REVIEW ON THE PERFORMANCE LIMITS OF A LARGE SUPERCONDUCTING MHD-MAGNET

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Abstract

The magnet under discussion has been built for research in closed-cycle-MHD energy conversion to be in operation with the largest existing loop "Argas". Special features of the design are great accessibility for diagnostics and sufficient space for the electrodes. The design was made for 4T and will be described shortly. The magnet coil design created energizing problems which have been investigated using different power supplies, i.e. different charging circuits. Thereby interesting effects could be observed. They can be explained by an imperfect part of either the wire or the winding in one of the coils and by the special winding construction with shunting strips across each layer.

I. Introduction

The magnet construction started 1968, which explaines why partially very conservative construction rules have been used, based on the knowledge at this time. The work has been carried out by the Gardner Cryog. Comp.,Penns.,USA. The special type of construction caused many problems for the operation. In the first period of the operation, 1970/71, experiences with the refrigeration loops had to be yielded, because no comparable system, directly cooled by a refrigerator, was running at this time. This will be summarized briefly in chapter 3. In this paper we emphasize, in particular, the discussion of the results of many energizing processes with different charging circuits carried out to investigate the performance limits caused by the special winding type. Probably this winding type is also responsible for the observed interaction effects with the conducting MHD-plasma during the operation of the magnet in the Argas MHD-loop, discussed in chapter VI.

II. Construction of the Magnet

A description has been given in a previous paper[1]. Fig 1 shows the principles of the cryostat construction and the geometrical dimensions as an optimal solution for maximal accessibility to the center from all sides, required for MHD-research purposes. Each coil is contained in its own cryostat. This cryostats are held apart from each other by four compression tubes surrounding the room temperature access.The tubedimensions are calculated with respect to the large attracting mechanical forces between the coils up to 10^6 lb. There is a space along the outer face of the coil dewars to aid cooling. The remainder of the helium part of the system consists of a liquid storage volume above each coil dewar, provided by tubes in longitudinal direction and larger tubes between the coil faces at each end of the dewar. The total volume for liquid helium is about 250 ℓ inside the coil dewars and 300 ℓ in the reservoir. To minimize radiation to the liquid helium temperature parts or sections of the system, all 4,4 K surfaces are wrapped with foil.

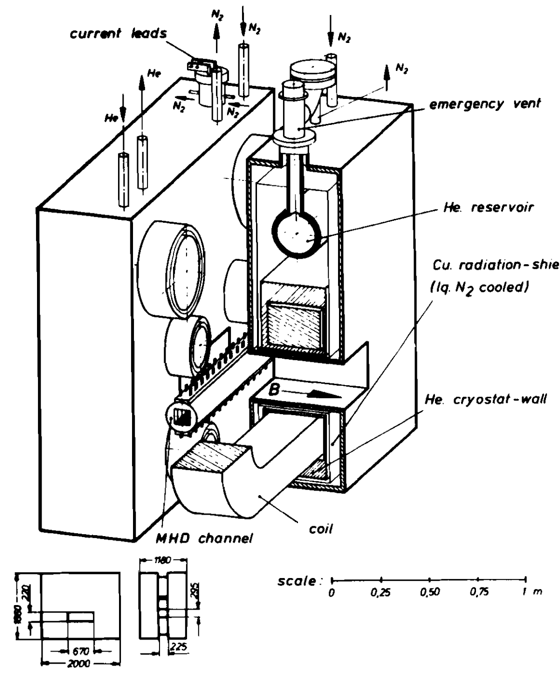

Fig.1. Design principles of the magnet.

A copper radiation shield surrounds the helium dewar inside the vacuum space. Tubes are welded on it which are cooled by a liquid nitrogen flow from a refrigeration system described below. The shield is suspended from the coil dewars by spacers and is not connected to the vacuum jacket. The emergency vent on top of one coil dewar is designed so that the helium dewar will not have to stand excessive pressure($\leq$ 45 lb /in^2) even if the full energy of the coils ($\leq$10MJ) is dumped in to the liquid helium.

The main current leads are optimized for 500 A and are liquid nitrogen cooled near their ends.

The magnet with a total weight of about 22 000lb can be moved on a trolley even in liquid helium filled condition without a disconnection of the refrigerator because of the partial flexible helium transfer line.

