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Overview about Recent Progress on Magnets in IMP

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Abstract: High-field conventional magnets and superconducting magnets for three new projects, which can include Heavy Ion Medical Machine (HIMM), High Intensity heavy ion Accelerator Facility (HIAF), and Accelerator Driven sub-critical System (ADS) project, are under construction or design at Institute of Modern Physics (IMP). In conventional magnet of HIMM, air trim slot and removable pole were used jointly for improving the conventional magnets' quality. The measurements of the magnetic field distribution in the median plane of the working area have been carried out. Results from Opera-3D simulation show good agreement with the measurement data. For superconducting dipole coil prototype in HIAF Project, which is in design phase, the R&D of cable-around-conduit conductor, 80 K thermal shield , the coil case and a smart coupled mechanical analysis method were described. And for SC solenoid magnet of C-ADS Injector-II, which is in test phase, magnetic field and strain measurement technology at IMP were introduced during excitation and quench. The present results and methods may provide some basis experiences on the construction of the magnet at IMP.

Key words: accelerator facility; normal conducting magnets; superconducting magnet; superconducting cable

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1 Introduction

With the development of physical science and technology, more and more magnets are being used in large electromagnetic scientific instruments and equipments with features of large volume and intense magnetic fields. Nowadays, about 30 000 accelerators in operating in the world today, a majority is for applications in scientific (about 20 000 systems worldwide). There are two major categories of industrial applications: materials processing & treatment, and materials analysis. Accelerators are also applied for environment protection, such as purifying drinking water, treating waste water, disinfecting sewage sludge and removing pollutants from flue gases. In these accelerators, conventional magnets and superconducting magnets are included. And these magnet technologies are also improved with the increasing of physical demand[1]. The large Hadron Collider in CERN is the largest accelerator in the world, the magnets of which present no resistance to the passage of the electrical current, will be operated at a temperature of 4.2 K and are at the forefront of magnet technology[2]. Up to now, accelerators have been established in some of the developed countries in the North American, Europe and China. And magnet technology has also been developed on medical machine in the United States, Japan and Germany. A series of new projects for heavy-ion therapy have been also proposed, such as the Med-AUSTRON in Austria and the ETOILE in Lyon. The Italian CNAO heavy-ion herapy facility in Pavia near to Milan was started in 2005 and was

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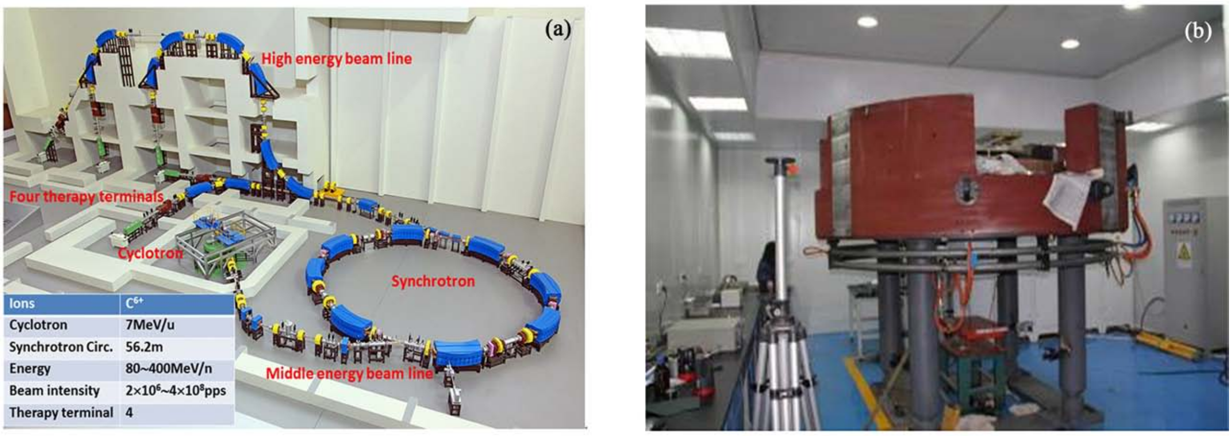
expected to treat patients in 2008.

