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Recent Main Events in Applied Superconductivity in China

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***Abstract*—With strong support from China government bodies such as the National High Technology Research and Development Program of China, National Natural Science Foundation of China and the National Basic Research Program of China, the field of applied superconductivity in China has been developed in different areas. Especially in the fusion application area, the first fully-superconducting tokamak, EAST (Experimental Advanced Superconducting Tokamak), has been successfully constructed and commissioned in the last two years. Based on the requirement from the ITER project, high performance Bi-2223 HTS tape, and Nb_3Sn and NbTi strands have been developed as well. In the area of HTS applications for electric power systems, R&D has been focused on superconducting power cable, superconducting magnetic energy storage, superconducting transformer, superconducting fault current limiters. In this paper, the recent progress in applied superconductivity in China is reported.**

***Index Terms*—Superconductivity, EAST, ITER, HTS**

I. INTRODUCTION

DURING the past five years, with strong support from Chinese government bodies such as the National High Technology Research and Development Program of China (863 programs), National Natural Science Foundation of China (NSFC) and the National Basic Research Program of China (973 programs), and China industrials involving, the field of applied superconductivity in China has been developed in different areas. In the large scale projects, such as EAST (Experimental Advanced Superconducting Tokamak), ITER (International Thermal-nuclear Experimental Reactor) and FAIR (Facility for Antiproton and Ion Research) projects, institutes and industrials have cooperated well together to design and fabricate different large scale superconducting conductors and magnets. In the municipal applied superconductivity area, R&D has been focused on high critical temperature superconducting (HTS) applications, such as HTS tape performance improvement, superconducting power cable, superconducting magnetic energy storage (SMES), superconducting transformer, superconducting fault current limiters (SFCL). Further R&D on Magnetic levitation (Maglev) has continued forward to the superconducting HTS Maglev test line.

II. THE EAST SUPERCONDUCTING MAGNET SYSTEMS

The EAST (Experimental Advanced Superconducting Tokamak) is a large scale scientific project which was approved by the China government as a national project in 1998. The scientific and the engineering missions of the EAST project are to study physics issues of the advanced steady-state tokamak operations and to establish technology basis of full superconducting tokamaks. It began the construction phase from 2000. The core of EAST project is a full superconducting tokamak with a non-circle cross-section of the vacuum vessel and active cooling plasma facing components. The EAST superconducting tokamak machine has 10 m highness, 7.6 m diameter and 414 tons. There are two superconducting magnet systems in the tokamak machine. One is superconducting toroidal field (TF) magnet system which is consisted of sixteen D-shaped coils. Another one is superconducting poloidal field (PF) magnet system which consists of a six central solenoid (CS) coils and three pairs of big circle coils. The biggest PF coil has an outer diameter of 7.6 m. The total superconducting magnet system of the EAST has 194 ton cold mass at 4.5 K. The EAST experimental system has been set up in the institute of Plasma Physics, Chinese Academy of Sciences (ASIPP) and transited its construction phase to its first physical operation phase after the first plasma was performed in September 2006. Fig.1 shows the EAST experimental system [1].

Most of superconductivity technologies have been developed by ASIPP, such as CICC (Cable-in-Conduit Conductor), large scale superconducting coil winding, VPI

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(Vacuum Pressure Impregnations), final accuracy machining of the TF cases, cryogenic test of superconducting coils, survey control technique, assembly and commissioning. During the past five years, the main R&D mainly focused on the design, fabrication and test of 16 kA CICC and the large scale superconducting magnet. The main parameters of the TF/CS/PF conductors are listed in Table I. The test results shown the performances of all superconducting magnets are well satisfied. Fig. 2 and Fig. 3 show the fabricated TF coil and PF coil separately. The stored energy of the TF superconducting magnet system is 400 MJ at the updated operation.

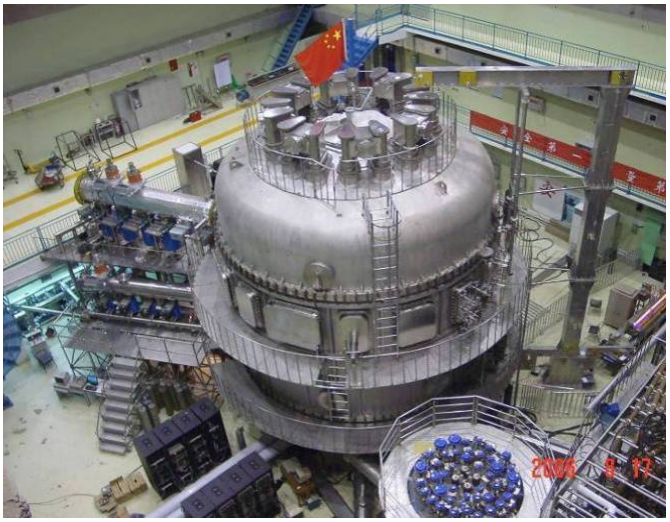

Fig. 1. Final assembly of the EAST experimental system.

TABLE I PARAMETERS OF THE TF/CS/PF CICC OF EAST

Conductor	**TF (Upgrade)**	**CS**	**PF**
Configuration	(2SC+2Cu)×3×4×5+1Cu Cable		(1SC+2Cu) ×3×4×5+1Cu Cable
Number of SC strands	120		60
Number of Cu strands	120+21		
Diameter of SC strands	0.87 mm		
Diameter of Cu strands	0.98 mm		0.98 mm/0.87 mm
Coating thickness	~2 μm Pb-30Sn-2Sb	~2 μm Ni	~3 μm Ni
RRR of Cu strands	> 100		
316LN Conduit thickness	1.5 mm		
Size of CICC	20.4 × 20.4 mm^2	20.35 × 20.35 mm^2	18.6×18.6 mm^2
Void fraction of CICC	35.0%		0.359%
Peak field	5.8 T (6.72 T)	4.5 T	1.5 T
Operating temperature	4.2 K (3.8 K)	4.2 K	
Operating current	14.3 kA (16 kA)	14.5 kA	

A test facility system that mainly consists of a big cryostat of 3.4 m in diameter and 6 m in height, a power supply system of 80 MW and a cryogenic and refrigerator system of 500 W/4.5 K was set up to test superconducting coils at operation temperature. Even four big PF coils with outer diameters from 5 m to 8 m had been qualified by testing a model coil made of same conductor in similar operation conditions. Totally twenty-nine cryogenic tests were performed, in which sixteen TF coils, one CS coil, two divertor coils, one PF model coil and one CS subassembly were tested. The performances of electromagnetics, mechanics, hydrodynamics of each coil were checked. Especially the test of one CS prototype coil that will suffer extreme flux changing at 7 T/s in 60 ms during plasma initiation had shown very good results. The test results of all sixteen TF magnets are very similar and satisfy the engineering requirements.

Fig. 2. One of the TF coils of the EAST machine

Fig. 3. One of the PF coils of the EAST machine.

