PHYSICAL AND NUMERICAL MODEL OF HTS MAGNET FOR 7.3 KJ SMES SYSTEM

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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 generated by the flow of DC current in a coil of superconducting material that has been cryogenically cooled. The SMES recharges within minutes and can repeat the charge/discharge sequence thousands of times without any degradation of the magnet.

This paper described a 7.3 kJ conduction – cooled, high – Tc superconducting (HTS) magnet for SMES system. This magnet consist of 15 pancake – coils wound with Bi-2223 High Strength Wire with critical current 140 A at 35 K.

Key words – Energy Storage Systems, superconductivity, SMES, superconducting electromagnet for SMES

1. ENERGY STORAGE SYSTEMS OVERVIEW

Over the years a lot of energy storage systems for electrical energy were developed. The most frequently used systems are show in Fig.1.

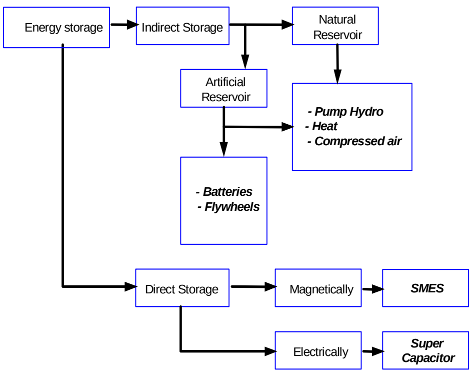

Fig. 1. Overview of Energy Storage Technologies [1]

They can be divided in to indirect storage (into a natural or artificial reservoir) by using an intermediate medium, for example: heat, compressed air, batteries, flywheels, and direct storage into the magnetic field (SMES) or electric field (super capacitor) of an inductor [1].

Some of mentioned storage technologies in particular Superconducting Magnetic Energy Storage system will be discuss shortly.

1.1. FUEL CELLS

Fuel cells, like all electrochemical cells, convert stored chemical energy directly into electrical energy [2]. The most favoured and common fuel used in these cells is hydrogen. The combustion of hydrogen in oxygen produces only water, which is not a pollutant, and also hydrogen has a very high energy density when compared with other fuels. Figure 2 shows the operation of the fuel cells.

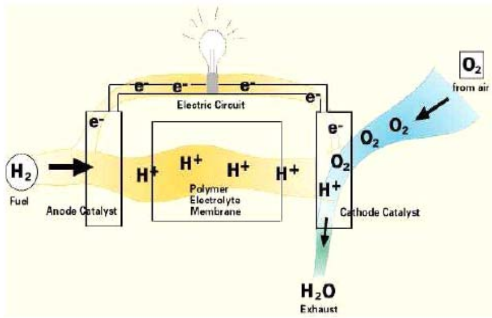

Fig. 2. Operation of the hydrogen fuel cells [2]

A fuel cell consists of two electrodes, known as the anode and cathode that are separated by an electrolyte. Oxygen is passed over the cathode and hydrogen over the anode. Hydrogen ions are formed together with electrons at the anode. The hydrogen ions migrate to the cathode through the electrolyte and the electrons produced at the anode flow through an external circuit to the cathode. At the anode they combine with oxygen to form water. The flow of electrons through the external circuit provides the current of the cell.

1.2. COMPRESSED AIR ENERGY STORAGE

In Compressed Air Energy Storage (CAES), off - peak power is taken from the grid and is used to pump air into a sealed underground cavern to a high pressure. The pressurized air is then kept underground for peak use. When needed, this high pressure can drive turbines as the air in the cavern is slowly heated and released. Components of the system CAES system are show in Fig. 3. [2]

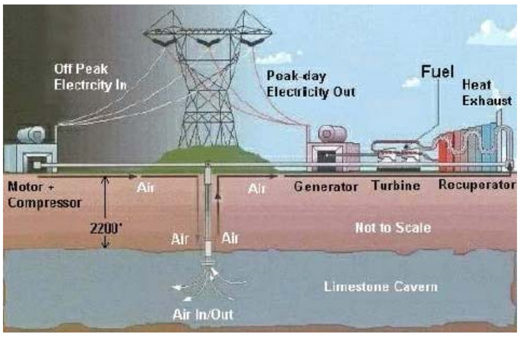

Fig. 3. Components of a CAES system [2]

Main parts of the system are: cavern, compressor to compress the air, and turbine. There are many geologic formations that can be used in this scheme. These include naturally occurring aquifers, solution-mined salt caverns and constructed rock caverns. In general, rock caverns are about 60% more expensive to mine than salt caverns for CAES purposes.

