TWO ALTERNATE HIGH GRADIENT QUADRUPOLES; AN UPGRADED TEVATRON IR AND A "PIPE" DESIGN , *

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The present Fermilab IR quadrupole lenses achieve a 50% increase in gradient over their predecessors. This was accomplished by the following developments: a) a more dense winding (Kapton insulation only, eliminating the fiberglass-epoxy), b) an improvement in critical current density to J_c(5T, 4.2K) = 3 kA/mm^2 and c) a higher aspect ratio cable >11/1 and d) finer strand (0.53 mm diameter). The natural evolution of this design to the CERN 70 mm aperture quadrupole results in the following : a) a reduction in operational temperature (4.8K - 1.9K), b) improvement of J_c(10T, 2.0K) > 2 kA/mm^2 and c) a higher aspect ratio cable > 13/1 and d) finer strand (0.48 mm diameter). These two-layer designs should achieve the required operational gradient of 250 T/m with at least a 5% margin on the short-sample load-line intersection. These high current densities also require turn-off times < 0.2 s after transition to the normal state. Such a short time requires an advanced protection heater design. The status of the design and the experimental development will be reported. New design concept quadrupole calculations are presented as well. This concept, using an active flux return is being proposed as a possible candidate design for a future higher gradient requirement.

I. INTRODUCTION

With the U.S. cancellation of the SSC project, the only large approved hadron accelerator project is CERN's LHC [1]. One of the more critical elements in the performance of a collider is the quadrupole lens at the beam collision points. These quadrupoles, usually referred to as the "insertion quads" normally form a set of triplets around the interaction region. Their focal power directly affects the luminosity available at the crossing point. In order to achieve as high a gradient as possible, the CERN design team has proposed a very efficient high gradient quadrupole which is based on a graded four-layer winding structure [2]. At Fermilab's Tevatron, an upgraded two layer winding quadrupole has been in operation since 1989, and has provided a 50% higher gradient than it's predecessor. The quadrupole was basically state of the art when it was designed in 1985 [3]. Since then however, improvements have been made in cabling, conductor performance, etc. Naturally, operation of a modernized version of this design can provide higher capabilities. This improved two layer design can serve as an alternative to the more intricate graded four layer design now envisioned for the LHC, provided it can obtain the proposed gradient. An outline for the development program required for the implementation of this option is as follows :

I Raise the coil current density by
- A. Improved conductor performance at high field by
  1. Lowering the temperature to superfluid helium at 1.8 K
  2. New higher j_c ternary material (NbTiTa)
  3. Concentrating artificial pinning center work on high field jc's.
- B. Better coil quench protection, thus lowering the copper volume required by
  1. Increasing the quench detection sensitivity
  2. Improving the protection heater design to produce a shorter current decay time (more distributed quench)
- C. Implement a "wind and react Nb_3Sn" technology into the quadrupole program [4].

II Increase the cable aspect ratio (more turns closer to the aperture) to increase magnetic efficiency
- A. Coupling problems need to be addressed
  1. Higher and more consistent strand/strand resistances
  2. Reduction of the filament size (<6 μm) and a better inherent magnetization value.

II. THE ALTERNATE DESIGN PARAMETERS

The proposed conductor parameters are given in Table 1. These parameters have been achieved, however, in some cases it was only on a few laboratory samples. No improvement is necessary however to achieve the operational field plus a five percent margin point for the conductor current density.

Table 1 Conductor parameters

Alloy	NbTiTa
Strand diameter (mm/inch)	$0.4775\ /\ 0.0188^{+0.0000}_{-0.0002}$
Strand twist pitch (twists/cm)	1 (left)
Number of strands	44
Copper to superconductor ratio	1.5/1
Number of filaments, spacing	2450, <0.2 μm
j_c at 1.8 K, 10 T (A/mm^2)	2390(~1850 ternary[5])
Cable twist length	89.27 mm (right)
Cable dimensions and keystone angle	0.792x10.744 mm 0.940 degrees

Even though the minimum conductor performance numbers have been achieved, the higher design goal values would allow the limitations to be removed.

* This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, High Energy Physics Division, U.S. Department of Energy, under contract No. DE-AC03-76SF00098.

The margins are increased in other critical areas if they are obtained. The higher aspect ratio cable will certainly require strand to strand cross-over resistances which are higher and well controlled to minimize ramp rate effects of quenches, harmonics, their variations in magnitude as well as their change with respect to time. The present Tevatron quadrupole has up to a 20% linear degradation of achievable peak gradient with ramp rates up to 200 A/s [6]. This sensitivity can and should be substantially reduced. The parameters of the cold mass including the winding and iron shield are given in Table 2. The two layer quadrupoles that had been previously constructed for the Tevatron have a history of training. They have on the average required approximately 10 quenches to reach the estimated short sample (or slightly above) critical current [6].

