SUPERCONDUCTING MAGNETS

R. Perin, CERN, 1211 Geneva 23, Switzerland

Abstract

Superconducting magnets have become essential components of hadron accelerator/colliders and compact electron accelerators. Their technology has greatly progressed in recent years thanks to the Tevatron and HERA operation experience, the production of the RHIC magnets and the intense R&D programs for SSC, UNK and LHC. For the LHC, at present the most important and advanced project, dipoles, quadrupoles and corrector R&D magnets have been successfully built in industry and laboratories. Major milestones have been recently passed with test and measurement of several industry made, 10 m long, twin-aperture dipoles and the successful operation of a "string" test facility simulating the basic machine half-cell.

I. INTRODUCTION

High Energy Physics has been for almost three decades the prime promoter of applied superconductivity, magnets and r.f. cavities, identified as the means to reach higher energy saving cost and space occupancy. Superconducting magnets have be come the key to higher energies in hadron accelerator/colliders, and are more and more applied in experiments for momentum analysis of secondary particles. In low energy machines superconducting magnets are used in industrially made compact electron accelerators as, e.g. "portable" synchrotron light sources and small cyclotrons for medical applications [1, 2].

This paper covers only a few aspects of the main magnets of the high energy colliders presently under construction and is mainly focussed on the dipoles because of their importance in the economy of the projects and of their technical difficulties.

The evolution in field and field gradient of superconducting main magnets for accelerators is recalled in Table I.

Improvement in performance of superconductors [3, 4], better insulation systems and force containment structures and refinements in manufacturing have permitted to raise field and gradient. A bold step is being made with the LHC using the superfluid helium technique, thus enhancing the performance of the traditional NbTi superconductor, and by the adoption of the two-in-one configuration leading to a considerable reduction of costs and space occupancy.

Table I
Design parameters of superconducting main magnets in accelerator/colliders

	Dipoles			Quadrupoles			Operation temperature
	Central field (T)	Coil aperture (mm)	Eff. unit length (m)	Field gradient (T/m)	Coil aperture (mm)	Eff. length (m)	(K)
TEVATRON	4.4	76.2	6.1	75.8	88.9	1.7	4.6
HERA	4.7	75	8.8	91.2	75	1.9/1.7	4.5
RHIC	3.5	80	9.5	71.8	80	1.1	4.6
UNK	5.0	80	5.7	96.1	80	3.0	4.6
SSC	6.6	50	15.2	206	40	5.2	4.35
LHC	8.4	56	14.2	220	56	3.0	1.9

II. SSC MAGNETS

The SSC magnet development programme, presently ended due to the unfortunate termination of the project, has been during a decade the main stimulation of accelerator magnet progress and has led to many advancements in understanding, design, materials and fabrication techniques [5]. Most of the prototype dipoles were built at BNL and FNAL. Their quench performance at the operation temperature of 4.35 K was excellent with little training. Their field quality was generally within requirements, only the drift of the skew quadrupole component at injection needed to be better controlled. Full length prototype quadrupoles were built at LBL. Typically they exhibited training from 6.6÷7.2 kA to 8 kA and some retraining after thermal cycling. Their field quality was better than specified. Some 1 m long model quadrupoles were manufactured by a US/German consortium. They reached the conductor short sample limit, 8.4 kA, after a few quenches starting at about 7.5 kA.

