# HIGH AND ULTRA-HIGH GRADIENT QUADRUPOLE MAGNETS *

W.O. Brunk and D.R. Walz

*Stanford Linear Accelerator Center*
*Stanford University,, Stanford, California, 94305*

## Abstract

Small bore conventional dc quadrupoles with apertures from 1 to 2.578cm were designed and prototypes built and measured. New fabrication techniques including the use of wire electric discharge milling (EDM) to economically generate the pole tip contours and aperture tolerances are described. Magnetic measurement data from a prototype of a 1cm aperture quadrupole with possible use in future $e^+/e^-$ super colliders are presented. At a current of 400A, the lens achieved a gradient of 2.475 T/cm, and had an efficiency of 76.6%.

## 1. Introduction

Successful operation of the Stanford Linear Collider (SLC) is based on acceleration of intense single rf-bunches of positrons and electrons up to energies of ~50 GeV, followed by transport over a distance of ~1.4 km through two independent magnetic arc systems to an interaction point. There, these bunches must be brought to collision with spot sizes $2\sigma \leq 3\mu$m. This requires quadrupole lenses having gradient-length products $\int G d\ell \sim 10$T along the last half of the linear accelerator, and $\leq\sim 110$T in the special matching sections of the arcs and the final focus. Moreover, beam optical and cost considerations demand series operation of groups of as many as eight quadrupoles from one power supply with precise tracking (1 part in $10^3$) over an energy interval of $25 < E_o < 55$ GeV. Space limitations require short quadrupoles and high field gradients to achieve the necessary strength. Conventional iron-core dc quadrupoles can meet these criteria only for small apertures. Those quadrupoles which are located in the linac are limited to an aperture of $\geq 2.578$ cm. The combined function arc magnets have an aperture of 1.27 cm. Beam spot sizes of several tens to hundreds of microns in the arcs and final focus matching sections allow the use of quadrupoles which also have apertures of 1.27 cm.

## 2. Accelerator Quadrupoles

The existing disc-loaded waveguide structures in the SLAC linac limited the quadrupoles to an iron length of ~10.5cm. Thus, the required gradient had to be ~1T/cm to achieve the necessary $\int G d\ell = 10$T. Extensive studies using the two-dimensional computer code "POISSON" indicated that, with judicious juggling of the pole tip shape and coil slot depth and width, a quadrupole achieving a gradient of 1T/cm in a 2.578 cm aperture was feasible. A prototype of such a magnet was built and measured. The results confirmed the computer predictions, lending encouragement to try for higher gradients from smaller apertures.

This magnet was fabricated as a four-part, split quadrupole with multi-turn coils. Precision stamped laminations of 16-gauge, C1005 steel were used to stack the core, requiring no further machining of the pole tip contour. A total of ~200 such quadrupoles are being constructed for installation in the linac.

* Work supported by the Department of Energy, contract DE – AC03 – 76SF00515.

## 3. Linac-to-Arcs Matching Section Quadrupoles

Eight quadrupoles having an aperture of 2.065 cm were designed and built for installation in the linac-to-arcs matching sections. The strongest required $\int G d\ell \sim 50$T. The cores were made of 0.0235 cm thick C1005 steel laminations, which were stacked into quadrants, welded and annealed. Then all four quadrants of one magnet were mounted on a planer with a hydraulic contour attachment to follow a template for machining of back leg contact surfaces and pole contours with a single point cutting tool. First measurements after assembly showed bore variations of as much as 0.018 cm between magnets. Corrective machining reduced these variations to ~0.005 cm, about twice the desired tolerance of 1 part in $10^3$. Magnetic measurements of strength and harmonic analysis followed. Two groups of four magnets of three different lengths were found to track over the required range of currents to within 0.3%. After beam transport studies verified that such a variation in strength in these lenses had no effect on the beam spot size, and thus expected luminosity at the interaction point, the magnets were installed to be powered by one power supply per group. The harmonic contents of all magnets were well within desired limits.

