General Survey of Tohoku Hybrid Magnet System(Part I. Establishment and Tests of Hybrid Magnet System at HFLSM)

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journal or publication title	Science reports of the Research Institutes, Tohoku University. Ser. A, Physics, chemistry and metallurgy
volume	33
number	2
page range	221-237
year	1987-03-10
URL	http://hdl.handle.net/10097/28282

General Survey of Tohoku Hybrid Magnet System*

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(Received December 17, 1986)

Synopsis

Outline of Tohoku Hybrid Magnet system is briefly described. High Field Laboratory was established in the Research Institute for Iron, Steel and Other Metals, Tohoku University, in 1981, for accelerating research and development of high field superconducting materials. Three hybrid magnets generating magnetic fields more than 20 T have been constructed as its main apparatuses. The strongest hybrid magnet, HM-1, could produce 31.1 T in November, 1986, which was the world record as this kind of hybrid magnet. Several important features of the hybrid magnet system are introduced which will be also useful to understand the following papers.

I. Introduction

There are two methods for producing high magnetic fields above 10 Tesla in a stady state. One of them is a high-power water-cooled resistive magnet (WM), the record of its highest field is 23.4 Tesla (T) in Grenoble[1]. The other is a superconducting magnet (SM), its highest record was 17.5 T[2] by National Research Institute for Metals (NRIM) in Japan in 1977. Recently this record[3] was renewed to 18.1

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* The 1809th report of the Research Institute for Iron, Steel and Other metals.

T[4] by NRIM itself. The only one method of obtaining the magnetic field more than 25 T is the hybrid magnet system at present, where a magnet consists of an inner high-power water-cooled magnet and an outer superconducting magnet. This hybrid magnet can generate the sum of both field values. This idea was originally proposed by Wood and Montgomery[5] as an economical method of achieving high magnetic fields. The successful example of this kind of device is the Clarendon hybrid magnet at Oxford, where the field strength up to 16 T was produced in the working bore of 50 mm[6][7]. F. Bitter National Magnet Laboratory (FBNML)[8] in MIT fabricated two hybrid magnet systems, employing the same NbTi superconducting coil. They could produce 25.4 T for the Catholic University of Nijmegen by use of an axially-cooled resistive magnet with 32 mm bore and also 30.1 T by the use of a radially-cooled magnet with the same size bore for MIT itself before the transport to Nijmegen. The "Service National des Champs Intenses" (SNCI) of CNRS together with "Hochfeld Magnetlabor des Max Plank Institute" also had a plan to make a hybrid magnet up to 30 T in an inner bore of 50 mm at Grenoble.[9] In spring of 1987, they succeeded to generate 28 T according to J. Flouquet.[10] The Kurchatov Institute of Atomic Energy at Moscow succeeded an operation of the hybrid magnet up to 25 T[11] in a clear bore of 28 mm, where a NbZr superconducting coil was employed.

In 1981, the Research Institute for Iron, Steel and Other Metals at Tohoku University established the High Field Laboratory for Superconducting Materials (HFLSM) for accelerating research and development of high field superconducting materials which would be used in superconducting magnets for nuclear fusion reactors. Because there were not only several superconducting magnets producible more than 10 T for researches on condensed matters in Japan at that time except the NRIM superconducting magnet, it was discussed to prepare in a hurry some superconducting and resistive magnets which can generate more than 10 T for use in superconducting material research for fusion. Then HFLSM was established. Three types of hybrid magnets which could produce very high fields more than 20 T were constructed as principal equipments of the new laboratory.

In the present paper, a survey of Tohoku Hybrid Magnet System is given. Furthermore, the next step to aim higher magnetic field of about 35 T will be proposed. In Appendix I, the floor layout and schematic arrangement of total equipments including power supply, cooling system, and computer and control system will be given. Furthermore in Appendix II comparison of the present system with other hybrid magnet ones in the world will be described.

Design and construction of three kinds of superconducting magnets and several resistive magnets are in detail described and discussed in the following papers[12)13)]. Cryogenic systems in the High Field Laboratory for Superconducting Materials is also described[14)]. Power supply and cooling system for resistive magnets as well as operation and control system for hybrid magnets are also described in the following papers[15)16)]. How to measure and determine field intensities produced by the hybrid magnet system is also studied in one of following papers[17)].

As regards Tohoku Hybrid Magnet System, plan, construction and occasional results have already been reported.[18-25)] The present and following six papers in Part I are reports summarized on the Tohoku Hybrid Project. It should be added that, though the famous pulsed ultra-high field laboratories[26)27)] are lively in existence in Japan, this paper concerns only with the steady and high magnetic field system in Tohoku University.

