SUMMARY OF INTERNATIONAL PROGRESS ON SUPERCONDUCTING MAGNETS*

William S. Gilbert

Lawrence Berkeley Laboratory
University of California
Berkeley, California

February 28, 1973

Summary

Superconducting pulsed magnets for use in high field synchrotrons and storage rings and dc dipoles and quadrupoles for use in beam transport lines are reviewed. Operating and construction plans for the immediate future are presented.

Introduction

The largest scale use of superconducting magnets to date has been in the field of high energy physics. Ever since superconductivity was discovered by Kamerlingh Onnes in 1911, the concept of lossless electromagnets has attracted the attentions of a number of prominent physicists, metallurgists, and other specialists. The continuing advances in solid state and metal physics resulted in the discovery and development of hard, type II, high field superconductors in the 1950's. Several high field alloys and compounds were fabricated and in 1961, Kunzler at Bell Labs produced a 7.0 Tesla field in a solenoid wound with Nb_3Sn wire. Within two years a 10 Tesla field was produced with Nb_3Sn wire in a small bore solenoid.

Vigorous efforts were launched to build a variety of superconducting magnets since the benefits were obvious but the full extent of the difficulties were not. The first major difficulty was the brittle nature of the high critical field, high critical temperature superconductor Nb_3Sn, which made magnet fabrication difficult for small simple solenoids and not feasible for those magnets in which the fragile wires would be subjected to large forces. Flexible Nb_3Sn ribbon conductor was developed and the mechanical problem was thereby partially solved but at the cost of creating a conductor unstable against flux movement. Solenoids have been developed with fields as high as 150 kG using the ribbon conductors but larger magnets and saddle shaped windings have suffered badly degraded performance due to this flux jump instability. Diamagnetic currents in the relatively wide ribbon also make it difficult to construct high precision magnet fields -- magnetic field errors of less than one part in 10^3.

The ductile alloy NbTi is strong and easy to fabricate but has a lower critical field and temperature than Nb_3Sn. Early NbTi conductor showed degraded performance due to flux jump instability. The development of stable twisted multifilament NbTi - copper composite in 1968-1969 marks the beginning of the growing successful programs in accelerator and transport type magnet development. The relatively small apertures required in accelerators and beam transport lines result in the need for the highest possible current densities in order for the superconducting magnets to compete most favorable with the conventional room temperature alternatives. Extremely large volume magnets as are found in bubble chamber magnets are attractive on a simple electrical power saving basis. This power saving is not as dramatic with the smaller aperture accelerator magnets.

Superconducting magnets are only lossless at a constant magnetic field. A hysteresis loss occurs upon every field change so a pulsing field, as is intrinsic to a synchrotron, results in a cyclical or ac loss. For this reason pulsed magnets require more development effort than do dc magnets and so we consider them separately. Recently, storage rings have become of increasing physics interest so hybrid magnets of very slow pulsing rate have been studied.

Why Develop Superconducting Magnets?

As will be developed later in this paper, an impressive number (>10) of NbTi conductor magnets have operated at or above 40 kG peak field, both for pulsed and non-pulsed operation. Reliable operation of similar systems in the 40 - 60 kG field range can be confidently projected in the next few years. It seems appropriate to ask, at this time, what advantages are in prospect for the users of superconducting magnets to compensate for the trouble and expense of supporting this new technology. Table I lists some of the Pros and Cons of superconducting magnet systems vis a vis conventional magnets.

TABLE I - S.C. Magnets' Virtues

PROS	CONS
Zero power dissipation - dc Low power dissipation - ac	Requires liquid helium cryogenic system Losses are at 4.2°K (500 watts/watt)
High current density	- - - - - -
High field (20 - 100 KG) capability	- - - - - -
Compact magnets - less shielding	- - - - - -
Field stability - persistent mode	Field instability - flux jumps. Poor field quality-diamagnetic effects.
Economy - will cost less	But now costs more.
10^{-9}- 10^{-10} Torr vacuum-Cryopumping.	Requires extra vacuum system for thermal insulation.
New field - Improvements are likely.	Present magnets are well developed. We have enough troubles as it is.
Reduced scale of accelerators and beam-lines.	