1.3. SUPERCAPACITOR

Capacitors are some of the most essential building blocks of electronic circuits to hold DC voltages [2]. Based on the same principle, but on a much larger scale, it is conceivable that capacitors could be used to store energy for extended periods of time. Figure 4 presents the idea of supercapacitor operation and the commercial supercapacitor offered by ESMA.

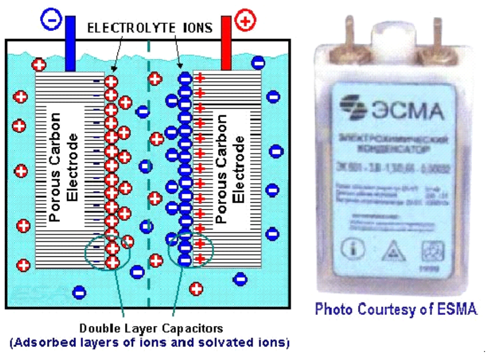

Fig. 4. Operation of the supercapacitor and commercial supercapacitor offered by ESMA [2]

The capacitance of the capacitor is 80 kF, and the energy stored about 90 kJ.

1.4. FLYWHEELS

About 20 years ago, flywheels were thought of as a method of storing kinetic energy [2]. The diagram shows the schematic diagram of the flywheel (Fig.5.).

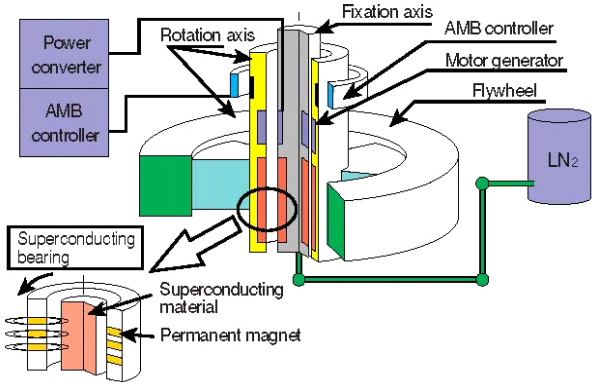

Fig. 5. Schematic diagram of the superconducting magnetic bearing flywheels

A flywheel storage device consists of a flywheel that spins at a very high velocity and an integrated electrical apparatus that can operate either as a motor to turn the flywheel and store energy or as a generator to produce electrical power on demand using the energy stored in the flywheel. The use of magnetic bearings and a vacuum chamber helps reduce energy losses. In last time the superconducting bearing was used. A proper match between geometry and material characteristics influences optimal wheel design. Flywheels have been proposed to improve the range, performance and energy efficiency of electric vehicles. The picture presents the commercial 6 kWh flywheel (Fig.6.).

Fig. 6. Commercial 6 kWh flywheel [2]

1.5. SUPERCONDUCTING MAGNETIC ENERGY STORAGE – SMES

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 in a coil of superconducting material that has been cryogenically cooled [2]. This diagram on Fig.7 shows the idea of storing energy in magnetic field.