II. Outline of Tohoku Hybrid Magnet System

Because we had been holding techniques to build and operate Bitter type magnets up to 10 T since 1957[28)29)] and also we had some experiences for making and employing small superconducting magnets up to 10 T with 30 to 50 mm bore, our plan was developed under the idea which started from the established technology, extended to generation of higher fields and finally reached to the highest level throghout the world in the development of strong steady field magnet. After fabricating successfully two 12.5 T Bitter magnets[30)31)] operated by our old 3.5 MW power supply[28)], we built three hybrid magnets named HM-1, HM-2 and HM-3 as shown in Fig. 1, where they were numbered from the strongest magnet to weaker ones in turn. A hybrid magnet consists of an inner water-cooled resistive magnet and an outer superconducting magnet. It is called that HM-3 consists of WM-3 and SM-3 for example. This is also the same in HM-2 and HM-1. In Table 1 are shown main characteristics of HM-1, HM-2 and HM-3.

HM-3 and HM-2 were fabricated in 1981[21)], while HM-1 in 1983[24)]. These were manufactured by Toshiba Corporation, except SM-3 fabricated by Mitsubishi Electric Corporation. Both SM-3 and SM-2 were made by employing NbTi multifilamentary conductors. SM-1 was made by employing a multifilamentary Ti-doped Nb_3Sn conductor for the inner section and multifilamentary NbTi ones for the outer two sections, because a technique for fabricating Ti-doped Nb_3Sn

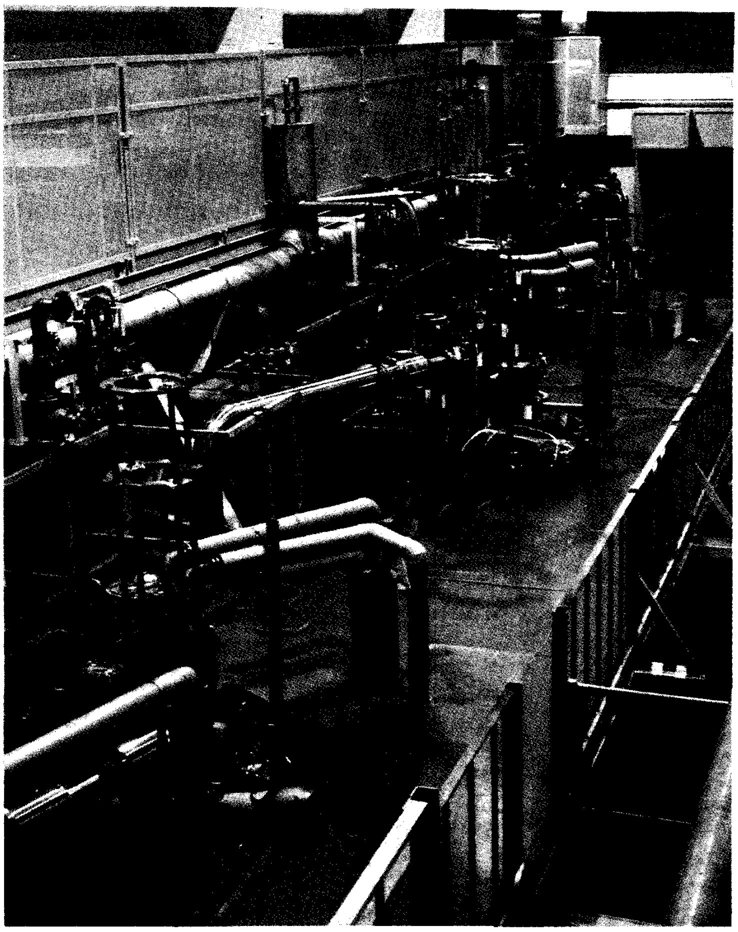


Fig. 1 Three Tohoku hybrid magnets. HM-3, HM-2 and HM-1 are seen from front to back.

Table 1. Main Characteristics of HM-1, HM-2 and HM-3.

Magnet	Effective Bore (mm)	Central Field (T)	Power (MW)	Rated Current (A)	Type
HM-1	52 / 32	29 / 31			
SM-1	360	12	—	1456	Nb_3Sn-fm, NbTi-fm cryostable DP
WM-1a	32	19	7.1	22500	Polyhelix
WM-1b	52	17	7.4	22300	Polyhelix
HM-2	52	23			
SM-2	360	8	—	1470	NbTi-fm-cryostable DP
WM-2	52	16	6.7	21400	Double Bitter
HM-3	32	20			
SM-3	220	8	—	780	NbTi-fm-compact solenoid
WM-3	32	12.8	3.4	11500	Single Bitter

DP: Double Pancake, fm: fine-multicored

conductor developed rapidly in Japan in recent years. Most of these conductors were fabricated by Furukawa Electric Corporation.