With the exception of special advantages associated with high current density (25 kA/cm^2 at 5T) the chief potential advantages of superconducting magnet systems are reduced capital and operating costs and more compact accelerators and beam lines based on the higher available magnetic field. Beam lines have been studied by Meuser[1] and Smith and Haskell[2]. Meuser compared a complete experimental area for the 200 GeV accelerator and

* This work performed under the auspices of the Atomic Energy Commission.

replaced the 164 conventional magnets with equivalent superconducting magnets with peak fields of 40 kG. The capital plus the 10 year operating costs of both systems were the same within estimating error. Smith and Haskell compared only the capital costs of focusing elements for beams of 1-1000 GeV energy with the superconducting elements operating up to peak fields of 100 kG. They found that at the higher energies and the higher fields the superconducting costs were as much as an order of magnitude lower than the conventional. But at lower energies and fields of about 40 kG the costs were comparable.

Synchrotron and storage ring peak energies scale with peak magnetic field so the examples of higher energy accelerators at present sites through the use of superconducting accelerator magnets are numerous. Many feel that the present sites are as large as may be provided for the forseeable future so the only way to achieve still higher energy is through increased guide field. It also appears that the cost per GeV should be lower with superconducting magnets.

Nb_3Sn Ribbon Transport Magnets

Nb_3Sn in the form of a thin relatively wide ribbon has been produced by RCA (now CSCC), GE (now Intermagnetic General), CSF, and a few other companies on a smaller scale. A number of high field solenoids and Helmholtz coils have been built. A few special shape magnets for fusion research have been built as has a beam septum magnet at BNL. Our interest here is with dipoles and quadrupoles that have been built for beam transport. Table II lists this data.

All these magnets were badly degraded (50-75% short sample) due to flux jumping in the ribbon conductor and the peak fields were less than 50 kG which can be more reliably and cheaply achieved with NbTi conductor magnets. No laboratory reported plans to built transport magnets using the ribbon Nb3Sn conductor.

One program to use an improved ribbon tape in fusion research is planned at Lawrence Livermore Laboratory[3]. This improved ribbon would incorporate a nickel instead of a stainless steel structural substrate to improve thermal conductivity and flux jump stability. Pure aluminum might also be used for improved dynamic stability. If these improvements succeed, a complex magnet winding with fields of 100 kG and current density of 7000 A/cm^2 is planned.

Figures 1 - 3 show some of the Nb3Sn magnets listed in Table II. It should be pointed out that many

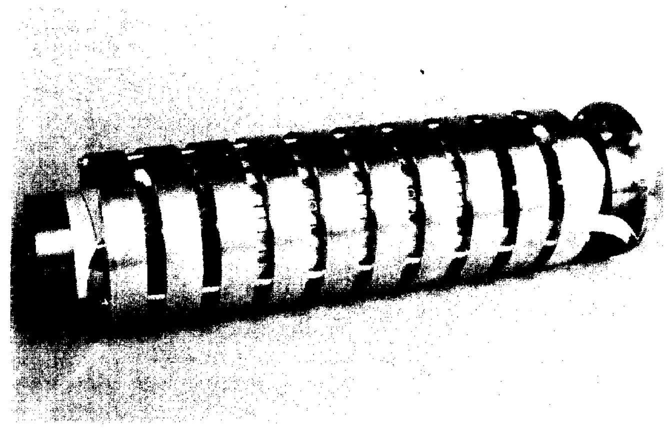

Figure 1 - IGC Dipole (Nb_3Sn)

