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Magneto-structural analysis of the fermilab TQC Nb_3Sn high gradient quadrupole end region

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Abstract

The Fermilab TQC magnets are Nb_3Sn technological quadrupoles based on the collar-yoke-skin mechanical structure. These magnets, with an aperture of 90 mm, have a design gradient in excess of 200 T/m. In operation the conductor is subjected to forces which tend to pull it away from the poles and endparts to which it is bonded. Given the implications of bond failure for quench initiation, it is of interest to simulate the behavior of these interfaces. The ANSYS general purpose finite element program is used to perform both the magnetic and structural analyses. Interface elements between bonded parts are monitored during assembly, cool down, and excitation, and the birth–death capability of the program is applied to remove from the solution those portions of the interface which experience a tensile stress in excess of a presumed bond failure stress. The cracking of previously bonded interfaces can be tracked graphically over the range of operation. Emphasis will be placed on the details of the magnetic simulation, the implementation of various interface conditions, and the effects (and shortcomings) of material property models.

Keywords: Superconducting magnets; Finite element analysis; Nb_3Sn

1. Introduction

The Fermilab TQC (Technological Quadrupoles – collared) magnets are Nb_3Sn technological quadrupoles with a 90 mm aperture and a design gradient in excess of 200 T/m. They are based on the collar-yoke-skin mechanical structure which has been used successfully in previous Fermilab accelerator magnets [1,2]. Currently, development is centered on 1 m long prototypes to demonstrate feasibility.

The magnet is shown in cross-section in Fig. 1. It consists of four coils constructed of rectangular (Rutherford-type) cable using the wind-and-react method. After reaction, each coil/endpart assembly is impregnated with epoxy, bonding the conductors to the aluminum bronze endparts and wedges, as well as the inner and outer layer of the coils to each other. The inner layer of each coil uses two current blocks, designated Block 1 and Block 2, with 6 and 12 turns, respectively; the outer layer uses one current block, Block 3, with 16 turns. In the Fermilab coil, the inner coil pole piece is bonded to the inner coil; the outer coil pole piece is integral with the collar, which allows for alignment during assembly. The collars themselves are 1.5 mm thick, interleaving Nitronic 40 stainless steel laminates, typically stacked and tack-welded in the *z*-direction before magnet assembly to form manageable collar packs a few inches in length.

Ferromagnetic yoke laminates 1.5 mm thick are used in the straight section of the magnet; toward the end of the coils, stainless steel laminates are used. This is done to reduce the field in the end region.

The conductor geometries in the end regions, and their relationship to each other and to the end of the ferromagnetic portion of the yoke, are shown in Fig. 2. Fig. 3 shows the inner coil blocks of one coil mated with the endparts prior to reaction and impregnation.

After coil winding, reaction, and impregnation, there are three steps in the assembly of the magnet. First, four coils

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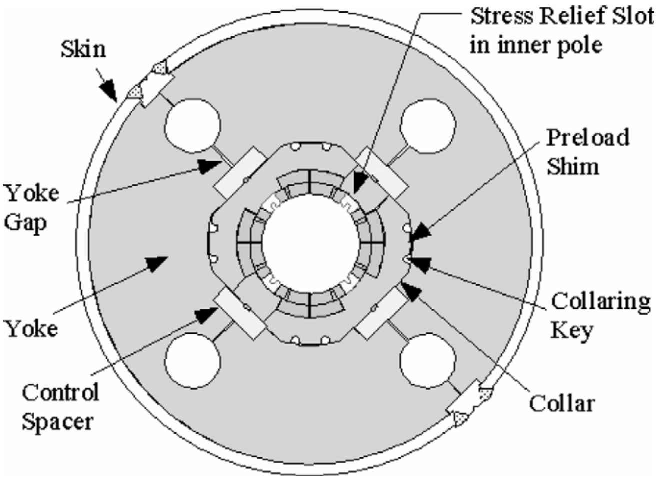

Fig. 1. Cross-section of Fermilab TQC quadrupole.

