A New Concept in Bitter Disk Design

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***Abstract*- A new concept in cooling hole design in Bitter disks that allows for much higher power densities and results in considerably lower hoop stresses has been developed and successfully tested at the National High Magnetic Field Laboratory (NHMFL) in Tallahassee, FL. The new cooling hole shape allows for extreme power densities (up to 12 W/mm^3) at a moderate heat flux of only 5 W/mm^2. The new concept also reduces the hoop stress by about 30-50% by making a Bitter disk compliant in the radial direction through staggering small width and closely spaced elongated cooling holes. Finally, the design is optimized for equal temperature.**

I. INTRODUCTION

High magnetic fields are a very important tool for condensed matter physics and chemistry, biology, and material science research [1],[2]. Superconducting magnets can provide high magnetic fields up to about 22 T due to the limitation on critical current at these fields [3]. Resistive magnets are still the only way for generating high DC magnetic fields.

The most widely used configuration of a resistive magnet is the Bitter magnet. It was invented by Francis Bitter at the Massachusetts Institute of Technology (MIT) in Cambridge, MA, in 1936 [4]. A Bitter coil is constructed of perforated copper disks and insulators that are stacked to form a thick monolayer winding. High pressure cooling water is pumped axially through circular cooling holes that are aligned carefully to ensure sufficient and uniform heat removal. The copper disks have a current distribution that is inversely proportional to the radius. This configuration uses power more efficiently than uniform current density magnets and is much easier to cool. There are a few drawbacks, however, 1) the current density distribution, being maximum at the inner radius, results in a very high power density and stress at that location; 2) stresses are increased at the inner radius of thick coils due to the fact that the outer part would like to strain more than the inner part; 3) circular cooling holes result in stress concentrations; and 4) the radial slits in the disks weaken the structure.

In the early 1960's, B. D. Montgomery at MIT developed the radially cooled Bitter magnet to improve the cooling at the inner radius. Drawbacks are that the hydraulic path becomes rather complicated for designs with many coils and that the high stress at the inner radius still limits the performance. In 1986, the radially cooled continuous helix (monohelix) was introduced by Robert Weggel at the FBNML [5]. A high strength hollow cylinder billet was machined into a helix. It is obvious that the manufacturing process is expensive and that this approach still does not solve the principal problem of thick coils: the hoop stress increase at the inner radius due to the radial stress generated by the differential straining over the radius. Weggel worked also on several cooling hole designs as shown in Fig. 1. He introduced the concept of elongated cooling holes for the axially cooled Bitter coils to increase the cooling efficiency through larger cooling surface [6].

Y. Nakagawa used the elongated hole configuration for the design of the insert of his 20 T hybrid magnet, Fig. 2 [7].

Early in the 1980's, a completely different approach, ("polyhelix magnet"), was developed by one of the authors of this paper (H.-J. S.-M.) at the Max-Planck-Institut für Festkörperforschung and Centre National de la Recherche Scientifique (MPI-CNRS) in Grenoble, France [8]. The polyhelix configuration is constructed from many concentric single layer coils (helices). Helices can be made two ways: 1) wound from a rectangular cross-section copper wire; 2) machined from a solid thin cylinder similar to the monohelix concept. This type of construction overcomes the high stress issue and, in addition, allows the designer to optimize the dimensions, current density, and material of each helix. The constraint on the ability to get even higher fields from the expensive polyhelix configuration is the limited cooling surface per copper volume.

As the performance of high field magnets is limited by the ultimate stress and power density levels that can be safely supported, we decided to develop a new concept that combines the advantages of the different technologies. In this article, we show that elongated cooling holes can significantly reduce stresses if their locations and shapes are optimized to form a staggered distribution compared to an aligned distribution. We demonstrate that this new pattern also allows for drastically increased cooling performance.

