equal proportions with about 2% vanadium, can normally be obtained in almost any shape; however, only 4 inch rolled stock was available within six months. This material was obtained and forged into blocks approximately $2.5 \times 4.5 \times 13$ inches. The forging was done at an estimated temperature of 1040° C, and the pieces were allowed to cool under ambient conditions. We followed an annealing procedure suggested by E. Hoyer of LBL.[2,3] Values of intrinsic induction (B-$\mu_o H$) of 2.26 Tesla were measured at LBL (see Fig. 1). The B-H curve deviates from the GE chart for Permendur, which is shown for reference. This may be due to heat treatment and/or chemical differences in the material. Our computations and measurements agree best when using the LBL table.

We were cautioned to do a second anneal before final finishing. This second anneal caused the material to expand laterally about 0.005 inches and to shrink about 0.020 inches in length. This may have been a stress relief process due to the forging.

## DESIGN CALCULATIONS

Configuration for the magnets are shown in Figs. 2 and 3. These are 9° bend magnets. Each pole end face is rotated ± 4.5° about the y axis so that the beam enters and exits at right angles to the pole face. The first computer studies were done with POISSON. Previous work had shown that good field widths predicted by POISSON were too high by a factor of two when compared to measurements of $\int B_y\,dz$ distribution for this type of magnet. TOSCA[4] runs and measurements show that two-dimensional calculations are only good at the center of the magnet. Even though the ratio of length-to-gap is about 15 for this magnet, it is highly saturated at the pole edges. The magnets were required to have a value of $\int B_y\,dz$ of 0.604 Tesla-meters at a current of 355 amps for operation at 1.153 GeV. A value of 0.634 Tesla-meters at 395 amps was required for operation at 1.21 GeV. The good field required was ± 28 mm in x for a decrease of $\int B_y\,dz$ of 0.25%. The good field for the original magnets was ± 15 mm. The magnets were made stronger by 0.9% to correct for measured losses to neighboring quadrupoles. Strength adjustments were done by varying the length of the magnets with thin shims located between the poles and the pole ends. A further adjustment can be made by trim windings. This allows operation at two energies.

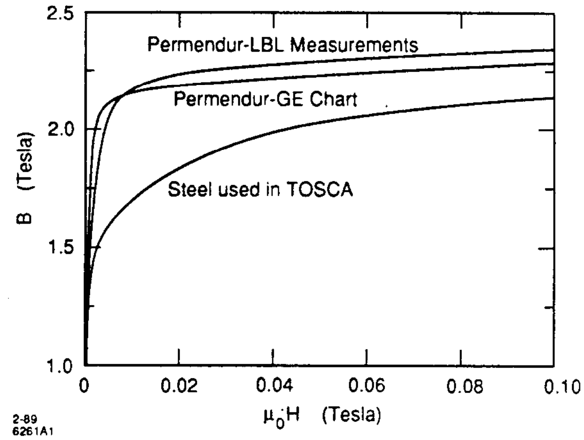


*Fig. 1. Graph of B vs. H.*

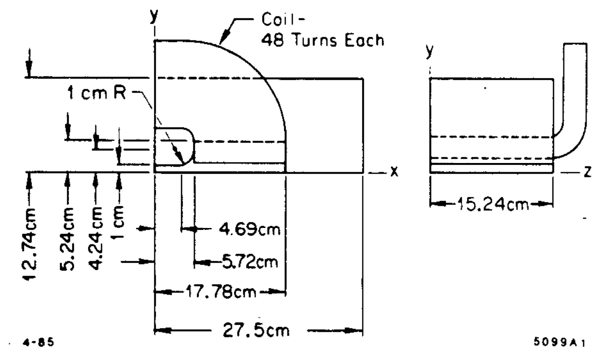


*Fig. 2. Configuration for the new SLC SLTR bend magnets.*

While simply replacing the steel poles with Permendur would increase the good field width, the resulting good field does not meet that required. A narrow pole with edge shimming was designed which did meet the requirements, but this design was overruled in favor of a flat pole for simplicity of construction. A flat pole must be made wide, and the loss in efficiency creates a

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problem with strength, since the current could not be increased. POISSON and TOSCA studies showed that strength could be increased about 2% by recessing the pole piece into the steel yoke by 2 cm. This was accomplished by sandwiching the base of the pole between two finely ground steel blocks. A square pole end incréased strength, but decreased the good field width. This was compensated by shaping the pole ends with a small notch, or swallow-tail. TOSCA was quite useful and accurate in studying such end effects.

