Recent Progress of Superconducting Magnet Technology in China

Luguang Yan

***Abstract*—The superconducting magnets were developed for all kinds of applications in China. With the growth of economy in China, some national projects of applied superconductivity are started in the basic sciences and engineering R&D in the recent years. The projects for the high magnetic field superconducting magnet applied in the scientific instruments, 40 T hybrid magnet system, high energy accelerator magnet, fusion engineering and special industrial system are supported by the central or local governments. For the high temperature superconductivity (HTSC) applications, some high temperature superconducting magnets were developed for fast charge and AC applications. The paper reviews the recent progress of superconducting magnet technology in China.**

***Index Terms*—Accelerator magnet, fusion, HTS magnet, LTS magnet, scientific instruments.**

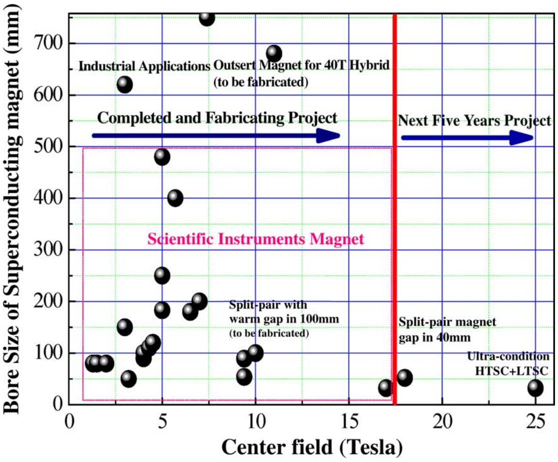

Fig. 1. Profiles of the center field vs. the bore size of the magnet.

I. Introduction

THE superconductivity technology has been developed since the sixties of last century in China. After that, a lot of research and development works were conducted on the high magnetic field superconducting magnet technology applied in the electric machines, magnetohydrodynamic power generation, magnetic separation, magnetic resonance imaging, nuclear magnetic resonance, separate iron from coal in the harbor and scientific instruments [1]. A large scientific project for fusion engineering was started since 2000 and was completed and operated in the 2006. After that, China joins the ITER project. In order to extend the basic science research, the National Development and Reform Commission has supported the development of 40 T hybrid magnet. The main parameters of the high magnetic field superconducting magnets fabricated since 2002 and some future projects using them in the extreme physical environments are summarized in Fig. 1. Recently, with the development of high temperature superconducting (HTSC) technology, some HTSC prototypes for superconducting magnetic energy storage, motor, generator, current limiter and transformer were fabricated and tested in the power station [2]. The quite good achievements both in basic research, magnet and cryogenic technology are obtained in the recent years.

II. Superconducting Magnet Technology Applied in Scientific Instruments and Industries

A. *Conduction-Cooled High Field Superconducting Magnet*

The high field conduction-cooled magnets fabricated by the high and lower temperature superconductors cooled by GM and pulse tube cryocoolers are designed, fabricated and operated for the scientific instruments used in the material processing, high stored energy density system, gyrotron, characteristics of superconducting wire/tapes test devices, space detector, magnetic surgery system, magnetic resonance imaging and nuclear magnetic resonance in the Institute of Electrical Engineering, Academia Sinica (IEECAS).

The development of the first conduction cooled low temperature superconducting (LTS) magnet with the center field of 6.5 T and a room temperature bore size of ϕ180 mm was completed in 2004. After that, all kinds of high magnetic field conduction-cooled superconducting magnets with the warm bore diameters in the range of 50 mm $\sim$ 250 mm and the maximum center field of 5 $\sim$ 10 T for the material processing devices and scientific instruments have been fabricated and delivered to our customers. To be satisfied to the requirements of the high power microwave devices, the superconducting magnets with the complex magnetic field distribution and with the diameter of warm room of Φ80 $\sim$ 120 mm and the center field of 1.3 $\sim$ 10 T was designed, fabricated for high power gyrotron clients [2], [3]. Besides, a HTS magnet technology for some potential advantages

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The author is with the Center of High magnetic field superconducting magnet science and technology, Institute of Electrical Engineering, Academia Sinica, Beijing, China (e-mail: lgyan@mail.iee.ac.cn).

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for the scientific instruments and other applications was developed. The magnet operated with a GM cryo-cooler at 10 K and the center field of 3.22 $\sim$ 5 T at various ramping rates with 0.1 $\sim$ 5.06 A/s was fabricated for the industry wasted-water treatment in 2005 [4]. After that, a HTS magnet with solid nitrogen protection technique was developed and used for high power SMES in 2007 [5]. A 10 T split-pair superconducting magnet with the warm horizontal split-gap of 100 mm and the warm vertical bore of 100 mm is designed and will be fabricated for special material growth. With the rapid increasing demand for NMR superconducting magnets, the high magnetic field superconducting magnets with center field of 9.4 $\sim$ 11.75 T for NMR system with zero evaporation of liquid helium are designed and fabricated. IEECAS is taking part in the international cooperation program on the Alpha Magnetic Spectroscopy (AMS) to develop super-stable magnet cooled by super-fluid helium with heat exchanger. For the medical applications, IEECAS is co-operating with Time Medical Ltd to develop a 1.5 T magnetic resonance imaging system.

A conduction-cooled superconducting magnet for material processing was designed and fabricated in 2009 as shown in Fig. 2. The superconducting magnet system consists of three coils including an $\mathrm{Nb_3Sn}$ coil and two NbTi coils. $\mathrm{Nb_3Sn}$ coil is fabricated using ϕ1.0 mm superconducting wire, which generates a center field of 3.96 T. NbTi coils with inner and outer coils are fabricated using ϕ1.0 mm and 0.65 mm, which generate the center field of 6.04 T. The superconducting magnet system can generate 10 T central magnetic field with the warm bore diameter of 100 mm. A stainless steel former is employed for the $\mathrm{Nb_3Sn}$ coil to support the electromagnetic force. To improve the thermal connection between the superconducting coils and 4 K GM cryocooler, a brass former is used for the NbTi and $\mathrm{Nb_3Sn}$ superconducting coils. The former is with a 2 mm width slot along axis to reduce the eddy current losses during the charging magnets stage. The $\mathrm{Nb_3Sn}$ and NbTi superconducting coils are connected in series to the same power supply. The operating current of magnet system is 116 A. The cooling power of the cryocooler is 45 W at 40 K on the first stage and 1.5 W at 4.2 K on the second stage, respectively. The vacuum of cryostat was measured to be $10^{-4}\ \mathrm{Pa}$ before the superconducting magnet was cooled. The temperatures of the magnet are about 3.87 K and 3.8 K for the top and bottom of the superconducting magnet after cooling about 90 h. To limit the AC losses in magnet, the ramping rate of current is set to be 0.033 A/s. After three times training, the superconducting magnet is charged to the full field of 10.3 T. The magnet has been stably operated in the laboratory providing all kind of physics experiments.