The magnet currents are transferred by two superconducting feeder systems. Each feeder system consists of current leads box, superconducting transferring lines and terminal connecting boxes to the machine. The feeder cables are NbTi CICC, similar with the conductor used for the coils. To charge all PF coils independently, totally thirteen pair current leads and superconducting cables are needed. The maximum operation current of the EAST magnet system is 16 kA. To reduce the cryogen consuming, the high temperature critical current leads (HTS-CLs) were employed. Each HTS-CL consists of three parts: a lower part, a middle part and an upper part. The lower part contains NbTi strands which are connected down to superconducting NbTi cables and was cooled by supercritical helium. The middle part is HTS part made by multi-layer of Bi-2223 tapes and is cooled by liquid nitrogen (LN_2). The upper part made of copper is connected up to power cable in the air and down to the middle part. The HTS part is composed of 50 stacks of Bi-2223 tapes that are installed in the grooves along the shunt circumference. Each stack is composed of 7 Bi-2223 tapes. A new low thermal conductivity Bi-2223 HTS tape with Ag-4at%Au sheath instead of pure Ag was developed by Innova Superconductor Technology Co., Ltd. (InnoST) [2]. Before the installation, all HTS-CL modules have been tested at the same operation condition. The major performance such as critical current, stability, loss of coolant, hydraulics, heat load and joint resistance were tested. The higher critical current was measured at 27.3 kA. Fig. 4 shows one of the HTS-CL test results. It shows 27 kA critical current and slightly changed LN_2 levels and the temperatures. During the first engineering commissioning in 2006, four pairs of HTS-CL for PF coils were used successfully. It was the first time in the world to employ HTS-CLs in a superconducting tokamak. Now all other nine pairs of leads have been replaced with HTS leads. Therefore the total heat loads of the current leads to 4.5 K have been reduced from about 1 kW to 120 W.

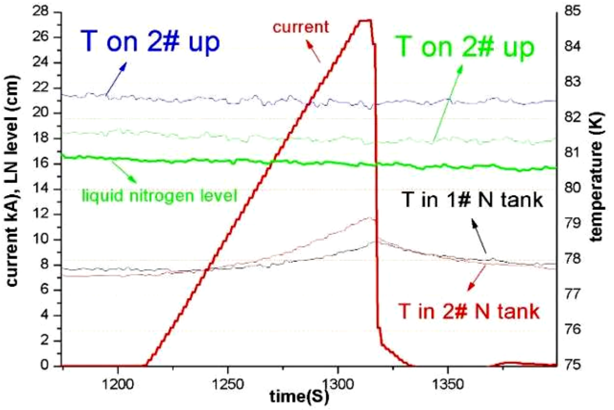

Fig. 4 One of the HTS CLs test results

To monitor the operation state of the key components, about 400 different thermosensors have been installed for temperatures measurement and monitoring. A machine diagnostics system which consists of the quench detection system, the temperature monitoring system, the CICC joint resistance measurement system and the stress/strain monitoring system was instrumented. From the co-wound wires with CICC, totally thirty-one voltage sensor wires were used for the TF and CS/PF superconducting coils for quench detection. The multi-compensation technologies have been developed, because the coupling signals among the CS/PF coils are very strong. The temperatures on the superconducting magnets, the thermal shields, the feeders including current leads and superconducting cables can be checked and recorded by the temperature monitoring system. The resistance measurement system checked totally eighty-seven CICC joints. Strain gauges were used on TF cases and the cryogenic supports to monitor the deformations and stresses due to the temperature change and electromagnetic forces.

A cryogenic and refrigerator system of 1050 W/3.5 K + 200 W/4.5 K + 13 g/s LHe + (13-25) kW/80 K was designed and integrated by the cryogenic team of ASIPP according to the head loads estimation of the EAST system. Four turbine modules and the aluminum plate-fin type heat exchangers were installed inside a cold box. An oil ring pump has been employed to reduce the helium suction pressure to 0.37 bar at the volumetric flow rate of 3100 Nm^3/h for ensuring 1050 W/3.5 K refrigeration ability.

Two engineering commissioning have been performed successfully in 2006. The first engineering commissioning started with the pumping of the device in February 2006. After 14 days, the cryogenic and refrigerator system cooled down the superconducting magnets to the superconducting phase successfully. The thermal shield was kept stably at about 80 K. The initial charges combined with PF coils and TF coils with lower currents were done especially for the debugging and adjusting of the quench detection system. 260 charges on PF coils and central solenoid and the charge combined with PF coils and TF coils together were done successfully. The TF magnet system was only charged up to 8.2 kA which is about 57 % of the design value of 14.3 kA, due to the small leakage on the HTc current leads. The longest pulse for the TF is 5000 s. The second engineering commissioning began in July 2006. After the magnet system was cooled down to about 5 K, the TF system was energized to 14.5 kA. After 600 s, the quench protection system was induced. The toroidal field at the major radius of 1.7 m is 3.55T which is higher than the designed value of 3.5 T. Fig. 5 shows the current of 14.5 kA in the TF superconducting magnet system. To fulfill the mission of the first plasma operation, the current varying rates of the poloidal magnets have been specified to be 20 kA/s for 60 ms, 10 kA/s for 160 ms and 5 kA/s for steady-state operation with sufficient safety margin. Nine pairs of copper current leads and four HTS-CLs worked properly and passed the testing. Most of eighty-seven CICC joint resistances are less than 10 nΩ. The very important result from the cryogenic and refrigerator system was successfully operating the superconducting magnet system at 3.8 K. So, it is possible to increase the operation current of the TF magnet system from nominal value of 14.3 kA to upgraded value of 16.3 kA and the toroidal field at the major radius of 1.7 m can be increased from 3.5 T to 4 T.

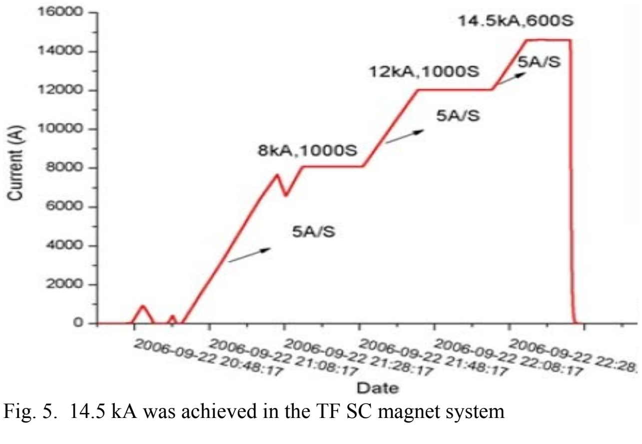

Fig. 5. 14.5 kA was achieved in the TF SC magnet system

With the successful design, fabrication and operation of the EAST large scale superconducting magnet systems, the superconductivity technology basis was set up in China. During the construction of the EAST experimental system, a lot of ITER-related technologies, such as CICC technology, large scale superconducting magnet technology, HTS current leads technology, superconducting magnet testing technology, large scale cryogenic technology, power supply system technology, etc,. have been developed.

III. ITER SUPERCONDUCTIVITY R&D IN CHINA

In the beginning of 2003, the China government decided to join the ITER (International Thermal-nuclear Experimental Reactor). By in-kind contribution, China procurement packages are related to twelve procurement packages, and four of them are applied superconductivity, such as Feeders, TF conductors, PF conductors and correction coils. Supported by China 973 programs and 863 programs and cooperating with China industrials, ASIPP lunched the R&D programs on the key technologies of the superconductivity technology for the ITER project in China.

A. R&D of ITER Superconducting Conductors

China will offer about 6.7 km TF conductors with 30 tons Nb_3Sn strands, 44 km PF conductors with 140 tons NbTi strands and some additional 8 km conductors for CC (correction coils) and feeders with 6 tons NbTi strands. The technology of multifilament NbTi and Nb_3Sn strands have been developed by Northwest Institute for Nonferrous Metal Research/Western Superconducting Technologies Co., Ltd. (NIN/WST).