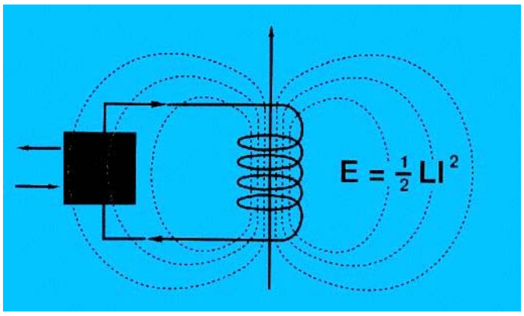

Fig. 7. Idea of SMES works [4]

The energy stored in the magnetic field depends on the value of coil inductance and current flowing throw the coil. The bigger current and inductance the bigger stored energy. If the coil is wound using a conventional wire such as copper, the magnetic energy would be dissipated as heat due to the wire's resistance to the flow of current. However, if the wire is superconducting (no resistance), then energy can be stored in a persistent mode, virtually infinitely. Superconductors have zero resistance to DC electrical current at low temperatures so that ohmic heat dissipation is eliminated. In other hand the current density of superconductor is at least order of magnitude bigger than copper. It caused that the current in superconducting winding is bigger than current in cooper winding [4].

Next diagram (Fig.8.) shows the simple set – up of the SMES system.

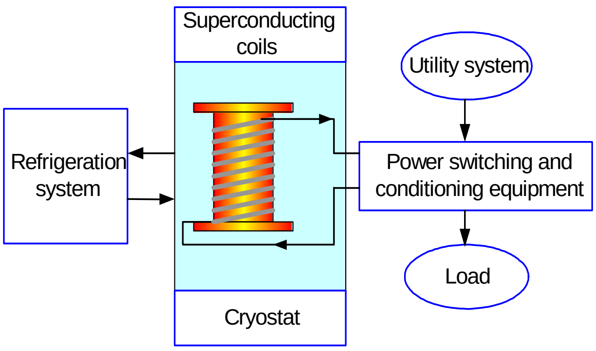

Fig. 8. Basic set – up of the SMES system [2]

This system includes a superconducting coil, a power conditioning system, a cryogenically cooled refrigerator for cooling the coil, and a cryostat/vacuum vessel. The basic operation of a complete SMES system is very simple. The transmission voltage (from the AC network) is first stepped down from a few hundred kV to several hundred volts using a step-down transformer. This is then converted into DC which is fed into the superconducting coil. Hence when the power flows from the system to the coil, the DC voltage will charge up the superconducting coil and the energy is stored in the coil. The maximum energy stored depends on the design of the device. When the AC network requires a power boost, the coil discharges and acts as a source of energy. The DC voltage is converted back into AC voltage through the converter.

Rated power versus energy for SMES in comparison with other most important energy storage systems is show in Fig.9.

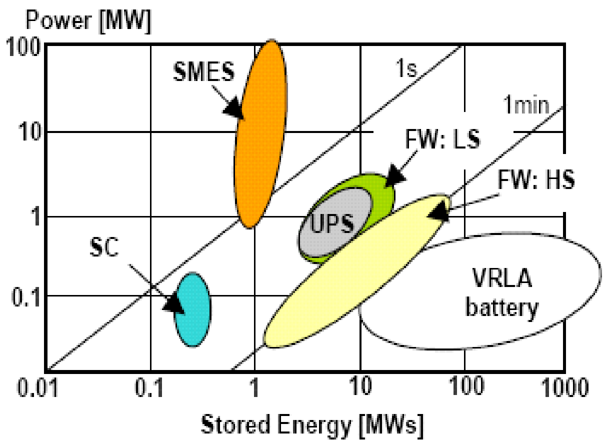

Fig. 9. Rated power versus energy for SMES for most important energy storage systems [1]

We can mention that conventional storage systems (rotating UPS, flywheel and traditional batteries) are preferable when there is the need for emergency power during a rather long time (this time is longer than 1 min). On the other hand, SMES and SC systems are able to inject stored energy within seconds into the grid. Therefore, the most viable applications of SMES and SC systems are improving power quality by absorbing voltage sags and providing peak power when necessary. The power of SMES rated from 1 to 100 MW is much bigger than power of other storage system. The storage energy is about 1 MWs [1].

Diagram in Fig. 10 present perspective application of SMES and their localization in various power engineery systems.

