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Magnetization, Low Field Instability and Quench of RHQT Nb_3Al Strands

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***Abstract*— Since 2005, we made and tested three RHQT Nb_3Al strands, one with Nb matrix and two with Ta matrix, which are fully stabilized with Cu electroplating. We observed anomalously large magnetization curves extending beyond 1 to 1.5 Tesla with the F1 Nb matrix strand at 4.2 K, when we measured its magnetization with a balanced coil magnetometer. This problem was eliminated with the Ta matrix strands operating at 4.2 K. But with these strands a similar but smaller anomalous magnetization was observed at 1.9 K. We studied these phenomena with FEM. With the F1 Nb matrix strand, it is explained that at low external field, inter-filamentary coupling currents in the outer layers of sub-elements create a shielding effect. It reduces the inside field, keeps the inside Nb matrix superconductive, and stands against a higher outside field beyond the Hc of Nb. At an even higher external field, the superconductivity of the whole Nb matrix collapses and releases a large amount of energy, which may cause a big quench. Depending on the size of the energy in the strand or the cable, a magnet could quench, causing the low field instability. Some attempt to analyze the anomaly with FEM is presented.**

***Index Terms*—FEM, Instability, Magnetization, Nb_3Al Strand.**

I. INTRODUCTION

RECENTLY practical Cu stabilized Nb_3Al strands are being produced with a length of over 1 km, and successfully applied for the model magnets of high field accelerator magnets [1]. These strands are made by electroplating Cu at NIMS (National Institute for Material Sciences) in Japan [2]. Two different types of the RHQT (Rapid Heating-Quenching Transformation) Nb_3Al strands were developed at NIMS and their characteristics were studied. The first type F1 strand is made with Nb matrix [3], and the second type F3 and F4 strands, are made with Ta matrix [4]. Using these strands we made Rutherford cables and small racetrack magnets. The F4 strand was successfully tested for its application in a small racetrack magnet to its full short sample data [1].

As the RHQT Nb_3Al strands are heated up to 2000 C° during strand production, pure Nb or Ta is used as the matrix element between Nb_3Al sub-elements. Because these materials are superconducting at 4.2 and 1.9 K respectively, they exhibit their characteristic magnetization, and present disturbances at low field regions. The cross-section of the 1 mm diameter F1 Nb matrix strand is shown in Fig. 1, together with a detailed picture of its sub-elements. Each sub-element has a small central Nb core, and is separated by a roughly 3 µm layer of Nb from its neighboring sub-elements. Major parameters are listed in the Table I. During magnetization tests of the F1 strand, we observed very large flux jumps. This phenomenon is reported in the previous paper [5].

The Ta matrix F4 strand is shown in Fig. 2, with a detailed picture of their sub-elements. They are separated from each other by 5-7 µm of Ta, and each sub-element has a small Ta core. The characteristic parameters of the F4 strand is shown in Table I, together with the F3 strand, which was also made with Ta matrix.

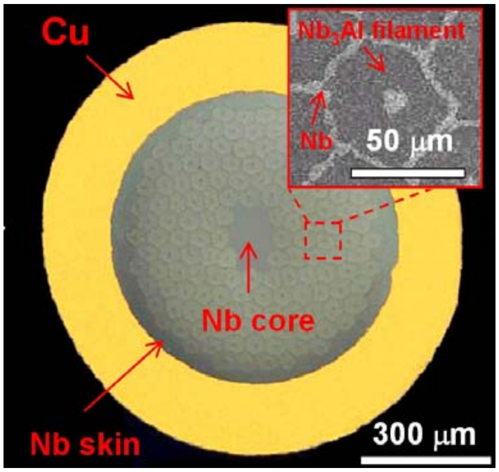

Fig. 1. Cross section of a Cu stabilized F1 Nb_3Al strand. It has a Nb center. The inter-filament matrix is Nb, as shown in the insert, as is the skin matrix. Each sub-element also has a very small Nb core.

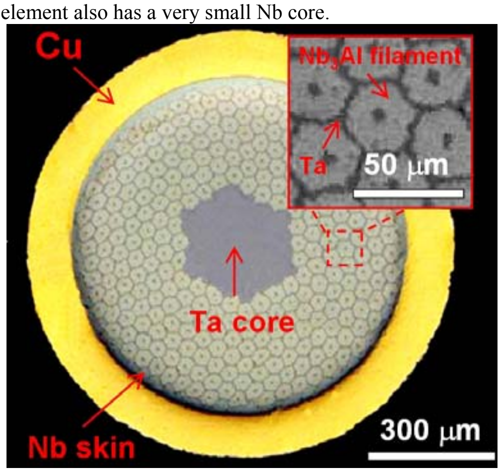

Fig. 2. Cross section of a Cu stabilized F4 Nb_3Al strand. It has a Ta center core and Ta inter-filament matrix. The outermost skin matrix is Nb. The insert shows the sub-elements with tiny Ta cores.