The composition of the NbTi alloy is shown in the Table II below. Using transmission electron microscopy (TEM), the influence of treatment conditions on the microstructure was investigated to find relations between the alloy microstructure and the NbTi wire critical current densities at 4.2 K. Nb barrier was used to prevent Cu-Ti compound formation on the interfaces between NbTi filaments and Cu matrix so as to reduce the effect of extrinsic factors on Jc. The heat treatment time and temperature are typically in the range of 40 hrs to 80 hrs and of 380 °C to 420 °C. As a results, up to 24 vol.% of α-Ti has been produced by multiple heat treatment. The optimized wire was found to exhibit α-Ti precipitates about 5 nm, separated by 25 nm. The average α-Ti ribbon thickness for the optimized wire ranged from 4.2 nm to 5.1 nm which were close to the coherence length (~5 nm). The higher heat treatment temperature is beneficial to increase Jc value at 4.2 K, but the Jc value slightly decreases with increasing heat treatment times. Folding degree of α-Ti precipitates is likely the main factor to improve wire performance. Strong folding degree of α-Ti precipitates is beneficial to get higher performance.

TABLE II ELEMENTS COMPOSITION OF NBTI ALLOY

C	N	H	O	Fe	Al	Cr	Cu	Si	Nb47Ti
0.01	0.01	0.001	0.02	0.0065	0.002	0.001	0.005	0.01	Bal

The internal tin process was employed to fabricate Nb_3Sn strands according to the ITER specifications. Sn-Ti core rods with the Ti content of 2-3 wt% were fabricated by the electric beam melting, while Ta barrier was used as diffusion barrier. The weight of billets with 19 subfilaments could reach 50 kg and the unit length of final strands with a strand diameter of 0.82 mm could be 3000-5000 m. The Nb filament thickness after the final cold-working is 5 μm. Heat treatments for Nb_3Sn strands in vacuum or Ar atmosphere were divided into two stages of low-temperature treatment (< 575 °C) for bronzing process and high-temperature treatment (600 °C - 700 °C) for formation of superconducting Nb_3Sn phase through solid state diffusion. The total heat treatment time is about 300 hrs - 400 hrs. The cross sectional view of Nb_3Sn strands is shown in Fig. 6. To obtain high Jc properties of the Nb_3Sn stands, the processing parameters were optimized and series of experiments were performed.

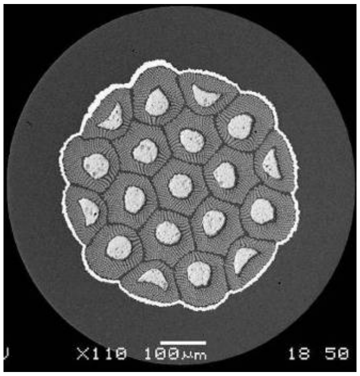

Fig. 6. The cross-section of Nb_3Sn strand of ∅ 0.77 mm.

Critical current of the Nb_3Sn strands, as a function of field, temperature and axial strain has been clearly investigated. The axial strain tests were performed at the University of Twente on the Pacman spring device. The Nb_3Sn strands of NIN/WST show low sensitivity for the axial strain. Within applied strain scope of $-0.6\ \% < \varepsilon < 0.65\ \%$, the n-value of NIN/WST strands achieved the ITER requirement. The critical current Ic of the strands was determined by a criterion of 0.1 μV/cm in different magnetic fields. The Jcn of strands reached 1250 A/mm^2 at 4.2 K and 12 T. The non-Cu hysteresis loss is 540 mJ/cm^3 (±3 T, 4.2 K), and the n-value is 31. After heat treatment the sample was transferred carefully to the Pacman spring and fixed with Sn-5 wt%Ag solder at about 500 K. The strain homogeneity remains within ±1.5 % along the sample. Two layout, six billets Nb_3Sn by the internal tin route and 120 kg NbTi strands have been produced in 2007 by NIN/WST. Long multifilamentary Nb_3Sn strands with a unit length more than 2 km have been successfully fabricated by internal tin process in NIN/WST [3].

A test facility for Nb_3Sn and NbTi strand superconducting properties test has been set up in ASIPP [4]. It has a bore of ∅70 mm, maximum fields of 14.8 T at 4.2 K and 16.5 T at 2.2 K, 0.5% field homogeneity over ∅32 mm and 17.5 mm axially about field center. A 600 A/ 5 V sample current source with current accuracy better than 0.2% and current ripple less than 0.1% has been set up. A device for testing critical current versus strain has been manufactured and now under commissioning.

With the cooperation from China industrials, six copper dummy TF cables and four TF superconducting cables were fabricated. Strand coating lines have be set up and 100 kg Nb_3Sn and 50 kg Cu strands have been plated by Cr. About 2 tons and 100 m TF 316 LN conduits were produced. Macrostructure, mechanical property at room temperature, nondestructive test (ultrasonic inspection, eddy current inspection), magnetic permeability, helium leak test, dimensional examination and chemical composition were performed. A 600 m long jacketing line is ready in ASIPP and fully equipped with non-destructive test (NDT) equipments for radiographic and ultrasonic inspection, dye penetrate test and local helium leak checking on line. Three 1000 m new jacketing lines are under construction in ASIPP now. A special multi-rollers jacket machine and an automatic welding machine for the TF conductor have been developed and tested successfully by producing 6 m dummy conductor in 2007, see Fig. 7. A PF jacket machine is fabricated and the commissioning is underway. Additional welding machine, NDT equipment and conductor receiving device for PF conductor are under commissioning.

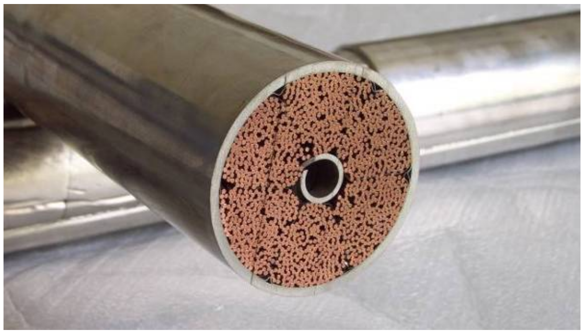

Fig. 7. A dummy TF conductor

B. *R&D of ITER Feeders with HTS Current Leads*

China will supply the total of thirty-one feeders for ITER. The ITER superconducting magnets and associated structures require high-pressure, supercritical helium and large electrical power as well as instrumentation, all of which have to be routed from the outside of the machine through the cryostat to the magnets. This is accomplished by the so-called feeders. Typically a feeder contains a pair of superconducting busbars, two or more cooling pipes, and high as well as low-voltage instrumentation cables. The vacuum inside the feeders is, for the most part, common with that of the main cryostat.

The ITER feeder system includes nine TF feeders, six PF feeders, six CS feeders and five CC feeders. In addition, there are three structure cooling feeders supplying the TF coil cases and inter-coil structures and the CS pre-compression structure with liquid helium. Finally there are two instrumentation feeders. Each typical feeder consists of a dry box (DB), coil terminal box (CTB), s-bend box (SBB), cryostat feed-through (CF) and in-cryostat feeder (ICF).

ASIPP is in charge of the development of the feeders and has focused on the R&D of HTS current leads. According to the ITER feeder documents, 68 kA for TF coils is the highest rated current. The HTS-CL leads have a very rigorous safety requirement for helium coolant stoppage and HTS quench such as: burnout time from quench detected >13 s, loss of flow accident (LOFA) time > 400 s, and so on. To develop the first 68 kA HTS current lead prototype, a pair of 68 kA trial current leads has been designed and is under fabrication in ASIPP. Each 68 kA HTS-CL consists of five parts: a HTS module containing ninety HTS tape stacks and shunt/support cylinder, a LTS (low critical temperature superconducting) joint module connecting the HTS current lead to the superconducting busbar, a HEX (resistive heat exchanger) with the splice to the room temperature busbar, an electric insulator module connecting the lead to CTB and instrumentation for temperature and voltage measurement or monitor. The major components of 68 kA HTS trial leads are shown in Fig. 8. The major parameters of 68 kA HTS current leads are listed in Table III [5].