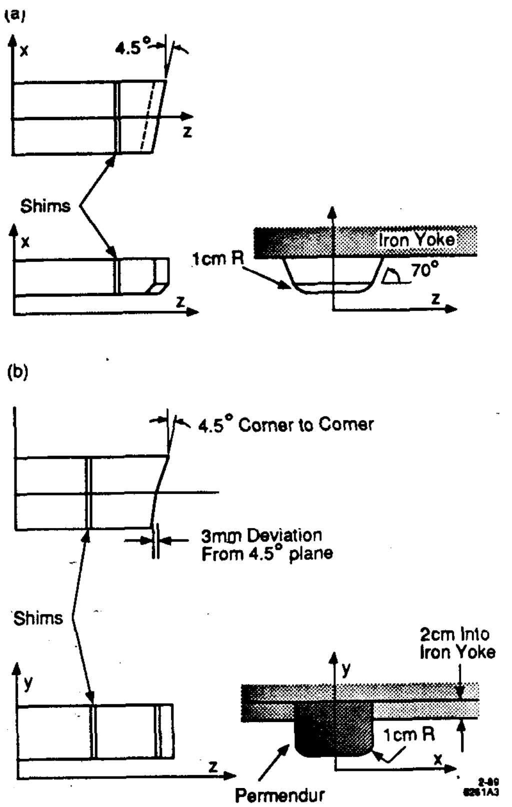


*Fig. 3. Pole configurations for the old and new SLC SLTR Bend Magnets.*

## MAGNETIC MEASUREMENTS

Two methods were used: (1) a moving Hall probe, and (2) an integrating long wire.

Moving probe measurements were made using a Hall probe digital gaussmeter with an IEEE488 interface to a microcomputer. The probe was set on a precision lead-screw cross-slide assembly so that the probe could be moved both along the longitudinal axis (z) and the transverse axis (x). Precision lead screwslides were driven by Slo-syn stepping motors controlled by two Camac Stepping Motor Controllers (SMC) interfaced to a microcomputer. The magnetic field strength (IEEE digital gaussmeter) and the excitation current(IEEE digital volt-meter) were read each time the probe stopped moving in the z direction. The measurement accuracy was approximately 0.01% for the gaussmeter readings, and the excitation current varied less than 0.001% during each longtitudinal survey. The precision lead screws were accurate to within 5 microns. This method gave an accurate shape of the B-field in both x and z directions. Some results of these measurements are shown in Figs. 4 and 5.

Integrating long wire measurements were made using a 10-turn long wire (coil) that was stretched through the magnet. The wire was moved in the transverse direction (x) by two high precision stepping motor slides. The distance moved was read as well as the coil output in volt-seconds (digital voltmeter) and recorded by a microcomputer. The accuracy of this method was approximately 0.03%. This method was used for measuring the absolute strength ($\int B_y\, dz$) at different transverse (x) locations.

