Superconducting Magnets for ECRIS – Design Aspects and Industrial Production

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Abstract Superconducting magnets are widely used in ECR ion sources. The intensity and form of the magnetic field plays an important role in the way towards higher performance sources. During the development steps, the design principles and geometries had to be adapted to reach higher fields using state-of-the-art technologies and design tools. Production, assembly, and tests of these superconducting magnets are presented and a short outlook on possible future developments is given.

Key words superconductivity, ECR ion source, design, test

1 Introduction

The request for high charge states of ions in ECR ion sources necessitates higher values both of the axial as well as the radial magnetic field. Within ACCEL, two superconducting magnet systems had been built, and a third system is under construction. For the first system for the SERSE ion source at the INFN/Catania, Italy[1], ACCEL had built the entire cold mass, which is the superconducting coils with all structural material, and assembled it into the completed helium vessel, to be installed into an already existing cryostat. This source is operating at frequencies up to 18GHz now since many years.

The second system for the SECRAL source, operated at the IMP in Lanzhou, China, was designed for up to 28GHz operation frequency. There, the scope of supply comprises the entire magnet system with cryostat and all ancillary electronics and power supplies. This ECR ion source has produced the first experimental results during the last year.

A third system is under construction, with even higher magnetic fields, called MS-ECRIS, under a contract of ISIBHI collaboration.

To reach even higher fields of each subsequent system specification, the design principles of the superconducting magnet had to be adapted or even changed, especially with respect to the sextupole.

2 Magnetic design

2.1 Axial and radial field shape

The magnetic field minimum for ECR should have a positive magnetic field gradient in all directions. This is realised by the axial minimum of a solenoid configuration and usually by the quadratic field shape of a sextupole.

2.2 Realisation by superconducting coils

An ideal sextupole would be built by the current distribution of three intersecting ellipses. Such a distribution, however, hardly fulfils the requirements of manufacturability, economics, and structural mechanics. Different winding geometries satisfy this

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boundary condition to a different degree.

2.2.1 Racetrack coils

The first, native approach to a long sextupole is a set of racetrack coils. Racetrack coils are widely used in superconducting magnets, e.g. in wiggler magnets with typically tens of coils per magnet system. The design and behaviour of these coils is well known, the manufacturing is rather straightforward due to the two-dimensional conductor path and the straight sides.

Racetrack coils have been used for the sextupole of the SERSE superconducting magnet. An additional spacer in the coil heads reduces the maximum field on coil head part of the winding, shifting the maximum to the position of the solenoids' maximum radial content along the straight part of the sextupole, see Fig. 1.

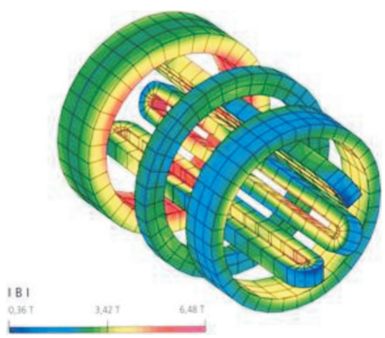

Fig. 1. Magnetic flux density on the sextupole and solenoids of SERSE under design currents.

2.2.2 'Advanced' racetrack coils

When considering the cross section of the racetrack configuration, by geometrical reasons there are two triangles which are not filled with conductor. Unfortunately, these triangles are the positions where the conductor is most effective, that is in the centre of the pole winding and towards the inner diameter of the coil arrangement, as shown in Fig. 2. The 'advanced' racetrack provides both a higher number of windings and an improved distribution.

For the particular layout of the SECRAL magnet with the solenoids inside the sextupole, this design has been chosen. The solenoids are particularly shorter than the sextupole coils, which allows keeping a two-dimensional conductor path for winding, and nonetheless having a larger solenoid outer radius than the inner radius of the sextupole winding corners at the coil heads.

