FABRICATION OF A PROTOTYPE OF A FAST CYCLING SUPERFERRIC DIPOLE-MAGNET

G. Sikler, W. Gärtner, A. Wessner, Babcock Noell GmbH, Würzburg, GERMANY
E. Fischer, E. Floch, J. Macavei, P. Schnizer, C. Schroeder, F. Walter, D. Krämer,
GSI, Darmstadt, GERMANY

Abstract

GSI had manufactured a prototype of a fast cycling superconducting dipole magnet at Babcock Noell GmbH (BNG). This is the first full size magnet for the SIS 100 synchrotron at the future Facility for Antiproton and Ion Research (FAIR) in Darmstadt. In close collaboration between GSI and BNG the magnet was technologically developed, manufactured, and assembled. The system was successfully tested at GSI reaching the nominal (i.e. the designed) cycling performance, including the high ramping rate of 4 T/s and the maximum field of 2.1 T. The superconducting cable and the coils are particularly subject to strong mechanical and thermal stresses. Here we describe the details on the fabrication of these components and give an outlook on possible improvements of the manufacturing technologies, applicable to future prototypes and series magnets for SIS 100.

INTRODUCTION

FAIR, large scale accelerator complex will provide ion and anti-proton beams of unprecedented properties to many experiments from various fields of fundamental research [1]. One of the accelerators to be built is the SIS 100. It is a super-conducting synchrotron for heavy ions and serves as a driver for all subsequent storage and accelerator rings.

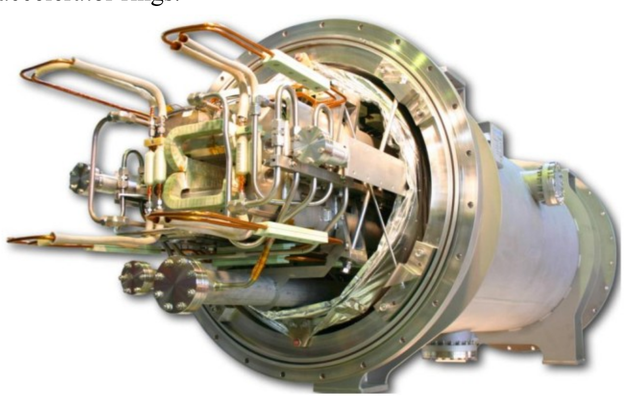

Figure 1: Photograph of the first prototype of a SIS 100 dipole magnet. The front part of the cryostat is opened to see the cold mass of the magnet. The vacuum beam pipe was inserted later.

The magnets of the SIS 100 will be ramped with high rates. (Figure 1 shows a photograph of the first dipole prototype.) The dipoles e.g. will be ramped with 4 T/s to their maximum field of 2.1 T during the acceleration process. The fast cycling mode induces eddy currents in all the electrically conducting parts of the magnet, i.e. the iron yoke, the coil, the cable and the superconducting (sc) wire itself. The design of cable, coils and yoke is optimized to reduce the eddy currents as much as possible. For the remaining contributions and the dominating hysteresis losses the dissipated heat has to be extracted efficiently from the magnet components, especially from the sc cable. To maintain superconductivity the temperature has to stay below its critical value at all times and over the entire length of the superconductor. The corresponding special demands for the design of cable and coils will be sketched in the following sections. But the main focus will remain on the technical implementation during manufacturing and assembly of the prototype magnet. The first test results and their evaluation are reported in [2].

FABRICATION OF SC CABLE – TYPE SIS 100

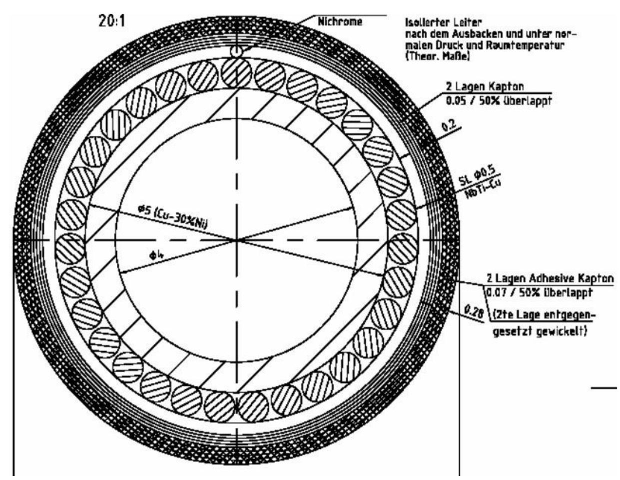

Figure 2: Schematic view of the cross section of the cable. The 31 sc strands are wound on the central cooling tube. They are kept in position and forced on the tube by a wrap of a fine wire. On the outside there are four layers (each half overlapping) of isolation tape.

