FERMILAB-CONF-05-427-TD

Three Dimensional FEM Quench Simulations of Superconducting Strands

Ryuji Yamada and Masayoshi Wake

Abstract— **The detailed phenomena in quench starting of Nb_3Sn strands are simulated in 3-D and in time using ANSYS and FEMLAB programs. The current sharing between the superconductor and copper stabilizer in strands at the beginning of a quench was studied and displayed in time. The differences in copper configuration and RRR value of copper were found to have large effect to the stability and quench propagation velocity. The MPZ theory was found to be effective for 3D multifilament situation**.

***Index Terms*—Finite Element Methods, MPZ, Quench simulation, Superconducting strand.**

I. Introduction

The thermal stability and quench propagation has been a major issue of the superconducting magnet technology. Analytical solutions for mono-filament conductors can be found in every text book of superconductivity [1]. However, the real situation of the magnet and superconducting strand has much more complicated geometry. Superconducting strands are made of multi-filaments and the current sharing among these filaments and stabilizing copper is the important feature of the phenomena. True multi-filament situation has been difficult to handle even in a numerical solution. It was thought to require too much computer resources. But today's computer environment is far different from that of a few years ago. It is now possible to do the complete FEM analysis of realistic superconductors. In the last several years, we have developed the 3-D computer simulation of magnet quenches [2-4]. Now we want to investigate the starting points of quenches in strands.

In the last decade, many people with proficiency in computer programming started simulating the thermal electromagnetic analysis of superconductor, low and high T_c superconductor as well, successfully in two-dimensional analysis [5, 6]. Also FEM was applied to partially solve the quench simulation successfully in three-dimension YBCO bulk material [7]. But these solutions were limited to a part of the phenomena. These people developed their own programs to simulate the quenches. We are trying to solve the quench problem using commercially available programs so that the solution can be generalized and complete in all the aspects.

From our recent investigation of the test results of Nb_3Sn high field model magnets, we realized the maximum quench current is determined in many cases with the values of RRR of copper stabilizers, as well as the energy size of flux jump [4]. With a small RRR value of Nb3Sn like 10, which is caused by the contamination of the stabilizer copper by Sn leakage, the resistivity of the copper is increased, bringing more Joule heating to the strands at the time of disturbance. At the same time, the thermal conductance of the copper is drastically reduced, contributing much less for the heat distribution of this thermal disturbance along the axis of the strand [4]. Thus we know the RRR value is essential for the stability of stands, as well as the stability of magnets.

We want to understand the importance of the RRR value for the stability of a strand as well as for a magnet by simulating the quench behavior of strands with different RRR values. Therefore we developed 3 D computer simulation methods to investigate the quench problems and they are reported in this paper.

When we test the short samples of superconducting strands, the strands are exposed to liquid He. But the surface of strands in the cable of a magnet is covered with the insulation layer and not directly exposed to liquid He. This insulation affects the minimum quench energy.

II. Quench simulations of Nb_3Sn Strands with ANSYS and FEMLAB

For the study of 3D simulations, we used two commercial FEM programs; ANSYS, supported by ANSYS. Inc. and FEMLAB, supported by COMSOL Inc. With FEMLAB we used it within its capability of multi-physics, for solving thermal electromagnetic combined problems. Current distribution, heat generation and the thermal conduction are handled simultaneously. Due to the very steep non-linearity, it is necessary to make very small time steps in the order of μsec for transition phenomena.

ANSYS can also handle multi-physics problems but we used APDL programming to better control the solution. Since superconducting transition is a very non-linear phenomena ANSYS standard package often fails to give the solution in multi-physics problem. In our simulation, the superconducting to normal transition was separated from the standard non-linear solution. APDL program analyzes the thermal solution given by ANSYS and calculate super-to-normal transition and heat generation at each point for the next cycle of ANSYS program

Manuscript received September 20, 2005.