## 4. Arcs and Final Focus Matching Section Quadrupoles

Experience up to this point gave encouragement for development of lenses with much smaller apertures capable of generating much higher field gradients and strength. The desire to develop such high-gradient lenses was driven by the need to economically achieve large beta values in a limited space.

In these matching sections, a system of optically related quadrupoles and their power supply is required to be set to within 0.1% of the correct value and to track and operate within this ±0.1% band. If this variation is divided evenly between the power supply and the magnets in the series string, it means that each magnet must have the same gradient over a range of currents within 1 part in 2,000, or 0.05%. For identical steel characteristics, and no gaps other than the aperture, all 1.27 cm aperture quadrupoles connected in a series string must then have the same apertures to within 1.27/2,000, or 6.4 x $10^{-4}$ cm. This variation is almost an order of magnitude less than standard run-of-the-mill, single-point machine tools can produce. Broaching should theoretically produce apertures of required shape and tolerance. This idea was not pursued beyond the inquiry stage because of expensive tooling and an expected lengthy R & D program.

For one optics solution, the longest lenses have a core length of ~1.2m. Two prototypes of such magnets were built to compare. One was a conventional four-piece quadrupole with water-cooled, eight-turn coils. The core structure was made from 16-gauge C1005 laminations stacked and welded into quadrants, then finish-machined on a planer and bolted together to result in a 1.27 cm aperture quadrupole structure.

0018-9499/85/1000-3651$01.00© 1985 IEEE

The second prototype resulted from an idea advanced by G. Fischer, namely to produce a quadrupole from one-piece, cruciform-type laminations held together with four symmetrically placed through-bolts or tie-rods. The same 16-gauge C1005 material was used, and the stack clamped to a rigid box structure to assure straightness and freedom from twist. Single-turn, water-cooled copper coils were fabricated, inserted in hairpin fashion and brazed into a low-impedance, four-coil quadrupole circuit. The idea was to run the quadrupoles in series with all the combined-function arc magnets, but at a less convenient current of ~2,000A.

Both prototypes were magnetically analyzed. They had approximately equal and acceptable non-quadrupole harmonic content of 1 to 2 x $10^{-3}$. The $\int G d\ell$ vs. I for both magnets is shown in Fig. 1. It is according to prediction. While both magnets lived up to expectations as single units, it was not clear that the four-piece quadrupole could reliably be produced in large numbers for series-string operation. The single-piece quadrupole can probably meet this requirement, but proved to be relatively expensive to fabricate, in addition to being burdened by the high-current, low-impedance characteristics.

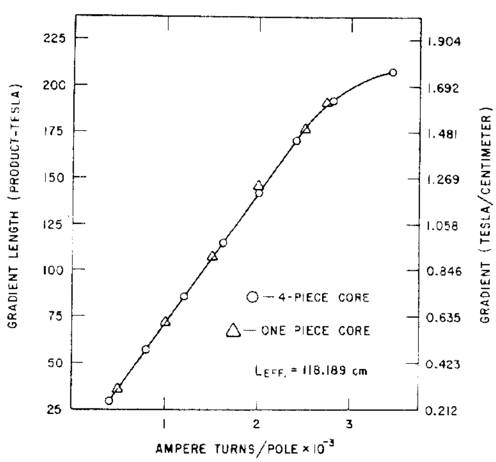


Fig. 1 - - $\int G d\ell$ vs. I As Measured

In addition to lenses with $\int G d\ell$ ~110T, there are many others required in the interval $15 \leq \int G d\ell \leq 50$T. For a core length of 12 to 15 cm, wire electric discharge milling (EDM) can economically produce pole tip contours at least as accurate as the one-piece laminations produced form one die, and perhaps a factor of two better. The next step was to expand this concept to longer lenses made up of several 12 to 15 cm long modules, and incorporating standard multi-turn coils.

Several laminated (16–gauge) four-piece core modules were constructed. They were welded, annealed, back leg surfaces ground, and then all four quadrants bolted and dowelled together to grind the end faces flat and parallel. Then the pole contours were machined by wire EDM to a tolerance of $\pm 5\mu m$. After considerable difficulties during the conventional machining process, one useable 15 cm core was finished. Coils were installed, and the magnet analyzed (see Fig. 2).