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TABLE I
Specifications of F1, F3 and F4 Nb$_3$Al Round Strands

Strand ID	F1	F3	F4
Magnet made and tested	SR04	SR05 (not tested)	SR07
Strand Dia. (with Cu)	1.03 mm	1.00 mm	0.99 mm
Strand Dia. (without Cu)	0.72 mm	0.70 mm	0.78 mm
Number of Filament	144	222	276
Physical Filament Dia.	50 μm	38 μm	35.8 μm
Cu/non-Cu ratio	1.0	1.0	0.61
Filament Barrier	Niobium	Tantalum	Tantalum
Central Core of Filament	Niobium	Tantalum	Tantalum
Central Dummy Filament	Niobium	Tantalum	Tantalum
Most-Outsider Matrix	Niobium	Niobium	Niobium
Area Reduction (AR)	71.6 %	71.6 %	65.3 %
Cu Ion Plating Speed	120 m/h	120 m/h	120 m/h
Cu Electroplating Speed	2 m/h	5 m/h	7 m/h
I_c (4.2 K, 12 T)	582.9 A	581.3 A	645.9 A
I_c (4.2 K, 15 T)	351.5 A	343.0 A	376.5 A
non-Cu J_c (4.2 K,12 T)	1,400 A/mm^2	1,481 A/mm^2	1,352 A/mm^2
non-Cu J_c (4.2 K, 15 T)	844.2 A/mm^2	873.8 A/mm^2	788.3 A/mm^2
n value (4.2 K, 12 T)	40.3	49.9	40.0
n value (4.2 K, 15 T)	35.5	40.3	34.3
RRR (20K/300K)	150-200	80-170	150-250
Twist Pitch (mm)	362	11-362, ∞	45

The F1 Nb matrix strand showed anomalous magnetization and the Rutherford cable and the magnet SR04 based on this F1 strand showed premature quenches due to the low field instability [6]. Their anomalous instabilities are due to the Nb matrix and partially because they did not have adequate twisting in their strands [5]. But with the use of the Ta matrix Nb$_3$Al strand, we could successfully eliminate this low field instability for cable and magnet applications [1].

II. Magnetization Data of Nb$_3$Al Strands

A. *Magnetization Measuring Methods*

For the data presented in this paper, we used the Balanced Coil Magnetometer with magnetic field sweeping using coiled samples wound from one meter long Nb$_3$Al strands [7]. In this case, the magnetization data includes the effects from end condition, angle, twisting, as well as eddy current.

We also measured the magnetization of these strands using a SQUID and Vibration Coil Method in a steady magnetic field. In these cases, data curves are quite different and did not show any anomaly. We think this is because their samples are quite short, 2 mm, and give data more related to the material itself. This effect was also checked using Moving Sample Method to make sure that it is not due to the sweep rate of the measurement. The sample length of Moving Sample Method was 2 to 20 mm and its data showed an intermediate behavior.

B. *Nb$_3$Al strands with Different Matrix*

We made two kinds of Nb$_3$Al strands; one with Nb matrix, F1, and the other with Ta matrix, F3 and F4. The Tc of Nb is 9.25 K and that of Ta is 4.4 K. The Bc2 of Nb is about 0.3 to 0.4 Tesla, less than 0.5 Tesla. Their magnetization behaviors are different. Therefore, the magnetization anomaly is apparently caused by the superconductive state of Nb matrix. This large magnetization extends to a field as high as 1.5 T that is well beyond the critical field Bc2 of Nb and occasionally showed large flux jumps.

C. *Magnetization curve of F1 Nb Matrix strands*

The magnetization curve of a 900 mm F1 Nb$_3$Al strand is shown in Fig. 3, which was measured using the balanced coil magnetometer [5]. The field sweep was from 0 to 3 Tesla at 1 Tesla/min, and was run twice in sequence. The first loop has a big flux-jump step at 1.2 and 1.75 Tesla, but not in the second loop. Once the flux has penetrated inside there is no more anomaly. This huge flux jump has caused the low field instability for F1 Rutherford cable and F1 SR04 magnet [6].