II. COOLING HOLE CONFIGURATION

A. The Concept of Staggered Cooling Holes

The elongated holes adopted by Weggel and Nakagawa are radially aligned as shown in Fig.1 and Fig.2. For comparison, we will refer to this type of arrangement as an aligned cooling hole distribution. For this type of cooling

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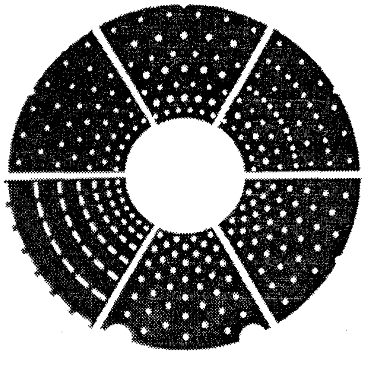

Fig. 1 Successive stages in cooling hole developments [6].

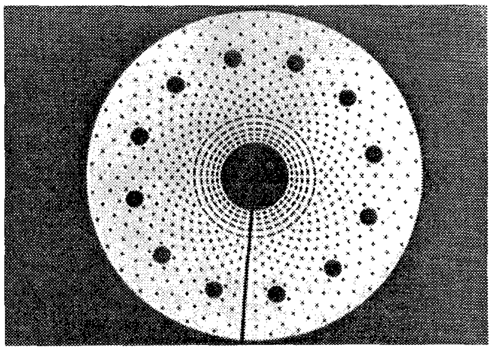

Fig. 2 A Bitter disk with elongated and circular holes [7].

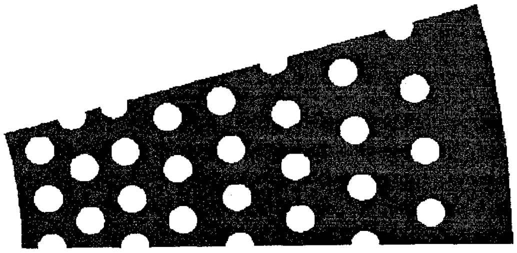

Fig. 3a Circular cooling hole distribution.

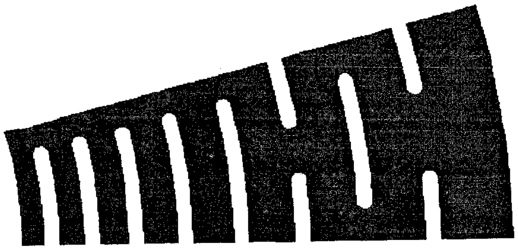

Fig. 3b Aligned elongated cooling hole design with semi-circular ends.

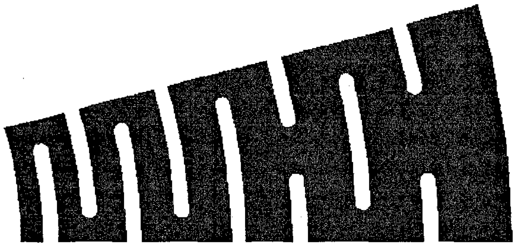

Fig. 3c Staggered elongated cooling hole design with semi-circular ends.

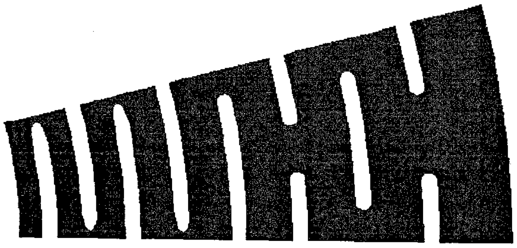

Fig. 3d Staggered elongated cooling hole design with semi-elliptical ends.

hole arrangement, stresses at the inner radius computed by finite element calculations follow quite well the stress equation in [10]. This derivation is based on equal moduli and Poisson's ratios in the hoop (tangential) and radial direction. The reason for higher stresses at the inner radius is that the outer bands in a Bitter disk strain more and therefore, radial stresses are set up that increase the hoop stress at the inner radius considerably. The rationale behind the polyhelix concept, and also to some extent the poly-Bitter concept, is to suppress the tensile radial stress transmission. In these designs, the current carrying rings in a thick coil become mechanically independent reducing the hoop stress on the inner bands and increasing the strain on the less stressed outer bands. Similar reduction in the stress at the inner radius in a thick disk can be obtained if somehow the disk is made more compliant in the radial direction (smaller effective elasticity modulus in the radial direction). We show here that this can be accomplished by the right choice of cooling hole geometry and pattern. Fig. 3 shows Bitter disks with different cooling hole arrangements, designed for the same dimension, hydraulic diameter, and cooling surface. Table 1 shows the results of the electrical, thermal, and mechanical finite element analysis of these different cooling hole concepts. For comparison, we also give the results using the well known equation from [10].