The outer SM in the HM system becomes so heavy and large that it takes a long time to precool from room temperature prior to the transfer of liquid helium (LHe) into cryostat. SM-3 and SM-2 are cooled down by use of two Philips cryogenerators (PGH 105). SM-1 is precooled by helium gas and cooled by transferred LHe, respectively, by use of a long (80 m) transfer line from a Sulzer Japan-Oxygen He liquefier-refrigerator which has refrigeration capacity of 225 W at 4.5 K and can produce LHe of 130ℓ/hr. This He liquefier-refrigerator is also used for LHe supply to SM-3 and SM-2. The detail of our cryogenic system[32)] can also be seen in one of following papers[14)], which gives outline of the whole cryogenic system in HFLSM.

WM-3 and WM-2 are a single coil and a double Bitter coil, respectively, while WM-1 is not the Bitter type but the polyhelix one. There are two kinds of polyhelix magnets[24)] depending on their inner bore diameters in HM-1 which we call WM-1a with 32 mm bore and WM-1b with 52 mm bore. Materials of WM coils are Ag-doped Cu conductor or Al_2O_3-dispersion-strengthened Cu (Glidden Metals, USA). Their details are given in one of following papers[13)].

The 8 MW power supply[20)] (350 V, 23,0 KA) consisting of two identical 4 MW units was manufactured over the 1982 to 1983 fiscal years, where thyristers system was adopted. The cooling system [18)20)] using turbo-refrigerators provides the most excellent feature, where the deionized water circulating through WM is directly chilled. The temperature of purified water is always kept between 6 and 10°C regardless of the ambient temperature. This results in the long life of WM itself. Details appear in one of the following papers[15)].

In an operation of HM, firstly a current of SM reaches to a specified maximum value and then a current of WM is added. Such an operation system is controlled by a computer, TOSBAC 7/70B, which starts or stops the power supplied to both SM and WM and sets on a sweeping pattern of operating current through the magnet. This computer system describes an operating condition, and warns against various troubles happened in the total HM system. Details of such a system are also described in one of following papers[16)].

III. The most compact hybrid magnet; HM-3

HM-3 shown in Fig. 2 consists of an inner water-cooled resistive magnet WM-3 and a superconducting magnet SM-3. In Table 1 are included main characteristics of HM-3.

In order to make SM-3 as light as possible and then to save the quantity of LHe to cool it, we tried compact design for HM-3, keeping an inner bore diameter more than 30 mm as an experimental space. Then the inner WM-3 became a single Bitter coil with cooling-holes of axial flow type. In SM-3, the multifilamentary NbTi coil was layer-wound without LHe channels, in which a fully crystable design was avoided, where the stainless steel cryostat was T-shaped to ensure enough quantity of LHe. After precooled to 30 k using cryogenerator, only about 180 ℓ of LHe were required to realize the operating condition.

Single magnet tests of WM-3 and SM-3 can produce magnetic fields of 13 T at 11.5 kA and of 8 T at 780 A, respectively. In the regular operation, HM-3 used to produce total field up to 20.2 T, where SM-1 remained 7.5 T. And HM-3 could produce the maximum field of 20.5 T.

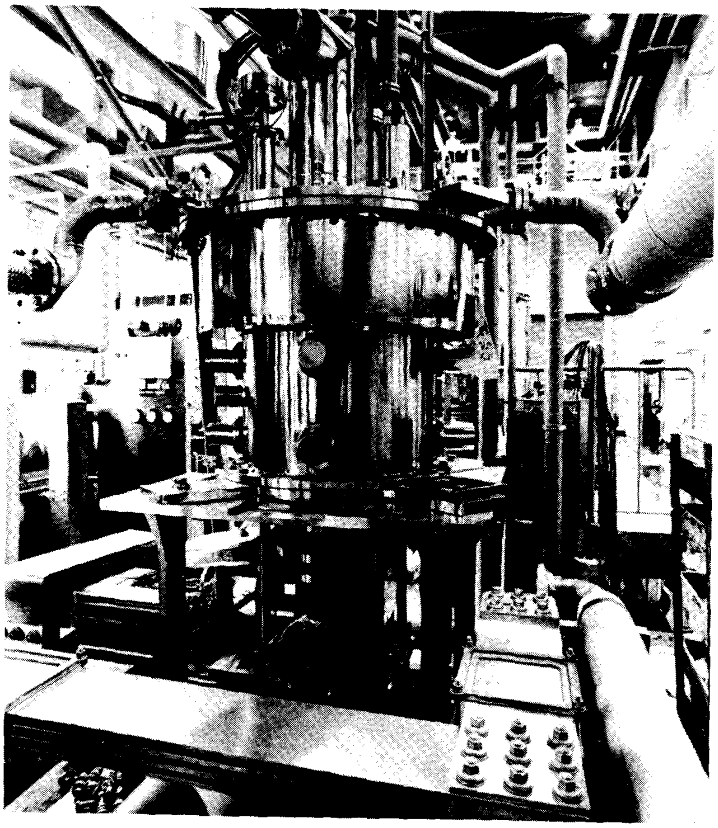


Fig. 2 Photograph of HM-3

IV. The most convenient hybrid magnet; HM-2

HM-2 shown in Fig. 3 consists of an inner WM-2 and an outer SM-2. In Table I are also included main characteristics of HM-2. Though HM-2 was firstly designed as the magnet with inner bore of 30 mm which can produce 25 T, it was pointed out that HM with a wider bore would be convenient for experimentalists. As the result this magnet with an inner bore of 52 mm was fabricated to be able to generate about 23 T.