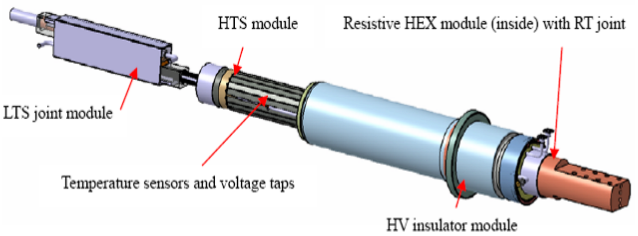

Fig. 8 Major components of 68kA HTS trial leads

TABLE III MAJOR PARAMETERS OF HTS CURRENT LEADS

Rated current	68 kA	
Temperature at HTS warm end	65 K	At operating current 68 kA
Operating temperature margin	20 K	At warm end temperature of 65 K
Joint resistance at 65K	< 10 nΩ	
Joint resistance at 5K	< 5 nΩ	
Joint type	Twin box	
LOFA time	> 400 s	At full current
Hot spot temperature	< 200 K	160 K for design
Burnout time from quench (3 mV)	>13 s	Including 2 s delay
Temperature at HEX warm end	300 K	Design for 25 °C cooling water only
Helium temperature at HEX inlet	50 K	
Maximum helium pressure in HEX	6 bar	
Maximum heat leak at cold end	15 W	
Maximum HV	30 kV	Double insulation, Paschen resistant
External magnetic field	50 mT	

HTS module is the key component which consists of ninety HTS tape stacks, shunt/support and two OFHC (oxygen-free high conduction copper) ends. Before welded on, the critical current of each stack was tested. Fig. 9 shows the measurement result of eight AMSC (American Superconductor) HTS tape stacks made of twelve tapes each. Based on 1μV/cm criterion the stack critical currents (Ic) are 720-826 A. The HTS module of the 68 kA trial lead has an operating margin about 65% according to the average load line. Shunt design is very important for the HTS current lead safety. The 68 kA HTS module comprised eighteen panels. Each panel consists of five HTS stacks and a Cu-Be bronze shunt. In order to prolong the burnout time after HTS quench, a binary shunt concept was designed, which consists of stainless steel and Cu-5Sn-0.2P bronze (for the warm section) cylinders. The burnout time has been tested by 1/90 full bronze (Cu-2.0Be) shunts and binary shunts (Cu-2.0Be-SS). The test results show their temperature rising rates are similar. Based on the test results, a binary shunt structure with a bronze of 3131 mm^2 cross-section and 200 mm length and a stainless steel of 2732 mm^2 cross-section and 110 mm length has been proposed. By numerical simulation, the burnout time will be 17 s from 100 K to 180 K which is much longer than required value of 13 s. The calculation shows the total heat leak is 12 W for an effective length of 0.31 m. It is possible to reduce the total heat leak to 9.3 W if the effective length increases to 0.4 m for the prototype leads.

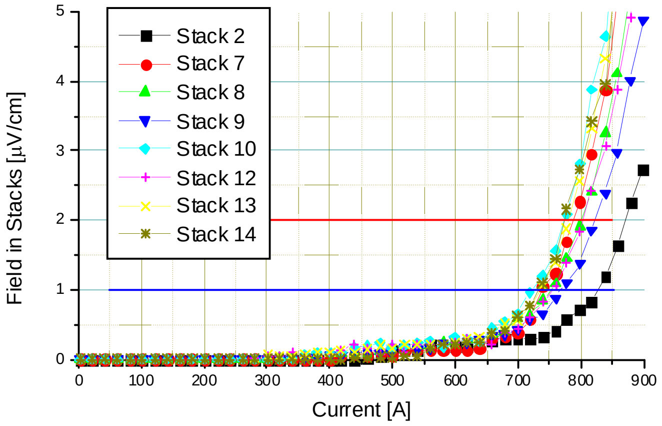

Fig. 9 The measurement result of eight AMSC HTS tape stacks made of twelve tapes each.

The LTS module consists of three components: box-type joint to the superconducting busbar, cylinder-shaped LTS link joined to the HTS module and SHe (supercritical helium) jacket with inlet ports. There are 90 NbTi/Cu wires with a cross-section of 2.7 mm × 1 mm in the lead side, and each one links to a HTS stack. Taking into account the LOFA time of 400 s the LTS should have an OFHC shunt.

The HEX operates in the temperature range 65 K to room temperature and is cooled by 50 K helium flow at inlet pressure of 3 bars. To improve heat exchange, the zigzag type fins with average heat transfer coefficient h_{Pw} = 1200 W/K-m was investigated. The results show the contact resistance can be 2-3 nΩ level. With 0.15 m length of the cold section, 400 s LOFA time can be achieved. The total pressure drop through the HEX is 0.924 bar for the condition of a helium mass flow rate of 4.3 g/s and inlet temperature/pressure of 50 K/3 bar.

For safety, all current leads should withstand a 30 kV test voltage. An insulation module has been employed and functions as an insulator in atmosphere between the current lead and CTB connected to ground, providing double insulation for HEX section, and as a major mechanical link to CTB.

To investigate the performance of the trial lead, extra temperature sensors and voltage taps are needed to measure LOFA/burnout times and contact resistances between HEX and HTS module, between HTS module and LTS module, and box-type joint.

Following key technologies have been developed: solders with lower resistivity, inductive-heating brazing between the shunt module and HEX, glass-epoxy insulation on a stainless steel tube directly, explosion-bonding technology for Cu-SS plate for the joints. Considering melting point and contact resistivity, Sn-3.8Ag-0.7Cu is better than Sn-40Pb for HTS stack soldering due to its higher melting point and lower resistivity; Bi-18.8Sn-21.2Pb is the best solder for the box-type joint contact due to its lower melting point and lower resistivity.

The test of the 68 kA trial current lead has been prepared in ASIPP. Following test items will be done:

1) Current carrying capacity at different warm end temperatures (65 K/75 K/ 80 K), the criterion is the voltage drop over the HTS module be less than 0.5 mV. 68 kA DC test for a minimum of 2 hours.
2) Resistive HEX voltage drop and contact resistances of HTS-resistive HEX joint and HTS-LTS joint. Voltage drops on the resistant HEX, warm/cold joints of HTS stacks to HEX and LTS.
3) Flow consumption, such as 50 K helium mass flow rates of 68 kA and zero current, the warm end temperature of HTS module should reach 65±2 K.
4) Heat load at 5 K, by measuring SHe mass flow rate and inlet/outlet temperatures of HTS module cold ends.
5) Pressure drops of 50 K GHe and 4.6 K SHe mass flows.
6) LOFA test: ramp current to 68 kA, stop helium mass flow, record the temperature rise at 95%, 80%, 70% positions (from bottom) of HTS module, switch off power supply when the maximum temperature reaches 160 K.
7) Electrical insulation test: Apply gradually increasing voltage between lead and ground up to 30 kV or 50 μA, whatever occurs first. Paschen test with filled RT helium into CLTB at pressure ~ 1 mbar and apply test voltage between current leads and CLTB step by step until the leakage current reaches 50 μA.

