HTS magnet for 7.3 kJ SMES system

G Wojtasiewicz1, T Janowski2, S Kozak1,3, B Kondratowicz-Kucewicz1, J Kozak1, P Surdacki2 and B A Glowacki4

1Electrotechnical Institute in Warsaw, Nadbystrzycka 38A, 20-618 Lublin, Poland
2Lublin University of Technology, Nadbystrzycka 38A, 20-618 Lublin, Poland
3CERN, Accelerator Technology Department, Geneva, Switzerland
4University of Cambridge, Pembroke Street, CB23QZ, United Kingdom
E-mail: grzegorz@asppct.pl

Abstract. One of the most promising power applications of high – Tc superconductors are Superconducting Magnetic Energy Storage (SMES) systems for storing and instantaneous discharging large quantities of power. The SMES system stores energy in the magnetic field generated by the flow of DC current in a coil of superconducting material that has been cryogenically cooled. This paper describes design of a 7.3 kJ conduction – cooled, high – Tc superconducting (HTS) magnet for experimental SMES system. This magnet consists of 14 single pancake – coils wound with Bi-2223 High Strength Wire with critical current of 115 A at 77 K. The operating current of the magnet is 135 A at 35 K. The described magnet is cooled in high vacuum cryostat using two-stage G-M cryocooler SRDK-408.

1. Introduction
Superconducting magnetic energy storage, SMES, system is a device for storing and instantaneously discharging large quantities of power. It stores energy in the magnetic field created by the flow of DC current in a coil of superconducting material that has been cryogenically cooled [1].

This paper describes the first approach to construct and investigate the SMES that has been undertaken in the Laboratory of Superconducting Technologies of Electrotechnical Institute in Warsaw. Actually, so far it has been also the first attempt to undertake research in the field of SMES systems in Poland.

2. Design of The Superconducting Pancake Coil For SMES Magnet
The most important element of SMES is superconducting magnet which stores electric energy in form of magnetic field [1]. FLUX 2D software package has been used in design and optimization of magnet windings. Numerical model of the winding has been conducted. Changing initial technical and electrical parameters resulted in several construction solutions depending on the number of pancake coils of superconducting magnet. During project designing stage the length of superconducting tape was prefixed to 1500 m and the outer diameter of the coil, 2a2, was equal 360 mm, which also was predefined by cryostat’s diameter. Therefore the inner radius of analysed coils will vary accordingly as specified in Table 1. Basic technical and electrical parameters of magnet like: inductance of winding, magnetic flux density, inner and outer radii of the winding as well as operating current and stored energy, defined by number of pancake coils of the magnets, number of layers and turns are presented in Table 1 [2] [3]. The values of operating current and respective energy stored in the winding are given depending on operating temperature of the superconducting winding. The obtained solutions
consider electromagnets with (grey colour on table) and without interlayer between the pancake coils, which influences total height of the winding and other parameters of the electromagnet, like inductance, critical current, stored energy. To choose the solution for the realization it is necessary to consider the possibility to store higher amount of energy at optimal winding geometry.

| No of design | No. of coils | No. of Layers | Inner radius \(a_{1}\), mm | Height of coils \(h\), mm | Inductance \(L\), H | \(B_{\text{max}}\) (100 A) | \(I_{C}(35 \text{ K})\) | \(E_{C}(35 \text{ K})\) | \(I_{C}(50 \text{ K})\) | \(E_{C}(50 \text{ K})\) |
|--------------|--------------|--------------|-----------------------------|-----------------------------|------------------|-----------------------------|------------------|------------------|------------------|------------------|
| 1            | 6            | 297         | 87.9                        | 40.2                        | 0.78             | 1.55                        | 123              | 5908             | 62               | 1491             |
| 2            | 6            | 297         | 87.9                        | 25.2                        | 0.86             | 1.81                        | 117              | 5849             | 58               | 1446             |
| 3            | 8            | 200         | 118.0                       | 53.6                        | 0.81             | 1.36                        | 128              | 6631             | 65               | 1702             |
| 4            | 8            | 200         | 118.0                       | 33.6                        | 0.91             | 1.62                        | 121              | 6643             | 61               | 1667             |
| 5            | 10           | 152         | 132.9                       | 67.0                        | 0.80             | 1.25                        | 131              | 6871             | 67               | 1782             |
| 6            | 10           | 152         | 132.9                       | 42                          | 0.91             | 1.56                        | 123              | 6835             | 62               | 1724             |
| 7            | 12           | 123         | 141.9                       | 80.4                        | 0.78             | 1.21                        | 132              | 6813             | 67               | 1774             |
| 8            | 12           | 123         | 141.9                       | 50.4                        | 0.90             | 1.45                        | 125              | 7081             | 63               | 1803             |
| 9            | 14           | 104         | 147.8                       | 93.8                        | 0.76             | 0.99                        | 139              | 7359             | 72               | 1961             |
| 10           | 14           | 104         | 147.8                       | 85.8                        | 0.89             | 1.36                        | 128              | 7292             | 65               | 1872             |
| 11           | 15           | 96          | 150.2                       | 100.5                       | 0.75             | 0.95                        | 140              | 7331             | 72               | 1962             |
| 12           | 15           | 96          | 150.2                       | 63.0                        | 0.88             | 1.31                        | 129              | 7360             | 66               | 1898             |
| 13           | 16           | 89          | 152.4                       | 107.2                       | 0.73             | 0.9                         | 142              | 7305             | 74               | 1966             |
| 14           | 18           | 79          | 155.5                       | 120.6                       | 0.71             | 0.86                        | 143              | 7298             | 74               | 1974             |

