SC AND HTS-RELATED ACTIVITY AT IHEP

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Abstract

The SC program at IHEP of NRC "Kurchatov Institute" has been developed intensively in the 1980s in the framework of the UNK project. More than a hundred of models of the SC magnets of various designs, and then the pilot batch consisting of 25 full-scale dipoles and 4 quadrupoles have been designed, manufactured and tested at IHEP. Two SC magnetic systems of Electron Lens for the Tevatron collider (USA) were developed, manufactured and successfully brought into operation. Development of fast-cycling SC magnets for SIS300 accelerator and wide-aperture high gradient quadrupole magnets for Plasma Experiments within the FAIR project (European Research Centre of Ions and Antiprotons, Germany) is discussed. Racetrack and annular coils from HTS-2G tape for electrical machines that were developed, manufactured and tested are reported. Test and trial results with HTS dipole magnets employing Bi2223 as well as second-generation HTS are also reviewed.

SC MAGNETS FOR UNK PROJECT

New generation of high energy proton accelerators is based on superconducting (SC) magnets. In the early eighties of the last century the special cryogenic and superconducting facilities have been created at IHEP in frame of UNK project. In collaboration with Bochvar's institute SC NbTi wire of 0.85 mm diameter with 8910 of 6 micron filaments was developed. More than 100 SC magnet models and pilot batch consisting of 25 full scale 6 m dipoles (Fig. 1) as well as four quadrupoles were developed, produced and tested at IHEP [1] - [2]. The main characteristics of the magnets are presented in Table 1.

Table 1: The Main Characteristics of UNK SC Magnets

Parameters	Dipole	Quad
Magnetic field, T	5.11	
Field gradient, T/m		97.4
Operating current, kA	5.25	5.25
Field ramp rate, T/s	0.11	
Rate of central gradient, T/m/s		2.1
Number of layers	2	2
Strand number in cable	19	19
AC losses, W	5.5	2
Stored energy, kJ	570	180
Inductance, mH	45	13
Coil inner diameter, mm	80	80
Length of the coil, mm	5800	3100
Length of the cryostat, mm	6420	4165
Mass of magnet, kg	6000	1600

Figure 1: UNK SC dipole magnet.

SC MAGNETIC SYSTEM OF TEVATRON ELECTRON LENS

In 1999 – 2003 two SC magnetic systems of Tevatron Electron Lens for Fermilab, USA were developed and produced. These systems were placed and operated at TEVATRON accelerator (Fig.2). The system consisted of seven SC and ten copper magnets [3]. Main SC solenoid had 6.5 T nominal magnetic field, 2.5m length, 152 mm coil inner diameter. The solenoid coil was wound by the Rutherford type cable from 10 SC wires of 0.85 mm diameter. Turn number of the solenoid is 7238 and nominal current – 1800 A. Six SC steering dipoles were placed over the solenoid. Two dipoles of 1840 mm length were arranged in the centre and four dipoles of 250 mm length in the end parts of the solenoid. The central dipole produced 0.2 T magnetic field at 50 A current and end dipole – 0.8 T at 200 A. All dipoles were wound by cable transposed from 8 SC wires of 0.3 mm diameter.

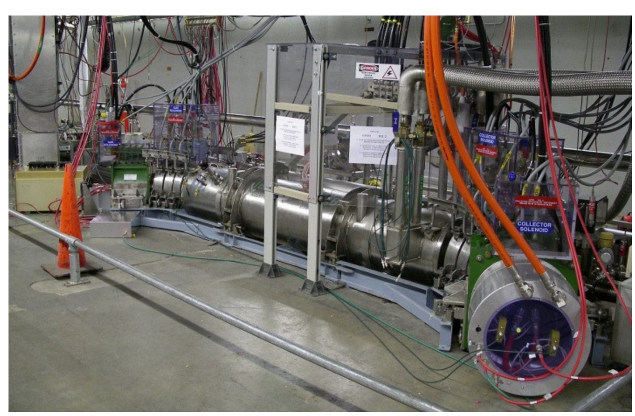

Figure 2: SC magnetic system of Tevatron Electron Lens.

The system included gun and collector solenoids with 250 mm inner diameter, 474 mm outer diameter, 300 mm length which produce 0.4 T magnetic field in aperture. Copper corrector coils were inside these solenoids. Three bending electron beam solenoids with 390 mm inner diameter, 500 mm outer diameter, 72 mm length were between cryostat and gun solenoid and the same between cryostat and collector solenoid. Turn number and nominal current of the solenoid were 48 and 357 A. Gun, collector and bending solenoids were produced from copper cable with 8.25×8.25 mm^2 cross-section with 5.5 mm diameter hole for water cooling.