R. Yamada is with Fermi National Accelerator Laboratory, Batavia Illinois, 60510 USA (phone: 630-840-3660; fax: 630-840-3369; e-mail: yamada@ fermilab.gov).

M. Wake is with High Energy Accelerator Research Organization, 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan. (e-mail: wake@post.kek.jp).

run. The solution is continued as time progresses. The advantage of such use of APDL programming is the versatility of the application. Not only the temperature, but also the resistance, normal zone length, observed voltage and any other things happening in the real situation can be simulated.

A. Analysis with FEMLAB

Short sample test of a superconducting strand in liquid He at 4.2 K is simulated with FEMLAB. A monolithic strand of 1mm diameter was simulated first in 2-D, using the axi-symmetic case. Then it was changed into 3-D simulation. A 31 mm long strand is used with the central 1mm part is used for inputting the thermal disturbance. A current of 800 A is passed through the strand. At the beginning all of the current is passing through the central superconducting part. By applying the energy pulse to the central part for 10 µsec, the temperature and the current distributions along the strand length can be simulated

At the disturbance time, the most of current go through the copper stabilizer, and it generates the Ohmic loss and heat up the strand. At the same time, the surrounding liquid Helium is cooling the strand, and generated heat is transmitted axially through the copper stabilizer. Therefore if the RRR value is small, the copper stabilizer generates more heat, and thermally transmits less heat along the strand. Compared to the strand with high RRR value, it generates more Joule energy and less transmit heat to neighboring copper region, thus increasing local stabilizer temperature much higher [4]. In Figure 1, the simulated strand is shown after 2 ms. The cross sections of the strand at every 1 mm are shown, with the current distribution marked with arrows. It is clearly shown the current is bypassing the heated superconductor at the disturbance point. In this case the minimum quench energy was 40 µJ. By changing the amount of disturbance energy, we can observe the quench will propagate or recover by itself.

B. FEM model with ANSYS

The FEM program ANSYS can also handle the multi-physics problems. The advantage of using commercial FEM program is

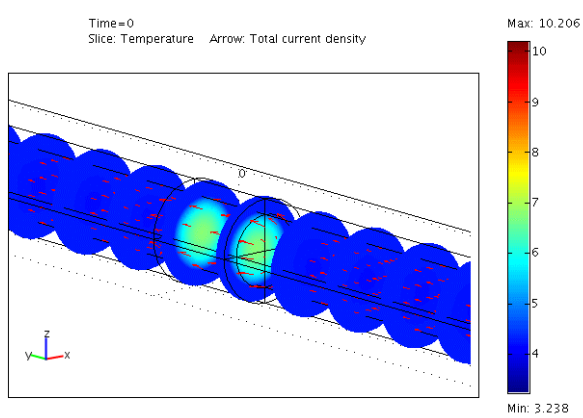

Fig. 1. 3D animation of quench recovery of a monolithic strand, made by FEMLAB. At the central 1 mm long part, energy of 40 µJ was given. The local current is shown bypassing the central superconductor.

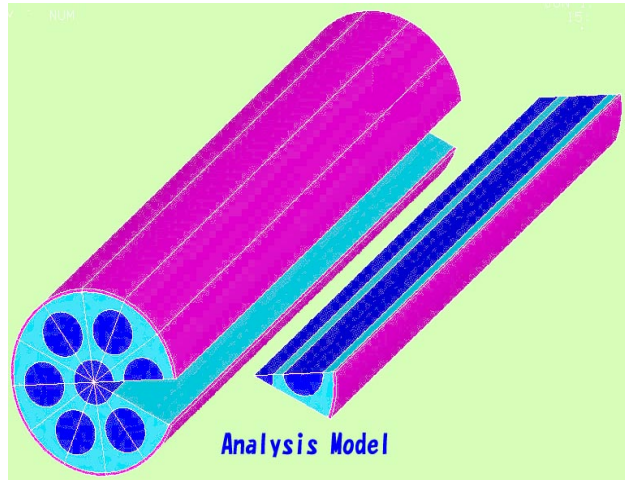

Fig.2. The 7-strand simulation model. 7-filament modules of diameter 0.22mm mounted in copper stabilizer forming a 1mm-diameter superconducting strand. A layer of epoxy of thickness 0.1mm covers the surface of the strand. The simulation model uses 30-degree symmetry to reduce the meshing size.