Fig. 2. High magnetic field conduction-cooled superconducting magnet with warm bore size of 100 mm and center field of 10 T (fabricated: 2009).

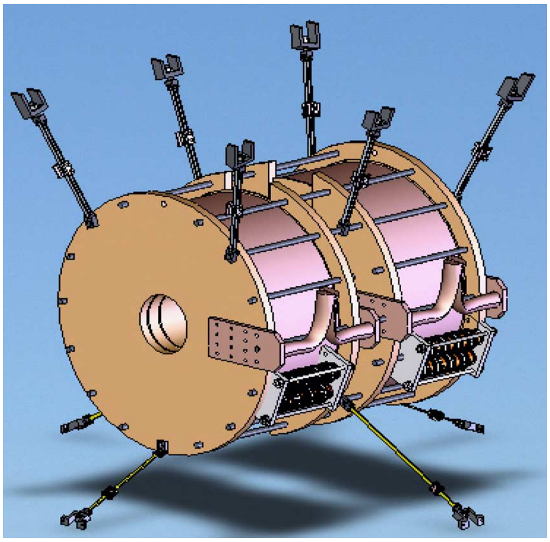

Fig. 3. Configuration for magnet with warm bore size of 100 mm and warm split gap in 100 mm and the center field of 10 T.

To study the special material growth, a large split gap superconducting magnet is designed and fabricated. The magnet with the warm bore size of Φ100 mm and the warm horizontal split gap of 100 mm consists of one-pair HTS coils and six-pairs LTS coils fabricated by two-pairs $\mathrm{Nb_3Sn}$ and three-pair NbTi coils. The configuration of the coils is illustrated in Fig. 3. The HTS coil consists of 13 double pancake coils with inner radius of 70 mm, outer radius of 110 mm, and height of 144 mm, respectively. The total turns are 2288 and total length of HTS tape is about 1.3 km. The $\mathrm{Nb_3Sn}$ superconducting coils are graded and fabricated by superconducting wire with diameter of 1.55 mm and 1.35 mm and Cu/non-Cu ratio of 1.3. The critical current density at 4.2 K and 10 T is about 855 $\mathrm{A/mm^2}$. The outer NbTi superconducting coils are fabricated by graded wire with diameter of 1.35 mm and 1.25 mm. The critical current density is about 2650 $\mathrm{A/mm^2}$ at 4.2 K and 5 T. The magnet will be cooled by two GM cryocoolers with the total cooling power of 3 W at 4.2 K. The cryogenics consists of coils, supported configuration and radiation shield at the temperature of 45 K. The height of the cryostat is about 710 mm and diameter in 740 mm and total height in 1500 mm. The total attractive force between two coils is about 235 ton. The total weight of the superconducting magnet system is about 530 kg.

Fig. 4. The test bed for the HTS tape and LTS wire (fabricated:2007).

For the goal of superconducting magnet applied in the advanced testing device for high temperature superconducting (HTS) wire and sample coils, a wide bore conduction-cooled superconducting magnet with the available warm bore of ϕ186 mm and the center field of 5 $\sim$ 6 T for the background magnetic field was designed, fabricated and tested. A sample cryostat with two-GM cryocoolers is inserted in the background magnet. The system allows sample tests to be performed in a repeatable and reliable fashion. The superconducting magnet is shown in Fig. 4. The field uniformity $\Delta B/B$ of the magnetic field should be lower than 1% within a central region of $\phi 50 \times 50$ mm and lower than 5% within the region of $\phi 100 \times 100$ mm. The ramping rate of superconducting magnet is limited to 0.05 A/s to the full field operation. The total cooling time for the system is about 78 h. The sample cryostat includes two GM cryocoolers with the second stage operated at 10 K and 4 K, the hybrid current leads, holder of sample and other parts. It is important to assure temperature stability during measurement $(T < 0.5\ \mathrm{K})$ to achieve the accurate measurement of the critical current in the HTS samples. The sample cryostat and holder equipped with all necessary wires for the currents, voltages and temperature measurements. The temperature sensors are attached to check the sample temperature directly during measurement. It is reliable and reproducible to measurements of the current-voltage characteristics $(\text{noise level} < 100\ \mathrm{nV})$ and determination of the critical current [6].

For the requirements of microwave devices, all kinds of magnets have been fabricated for the microwave devices used in the Gyrotron. Such as, a conduction-cooled magnet with center field of 1.3 $\sim$ 10 T and warm bore of Φ100 mm have been designed, fabricated and delivered to our users. The electromagnetic structure of the magnet was designed on the basis of the hybrid genetic optimal method. The superconducting magnet has the adjustable length of homogeneous regions with the lengths from 200 mm to 250 mm. Also the superconducting magnet can generate the multi-homogeneous regions with the lengths of 200, 250 and 320 mm. The homogeneity of magnetic field is about $\pm$0.5% with the constant homogenous length and $\pm$1.0% for adjusting homogenous length. All of the homogeneous regions are starting with the same point and the field is decayed to 1/15–1/20 at a stretching distance of 200 mm. The superconducting magnet is cooled by one 1.5 W at 4 K GM refrigerator. The configuration of superconducting magnet with superconducting coils and copper coils is illustrated Fig. 5. The homogeneous region length of 320 mm with maximum center field of 1.3 T generated by main coils 1, 2 and compensating coils of 3 and 5. In order to extend the magnetic field decayed from 200 mm to 300 mm, it needs to use the normal copper coils. Therefore, the homogeneous region length of 320 mm with field of 1.3 T is generated by main and compensating coils of 1, 2, 3, 5, 6 and 7 for superconducting coils and 8, 9 and 10 for copper coils. The homogeneous region length of 250 mm with field of 4 T, and magnetic field can be adjustable through the main and compensating coils of 1, 2, 3, 5, 6 and 7. The magnetic field profile can be controlled by adjusting the current of cathode compensation coils of 6 and 7. The total superconducting coils should have five high temperature superconducting current leads. The adjusting copper coils of 8, 9 and 10 are used to change the operating current to correct the magnetic field distribution in the homogenous regions. The main field distribution is illustrated in Fig. 6. For the requirements of our customers, the superconducting magnets with all kinds of magnetic field distribution are fabricated. The characteristic parameters of the magnets are listed in the Table I. All the superconducting magnets are based on the conduction-cooled technology.