HIGH FIELD FAST CYCLING SPERCONDUCTING MAGNETS

High field fast cycling magnets were developed and produced for the SIS300 accelerator of the FAIR project, Germany. The high field fast cycling dipole for the SIS300 is shown in Fig. 3 and its parameters are presented in Table 2 [4].

Figure 3: High field fast cycling dipole magnet.

Table 2: Parameters of the High Field Fast Cycling Dipole

Parameter	Value
Magnetic field, T	6
Operating current, kA	6.72
Field ramp rate, T/s	1
Number of layers	2
Strand number in cable	36
AC losses (calc.), W/m	4.7
In the coil	3.4
In the iron yoke	1.3
Stored energy, kJ	260
Inductance, mH	11.7
Coil inner diameter, mm	100
Length of SC coil, m	1
Mass of magnet, ton	1.8

A special design of SC wire and cable with stainless steel core was developed for this dipole. 6.8 T magnetic field in aperture of the dipole was reached and the magnetic field did not reduced up to 1.2 T/s ramp rate (Fig.4). The dipole with these parameters is unique in a world practice.

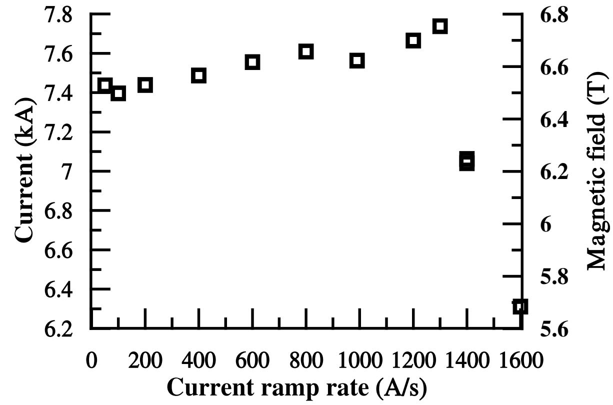

Figure 4: Ramp rate dependence of the high field fast cycling dipole.

A prototype of the SIS300 fast cycling quadrupole was produced and tested in 2011. Design parameters of the quadrupole are 45 T/m central gradient, 10 T/m/s ramp rate, 125 mm inner diameter and 1 m effective length [5]. Fig. 5 shows a general view and Table 3 presents main parameters of the quadrupole.

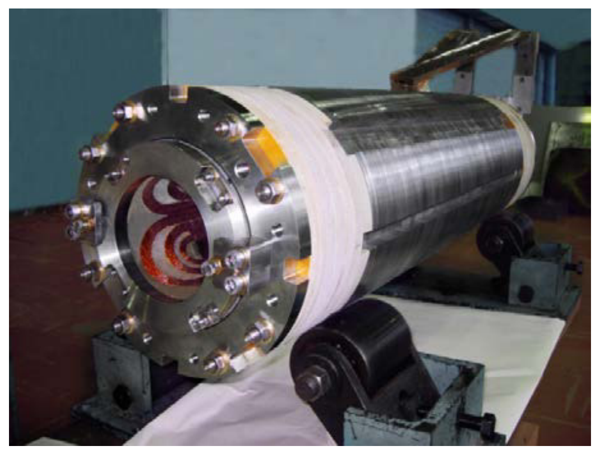

Figure 5: SIS300 fast cycling quadrupole prototype.

Table 3: Parameters of the SIS300 Quadrupole Prototype

Parameter	Value
Central gradient, T/m	45
Rate of central gradient, T/m/s	10
Operating current, kA	6.26
Maximum magnetic field on coil, T	3.51
Temperature margin in SIS 300 cycle, K	1.54
Stored energy, kJ	3.8
Inductance, mH	2
Number of turns in coil	80
Inner diameter of coil, mm	125
Thickness of collars, mm	22
Thickness of iron yoke, mm	52
Effective length, m	1

The quench current of the quadrupole reached 8.734 kA in fifth quench that corresponds to 40% current margin. Measurements of the quench current of the quadrupole at various ramp rates showed that the quench current was higher than 8.5 kA up to 5 kA/s (2.8 T/s) ramp rate.