The magnetic behavior as later on being discussed in the paper depends on the special winding construction, so a more detailed description shall be given here. The conductor has the following specifications:

- -material: T 48 NbTi from Supercon
- -dimensions: 0,57 x 0,114 in.
- -current-field requirement: 500A at 80kG
- -copper to superconductor ratio: 2,33:1
- -number of superconducting strands: 21
- -twist rate of strands: 1/4 ft
- -insulation: black copper oxide

Fig. 2 shows a microphotograph of the conductor, fig.3 typical short sample data together with the calculated peak field on the conductor and the central field of the magnet.

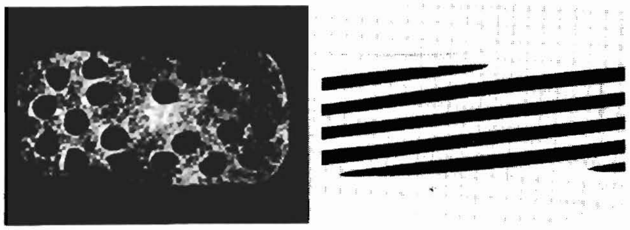

Fig. 2. Cross sections of the used conductor.

Each of the coils, which are connected in series consists of 91 layers with 89 turns each. The resulting inductance is 115 Henry. The layers are separated from each other by fiber glass strips, whereas turns in a layer are separated from each other by a nylon thread of 0,005 in. diameter, wound around the conductor with a pitch of about 2,5 in. Therefore a direct helium cooling of the total conductor surface is provided, but probably on account of the possibility of small mechanical motions of the conductor. Using the theory of cryogenic conductor stabilization[2] with the given conductor dimensions, a recovery current of about 500 A results, if the heat transfer is assumed at 0,1W/cm^2. Therefore the winding should be fully stabilized at the design current of 420 A with an mean current density of 6500 A/cm^2.

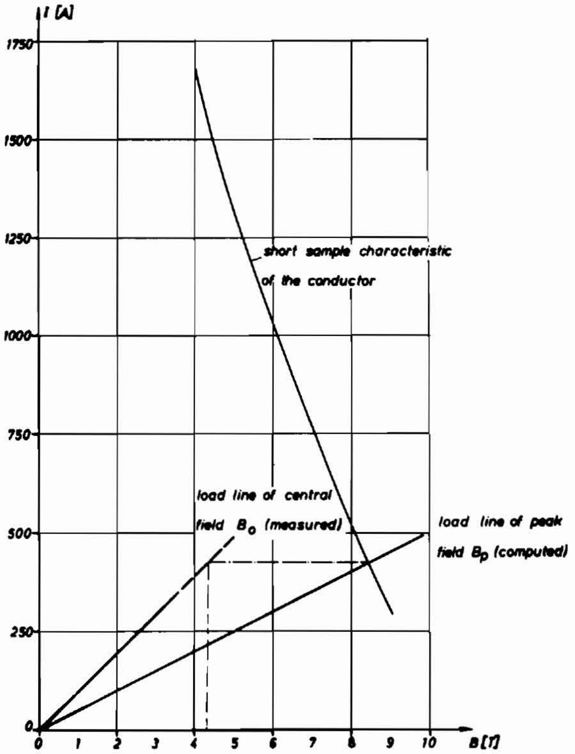

Fig.3. Short sample data of the conductor together with the calculated peak field at the conductor and the central field of the magnet.

A special feature of the design is the use of internal shunts, introduced to minimize the danger of damage to the winding during a quench. Each layer has four strips of phosphor bronze foil soft-soldered to and connecting the first and last turn. The resistance of each strip is 0,25 Ω and it is loosely covered with mylar insulation. This technique, no longer used in modern magnet design, caused most of the effects during the energizing processes, which will be discussed later.

Fig. 4 shows the calculated and measured field distribution along the axis also outside of the magnet in the stray field region.

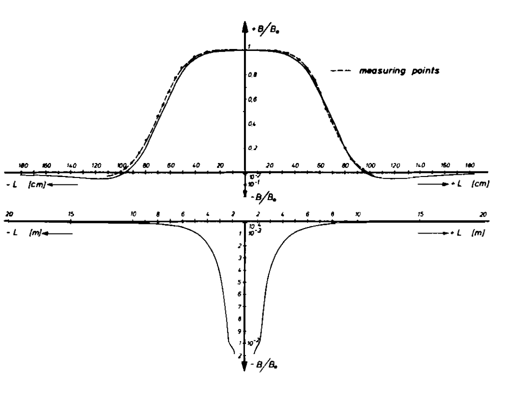

Fig. 4. Field distribution along the axis of the magnet.