B. Maximum Stress and Peak Stress

In our analysis of the results, we focus on two issues: 1) the maximum stress at the inner radius that is the real limiting stress level for the magnet design, and 2) the peak stress generated by the geometry of the cooling holes. The peak stress occurs at the surface of the cooling holes and is

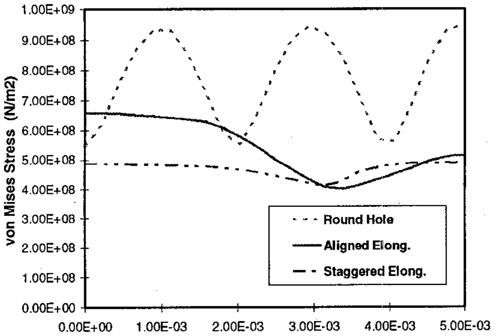

Fig. 4 The von Mises stress distribution on the inner radius for the different cooling hole configurations shown in Fig. 3a-3c.

TABLE 1

COMPARISON OF DIFFERENT COOLING HOLE CONFIGURATIONS

Cooling hole pattern	Round	Elongated			
		Aligned	Staggered		
Ellipse aspect ratio			1.0	2.0	3.0
T_{max} at midplane (°C)	81.2	81.4	75.4	75.4	75.4
Peak current density, J_{peak} (A/mm^2)	1157	744	739	691	658
J_1,current density at inner radius, a_1 (A/mm^2)	830	671	670	666	663
Max. stress at a_1 (MPa)	920	655	487	473	453
Max. stress (formula [10])	762	616	614	610	608
Peak stress (MPa)	1388	855	759	693	669
J_{peak}/J_1	1.39	1.11			
Peak stress/max. stress	1.51	1.30			
Current (kA)	13.3	13.2	13.2	13.3	13.3
Voltage (V)	194	162			
Power (MW)	2.58	2.14			

very localized, but it can become important for fatigue life of hard, cold-worked conductors with limited elongation.

As shown in table 1 and Fig. 4, the maximum von Mises stress at the inner radius is reduced considerably by going from circular to elongated to staggered cooling holes (from 920 to 655 to 487 MPa). The results also indicate the negative influence of the round cooling holes on the current path. The voltage drop is 20% higher for the configuration with round cooling holes compared to the aligned one.

Circular holes cause current density and stress concentrations. Table 1 shows considerable reduction in peak stress by going from round to aligned to staggered cooling hole distribution (from 1388 to 855 to 759 MPa). Further reduction in peak elastic stresses can be achieved by using elliptical cooling hole ends compared to circular (from 759 to 693 to 669 MPa).

Circular tie rods also result in stress and current density concentration. In Fig. 5, we show two cooling hole designs, (aligned with circular tie rod and staggered with elongated tie rod). Fig. 6 shows the stress vs radius at zero angular position for both cases. The staggered cooling hole distribution and the elongated tie-rod hole reduce drastically the peak stresses at the hole surfaces and the maximum stress at the inner radius.

C. Maximum Power Density

An important limitation in magnet design is the performance reduction imposed by the maximum power that can be dissipated. It has been shown [9] that the inner region of high field magnets is not only stress limited but also power density limited. It was the initial aim and motivation of this study to develop a design that could accept higher power densities. The chosen cooling hole shape, essentially a long slit, is the optimum form for increased cooling surface without creating a penalty in the radial space factor. The successful operation of the 30 T magnet demonstrates that in the thin band at the inner radius, power densities of 12 W/mm^3 can be safely handled.

Fig 5a Aligned cooling hole pattern and circular tie rods.

Fig 5b Staggered cooling hole pattern and elongated tie rods.