WM-2 with the inner bore of 52 mm consists of double Bitter coil with the similar cooling holes to those of WM-3. Multifilamentary NbTi conductors were wound in 24 double pancakes with LHe channels under the basic idea of fully cryostable design. Then SM-2 became much heavier than that of SM-3, resulting in long period operation of the cryogenerator and a larger amount of LHe (ca. 500 ℓ) needed to cool down before its operation.

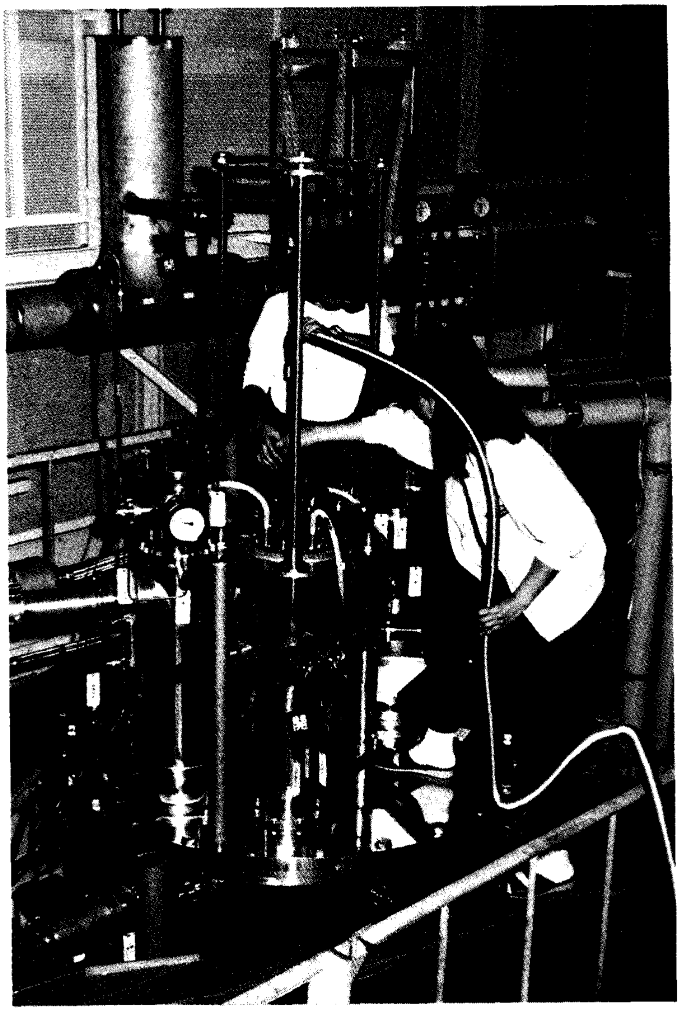


Fig. 3 Photograph of HM-2

Single magnet tests of WM-2 and of SM-2 can produce 16.1 T at 22.5 kA and 8 T at 1460 A, respectively. In the regular operation, HM-2 produces total field of 23.2 T where SM remains 7.5 T. And HM-2 could generate the maximum field of 23.6 T.

V. The strongest hybrid magnet; HM-1

Because above two hybrid magnets employ the Bitter type coils and NbTi superconducting coils, we did not need to develope new techniques for fabricating each magnet itself but were required to pay careful consideration to combine such two kinds of magnets. However, the important purpose to construct HM-1 was to reach the field more than 30 T and also to practice the Nb_3Sn conductor with a rather larger size. The maximum field required for Nb_3Sn superconducting magnet, SM-1, was determined to be 11-12 T. Therefore the water-cooled resistive magnet, WM-1, was requested to produce 18-19 T. Since our power source of resistive magnet was limited to 8 MW, it was thought that newly designed polyhelix type magnet should be developed instead of Bitter type magnet. The process of development of multifilamentary Ti-doped Nb_3Sn in our laboratory was described in ref. 22 and design of polyhelix coil in ref. 23.

Fig. 4 and 5 are photograph and cross-section of HM-1, where its characteristics are also included in Table I. We have two types of polyhelix magnets. One is WM-1a having an inner bore of 32 mm, and the other WM-1b having an inner bore of 52 mm. WM-1a and WM-1b consisted of 12 and 10 concentric helices made of Ag-doped Cu conductor, respectively. These helices are electrically connected in series and parallel to give a suitable value of electrical resistance. SM-I is composed of 42 double pancakes. One pancake is graded in three sections. The innermost section was made of Ti-doped Nb_3Sn and the other two were made of NbTi conductors.