The last important activity on the SSC magnets, after the decision to terminate the project, was the power test of a full cell of the machine, comprising ten dipoles, two quadrupoles and three spool pieces [6]. The very valuable experience gathered with this test will help any future accelerator project using superconducting magnets and in particular the LHC. Among the results of general interest the following should be mentioned:

- There was no evidence of quench propagation between adjacent quarter cells (the string was subdivided into quarter cells) by heat transported through helium. Propagation occurred instead because of a too fast down-ramp rate during the current decay through an external dump resistor, which caused quenching of dipole inner coils in other quarter cells.
- The finding of considerable over voltages to ground at quench in a string of magnets protected by the same by-pass diode. It has been shown that this is mainly caused by differences in the normal resistance at low temperature of the outer coils (those fired by the strip heaters). The cure is a better matching of magnets in this respect and in diminishing as much as possible the quench start time in the different magnets by using more efficient heaters. These observations have already had important consequences in the evolution of the LHC magnet quench protection system. The idea of protecting the half cell magnets by a set of diodes grouped in the short straight section has been abandoned in favour of the initial scheme with a set of two diodes placed in superfluid helium and connected across the magnet terminals.
- A catastrophic failure of the insulating vacuum in a half-cell was simulated by opening a valve to air. The system did not suffer from this type of event, dispelling the fears raised by some computer simulation models and confirming the results obtained at CERN with a similar test performed on the TAP magnet by breaking the insulation vacuum with helium, thus simulating a failure of the helium tank [7]. Also in this test (which is considered more severe, since helium cannot freeze as air does on the thermal screens) no damage was produced.

III. UNK SUPERCONDUCTING MAGNETS

A number of dipoles had been successfully tested in the past years. The results were satisfactory regarding quench performance, losses at ramp, field quality and reproducibility. Because of the known difficulties the series production of these magnets could not be launched. Last year a string of four dipole magnets has been successfully tested [8] and the work is continuing as we will hear in this conference.

IV. MAGNETS OF THE RELATIVISTIC HEAVY ION COLLIDER (RHIC)

Construction and testing of the RHIC magnets will be presented in a next talk by P. Wanderer [9] and more details will be given at this conference.

The cross-section of the main dipole is shown in Fig. 1. The design is very clever in its simplicity with coils wound in only one layer of a 30 strand cable and coil clamping provided by the steel laminations of the yoke assembled in "collars" style and encased by a stainless steel shrinking cylinder. The design of the quadrupoles follows the same principles. After intense R&D at BNL the series manufacturing of dipoles and quadrupoles was entrusted to a firm, to which the required technology was transferred. Complete dipoles in their cryostat are delivered to BNL by the industrial company. On the contrary, the quadrupole magnets (manufactured by the same firm), the sextupoles (manufactured by another company), the corrector coil assemblies (manufactured at BNL) and the beam position monitors are all combined into cold mass units and inserted into common cryostats at the Laboratory.

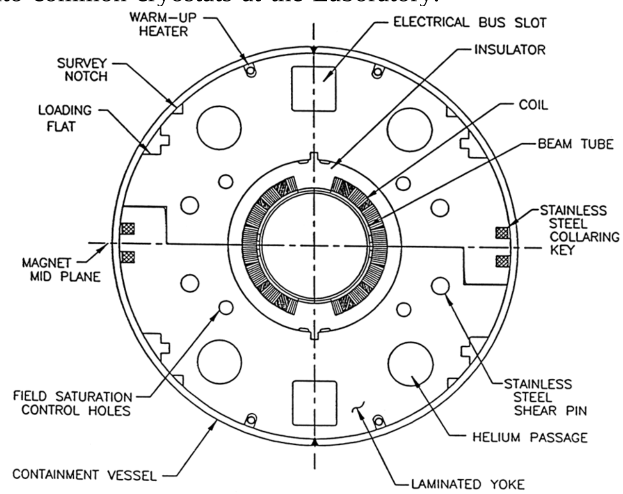

Figure 1: Cross-section of RHIC dipole cold mass.

The production of all these components is successfully proceeding according to schedule and the first important milestone of 30 produced dipoles was passed in September 1994. All these magnets and several others have been tested and measured and are now installed in the RHIC tunnel. The quench performance shows that these magnets have a good margin with respect to the specified operation field.

V. LARGE HADRON COLLIDER (LHC) MAGNETS

The up-to-date design of the Large Hadron Collider will be presented at this conference by L. Evans.