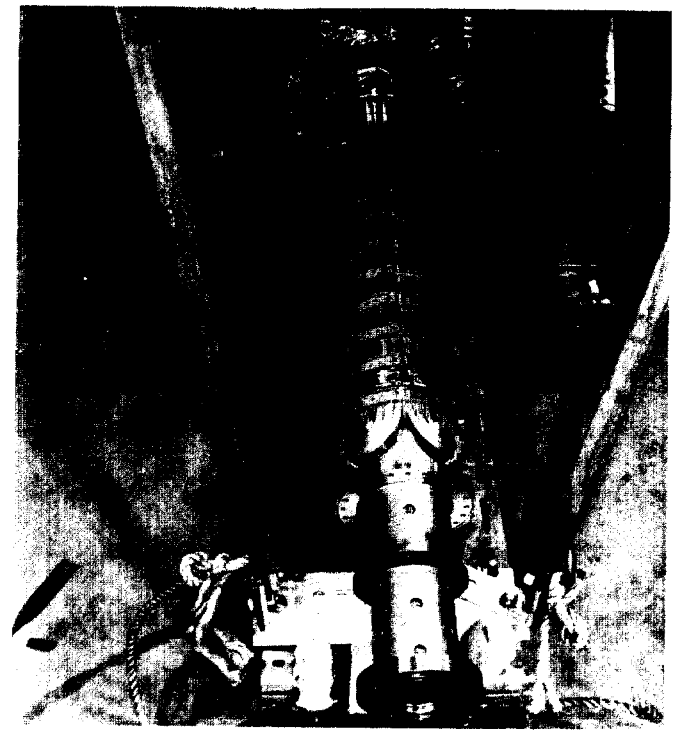

Figure 2 - BNL Quad (Nb_3Sn)

TABLE II - Ribbon Nb_3Sn Transport Magnets

Organization	Type	Bore Diam. cm	Length cm	Peak Field kG (Gradient kG/cm)	Stored Energy kJ	Date Tested	Warm Bore Cryostat	Comments
General Electric	Quad	7.2	20	26 (7.2)	3	1969	No	General Electric superconducting business is now conducted by Intermagnetics General Corp.(IGC)
	Dipole	7.2	20	21	4	1970	No	
BNL	Quad	10	60	32 (5.5)	19	1968-69	No	2 built.
	Dipole	9.5	100	43	60	1971	Yes?	Close fitting iron core in helium
Siemens for IEKP Karlsruhe	Quad	15.5	100	29 (3.5)	76	1970	Yes	Warm bore aperture = 12 cm.
Hitachi	Quad	6 ?	--	30 (10)	--	--	--	IGC Nb3Sn tape.

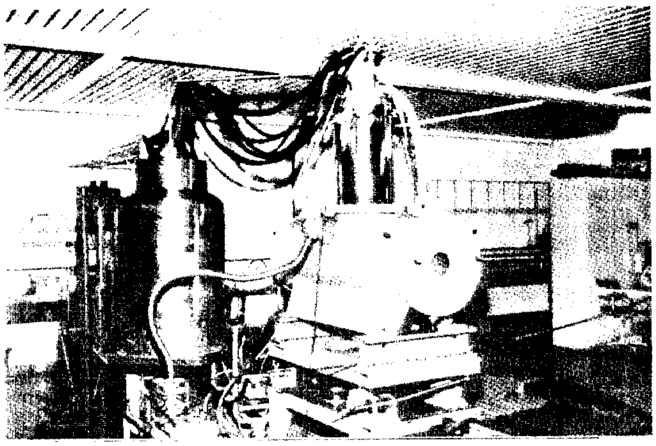

Figure 3 - Siemens (IEKP) Quad in Cryostat

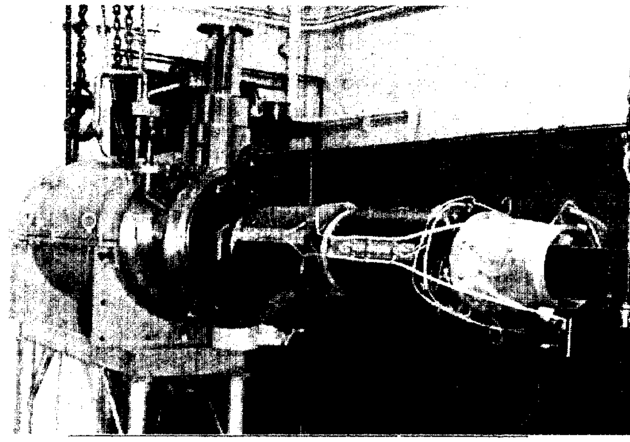

Figure 4 - LASL Quads - Cryostat

smaller, developmental, or unsuccessful magnets have not been listed in the Nb_3Sn table above nor in the NbTi tables to follow.

NbTi-Composite Transport Magnets - Quadrupoles

The early single core NbTi-copper conductor was flux jump unstable unless overly thick copper was used. Therefore, except in the case of solenoids, magnet performance was excessively degraded and average current densities were low. Transport magnets were successfully built soon after multifilament conductor was developed, and even more so after the roles of twisting and intrinsic stability were understood. In Table III we list a number of successful quadrupole transport magnets. Figures 4 - 6 illustrate some of the magnet systems appearing in Table III.