Recently, the magnets on the basis of normal conductor and superconductor are designed, fabricated and operated for heavy ion accelerator, storage ring project and physics experimental setups by Institute of Modern Physics(IMP), Chinese Academy of Sciences(CAS). Three new big projects at IMP in Lanzhou, China, that are being constracted or designed, so simultaneously their magnets are also being manufactured or designed too. They include Heavy Ion Medical Machine (HIMM), Accelerator Driven sub-critical System (ADS) project and High Intensity heavy ion Accelerator Facility (HIAF). Massive block iron and laminated yoke normal conducting magnets were used in these accelerators' complicated magnet systems. And large and complex superconducting magnets will also be designed and constructed.

In this paper, magnet technology of HIMM was introduced for its main parts. The main features of magnet system were also described. As one of the 12th five year plan of China, HIAF will also be introduced for our overall goals and specific design. Some key superconducting magnet systems, such as the SC LINAC and the dipole magnets system of other rings, will be argued. Some main design parameters will be showed for safety design of entire system. In addition, the high field superconducting solenoid had been described for a new high intensity 10 MeV proton superconducting SC LINAC in ADS project. These technical summaries will be necessary for the operation of the three newbig projects in future.

2 High-field conventional magnets

Wilson first realized the medical therapy function of the inversed dose profiles of ions in 1946[11]. Up to now, heavy-ion cancer therapy equipment has been established only in some of the developed countries. From 1975, the Lawrence Berkeley Laboratory collaborated with the University of California, San Francisco Medical Center started the heavy-ion cancer therapy. Many magnet technologies had been applied to these projects. For example. in Germany, the carbon therapy with active particle-beam delivery systems initiated at GSI collaborated with the University of Heidelberg in 1997. More than 400 patients have been treated very successfully with the high local control rates about 83% to 100%. However, since magnet technology was limited, volume of these medical therapy equipments was developed to large. They only can be used for researching. Now, applying some optimization magnet design techniques, commercial HIMM facilities are currently under construction at IMP for tumor therapy of hospital in Lanzhou and Wuwei city, Gansu province, respectively[1−2]. This therapy machine consists of an ECR Ion Source, a compact cyclotron injector, the middle energy beam transporting line, a synchrotron, a high energy beam transporting line and four therapy terminals, as shown in Fig. 1(a). The cyclotron magnet for HIMM (see Fig. 1(b)) is



Ions	C^{6+}
Cyclotron	7MeV/u
Synchrotron Circ.	56.2m
Energy	80~400MeV/n
Beam intensity	2×10^6~4×10^8pps
Therapy terminal	4

Fig. 1 (color online) The layout of HIMM (a) and the magnet compact cyclotron injector (b).

made from massive iron blocks. It consists of 8 sectors with a hill angle of 56 degree and valley angle 34 degree. The varying range of each gap is from 70 to 80 mm. The maximum average field is about 1.2 T. The measurements of the magnetic field distribution in the median plane of the working area have been carried out. Results from Opera-3D simulation show good agreement with the measurement data.

The circumference of HIMM synchrotron is only about 56.2 m, and it can accelerate carbon ions up to energy of 400 MeV/u. When ions are injected into the synchrotron, a stripper foils is used to strip electron. The synchrotron of HIMM includes 8 dipoles, 12 quadrupoles, 9 sextupoles and 8 correctors. The main parameters of magnet system are shown in Table 1. In general, technologies of the HIMM synchrotron magnets are similar to Cooling Storage Ring (CSR) project whose magnets were successful completed 8 years ago. Magnets of synchrotron and the high energy beam line are made from laminated steel sheet to reduce eddy current.

Table 1　The main parameters for synchrotron magnets.

Magnet type	Number	Magnetic field	Aperture	Effective length
Dipole	8	0.2∼1.66 T	68 mm	3.14 m
Quadrupole	12	7.5 T/m	40 mm	0.2/0.35 m
Sextupole	9	40 T/m^2	50 mm//94 mm	0.15 m

Because of dipole's high requirement for magnetic field quality, two optimizing methods are adopted. (1) Air trim slot: One air trim slot (60 mm×40 mm) was adopted to improve the magnetic field homogeneities from the lower field up to the maximum field of 1.66 T. (2) Removable pole: four removable poles made from glued lamination are adopted to improve the integral field homogeneity. In designing stage for trim slot and removable pole structure, the Opera 2D and 3D software is used to optimize its magnetic field. Due to its ramping magnetic field (1 T/s), high magnetic field repeatability and uniformity requirements, laminated silicon steel sheets (its thickness is only 0.5 mm) were used. In addition, the bending angle of the dipole is 45 degree and the bending radius is 4 m, so the Sagitta is very large (about 304 mm), which would increase the difficulty of lamination stacking process. To improve the uniformity of steel lamination factor and the magnetic field homogeneity, the multi-segments lamination method and whole welding technology were adopted for this kind of dipole magnet (see Fig. 2). The magnetic field distribution has been measured by long coil system and hall probe mapping system. After several iterations of measurements and shimming process, the integral field homogeneity reached $\pm 2\times10^{-4}$ in reference field ($B = 0.2$ T), while the physical requirement is $\pm1.5\times10^{-4}$. The addition removable poles chamfering would be added to further improve the integral field distribution. And using the specially constructed magnetometer, the measurements of the magnetic field distribution in the median plane of the working area are carried out. And the simulation predictions and the experimental data show a good agreement (see Fig. 3).

