Failure Analysis of 75T Pulsed High Field Magnet in WHMFC

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Abstract —A designed 75T magnet in WHMFC failed at the peak field of 67T. The whole winding was pushed out from the stainless steel shell (SSS), which is a quite different failure than what have been observed before. The numerical simulations show that the asymmetric structure of the SSS induces unexpected 48 kN axial unbalanced magnetic force on the winding. The simulation also shows that the highest stress in the G10 flange reaches to 100 MPa, which is much higher than the break strength of G10. As a result, the axial unbalanced force induced by asymmetry destroyed the G10 flanges and pushed the whole magnet winding out from the SSS.

I. INTRODUCTION

High magnetic fields are powerful tools for studying the properties of matter because they couple directly to the electronic charge and magnetic moments of the protons, neutrons and electrons of which matter is made up. They have been used for research in many scientific disciplines, including solid state physics, chemistry, medicine, plasma science and high-energy physics. Pulsed magnets have played and will play an important role for generating high fields, primarily because they can generate much stronger magnetic fields and this in an economical way. The performance of pulsed magnets is governed by the ability of the materials to withstand the Lorentz forces. As an isotropic material, stainless steel can distribute the stress evenly in the axial direction and thus increase the stability of the coil. Stainless steel shell (SSS) are used in almost all pulsed magnets.

The schematic model of the designed 75 T magnet with SSS is shown in Fig.1. The magnet winding is wound from 10 layers of soft copper wire. The bore radius of the magnet is 5 mm, the axial length 100 mm. Each layer of the copper wire is reinforced with a layer of Zylon fiber composites. The winding is inserted into a 5 mm thick stainless steel shell reinforced with 20 mm thick carbon composites, so that the magnet can survive from the huge Lorentz force [1]-[2]. At the two ends, the winding are tightened by 20 mm thick G10 flanges.

Because the stainless steel is conductive, the coupling between the magnet winding and the SSS induces eddy current, resulting in axial magnetic force [3]-[4]. The equivalent axial magnetic force on the whole SSS is the difference between the force on the top and bottom half. When the SSS is symmetric about mid-plane of the magnet winding, the equivalent axial magnetic force is zero. The magnets with symmetric SSS normally fail in the mid-plane, where the stress is the highest [2]. In this magnet, the top end of the SSS is longer than the bottom end in order to fix the contacts with epoxy and fasten the winding in the axial direction. The length of the top and bottom end is 70 and 30 mm, respectively, which make the SSS asymmetric in the axial direction.

II. THE MAGNET FAILURE

The magnet was energized by a 3.2mF / 25 kV capacitor bank. At 18.5kV charge voltage, the peak field reached at 61.2 T. In the next pulse, the charge voltage increased to 20.5kV, peak field of 67 T was expected. However, the magnet failed violently just at the moment when the field reached at the peak value. The pulsed magnetic field waveform of 61.2T and the failure shot are shown in Fig. 2. The magnet after failure is shown in Fig.3. It is obvious that the whole winding was pushed out from the SSS. The bottom G10 flange was torn into pieces and several bolts broke, while the SSS and carbon composite were almost intact. This is a quite different failure than what we have observed before [5]-[7]. The particular failure indicates unexpected strong axial force in the winding.

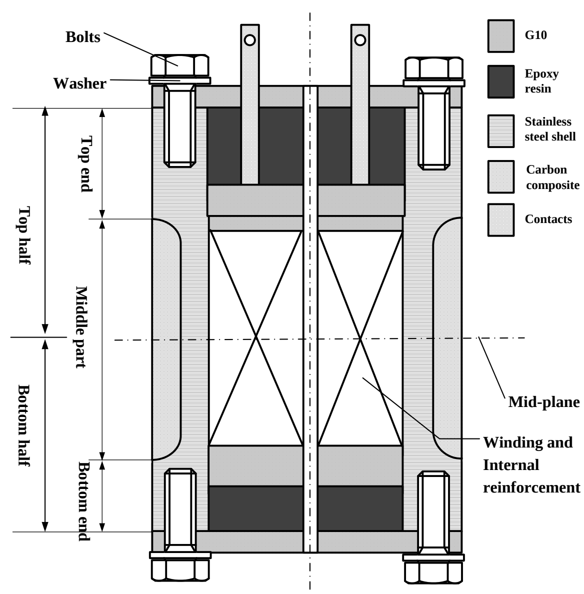

Fig.1. Schematic model of the designed 75T magnet

III. THE MAGNET FAILURE ANALYSIS

The axial magnetic force on the top-half, bottom-half and the whole SSS has been calculated during the magnetic pulse. Fig. 4 shows the calculated results. Because of the asymmetry of top and bottom ends of the SSS, eddy current in the top-half is higher, which gives higher axial magnetic force. The equivalent axial magnetic force on the whole SSS has the tendency to push the winding to the bottom of the SSS.