its graphic display and the easy construction of the geometrical model. Figure 2 is the analysis model used in the ANSYS calculation. 3D geometry is generated with the ANSYS utility. Recent internal-tin high current density Nb3Sn conductors are made of filament bundles that contain many filaments coupled together. These filaments in the model can be interpreted as such filament bundles. Actually, there are two types of conductor models regarding the copper stabilizer arrangement as shown in Fig.3. Bronze method, DT method [8] and RHQT Nb_3Al [9] have the stabilizer copper just in the strand outer surface (Model B), while RRP and PIT have copper in adjacent to the filaments / filament bundles (Model A). The location of the copper affects to the stability characteristics. In the model study, an additional bronze layer was artificially added to the (A) model to compensate the effect of bronze heat capacity. Since the cooling of the conductor is limited by epoxy, this artificial layer does not affect to the cooling of the conductor. Both models have exactly the same amount of materials with different geometry. The copper to superconductor ratio is 1.0

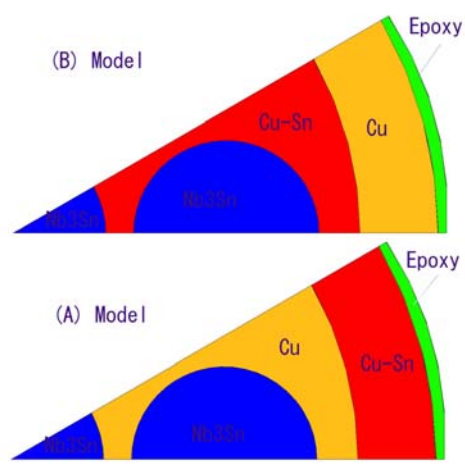

Fig. 3. Two Types of Model.
(A) Model represents NbTi, PIT and RRP. (B) Model represents DT, Bronze method and Nb_3Al conductors

for both cases. Figure 4 shows the temperature profile during the propagation of the normal zone. It is interesting that the temperature distribution patterns are very different depending on models. In the (A) model, representing a PIT or RRP conductor, the heat generation occurs in the copper at very close to the superconductor. On the other hand, model (B), representing a DT conductor or a bronze method conductor, the heat generation happens in the stabilizer close to the surface and the heat is conducted to the superconductor through the bronze part of the conductor. The wave front of quench propagation advances not in the superconductor but in the copper part of the conductor in both cases. Shape of the quench front is therefore different. The quench characteristics are different accordingly.

C. *Heating initiated Quenches*

The quench of a strand can be initiated by a heat input to the model strand. Figure 5 is the plot of normal zone length for different heat inputs. The heat was given at the surface of the conductor simulating friction heat by the wire motion or a crack of epoxy. Recovery to the superconductivity is seen for small disturbances but the heat greater than a threshold generates a quench. The minimum quench energy (MQE) is found from this plot. For the quenches induced by the heat greater than MQE, slope of the normal zone is the same regardless the heating energy. Thus the quench propagation velocity is defined as a function of current. Comparison of two models in regard to quench propagation is plotted in Fig.7. Quench propagation velocity is clearly affected by the configuration of the strand The quench propagation velocity in (A) model is faster than the (B) model. Since the copper is located close to the surface, the effective Steckley's parameter, α, become effectively small in (B) model. This explains the fact that the observed quench propagation velocity in bronze method Nb_3Sn magnets are often reported very slow compared to the NbTi propagation velocities.