Table 2 Winding and cold mass parameters

	Inner layer	Outer layer
Number of turns per pole	22, 1 wedge	32, 1 wedge
Inner dia. w/o insulation	70.00 mm	92.14 mm
Outer dia. w/o insulation	91.64 mm	113.78 mm
Cable length / mass	231 ft/pole	336 ft/pole
Heater composite Kapton / Cu or w/o Cu steel	12.5 μm s.s. with 8 μm	total 17 μm ground insul.
Coil inductance /unit l.	8.74 mH/m	
Calculated field harmonics $(1/(cm)^{N-1})x10^4$	b(6) = b(10)= b(14)=	0.31 0.0057 0.00005
Transfer function	41.37 T/mkA	
Iron shield diameters	13.6 cm (ID)	30.5 cm (OD)

This problem, though not fatal, should be addressed. The superfluid tests of those quads were not completed to the (estimated) short sample current due to marginal protection heaters.

When measured, the series of thirty plus low-beta Fermilab quads were found to have a few units of harmonics due to construction variations and distortions. The largest was found to be the out of phase sextupole term. The updated version of the two layer coil has the following features which should alleviate or at least reduce the problems previously found in the older series as well as simplifying construction when compared to a four layer graded structure. The outer winding is actually radial. This enables an easier and more symmetric loading of the inner winding. The pole angle is exactly the same for the inner and outer windings. This again facilitates the uniform loading.

A 60 mm quadrupole load line intersects the short sample surface at 310 T/m , whereas a 70 mm aperture would intersect at 265 T/m. This illustrates the effect of the aperture on the maximum gradient, the comparison was made between 60 mm and 70 mm bore size two layer windings. If the two layer structure turns out to be accurate enough and the beam is collimated well enough, then a reduction in aperture to 60 mm would increase the gradient margin significantly. The single wedge will allow the ends to be integrally corrected for one harmonic.

There are some rather general comments that can be made about coil protection and examples given to illustrate these points. The current decay time constant after a quench for the existing Tevatron quadrupoles is required to be less than 500 ms at 4.8 K, where the old double strip heaters work well. The required time constant reduces to 250 ms at 1.8 K, and the strip heaters are then marginal. The time constant for the LHC four layer quad must also be less than 250 ms, as well as for the alternate two layer design. The two layer design has an inductance on the order of 8.7 mH/m, the four layer has about 24 mH/m, therefore both must have a very effective state of the art quench protection heater and detection system, the more critical obviously being the four layer structure. There have been photo-etched stainless steel heaters that are partially copper plated, sandwiched between Kapton films, which are capable of producing the down ramps needed. The advantages of the high aspect radio cables and finer strands are shown in Figure 1. These cables result in approximately the same maximum winding temperature versus current decay time after quench for a given initial current.

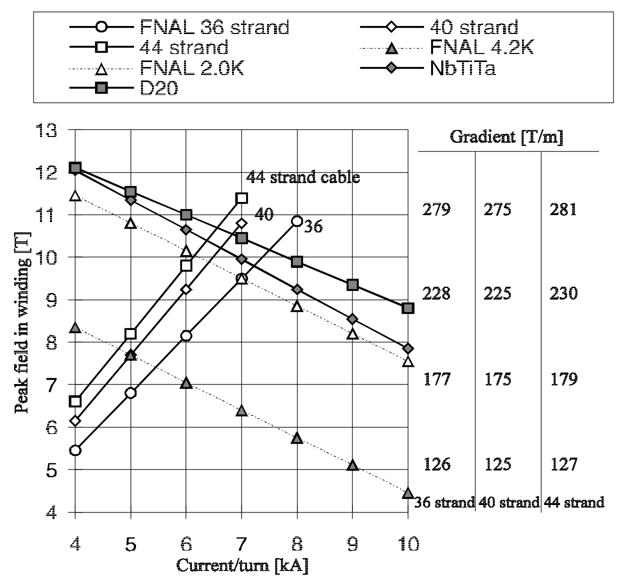

Figure 1 Alternate two layer design LHC IR quadrupoles

III. AN ALTERNATE ACTIVE FLUX RETURN "PIPE-QUADRUPOLE"

Another important issue in the design of an IR quadrupole is the large radiation load in the magnet. This radiation might cause a significant temperature rise in the winding package when it is not adequately cooled. This problem will become especially important for possible future higher luminosity accelerators. A Nb_3Sn quadrupole design that significantly reduces the radiation heating problem at the expense of more superconductor is presented here. The design is an extrapolation of a so-called pipe-dipole [7] to a quadrupole geometry. The magnet is essentially built with four intersecting elongated toroids, of which the inner coils provide the high gradient and harmonics optimization, and the outer coils an active flux shield. The whole structure is wound on a stainless steel “pipe”, and contained in a relatively small iron yoke. The design concept is illustrated in Figure 2. The figure shows a cross-section of one quadrant of the magnet, in which the inner coil at the bottom returns to the right outer coil, and the top outer coil to the left inner coil. The diameter of the entire structure is about 40 cm.