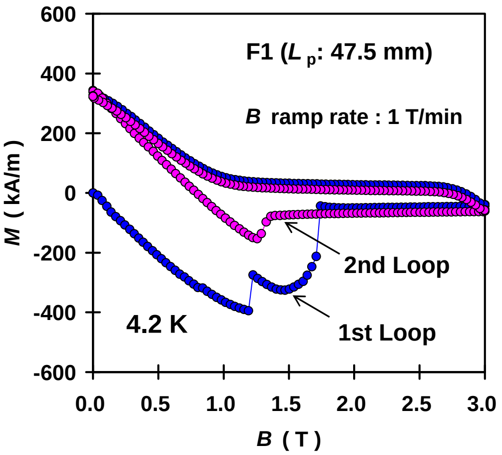

Fig. 3. Magnetization curve of the F1 Nb$_3$Al strand measured with a balanced coil magnetometer at 4.2 K. An abnormally large magnetization loop and a big flux-jump are observed beyond one Tesla, which occurs at a higher field than the Bc2 value (below 0.5 Tesla) of Nb. There is no abnormally big jump in the second loop.

D. *Comparison between F1 Nb matrix Strand and F3 Ta matrix Strand*

For these tests, we used F1 and F3 samples with a twist pitch from 45 to 47.5 mm. We tested both samples at 4.2 and 1.9 K. Fig. 4 shows data of both samples at 4.2 K. It shows

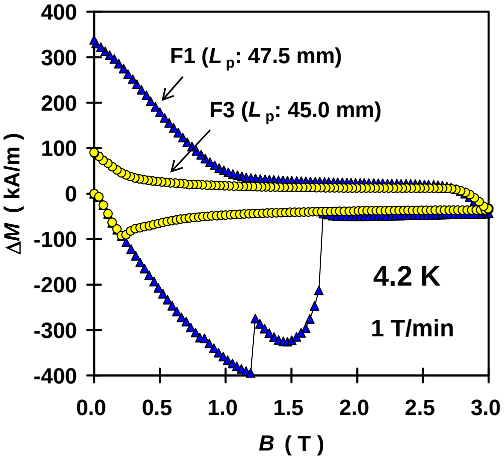

Fig. 4. Magnetization curves at 4.2 K of F1 Nb matrix strand and F3 Ta matrix strand.

that the F1 strand has an anomaly at 4.2 K even if it has a reasonable twist of 47.5 mm. But the Ta matrix F3 strand does not show any anomaly at 4.2 K.

The test data of F3 Ta matrix strand at 4.2 K and 1.9 K are shown in Fig. 5. The data show it has a similar anomaly at 1.9 K, in a smaller scale than that of F1 Nb matrix strand at 4.2 K. But it is not showing the anomaly at 4.2K, while its Tc is 4.4 K. This anomaly may be due to Ta matrix, but it might be related to the Nb skin coating.

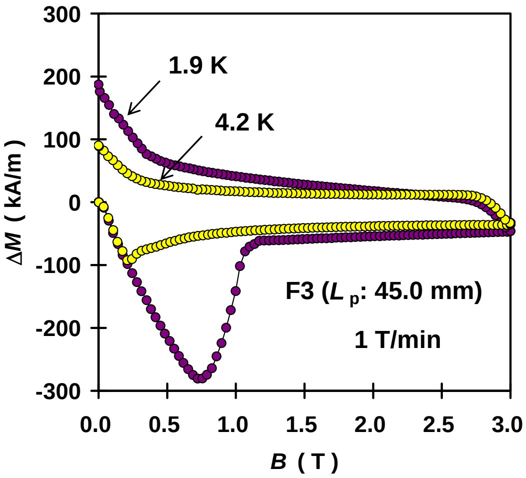

Fig. 5. Magnetization curves of F3 Ta matrix strand at 4.2 and 1.9 K.

E. Magnetization of Nb Matrix

To see the magnetization effect of Nb matrix, the F1 Nb matrix strand sample without heat treatment was tested. Its test result is shown with a solid line in Fig. 6. As expected it showed its magnetization curve below 0.5 Tesla, and showing its peak at 0.25 Tesla. We need a similar test with the F3 strand at 4.2 and 1.9 K to see any Nb skin effect of F3 strand.