Many power supplies with different electronic control systems and different crowbar resistors have been tested. Best result yielded the circuit sketched in Fig.5 with a new state-of-the-art high current power supply of the Siemens Comp. Its special feature is an electronically controlled current rise, rather than using a motor driven potentiometer , and a variable time constant for the stability control adjustable to any load inductance.

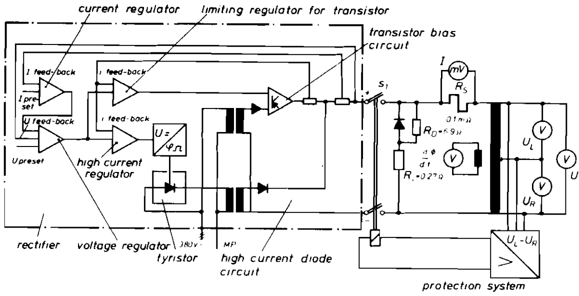

Fig. 5. Charging circuit of the magnet with electronic power supply and quench protection circuit.

III. Cryogenic Supply and its Performance.

To provide a continuous economic long time operation of the system two refrigeration circuits were considered, one for the helium and one for the nitrogen section. Fig.6 shows the principles of these circuits with a capacity of 67W at 4,4 K for the helium system and 2 400W at 80 K for the nitrogen system, respectively. The overcapacity of the He-refrigerator,

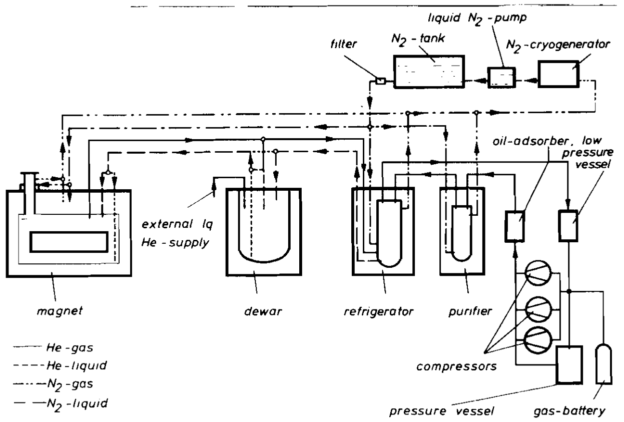

Fig. 6. Refrigeration circuits for magnet operation.

manufactured by the German Linde Comp., was only small, resulting in a larger gas back-stream during the energizing processes, which caused some difficulties to keep the system in equilibrium. It has been discussed more detailed in another paper[3] with the following basic results:

- observation of dynamic heat loss oscillations during the cool-down periods,
- boil-off gas measurements of the system in liquid He-filled condition showing values between 12-14 Nm^3/h, indicating heat losses of the cryostat of 12-14 W,
- in the contrary the total refrigeration consumption was about 45W which can only be explained by large losses on the bayonet-couplings to the transfer line system.
- subcooling of the expansion machine, causing a reduced refrigeration power when more back gas is present by additional losses, e.g. by the magnetisation currents during energizing.
- cool-down time of 200 h from room temperature to liquid helium temperature using only the refrigerator.

IV. Results of Energizing Tests.

The problems of energizing such a large system with stored energies above 5MJ and an inductance of more than 100 Henry has been investigated very carefully. In spite of the fully stabilized lay-out of the winding premature fast quenches have been observed, for which we did not have a sufficient explanation for quite a while.

With the first conventional power supplies in use flux jumps occurred, starting mostly at the right side coil. Ripples in the output voltage trigger more and larger flux jumps in spite of the large smoothing coil inductance, and cause consequently a larger helium boil-off. With the above-mentioned modern power supply only a few flux jumps occurred and a better understanding resulted from the observation of the following effects:

Firstly if the time constant of the control circuits are switched to very small values, which means a very sensitive regulation, the right side coil voltage and subsequently the total voltage oscillates with an amplitude of about 50% of the mean value and a frequency of about 2 Hz, in the current hold mode of the power supply. This indicates small periodic effects inside the coil caused perhaps by mechanical vibrations of a winding or being a resonance phenomenon of the system magnet & control circuits.

Secondly a complex process seems to occur statistically during the energizing period, demonstrated in Fig. 7. The right side coil voltage increases suddenly, accompanied by a current increase and gets back to its original value.