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At present a design of wide-aperture high gradient quadrupole magnets for Plasma Experiments in the FAIR has been developed [6]. The quadrupole cross section and main parameters are shown in Fig.6 and Table 4.

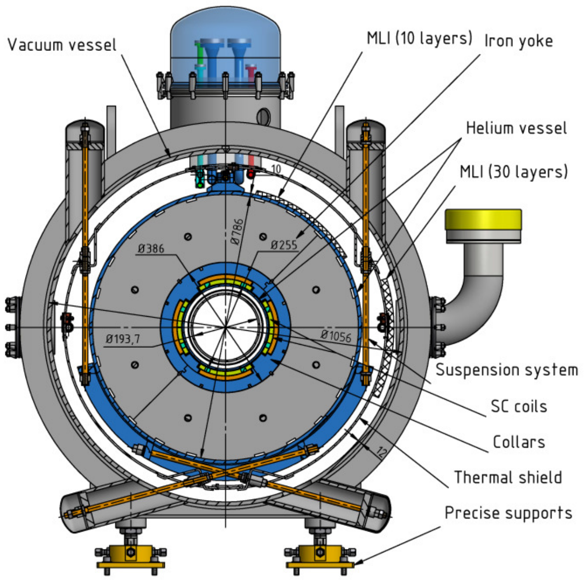

Figure 6: Wide-aperture quadrupole cross section.

Table 4: Parameters of the Wide-Aperture Quadrupole

Parameter	Value
Central gradient, T/m	37.6
Inner diameter, mm	260
Maximal field, T	5.9
Operating current, kA	5.73
Total magnetic force/octant, kN/m	1454
Total energy in the magnet, kJ/m	613.5
Inductance, mH/m	36.5
Length of magnet, m	1.89

DEVICES ON THE BASIS OF FIRST GENERATION HTS

In 1998 – 2000 first in Russia 600 A HTS current leads on basis of Bi2223 were developed in collaboration with Bochvar's institute in frame of contract with CERN, Switzerland [7]. First current lead had 33 HTS tapes with Ag+10%at.Au matrix, second - 16 HTS tapes and third current leads – 14 HTS tapes with Ag+1%at.Au matrix (Fig.7). These current leads consist of resistive part cooled by 20K helium gas and HTS part cooled by helium vapor. The resistive part consists of 2300 copper wires of 0.13 mm diameter which are placed into stainless steel tube of 11 mm inner diameter and 500 mm length. HTS part is 400 mm length. The third current leads had characteristics qualified for LHC: Heat leak to liquid helium is 0.08W at 600A current; resistance of HTS – resistive contact equals 220 nohm, resistance of HTS – NbTi wire contact – 6 nohm; helium flow rate cooling the resistive part – 0.04 g/s; pressure drop of the helium flow –5 kPa.

Figure 7: 600 A HTS current leads.

The next step in application of HTS is development of first in Russia HTS dipole in 2001 [8]. The dipole has 280x345 mm^2 cross section and 590 mm length (Fig. 8). 1T magnetic field was reached at 25 A current and 65 K temperature in 21×70 mm^2 aperture of the dipole. "Race-track" type coil was wound by 3.8×0.25 mm^2 HTS tape which consists of Bi2223 filaments in silver matrix. The coil was placed into yoke made from electric steel.

Figure 8: HTS dipole magnet on Bi2223 basis.

DEVICES ON THE BASIS OF SECOND GENERATION HTS

Full-scale racetrack coils for the rotors of the prototype of 200 kW SC synchronous motor (Fig.9) and the prototype of 1 MVA SC synchronous generator were produced and tested at IHEP [9]. The second generation (2G) HTS tape of the "American Superconductor Corporation" with cross section with insulation 4.93×(0.32 – 0.40) mm^2 was used. Insulation of HTS tape was made of a polyimide film, the total thickness of the insulating layer on one side was 76 microns. Critical current of the HTS tape (1 μV/cm, 77 K, self field) was equal 94 – 116 A. Basic parameters of the SC synchronous motor and generator coils are presented in Table 5.