A new test facility for the ITER HTS current leads is prepared by modification of the existing test equipment in ASIPP. It consists of HEX cooling flows which are fed from the refrigerator directly or through the cold ends of the HTS modules and the U-shaped busbar, valve V1 which generates a flowing resistance and controls the mass flow through the cold ends, and V4&5 control the two leads mass.

C. Analyses of ITER Correction Coils

China will contribute the total of eighteen correction coils (CC) for ITER. The correction coils are designed with ground insulation and a protective steel outer case with thickness of 20 mm. The case is clamped to the TF coil cases at suitable locations by bolts. The bolt reacts in tensile force only. Sliding along the correction coil perimeter with respect to the TF cases is partially allowed at the supports. There are two insulation breaks along the coil perimeter.

Based on the data from the ITER organization, the electromagnetic and structure analyses have been performed by ASIPP [6]. Electromagnetic force calculations are done for the maximum CC current of 180 kA. 3D models including the CC cases and ground insulation are created. The distribution of the magnetic field, electromagnetic forces at different moments such as SOF (Start of Flattop), EOB (End of Burn) and XPF (X-Point Formation) were calculated and analyzed. The current condition at EOB is for the calculation of the electromagnetic forces. The electromagnetic force along the perimeter of one bottom CC is shown in Fig. 10. The maximum Von Mises stress is 45 MPa. The corresponding displacement is 0.244 mm.

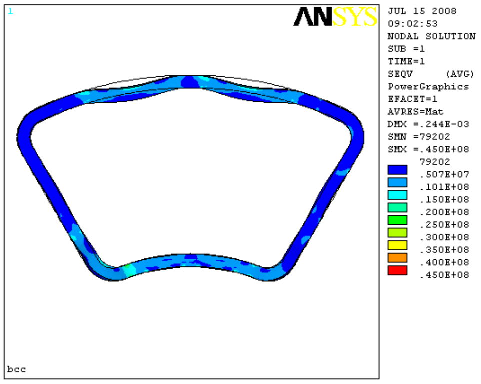

Fig. 10 The Electromagnetic force along the perimeter of one bottom CC

IV. OTHER SCIENTIFIC SUPERCONDUCTING PROJECTS

There are two major scientific superconducting projects in China right now. One is the international cooperation project FAIR, another one is newly approved as a national high field magnet facility in Hefei, China.

A. *FAIR Super-FRS/CR Dipole Prototype Magnet*

FAIR is an international research facility for beams of ions and antiprotons. It will be built in GSI (Gesellschaft für Schwerionenforschung mbH) at Darmstadt, Germany. Based on the cooperation agreement, as main partners, ASIPP and the Institute of Modern Physics, Chinese Academy of Sciences (IMPCAS) have started a R&D program for a prototype superconducting dipole magnet for the superconducting fragment separator (Super-FRS) and the Collector Ring (CR). ASIPP is in charge of the engineering design, fabrication and testing of superconducting coils, including quench protection system for 24 CR magnets. Fig. 11 is the overview of the dipole prototype magnet.

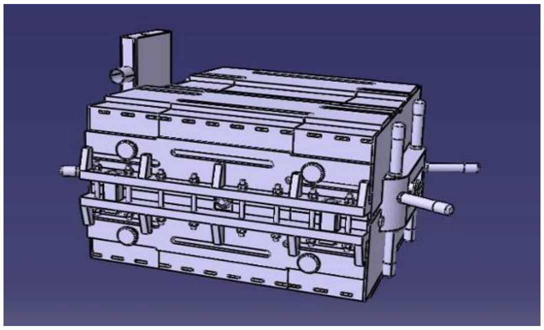

Fig. 11 The overview of the SUPER-FRS/CR dipole prototype magnet

The superconducting dipole magnet consists of two coil windings with case, thermal shield, support, cryostat and current leads [7]. Table IV lists the main parameters of the superconducting dipole magnet. Design of superconducting dipole coil is based on the magnetic field analysis with OPERA-3D by IMPCAS. Each superconducting coil is constructed with 560 turns with 28 layers and 20 pancakes. The NbTi/Cu conductor is from Oxford Instruments. The conductor parameters have been confirmed by testing. The parameters of the conductor are listed in Table V. The inductance of coils is about 21.4 H and the store energy is about 0.44 MJ with the operation current of 246 A. The coil case is a strong frame structure made of 316 LN stainless steel to withstand electromagnetic forces. Fig. 12 shows the electromagnetic forces distribution on the coils. The summarized forces in the vertical direction are 214 kN. The results of the case stress calculation show the maximum Von Mises stress on the coil case is 123 MPa and the maximum distortion is 0.3 mm. The thermal shield is made by copper sheet of 2 mm thickness with cooling pipes welded on. Multi-layers insulation is used. The cryostat is made of 8 mm thickness 316 L stainless steel.

TABLE IV MAIN PARAMETERS OF THE DIPOLE MAGNET

Design	Superferric H-type, straight
Cooling	Pool cooling
Maximum field in the beam duct	1.62 T
Minimum field in the beam duct	0.15 T
Peak field on the coil	1.19 T
Bending angle	15 degree
Edge angles (entrance / exit)	0 degree
Yoke angles	15 degree
Curvature radius	8.125 m
Effective path length	2.126 m
Useable horizontal aperture:	±190 mm
Sagitta	70 mm
Total horizontal good field area	± 225 mm
Useable vertical gap	±70 mm
Vertical pole gap height	±85 mm
Integral field quality (relative) $\frac{\Delta(\int Bdl)}{\int Bdl}$	3×10^{-4} (B=0.15 to 1.2 T) 1×10^{-4} (B=1.2 to 1.6T)

TABLE V MAIN PARAMETERS OF THE NBTI CONDUCTOR

	Nominal Parameters	Tested Results
Dimension of Conductor	1.17×1.93 mm^2	
Filament Diameter	50-105 μm	66 μm
Number of the filaments in core wire	55	55
Twist pitch on filaments	13	13
Ratio of Cu and no Cu in conductor	14	10.7
n-values	84±9	100
RRR of Cu in strand	107±11	133
Operating temperature	4.2 K	
Critical current@4.2 K & 4 T	560 A	657 A
Critical current@4.2 K & 2 T	774 A	
Critical current@4.2 K & 1.6 T (Ic)	813 A	
Operating current (Iop)	246 A	
Current density of the conductor	109 A/mm^2	
Iop/Ic	0.3	
Current sharing temperature (Tcs)	7 K	
Temperature margin (Tcs – Top)	2.8 K	

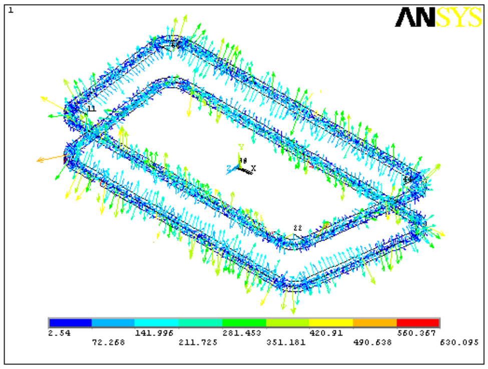

Fig. 12 The electromagnetic forces distribution on the coils

Dump resistor (DR) is selected for the quench protection for the 24 CR magnets. Based on the hot spot temperature of 150 K and the value of RRR (B, T) of 100, the quench $\int I^2t$, the time constant and the dump resistor can be calculated as 1.08×10^6 A^2s, 31 s and 10.83 Ω separately. Considering the total voltage of 24 magnets is about 2664 V when the current is dumped with a time constant 31 s, to limit ground voltage of the coil below 500 V, the total resistor must be divided into three resistors. So, at the beginning of the current dump, the voltage on each dipole is limited to 111 V.