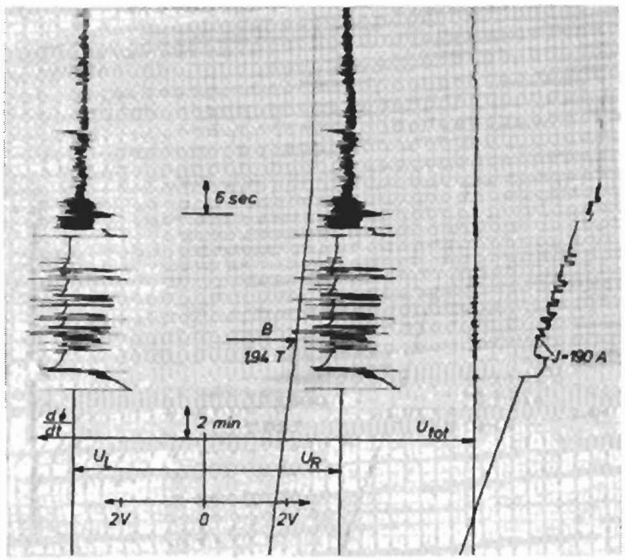

Fig. 7. "Strange"-effects during charging.

One possible explanation would be a partial winding shorting, but this can only be effective if these turns were simultaneously normally conducting. A more probable explanation can be given by considering the described shunt strips across each layer. If we assume one layer will become normally resistive by some reason, its resistance will be about 10,5 mΩ. The resistance of the strips is 45 mΩ, so that now about 20% of the current flows through the strips instead through the turns of the layer. To compensate for this in order to achieve constant flux, the current must become higher.

We feel that the above-described effects are the reason for premature quenches, because any time, when such voltage increase sets on above 30 kG, the system quenched. The recorder diagrams showed obviously that the process mostly starts at the right side coil, so that we think the effect can be traced down to an imperfect piece of wire or winding, here.

A further indication for the above discussed shunting process can be derived from Fig. 8. Plotted here is the relation between field strength and current. The arrows indicate the time of such shunting processes, which also change the B/I-relation. Another reason for the deviation of the theoretical line is due to magnetisation currents, discussed later.

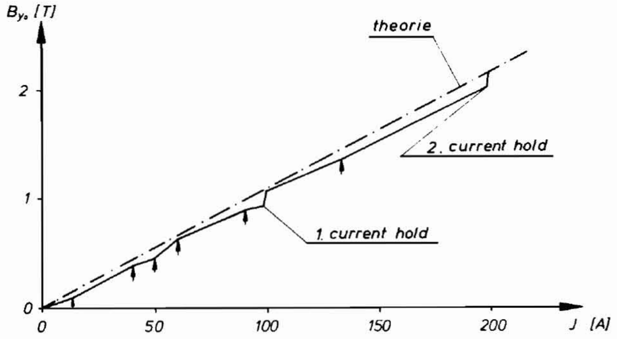

Fig. 8. Field strength versus current for an energizing process, the theoretical curve for comparison.

One of the premature quenches has been recorded by a fast light beam recorder. At the time when the crowbar has been activated, about ten percent of the windings must have been shunted under quenched condition, because the inductance was only about one percent of the original value, indicated by the relation U = -L.di/dt during the discharge process. In the moment after opening the power break at 290 A a coil voltage of 48 V could be measured. Using these values and the value of 0,27 Ω for the discharge resistor, an internal discharge resistance of 0,43 Ω can be calculated. Assuming that all turns are normally resistive, the total internal resistance is 1,45 Ω. If only ten percent were normally resistive, this were equal to the state that about $1/\sqrt{10}$ layers are shunted, so, the total internal resistance would be 0,45 Ω, in good agreement with the above estimated value.

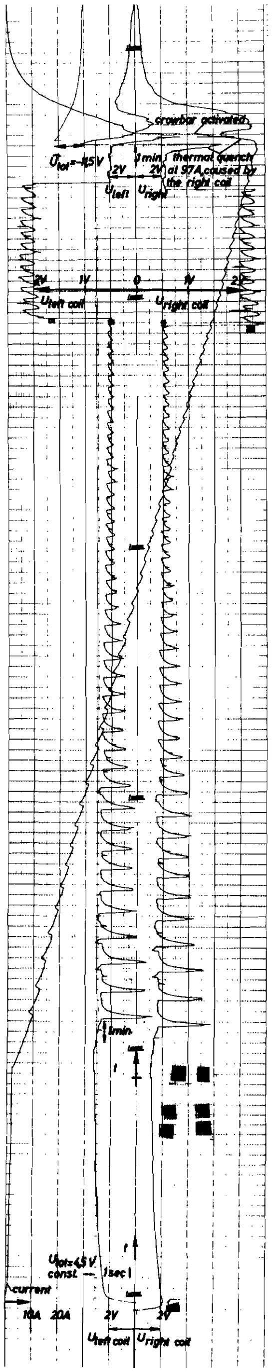

Fig. 9. Records of an energizing process with vapor cooled windings.