Single tests of SM-1 could produce 12.0 T at 1450 A, which was the maximum field in Nb_3Sn magnets of this kind of size. WM-1a could produce the field value of 19.6 T. HM-1a which combined these two magnets could produce 29.3 T in clear bore of 32 mm in April, 1984, where SM-1 and WM-1a produced 10.0 T and 19.3 T, respectively. After careful examination of SM-1 over about one year, we obtained 30.7 T in May, 1985, where SM-1 and WM-1a produced 11.1 T and 19.6 T, respectively. Furthermore, we succeeded to reach 31.1 T in the same bore in November, 1986, which was the final goal of this project where SM-1 and WM-1a generated 11.7 T and 19.4 T, respectively. J_c and H_{c2} of several advanced superconducting materials were measured in HM-1a in May, 1985[33] and also in November, 1986, which is included in the following paper[34].

Since the clear bore of 32 mm in HM-1a is rather small, we replaced it into WM-1b with clear bore of 52 mm after measurements of J_c and H_{c2} of several superconducting materials in HM-1a[33][34]. This HM-1b could also produce 28.1 T in November 1986. This magnet HM-1b will be open to scientists and engineers from beginning of 1987.

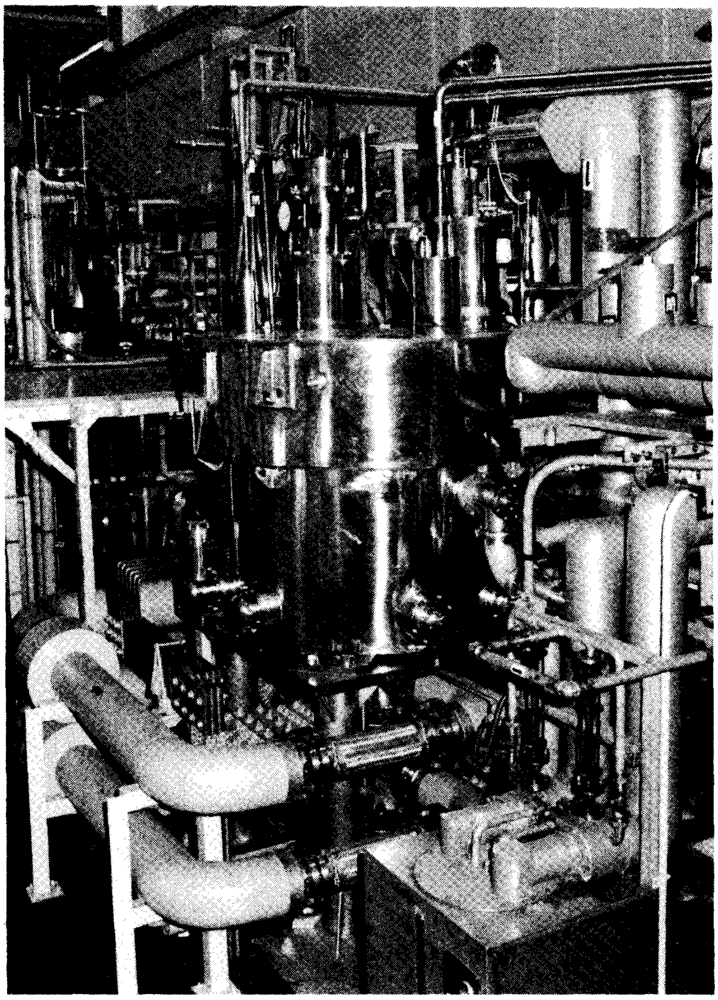


Fig. 4 Photograph of HM-1

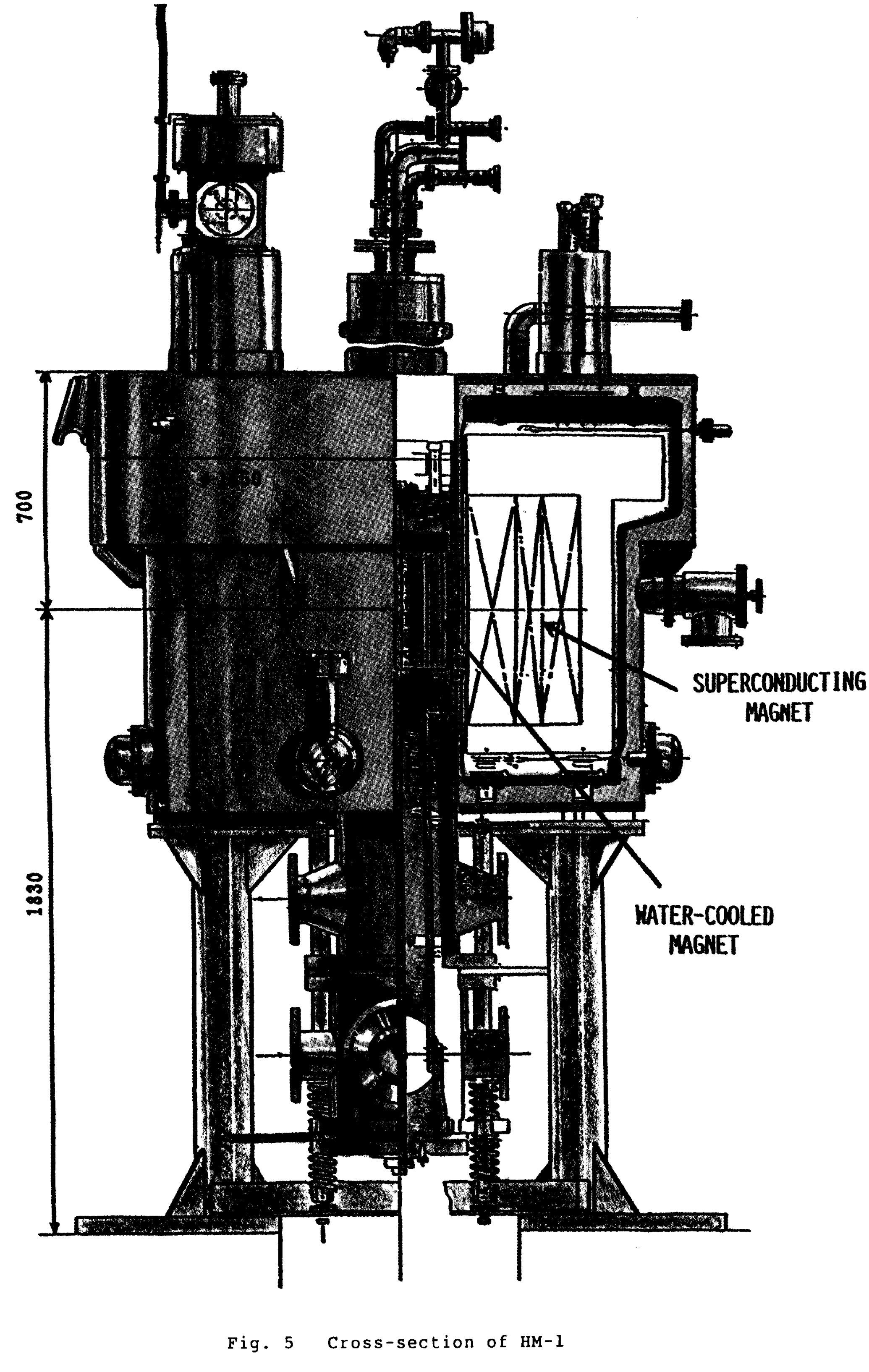


Fig. 5 Cross-section of HM-1

VI. Future Plan

We would like to describe our future plan to obtain stronger field more than 31 T. Recently we succeeded to obtain 16.7 T in 50 mm bore by use of a Ti-doped Nb_3Sn coil backed up by a 8.5 T NbTi superconducting coil, where both magnets were immersed and operated in pressurized He II cryostat apparatus, which is in detail discussed in a separate paper[35). This was the highest record among various Nb_3Sn superconductors, though this record was very recently renewed by Kyushu University group[36), where they could obtain 17.1 T at 4.2 k and opened a new 17 T age for Nb_3Sn magnet.

Our SM-1 could generate 12 T in an inner bore of 420 mm and also an outer part of the new superconducting magnet at National Research Institute for Metals produced 14.2 T in 180 mm bore[4). Therefore we expect that a new superconducting magnet which will produce the field up to 15 T at 4.2 k (or 16 T at 1.8 k) can be designed and fabricated at least in Japan, where this magnet has the storage energy of about 60 MJ.