TABLE III - Composite NbTi - Quadrupole Transport Magnets

Organization Group	Winding Bore Dia cm	Length cm	Peak Field kG	G kG/cm	Stored Energy kJ	Date Tested	Warm Bore Cryostat	Comments
Oxford Inst. Co. - CERN	13	75	45	5.7	200	1970	No	Untwisted multifilament conductor.
Los Alamos Scientific Laboratory	20 (15 warm)	~40 (each)	40	3	40 (each)	1970	Yes	Doublet in 1 Cryostat. Persistent mode operation. Magnetic fields mapped. Possible beam line use 1973 (2 quadrupoles)
CERN Morpurgo	3	30	25	14.2	small	1970	Yes	In use for hyperon physics experiment for about 2 years. (2 quadrupoles)
	3	60	25	14.2	1 - 2	1970	Yes	
Asner-Leroy	13 (9 warm)	90	~40	5	25	1972	Yes	Close fitting, liquid helium temp. iron.
SACLAY	26 (20 warm)	68	45	3.5	670	1971?	Yes	Doublets used in Saturne physics experiment in 1972. Pion fluxes increased by factor of 2.6. (2 quadrupoles, O.G.A.I and O.G.A.II).
	36 (30 warm)	67	40	2.3	770	1972	Yes	
LBL	25 (20 warm)	63 (each)	45	2.8	190 (each)	1971 1972 (in cryo)	Yes	Doublet in single cryostat Bevatron beam line 1973. (2 quadrupoles)
NAL R. Fast	10	300	~22 (12 at pole)	2.5	45	1972	Yes	Iron dominated magnetic circuit.
Energy Doubler Group	10	300	[15-30]	[2-4]	--	[1973]	Yes (Cold)	High current density-- conductor dominated magnetic circuit.
Siemens for IEKP, Karlsruhe	6	30 for doublet	~20	3	small	1972	No	In helium-cold bore of proton linear accelerator. Iron core. Seven more doublets to follow.

