Fabrication of “TAMU3”, a “Wind/React” Stress-Managed 14T Nb₃Sn Block Coil Design

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Abstract. The third phase of a high field dipole technology development, a full set (2+) of Stress-Managed winding modules is being fabricated. The dipole fabrication uses tooling, fixtures, procedures and technology modified and updated based on the second phase work and results reported plus new material developments and higher performance strand. The strand was furnished by the DOE HEP Nb₃Sn conductor development program. The modules’ cables were processed and cabled by the LBNL facility using the latest procedures developed. There were several new materials and processes introduced in this third phase to improve performance or simplify the fabrication which will be discussed. If all the performance inherent in the strand were to be achieved then the peak field should be higher than 14 T. The containment and flux return structure are the same as used in phase 2. This phase of the development will constitute the outer winding modules of a “Collider” prototype Block dipole with Stress-Management. The lessons learned and the results obtained will be discussed.

1. Introduction
The Texas A&M University Accelerator Research Lab continues the development of a new approach to the design and construction of Nb₃Sn magnets with the next phase prototype for high field (>10T) wind & react based magnet coils. This third developmental phase incorporates, internal coil stress-management, relaxed tolerances, and a simple construction via bladder preloading, reduction of ac losses and snap-back via field/conductor orientation, and the inclusion of flux plates (for injection field harmonic suppression, not applicable for phases 2 and 3) of the earlier phases[1,2]. TAMU3 will additionally utilize “high Jₑ(12T, 4.2K) Nb₃Sn Rutherford type performance cable” in the range of 2.5 to 3.0 kA/mm². There have been major improvements in materials and their properties resulting in simplification of several of the third phase processes. These improvements have resulted in a more homogeneous (metallic) and robust winding module which display improved mechanical, thermal, and electrical characteristics while resulting in a simpler process. The processes and results from the earlier two phases have been reported in previous publications [1, 2, 3, and 4].

2. Design Features
The TAMU3 winding cross section is given in Figure 1. TAMU3 consists of the two outer winding modules of the anticipated “Final Phase” of the program or TAMU5, see figure 2. The main TAMU3 parameters are given in table 1. Some significant changes in TAMU3 versus TAMU2 are: the single winding module in a mirror configuration has been replaced with two outer winding modules which contain high current density Nb₃Sn strand, more than twice to three times that of TAMU2. This

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Table 1. Major Magnet Design Parameters

| Parameter                        | TAMU3 initial | TAMU3 final | units |
|----------------------------------|---------------|-------------|-------|
| Max. Field(strand short sample)  | 14.0          | 14.1        | T     |
| Operating Current                | 15.60         | 13.93       | kA    |
| Stored Energy                    | 0.41          | 0.42        | MJ/m  |
| Max. Lorenz Force                | 5.2           | 5.2         | MN/m  |
| # strands-inner Cable            | 30            | 30          |       |
| Strand diameter                  | 0.8           | 0.8         | mm    |
| \( J_c (12T, 4.2K) \)            | 2750          | 2500        | A/mm² |
| \( J_c (14T, 4.2K) \)            | 1695          | 1540        | “     |
| \( J_{copper} \) (quench)       | 2575          | 2310        | “     |
| # turns in inner                 | 12            | 13          | turns |
| # turns in outer                 | 19            | 22          | “     |
| #-strands-outer Cable            | 34            | 34          |       |
| Strand diameter                  | 0.7           | 0.7         | mm    |
| \( J_{copper} \) (quench)       | 2300          | 2130        | A/mm² |
| \( J_c (9.6T, 4.2K) \)           | 2540          | 2310        | “     |