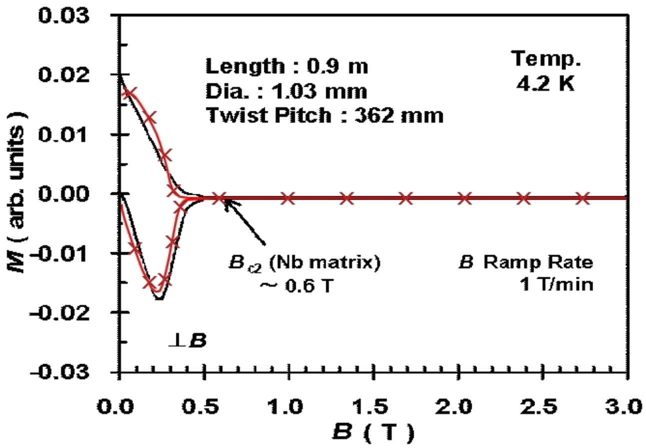

Fig. 6. Magnetization curve of Nb. This was observed using a F1 Nb matrix strand sample at 4.2 K, which was not heat treated. The line represented with X marks added is the simulated result with Comsol FEM.

III. COMPUTER SIMULATION OF MAGNETIZATION

We have been successful in making a computer simulation on magnetization curves using ANSYS [8], [9].

A. One Dimensional Slab Model

With increased computer power, the slab model [10] of magnetization can be solved easily. Still, this simple model is very useful for checking simulation results of FEM programs.

By changing pinning parameters (gamma), the different magnetization curves can be displayed for different models, including Kim's, Bean's, and Yasukouchi's. Fig 7 is an example of the display for such simulation. The model works real-time, responding to the sweeping external field [11].

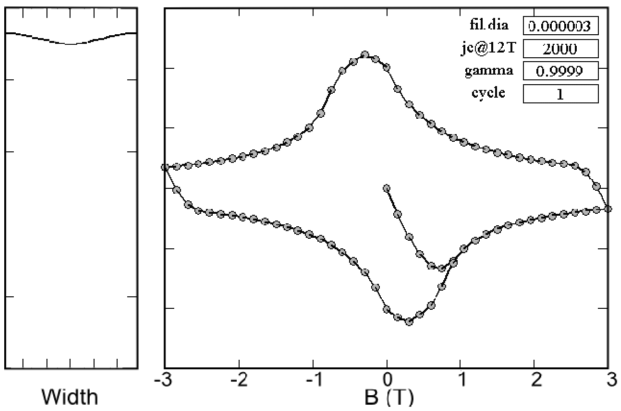

Fig. 7. Magnetization curve and internal field distribution of the slab model using Power Point screen; The left graph is the field distribution inside the conductor and the right graph shows the magnetization as a function of field. Both y-axes are in arbitrary units. Graphs moves in real time responding to the excitation B. The displayed simulation result is for the Kim model [11].

B. Consideration for Simulation of Anomaly

The large magnetization extending beyond the critical field of Nb can be understood by the shielding current in the Nb_3Al filaments. The interior of the conductor is kept at low field by this shielding current and the superconductivity of Nb matrix remains beyond 1T of the external field. The flux jump occurs when the inter-connect current running between filaments exceeds the critical current of Nb matrix.

We have demonstrated the feasibility of this mechanism using a 2D ANSYS model [9]. However, the combined behavior of the shielding current of Nb_3Al filaments and the magnetization of the whole strand needs to be modeled by a 3-D finite element program with total multi-physics features, including the thermal effect.

The analysis of the magnetization anomaly is much more complicated than the simple model shown. Total multi-physics required for this analysis may be difficult to handle with ANSYS. ANSYS is efficiently optimized to solve known problems. On the other hand, Comsol [12] allows users to define basic equations for analysis and has the possibility to simulate the entire phenomena. We worked on a technique to simulate the magnetization of Nb_3Al strands.

In the following analysis, we simulated the magnetization basically by using the Comsol Multi-Physics described by a paper by Z. Hong [13]. It is a 2-D calculation, in which the cross section of the strand is in the x-y plane. This simulation is done assuming the strand is infinitely long; corresponding to no twisting. The external field is directed in the direction from the top to the bottom of this plane. The equations used in Comsol are Maxwell equations with degree of freedom, Hx and Hy, together with the induced Jz value.

1) Magnetization of Nb Matrix

Using Comsol, we simulated the effect of the matrix Nb, assuming the whole superconductor area of the F1 strand is made of all Nb. Its simulated result is shown in Fig. 6 with a line dotted with X's. We assumed simply the Jc of Nb is 300

A/mm^2 from 0 to 0.2 Tesla and linearly decrease to zero at 0.3 Tesla. The n-value we used is 17 in this case.