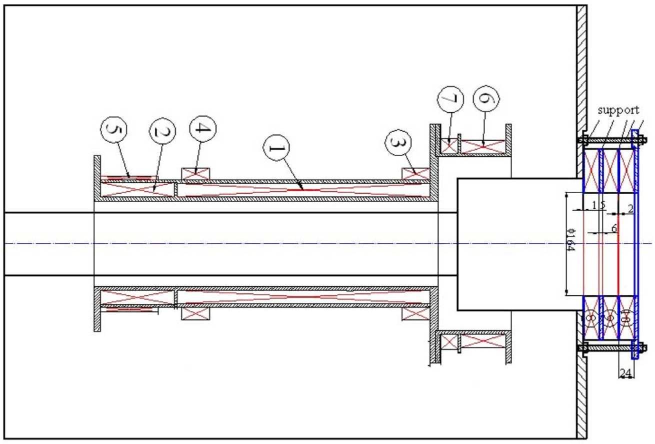

Fig. 5. Superconducting magnet with 10 coil arranged with the same axis, The superconducting coils are installed in cryostat, the copper coils are located outside of cryostat and fixed on the flange of cryostat, they are cooled by air convection. The superconducting coils are cooled by GM cryocooler.

B. Superconducting Magnet System With Zero Evaporating LHe

Applications of superconducting magnet system are restricted due to the requirements to refill liquid helium and nitrogen periodically. In order to overcome the problem, a large bore NbTi superconducting magnet cooled by liquid helium and GM cryo-coolers was designed, fabricated and operated. The superconducting magnet is with operating current of 350 A, maximum energy storage of 1.2 MJ as shown in Fig. 7(a) [7]. The coil has the bore size of ϕ480 mm, outer diameter of 550 mm and height of 500 mm, respectively. The cryogenic system takes two GM cryo-coolers to cool the whole system.

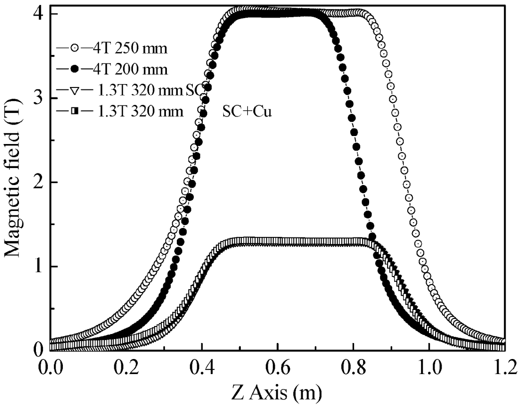

Fig. 6. Magnetic field distribution for various homogeneous region lengths.

TABLE I
MAIN PARAMETERS FOR MAGNET FOR GYROTRON

	B (T)	**$\Delta B/B$**	bore	Lengths of homogeneity region
1	4.2	0.1 %	80 mm	150 mm and 250 mm
2	5.0~10	0.01 %	100 mm	100 mm
3	4.3	0.3 %	120 mm	50 mm
4	1.3	0.5 %	80 mm	200 mm/300 mm
5	4-5	0.1 %	100 mm	200 mm/320 mm/250 mm
6	1.5-1.8	0.1 %	80 mm	140 mm/200 mm
7	3.2-4.0	0.1 %	100 mm	260 mm/300 mm
8	5	0.05 %	120 mm	20 mm
9	5	0.1 %	250 mm	50 mm

The normal operating temperature of the magnet is about 3.8 K by reduced pressure of liquid helium. The high temperature superconducting current lead of Bi2223 is used and cooled by one GM cryocooler [6]. The second large scale superconducting magnet with four parallel solenoids was designed, fabricated and used in the high energy storage density magnet. The superconducting magnet is with the maximum field of 6.4 T, operating current of 490 A, energy storage of 2 MJ and stored energy density of 1.4 $\mathrm{MJ/m^3}$. The ZnO resistor is employed to protect the superconducting magnet. The third superconducting magnet, as shown in Fig. 7(b), was fabricated on the basis of four-parallel solenoid with capacity of 1 MJ and output power over 1 MWatt. The stored energy density of this magnet system is more than 1.54 $\mathrm{MJ/m^3}$. All the three high magnetic field superconducting magnet system were designed and fabricated and delivered to our users. These has been operated over than half year. The level of liquid helium is not reduced during the operation.

On the basis of the requirements of high magnetic field nuclear magnetic resonance, the superconducting magnets are fabricated with various diameters of superconducting wire to improve the performance and reduce the weight in magnet. The superconducting magnet with the available-bore of $\phi 54$ mm and center field of 9.4 T is cooled by liquid helium as shown in Fig. 8. In order to reduce the liquid helium evaporation, a two-stage 4 K pulse tube refrigerator is employed. The superconducting magnet with active shielding is employed which protected by copper shield during the quench of the shield coils.


(a) (b)

Fig. 7. (a) Configuration of solenoid and (b) four-parallel-solenoid magnet.

Fig. 8. Configuration of superconducting magnet with cryostat.

C. High Temperature Superconducting Magnet With Solid Nitrogen Protection

A conduction-cooled HTS magnet system through a solid nitrogen protection was developed. The HTS magnet system was used to investigate fast discharging performances with the constant output voltage. The main parameters are listed in Table II. The high temperature superconducting magnet consists of 14 double pancakes wound with Bi2223 tape with tape length of 200 m. The magnet has an outer diameter of 212 mm and a clear bore of 108 mm. Cryostat for the HTS magnet system is designed to cool the coils with a GM cryo-cooler together with the solid nitrogen protection technology. The superconducting magnet is fabricated and tested. The operating current

TABLE II
MAJOR PARAMETERS OF BI HIGH TEMPERATURE COIL

Characteristics	Parameter
Inner Diameter	108 mm
Outer Diameter	250 mm
Height	172 mm
Number of double pancake	14
Turns	5096
Self inductance	2.5 H
Operating temperature	10
Operating current	155 A
Center field B_0	4.31 T
Energy storage	30 kJ