“Rutherford Cable” has been through one or two cycles of annealing and re-sizing (re-rolls) in order to minimize the expansion/contraction during the \( \text{Nb}_3\text{Sn} \) formation heat treatment [5]. Another major component and/or procedure(s) advancement was accomplished with the “braided on” insulation sleeve with regard to efficiency (thickness), strength, ruggedness (resistance to fraying when handling), and the effects, if any, on the subsequent fabrication processes [6]. Our European colleagues mentioned in an LBNL seminar they had received a sample of polyimide-sized S2 fiberglass insulation fabric [7]. They reported that the sizing was stable through the diffusion heat treatment for \( \text{Nb}_3\text{Sn} \) and therefore might lead to a simpler, more robust insulation system. Our previous studies indicated that the efficiency of the S2 fiberglass braided insulator could be improved with finer filaments. These facts convinced us to pursue getting Silane sized 5.5 micron filaments of S2 and then have it braided on the cable with a high count braider. First we worked with AGY.
(Advanced Glass Yarns, Inc USA) to develop a silane-sized yarn containing 204 5.5 µm diameter filaments of S2 Glass. Then we worked with A&P Technologies, (USA) to braid the yarn directly onto the Rutherford cable. Table 2 summarizes the mechanical, thermal, and electrical property data obtained from “10turn stack” winding block tests. From these data, it is apparent that this approach has many advantages; such as 40 – 65% or more decrease in insulator volume, and yet superior epoxy wetting properties that lead to excellent electrical and mechanical characteristics of the winding.

Table 2. Mechanical, Thermal, and Electrical Data obtained from “10turn Stacks” (inner block conductors).

| Type                      | Description                          | Units   |
|---------------------------|--------------------------------------|---------|
| **Mechanical**            |                                      |         |
| Cable dimensions          | inner                                | 1.4155  |
| (bare)                    | outer                                | 1.2079  |
| (w/insulation)            | inner                                | 1.5255  |
| Under a pressure of ~2MPa | outer                                | 1.3179  |
| Dry Cable Stack Pressure  | limit                                | ~21     |
| Fabrication-10t Stack    | Pressure                             | 2 – 3   |
| **Preliminary**           | Shear force to delaminate cable      | Force per evaporated Sizing  | 4.7 x 10⁵ N/m |
| interfaces ~ 1 cm wide    | in middle of “10turn stack”          |         |
| Thermal                   | Integrated Shrinkage 77K–300K (10t Stack) | (L(77K) – L(300K))/L(300K) | 2.65 ± .15x10⁻³ |
| Electrical                | Electrical Insulation (turn/turn)     | LowVoltage A few volts | >2.0 x 10⁷ Ω |
|                           |                                      | Max. Volts 300 volts | ≥1.3x10⁰¹ Ω |
|                           |                                      | (Turn/turn) 350 volts | .7–6. x 10¹¹ Ω |

2.1. Stress-Management
As seen from figures 1 and 2 the winding blocks are segmented into sub-blocks enclosed and supported by a box titanium/inconel pier/beam structure; therefore reducing the load on the outer turns of each sub-block. The pier/beam structure then transfers the force to the iron return yoke which is held together by the Aluminum Stress cylinder. This strategy plus the introduction of a soft spring on the inside of the outer block windings next to the titanium/inconel pier does not allow the force to be seen by the outer turns next to the spring. The principle reason for modification of this procedure for TAMU3 is to remove the questions as to the loading of the spring during the heat treat and subsequent impregnation. There is a set of threaded holes in the middle and central piers at the same axial position. Utilizing hardened threaded pins, and a very accurate set of solid blocks, simulating a coil winding, it should be possible to cross calibrate and check the spring’s deflection and thus their load. This measurement coupled with the readings from the capacitance transducers should effectively set the capacitors’ zero and determine coil preload.

2.2. Coil Module
The coil assembly modules contain all the elements to operate as an independent unit. The module contains NbTi/Nb₃Sn/NbTi lead splices (the thick skin that provides the stiffness), voltage taps and protection heater traces and any other instrumentation traces as required. This approach facilitates module replacement when required. The development protocol uses the same Al cylinder and iron flux return yokes for all the subsequent phases. See figures 3, 4, 5, and 6.