After assessing the difficulties experienced during non-EDM machining and analyzing cost implications, it was decided to abandon the luxury of using laminations in order to

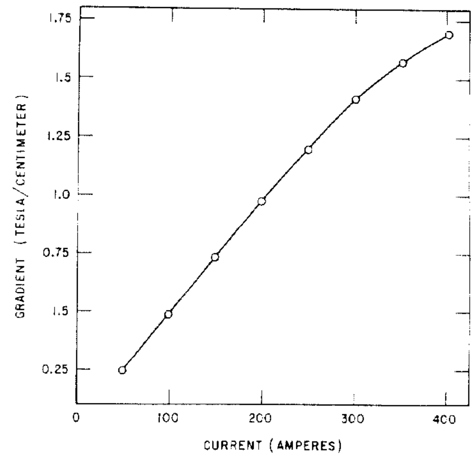


Fig. 2 - - Gradient vs. Current of Four-Piece, 1.27cm Aperture Laminated Quadrupole Module

be able to shuffle and average out steel magnetic variations. Since the quantity of steel required for any given group of magnets is small, the core blocks can be cut from one plate of steel with the expectation that, over such a small volume, variations in magnetic characteristics will be minimized. With this plan, core blocks can be machined and ground to the same size withing ~$25\mu m$ and, after assembly into a core module, pole tip contours of all four blocks cut by wire EDM in one set-up. This approach minimizes machining costs, because only small amounts of steel are removed from square shapes on standard milling machines and grinders. The only critical operation is the generation of the aperture and pole contour by numerically-controlled wire EDM. Once programmed correctly, this operation will produce a part-to-part tolerance of ~ $\pm 2.5\mu m$.

Multiple-module assemblies are made by inserting a precision ground plug of same diameter as the aperture into adjacent modules, which are, after proper alignment, clamped end-to-end and welded together. After an appropriate number of modules are joined in this manner, the core can be unbolted for insertion of coils, and then reassembled to original machine precision. The adopted SLC optical configuration requires approximately 50 lenses having an aperture of 1.27 cm made up of from one to five modules each. Typically, four to eight of these magnets, not necessary all having the same length, are connected in a series to one power supply.

Magnetic measurement of these small aperture quadrupoles poses some unique problems. For apertures less than ~1.9 cm, a rotating coil is not rigid enough to be centered precisely on the aperture. Instead, a taut wire coil is translated across the aperture in steps by computer control. The $\int G d\ell$ is then calculated from the output voltage. The present apparatus allows translation only along one of the coordinate axes. Thus, a calculation of harmonic content of the field is difficult if the desired accuracy of one part in $10^3$ is to be met. The computer code "POISSON" calculates harmonic content, but only allowed harmonics are computed, *i.e.* 12 pole, 20 pole, 28 pole, etc. Moreover, for small apertures, it is difficult to obtain enough mesh points over which a smooth interpolation between mesh points may be made. The 12–pole calculation usually agrees with rotating coil measurements within a few percent, but all higher harmonics values are more a function of the granularity of the mesh than the actual harmonic content of the field.

The SLAC Magnetic Measurements group is currently developing a rotating coil form made of silicon carbide, which should be stiff enough to measure the longest (~3/4m) of the 1.27 cm aperture quadrupoles.