The design of the new SIS 100 cable (see Fig. 2) is based on the sc cable of the Nuclotron type from the JINR in Dubna. 31 superconducting strands of a diameter of 0.5 mm each are wound around a tube made from Cu/Ni alloy. Two-phase Helium will flow through this central tube providing a very efficient cooling and removal of the dissipated heat from the sc wires and the cooling tube itself. To enhance the heat transfer between strands and tube and to maintain the position of the wires also against strong magnetic forces, the sc wire is tightly wrapped onto the tube with a fine wire made from Cr/Ni. The wire has a diameter of 0.2 mm and is wrapped with a pitch of 0.4 mm. Finally four layers of polyimide tape are wrapped around the cable as an electrical insulation and mechanical protection.

A sufficient amount of cable for the dipole prototype, for one additional full-size test coil and various cable pieces for winding and bending tests was fabricated during the project. For this purpose an existent cabling machine was procured and modified to fulfil the special requirements for this type of cable. Figure 3 shows a photo of the planetary strander cabling machine. (Formerly it was used by Kabelwerke Brugg to produce a part of the Rutherford cable for the LHC project at CERN.) The taping stations for the polyimide tape and the wire wrapping unit for the Cr/Ni fine wire had to be installed as new components.

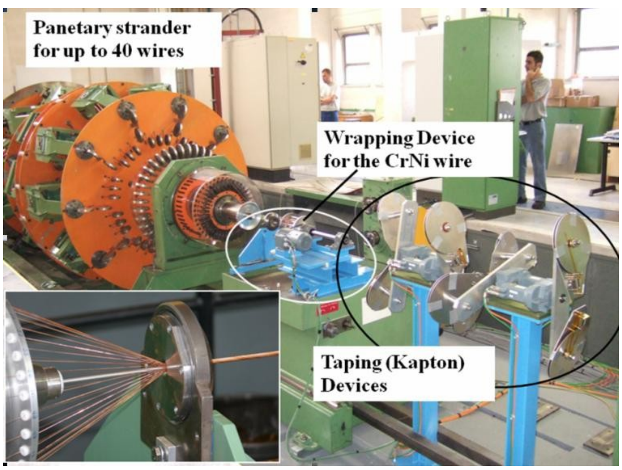

Figure 3: Cabling machine during its commissioning. From left to right: the planetary strander which can accommodate coils for up to 40 strands, the fine wire wrapping device, and the polyimide tape stations. Not shown are the caterpillar unit and the reservoir coil for the cooling tube and the re-winder for the final cable. The insert left below shows in more detail the cabling eye, where the 31 strands merge and are wound on the tube.

The very short pitch for the fine wire requires a rather high revolution frequency for the spinning device. During the production the spinning head was rotating with 705 turns per minute, being the leading limitation for the speed of the cabling process. The wire was wrapped under a pulling force of 5 – 10 N, which is considerably close to the force needed to rip it apart. A broken Cr/Ni wire defines the end of a useful cable length, since a re-joining of the fine wire would lead to an unacceptable imperfection of the cable. For a series production the Cr/Ni wire is recommended to be as thick as 0.3 mm to ensure a reasonably higher grade of process stability.

FABRICATION OF THE COILS

During the expected operation time of the SIS 100 the magnets will experience more than $2 \cdot 10^8$ ramping cycles. Protecting the cable and the winding pack against movement and fatigue under the strong dynamical forces and due to thermal cycles was the main scope of the coil design. The key parts of the new concept are structural elements (see Fig. 4) made from glass-fibre reinforced plastic (GRP), i.e. G11. They fill the entire empty volume of the coil which is not occupied by the cable itself. Like this the winding pack becomes a compact solid structure, which shows (nearly) now gaps and spaces providing perfect mechanical support from all sides over the entire length of the cable.

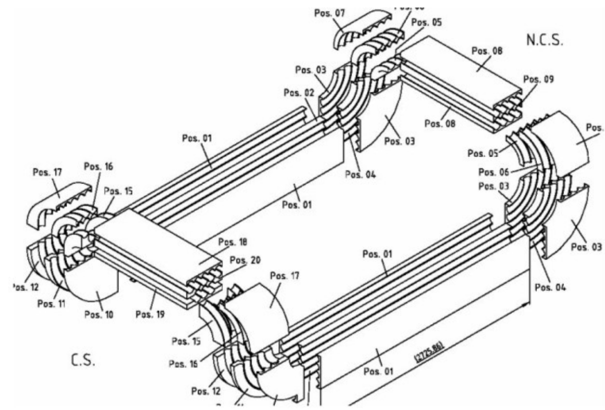

Figure 4: Exploded view of the complete set of structural elements for the upper SIS 100 dipole coil (not in scale). The coil structure (2 layers, 4 turns each) is clearly reproduced by the G11 pieces such that the cable is firmly kept all over its length.

Prior to this prototype manufacturing GSI and BNG jointly developed the design of the new coils and the required GRP pieces including an appropriate winding scheme and tooling concept. Afterwards several test pieces of the coil winding pack were produced for which the relevant mechanical and thermal properties were experimentally determined [3].

The fabrication of the SIS 100 coils is done in several steps which are detailed in the following. Before the coil winding, the GRP pieces are coated with a special polyimide glue on their inside, where they will come into contact with the cable. The polyimide glue will become adhesive during the heat treatment and glues the cable locally to the surrounding G11 framework. This will enforce the internal stability of the winding-pack compound.