A full-scale test coil has been fabricated and tested in 2007 at ASIPP. Six tests have been done successfully. Using a heater assembled inside of coil, quench tests were performed at 50 A, 100 A and 250 A with dump resistance of 0.5 Ω, 1.0 Ω and 2.8 Ω respectively. In the sixth charge, the current is ramped up to 400 A by ratio 3.3 A/s. By using of a heater, a quench was induced. While energy release resistance of 0.5 Ω was selected, the hot spot temperature of 35 K was tested. The temperature on the coil case increased up to 20 K. Helium pressure increased from 1.3 bar to 2.5 bar. The current and temperature were shown in Fig 13. The test results indicated the coil superconducting stability is satisfied. The conductor, coil design and manufacture technology were validated.

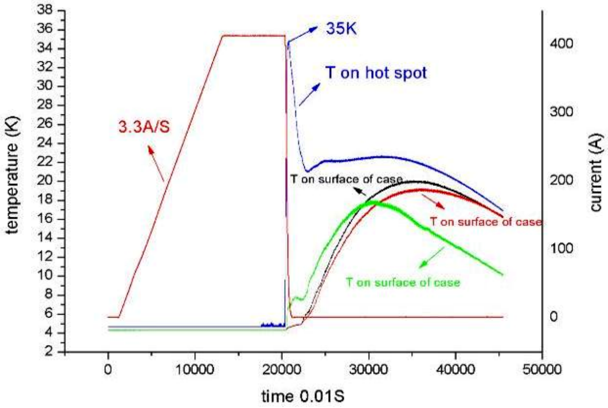

Fig. 13 The current and temperature verifying of the test coil

The prototype dipole magnet will be finally fabricated and assembled with yoke made by IMPCAS in the end of 2008.

B. *40 T Hybrid High Magnet Field Facility*

A 40 T hybrid high field magnet facility has been approved as a national project by China government in 2007 and started construction in 2008. The main purpose of the project is to set up a series of high-field steady state magnets from 20 T to 40 T, including a 40 T hybrid magnet, four 20 T to 36 T water cooling magnets and one 20 T, 800 MHz superconducting NMR. Now the main effort has been focused on a superconducting magnet with 11 T in the center of the bore of 580 mm in diameter at room temperature (RT). Together with 30 T/20 MW water cooled magnet, the hybrid magnet will produce 40 T at the center of the bore of 32 mm in diameter at RT. The superconducting magnet consists of four concentric coils in layers; three of them inside will be made by Nb_3Sn CICC and the outer coil will be made of NbTi CICC. The operation current and temperature will be 14.4 kA and 4.5 K.

V. SUPERCONDUCTIVITY MUNICIPAL APPLICATIONS

The activities of superconductivity application R&D in China are mainly supported by China 863 programs and industrials. Except for the HTS-CL applications in large scale scientific projects such as the HTS-CL in the EAST and ITER, the application R&D mainly focused on the HTS tape performance improvement and the applications in electric power grids such as power cable, superconducting fault current limiter (SFCL), HTS power transformer and HTS superconducting magnet energy storage (SMES). Further efforts for the R&D of the HTS magnetic levitation (Maglev) were made on HTS Maglev measurement systems toward the superconducting HTS Maglev test line.

A. *Progress in the HTS Tape Performance*

The first production line of Bi-2223/Ag HTS tapes was set up in the end of 2001 with an annual production capacity of 200 km at Innova Superconductor Technology Co., Ltd. (InnoST), Beijing, China. In 2003, the production capacity was up to 300 km [8]. Up to now, the critical current (Ic) of InnoST's HTS tape reached 110 A (77 K, 0 T) and the engineering critical current density Je has reached 11 kA/cm^2. During the past tree years, tremendous R&D efforts have been made in improving the application properties of HTS tape, such as reducing AC losses and thermal conductivity, increasing insulating properties and so on. Meanwhile, InnoST makes special efforts in reducing the manufacture cost by developing some innovative techniques. The goal is to increase the Ic to 150 A, while reducing the manufacture cost to $ 60 /kAm by the end of 2009. During the EAST construction, a lower thermal conductivity HTS tape was required. InnoST has produced a new low thermal conductivity Ag-4at%Au sheath Bi-2223 tapes and successfully used in the EAST HTS-CLs [2]. The tape has 4.2 mm × 0.22 mm cross-section with 61 filaments. Ic is more than 80 A at 77 K, self-field.

Another Bi-2223 tape production line was built in 2003 in NIN with annual production about 200 km. During the last two years, the "bubbling phenomenon" and "assuaging" problem have been considerably suppressed by optimizing the processing parameters. Especially by the so-called second post process, 3221 phase can be eliminated and the grain connection improved effectively. The critical current of each tape with 4.2 mm × 0.23 mm cross-section is more than 80 A.

B. *HTS Power Cable Applications*

By cooperating with some institutes and universities in China, InnoPower started a 35 kV/121 MVA superconducting cable project in 2002. The system was installed and commissioned successfully at Puji Substation of China Southern Power Grid in 2004 [9]. The system consists of three 33.5 m cables, six terminations, and one closed-cycle liquid nitrogen cooling station. The cable was constructed by helically wrapping layers of HTS tape made by InnoST around a corrugated stainless steel tube, which served as a flexible former. A flexible cryostat made of corrugated stainless steel tubes with an inner diameter of 43 mm and outer diameter of 70 mm houses the former tube and the cable. Liquid nitrogen flows through inside the former, the gaps between the tapes and the inside wall of the cryostat. A 11.9 mm thick cross-linked polyethylene (XLPE) was used for the dielectric layer. The diameter of the finished cable is 112 mm. The overall linear specific mass of the cable is 9.2 kg/m. The structure is shown in Fig. 14. The current lead of the terminations is made of braided copper wires. Epoxy resin/fiber glass tube is used for the LN_2 pipe feed through, which provides a LN_2 flow path as well as electrical insulation between terminations and the LN_2 transport lines.

The cable replaced a part of the 35 kV outdoor bus-line, distributing electricity to a town with about 100,000 population and four industrial customers including two metallurgical refineries. Fig. 15 is the overview of the cable installation site. 3-phases cables are set in parallel with a 90 degree bent angle. From 2004, the system has delivered more than 300 million kWh of electricity and is still in operation now. The operation of the cable system is automatically controlled. The system has experienced several breakdowns since the commissioning mainly due to the fault of the cryogenic system. Scheduled maintenance is scheduled about twice a year, which includes checking and replacement of the bearings of the pumps, pressure checking of the refrigerator compressors and vacuum checking of the cables and termination cryostats. The cable system has been in operation almost continuously for four years. No degeneration is observed by examination of the DC resistance and the electrical insulation of the cables and terminations [10].

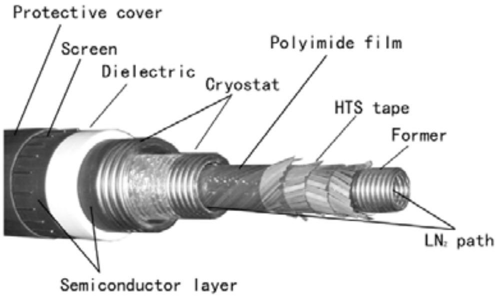

Fig. 14 The structure of the 35 kV/121 MVA 35 kV/121 MVA HTS cable

Fig. 15. The overview of the 35 kV/121 MVA cable installation site.