A re-optimization of the accelerator/collider with the aim of maximizing global dipole occupancy in the arcs led to a new lattice based on 23 cells per octant and three main dipole magnets per half-cell. The layout of the new standard half-cell is shown in Fig. 2. Considerations on beam stability, reliability and cost has led to some changes in the magnet characteristics. The coil aperture is increased from Ø 50 mm to Ø 56 mm and the magnetic length of the dipole units is extended to 14.2 m. The operational field of the dipoles is 8.4 T for a proton beam energy of 7.0 TeV [10, 11].

A. Dipoles

1. Main features

The main parameters of the dipole magnet are listed in Table II and the cross-section is shown in Fig. 3.

The basic design features of the first R&D dipoles which have been confirmed by the results of the R&D programme, i.e. cooling with superfluid helium at 1.9 K, two-in-one configuration, two-layer coils, aluminium alloy collars common to both apertures, vertically split yoke and stainless steel shrinking cylinder are maintained. With respect to the first generation R&D dipoles a number of changes have been introduced in the new design to match the larger aperture and the reduced field requirements and to make the construction simpler. The cable width is reduced from 17 mm to 15 mm.

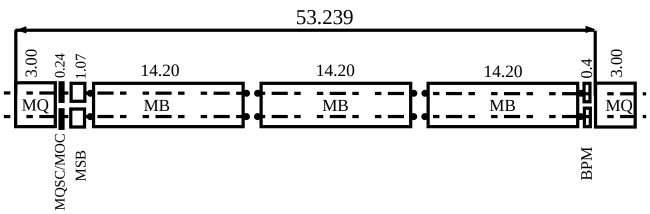

Figure 2: Schematic layout of the LHC half-cell.

MB:	Dipole magnets.	MQ:	Lattice quadrupoles.
MQSC:	Skew quadrupoles.	MQC:	Octupole
MSB:	Combined sextupole and dipole corrector.		
BPM:	Beam position monitor.		
- o -:	Local Sextupole or decapole corrector.		

Table II
Dipole Parameters

Operational field		8.4	T
Coil aperture		56	mm
Magnetic length		14.2	m
Operating current		11'500	A
Operating temperature		1.9	K
Coil turns per aperture	inner shell	30	
	outer shell	52	
Distance between aperture axes		180	mm
Outer diameter of cold mass		580	mm
Overall length of cold mass	~	15	m
Overall mass of cryomagnet		31	t
Stored energy for both channels		7.4	MJ
Self-inductance for both channels		119	mH
Resultant of e-magnetic forces in the			
first coil quadrant	$\sum$Fx (1.70 MN/m)	24.0	MN
inner layer	$\sum$Fy (- 0.14 MN/m)	- 2.0	MN
outer layer	$\sum$Fy (- 0.60 MN/m)	- 8.5	MN
Axial e-magnetic force on magnet ends		0.52	MN

The number of yoke parts is reduced from 4 to 2 making the structure less sensitive to dimensional tolerances on stacked laminated assemblies. The wanted field distribution at all field levels is maintained by the insertion of magnetic steel pieces in the collars. These steel inserts, punched out of the 6 mm thick steel sheet of the yoke laminations, are at the same time used to firmly lock pairs of collars together.

Strands (ø 1.065 mm for inner layer and ø 0.825 mm for outer layer) and cables of the new design have already been produced and delivered to CERN. One particular problem is that of current sharing among strands distorting the magnetic field during ramping. The effect at injection field would be acceptable with a contact resistance ranging between 6 and 10 $\mu\Omega$. An interstrand resistance of 10 $\mu\Omega$ has been set as the goal of a development programme. A number of coating materials for the cable strands, as well as resistive barriers are under investigation.