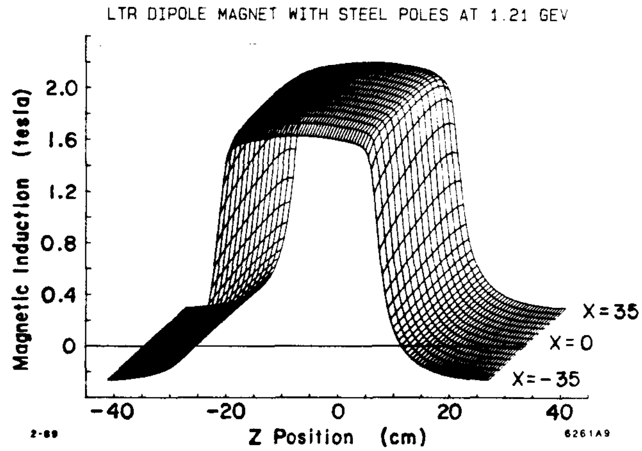


*Fig. 4. $B_y$ vs. z and x for the original steel pole.*

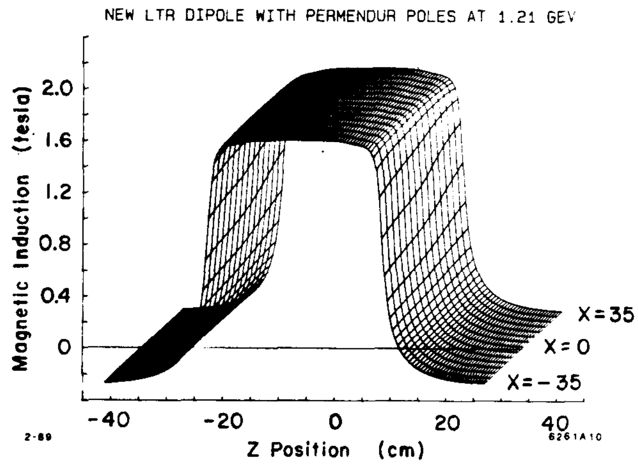


*Fig. 5. $B_y$ vs. z and x for the new permendur pole.*

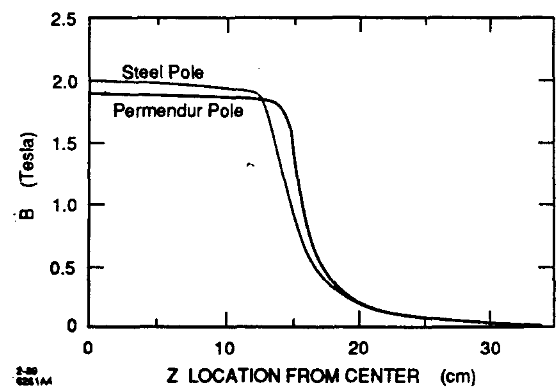


*Fig. 6. $B_y$ vs. z for the original steel pole magnet and for the new permendur pole magnet.*

## RESULTS

The final magnets were within 0.1% of their required strength at 1.21 GeV and had good field regions of ± 32 mm in x at 1.153 GeV and ± 30 mm at 1.21 GeV. The good field was defined as the value of x where $\int B_y\, dz$ is down 0.25%. The field distributions along the z axis for both the new and old designs are given in Fig. 6. Note that the Permendur pole runs at a lower value of $B_y$ at the center of the magnet, but has a sharper edge. Hall probe measurements indicate that the corners of the

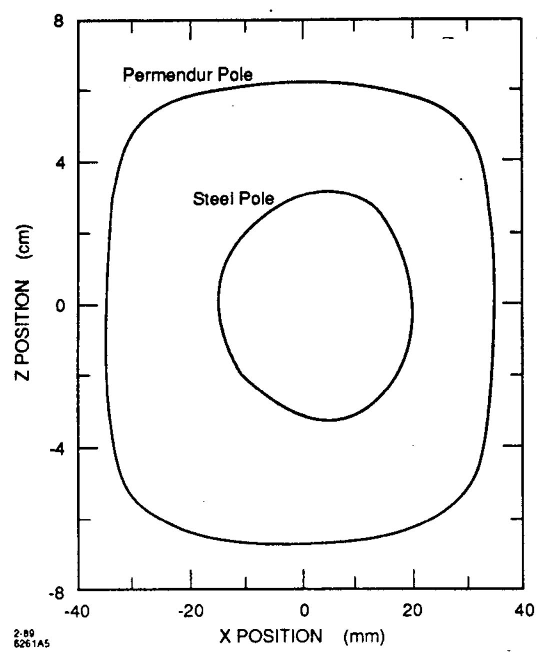


*Fig. 7. Contours of $B_y/B_o$ of 99.75% for the steel pole and the permendur pole magnets.*

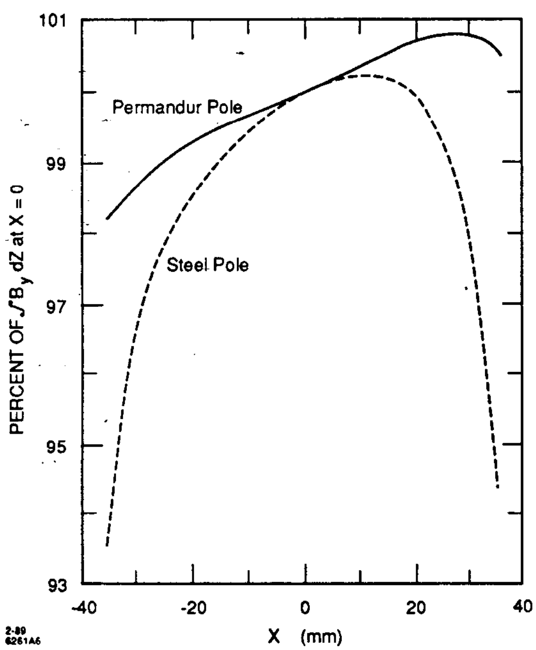


*Fig. 8.* $\int B_y\, dz$ *vs.* $x$ *at 1.21* GeV.