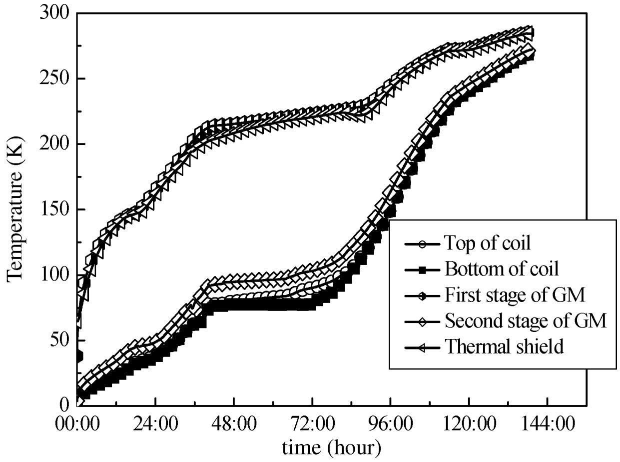

Fig. 9. Profiles of temperature vs. time in the superconducting magnet system.

is about 155 A with ramping rate of 5 A/s. It can generate a central magnetic field of 4.31 T at a temperature of 20 K. To acquire experiences of stand-alone operation of the HTS magnet system, the solid nitrogen was used to keep the magnet temperature constant in 40 hs after the cryo-cooler to be shut down. The profiles of temperature vs. time in the HTS magnet are shown in Fig. 9.

D. Development of Test Cryostat for AMS02

The Alpha Magnetic Spectrometer (AMS) is a high-energy particle detector to explore anti-matter, dark matter and the origin of cosmic rays in space. Compared with the first generation of AMS detector (AMS01), the second generation (AMS02) was fabricated in SCL utilizes a superconducting magnet, instead of a permanent one, to provide the required transverse magnetic field. The AMS02 superconducting magnet consists of 12 racetrack coils and a couple of Helmholtz coils, which are distributed circumferentially to provide a magnetic dipole field. Before the superconducting magnet is assembled in the flight-cryostat, the characteristics should be checked. The coils are tested in the big cryostat with superfluid helium. The cryostat with the diameter of 3.6 m and the length of 1.65 m was designed and fabricated and tested in Space Cryo-magnetic Company Ltd, IEECAS, and Lanzhou Vacuum Equipment Company. The main configuration is shown in Fig. 10.

Fig. 10. Test cryostat for Alpha magnetic spectrometer-02 (fabricated:2006).

Fig. 11. 3 T solenoid, cryostat and measurement system.

E. Development of Superconducting Magnet With LHe

A 3 T superconducting solenoid has been successfully designed, fabricated and tested, used it to calibrate Hall sensor in high field in Institute of Modern Physics, Academia Sinica (IMPCAS) as shown in Fig. 11. Several coaxial coils are used to produce a homogeneous magnetic field. The results show that the magnet can be operated stably with the operating current better than $\pm 2 \times 10^{-5}$, the central magnetic field of 3 T, the field homogeneity of $\pm 4.95 \times 10^{-5}$ in the size of $\phi 30\ \mathrm{mm} \times 30\ \mathrm{mm}$ [8].

Penning traps are devices that use both a magnetic field and an electric field to capture ions. The central field is 7 T with a uniformity of 3×10^{-7} in the two regions of interest (ROI), lying 220 mm apart. However, due to the manufacturing and winding tolerances, it is impractical to achieve such a high homogeneity only with the main coils. So we first design the main coils with a lower homogeneous field (10^{-5}) and then the superconducting shim coils and passive shim pieces are used to reach the required homogeneity.

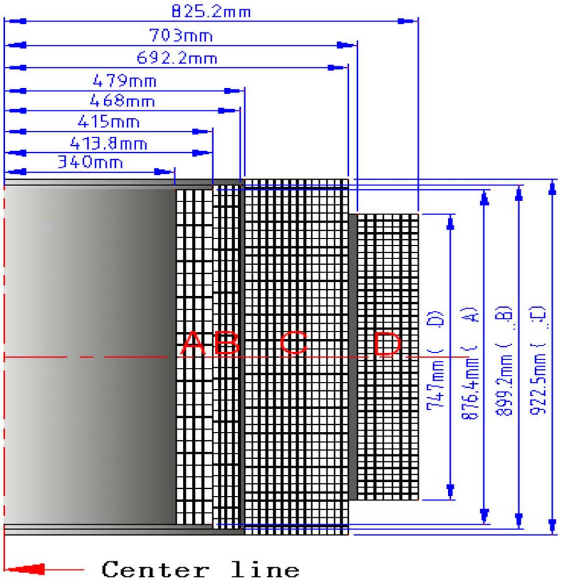

Fig. 12. Superconducting outsert showing coil A, B,C, and D.

III. PRELIMINARY DESIGN OF SUPERCONDUCTING OUTSERT MAGNET FOR 40 T HYBRID MAGNET SYSTEM

The 40 T hybrid magnet system project was proposed in the year of 2005, and got the approval in 2007. The 40 T hybrid magnet will be designed and constructed at the High Magnet Field Laboratory, Ademica Sinica (HMFLCAS), and the construction of the hybrid magnet is planned to be completed in 2013. The hybrid magnet consists of a resistive insert providing 29 T and a superconducting coil providing 11 T for 40 T on axis over a 32 mm bore. The outsert with 580 mm room temperature bore consists of two sub-coils: the inner one (coil C) is a layer wound of $\mathrm{Nb_3Sn}$ conductor, and the outer one (coil D) is a layer wound of NbTi conductor; both of the conductors adopt a cable-in-conduit conductor, and will be cooled by 4.5 K force-flowed supercritical helium.

For the future upgrade, two $\mathrm{Nb_3Sn}$ subcoils (coil A and coil B) will be inserted into the 11 T superconducting outsert, and the maximum field in the superconducting magnet will be more than 14 T. Moreover, the resistive insert will be upgraded to 31 T and bring the total system central field above 45 T. Fig. 12 is the cross-section of the outsert for the hybrid magnet. The strain sensitivity is especially important in the application of $\mathrm{Nb_3Sn}$ strand where significant degradation has been associated with localized strains from large transverse Lorentz forces. For the design of the superconducting outsert of 40 T hybrid magnet, it is convenient to take advantage of the recent development of high strength wires made by restacked-rod process (RRP) by Oxford Instrument, Superconducting Technology (OIST). $\mathrm{Nb_3Sn}$ strands with critical current densities above 2100 $\mathrm{A/mm^2}$ (12 T, 4.2 K) will be selected in order to achieve the required central field and to keep the magnet compact. The OIST recommended the typical heat treatment schedule for the $\mathrm{Nb_3Sn}$ strand is 210°C (48 h), 400°C (48 h) and then 650°C (50 h). NbTi strands with higher copper ratio will be selected in order to ensure enough thermal protection when quenching.

