Radiation-Resistant Magnets for the J-PARC

K. H. Tanaka, E. Hirose, H. Takahashi, K. Agari, T. Watanabe, A. Toyoda, Y. Sato, M. Minakawa, H. Noumi,
Y. Yamanoi , M. Ieiri, Y. Katoh, Y. Yamada, Y. Suzuki, M. Takasaki, T. Birumachi, S. Tsukada, T. Ozawa,
Y. Saitoh, K. Kato, and K. Yahata

Abstract—Continuity R&D work is reported here on the radiation resistant magnets for the Japan Proton Accelerator Research Complex (J-PARC). The main accelerator of the J-PARC is the 50 GeV-15 mA proton synchrotron (50GeV-PS) with beam power of 750 kW. The radiation resistant magnet is the key technology to realize the external beam lines and experimental facilities of the J-PARC 50GeV-PS.

The radiation resistant technologies we have selected for the J-PARC are; (1) Polyimide Resin Insulation (PI) for up to 10^8 Gy and, (2) Mineral Insulation magnet Cables (MICs) with larger cross sections for higher radiation dose up to 10^{11} Gy. Approximately 20 polyimide insulation magnets and 10 MIC magnets are designed for the external beam lines of the 50GeV-PS. The fabrication of those magnets has already started in 2005 and will continue until the end of 2007.

Index Terms—high intensity beam handling, KAON factory, mineral insulation cable, polyimide insulation, radiation resistant magnet.

I. INTRODUCTION

The construction of the Japanese high-intensity Particle Accelerator Research Complex (J-PARC) [1] [2] was approved by the Japanese Government in 2000 and started in 2001. The construction site of the accelerators is the Tokai campus of the Japan Atomic Energy Research Institute (JAERI) since the J-PARC is the joint project of the High Energy Accelerator Research Organization (KEK) and JAERI. The construction will be completed by the end of 2007 and experiments will start in 2008. The latest photograph of the J-PARC construction site is shown in Fig. 1.

The main accelerator of the J-PARC is the 50 GeV proton synchrotron (50 GeV-PS), whose beam intensity designed is 15 mA. The beam power of the 50GeV-PS reaches 750 kW, which is approximately 10 times higher than the existing multi-GeV accelerators. The main application for this high-power 50 GeV proton beam is the intense production of kaons, pions, and many other unstable and/or rare elementary particles such as antiprotons which will hopefully allow significant progress in both nuclear and particle physics. The J-PARC 50 GeV-PS is the first real KAON Factory [3] accelerator in the world.

Two external beam lines are under construction for the 50 GeV-PS. One uses resonant slow extraction for the counter experiments and the other uses single-turn fast extraction for the neutrino beam facility, which is dedicated to a long baseline oscillation experiment, T2K, in combination with Super-KAMIOKANDE cosmic neutrino observatory [4]. As injectors for the 50 GeV-PS, the rapid cycle 3 GeV proton synchrotron (RCS) and a 400 MeV linear proton accelerator (LINAC) are under construction. Beams from these low energy accelerators will be used solely for nuclear transmutation studies and material and life science studies, respectively. The power of the LINAC and RCS beams will also reach approximately 1MW.

II. RADIATION RESISTANT MAGNETS

With the increasing intensity and power of accelerated beams, the problems of radiation damage and induced radio activity have become serious. Assuming that the beam loss of some fraction of the accelerated and extracted beams is unavoidable, the radiation damage to the accelerator components increases proportionally to the intensity and/or power of the accelerated beams. For external beam lines, this assumption is especially right since the extracted beam is dissipated, by design, at the secondary-particle production targets placed in the external beam lines. The situation should be the same at the beam dump. This simple expectation forces us to prepare much more radiation resistant electromagnets than conventional electromagnets since the magnets have to be operated at the closest locations to the beams. The radiation life of the electromagnets is determined by the radiation resistance of the magnet-coil insulation. In most cases, the excitation coils of conventional magnets are insulated by epoxy resin reinforced by glass cloths, whose radiation life is around 10^7 Gy. This life limitation is insufficient for MW-class high intensity accelerators such as J-PARC. The absolute beam loss can reach a serious level for conventional epoxy insulation even

Manuscript received September 20, 2005. This work was partly supported by a Grant-in Aid for Scientific Research (No. 15340084 and No. 17204019) of the Japan Ministry of Education, Culture, Sports, Science and Technology.