Fig. 2　(color online) The fabricated quarter lamination steel and the first dipole of HIMM.

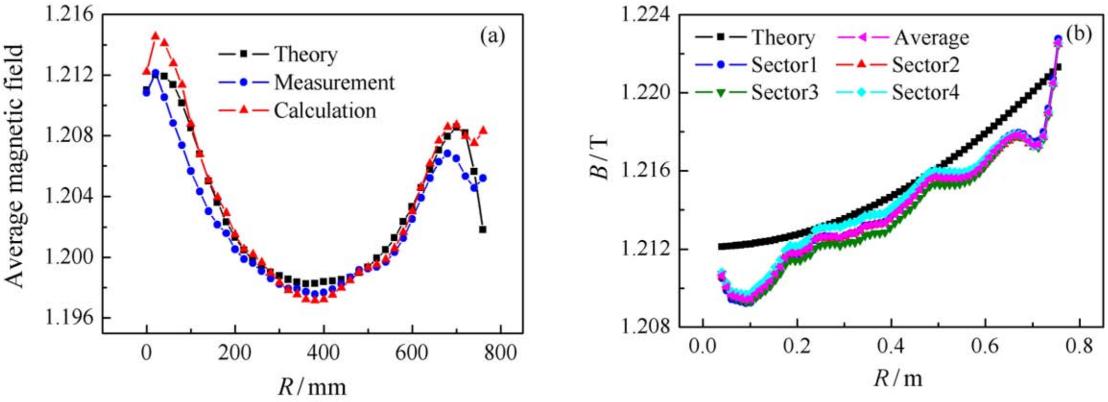


Fig. 3 (color online) The contrast among theory, simulation predictions and the experimental data for the cyclotron magnet, Isochronous magnetic field of static equilibrium orbit on the cyclotron magnet.

In addition, the two halves structure is adopted in quarupole magnet and three-fragment structure is adopted in sextupole. To simplify the process of assembling, the removable pole was not adopted. The pole end shape would be chamfered directly based on the magnetic field mapping results.

Four high energy beam transporting lines include 11 dipoles, 31 quadrupoles, 10 scanning magnets and 15 correctors. Laminated steel sheets and technologies were applied to all these magnets.

3 Superconducting magnets

3.1 R&D of superconducting dipole coil prototype for HIAF project

The heavy ion accelerator facility, HIAF has been promoted and will be constructed by IMP, CAS[3]. It is shown in Fig. 4. The accelerator facility, as one of the 12th 5-year plan projects of China, will become a national user facility in China. This advanced facility will provide high intensive ion beam for high-energy nuclear science. The exploring of high energy density physics (HEDP) and radioactivity nuclear physics will be its most important goals. The magnet system of HIAF project will exist in: high intensity ion source, high intensity pulse SCLINAC, multi-function booster and ions collector ring, long straight ion collider, electron collider and large acceptance RIBs line.

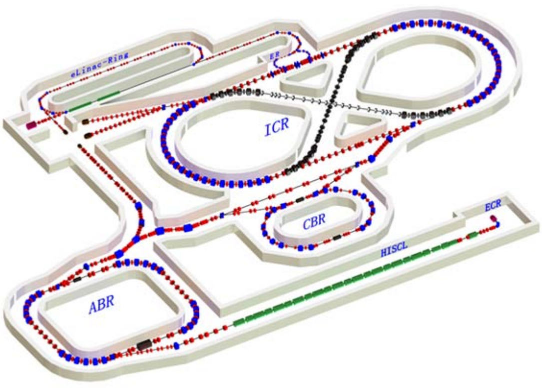


Fig. 4 (color online) Conceptual layout design of HIAF[9].