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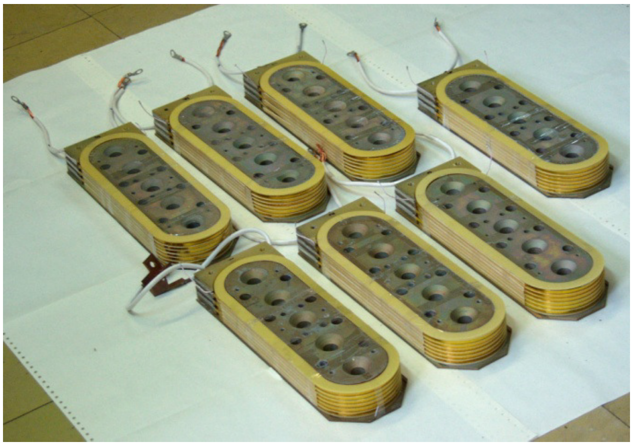

Figure 9: The HTS coils of SC 200 kW motor.

Because of the above mentioned dispersion of tape thickness from 0.32 to 0.40 mm the number of turns in motor coils was in the range of 188 - 205 and 381 - 393 in generator coils. Critical current of motor and generator coils at the coil voltage drop corresponding to 1 μV/cm was in the range of 46 – 53 and 42 – 47 A respectively.

Table 5: Basic parameters of the coils of the SC synchronous 200 kW motor and 1 MVA generator

Parameter	Motor 200 kW	Generator 1 MVA
Length, mm	334	587
Width, mm	114	187
Height, mm	40	50
Number of layers	6	6
Number of turns in the coils	188-205	381-393
Critical current of the coils (1 μV/cm, 77 K), A	46-53	42-47
Inductance, mH	45-51	42-43
Weight of coil with pole, kg	13	51
Number of coils	6	10

Two annular 2G HTS excitation coils for a 1 MVA superconducting synchronous generator were manufactured and successfully tested in a forced liquid nitrogen flow cooling mode inside their own cryostats (Fig.10) [10]. The coils were wound using 2G HTS tape produced by “SuperOx”. The tape had cross section without insulation 12.0×0.15 mm^2. IHEP developed equipment and technology of 2G HTS tape insulation. The “SuperOx” HTS tape was insulated with a polyimide film, the thickness of the tape insulation was 26 microns. Minimum critical current of the HTS tape (1 μV/cm, 77 K, self field) was equal 300 A. Main parameters of the annular excitation coil are presented in Table 6. The measured values of the critical current of 116 A and 126 A at 78 K temperature and the voltage drops on coils corresponding to 1 μV/cm criterion are in line with the current threshold for thermal runaway and the increase of the normal zone. Critical current value for the coil #1 is slightly lower than that for the coil #2. We believe that this difference can be explained by variation of the characteristics of the particular HTS tape used in these coils. The threshold current values for both coils exceed the maximum operating design current of 115 A.

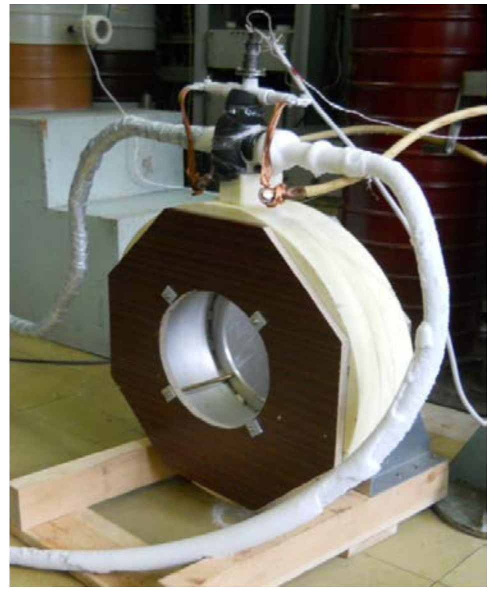

Figure 10: Test of cryostat with 2G HTS annular coil for the 1 MVA superconducting synchronous generator.

Table 6: Main Parameters of the HTS Annular Coil

Parameter	Value
Coil axial thickness, mm	25
Coil inner diameter, mm	491
Coil outer diameter, mm	557
Number of layers	2
Number of turns in the coil	306
Maximum operating current, A	115
Inductance, H	0.4
Axial magnetic field, T	0.25
Weight of the coil with cryostat, kg	28

A HTS dipole magnet (Fig.11) with a 1 T central field in 80×40 mm^2 aperture has been designed fabricated and successfully tested [11].