The expected field errors originated by the coil and yoke configuration are well within the requirements at all field levels. The computed persistent current sextupole and decapole components at injection field (~ 0.56 T) are

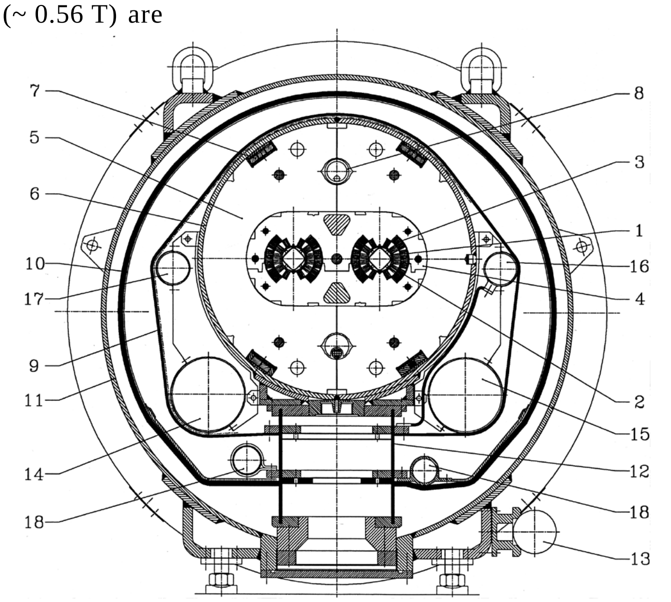

Figure 3: Cross-section of LHC dipole in its cryostat.
1. Beam screen, 2. Beam pipe, 3. Superconducting coils, 4. Non-magnetic collars, 5. Iron yoke, 6. Shrinking cylinder/HeII vessel, 7. Sc.. bus-bars, 8. Heat exchanger pipe, 9. Radiative insulation, 10. Thermal shield (55 to 75 K), 11. Vacuum vessel, 12. Support post, 13. Alignment target, 14. 1.8 K GHe pipe, 15. 20 K GHe pipe, 16. 4.5 K GHe pipe, 17. 2.2 K GHe pipe, 18. 50÷75 K GHe pipe.

- 3.58×10^{-4} and 0.18×10^{-4} respectively (in units of 10^{-4} of Bo at r = 1 cm). These systematic error components are, however, corrected by small sextupole and decapole magnets located at each dipole end. More studies are necessary on some effect of persistent and eddy currents at injection, in particular concerning the skew quadrupole component. Great care must be applied in the interpretation of the magnetic measurements at this low field: e.g. in the presence of the above mentioned persistent current sextupole, a 1 mm misalignment of the measuring coil with respect to the dipole axis (which is quite possible) produces an apparent skew or normal quadrupole of 0.7 units, having a sign which depends on the direction of the probe coil eccentricity.

The quench protection system is based on the so-called "cold diode" concept [12]. The diodes will be installed in the HeII cryostat of each dipole and quadrupole unit. In each twin dipole, a set of two series connected diodes is connected across the terminal. This solution provides safe blocking voltage at ramp and a welcome redundancy: in case of failure of one diode, the LHC can still run albeit at reduced ramp rate.

2. Status of R&D programme

a) Twelve 1.3 m long dipole models have been constructed and tested. Initially all models were built in industry, then a magnet building facility was set up at CERN about three years ago, because of the need for detailed investigations and rapid turnaround. One twin-aperture and two single-aperture models were built in Japan by KEK in collaboration with industrial companies [13]. Detailed results of several models have been reported elsewhere [14, 15]. No difference in quench performance was seen between single-aperture and twin-aperture models. All models have largely exceeded 9 T, with the best reaching 10.5 T. The last single aperture KEK magnet, tested in February 1995, attained the conductor short sample limit at 10.2 T at 1.95 K after twelve training quenches [16]. A twin-aperture model built at CERN with SSC cables presented a quench behaviour similar to that of the other models, reaching the conductor short sample limit at 9.65 T after training. In all these magnets as well as in the 10 m long prototypes the great majority of quenches started in the magnet ends or in the region of the splice between the coil inner and outer layer [17]. The short model programme at CERN is therefore now concentrated on improving these critical regions.