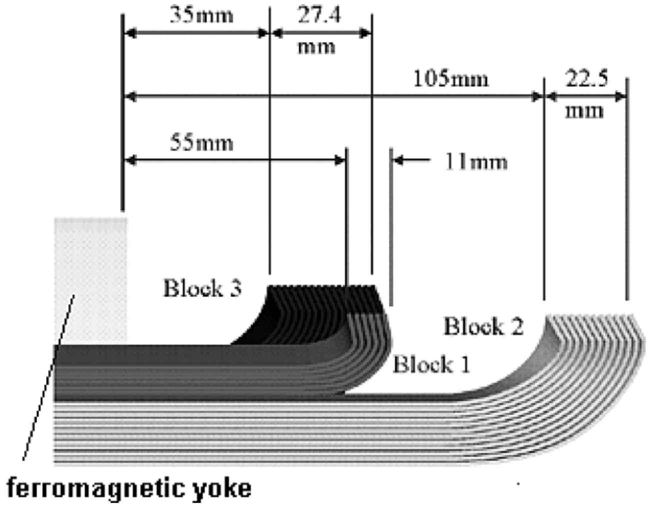

Fig. 2. Detail of the three current blocks in the end region.

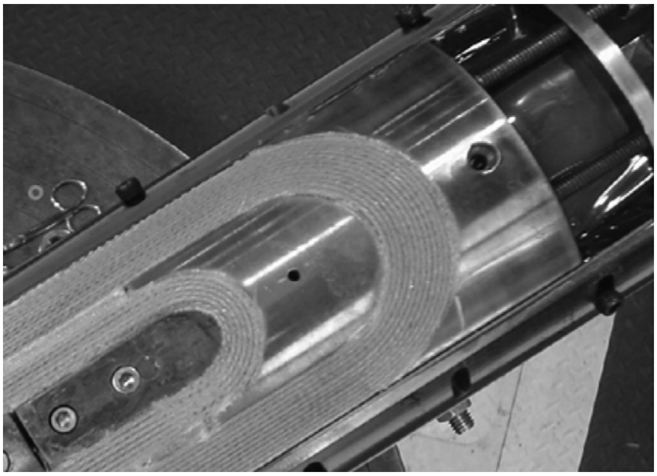

Fig. 3. Inner coil current blocks mated with endparts prior to final curing.

are placed in azimuthal contact, shimmed between their interfaces as required, and collars are keyed in place around the coils. Then, iron laminations are added, and the stainless steel skin is welded around the assembly, exploiting the shrinkage of the longitudinal skin weld to increase the azimuthal preload on the coils. Finally, a 50 mm thick stainless steel endplate is attached to the skin, and four jack screws reacting with this plate are used to place an axial preload of approximately 14 kN against the coils, as shown in Fig. 4.

The warm compression of the coils is controlled by the use of flat (not tapered) azimuthal shims between the coils, the radial shimming between the iron and the collars, the shrinkage associated with the closure weld on the skin, and the interaction of the yoke with the stainless steel spacers. Shim thicknesses, spacer dimensions, and weld details are determined primarily by mechanical, not numerical, modeling.

This method of construction creates some difficulty in determining the coil preload; the outer skin, where accurate hoop stress measurements are possible, interacts with the coil not through simple radial pressure, but through the radial and azimuthal stiffness of the collars, yoke, and spacers. The loading on the coil cannot be determined by a simple force balance against the skin stress, but must take into account the action of the collar/coil/yoke assembly.

The coil/endpart assembly is not subjected to any preliminary mechanical massaging to induce shakedown to elastic behavior prior to collaring; rather, the coil sees its first significant azimuthal compression during actual assembly in the magnet. This implies that the first magnet cycle will be substantially different from subsequent cycles, due to the well-known nonlinear stress–strain behavior of these coils [3]. This work does not address this effect.

During assembly, the different moduli of the coils and endparts produce Poisson strains which tend to pull the coils away from the endparts axially, creating tension in the bonds between those parts. During cool down, differential thermal contraction causes additional tensile stresses to develop in the bonds. Energizing produces still larger bond stresses; For example, at the 1.9 K operating current of 14 kA, each coil is subjected to axial Lorentz forces of 90 kN/quadrant, acting to separate them from the endparts. These forces are shown schematically in Fig. 5 for Block 3 of the coil.

This combination of forces can induce failure of the bonds, and subsequent opening of gaps between the coils and endparts. The behavior of epoxy bonds is understood to be an important factor in the stability of superconducting magnets [4]. Probable bond failure regions in the TQC quadrupole were indicated by early simulations in which the interfaces between current blocks and endparts were allowed to slide and separate. The failures are most likely to occur at the symmetry plane, where the current blocks are turning perpendicular to the magnet axis. This is shown in Fig. 6, where Block 1 and Block 3 have separated from their respective endparts at the symmetry plane