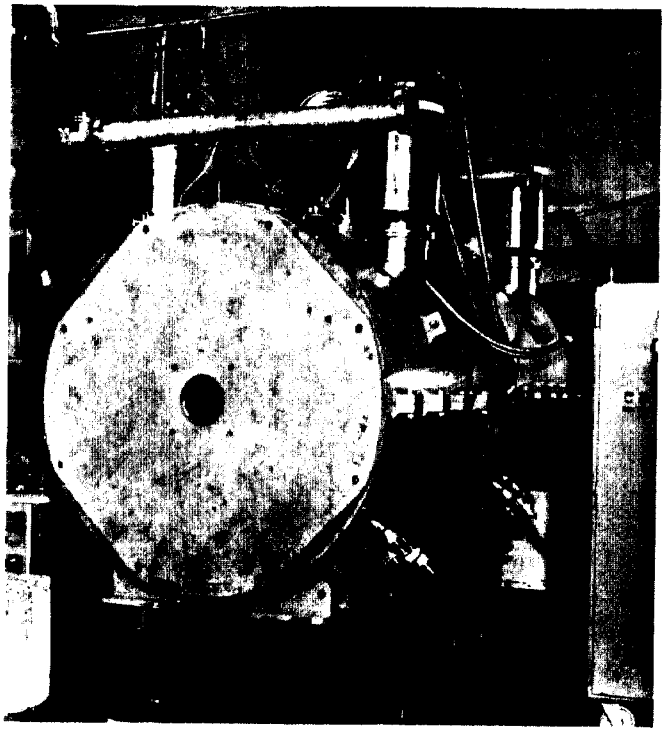

Figure 5 - Saclay Quads in Cryostats

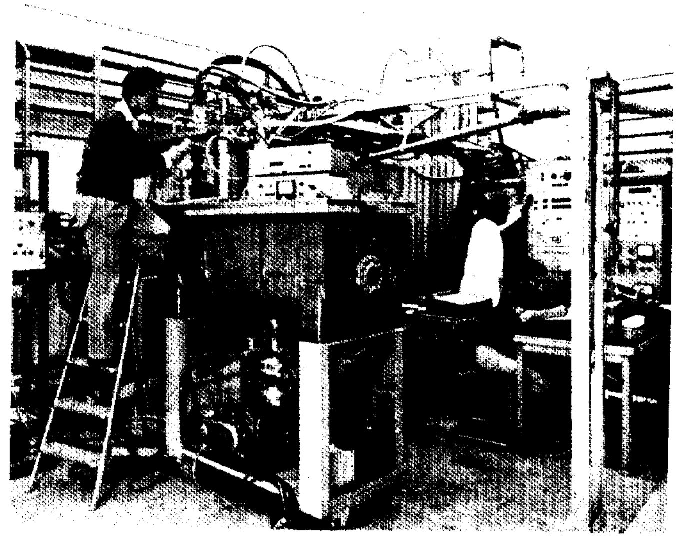

Figure 6. CERN Quad

NbTi Transport Magnets - Dipoles

Dipoles tend to be more difficult to build than quadrupoles since for equivalent sizes and peak magnetic fields, the forces and stored energy are greater in the dipole. Several successful dc dipoles have been built and more are planned in the immediate future. These are listed in Table IV. Figures 7 - 10 refer to some of these listed dipoles.

TABLE IV - Composite NbTi - Dipole Transport Magnets

Organization	Winding Bore Diam. cm	Length cm	Dipole Field kG	Stored Energy kJ	Date Tested	Warm Bore Cryostat	Comments
ANL	10	90	27	~50	1972	No	
	10	90	[35]	[~80]	[1973]	No	Design field. Magnet finished--testing to begin Feb. 1973
BNL Danby	8.5 (Cold bore)	50	46	64	1972	No	Two 183 cm long dipoles are to be in service at the BNL 30 GeV beam line to produce an 8° bend about July 1973. Cold iron -- window frame type construction.
"	8.5 (Cold bore)	183	[40]	[175]	[1973]	Yes (cold bore)	
CERN Kesseler	13.2 (warm)	195	34	370	1972	Yes	Beam operation at CERN-PS in summer 1973
LBL	10	~35	35	25	1969	No	Cold iron flux return.
	29 (20 warm)	83	40	655	1971 1972	No Yes	Installed -- Bevatron Beam Line -- 1973 warm iron flux return.
NAL R. Fast	5 x 13 (warm)	300	25	112	1972	Yes	76 cm long model tested in 1970.
"	20 x 60 (warm)	180	18	600	1972	Yes	Analysis magnet -- to be operated 1973. 2 large gap magnets to be built in 1973.
"	10 (warm)	300	~23	~120	1971	Yes	35 kG design. Fabrication by Airco - Temescal. Warm iron flux return.
Energy Doubler Group	7.6 x 12.7 (Cold bore)	300	[30]	--	[1973]	Yes (Cold bore)	High current density coils planned. Warm iron flux return
	7.6 x 12.7 (Cold bore)	300	[45]	--	[1973]	Yes (Cold bore)	High current density coils planned. Warm iron flux return