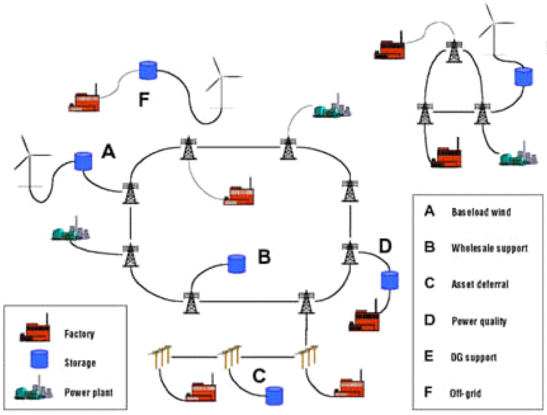

Fig. 10. Potential SMES applications [3]

Figure 11 shows 2 MJ SMES designed and made by ACCEL Instruments GmbH [5]. The SMES is connected by a DC link converter to the electrical grid of the plant. The system is designed for carrying over time of 8 s at an average power of 200 kW. The SMES electromagnet is wound of NbTi mixed matrix superconductor and cooled by liquid helium. The helium will be recondensed with a two stage cryocooler. Specification of the SMES system is given in table 1.

Table 1. Specification of 2 MJ SMES [5]

SMES	2 MJ SMES
• SMES Current	I_{SMES} = 1000 A
• Stored Energy	2.1 MJ
• Average power	200 kW
• Maximum power	800 kW
• Carry Over Time	>8 s
• DC Link Voltage	Up to 800 V
• Magnetic field	4.5 T
• Inductivity	4.1 H
• Magnet Diameter	760 mm
• Height	600 mm

fig. 11. 2 MJ SMES system [5]

2. DESIGN OF THE SUPERCONDUCTING PANCAKE COIL FOR SMES ELECTROMAGNET

Research project focused on the construction of SMES physical model has been carried out in the Laboratory of Superconducting Technology. The most important element of SMES is superconducting electromagnet which stores electric energy in magnetic field. FLUX 2D package has been used at designing and optymalization of electromagnet windings. Numerical model of the winding has been made. Changing initial technical and electrical parameters resulted in several construction solutions depending on the number of pancake coils of superconducting electromagnet. During project designing phase the length of superconducting tape was limited to 1500 m and the outer diameter of the coil was 360 mm which resulted from the cryostat's diameter.

The table 2 shows basic technical and electrical parameters of electromagnet like: inductance of winding, magnetic flux density, inner and outer radii of the winding as well as operating current and stored energy, depending on number of pancake coils of the electromagnets, number of layers and turns.

Table 2. Technical and electrical parameters of SMES electromagnet

No. Coils	No. Layers	No. Turns	R_1	R_2	h	L	$B_{(100\,A)}$	$I_{(35\,K)}$	$E_{(35\,K)}$	$I_{(50\,K)}$	$E_{(50\,K)}$
			mm	mm	mm	H	T	A	J	A	J
6	297	1782	87.93	180	40.2	0.782717	1.55	122.8669	5908.055	61.7284	1491.230
6	297	1782	87.93	180	25.2	0.859624	1.81	116.6559	5849.136	58.00464	1446.119
8	200	1600	118	180	53.6	0.811486	1.36	127.8409	6631.179	64.76684	1701.988
8	200	1600	118	180	33.6	0.905538	1.62	121.1306	6643.303	60.67961	1667.102
10	152	1520	132.88	180	67	0.801842	1.25	130.9091	6870.659	66.66667	1781.871
10	152	1520	132.88	180	42	0.909265	1.56	122.6158	6835.234	61.57635	1723.806
12	123	1476	141.87	180	80.4	0.781342	1.21	132.0616	6813.409	67.38544	1773.958
12	123	1476	141.87	180	50.4	0.900065	1.45	125.4355	7080.845	63.29114	1802.726
14	104	1456	147.76	180	93.8	0.764142	0.99	138.7818	7358.836	71.63324	1960.529
14	104	1456	147.76	180	58.8	0.892353	1.36	127.8409	7291.996	64.76684	1871.596
15	**96**	**1440**	**150.24**	**180**	**100.5**	**0.747185**	**0.95**	**140.0778**	**7330.556**	**72.46377**	**1961.733**
15	96	1440	150.24	180	63.0	0.881627	1.31	129.2175	7360.336	65.61680	1897.951
16	89	1424	152.41	180	107.2	0.727296	0.9	141.7323	7304.976	73.52941	1966.09
18	79	1422	155.51	180	120.6	0.712981	0.86	143.0843	7298.468	74.40476	1973.556

The values of operating current and respective energy stored in the winding are given depending on operating temperature of the superconducting winding. The lower temperature of the superconductor the higher operating current. The solutions consider electromagnets with (grey colour on table) and without interlayer between the pancake coils, which influences total height of the winding. To choose the solution for the realization it is necessary to consider the possibility to store higher amount of energy at optimal winding geometry.