D. *Different Disturbance Energy Location*

If the quench is caused by the crack of epoxy or the friction due to a wire motion, the heat is generated on the surface of the strand. Figure 5 is the result for such case. If the disturbance is due to flux jump, the heat is generated directly in the superconductor. The situation in this case is shown in Fig.6. The developments of quenches look very different depending on the location of the disturbance. The energy level to initiate a quench is quite different. The internal heating requires much less energy to cause a quench. Therefore the flux jump in the conductor can be a cause of quench even if the released energy is much smaller than the MQE determined by a heater experiment. Experiment using external heater often give a result with great stability.

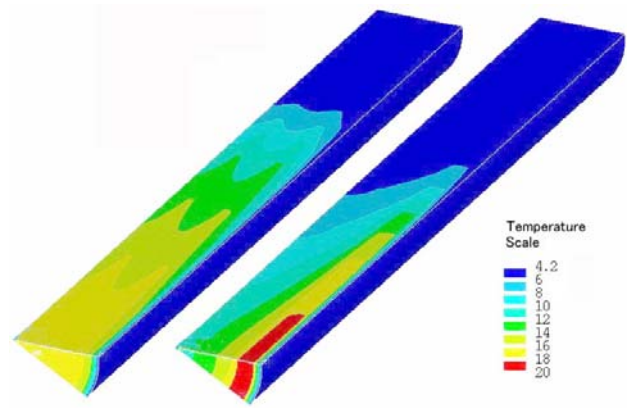

Fig. 4. Propagation of quench in model-strands. The location of copper in the strand affects the quench propagation property. Left (A Model) is the model with filament bundles mounted in copper. Right (B Model) is the model with filament bundles mounted in bronze.

E. *MPZ*

Although the MQE determined by Fig.5 and Fig6 are quite different, the minimum normal zone to start quench are almost the same for both cases. This supports the validity of minimum propagation zone (MPZ) theory [1] to discuss the stability of the conductor rather than using MQE. Whether normal zone shrinks or grows is determined by the size of initial normal zone (INZ). The energy necessary to create the same INZ depends on how and where the energy is deposited. The simulation giving INZ as a simulation parameter can determine MPZ. Figure8 is the example of the simulation. The analytical calculation for one dimensional continuum model gives the

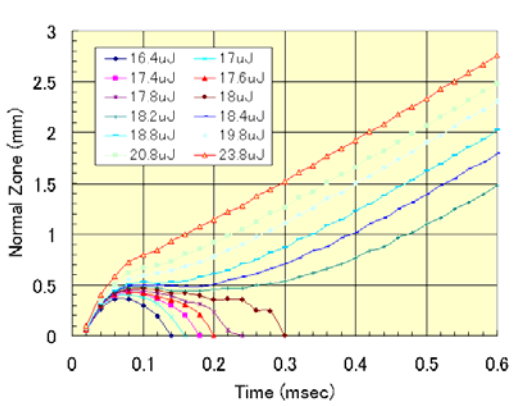

Fig. 5. Heater Initiated Quench.
(B) Model with 2000A/mm2 current density. Heater length is 1mm and the heat pulse duration is 10 μsec. MQE is determined 18 μJ and MPZ looks about 0.5 mm.

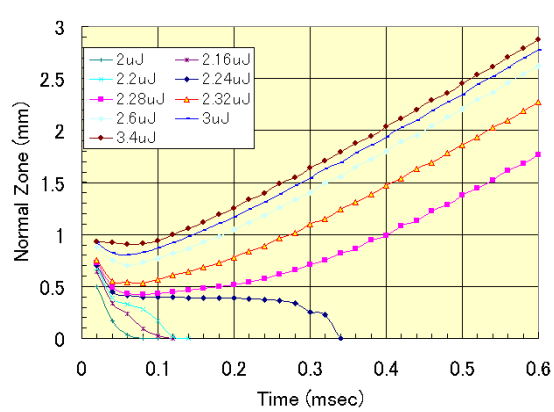

Fig. 6. Internal Heating Initiated Quench.
(B) Model with 200A/mm2 current density. MQE is 2.25μJ and MPZ is about 0.5mm.