Permendur pole are running at fields above 2.3 Tesla. A comparison of good field contours is given in Fig. 7. The distortion in x is due to the 4.5° pole rotations. Figure 8 shows the $\int B_y$ dz distributions accross the magnet. The slopes are due to the pole-end rotations, and the slight dip in the distribution for the new magnet is due to the swallow-tail correction. TOSCA runs showed that higher order corrections are possible, but they introduce unnecessary machining difficulties. In Fig. 9, we show the $\int B_y$ dz distribution when the linear term is subtracted from a fit to measurments. The excitation curves shown in Fig. 10 show that the Permendur magnet is more efficient at low currents because of the higher permeability, while less efficient at high currents because of the wide, flat pole design. The differences are made up by trim windings.

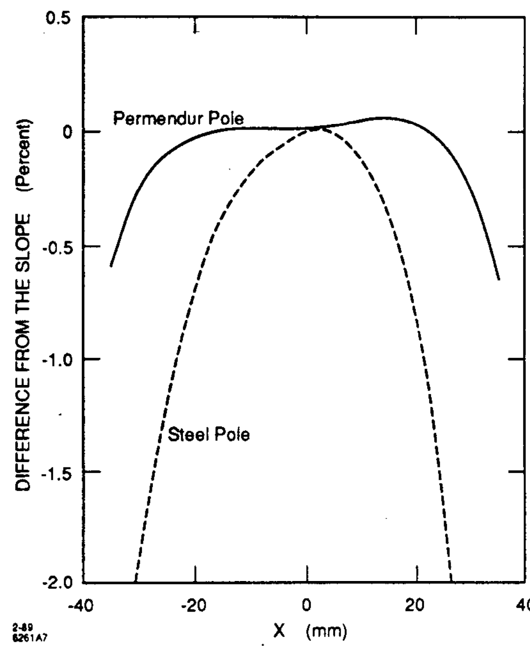


*Fig. 9.* $\int B_y\, dz$ *vs.* $x$ *with linear term subtracted.*

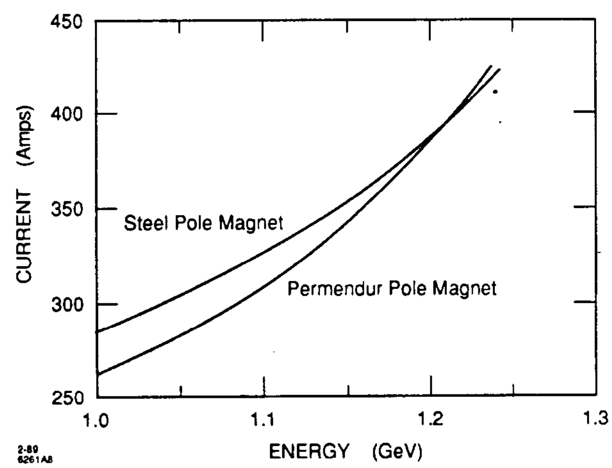


*Fig. 10. Current vs. energy setting for the steel pole and for the permendur pole magnets.*

## ACKNOWLEDGMENTS

TOSCA was run on the NMFECC Cray 2 where version 4.0 has been installed by John Stewart of LLNL. He has also written a non-interactive pre-processor. C. Perkins and B. Sukiennicki did the engineering for the prototype and for the final magnet design. We are grateful to E. Hoyer of LBL, and H. Shieh of BNL for information on Permendur.

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4. J. Simkin and C. W. Trowbridge, *Three-Dimensional Nonlinear Electromagnetic Field Calculations, Using Scalar Potentials,* IEEE Proceedings, vol. 27, Pt. B, No. 6, November 1980.