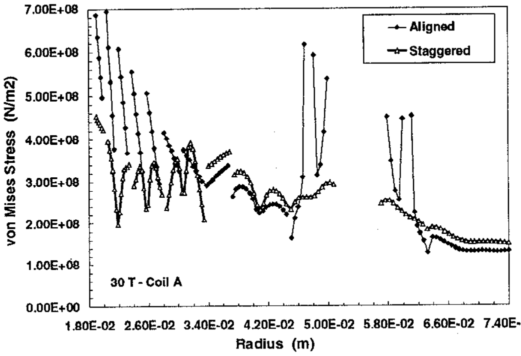

Fig. 6 Comparison between stress distribution for the disk geometries of Fig. 5a and 5b.

D. Equal Maximum Temperature

Together with this new concept, we also have reconsidered the traditional philosophy that suggests a magnet should be designed for equal heat flux. This criteria results in fewer cooling rings at the outer part and consequently higher maximum temperature due to the large spacing between the cooling holes. We decided to develop computing tools that design the cooling hole distribution for equal maximum temperature in the current carrying bands and allow for a different number of cooling holes and different cooling hole dimensions in each cooling ring. These tools were used to design our 30 and 34 T magnets.

Fig. 7 shows the maximum temperature design for the inner coil of the 30 T magnet. A reduction in maximum temperature of 12.6 °C can be achieved resulting in 2.5% power saving.

III. APPLICATION OF THE NEW CONCEPT

Table 2 shows a comparison between the two inner coils of our 27 T and 30 T magnets. The radial dimensions of the two coils are equal. The height of the inner coil of the 30 T design is shorter than that of the 27 T one, and its power is almost twice as much. In spite of the large power density in the 30 T design (12 W/mm^3) compared to the 27 T (4 W/mm^3), the temperatures of the two coils are close due to the increase in the cooling surface of the elongated cooling holes in the 30 T design. Nevertheless, the space factor for the high power density 30 T design is reduced only from 0.79 for 27 T to 0.74 for 30 T.

The cooling hole pattern was made through the use of chemical etching, which was introduced by one of us (M. D. B.) in the axially cooled resistive magnet manufacturing [11]. Our two 30 T magnets are being operated successfully since they were put into service in March and April 1995.

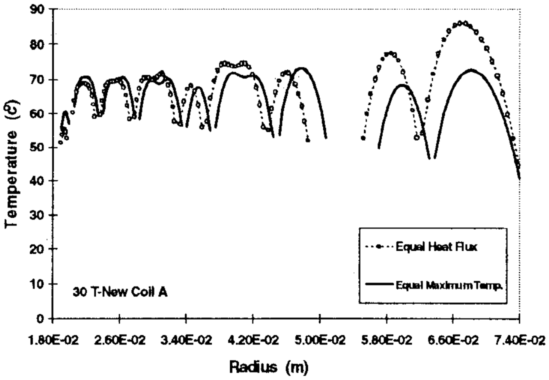

Fig.7 Temperature distribution for equal heat flux and equal maximum temperature criterion for our 30 T design.

TABLE 2.
COMPARISON BETWEEN THE TWO INNERMOST COILS OF OUR 27 T AND 30 T MAGNETS

Coil	27 T	30 T
Inner radius (mm)	19.0	19.0
Outer radius (mm)	74.0	74.0
Height (mm)	209.2	174.0
Field contribution (T)	10.4	13.4
Central field (T)	27.0	30.0
Material	Glidcop	CuBe
Power (MW)	2.43	4.54
Current (kA)	35.0	35.0
Heat flux (W/mm^2)	4.46	5.39
Power density (W/mm^3)	4.91	12.02
Type of cooling hole	round	elongated
Hydraulic diameter (mm)	1.20	1.20
Number of cooling holes	624	322
Surface of cooling holes (m^2)	0.4713	0.7883
Cross section of cooling holes (mm^2)	705.7	1432.0
Flow rate (l/s)	16.	31.
Average temp. (°C)	60.6	64.8
Maximum temp. (°C)	86.9	97.0
Space factor	0.79	0.74

IV. CONCLUSION

A new concept of shape and distribution of cooling holes in Bitter disks developed at the NHMFL combines the advantages of both Bitter and polyhelix magnets. It results in considerable reduction in stresses and maximizes cooling efficiency. The use of elongated tie-rods has similar advantages. The trouble-free operation of our two 30 T magnets is a successful experimental verification of the new concept.

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