Figure 7 - CERN Dipole

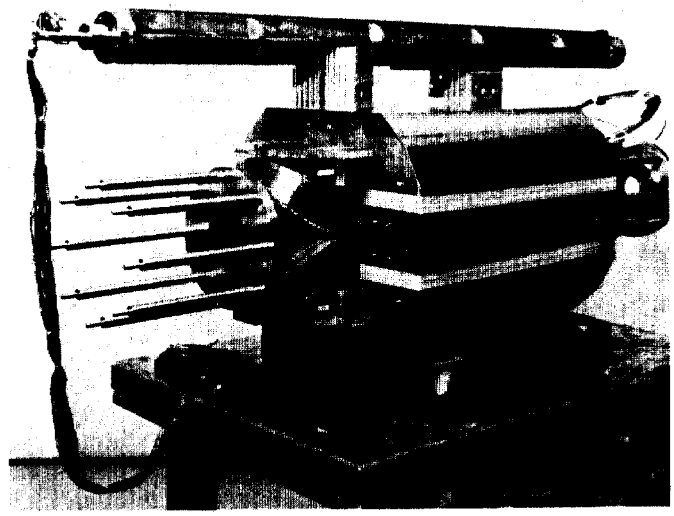

Figure 9 - BNL Dipole

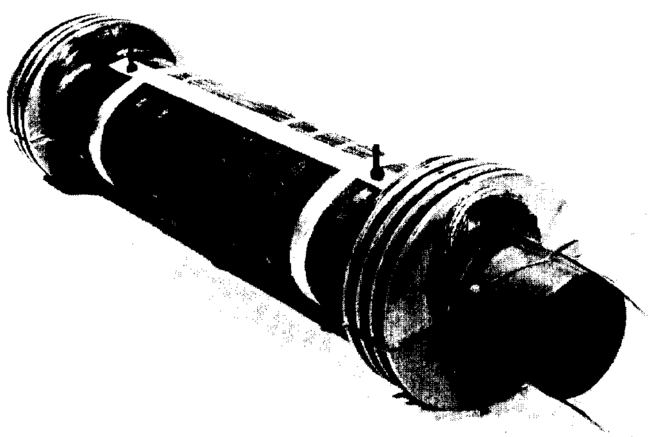

Figure 8 - ANL Dipole

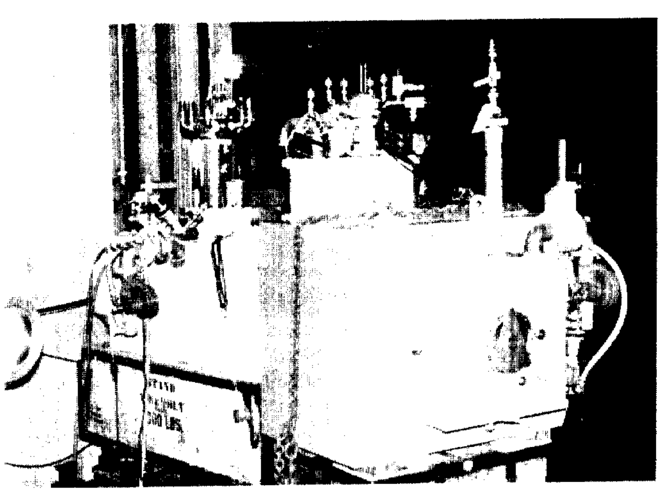

Figure 10 - LBL Dipole and Quad Doublet

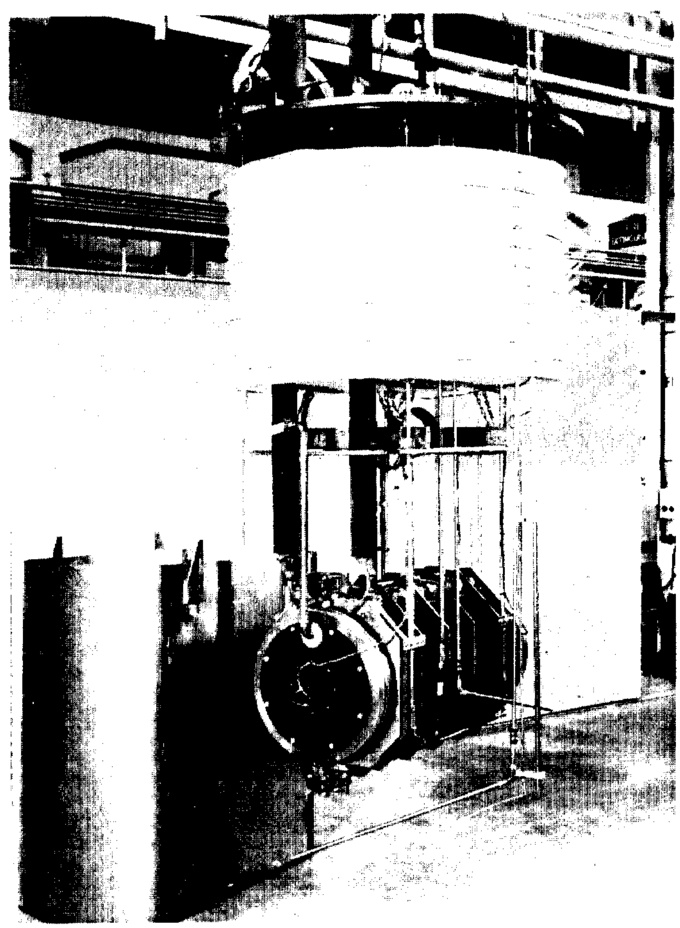

Figure 11 - RHEL AC4

Pulsed Accelerator Magnets

NbTi filaments of the smallest possible dimension (test magnets have been made containing 4-5μ diameter filaments) have been developed in order to reduce the hysteresis loss associated with pulsed magnets. Although the technical problems associated with the building of low loss, high field, pulsed dipoles are severe, impressive progress has been made -- in large part due to considerable efforts by a number of major accelerator laboratories, both in this country and in Europe. In fact, higher dipole fields have been achieved in pulse magnets than in dc transport dipoles.