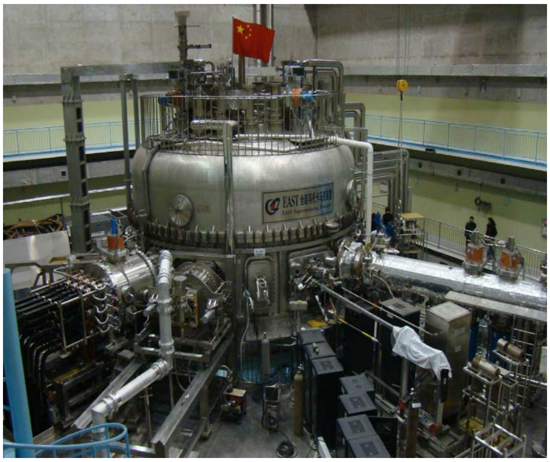

Fig. 13. EAST experimental system with full CICC.

The $\mathrm{Nb_3Sn}$ cable-in-conduit conductor(CICC) of the outsert must safely, stably, and reliably operate under steady state conditions and must provide enough margins against the irreversible degradation of the strand performance under cyclic load, fluctuation of the operating temperature, and AC losses generated in the composite conductors when charging or discharging the hybrid magnet. For the $\mathrm{Nb_3Sn}$ conductor of the superconducting outsert, the rectangular configuration will be selected in order to reduce the electromagnetic pressure of the cable. The structural analysis of the superconducting outsert has been preformed by optimizing the geometry of the conduit with the aim of withstanding the same loading using a lower amount of conduit material, and allowing more compact windings for the same field production.

IV. FUSION ENGINEERING FOR EAST AND ITER

The EAST (Experimental Advanced Superconducting Tokamak) as shown in Fig. 13 is to study physical issues of the advanced steady-state tokamak operations and to establish technology basis of full superconducting Tokamak. The system was fabricated in the Institute of Plasma Physics, Academia Sinica (CASIPP). The superconducting Tokamak includes two kinds of superconducting magnet systems. One is toroidal field (TF) magnet system consisting of sixteen D-shaped coils. The other is poloidal field (PF) magnet system consisting of six central solenoid (CS) coils and three pairs of big circle coils. The biggest PF coil has an outer diameter of 7.6 m.

In the beginning of 2003, the Chinese government decided to join the ITER (International Thermal-nuclear Experimental Reactor). The main research and development of the programs includes Feeders, TF conductors, PF conductors and Correction Coils. CASIPP will supply the total of thirty-one feeders for ITER. Typically a feeder contains a pair of superconducting busbars, two or more cooling pipes, and high-voltage as well as low-voltage instrumentation cables. The ITER feeder system includes nine TF feeders, six PF feeders, six CS feeders and five CC feeders. The development of the feeders is focused on the R&D of HTS Current Lead. The first full-scale prototype experimental component for ITER project, a HTS current lead successfully operated at 85 kA for 65 minutes and at a

Fig. 14. HTS bus-bar for ITER.

maximum steady current of 90 kA for 4 minutes. The maximum current level has been establishes a new benchmark for related research in the world. The configuration is shown in Fig. 14. CASIPP has started R&D on four types of SC conductors for ITER toroidal field magnet, poloidal coils, correction coils (CCs) and the feeders; design 18 CCs, 31 feeders for all the SC magnets. CASIPP has made a great progress in the R&D for HTS current leads operating at 90 kA for 4 minutes.

V. SUPERCONDUCTING MAGNET SYSTEM FOR ACCELERATORS

The superconducting magnets for accelerator applications have been developed for the upgrade of the accelerator. The main applications are related to the detector, IR magnet and MICE (Muon Ionization Cooling Experiment).

A. *Superconducting Magnet for Detector and IR System*

The superconducting solenoid magnet for Beijing Electro Positron Collider in the Electromagnetic Spectrometer (BESIII) enables accurate momentum measurements for charged particles. The main parameters of the solenoid are summarized in Table III. The Superconducting Solenoid Magnet (SSM) is designed to provide a uniform 1.0 T axial field in a warm volume of 2.75 m diameter. The BESIII superconducting magnet is constructed in the IHEP. It is the first superconducting magnet of this type built in China. The 0.7 mm diameter NbTi/Cu strands are formed into the Rutherford cable measuring 1.26 mm × 4.2 mm. The Rutherford cable is imbedded in the center of a stabilizer made of high purity (99.998%, RRR 500) aluminum with outside dimensions of 3.7 mm × 20.0 mm. One layer of 0.075 mm thick Upilex-Glass-fiber (glass fiber enforced polyimide) film is used for turn-to-turn insulation of the coil winding. Two layers of Upilex-Glass-fiber film attached to the support cylinder by a layer of 0.07 mm epoxy provide the ground insulation. Fifteen layers of super insulation films separate the LN_2 thermal shield and the liquid helium cooled cold mass. The thermal shield is isolated from the vacuum vessel by fifty layers of super insulation. The superconducting magnet is indirectly cooled by forced flow of two phase helium through cooling tubes wound on the outside surface of the support cylinder to an operating temperature of 4.5 K [9].

The superconducting IR magnets (SIM) as shown in Fig. 15 are installed completely inside the BES-III detector and operated in the detector solenoid field of 1.0 T. Each magnet cryostat is supported by a movable stage that is located outside the detector. The SIM is designed and built by BNL and Institute of High Energy Physics (IHEP). The quench protection system for magnet consists of the quench detector and the quench protection assembly.

TABLE III
MAIN PARAMETERS OF THE SOLENOID

Items	Parameters
Cryostat radius: outer/inner	1.7 m/1.375 m
Cryostat length	3.91 m
Coil mean radius	1.482 m
Coil length	3.52 m
Superconductor	NbTi/Cu (1:0.9)
Stabilizer	Pure aluminum
Cable dimension	3.7 mm × 20 mm
Number of turns	848
Nominal current	3,369 A
Central field	1.0 T
Total weight	15 t
Effective cold mass	3.6 t
Inductance	1.7 H
Stored energy	9.8 MJ
Coolant	Liquid helium at 4.5 K

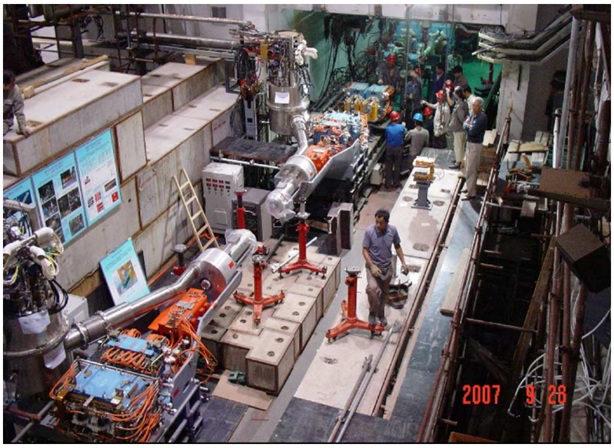

Fig. 15. BEPCII Superconducting IR Magnets.