The superconducting dipoles will be designed and fabricated for ABR-25 (multifunction booster ring) of HIAF project. It is one of the most important components in this accelerator facility. According to the overall physical requirement, the superconducting dipole system of ABR-25 (see Fig. 5(a)) is planned to use fast pulse superconducting magnets. A maximal field of 2.25 T is provided through the yoke pole and with the ramping rate of 1.125 T/s. And since large aperture is required (its aperture is larger than the one in the superconducting dipoles of Nutron and FAIR), warm lamination type iron yoke was chosen. In addition, different from other superconducting magnets, which usually used cable-in-conduit conductor (CICC) to wind. Considering the superconducting magnet need to bear pulse, two twelve-turns superconducting coils are wound using cable-around-conduit conductor based on NbTi strands (see Fig. 5(b)). It is the first application for pulse superconducting dipole until now. The superconducting cable consists of an internally cooled Cu-Ti tube, whose inner and outer diameter is 6 mm and 7 mm, respectively. The strands are tightly wrapped by the 0.3 mm Ni-Cr wire. Meanwhile, the polyimide film and glass-fiber tape are wrapped at out layer for insulation. The coils will be impregnated with the epoxy resin CTD-101 to obtain the mechanical stiffness. The resin was chosen for its high fluidity and its ability to resistant radiation. For quench detection, the co-wound wire is imbedded in the gaps among cables. The two coils are installed in a stainless-steel coil case. An 80 K thermal shield is placed around the coil case to limit the heat radiation from the cryostat. Since the current-carrying dipole coils of the superconducting magnet are exposed to large Lorentz forces, which can be induced by its transient and strong magnetic field (1.125 T/s) and lead to the remarkable deformation of the magnet coils. Contrarily, the deformation of coils will alter the magnet structure and disturb the quality of the magnetic field during excitation and quench.Therefore, magnetoelastic analysis has been developed in order to assist, at least redundantly, the structure design of superconducting magnet with hollow tube superconducting cable under high field. It is performed in detail by solving the Maxwell's equations and the equilibrium equations of mechanical deformation. During the structure analysis, the current in the coil is considered as the function of its displacement, and the Lorentz force is also considered as external body force[10]. Finally, the coupled magnetoelastic analysis results were recommended that the eight titanium alloy rods are used for cold mass supporting, and four of them in each corner of coil are used for position adjustment, and two of them are used to support against the electromagnetic force. The design of the cable and coil has been finished and the first 270 m cable has been fabricated. The prototype coils have been wound in September, 2013.

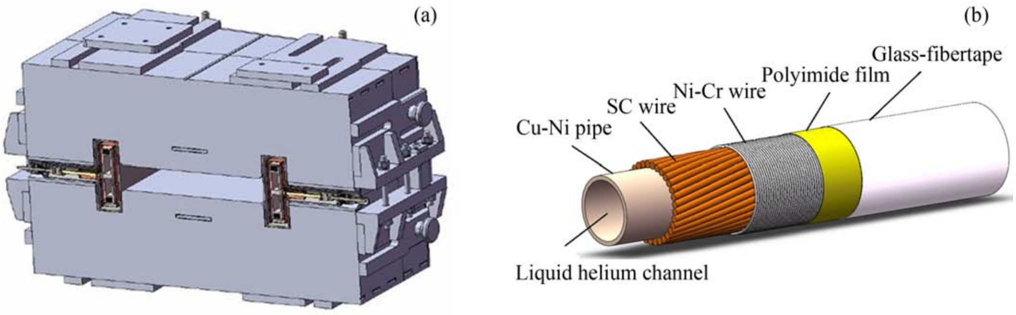


Fig. 5 (color online) The superconducting dipole magnet of HIAF and the hollow tube superconducting cable.

3.2 Test of superconducting solenoids for ADS project

ADS is the effective tool for transmuting the long-lived transuranic radionuclides into shorter-lived radionuclides. A project called China Accelerator Driven sub-critical System (C-ADS) is being studied at the CAS. IMP is in charge of the development of the high current beam injector II. Different from conventional magnet technology in other ADS facilities, the superconducting (SC) solenoids (see Fig. 6) are used to provide strong magnetic field to focus the beam. Four racetrack coils are also integrated into the solenoid to produce two steering dipoles for beam-centroid corrections. Two bulking coils are used to minimize the stay field. All coils of

Fig. 6 (color online) Superconducting solenoid of C-ADS injector-II with helium vessel.