K. H. Tanaka (corresponding author to provide phone: +81-29-864-5599; fax: +81-29-864-5362; e-mail: kazuhiro.tanaka@kek.jp), E. Hirose, H. Takahashi, K. Agari, T. Watanabe, A. Toyoda, Y. Sato, M. Minakawa, H. Noumi, Y. Yamanoi, M. Ieiri, Y. Katoh, Y. Yamada, Y. Suzuki, and M. Takasaki are with the Beam Channel Group, Physics Division III, Institute of Particle and Nuclear Studies (IPNS), High Energy Accelerator Research Organization (KEK), Oho 1-1, Tsukuba-shi, 305-0801, Japan.

T. Birumachi and S. Tsukada are with the Copper Tubes Manufacturing Department, Tsuchiura Works, Hitachi Cable, Ltd., Kidamari 3550, Tsuchiura-shi, 300-0026, Japan.

T. Ozawa, Y. Saitoh, K. Kato and K. Yahata are with the TOKIN Machinery Corporation, Koriyama 6-7-1, Taihaku-ku, Sendai-shi, 982-0003, Japan.

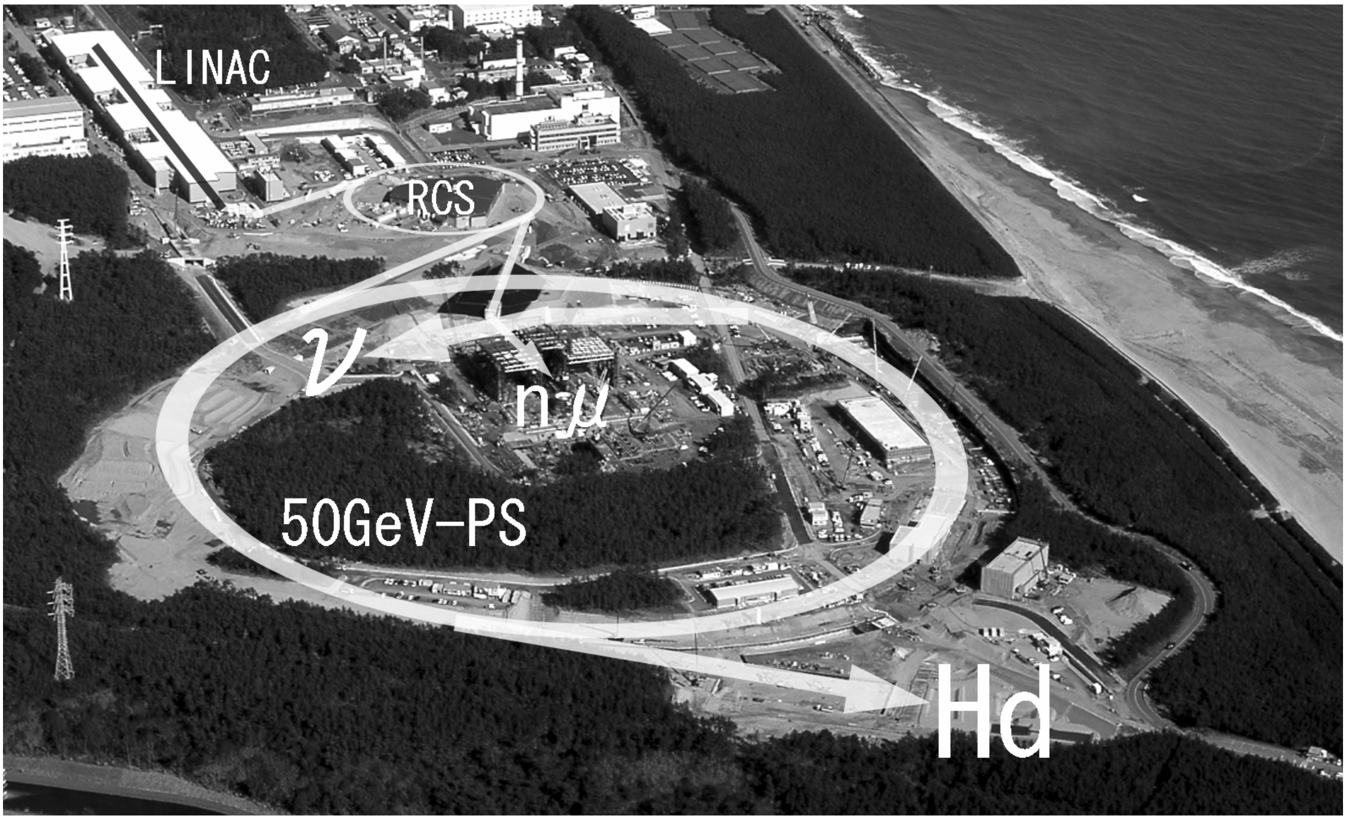

Fig. 1. Construction site of J-PARC at Tokai campus of JAERI. “Hd” means the hadron beam facility for the nuclear particle physics experiments with slow extraction beam from the 50GeV-PS. “n” indicates the neutrino beam facility which is completely underground and can not be seen. “nm” shows the location of the pulsed neutron and muon sources prepared for the matter and life science studies.