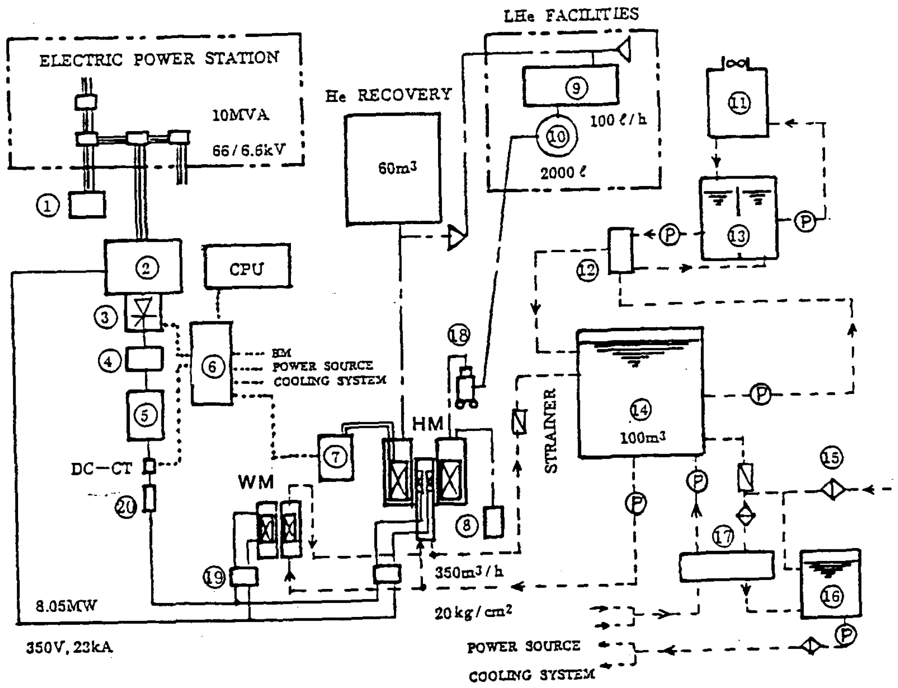
On the other hand, since our power supply of resistive magnet is limited to be 8 MW, its maximum field may be at most 20 T. Therefore we are now discussing whether 35 T hybrid magnet with 30 mm bore (HM-α) or 33 T hybrid magnet with 50 mm bore (HM-λ) can be fabricated in near future.

We appreciate very much the Ministry of Education, Science and Culture, Japan, for their financial support to Tohoku Hybrid Magnet Project. We would like to express our sincere thanks to the late Professor Ko Yasukochi, without whom this project could not be performed. We would also like to thank Mrs. K. Sato, Ms. Y. Chiba, Ms. A. Kato, Ms. Y. Komada and Ms. C. Shibata for typing all the manuscripts in the present special issue.

Appendix I

Arrangements of total magnet system and floor layout of the building

In Fig. 6 is shown a schematic arrangement of total equipments including power supply, cooling system and computer and control system in order to help understanding of this special issue. Our HFLSM building has total area of about 2500 m^2 where the layout is shown in Fig. 7.



1 AC FILTERS	9 He LIQUEFIER	17 HEAT EXCHANGER
2 TRANSFORMER	10 LHe RESERVOIR	18 STORAGE VESSEL
3 THYRISTORS	11 COOLING TOWERS	19 CHANGE OF SWITCH
4 PASSIVE FILTERS	12 WATER REFRIGERATORS	20 POLE CHANGE OF SWITCH
5 ACTIVE FILTERS	13 RESERVOIR	P WATER PUMP
6 CONTROL BOARD	14 DEIONIZED WATER	
7 SM POWER SOURCE	15 ION EXCHANGE RESIN	
8 He REFRIGERATOR	16 SERGE TANK	

Fig. 6 Schematic equipment arrangement of total hybrid magnet system.