Results of the analysis of obtained construction solutions of superconducting electromagnet, given in table 2, are presented on following charts (Fig. 12-17).

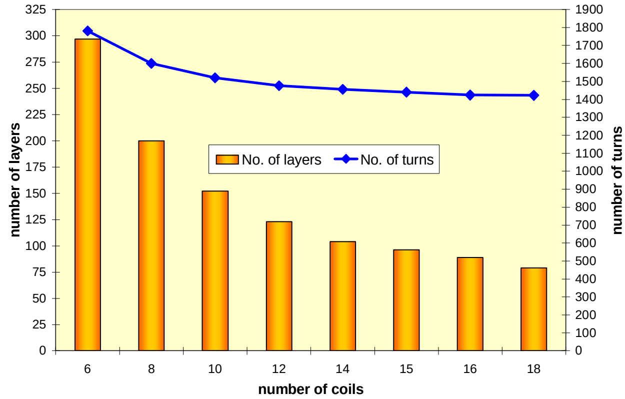

Fig. 12. Number of layers and number of turns of superconducting winding at number of pancake coils

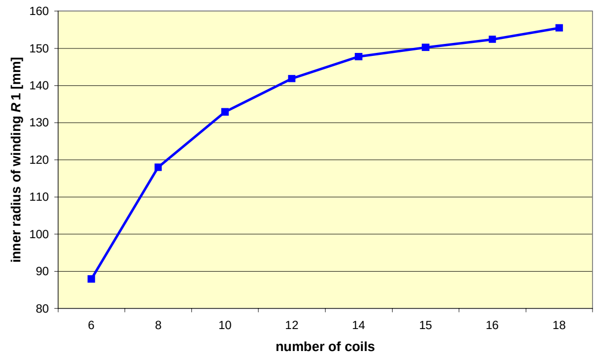

Fig. 13. Inner radius of superconducting winding at number of pancake coils

The Fig. 12 shows number of layers and number of turn of superconducting winding at number of pancake coils. It proves that the higher number of pancake coils the lower number of layers and the lower number and turns. Diagram in Fig.13 shows inner radius of the superconducting winding at number of pancake coils. It proves that along with the number of pancake coils the radius of the coil increase.

Next two charts (Fig.14. and Fig. 15.) present inductance and magnetic flux density of the superconducting winding at number of pancake coils and total height of the winding. It results from them that along with the increase in 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 results are given for the winding with and without interlayers. In case of the winding without interlayers obtained values of inductance and magnetic flux density are higher.

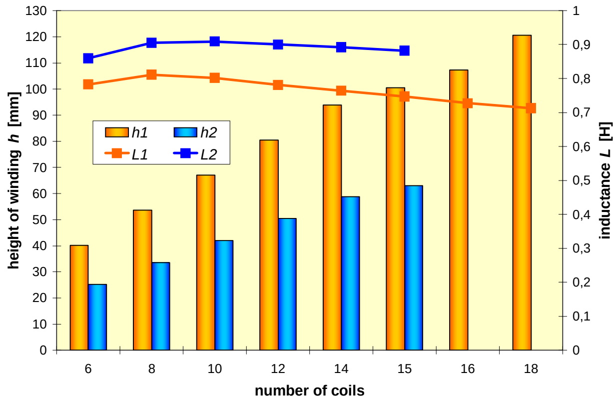

Fig. 14. Inductance of the superconducting winding at number of pancake coils and total height of the winding: h_1 – height with the interlayer; h_2 – height without interlayer