2) *Magnetization of Nb$_3$Al Sub-element*

The simulation of a Nb$_3$Al conductor with single sub-element is shown in Fig. 8. Also, we used a n-value of 17. Compared to the experimental curve of Ta matrix Nb$_3$Al strand at 4.2 K, shown in Fig. 5, it is reasonably well reproduced and close to the standard slab model shown in Fig.7. Therefore the FEM model is at least successful in representing the usual magnetization behavior like a F3 conductor. The Jc value, used in this simulation is expressed by:

$$J_c = \frac{17600}{0.25+\sqrt{B}}\left(1-\frac{B}{28}\right)^2 \qquad \text{Jc: A/mm}^2\text{, B: T.} \qquad (1)$$

3) *Simulation of Nb matrix Nb$_3$Al Strand*

Comsol simulation of the whole Nb matrix F1 strand with 102 sub-elements together with Cu stabilizer is being investigated. The data with a rather small n-value of 3, for the faster convergence of calculation, are shown in Fig. 9 at the external field of 0.575 Tesla.

From the simulation, we can observe at very low field below Hc of Nb, the shielding currents are induced on the outer surface of the Nb and in sub-elements in a cosine-theta distribution. This expunges the field from the interior of the strand, causing an enlargement of the effective diameter of the strand. With many sub-elements, the shielding mechanism becomes complicated.

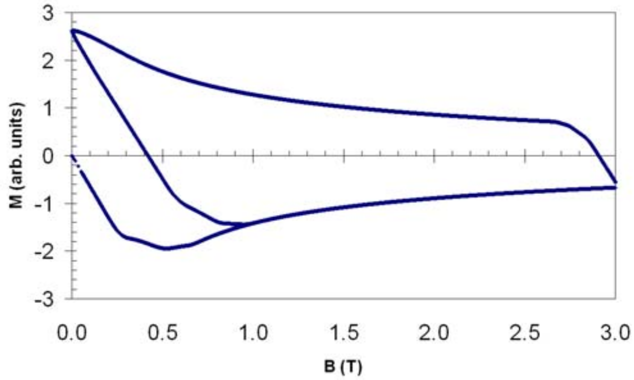

Fig. 8. Simulated magnetization curve of a single Nb$_3$Al sub-element with dia. of 50 μm using Comsol.

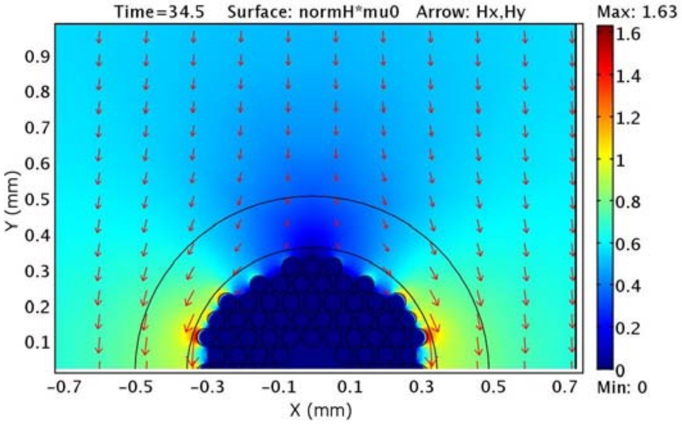

Fig. 9. Nb matrix Nb$_3$Al strand at the external field B =0.575 Tesla, simulated by Comsol. The induced currents in the sub-elements and Nb matrix on outer layer are generating a shielding field to keep the inside field low.

IV. CONCLUSIONS

The abnormally large magnetization of the Nb matrix Nb$_3$Al strand, F1, is suggested to be caused by the shielding current effect. We are trying to explain that these phenomena are related to the inter-filament coupling current though the Nb material.

The simulation using Comsol was successful to calculate magnetization, a highly non-linear phenomena difficult for FEM. However, we still have to develop the simulation to verify the theory. The simulation has to include the effect of twisting filaments in 3D geometry. The goal of the analysis is to show the big flux jump. We think the inter filament current going through the Nb matrix will eventually exceed the Jc of Nb, and cause a big flux jump.

The computer simulation using commercial FEM is progressing rapidly and proving to be a very useful technique for simulation. With recent rapid progress of PC computer's capacity, these techniques can be applied to more complicated problems.

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