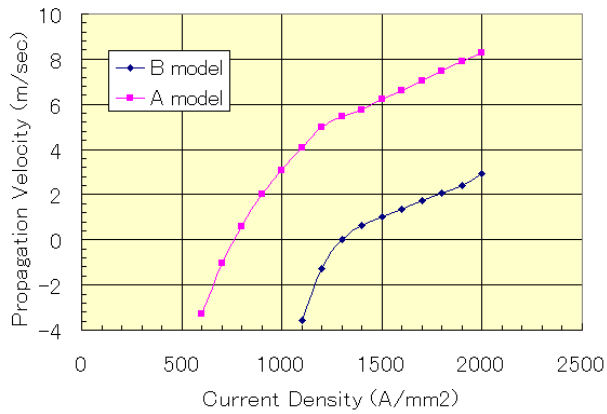

Fig. 7. Quench Propagation Velocity.
40μJ of energy was given to the 1mm section of the superconductor. Negative velocity is the recovery speed after normal zone was created by the thermal diffusion of initial heat pulse.

MPZ as the function of the current, J, thermal conductivity, k, and resistivity, ρ as:

$$MPZ = \frac{r}{r+1}\sqrt{\frac{2k(\theta_c - \theta_b)}{J^2 \rho}} \qquad (1),$$

where r is the copper ratio and θ_c and θ_b are the conductor and bath temperature [1]. This expression was confirmed also applicable to the 3D-multifilament case from this simulation. Figure 9 depicts the current dependence of the MPZ.

F. RRR values and MPZ

The behavior of MPZ characteristics is also dependent on the resistivity. The RRR of the copper stabilizer is the dominant parameter for this aspect. Figure 9 also shows the difference due to RRR of the copper. The large RRR (=100) gives larger MPZ than the small RRR (=50). It is clearly confirmed through this simulation that the RRR value of the copper stabilizer has a large effect in the stability of the conductor. Contamination of copper due to the over reaction of the conductor is a serious problem for the stability of Nb3Sn magnets. It is important to keep the RRR of the copper at high level to produce a successful Nb3Sn magnet [4].

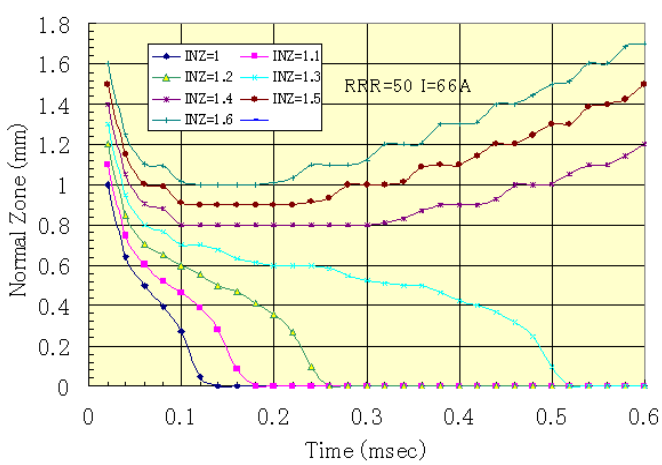

Fig. 8. Determination of MPZ.
The MPZ of the RRR=50 conductor is found 1.35mm at Current 66A from this simulation result.

III. Conclusions

A three dimensional multifilament strand was simulated by FEM models to study the stability. The simulation successfully distinguished the difference of the conductor structure and heating condition. The superconductor is much more sensitive to the internal heating than external heating. The MPZ theory developed for analytical model was confirmed by this simulation. The effect of RRR of the copper stabilizer is also important to have stability of the conductor as predicted in our earlier paper [4]. The animation of quenches is very intuitive and helpful to understand the situations.