## 5. Quadrupole Design Considerations

The experience with the quadrupoles described above, as well as the insight gained from numerous computer studies, leads to several generalizations about high gradients in conventional quadrupole structures. It has been found that saturation in the pole base limits the pole tip field to 1 to 1.1T, where the pole base is defined as the area where the pole flanks join the coil pockets. Any increase in ampere-turns per pole above this level merely increases the volume of pole base iron, which is at flux densities of 2.1 to 2.2T, while the pole tip flux increases very little. In the rotated coordinate system of the poles, the equilateral hyperbola is given by $xy = a^2/2$. It was found that the optimal $x_{max} \sim 1.6a$, where a is the aperture radius. Extending the hyperbola out further decreases the 12-pole content of the field, but also increases the pole base saturation. Conversely, reducing the extent of the hyperbola decreases the pole base saturation, while it simultaneously rapidly increases the 12-pole content of the field. Theoretically, the coil should be located as close to the aperture as geometry and current density will permit. However, moving the coil in increases the pole flank angle, shortens the pole somewhat, and decreases the pole base area. The net effect of all these variables is that coil location has little effect on magnetic efficiency, defined here as the ratio of ampere-turns required to drive the aperture flux to the total ampere-turns required to generate this aperture flux in an iron magnet. Coil current densities also have an effect on magnet efficiency, but economic considerations (power costs) show that current densities in excess of ~900A/cm$^2$ are not cost-effective. The relationship of quadrupole gradient versus aperture for magnetic efficiencies $\geq$ 80% is shown in Fig. 3. Computer simulations show that if the pole is made of a cobalt-iron alloy, which saturates at ~2.4T, the pole tip field can be pushed to perhaps 1.25 to 1.3T. But this material is expensive, not readily available, and hard to machine.[1]

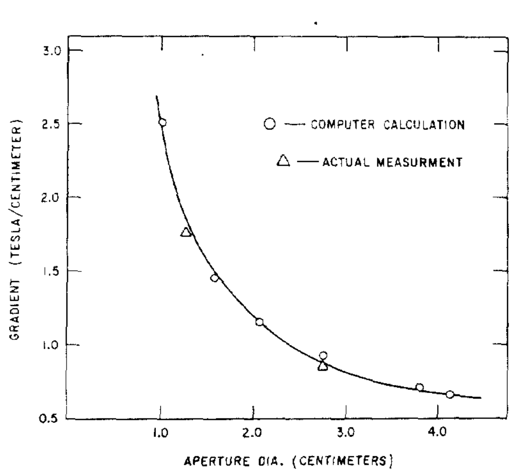


Fig. 3 - - Gradient vs. Quadrupole Aperture

## 6. A Future 1cm Quadrupole

Future $e^-/e^-$ super colliders are expected to have beams with even smaller transverse dimensions than the SLC and some requirements could, perhaps, be satisfied with 1 cm aperture lenses. A prototype of such a lens was designed and built. Computer studies showed that gradients up to 2.5T/cm could be achieved. The pole tip field is 1.25T, the magnetic efficiency, ~81.3%, and the current density in the 8-turn per pole copper coil is 1153A/cm$^2$. A computer-generated flux plot is shown in Fig. 4. The core length of the prototype is 15.24 cm, the effective magnetic length ~15.74 cm, and the aperture 0.998 cm. The lens was powered to 400A, and achieved a gradient of 2.475 T/cm. At this excitation, the efficiency was 76.6%. Harmonic analysis was still in progress at press time.

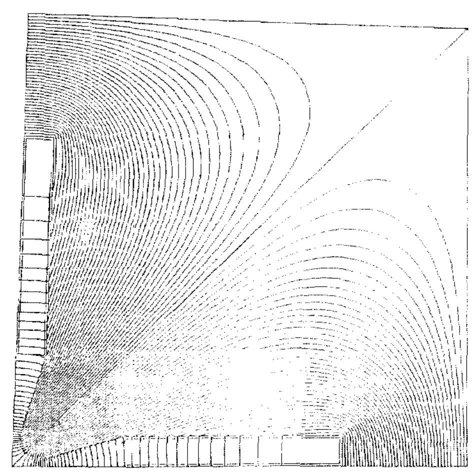

Fig. 4 - - Computer-Generated Flux Plot of 1 cm Quadrupole at 2.5 T/cm


## Acknowledgements

The authors would like to thank R. Early, G. Fischer, D. Leith, J. Murray, J. Seeman and R. Stiening for their helpful suggestions and interest in this project. A debt of gratitude is also owed to J. Cobb and D. Jensen of the SLAC Magnetic Measurements Group, to M. Studzinski, who did the art work, and to K. Fraser, who prepared this manuscript.


## References


[1] W. Brunk, "QD Type Quadrupoles for Higher Gradients", Collider Note No. CN-73, Stanford Linear Accelerator Center, June 3, 1981.