b) After the success of the first 10 m long magnet, named TAP, made with HERA-type coils mounted in a twin-aperture structure, seven 10 meter long prototypes have been ordered to industry and the first four have been delivered and tested at CERN. The first two, CERN-INFN1 (MTP1A1) and CERN-INFN2 (MTP1A2), were funded by the Italian "Istituto Nazionale di Fisica Nucleare" (INFN). The quench behaviour of the tested magnets is shown in Fig. 4. In the first three magnets all quenches occurred at "singular" places, the splice and the coil ends, as in short model magnets. The fourth one, MTP1N1, manufactured by a different company, had a different behaviour. Training was longer, and, contrary to the previous experience in short and long magnets, all quenches started in the regular straight part, almost all in the outer layer of the same pole of one aperture. As this indicates the existence of a weak point, it has been decided to disassemble this magnet and to reassemble it at CERN in order to find out the cause of the anomaly. On the other hand, this magnet had a different design of the splice region, probably a good one, since no quench occurred there. The field distribution and orientation were measured in the first three magnets in both apertures in 11 positions along the longitudinal axis, at three field levels, 0.58 T, 6 T and 8.65 T at 1.9 K and at room temperature. The multipole errors are close to the expected values in both apertures. The orientation and parallelism of the B vector was also measured: the first magnet exhibits some torsion (~ 10 mrad), the second and the third a negligible amount, further in all three the parallelism of the B vectors is better

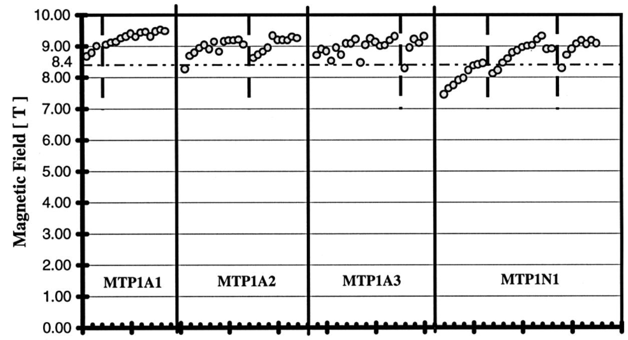

Figure 4: Quench history of the first four 10 m long prototype LHC dipoles.

than 0.2 mrad (Fig. 5). The correlation between measurements taken at room temperature and at 1.9 K was found to be very good, both concerning multipole errors and field orientation, in all three magnets. The quench protection system worked satisfactorily and the maximum temperatures and voltages were as expected.

The first two dipoles are now installed, together with a prototype short straight section, in a "string" test facility simulating the basic half-cell.

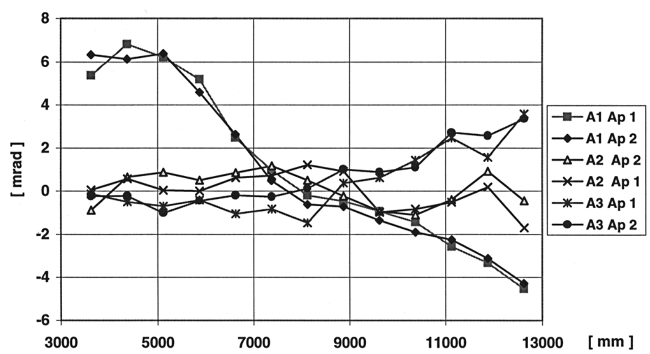

Figure 5: Field orientation in both apertures of MTP1A1, A2 and A3 prototypes.

B. Quadrupoles

The main parameters of the lattice quadrupoles are listed in Table III. Two full size quadrupoles of 56 mm aperture and 3 m length have been designed, constructed and tested at CEN, Saclay (F) in the frame of a CERN-CEA Collaboration [18]. The design gradient was reached for the two magnets after very few training quenches (Fig. 6).