References

[1] M. N. Wilson, Superconducting Magnets. Oxford: Clarendon Press, 1983, p.76.

[2] R. Yamada, E. Marcin, Ang Lee, Masayoshi Wake and Jear-Miche Rey. “2D/3D Quench simulation using ANSYS for epoxy impregnated Nb3Sn high field magnets”, *Proceeding of 2001 Particle Accelerator Conference*, pp.3424-3426, June 2001.

[3] R. Yamada, E. Marscin, A. Lee, and M. Wake, “3D ANSYS Quench Simulation of Cosine Theta Nb3Sn High Field Dipole Magnets”, *IEEE Trans. Appl. Supercond.*, vol.14, no.2, pp. 291-294, 2004.

[4] R. Yamada and M. Wake, “Quench Problems of Nb3Sn Cosine Theta High Field Dipole Model Magnets”, *IEEE Trans. Appl. Supercond.*, vol.15, pp. 1140-1143, 2005.

[5] T. Kurusu, H. Hashizume and S. Toda, “Coupled thermo-electromagnetic analysis of type-II superconductors”, *IEEE Trans. on Magnetics*, vol. 29, no.2, pp. 1550-1553, March 1993.

[6] H. Hashizume and S. Toda, “Electromagnetic thermal analysis of low/high Tc superconducting wire”, *IEEE Trans. on Magnetics*, vol.34, no. 5, pp. 3016-3019, September 1998.

[7] R. Pecher, M. D. McCulloch, S.J. Chapman, L.Pigozhin and C.M. Elliot, “3D-modelelling of bulk type-II superconductors using unconstrained H-formulation”, Proceedings of the 6th European Conference on Applied Superconductivity (EUCAS), Sorrento, Italy, (Sept.14-18) 2003.

[8] M. Wake, T. Shintomi, S. Nakayama, K. Egawa, Y. Kubo, T. Nagai, T. Sone, K. Hiramoto, O. Taguchi, H. Kitakoga,"Development of High Current Densitu Nb3Sn Conductor with Distributed Tin Configuration", Advances in cryogenic engineering,vol 50 p410-416 (2004)

[9] R. Yamada, G. Ambrosio, E. Barzi, V. Kashikin, A. Kikuchi, I. Novitski, T. Takeuchi, M. Wake and A. Zlobin, “Design Study of 15 Tesla RHQT Nb_3Al Block Type Dipole Magnet”, *presented at this conference*, September 2005.

[10] M. Wake, T.S. Jaffery, T. Shintomi, K. Mimori,H. Sugawara, R.M. Scanlan, A.D. McInturff, A.F. Lietzke , "Nb3Sn Insertion Coils for the Magnet Development", *Proc. MT-15* pp103-106 1998.

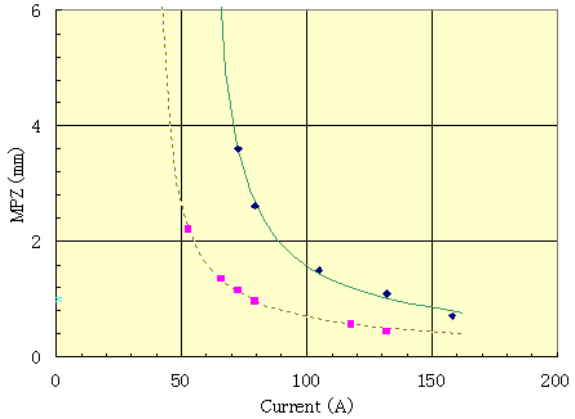

Fig. 9. The MPZ determined from the simulation.
It is seen that the MPZ is an inverse function of the current and also depend on the RRR of the conductor. Solid line is for the case of RRR=100 and broken line is for RRR=50.