Another successful and longer HTS power cable system is the Changtong cable project. It is a 3-phase, 75 meter long, 10.5 kV/1.5 kA HTS power cable of warm-dielectric design, which was mainly developed by the Institute of Electrical Engineering Chinese Academy of Sciences (IEECAS) and installed and demonstrated in a distribution grid of Changtong Power Cable Factory in Baiyin, China in the end of 2004. The HTS tapes are the stainless steel-reinforced multi-filamentary Bi-2223/Ag hermetic tapes from AMSC. Each cable consists of 36 Bi-2223 tapes spirally reeled into two layers on the corrugated pipe and soldered to the copper terminals by low-melting-point alloy solder. The cryostat consists of two concentric corrugated stainless steel tubes, and the insulation technique for the HTS cable is designed to be compatible with that of conventional copper cable. The outer diameter of the cryostat is 92 mm. It is made up of three sections connected in series, the length of each cryostat is 25 m. The final diameter of the cable is 117 mm.

The 10.5 kV/1.5 kA HTS power cable was installed in a wave shape, simulating the practical laying situation. Fig. 16 is the installation of the 75 m HTS power cable. In preliminary tests, the critical current is up to 5.3 kA of direct current (DC) at 74 K, the cable's rated voltage is 10.5 kV, and it has conducted up to 1,600 Amperes (at 400 volts) of alternating current (AC), limited only by the load available at the site. The parameters of the cable are listed in Table VI. The HTS power cable operates at a local 6.6 kV live distribution grid and has been operating stably and reliably over 7000 hours without any breakdown since December 2004 [11].

Fig. 16. The installation of the 75 m 10.5 kV/1.5 kA HTS power cable

C. HTS Power Transformer Applications

A 630 kVA 10.5 kV/0.4 kV 3-phase HTS power transformer was successfully developed and tested developed by IEE in collaboration with the Tebian Electric Company (TBEA) in November 2005 in China. The main parameters for the transformer are listed in Table VI, and overview of the transformer is shown in Fig. 17. The windings were wound by hermetic stainless steel-enforced multi-filamentary Bi-2223/Ag tapes. The structures of primary windings are solenoid of 8 layers with insulation and cooling path in series, and that of secondary consists of 23 double pancakes connected in parallel. All windings are wound with a strand consisting of two parallel transposed multi-filamentary tapes to prevent unbalanced current distribution. Toroidal cryostat is made from electrical insulating GFRP materials with room temperature bore for commercial amorphous alloy core with five limbs. The routine tests for the transformer were done according to the national standard. Fundamental characteristics of the transformer are obtained by standard short-circuit and no-load tests, it is shown that the transformer meets operating requirements in live grid.

TABLE VI DESIGN PARAMETERS OF THE 630 KVA TRANSFORMER

Voltage (primary/secondary)	10.5/0.4 kV
Current (primary/secondary)	34.64/909.33 A
Magnetic flux density	1.275 T
Operation temperature	77 K
Operation frequency	50 Hz
Impedance	2.45 %
Vector group	Yyn0+d7
Rated current	330 A DC at 77.3 K
Impulse voltage	75 kV
Sudden short circuit cuurent	2×rated current
Efficiency	98.3 %

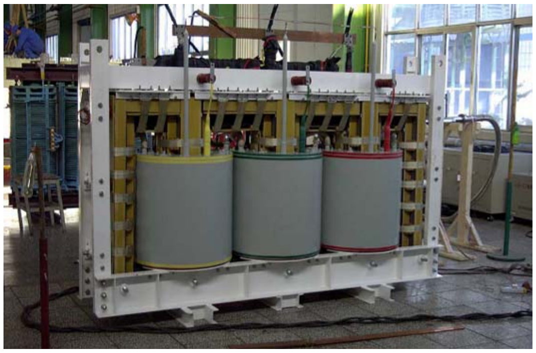

Fig. 17. Overview of the 630 kVA 10.5 kV/0.4 kV transformer

To investigate the possibility to use HTS power transformer as an alternative in electric locomotive, a single phase HTS transformer with rated parameters of 25 kV/6.6 kV/300 kVA was designed and fabricated by Zhuzhou Locomotive Company. Tests show that the efficiency is up to 99.87% if the cryogenic loss is excluded.

D. Superconducting Fault Current Limiters Applications

An outer-door-use 3-phase, 35 kV/90 MVA Saturated Iron-core SFCL (SISFCL) was developed by InnoPower and installed at Puji Substation of China where the 35 kV/121 MVA superconducting cable system was installed in May 2008. It is under commission now. The installation of SISFCL is shown Fig. 18.

Fig. 18. The installation of 35 kV/90 MVA SISFCL.

A compact core structure of SISFCL was proposed with iron-cores, AC coils and the cryostat containing the DC superconducting coil. In the core configuration, six iron-core frames are arranged in a hexagonal structure. The edge vertical limb of each iron-core frame is surrounded by an AC coil. A pair of AC coils is connected in series as one phase element of the three phase device. Its configuration minimizes the inductive voltage on the DC coil during normal operation. On the other hand, the two AC coils in one phase are connected such that the magnetic flux created by the phase current is equal in magnitude but in opposite direction at central column. The inductive voltage on the DC coil during normal operation can be greatly minimized.

A so-called DC bias control circuit was invented in 35 kV/90 MVA device [12]. The circuit mainly consists of a DC current supply, a high speed switch and an energy release unit. The DC current supply provides the current to the DC coil and magnetizes the iron core. When a short-circuit fault is detected, the high-speed switch made by High Voltage Insulated Gate Bipolar Transistor (HVIGBT) will switch on the magnetizing circuit. The magnetic energy stored in the iron cores is then released through the energy release unit. ZnO piezoresistors in the energy release unit also suppress the voltage surge caused by the quick opening of the magnetizing circuit, protecting the elements of the circuit. The total time from the fault detection to the complete release of the magnetic energy is less than 5 ms. Via the function of demagnetization, the device enters the high impedance state for current limiting. Table VII lists main parameters of the 35 kV/90 MVA SISFCL.

TABLE VII MAIN PARAMETERS OF THE 35 kV/90 MVA SISFCL

Rated voltage	35 kV
Rated current	1,500 A
Weight	27 t
Height	4,200 mm
Diameter	4,000 mm
Installation	out door
Insulation grade	H
Max. expected fault current	41 kA
Max. limited current	20 kA
Impedance at normal operation	< 0.35 Ω
Fault detection time	< 1 ms
Reaction time	< 5 ms
Restoration time	< 800 ms

A 10.5 kV/1.5 kA 3-phase HTS SFCL with HTS coil of 6.24 mH was developed at IEECAS. It employs an improved bridge-type FCL and IGCT switches together and has demonstrated long-term reliable operation in a real 10.5 kV substation located in Hunan, China. At normal operation, the line current flows through the bridge and the IGCT switches are switched-on. Therefore, it performs just like the bridge-type FCL. During fault condition, the first peak is limited by the HTS coil which is against the rapid ramping of the current. When the current of the HTS coil reaches a set value, the IGCT switches are then switch off, and the resistors are plunged into the line, the fault current is then limited by both the HTS coil and the resistors. So the steady-state fault current can also be restricted effectively. Each HTS coil was structured by ten double pancakes. Four of them at the end of the coil are made of two parallel Bi-2223 tapes and the other six were made with single tapes. The cryostats for the HTS coil were made of epoxy material, about 1100 mm in outer diameter and 1400 mm in height. In a three-phase-to-ground short circuit test of grid, the prospective fault current of 3.5 kA was limited to 635 A at the pre-setup short-circuit point successfully. The main parameters of the SFCL are listed in Table VIII.