B. *MICE/Mucool Superconducting Coupling Magnet*

The MICE coupling magnet consists of a single 285 mm long superconducting solenoid coil developed by Harbin Institute of Technology. The superconducting coil is wound on a 6061 aluminum mandrel that is fit into a cryostat vacuum vessel. The inner radius of the coil is 750 mm and its thickness is 110 mm at room temperature. The coil assembly comprises the coil with electrical insulations and epoxy, and the coil case made of 6061-T6-Al including the mandrel, end plates, banding and cover plate, as shown in Fig. 16. The bobbin, the end plates and the cover plate are 19 mm, 18 mm and 45 mm thick, respectively. The length of the coil case is 329 mm. The coupling solenoid will be powered by a single 300 A/0 ∼ 20 V power supply connected to the magnet through a single pair of leads that are designed to carry a maximum current of 250 A. The magnet is to be passively protected by cold diodes and resistors across sections of coil and by quench back from the 6061 Al mandrel in order to lower the quench voltages and the hot spot temperature.

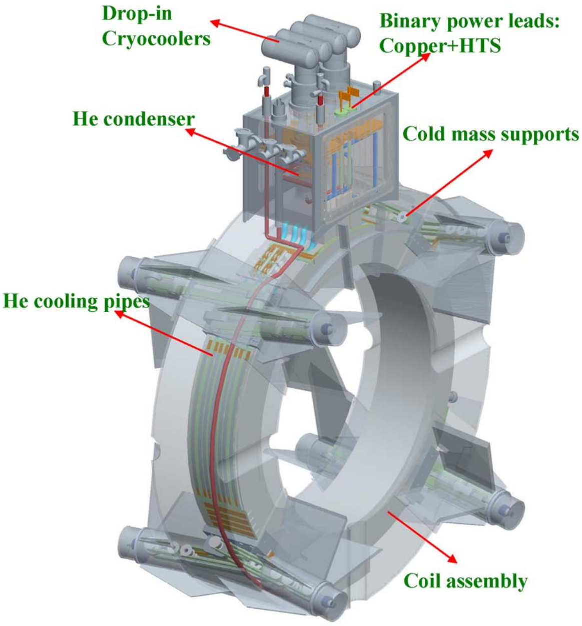

Fig. 16. Configuration of coupling magnet cryostat.

Fig. 17. Configuration of dipole magnet for GSI CR ring.

It was to be cooled by liquid helium flow through cooling tubes embedded into the coil cover plate by two 1.5 W cryocoolers. The coupling magnet cold mass support is a self-centering support system so that the magnet center does not change as the magnet is cooled down from 300 K to 4.2 K [10].

C. Development of CR Magnets

The super-ferric dipole prototype of Super-FRS is with the width of 2200 mm, the central length of 2020 mm and height of 725 mm, respectively. The CR magnets has been built by FCG (FAIR China Group including IMPCAS, CASIPP and IEECAS) in cooperation with GSI, the configuration of dipole magnet for GSI CR ring is shown in Fig. 17. IMPCAS is responsible for the test of the whole system, the magnetic field optimization and the development of the 50 tons lamination iron yoke. CASIPP is responsible for the fabrication of superconducting coils and cryostat. IEECAS contributes to the design of the coils.

The dipole has the homogeneous region with the width of 380 mm and height of 140 mm, the homogeneity reach to $\pm 3\times 10^{-4}$. The passive air slot and chamfered removable end poles guarantee that the magnetic field distribution is homogeneous at both low and high field level. The Super-FRS superconducting dipole is a super-ferric superconducting magnet with the warm iron yoke which is laminated due to magnetic field ramping, and the H type yoke is made of 0.5 mm thickness laminating electrical steel which was stamped and glued to blocks and machined to the 15 degree angle sector shape. The superconducting coils were wound by multi-filamentary NbTi wires with higher copper to non-copper ratio and operated in liquid helium temperature. The coils are positioned in the helium cryostat with the multi-layer insulation structure. The total weight of the magnet is more than 52 tons. The magnetic field measurements indicate that the field homogeneity is about $\pm 2 \times 10^{-4}$ at different magnetic field levels (0.16 T–1.6 T), which is better than the design requirements. The whole experiment system, which consists of superconducting magnet, current supply, quench protection system, data acquisition and helium recovery system had been tested. The success of the superconducting dipole has verified the design of the magnet system, including coils, cryostat and mechanical structure.

VI. HIGH TEMPERATURE SUPERCONDUCTING MAGNET FOR POWER APPLICATIONS

Power technology is of great importance in the development and innovation of the power grid in the near future due to taking full advantages of the zero resistance, high engineering current density and state transition properties of HTS. The HTS superconducting fault current limiter (SFCL) suppresses fault current to greatly improve stability and reliability of the power grid, superconducting magnetic energy storage system (SMES) enhances electrical power quality and acts as peak load shifting device, and superconducting transformer and superconducting motor enormously reduce quantity of the devices and volume while at the same time increase efficiency, and so on.

A. High Temperature Superconducting Magnet for SFCL

In August 2005, the first superconducting fault current limiter (SFCL), with capacity of 10.5 kV/1.5 kA was fabricated and operated at Gaoxi substation in Hunan Province in southern China. The SFCL was developed by IEECAS, and severe three-phase earthing short circuit experimentation in real distribution grid has been conducted before its operation in distribution grid. The configuration of the high temperature superconducting coils is illustrated in Fig. 18. The experimental results show that the SFCL is of excellent fault current limiting performance, i.e., it can suppress the fault current from 3500 A (without SFCL) to 635 A (with SFCL) with a response time of 2 ms and recovery time of 12 ms. The SFCL operates very well in the grid for more than 11000 hours, and was decommissioned in the beginning of this year for the reason that the substation's capacity be expanded [11].