2.3. Bladder Preload
The use of metal filled bladders was first employed by Clyde Taylor (LBNL) in order to properly support an ion source sextupole [8]. The large cylindrical bladders between the Al Stress-Cylinder
Figure 3. A partially transparent drawing of the outer winding module.

Figure 4. This drawing shows the fully assembled TAMU3 with half of the return yoke transparent.

Figure 5. This is an outer winding module being wired to a trace in preparation for impregnation.

Figure 6. A completed outer winding module waiting its insertion in the iron yoke return.

The iron return yokes (indicated in figure 7a) are pressurized to >14 MPa. Their pre-load provides the rectangular opening of the return yoke with the ability to appear practically infinitely rigid, thus serving as the boundary to transmit the Lorentz force loads outward. Figures 7a and 7b are photos of the Bladder Heating/Pressurizing Apparatus showing the coaxial heating/pressure lines and valves. The only modifications to this apparatus were more temperature controllers and independent heating units for the valves next to the bladder stubs. These bladders are a “perfect surface” smart shim, which is more economical to fabricate than a perfectly machined and polished surface.

2.4. Axial Force-Management

The axial force is to be transferred from the turns to the middle titanium pier and titanium shims on the end-shoe winding-faces; both of these elements are being loaded by the upper and lower bladders up to 2 – 3 MPa. These loads are more pronounced when cold for the Ti elements because of their lower overall shrinkage. The yoke end plates are instrumented with strain gauge bridges mounted on brass compression pucks. Due to a wiring harness mistake, the bridges were not sensitive enough for TAMU2 testing to be convincing [6], but hopefully that problem will not be repeated.

2.5. Design and Component Evolution Effects

One of the most pronounced effects of the design evolution can be seen in the reduced operating current to generate 14 T as shown in figure 8. This more conservative value can either be used to obviously increase the magnetic field with yet higher performance conductor. It should be noted that the turn’s distribution is optimized for the TAMU5 configuration not TAMU3.
Figure 7a. This Bladder Heat/Pressurize Apparatus photo shows the two vertical lines connecting to the circular bladder between the Al stress-tube and iron return yoke.

Figure 7b. This photo of the rest of the bladder apparatus shows the cooling/heat exchange zones.

Figure 8. This is the Load line for TAMU3 as presently configured with the proposed critical cable current versus field.

3. Fabrication

3.1. Cable Preparation and Insulation
The TAMU2 “ITER” cable was braided directly with 10 micron plus diameter filaments by New England Electric Company, USA, which resulted in an insulation fabric 95 microns thick under a ~2 MPa load. The cable for TAMU3 only requires the braiding operation, without a standard sizing removal step, as well as a resizing step of polemic acid and subsequent volatizing heat treatment step therefore it is fundamentally a simpler, faster, and lower risk process.
3.2. Heat Treatment
The TAMU3 Heat Treatment has only two holds (steps), so here again another simplification saving two days in the fabrication process. The Nb$_3$Sn formation Heat treatment will be a little conservative to make sure the RRR of the copper stabilizer will be in the double digits.

3.3. Bladder Preload
The flow blockage problems with the valves on the heat/pressurize lines during periods of little or no metal flow, should be over with independent temperature adjustment.

4. Conclusion
One of the major mile stones in the development program has a high probability of being accomplished during this phase, namely operating in the High Field and Force region. This mile stone will provide a reality check on of the thoroughness of the design criteria and our ability to execute the design. If we have executed well, this will be a definitive test of this approach to “Stress-Management” and possibly Nb$_3$Sn will have its strain limited “efficient engineering current density versus field” limit removed. The quench protection heater efficiency should improve due to the shorter delay of heat transfer across the thinner insulation. The innovations embodied in TAMU3 should pave the way for developing dipoles up to much higher fields. A design has been proposed to extend the approach to use Bi-2212 inner windings, perhaps opening the path to 25 T and an LHC Tripler [9]. Process simplification may allow a higher energy HEP frontier machine to be affordable.

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