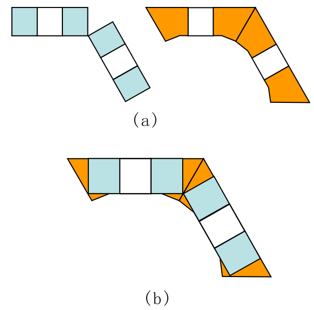

Fig. 2. 1/3 (two coils building 120°) of the cross section of a sextupole; (a) comparison of racetrack and 'advanced' racetrack; in the 'advanced' racetrack geometry the conductor is placed more effectively; (b) direct comparison of the conductor placements.

2.2.3 Cos θ-coils

The largest number of superconducting coils with transverse fields, that is dipoles, quadrupoles, etc. – as opposed to solenoids – with the highest fields and gradients, has been built for accelerator magnets. Usually the technique of clamping the coils by collars is used in these magnets, resulting in high performance magnets, operating at high magnetic fields and Lorentz forces. When designed and manufactured properly, these magnets have an excellent quench and training performance, requiring no or only a few training quenches to their maximum performance.

To cope with the large forces of the high fields in the MS-ECRIS coils, this winding and collaring technique was adapted to these sextupole coils. Since kA-class cables are not favourable for the source operation from a cryogenic point of view, a ribbon design was employed, wherein five insulated rectangular superconducting wires are glued together building one strip, or ribbon. This ribbon of five insulated wires is wound to a double-pancake (see Fig. 3), finally resulting in one circuit by connecting the five wires in series. For each pole, two of these double-pancakes are stacked to build in total a four-layer geometry. Spacers and wedges are introduced to trim the mechanical dimensions as well as to reduce the field in the coil heads.

Figure 4 gives a comparison between the size of the sextupole collar and a collaring sample of a 'wide bore' quadrupole MQY of the LHC, CERN.

Fig. 3. MS-ECRIS sextupole double-pancake after curing.

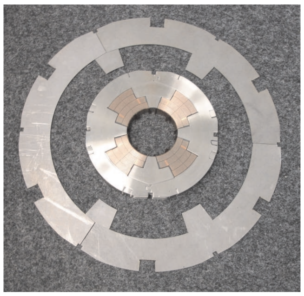

Fig. 4. Collar for the MS-ECRIS sextupole and collared CERN LHC MQY sample for size comparison.

2.3 Design tools

All coil geometries had been designed and optimised by using the 3 D FE codes Opera and Tosca from VectorFields. The stored energies as well as the inductance matrices have been calculated as an input to a proprietary quench simulation code. In the design, a large safety margin with respect to the critical current of the superconducting wires has been chosen, which always is a compromise with respect to winding package size, copper to superconductor ratio, and availability of the superconductor. Magnetic shielding calculations have been performed, the model is shown in Fig. 5. The eddy currents in the radiation shield induced during a quench can damage the shield, therefore a transient calculation of these eddy currents is performed. The Lorentz force densities in the coils are calculated and transferred as an input to a 3 D structural analysis model (software package ADINA). In this structural analysis, the stresses on the coil straights and coil heads as well as on the structural materials like collars and spacers are calculated. The ideal thickness of a mechanical shim has been found by calculation and optimisation to firmly clamp the coils during cool-down and operation. There are two important but contradicting aims: maintaining the coils under compressive prestress under all conditions to avoid conductor movement, and keeping the stresses on coils and structural materials within safe limits.

The mechanical design and construction is performed on a 3 D AutoCAD Inventor platform.

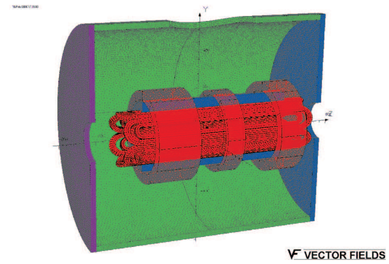

Fig. 5. Magnetic model for MS-ECRIS.