The winding itself starts with lining up all G11 pieces belonging to the innermost layer on a winding core. Afterwards the first (inner) layer of the coil is wound turn by turn and laid into the G11 pieces. In the head regions of the coil the cable is pre-bent to fit the final radii as accurately as possible. After the inner layer is positioned and fixed the intra-layer G11 pieces are placed and fixed into position, followed by the winding of the outer coil layer as described above. Finally the outermost layer of structural elements is placed. A snapshot during the winding process is shown in Fig. 5.

After winding the pole it is baked under pressure being well supported from all sides by precisely machined pressing blocks and wedges. The temperature is raised and kept for several hours in a controlled way, to avoid thermal gradients across the coil and to control the expansion of the different materials of the compound. The heat is necessary to let the polyimide glue polymerize and to become adhesive. The mechanical pressure, which is controlled and adjusted according to the thermal expansion, supports the gluing and presses the coil into its final and very accurate shape and dimensions.

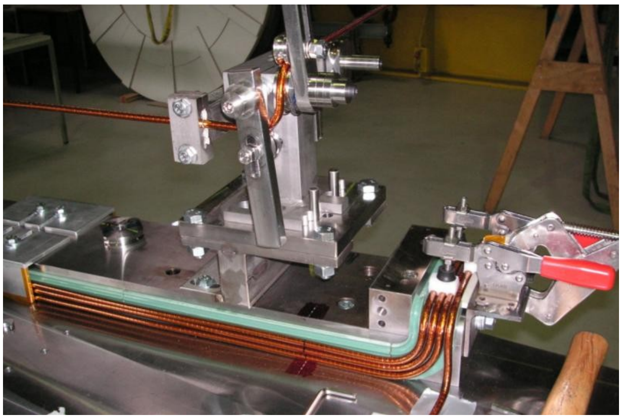

Figure 5: Photo during the winding process. The 4th turn of the inner layer is just being pre-bent to fit into the framework created by the innermost G11 pieces. Besides the coil in progress, the winding core the (pre-) bending tooling and various clamping elements are visible.

Figure 6: Photo of the head part of a readily baked coil. The insert shows the baking press which was used.

The gluing supports the formation of a compact winding pack compound, which inhibits internal motion of the cable. The shape precision is very important since the coil has to fit tightly with the iron yoke to avoid any motion under magnetic, dynamic forces. Figure 6 shows a photograph of a coil after its baking-pressing procedure. Even for the comparably complex shape of the coil heads the shape tolerances are all well below 0.05 mm. This is owned to the high geometrical accuracy of the pressure blocks and -wedges, which give the coil its outside dimensions and the G11 elements themselves.

After the completion of the two dipole half coils they are merged and wrapped with a glass fibre tape (see Fig. 7) which was pre-impregnated with resin. The glass tape gives additional stability to the winding pack compound. The heat treatment for the resin is performed again in a backing press with respectively shaped blocks and wedges defining the outside geometry of the coil, such that it fits tightly into the inner geometry of the iron yoke.

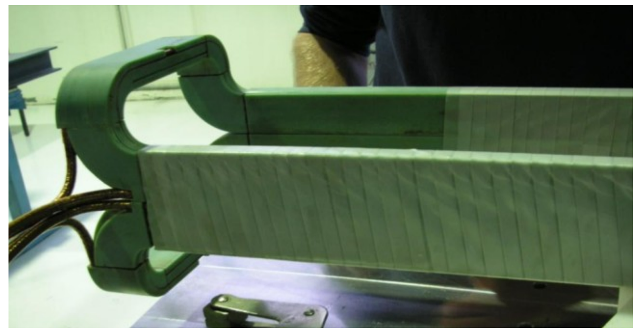

Figure 7: Photo of the double half coil during wrapping of the glass fibre tape.

CONCLUSION AND OUTLOOK

The fabrication of the SIS 100-cable was done mainly automatically by the presented cabling facility. The setup is considered to be well suited for the series production of sc cable for the SIS 100 magnets after minor modifications to enhance the process stability.

The coil manufacturing is dominated by manual procedures such as assembly works and the winding itself. The implementation of a higher grade of automation is hardly more economic and not desirable in view of quality. Therefore the process of coil winding appears to be the bottleneck for the throughput during a series production. To enhance the rate of coil-production, parallel manufacturing lines should be employed. Despite their complexity the winding table, winding core and pre-bending tools can be duplicated easily.

Both, for the production of the cable and coils the technical implementation is considered to be capable for a series of SIS 100 magnets. Nevertheless the procedures and the tooling have to be adapted and optimized for the final design as a curved single-layer dipole and possibly other SIS 100-magnets.

REFERENCES

[1] http://www.gsi.de/fair/overview/info/index.html

[2] Fischer et al., “Fast Ramped Superferric Prototype Magnets of the FAIR Project“, (proceedings of PAC09, Vancouver 2009).

[3] IEEE Transactions on Applied Superconductivity, Vol. 17. No2 June 2007, pp 1169- 1172 (Proceedings of ASC 06, Seattle, USA, Sep. 2006).