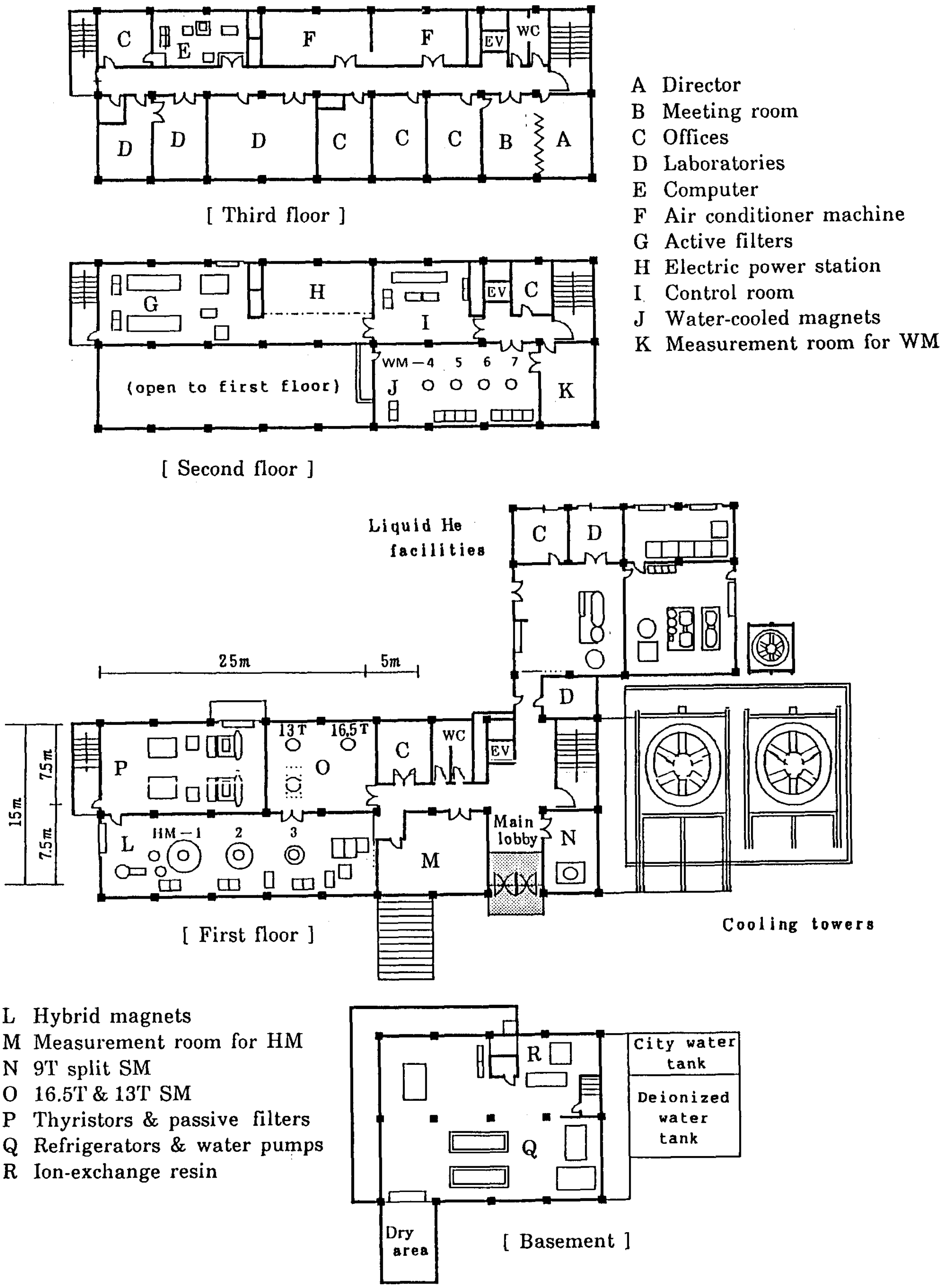


Fig. 7 Floor layout in HFLSM building

Appendix II

The present status of hybrid magnet projects in the world

Table 2 gives the present status of hybrid magnet projects throughout the world. This Table was chiefly summarized on the basis of data till September, 1985, when 9th International Conference of Magnet Technology (MT9) was held at Zurich, Switzerland. We add recent data by us and also those in Grenoble[10]. We would like to several comments about Table 2.

The Francis Bitter National Magnet Laboratory (FBNML), MIT, is the largest facility in the world for the generation of intense steady magnetic field having the power supply of 10 MW[37]. They began to construct the hybrid magnet in early 70's and completed it in 1977 by producing 25.4 T[8] in a 32 mm bore with 5 MW. Before transporting to Nijmegen, they also succeed to generate 30.1 T[8] by combining Nijmegen SM with MIT 9 MW resistive magnet. (We should say that the success of our project owes to ref. 8.) Moreover, they constructed two hybrid magnets for MIT generating 24.0 T and 30.1 T. Furthermore, FBNML has recently succeeded to produce dc magnetic field of 33.6 T[38] in 30.1 T hybrid magnet by adding 3.5 T obtained

Table 2. Present status of hybrid magnet projects in the world.
COD and CID mean coil outer and inner diameter, respectively.
* is the test result by MIT.(See the text.)

Location State		SM					WM					HM	References
		OD mm	COD mm	CID mm	bore mm	field T	COD mm	CID mm	bore mm	power MW	field T	field T	
Tohoku Univ. Japan	HM-3	711	435	290	220	8.0	185	38	32	3.1	13.0	20.5	21
	HM-2	1300	922	420	360	8.0	320	60	52	6.3	16.0	23.2	21
	HM-1b	1450	1094	430	360	12.0	300	60	52	7.0	17.0	28.1	Present Paper
	HM-1a						300	38	32	7.4	19.6	31.1	
MIT USA						7.0	333	60	54	7.3	17.0	24.0	
			710	400		7.5	330	41	33	8.7	22.9	30.1	8
Nijmegen Univ. The Netherlands		1360	889	406	356	8.5	333	38	32	5.2	17.0	25.4	8
			883	420		11.0						28.5*	39
Kurchatov USSR			700	376		6.9	275	48	28	5.6	18.0	25.0	11
Oxford UK				284	240	6.5	200	53	50	1.6	9.5	20.0	40
Grenoble France + FRG			1087	500		11.0			50	10.0	20.0	28.0	10

with Ho pole pieces, though the effective space is only 12 mm diameter pole face with 2 mm gap between pole faces. On the other hand, MIT constructed 28.5 T new hybrid magnet[39] for Nijmegen Univ., which is also expected to generate 30 T in a pressurized He II cryostat in future.

Oxford firstly constructed a hybrid magnet generating 16 T with only 2 MW power source[6][7]. Recently their field record has increased to 20 T according to one of us[40].

Recently Grenoble has finished their HM test, and obtained 28 T in an inner bore of 50 mm[10]. This magnet together with our HM-1b will be most useful in the world in near future.

In addition to these projects, China is planning to build HM which is similar to our HM-3[41].

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