The saturated iron core superconductive fault current limiter (SICSFCL) has unique advantages in fault current limitation, especially in high-voltage super-capacity power grids. With the non-linear characteristic of iron core's magnetic permeability,

Fig. 18. The 10.5 kV/1.5 kA three-phase SFCL by IEECAS.

Fig. 19. HTS coils used in 35 KVA SCFL in InoST Power.

SICSFCL is able to present a very low impedance at normal transmission state, and convert to a high impedance at the moment of short-circuit fault occurring. However, this non-linear characteristic also makes some trouble both in the design and in the utilization of SICSFCL. Especially in complex power grids, it is almost unsolvable to calculate the current limitation of SICSFCL through the conventional numerical method. The 35 kV/1.5 kA SFCL was fabricated by Innost power and used in distribution grid at a substation in Yunnan Province in southeast of China [12] (Fig. 19).

B. HTS Coil for Transformer

China developed and energized its first three-phase HTS transformer successfully in distribution grid at Changji City, Xinjiang Uygur Autonomous Region in northwest of China from 2005 [13]. The HTS transformer with 630 kVA/10.5 kV/0.4 kV is developed through collaboration between IEECAS and Tebian Electric Apparatus Stock Co., Ltd. (TBEA), supplied power for a cable factory of TBEA. The transformer utilizes amorphous alloy cores, and passed the industrial standard test. The HTS coils are shown in Fig. 20.

Fig. 20. HTS coil for 630 kVA/10.5 kV/0.4 kV three-phase.

C. High Temperature Superconducting Magnet for SMES

IEECAS developed a new kind of superconducting power device named fault-current-limiting superconducting magnetic energy storage system (FCL-SMES), which integrates the functions of SFCL and SMES into just one device, so as to reduce cost and optimize system structure. The 100 kJ/25 kVA FCL-SMES prototype is the first one of its kind in the world and laboratory tests show that it has good performance. Based on the FCL-SMES prototype, IEECAS developed the HTSC SMES, with capacity of 10.5 kV/1 MJ/0.5 MVA, which is now under routine test and experimentation. The main parameters of the superconducting coils are listed in Table IV. The configuration of the magnet is illustrated in Fig. 21. The magnet is energized in distribution grid. The China Electric Power Research Institute developed the HTSC SMES for the application of SMES, which is very important in power system. There are several common power quality problems in power system. In these problems, voltage drop of 20 percent is a frequent fault and voltage sag of one phase is more common than other two faults. What we can do is to use the energy stored in SMES to compensate the voltage drop. The HTSC magnet in the SMES system is shown in Fig. 22.

D. High Temperature Superconducting Magnet for Motor

The racetrack-shaped superconducting coils for motor with capacity of 30 kW is developed by Innost Superconductivity LtD.. The motor consists of 6 racetrack-shaped HTSC coils. The configuration of racetrack-shaped HTSC coil and the motor of 30 kW are illustrated in Fig. 23.

VII. ADVANCED ANALYSIS AND DESIGN TECHNOLOGY FOR THE HIGH MAGNETIC FIELD MAGNET

The analysis and design technologies for the electromagnetic, quench and stress analysis in the superconducting magnet

TABLE IV
MAIN DESIGN PARAMETERS OF THE SMES COILS

Parameters	Value
Inner diameter (mm)	400
Outer diameter (mm)	568
Height (mm)	645
Number of double pancakes	44
Number of tapes	82
Total length of Used HTS tape (km)	16.4
Inductance (H)	6.28
Operating current (A)	564
Max. Br (T)	2.39
Max. B (T)	5.72
Operating Temperature (K)	4.2
Stored energy (MJ)	1.0
Breakdown voltage (V)	2000

Fig. 21. HTS coil for 1 MJ SMES fabricated in IEECAS.

Fig. 22. HTS coil for SMES fabricated in CEPRI Race-track-shaped superconducting coils.

system have been developed for the high homogenous superconducting magnet including NMR and MRI.

Race-track-shaped superconducting coils.

Fig. 23. Configuration of 30 kW motor with HTSC cooled by liquid N_2.

A. *Design Algorithm of High Homogeneity MRI and NMR*

An optimization design method of short-length actively shielded and opened structure superconducting MRI magnets is suggested in the paper. Firstly, the section of the solenoid coil is simplified as a current loop with zero section to solve a linear programming problem. The position coordinates in the radius and axial, and current for the loop can be calculated by the linear programming method. Then, the cross-section of the coil is optimized with a genetic algorithm to get appropriate section size. The method of linear programming, especially combining with genetic algorithm, reduces optimizing variables, which makes the design of a magnet feasible.

Magnetic field generated by a superconducting solenoid coil with rectangular-shaped cross section can be calculated by five parameters, such as position coordinates, size of cross-section, current density etc. The relationship between magnetic field and position coordinates and size of geometries is nonlinear. If the superconducting solenoids are assumed to be a series of ideal current loops located at the center of squares, the magnetic field in the space can be only determined by the position coordinates and current. In the design, the radii of the main and shield coils can be decided in advance, the n current loops generates the magnetic field at m target points can be calculated on the basis of $\boldsymbol{AI} = \boldsymbol{B}$, where $\boldsymbol{B}$ is the matrix with m row, $\boldsymbol{A}$ is the field at the m^{th} target point due to unit current in the n^{th} feasible coil, $\boldsymbol{I}$ is the current matrix with n rows. The requirement of superconducting wires for coils used in the fabrication is a very important part in a design. It can dictate the total cost of a superconducting magnet system. The inequality constraint for a minimum superconducting wire design for high homogeneous magnetic field can be transferred to following optimization problems. The optimization problem can be treated as a linear problem and can

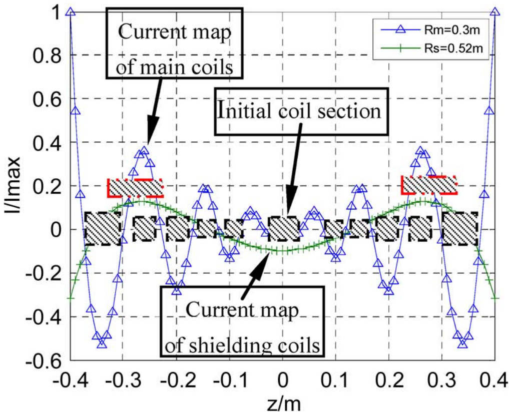

Fig. 24. Current distribution map for the superconducting coil distribution in the superconducting magnet.

be calculated with arguments of current I. The position coordinates $(r_{\mathrm{i}}, z_{\mathrm{i}})$ for each current loop is randomly generated. As an example for an open structure MRI magnet, a possible current distribution based on the methods is plotted in Fig. 24, which is the bulks according to linear optimization solution, and each of them has a rectangular cross sections. After the current bulks are determined, a nonlinear algorithm is employed to decide the accuracy size of each coil. The genetic algorithms have been given considerable attention lately and have been applied to problems in electromagnetic field computation. The genetic optimization method is a global optimization method and can treat large-scale, multi-value and discrete optimization problems with very fast calculation speeds. The code for the genetic optimization method is employed the MATLAB genetic toolbox, the mutation number is 100, the number of generation is equal to 300, and the adaptive crossover is used in the code.