In one of these quadrupoles an experience of field modulation has been successfully performed, as a preparation for the precise measurement of the LHC beam position with respect to the magnetic axis of the quadrupoles, the so-called k-modulation method [19]. This is particularly important for a superconducting machine, in which the quadrupole magnet axis is difficult to report to the external fiducials.

Table IV
Main Parameters of LHC lattice quadrupole magnets

Operational field gradient	220	T/m
Coil aperture	56	mm
Magnetic length	3.00	m
Operating temperature	1.9	K
Distance between aperture axes	180	mm
Yoke outer diameter	~ 450	mm

C. Continuation of the R&D programme

The other three 10 m long magnets will be delivered to CERN in the coming months. Short models of the new design are being manufactured at CERN. Ten metre long collared coils and other components have been ordered to industry. Manufacturing of a final length (Lm = 14.2 m) prototype has started in the frame of a new collaboration agreement between INFN and CERN.

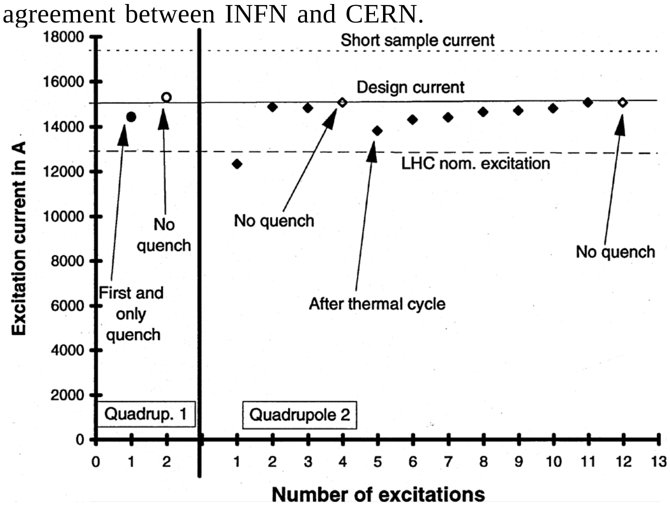

Figure 6: Quench history of the two prototype quadrupoles.

VI PERSPECTIVES FOR HIGHER FIELDS

The quest for higher fields continues to be motivated by economy in space, capital investment and operation cost, but the way is a very difficult uphill one [20].

A 11.5 T twin-aperture model using Nb_3Sn superconductor has been designed by a FOM-UT-NIKHEF-CERN collaboration [21]. A single-aperture version of this magnet is at the final assembly stage and results should come very soon. At LBL an experimental dipole, called D20, designed for a central field of 13 T and featuring a 4 layer coil wound with Nb_3Sn conductor is in an advanced assembly phase [22]. A dipole for the same design field had been studied at DESY. Thirteen tesla is probably the highest field which could be achieved in the classical cos φ coil configuration using Nb_3Sn superconductor. "Block-coil Dual Dipoles" or the so-called "Pipe Dipole", as proposed by LBL and TAC [23], may be the way in the future to reach higher fields, perhaps using new HTS superconductors when they become available in technically usable form. If working models based on these concepts would be built, a lot of interesting ideas could be tested, e.g. the proposed porous inorganic insulation. In the author's opinion, such high field magnets may find applications for special use where a few units of exceptional characteristics are indispensable or produce large benefits. The first practical application could be in second generation low-beta quadrupoles for the LHC.

Large scale applications of the size of the LHC do not appear feasible in a near future. The use of NbTi superconductors has permitted a factor 5 gain in beam energy for the same accelerator size. To gain another factor five is impossible; a factor two, requiring about 17 T central field, may be thought of, but will require a tremendous R&D effort.