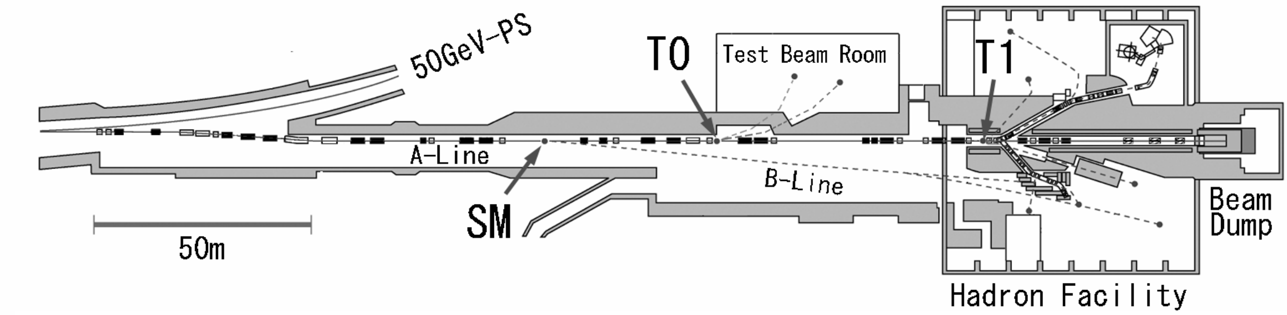

Fig. 2. Hadron beam facility (Phase 1) of the J-PARC 50 GeV –PS. Approximately 42 electromagnets will be prepared in the main primary beam line A in order to transport the extracted proton beam to the main production target T1 and to the beam dump. Black squares indicate quadrupoles and white squares mean dipoles including steering magnets. The small target T0 will be set at the middle of the A line in order to provide secondaries to the test beam room. SM means the switching/splitting magnets where the branch line B will start. Putting a small target at the SM location, the B-line can be used as the high momentum secondary line. Magnet locations at the downstream part from T1 are not yet fixed. In phase 2 of the J-PARC, the area of the facility will be expanded twice.

at the location where the relative beam loss ratio is only a small fraction. This means that conventional epoxy insulation magnets operated even in the usual beam transport lines may be replaced every year if the power of the extracted beam is ~1MW, which is unacceptable and unrealistic for the stable operation of the accelerator facility. In addition, we should consider that the magnets placed even in the ordinary places should be so radioactive that replacement itself is almost impossible without remotely controlled maintenance apparatus.

Thus we have continued a series of R&D studies on radiation-resistant magnets for the past 20 years [5]. Initially we developed a polyimide insulation (PI) magnet coil with boron free glass tape [5]. The radiation life of the PI coil was tested by the external beams of the 12 GeV Proton Synchrotron of the KEK (the KEK-PS) and found to be around 10^8 Gy and reached up to 10^9 Gy absorbed dose, which is one order of magnitude harder than the conventional epoxy insulation magnets. This technology was immediately employed in the magnets of the external beam lines of the KEK-PS and tested for more than 15 years without any serious damage. This great success enabled us to employ this PI coil technology in all the accelerator electromagnets of the J-PARC.

As a second step, we have developed mineral insulation magnet cables (MICs) [6] [7] with larger cross sections than ever [8] in order to assemble electromagnets that are large enough for 50 GeV proton beam transport. The reason that MIC technology was selected among several technical options of radiation-resistant magnet coils [9] is the ease of mass production of coils with various shapes. Finally we have developed new types of MICs with larger cross sections, which can handle the excitation current of 2000, 2500 and 3000 A at the maximum length of 60 m [8].