Special attention is called to recent results on Rutherford's AC4 pulse dipole which reaches 50.1 kG and pulses to 49 kG with a 2-second rise time or 4-second cycle[4]. Throughout the entire excitation range the sextapole component of magnetic field is less than $5x10^{-3}$ times that of the dipole. A number of other successful pulsed magnets are listed in Table V[5]. Figures 11 - 14 illustrate some of these magnets.

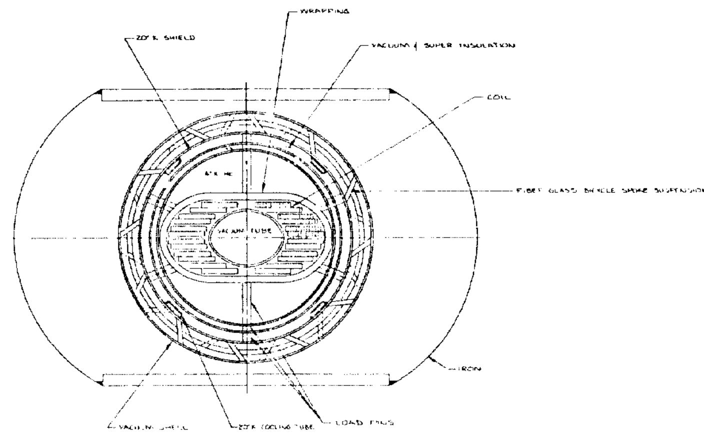

Figure 12 - NAL Doubler Magnet

TABLE V - NbTi Pulsed Dipoles - Accelerator Oriented

Organization	Winding Bore Dia. cm	Length cm	Dipole Field kG	Stored Energy kJ	Iron Flux Return	Minimum Rise Time	Date Tested	Warm Bore Cryostat	Comments
BNL	5	35	41	6	Yes	Very slow 50-100s	1972	No	10 dipoles tested - various conductors.
	8	90	[40]	[38]	Yes	" "	1973	No	2 identical magnets Isabelle Program
	8	290	[40]	[~120]	Yes	" "	[~1974]	Yes	Isabelle Prototypes. Metal impregnated cable
Karlsruhe IEKP	4 x 8	40	40	- -	Yes	Slow 10-20s	1973	No	DT - Race track coils. Upturned ends. InSn soldered cable
	8	140	[45]	[128]	Yes	" "	April 1973	?	D2a - Cos θ coils. InSn soldered cable
	8	[140-280]	[45]	[150-300]	Yes	Medium 5-10s	[1974]	Yes	D2b-D3 magnets in design stage
LBL	7.5	40	39	22	Yes	Very fast 0.5s	1972	No	8 dipoles tested in series.
	7.5	40	[45]	[29]	Yes	" "	April 1973	No	2 "identical" dipoles uniformity test.
	[10-14]	[100-200]	[45]	[>100]	Yes- cold or warm	" "	[1973 - 1974]	Yes	In design stage.
NAL	5	90	27	20	No	Very slow >30s	1972 - 1973	No	Energy Doubler program.
	3.8	30	30	6	No	Very slow >30s	1972 - 1973	No	
	5.5	90	[40-45]	[20-40]	Yes	Slow ~30s	[Mid-1973]	Yes (Cold)	4 magnets in this group
	5.5	600	[45]	[180]	Yes	Slow ~30s	[Late 1973]	Yes (Cold)	1 magnet in this group.
	5.5	600 each	[45]	[180]	Yes	Slow ~30s	[1974]	Yes (Cold)	10 magnets in this group.
RHEL	10 8	40	39 45	58 --	No	Very fast 1s	1971 1972	No	AC 3.
	9	50	50	82	Yes	" "	1972	No	AC 4.
	[9 - 10]	[100-200]	[45]	>150	Yes	" "	[1973 - 1974]	Yes	AC 5.
SACLAY	10	50	[60]	[280]	Yes	Med. 5-20s	Early 1973	Yes	MOBY
	11	150	[50]	[~700]	Yes	" "	[1973 - 1974]	Yes	ALEC