\(B_{\text{max}}\) - maximal field in axial direction for operating current 100 A

2.1. Results of Numerical Analysis

The analysis results of obtained construction solutions of superconducting magnet, given in Table 1, are presented in figures below. The symbols: 0.18/o-r and 0.16/o-r indicate the magnet without interlayers with outer radius respectively 180 and 160 mm, and the symbol 0.18/i-l indicate the magnet with interlayers and outer radius 180 mm.

From maximization of magnetic field strength point of view, considering resulting coil dimensions see Table 1, the optimal configured magnet should consist of 6 coils without interlayers (0.18/o-r).

![Figure 1. Inductance of the magnets vs. number of pancake coils.](image)

Inductance and magnetic flux density of the superconducting winding versus number of pancake coils is presented in Figure 1 – Figure 3. It is evident that with the increase of pancake coils number, that is increase of winding height, the inductance of winding, initially grows and then decreases, whereas magnetic flux density significantly decreases. Calculation’s results are given for the winding with and without interlayers, working in operating temperature 35 and 50 K respectively. For winding without interlayers, obtained values of inductance and magnetic flux density are higher. From maximal inductance point of view the optimal configured magnet should consist of 8 – 10 pancake coils without interlayers (0.18/o-r), but from magnetic field density point of view the magnet should consist of minimal number of pancake coils.
Figure 2. Magnetic flux density vs. number of pancake coils for operating temperature of 35 K.

Figure 3. Magnetic flux density vs. number of pancake coils for operating temperature of 50 K.

Figure 4 and Figure 5 present critical current of the magnet versus number of pancake coil. The decrease of superconductor’s operating temperature from 50 K to 35 K enables increase the value of critical current. From maximization critical current point of view the magnet should consist of maximal number of pancake coils at minimal value of axial magnetic field density (see Fig.2 and 3).

Figure 4. Critical current vs. number of pancake coils for operating temperature of 35 K.

Figure 5. Critical current vs. number of pancake coils for operating temperature of 50 K.

Energy of superconducting magnet versus number of pancake coils and operating temperature, 35 and 50 K respectively, are presented in Figure 6 and Figure 7. In both cases with the increase of pancake coils numbers, the energy stored in the winding increases. The value of energy is influenced by the value of operating current of the winding, the higher current the higher value of energy (see Fig. 4 and 5) and by the value of inductance (see Fig.1). From maximal energy point of view the optimal configured magnet should consist of 14 – 15 pancake coils with interlayers (0.18/i-l)

Figure 6. Energy vs. number of pancake coils for operating temperature of 35 K.

Figure 7. Energy vs. number of pancake coils for operating temperature of 50 K.
3. SMES Superconducting Magnets

After analysing achieved results, the optimized design of magnet was defined for the realization. The main optimization criterion of the electromagnet design was maximal stored energy, that was able to obtain for predefined parameters of the electromagnet (see section 2). This final magnet will consist of 14 pancake coils with interlayers connected in series. Figure 8 shown single pancake coil and its bobbin made from duralumin. Figure 9 show electromagnet’s pancake winding’s connected in series. Also, on Fig.9, we can see the interlayers between each of pancake coils which influences parameters of the electromagnets and act also as a electrical insulation of the coils. [2] [4].

![Figure 8. Diagram of single pancake coil of the electromagnet.](image)

![Figure 9. Diagram of SMES electromagnet.](image)

4. Conclusions

Numerical analysis of the model of the superconducting magnets for SMES system resulted in several construction solution depending on the number of pancake coils of the magnet. After analysis of numerical results the optimized magnet, should consists of 14 pancake coil. The bobbin of the single pancake coils will be made of duralumin. The magnet, under construction, will be cooled in high vacuum cryostat using two-stage G-M cryocooler.

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