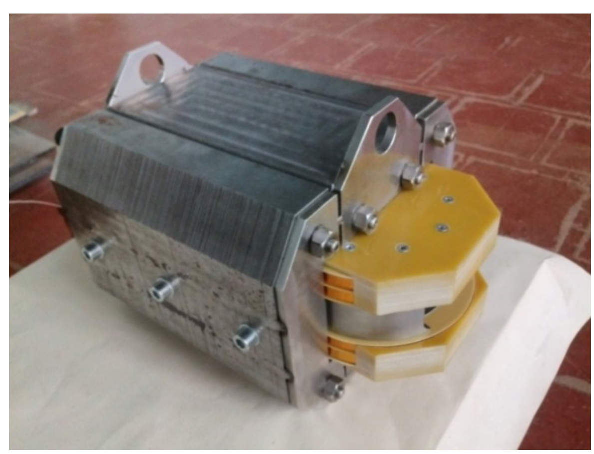

Figure 11: Dipole on the basis of second generation HTS.

The magnet coils were wound using 2G HTS tape produced by “SuperOx” (Table 7). IHEP insulated the HTS tape with a polyimide film, the thickness of the HTS tape insulation was 40 microns. Table 8 shows main design parameters of the HTS dipole.

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Table 7: Properties of the SuperOx 2G HTS Tape

Parameter	Value
Substrate	Hastelloy C276
Min critical current (77 K, self-field)	400 A
Tape width	12 mm
Tape thickness without insulation	100 μm
Silver coating	1.5 μm
Copper coating	20 μm per side

Table 8: Design Parameters of the HTS Dipole

Parameter	Value
Nominal magnetic field in aperture	1 T
Operating current	100 A
Number of coils	2
Number of layers in each coil	2
Number of turns in each coil	180
Total number of turns	360
Longitudinal magnet length	425 mm
Longitudinal coil length	418 mm
Coil straight section length	250 mm
Longitudinal yoke length	250 mm
Aperture dimensions	40×80 mm^2
Magnet mass	103 kg

Fig. 12 presents a result of the magnet test at various temperatures. At 77 K and 10 μV/cm the current in the HTS coil reached 113 A, generating the central field of 1.12 T. At 65 K and 10 μV/cm, the HTS coil current was 228 A and the central field was 1.66 T. In liquid helium bath, the maximum injected current of 847 A was limited by the power supply, and the central field was 3.03 T.

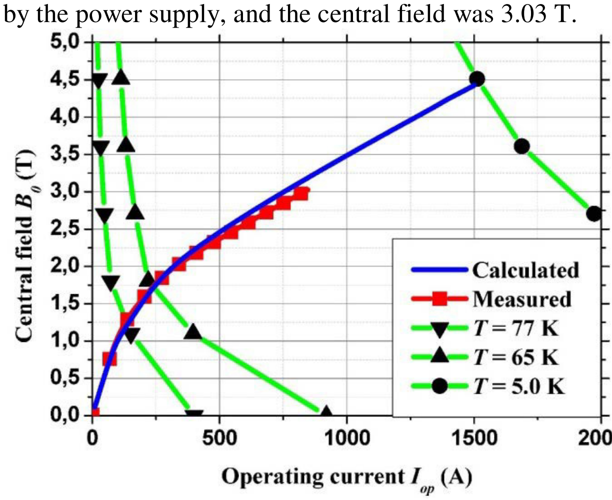

Figure 12: Measured and calculated dependences of the magnet central field on the operating current and field dependences of the 2G HTS tape critical current at 77, 65 and 5 K (green curves).

CONCLUSION

IHEP has meaningful experience and equipment for development and production of accelerator magnets on basis of superconductors. More than 100 SC magnet models and pilot batch consisting of 25 full scale 6 m dipoles as well as 4 quadrupoles were developed, produced and tested at IHEP. Two SC magnetic systems of Electron Lens were produced and operated at Tevatron, Fermilab, USA. High field fast cycling dipole with unique parameters in a world practice and quadrupole were developed and produced for the SIS300 accelerator of the FAIR project, Germany. Design of a wide-aperture high gradient quadrupole for final focus system of the HEDgeHOB beam line has been developed. First in Russia HTS current leads and dipole on the Bi2223 basis were manufactured and successfully tested. 2G HTS racetrack and annular coils for electrical machines were produced and tested at IHEP. Dipole on the basis of second generation HTS has been designed fabricated and successfully tested. At 77 K the central field of 1.12 T and 1.66 T at 65 K was reached. In liquid helium bath, the maximum injected current of 847 A was limited by the power supply and the central field was 3.03 T.

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