J-PARC is now in the construction stage. In 2005, the mass production of the radiation resistant magnets for the slow extraction beam (SEB) lines for the fixed target counter experiments of the 50 GeV-PS was started. As shown in Fig. 2, the number of magnets used for the SEB line is 42 where 13 MIC magnets and 17 PI magnets are included. The twelve magnets left are the conventional epoxy magnets, which will be replaced by PI coils later. The list of magnets can be seen in TABLE I. Construction of magnets for the fast extraction beam (FEB) line will start in 2006. Some details of the MIC and PI magnets are summarized in the following section.

III. Mass Production of Magnets

A. Polyimide Magnets

Polyimide insulation (PI) coils are commonly used at most magnets of the external beam line for both SEB and FEB. Polyimide resin is somewhat difficult to use, compared to epoxy resin. For example, a high curing temperature of approximately 250 centigrade is required. However the viscosity of the resin disappears at such high temperature. The coil must also be kept in an appropriate vessel in order not to lose the resin during the cure. Temperature uniformity is also essential to realize better quality of the coil insulation. For this purpose we recirculated hot water into the hollow center of the coil conductor during the cure. This recirculation was useful also to control the curing temperature. Vacuum impregnation is essential to prepare a void-free polyimide layer between the conductors.

Owing to such complicated treatment of polyimide resin, as well as the relatively high cost of polyimide resin itself, the price of the PI coil is 30-50% more expensive than the epoxy insulation coil with the same size and structure. In order to reduce the total cost of the beam line magnets, the iron yokes of the magnets are recycled from the existing magnets of the beam lines of the KEK-PS. The older existing magnets, which were almost all epoxy insulation coils, were replaced by newly prepared PI coils. In such modifications, most magnet parts except for the coil insulation resin were replaced by inorganic materials in order to extend the radiation lives of the magnets. For example, all the rubber insulation hoses connecting the water manifold and the coil water circuits were replaced by ceramic insulation pipes. Stainless steel tubes are brazed at both ends of the pipe in order to fix the insulation pipe to the

TABLE I
List of Magnets for
Primary Proton Beam Line (Slow Extraction)

No	Name	Specification	Weight(t)	Coils
1	h01	4D220M	4.6	MIC
2	v02	6D220M	8.0	MIC
3	q01	Q350M(QC2)	17.3	MIC
4	q02	Q350M(QC2)	17.3	MIC
5	h03a	8D337M(18D72)	38.0	MIC
6	h03b	8D337(18D72)	38.0	PI
7	v04	6D220V	8.0	PI
8	q03	Q350(QC2)	17.3	
9	q04	Q360(QC1)	18.0	
10	q05	Q360(QC1)	18.0	
11	h05	7D2117	33.0	PI
12	v06a	8D337V-M(18D72)	35.0	MIC
13	q06	Q360(QC1)	18.0	
14	q07	Q360(QC1)	18.0	
15	q08	Q420	6.0	PI
16	h07	6D220	8.0	PI
17	q09	Q360(QC1)	18.0	
18	q0A	Q360(QC1)	18.0	
19	v08	7D220V	9.0	PI
	SM	(Splitting point to B-Line)		
20	q11	Q430	9.0	PI
21	q12	Q350(QC2)	17.3	
22	h13	6D220	8.0	PI
23	q13	Q350(QC2)	17.3	
24	q14	Q360(QC1)	18.0	
25	v14a	8D340V	18.0	PI
26	h15	8D320	21.5	PI
	T0	(Target point for Test Beam Lines)		
27	q15	Q350(QC2)	17.3	
28	q16	Q350(QC2)	17.3	
29	h16	5D420	18.0	PI
30	q17a	Q430	9.0	PI
31	q17b	Q430	9.0	PI
32	q18	Q460	29.0	PI
33	v17	5D520V	18.0	PI
34	BS1	5D420	18.0	PI
35	q19	Q460	29.0	PI
36	q1A	Q350M(QC2)	17.3	MIC
37	BS2	8D320M	18.0	MIC
	T1	(Main production target)		
38	q1B	Q440M	32.0	MIC
39	h18	6D420M	22.0	MIC
40	q1C	Q460M	35.0	MIC
41	v19	6D520V-M	22.0	MIC
42	q1D	Q440M	32.0	MIC

2nd Column, h: horizontal bending magnet, v: vertical vending magnet, q: quadrupole magnet, BS: beam swinger [10] magnet. SM, T0, T1 indicate target locations shown in Fig. 2.

3rd Column, "Qabc" means quadrupole magnet with bore diameter of 5a cm and yoke length of (10b+c)x5 cm. "aDbcd" means dipole magnet with gapwidth of 5a cm and gap of 5b cm and yoke length of (10c+d)x5 cm. "V" means vertical bending magnet and "M" means MIC magnet. (Name) is magnet's nickname.