the magnet are made of multi-filament NbTi wire stabilized with copper. During our test, the low-temperature resistance strain gauges with a Wheatstone compensation bridge circuit consisting active and dummy gauges and low-temperature Hall sensors were used to measure its strain and magnetic field during excitation and quench. The central field can reach 8.2 T. The central magnetic field and strain of the magnet varying with the time during the excitation and quench is plotted at Fig. 7. The profiles of the loading and unloading excitation current and the corresponding central magnetic field of the SC magnet are shown in Fig. 7(a). And after two triangular cycle charging, the SC solenoid magnet was again energized at a rate of 0.5 A/s to a target value of 200 A. However, the intended target of 200 A was not reached as the coil quenched at 197 A. And Hoop strain in the SC magnet was also recorded synchronously during excitation and quench (see Fig. 7(b)).

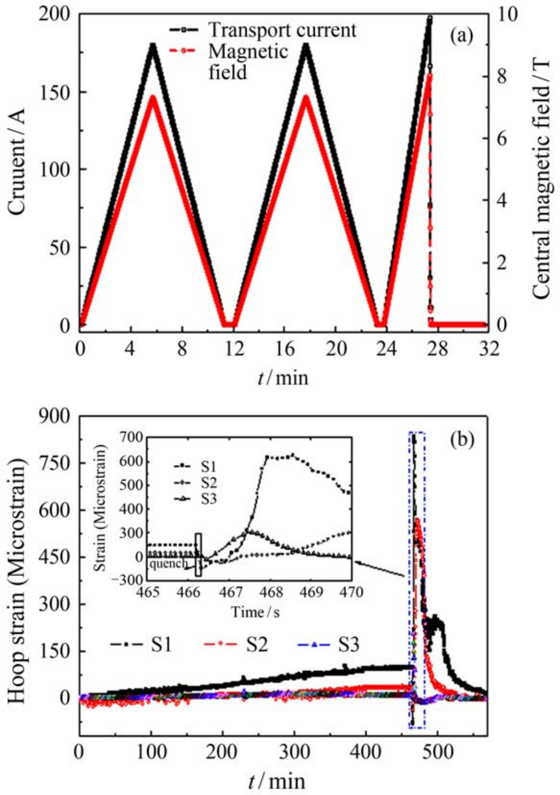


Fig. 7 (color online) Current and central magnetic field measurements during the excitation and quench and Hoop-strain measurements during the excitation and quench.

4 Summary

High-field conventional magnets and superconducting magnets for three new projects at IMP were under constructing or designing. For high-field conventional magnets conventional magnet, the technology of CSR magnet is adopted and further developed. The cyclotron magnet and dipole prototype have been built and successfully tested and shimmed; For Superconducting Dipole Coil Prototype for HIAF Project, cable-around-conduit conductors and 80 K thermal shield were applied for pulse superconducting dipole. A smart coupled mechanical analysis method was also described. In future, these experiences and magnets' characteristics can be helpful for the construction of the magnet at IMP, and for SC solenoid magnet of C-ADS Injector-II, the test of excitation and quench on the magnet were conducted experimentally. Magnetic field and strain measurement technology at IMP were introduced based on the SC solenoid.

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中国科学院近代物理研究所磁体工程进展概述

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摘要： 本文着重论述了中国科学院近代物理研究所目前正在研制的三大磁体工程，它们包括重离子治癌工程 (HIMM)，强流重离子加速器 (HIAF) 工程，以及加速器驱动次临界系统 (ADS)。在HIMM工程中的常规磁体建设中，着重介绍了联合运用钝化槽与活极头两项技术改善磁场品质的设计方法，并且运用Opera-3D设计软件，对该类高场常规磁体进行了数值分析，进一步地测量了该磁体磁场分布情况，相关的测量结果与数值模拟结果吻合良好。而对于正在处于预研阶段的HIAF工程中的快脉冲超导二极磁体，讨论了超导磁体的前期设计与结构优化技术，包括CACC超导线缆的结构设计，80 K冷屏与线圈盒结构的优化，力-磁耦合结构计算方法等。而在嬗变核废料处理的C-ADS注入器II中，核心部件是具有高磁场 (高达7～8 T) 的多层复合超导螺线管磁体结构，介绍了其在励磁和失超过程中相关磁学和力学多场实验测试工作。这些相关的设计和测量技术将为中国科学院近代物理研究所自主研制的磁体工程的物理和结构设计提供方法和指导。

关键词： 加速器设施；常规磁体；超导磁体；超导电缆

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