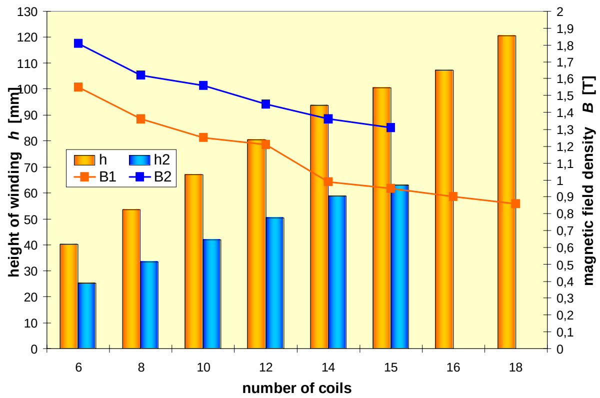

Fig.15. Magnetic flux density of the superconducting winding at number of pancake coils and total height of the winding: h1 – height with the interlayer; h2 – height without interlayer

Energy of the superconducting winding at number of pancake coils, total height of the winding and operating current is shown in Fig.16 and Fig.17.

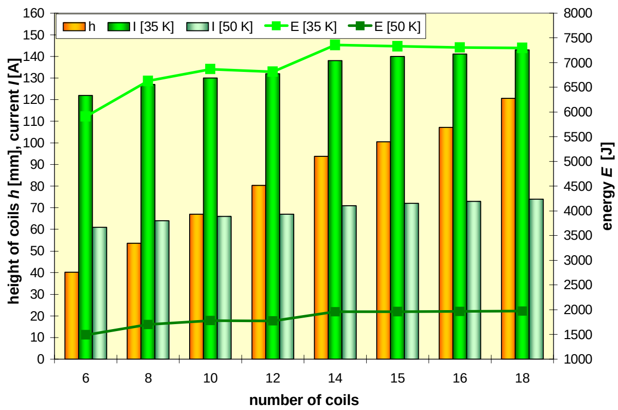

Fig. 16. Energy of the superconducting winding at number of pancake coils, total height of the winding and operating current: h – height with interlayer

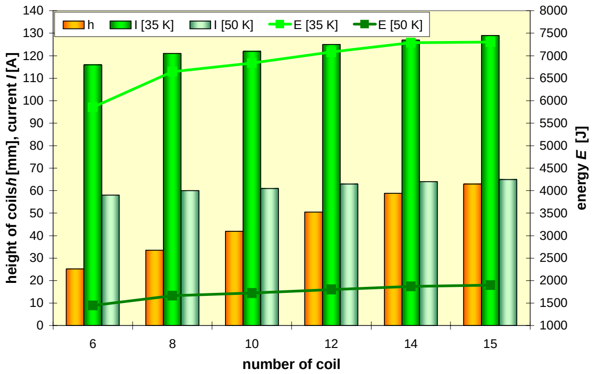

Fig. 17. Energy of the superconducting winding at number of pancake coils, total height of the winding and operating current: h – height without interlayer

Chart in Fig 6. for higher winding (with interlayers), chart in Fig.17. for lower winding.

In both cases with the increase of pancake coils numbers, the energy stored in the winding increases; the height of the winding in this case does not significantly influence this value. The value of energy is influenced by the value of operating current of the winding, the higher current the higher value of energy. The decrease of operating temperature of superconductor from 50 K to 35 K enabled to increase the value of current.

3. DESIGN OF SMES SUPERCONDUCTING ELECTROMAGNET

After analysing pervious results, the design of electromagnet with the parameters shown in table 3 was chosen for the realization.

Table 3. Specification of SMES superconducting electromagnet

Superconducting SMES electromagnet assembled with 15 pancake coil		
Length of the conductor	m	1500
No. of coils	-	15
No. of layers	-	96
No. of turns	-	1440
Inner radius R_1	mm	150.24
Outer radius R_2	mm	180
Height h	mm	100.5
Inductance L	H	0.747
Magnetic flux density $B_{(100\ A)}$	T	0.95
Current $I_{(35\ K)}$	A	140
Energy $E_{(35\ K}$	J	7330.5
Current $I_{(50\ K)}$	A	72.45

This electromagnet will be consist of 15 pancake coils with interlayers. The table 4 shows the parameters of HTS tape to construct the winding. The cross-section of HTS tape is shown in Fig.18.