5th Column, PI and MIC mean polyimide insulation coil and MIC coil, respectively.

manifold and the coil water circuit, respectively.

B. MIC Magnets

MIC magnets are employed at the upstream end of the external beam line, where the strong beam halo from the extraction devices of the accelerator is unavoidable. Several large bending magnets also employed the MIC coil since the scattered beam generated along the beam line will be swept out there. Some magnets placed at the immediately upstream part of the main production target, T1, and all the downstream magnets from T1 are MIC magnets. Very severe radiation generated by T1 can not allow any organic materials to be used in the neighboring locations of T1. The magnets at the downstream part of T1 are newly constructed ones, since the radiation situation should be the worst there. The other MIC magnets are assembled with the used iron yokes as shown in Fig. 3 and Fig. 4 in order to reduce costs.

Fig. 3, One quadrant of Q350 (QC2) coil made of MIC at the final inspection. Coil dimensions were carefully checked by using the standard plate referring to the existing iron yoke of QC2.

Fig. 4, New QC2 coils made of MIC mounted on the existing iron yoke. Old QC2 coils insulated by epoxy were removed and stored for future recirculation.

Coil windings using MIC was not difficult. However, it took unexpectedly large labor cost to treat the coil terminals to fit the coil terminal shape to the water manifold. The price of the MIC coil is, then, more than twice of the conventional epoxy insulation coil with the same size and performance. Further effort to reduce the MIC coil cost is necessary.

IV. SUMMARY

The mass production of radiation resistant magnets for the J-PARC external beam lines has been started and is going well. Most magnets for the slow extraction beam line will be prepared by the end of 2005 and some extra magnets will be made in 2006. The installation is scheduled in 2006 and 2007 and the beam will be introduced to the beam line in the middle of 2008. The construction of magnets for the fast extraction beam line will start in 2006.

The radiation resistant magnets thus constructed will be mounted in the plug-in magnet base, which will enable us to perform the automated magnet alignment and the quick disconnect of the cooling water, electric power, interlock signals and vacuum ducts. The details of the “plug-in” system of the magnets will be reported elsewhere [11].

ACKNOWLEDGMENT

The authors would like to express their thanks to professors Y. Totsuka, H. Sugawara, M. Kobayashi, S. Yamada, F. Takasaki, S. Iwata, K. Nakamura, K. Nakai and S. Nagamiya of KEK directorates for their warm encouragement throughout the present study.

REFERENCES

[1] J. Chiba et al., “JHF98,” KEK Proceedings 98-5, 1998.
[2] Joint Project team of JAERI and KEK, “The joint project for high-intensity proton accelerators,” KEK Report 99-4 and JAERI-Tech 99-056, July 1999.
[3] TRIUMF, “Kaon Factory Proposal,” 1985.
[4] S.H. Ahn et al., “Detection of accelerator-produced neutrinos at a distance of 250 km,” Physics Letters. vol. 511B, pp. 178-184, 2001.
[5] K.H. Tanaka et al., “Development of radiation-resistant magnets for high intensity beam lines,” Proceedings of the 11th International Conference on Magnet Technology (MT11), pp.725-728, 1989.
[6] K.H. Tanaka et al., “Development of radiation resistant magnets for JHF project,” IEEE Transactions. on Applied Superconductivity, vol.12, no. 1, pp. 278-281, March 2002 and other references are there in
[7] K.H. Tanaka et al., “Development of radiation-resistant magnets for JHF/J-PARC,” IEEE Transactions. on Applied Superconductivity, vol.14, no. 2, pp. 402-405, June 2004.
[8] A. Harvey, “Radiation-hardened magnets using mineral-insulated conductors,” Proceedings of the 4th International Conference on Magnet Technology (MT4), pp. 465-468, 1972.
[9] R.L. Keizer and M. Mottier, “Radiation-resistant magnets,” CERN 82-05, 1982.
[10] K.H. Tanaka et al., “Optical Design of Beam Lines at the KEK-PS New Experimental Hall,“ Nuclear Instruments and Methods, vol. A363, pp. 114-119, 1995
[11] E. Hirose et al., “Beam-Handling Magnet System for the J-PARC Neutrino Beam Line,” IEEE Transactions on Applied Superconductivity, submitted for publication at the 19th International Conference on Magnet Technology (MT19).