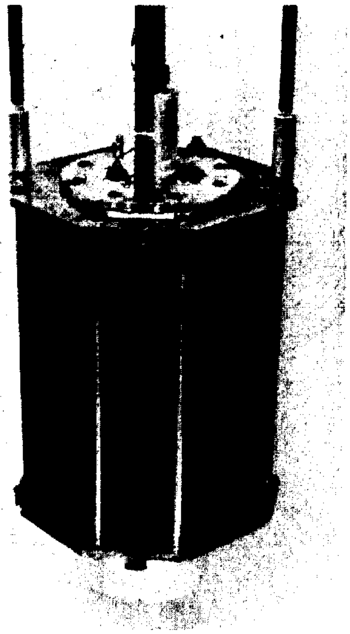

Figure 13 - LBL Pulse Dipole #8

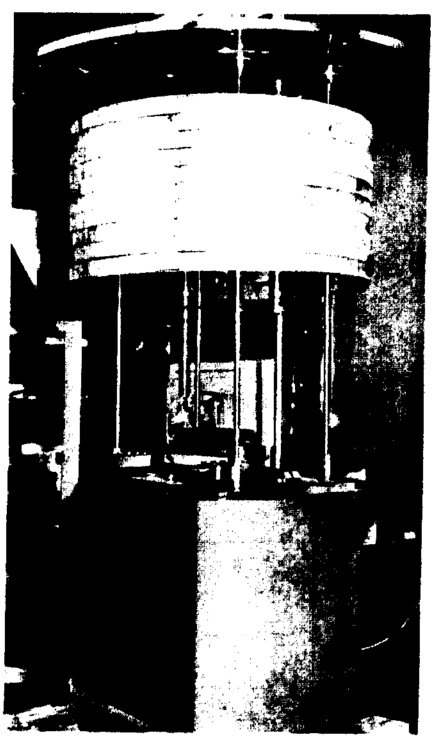

Figure 14 - IEKP DT Dipole

Evolutionary Development of Superconducting Magnet Systems

Although long range predictions are risky, superconducting projects one to two years in the future are already in the design or authorization stage due to the usual lead times. Tables III, IV, V contain the details of several ambitious transport and accelerator magnet programs. There is relatively little overlap in the detailed specifications since each laboratory's goals are different. The following similarities exist:

1. No laboratory is using ribbon Nb_3Sn -- All are using twisted mulifilament NbTi.
2. Magnet construction and testing is continuing. Degradation in performance still occurs. Field quality is being measured and improved.
3. Cryostat and cryogenic engineering development is being emphasized since these aspects generally lag the magnet development.
4. Long time and large scale operations of superconducting magnet systems are planned in order to move this technology from the magnet laboratory to the accelerator experimental beam area and to the accelerator itself.
5. Peak usable fields in the NbTi magnets will gradually rise from the present 40 kG to 60 kG in a few years.
6. Multifilament high field superconductors, such as Nb_3Sn and V_3Ga, might allow accelerator and transport magnets to operate at fields of 60 - 100 kG in 5-10 years.

Acknowledgements

I wish to extend my thanks to the superconducting magnet fraternity around the world who supplied me with their most recent results, plans, drawings and photographs. In order to make the comparisons that appear in the various tables, it was necessary to calculate some quantities that were not supplied -- any errors so generated are mine. All of the photographs in this paper were supplied by the laboratory that built the particular magnet. Many excellent photographs could not be used due to space limitations.

References

1. R. B. Meuser -"Secondary Beam Magnets for the 200 GeV Accelerator -- Conventional or Superconducting", Proc. 1967 Part. Accel. Conf. IEEE NS-14 No. 3.
2. P. F. Smith and G. P. Haskell, "Superconducting Focusing Systems in High Energy Physics", Nuc. Inst. and Methods 43(1966).
3. C. Taylor, LLL, Private communication, Feb. 1973.
4. J. H. Coupland, RHEL, Private communication, Jan. 1973.
5. A most comprehensive survey was prepared for the IVth International Conf. on Magnet Technology, Brookhaven, Sept. 19-22, 1972, by G. Bronca, P. Kircher, J. Perot, J. P. Pouillange, G. Prost, "Pulsed Superconducting Magnets".

Private communications from the various laboratories were received, Jan.-Feb., 1973.
ANL- J. R. Purcell; BNL - W. B. Sampson, G. Danby; CERN - G. Kesseler, M. Morpurgo, D. Leroy, A. Asner, P. E. Hanley (Oxford Inst.); IGC - C. H. Rosner; Karlsruhe (IEKP) - W. Schauer, M. A. Green; LASL - W. V. Hassenzahl; NAL - P. W. Fast, P. J. Reardon, B. P. Strauss; RHEL - J. H. Coupland; SACLAY - J. Perot.