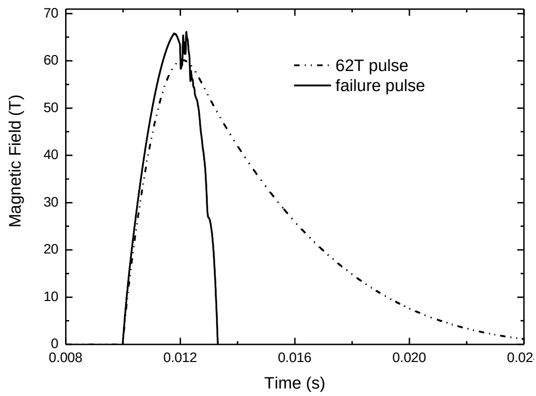

Fig. 2. Measured pulsed magnetic field waveform of 61.2T and the failure shot

Fig. 3. Photograph of the magnet after failure. The whole magnet winding has been pushed out from the SSS. The G10 flange at the bottom of the magnet was torn into pieces by the magnet winding and several bolts broke.

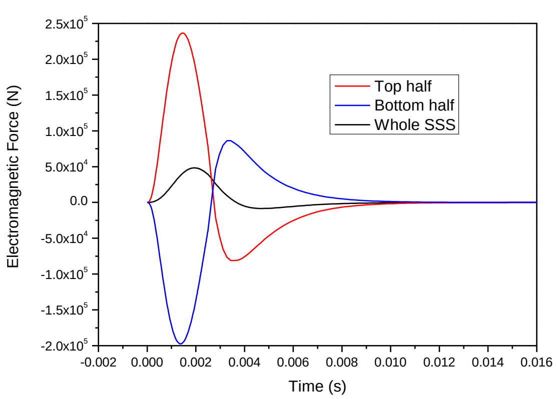

Fig. 4.The axial magnetic force applied on the top half, bottom half and the whole SSS. The unbalanced axial magnetic force is caused by the difference between the top half and bottom half.

Simulations show that the equivalent axial magnetic force reaches at 48 kN at the peak field of 67 T, which pushes the winding against the bottom G10 flange. Fig.5 shows the stress distribution in the G10 flange. The modulus of G10 is assumed to be 22 GPa. Simulation with linear mechanical properties shows that the highest stress at the inner surface of the bolt hole is 100 MPa, which is much higher than the break strength of G10, so the G10 flange would break at the peak field of 67T firstly.

After the G10 flange and bolts was damaged, there still has a large axial force on the winding. The winding was accelerated continuously, and finally pushed out from the SSS at very high-speed. The theoretical analysis agrees with the failure phenomena.

A second magnet has been manufactured and tested. The magnet is identical to the failed magnet except that the SSS is symmetric. Fields up to 75.5 T have been achieved without failure.

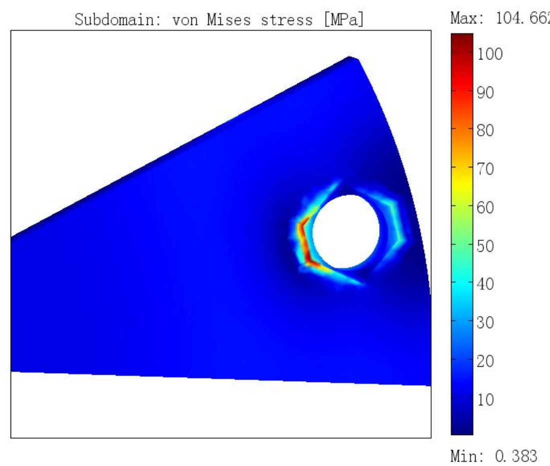

Fig. 5. The simulated stress distribution in the G10 flange surrounding the bolt at 67T. The calculated highest stress is 100 MPa by assuming linear mechanical properties

IV. Conclusion

SSS can distribute the stress evenly in the axial direction and thus increase the stability of the coil. However, the axial unbalances magnetic force caused by asymmetric structure of the SSS play a leading role in this magnet failure. It is recommended to make a symmetric magnet structure.

V. References

[1] Herlach F, Pulsed magnets *Rep. Prog. Phys.* vol. 62, pp. 859–920, 1999.

[2] Li L, “High performance pulsed magnets, theory, design and construction,” Ph. D. dissertation, K. U. Leuven, Belgium, 1998.

[3] T. Peng, et al., “Influence of a thick stainless steel shell on the field waveform of a pulsed magnet”, *J Low Temp Phys.*, vol. 159, pp. 341-344, 2010

[4] L Li, et al., “Insert coil design of the first 100 T non-destructive magnet” *IEEE Trans. Appl. Supercon.*, vol. 30, no. 1, March 2002.

[5] James R. Sims, et al., “The U.S.NHMFL 60 T long pulse magnet failure” *IEEE Trans. Appl. Supercon.*, vol. 12, no. 1, Jun. 2002.

[6] Charles A. Swenson, et al., “Performance of 75 T prototype pulsed magnet”, *IEEE Trans. Appl. Supercon.*, vol. 16, no. 2, pp. 1650-1655, Jun., 2006.

[7] Charles A. Swenson, et al., “80 T magnet operational performance and design implications”, *IEEE Trans. Appl. Supercon.*, vol. 18, no. 2, pp. 604-608, Jun., 2008.