VII. REFERENCES

[1] *M.N. Wilson et al., "The Compact Superconducting Storage Ring X-ray Source Helios 1", IBM Journal of Research and Development, Vol. 37 No. 3 pp. 351-371, May 1993.*
[2] *J. Gordon, M. Kruip, A. Reed, "Atom Smashers for Profit and Pleasure", Physics World, June 1994.*
[3] *A. Green, "Recent Status of Superconductors for Accelerator Magnets", ICFA Workshop on AC Superconductivity, KEK Proc. 92-14, pp. 100-108, 1992.*
[4] *D.C. Larbalestier, "New Developments in Superconductors for Accelerators", presented at this conference.*
[5] *R.I. Schermer, "Status of Superconducting Magnets for the Superconducting Super Collider", IEEE Trans. on Magn., Vol. 30, No. 4, pp. 1587-1594, 1994..*
[6] *P. Kraushaar et al., "The SSC Full Cell Prototype String Test", Proc. ASC, Boston, October 1994.*
[7] *B. Szeless, L. Williams, Private Communication, 1994.*
[8] *A. Alexandrov et al., "Investigation of the String of Four UNK Superconducting Magnets", Proc. IV EPAC Conference, EPAC-94, Vol. 3, p. 2313, 1994.*
[9] *P.J. Wanderer "Superconducting Magnet Construction and Testing for the Relativistic Heavy Ion Collider (RHIC) at BNL", paper presented at this conference.*
[10] *L.R. Evans, "Advanced Technology Issues in the LHC Project", presented at 1994 EPAC Conference, London, June 1994.*
[11] *R. Perin for the LHC Magnet Team, "Status of LHC Programme and Magnet Development", Proc. ASC-94, Boston, Oct. 1994.*
[12] *L. Coull, D. Hagedorn, V. Remondino, F. Rodriguez-Mateos, "LHC Magnet Quench Protection System", IEEE Trans. on Magn., Vol. 30, pp. 1742-1745, July 1994.*
[13] *A. Yamamoto et al., "Development of Twin-aperture Dipole Magnets for the Large Hadron Collider", Proc. ASC-94, Boston, October 1994.*
[14] *M. Bona, D. Leroy, R. Perin, P. Rohmig, B. Szeless, W. Thomi, "Design, Fabrication Variants and Results of LHC Twin-aperture Models", Proc. of MT12, Leningrad, 1991.*
[15] *The LHC Magnet Team, reported by R. Perin, "Status of the Large Hadron Collider Magnet Development", IEEE Trans. on Magn., Vol. 30, pp. 1579-1586, July 1994.*
[16] *A. Yamamoto, Private Communication, March 1995.*
[17] *J. Billan, A. Siemko, L. Walckiers, R. Wolf, "Quench Localization in the Superconducting Model Magnets of the*

LHC by Means of Pick-up Coils", Proc. ASC-94, Boston, October 1994.

[18] *P. Genevey et al., "Cryogenic Test of the First Two LHC Quadrupole Prototypes", Proc. ASC-94, Boston, Oct. 1994*

[19] *K.N. Henrichsen, Private Communication, April 1995.*

[20] *R. Perin, "State of the Art in High-field Superconducting Magnets for Particle Accelerators", Proc. 14th Int. Conf. on Part. Accel., Tsukuba, Aug. 1989, Vol. III, pp. 625-638.*

[21] *A. den Ouden et al., "First Test Results of the 11.5 T Nb_3Sn Single Aperture Dipole Magnet", Proc. ASC-94, Boston, Oct. 1994.*

[22] *R.M. Scanlan et al., "Fabrication and Preliminary Test Results for a Nb_3Sn Dipole Magnet", Proc. ASC-94, Boston, Oct. 1994.*

[23] *P.M. McIntyre, R.M. Scanlan, W. Shen, "Ultra-High-Field Magnets for Future Hadron Colliders", Proc. ASC-94, Boston, Oct. 1994.*