TABLE VIII PARAMETERS OF THE 10.5 kV/1.5 kA SFCL

Inner diameter of the coil	492 mm
Outer diameter of the coil	580 mm
Number of double pancake	14
Height	361.6 mm
Total length of HTS tape	2856.8 m
Inductance	6.24 mH
Ic (1 μV/cm)	500 A at 77.3 K
Rated current	330 A DC at 77.3 K
Operation voltage	10.5 kV
Lightning surge voltage	75 kV
Center magnet field	0.0758 T at 330 A
The maximum field	0.1053 T at 330 A

Various investigations and feasibility were studied [13] and have shown that combined SMES and SFCL may be a new way for substation applications. A prototype system named Fault-Current-Limiting SMES, of 100 kJ/1000 A/20 kVA rating, was developed by IEECAS. It mainly consists of a NbTi magnet with two coaxial and homocentric solenoids for reducing stray field, a three-half-bridge converter and a current regulator. The test has been performed on a three-phase short circuit and voltage sag. With SFCL-MES, the steady fault current is limited by 87%, the peak current is limited by 90% and the voltage sag of point of common coupling (PCC) is compensated completely. Moreover, the voltage of the critical load is maintained all along.

A 220kV/1200A HTS SFCL Project has started in InnoPower by cooperating with Tianjin Electric Power Corporation and Tianjin M&E Industry Holding Group. It will be installed in Tianjin municipal power grid in 2009.

E. *Superconducting SMES Applications*

During the past tree years, four superconducting SMES systems have been developed. Three of them are HTS systems.

Fig. 19. The 1 MJ/0.5 MVA HTS SMES system.

IEECAS has developed a 1 MJ/0.5 MVA HTS SMES and put the system into operation in a live power grid of 10 kV in late of 2006 at a substation in the suburb of Beijing, China. The HTS magnet, made by 16 km HTS tapes, has an inner diameter of 400 mm, an outer diameter of 568 mm and height of 645 mm. With operation current of 564 A at 4.5 K operation temperature, the storage energy and the maximum magnetic filed are 1 MJ and 5.72 T, separately. A quench protection system is designed to monitor critical voltages in the SMES coil and dissipates the stored energy through a dump resistor. The bath cooling was adopted and four cryocoolers were used to re-liquefy the evaporated helium. Fig. 19 shows the 1 MJ/0.5 MVA HTS SMES system.

A 35 kJ/7 kW conduction-cooled HTS SMES is developed by the Electric Power System Dynamic Simulation Laboratory (EPSDSL), Huazhong University of Science and Technology (HUST) in 2005. The magnet is composed of 32 double pancakes made by Bi-2223 tapes which were supplied by NIN/WST and operates at 20 K by conduction-cooled method. It has a maximum magnetic field of 3 T with a rated current of 100 A. A series of tests are successfully carried out to evaluate the performance. It is confirmed that the conduction-cooled magnet may also have good current carrying capability and thermal stability. The test results show the 35 kJ/7 kW HTS SMES can respond to active and reactive power demand independently with a response time of less then 8 ms. In a dynamic experiment, it was proved that the system can effectively damp the power oscillation caused by a short-circuit.

A 500 kJ/150 kVA SMES unit was successfully made and tested by Tsinghua University in collaboration with Tianwei Electric Group in the end of 2005. It is a current-source type SMES made by NbTi wires. The test results indicates that the system compensate the voltage sags well.

In China, a HTS SMES made by YBCO coated conductor has been under development with the support of the State Grid of China since 2007. As a part of the project, a SMES made of YBCO is investigated in China Electric Power Research Institute (CEPRI) and will be set up at the end of 2008 [14]. The system stores 0.38 kJ at 77 K and 3.42 kJ at 64 K; 20 kW converters for power conversion, quench protection system, online monitor and measurement system are included.

F. *Further Efforts on HTS Maglev*

After the first man-loading HTS Maglev test vehicle “Century” in the world was successfully developed by Applied Superconductivity Laboratory (ASCLab) of Southwest Jiaotong University (SWJTU), China in 2000, over 40,000 passengers have experienced its advanced technology. Up to now, “Century” has traveled back and forth for about 500 km [15]. After seven years operation, the levitation capability has maintained 95% of the original load level. More attention has been paid to permanent magnet guideway (PMG) optimization, propulsion method, gradeability, vibration characteristics, low speed running stability, AC magnetic field influences, test line consideration and so on.

For further optimization, with supporting by 863 programs and NFSC, an update HTS Maglev Measurement System (SCML-02) with more functions and higher precision was developed in 2004. By SCML-02, several PMG optimization designs have been tested. The present best design is regarded as the Halbach array PMG and its updated version. The advantage of Halbach design is to extensively use magnetic energy, while the disadvantage is possible inhomogeneous field along running direction at low height due to the leakage fluxes by magnet flux-collector. It indicates that iron flux-collector can be used in the future HTS Maglev test line combined with Halbach array PMG design. A self-developed HTS Maglev dynamic test system (SCML-03) was set up for test requirement of levitation performance at 0 to 300 km/h velocity as shown in Fig. 21. Multi-channel vibration analyzer is introduced to obtain vibration parameter of the HTS Maglev system. It was found that the resonance frequency remains about 10 Hz and it is a good hint for the future high-speed or super high-speed of HTS Maglev system.

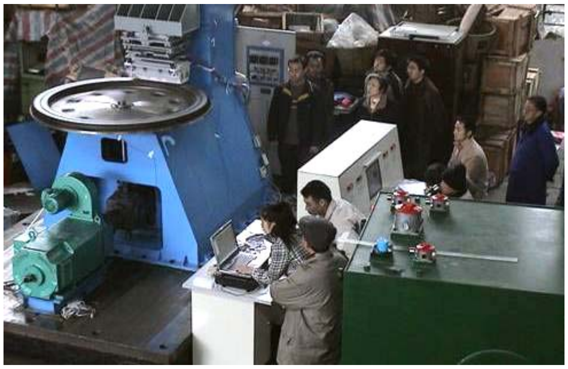

Fig. 21. HTS Maglev dynamic test system (SCML-03)

Based on the successful R&D, a 100 km/h HTS Maglev test line has been proposed and supported by China 863 programs. As a significant attempt, this on-going research plan will be an important step to the practical HTS Maglev system.

On the other hand, some basic R&D on the HTS Maglev launch assist technology for space vehicle is underway in some universities of China. A HTS maglev launch vehicle prototype with 2 g max acceleration and 30°angle was set up in ASCLab in 2006 [16]. In the College of Astronautics, Beihang University, Beijing, China, a demonstration HTS maglev test vehicle is built with four maglev units and two permanent magnet guideways with the length of 7 m. The net levitation gap is above 10 mm with the test vehicle weighs of 80 kg. As a result, the levitation force pressure is 2.47 N/cm^2, and the guidance force pressure at 20 mm lateral distance is 1.36 N/cm^2. The propulsive acceleration of the test vehicle is 1.2g, and the maximal velocity is up to 6 m/s. Fig. 22 shows the test platform of HTS maglev vehicle.

Fig. 22 The test platform of HTS maglev vehicle.

VI. CONCLUSION

During the last five years, the applied superconductivity has developed well with strong support from China government. Remarkable achievements have been reached in the large scale scientific projects, such as EAST, ITER and FAIR. Especially with joint effort from industrials, HTS applications have successfully demonstrated in municipal power grids. It is expected that applied superconductivities will be developed further within next few years with the ITER project, National high magnet field project and ongoing HTS projects in China as propelling engines.

ACKNOWLEDGMENT

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