One interesting test has been carried out with vapor cooled winding. The energizing process started at a time when only the bottom of the coil cryostats were filled with liquid He. Fig.9 shows the result. Recorded are current and both, coil voltages and total voltage. You can see here that sometimes parts of the right side coil went into the normally conducting state, accompanied by a current decrease (an energy i·L·di/dt is dissipated during this time). The time period and the amplitudes are decreasing with increasing field. You can hardly see on the figure, that a small heterodyne oscillation is present too, which could not be explained yet. At 10 kG the system quenched thermally due to insufficient vapor cooling, because the heat created locally by the energy dissipation could not anymore be carried away by the vapor.

V. Magnetization Currents.

In Fig.8 are also shown two points of "current hold", at 100 A and 200 A. Here, the magnetic field was still increasing for a considerable time. The coil voltage was about zero, so that no winding shorting can be the reason for this effect, only the magnetization currents in the copper matrix can explain this increase. A rise of 1,5 kG in 100 min. at 200 A constant, as measured, equals to a shielding current of 15 A. This current causes a lot of additional heat losses demonstrated by the recorded He-evaporation in Fig.10. This additional boil-off becomes zero during the current holding period. The figure shows also the boil-off during the charging process with a standard power supply which is obviously much larger.

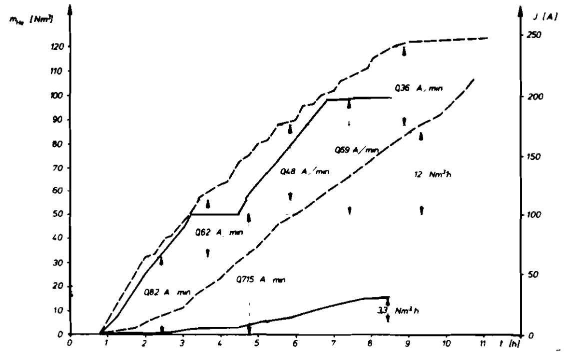

Fig.10. Additional He-boil-off during charging and constant current operation with two different power supplies.

VI. Interaction with the MHD-plasma.

During the operation of the Argas-MHD-loop, an especially interesting question was if interaction effects with the conducting MHD-plasma could be observed. Some time ago a pulsed MHD-generator has been operated with a superconducting magnet in the USSR[4]. The magnet had a twisted cable of Nb-Ti-Zr-wires and was operated in the persistent mode. No interaction with the pulses MHD-plasma stream has been observed. The result in our case is shown in Fig. 11. During the time of cesium injection, oscillations of large amplitudes of the left and right side coil voltage could be observed.

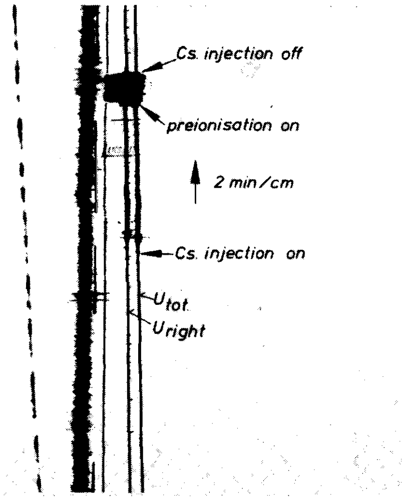

Fig. 11. Interaction effects between the coils and the MHD-plasma during an operation of the magnet in the MHD-test-loop.

Possibly, too, this performance is due to the special coil construction in connection with the above-mentioned effects.

VII. Summary.

Discussed are especially the effects on the performance limits of the magnet, designed for fields up to 42 kG. Thereby it has been found that an imperfect piece of wire or winding at the right side coil in connection with the special winding construction using shunting strips across each layer, is propably responsible for premature quenches observed statistically above 30 kG. In spite of a twist pitch of about 3 in., large magnetization currents are present also during slow energizing processes of about 50 A/h.

In operating the magnet together with the MHD-loop, interaction effects occur, indicated by oscillations of the coil voltages.

References

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4. V.A. Kirillin et al., Soviet Physics-Doklady, 12, 1059 (1968).