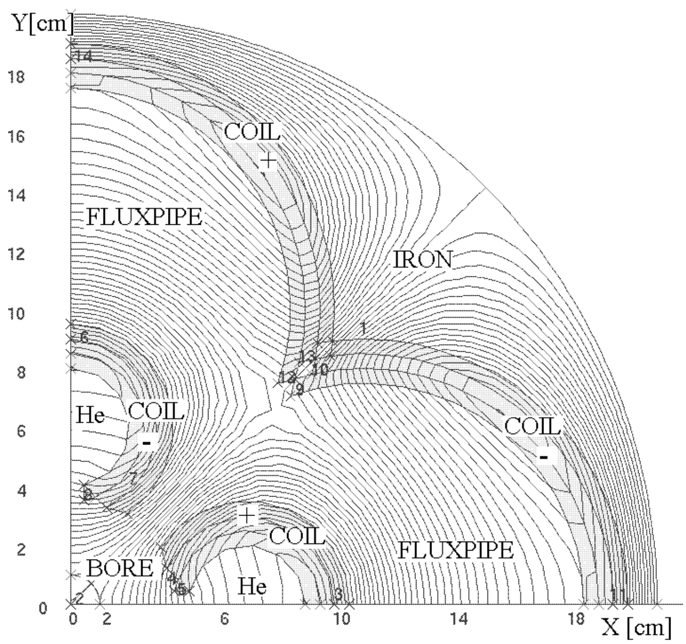

Figure 2 A conceptual Nb_3Sn "pipe-quadrupole"

The major benefit of this coil arrangement is the absence of conductor volume in the horizontal axis close to the beam-pipe, where the radiation load is the highest. The free volume within those coils can be used to cool the coils from the inside with a liquid helium cooling pipe. Due to the fact that the conductor windings are positioned further away from the bore, more conductor is needed than in a conventional quadrupole design.

The current design uses no internal iron within the “flux-pipe” to minimize the non-linearity of the field harmonics. The multipoles are minimized by shaping the area of the coil closest to the beam-pipe, and by grading the coils in three layers with two different conductors. It is possible to change the material in the flux-pipe to iron and shape it to minimize the unwanted field harmonics, however, the multipoles would become non-linear with current.

The gradient of the design can range between 280 T/m up to 350 T/m depending on the material used, and whether aggressive current grading is used. The maximum gradient of 350 T/m is obtained with a Teledyne Wah Chang Albany (TWCA) Modified Jelly Roll material at the short sample limit, however, this conductor has a fairly large effective filament diameter in the order of 50 μm after reaction. By using a more conservative conductor, i.e. not optimized for high current density, one can obtain a field gradient of about 280 T/m. This gradient is comparable to the maximum gradient for the LHC design, with the added benefit of a smaller quadrupole magnet and less sensitivity to radiation heating of the windings. With a total cross-section (including the iron yoke) of about half the size of a conventional quadrupole magnet, such a design has the advantages previously mentioned over the cosine-θ geometry.

The construction of a winding like this might look difficult at a first glance, but is actually quite simple. The conductor, which can be a standard Rutherford type cable, or even a tape, would be wound onto the flux-pipe material in segments, just like a toroid winding. The flux-pipe itself can be made out of a large stainless steel or iron rod by machining out the liquid helium conduits and slots for the inner coil. This automatically assures accurate placement of the conductors, which minimizes field harmonic errors due to imprecise winding. After winding the coil would be reacted, and then clamped in the iron outer yoke. The entire structure would then be held together by either an outer cylinder or a wire-wrap technique similar to the “D20” magnet [4].

In summary, a high gradient quadrupole with a “pipe” layout can be considered as a possible candidate for future large collider insertion regions. It is possible to fine-tune the design to obtain a good field-quality, the conductor is well cooled in case of a large radiation heat load, and the overall structure is smaller than a conventional quadrupole with a comparable field gradient.

IV. REFERENCES

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