2.4 Performance comparison

Table 1 lists the performance of the ECR ion source superconducting magnets. For SERSE and SECRAL, measured magnetic field values are given, for MS-ECRIS the specified values are referred to.

Table 1. Performance comparison of the sc-magnets.

	SERSE	SECRAL	MS-ECRIS
B_{axial} (injection)/T	2.7	3.67	4.5
B_{radial}/T	1.55	1.83	2.7
plasma chamber diameter/mm	130	126	180
upper operation rf frequency/GHz	18	28	37

3 Cryogenic concepts

The SERSE superconducting magnet uses liquid helium and liquid nitrogen for cooling. These liquids have to be supplied either from a dewar or a transfer line. The progress in small GM or PT-type cryocoolers over the last ten years made it feasible to build magnets with zero boil-off. The first stage of these cryocoolers is typically used to cool the radiation shield and the thermal intercept of the HTc current leads, whereas the second stage recondenses the evaporated helium. In MS-ECRIS a dedicated link system allowing the exchange of a cold head without warming up the cryostat will be integrated for higher availability of the system and considerably lower cost for maintenance. A cryogenic concept comparison of the three magnet systems described is given in Table 2.

Table 2. Cryogenic concepts.

	SERSE	SECRAL	MS-ECRIS
4K cooling concept	liquid helium refill	liquid helium refill	2-stage GM cooler, zero boil off
shield cooling concept	liquid nitrogen refill	shield cooler	2-stage GM cooler
current leads	all metal	HTc	HTc
liquid helium consumption	few litres/hour	∼1 litre/hour	zero

4 Test

After manufacture and assembly of the SERSE and SECRAL magnet systems, magnetic field measurements were performed to demonstrate the performance and field quality. A drive system with both a rotary and a linear drive, controlled by a LabView program, allows a full 3 D Hall probe or pick-up coil mapping of the field inside the bore.

Figure 6 gives a plot of the SECRAL radial field, measured on a radius of 60mm and 97.5% of full current.

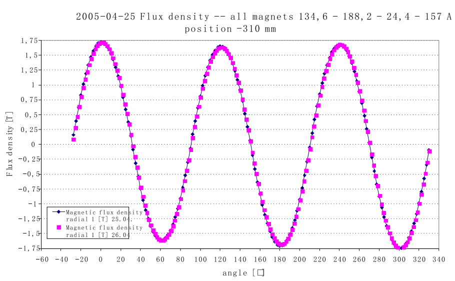

Fig. 6. Radial magnetic field of SECRAL measured with Hall probes.

5 Approaches to next generation superconducting ECR ion source magnets

During about the last ten years the magnetic field specification of leading edge ECR ion source magnets has almost doubled. Using NbTi conductor technology, no substantial increase in the fields attainable seem possible any more, since more sophisticated winding geometries have pushed the performance almost to the technical limits. Considerably higher fields seem possible only by introducing other conductor technologies. There are two promising candidates: using Nb_3Sn technology or HTc superconductors for the sextupole. With Nb_3Sn a number of prototype accelerator magnets have been designed, manufactured, and tested in a number of institutes and collaborations world-wide. There are still some problems with low field stability to overcome, but the main features could be demonstrated.

In HTc superconductors there is still a lack of engineering current density[2, 3] in magnetic fields below about 10T, when compared to e.g. Nb_3Sn. With reasonable progress on the recent YBCO (2nd generation) coated conductors with respect to manufacturing length, stabilisation for quench, and cabling / winding technique, this seems to become a promising candidate for future magnets.

6 Conclusion

The magnetic design of superconducting ECR ion sources has developed towards highly sophisticated systems, making use of manufacturing technologies of high field accelerator magnets.

In the most recent systems, the cryogenics has been improved allowing for reduced losses or zero boil off using small-scale cryocoolers commercially available.

Two superconducting ECR ion source magnets have successfully been built by ACCEL. A third system is almost finished in the design process and is under construction.

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