Table 4. Parameters of the HTS tape

Superconducting tape	HTS High Strenght Wire – Stainless Steel Laminated Wire	
Superconductor	Bi2223 ($Bi_2Sr_2Ca_2Cu_3O_{10}$)	
Thickness	mm	0.31
Width	mm	4.2
Min. bend diameter	mm	70
Critical current I_c	A	115
Critical temperature T_c	K	77

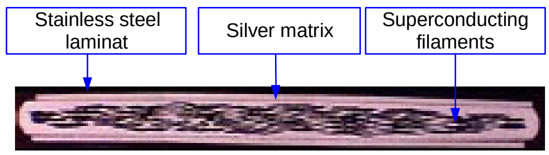

Fig. 18. Cross section of the HTS tape

The next drawings present construction elements of the superconducting electromagnet. Fig.19 shown single pancake coil and its bobbin made from duralumin; Fig.20 show electromagnets winding which consist of 15 pancake coils connected in series. Also, on Fig.20, we can see the interlayers between each of pancake coils. The interlayers act also as a electrical insulation of the coils.

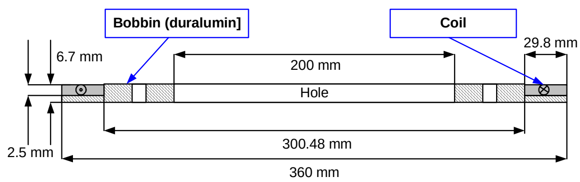

Fig. 19. Schematic diagram of single pancake coil

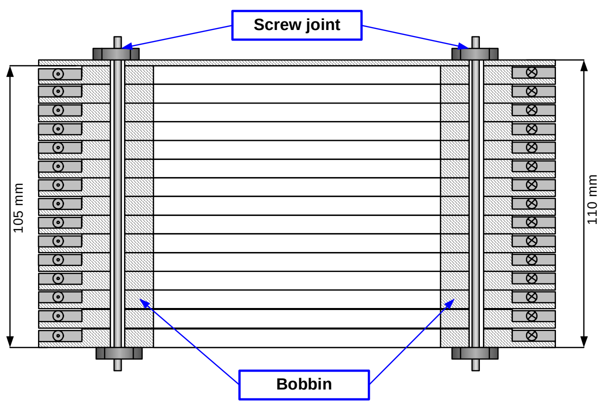

Fig. 20. Schematic diagram of SMES superconducting electromagnet

4. DESIGN OF SMES MODEL

This Fig. 21 shows SMES schema in particular superconducting electromagnet cooling system.

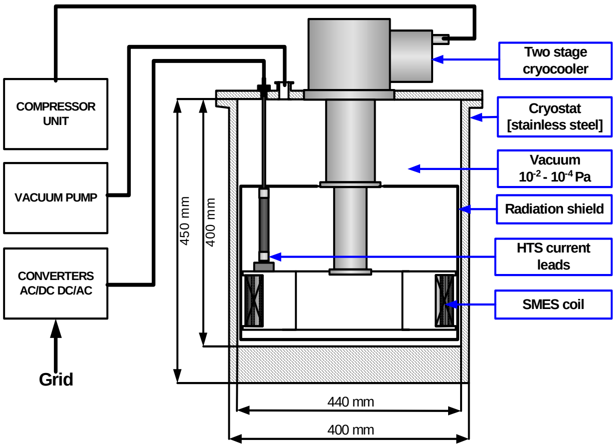

Fig. 21. Schematic diagram of the SMES and cooling system of SMES superconducting electromagnet

This system comprises the following elements: 4.2 K cryocooler SRDK 408 to cool superconducting winding, compressor unit, vacuum pump and cryostat in which winding is placed. The high vacuum inside the cryostat acts as a thermal super insulation. Superconducting current leads, to energize the coil, supplements this cryogenic system. Other part of SMES system is the power switching and conditioner equipment which connect the SMES with the grid.

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