B. Stress Analysis for the Multi-Sectioned Magnet

For the high magnetic field superconducting magnet, the training effect is related to a plastic hardening process. The structure of a superconducting magnet is in fact composite. In general, the composite materials contain more than one bonded material, each with very different structural properties such as superconducting wire and epoxy-resin in magnets that create many difficulties in stress-strain characteristics.

Composite structures of superconducting magnet contain both ductile and brittle constituents with different mechanical and thermal properties. The electromagnetic force is directly acted at the central of superconducting wire. Most common engineering materials exhibit a linear stress-strain relationship up to a stress level known as the proportional limit. Beyond this limit, the stress-strain relationship will become nonlinear, but will not necessarily become inelastic. Plastic behavior, characterized by non-recoverable strain, begins when stresses exceed the material's yield point, which is almost equivalent to proportional limit. The $\mathrm{Nb_3Sn}$ and NbTi superconductor wires yield at very low stresses (20–50 MPa) and therefore all wires behave elasto-plastically during energization. For the magnet design and manufacturing process, it is vital for us to be able to predict the maximum hoop strain in a coil and therefore to define an appropriate reinforcement. Such prediction is now become possible using detailed finite element analysis. The Lorentz force to equivalent model as shown in Fig. 25, is easily applied to the elements of wire in a detailed finite element model as shown in Fig. 26. The sequence in which loads are applied and in which plastic responses occur affects the final solution results.

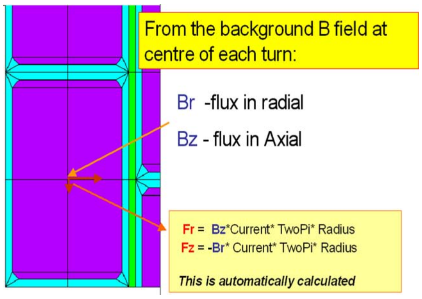

Fig. 25. Detailed finite element model for the magnets.

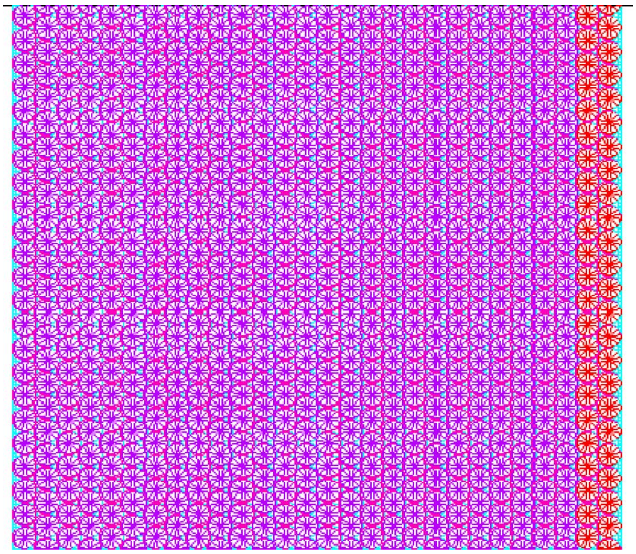

Fig. 26. Mesh for superconducting coils.

C. Quench Analysis for NMR and CICC Magnet

The quench analysis is important for high magnetic field superconducting magnet system. In order to make it simpler and more versatile for quench analysis in the complex structure superconducting magnet, the analysis methods consider the material property that is independent and can be called from any part of the program. It is easy to simulate a larger system of magnets, electrically independent, each consisting of multiple coils with different materials and different features. The analysis code is used to calculate the quench in the MRI, conduction cooled magnet and NMR superconducting magnet.

We have developed a numerical code to study the helium expansion and quench propagation in CICC. The temperature difference between the strands and helium is assumed to be very small due to the heating induced flow to generate high heat transfer of supercritical helium. The strong coupling of heat transfer at the front of normal zone generates a contact discontinuity in temperature and density. To obtain the converged numerical solutions, a moving mesh method is used to capture

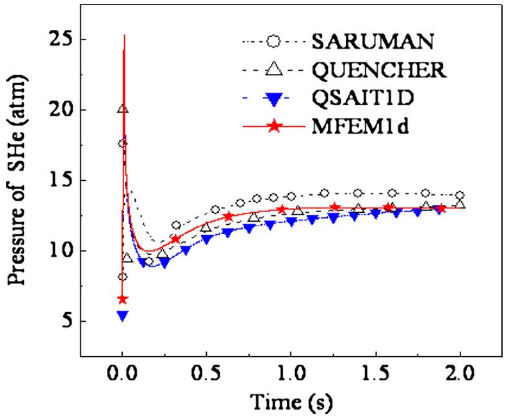

Fig. 27. Quench in CICC superconducting magnet.

the contact discontinuity in the short front region of the normal zone. The coupled equation is solved using the moving mesh FEM with the artificial viscosity term. The results are compared with other code as shown in Fig. 27 [13].

VIII. SUPERCONDUCTING MAGNET IN FUTURE PROJECT

The development of 25 ∼ 30 T high field superconducting magnet technology faces to the most technology challenges. Combined the HTS and NbTi, Nb_3Sn, a 25 T to be high field superconducting magnet with warm bore 52 mm is designed. A common setup is to mount the sample at the center of a Helmholtz-type coil which can provide a magnetic field of any direction at the sample position and also a guide field along the neutron flight paths around the sample. We have designed a 25 T magnet with split coils structure for the light source. The superconducting magnet will be operated in 1.8 K temperature and scattering angle of 8 degree.

IX. CONCLUSION

Under the support of the Ministry of Sciences and Technology, National Development and Reform Commission, National Natural Science Foundation of China, Chinese Academy of Sciences and local Governments, the quite good achievements in basic research, magnet and cryogenic technology are obtained in the recent years. Some future engineering, such as, very high magnetic field superconducting magnet and other high magnetic magnet system for extreme physical environments will be fabricated in the next five years.

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